



ν Electroweak Baryogenesis

Salvador Rosauro-Alcaraz, Pôle Théorie IJCLab

Portorož 2023

In collaboration with E. Fernandez-Martinez, J. Lopez-Pavon, J. M. No & T. Ota
Based on 2007.11008 & 2210.16279

Introduction

Planck Collaboration, arXiv:1807.06209

$$Y_B^{obs} = \frac{n_b - n_{\bar{b}}}{s} \simeq (8.59 \pm 0.08) \times 10^{-11}$$

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Generation of a BAU

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Sakharov's conditions

- C and CP violation
- B violation
- Out-of-equilibrium conditions

A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5 (1967) 32-35

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Generation of a BAU

Electroweak baryogenesis

Shaposhnikov, Nucl. Phys B287 (1987)

CP violation from CKM matrix

$B + L$ violation from sphalerons

Kuzmin, Rubakov & Shaposhnikov, Phys. Lett. 155B (1985) 36

1st order phase transition

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M. B. Gavela, P. Hernandez, J. Orloff & O.
Pene, arXiv:hep-ph/9312215

M. B. Gavela, P. Hernandez, J. Orloff, O. Pene
& C. Quimbay, arXiv:hep-ph/9406289

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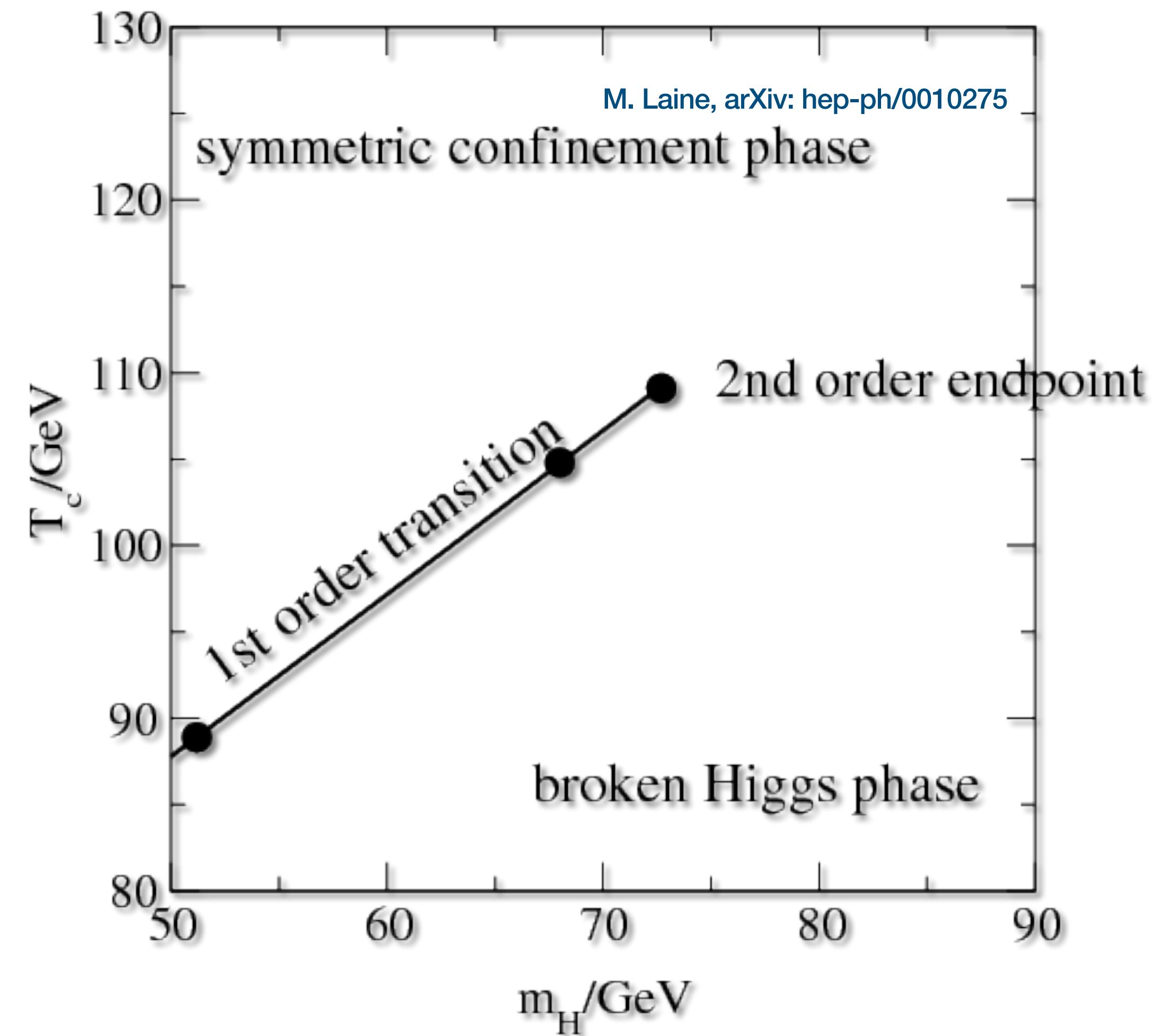
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$B + L$ violation from sphalerons

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~~1st order phase transition~~

K. Kajantie, M. Laine, K. Rummukainen, & M. E. Shaposhnikov, arXiv:hep-ph/9605288

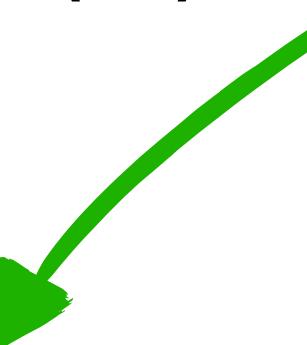


Electroweak baryogenesis and low-scale seesaws

P. Minkowsky, 1977
T. Yanagida, 1979
M. Gell-Mann, P. Ramon and R. Slansky,
arXiv:1306.4669
S. L. Glashow, 1980
R. N. Mohapatra and G. Senjanovic, 1980
Gonzalez-Garcia & Valle 1992
Malinsky et al., arXiv:0506296

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{\Phi} N'_R - \bar{N}'_L s Y_N N'_R + h.c. - V(\Phi^\dagger \Phi, s)$$

SSB $\rightarrow \langle h \rangle = v, \langle s \rangle = \omega$



Large mixing and CPV

$$\theta = \frac{v}{\sqrt{2}\omega} Y_\nu Y_N^{-1}$$

See talks by D. Dobur & P. Bolton

Bounded by EW precision
and flavour observables

S. Antusch & O. Fischer, arXiv:1407.6607
A. de Gouvea & A. Kobach, arXiv:1511.00683
E. Fernandez-Martinez, J. Hernandez-Garcia & J. Lopez-Pavon,
arXiv:1605.08774
And many more

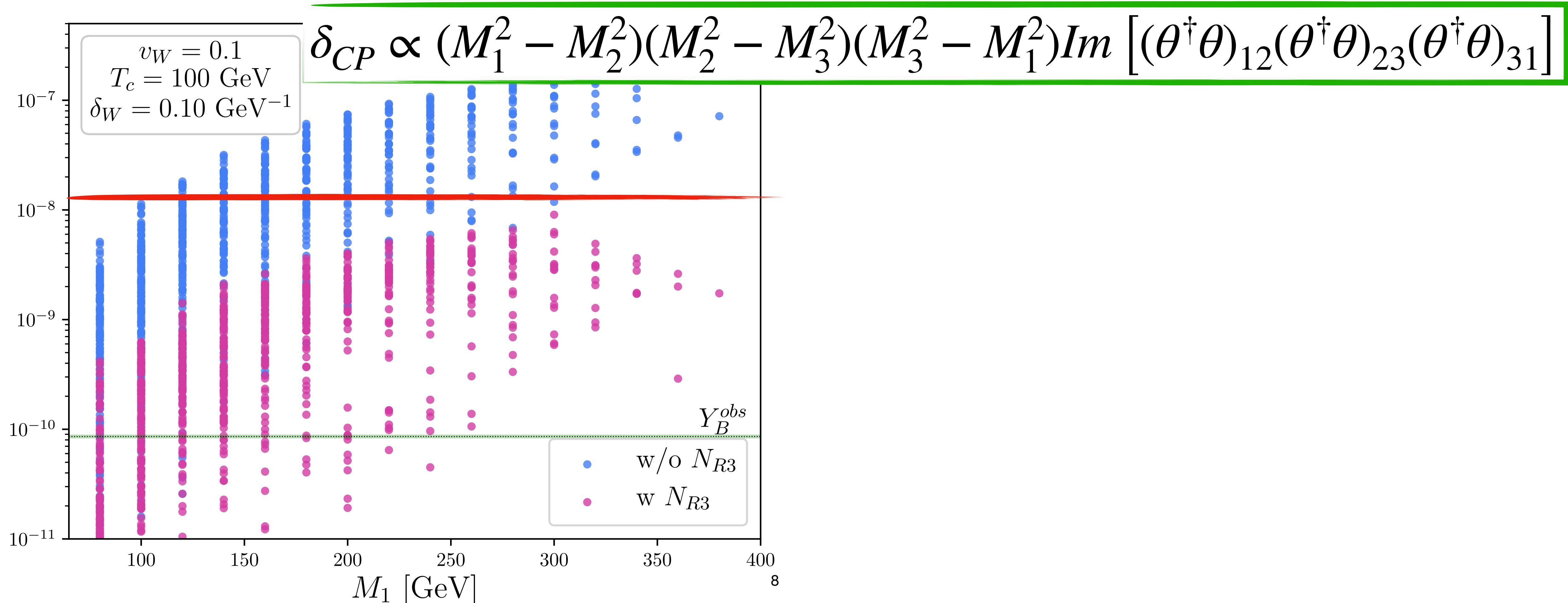
P. Hernandez & N. Rius, arXiv: hep-ph/9611227
E. Fernandez-Martinez, J. Lopez-Pavon, T. Ota & SRA, arXiv:2007.11008

See talks by Z. Berezhiani and by
M. Malinsky for alternatives

Electroweak baryogenesis and low-scale seesaws

$$\mathcal{L} \supset -\bar{L}_c Y_c \tilde{\Phi} N'_D - \bar{N}'_c s Y_{\Lambda} N'_D + h.c. - V(\Phi^\dagger \Phi, s)$$

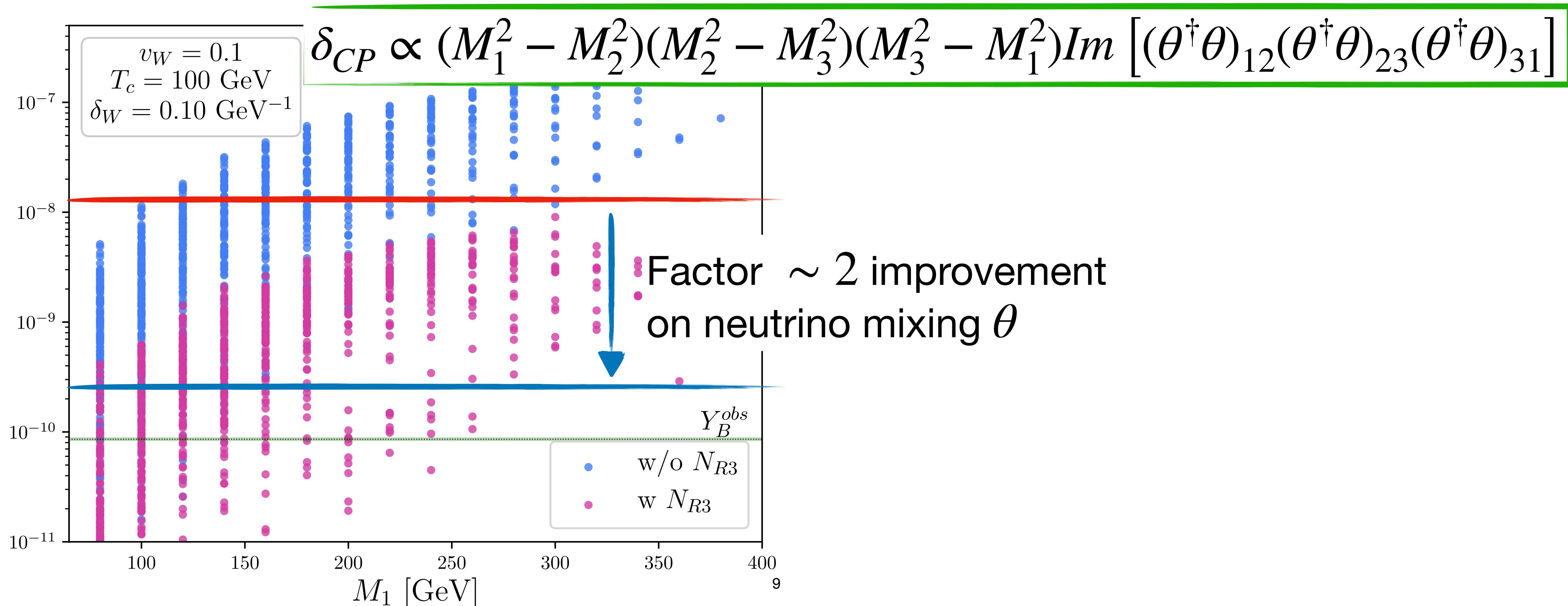
E. Fernandez-Martinez, J. Lopez-Pavon, T. Ota & SRA, arXiv:2007.11008



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Phase transition with dark sectors

Electroweak baryogenesis

Shaposhnikov, Nucl. Phys B287 (1987)

~~CP violation from CKM matrix~~

$B + L$ violation from sphalerons

Kuzmin, Rubakov & Shaposhnikov, Phys. Lett. 155B (1985) 36

~~1st order phase transition~~

Add singlet scalar s

M. Dine, P. Huet, R. L. Singleton, Jr & L. Susskind, Phys. Lett. B257 (1991)
J. R. Espinosa, T. Konstandin & F. Riva, arXiv: 1107.5441

Phase transition with dark sectors

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{\Phi} N'_R - \bar{N}'_L s Y_N N'_R + h.c. - V(\Phi^\dagger \Phi, s)$$

E. Fernandez-Martinez, J. Lopez-Pavon, T. Ota & SRA, arXiv:2007.11008

$$\begin{aligned} V(\Phi^\dagger \Phi, s) = & -\frac{1}{2} \tilde{\mu}_h^2 \Phi^\dagger \Phi + \frac{1}{4} \lambda_h (\Phi^\dagger \Phi)^2 + \frac{1}{2} \tilde{\mu}_s^2 s^2 + \frac{1}{4} \lambda_s s^4 \\ & + \frac{1}{4} \mu_m s \Phi^\dagger \Phi + \frac{1}{4} \lambda_m s^2 \Phi^\dagger \Phi + \tilde{\mu}_1^3 s + \frac{1}{3} \mu_3 s^3 \end{aligned}$$

[J. R. Espinosa, T. Konstandin & F. Riva, arXiv:1107.5441](#)

T. Robens & T. Stefaniak, arXiv:1501.02234

D. Butazzo, F. Sala & A. Tesi, arXiv:1505.05488

[A. V. Kotwal, J. M. No, M. J. Ramsey-Musolf & P. Winslow, arXiv:1605.06123](#)

[C. Chen, J. Kozaczuk & I. M. Lewis, arXiv:1704.05844](#)

[C. Chiang, Y. Li & E. Senaha, arXiv:1808.01098](#)

[M. Carena, Z. Liu & Y. Wang, arXiv:1911.10206](#)

[J. Kozaczuk, M. J. Ramsey-Musolf & J. Shelton, arXiv:1911.10210](#)

[E. Fuchs, O. Matsedonskyi, I. Savoray & M. Schlaffer, arXiv:2008.12773](#)

[A. Papaefstathiou & G. White, arXiv:2010.00597](#)

[S. Dawson, P. P. Giardino & S. Homiller, arXiv:2102.02823](#)

[M. Carena, J. Kozaczuk, Z. Liu, T. Ou, M. J. Ramsey-Musolf, J. Sherlon, Y. Wang & K. Xie, arXiv:2203.08206](#)

Scalar potential

Tree level

$$V(h, s) = -\frac{1}{2}\tilde{\mu}_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\tilde{\mu}_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\mu_m s h^2 + \frac{1}{4}\lambda_m s^2 h^2 + \tilde{\mu}_1^3 s + \frac{1}{3}\mu_3 s^3$$

J. R. Espinosa, T. Konstandin & F. Riva, arXiv:1107.5441

Minima located at $(\langle h \rangle, \langle s \rangle) = (0,0)$ and (v, ω)
separated by tree-level barrier

Analytical conditions to have

$$V(0,0) \sim V(v, \omega)$$

Scalar potential

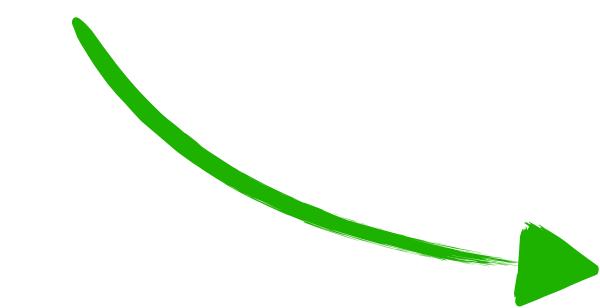
Tree level

$$V(h, s) = -\frac{1}{2}\tilde{\mu}_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\tilde{\mu}_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\mu_m s h^2 + \frac{1}{4}\lambda_m s^2 h^2 + \tilde{\mu}_1^3 s + \frac{1}{3}\mu_3 s^3$$

J. R. Espinosa, T. Konstandin & F. Riva, arXiv:1107.5441

Minima located at $(\langle h \rangle, \langle s \rangle) = (0,0)$ and (v, ω)
separated by tree-level barrier

Analytical conditions to have



$$V(0,0) \sim V(v, \omega)$$

Need to include finite T corrections

Scalar potential

One-loop - Finite temperature effects

High temperature approximation

J. R. Espinosa, T. Konstandin & F. Riva, arXiv:1107.5441
M. Quiros, arXiv:hep-ph/9901312

$$V_T(h, s, T) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\mu_m s h^2 + \frac{1}{4}\lambda_m s^2 h^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3$$

$$+ \left[\frac{1}{2}c_h h^2 + \frac{1}{2}c_s s^2 + m_3 s \right] (T^2 - T_c^2)$$

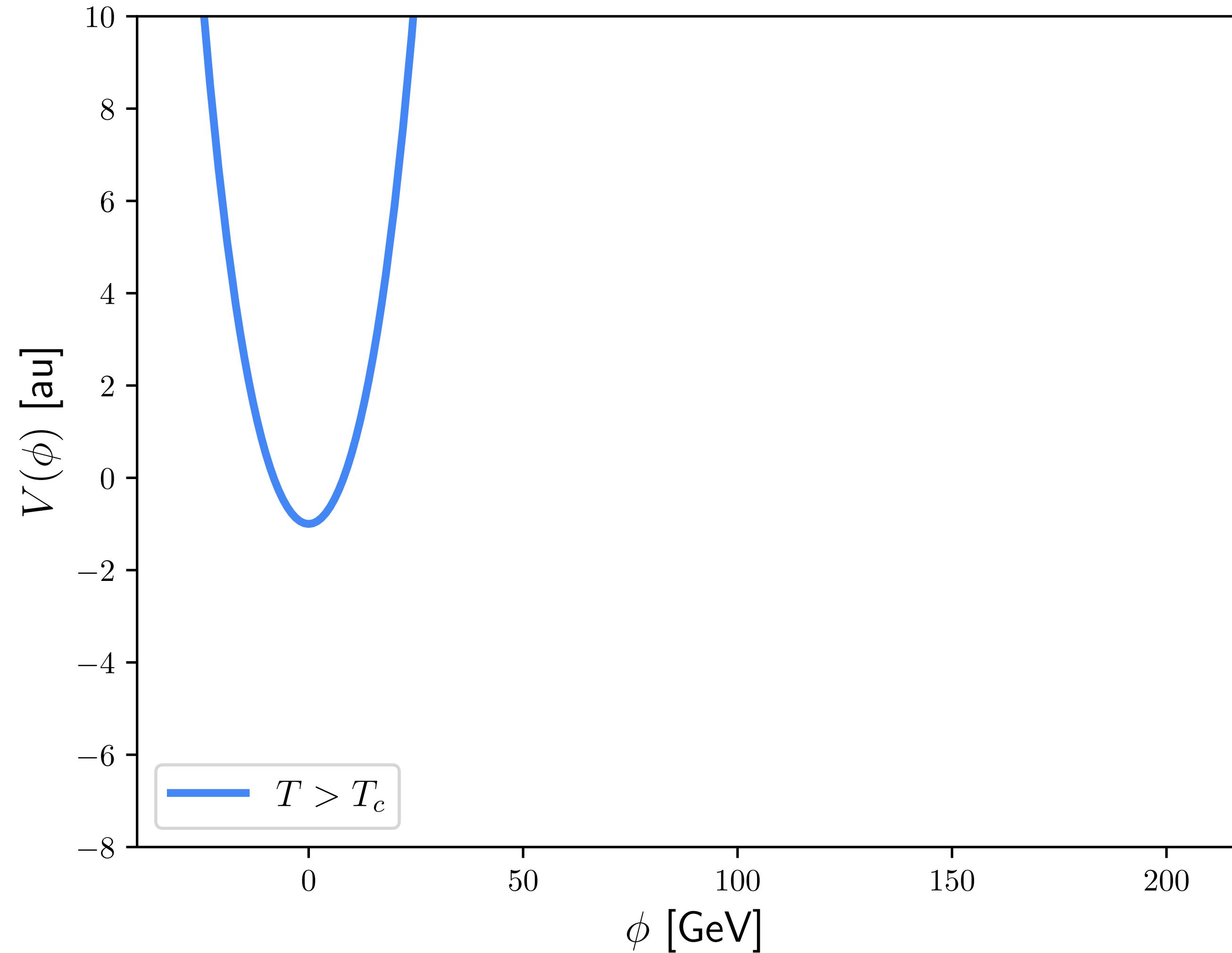


$$c_s = \frac{1}{12} [2\lambda_m + 3\lambda_s + 2\mathcal{Y}_N^2]$$

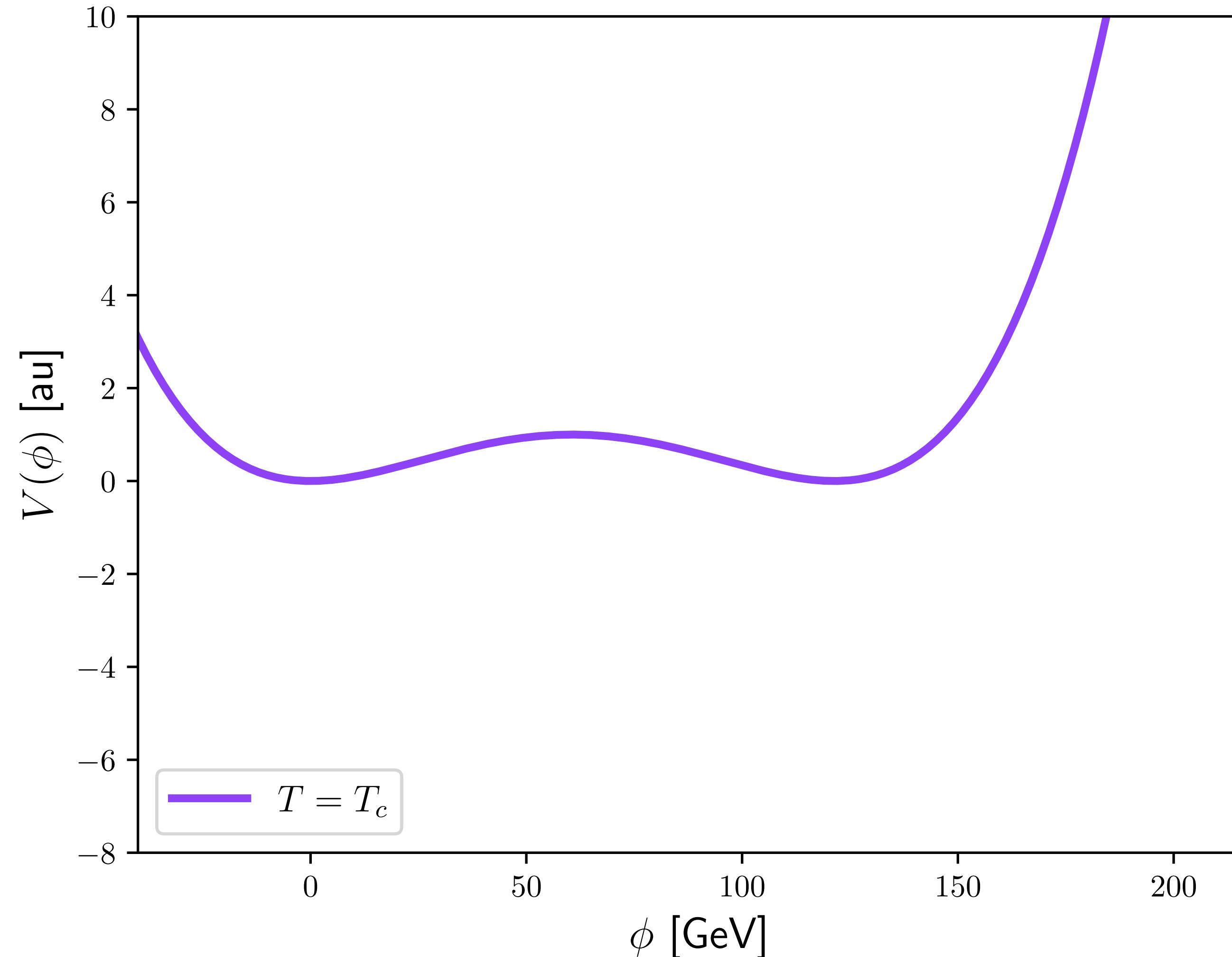
Neutrino Yukawa couplings

$$\mathcal{Y}_N^2 \equiv \text{tr}(Y_N^\dagger Y_N)$$

Nucleation



Nucleation



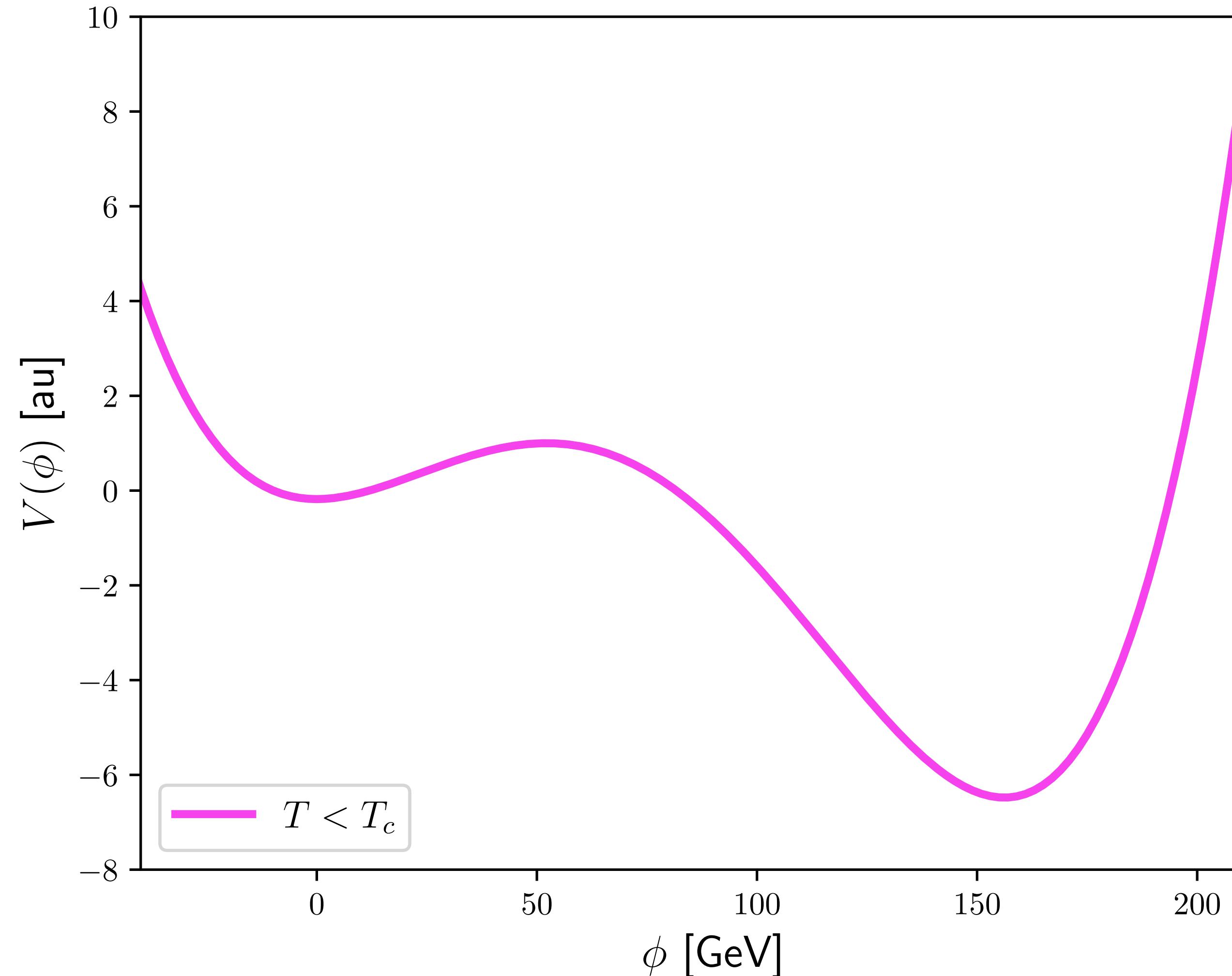
S. Coleman, Phys. Rev. D (1977)
A. Amarati, arXiv:2009.14102

$$\Gamma/V \sim e^{-S}$$

$$\lim_{T \rightarrow T_c} S \sim 1/\Delta V^3 \rightarrow \infty$$

The transition can only happen at $T < T_c$

Nucleation



$$\Gamma/V \sim e^{-S_3/T_N} \sim H(T_N)$$

$$S_3/T_N \sim 140$$

Need to solve
equations of motion

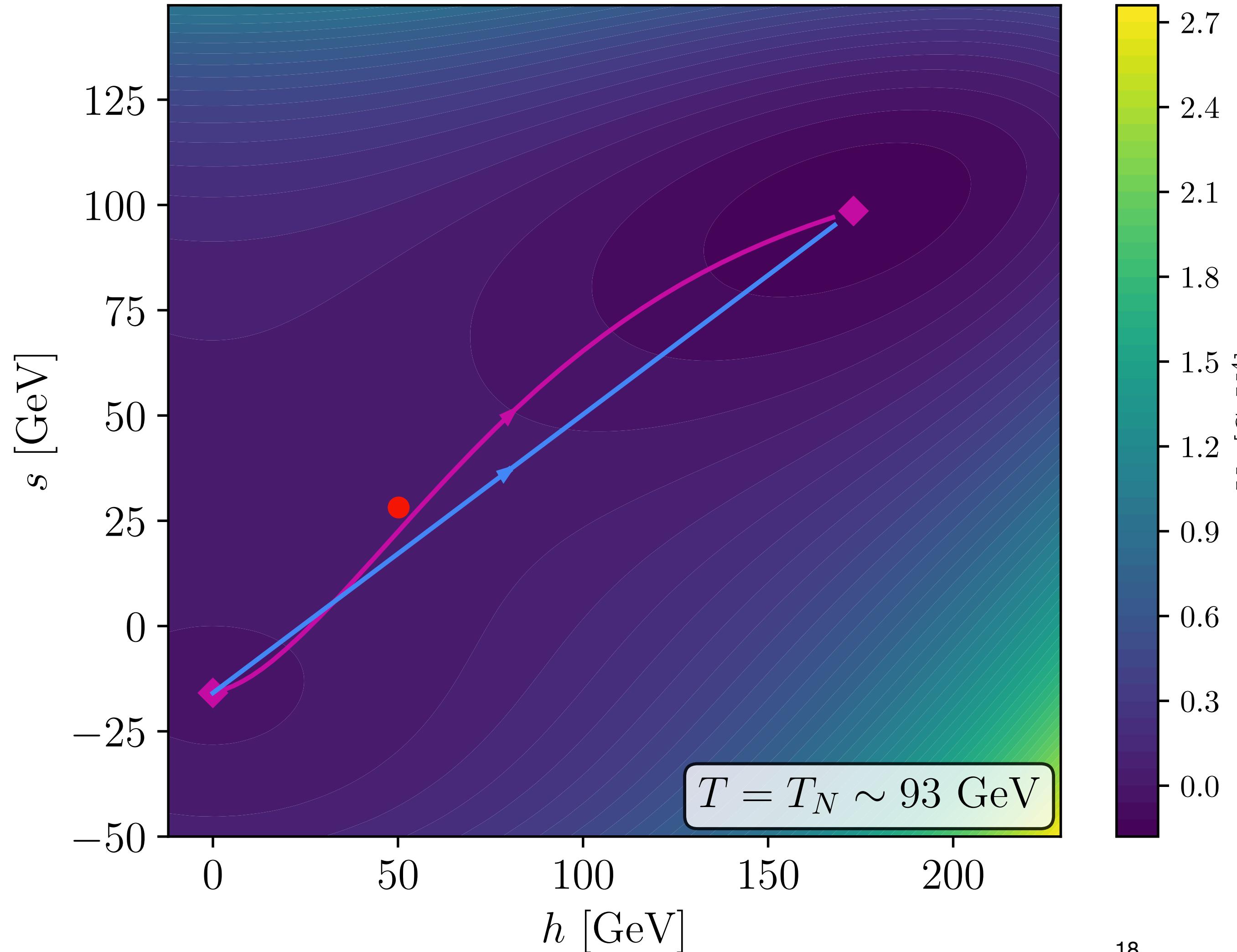
Wainwright, arXiv:1109.4189
Athron, Balazs, Bardsley, Fowlie, Harries & White, arXiv:1901.03714
Guada, Nemevsek & Pintar, arXiv:2002.00881

Talk by J. R. Espinosa

Poster by Marco Matteini based on arXiv:2202.04498

Nucleation

E. Fernández-Martínez, J. López-Pavón,
J. M. No, T. Ota & SRA arXiv:2210.16279



$$\Gamma/V \sim e^{-S_3/T_N} \sim H(T_N)$$

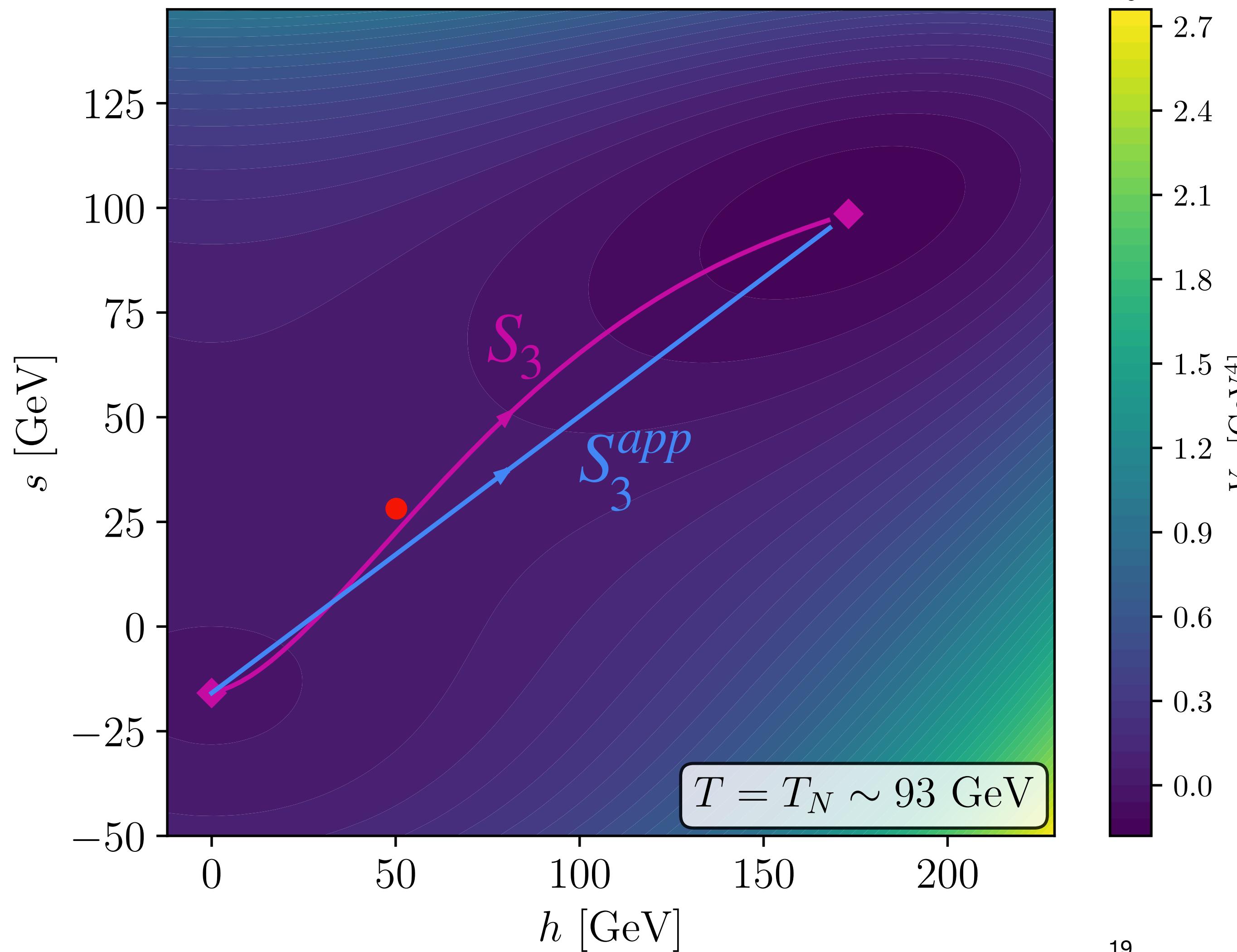
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Nucleation

E. Fernández-Martínez, J. López-Pavón,
J. M. No, T. Ota & SRA arXiv:2210.16279



Coleman, 1988
Cline, Morre & Servant, arXiv:hep-ph/9902220
Espinosa & Konstandin, arXiv:1811.09185

Use straight path between minima

$$S_3^{app} \geq S_3$$

$$S_3^{app}/T_N \sim 140$$

Efficiently scan the parameter space

Phenomenology

Constraints on scalar mixing

$$h = \nu_{EW} + \cos \xi H + \sin \xi S$$

$$s = \omega_{EW} - \sin \xi H + \cos \xi S$$

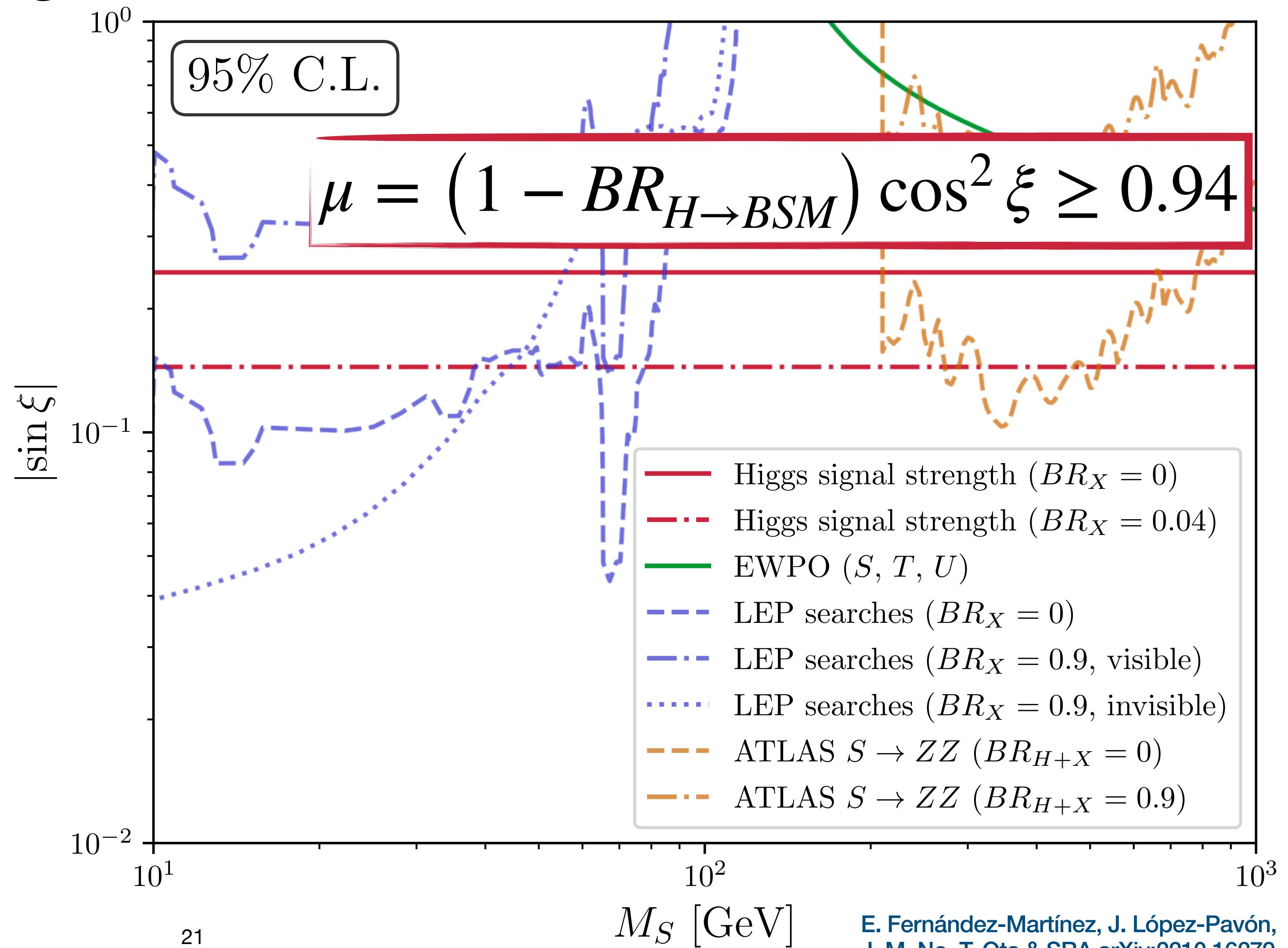
Phenomenology

Constraints on scalar mixing

Higgs signal strength

$$\mu \equiv \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}}$$

ATLAS Collaboration, arXiv:1909.02845
 CMS Collaboration, record/2706103



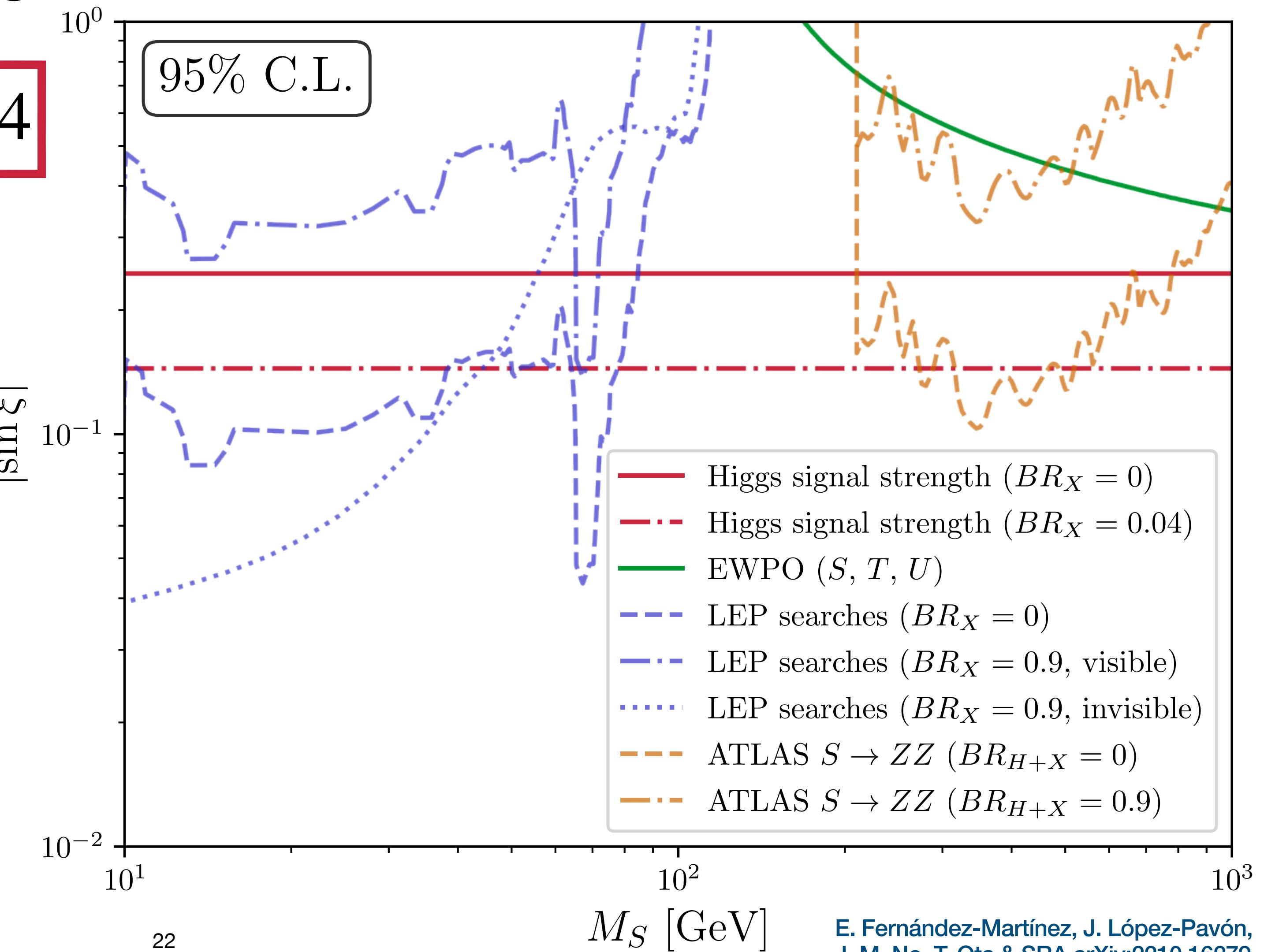
Phenomenology

Constraints on scalar mixing

$$\mu = (1 - BR_{H \rightarrow BSM}) \cos^2 \xi \geq 0.94$$

E. Fernández-Martínez, J. López-Pavón,
J. M. No, T. Ota & SRA arXiv:2210.16279

In our case, for example, $H \rightarrow N\bar{N}$



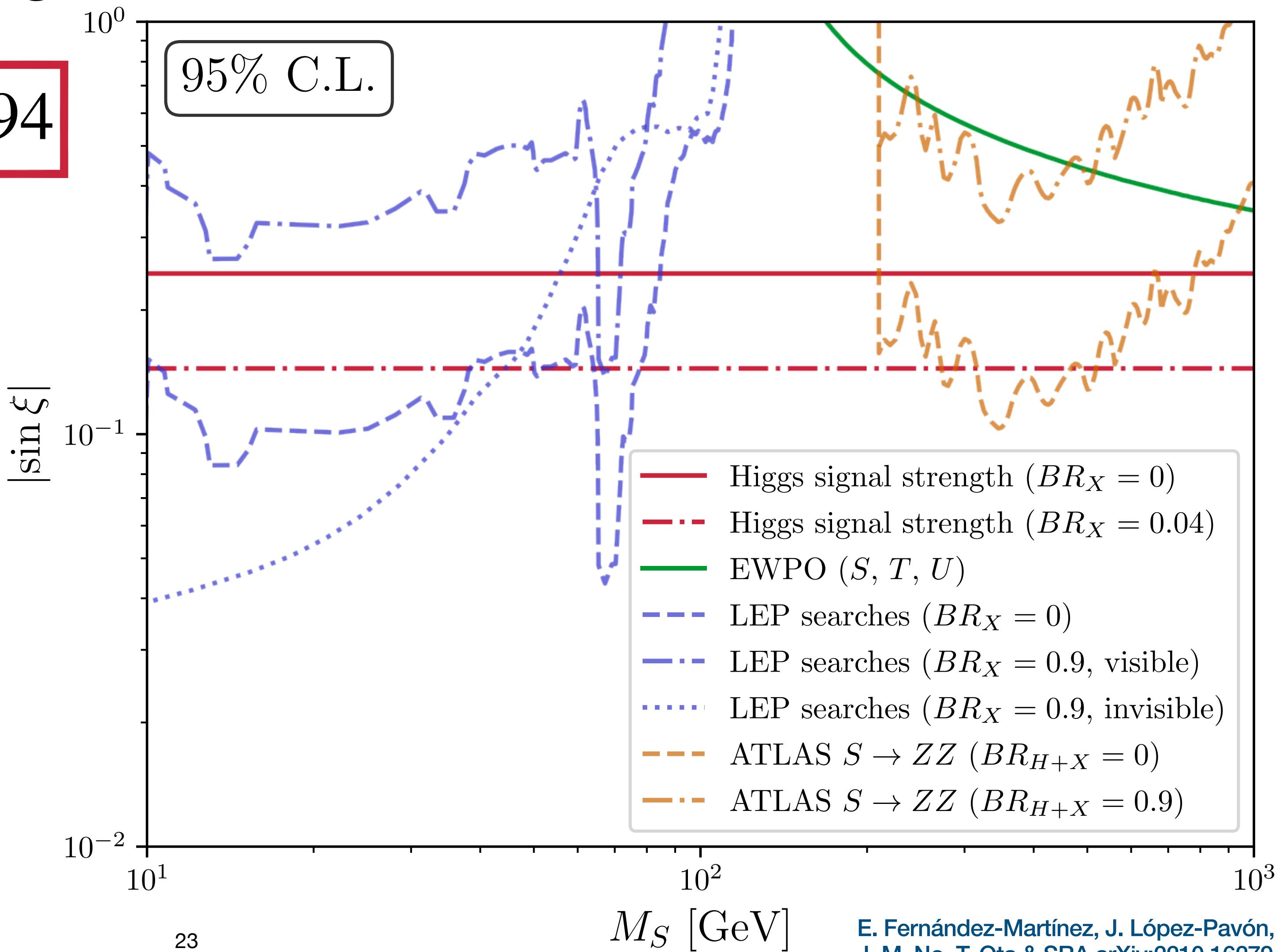
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E. Fernández-Martínez, J. López-Pavón,
J. M. No, T. Ota & SRA arXiv:2210.16279

EW precision observables



Phenomenology

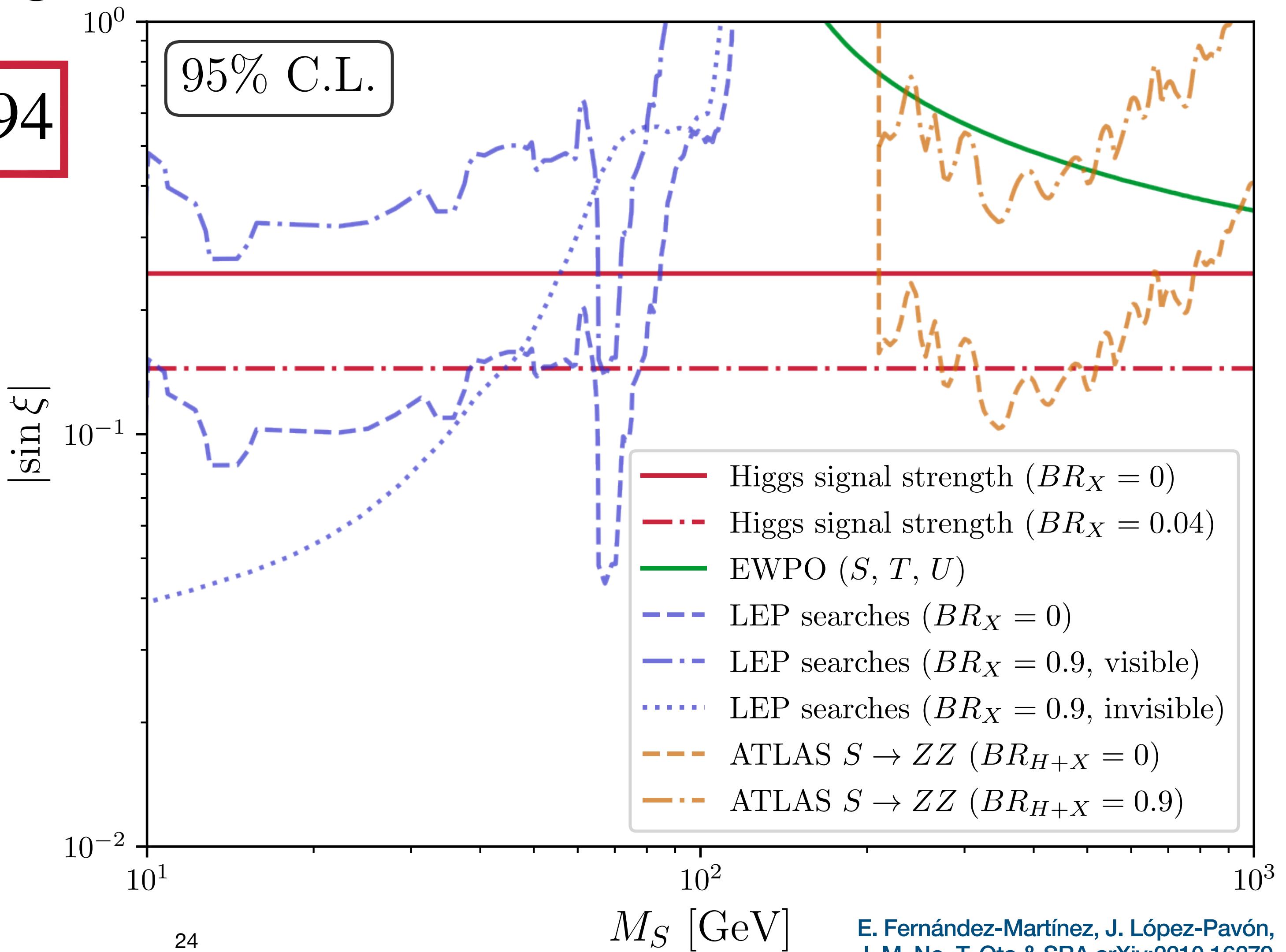
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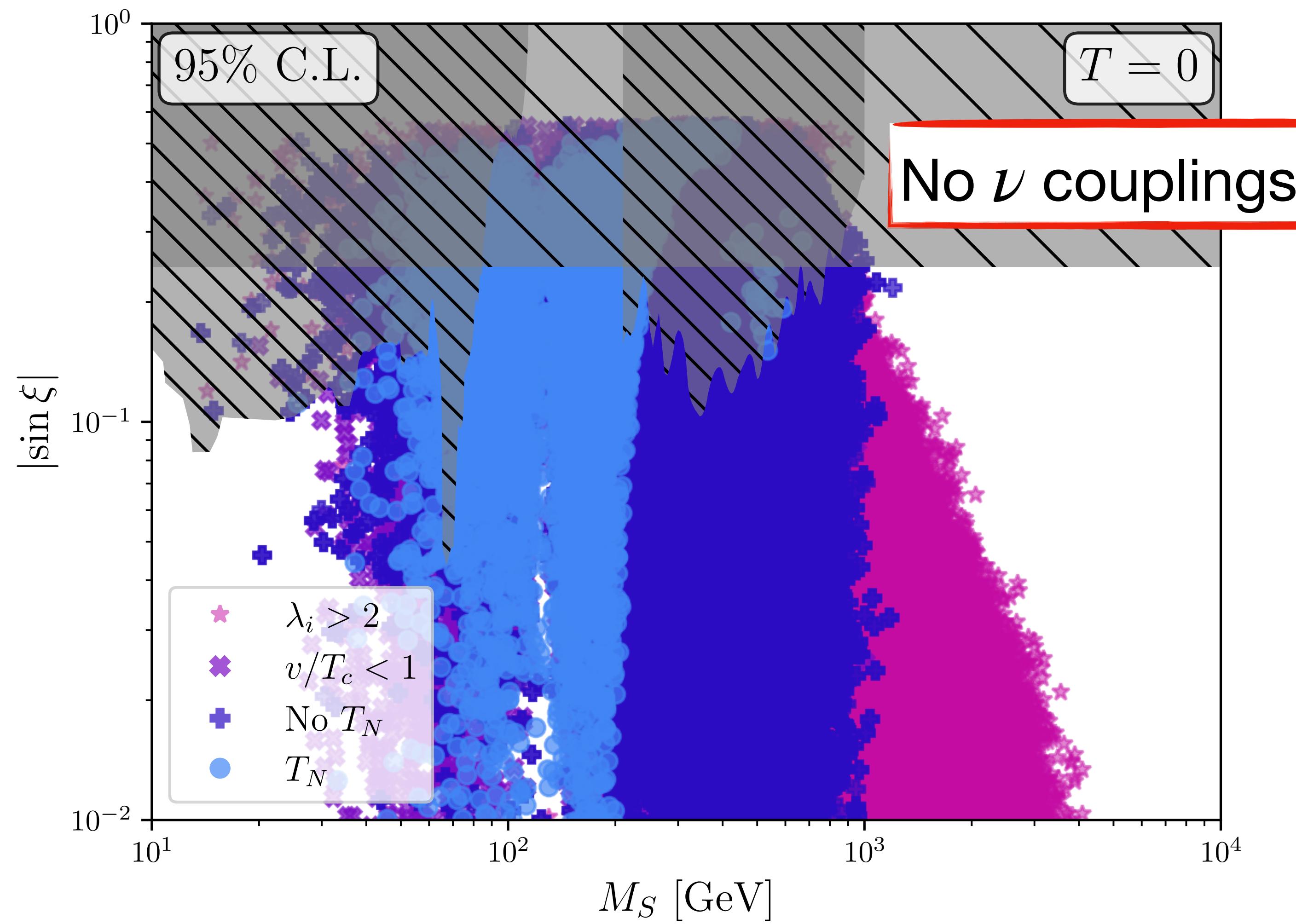
EW precision observables

LEP and LHC searches



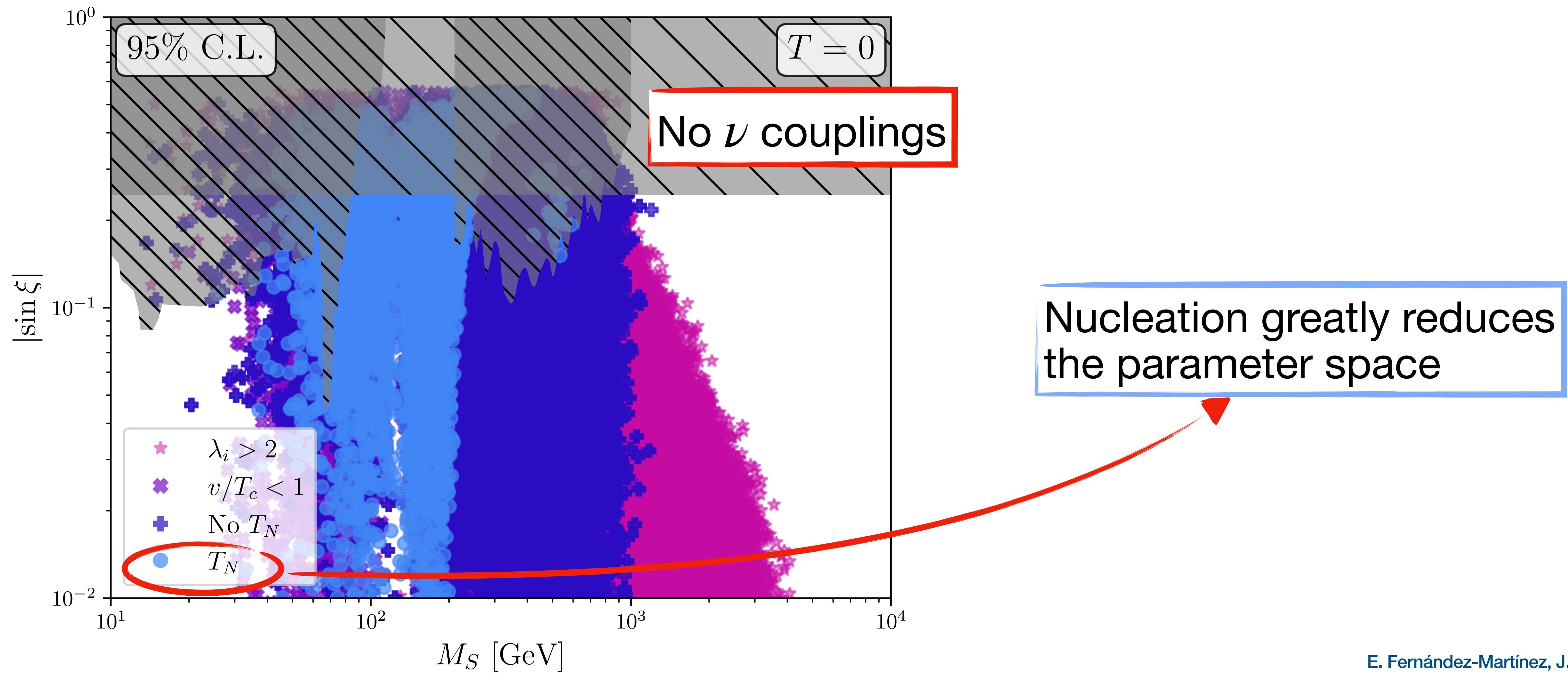
Results

Comparison w/o neutrinos



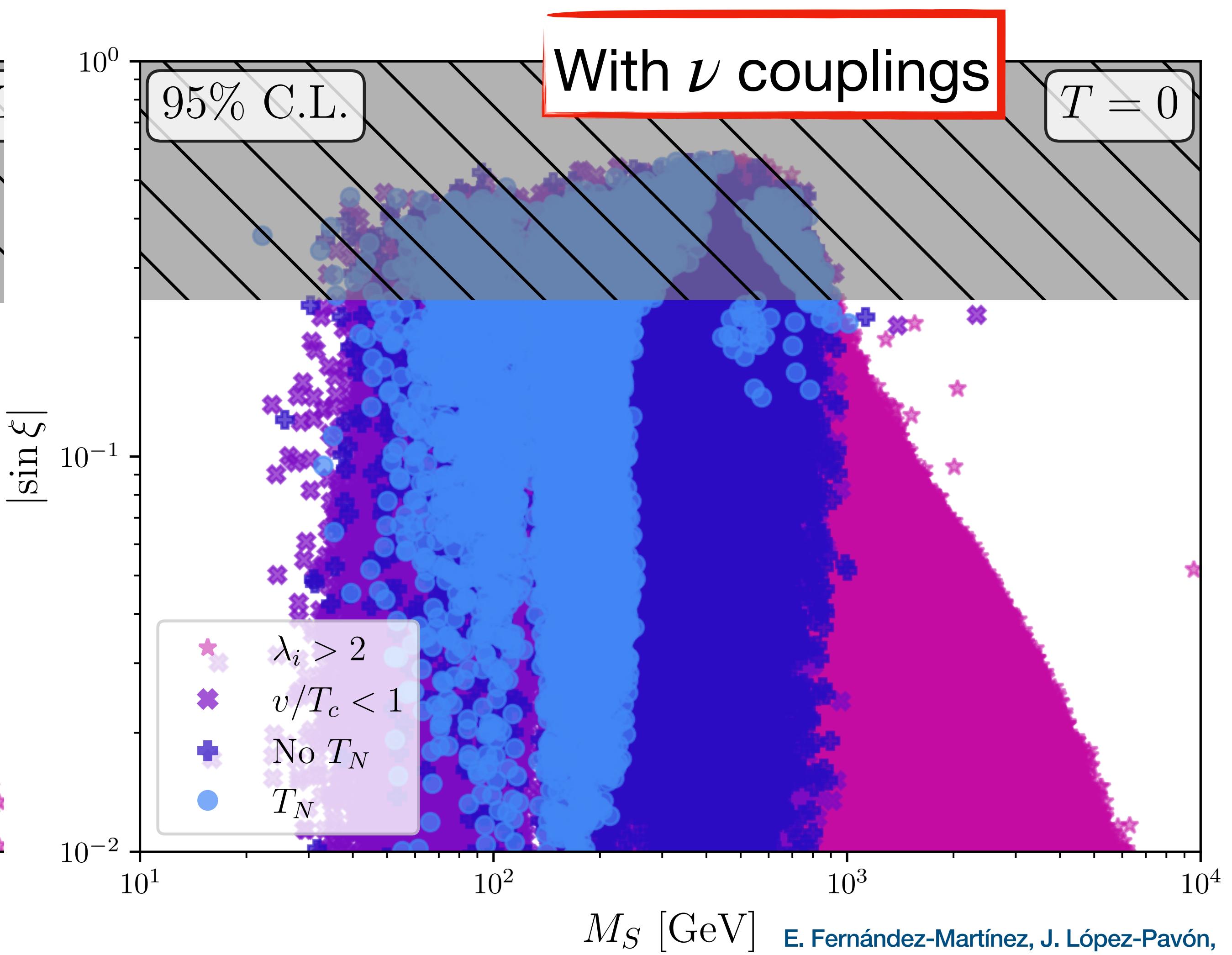
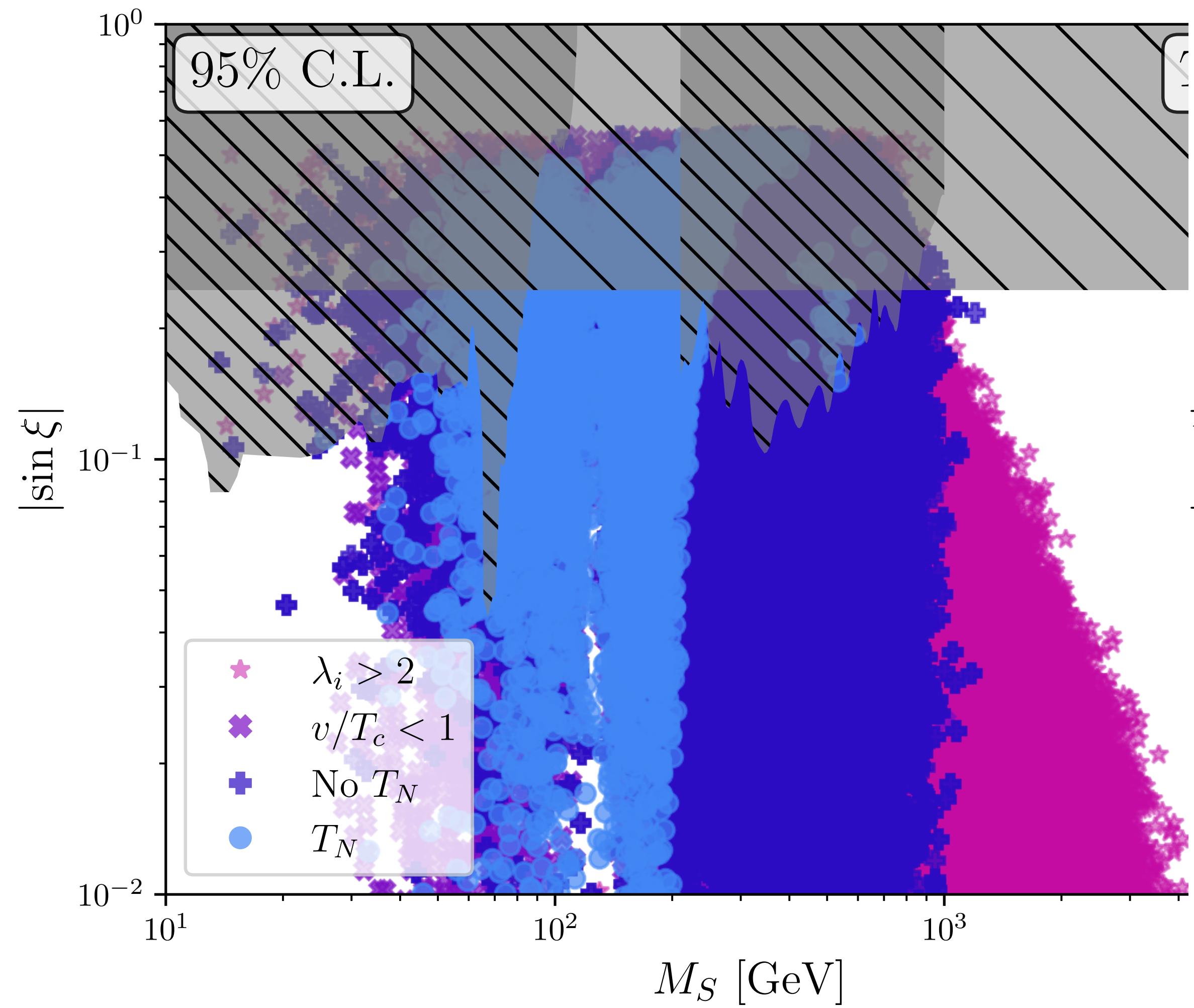
Results

Comparison w/o neutrinos



Results

Comparison w/o neutrinos



Results

Higgs decay to heavy neutrinos

E. Fernández-Martínez, J. López-Pavón,
J. M. No, T. Ota & SRA arXiv:2210.16279

$$\mathcal{L} \supset \frac{1}{\omega_{EW}} (\cos \xi S + \sin \xi H) \sum_i \bar{N}_i M_{N_i} N_i$$

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J. M. No, T. Ota & SRA arXiv:2210.16279

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Higgs signal strength measurements

$$(1 - BR_{H \rightarrow N\bar{N}}) \cos^2 \xi \geq 0.94$$

Results

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E. Fernández-Martínez, J. López-Pavón,
J. M. No, T. Ota & SRA arXiv:2210.16279

$$\mathcal{L} \supset \frac{1}{\omega_{EW}} (\cos \xi S + \sin \xi H) \sum_i \bar{N}_i M_{N_i} N_i$$

$M_{N_i} = Y_{N_i} \omega_{EW}$

Higgs signal strength measurements

$$(1 - BR_{H \rightarrow N\bar{N}}) \cos^2 \xi \geq 0.94$$

Two regimes

$$\gamma_N^2 = \sum_i Y_{N_i}^2 \left\{ \begin{array}{l} \boxed{\omega_{EW}^2 \gamma_N^2 < (M_H/2)^2} \\ \boxed{\omega_{EW}^2 \gamma_N^2 > (M_H/2)^2} \end{array} \right.$$

You can always escape the bounds

Results

Higgs decay to heavy neutrinos

$$\mathcal{L} \supset \frac{1}{\omega_{EW}} (\cos \xi S + \sin \xi H) \sum_i \bar{N}_i M_N$$

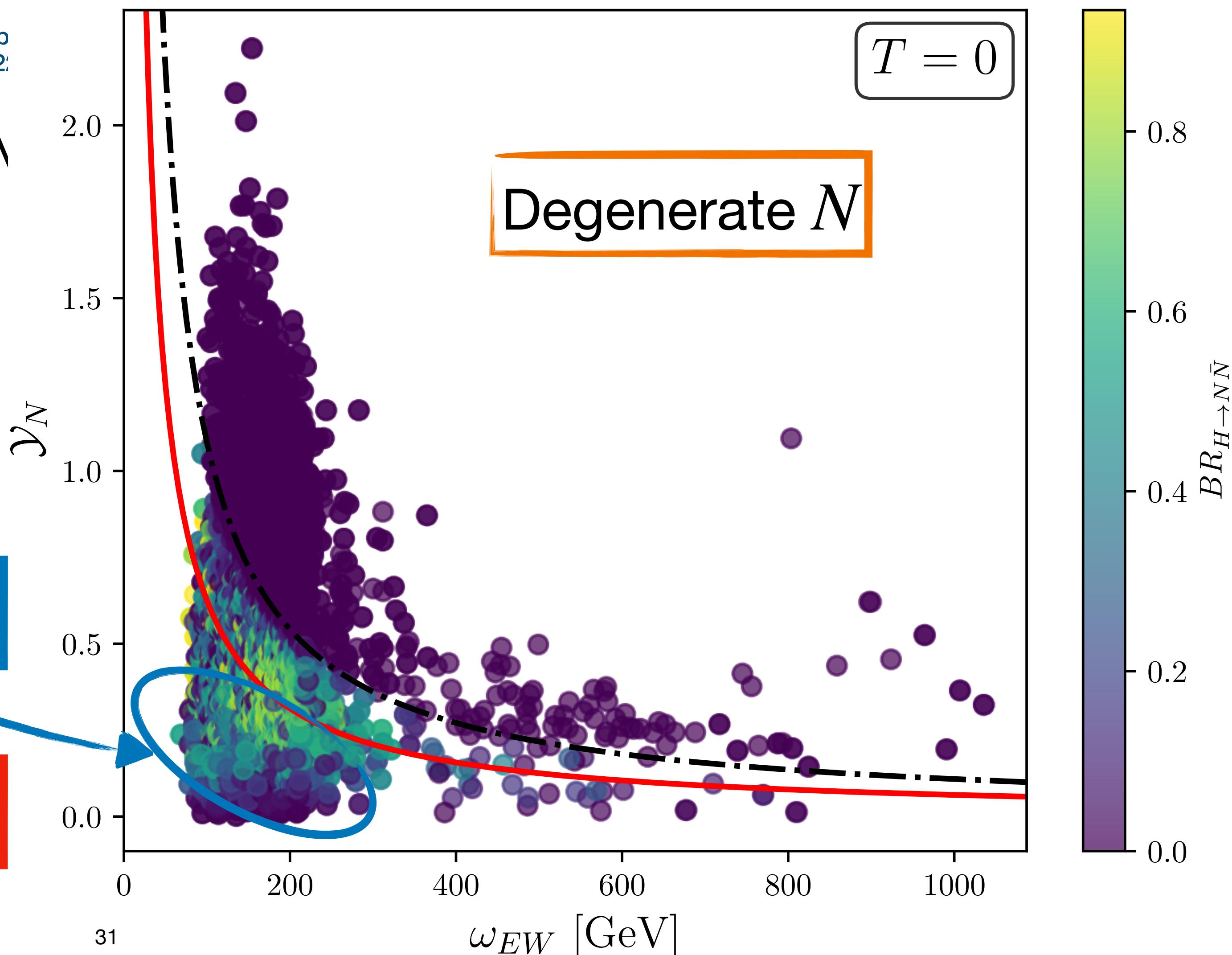
E. Fernández-Martínez, J. López
J. M. No, T. Ota & SRA arXiv:21

Higgs signal strength measurements

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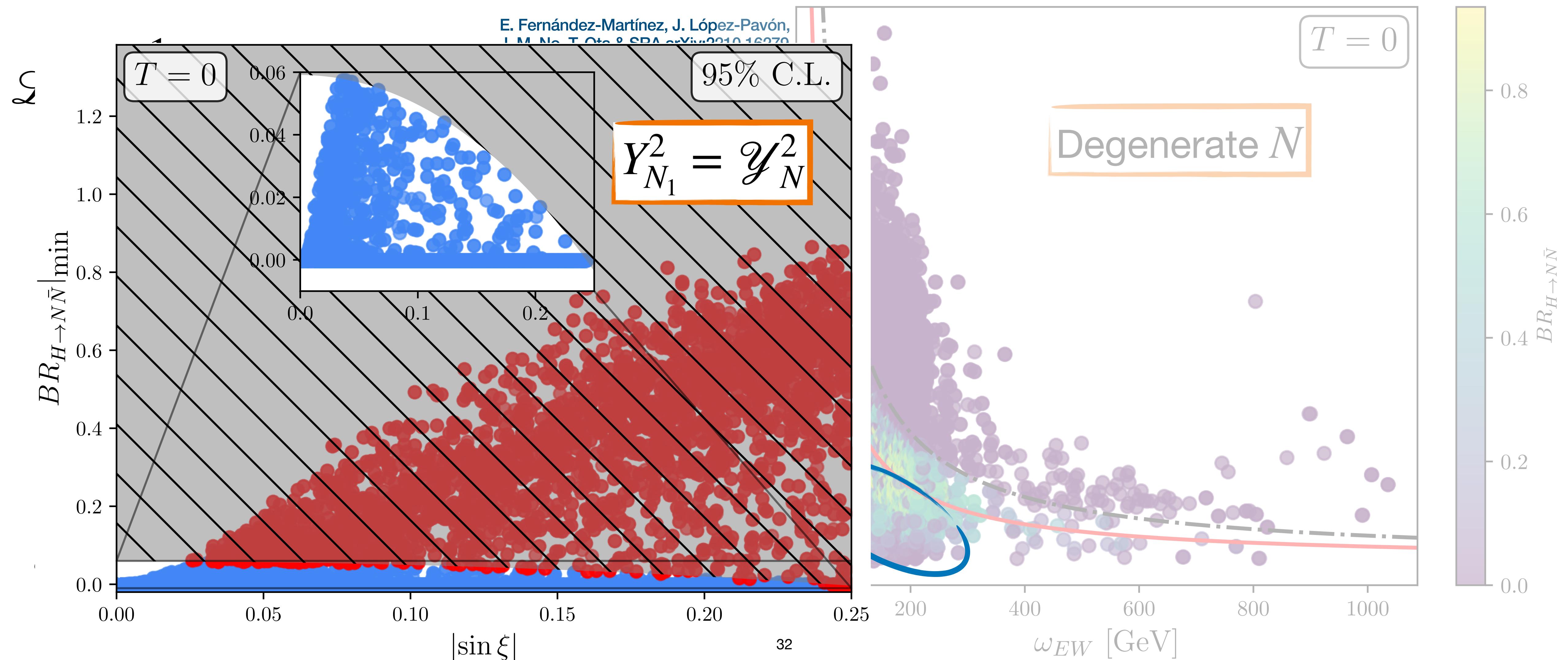
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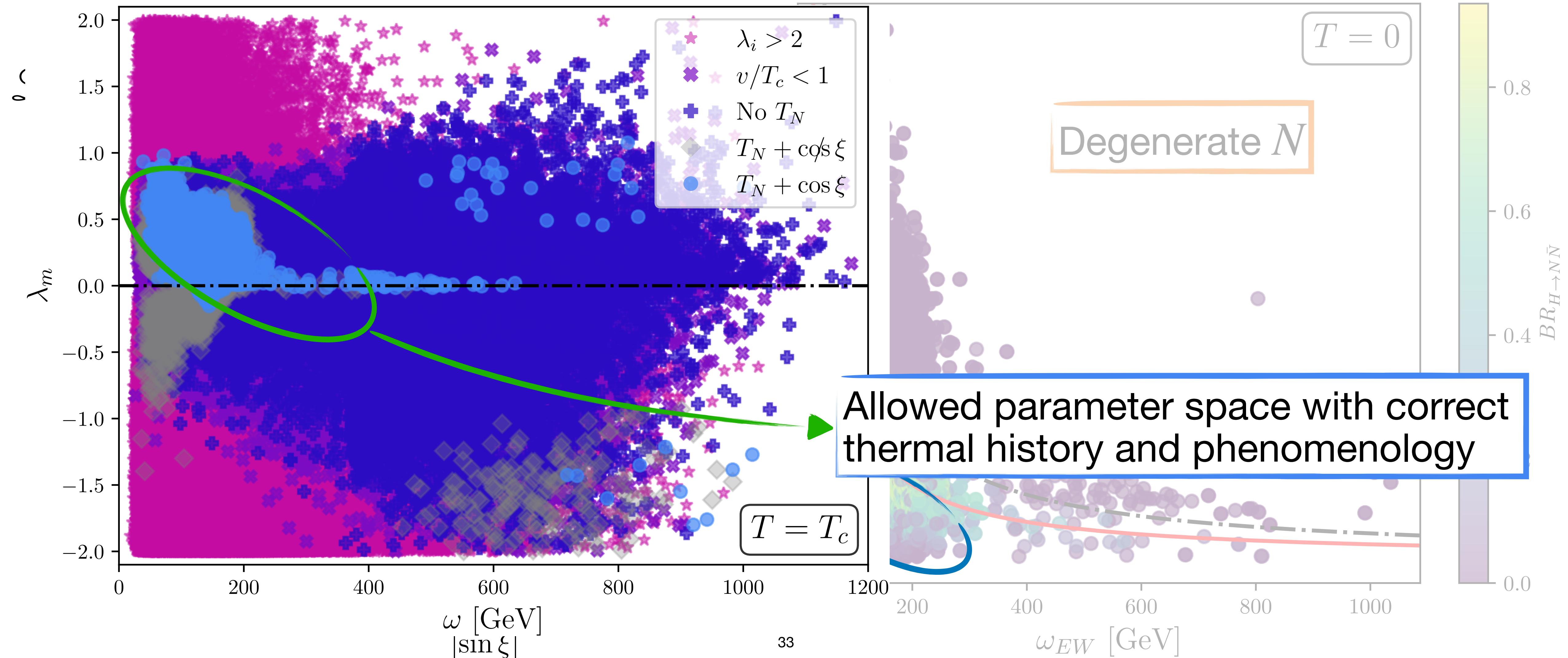
Results

Higgs decay to heavy neutrinos



Results

Higgs decay to heavy neutrinos



Conclusions

Early Universe

EW baryogenesis with heavy neutrinos at $\mathcal{O}(100)$ GeV could explain the BAU

Successful nucleation translates into a large reduction of the parameter space

Early Universe evolution is not affected much by ν -scalar interactions

Scalar dynamics sets the sum of Yukawa couplings,
setting how hierarchical neutrinos can be

Conclusions

Phenomenology

We could tell apart the case of just a singlet scalar or a non minimal dark sector in colliders

Thanks to scalar mixing, heavy neutrinos could be copiously produced in Higgs decays → Higgs signal strength measurements

Direct searches for a signal with prompt N decays or displaced vertices other than the usual Drell-Yan production should provide better constraints

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Thank you!

Back up slides

Electroweak baryogenesis with new physics

Electroweak baryogenesis

Shaposhnikov, Nucl. Phys B287 (1987)

~~CP violation from CKM matrix~~

$B + L$ violation from sphalerons

Kuzmin, Rubakov & Shaposhnikov, Phys. Lett. 155B (1985) 36

~~1st order phase transition~~

New sources of CP violation

Tight bounds from the electron's EDM

ACME Collaboration, Nature 562 (2018)

Introduce CP in some dark sector

ν masses in low-scale seesaws

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \bar{N}_L \phi Y_N N_R + h.c. - V(\phi, H^\dagger H)$$

After SSB

$$\mathcal{L} \supset -\bar{\nu}_L m_D N_R - \bar{N}_L M N_R + h.c.$$

$$m_\nu = 0, \quad \theta \equiv m_D M^{-1}$$

Explain light ν masses

Bounded by EW precision
and flavour observables

E. Fernandez-Martinez, J. Hernandez
& J. Lopez-Pavon, arXiv: 1605.08774

Inverse Seesaw

Gonzalez-Garcia & Valle (1992)
Malinsky et al., arXiv:0506296

$$m_\nu \sim \mu_L \theta^2$$

Electroweak baryogenesis and low-scale seesaws

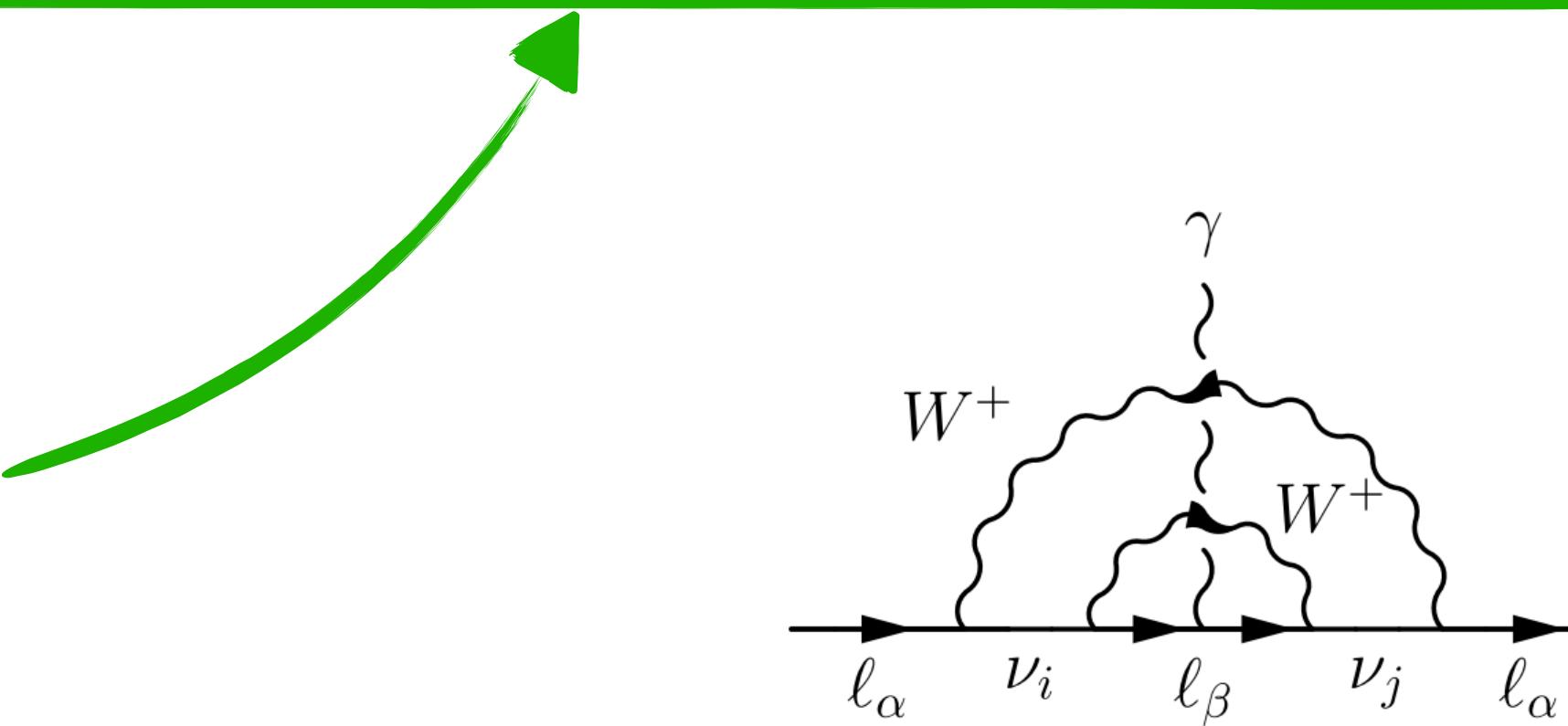
First proposed in

P. Hernandez & N. Rius,
arXiv: hep-ph/9611227

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{\Phi} N'_R - \bar{N}'_L s Y_N N'_R + h.c. - V(\Phi^\dagger \Phi, s)$$

$$\delta_{CP} \propto (M_1^2 - M_2^2)(M_2^2 - M_3^2)(M_3^2 - M_1^2) Im [(\theta^\dagger \theta)_{12} (\theta^\dagger \theta)_{23} (\theta^\dagger \theta)_{31}]$$

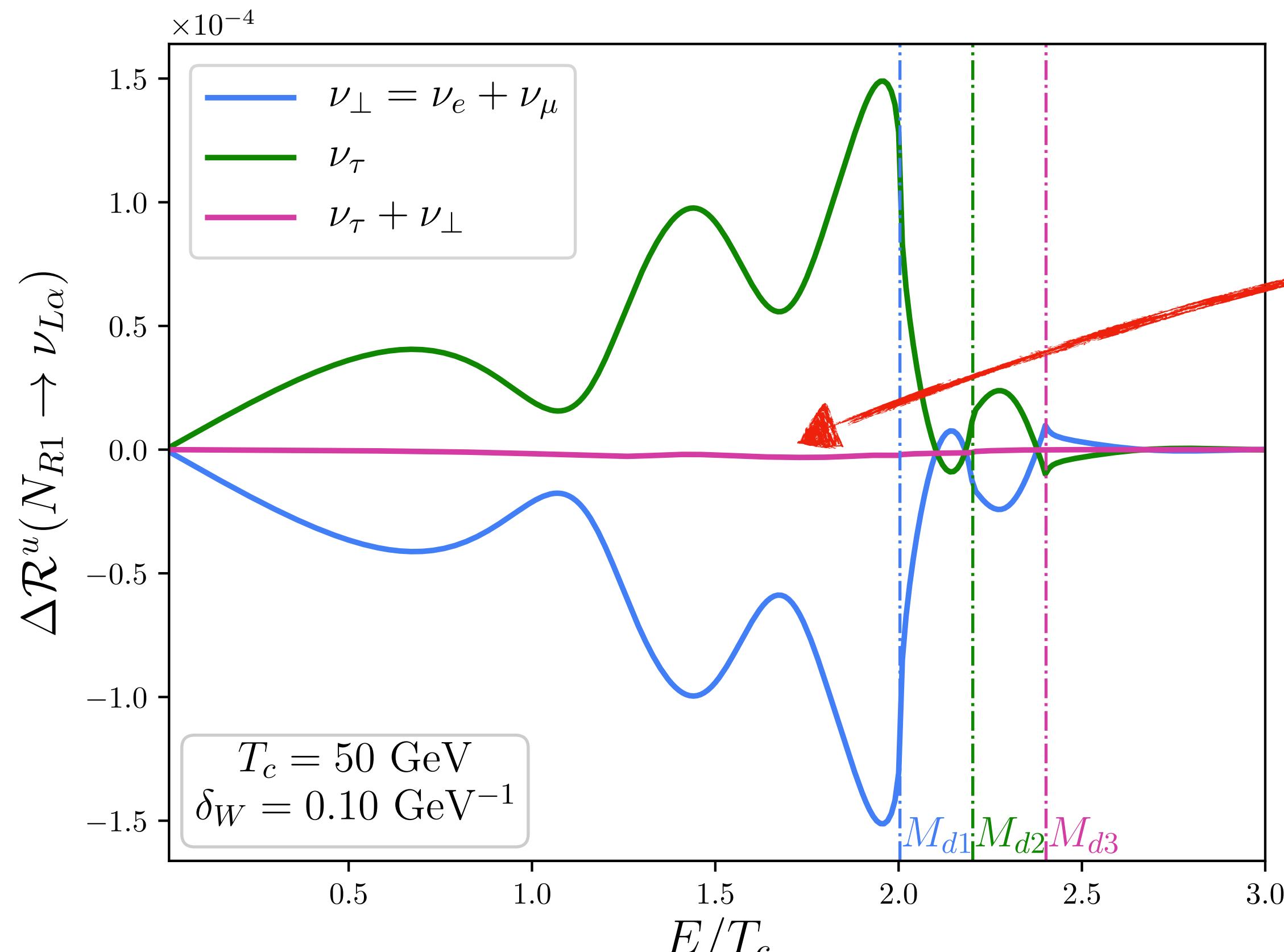
Hierarchical heavy neutrinos



Avoid electric dipole
moment bounds

A. Abada & T. Toma, arXiv: 1605.07643

Flavoured CP asymmetries



Reflection

Strong GIM cancellation
when summing over flavours

$$\sum_i \Delta \mathcal{R}^u (N_{Ri} \rightarrow \nu_{L\alpha}) \sim \int_z \sum_{i,j,\beta} f(z) m_{d_\alpha}^2 \operatorname{Im} \left(V_{Ria} V_{Ri\beta}^* V_{Rj\beta} V_{Rja}^* \right)$$

Diffusion equations

Flavoured scenario

Baryons

$$D_B \partial_z^2 n_B - v_W \partial_z n_B - 3\Gamma_S \mathcal{H}(-z) n_B - \Gamma_S \mathcal{H}(-z) \sum_{\alpha} n_{\nu_{\alpha}} = 0$$

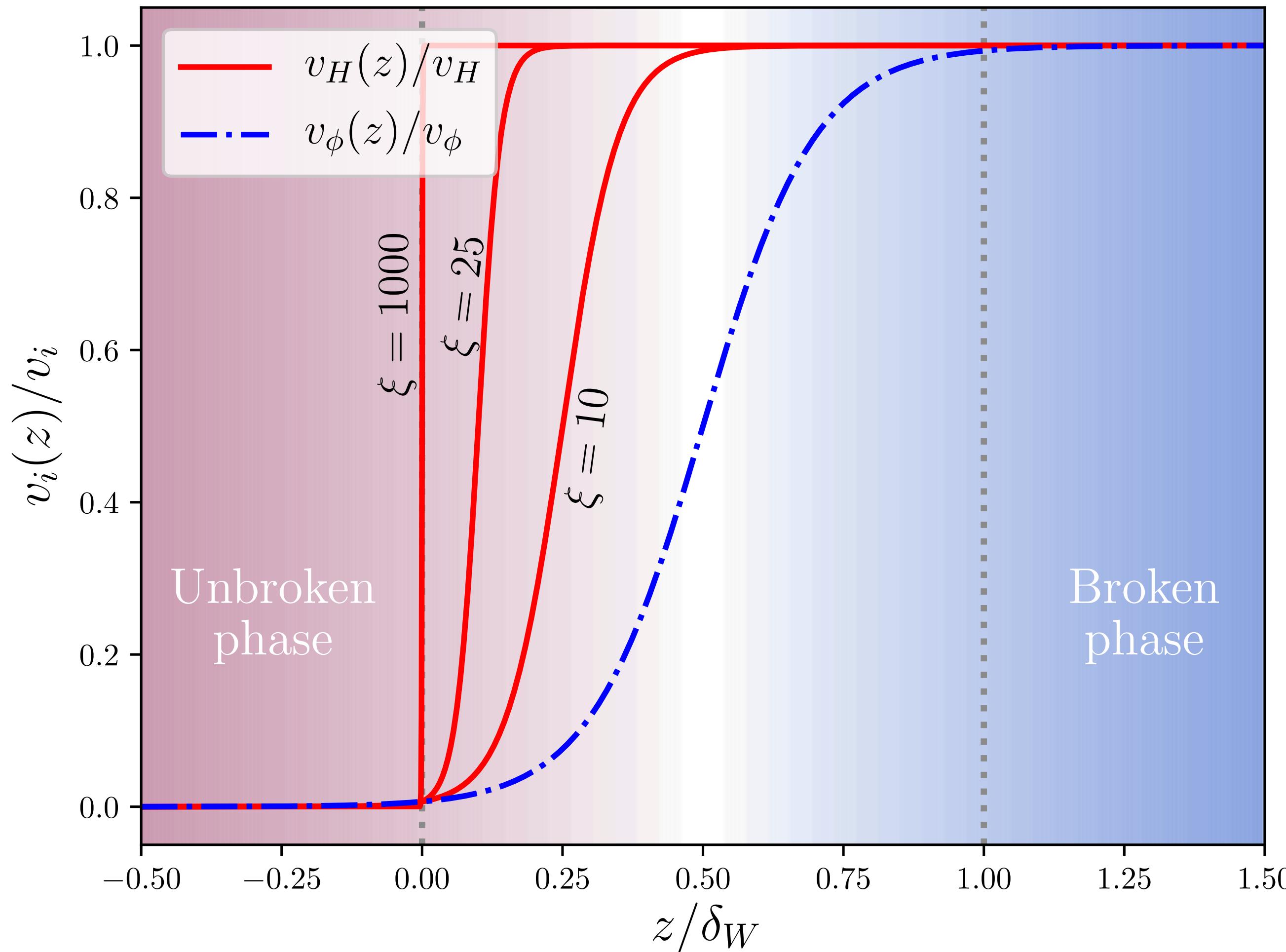
SM ν

$$D_L \partial_z^2 n_{\nu_{\alpha}} - v_W \partial_z n_{\nu_{\alpha}} - 3\Gamma_S \mathcal{H}(-z) n_B - \Gamma_S \mathcal{H}(-z) \sum_{\beta} n_{\nu_{\beta}} - \sum_i \Gamma_{N_{Ri}\nu_{\alpha}} \left(\frac{1}{2} n_{\nu_{\alpha}} - n_{N_{Ri}} \right) = \xi_L j_{\nu_{\alpha}} \partial_z \delta(z)$$

N_R

$$D_{Ri} \partial_z^2 n_{\nu_{N_{Ri}}} - v_W \partial_z n_{\nu_{N_{Ri}}} + \sum_{\alpha} \Gamma_{N_{Ri}\nu_{\alpha}} \left(\frac{1}{2} n_{\nu_{\alpha}} - n_{N_{Ri}} \right) = \xi_{Ri} j_{N_{Ri}} \partial_z \delta(z)$$

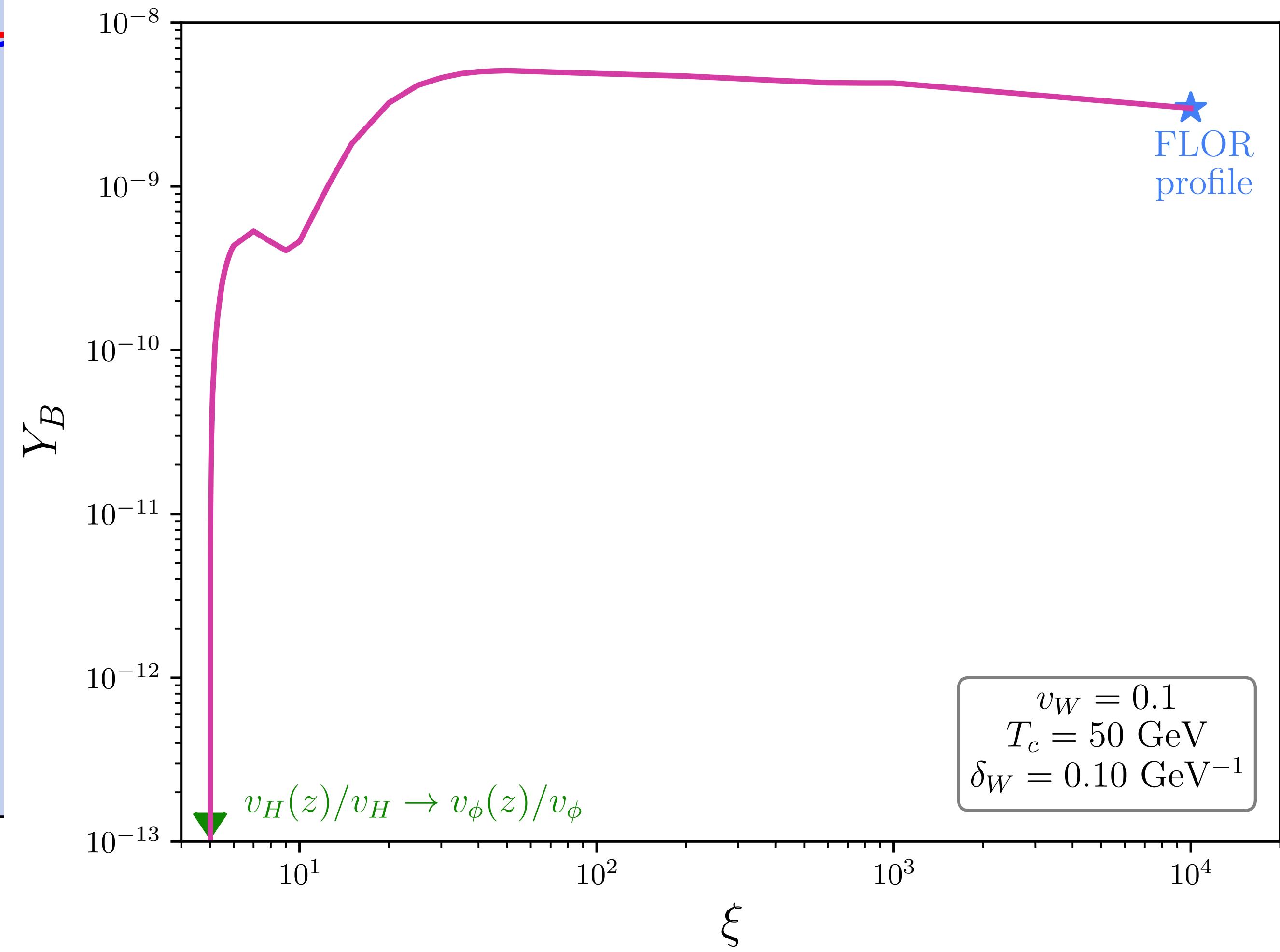
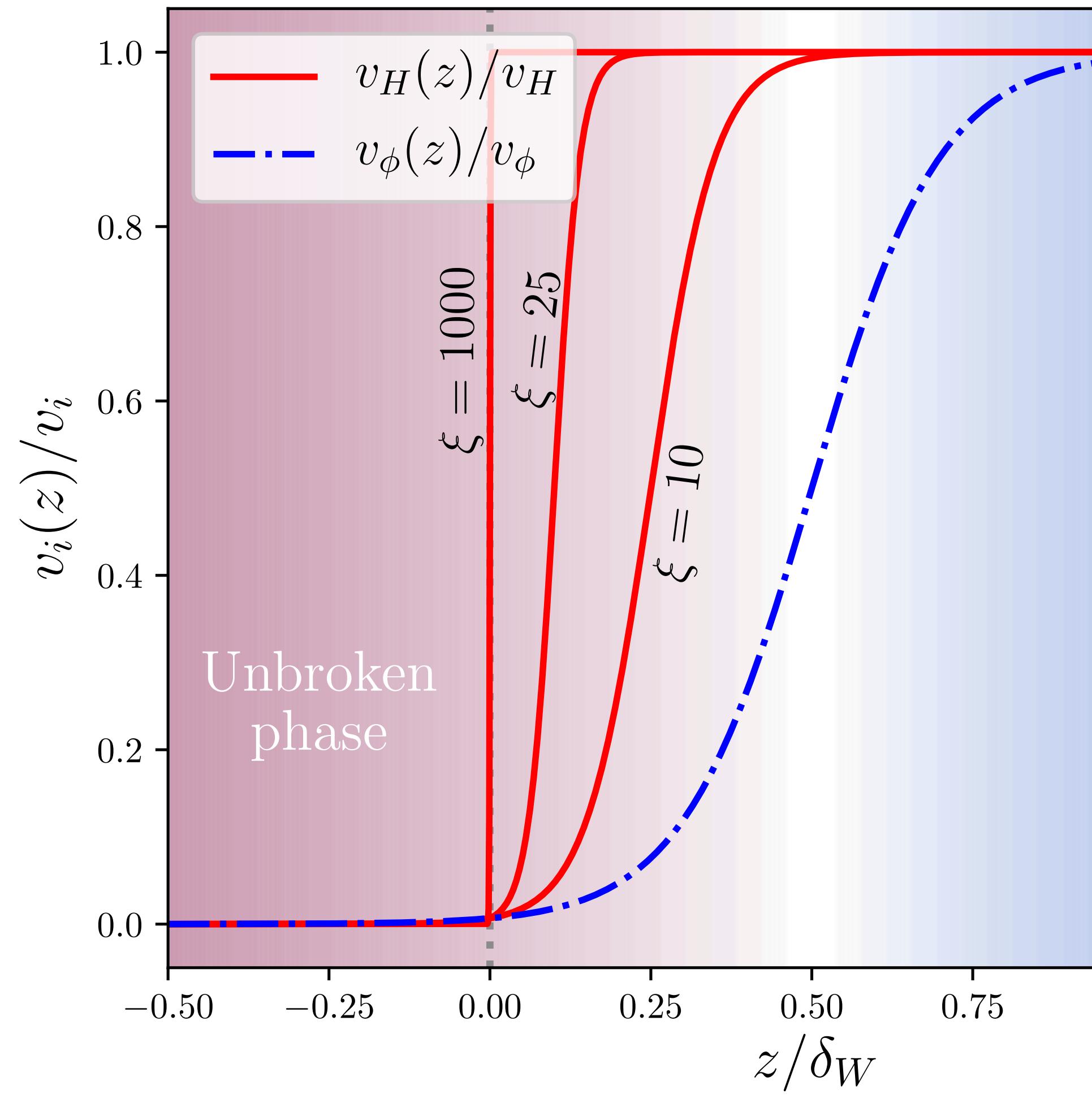
Effect of vev profiles



$$v_H(z)/v_H = \frac{1}{2} \left[1 + \tanh \left(\xi \frac{z - (5/\xi) \delta_W/2}{\delta_W} \right) \right]$$

$$v_\phi(z)/v_\phi = \frac{1}{2} \left[1 + \tanh \left(5 \frac{z - \delta_W/2}{\delta_W} \right) \right]$$

Effect of vev profiles



Scalar potential

Finite temperature effects

J. R. Espinosa, T. Konstandin & F. Riva, arXiv:1107.5441
M. Quiros, arXiv:hep-ph/9901312

$$\delta_\alpha V_T(h, s) = \frac{T^4}{2\pi^2} N_\alpha \int_0^\infty dx x^2 \log \left(1 \pm e^{-\sqrt{x^2 + M_\alpha^2/T^2}} \right) + \frac{T}{12\pi} \delta_{ab} N_\alpha [M_\alpha^3 - M_{T,\alpha}^3]$$

Physical mass as function of (h, s)

Thermal mass as function of (h, s)

Scalar potential

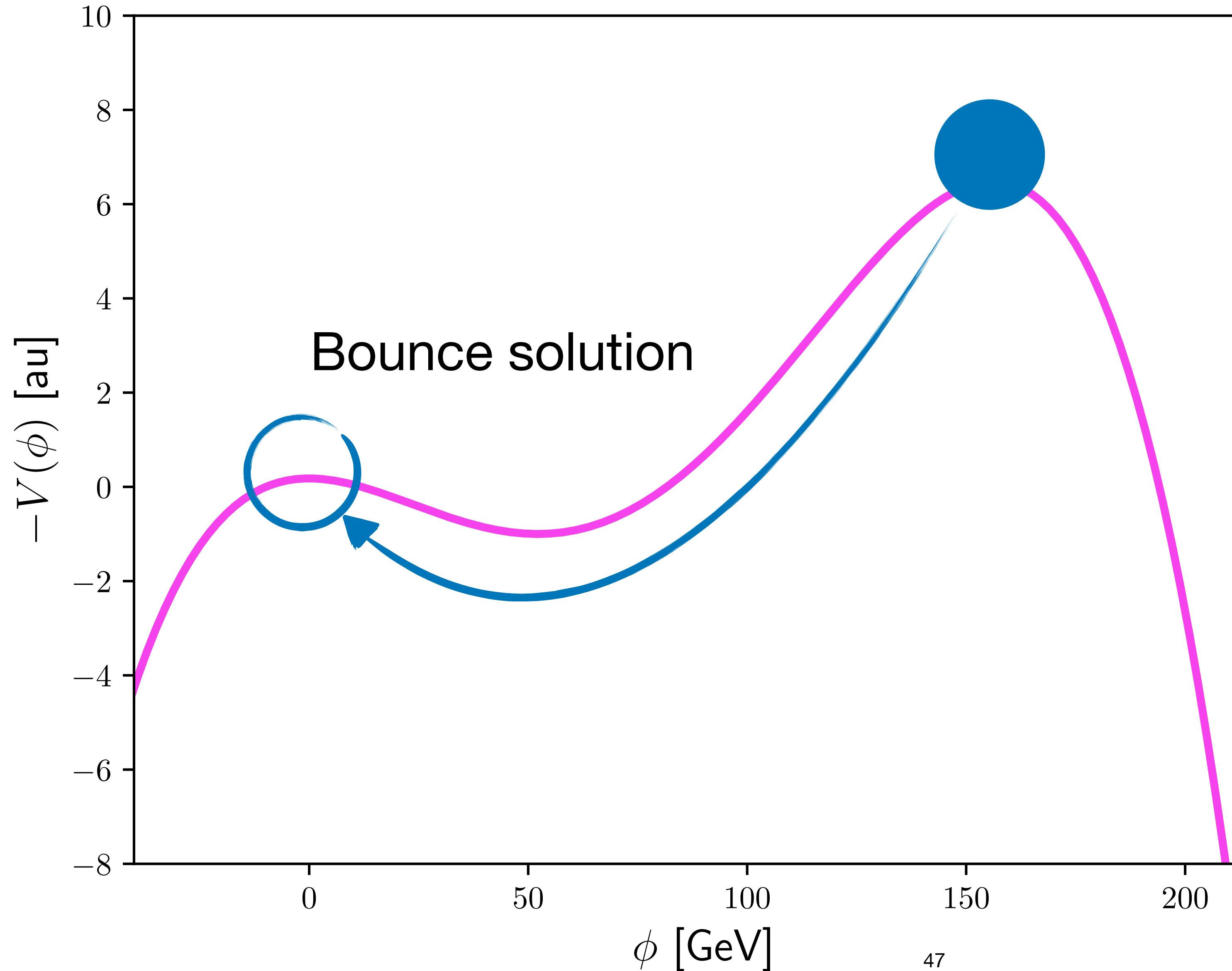
$$T = 0$$

$$\begin{aligned} V_T(h, s, T = 0) = & -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\mu_m s h^2 + \frac{1}{4}\lambda_m s^2 h^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3 \\ & - \left[\frac{1}{2}c_h h^2 + \frac{1}{2}c_s s^2 + m_3 s \right] T_c^2 \end{aligned}$$

Relation between potential terms at T_c and $T = 0$

$$\begin{aligned} \tilde{\mu}_h^2 &= \mu_h^2 + c_h T_c^2 \\ \tilde{\mu}_s^2 &= \mu_s^2 - c_s T_c^2 \\ \tilde{\mu}_1^3 &= \mu_1^3 - m_3 T_c^2 \end{aligned}$$

Nucleation



S. Coleman, Phys. Rev. D (1977)
A. Amarati, arXiv:2009.14102

$$\Gamma/V \sim e^{-S_3/T_N} \sim H(T_N)$$

$$S_3/T_N \sim 140$$

Need to solve
equations of motion

Results

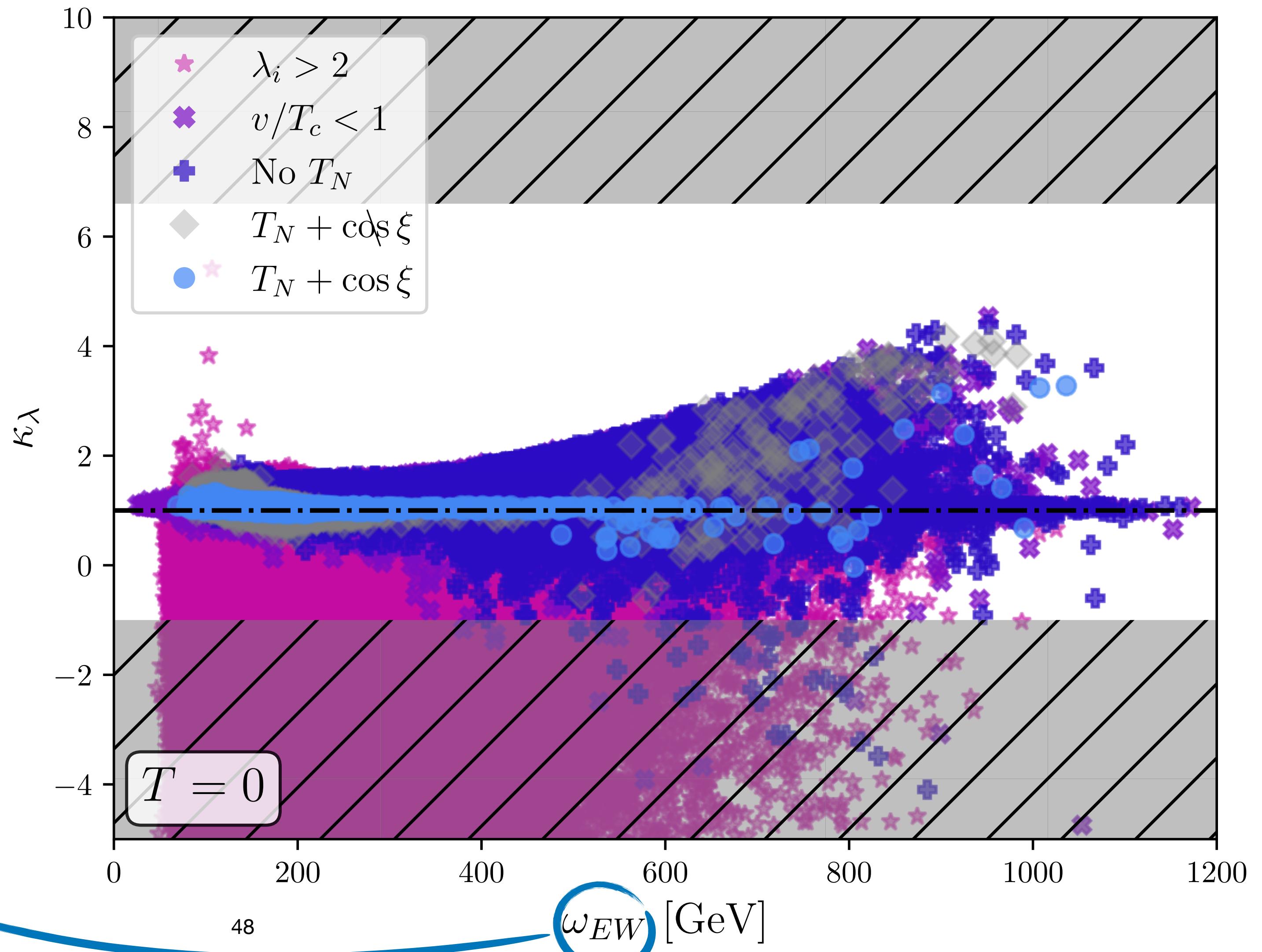
Higgs trilinear coupling

Deviation in Higgs boson trilinear

$$\kappa_\lambda \equiv \frac{\lambda_{HHH} + \Delta\lambda_{HHH}^{1-loop}}{\lambda_{HHH}^{SM}}$$

$$-1.0 \leq \kappa_\lambda \leq 6.0$$

Singlet vev controlling neutrino masses

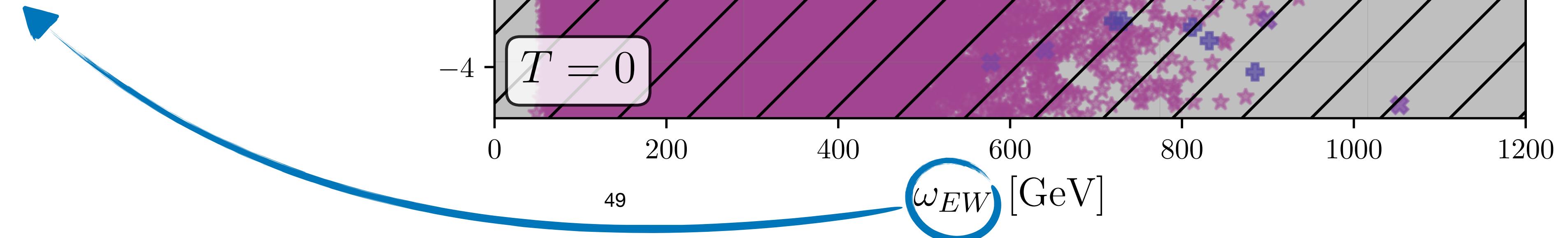


Results

Higgs trilinear coupling

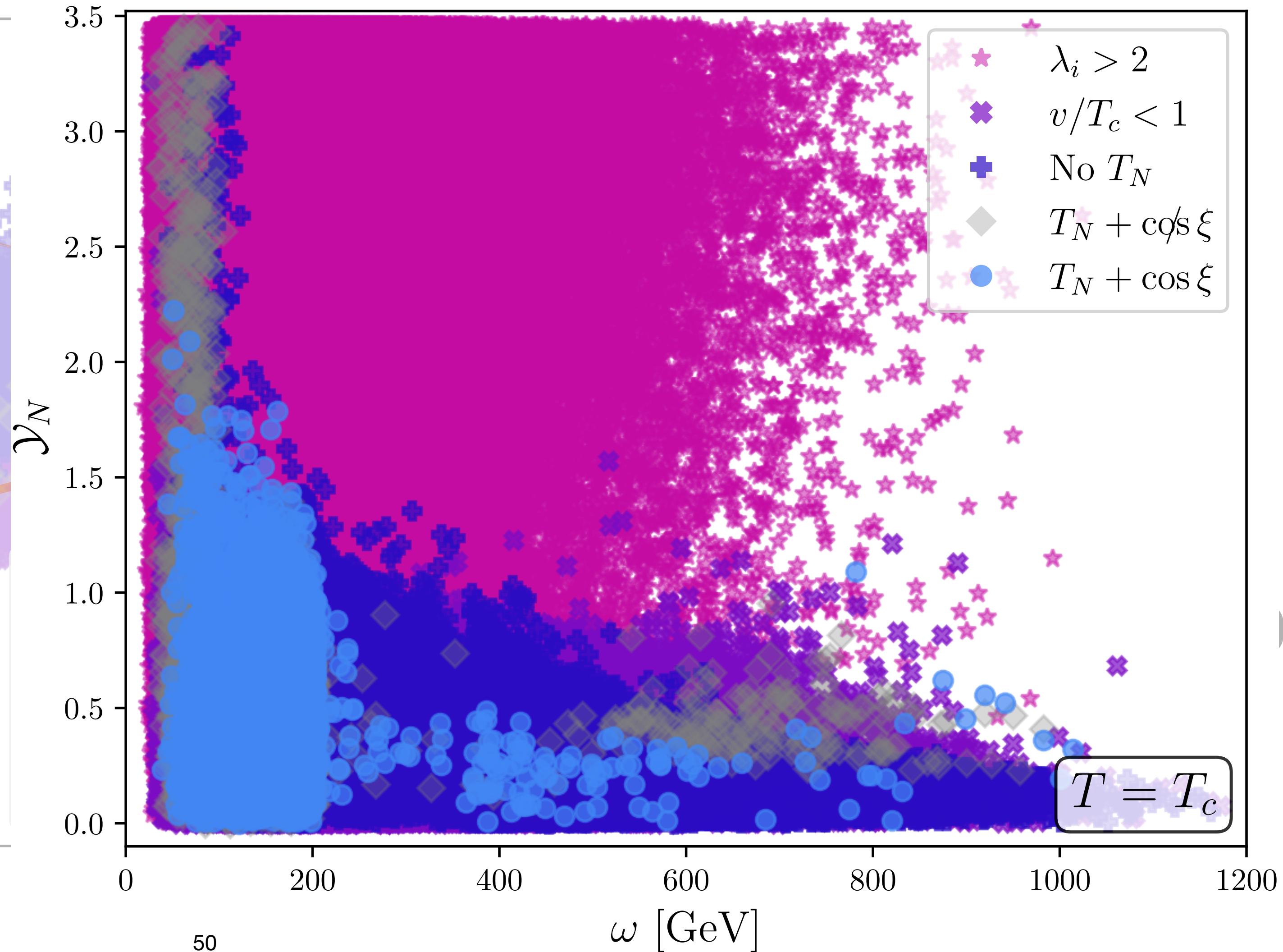
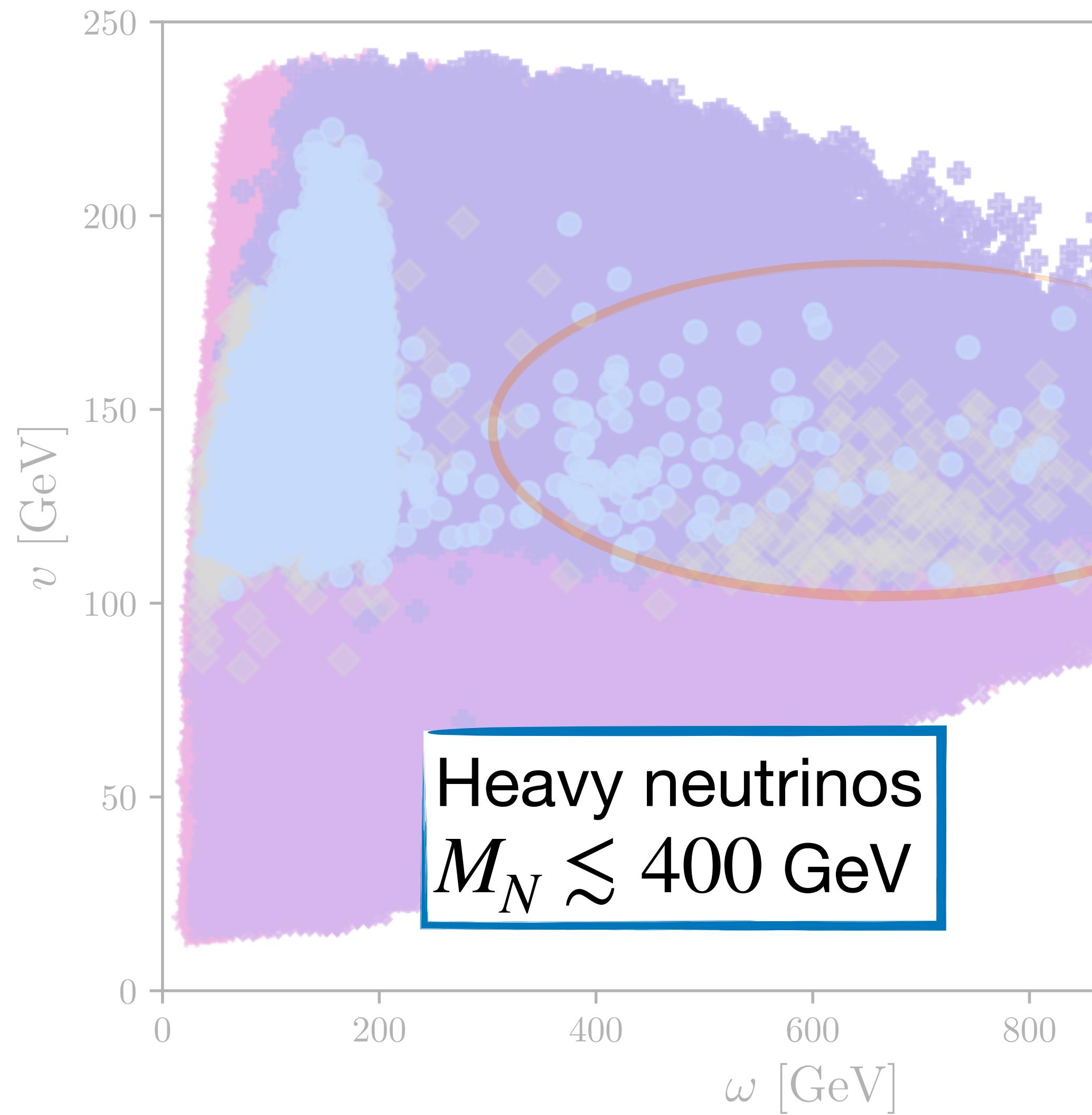
Significant deviations from 1
disfavor such scenario for a SFOPT

Singlet vev controlling
neutrino masses



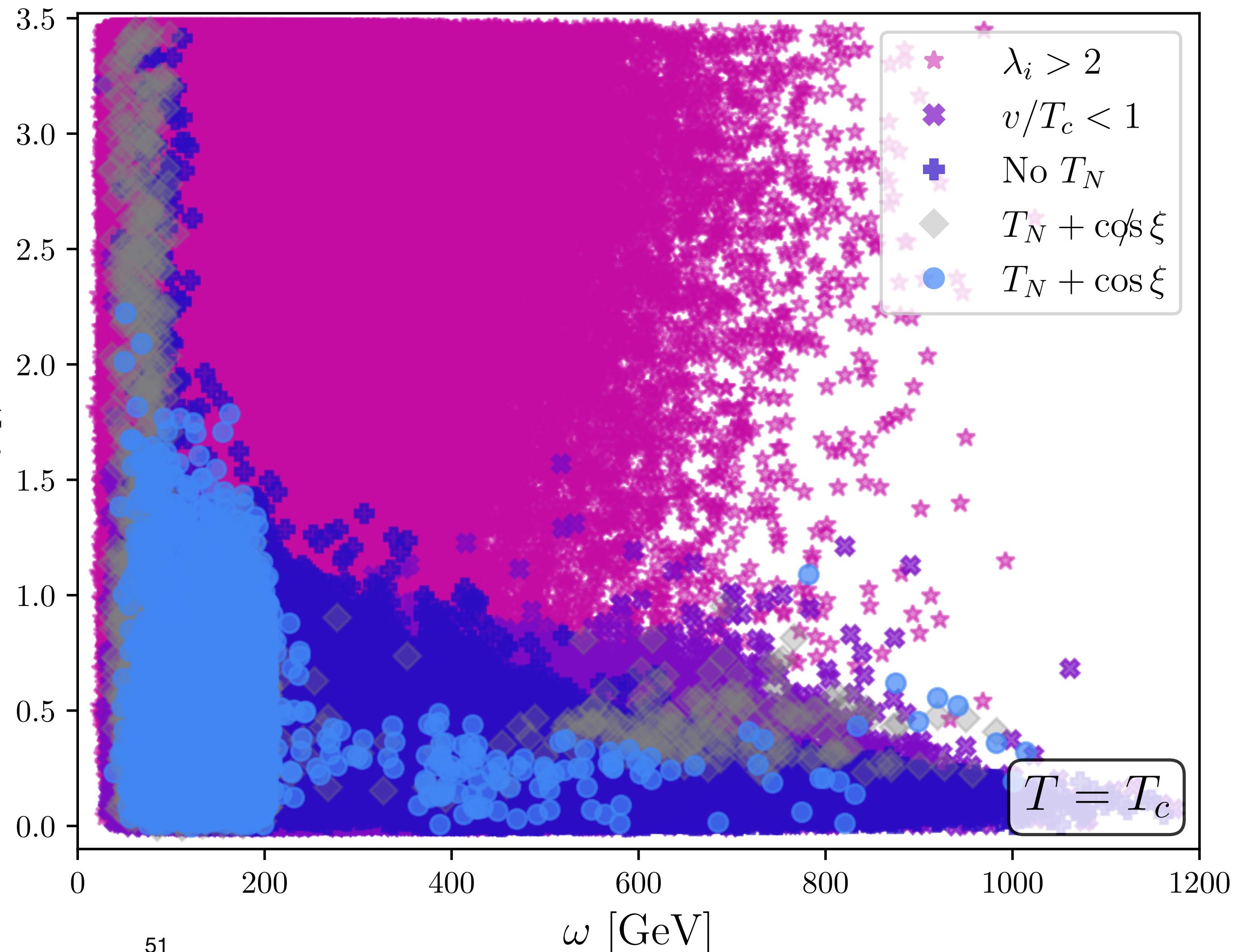
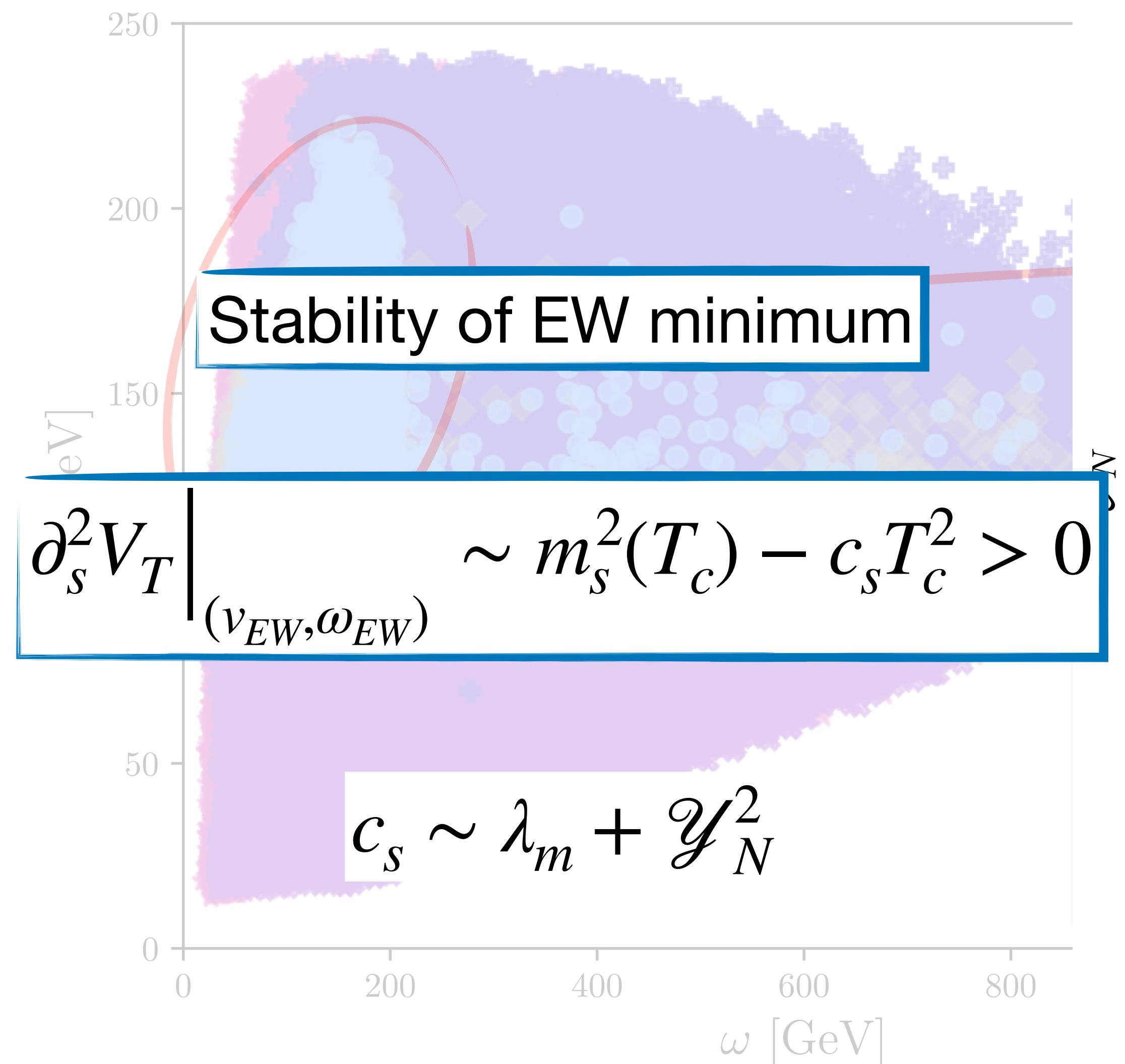
Results

Nucleation + constraints on $\cos \xi$



Results

Nucleation + constraints on $\cos \xi$



Results

Higgs decay to heavy neutrinos

E. Fernández-Martínez, J. López-Pavón,
J. M. No, T. Ota & SRA arXiv:2210.16279

$$\mathcal{L} \supset \frac{1}{\omega_{EW}} (\cos \xi S + \sin \xi H) \sum_i \bar{N}_i M_{N_i} N_i$$

Higgs signal strength measurements

$$(1 - BR_{H \rightarrow N\bar{N}}) \cos^2 \xi \geq 0.94$$

$$\Gamma_{H \rightarrow N\bar{N}} \sim \frac{\sin^2 \xi}{8\pi} M_H \sum_i Y_{N_i}^2 \left(1 - \frac{4\omega_{EW}^2}{M_H^2} Y_{N_i}^2 \right)^{3/2}$$

Results

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Maximum for degenerate N_i

$$\mathcal{Y}_N^2 = n Y_{N_1}^2$$

Minimum for hierarchical N_i

$$\mathcal{Y}_N^2 = Y_{N_1}^2$$