LOW-SCALE LEPTOGENESIS & HIDDEN-SECTOR BARYOGENESIS

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Testing CPV for Baryogenesis
ACFI, UMass Amherst

HARVEY MUDD COLLEGE

OUTLINE

- Overview of low-scale leptogenesis (~GeV RHNs)
- CPV and phenomenology of low-scale leptogenesis
- Hidden-sector baryogenesis (involving DM)

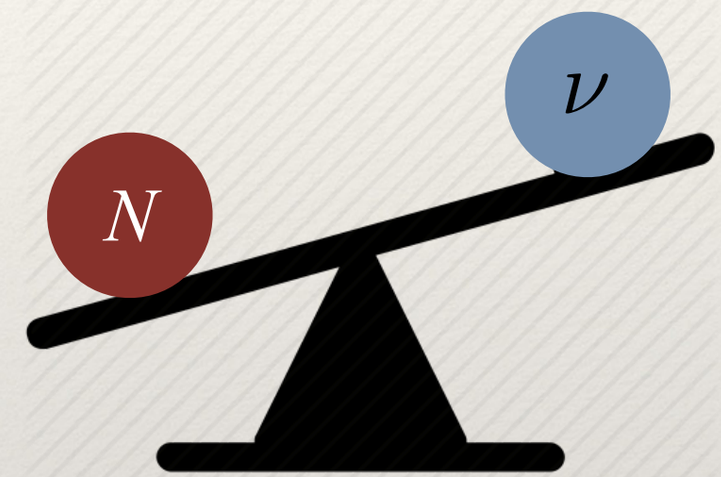
LEPTOGENESIS: MOTIVATION

Minkowski, PLB 67 (1977); Yanagida Conf. Proc C7902131 (1979); Mohapatra and Senjanovic, PRL 44 (1980)…

- See-saw mechanism is minimal, natural model for neutrino masses

$$\mathcal{L}_{\nu\mathrm{MSM}} = F_{\alpha I} L_\alpha \Phi N_I + \frac{M_I}{2} N_I^2$$

$$m_\nu \sim \frac{F^2 \langle \Phi \rangle^2}{M_N}$$



- Remarkably, 3 RH neutrinos at GeV-scale can account for neutrino masses, baryon asymmetry, DM!

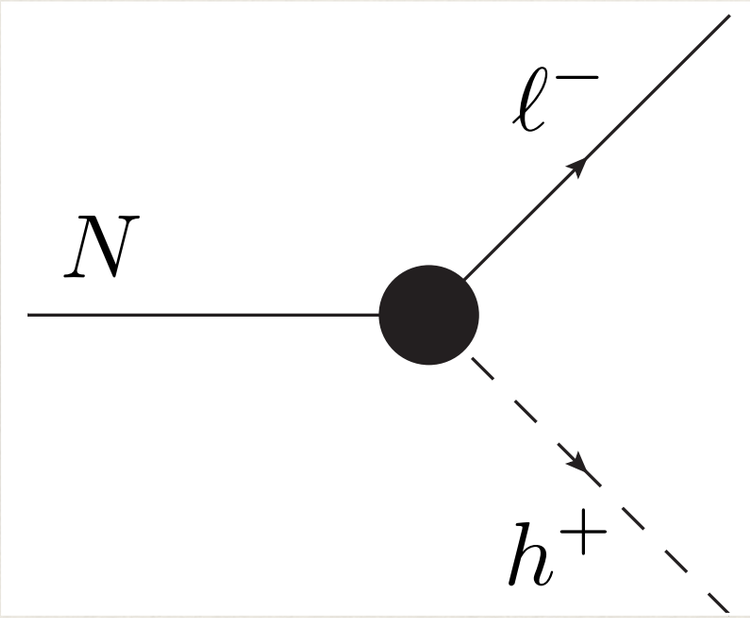
$$|F|^2 \sim 10^{-14} \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right) \left(\frac{m_N}{\mathrm{GeV}}\right) \left(\frac{100\ \mathrm{GeV}}{\langle \Phi \rangle}\right)^2$$

Asaka, Shaposhnikov hep-ph/0503065, hep-ph/0505013

LEPTOGENESIS: MOTIVATION

- Leptogenesis can proceed in two ways:

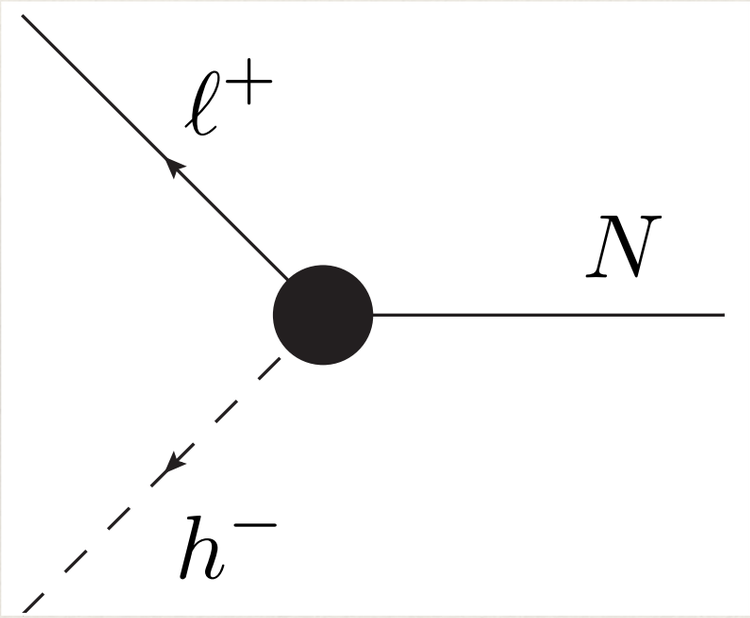
DECAY



(valid only for $M_N \gg T_{\mathrm{EW}}$)

Fukugita, Yanagida, Phys. Lett. B174 (1986) 45

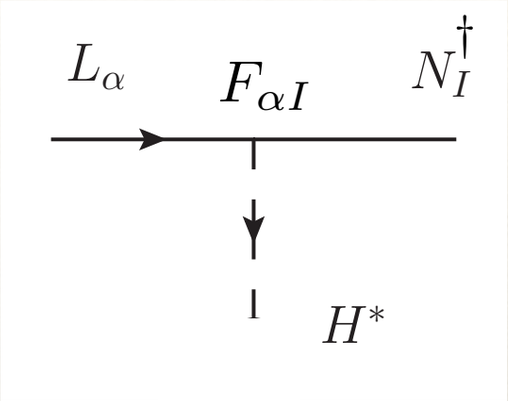
SCATTERING



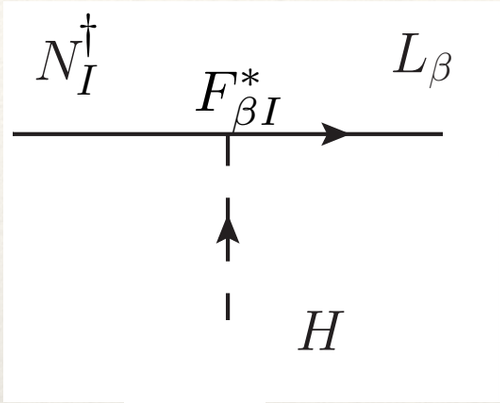
(mass can be below EW scale!)

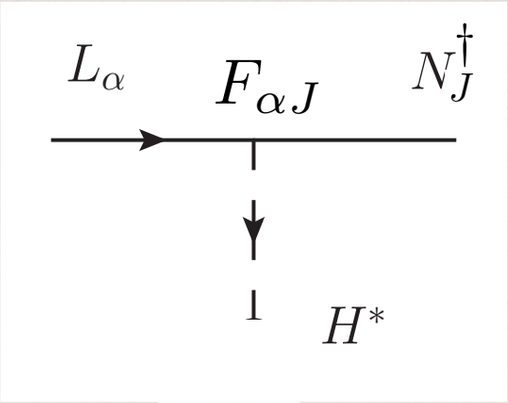
Akhmedov *et al.*, hep-ph/9803255
Asaka, Shaposhnikov, hep-ph/0505013

LEPTOGENESIS THROUGH SCATTERING

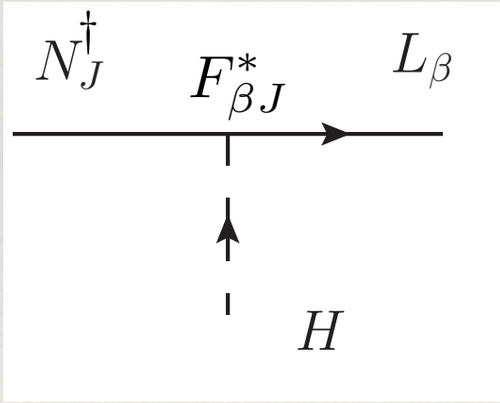


$e^{-i\omega_I t}$





$e^{-i\omega_J t}$



$$\omega_I - \omega_J \approx \frac{M_I^2 - M_J^2}{2T}$$

$$\Gamma(L_\alpha \to L_\beta) - \Gamma(\bar{L}_\alpha \to \bar{L}_\beta) \sim \mathrm{Im}(F^4)\,\mathrm{Im}\left[e^{i(\omega_I - \omega_J)t}\right]$$

LEPTOGENESIS THROUGH SCATTERING

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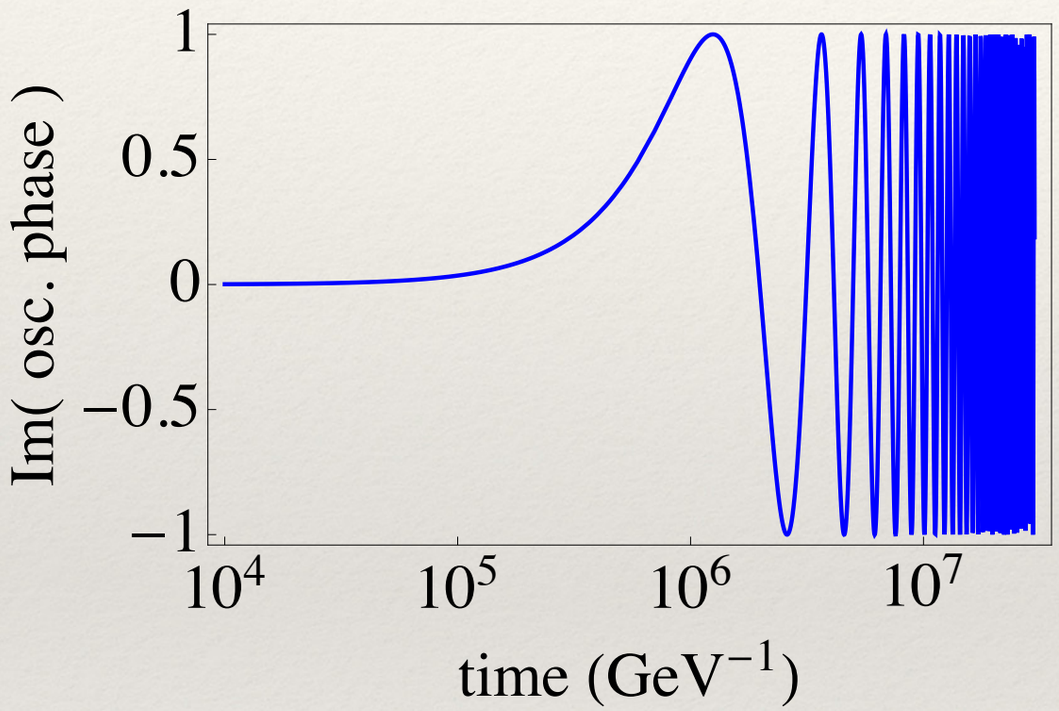
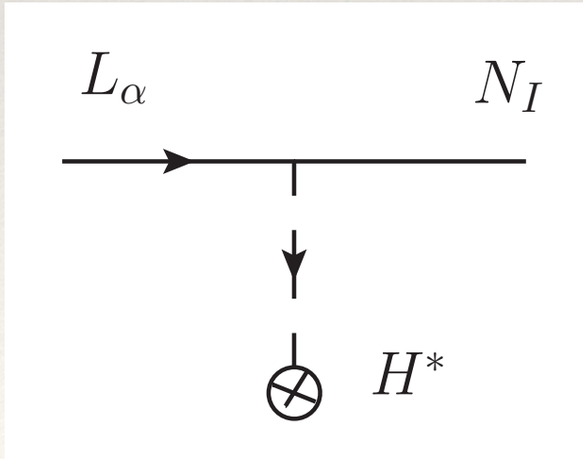


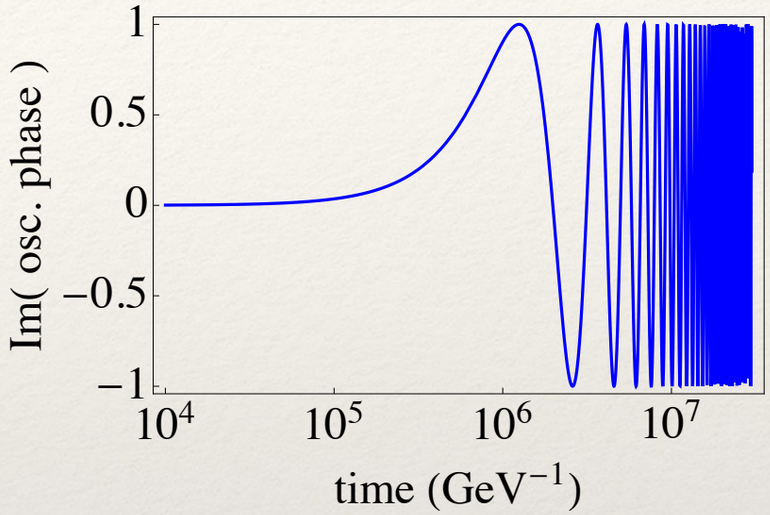
- Net asymmetry generation **stops** when $(M_3^2 - M_2^2)/T \sim H$

- This only gives a lepton flavour asymmetry, **not** lepton number asymmetry: need re-scattering



WHAT AFFECTS *CP* ASYMMETRY?

1. **Mass splitting.** More degenerate = later asymmetry generation and longer integration time



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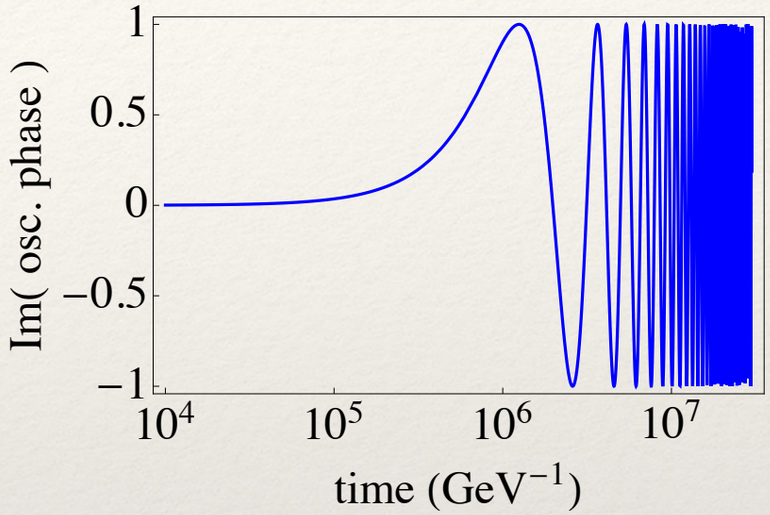

2. **Yukawa couplings.** Bigger = more scattering, larger asymmetry, but too big = equilibrium! (BAD)

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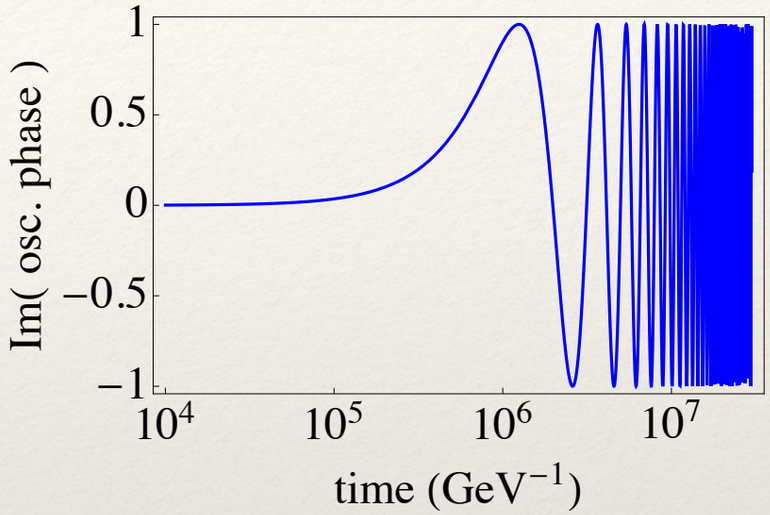

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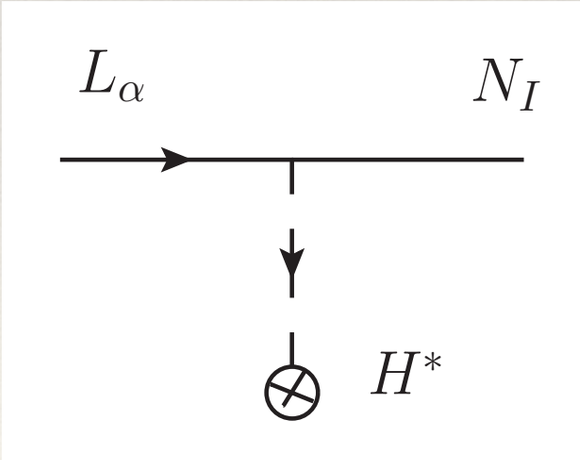

3. **Flavour differences.** To get flavour asymmetry, need flavour-dependent scattering rates!

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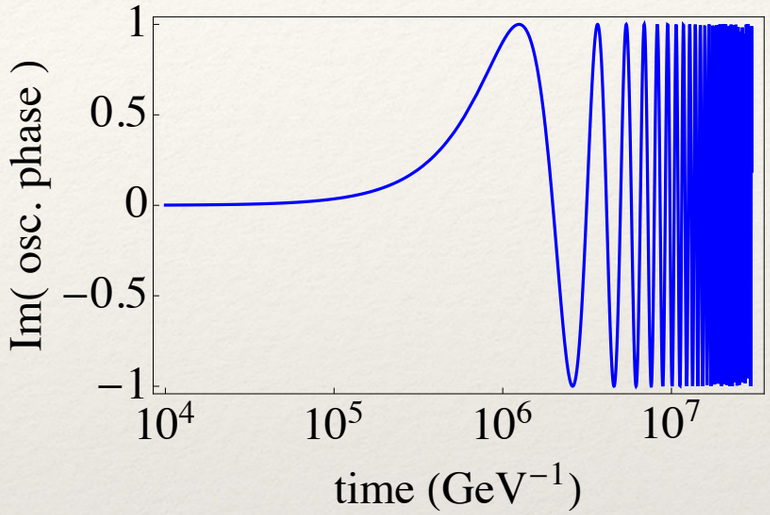

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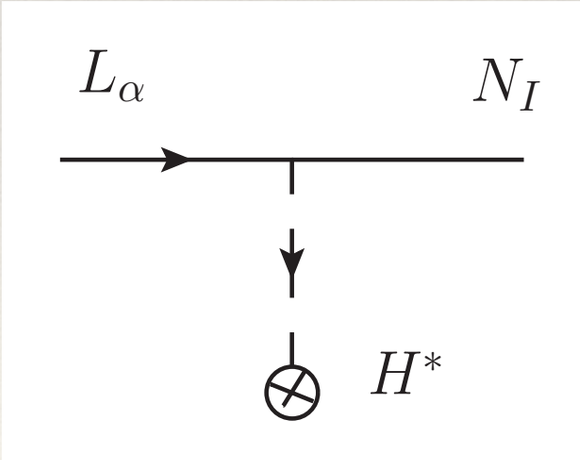

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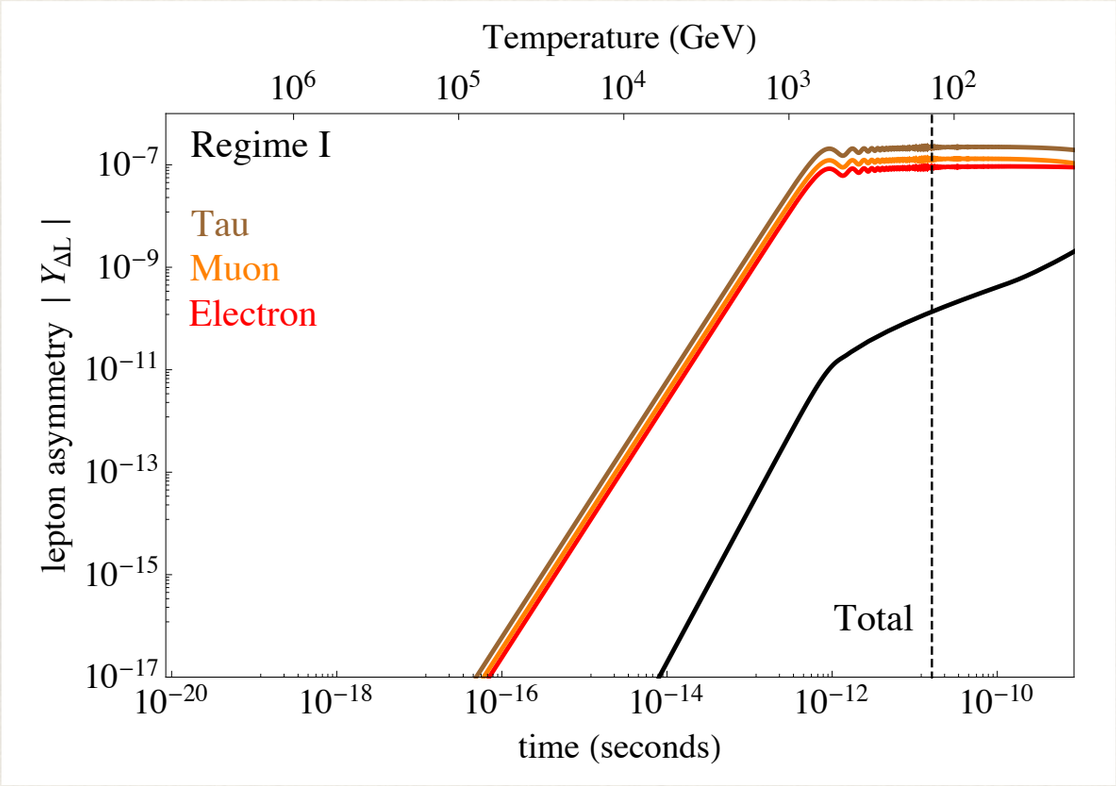
4. **CP phases.** Need to be non-zero, but also have other effects!

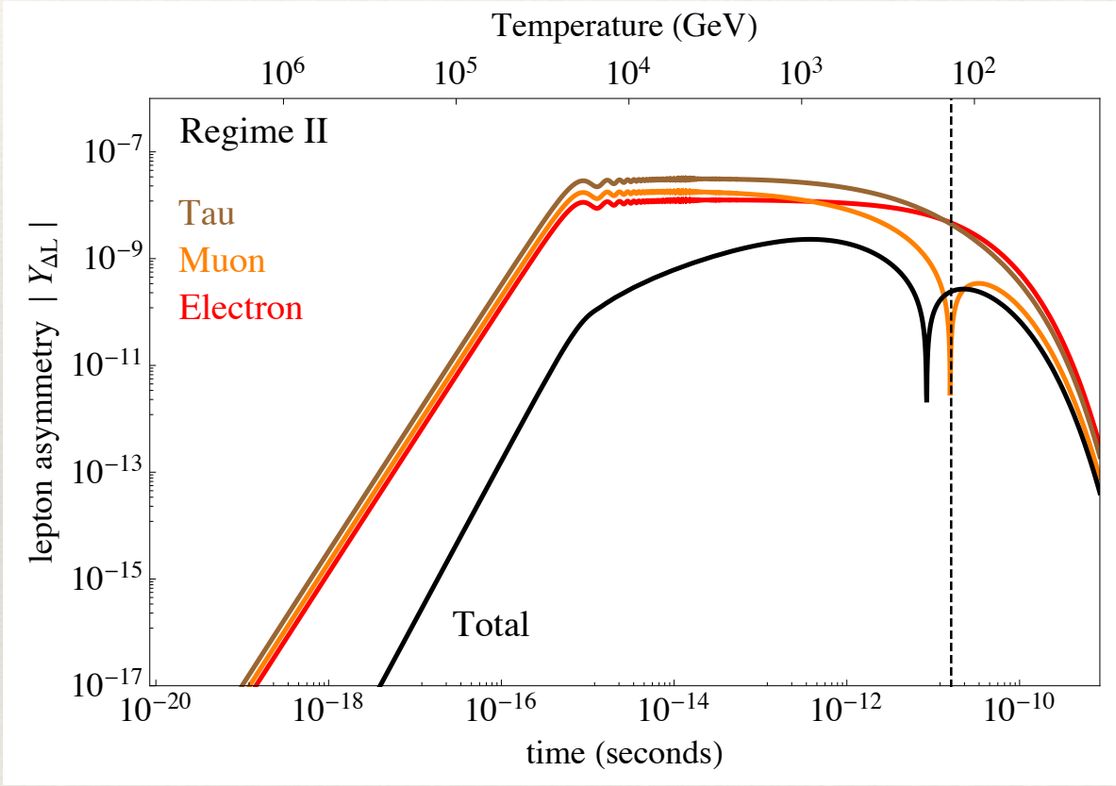
Canetti, Shaposhnikov, arXiv:1006.0133; Canetti *et* al., arXiv:1208.4607; BS, Yavin, arXiv:1401.2459

WHAT AFFECTS *CP* ASYMMETRY?

mass degeneracy



large Yukawa couplings



- dashed line indicates time of electroweak phase transition

BS, Yavin, arXiv:1401.2459

OUTLINE

- Overview of low-scale leptogenesis (~GeV RHNs)
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PARAMETERS OF THE MODEL

Casas, Ibarra, hep-ph/0103065

- Casas-Ibarra parameterization of Yukawa couplings:

$$F_{\alpha I} = \frac{i}{v} U_\nu \sqrt{m_\nu}\, R \sqrt{m_N}$$

- LH neutrino mixing matrix:

$$U_\nu = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- RH neutrino mixing matrix with complex mixing:

$$R = \begin{pmatrix} 0 & 0 \\ \cos\omega & \sin\omega \\ -\sin\omega & \cos\omega \end{pmatrix}$$

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- RH neutrino mixing matrix with complex mixing:

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$$\arg(\cos\omega) = -\tan(\mathrm{Re}\,\omega)\tanh(\mathrm{Im}\,\omega)$$

PARAMETERS OF THE MODEL

BS, Yavin, arXiv:1401.2459

- CP-violation for leptogenesis can arise from **any** of 3 sources :-(
- If $\mathrm{Im}\,\omega$ is large, asymmetry can be **maximized** for $\eta = 0,\ \delta = \pi$
- However, in this case the Yukawa couplings are enhanced

$$|F|^2 \sim \frac{m_\nu m_N}{v^2}\, e^{2|\mathrm{Im}\,\omega|}$$

- This can arise due to a fine-tuning in the Yukawa matrix **or** due to an approximate lepton number symmetry

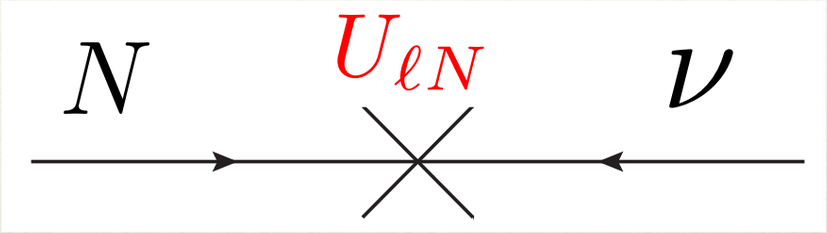
Shaposhnikov, hep-ph/0605047

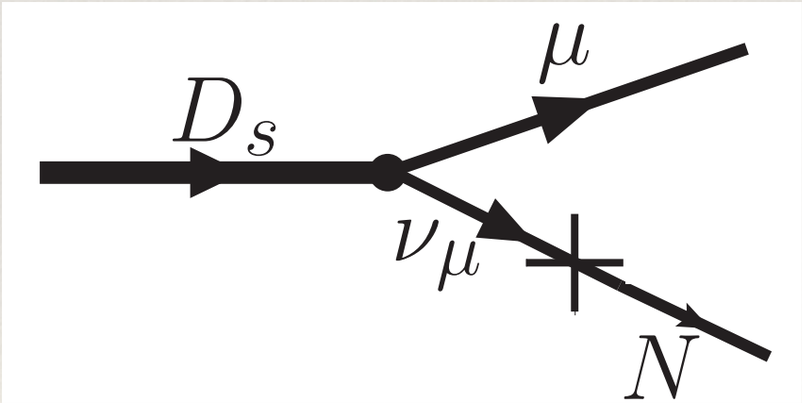
- In this **large-coupling regime**, rates involving *N* can be large!

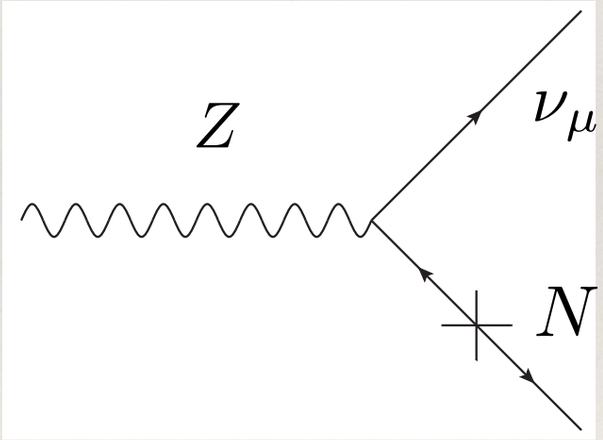
LARGE-COUPLING PHENO

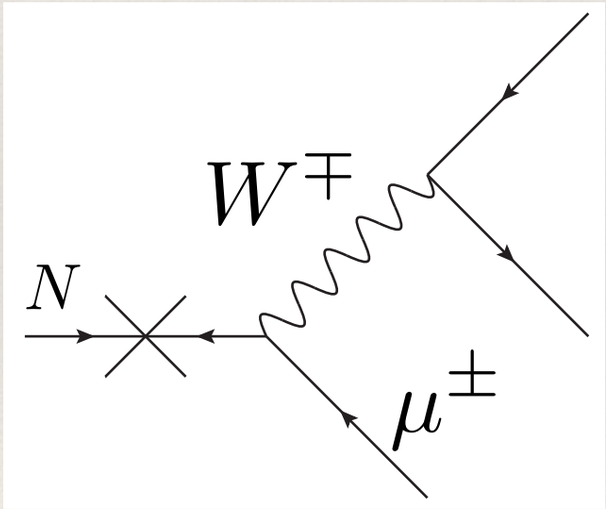
see *e.g.*, Gorbunov and Shaposhnikov, arXiv:0705.1729; Atre, Han, Pascoli, Zhang, arXiv:0901.3589; Deppisch, Dev, Pilaftsis, arXiv:1502.06541

$$U_{\ell N} = \frac{F_{\ell N} v}{m_N}$$





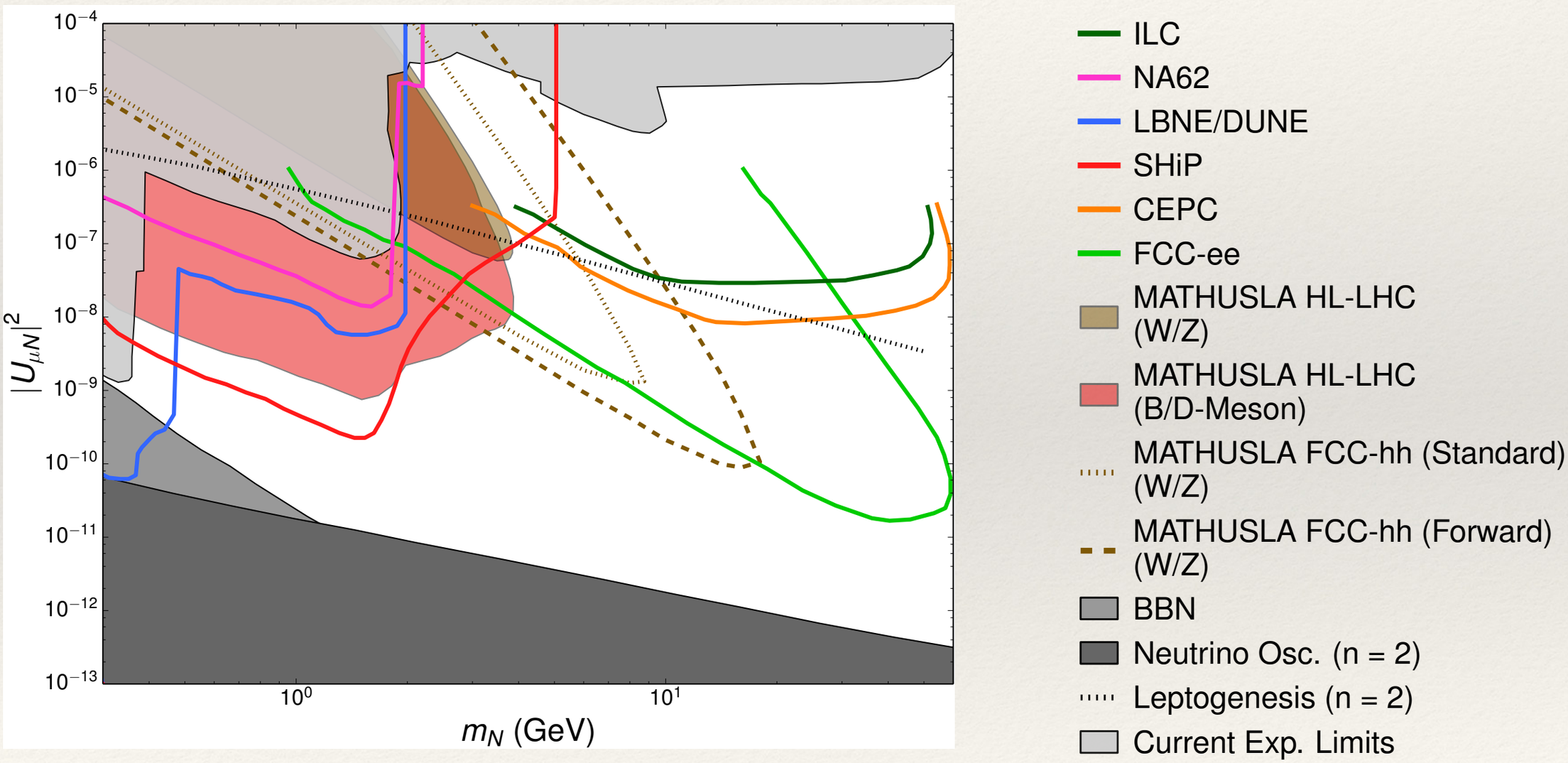




$$\Gamma_N \sim |V_{\mu N}|^2 G_{\rm F}^2 M_N^5$$

DIRECT *N* PRODUCTION

Drewes, Mohapatra, BS (*ed.*), "Theory Motivation for LLPs: Neutrino Masses", MATHUSLA theory case



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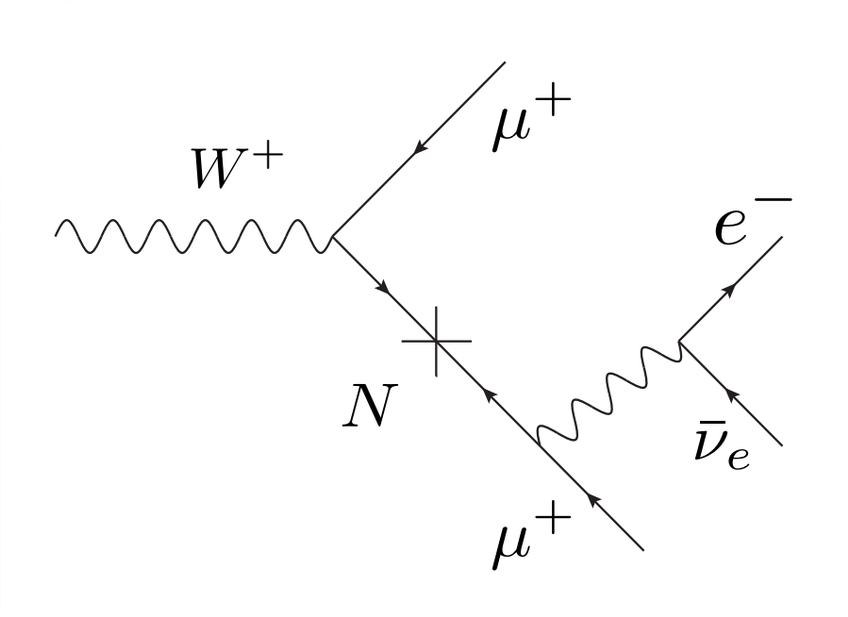
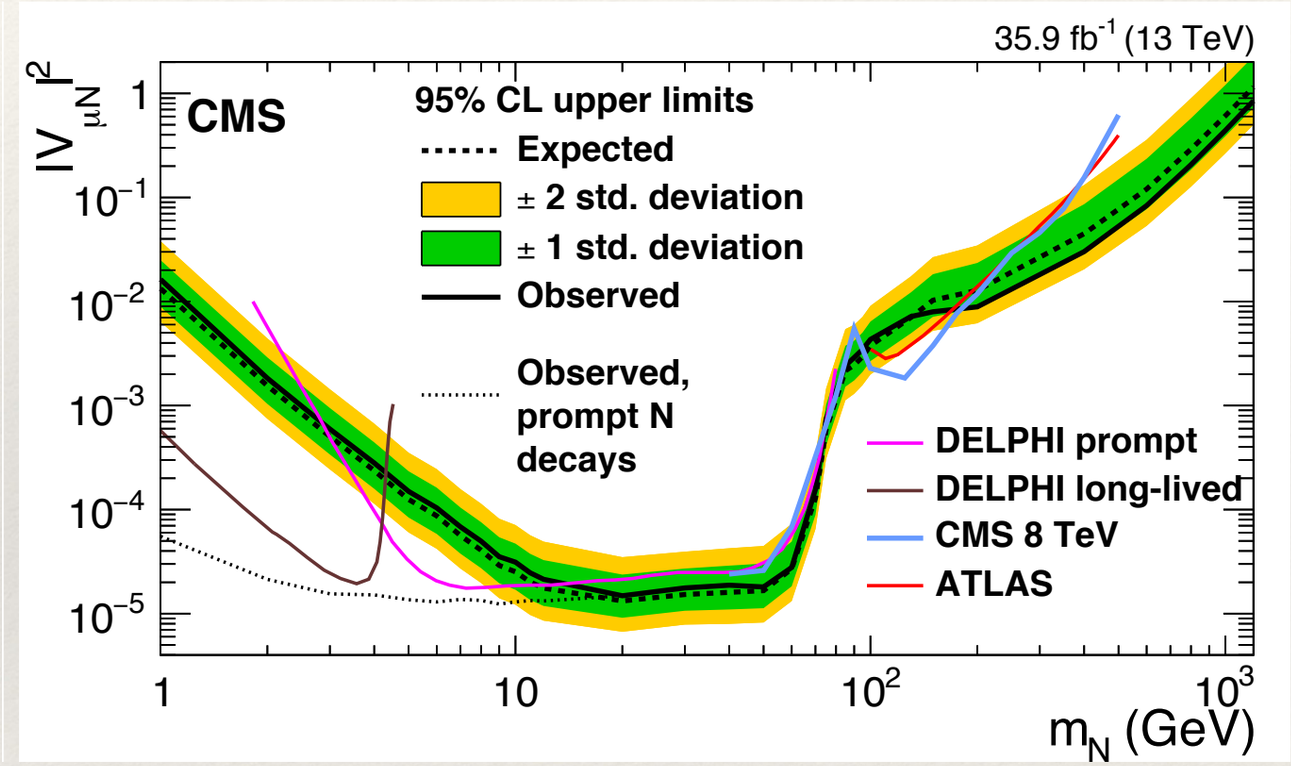
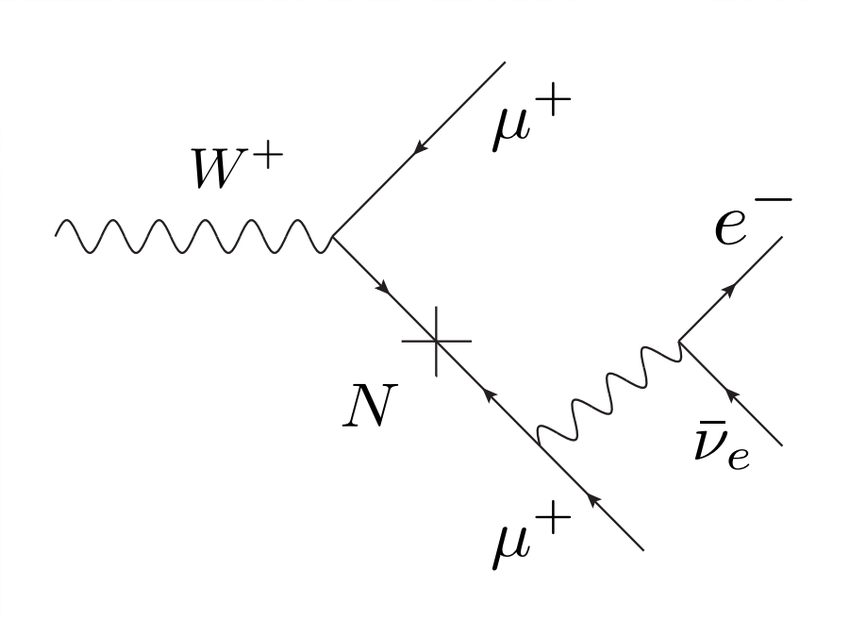


Izaguirre, BS, arXiv:1504.02470



CMS, arXiv:1802.02965

DIRECT *N* PRODUCTION



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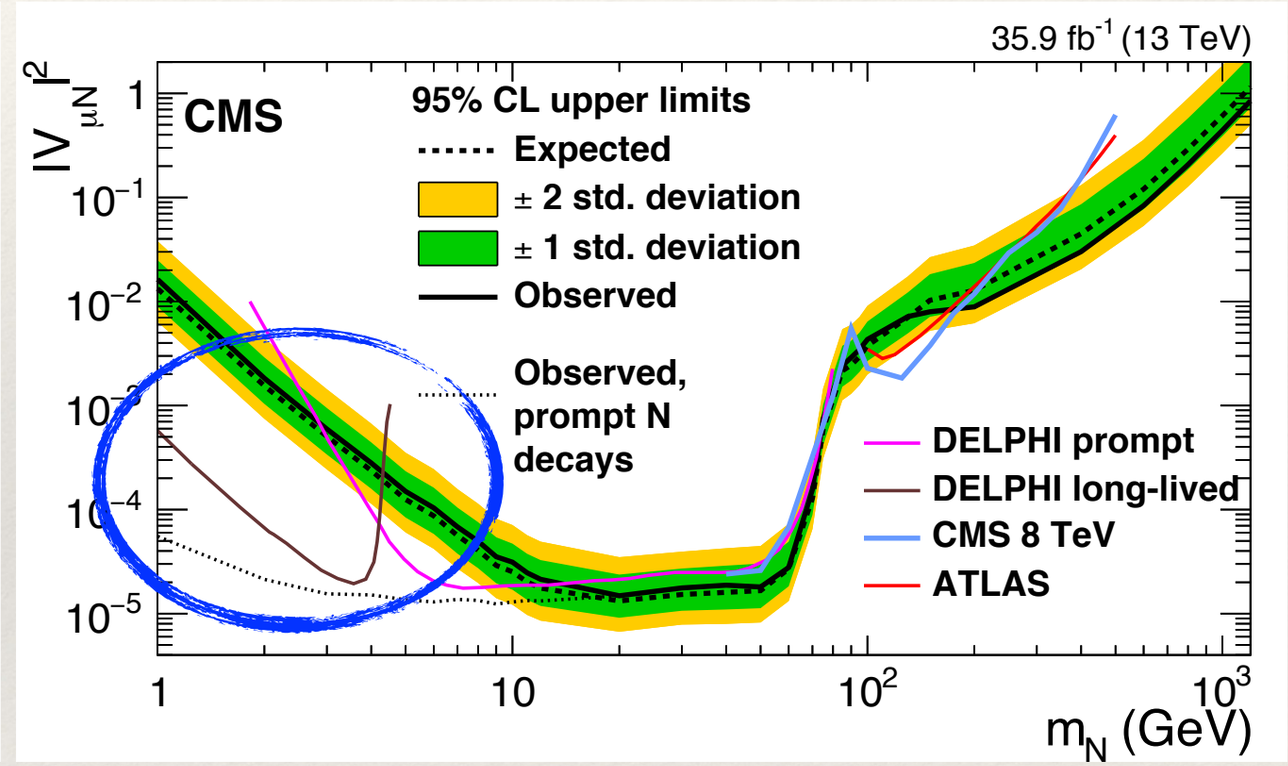


CMS, arXiv:1802.02965

displaced search can target this region

DIRECT PRODUCTION: CPV

Cvetič, Kim, Zamora-Saa, arXiv:1403.2555

- Because we directly produce *N*, we can also potentially observe its direct CP-violating decays!

$$\varepsilon \equiv \frac{\Gamma(N \to \ell^- W^{+*}) - \Gamma(N \to \ell^+ W^{-*})}{\Gamma(N \to \ell^- W^{+*}) + \Gamma(N \to \ell^+ W^{-*})} \sim \frac{\Gamma_N}{M_N} \frac{\Delta M / M_N}{\Delta M^2 / M_N^2 + (\Gamma / M_N)^2}$$

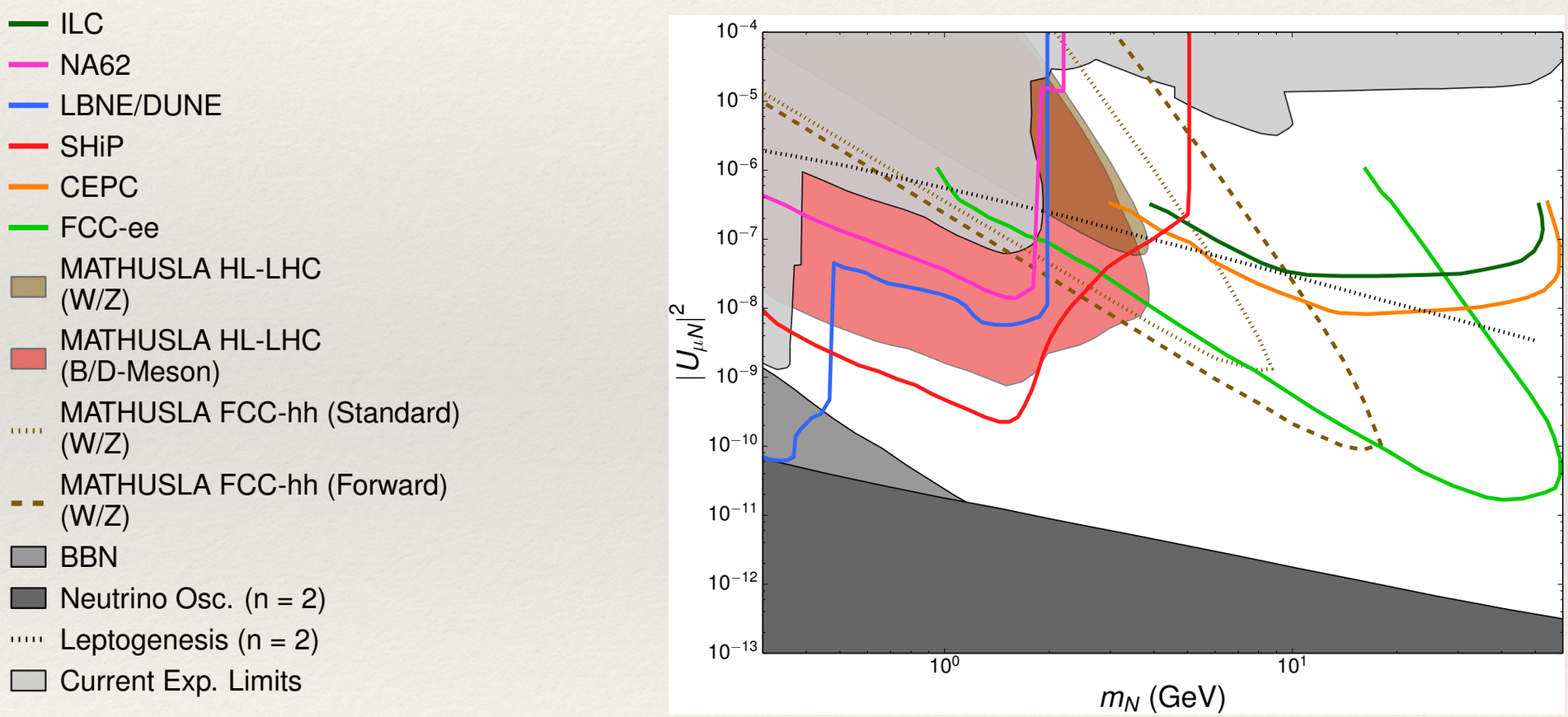
$$\Delta M = M_{N2} - M_{N1}$$

- Problem: coupling of *N* is tiny! $(\Gamma_N / M_N \lesssim 10^{-12})$

- However, this can be overcome with a mass degeneracy, $\Delta M \ll M_N$

DIRECT PRODUCTION: CPV

- Searches in meson decays are straightforward: look for lepton charge asymmetry in semileptonic decays



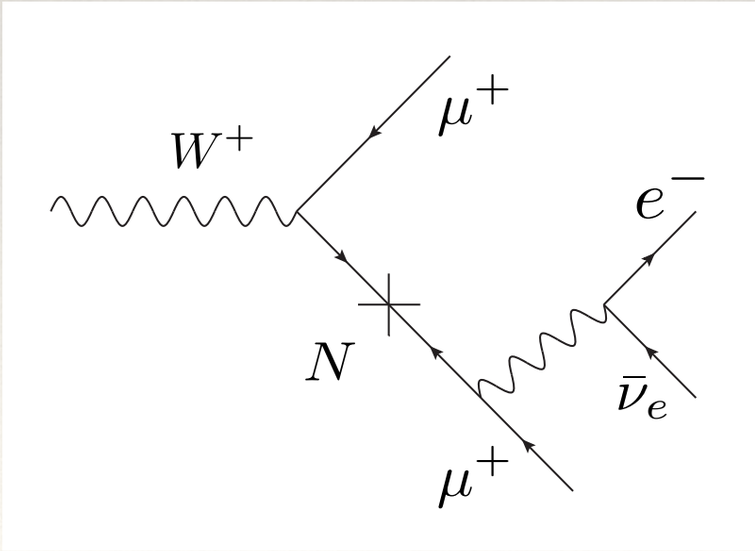
- In most optimistic scenario, maybe have sensitivity to $\varepsilon \sim 10^{-4}$

DIRECT PRODUCTION: CPV

Izaguirre, BS, arXiv:1504.02470

- For low-mass *N* at the LHC, semileptonic decays could have bigger backgrounds and be harder to reconstruct *N* mass peaks

- However, looking for a lepton asymmetry has challenges because backgrounds are very different for same-sign, opposite-sign



$$N \to \mu^+ e^- \nu_e \quad \text{vs.} \quad N \to \mu^- e^+ \bar{\nu}_e$$

DIRECT PRODUCTION: CPV

Challenges with direct observation of CPV:

- CPV is a higher-order effect, so we first have to discover *N*!
- Might be hard to disentangle Majorana nature from *CP* violation in some contexts
- No guarantee that *N* masses are sufficiently degenerate
    - Models exist with **no mass degeneracy** for low-scale leptogenesis Drewes, Garbrecht, arXiv:1206.5537; BS, Yavin, arXiv:1401.2459
    - However, in the nuMSM, *N* have to be extremely degenerate to account for late-time lepton asymmetry for DM production

$$\Delta M/M_N \sim 10^{-15}$$

OTHER SOURCES OF CPV

$$F_{\alpha I} = \frac{i}{v} U_\nu \sqrt{m_\nu}\, R \sqrt{m_N}$$

- LH neutrino mixing matrix:

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- While not strictly required for leptogenesis, other CPV phases typically non-zero
    - Leptogenesis requires flavour-dependent scattering rates
    - Maximal constructive/destructive interference occurs for e if

$$\delta + (\alpha_1 + \alpha_2)/2 = \pm\pi/2$$

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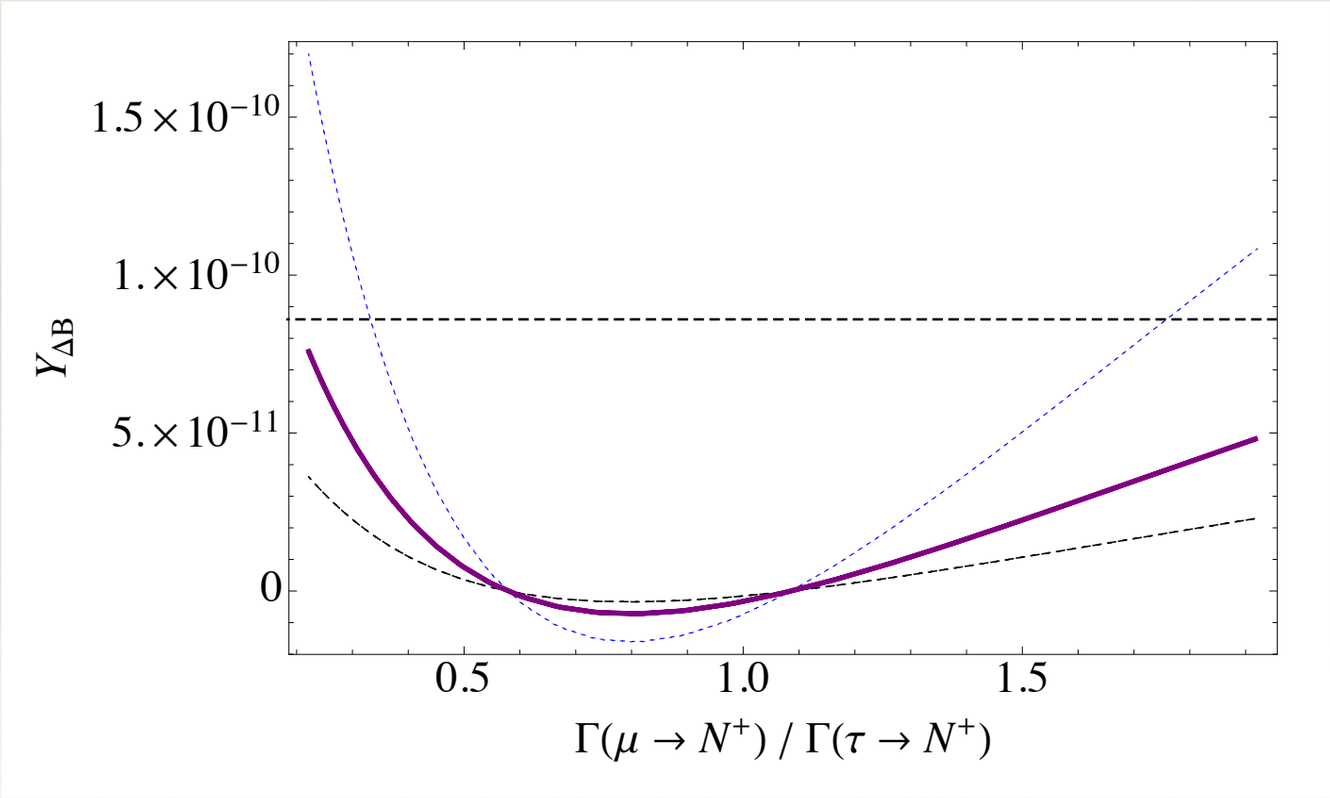
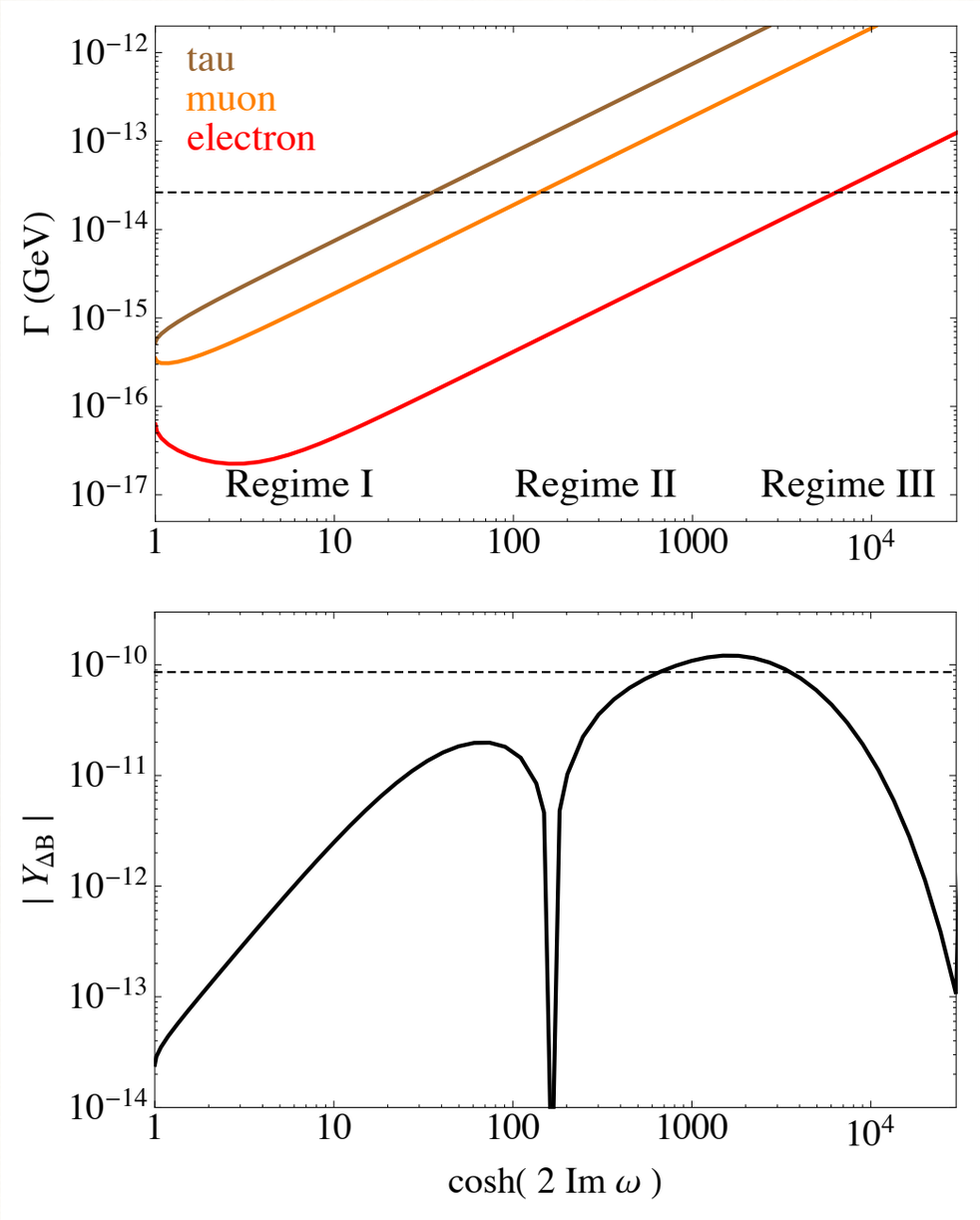


BS, Yavin, arXiv:1401.2459

OTHER SOURCES OF CPV

- Large Dirac/Majorana phases realize flavoured leptogenesis



$$\alpha_1 + \alpha_2 = -\pi/2$$

$$\delta = -\pi/4$$

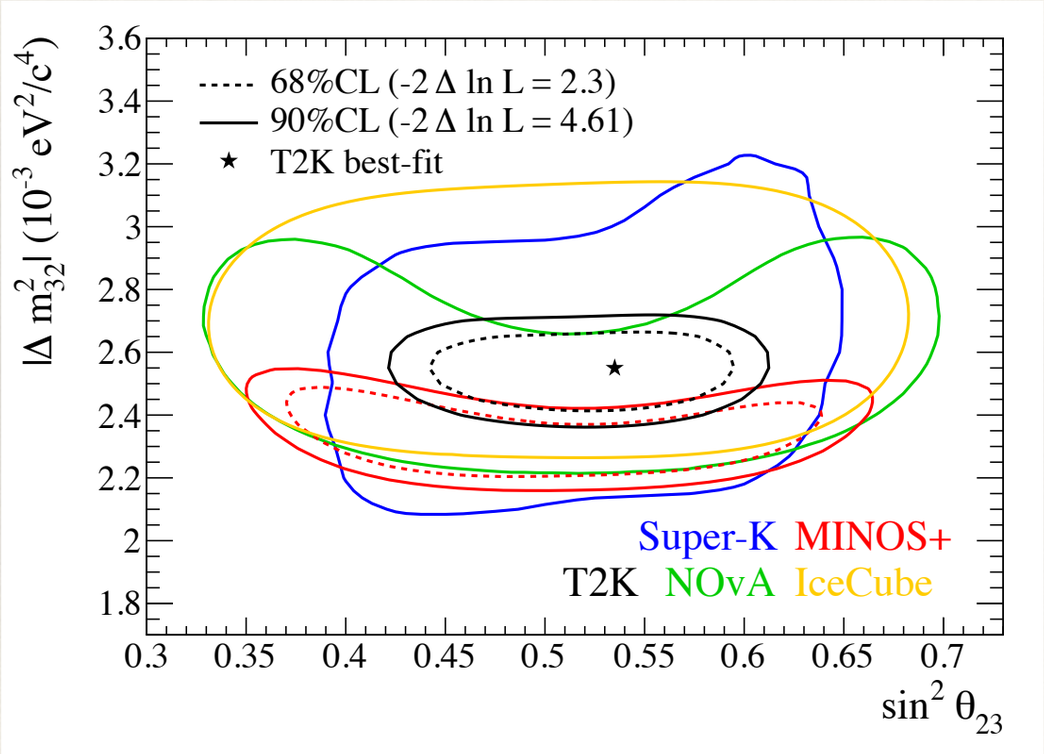
$$M_N = 1 \text{ GeV}$$

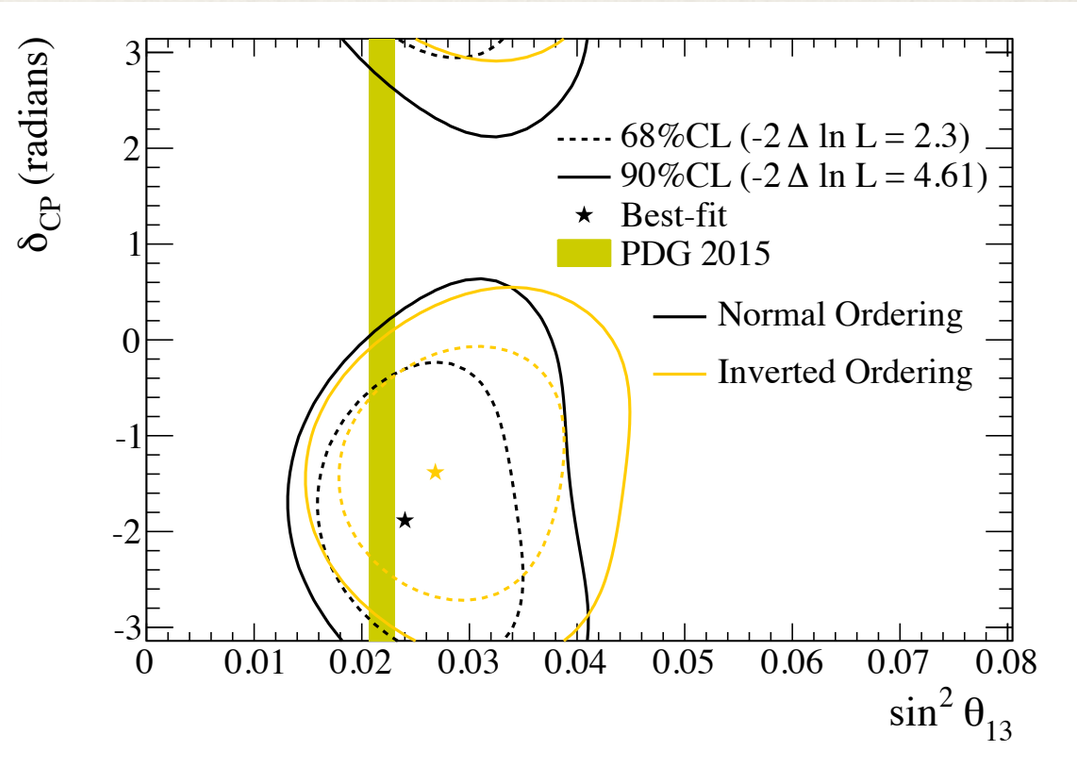
$$\Delta M = 10^{-3} \text{ GeV}$$

$$\mathrm{Re}\,\omega = \pi/4$$

DIRAC CPV PHASE

$P(\nu_\mu \to \nu_e)$ vs. $P(\bar{\nu}_\mu \to \bar{\nu}_e)$





T2K, arXiv:1701.00432

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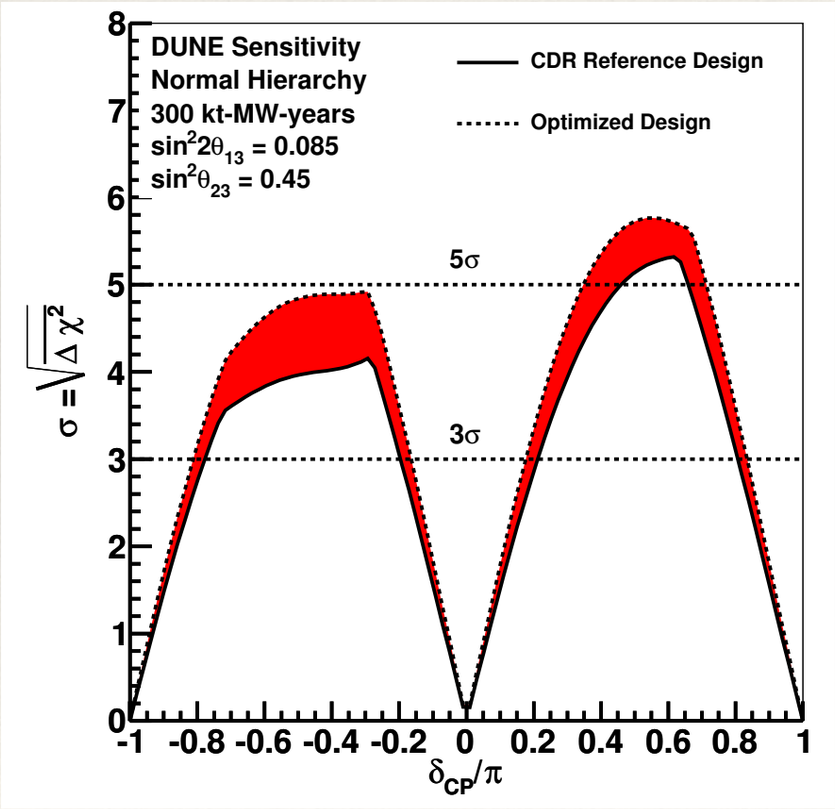
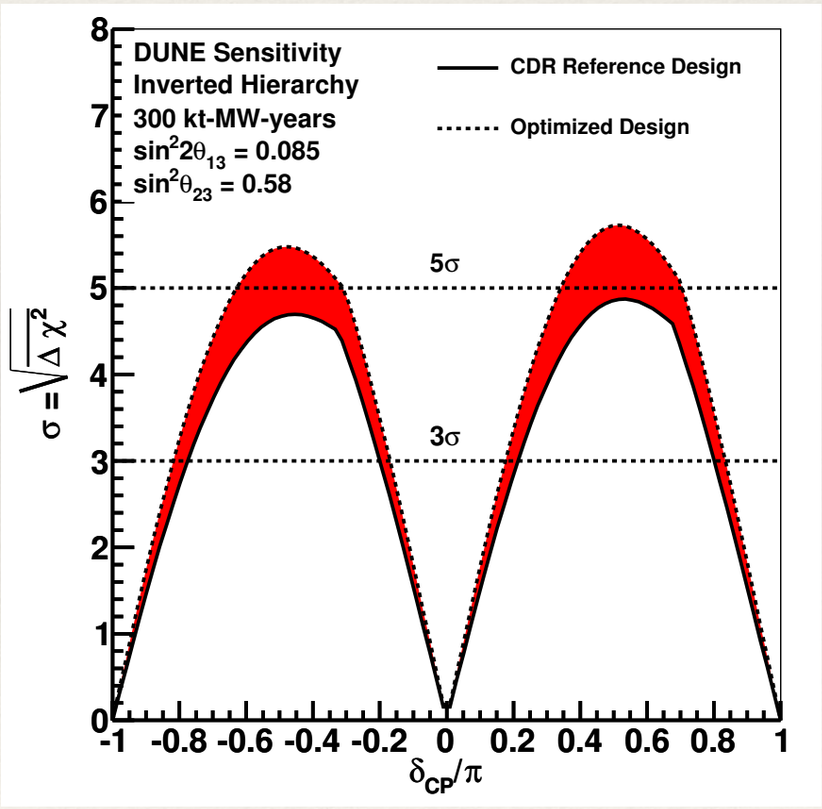
$$P(\nu_\mu \to \nu_e) \quad \text{vs.} \quad P(\bar{\nu}_\mu \to \bar{\nu}_e)$$





DUNE CDR, arXiv:1512.06148

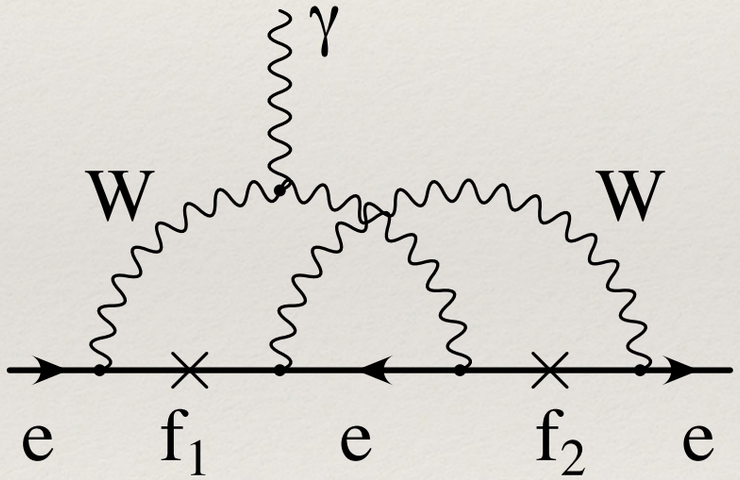
MAJORANA CPV PHASE

- Majorana phases are much trickier
- Do not have an effect on neutrino oscillations!
- Can have effects on neutrino-antineutrino oscillations in presence of **additional** lepton-number-violating effects
- Otherwise, most promising thing is to hope for observation of neutrinoless double-beta decay, extract Majorana phases indirectly if we already know other oscillation parameters (seems fraught!)

see e.g., de Gouvêa, Kayser, Mohapatra, hep-ph/0211394

OTHER PROBES: EDM

- What are the EDM prospects for leptogenesis?
    - EDMs non-zero at two loops but suppressed by tiny neutrino masses



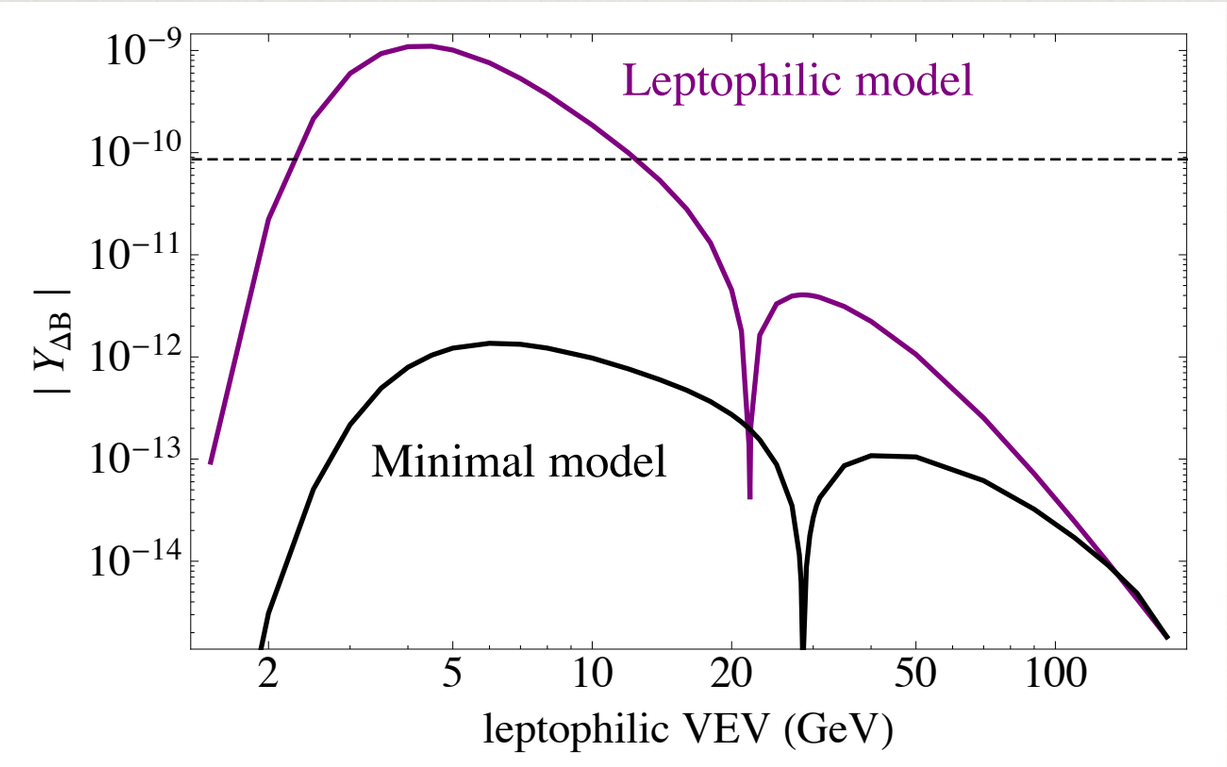
- With O(1) Yukawa couplings, $d_e \lesssim 10^{-33}\ e \cdot \mathrm{cm}$

Archambault, Czarnecki, Pospelov, hep-ph/0406089

OTHER PROBES: HIGGS

- Neutrino oscillation leptogenesis is enhanced if the Yukawa couplings to neutrinos are larger
    - Leptophilic 2-Higgs Doublet Model

BS, Yavin, arXiv:1401.2459



- Could have additional CPV couplings in extended Higgs sector
- Motivation for searching for leptophilic Higgs states

OUTLINE

- Overview of low-scale leptogenesis (~GeV RHNs)
- CPV and phenomenology of low-scale leptogenesis
- Hidden-sector baryogenesis (involving DM)

HIDDEN SECTOR BARYOGENESIS

- **Motivation:**
  - Need new physics to explain dark matter
  - Dark matter needs a departure from equilibrium
  - Baryon abundance set by asymmetry — DM too?

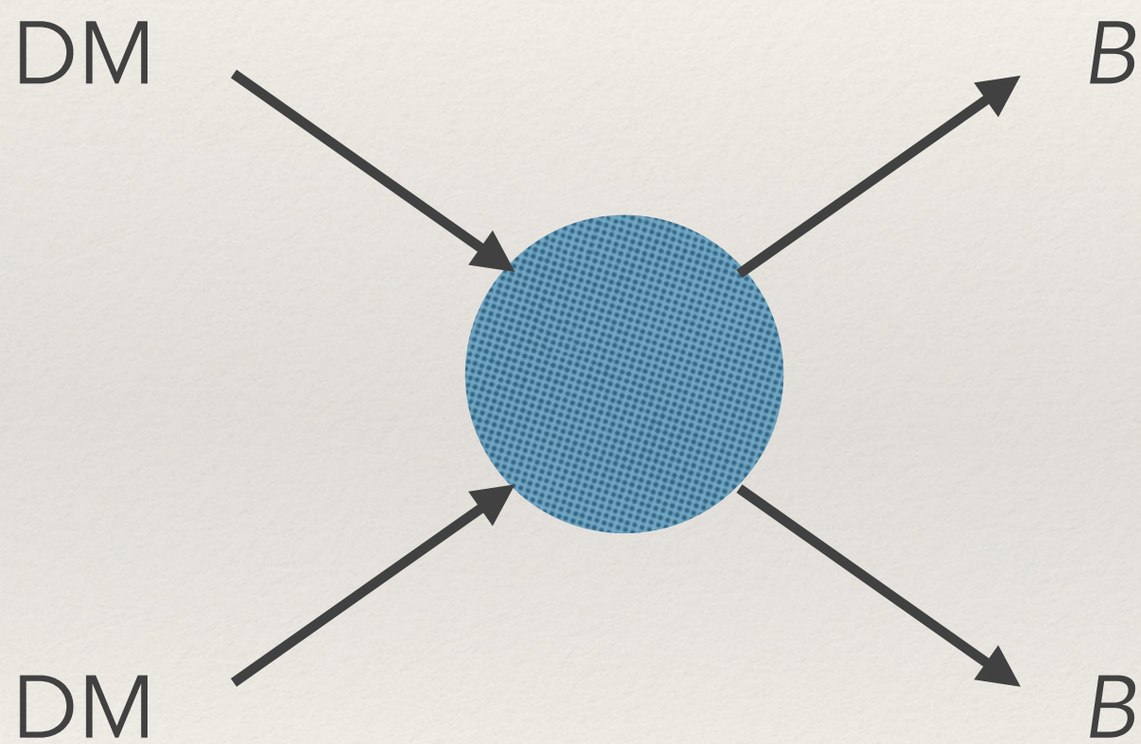
- **Mechanisms:**
  - Cogeneration/sharing of DM-baryon asymmetry
  - Baryon asymmetry could be **generated** in dynamics of hidden-sector particles

Nussinov, 1985; Dodelson, Widrow, 1990; Barr, Chivukula, Farhi, 1991; …; Kaplan, Luty, Zurek, 2009; Davoudiasl *et* al., 2010; Shelton, Zurek, 2010; Buckley, Randall, 2010; McDonald, 2011; Cui, Randall, BS, 2011; Zurek, 2013;…….

HIDDEN SECTOR BARYOGENESIS

Cui, Randall, BS, arXiv:1112.2704

- *E.g.*, baryogenesis during DM freeze-out ("WIMPy baryogenesis")



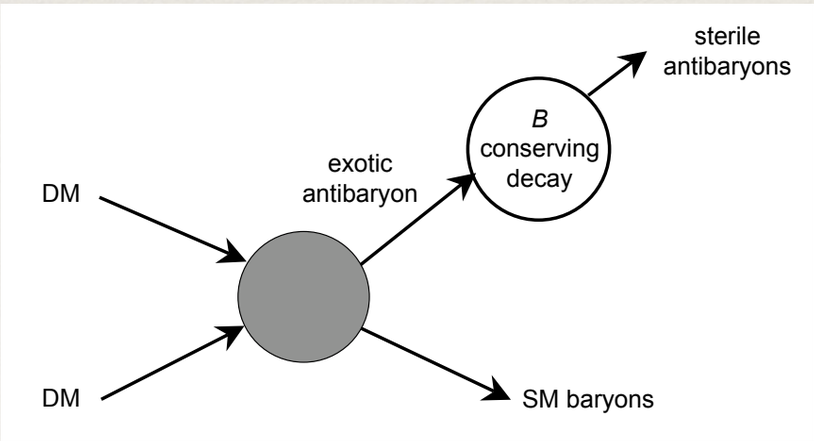
- DM-SM couplings violate baryon number
- DM-SM couplings violate *CP*

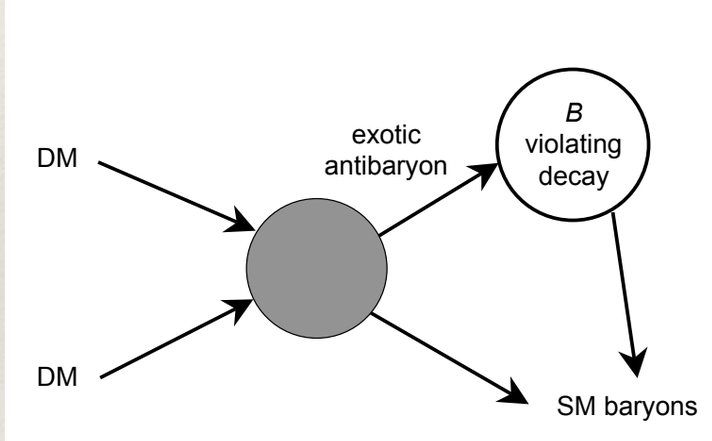
- What are implications for phenomenology?

HIDDEN SECTOR BARYOGENESIS

Cui, Randall, BS, arXiv:1112.2704

- Features of mechanism:
  - Heavy new state that carries/couples to baryon number (kinematic effects lead to a suppression of washout processes)



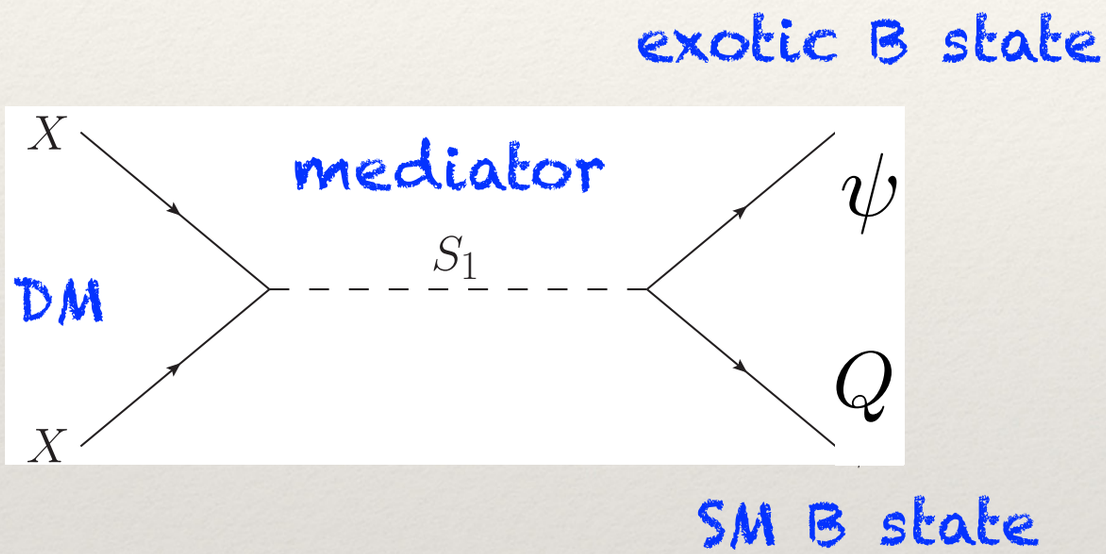


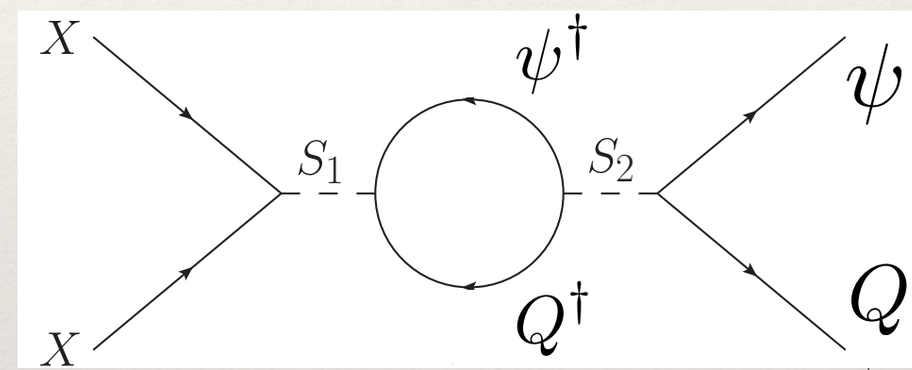
  - New particle carries SM quantum numbers, can be produed at colliders
  - Any effects of new CPV coupling?

HIDDEN SECTOR BARYOGENESIS

Cui, Randall, BS, arXiv:1112.2704

- Minimal model:





- *CP* phases in new Yukawa couplings

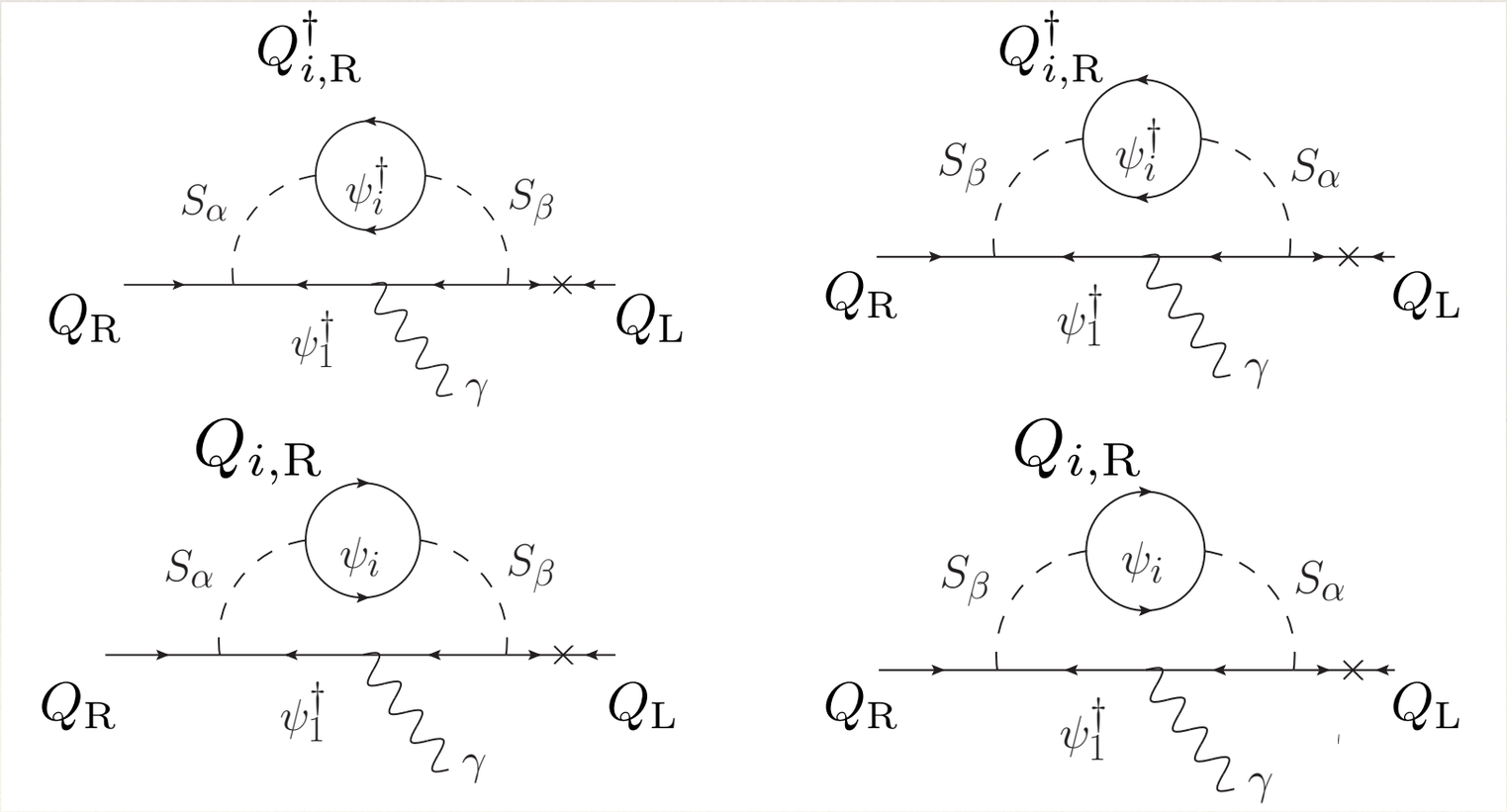
- In minimal model, new vectorlike ψ may only couple to one chiral quark state

$$\mathcal{L} \supset \lambda_\alpha \, S_\alpha \, u^c \, \psi$$

HIDDEN SECTOR BARYOGENESIS

Cui, Randall, BS, arXiv:1112.2704

- **Electric dipole moment:**
    - If vectorlike quark couples to only one chirality of SM quarks, the leading contribution to EDM vanishes



- Need to go to 3 loops for non-zero effect

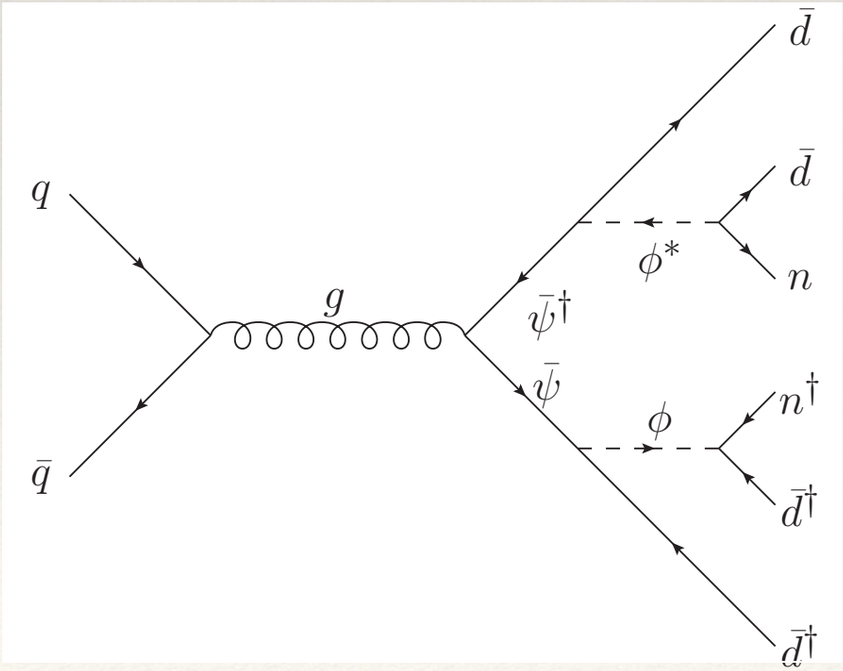
$$d_n \lesssim 10^{-31}\ e \cdot \mathrm{cm}$$

- In extended models, could have coupling to both LH+RH quarks

HIDDEN SECTOR BARYOGENESIS

Cui, Randall, BS, arXiv:1112.2704

- **Collider phenomenology:**
    - Can produce new vectorlike quark(s) at LHC
    - Due to constraints of not wiping out baryon asymmetry from ψ decays, typically ψ decays into other hidden-sector particles



- Current constraints for minimal model are on $m_\psi \lesssim 1.5 \text{ TeV}$
- Need for baryon number violation in decays could give more exotic signals in other models

Cui, Sundrum, arXiv:1212.2973; Cui, BS, arXiv:1409.6729

SUMMARY

- Low-scale leptogenesis and hidden-sector baryogenesis offer opportunities for experimentally discovering the physics of baryogenesis

- Multiple CP phases gives large parameter space, can give varied phenomenological predictions

- EDM, flavour, collider, and other probes give complementary coverage: all are needed to close in on low-scale baryogenesis!

BACKUP SLIDES

LIGHTNING REVIEW OF CPV

$$\mathcal{M}(a \to b) = x\, e^{i\phi}$$

$$\mathcal{M}(\bar{a} \to \bar{b}) = x\, e^{-i\phi}$$

$$\longrightarrow$$

$$|\mathcal{M}(a \to b)|^2 = x^2$$

$$|\mathcal{M}(\bar{a} \to \bar{b})|^2 = x^2$$

$$\Delta|\mathcal{M}|^2 = 0$$

LIGHTNING REVIEW OF CPV

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$$\Delta|\mathcal{M}|^2 = 0$$

$$\mathcal{M}(a \to b) = x_1\, e^{i\phi} + x_2$$
$$\mathcal{M}(\bar{a} \to \bar{b}) = x_1\, e^{-i\phi} + x_2$$

$$\longrightarrow$$

$$|\mathcal{M}(a \to b)|^2 = x_1^2 + x_2^2 + 2x_1x_2\cos\phi$$
$$|\mathcal{M}(\bar{a} \to \bar{b})|^2 = x_1^2 + x_2^2 + 2x_1x_2\cos\phi$$

$$\Delta|\mathcal{M}|^2 = 0$$

LIGHTNING REVIEW OF CPV

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$$\mathcal{M}(a \to b) = x_1\, e^{i\phi} + x_2$$
$$\mathcal{M}(\bar{a} \to \bar{b}) = x_1\, e^{-i\phi} + x_2$$

$$\longrightarrow$$

$$|\mathcal{M}(a \to b)|^2 = x_1^2 + x_2^2 + 2x_1x_2\cos\phi$$
$$|\mathcal{M}(\bar{a} \to \bar{b})|^2 = x_1^2 + x_2^2 + 2x_1x_2\cos\phi$$

$$\Delta|\mathcal{M}|^2 = 0$$

$$\mathcal{M}(a \to b) = x_1\, e^{i\phi + i\theta} + x_2$$
$$\mathcal{M}(\bar{a} \to \bar{b}) = x_1\, e^{-i\phi + i\theta} + x_2$$

$$\longrightarrow$$

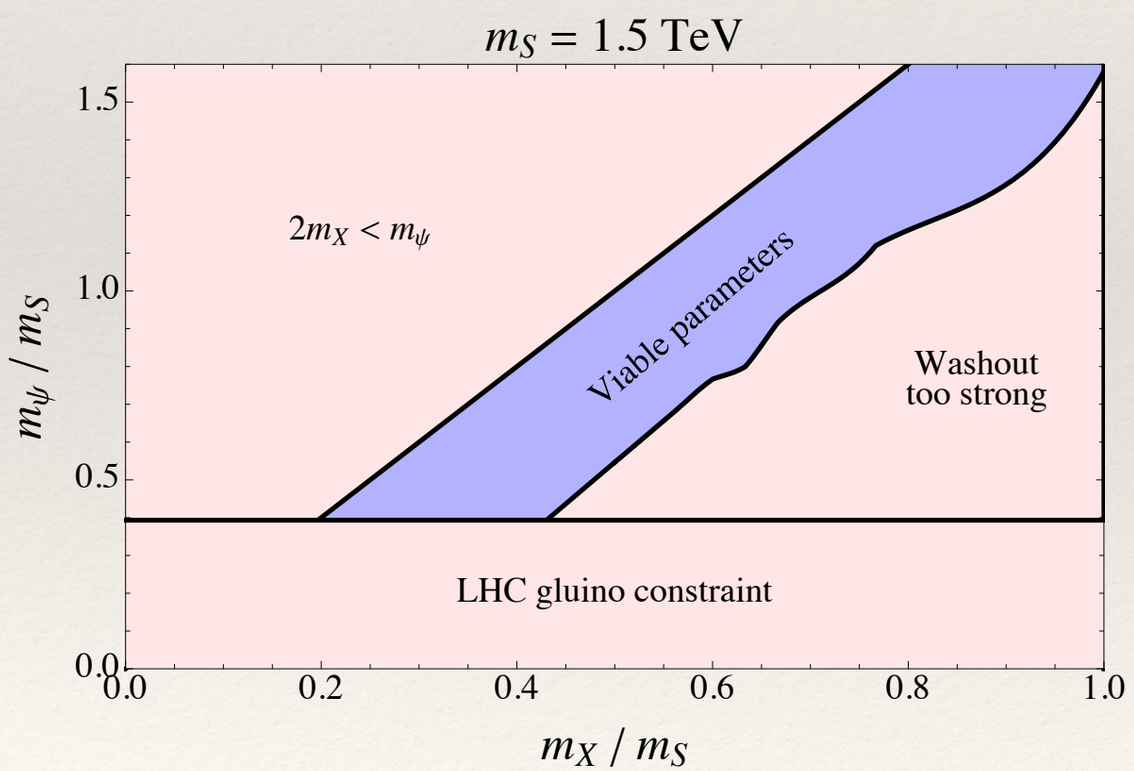
$$|\mathcal{M}(a \to b)|^2 = x_1^2 + x_2^2 + 2x_1x_2\cos(\theta + \phi)$$
$$|\mathcal{M}(\bar{a} \to \bar{b})|^2 = x_1^2 + x_2^2 + 2x_1x_2\cos(\theta - \phi)$$

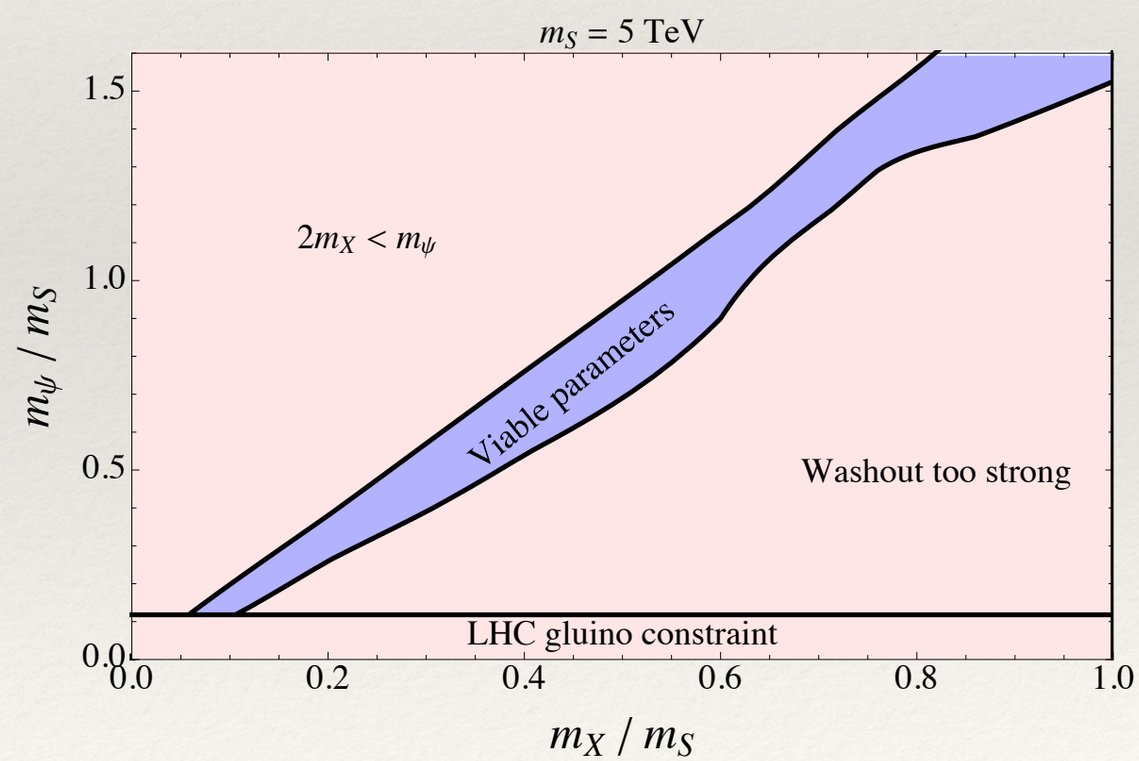
$$\Delta|\mathcal{M}|^2 = -4x_1x_2\sin\phi\sin\theta$$

HIDDEN SECTOR BARYOGENESIS

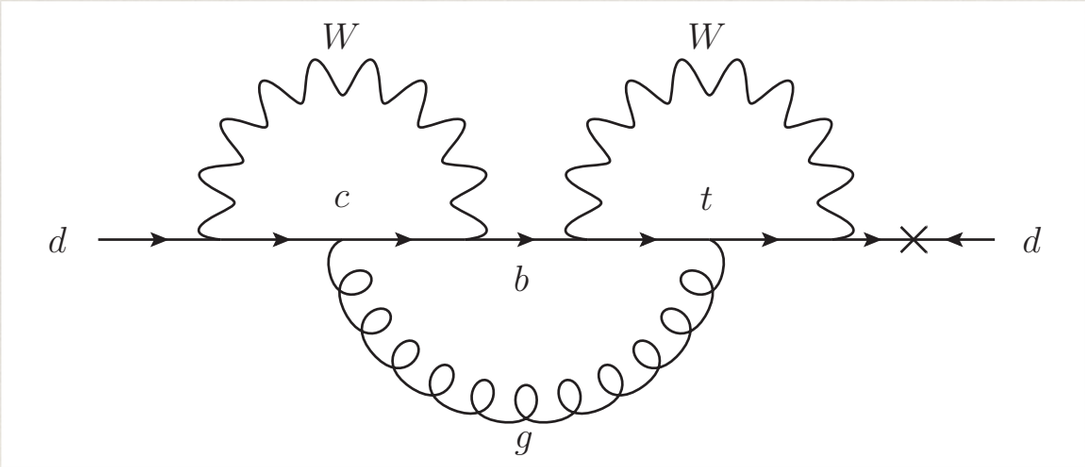
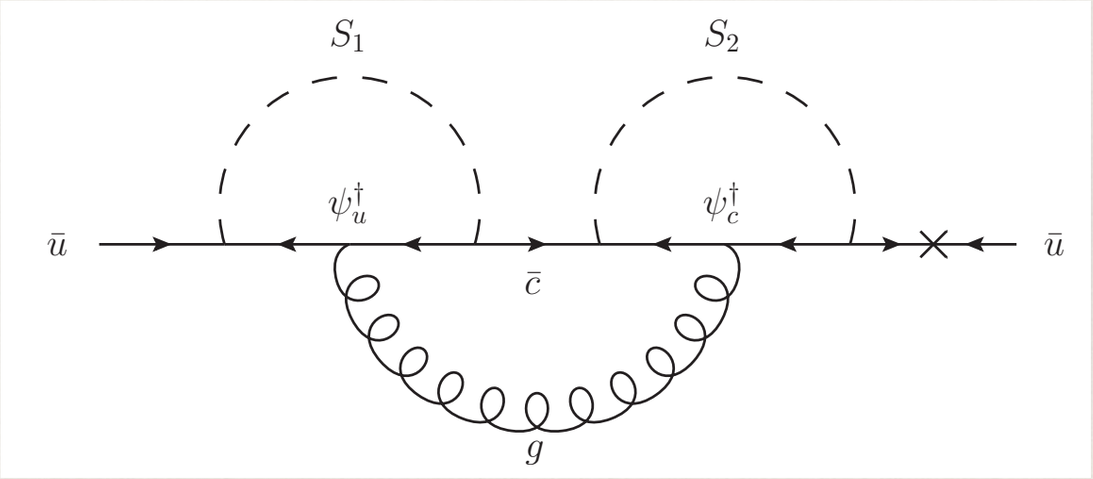
Cui, Randall, BS, arXiv:1112.2704

- Parameter space (gluino constraint on this plot is **old**, much stronger now…)





HIDDEN SECTOR BARYOGENESIS

Cui, Randall, BS, arXiv:1112.2704

- 3-loop EDMs in WIMPy baryogenesis