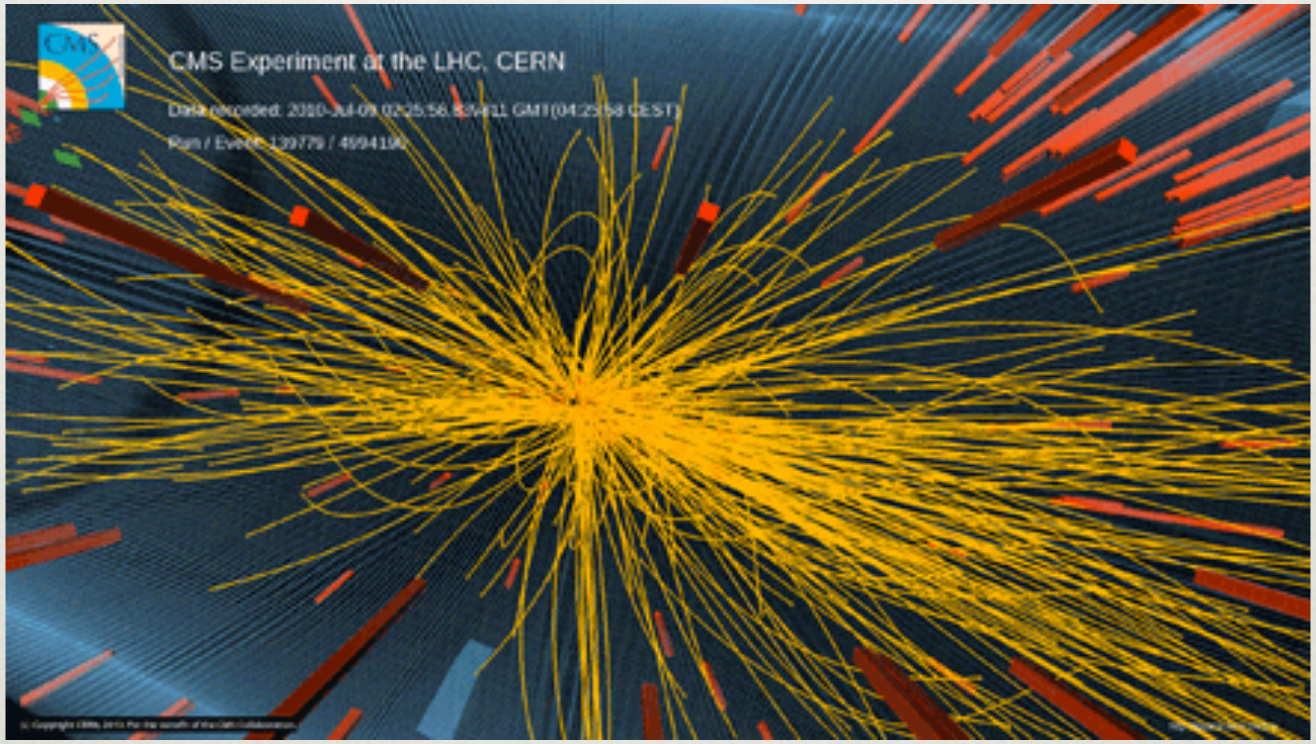
LOW-ENERGY SIGNS OF NEW PHYSICS AT HIGH-ENERGY COLLIDERS



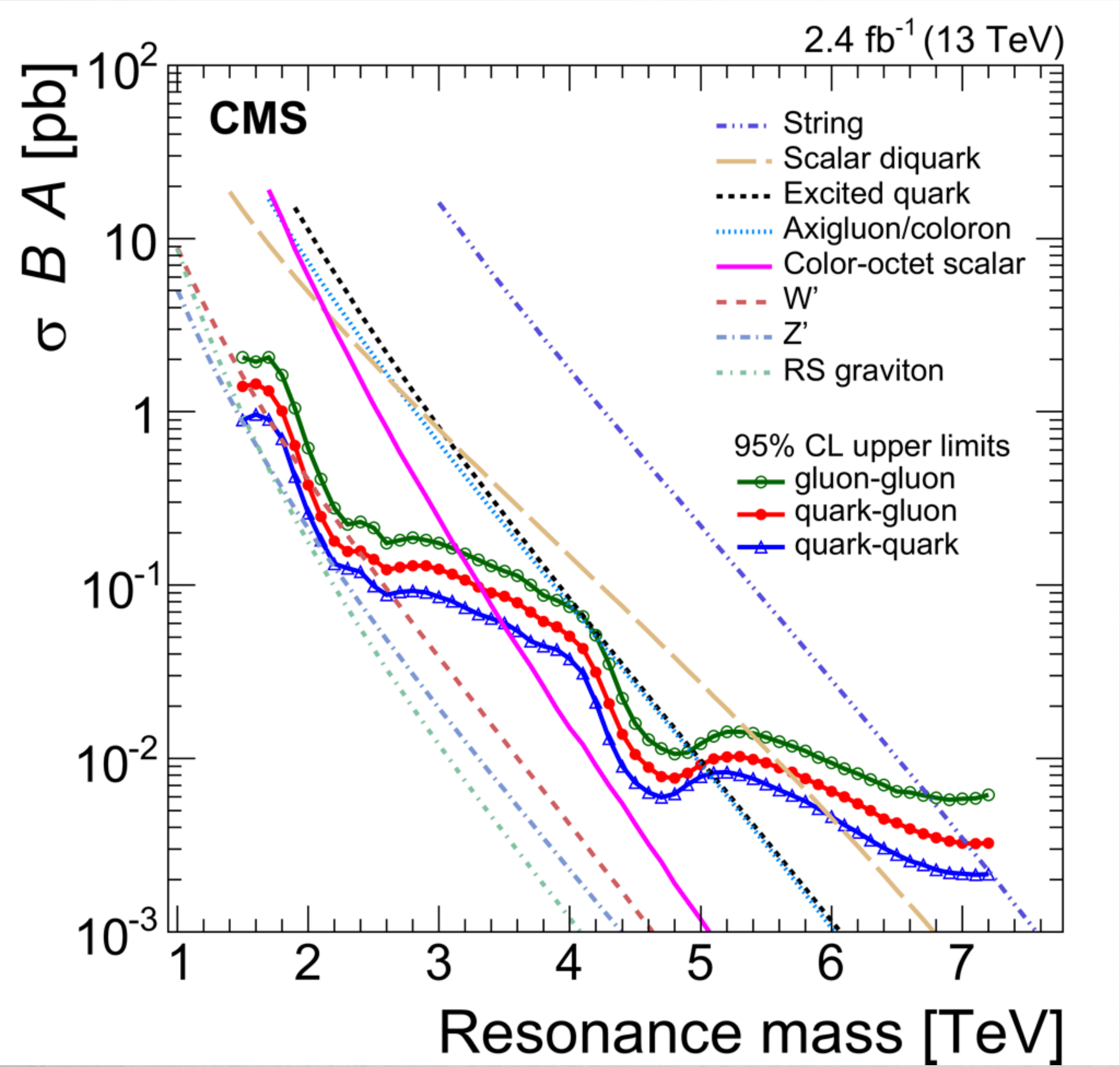
Brian Shuve -- SLAC

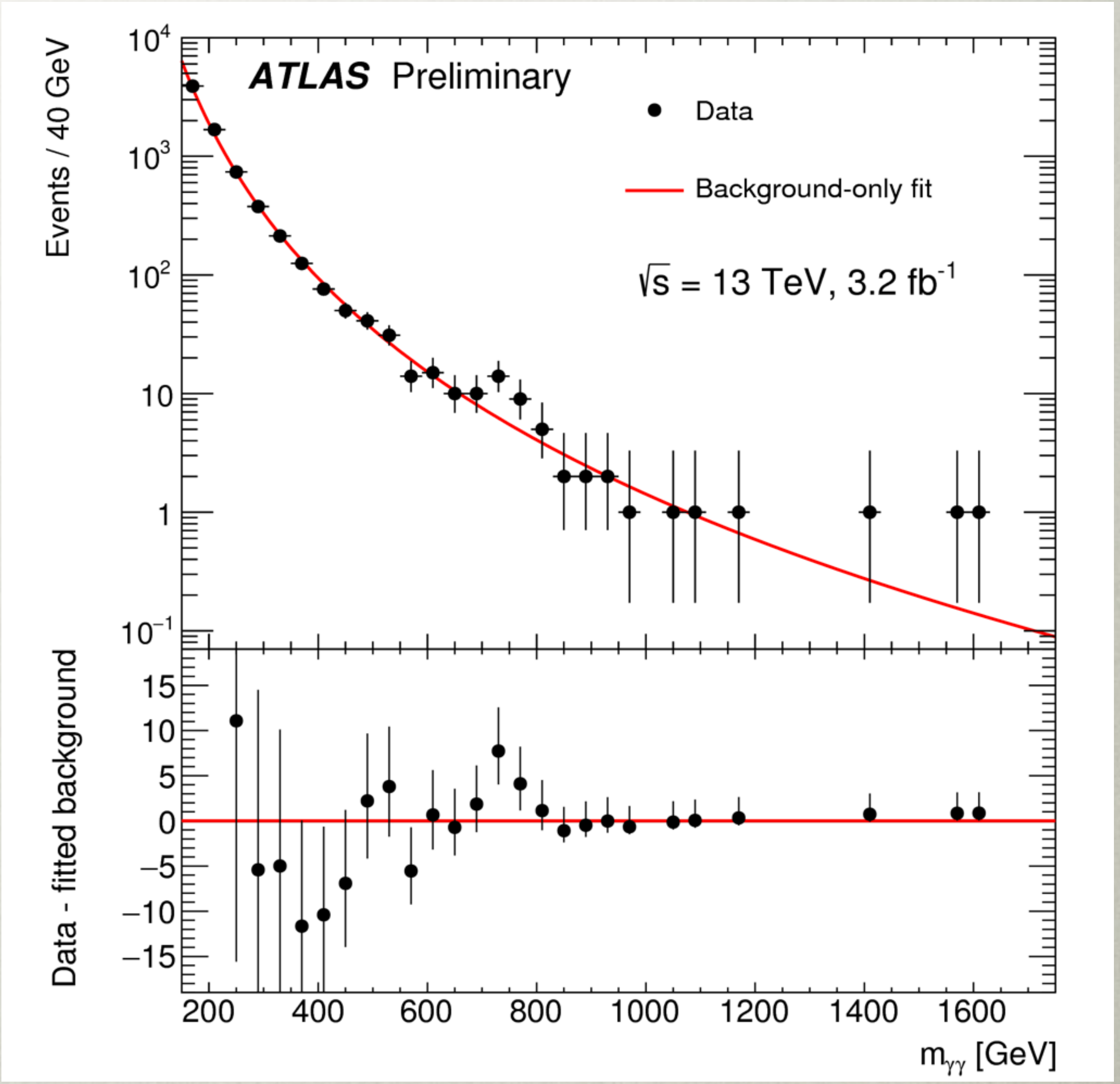
HEFTI Seminar, UC Davis

8 February 2016

Energy Frontier @ LHC

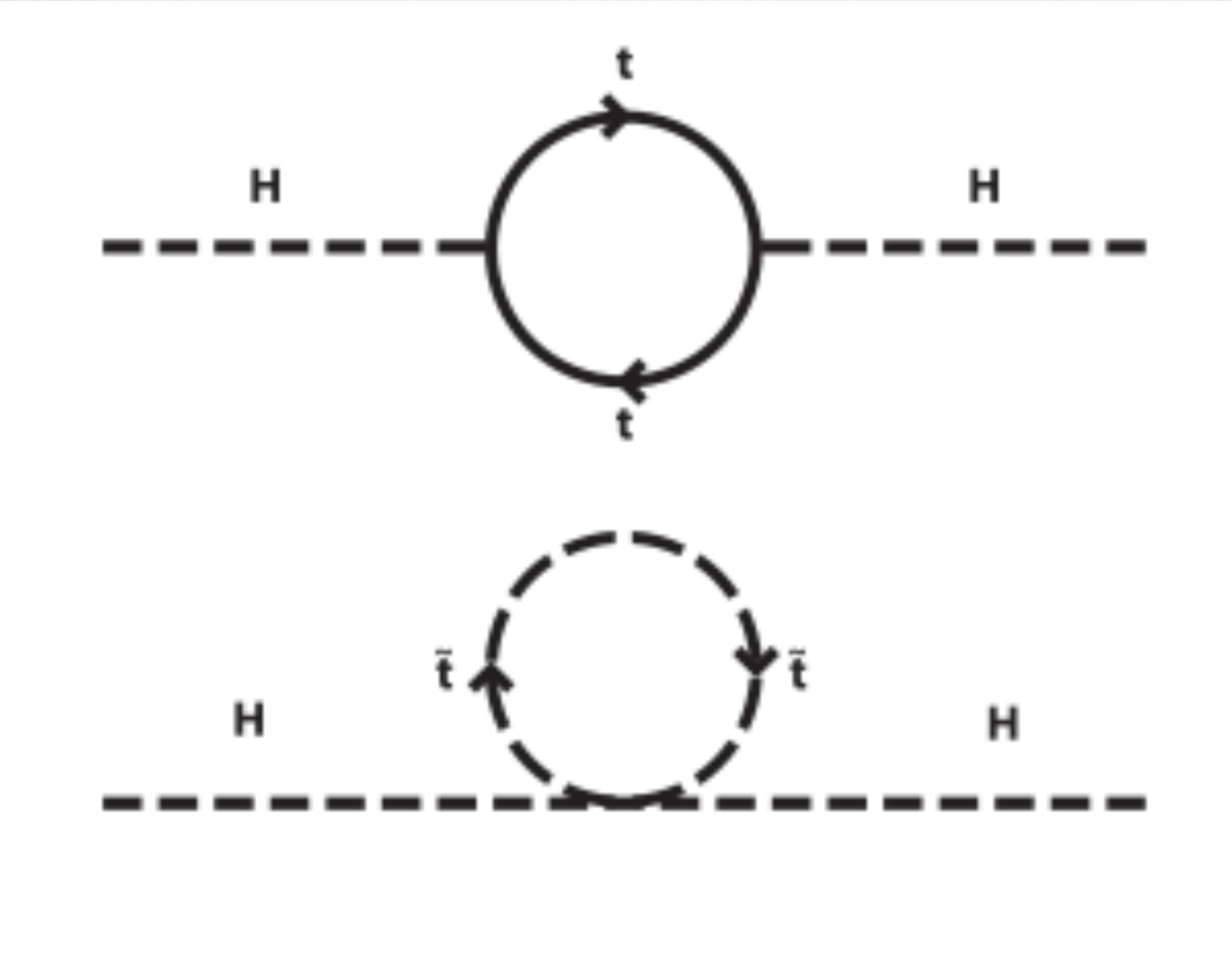
- Exploring new energy regimes



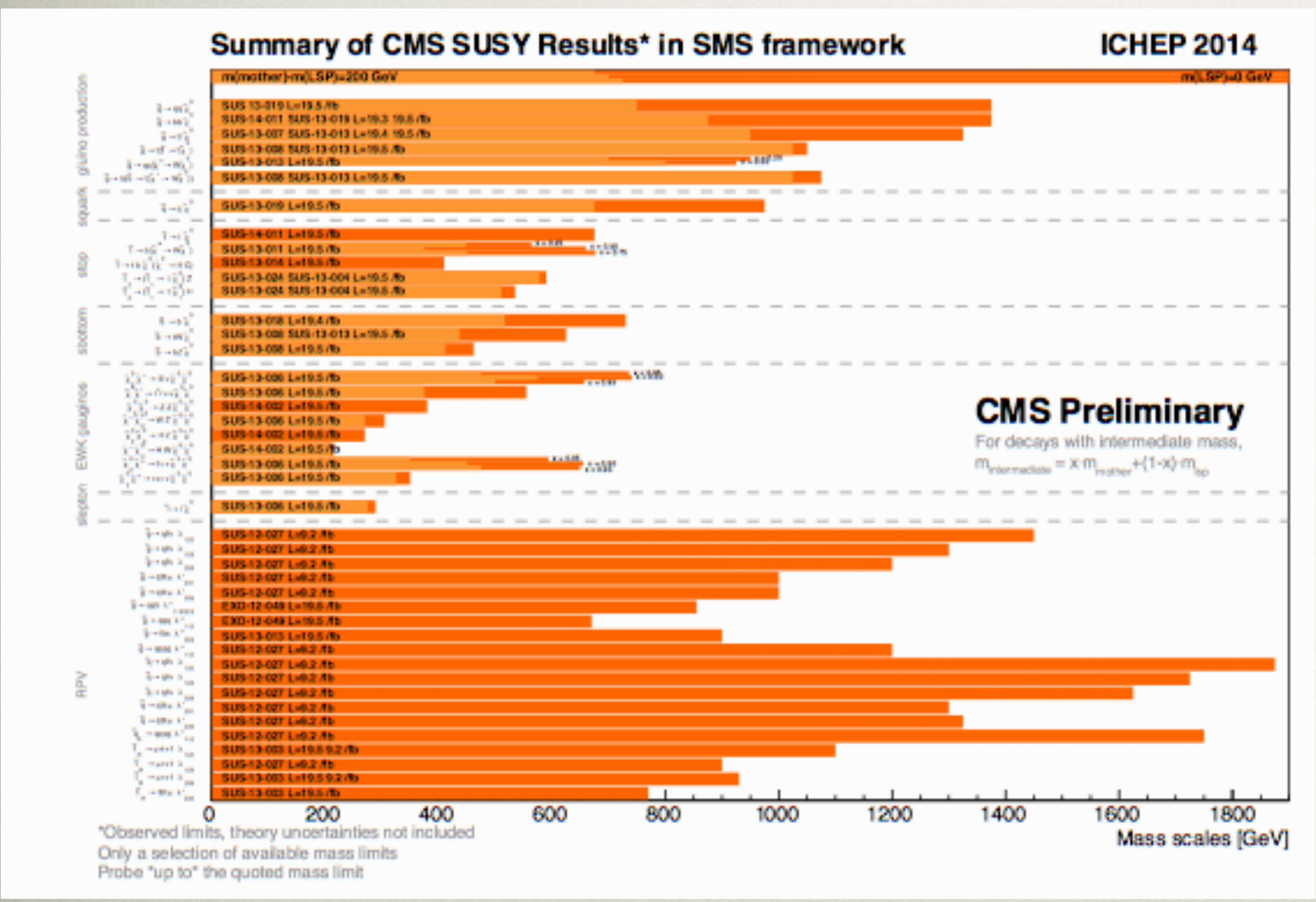


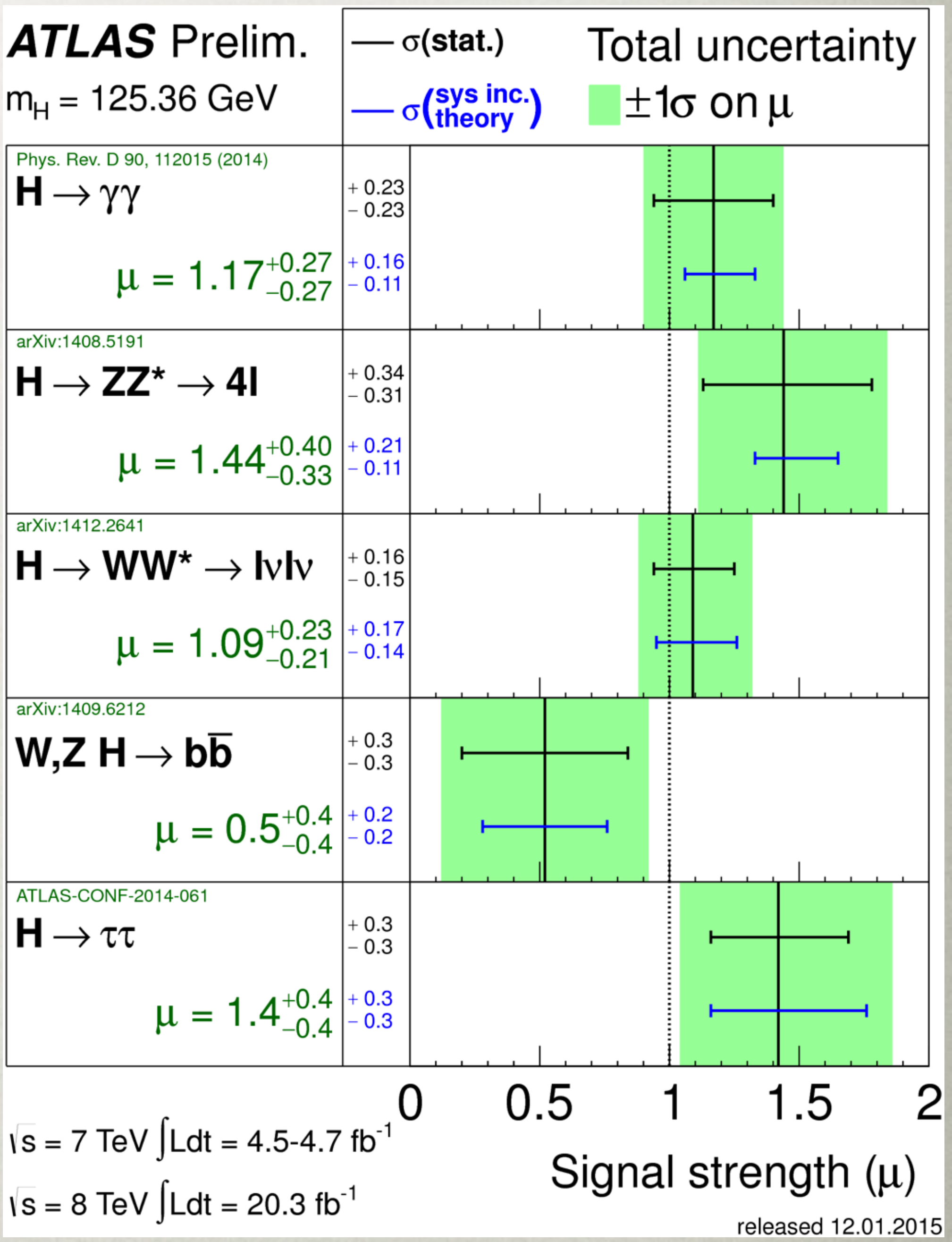
Energy Frontier @ LHC

- Expect new high-scale physics because of **naturalness**



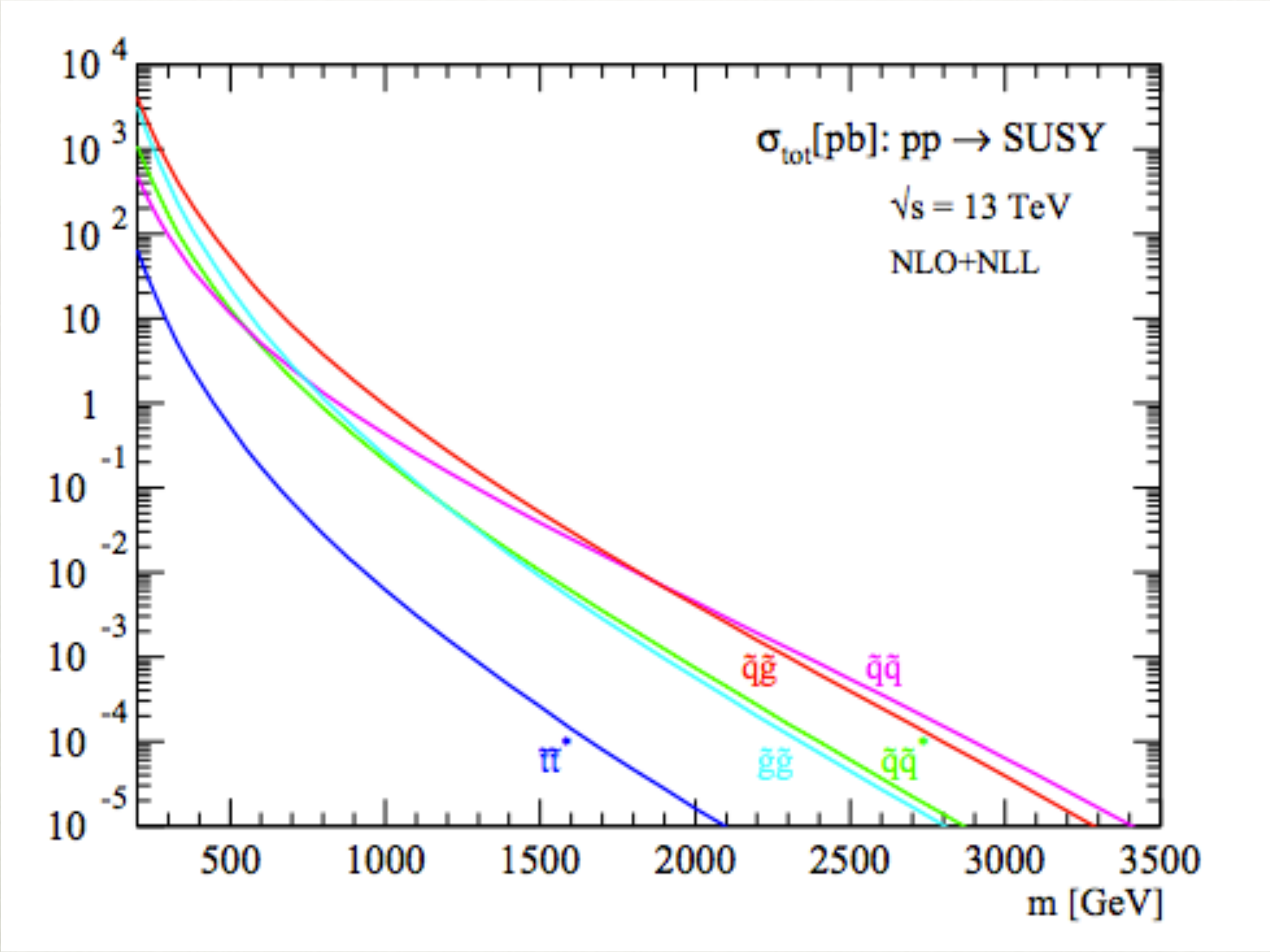
Energy Frontier @ LHC





Energy Frontier @ LHC

- Should be easy to find new, high-mass physics



- ...but diminishing returns set in quickly

Unsolved Mysteries of the SM

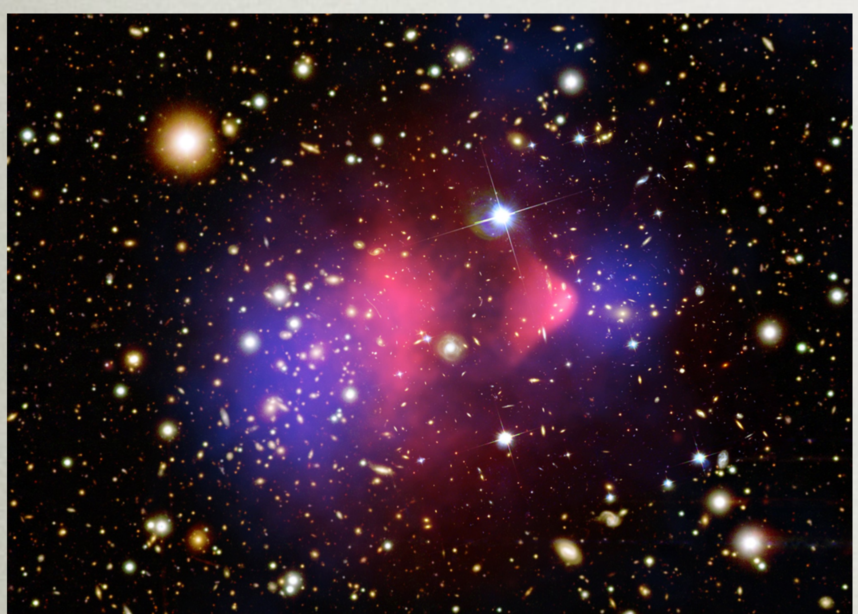
baryons | antibaryons

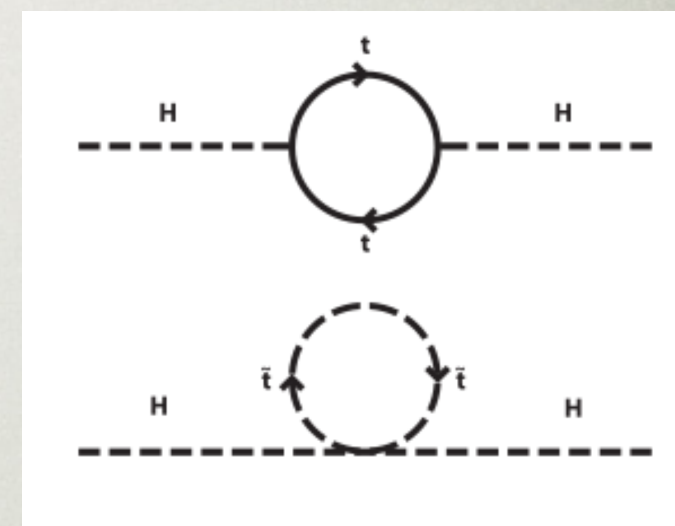
$\Omega_{DM} \sim 5\,\Omega_B$

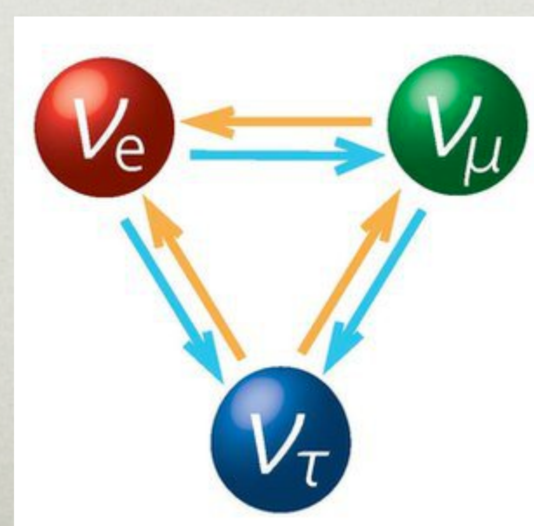
electroweak baryogenesis

leptogenesis

LSPs





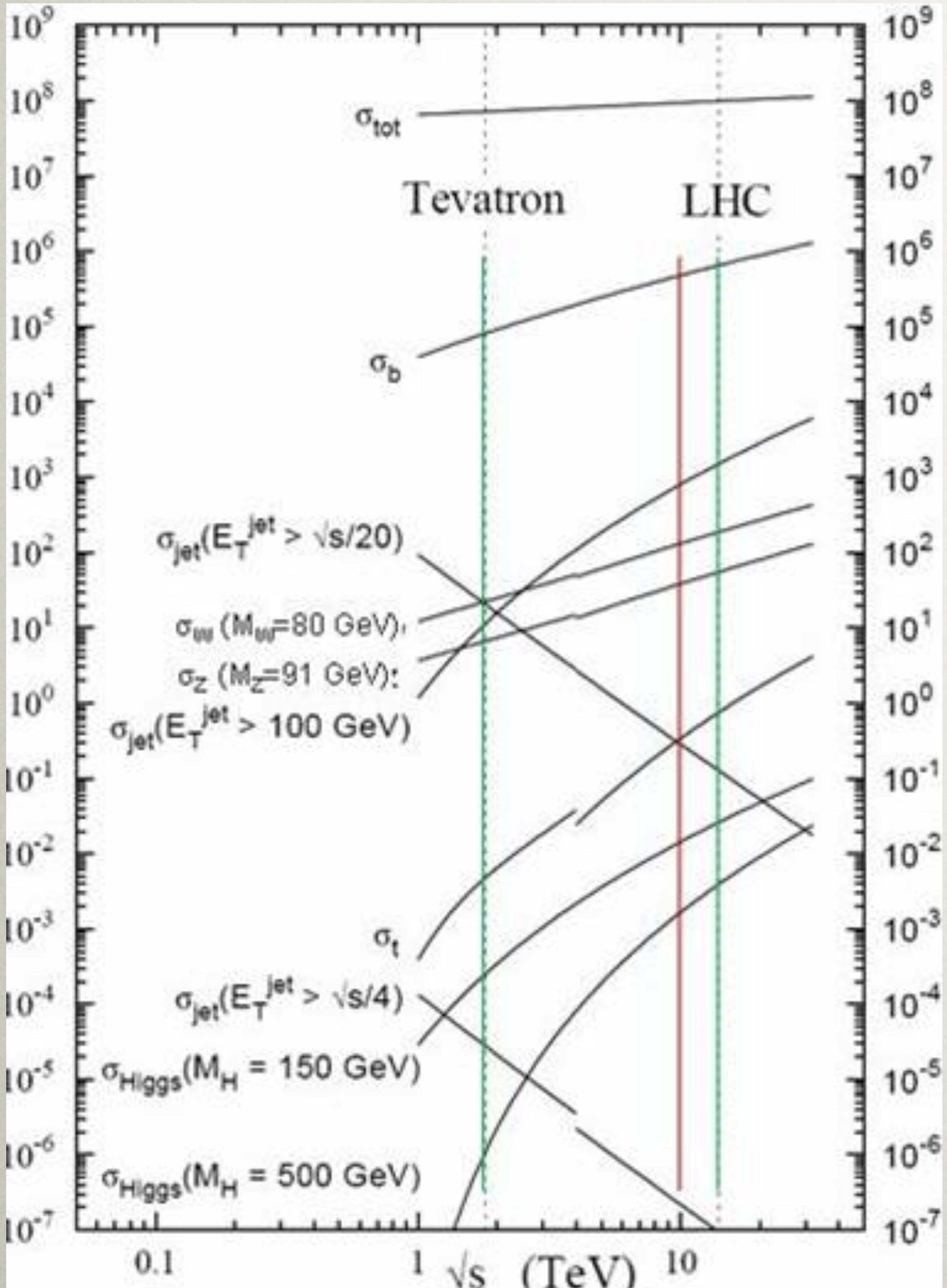


sterile neutrino DM

R-parity violation

....

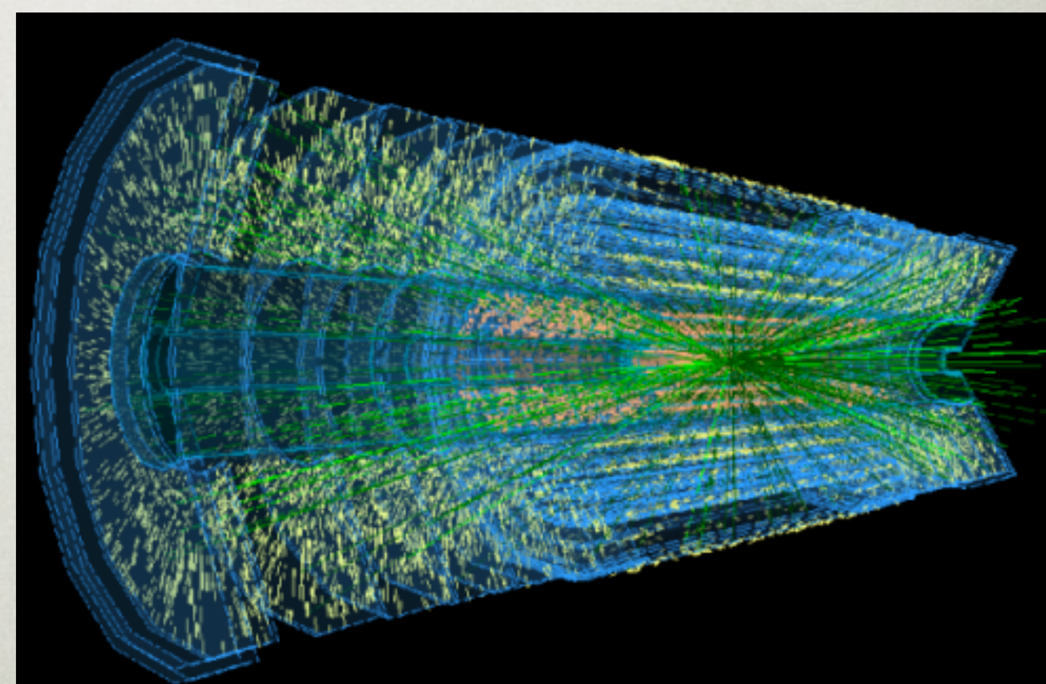
The LHC is High Intensity



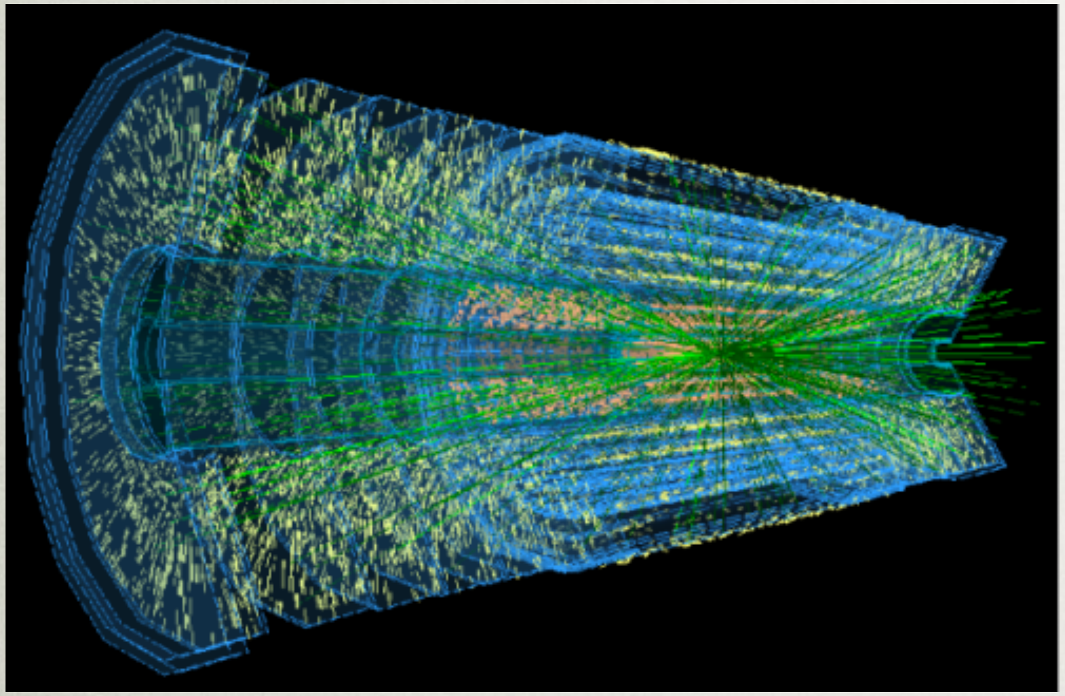
From J. Stirling

With 3000/fb @ 14 TeV:

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



Low-Energy Signatures



To see signatures of sub-weak masses, should be **spectacular**

Examples:

- long-lived particles
- multileptons

Low-Energy Signatures

Why long-lived?

$$c\tau(\pi^{\pm}) \sim 10\ \text{m}$$

$$c\tau(K^0_{\text{L}}) \sim 1\ \text{cm}$$

$$c\tau(D^{\pm}) \sim 0.1\ \text{mm}$$

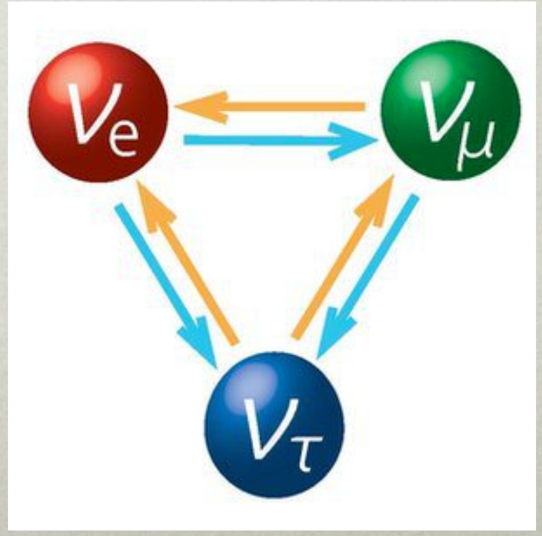
$$c\tau(B^{\pm}) \sim 0.1\ \text{mm}$$

$$c\tau(J/\psi) \sim 1\ \text{pm}$$

- Small mixing angles
- Approximate symmetries
- Decays through heavy, off-shell states (*W*)

Why multileptons?

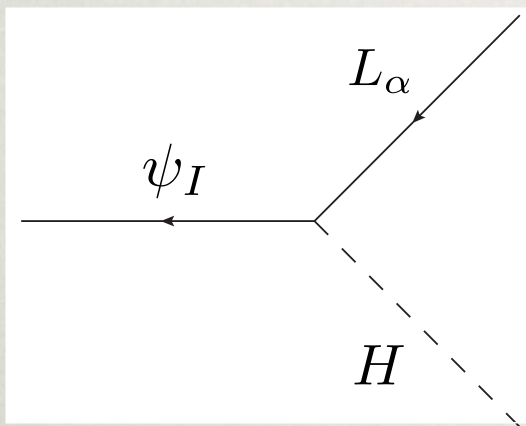
baryons | antibaryons



Hidden Sector Portals

- Dominant couplings of new singlets are via **renormalizable portals**

NEUTRINO PORTAL

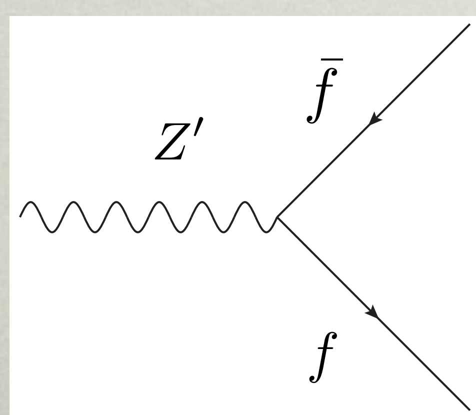


$$\mathcal{L}_\nu = y_{I\alpha}\,\bar{\psi}_I H L_\alpha$$

VECTOR PORTAL

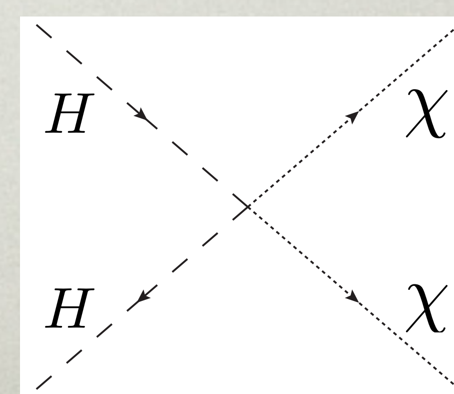
$$\mathcal{L}_{\text{vector}} = -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

Z′ PORTAL



$$\mathcal{L}_{Z'} = g_{Z'}\,\bar{f}_{\text{SM}}\gamma^\mu f_{\text{SM}} Z'_\mu$$

HIGGS PORTAL



$$\mathcal{L}_H = -\lambda |H|^2 |\chi|^2$$

Outline

- **Soft signatures of baryon and lepton number violation**
    - The neutrino portal and leptogenesis
    - The Z' portal: discovery of new B/L gauge forces

- **Soft signatures of dark matter**
    - The vector portal and inelastic dark matter

Motivations: Neutrino Masses

- Simplest UV completion: RH neutrinos (Type-I See-saw)

$$\mathcal{L}_{\nu\mathrm{MSM}} = F_{\alpha I} L_\alpha \Phi N_I + \frac{M_I}{2} N_I^2 \qquad (m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

- For fixed $\langle\Phi\rangle^2$ and m_ν ~ 0.1 eV, we have $M_N \sim \mathrm{GeV}\left(\frac{F^2}{10^{-14}}\right)$
  - Larger couplings also possible with additional symmetries

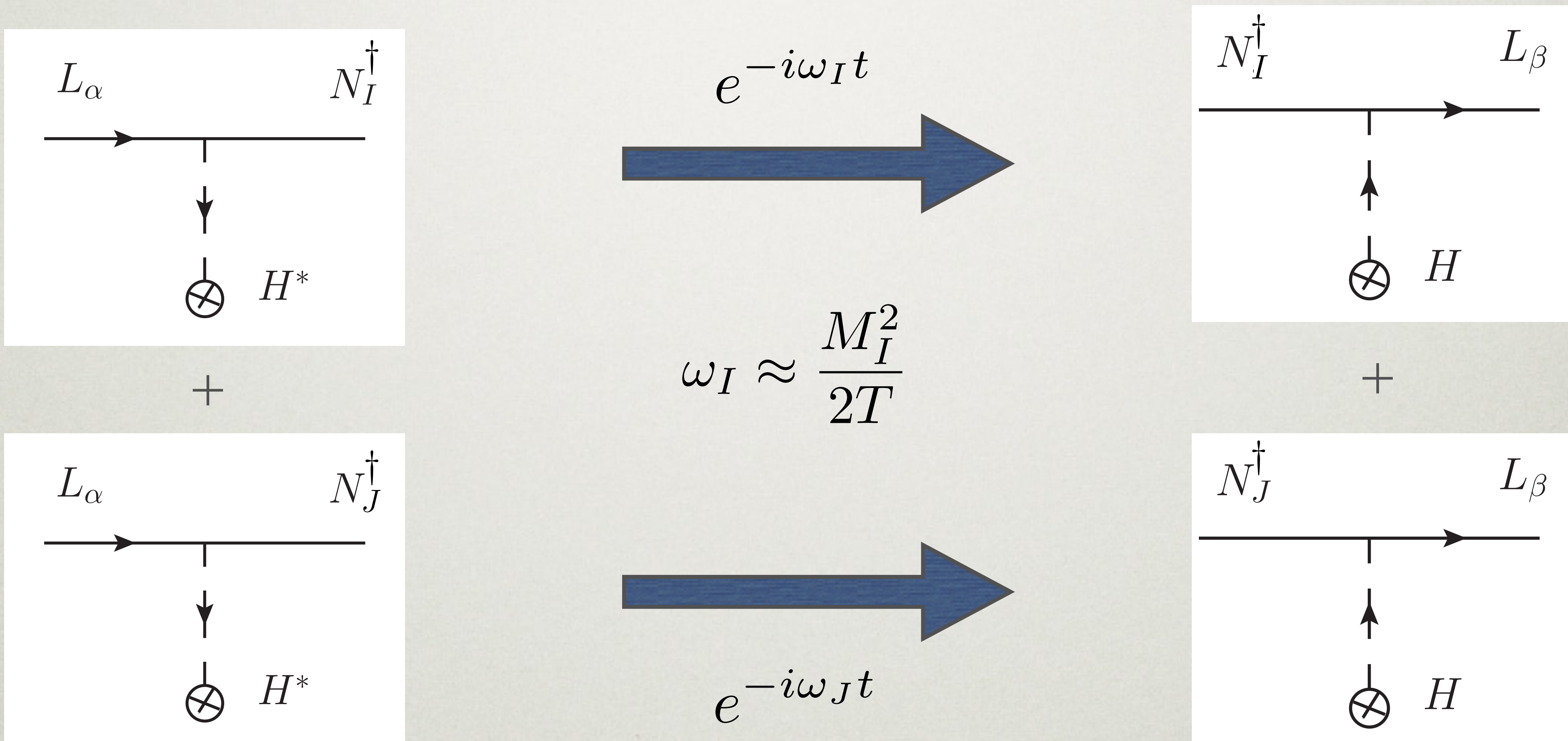
- Lepton asymmetry can also be generated by the **decay** of a primordial abundance of N (Fukugita, Yanagida 1986)

$$\Gamma(N \to L\Phi) \neq \Gamma(N \to \bar{L}\Phi^*) \qquad M_N \gtrsim 100\ \mathrm{GeV}$$

Motivations: Leptogenesis

- Asymmetry can also be generated by the **production and oscillation** of N

Akhmedov, Rubakov, Smirnov, hep-ph/9803255; Asaka, Shaposhnikov, hep-ph/0505013
for more natural models & pheno, see BS, Yavin, 1401.2459



$$\Gamma(L_\alpha \to L_\beta) - \Gamma(\bar{L}_\alpha \to \bar{L}_\beta) \sim \mathrm{Im}(F^4)\mathrm{Im}[e^{-i(M_I^2 - M_J^2)t/T}]$$

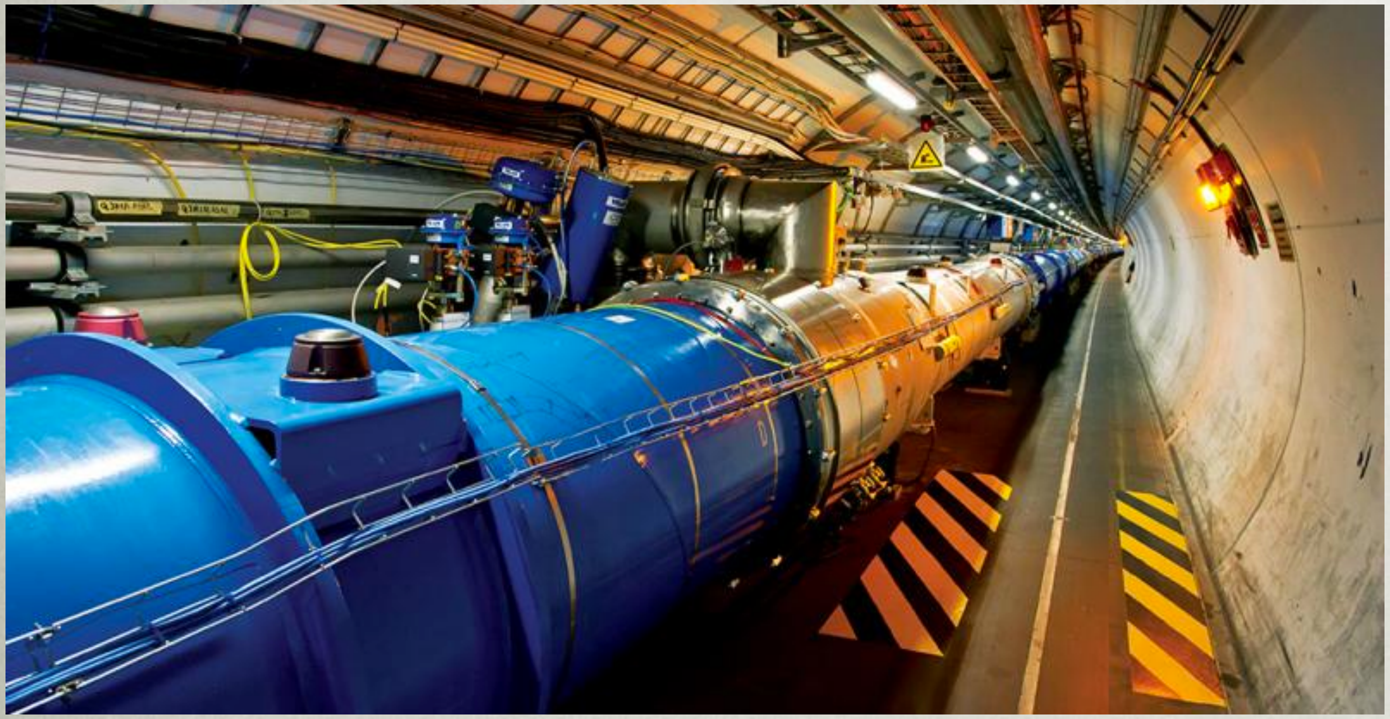
becomes large at $T \gg M$

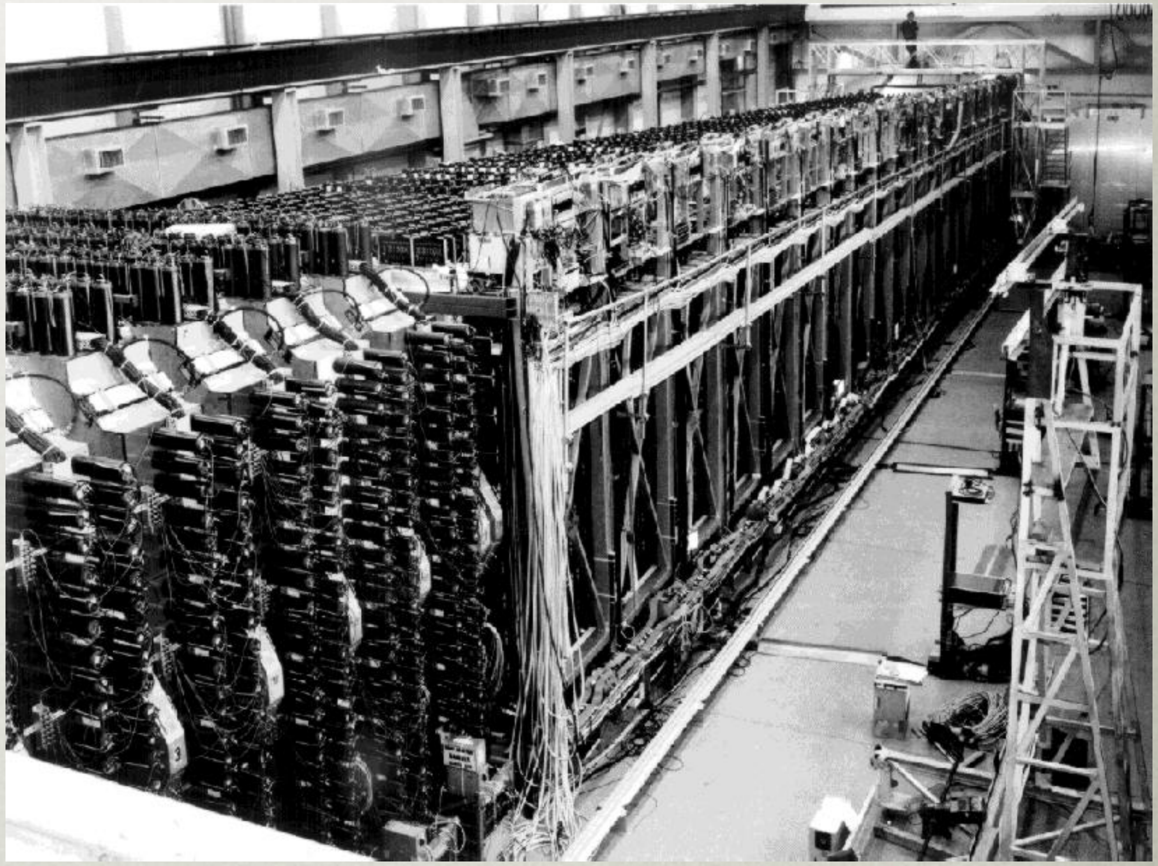
- Asymmetry lasts until after electroweak transition: $M_N \lesssim 100$ GeV

Motivations: Leptogenesis

$$M_N \lesssim 100 \text{ GeV}$$

- *N* can be directly discovered at accelerators!

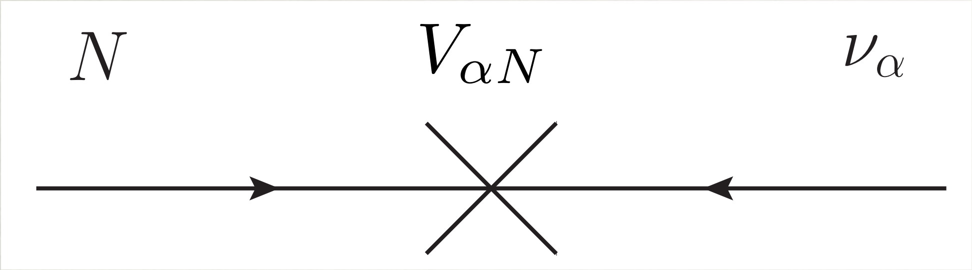




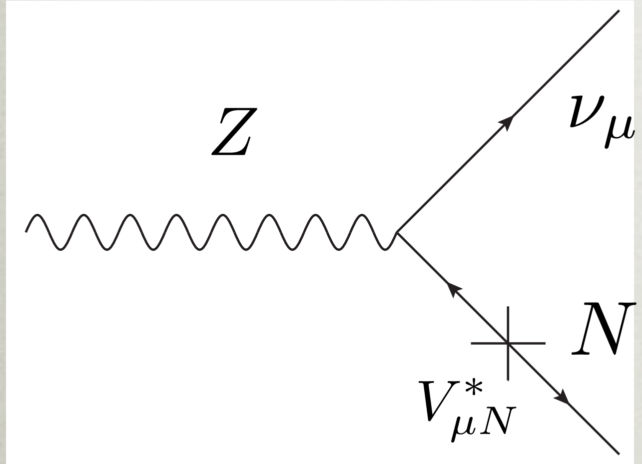
- Also indirect probes (BS, Yavin, 1401.2459)

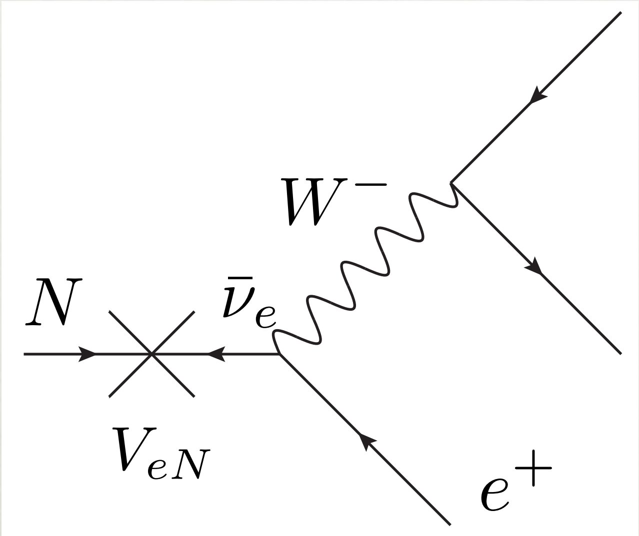
Neutrinos at Colliders

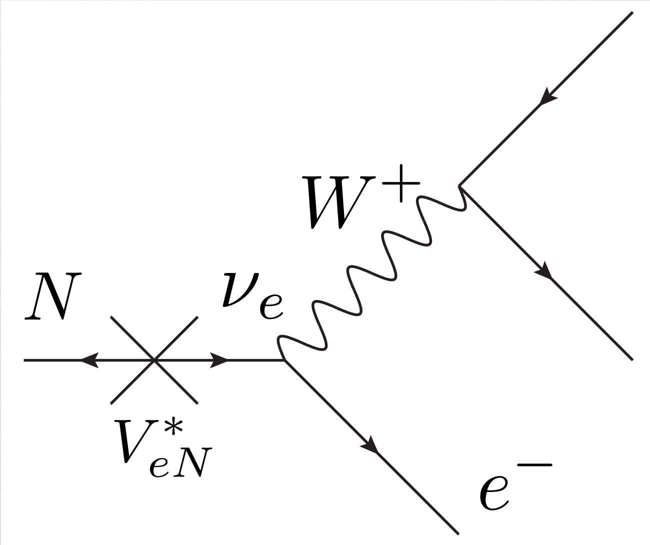
- After EWSB, the LH and RH neutrinos mix



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



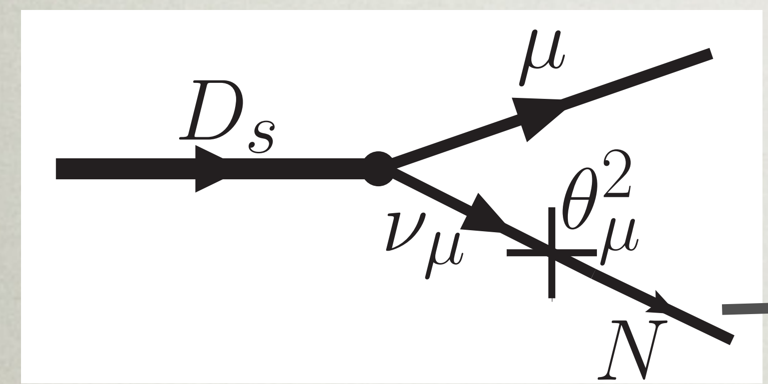


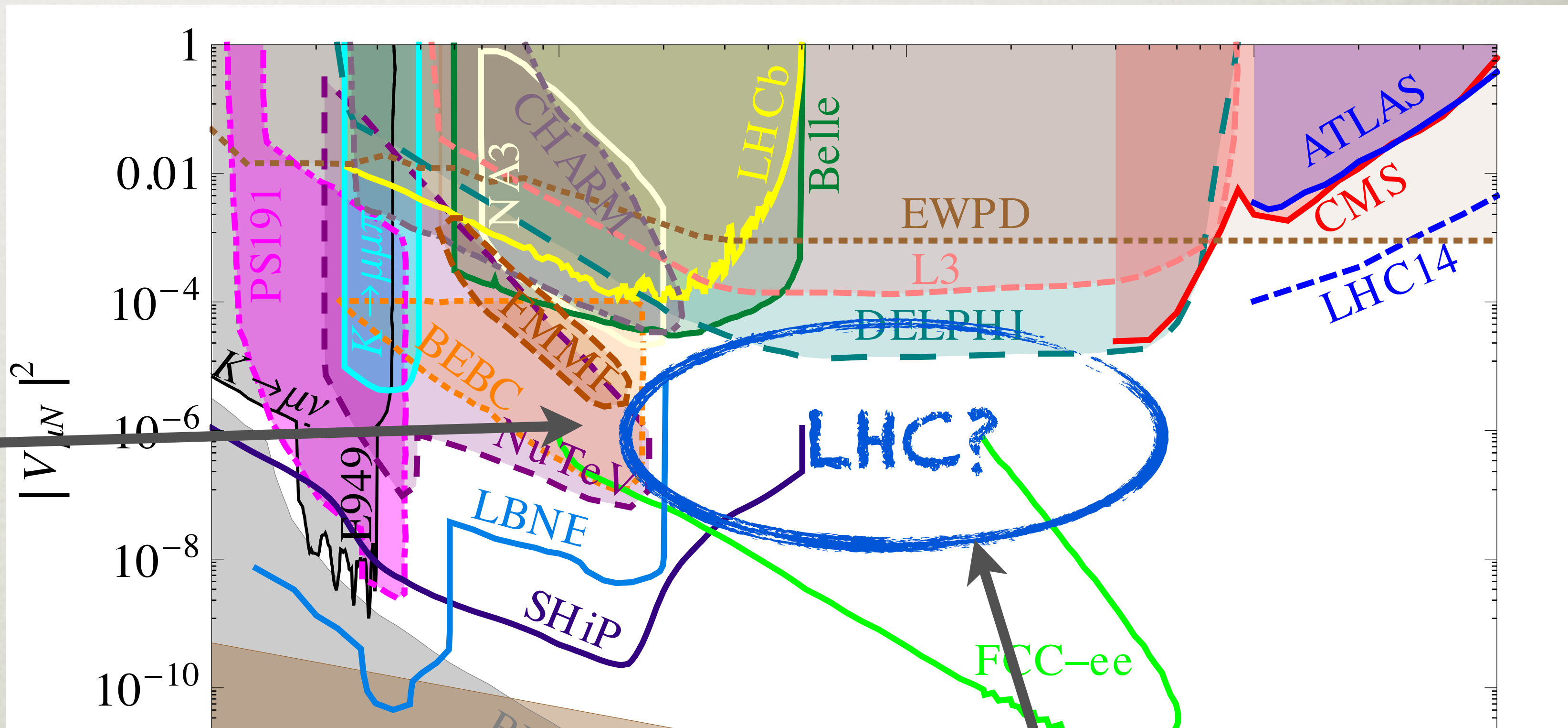


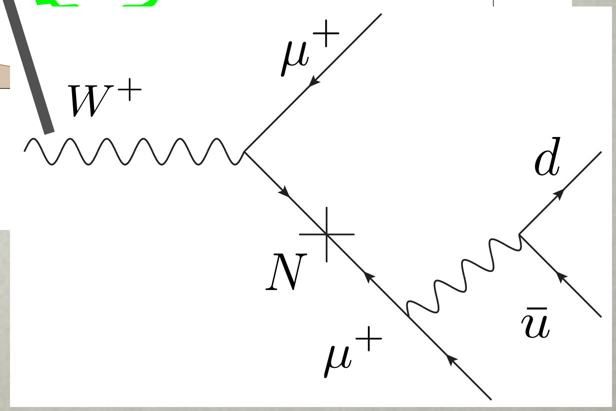
$$\Gamma_N \sim |V_{\alpha N}|^2 G_{\mathrm{F}}^2 M_N^5$$

Neutrinos at Colliders: Status

- **Simplified Model**
  - M_N
  - $|V_{\mu N}|$ (single-flavour mixing)







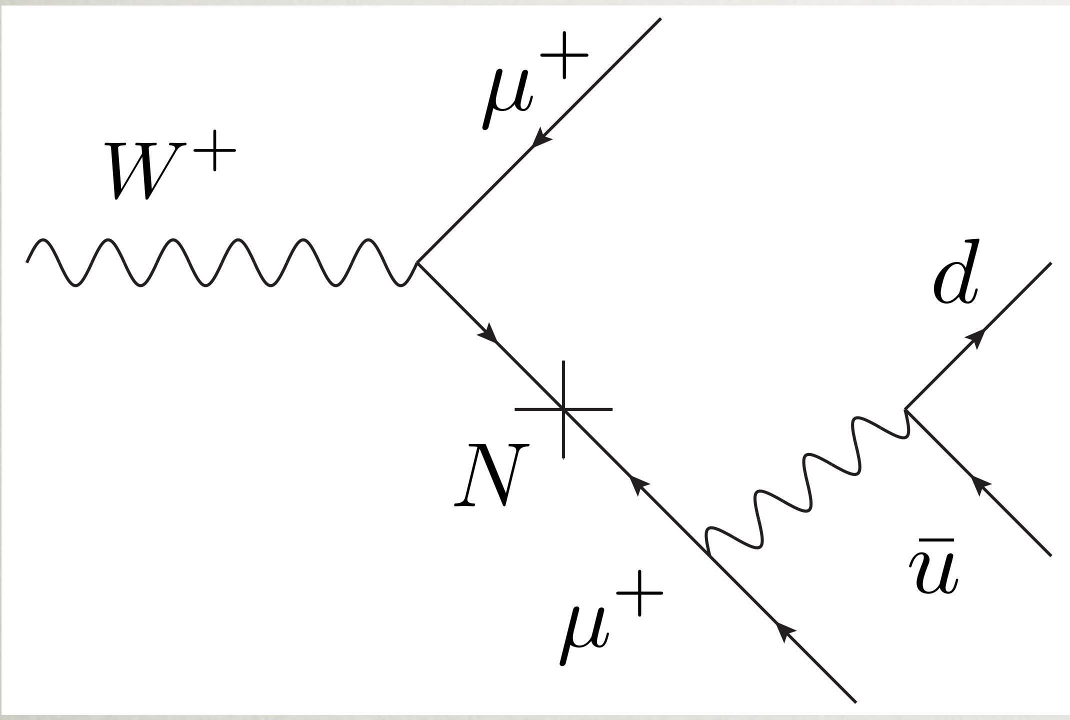
- SHiP: proposed SPS fixed target expt.

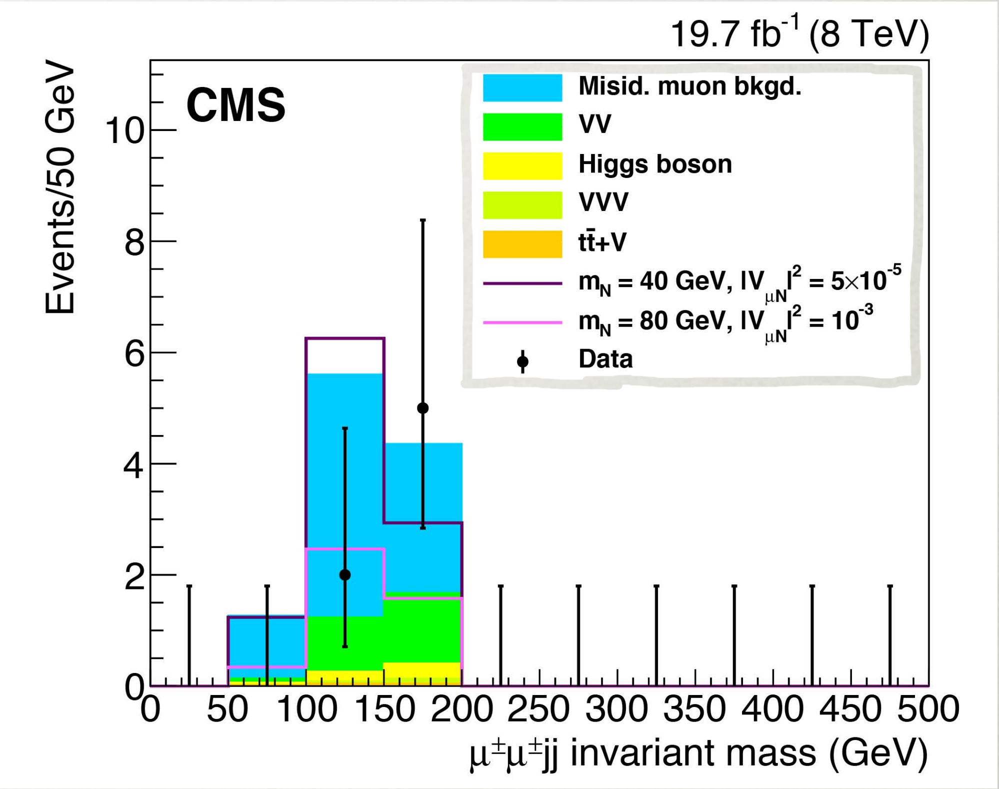
Deppisch, Dev, Pilaftsis, 1502.06541

RH Neutrinos at Colliders: Status

- Current strategy: fully reconstructible decay with same-sign leptons

(Keung, Senjanovic, 1983)





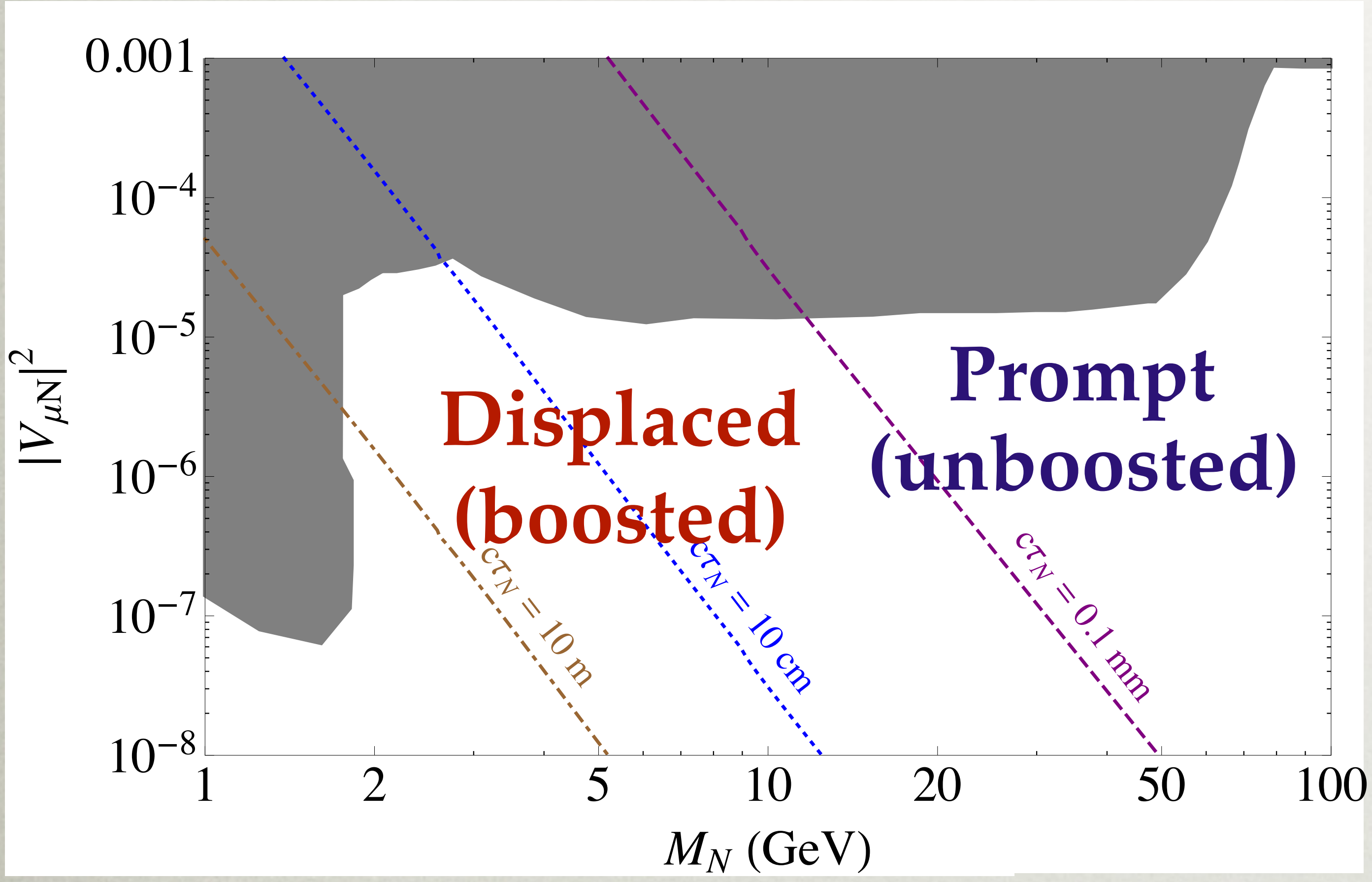
(arXiv:1501.05566)

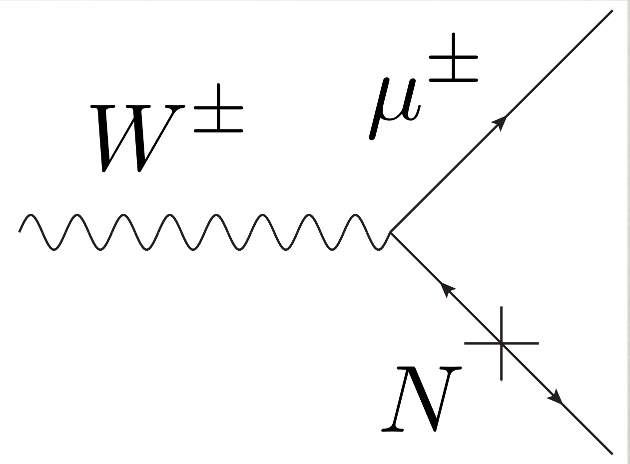
- We propose cleaner **fully leptonic signatures**

Izaguirre, BS, 1504.02470

(Proposed for heavy, Dirac *N*: del Aguila, Aguilar-Saavedra 2008, +de Blas 2009)

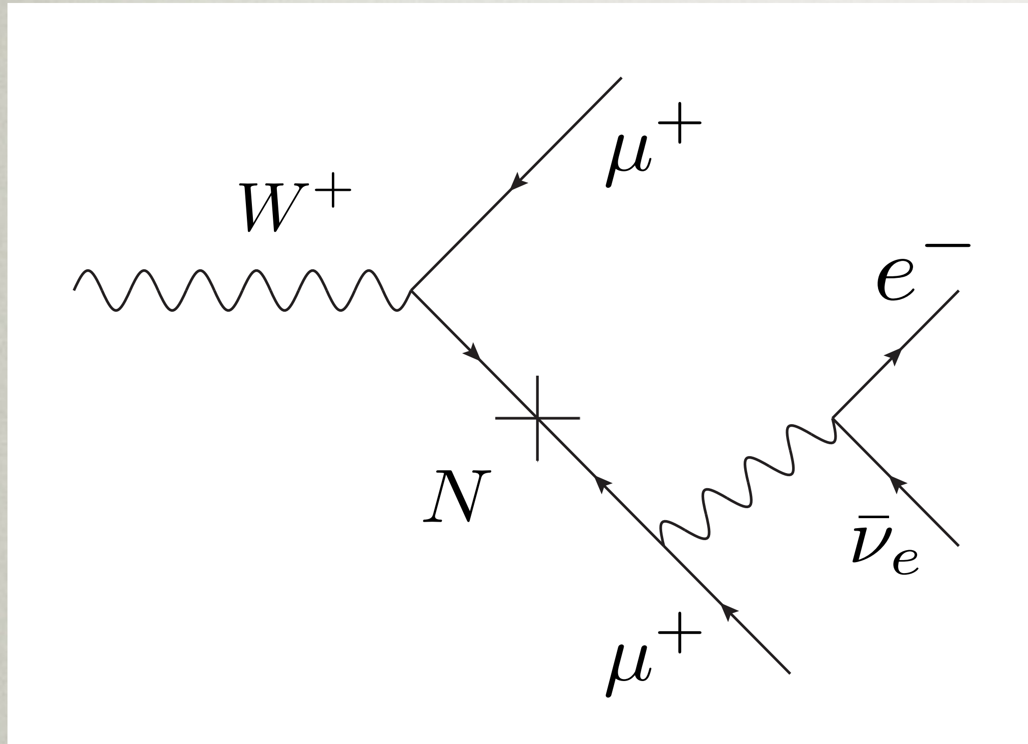
Neutrinos at the LHC





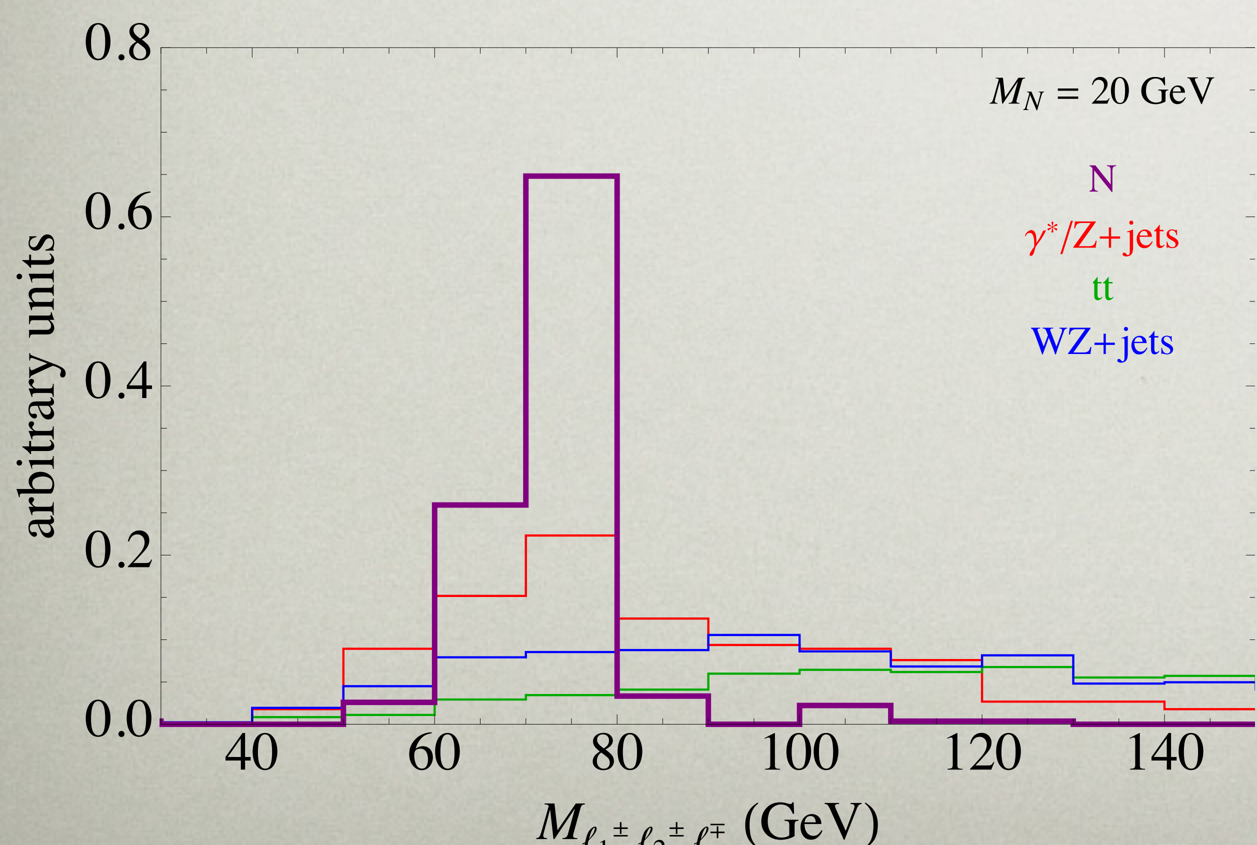
$$\Gamma_N \sim |V_{\alpha N}|^2 G_F^2 M_N^5$$

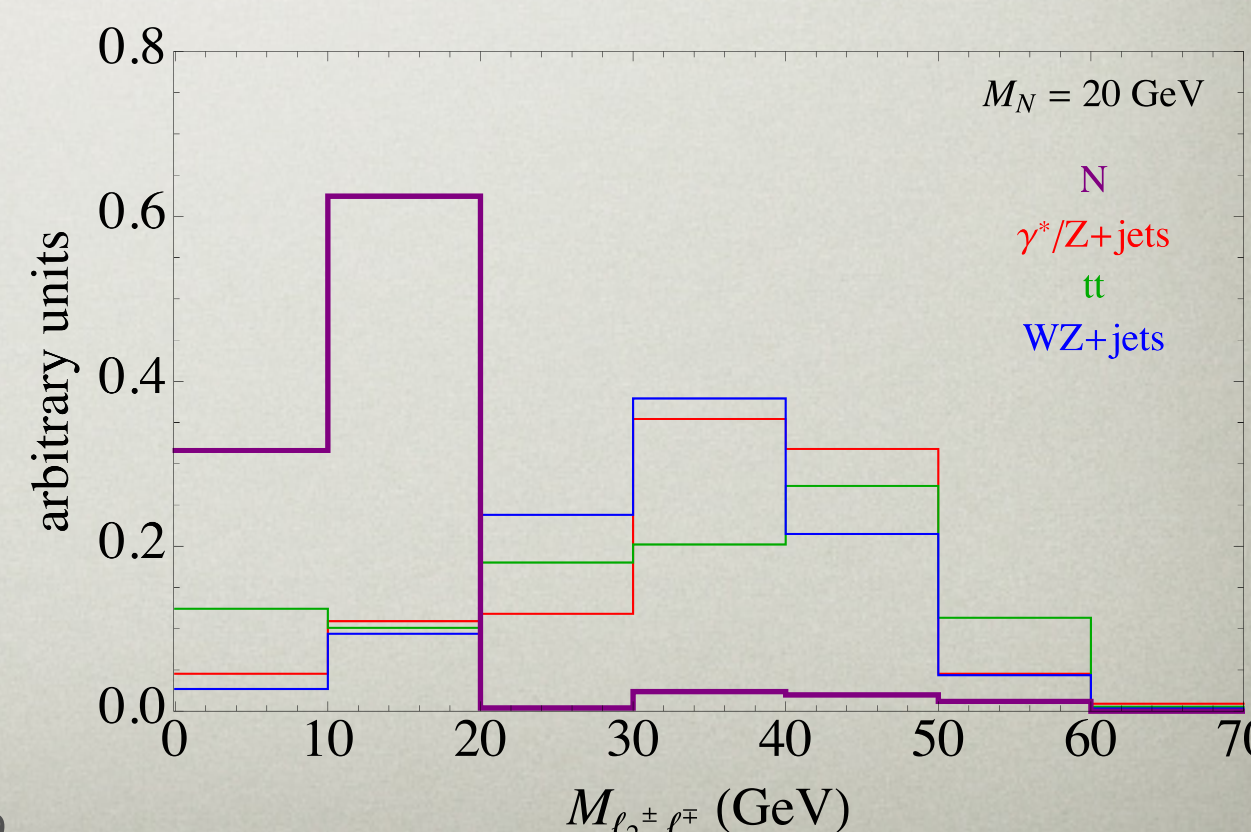
Prompt/Unboosted Signatures



Generic trilepton: large backgrounds from Z, top, diboson

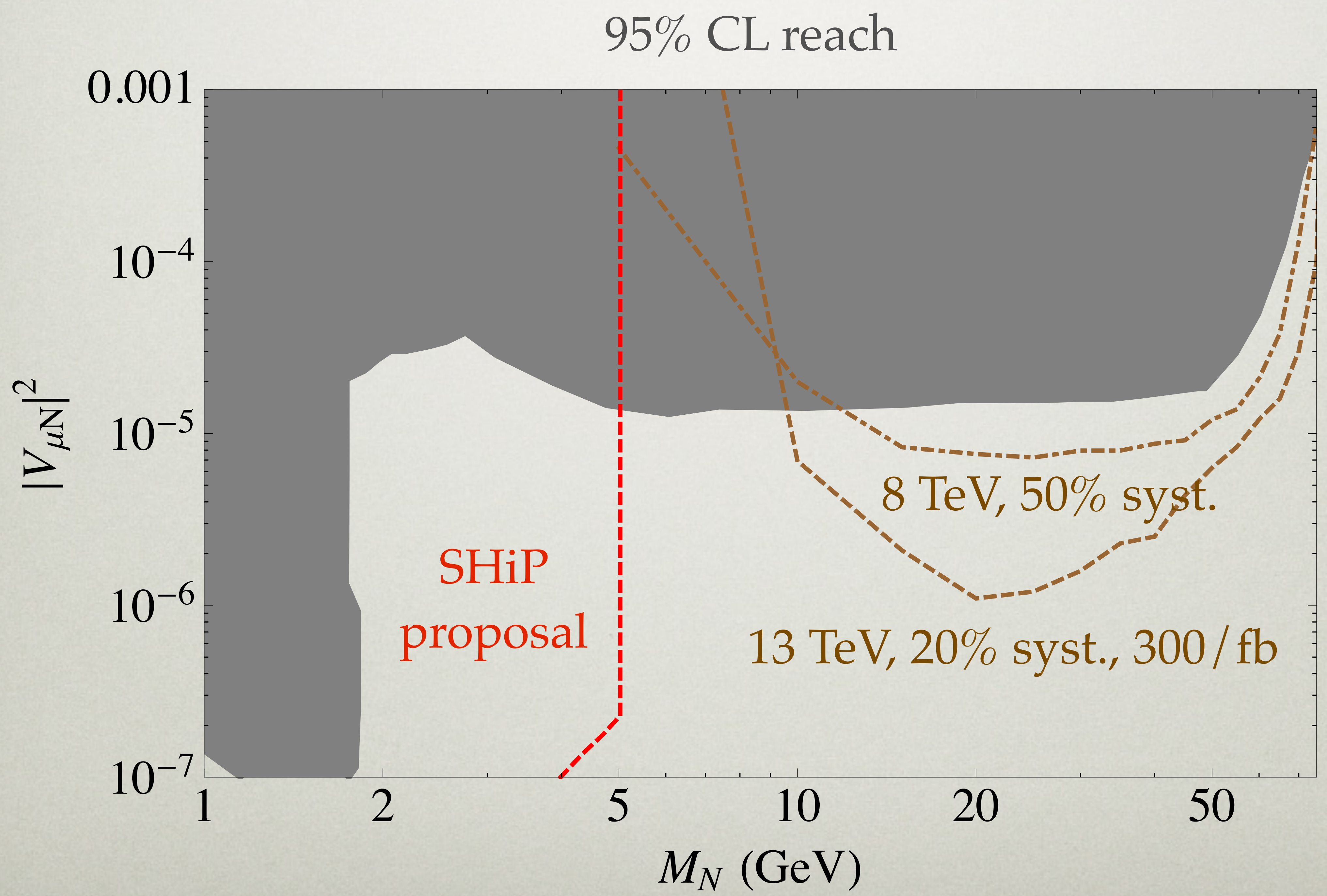
Majorana gives striking OSSF-0 signatures!



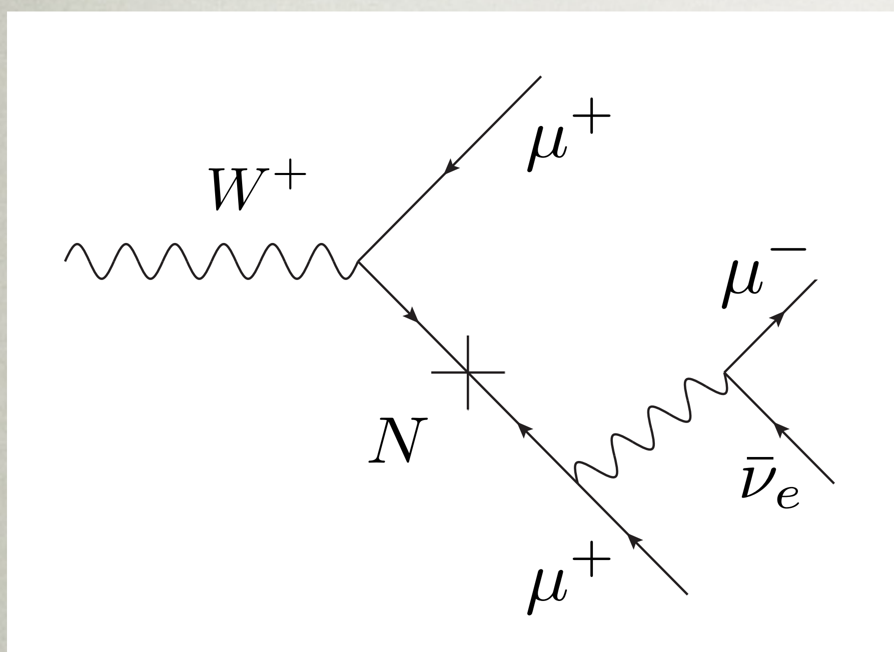


Prompt Neutrino Signatures

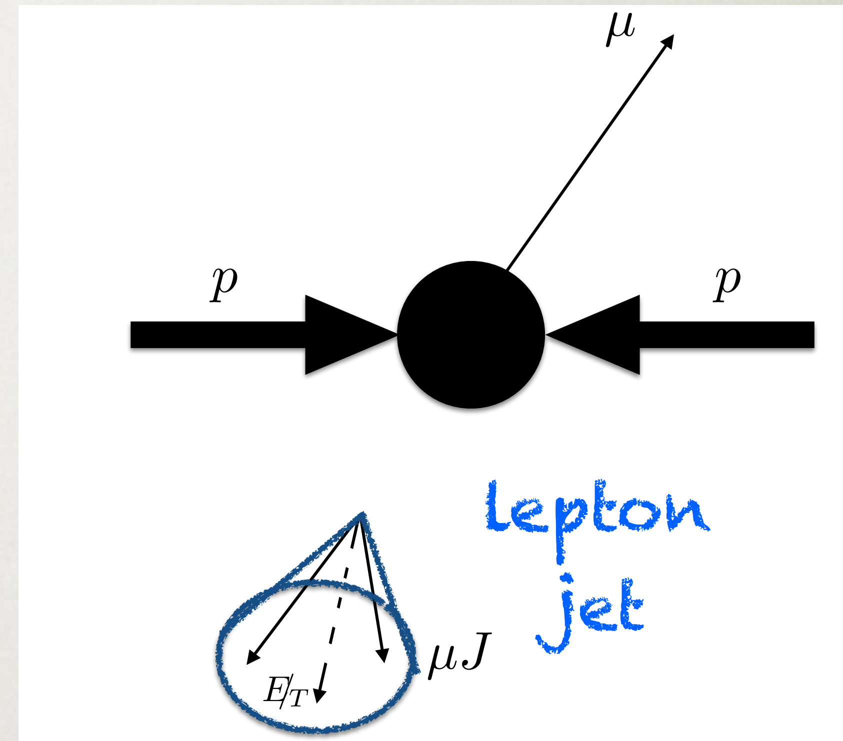
- Require 2 same-sign muons, 1 electron (all isolated, $p_T > 10$ GeV), trigger requirement, low hadronic/missing energy, kinematic cuts



Displaced/Boosted Signatures



$M_N \ll M_W$



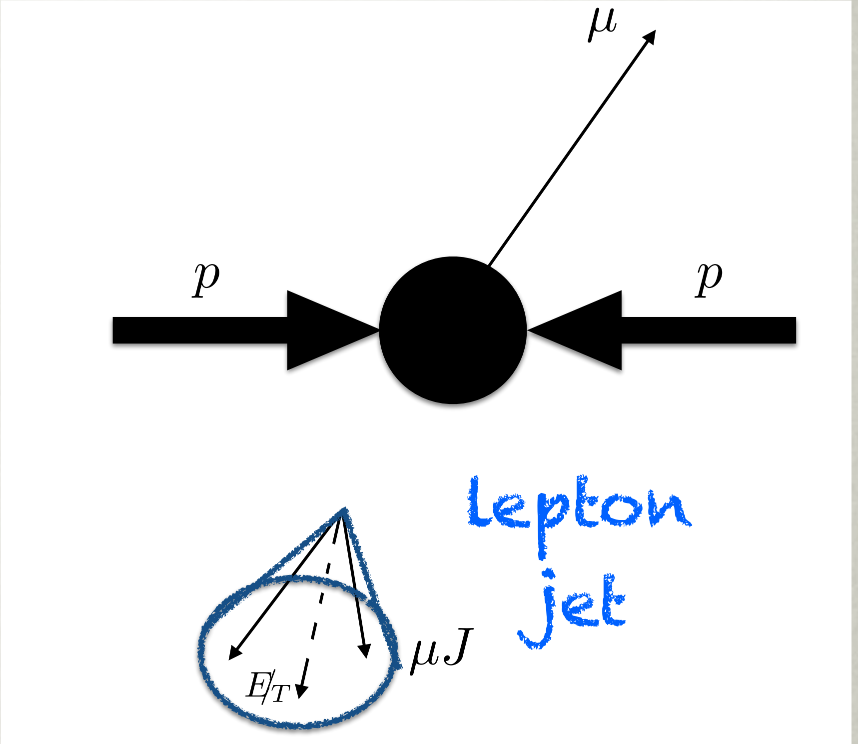
Arkani-Hamed, Weiner, 0810.0714

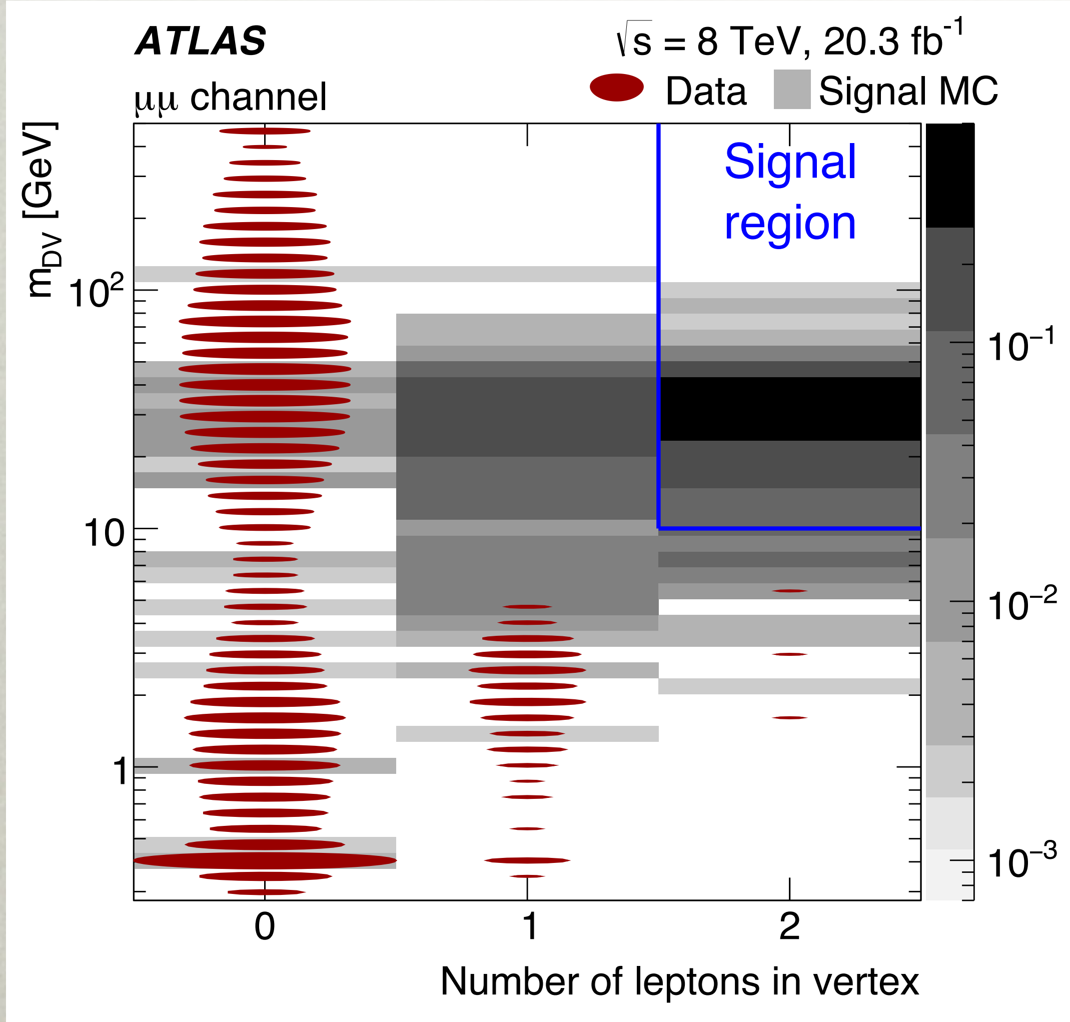
- Hadronic displaced vertices also possible, but backgrounds could be very large

(Helo, Hirsch, Kovalenko, 1312.2900)

Displaced/Boosted Signatures

- By contract, leptonic backgrounds expected to be negligible





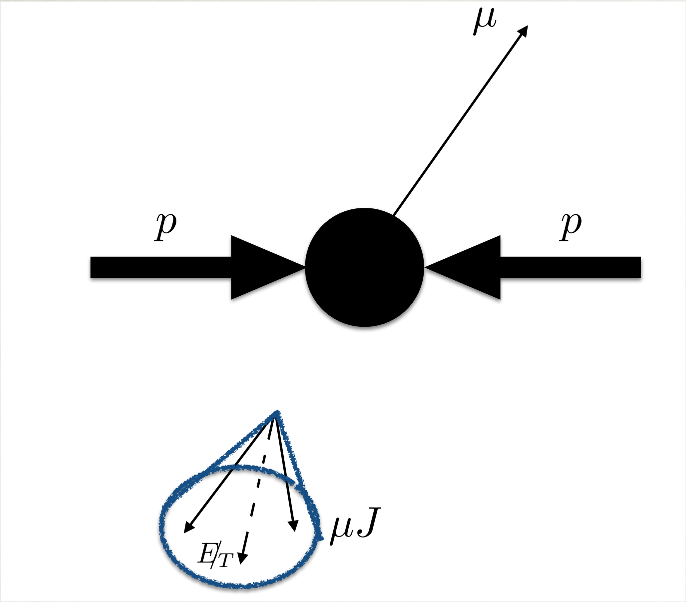
(a)

1504.05162

- Also by extrapolation from existing 2-LJ searches

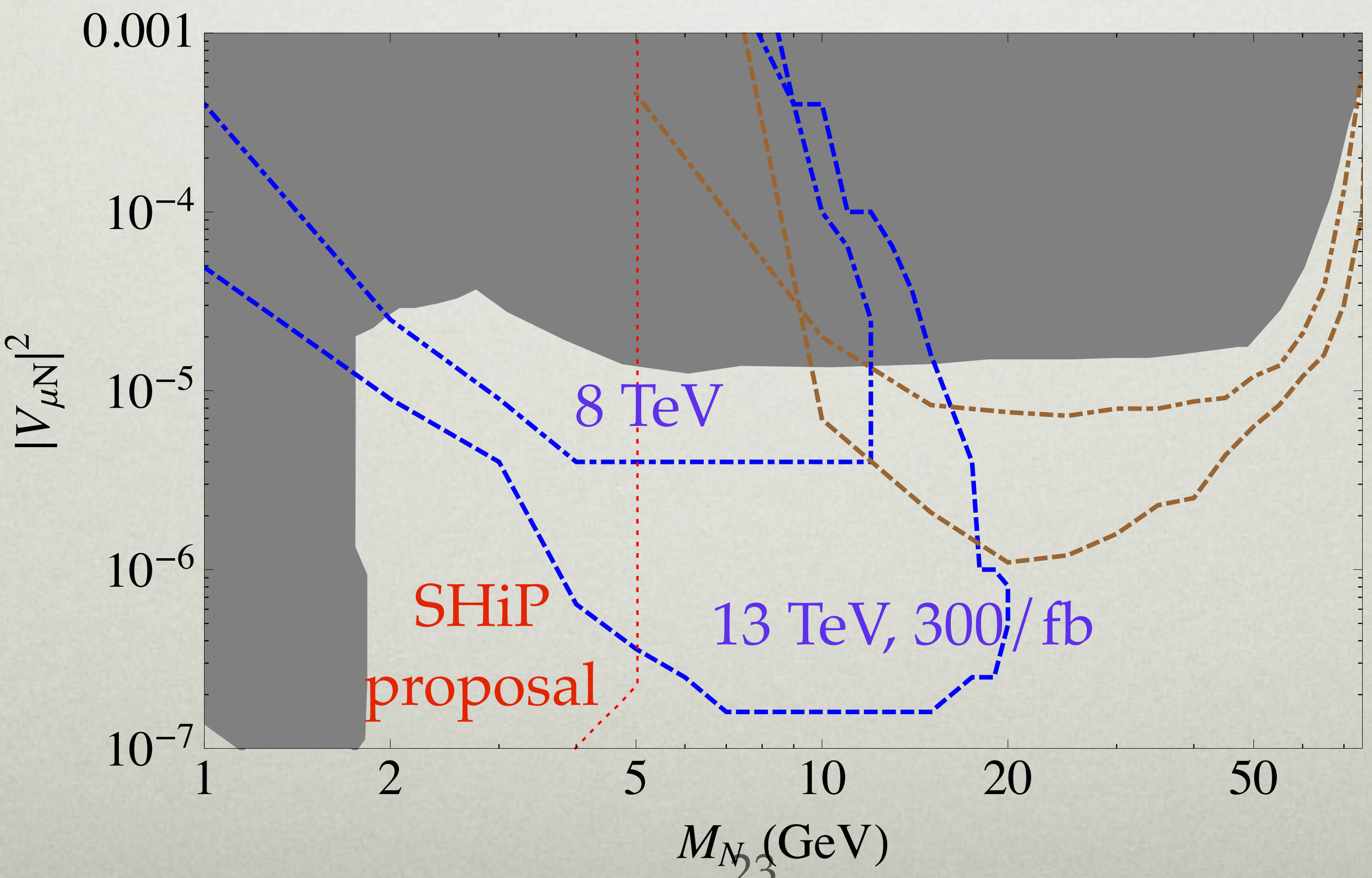
(ATLAS: 1409.0746)

Displaced trilepton 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)

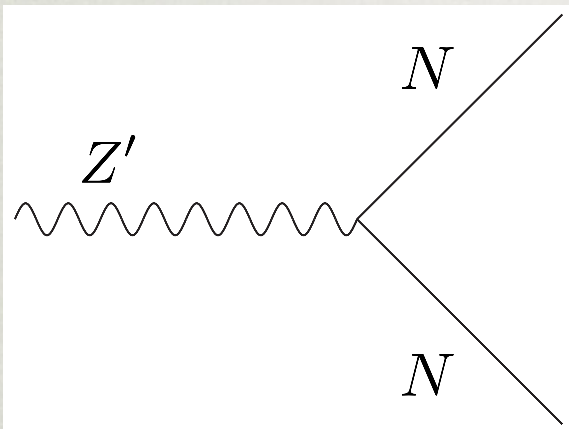


The *Z'* Portal:
Discovery of new *B*/*L* forces

B. Batell, M. Pospelov, BS, arXiv:1603.xyzab

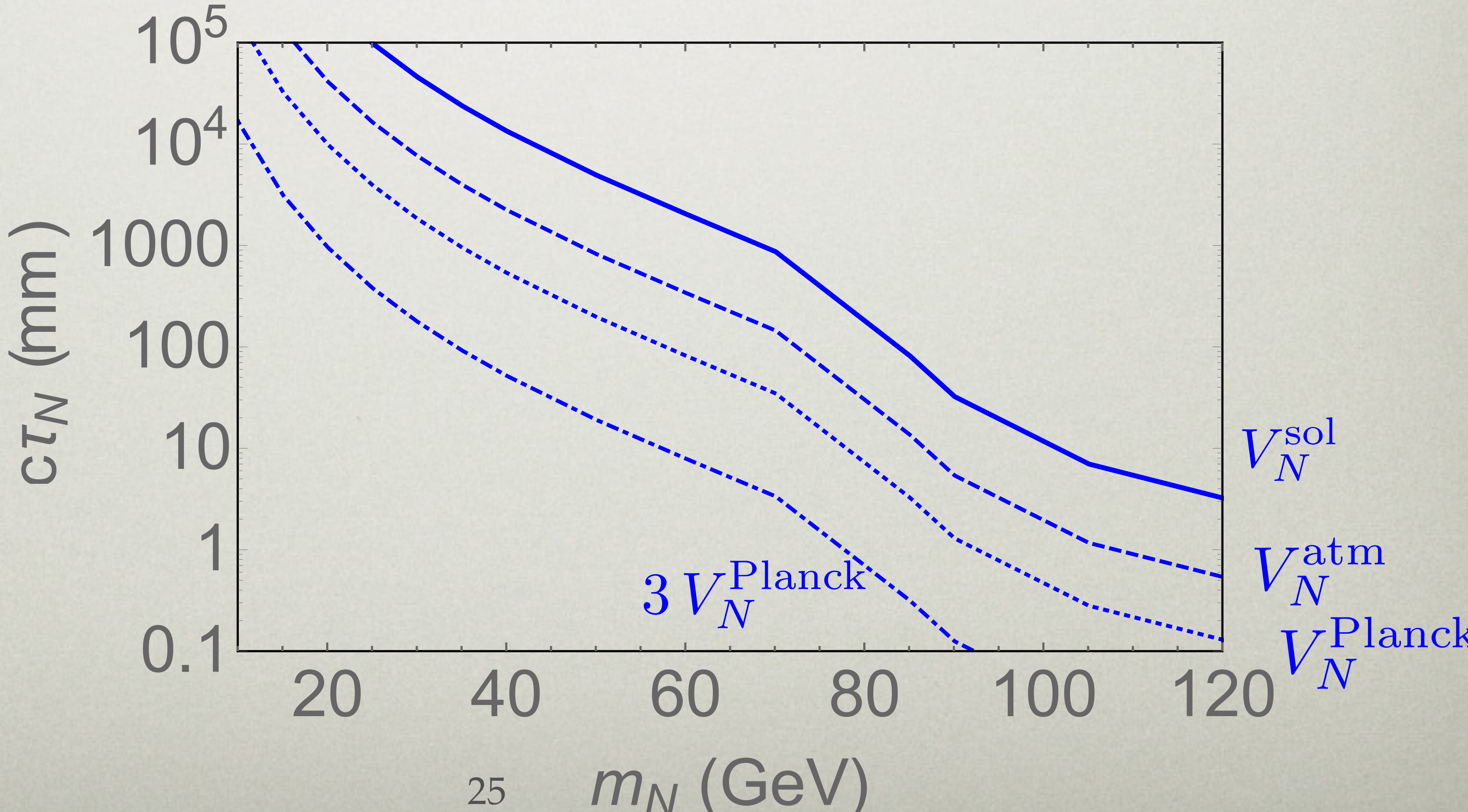
B/*L* gauge forces at colliders

- Simplest anomaly-free extensions of the SM (*B*-*L*, L_i - L_j, etc.)



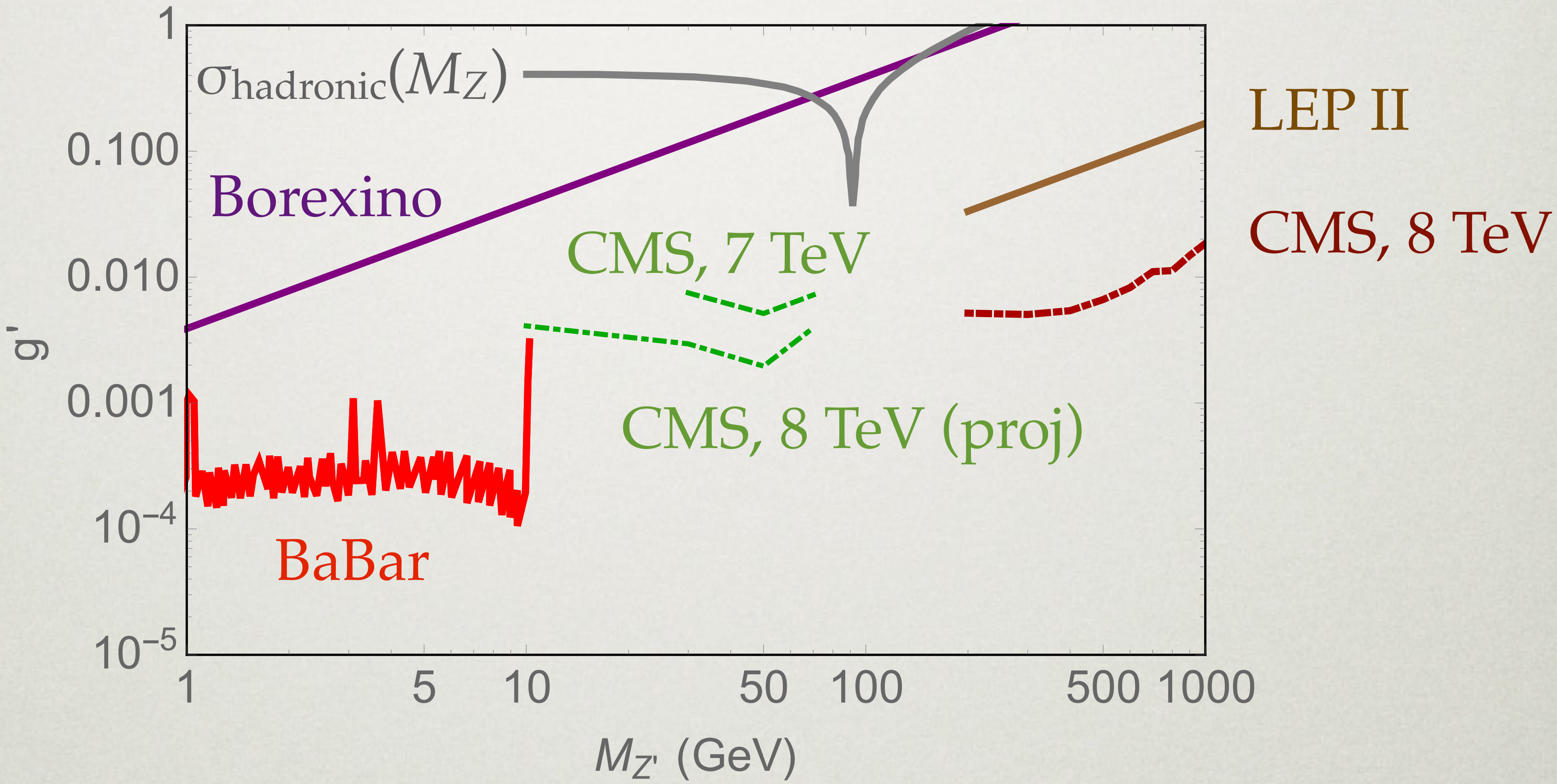
$$V_N \sim \sqrt{\frac{m_\nu}{M_N}}$$

- For m_ν ~ 0.1 eV, M_N ~ GeV, V_N ~ 10^{-5}



B-L gauge forces at colliders

- Current constraints on *B-L*:

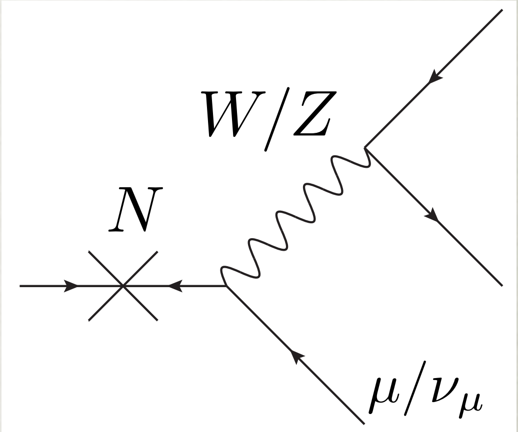


- Drell-Yan rate enormous (~10^5 / GeV bin), sensitivity ~ $\sqrt{\mathcal{L}}$

Drell-Yan constraints recast from Hoenig, Samach, Tucker-Smith, 1408.1075
Borexino constraints from Harnik, Kopp, Machado, 1202.6073

B-L gauge forces at colliders

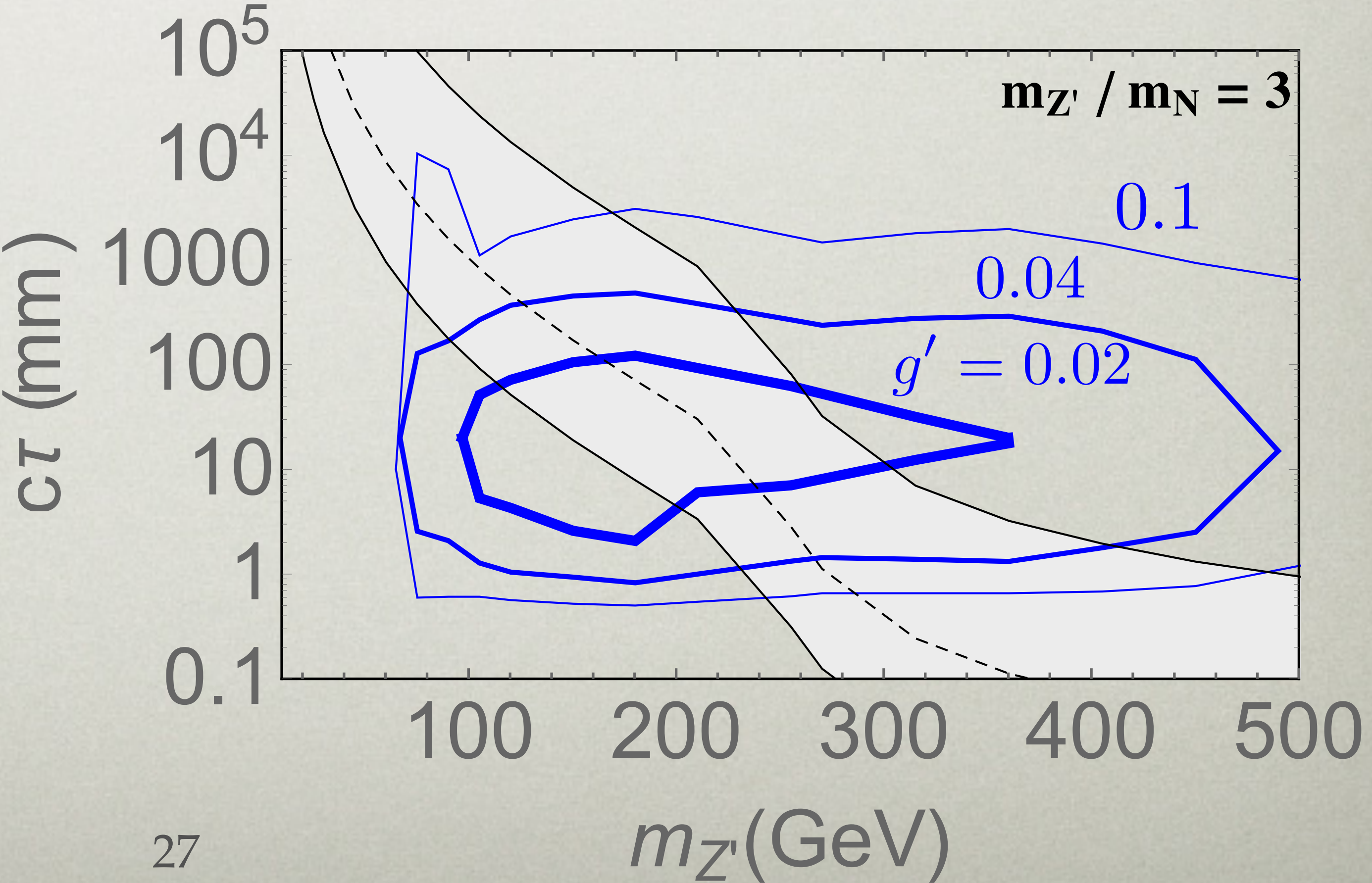
- *N* decays via (off-shell) W/Z
    - Get displaced muon in > 50% of decays
    - Use lepton triggers



- Current searches are background-free but have high thresholds or unnecessary restrictions

- CMS: displaced *e* + muon

(1409.4789)

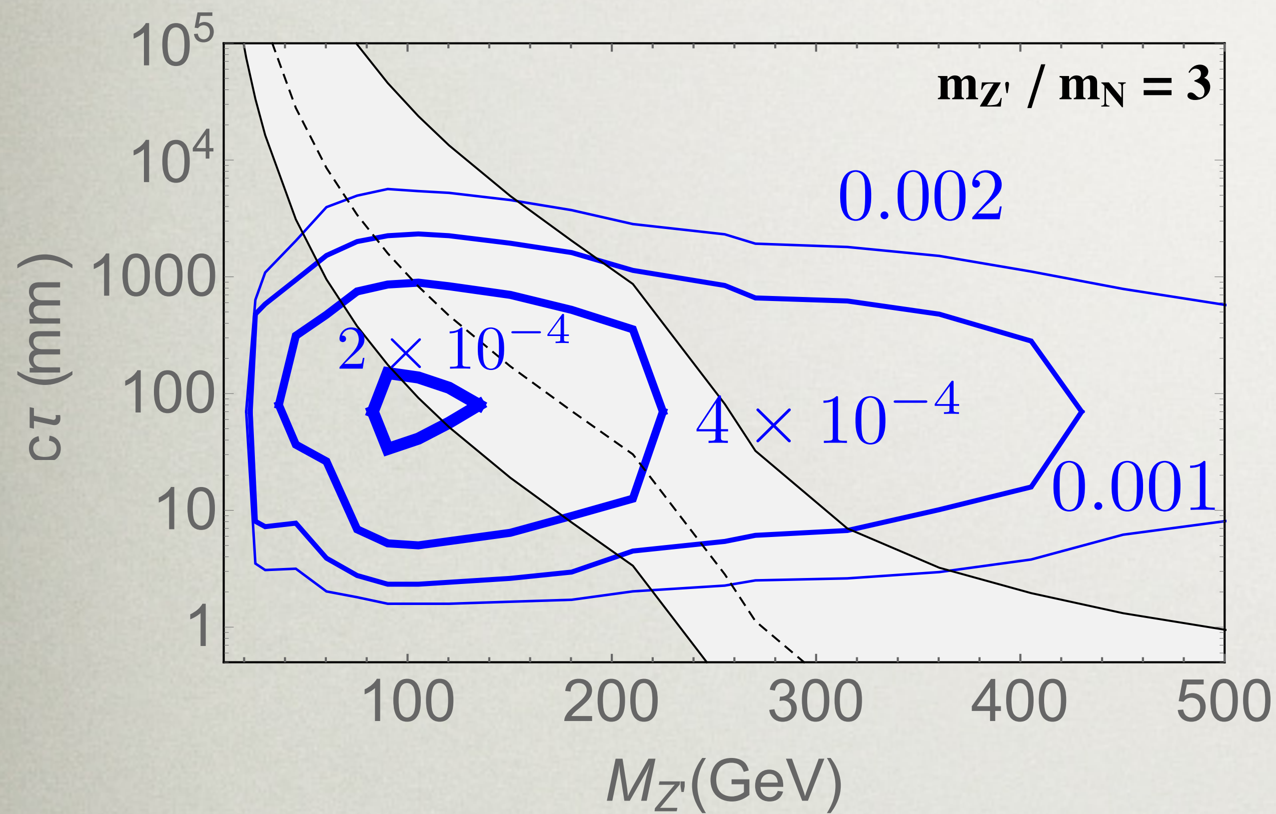


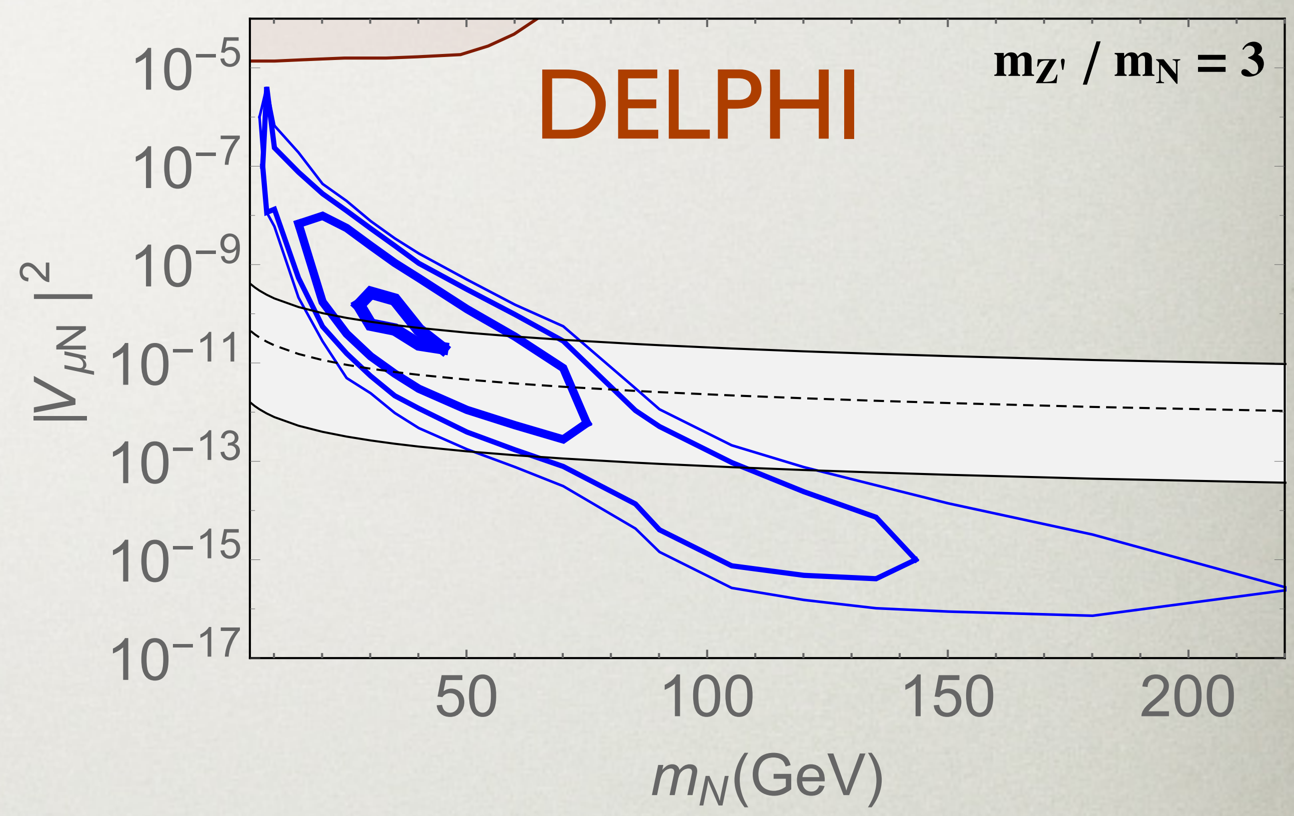
B-L gauge forces at colliders

Our approach: since current searches with 2 displaced leptons or 1 displaced lepton at displaced vertex are bkd-free, we require **both** of these in same event at HL-LHC

- Overly conservative, can relax some kinematic/selection requirements

B-L gauge forces at colliders





- At best, Drell-Yan limits would be:
  - **Below Z:** g′ ≲ 5×10^{-4} ($M_{Z'}$ ~ 50-60 GeV)
  - **Above Z:** g′ ≲ 10^{-3} ($M_{Z'}$ ~ 150-400 GeV)
- SHiP can reach g′ ~ 10^{-5} ($M_{Z'}$ ~ 1-10 GeV)!!

The Vector Portal & Inelastic Dark Matter

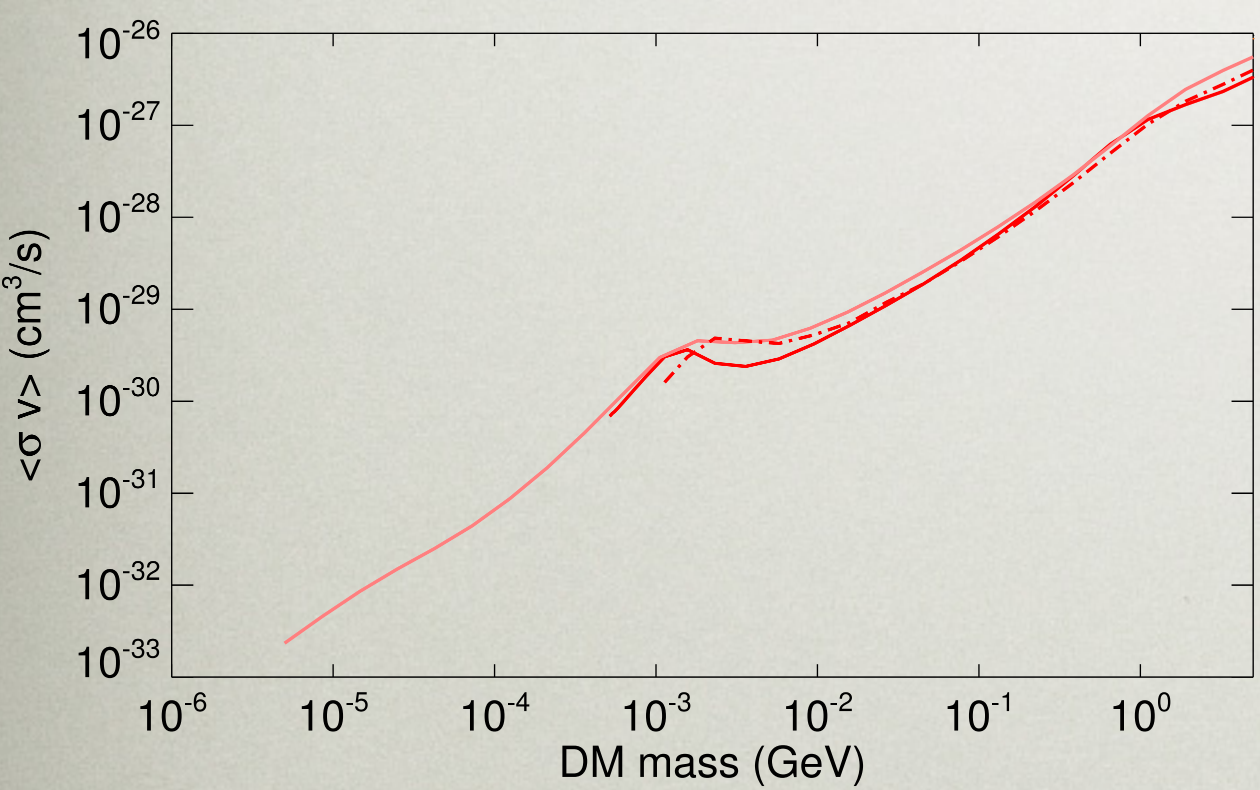
E. Izaguirre, G. Krnjaic, BS, arXiv:1508.03050

Discovering Dark Matter

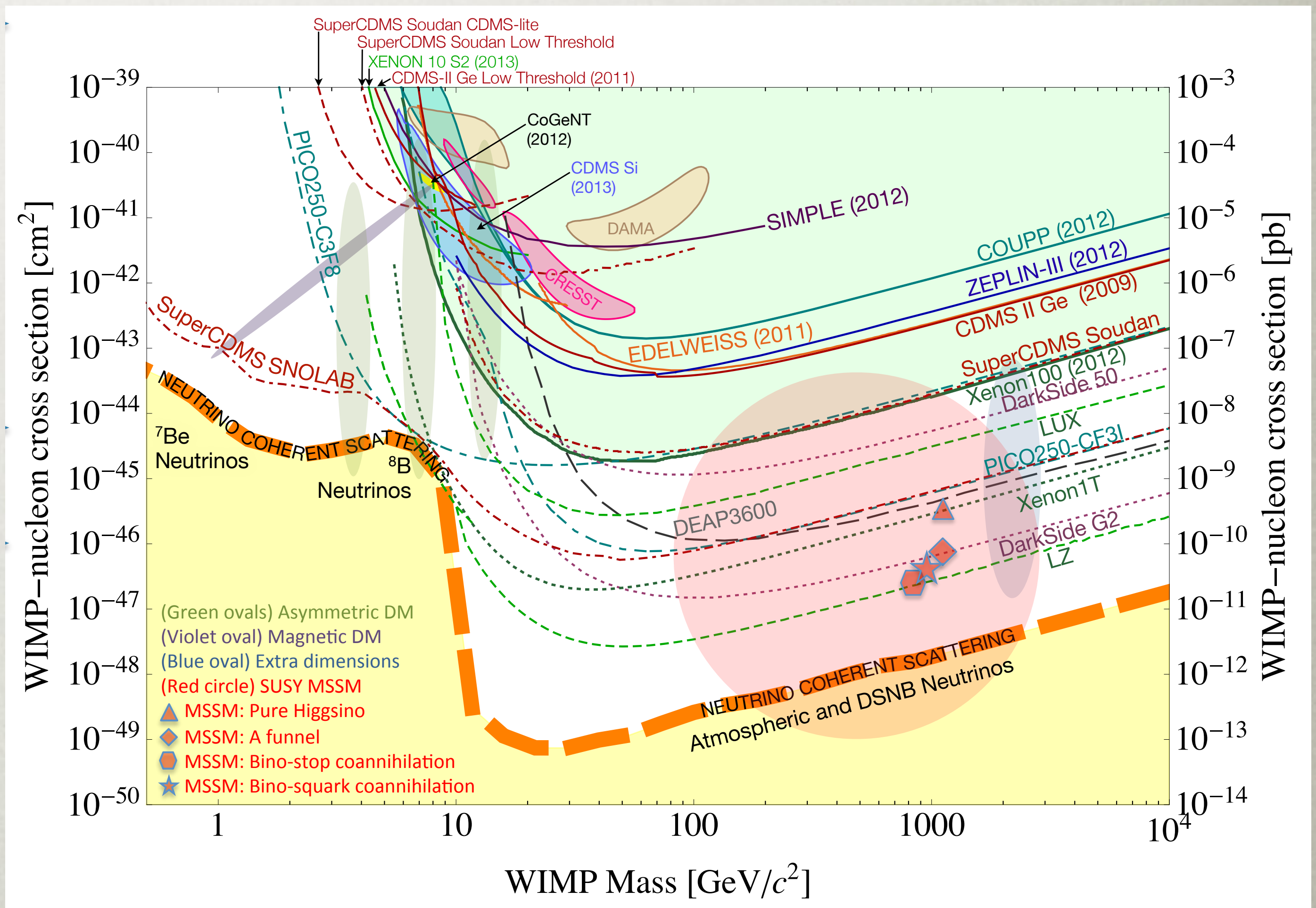
- Generically strong constraints on low-mass dark matter

CMB/indirect detection

direct detection

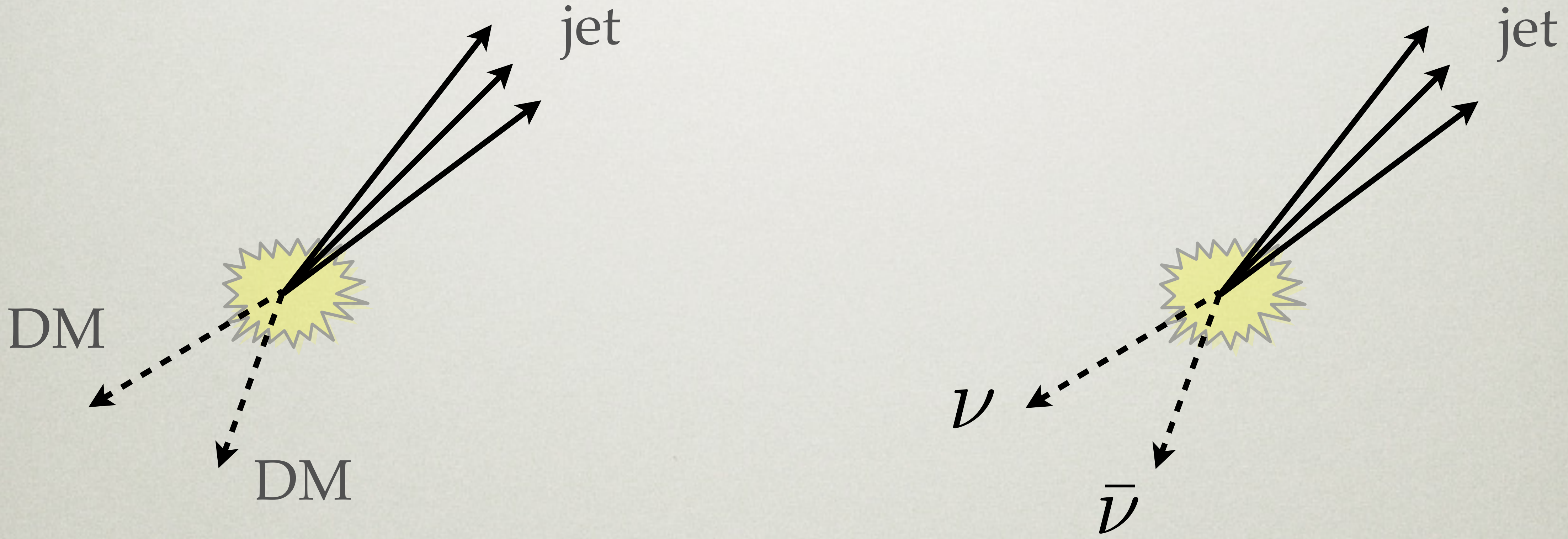


from Slatyer, 1506.03811



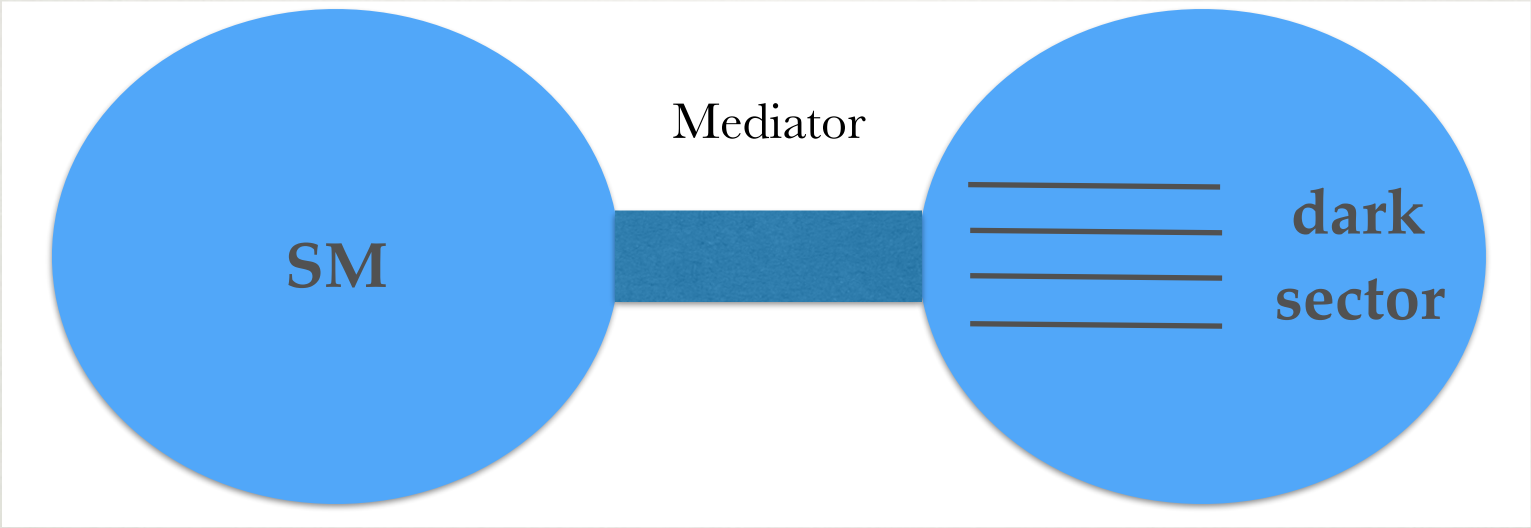
Discovering Dark Matter

- By contrast, high-energy colliders can be tricky...



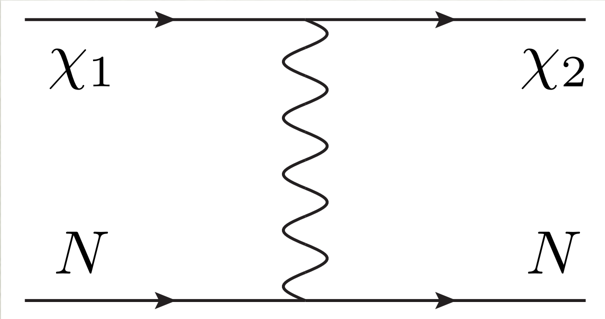
Dark Matter in a Dark Sector

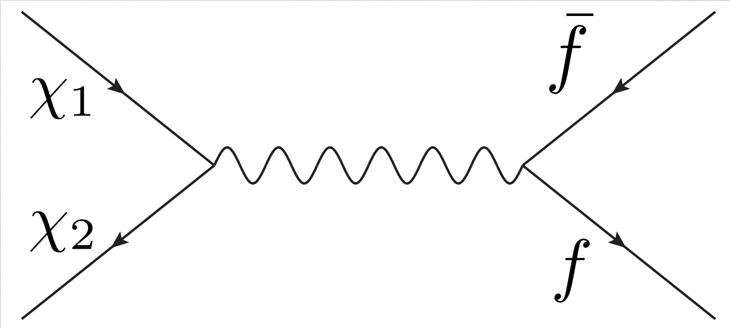
- In a **dark sector**, the situation can be flipped



- Ex: inelastic dark matter

(Tucker-Smith, Weiner, hep-ph/0101138)

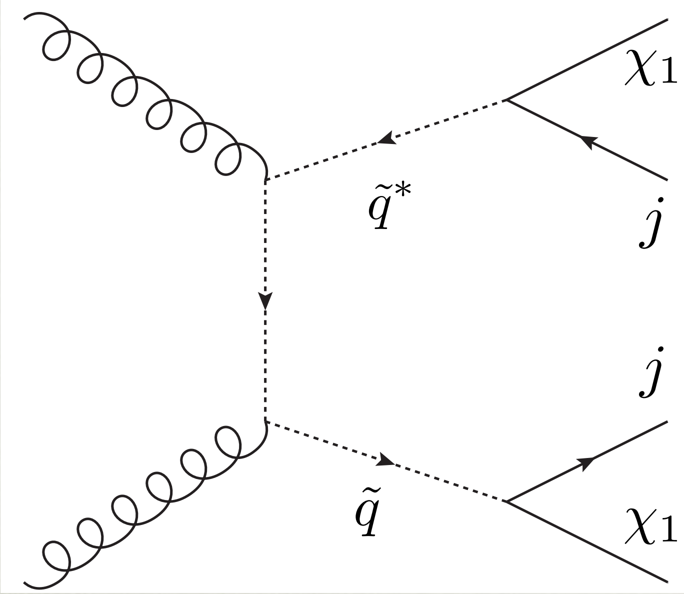




$$E_{\text{collider}} \gg \Delta M \gg E_{\text{DM}}^{\text{kin}}$$

Dark Matter in a Dark Sector

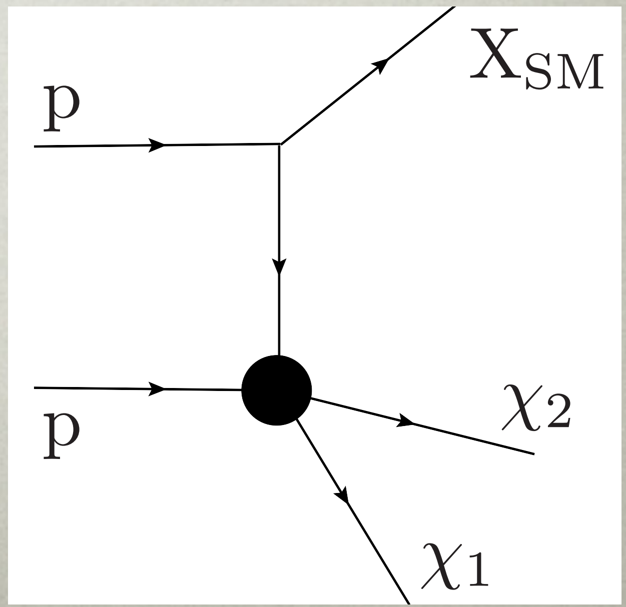
- For large splittings, decays of heavier DS states give **hard** objects



(Chang *et al.*, 1307.8120; An *et al.*, 1308.0592; Bai, Berger, 1308.0612; Papucci, Vicchi, Zurek, 1402.2285; Primulando, Salvioni, Tsai, 1503.04204)

- For small splittings, get conventional monojet **plus additional soft radiation** from heavier DS decay

(Bai, Tait, 1109.4144; Izaguirre, Krnjaic, BS, 1508.03050)



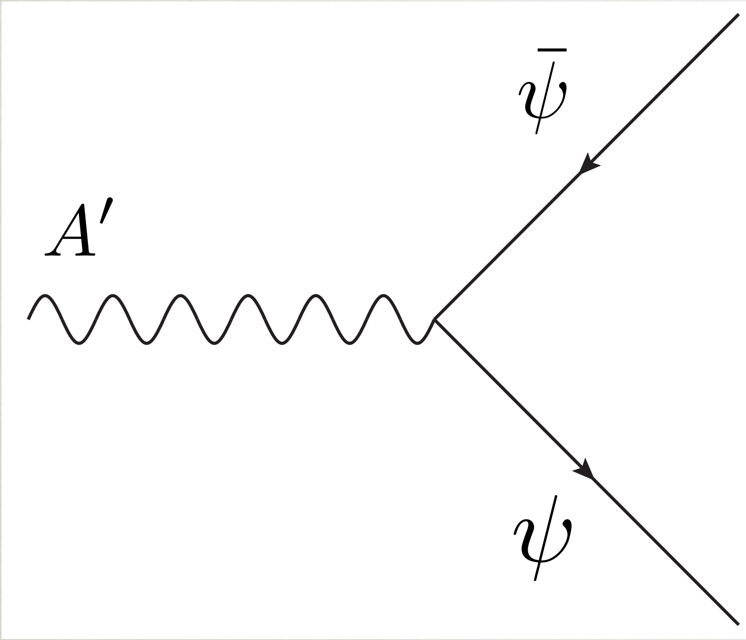
  - Similar to compressed SUSY searches

Recent examples: Giudice *et al.*, 1004.4902; Gori *et al.*, 1307.5952; Buckley *et al.*, 1310.4827, and many others...

An Inelastic Benchmark

(Izaguirre, Krnjaic, BS, 1508.03050)

- Dark matter with Higgsed dark QED



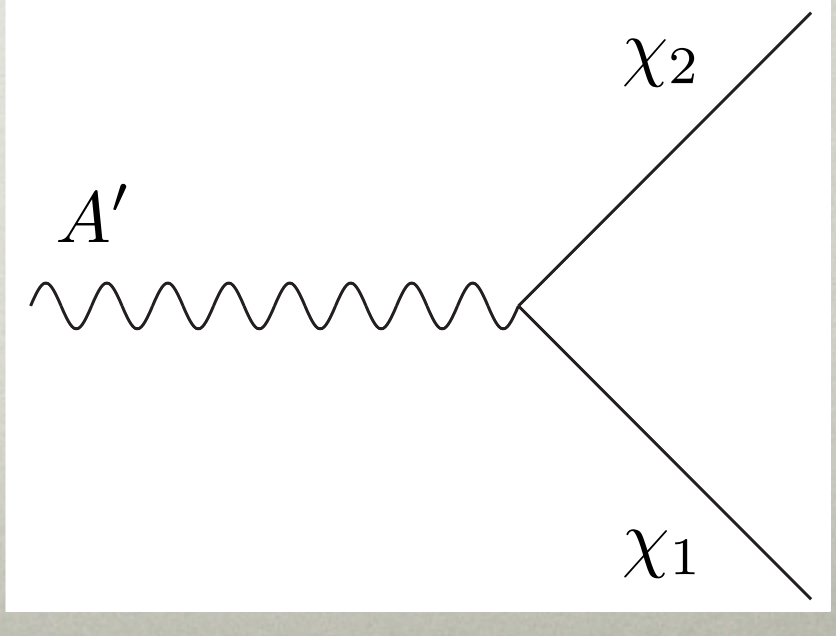
$$\mathcal{L}_\psi \supset -M_\psi \bar{\psi}\psi + \frac{y\langle\Phi\rangle}{2}\bar{\psi}^{c}\psi + \text{h.c.}$$

$$M_\psi \gg y\langle\Phi\rangle$$

$$M_{1,2} \approx M_\psi \pm \Delta/2 \qquad \Delta \equiv 2y\langle\Phi\rangle$$

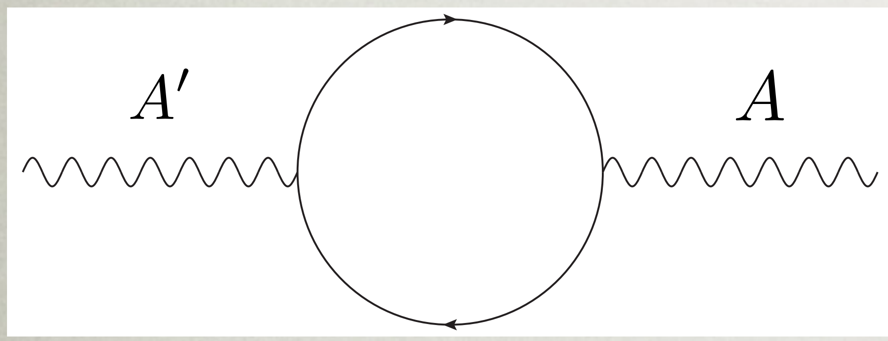
- Parity conservation = off-diagonal

$$\mathcal{J}^\mu_\chi = i\left(\chi_2^\dagger\bar{\sigma}^\mu\chi_1 - \chi_1^\dagger\bar{\sigma}^\mu\chi_2\right) + \mathcal{O}(\Delta/M)$$

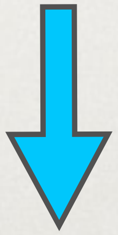


An Inelastic Benchmark

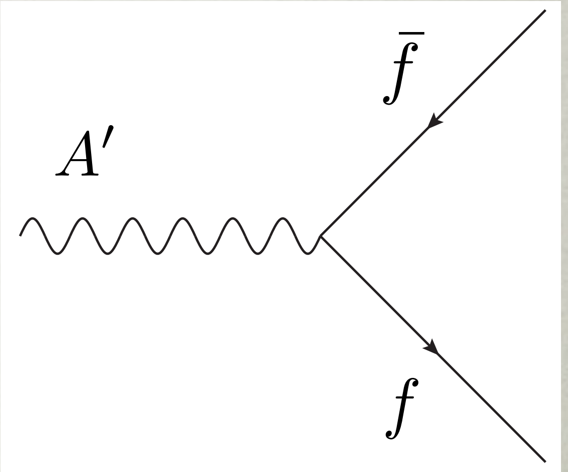
- Coupling to SM comes from kinetic mixing



$$\mathcal{L}_{\text{mix}} = -\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$



$$\mathcal{L}_{A'-\text{SM}} \approx e\epsilon J^{\mu}_{\text{SM}} A'_{\mu}$$

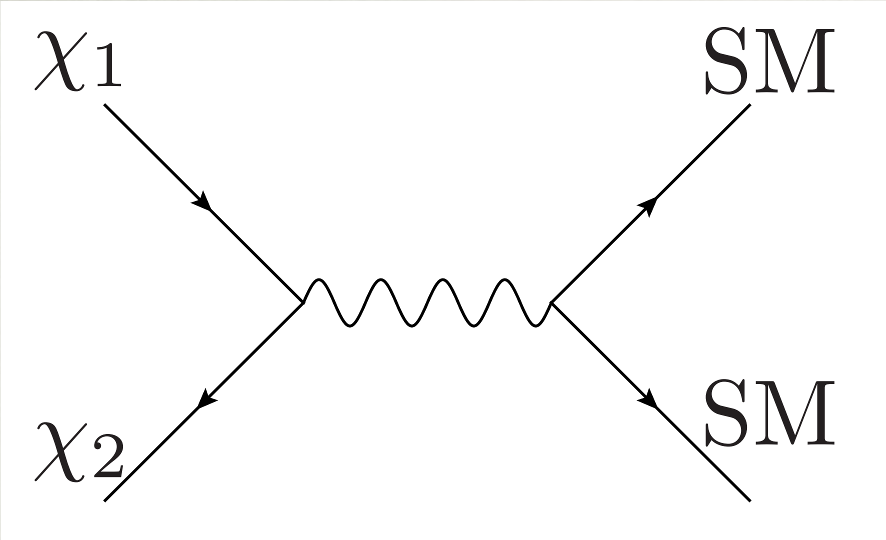


- We consider the spectrum hierarchy $\Delta \ll M_{1,2} \lesssim M_{A'}$

See also: "Secluded DM", Pospelov, Ritz, Voloshin, 0711.4866; Autran *et al.*, 1504.01386; Bai *et al.*, 1504.01395; Buschmann *et al.*, 1505.07549

Inelastic Freeze-out

- Many parameters -- choose a parameterization that connects freeze-out to lab probes



$$\langle \sigma v \rangle \propto \frac{\epsilon^2 \alpha_{\rm D} M_1^2}{M_{A'}^4} = \frac{y}{M_1^2} \qquad (M_{A'} \gg M_1)$$

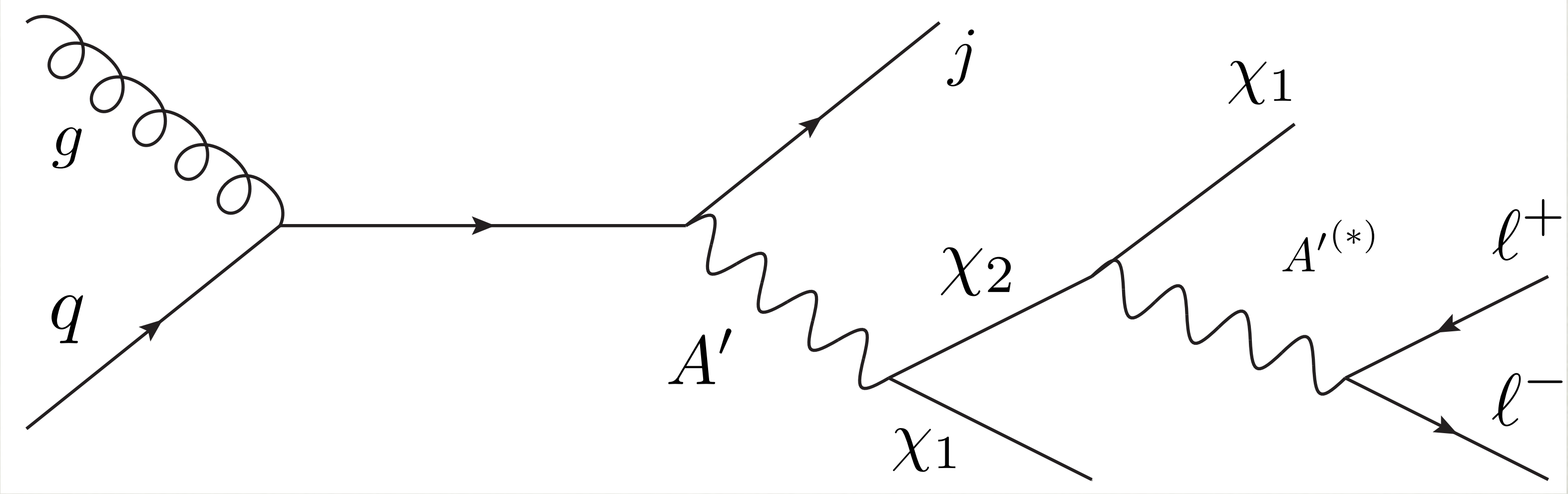
$$y \equiv \epsilon^2 \alpha_{\rm D} \left(\frac{M_1}{M_{A'}} \right)^4$$

- Abundance depends on y, M_1, while lab constraints depend on ε, $M_{A'}$
  - Choose large value of α_D to avoid over-stating bounds

(Izaguirre *et al.*, 1505.00011)

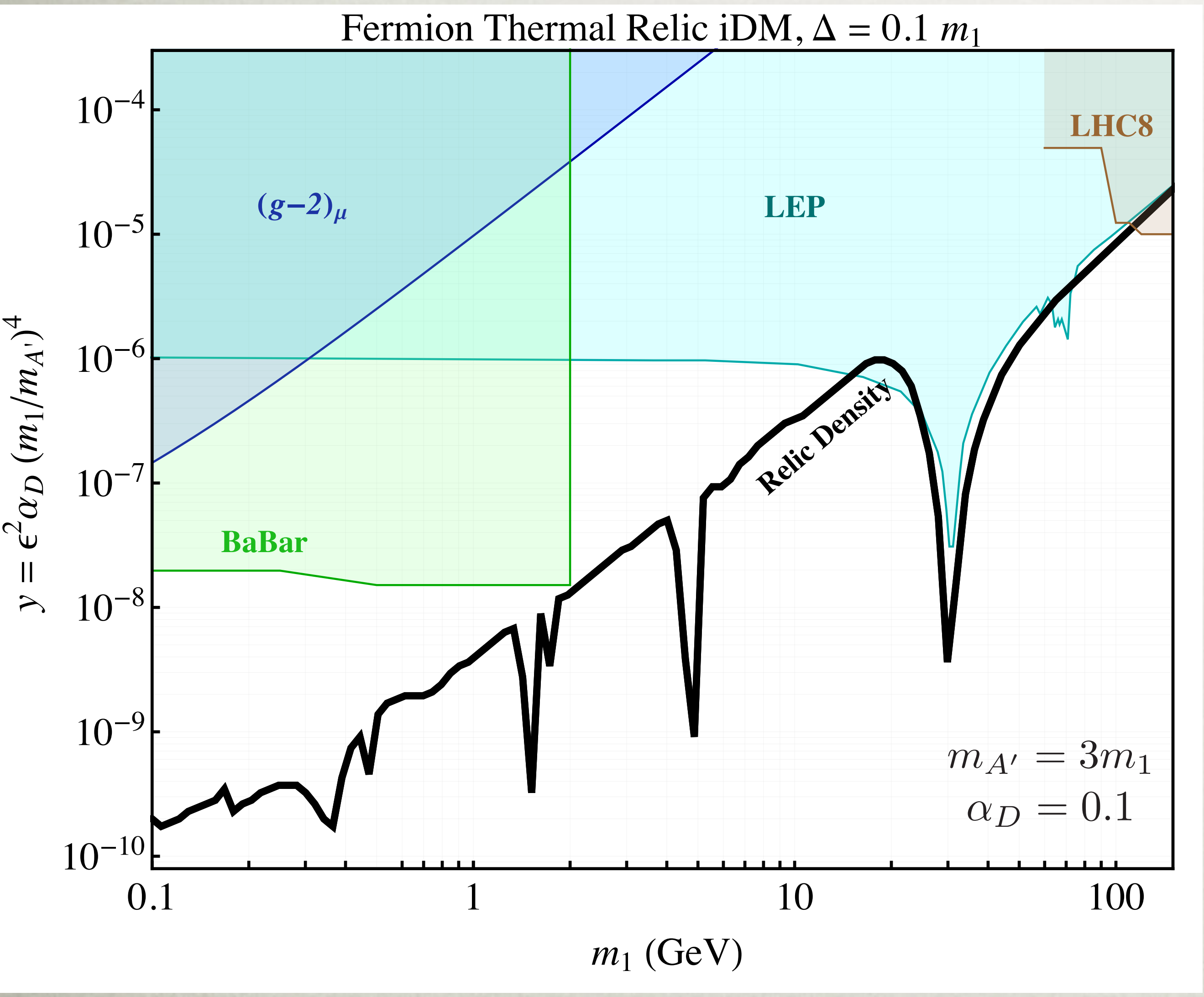
Inelastic Freeze-out

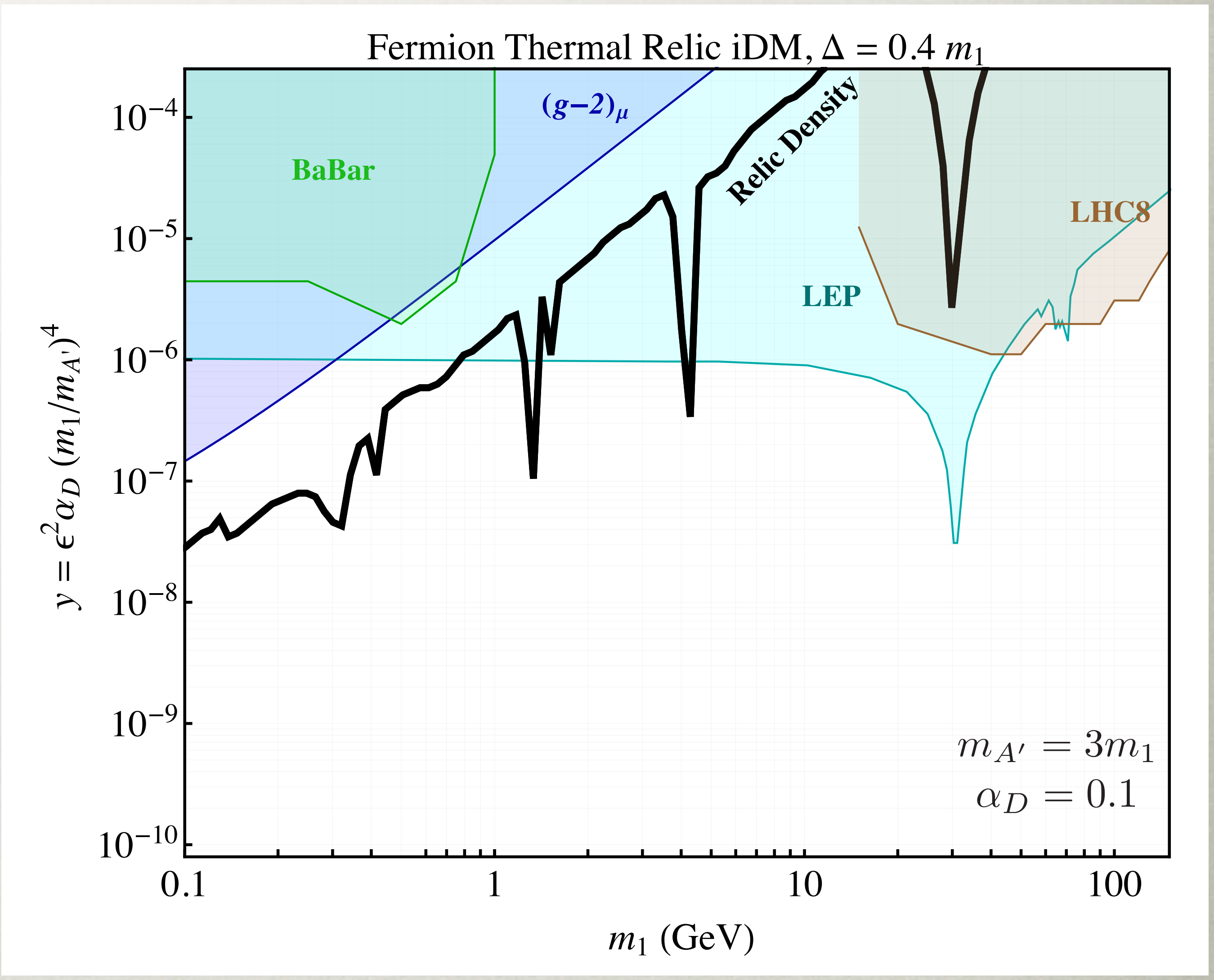
- Collider production:



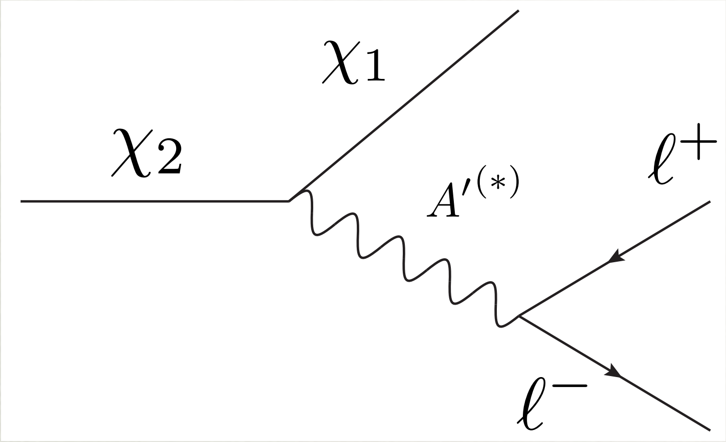
- Also have bounds from EWPT, monophoton, compressed SUSY

Current Status





Improving the Searches

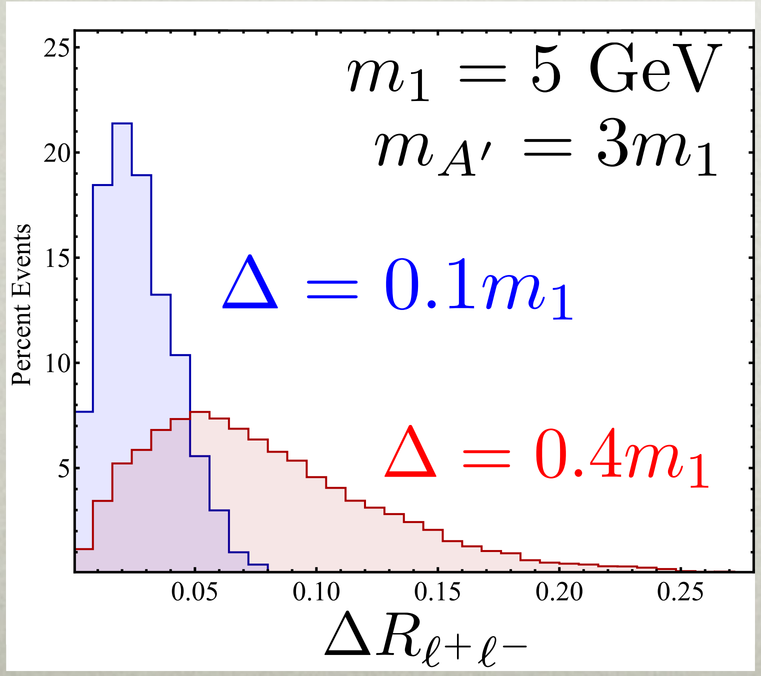


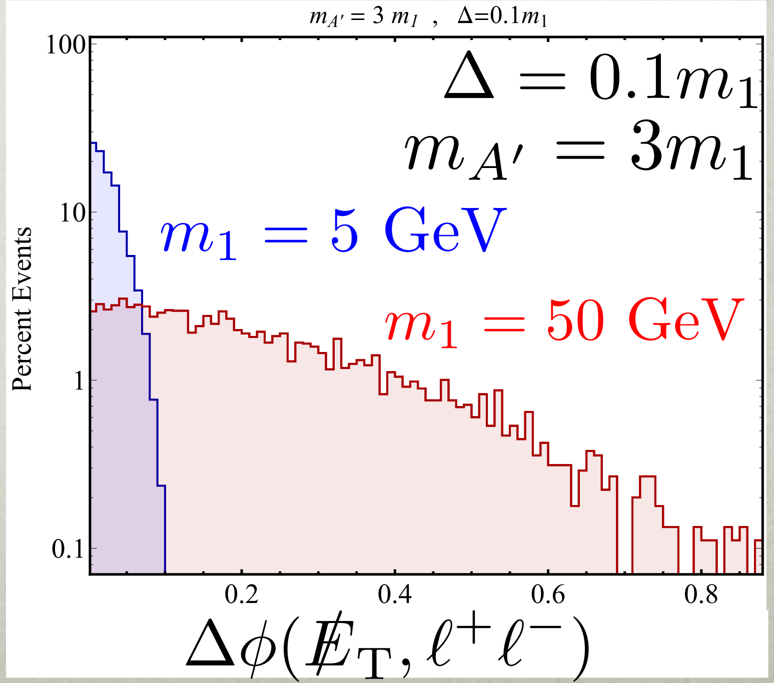
$$\Gamma_{\chi_2} \sim \frac{\alpha \alpha_{\mathrm{D}} \epsilon^2 \Delta^5}{M_{A'}^4}$$

- Get displaced decay!

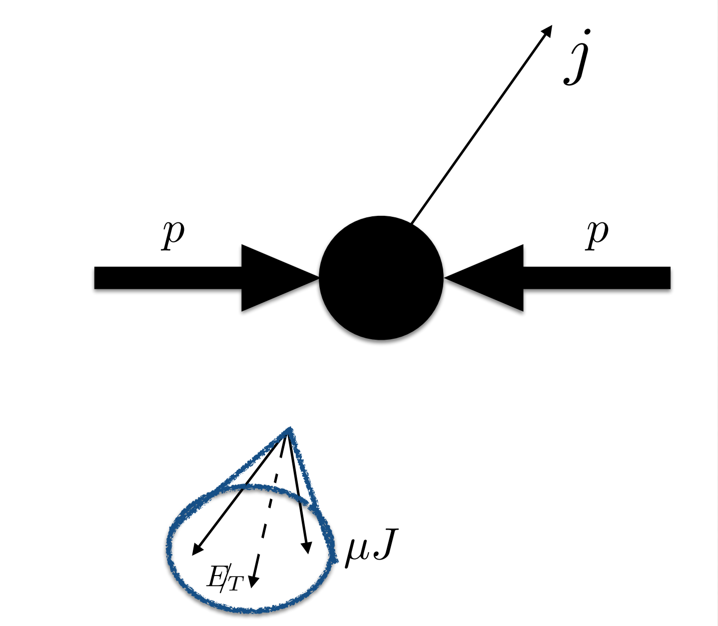
- The leptons are typically soft, so trigger on monojet + MET

- The DM produced through on-shell A', so typically **boosted**





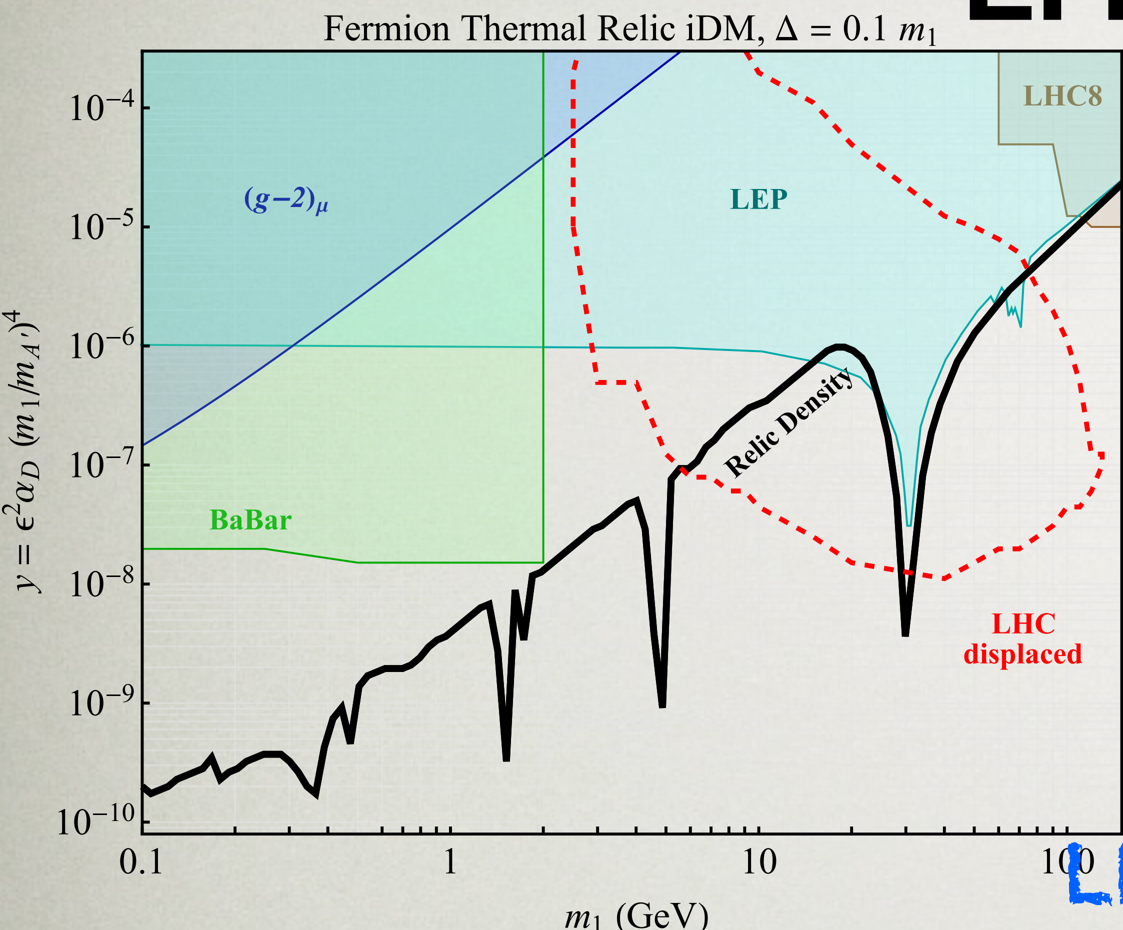
Improving the Searches

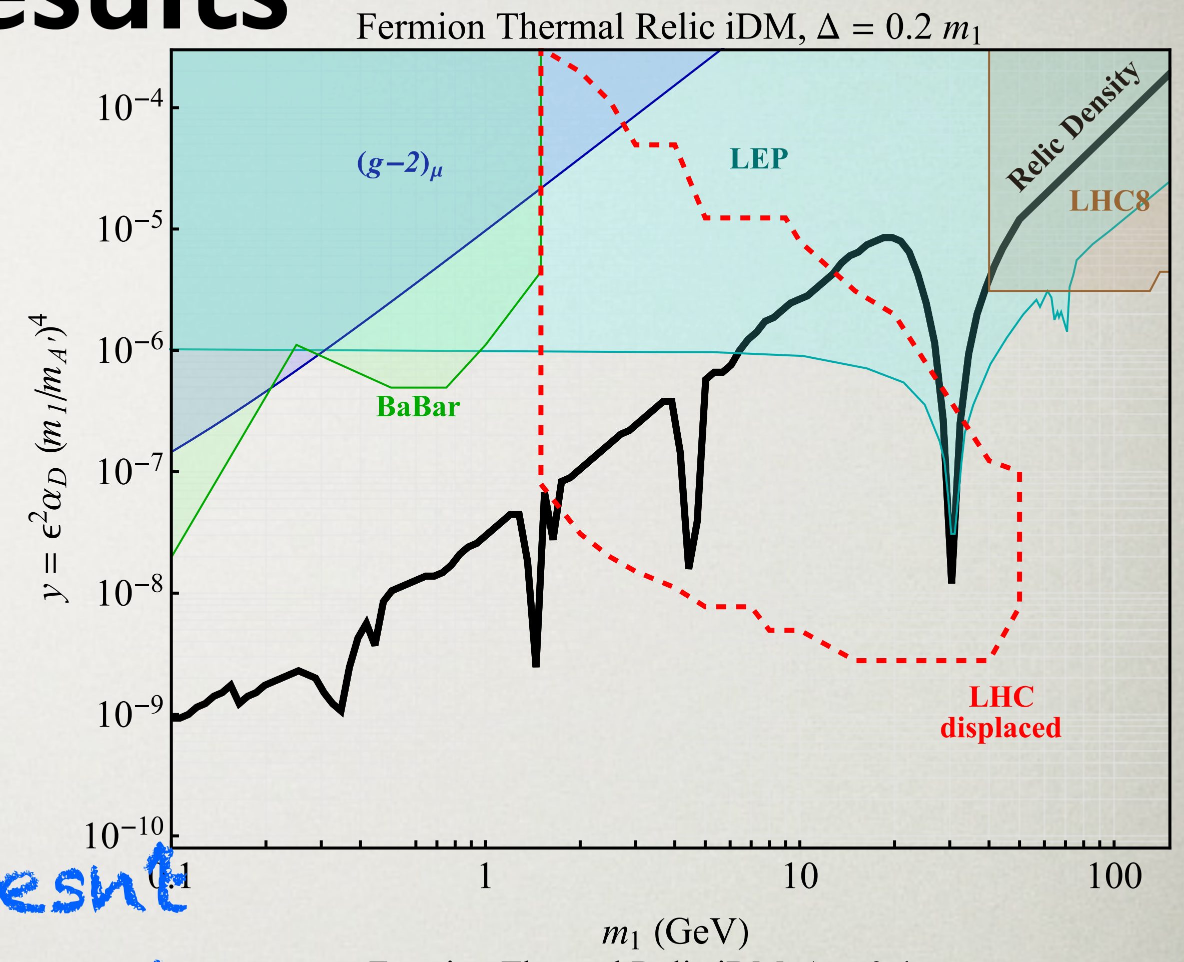


- Monojet + soft displaced lepton jet + MET
- Could be background free:
  plot sensitivity for **ten** signal events

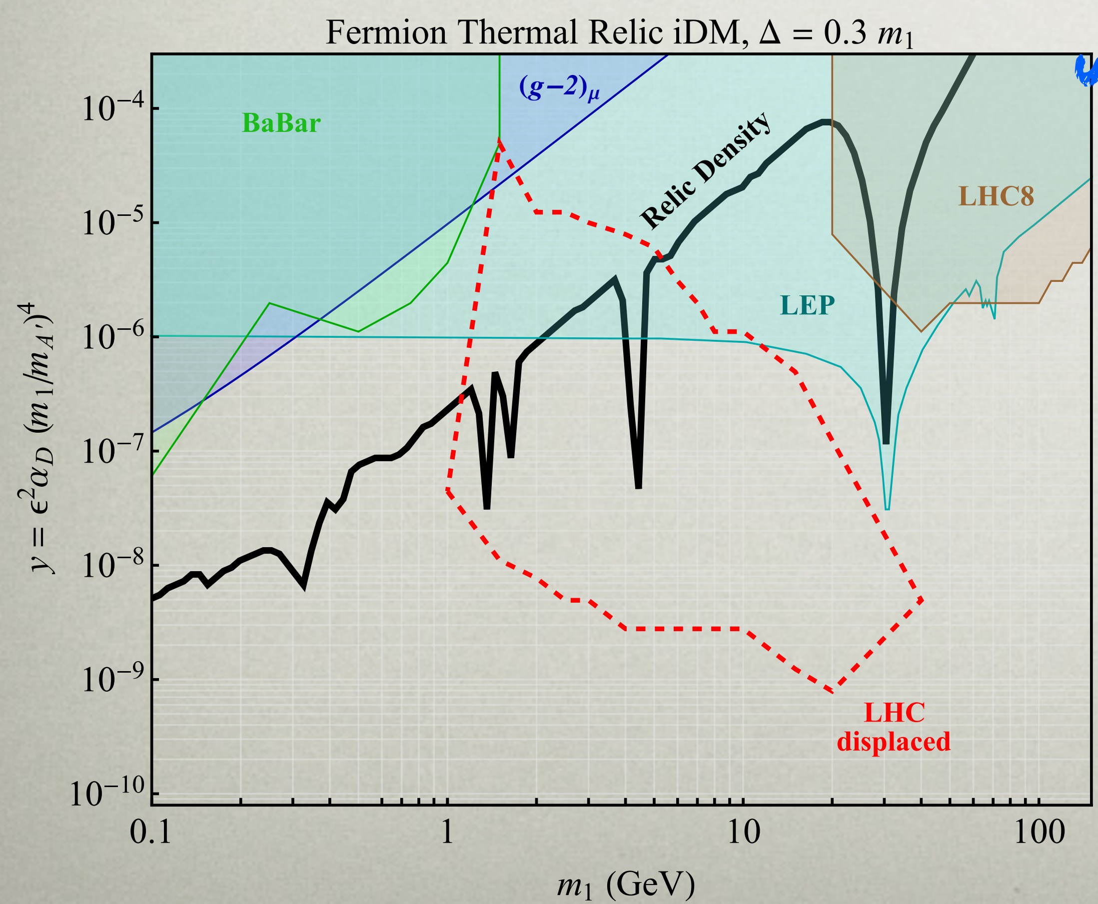
- Require $\not{H}_T > 120$ GeV
- Leading jet $p_T > 120$ GeV, veto 3rd jet $p_T > 30$ GeV
- Two displaced muon tracks, $p_T > 5$ GeV, crossing within 1 mm of one another
- $\Delta R < 0.4$ between muons
- $|\Delta\phi| < 0.4$ between lepton jet and MET

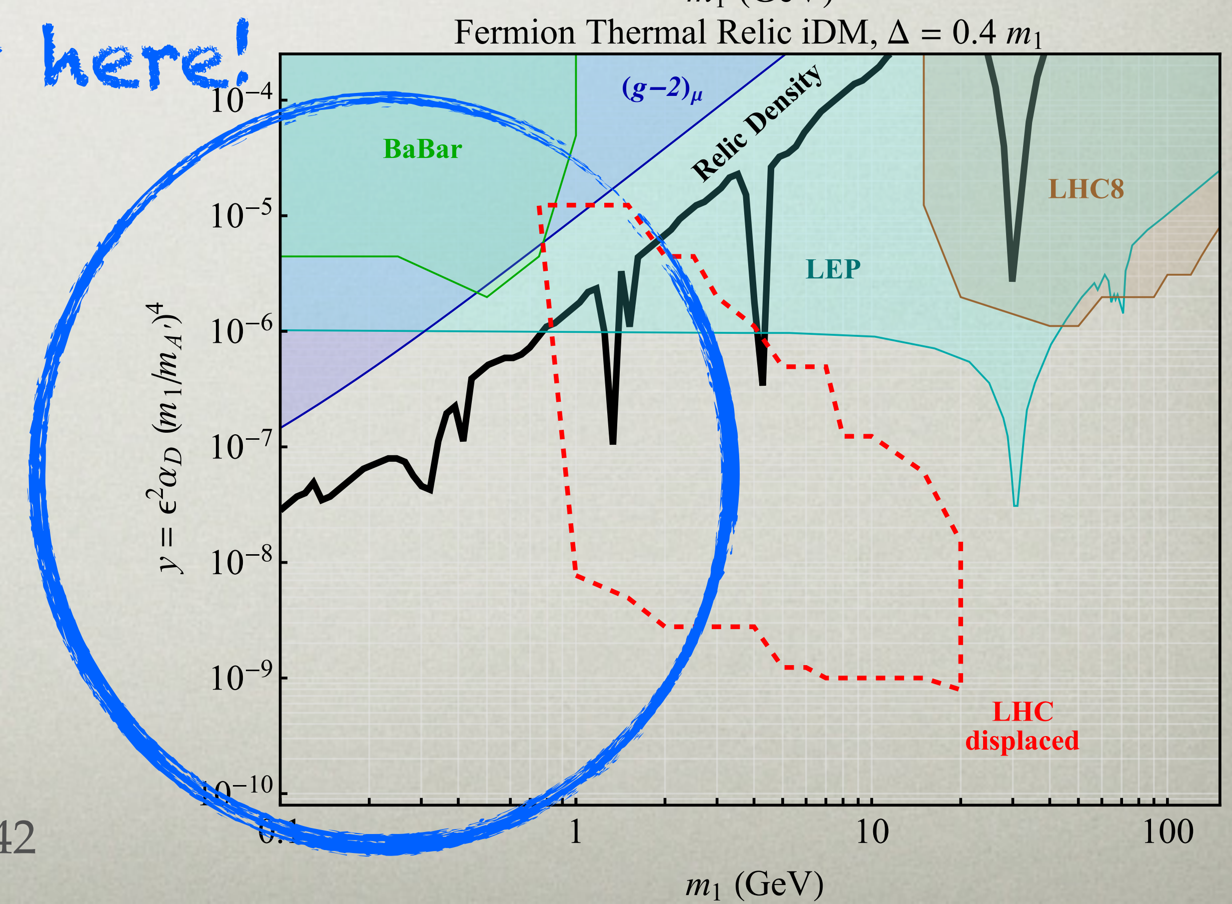
LHC Results





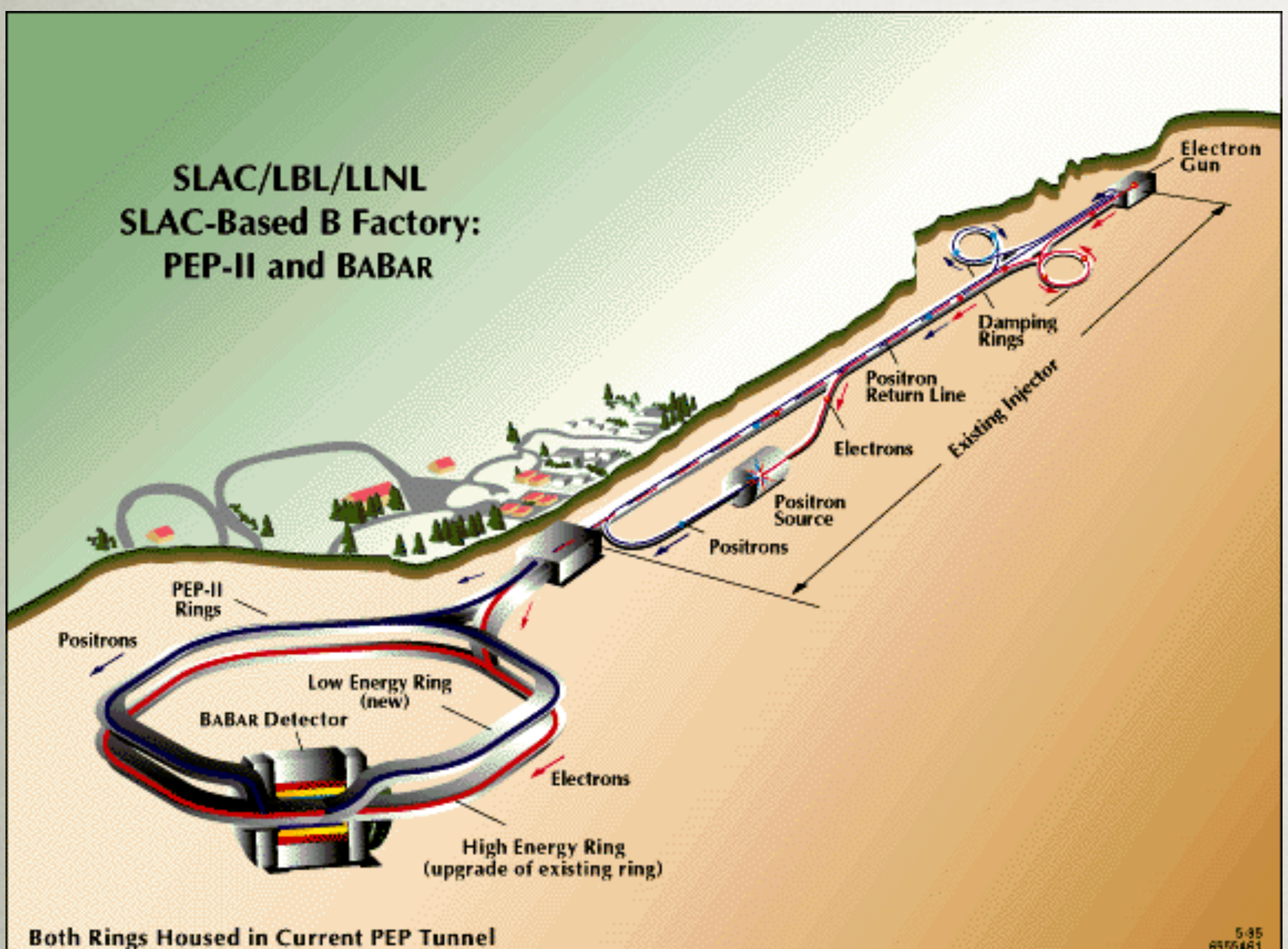
LHC doesnt work here!





What About Low-Mass DM?

- Can use a **lower energy** collider to study these scenarios!



LHC: **13 TeV**

BaBar/Belle II: **10.6 GeV**

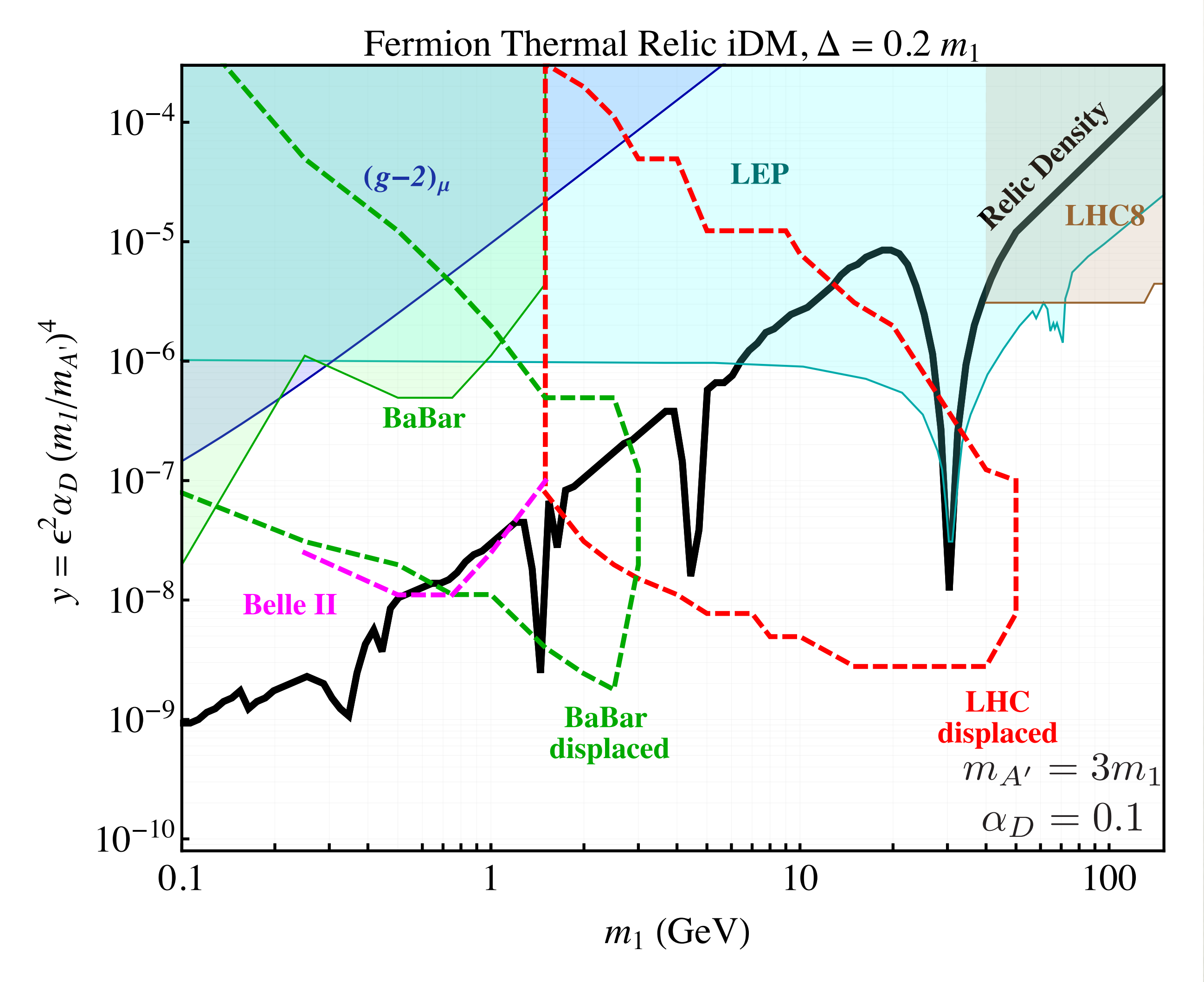
Other Collider Probes

1. **BaBar:**
   - Monophoton trigger for ~60/fb
   - Look for **monophoton** + displaced vertex (between 1-50 cm)
   - Need DV discrimination of 100-1000 for background-free search

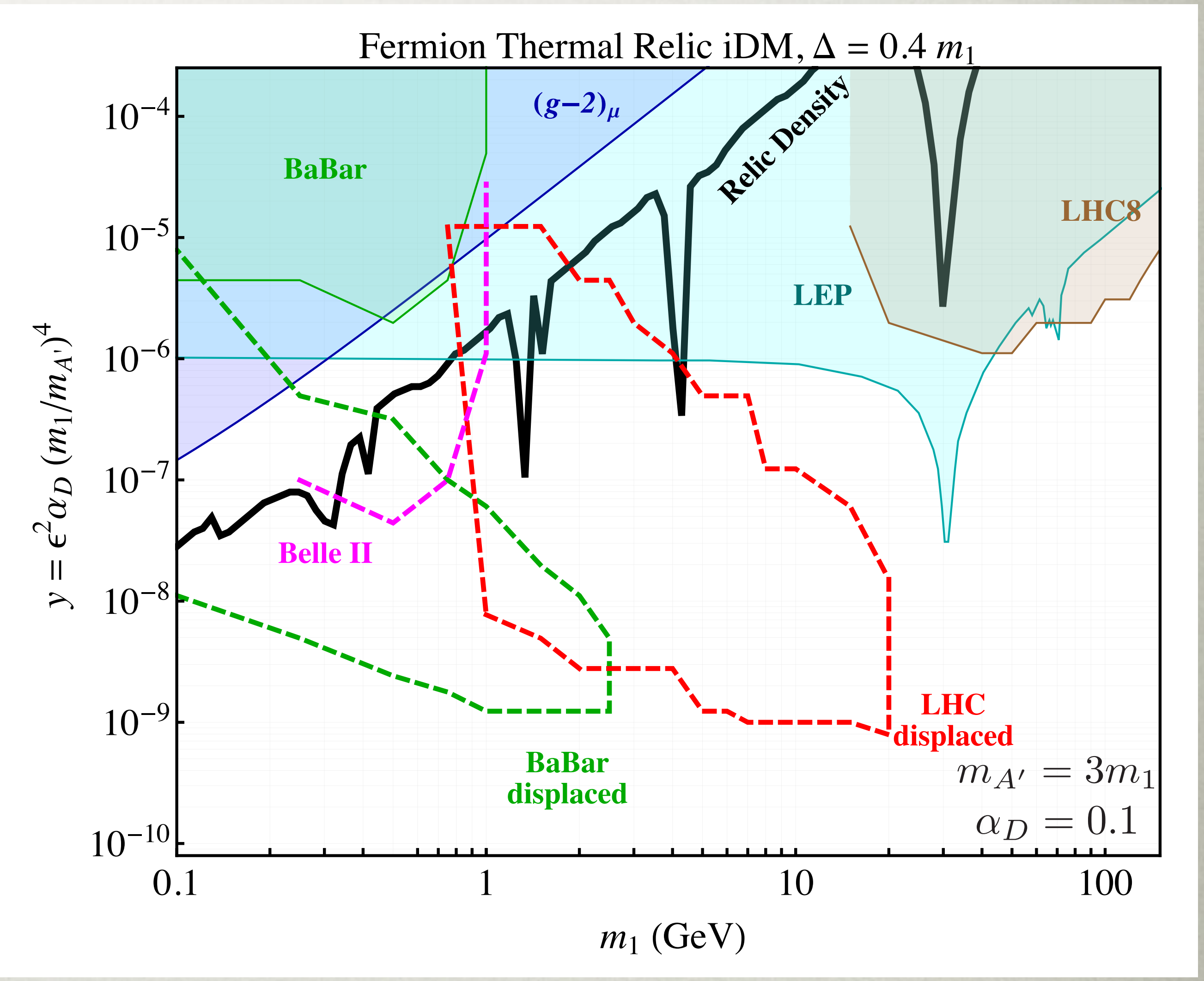
2. **Belle II:**
   - Looks like it will be instrumented with a monophoton trigger
   - Bounds from monophoton + missing energy search when tracks are below threshold/outside detector

(Essig *et al.*, 1309.5084)

LHC Results



Fermion Thermal Relic iDM, Δ = 0.2 m_1
$y = \epsilon^2 \alpha_D (m_1/m_{A'})^4$
m_1 (GeV)
(g−2)$_\mu$
LEP
Relic Density
LHC8
BaBar
Belle II
BaBar displaced
LHC displaced
$m_{A'} = 3m_1$
$\alpha_D = 0.1$



Fermion Thermal Relic iDM, Δ = 0.4 m_1
$y = \epsilon^2 \alpha_D (m_1/m_{A'})^4$
m_1 (GeV)
BaBar
(g−2)$_\mu$
Relic Density
LHC8
LEP
Belle II
LHC displaced
BaBar displaced
$m_{A'} = 3m_1$
$\alpha_D = 0.1$

Other Possibilities

- Can use monojet + soft object tagging for other DM scenarios

- *E.g.*, doublet/“pure Higgsino”

$\tilde{H}^{\pm}$

$\tilde{H}^{0}$

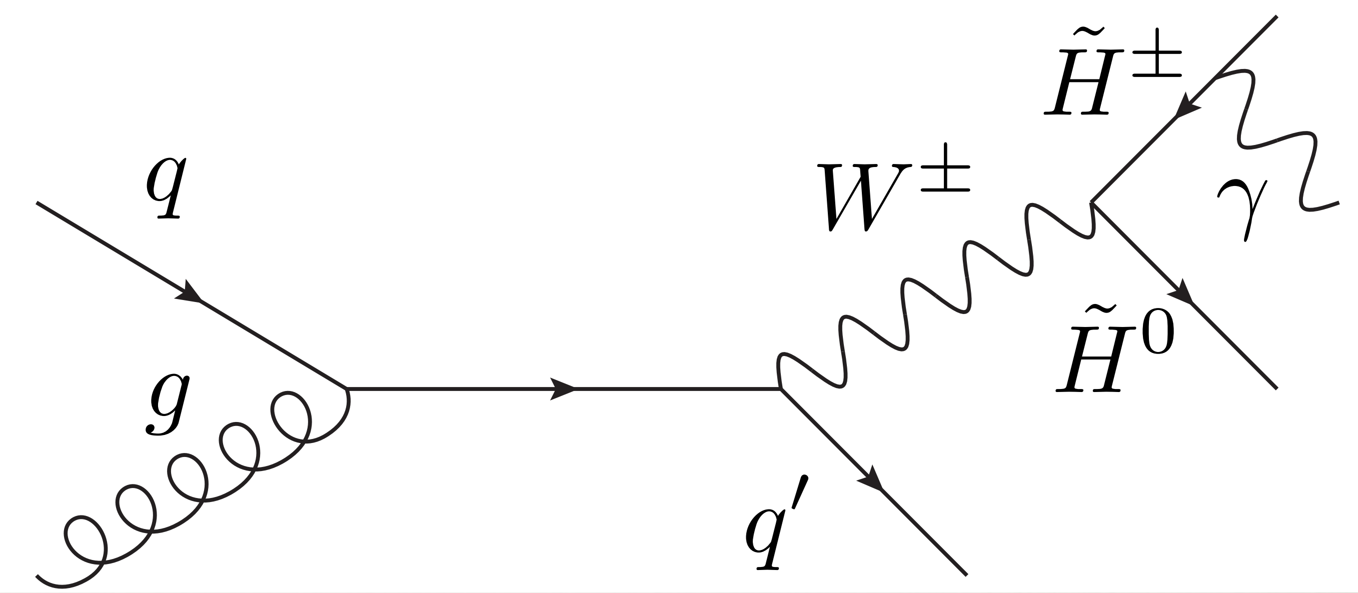
$$c\tau(\tilde{H}^{\pm} \to \tilde{H}^{0}\pi^{\pm}) \sim 5\ \mathrm{mm}$$

- Disappearing charged track, but **too short!**

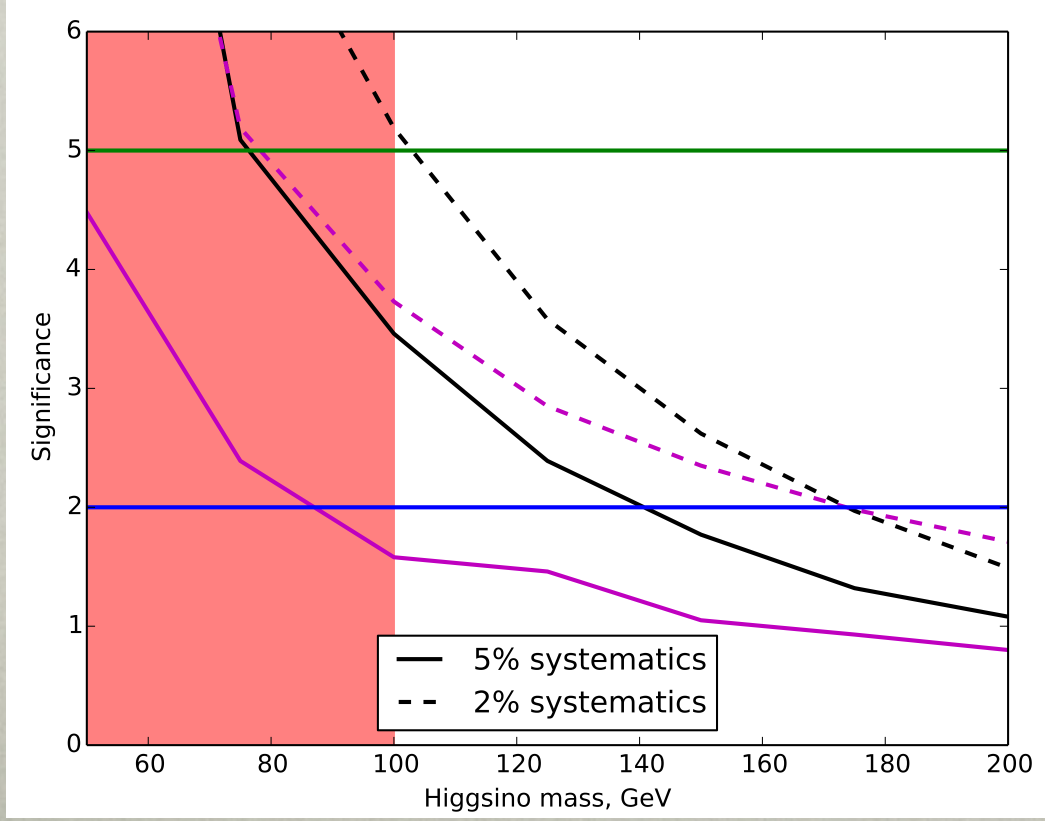
Thomas, Wells, hep-ph/9804359, ...

Other Possibilities

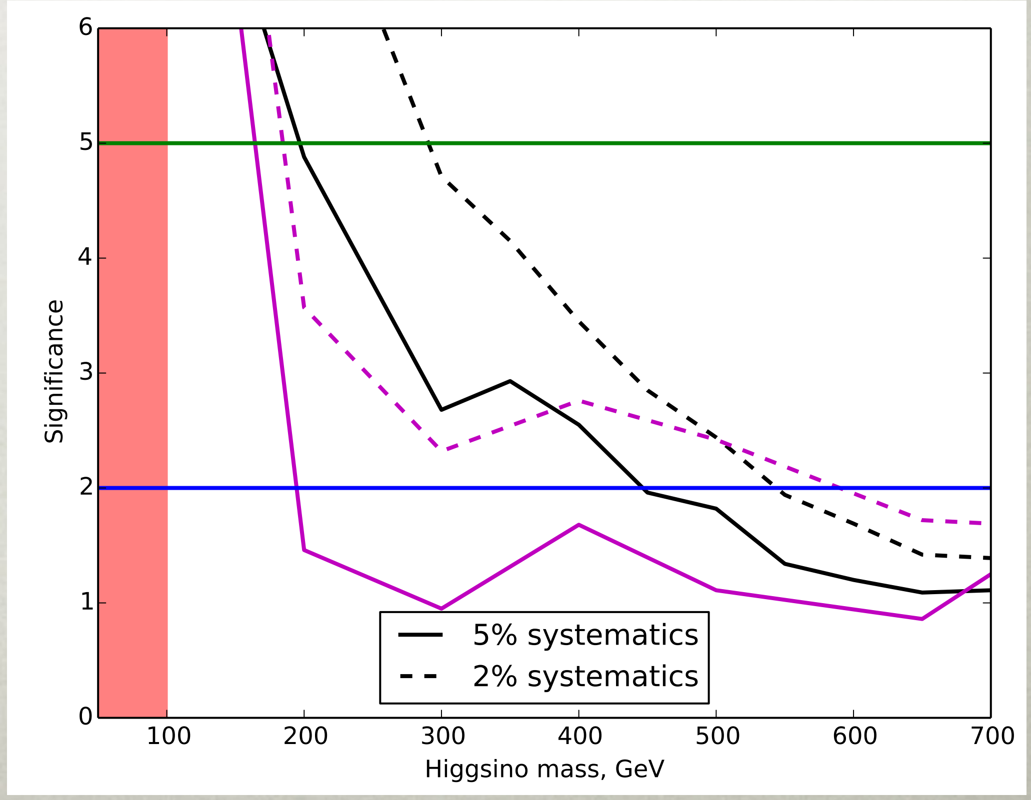
- Instead, use photon FSR
- Helps when systematics dominated



HL-LHC



100 TeV, 3/ab



(Ismail, Izaguirre, BS, preliminary!)

Summary

- New physics at or below the weak scale is motivated by naturalness, dark matter, baryogenesis, and neutrino masses

- Many diverse models and frameworks predict **similar signatures**

- In many cases backgrounds are so low that a discovery is possible even in very soft final states

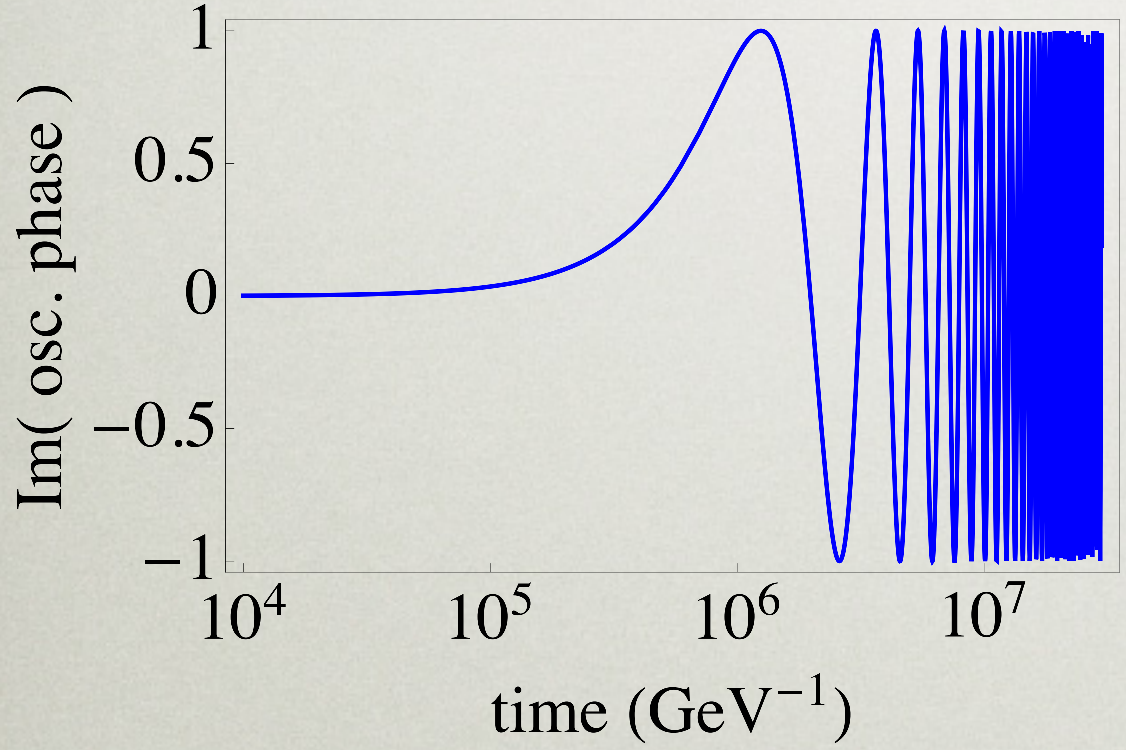
- Let's hope for discovery in both high- and low-mass new physics!

Back-up slides

Asymmetry Generation

- The CP-violating rate comes from the interference of the diagrams

$$\Gamma(L_\alpha \to L_\beta) - \Gamma(\bar{L}_\alpha - \bar{L}_\beta) \propto \mathrm{Im}\left[\exp\left(-i\int_0^t dt' \, \frac{M_3^2 - M_2^2}{2T(t')}\right)\right] \mathrm{Im}\left[F_{\alpha 3} F^*_{\beta 3} F^*_{\alpha 2} F_{\beta 2}\right]$$

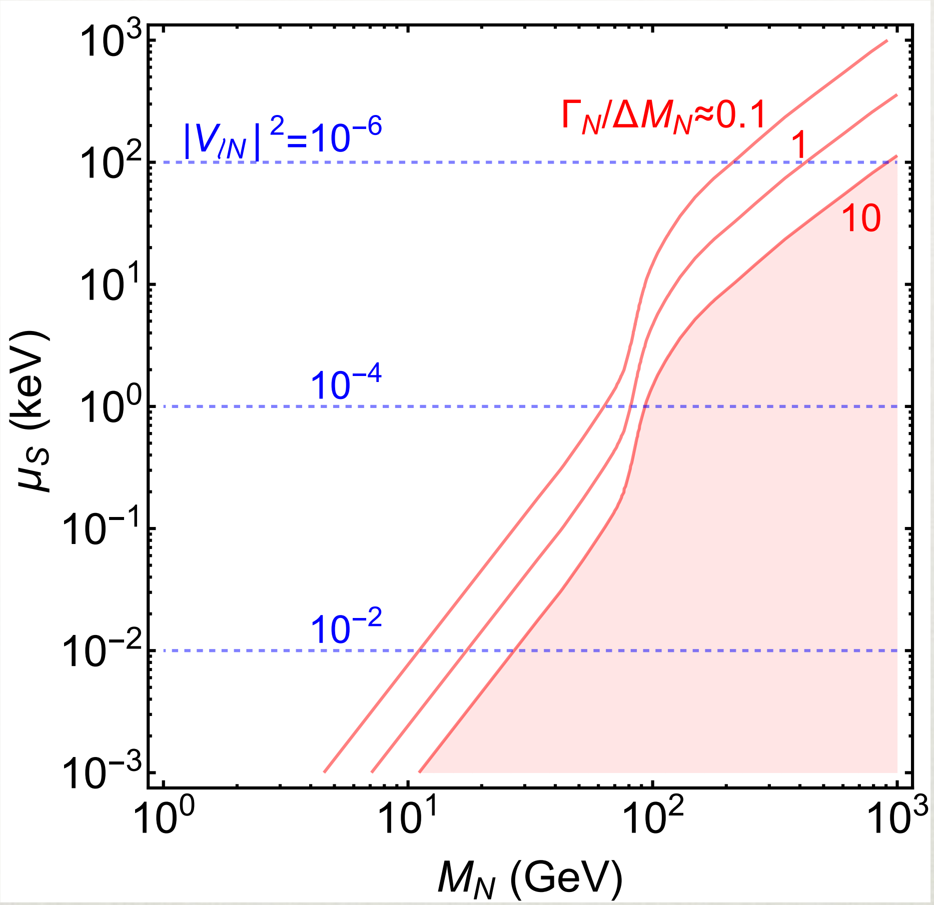


Asymmetry generation effectively **stops** when

$$(M_3^2 - M_2^2)/T \sim H$$

$$(T \gg M_N)$$

- Asymmetry is **larger** for oscillation at **later** times because integration time is longer



|V_lN|^2=10^-6
10^-4
10^-2
Γ_N/ΔM_N≈0.1
1
10
μ_S (keV)
M_N (GeV)

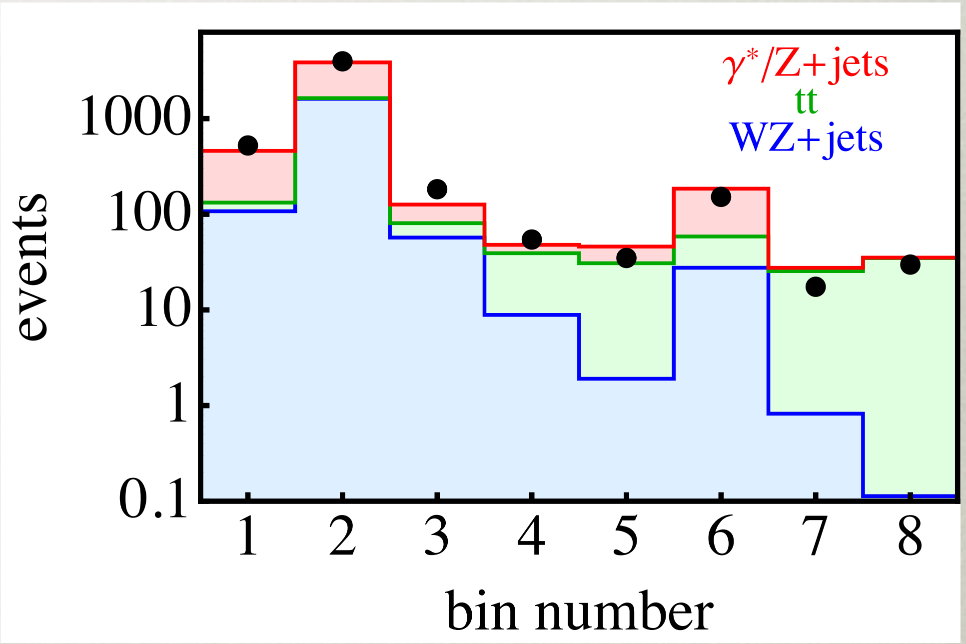
Resolved prompt decays

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

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

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

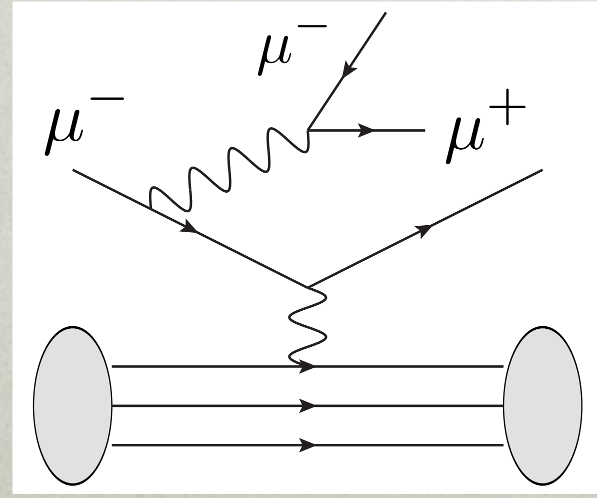
0b 1b

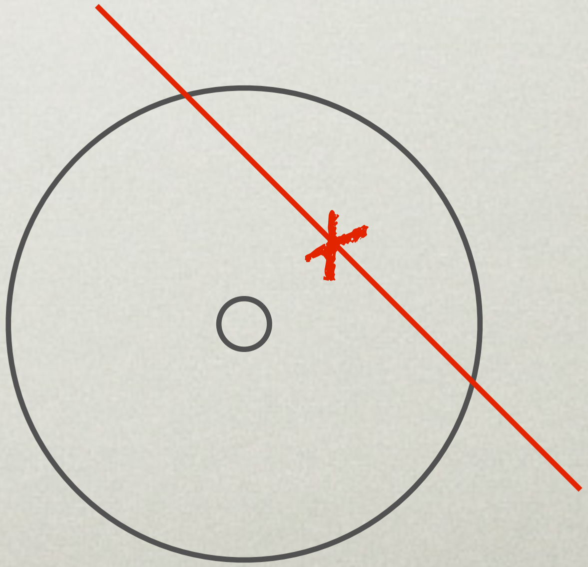
Also checked method with ATLAS same-sign muon & CMS same-sign muon + jets analyses

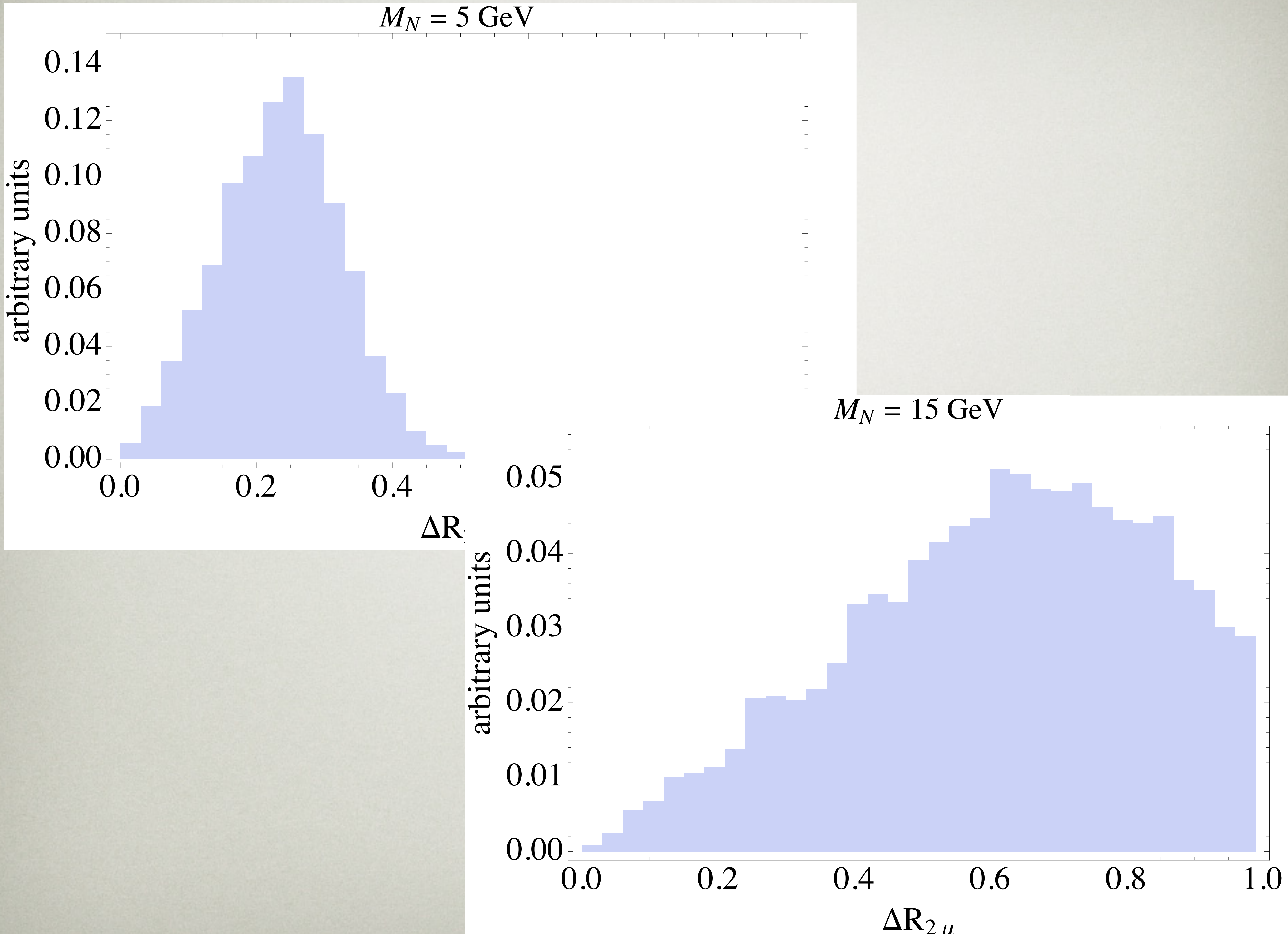
Lepton jets from RH neutrinos

- ATLAS has a lepton jet search, but it is for a **pair** of muon jets
  - Veto reconstructed tracks in inner detector (no displaced vertex reconstruction), but require track impact parameter to be in inner detector
  - They see ~10 background events

- There are some unknowns in extrapolating results to single lepton jet
  - Extrapolation based on single cosmic muon flux gives vanishing result!
  - Can get "muon bundles" from muon trident production
  - Single cosmic muon can fake back-to-back muons from inner detector



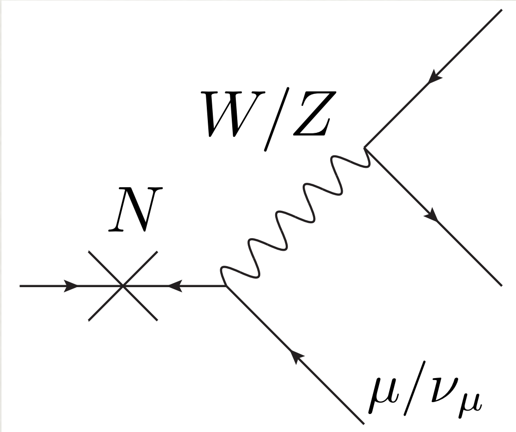




M_N = 5 GeV
arbitrary units
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0
0.2
0.4
M_N = 15 GeV
arbitrary units
0.05
0.04
0.03
0.02
0.01
0.00
0.0
0.2
0.4
0.6
0.8
1.0
$\Delta R_{2\mu}$

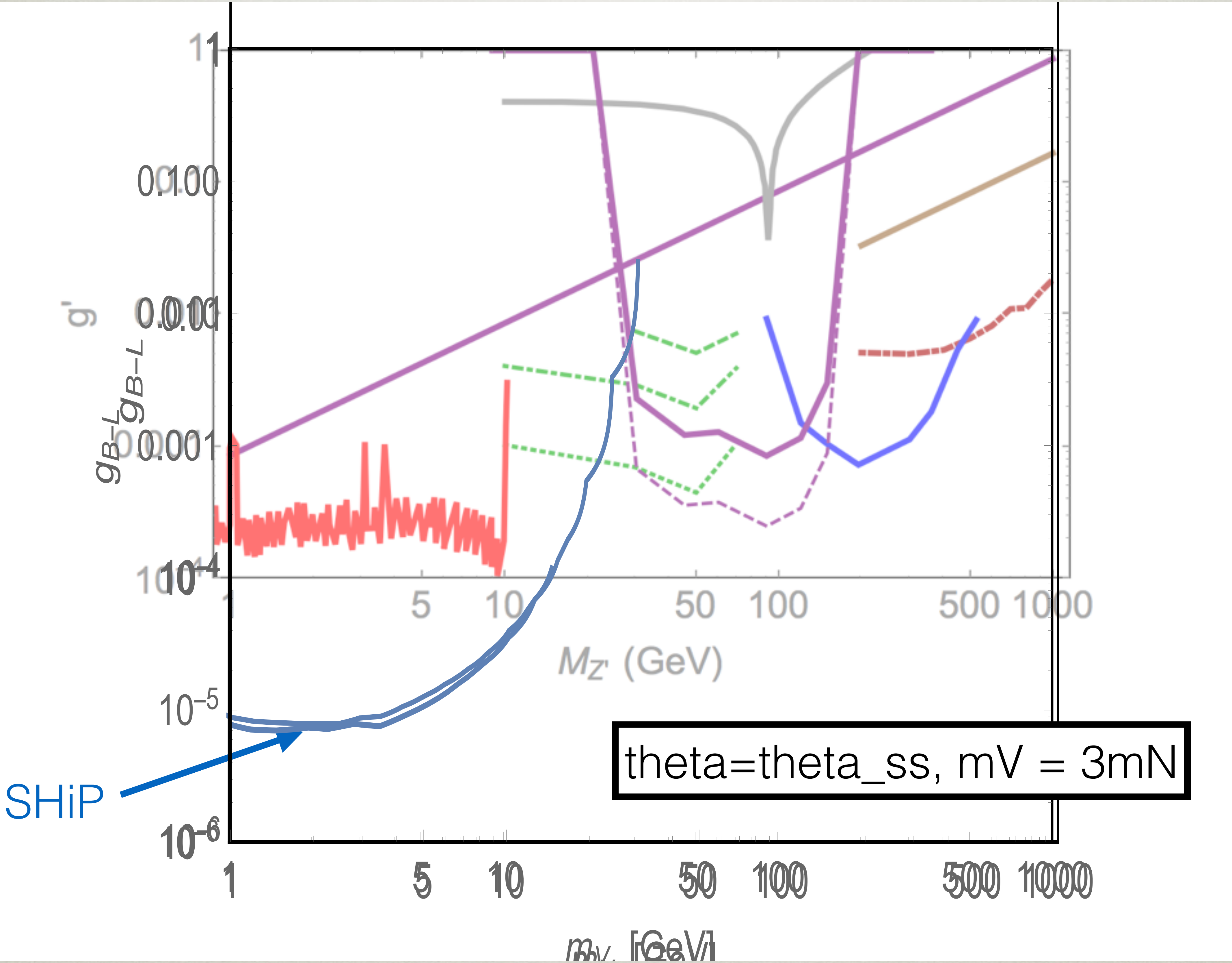
B/L gauge forces at colliders

- *N* decays via (off-shell) W/Z
    - Get displaced muon in > 50% of decays
    - Use lepton triggers

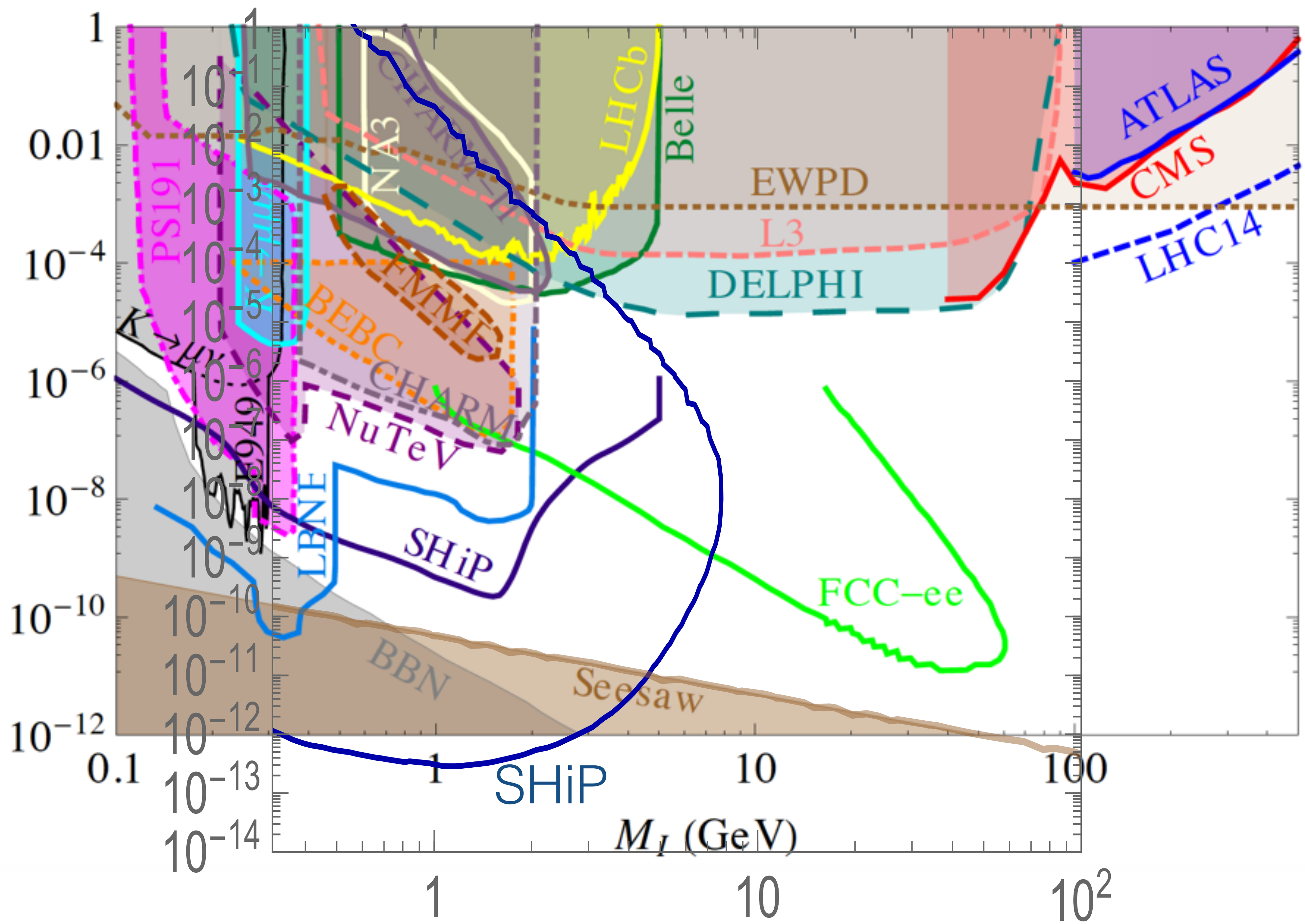


- Current searches have high thresholds, unnecessary restrictions
    - 1 electron and 1 muon, not required to reconstruct vertex, > 1 mm displacement, 0.05 bkd events (CMS, 1409.4789)
    - Pair of electrons or muons at vertex, $m_{\ell\ell} > 15$ GeV, > 0.2 mm displacement, 0 bkd event prediction with 0 bkd in control region (CMS, 1411.6977)
    - Pair of leptons at vertex, leading lepton > 50-100 GeV, $m_{\ell\ell} > 6$ GeV, ≥ 1 mm displacement, 10^{-3} bkd events (ATLAS, 1504.05162)
    - Muon + at least 4 tracks at vertex, muon > 50 GeV, $m_{\ell\ell} > 6$ GeV, ≥ 1 mm displacement, 10^{-3} bkd events (ATLAS, 1504.05162)

- We require one of the above + some other displaced object → expect bkd-free

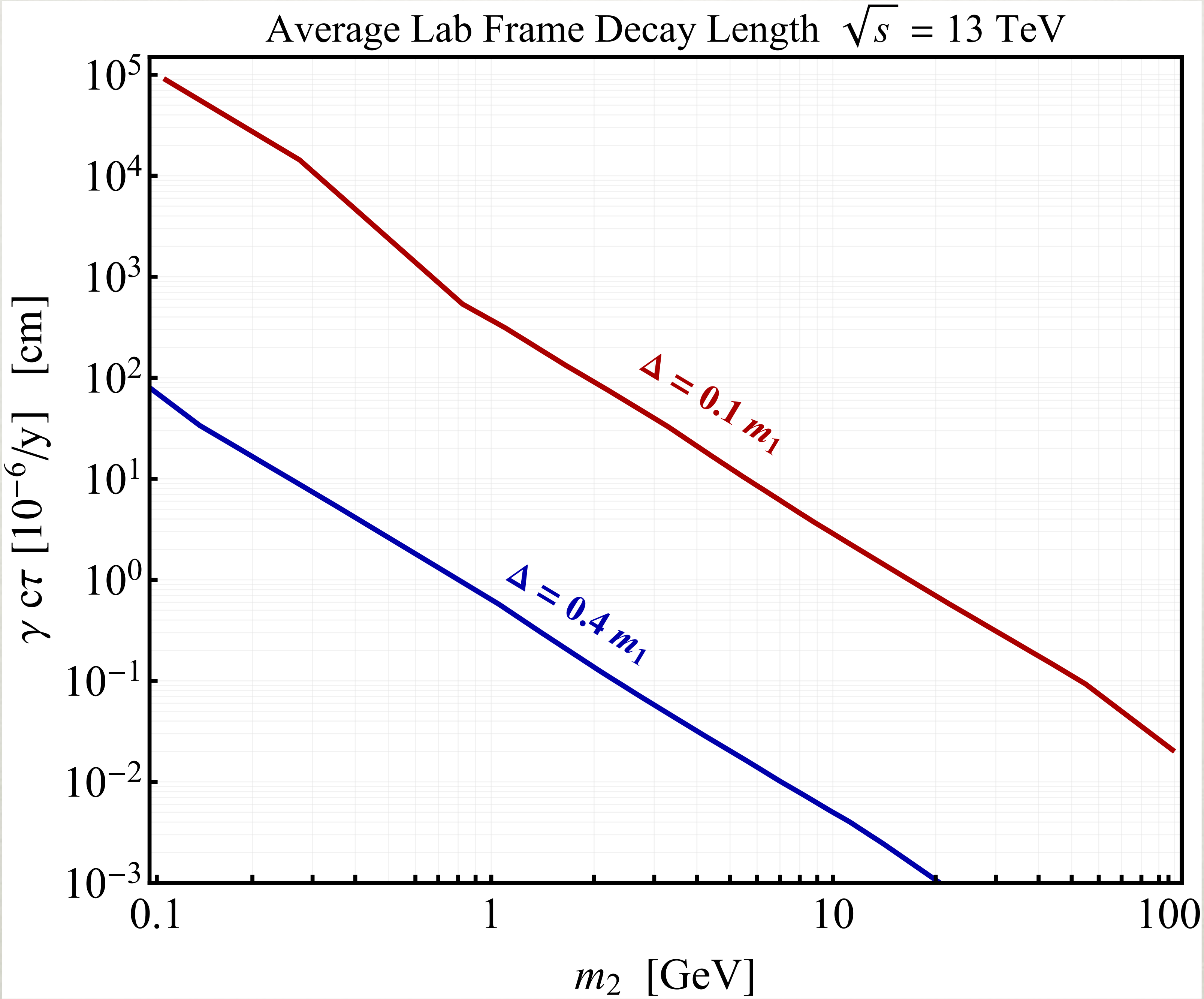

theta=theta_ss, mV = 3mN
SHiP
$M_{Z'}$ (GeV)
g'
g_{B-L}
10^{-5}
10^{-6}
1
5
10
50
100
500
1000

g’ = 0.001, mV = 3mN

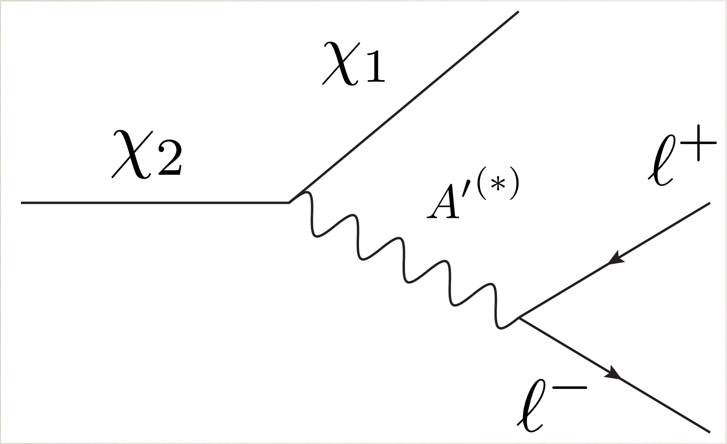


PS191
K → μν
E949
LBNE
SHiP
NA3
CHARM
LHCb
Belle
EWPD
L3
DELPHI
FMMF
BEBC
NuTeV
FCC−ee
BBN
Seesaw
ATLAS
CMS
LHC14
SHiP
$|U_{\mu I}|^2$
M_I (GeV)

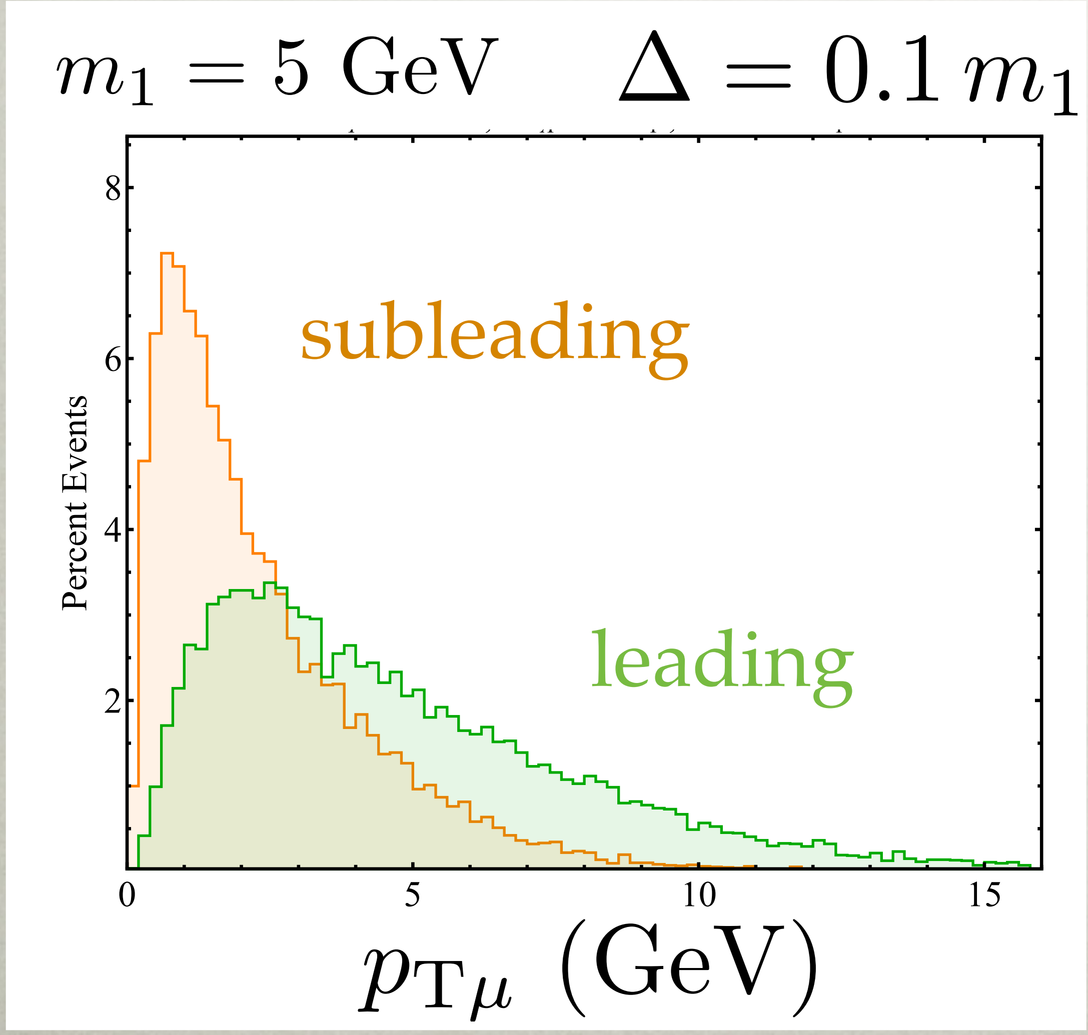
iDM Lifetimes

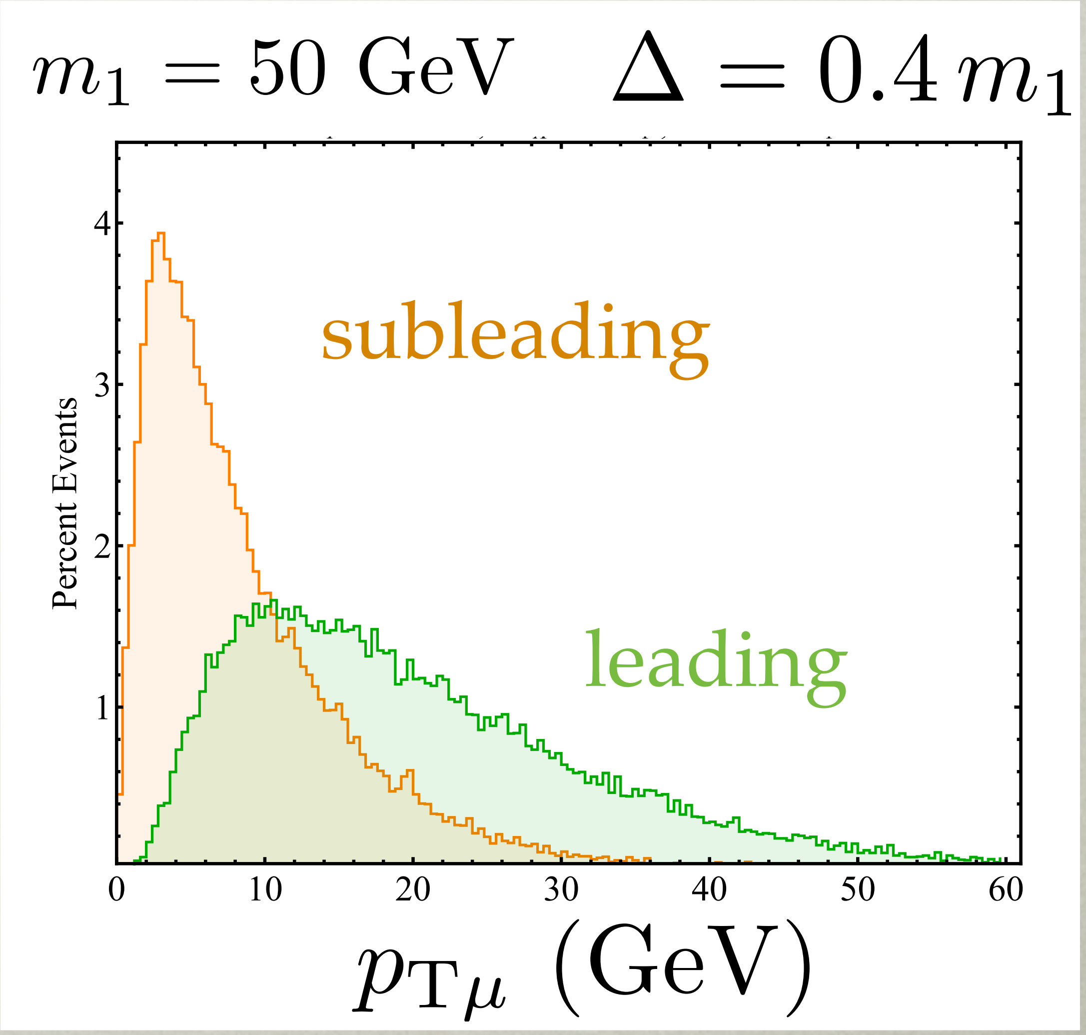


Improving the Searches



- For small splittings, leptons are soft, so trigger on monojet + MET





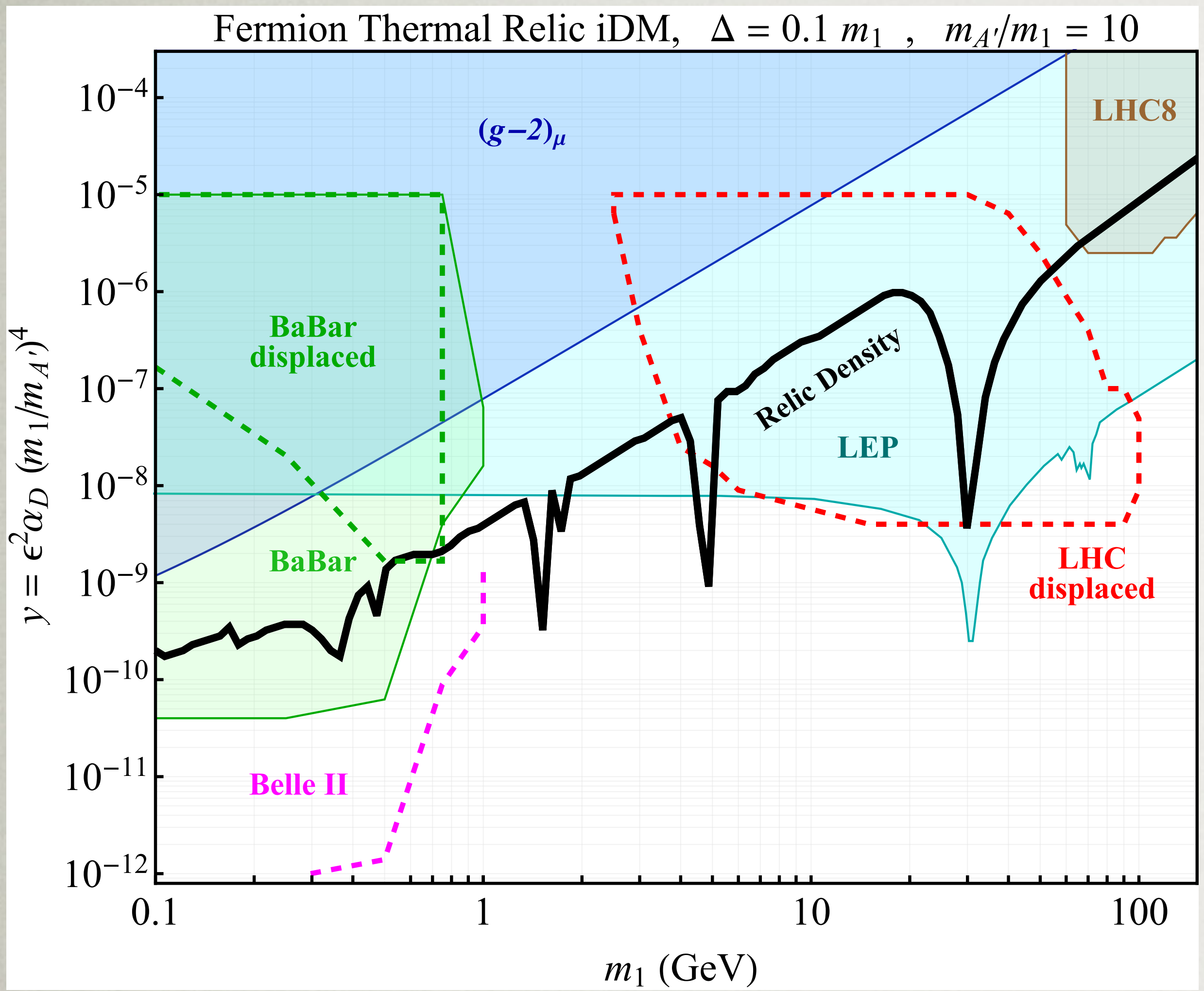
Backgrounds

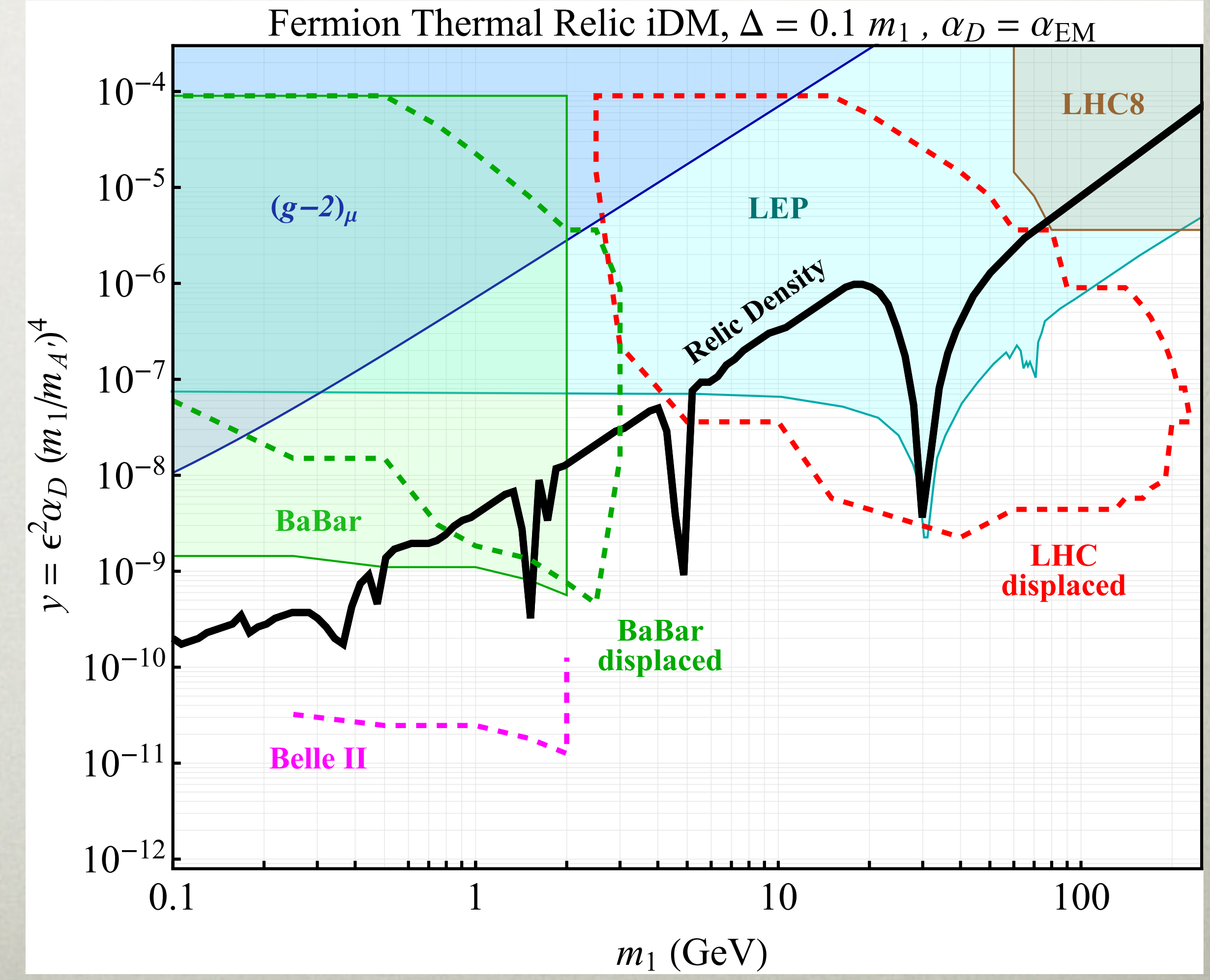
- Random track crossings
  - Can't do first principles estimate
  - We look at QCD events ($p_{\mathrm{Tj}} > 120$ GeV, no MET cut) and find the efficiency for two isolated muon tracks satisfying the signal requirements
  - We find no events, bounds QCD contribution < 100 fb
  - Adding requirement for additional invisible Z/W, kinematic requirements leads to expectation of ≲ few events

2. **Photon conversion to muons**
   - Cross section for Z + jet + gamma is ~ 100 fb after jet p_T, photon E_T cut
   - Even though the probability for conversion to leptons is $O(1)$, the ratio of e/mu is

$$\frac{\sigma(\gamma \to \mu\mu)}{\sigma(\gamma \to ee)} \sim \frac{m_e^2}{m_\mu^2}$$

3. **Pile-up crossings**
   - Since LJ is collinear with χ_2, require that muons point back to same vertex as jet


Fermion Thermal Relic iDM, Δ = 0.1 m_1 , $m_{A'}/m_1$ = 10
$y = \epsilon^2\alpha_D\,(m_1/m_{A'})^4$
m_1 (GeV)
$(g-2)_\mu$
LHC8
BaBar displaced
BaBar
Relic Density
LEP
LHC displaced
Belle II


Fermion Thermal Relic iDM, Δ = 0.1 m_1 , $\alpha_D = \alpha_{EM}$
$y = \epsilon^2\alpha_D\,(m_1/m_{A'})^4$
m_1 (GeV)
$(g-2)_\mu$
LEP
LHC8
Relic Density
BaBar
BaBar displaced
LHC displaced
Belle II