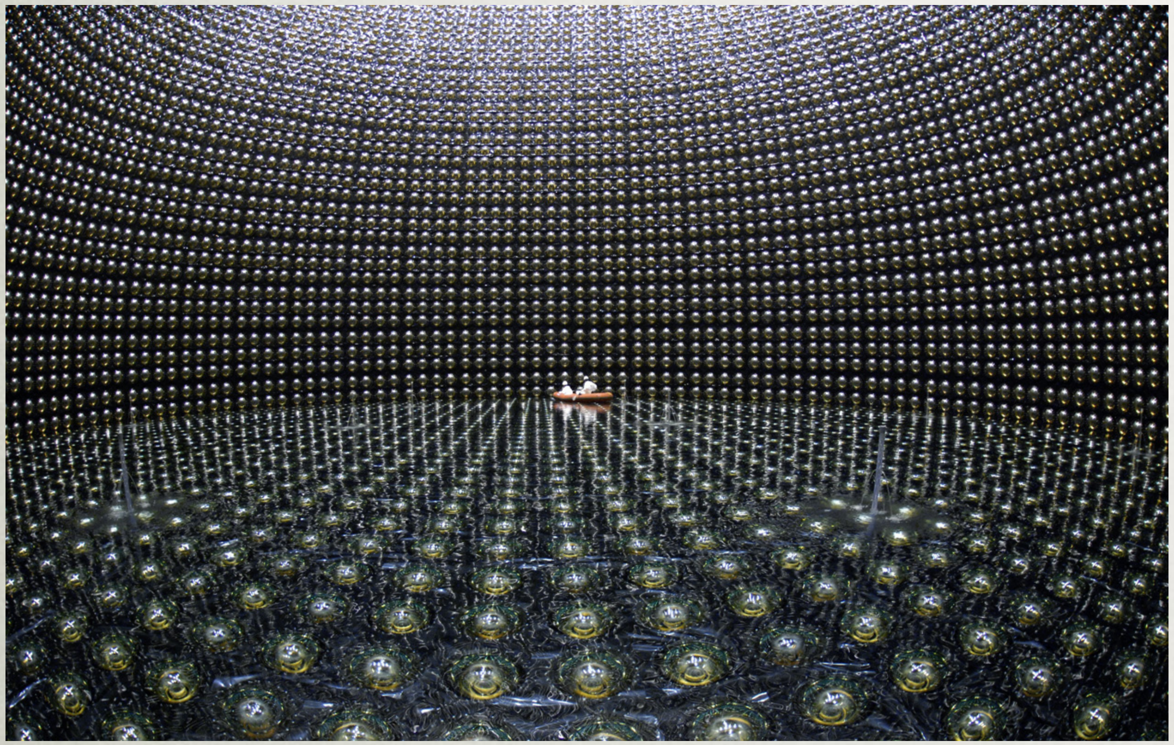
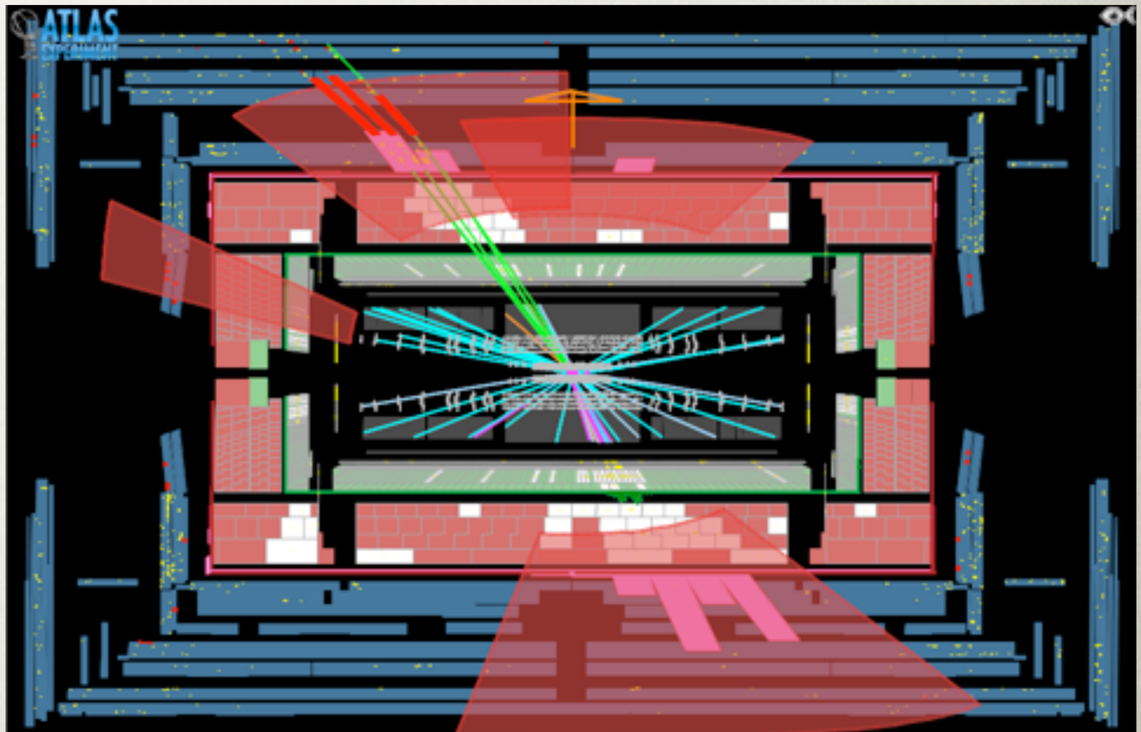
STERILE NEUTRINOS

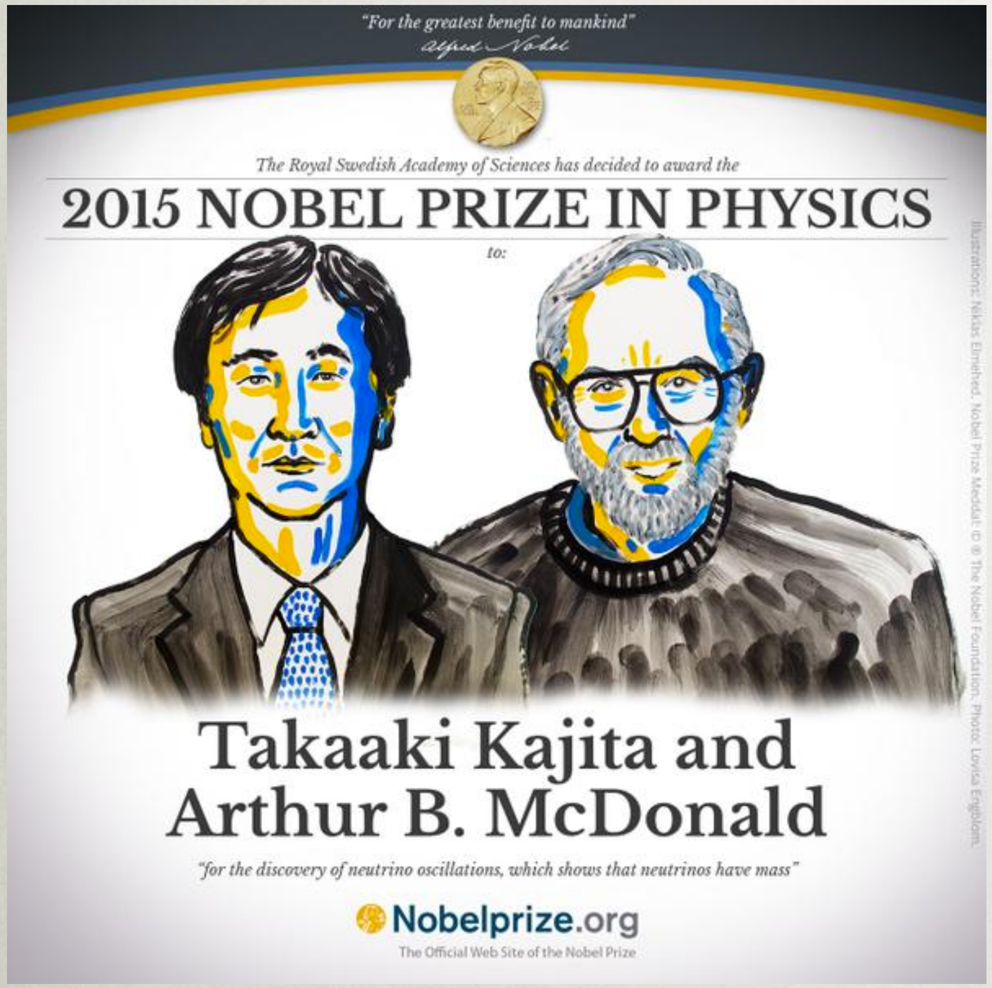


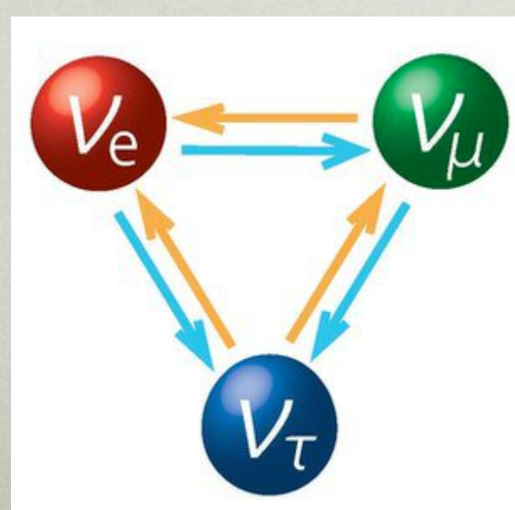


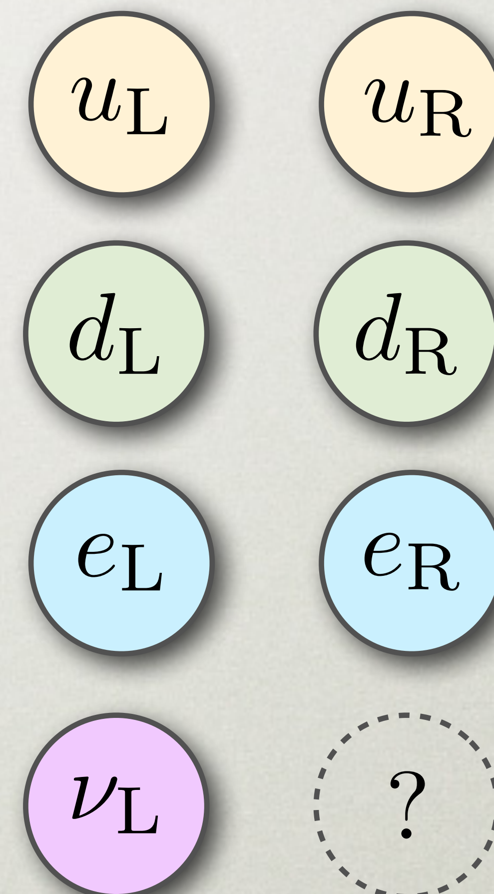
Brian Shuve — SLAC

Digging Deeper @ LHC Run2 — 02/25/2017

Neutrinos Need BSM Physics!

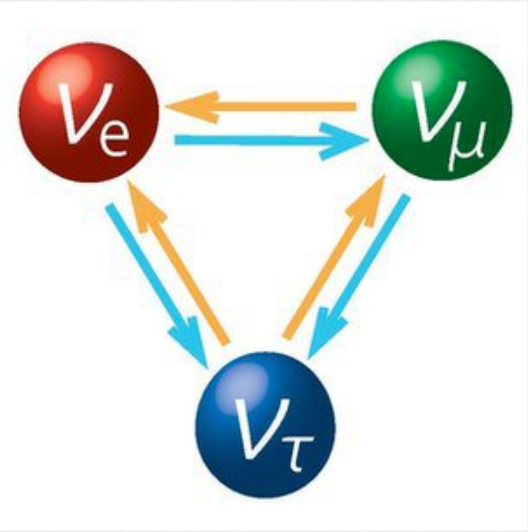






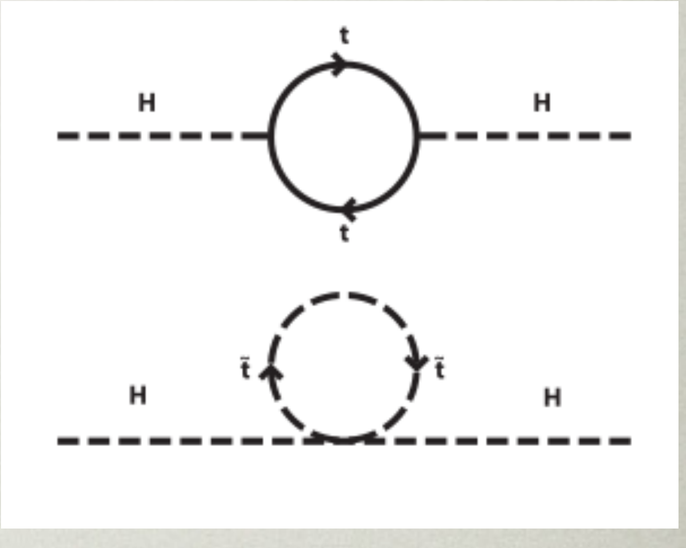
Neutrino Connections

sterile neutrino DM?



R-parity violation?

leptogenesis?



baryons	antibaryons

The See-Saw Mechanism

- SM neutrino masses can come from RH neutrinos, *N*

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

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

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

- For fixed $\langle H\rangle$ and m_ν ~ 0.1 eV, we have $M_N \sim \mathrm{GeV}\left(\frac{y^2}{10^{-14}}\right)$
  - *N* can be light, but we expect it to be (very) weakly coupled!
  - With additional symmetries, coupling can be **much** larger

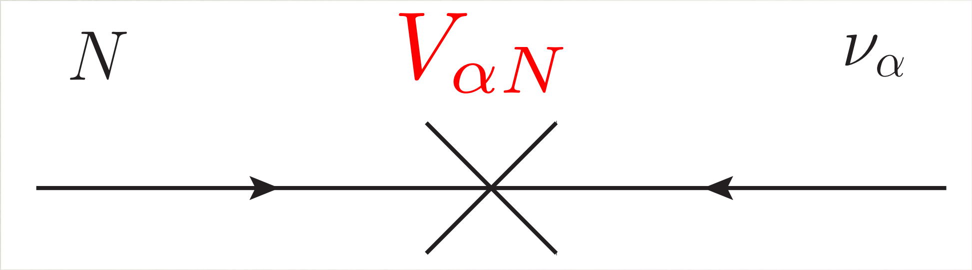
Mohapatra and Valle, 1986; Casas and Ibarra, 2001; Shaposhnikov, 2006; …

Outline

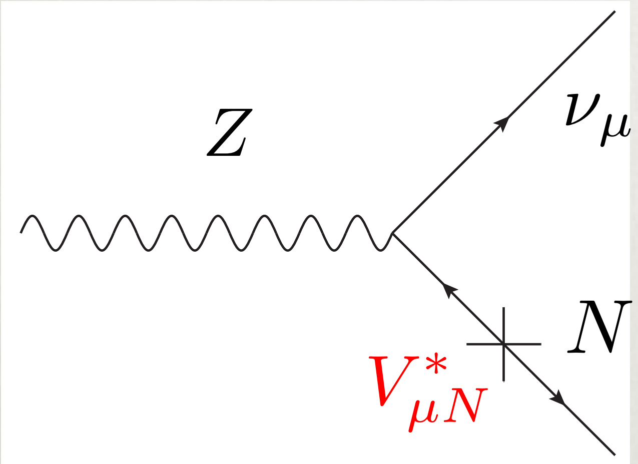
- **Tests of minimal see-saw (*N* only)**
  - ATLAS/CMS
  - LHCb & *B*-factories

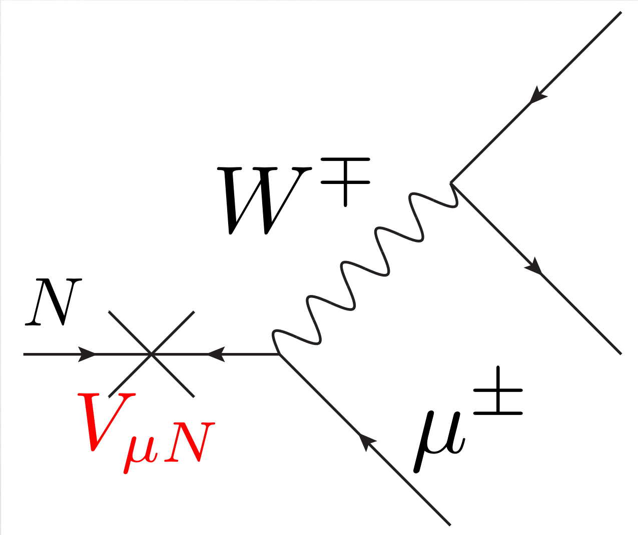
- **Portal models**
  - Vector portal
  - Scalar portal
  - Other portals

Testing the See-Saw



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



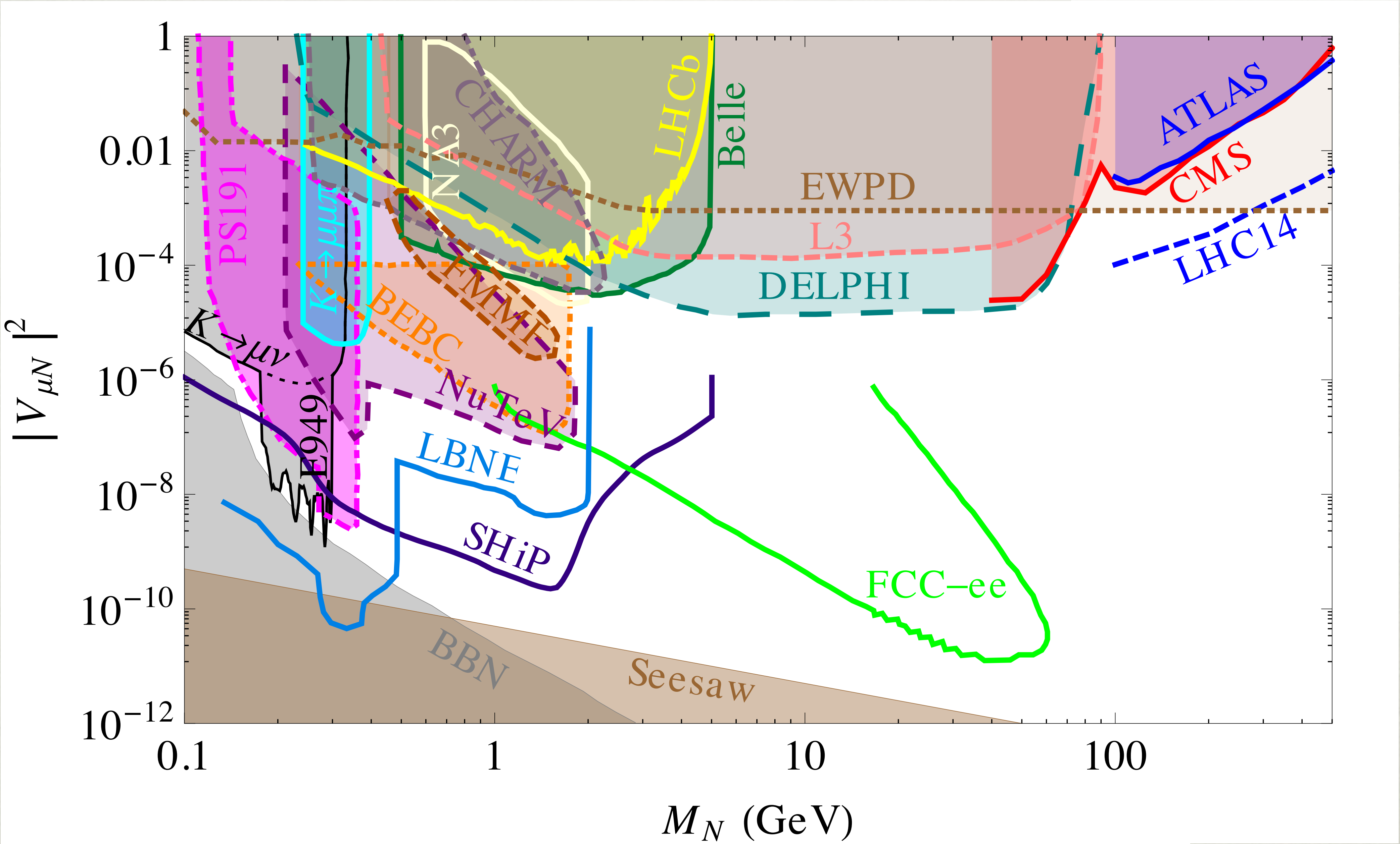


- Below weak scale, decay is through **off-shell gauge bosons**, often long-lived
- Consider a simplified model with M_N, $|V_{\mu N}|$ as free params.

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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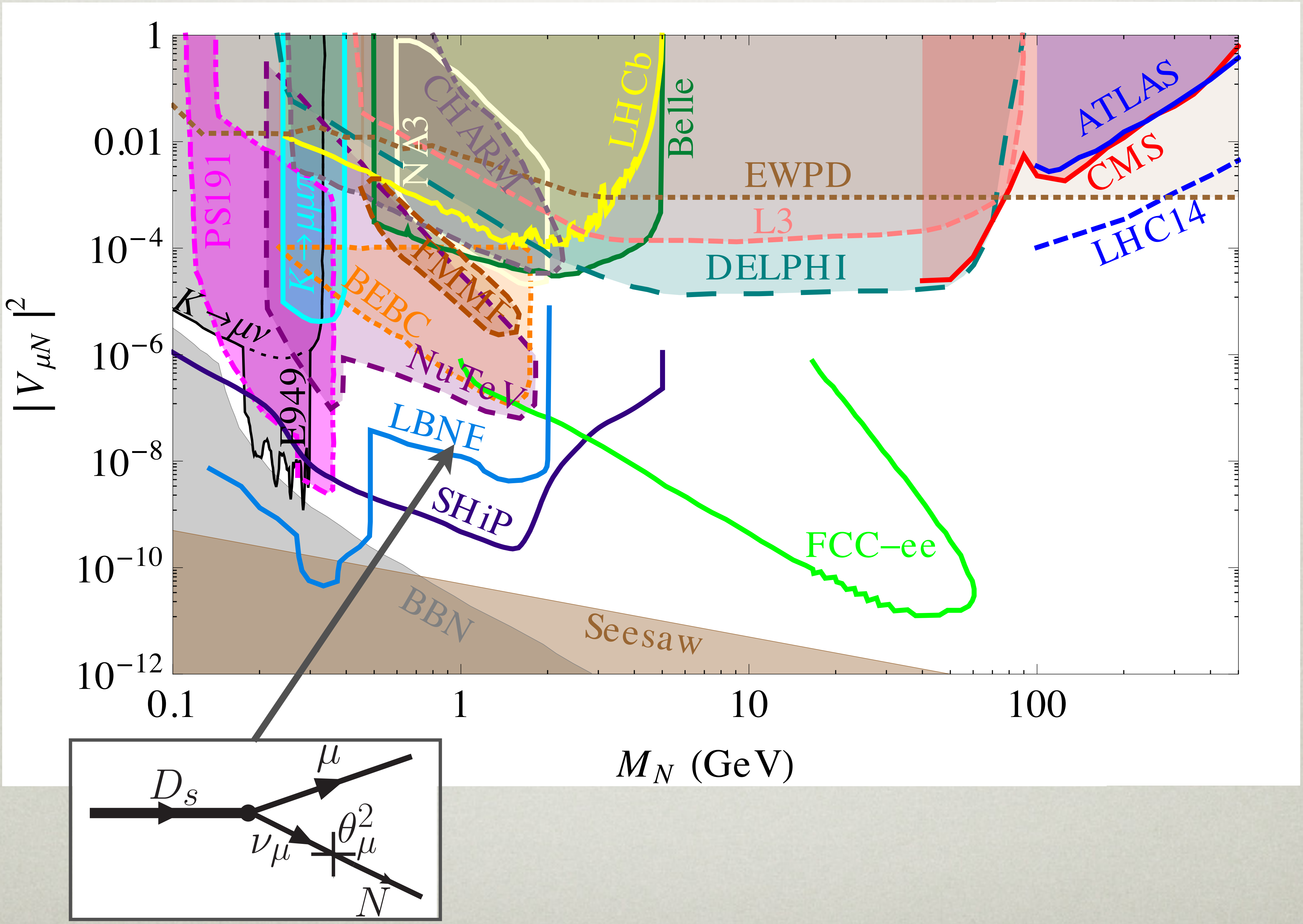

SHiP/DUNE

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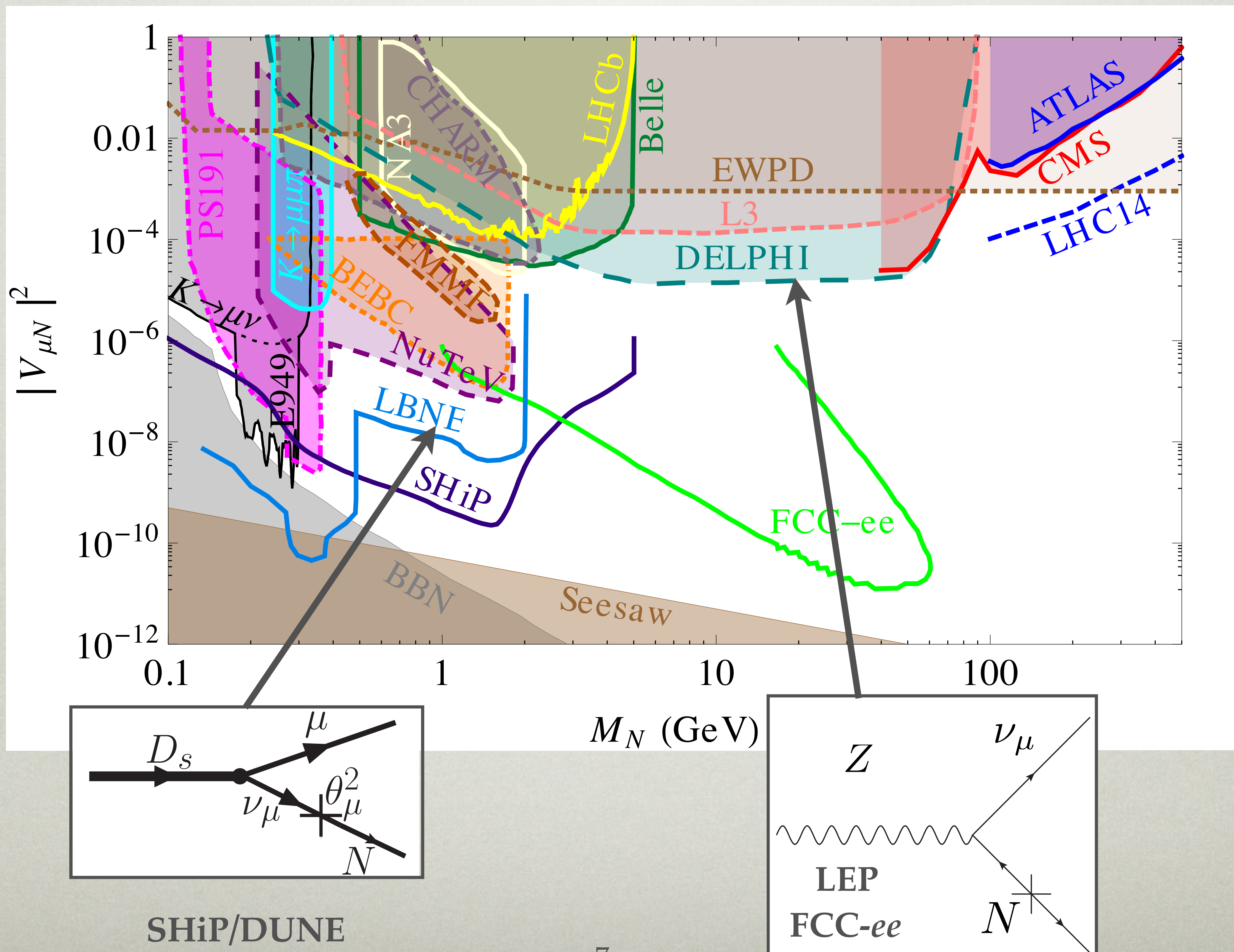

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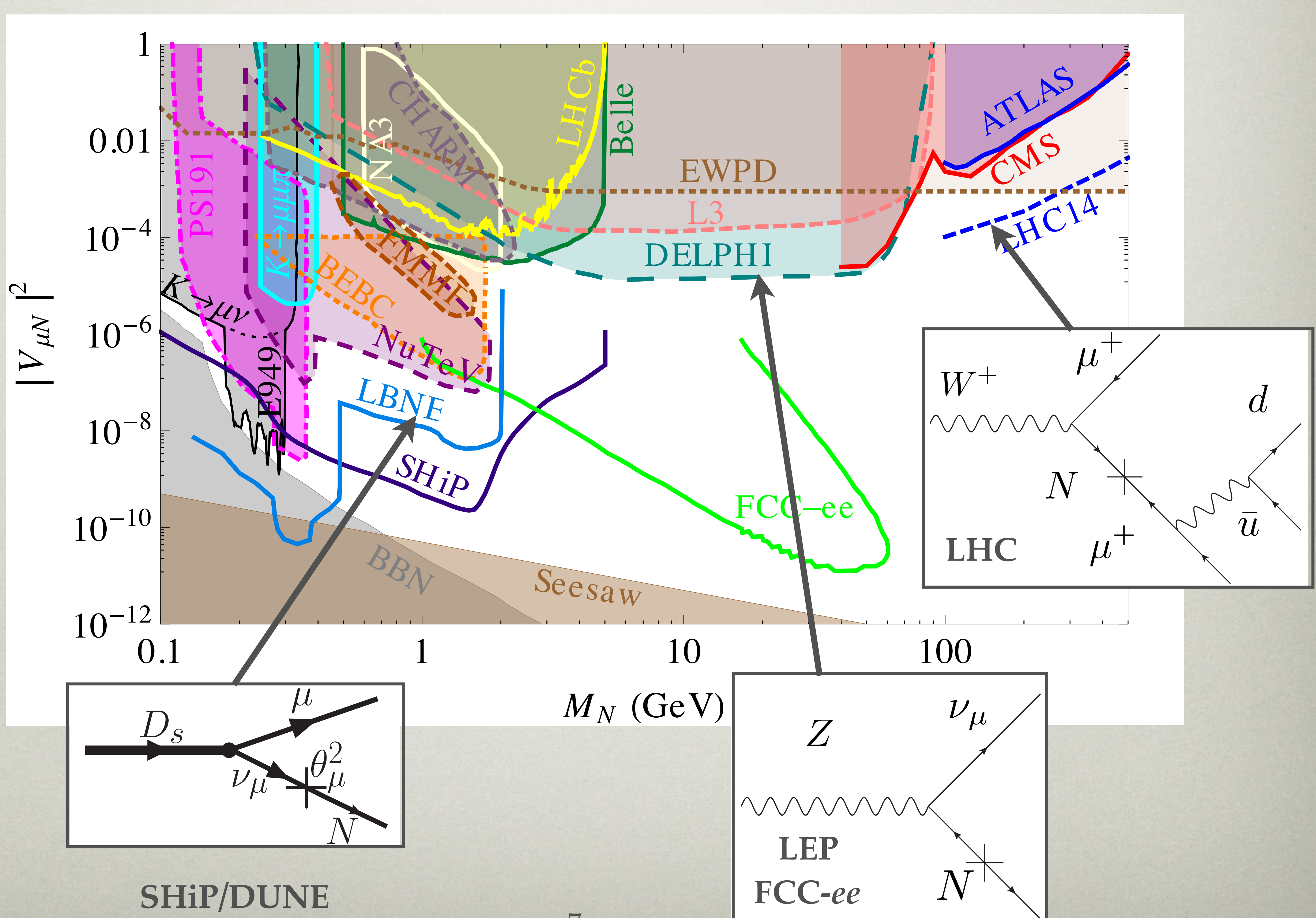


SHiP/DUNE

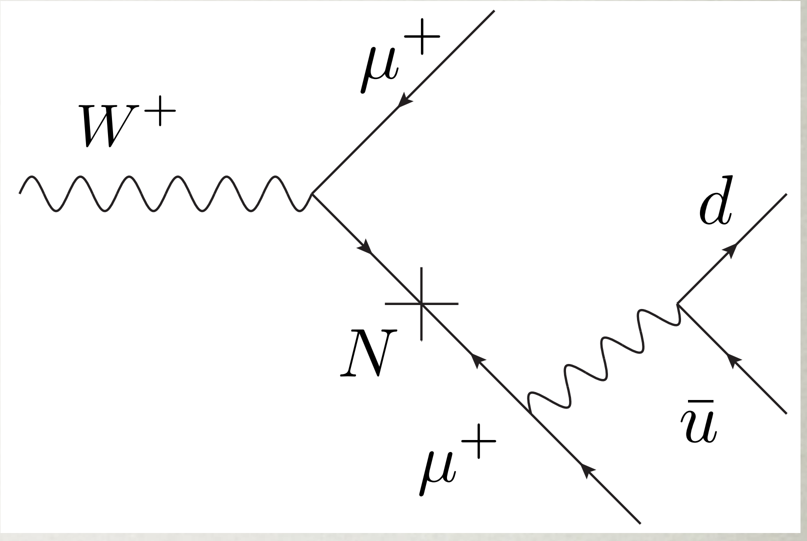
Neutrino collider signatures

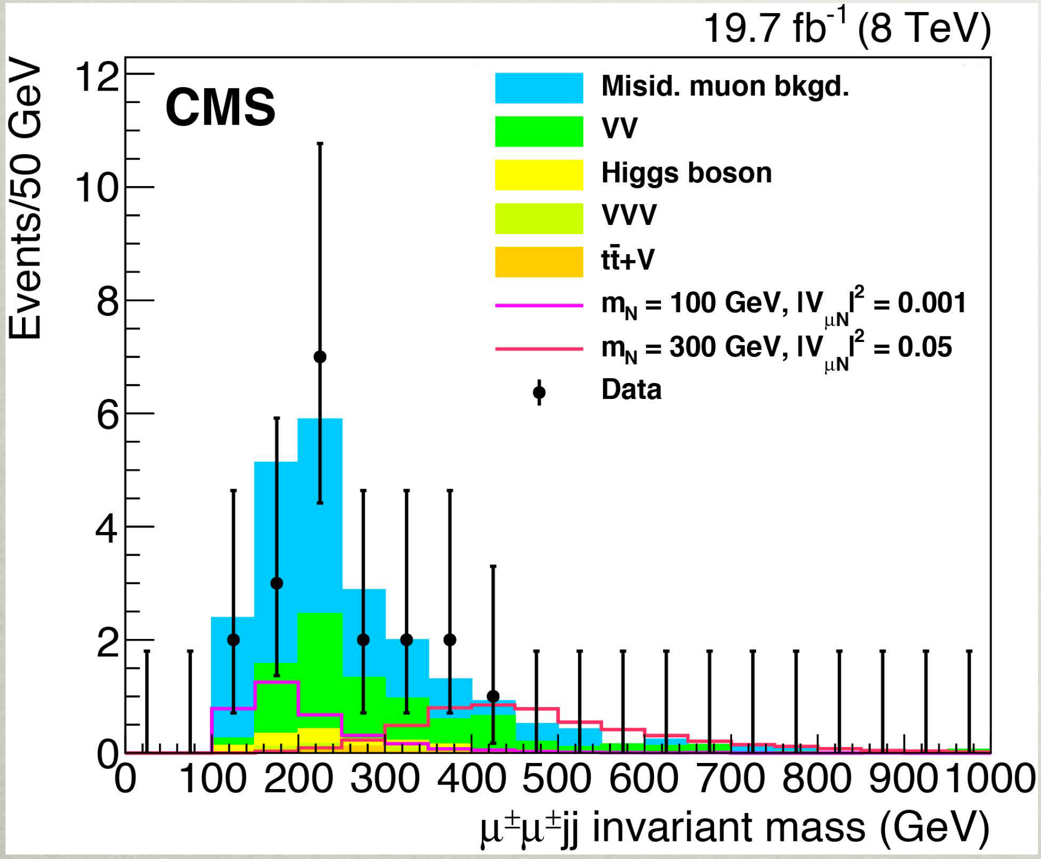
- Work very well for masses well above weak scale!

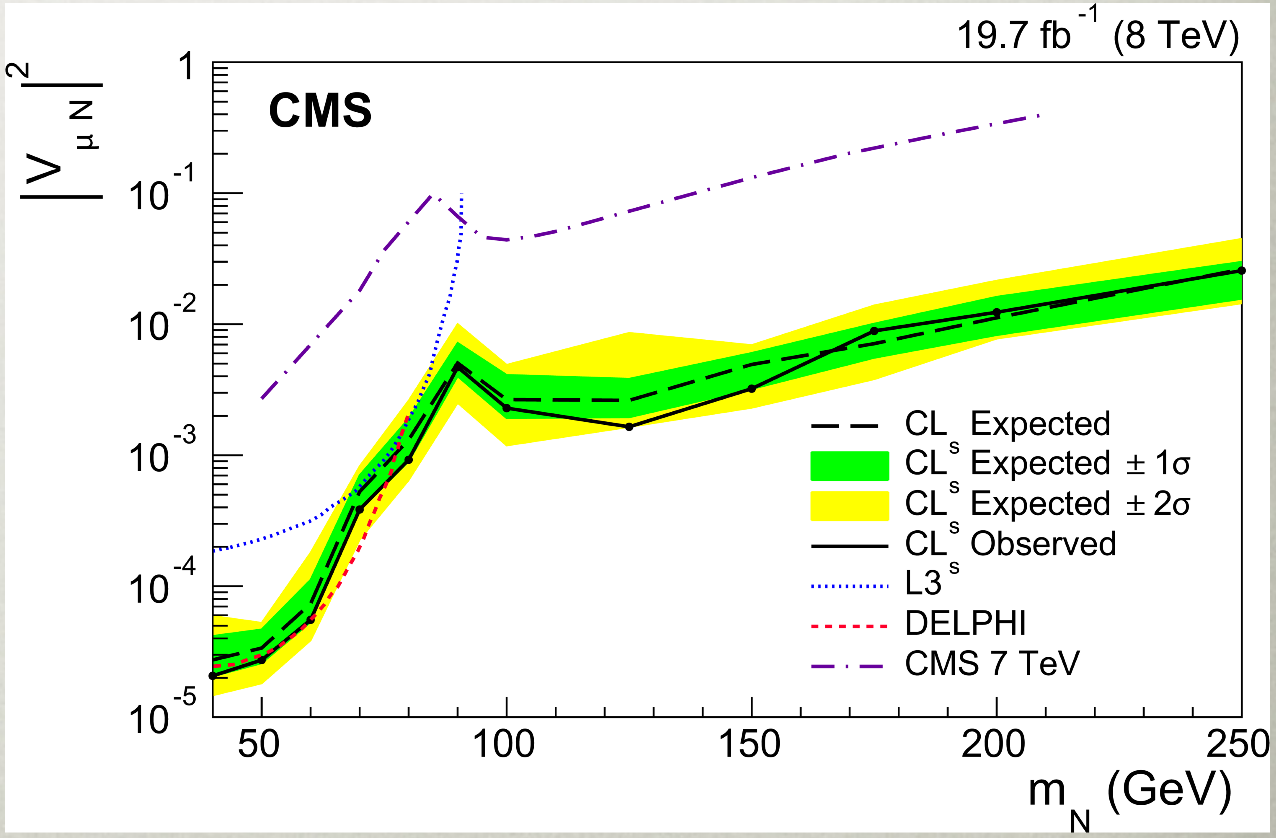
  Keung, Senjanovic, 1983; D. A. Dicus, D. D. Karatas, and P. Roy, 1992; Pilaftsis, 1993; Datta, Guchait, Pilaftsis, 1993; Han and Zhang, 2006; Atre, Han, Pascoli, Zhang, 2009; …

- Calculable & predictive rates from Drell-Yan and photon-*W* fusion

  Dev, Pilaftsis, Yang, 2013; Alva, Han, Ruiz, 2014





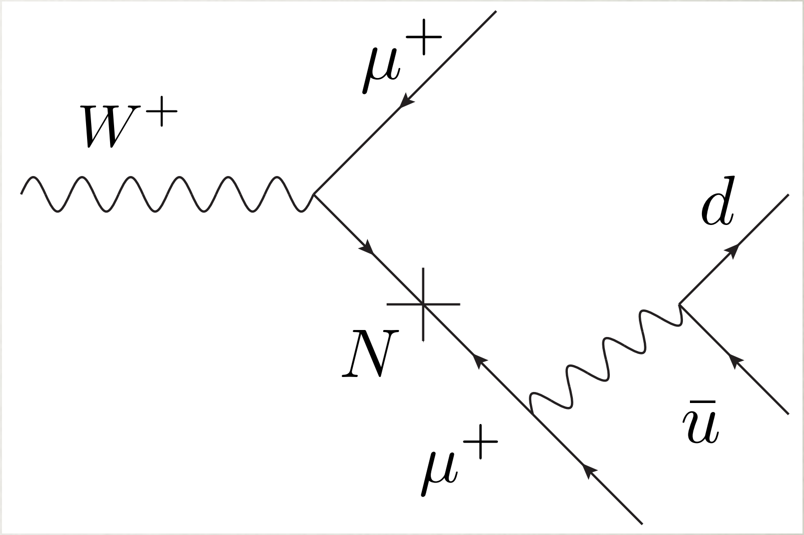


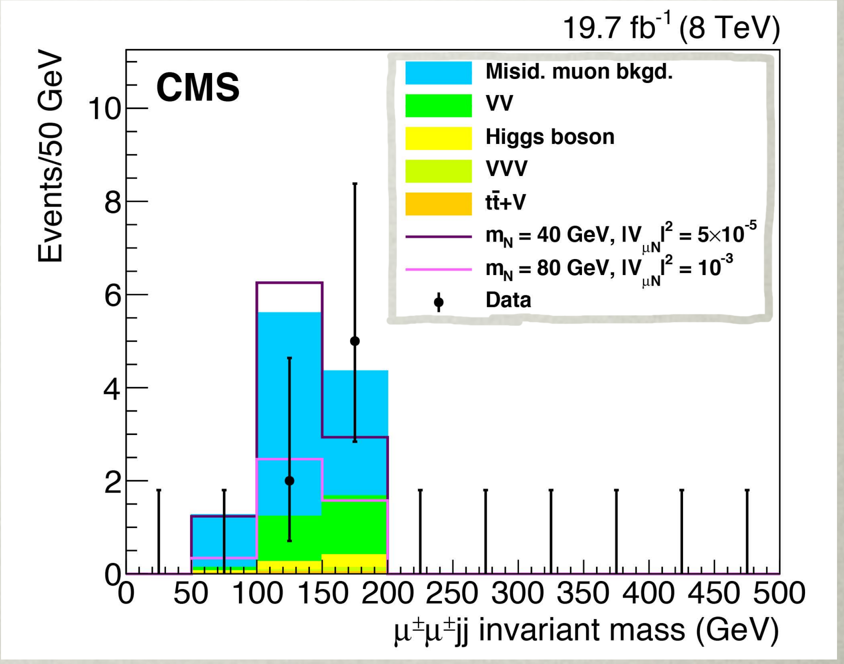
Neutrino collider signatures

- Lower masses….maybe not as much

- Limits not currently improved over LEP, even though >100x more W bosons than LEP's Z bosons

- Worth pushing these searches and seeing if other alternatives exist



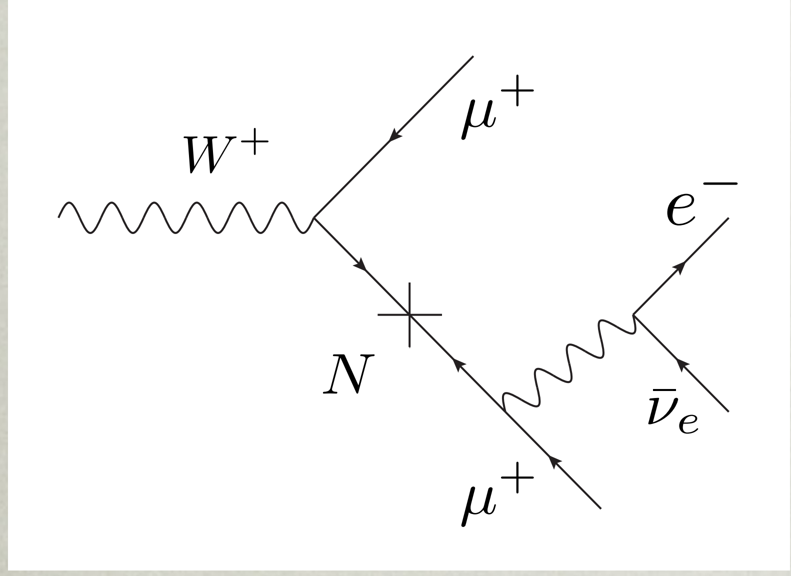


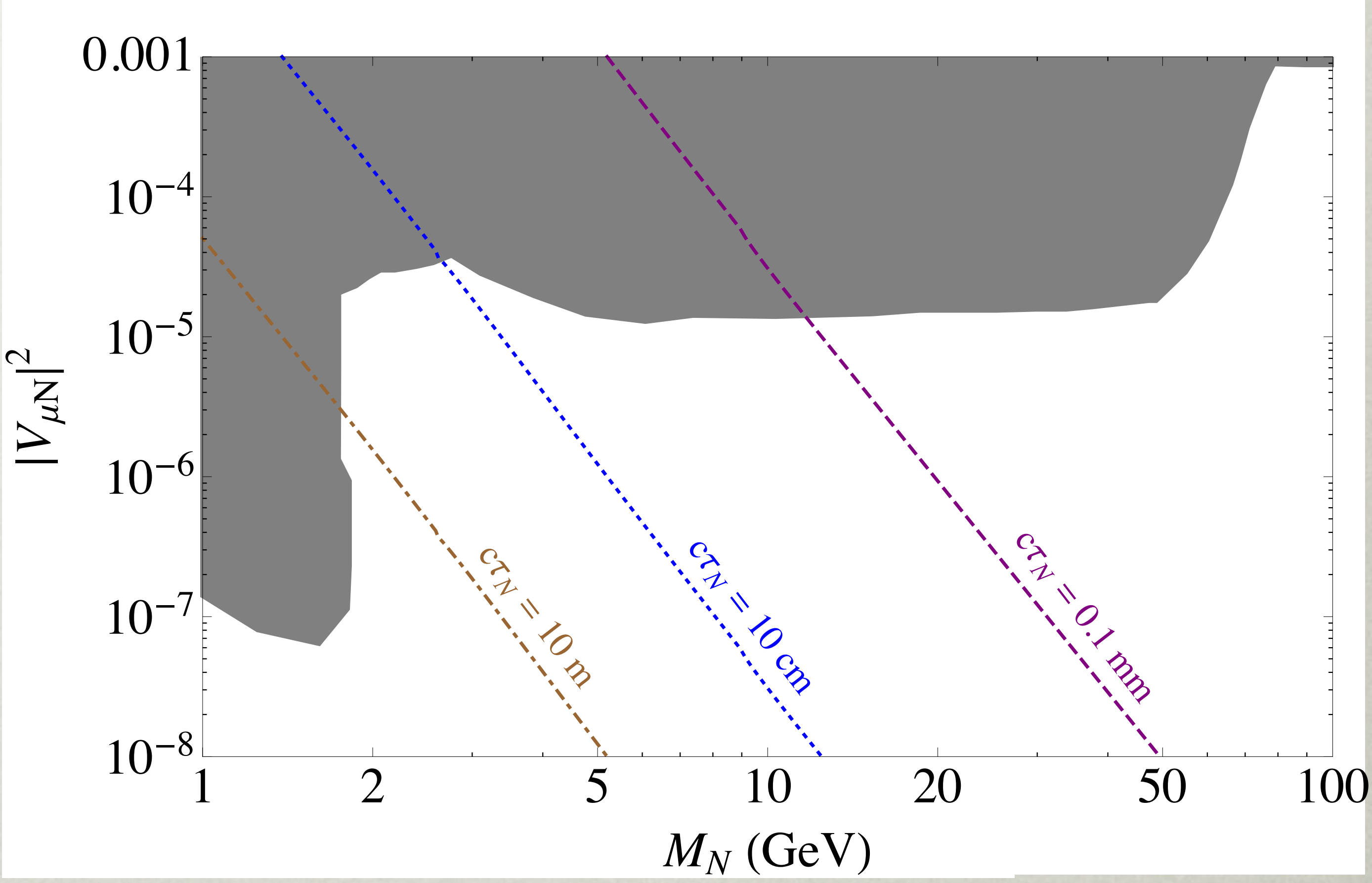
(from arXiv:1501.05566)

Intermediate neutrino prospects

- Consider purely leptonic signatures that can be **cleaner** and have **lower thresholds**
    - Complementary signature to semi-leptonic decays
    - Until now, most leptonic decay proposals focus on non-LNV decays

del Aguila and J. Aguilar-Saavedra, 2008 & 2009





Izaguirre, BS, 2015

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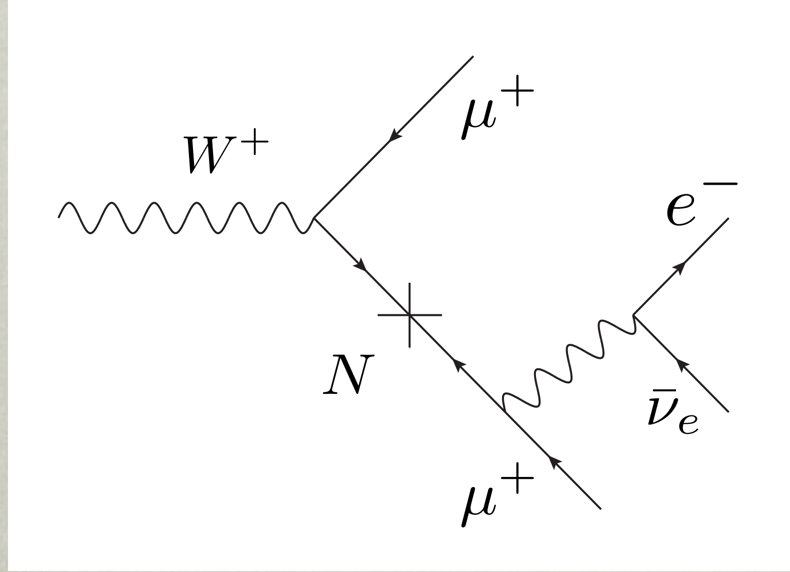
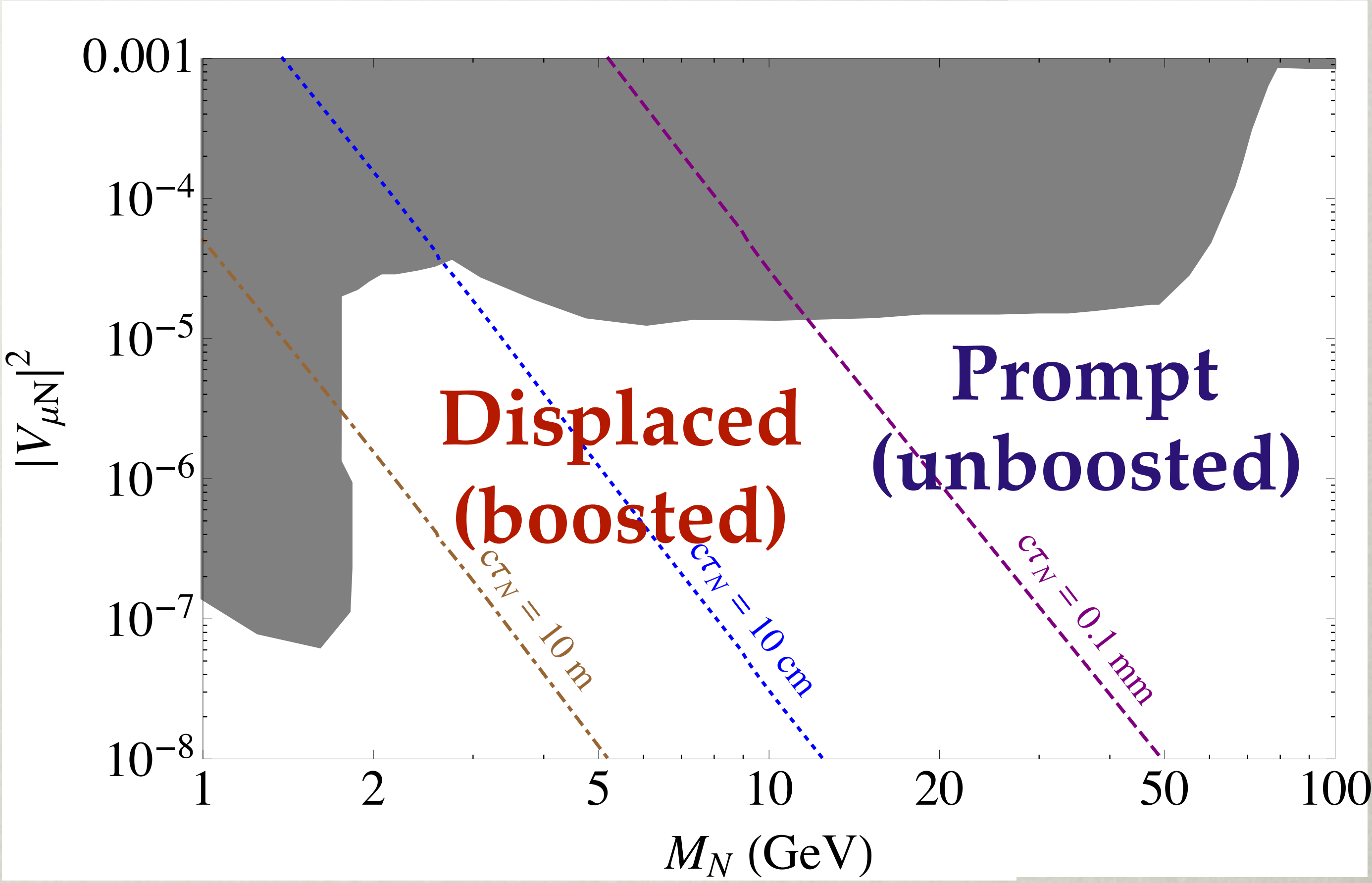
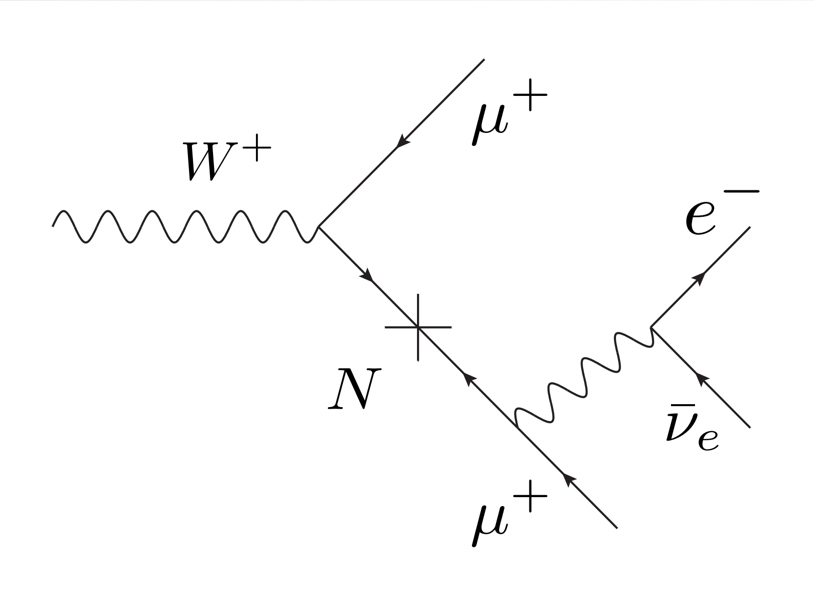




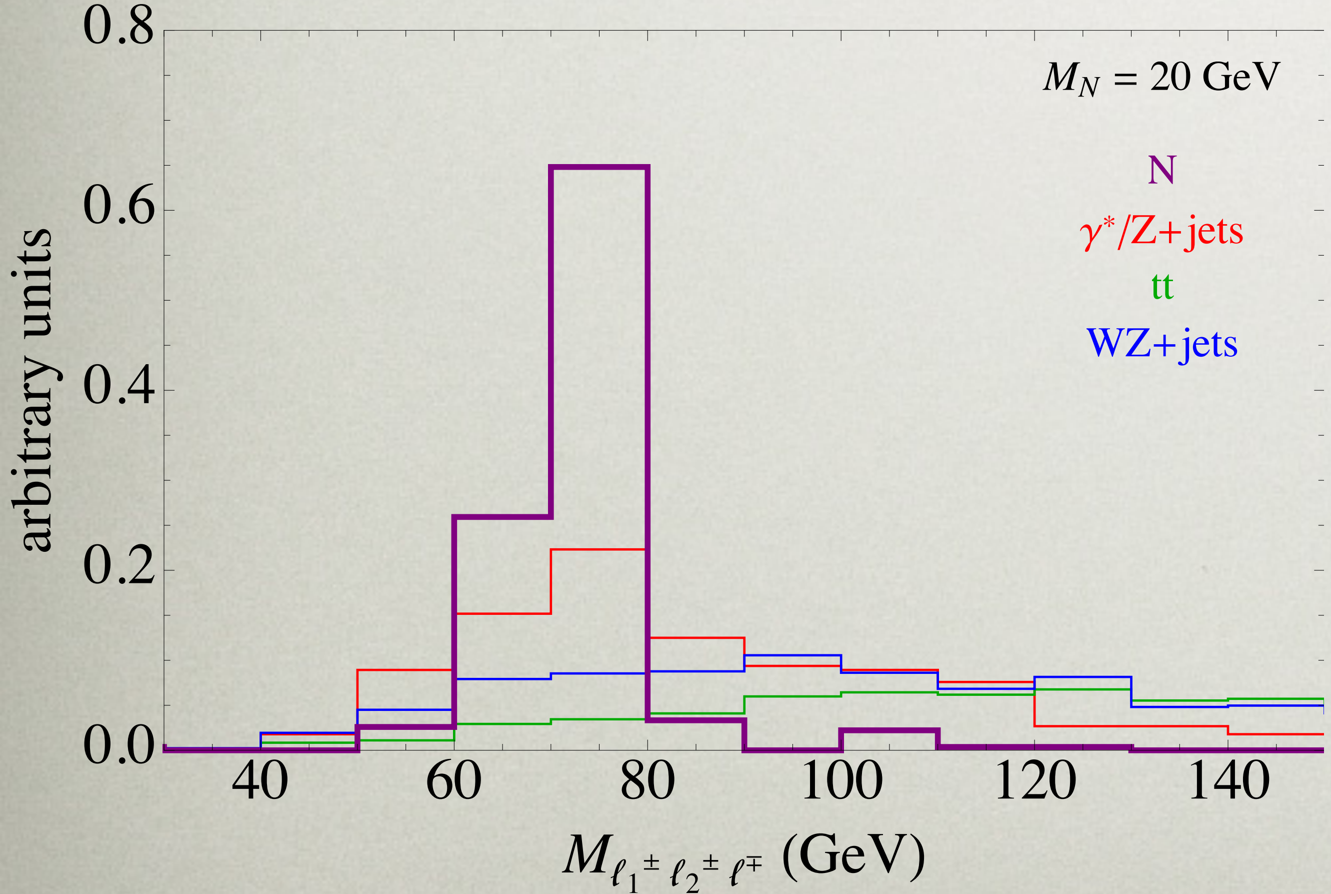
Izaguirre, BS, 2015

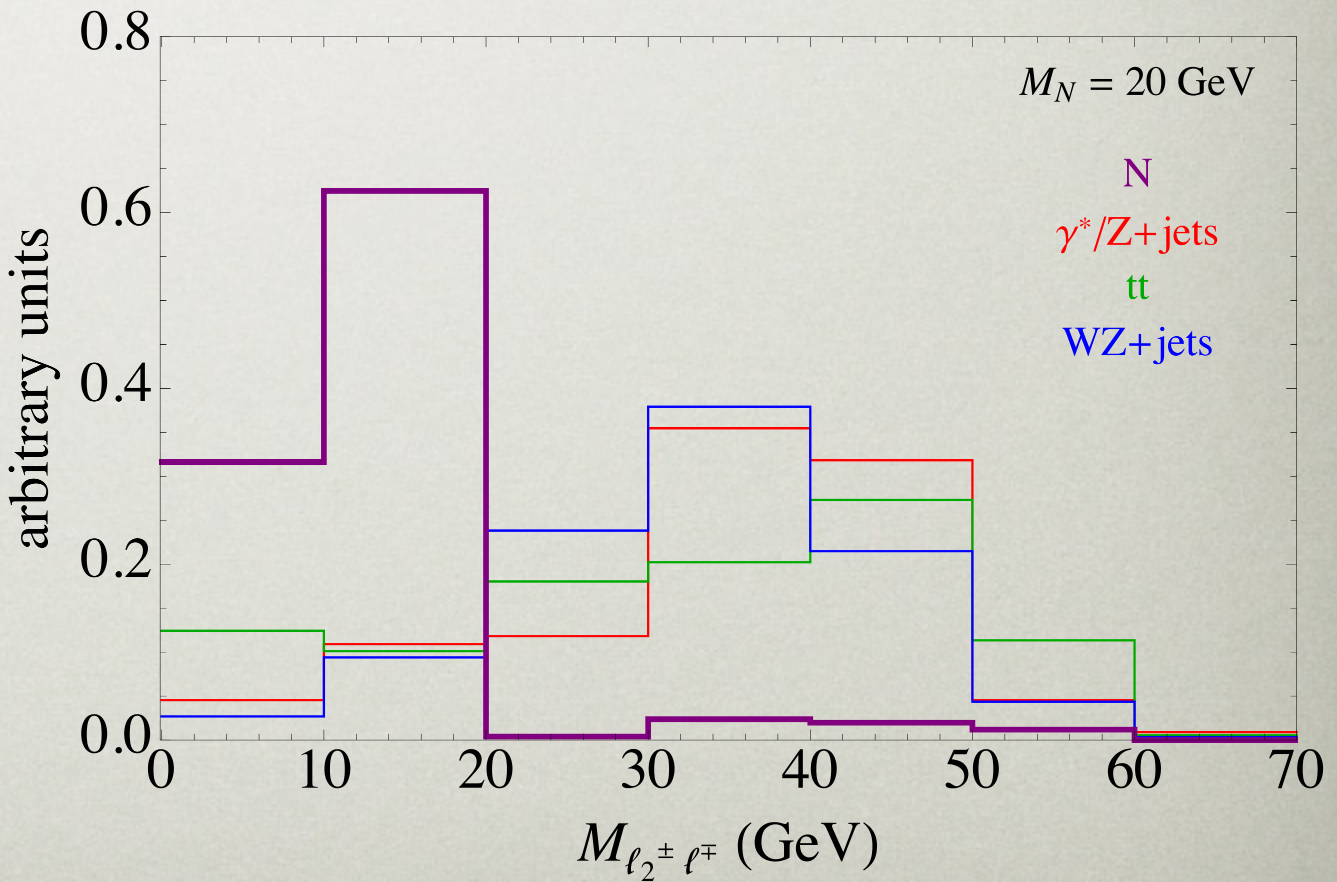
Prompt trilepton signatures



- Majorana N gives striking trilepton, OSSF-0 signatures!
- Similar to CMS trilepton search

(CMS, 1501.05566)

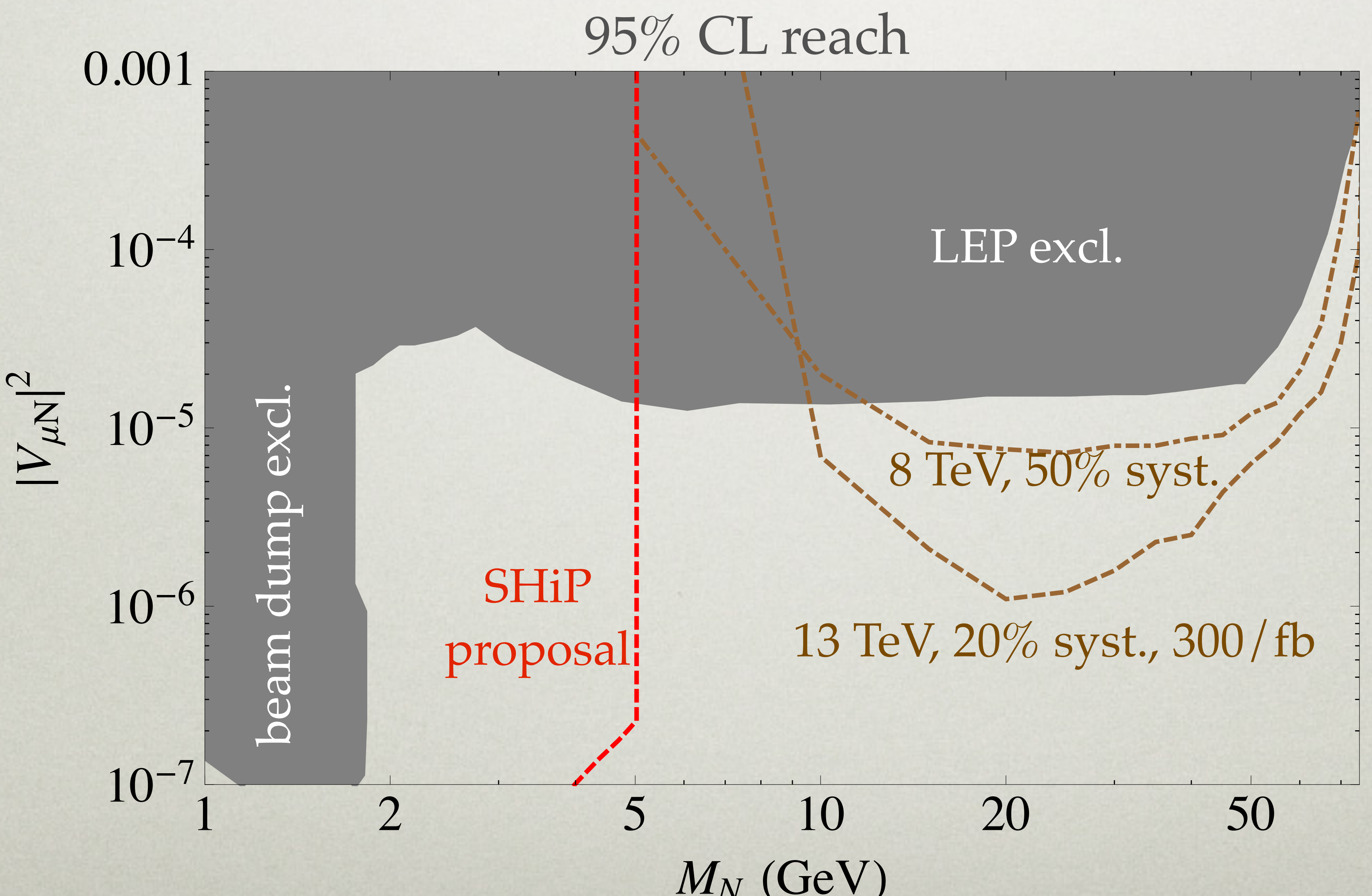




Izaguirre, BS, 2015

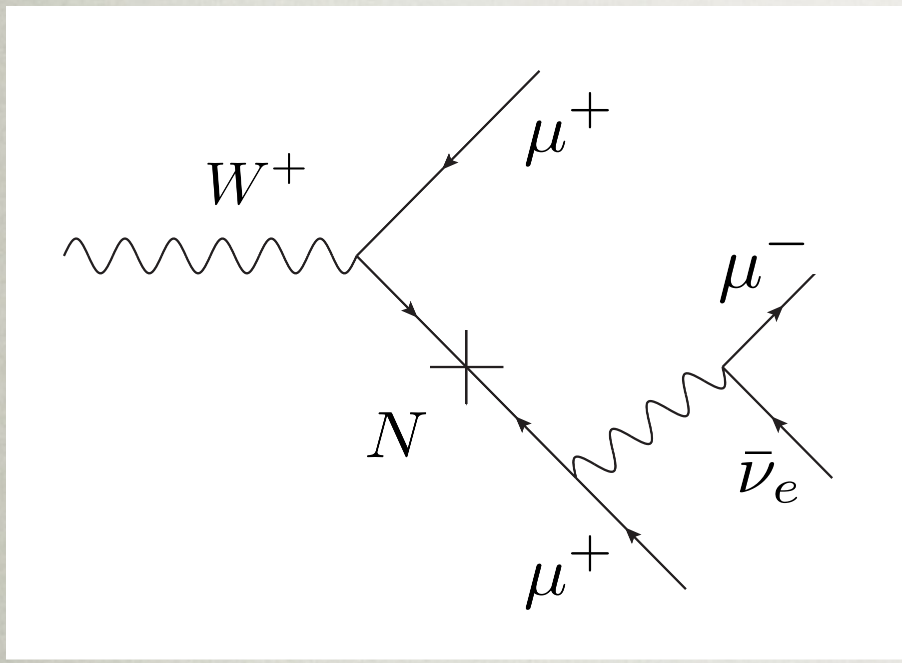
Prompt trilepton signatures

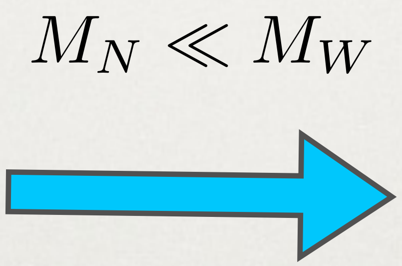
- Selections:
  - Three prompt, isolated leptons with $p_T > 10$ GeV, leading > 20 GeV
  - Two same-sign muons, opposite-sign electron
  - $H_T < 50$ GeV, MET < 40 GeV (suppresses top, tau backgrounds)
  - 80 GeV > $M_{3\ell}$ > 60 GeV, mass-dependent $M_{2\ell}$ selection

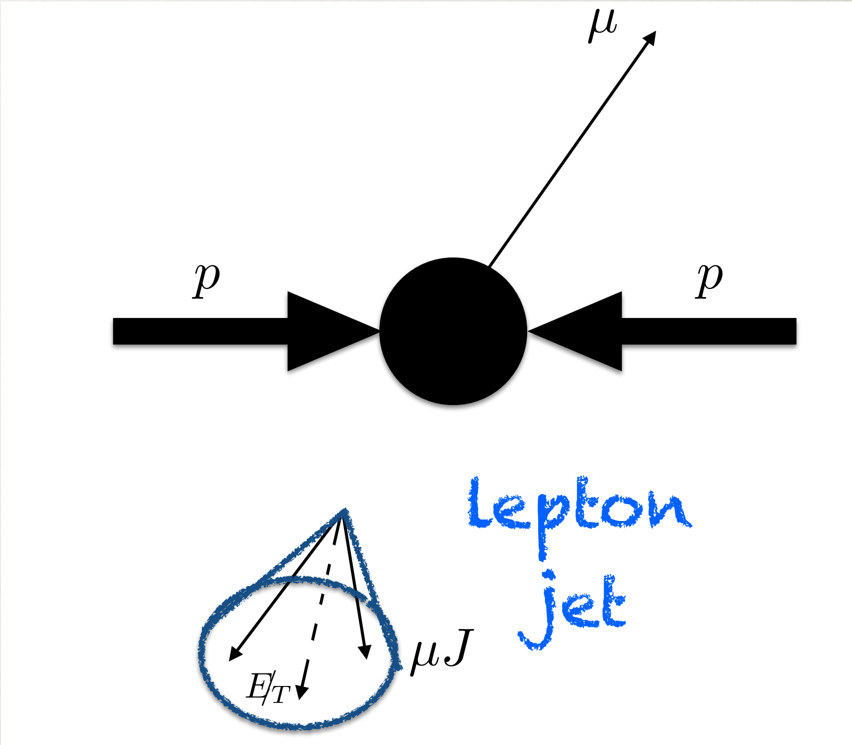


Izaguirre, BS, 2015

Displaced/Boosted Signatures







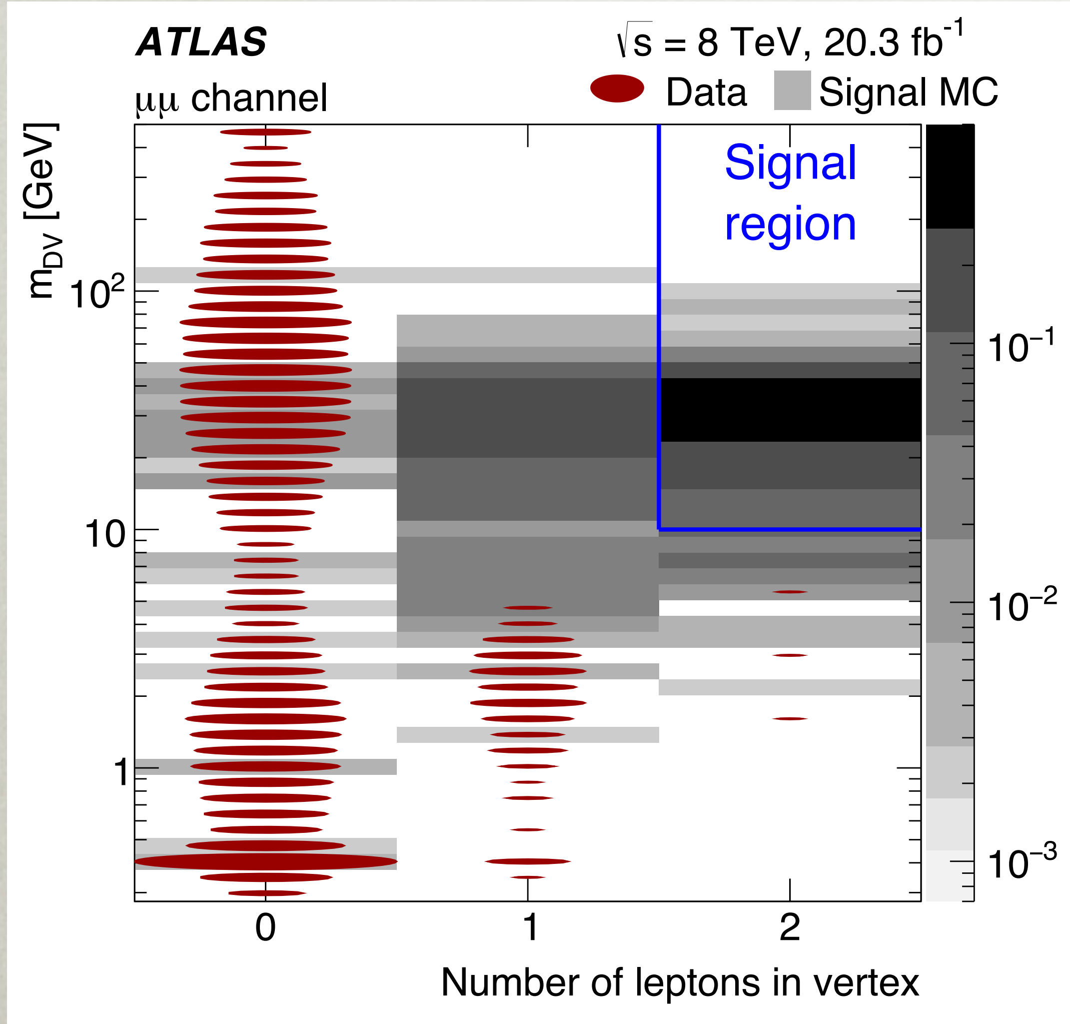
Arkani-Hamed, Weiner, 2008; …

- Hadronic displaced vertices also possible, but backgrounds could be large

Helo, Hirsch, Kovalenko, 2013

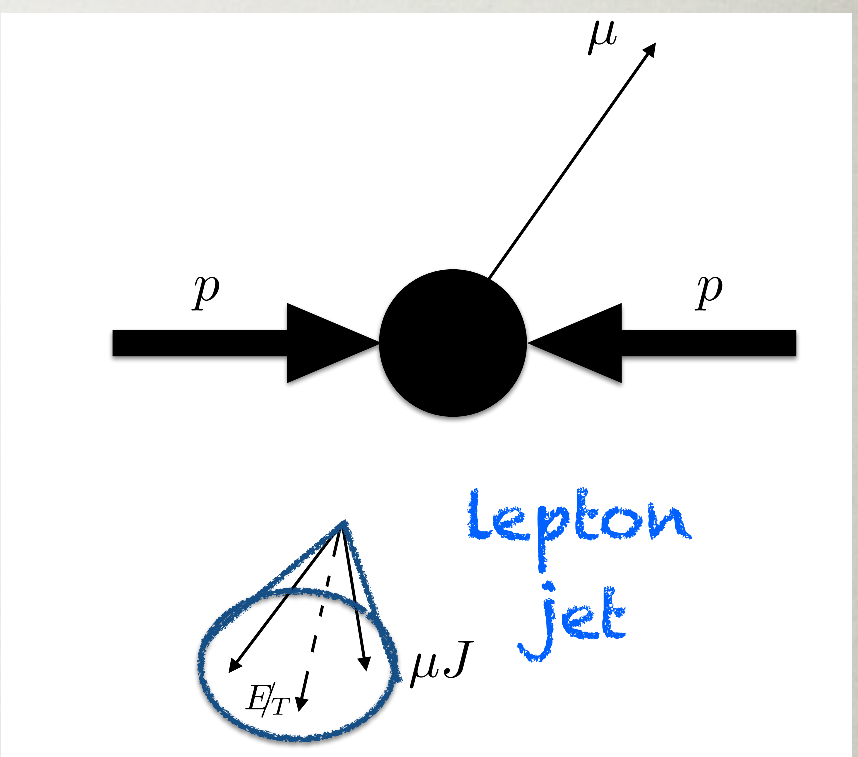
Displaced/Boosted Signatures

- By contrast, leptonic backgrounds expected to be negligible



(a)

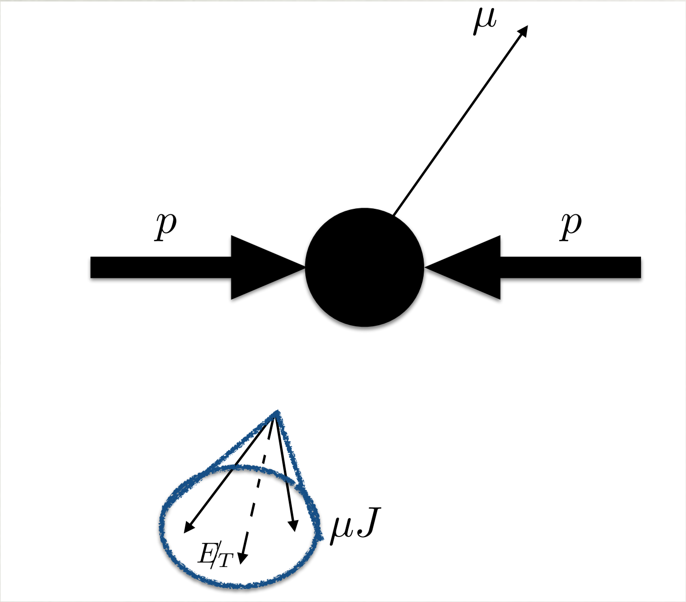
ATLAS, arXiv:1504.05162



- Also by extrapolation from existing 2-LJ searches

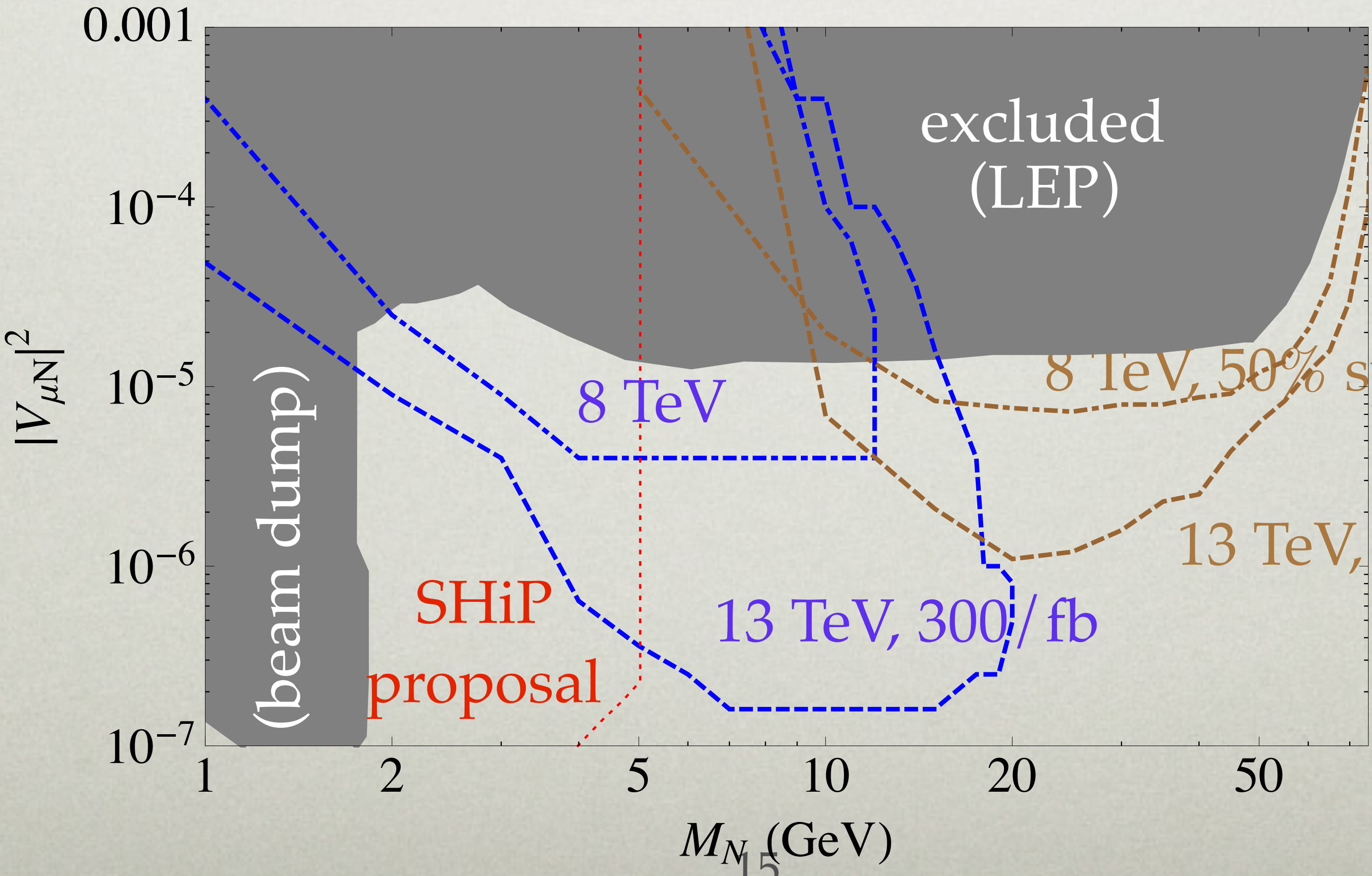
(ATLAS, arXiv:1409.0746)

Displaced/Boosted Signatures



- LJ selections:
  - Hard lepton for trigger, two soft muons in MS
  - Expect ~zero backgrounds when require a displacement of > 1 mm
  - Veto back-to-back muons

95% CL reach (signal yield ≳3)



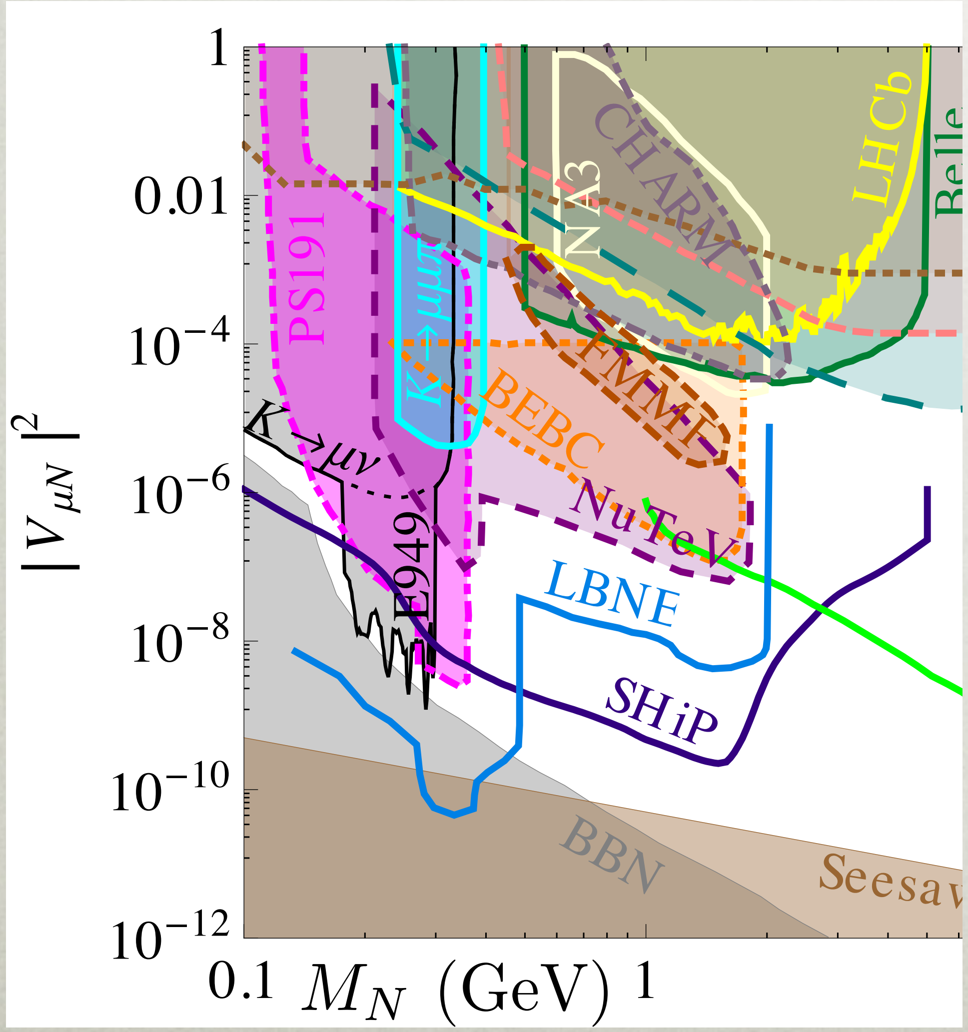
Izaguirre, BS, 2015

LHCb vs. *B*-factories

- At lower masses, experiments can be sensitive to **rare meson decays**

$$B^\pm \to \ell^\pm N,\ N \to \ell^\pm \pi^\mp$$

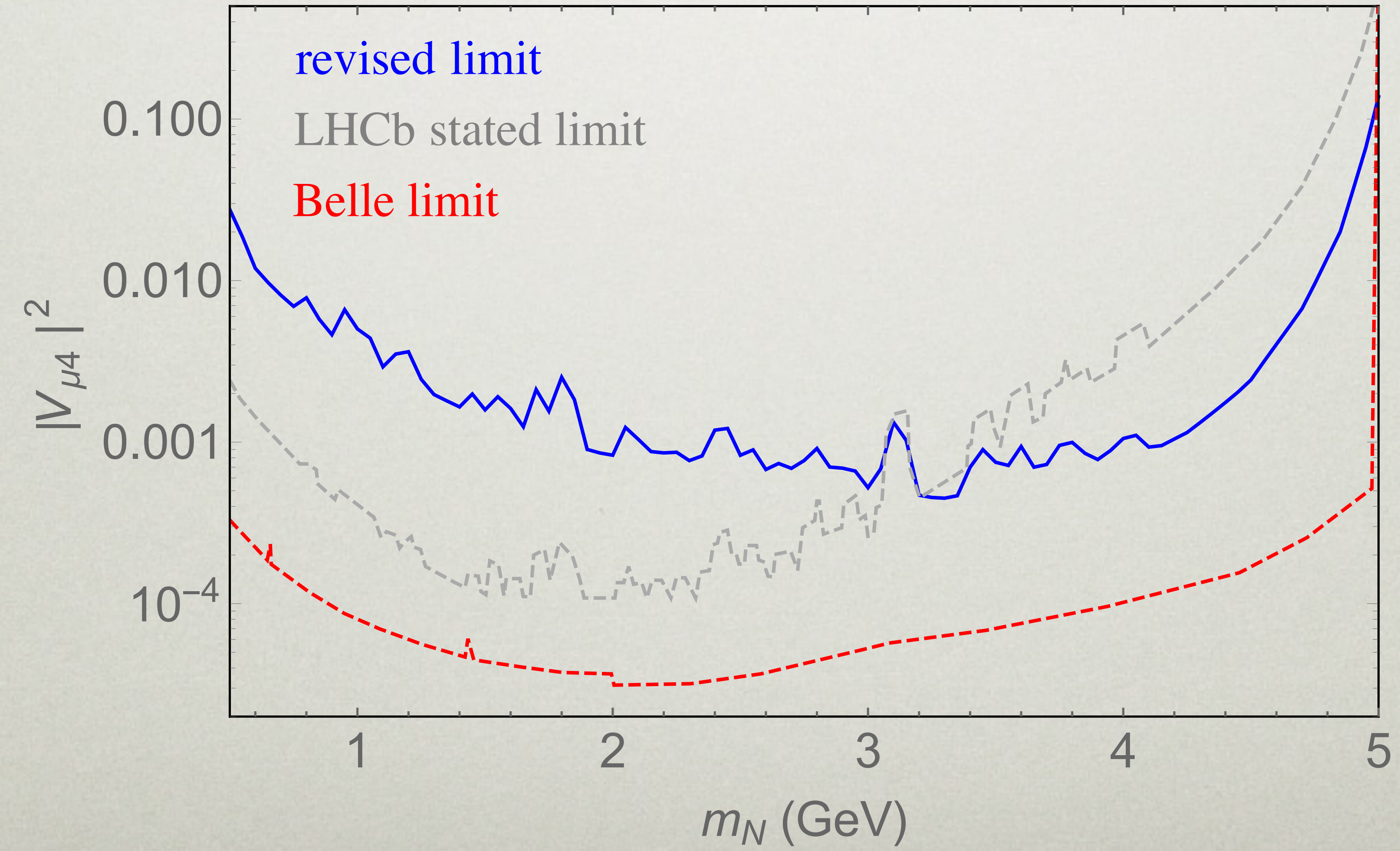
Shrock, 1981; Gronau, 1982; …
Gorbunov and Shasposhnikov, 2007; Atre, Han, Pascoli, Zhang, 2009



- Why does Belle do better than LHCb for a **rare**, **spectacular** decay?

LHCb vs. *B*-factories

- However, there were several issues with the LHCb analysis
  - Helicity suppression of leptonic *B* decay not included (LHCb, arXiv:1401.5361)
  - "Phenomenological" treatment of *N* width to incorporate inclusive decays gave unphysical mass-dependence
  - Other effects…each individual factor changes result by up to ~10^4



BS, Peskin, 2016

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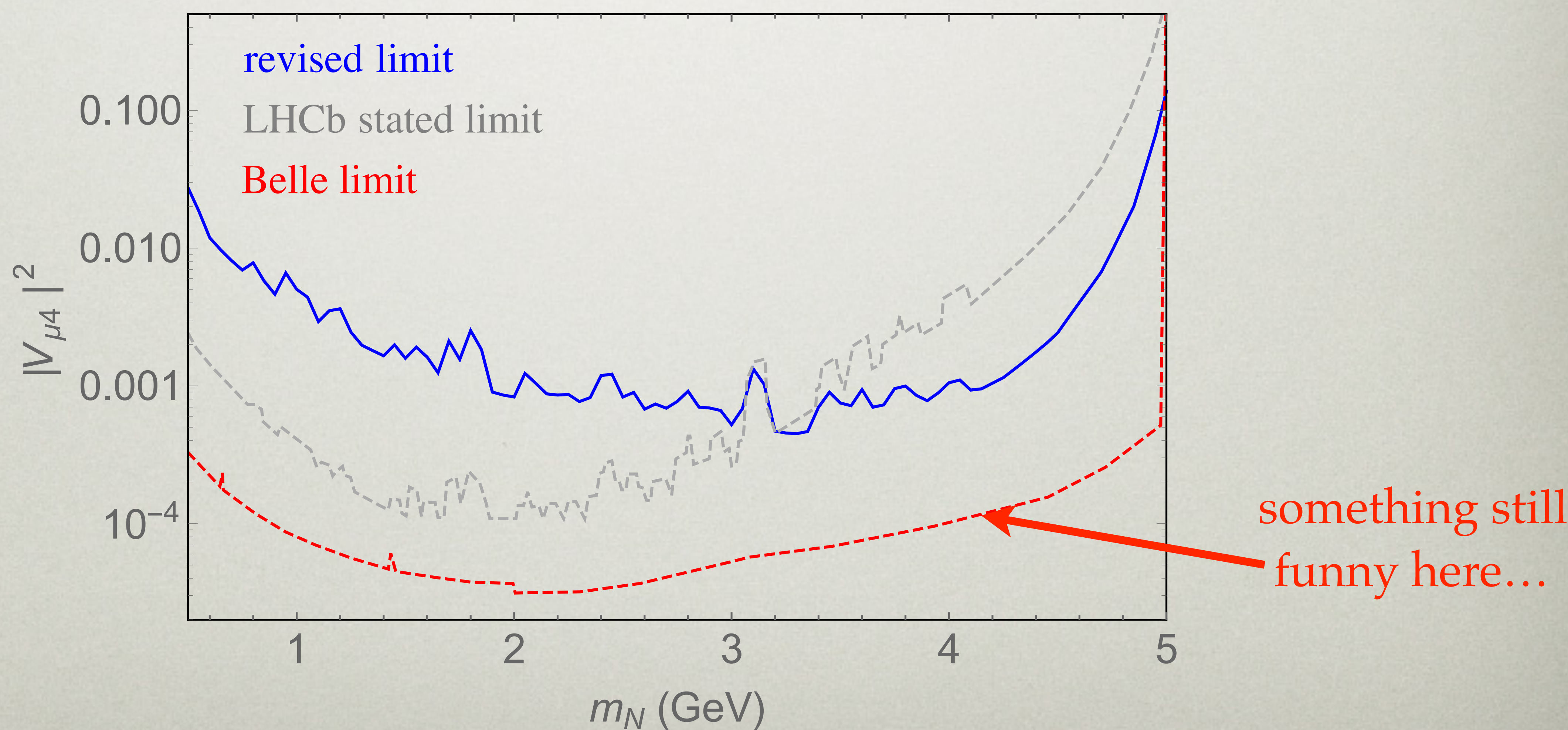
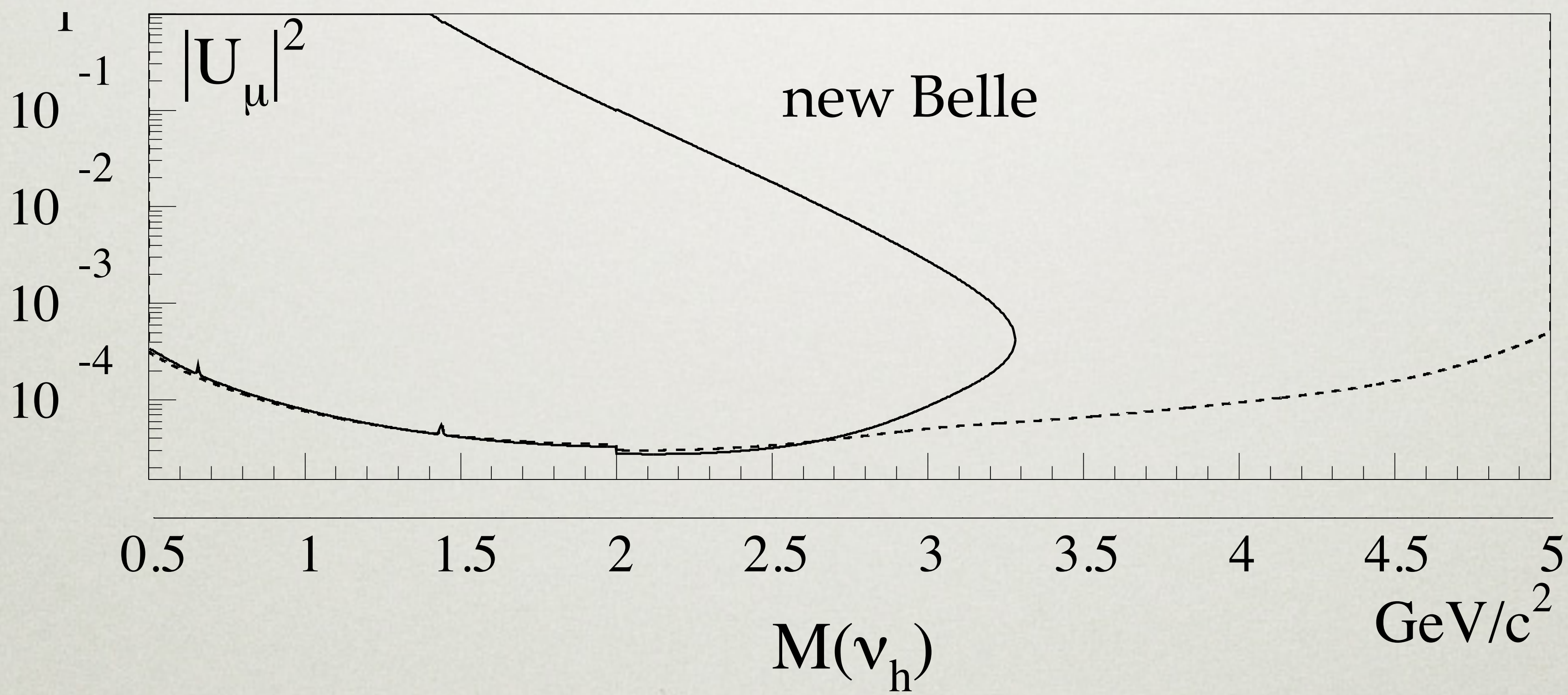


BS, Peskin, 2016

LHCb vs. *B*-factories

- Fresh off the press…a Belle update
  - Erroneously assumed that all *N* had typical lifetime outside detector, erratum released this week:

Belle, 1301.1105



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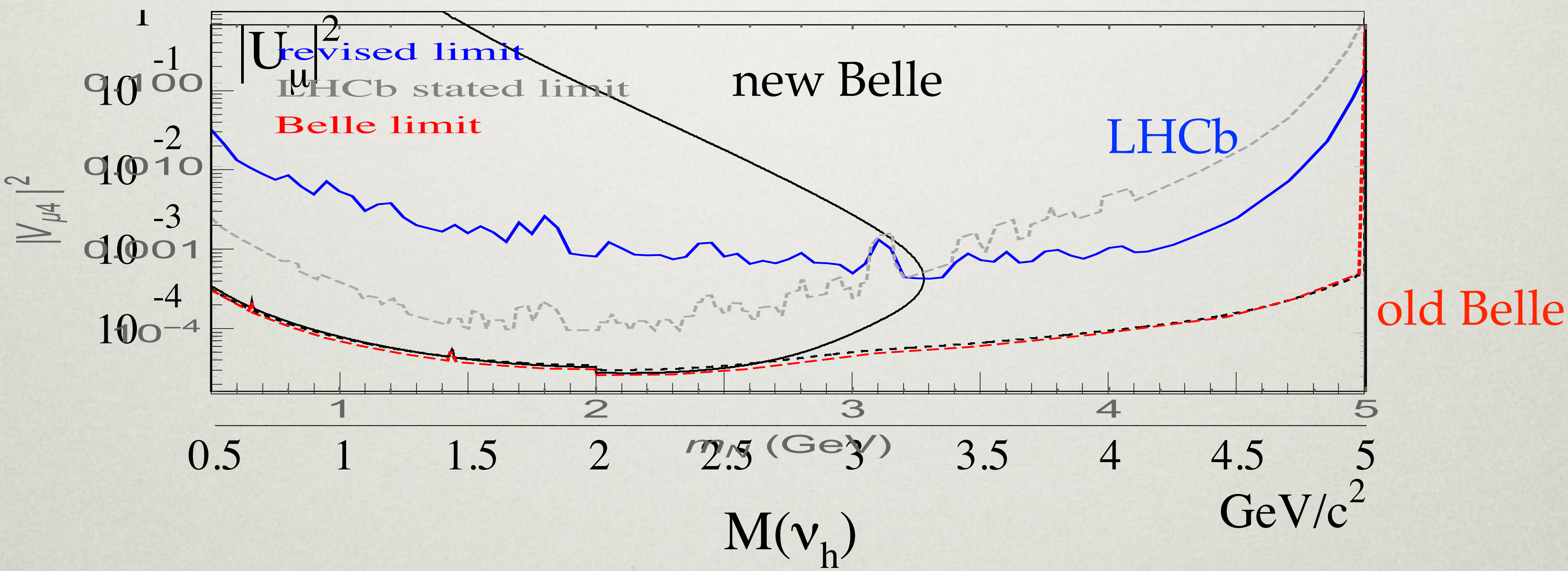

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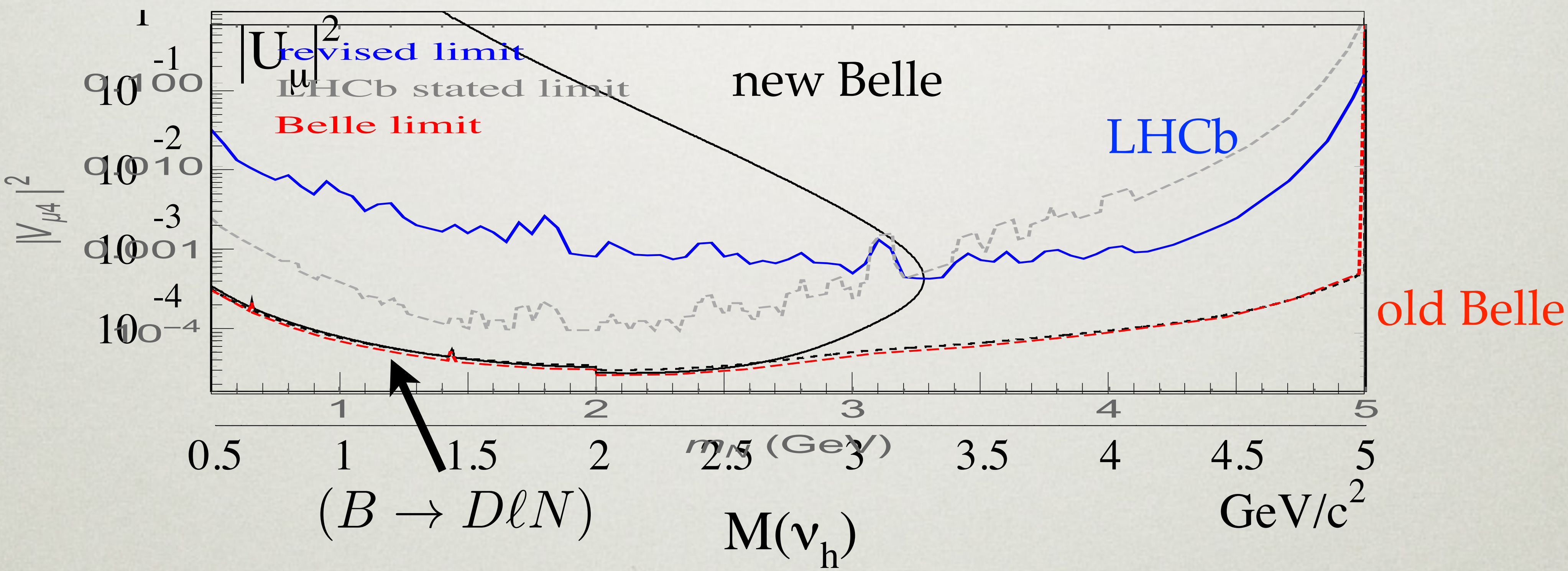


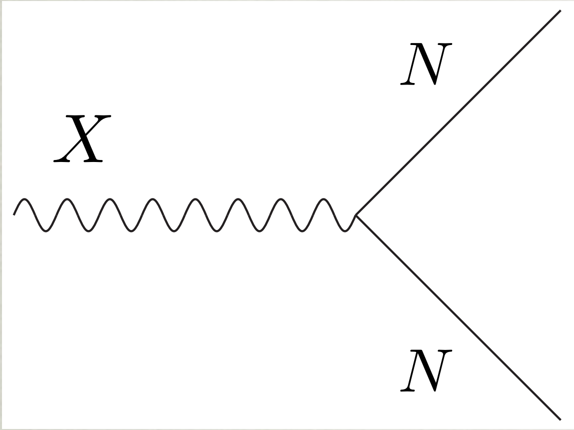
  - LHCb can do better, but needs to include non-Cabibbo suppressed decays (*e.g.* leptonic B_c decays)

Outline

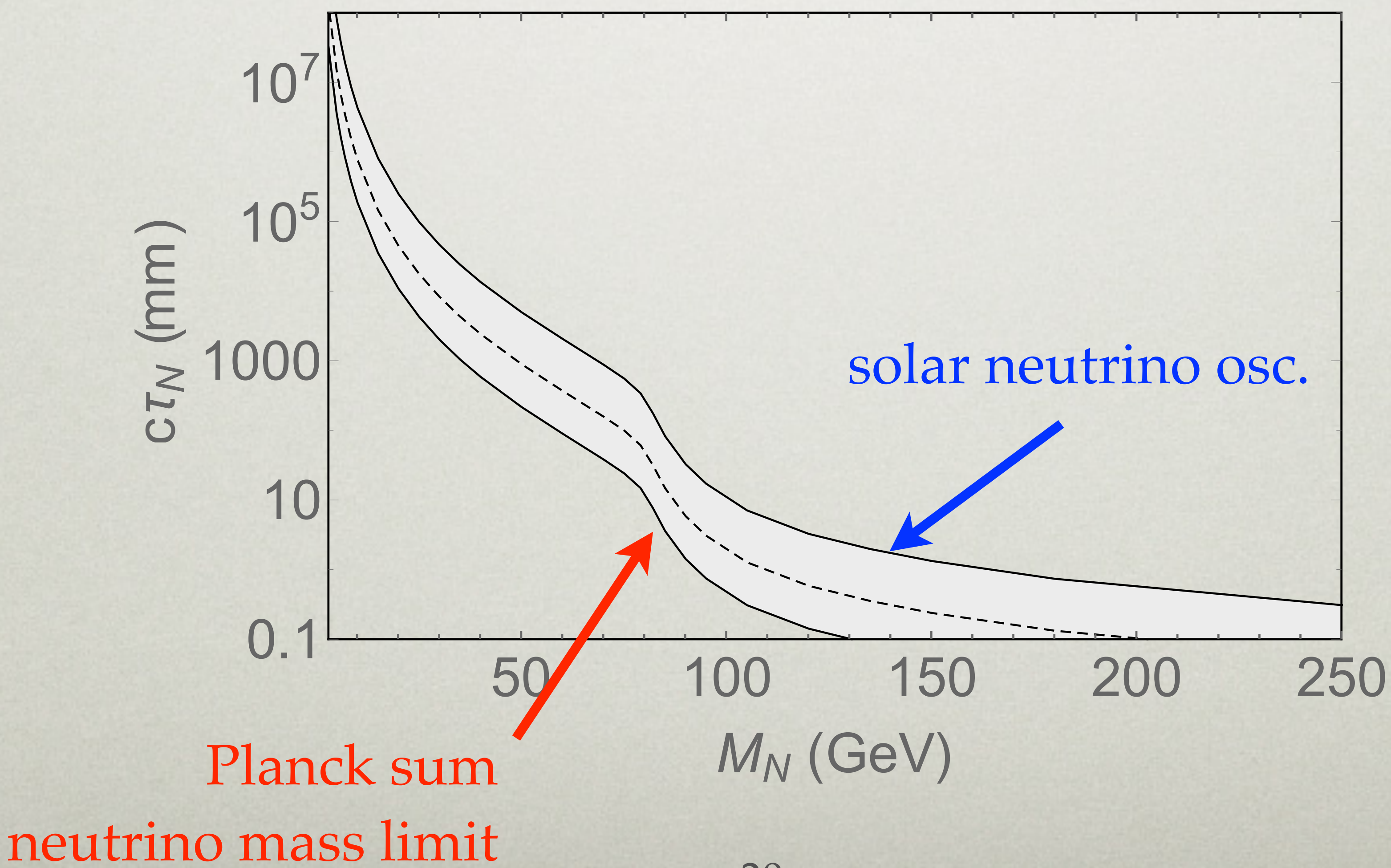
- **Tests of minimal see-saw (*N* only)**
    - ATLAS/CMS
    - LHCb & *B*-factories

- **Portal models**
    - Vector portal
    - Scalar portal
    - Other portals?

Beyond the Minimal See-Saw

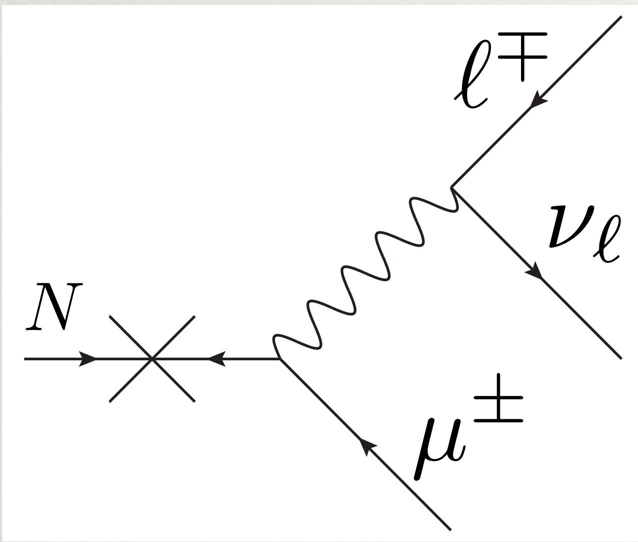


- New production modes **independent** of mixing angles
- Can probe naïve see-saw parameters!
- Decay of *N* still proceeds via mixing

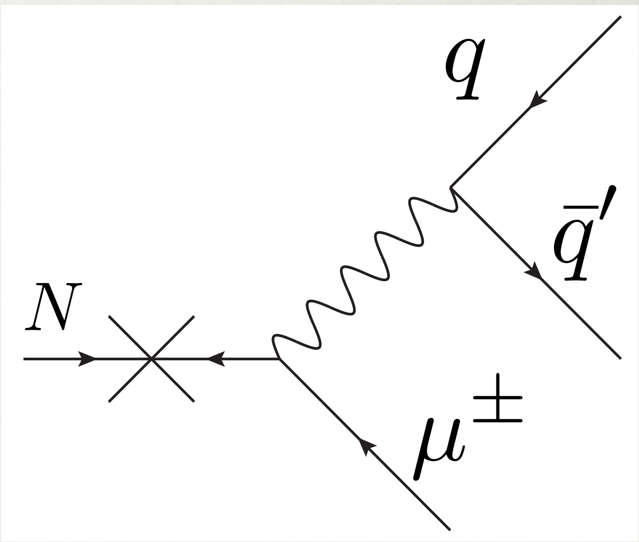


Long-Lived Searches

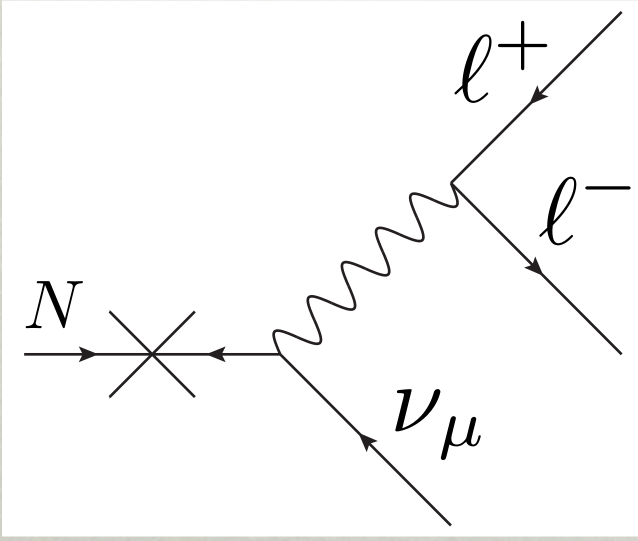
- What do the X decay to NN look like? (resolved only for now)



ATLAS displaced dilepton (1504.05162)
CMS displaced dilepton (1411.6977)
CMS “displaced SUSY” (1409.4789)



ATLAS displaced lepton + tracks (1504.05162)
ATLAS displaced jets (1504.03634)
CMS displaced jets (1411.6530)
CMS “displaced SUSY”



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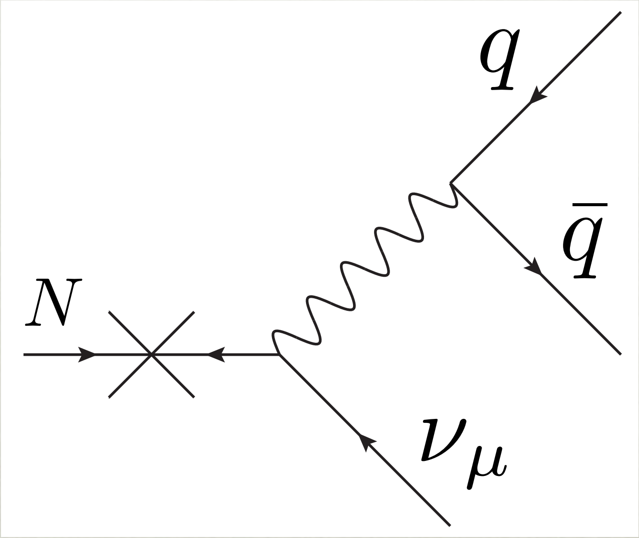
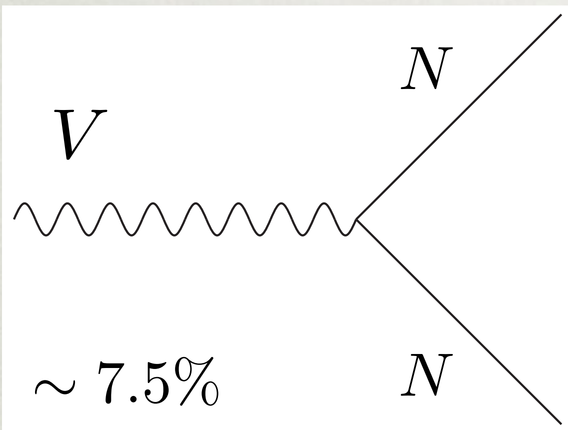


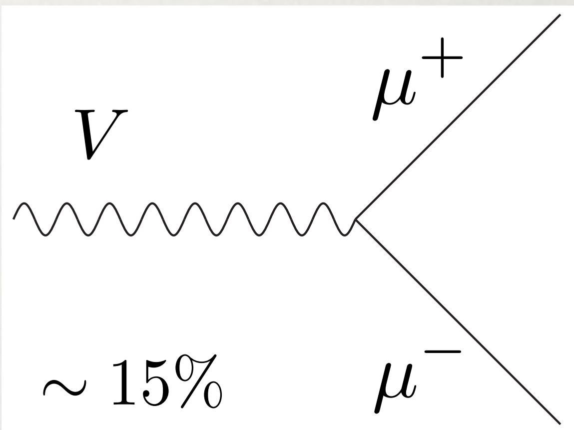
ATLAS displaced jets
CMS displaced jets

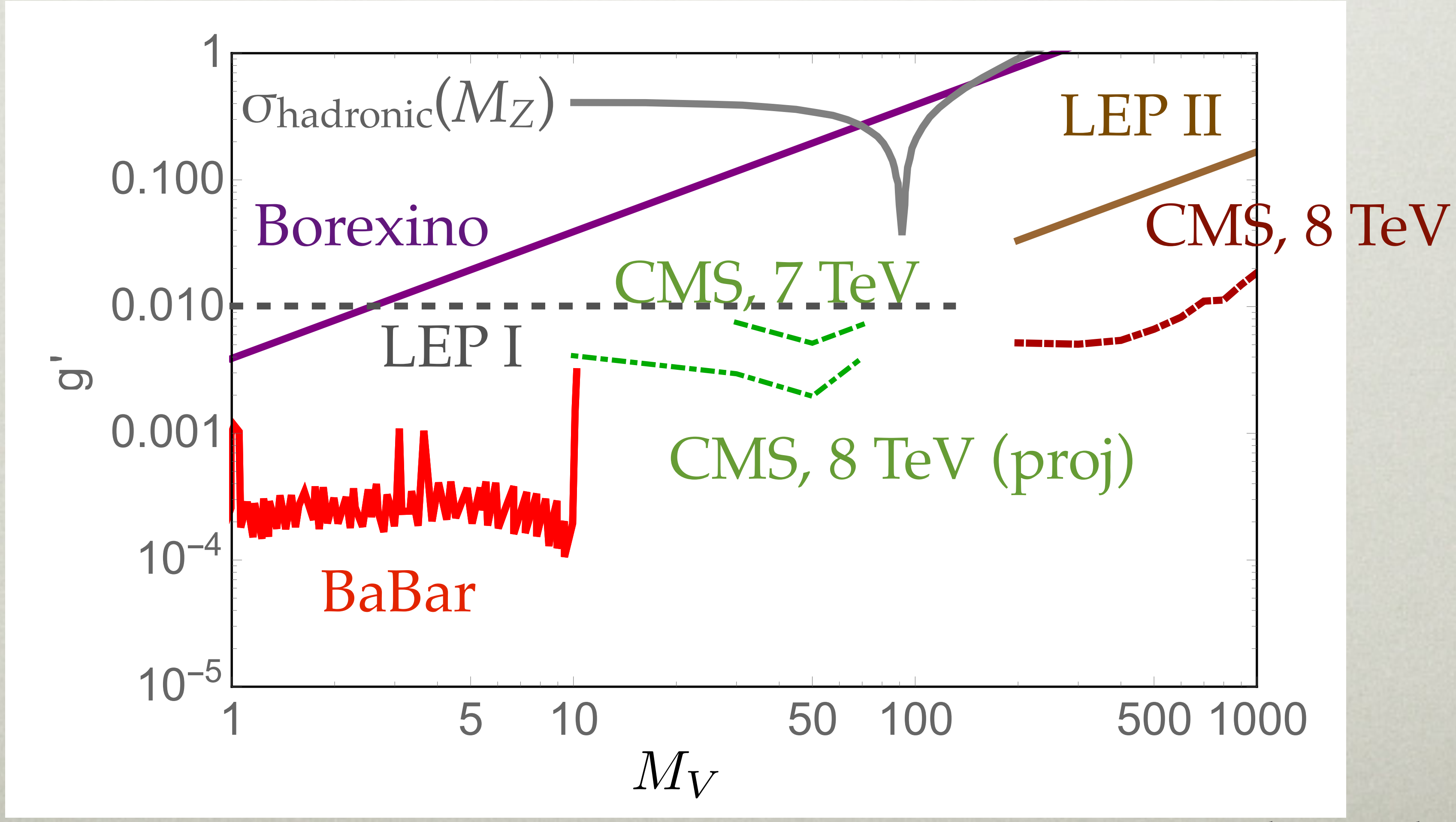
The Vector Portal

- Concrete scenario: vector V couples to B-L (all quarks, leptons); Drell-Yan production

Mohapatra, Marshak 1980; Huiti *et al.*, 2008; Aguilar-Saavedra, 2009; Basso *et al.*, 2009; Fileviez Perez, Han, Li 2009





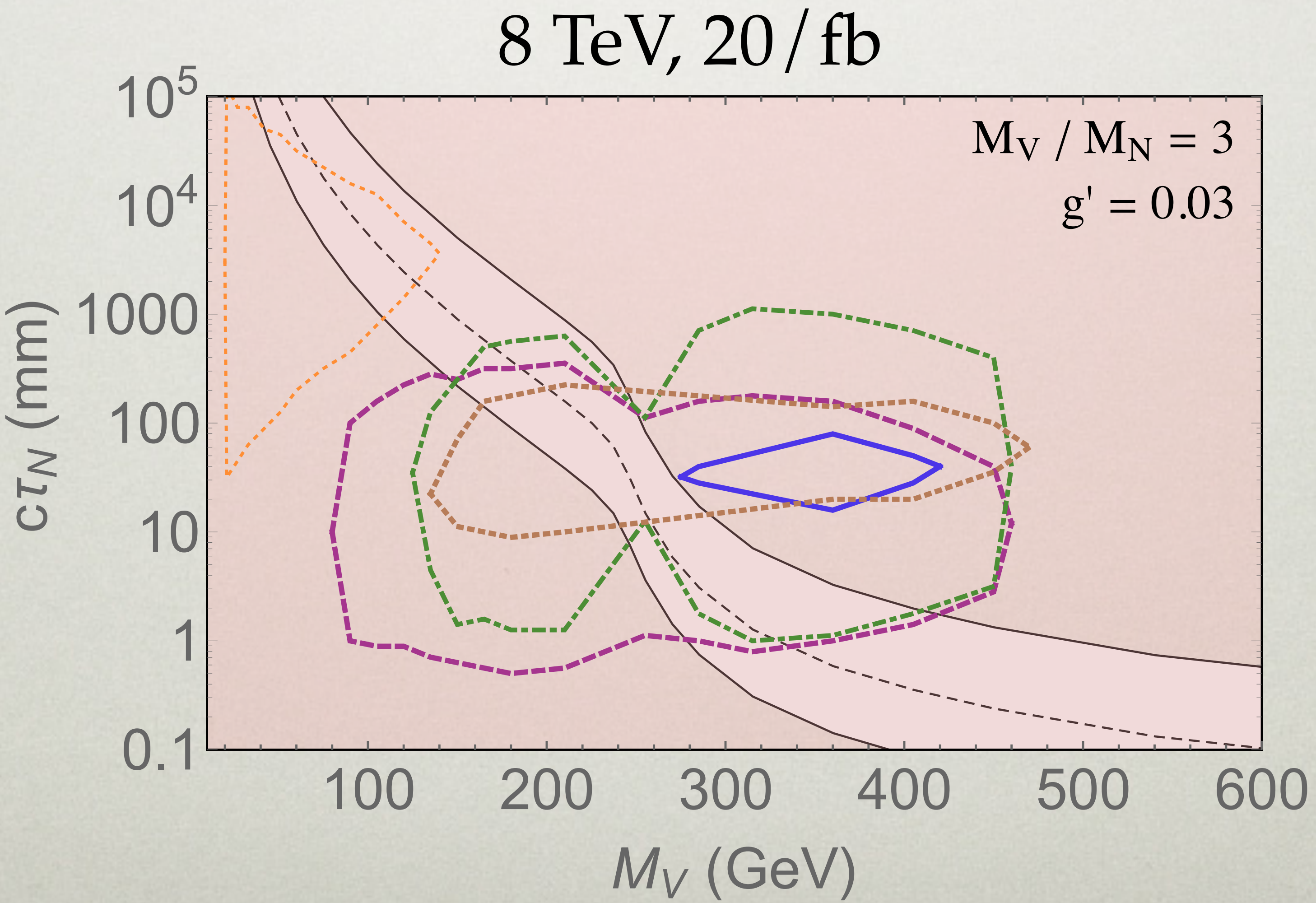


see, *e.g.*, Appelquist, Dobrescu, Hopper, 2002; …
Hoenig, Samach, Tucker-Smith 2014; …

The Vector Portal

- How do they size up? (usual caveats about theorist recasts!)

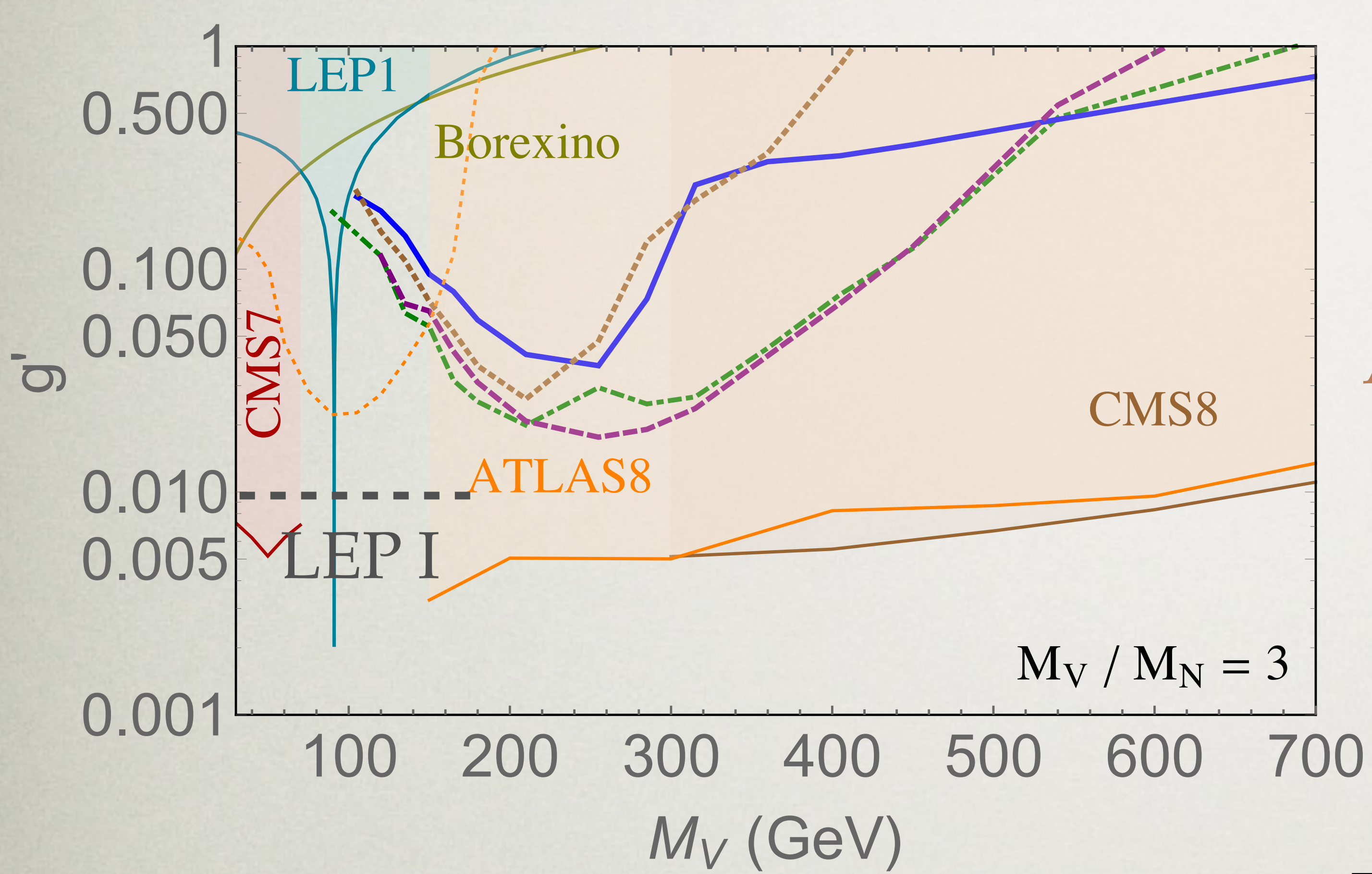
ATLAS displaced jets (MS)
CMS displaced dilepton
CMS "displaced SUSY"
ATLAS displaced dileptons
ATLAS displaced lepton + tracks



Batell, Pospelov, BS, 2016

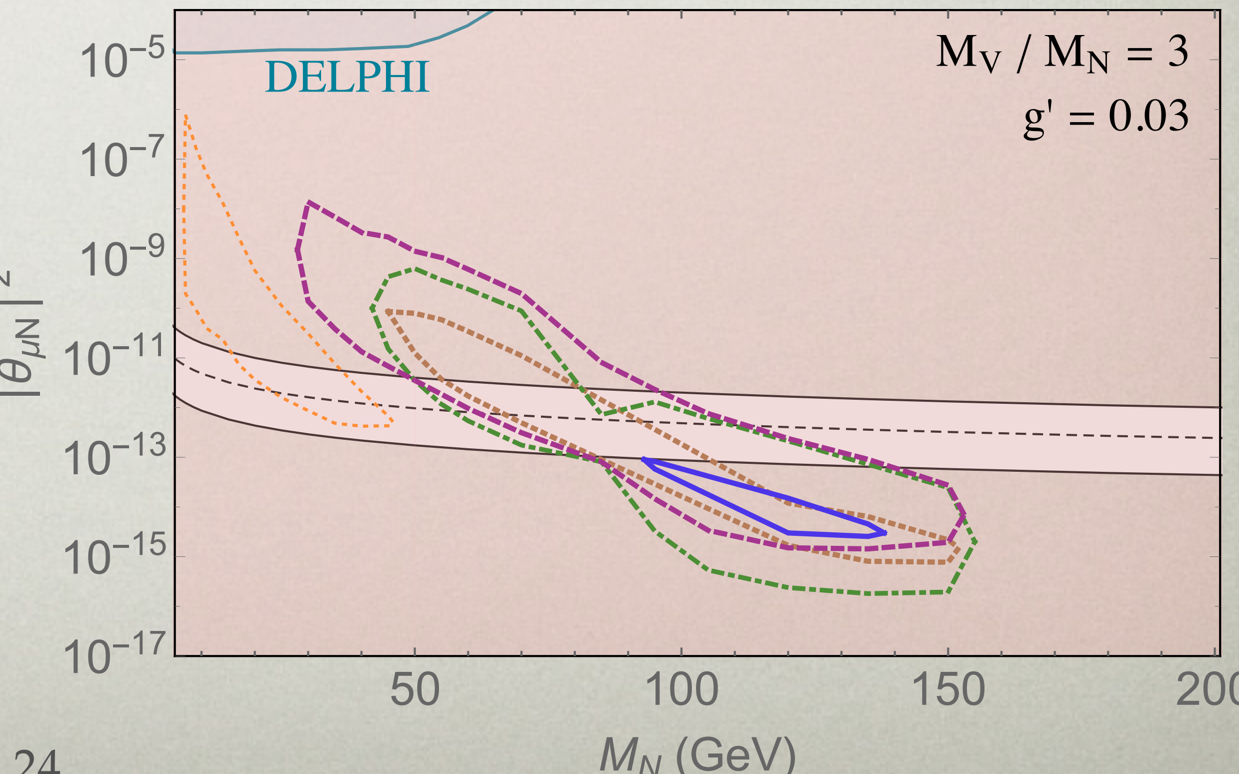
The Vector Portal

Batell, Pospelov, BS, 2016

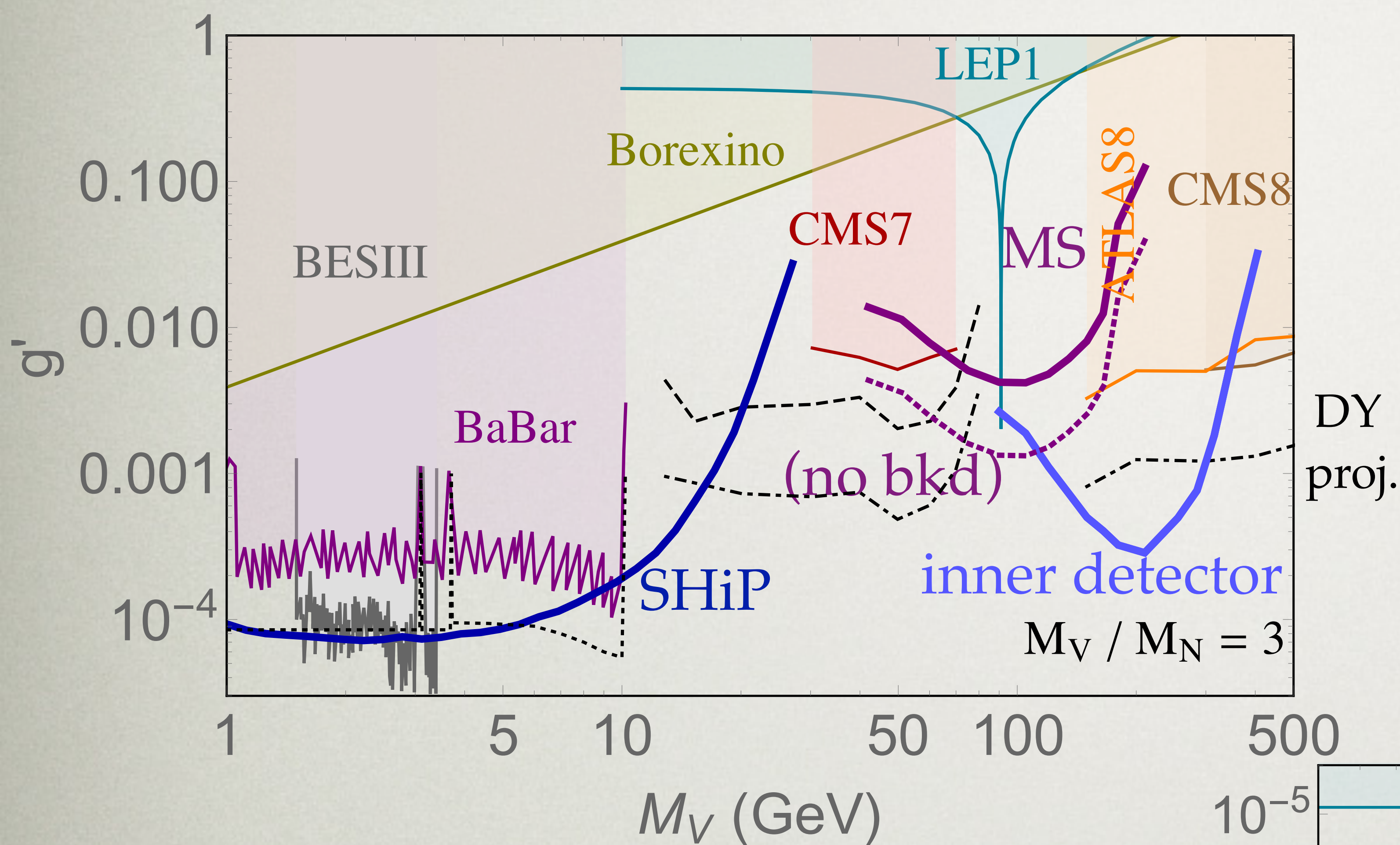


ATLAS displaced dileptons
ATLAS displaced lepton + tracks
ATLAS displaced jets (MS)
CMS displaced dilepton
CMS "displaced SUSY"

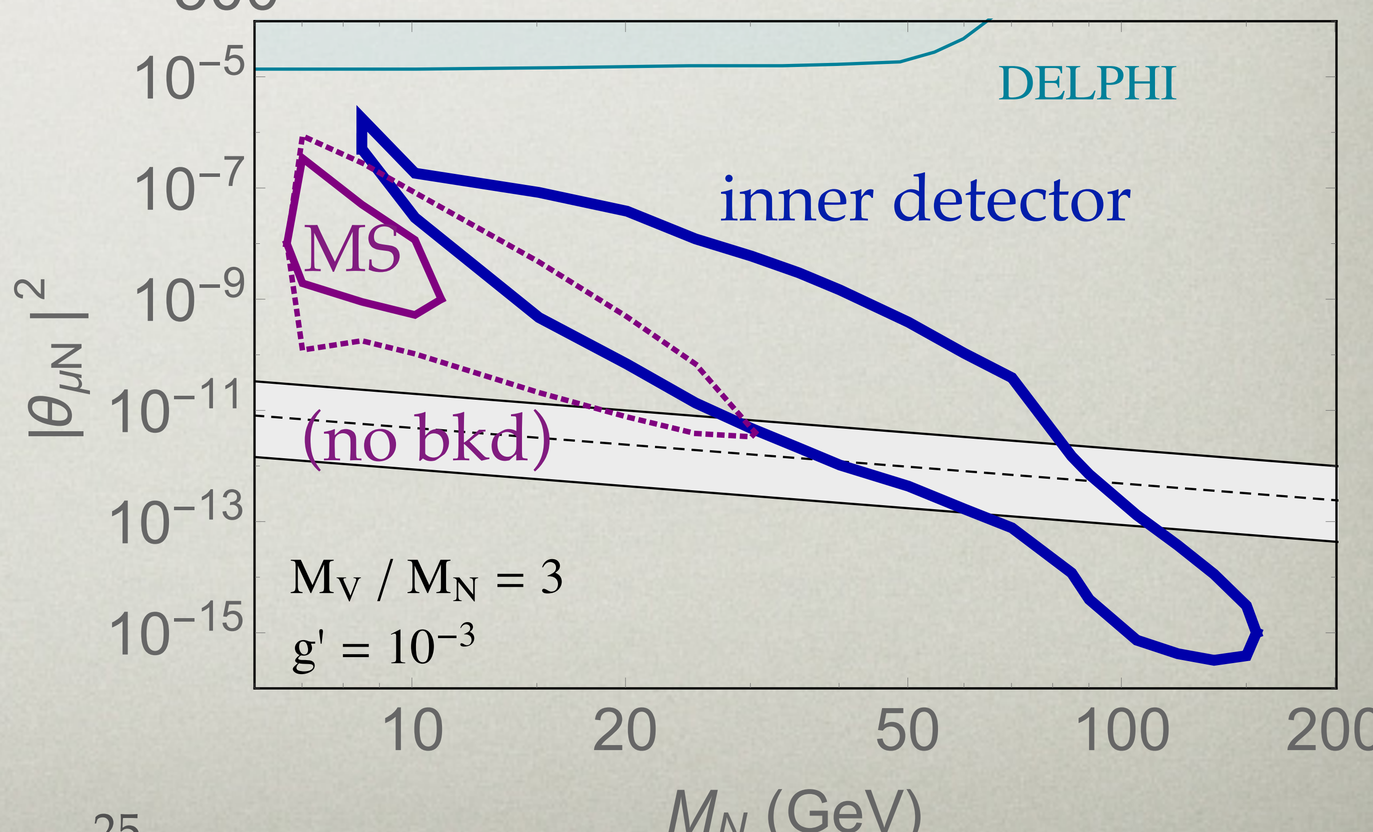
- Sensitive to see-saw parameters, but *V* already strongly constrained!



The *B-L* See-Saw In The Future



- Projections for 3000/fb
- 1 DV with 1 muon (5 tracks total), $m_{track} > 6$ GeV
- Require high-IP lepton **not associated with 1st DV**



Batell, Pospelov, BS, 2016

The Vector Portal

- Can also consider other vector portal scenarios…

Kinetic Mixing Portal: $$\mathcal{L} = -\frac{\kappa}{2} V_{\mu\nu} B^{\mu\nu} + g' V_\mu \bar{N}^c \gamma^\mu \gamma^5 N$$

Holdom, 1986

- Now, **dominant decays** of *V* are into *NN*, DV searches only discovery mode

Batell, Pospelov, BS, ongoing work

Left-Right Symmetry: $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R}$

$$pp \to W_\mathrm{R}^\pm \to \ell^\pm N$$

Pati, Salam 1974; Pati, Mohapatra, 1975; Mohapatra, Senjanovic, 1975
Keung, Senjanovic, 1983; Frank *et al.*, 2010; Das *et al.*, 2012; Han, Lewis, Ruiz, Si, 2012

- Typically in **high-mass** regime, can get very boosted *N* (“neutrino jets”)

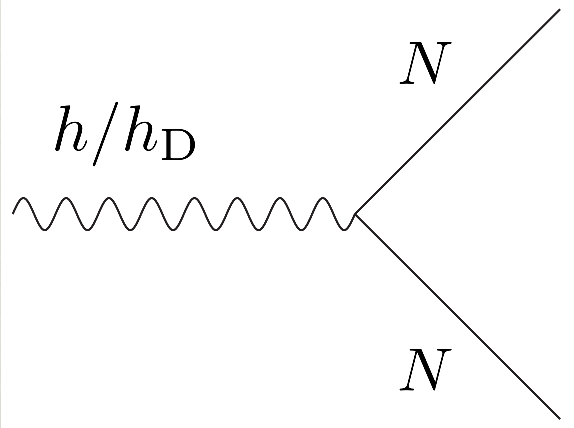
Mitra, Ruiz, Scott, Spannowsky, 2016

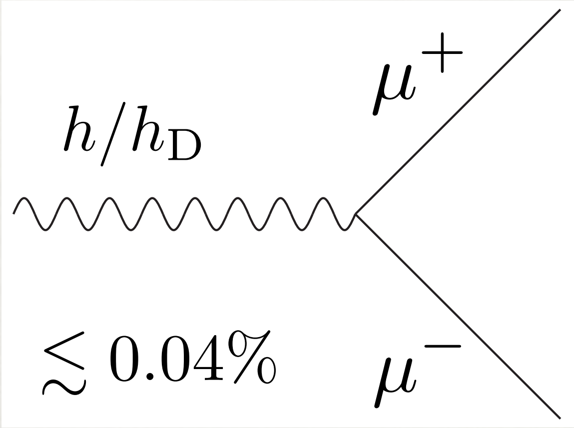
- Other possibilities: dipole couplings, …

The Scalar Portal

- Singlet scalar can also couple to *N*, mix with SM Higgs

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





- Model-independent singlet-Higgs mixing angle < 0.3

- **Current** limits from DVs in Run1 are already ~ 0.01 from DVs in rare Higgs decays!!

Batell, Pospelov, BS, ongoing work

Other Portals

- Other "types" of see-saw with new SM-charged fields
  - Type II predicts existence of **new triplet Higgs**

    Schecter and Valle, 1980; Magg and Wetterich, 1980; Cheng and Li, 1980; …
    Pheno: Akeroyd, Aoki, 2005; Han *et al.*, 2007; Akeroyd, Aoki, Sugiyama, 2007; Akeroyd, Chiang, 2009; Melfo *et al.*, 2011; …

  - Type III predicts existence of **new triplet fermions** that mix with SM leptons

    Foot, Lew, He, Joshi, 1980;
    del Aguila and Aguilar-Saavedra, 2008; Franceschini *et al.*, 2008; Fileviez Perez, 2009; Li, He, 2009; Arhrib *et al.*, 2014

- Or, the Higgs coupling to neutrinos could be different from SM
  - *e.g.*, leptophilic 2HDM

    Barnett *et* al., 1984; Barger, Hewett, Phillips, 1990; Grossman, 1994;
    Su and Thomas, 2009; Buckley, Field 2015; …

  - larger Yukawa coupling than expected: enhance asymmetry from leptogenesis & give more "natural" parameters

BS, Yavin, 2014

Summary

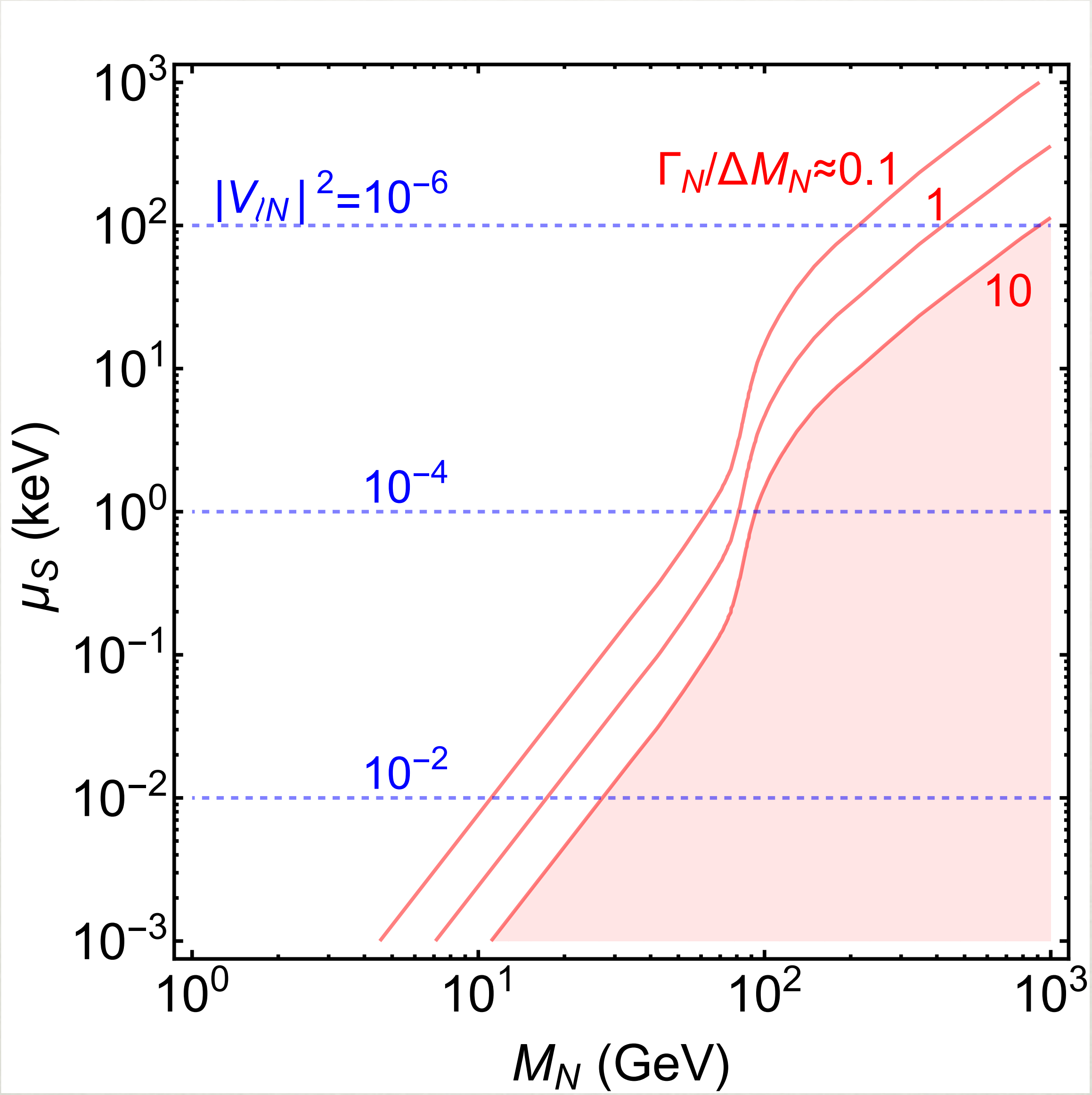
- New right-handed neutrinos are well motivated targets for searches at colliders & can give spectacular signatures!

- See-saw models generically predict macroscopic lifetimes within reach of LHC & SHiP, but rates can be small

- Need to “dig deeper” for low-mass RHNs, as well as more comprehensive searches for high-mass/portal production

Back-up slides

plot taken from Deppisch, Dev, Pilaftsis, 2015



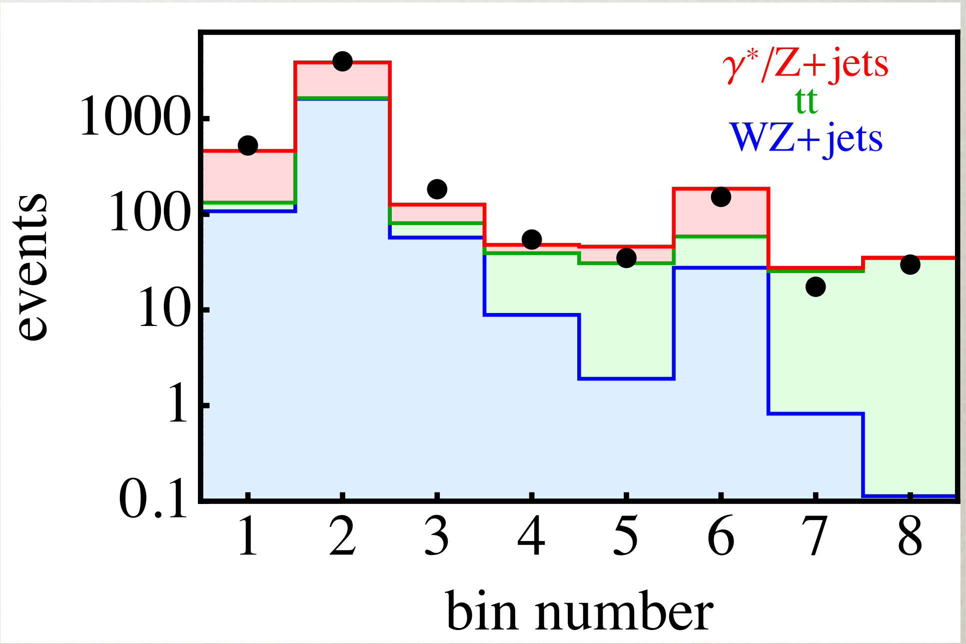
Resolved prompt decays

- Problem: these backgrounds are dominated by **jets faking lepton**
- A “fake simulator” for theorists has been proposed (Curtin, Galloway, Wacker 2013)

$\epsilon_{j\to\ell}$ = p_T-dependent probability of jet faking lepton $\times$ map from jet kinematics to lepton kinematics

CMS trilepton search (low HT, low MET)

MadGraph 5 + Pythia 6 (matched)



OSSF1, < Z | OSSF1, = Z | OSSF1, > Z | OSSF0 | OSSF1, < Z | OSSF1, = Z | OSSF1, > Z | OSSF0

0b 1b

Also checked method with ATLAS same-sign muon & CMS same-sign muon + jets analyses

The *B-L* See-Saw In The Future

Can we do better?

- The ATLAS MS search is good & hard to model, so we refrain from further speculation there (but see Coccaro *et al*, 2016)
- Displaced objects are **quite soft** ($Z' \to 6$ fermions), many searches require at least 1 very energetic lepton/object
- Vertex reconstruction efficiency small in some searches
- Other requirements can hurt, such as only using OS and/or OF leptons, vetoing additional leptons, …

The *B-L* See-Saw In The Future

Test study:

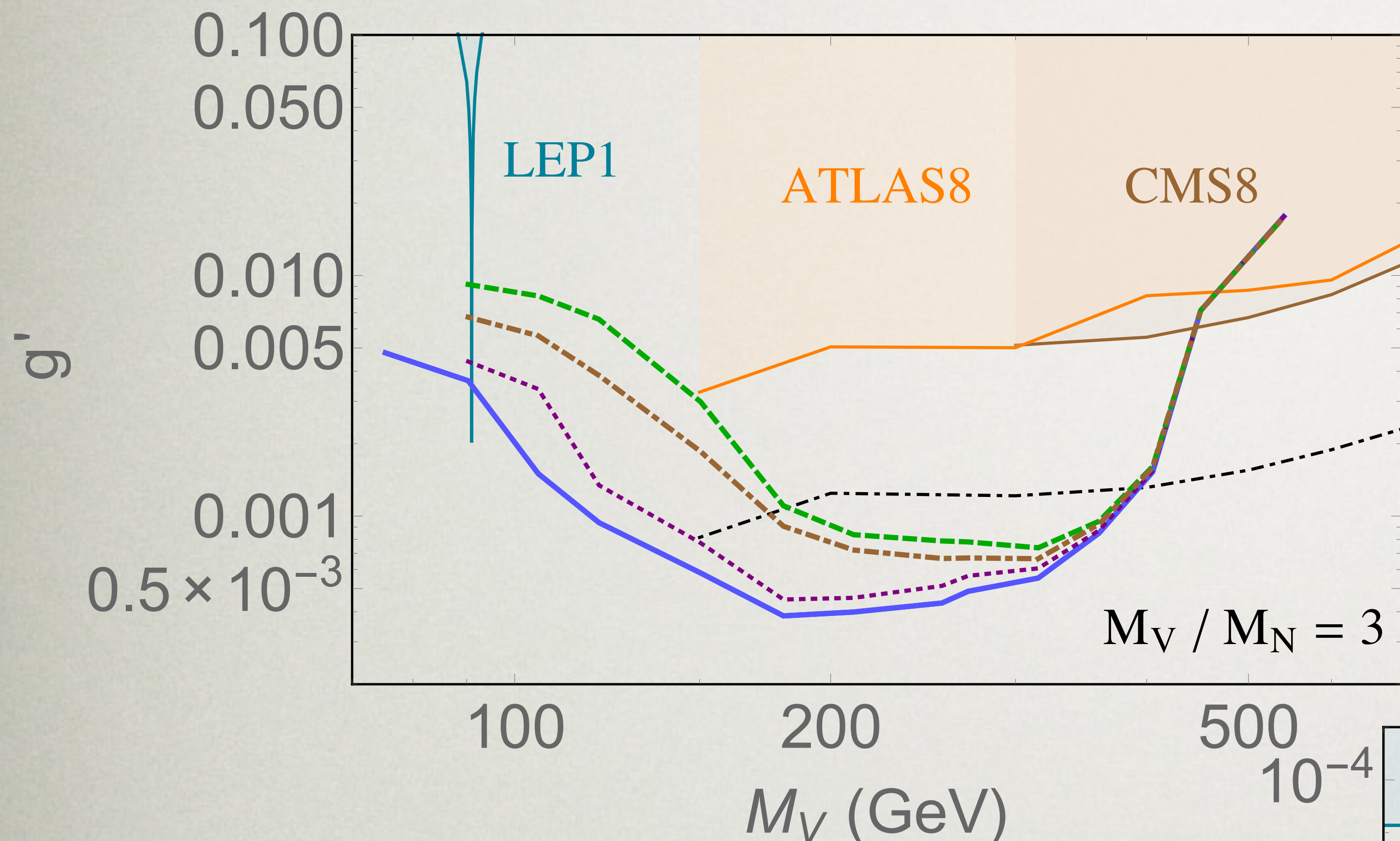
- Exploit multi-lepton, multi-displaced signatures
- Reduce thresholds/selections as much as trigger will allow
- Suppress increased backgrounds by requiring additional, unassociated displaced lepton/object
- **Caution: analysis depends on theorist modelling, so should be taken with grain(s) of salt!**

The *B-L* See-Saw In The Future

Selections:

- Trigger: dimuon (each > 15 GeV; also considered > 25 GeV)
- Require 1 DV with 1 muon (5 tracks total, > 1 GeV each), m_{track} > 6 GeV, veto back-to-back leptons, require IP of tracks and radial vtx position to be > 1 mm
- Require a high-IP lepton **not associated with 1st DV**
- Apply lepton ID efficiencies, track ID efficiencies as function of impact parameter (borrowed from CMS)
- We also did an analysis with more "pessimistic" track/DV tagging based on Liu, Tweedie 2015

The *B-L* See-Saw In The Future



baseline

stricter trigger

more pessimistic tagging

stricter trigger + more pessimistic tagging