Phenomenology before and after the Standard Model Symposium
University of Wisconsin-Madison

# Fun in and Beyond the Standard Model

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# On a Beautiful Summer Day, a Badger is Wondering

- Why is this acorn the size of a coffee mug (bigger than I expect)?
- Why do the shadows of the Terrace chairs, tables, and myself all look the same?
- Why there are three flavors of ice cream?
- How many generations are there?
- Why are we even here in the first place?
- How can I test my theories?


# On a Beautiful Summer Day

- At the Terrace, I asked my share of those questions, with Vernon, and fellow badgers
- Of course, some badgers are smarter than others


# SuperSymmetry!

- Why is this acorn bigger than I expect?
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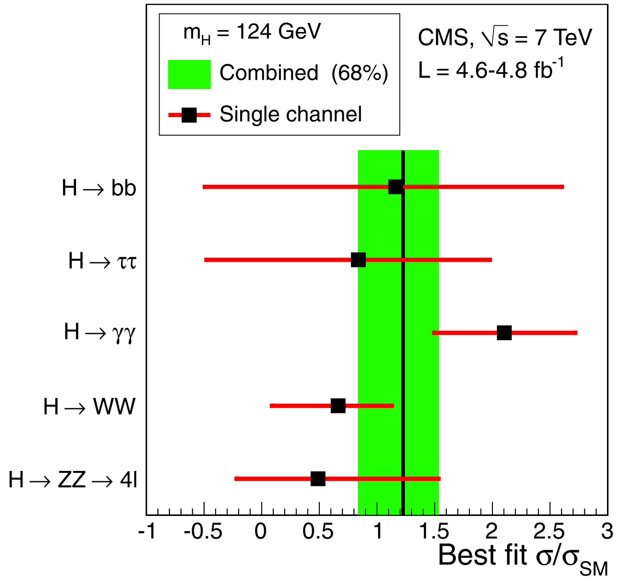
# Some Acorns are Big, Some Bosons are Heavy

- In 2012, the Higgs boson is discovered, and its mass is measured ~ 124 GeV
- Hmm, a bit too heavy for Supersymmetry!!
- With Howie, Vernon, Azar Mustafayev, and Xerxes Tata, we showed how a Natural SUSY spectrum can be generated radiatively.
- No large cancellation to get the right Z boson mass




CMS, 2012

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2$$

# Some Acorns are Big, Some Bosons are Heavy

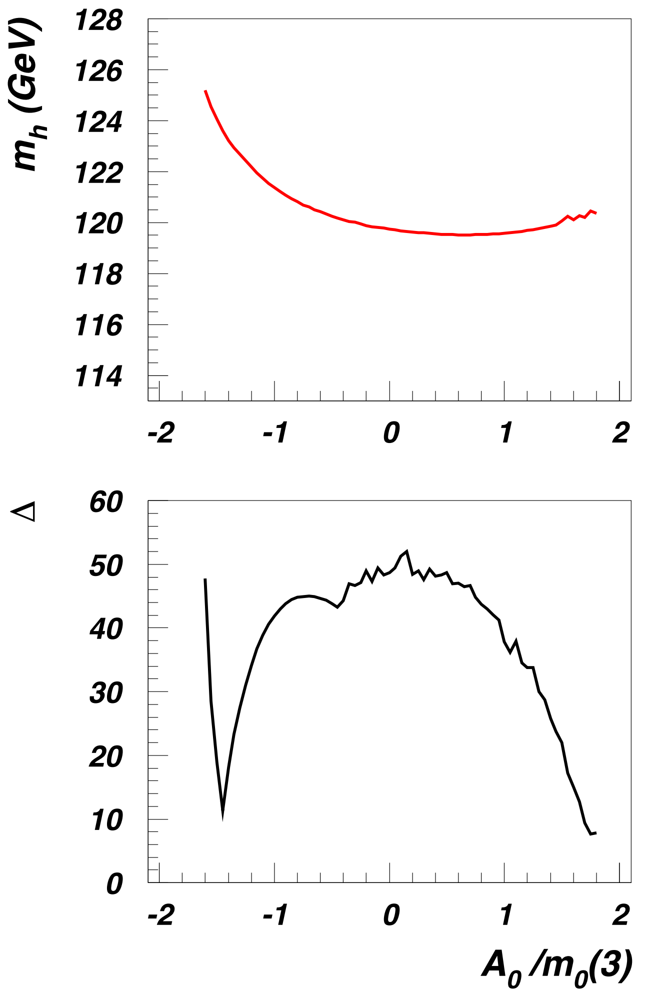
Major contribution

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2$$

$$\Sigma_u^u(\tilde{t}_{1,2}) = \frac{3}{16\pi^2} F(m_{\tilde{t}_{1,2}}^2) \times \left[ f_t^2 - g_Z^2 \mp \frac{f_t^2 A_t^2 - 8 g_Z^2 (\frac{1}{4} - \frac{2}{3} x_W)\Delta_t}{m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2} \right]$$

Large mixing is preferred to naturalness
Also, good for the Higgs mass!

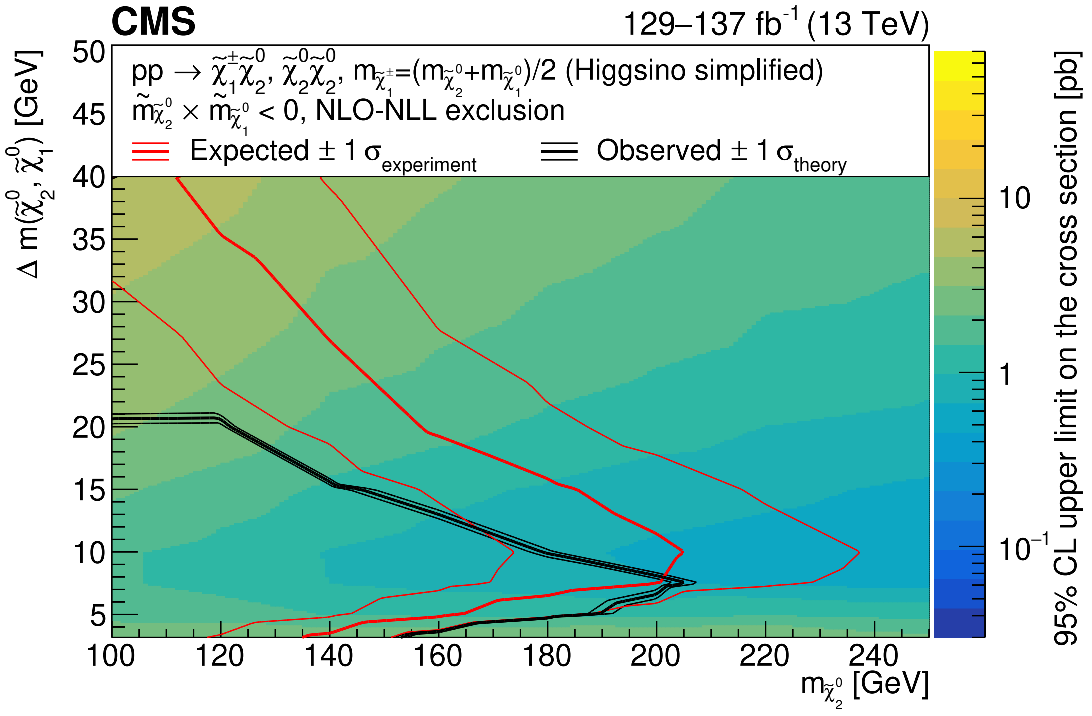
$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3g^2}{8\pi^2}\frac{m_t^4}{m_W^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

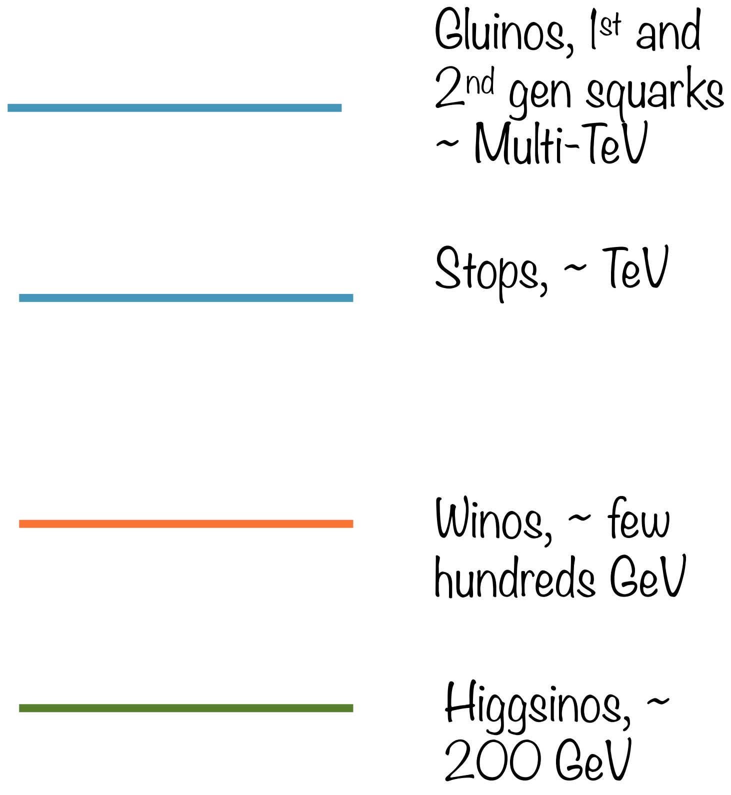



H. Baer, V. Barger, PH, A. Mustafayev, and X. Tata 2012

# Unique Signatures

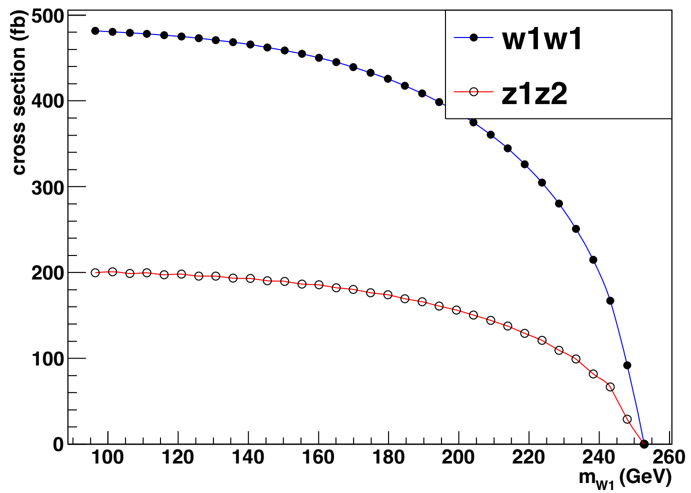
- Usual gluino, squark, stop searches
- Light (almost degenerate) Higgsinos, soft dilepton /trilepton + missing energy, ~ 200 GeV

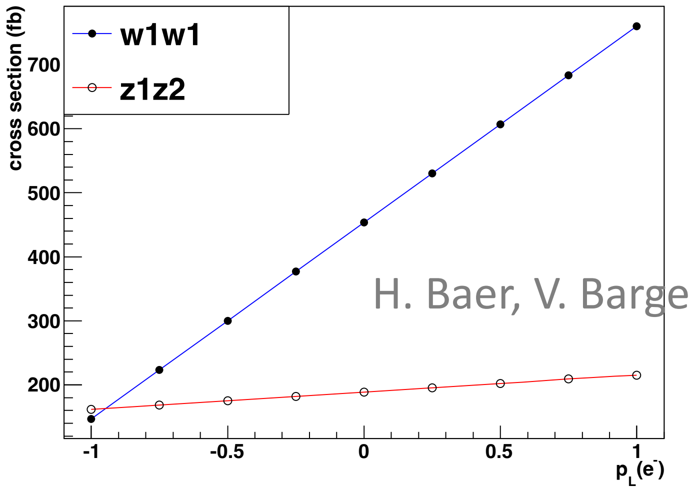


# Future Lepton/Muon Colliders

- For a lepton/muon collider with $\sqrt{s} = 500\ \mathrm{GeV}$, the EW-ino pair production cross section is around few hundred fb.
- Signatures
  - Soft multi-jet + missing energy
  - Soft lepton + jet + missing energy
  - Soft dilepton + missing energy
- SM backgrounds such as WW can be suppressed by $\not{m} = \sqrt{\not{E}^2 - \not{p}^2}$ distributions
- The cross section varies with the beam polarization, but not as steep as wino pair production -> Extract the gaugino/higgsino content in neutralinos and charginos

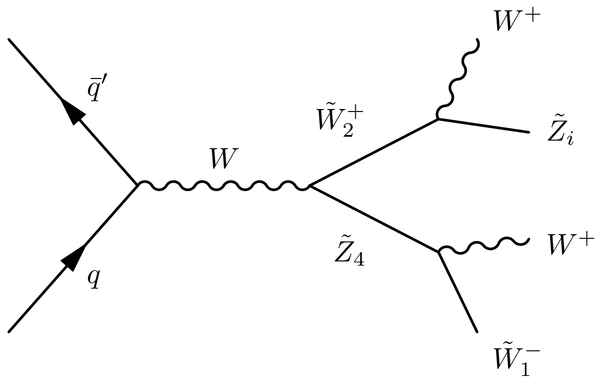



H. Baer, V. Barger, PH 2011

# Unique Signatures

H. Baer, V. Barger, P.H, D. Mickelson, A. Mustafayev, W. Sreethawong, and X. Tata 2013




- Wino pair production – same sign diboson + missing energy
- More powerful reach for $m_{1/2}$ than gluino pair production

Gluinos, 1st and 2nd gen squarks ~ Multi-TeV

Stops, ~ TeV

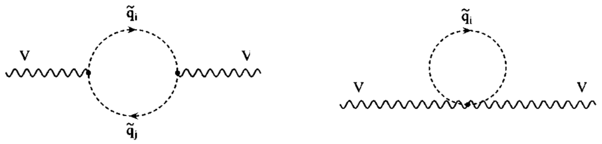
Winos, ~ few hundreds GeV

Higgsinos, ~ 200 GeV

# Another Boson Appears to be Heavy

- In 2012, W mass is measured to be $80,385 \pm 15$ MeV

$$\boxed{M_W^{\rm exp} - M_W^{\rm SM} = 24 \pm 15\ {\rm MeV}.}$$

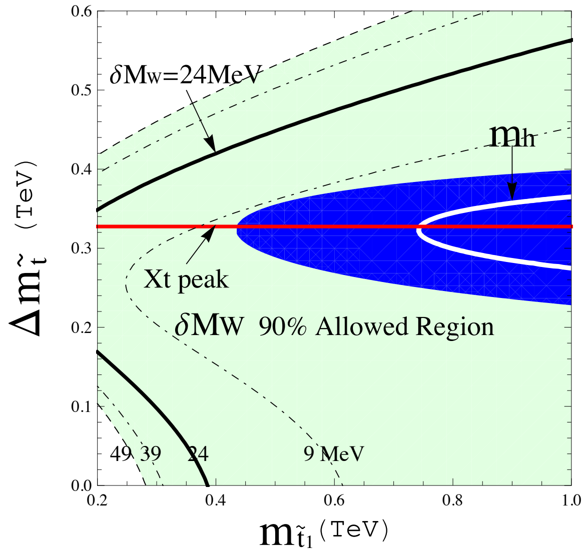


- With Vernon, Wai-Yee, and M. Ishida, we analyze its implication to the SUSY spectrum

$$\delta M_W \simeq \frac{M_W}{2}\frac{c_W^2}{c_W^2 - s_W^2}\Delta\rho_0,$$

$$\Delta\rho_0 = \frac{3G_F}{8\sqrt{2}\pi^2}[-s_{\tilde{t}}^2 c_{\tilde{t}}^2 F_0(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2) + c_{\tilde{t}}^2 F_0(m_{\tilde{t}_1}^2, m_{\tilde{b}_L}^2) + s_{\tilde{t}}^2 F_0(m_{\tilde{t}_2}^2, m_{\tilde{b}_L}^2)](10)$$

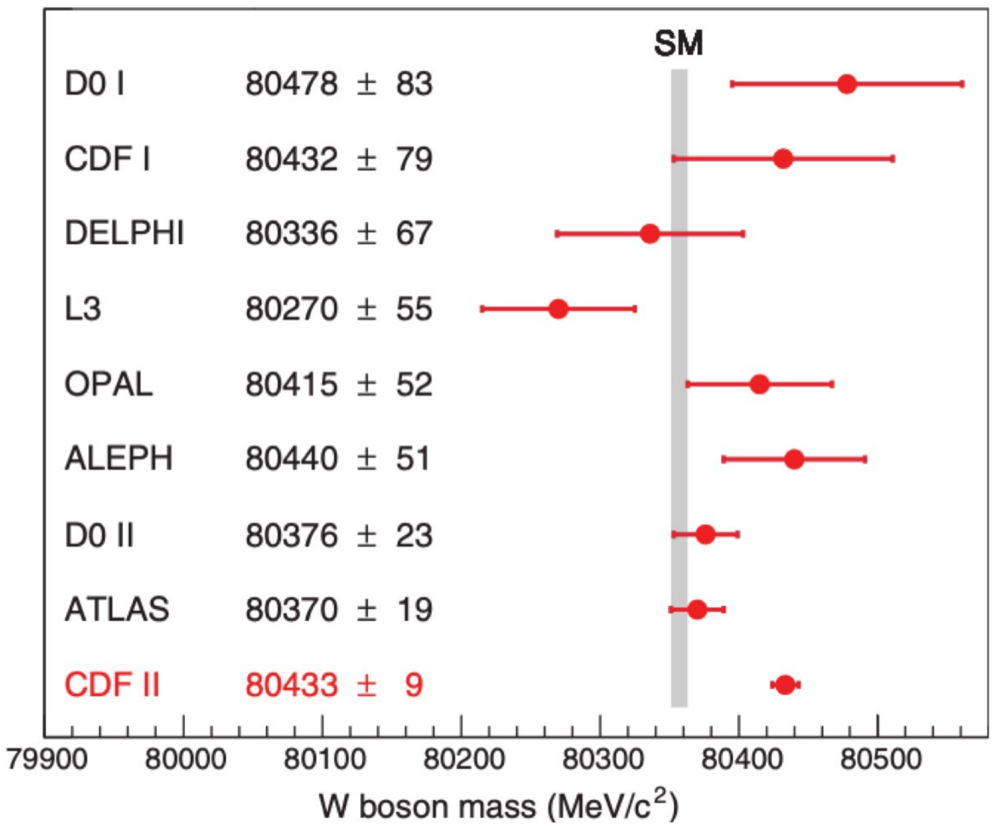
$$F_0(a,b) \equiv a + b - \frac{2ab}{a-b}\ln\frac{a}{b}$$




V. Barger, PH, M. Ishida, W.-Y. Keung 2012

# Fast Forward to 10 Years Later

- In 2022, CDF updated their W mass measurement $M_W^{\text{CDF}} = 80.4335 \pm 0.0094 \text{ GeV},$
- With Vernon, Cash Hauptmann, and Wai-Yee, we revisited the problem.
- This time, just the tree-level
- Extend the SM gauge group with a new U(1) group. The “Z boson” is now a linear combination of Z and Z’. The W mass is shifted at the tree-level



# A Concrete Model

- Consider $E_6$ models,

$$\begin{aligned} E_6 &\to SO(10) \times U(1)_\psi \\ &\to SU(5) \times U(1)_\chi \times U(1)_\psi \\ &\to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi . \end{aligned}$$

- Two additional gauge bosons, $Z'$, and $Z''$

$$\begin{aligned} Z' &= Z_\chi \cos\theta_{E_6} + Z_\psi \sin\theta_{E_6} \\ Z'' &= -Z_\chi \sin\theta_{E_6} + Z_\psi \cos\theta_{E_6} . \end{aligned}$$

- Also allow for kinetic mixing, $\frac{\sin\chi}{2} B_\mu Z'^\mu$
- Assume only the lighter state around the TeV scale

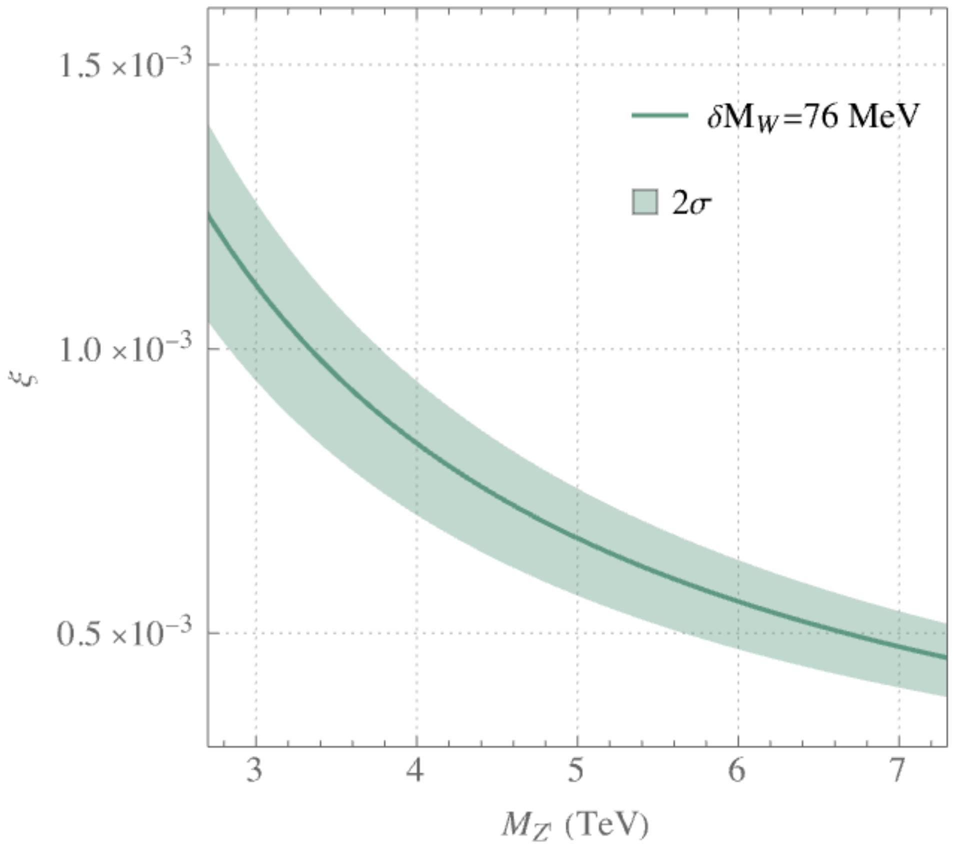
V. Barger, C. Haumptmann, PH, W.-Y. Keung 2023

# Modifications to $M_W$

$$\boxed{\delta M_W \approx \frac{1}{2M_W}\frac{c_W^4}{c_W^2 - s_W^2}\xi^2\left(M_{Z'}^2 - M_Z^2\right)}$$

Only depends on $M_{Z'}$ and Z-Z' mixing $\xi$

- Constraints from direct Z' searches
- Precision Z-boson measurements

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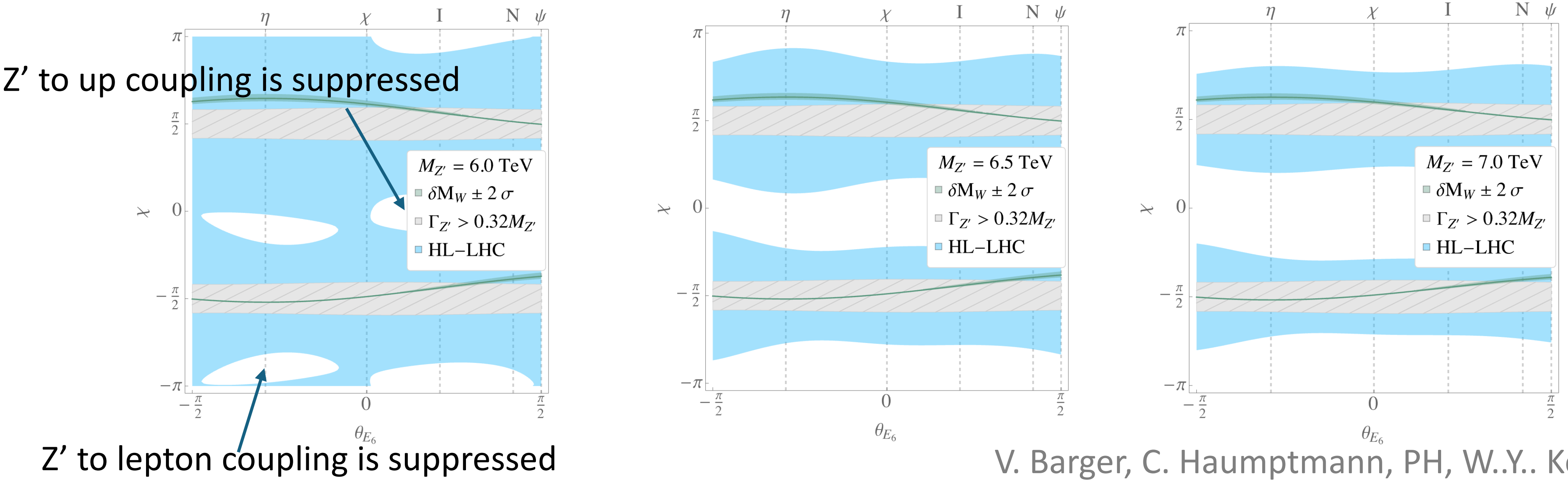
# Z’ Searches

- Direct constraints from pp -> Z’ -> ll at the LHC
- Depends on the Z’ mass, kinetic mixing, and $\theta_{E6}$. Z’s lighter than 5.5 TeV are highly constrained.
- Z pole constrains are easily satisfied




V. Barger, C. Haumptmann, PH, W.Y.. Keung 2023

# Higgs Mass

- Extend the SM gauge group -> additional D-term contribution

$$\frac{g_{Z'}^2}{2}(Q'_{H_d}|H_d^0|^2+Q'_{H_u}|H_u^0|^2+Q'_s|S|^2)^2$$

Increase the Higgs mass at the tree level

- As in the NMSSM, $\lambda S H_u H_d$ in the super potential

Increase the upper bound of the Higgs mass

- Upper bound of the Higgs mass,

$$\begin{aligned} m_h^2 =& M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \\ &+ g_{Z'}^2 v^2 (Q'_{H_d} \cos^2\beta + Q'_{H_u} \sin^2\beta)^2. \end{aligned}$$

- Higgs mass receives extra contribution at the tree level -> stop sector is less constrained

V. Barger, C. Haumptmann, PH, W..Y.. Keung 2023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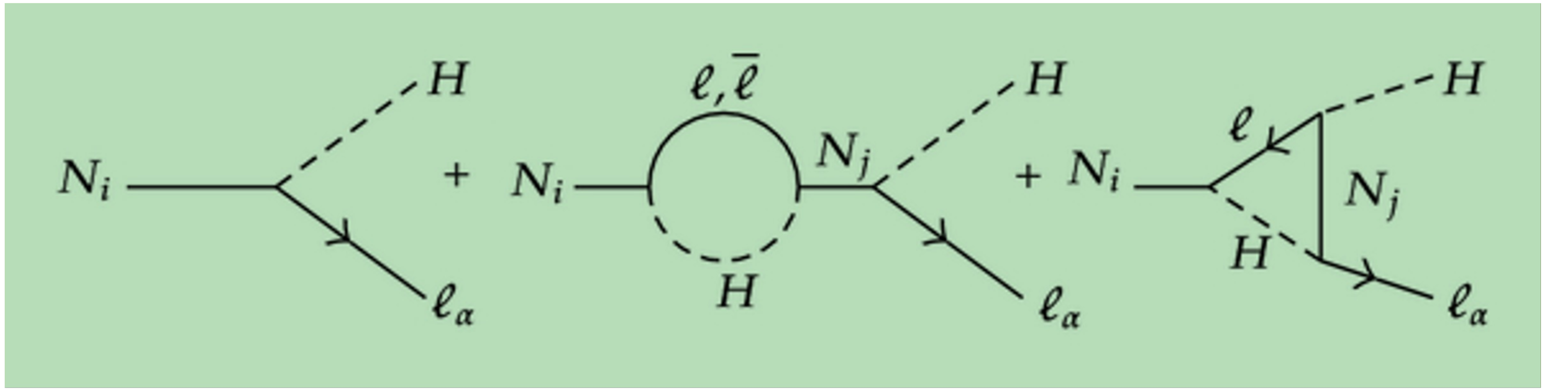
# He Thinks Hard on His Way Home

Leptogenesis!!

# Leptogenesis

Generate the Baryon asymmetry through the lepton asymmetry




$$\mathcal{L} \supset -\sum_{i,j} \left( \lambda_D^{ij} \bar{\ell}_L^i \tilde{H} \nu_R^j + \text{h.c.} \right)$$

1. The Right Handed Neutrinos, decay (CP violating) asymmetrically

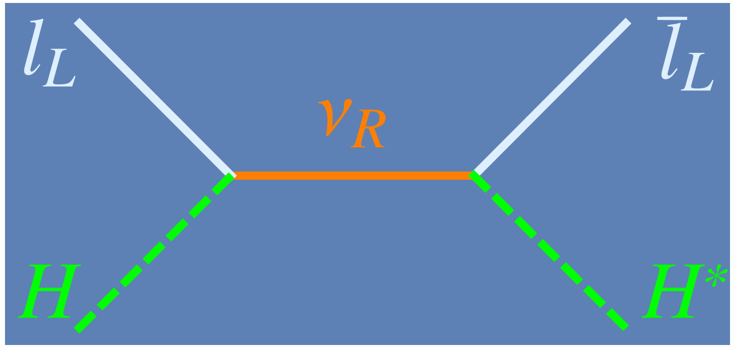
$$\epsilon_i = \frac{\sum_j \Gamma\left(\nu_R^i \to \ell_L^j H\right) - \Gamma\left(\nu_R^i \to \bar{\ell}_L^j H^*\right)}{\sum_j \Gamma\left(\nu_R^i \to \ell_L^j H\right) + \Gamma\left(\nu_R^i \to \bar{\ell}_L^j H^*\right)} \propto \text{Im}\left[\left(\lambda_D \lambda_D^\dagger\right)^2\right]$$

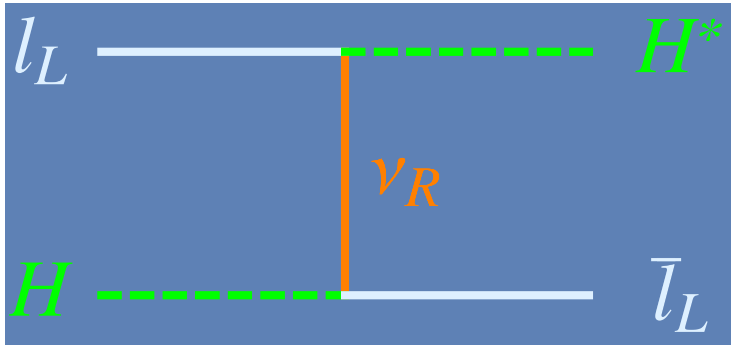
M. Fukugita, T. Yanagida, 1986
Luty 1992

2. Part of the generated asymmetry will be converted to a baryon asymmetry (about order one, detailed calculation gives 28/79)

# Difficulties in Leptogenesis

3. Inverse decays and scattering wash out the generated asymmetry



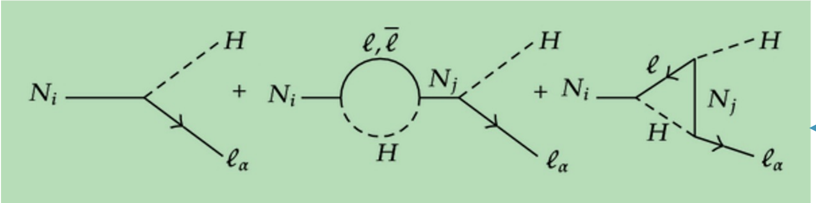




Only 1% of the generated asymmetry will survive

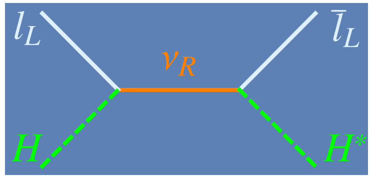
How to fix this?

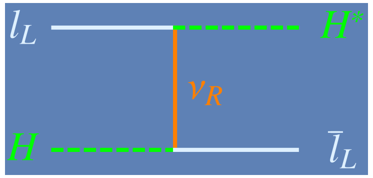
# Difficulties in Leptogenesis

- Naively, the strong washout effect is unavoidable




Competition



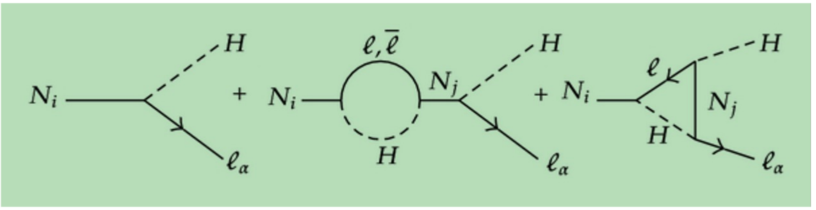




T~M

- The RHN decouples from the thermal bath at T~M
- What if the cosmic temperature changes discontinuously?

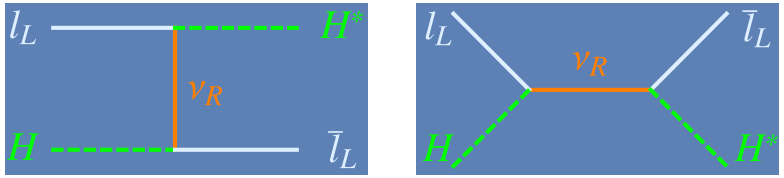
# Difficulties in Leptogenesis

- The RHN decouples from the thermal bath at T~M
- Only if the cosmic temperature changes discontinuously, the RHN decays, generates the lepton asymmetry. Then the temperature falls T<<M, the washout effects are Boltzmann suppressed
- All the generated asymmetry is survived




T~M

T changes discontinuously

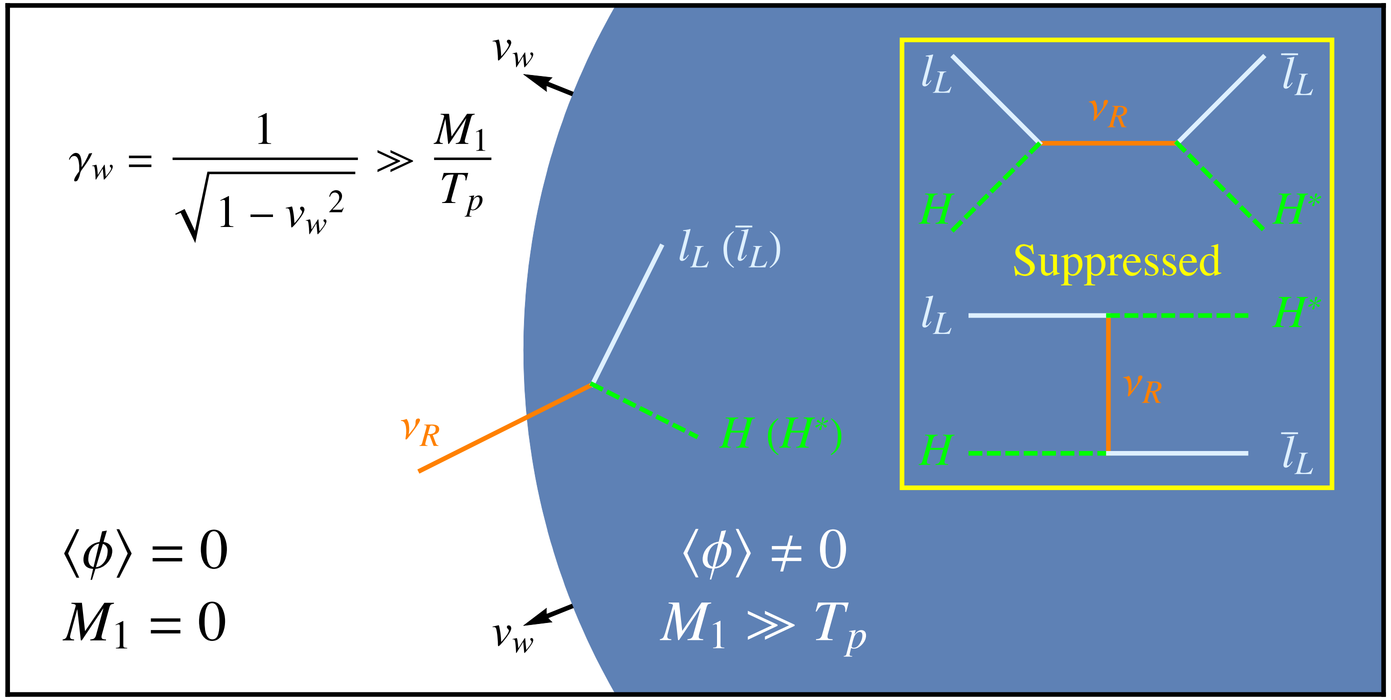



T<<M

# Solution #1 – Mass Jump

- The cosmic temperature can not change discontinuously, but the mass of the RHNs can -- first-order PT!

$$\mathcal{L} \supset -\sum_{i,j} \frac{1}{2}\left(\lambda_R^{ij}\bar{\nu}_R^{i,c}\nu_R^j \frac{\phi}{\sqrt{2}} + \text{h.c.}\right),$$

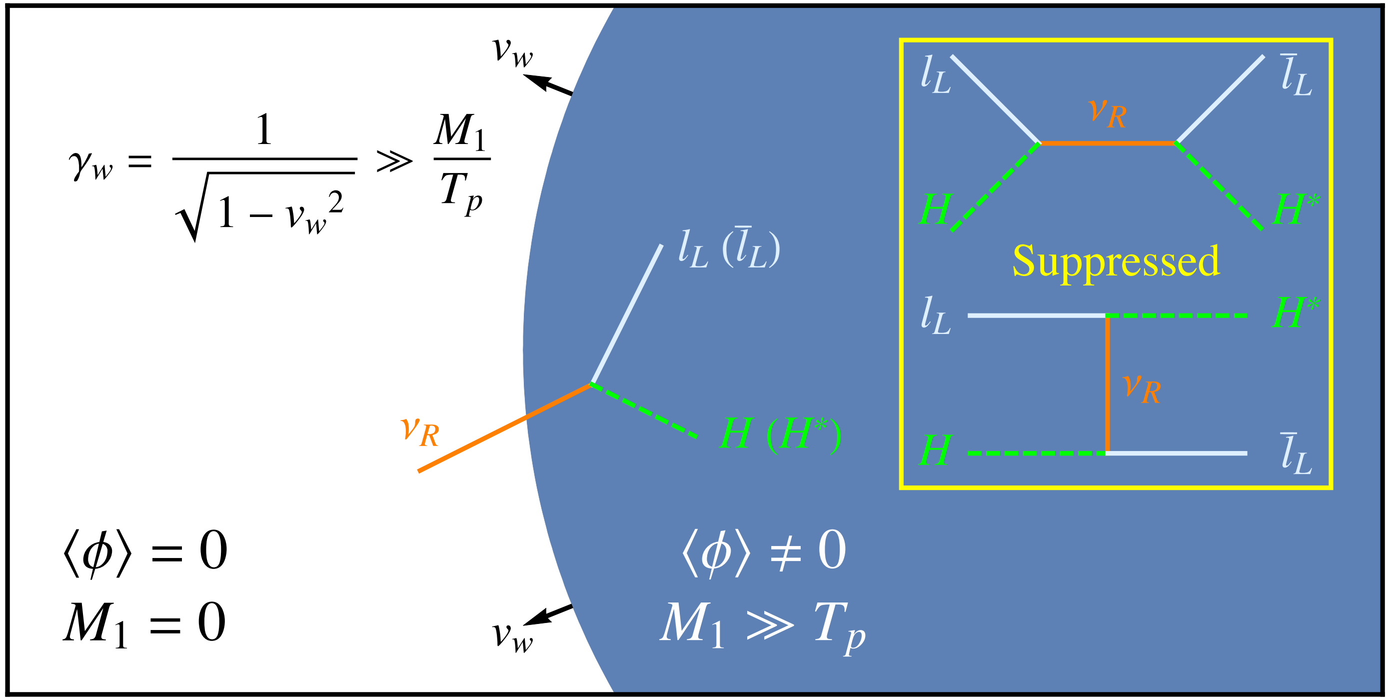



- The RHNs are massless in the old vacuum
- During the PT, the RHN gains mass $M_1$ – mass changes discontinuously
- If $M_1 >> Tp$, the washout effects are Boltzmann suppressed

PH, K. P. Xie 2022

# Wait – $M_1$ >> $T_p$, How Can That Happen?

$M_1$ >> $T_p$, how?




- If the phase transition is very strong, the bubble wall can be relativistic
- Although in the plasma frame, RHNs are in thermal equilibrium, they have very high energy in the wall frame
- They can penetrate into the true vacuum, and decay immediately

PH, K. P. Xie 2022

# Solution #1 – Mass Jump

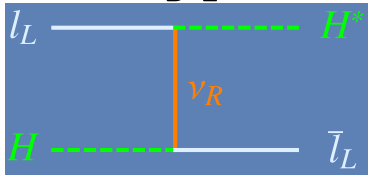
$$\mathcal{L} \supset -\sum_{i,j} \frac{1}{2}\left(\lambda_R^{ij}\bar{\nu}_R^{i,c}\nu_R^j\frac{\phi}{\sqrt{2}} + \text{h.c.}\right),$$

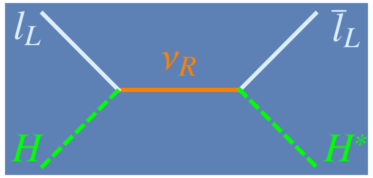
T

At at high temperature, the universe is in the symmetric phase, RHNs are massless, and in thermal equilibrium

$T_p << M_1$

- Phase Transition. The scalar field phi acquires a vacuum expectation value, and the RHN gains mass $M_1$ in the true, new vacuum
- $M_1 >> T_p$, RHN decays, generates the asymmetry
- Ultra relativistic bubble walls, RHNs penetrate into the true vacuum
- $U(1)_{B-L}$ models can do the job

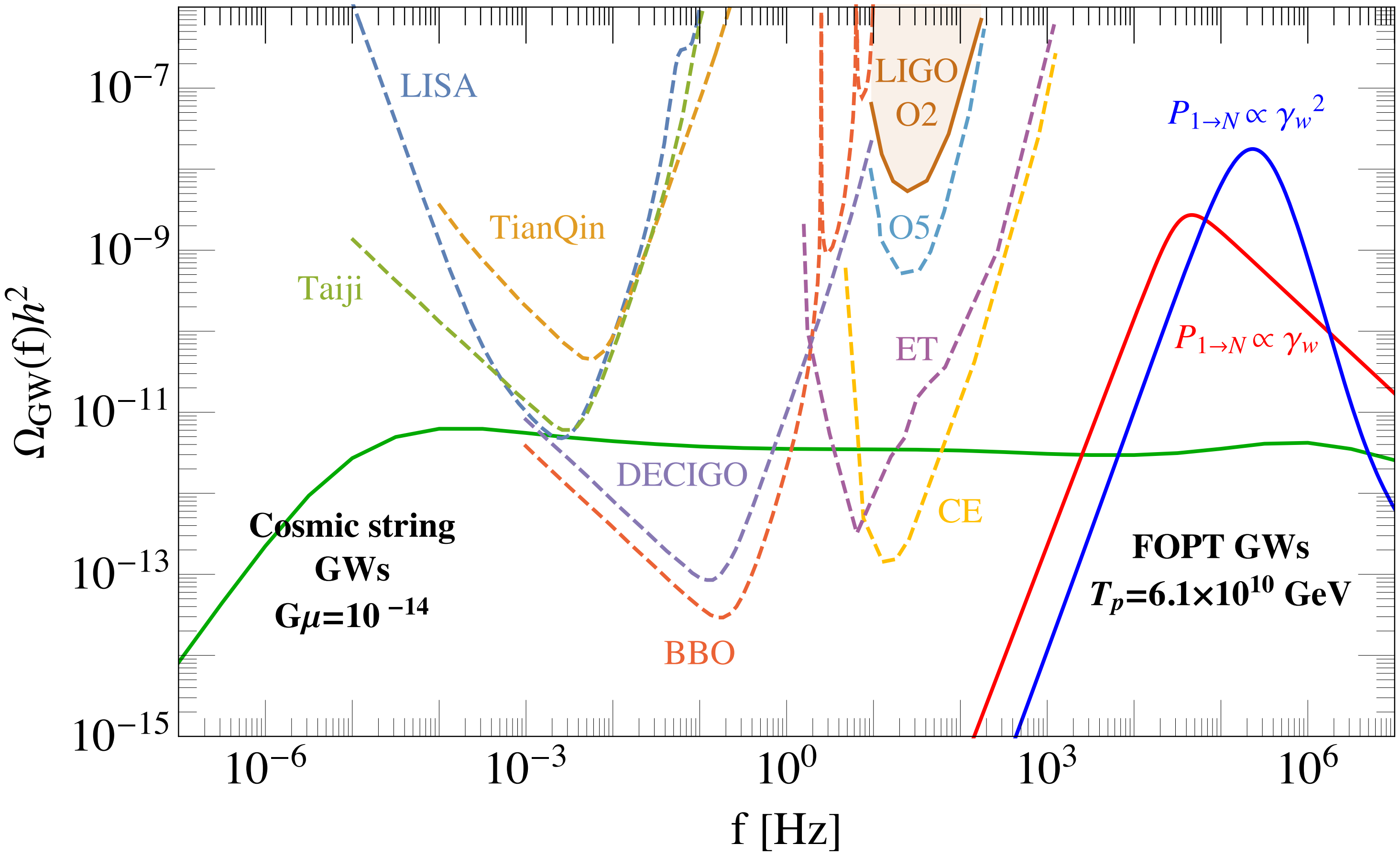



Washouts are suppressed!

PH, K. P. Xie 2022

# Gravitational Wave signal



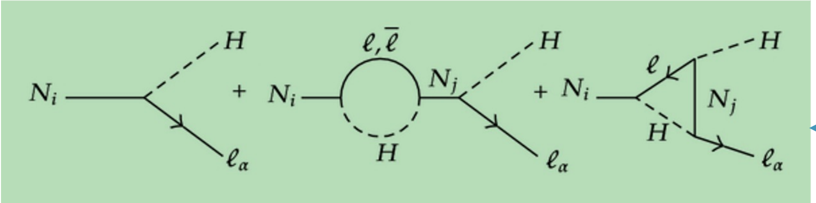

~O(30) enhancement

PH, K. P. Xie 2022

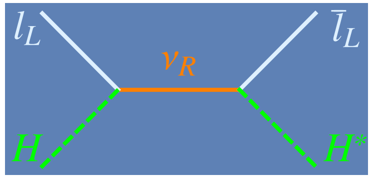
$$M_1 = 2.5\times10^{11}\ \text{GeV},\quad \lambda_{R,1}=0.3,\quad \lambda_{R,2}=\lambda_{R,3}=4\lambda_{R,1},\ \lambda_{\phi s}=3.5\quad g_{B-L}=0.05$$

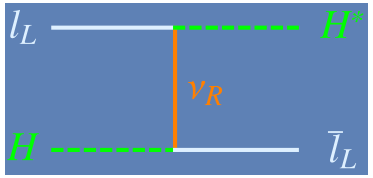
# Solution #2 – T-Dep Couplings

- Naively, the strong washout effect is unavoidable




Competition

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- The washout processes are only active at a much lower T

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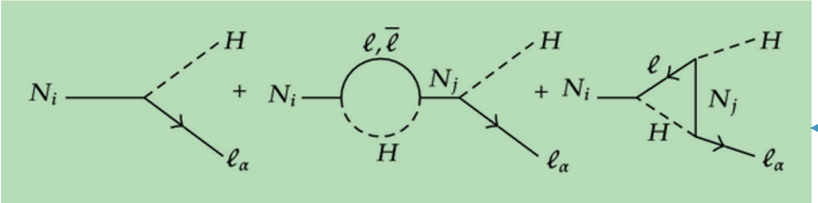


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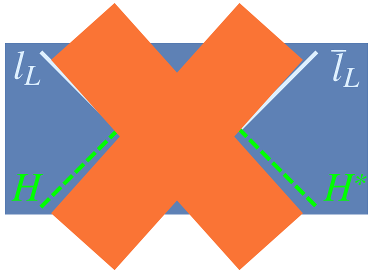
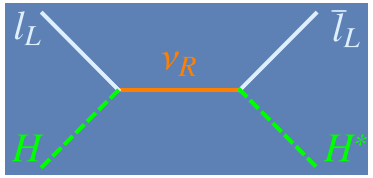
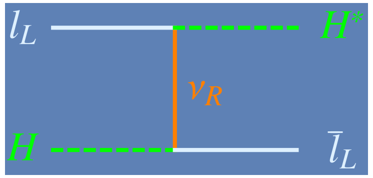




T~M

- The RHN decouples from the thermal bath at T~M
- The washout processes are only active at a much lower T
- Wash out is Boltzmann suppressed
- All the generated asymmetry is survived



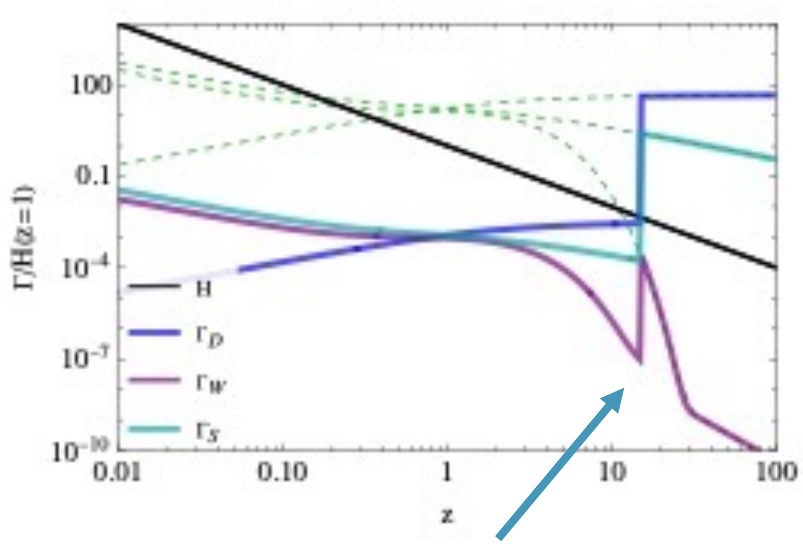
# Solution #2 – T-Dep Couplings

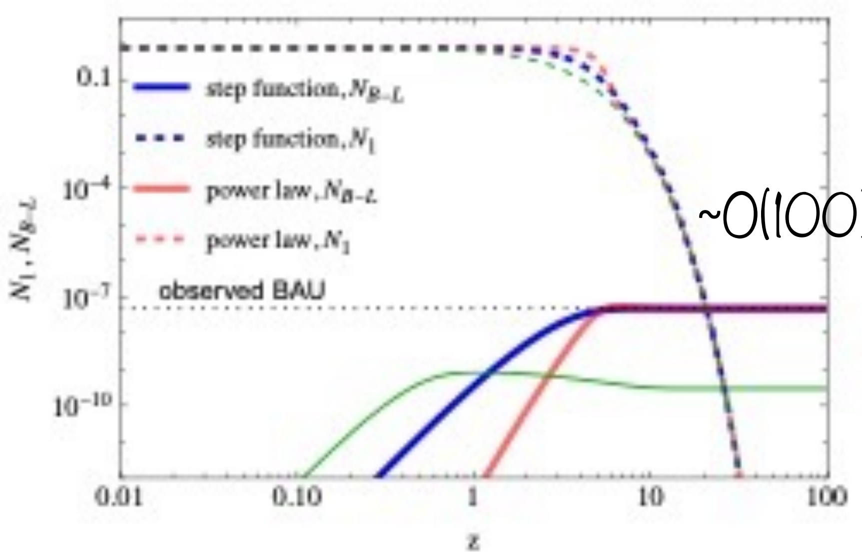
- Take

$$\lambda_{D,\mathrm{s}}(z) = \begin{cases} b_\mathrm{s}\,\lambda_D, & z < z_\mathrm{s} \\ \lambda_D, & z \geq z_\mathrm{s} \end{cases}$$

$$\mathcal{L} \supset -\sum_{i,j}\left(\lambda_D^{ij}\bar{\ell}_L^i \tilde{H}\nu_R^j + \mathrm{h.c.}\right)$$

$$z \equiv M_1/T$$




~O(100) enhancement

Wash out is turned on when it is already Boltzmann suppressed

PH, T. Xu 2023

# RHNs are Pretty Heavy

- The Davidson-Ibarra bound, assuming there is a mass hierarchy between the RHNs, for a given mass of the lightest one, the upper bound for CP violation

$$|\epsilon_1| \leqslant \frac{3}{8\pi}\frac{M_1(m_3 - m_1)}{v_{\mathrm{EW}}^2} \approx 10^{-5} \times \left(\frac{M_1}{10^{11}\ \mathrm{GeV}}\right)\left(\frac{m_\nu}{0.05\ \mathrm{eV}}\right)$$

Davidson and Ibarra, 1992

- In the previous two scenarios, the RHNs are pretty heavy, at least ~O($10^9$) GeV – only handles are GW signals
- Possible way to bring the mass scale down?

# Scenario #3 -- Neutrinophilic 2HDM + Resonant Enhancement

See for example, Flanz et al, 1996, Pilaftsis, 1997, Dev et al, 2017 ….

- Resonant leptogenesis
  - Enhance the CP asymmetry through the interference between nearly degenerate RHN states
  - Possible to have $M_{1,2}$ around the TeV scale
  - Cost, $\Delta M/M \sim 10^{-9}$
- Neutrinophilic Two-Higgs Doublet Model

$$\epsilon_{1\alpha} \sim \frac{M_1}{v^2}$$

  - Introduce a second Higgs doublet, with vev $v_2 << v_{SM}$
  - To avoid strong $\Delta L = 2$ washout,

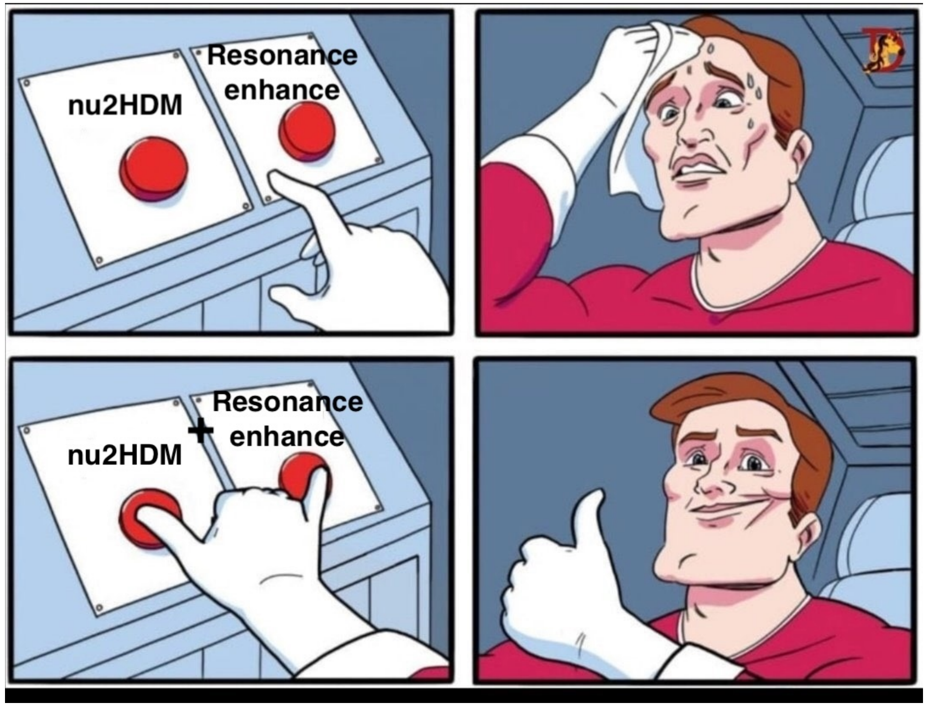
$$\Gamma_{\Delta L=2} \sim \frac{T}{v_2^4} \sum m_{\nu_i}^2 \Rightarrow M_N \gtrsim 10^5 \mathrm{GeV}$$

# Scenario #3 -- Neutrinophilic 2HDM + Resonant Enhancement

$\nu$2HDM + Resonance Enhancement ✓

Kairui Zhang, Pheno 2025

- Combined framework enhancements:
  - Balances strong Yukawas from resonant enhancement with $\Delta L = 2$ washout constraints from $\nu$2HDM
  - Achieves much lower $M_i \sim$ TeV
  - Small $v_2 \ll v_{\mathrm{SM}}$ reduces tuning to $\Delta M/M \sim 10^{-2} - 10^{-3}$



# Scenario #3 – Neutrinophilic 2HDM + Resonant Enhancement

Kairui Zhang, Pheno 2025

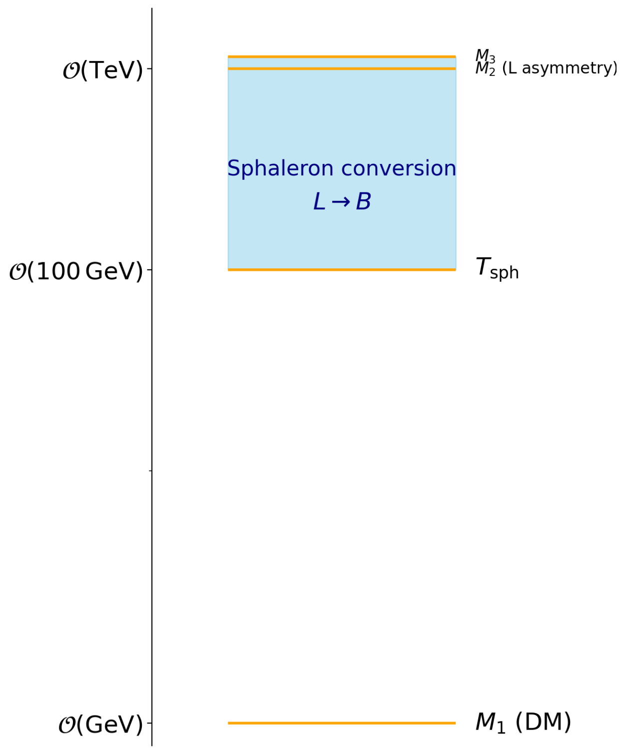
- $N_2$ and $N_3$ at the TeV scale with

$$\Delta M/M \sim 10^{-2} - 10^{-3}$$

- Mass pattern,

$$(\mathcal{O}(S), M - \mathcal{O}(S), M + \mathcal{O}(S))$$

- A natural light DM candidate
- $N_1$ decouples after sphaleron freeze-out. BAU is already frozen when $N_1$ becomes thermally important
- Rich pheno – colliders, light DM




# How Many Generations?

- Natural SUSY: Vernon, Howie (1st), Azar Mustafayev (2nd, Baer), and Xerxes Tata(1st)
- Higgs mass and W mass: Vernon, Wai-Yee(1st), Cash Haumptmann(2nd , PH), M. Ishida
- Leptogenesis: Ke-Pan Xie (2$^{nd}$, PH), Tao Xu (3rd , T. Han-> K. Wang), Kairui Zhang (1st + 2nd,  Baer)


# On Wisconsin!

- I had a lot of fun with particles in and beyond the SM.
- I am a strong believer of physics beyond the SM (How sure I am? I name my older daughter after that)
- I had my best five years in life at the phenomenology institute
- At the phenomenology institute, I learned some physics, discovered what I want to do in life, met the best mentors, and made life-long friends (How much I appreciate the pheno institute? I wear my pheno hat to every Wisconsin vs Nebraska game)
- On Wisconsin!