Particle Physics-Astrophysics-Cosmology Webinar @ Nanjing Normal University
April 26, 2023

Phenomenological Studies of the Georgi-Machacek Model

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Base on: Ting-Kuo Chen, CWC, Cheng-Tse Huang, Bo-Qiang Lu, Phys.Rev.D 106 (2022) 5, 055019

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NCTS

Plan of the Talk

- Motivations
- Review of the Georgi-Machacek model
- Global fit
- Electroweak phase transitions
- Gravitational waves
- Predictions for collider observables
- Summary

An Extended Higgs Sector

- Other than usual symmetries, we have no guiding principles in constructing the scalar sector:
  ➠ representations?
  ➠ number of copies?
  ➠ additional symmetries? (discrete/continuous/gauged)
  ➠ linking to new physics? (SUSY, DM, neutrino mass, EWBG, etc)

cf. 3 generations of fermions and 3 gauge interactions

- Extensions of adding scalar singlets and doublets have been explored considerably by most people.
- Can one also add triplets? What are their functions? What novel features can they lead to?

Motivation for Complex Higgs Triplet Field

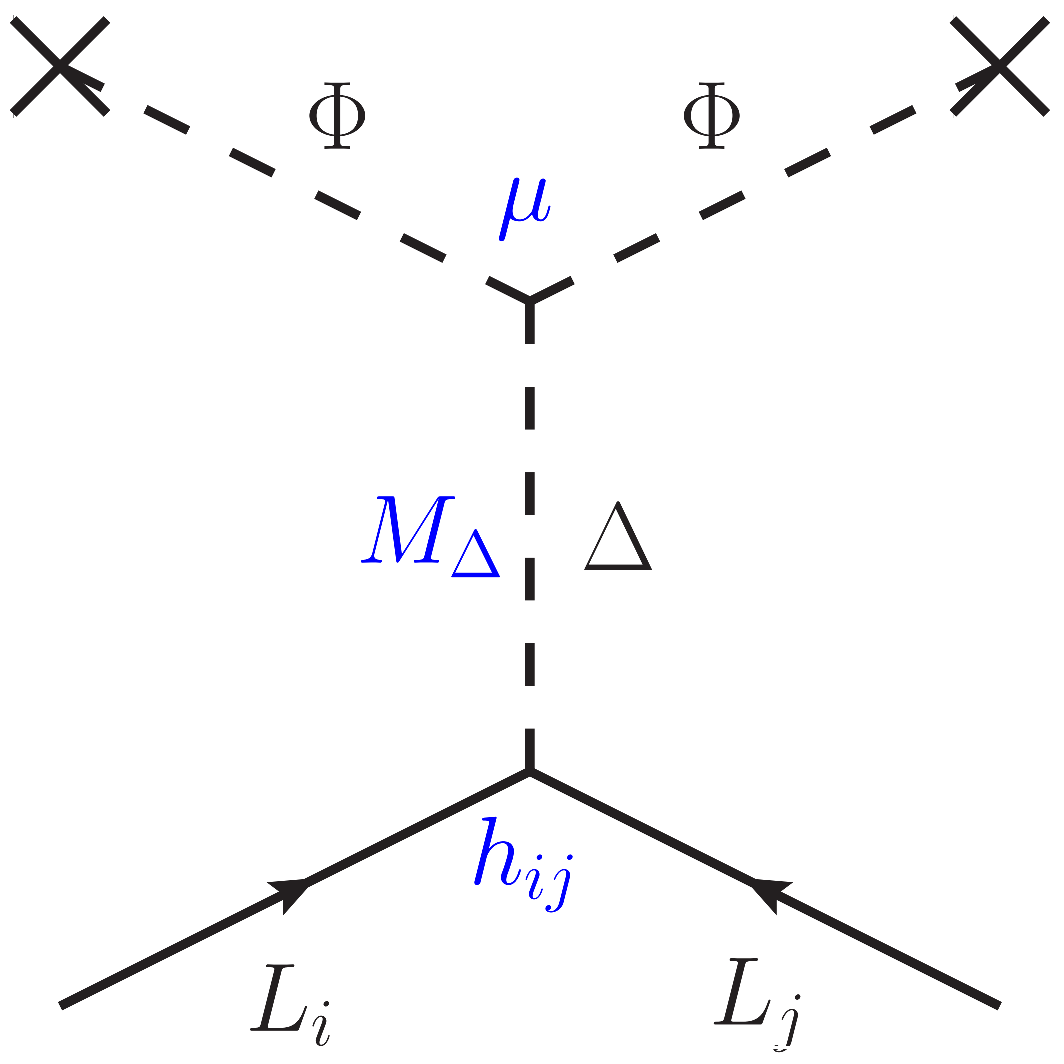
- With the introduction of a complex Higgs triplet field Δ, one can give Majorana mass to left-chiral neutrinos.

Konetschny, Kummer 1977
Schechter, Valle 1980
Cheng, Li 1980
Gelmini, Roncadelli 1981

- Relevant Yukawa interactions:

$$-h_{ij}\psi_{iL}^T C i\sigma_2 \Delta \psi_{jL} + \mathrm{H.c.}$$

and Δ can be induced to attain a VEV from EWSB:



Type-II seesaw mechanism

$$M_\nu = \sqrt{2} h v_\Delta = h \frac{\mu v_\phi^2}{m_\Delta^2}$$

Electroweak ρ Parameter

- In models with an extended Higgs sector, at tree level

$$\rho_{\text{tree}} = \frac{\sum_i v_i^2 \left[T_i(T_i+1) - Y_i^2\right]}{\sum_i 2Y_i^2 v_i^2}$$

➠ safe to add an arbitrary number of singlets, doublets, and so on; but nontrivial for other representations

- Add a triplet to SM and for small VEV's
  - $\xi\ (Y=0)$ ➠ $\rho \simeq 1 + \frac{4v_\xi^2}{v_\phi^2} \Rightarrow v_\xi < 3.6\ \text{GeV}$

@ 95% CL

  - $\chi\ (Y=1)$ ➠ $\rho \simeq 1 - \frac{4v_\chi^2}{v_\phi^2} \Rightarrow v_\chi < 1.0\ \text{GeV}$

Higgs triplet model

➠ Georgi-Machacek model with custodial symmetry

Georgi-Machacek Model

"All models are wrong, but some are useful."
— George E.P. Box

Higgs Potential in GM

- The model realizes the minimal Higgs sector containing isospin triplet fields while maintaining custodial symmetry.

Georgi, Machacek 1985
Chanowitz, Golden 1985

- The most general Higgs potential allowed by gauge and Lorentz symmetries:

assume $m_1^2 < 0,\ m_2^2 > 0$

$$V(\Phi,\Delta) = \frac{1}{2}m_1^2\mathrm{tr}[\Phi^\dagger\Phi] + \frac{1}{2}m_2^2\mathrm{tr}[\Delta^\dagger\Delta] + \lambda_1(\mathrm{tr}[\Phi^\dagger\Phi])^2 + \lambda_2(\mathrm{tr}[\Delta^\dagger\Delta])^2$$
$$+ \lambda_3\mathrm{tr}[(\Delta^\dagger\Delta)^2] + \lambda_4\mathrm{tr}[\Phi^\dagger\Phi]\mathrm{tr}[\Delta^\dagger\Delta] + \lambda_5\mathrm{tr}\left[\Phi^\dagger\frac{\sigma^a}{2}\Phi\frac{\sigma^b}{2}\right]\mathrm{tr}\left[\Delta^\dagger T^a\Delta T^b\right]$$
$$+ \mu_1\mathrm{tr}\left[\Phi^\dagger\frac{\sigma^a}{2}\Phi\frac{\sigma^b}{2}\right](P^\dagger\Delta P)_{ab} + \mu_2\mathrm{tr}\left[\Delta^\dagger T^a\Delta T^b\right](P^\dagger\Delta P)_{ab}$$

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ -(\phi^+)^* & \phi^0 \end{pmatrix}, \quad \Delta = \begin{pmatrix} (\chi^0)^* & \xi^+ & \chi^{++} \\ -(\chi^+)^* & \xi^0 & \chi^+ \\ (\chi^{++})^* & -(\xi^+)^* & \chi^0 \end{pmatrix}, \quad P = \frac{1}{\sqrt{2}}\begin{pmatrix} -1 & i & 0 \\ 0 & 0 & \sqrt{2} \\ 1 & i & 0 \end{pmatrix}$$

-decoupling limit: $m_2 \to \infty$

-v_Δ induced by v_ϕ through μ_1

Georgi-Machacek Model

- The Higgs sector includes SM doublet field $\phi(2,1/2)$ and two triplet fields $\chi(3,1)$ and $\xi(3,0)$, arranged as:

Georgi, Machacek 1985
Chanowitz, Golden 1985

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ \phi^{-} & \phi^{0} \end{pmatrix}, \qquad \Delta = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ \chi^{-} & \xi^{0} & \chi^{+} \\ \chi^{--} & \xi^{-} & \chi^{0} \end{pmatrix}$$

$SU(2)_L$

$SU(2)_R$

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Georgi, Machacek 1985
Chanowitz, Golden 1985

$$\Phi = \begin{pmatrix} v_\phi & \phi^+ \\ \phi^- & v_\phi \end{pmatrix}, \qquad \Delta = \begin{pmatrix} v_\Delta & \xi^+ & \chi^{++} \\ \chi^- & v_\Delta & \chi^+ \\ \chi^{--} & \xi^- & v_\Delta \end{pmatrix}$$

- Take $v_\chi = v_\xi \equiv v_\Delta$ (aligned VEV, as required by custodial symmetry).
  ➠ SU(2)$_L$×SU(2)$_R$ → custodial SU(2)$_V$
  ➠ $\rho = 1$ at tree level

*Such a symmetry is broken by radiative effects. But $\rho = 1$ can be restored by renormalization.

Features of GM Model

- A large triplet VEV v_Δ is allowed.
  ➠ focus on $v_\Delta \sim \mathcal{O}(10)$ GeV regime
  ➠ triplet having larger couplings with W/Z than leptons

Vacuum Expectation Values

- The VEV's are subject to the constraint

$$v^2 = v_\phi^2 + 8v_\Delta^2 = \frac{1}{\sqrt{2}G_F} = (246\ \mathrm{GeV})^2$$

with two mixing-angle definitions seen in the literature:

$$\tan\beta = \frac{v_\phi}{2\sqrt{2}v_\Delta} \quad \text{or} \quad \tan\theta_H = \frac{2\sqrt{2}v_\Delta}{v_\phi}$$

- One could attribute EWSB entirely to v_Δ ($\simeq 87$ GeV) while keeping $v_\phi = 0$.

Georgi, Machacek 1985
Chanowitz, Golden 1985

- Perturbativity of top Yukawa coupling demands $v_\Delta \lesssim 80$ GeV.

➠ other constraints later

Features of GM Model

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- There exists a doubly-charged Higgs boson that can lead to like-sign LNV and even LFV processes at tree level.
  - ➠ providing a link between neutrino and LHC physics

Higgs Spectrum

SU(2)$_L$ × SU(2)$_R$

SU(2)$_V$

1 complex triplet +
1 real triplet

Δ: **3** ⊗ **3**

5 ⊕ **3** ⊕ **1**

1 complex doublet

Φ: **2** ⊗ **2**

3 ⊕ **1**

$$\tan\beta = \frac{v_\phi}{2\sqrt{2}v_\Delta}$$

$$v^2 = v_\phi^2 + 8v_\Delta^2 = \frac{1}{\sqrt{2}G_F} = (246\ \mathrm{GeV})^2$$

mixing angle β

mixing angle α

$$H_5 \equiv \begin{bmatrix} H_5^{++} \\ H_5^{+} \\ H_5^{0} \\ H_5^{-} \\ H_5^{--} \end{bmatrix}$$

CP-even

m_{H_5}

quarkphobic

$$H_3 \equiv \begin{bmatrix} H_3^{+} \\ H_3^{0} \\ H_3^{-} \end{bmatrix}$$

CP-odd

m_{H_3}

gaugephobic

$$\Phi_3 \equiv \begin{bmatrix} w^{+} \\ z^{0} \\ w^{-} \end{bmatrix}$$

$$H_1 \equiv [H_1^0]$$

m_{H_1}

h (125 GeV)

m_h

CP-even

There are 5 new physical parameters

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- There exists a doubly-charged Higgs boson that can lead to like-sign LNV and even LFV processes at tree level.
  - ➠ providing a link between neutrino and LHC physics
- The SM-like Higgs can have stronger/same/weaker couplings with weak bosons (simplest model for this).

Neutral Higgs Couplings

- Introduce coupling scale factors ($V = W, Z$; $F =$ quarks):

$$\kappa_F = \frac{g_{\varphi FF}}{g^{\rm SM}_{hFF}}\ ,\quad \kappa_V = \frac{g_{\varphi VV}}{g^{\rm SM}_{hVV}}\ ,\quad \lambda_{ij} = \frac{\kappa_i}{\kappa_j}$$

depending only on α and β (or v_Δ)

group factor that makes it possible for the entire factor to be greater than 1 (mixing required)

	Higgs	κ_F	κ_V	
	h	$\dfrac{\cos\alpha}{\sin\beta}$	$\sin\beta\cos\alpha - \sqrt{\dfrac{8}{3}}\cos\beta\sin\alpha$	
suppressed by α	H_1^0	$\dfrac{\sin\alpha}{\sin\beta}$	$\sin\beta\sin\alpha + \sqrt{\dfrac{8}{3}}\cos\beta\cos\alpha$	➠ $\lambda_{WZ} = +1$
gauge-phobic	H_3^0	$i\eta_f\cot\beta$	0	
quark-phobic	H_5^0	0	$\kappa_W = -\dfrac{\cos\beta}{\sqrt{3}}$ and $\kappa_Z = \dfrac{2\cos\beta}{\sqrt{3}}$	➠ $\lambda_{WZ} = -1/2$

$\eta_f = +1$ for up-type quarks and -1 for down-type quarks and charged leptons.

independent of α; proportional to v_Δ

$$\text{2HDM}: \tan\beta = \frac{v_u}{v_d} \quad \text{and} \quad \text{GM}: \tan\beta = \frac{v_\phi}{2\sqrt{2}v_\Delta}$$

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  - ➠ cf. loop-induced in models such as 2HDM

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  ➠ cf. loop-induced in models such as 2HDM
- The Higgs decay pattern is mainly controlled by v_Δ and mass hierarchy.

Higgs Decay Pattern

CWC, Yagyu JHEP 2012

$\Delta m < 0 \ \ (m_{H_5} > m_{H_3})$

$H_5^{++} \to H_3^+ W^+ \ , \ H_5^+ \to H_3^+ Z / H_3^0 W^+ \ , \ H_5^0 \to H_3^\pm W^\mp / H_3^0 Z$

$H_3^+ \to H_1^0 W^+ \ , \ H_3^0 \to H_1^0 Z$

$\Delta m > 0 : \ (m_{H_3} > m_{H_5})$

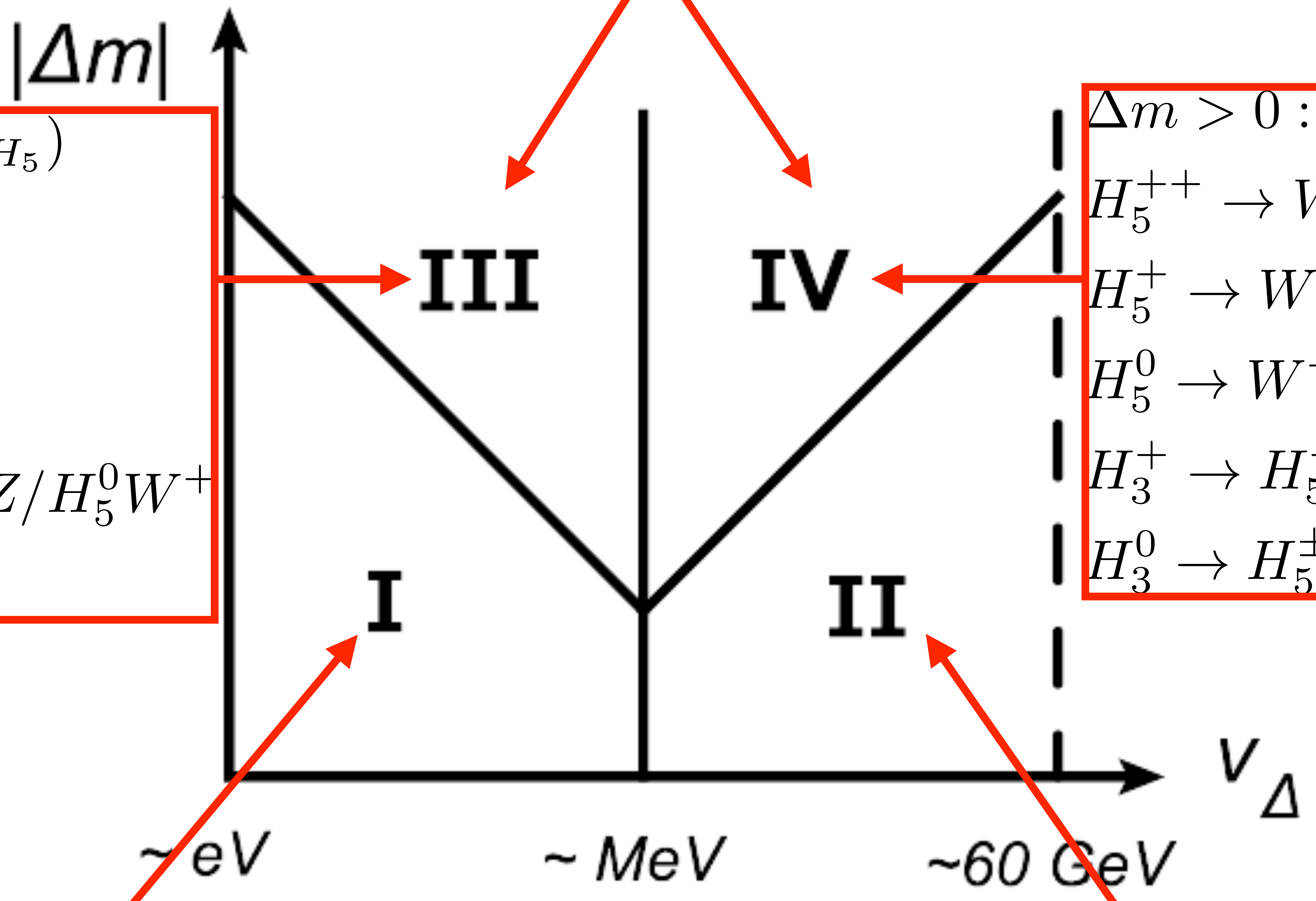
$H_5^{++} \to \ell^+ \ell^+$

$H_5^+ \to \ell^+ \nu$

$H_5^0 \to \nu\nu$

$H_3^+ \to H_5^{++} W^- / H_5^+ Z / H_5^0 W^+$

$H_3^0 \to H_5^\pm W^\mp / H_5^0 Z$



$\Delta m > 0 : \ \ (m_{H_3} > m_{H_5})$

$H_5^{++} \to W^+ W^+$

$H_5^+ \to W^+ Z$

$H_5^0 \to W^+ W^- / ZZ$

$H_3^+ \to H_5^{++} W^- / H_5^+ Z / H_5^0 W^+$

$H_3^0 \to H_5^\pm W^\mp / H_5^0 Z$

$H_5^{++} \to \ell^+ \ell^+ \ , \ H_5^+ \to \ell^+ \nu \ , \ H_5^0 \to \nu\nu \ ,$

$H_3^+ \to \ell^+ \nu \ , \ H_3^0 \to \nu\nu .$

$H_5^{++} \to W^+ W^+ \ , \ H_5^+ \to W^+ Z \ , \ H_5^0 \to W^+ W^- / ZZ \ ,$

$H_3^+ \to \tau^+ \nu / c\bar{s} / t\bar{b} \ , \ H_3^0 \to b\bar{b} .$

Global Fit

"Don't sit, get fit!"

— Gym ad

Theoretical Bounds

- We consider three different sets of bounds at the tree level:
  - vacuum stability, ensured as long as all the quartic terms of the scalar potential remain positive for all possible field configurations

    Hartling, Kumar, Logan 2014

  - perturbative unitarity, by requiring that the largest zeroth partial-wave mode of all $2 \to 2$ scattering channels be smaller than 1/2 at high energies

    Aoki, Kanemura 2008

  - unique vacuum, with no alternative global minimum in the scalar potential to the custodially-conserving vacuum

    Hartling, Kumar, Logan 2014

Experimental Constraints

- We will impose two types of experimental constraints:
  - Higgs signal strengths (for $X = WW,\ ZZ,\ b\bar{b},\ \tau^+\tau^-,\ \mu^+\mu^-,\ \gamma\gamma,\ Z\gamma$):

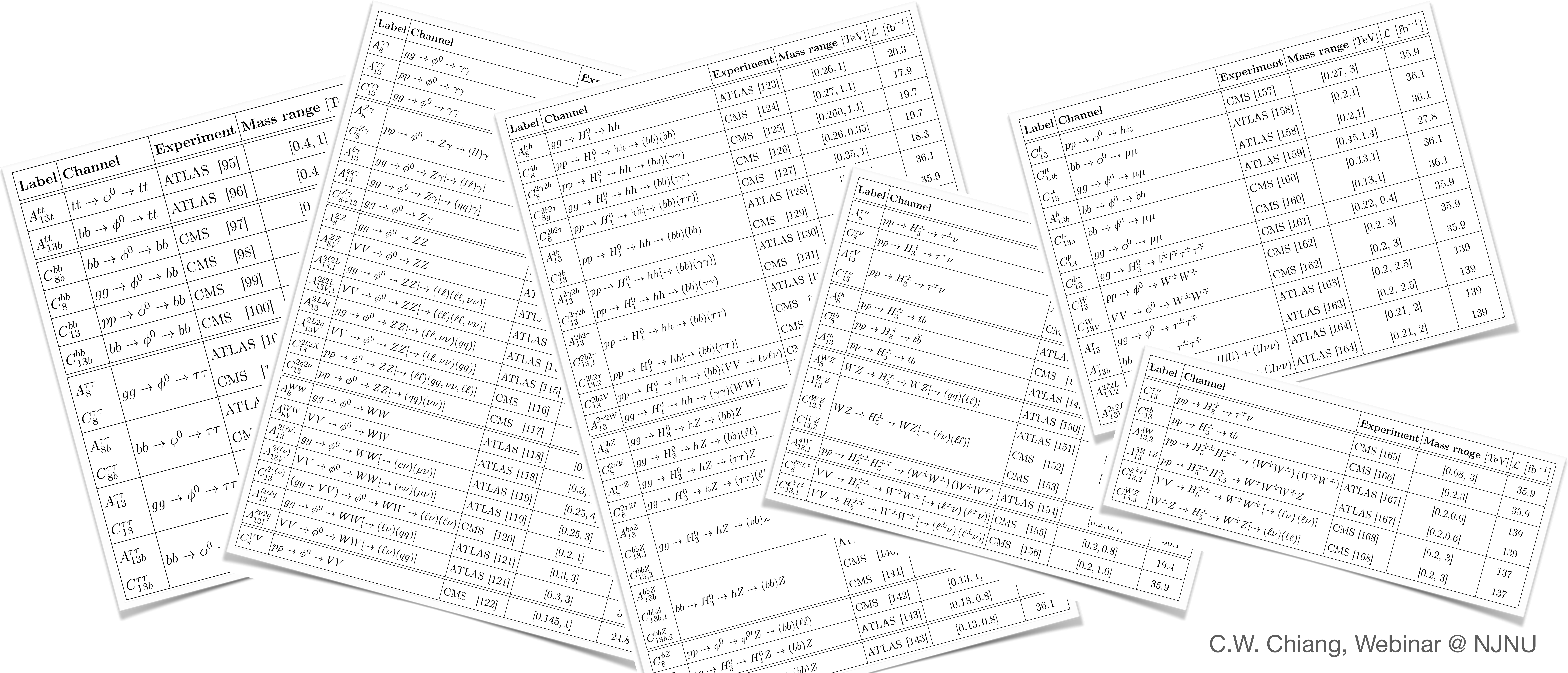
$$\mu_X \equiv \frac{\sigma^{\rm EXP}(pp \to h \to X)}{\sigma^{\rm SM}(pp \to h \to X)} \iff \frac{\sigma^{\rm GM}(pp \to h \to X)}{\sigma^{\rm SM}(pp \to h \to X)}$$

			$b\bar{b}$	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$Z\gamma$	$\mu\mu$
		SM Br	57.5%	21.6%	6.3%	2.7%	2.3‰	1.6‰	0.2‰
LHC	ggF_8	87.2%	–	[61, 62]	[63, 64]	[65, 66]	[67, 68]		
	ggF_{13}	87.1%	–	[29, 69]	[29, 70, 71]	[29, 72]	[29, 73, 74]	8 TeV	8 TeV
	VBF_8	7.2%	–	[61, 62]	[63, 64]	[65, 66]	[67, 68]	[75, 76]	[77]
	VBF_{13}	7.4%	[31, 78]	[30, 69]	[29, 70, 71]	[29, 72]	[29, 73, 74]		
	Vh_8	5.1%	[79, 80]	[62, 81]	[63, 64]	[65, 66]	[67, 68]		
	Vh_{13}	4.4%	[31, 82]	[69, 83]	[71]	[29, 72]	[29, 73, 74]	13 TeV	13 TeV
	tth_8	0.6%	[84, 85]	–	–	[65, 66]	[67, 68]	[33, 34, 86, 87]	[88, 89]
	tth_{13}	1.0%	[31, 32, 90]	[69, 91, 92]	[29, 91, 92]	[72, 91, 92]	[29, 73, 74]		
CDF/D0	Vh_2		[93, 94]						
	tth_2		[93]						

inputs from various sources

Experimental Constraints

- We will impose two types of experimental constraints:
  - direct search bounds on exotic scalar bosons:



Global Fit with the `HEPfit` Package

- Our global fits utilize the `HEPfit` package which is based upon a Bayesian statistics approach.

De Blas et al 2020

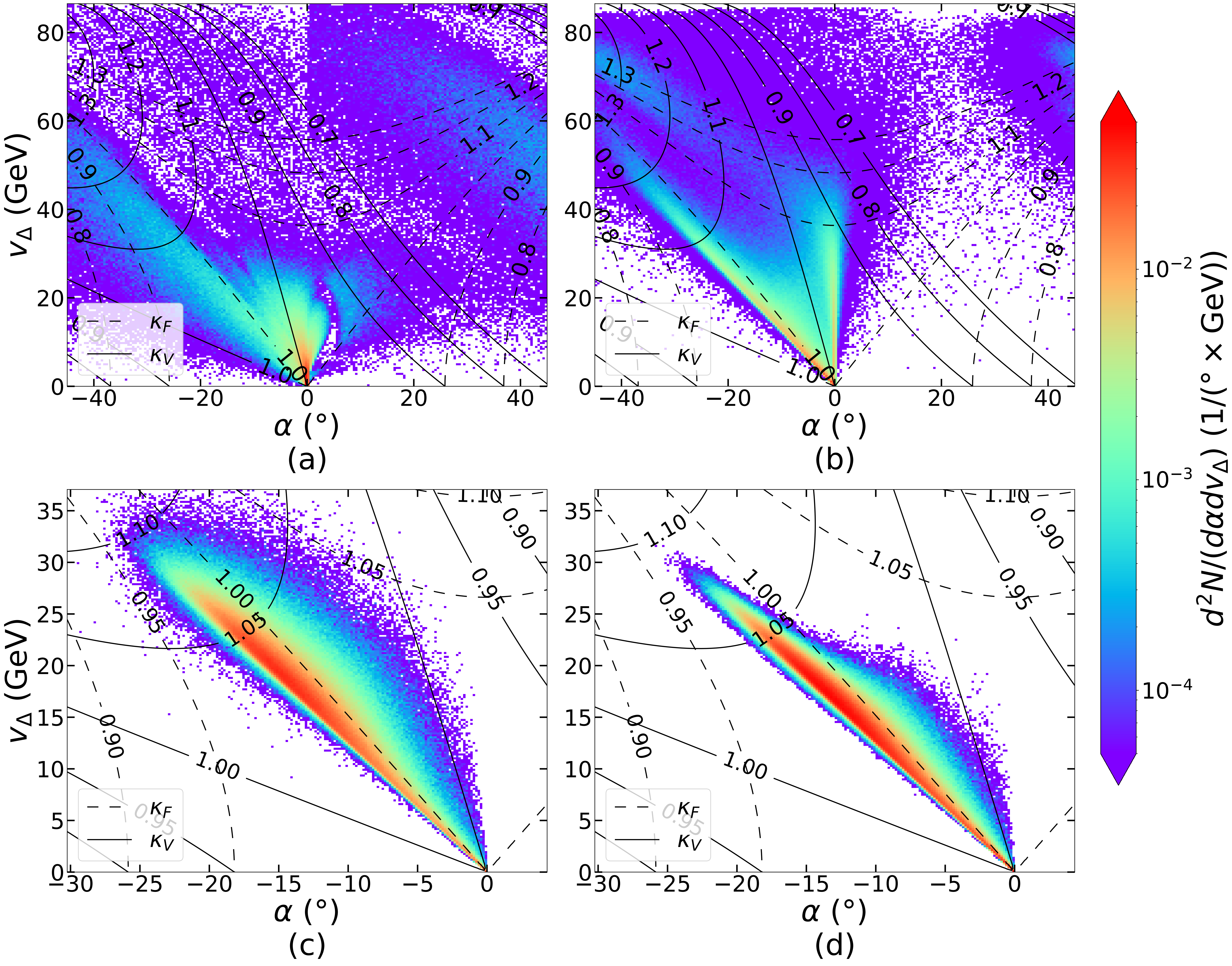
- In addition to the experimental data that determine the likelihood, a prior that specifies the *a priori* distributions of the model parameters is required.
- Use Bayes' rule to obtain a posterior iteratively.
- Based on the final posterior probability, we sample the restricted parameter space and attribute the allowed parameter ranges with different confidence levels (CLs).

Global Fit Result

(a) only the prior imposed
(b) (a) + theoretical constraints
(c) (b) + Higgs signal strengths
(d) (c) + direct search constraints

- Start out around origin (decoupling limit) in (a).
- Move toward $\kappa_F \sim 1$ in (b), favoring some mixing ($\alpha < 0$) between Φ and Δ scalars.
- More defined region in (c) around $\kappa_F \sim 1$, and $\kappa_V > 1$ favored by $\mu_{W,Z} > 1$.
- A smaller region in (d), as restricted by direct searches.

κ_F: dashed contours; κ_V: solid contours



C.W. Chiang, Webinar @ NJNU

Electroweak Phase Transitions

"Life is pleasant. Death is peaceful. It's the transition that's troublesome."

— Isaac Asimov

High-T Thermal Potential

- Assume that the EWPT takes place at a sufficiently high temperature such that the one-loop thermal corrections dominate over the $T = 0$ Coleman-Weinberg potential, allowing an expansion of the thermal corrections to $\mathcal{O}(T^2)$.

- The overall potential at $T > 0$ is given by

primary source of potential barrier

$$V_T^{HT}(\vec{h}, T) = V_0(\vec{h}) + \frac{1}{2}\left(\Sigma_\phi h_\phi^2 + \Sigma_\chi h_\chi^2 + \Sigma_\xi h_\xi^2\right) T^2$$

where V_0 is the tree-level potential, $\overrightarrow{h} = (h_\phi, h_\xi, h_\chi)$ and the thermal mass contributions

$$\Sigma_\phi = \frac{3g^2}{16} + \frac{g'^2}{16} + 2\lambda_1 + \frac{3\lambda_4}{2} + \frac{1}{4}y_t^2 \csc^2\beta$$

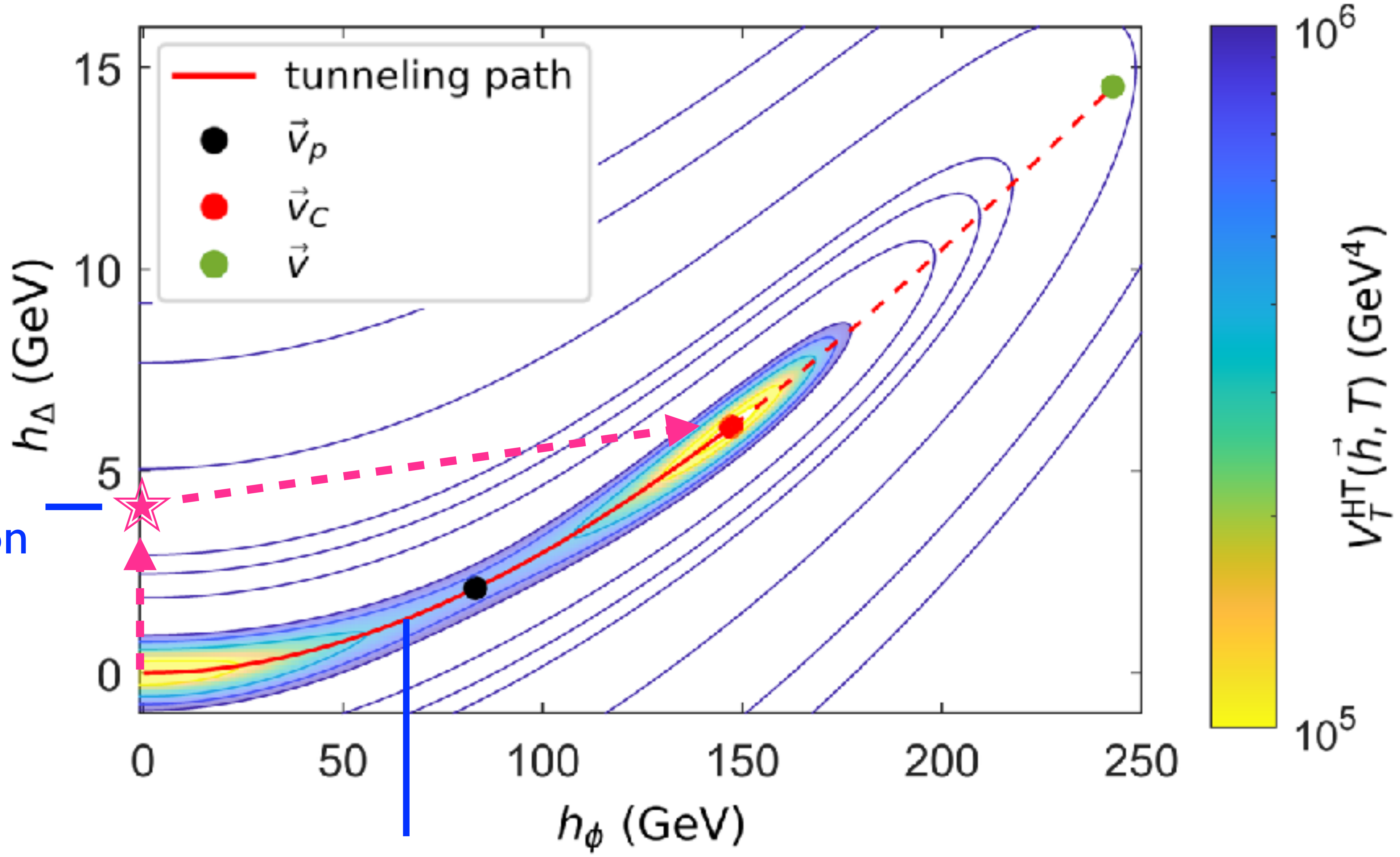
$$\Sigma_\chi = \frac{g^2}{2} + \frac{g'^2}{4} + \frac{11\lambda_2}{3} + \frac{7\lambda_3}{3} + \frac{2\lambda_4}{3}$$

$$\Sigma_\xi = \frac{g^2}{2} + \frac{11\lambda_2}{3} + \frac{7\lambda_3}{3} + \frac{2\lambda_4}{3}$$

Schematic View of A One-Step Phase Transition

- Numerically, we find that the h_ϕ^2 term, in particular, in the thermal potential can lift the potential much higher than V_0 when $\overrightarrow{h}$ is small and T is high.
- On the other hand, V_0 plays the main role in determining the tunneling path, which is crucial to the phase transition characteristics.

example of a possible two-step phase transition



example of a possible one-step phase transition

Search for Sufficiently Strong EWPT

- First, take the data generated by `HEPfit` and numerically solve for the critical temperature, T_C, and the corresponding VEV, $\overrightarrow{v}_C$, using

$$V_T^{HT}(\vec{v}_C, T_C) = V_T^{HT}(\vec{0}, T_C) \quad \text{and} \quad \nabla V_T^{HT} = \vec{0}$$

  as required for the existence of two local minima.

- Then use the `cosmoTransitions` package Wainwright et al 2012
  (a) to determine the order of the EWPT, and
  (b) to calculate the bubble dynamics.

- Among all the samples passing the `HEPfit` global fit, we have found no two-step EWPTs, contrary to what is claimed in the literature. cf. Zhou, Cheng, Deng, Bian, Wu 2019

- This is likely because we have performed a comprehensive phenomenological scan (particularly the direct search bounds) of parameters, particularly in the larger v_Δ space rather than the smaller v_Δ space (as in the above reference).

Scatter Plot of Critical VEVs

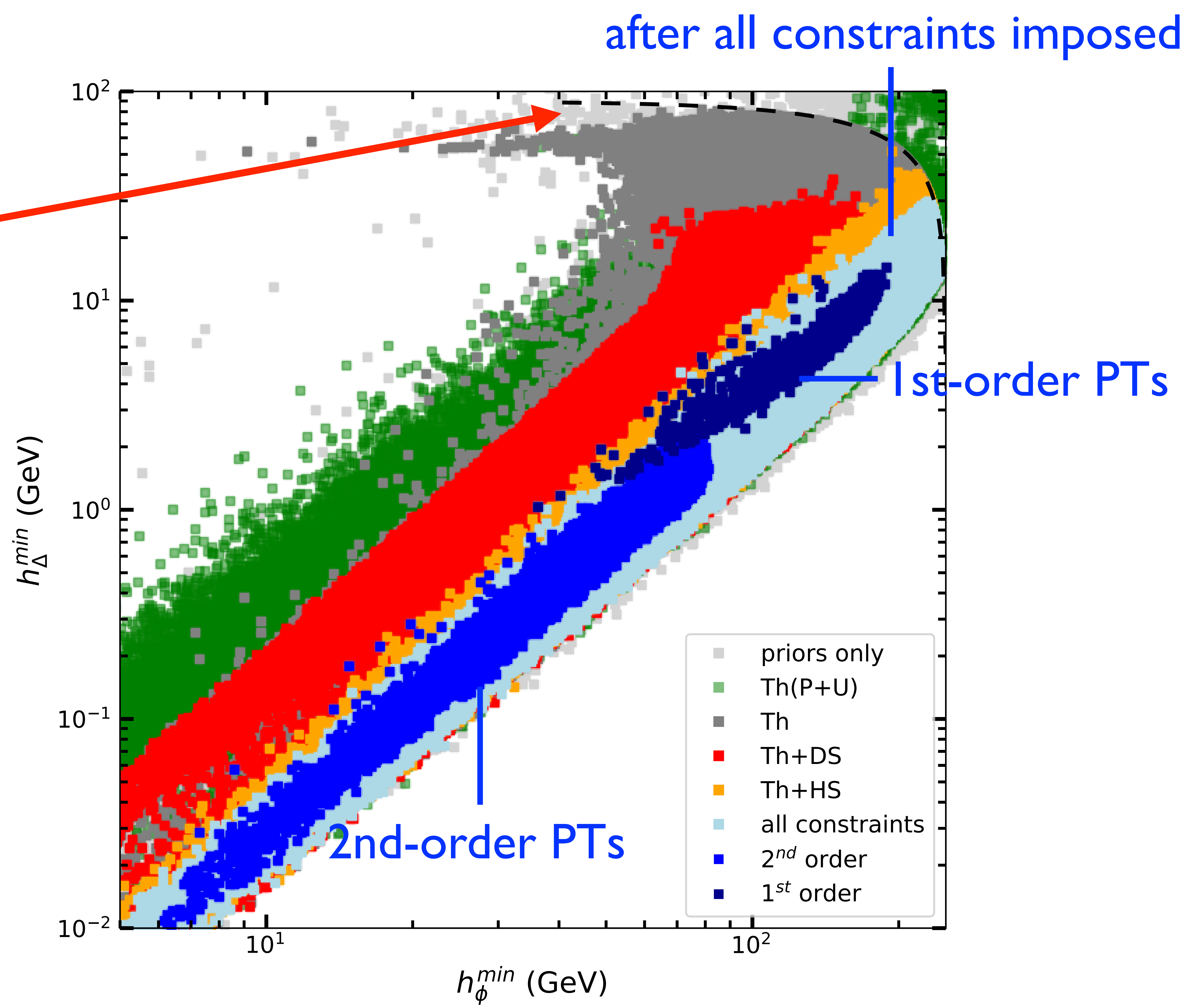
- After imposing theoretical constraints, we observe that the stability condition would exclude the data with

$$|\vec{v}_C| = \sqrt{h_\phi^{min\,2} + 8h_\Delta^{min\,2}} > 246\ \mathrm{GeV}$$

(green vs dark grey dots).

- Experimental constraints restrict the magnitude of v_C's of the strong first-order EWPTs and put limitation on the values of v_C/T_C.
- This implies that the collider measurements are good probes to the EWPT behavior of the GM model.

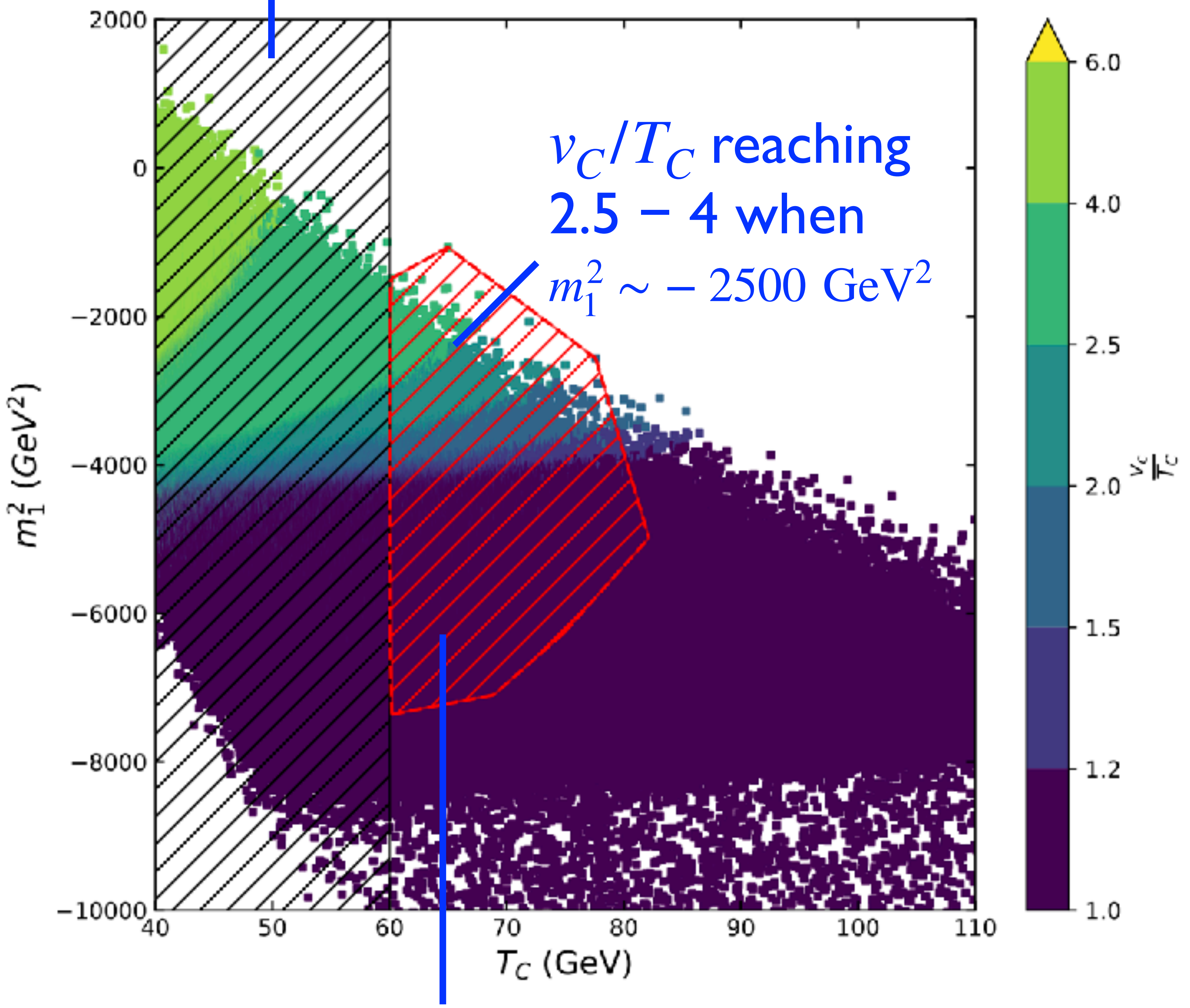
colored dots are stacked from bottom up



Impact of m_1^2 on Phase Transition Parameters

- The doublet mass m_1^2 plays a crucial role in determining the strength of the EWPT, characterized by v_C/T_C.
- As m_1^2 increases (decreases), V_0 becomes shallower (deeper) in the h_ϕ -direction, and the potential barrier becomes wider (narrower).
  ➠ smaller (larger) thermal corrections to lift broken VEV to the critical value
  ➠ lower (higher) T_C and larger (smaller) v_C
  ➠ larger (smaller) v_C/T_C

$T_C \leq 60$ GeV,
where high-T expansion breaks down



some of the points herein feature 1st-order PTs

Gravitational Waves

"I would like to mention astrophysics; in this field, the strange properties of the pulsars and quasars, and perhaps also the gravitational waves, can be considered as a challenge."

— Werner Heisenberg

Bubble Dynamics

- The information of the stochastic GWs generated by the bubble dynamics of the strong first-order phase transitions can be completely accessed with two primary parameters: α_{GW} and β_{GW}/H_n.

Kamionkowski, Kosowsky, Turner 1994

- First, the strength parameter

potential difference between symmetric and broken phases at T

bubble nucleation temp.

$$\alpha_{GW} = \frac{1}{3\omega_s}\left[T\frac{d\Delta V_T^{HT}(T)}{dT} - \left(1+\frac{1}{c_s^2}\right)\Delta V_T^{HT}(T)\right]\Bigg|_{T=T_n}$$

enthalpy density of hydrodynamics in the plasma of the symmetric phase

speed of sound

Giese, Konstandin, van de Vis 2020
Giese, Konstandin, Schmitz, van de Vis 2021
Guo, Sinha, Vagie, White 2021

is related to the maximum available energy budget for GW emissions.

Bubble Dynamics

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Kamionkowski, Kosowsky, Turner 1994

- Secondly, assuming that the percolation takes place soon after the nucleation of the true vacua, one can use the condition $T_* \simeq T_n$, where T_* denotes the GW generation temperature, and

3D on-shell Euclidean action of the instanton

$$\frac{\beta_{GW}}{H_n} = T_n \frac{d}{dT}\left(\frac{S_3(T)}{T}\right)\bigg|_{T=T_n}$$

Hubble constant at nucleation temp

defines the characteristic frequency of the GW spectrum produced from the phase transition.

Gravitational Waves Spectra

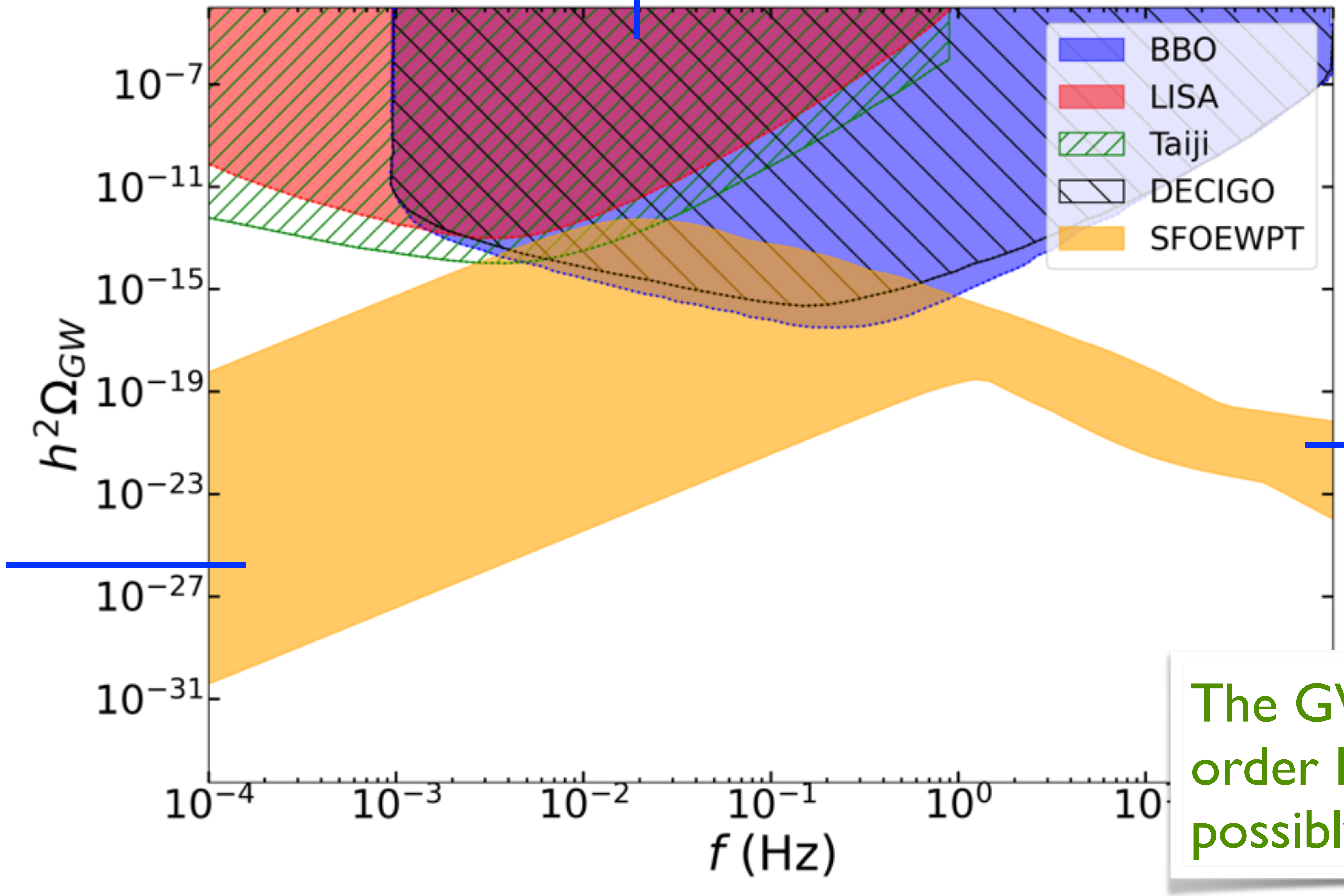
- The main sources of the GWs generated during EWPTs are bubble collisions, sound waves, and turbulence.

Caprini et al 2016
Cai, Sasaki, Wang 2017

- Approximate formulae of the GW spectra from these sources can be found in the literature.

Huber, Konstandin 2008
Jinno, Takimoto 2017
Caprini, Durrer, Servant 2009

sensitivities of various GW experiments



When the phase transition strength is stronger, T_C tends to be lower, and so does T_n, leading to a larger $\alpha_{GW} \propto T_n^{-2}$ and a smaller $\beta_{GW}/H_n \propto T_n$.

band swept out by the GW spectrum curves based upon 2000 data points

The GWs induced from the strong 1st-order EWPTs of the GM model can possibly be detected by all but LISA.

Predictions

"Prediction is difficult — particularly when it involves the future."

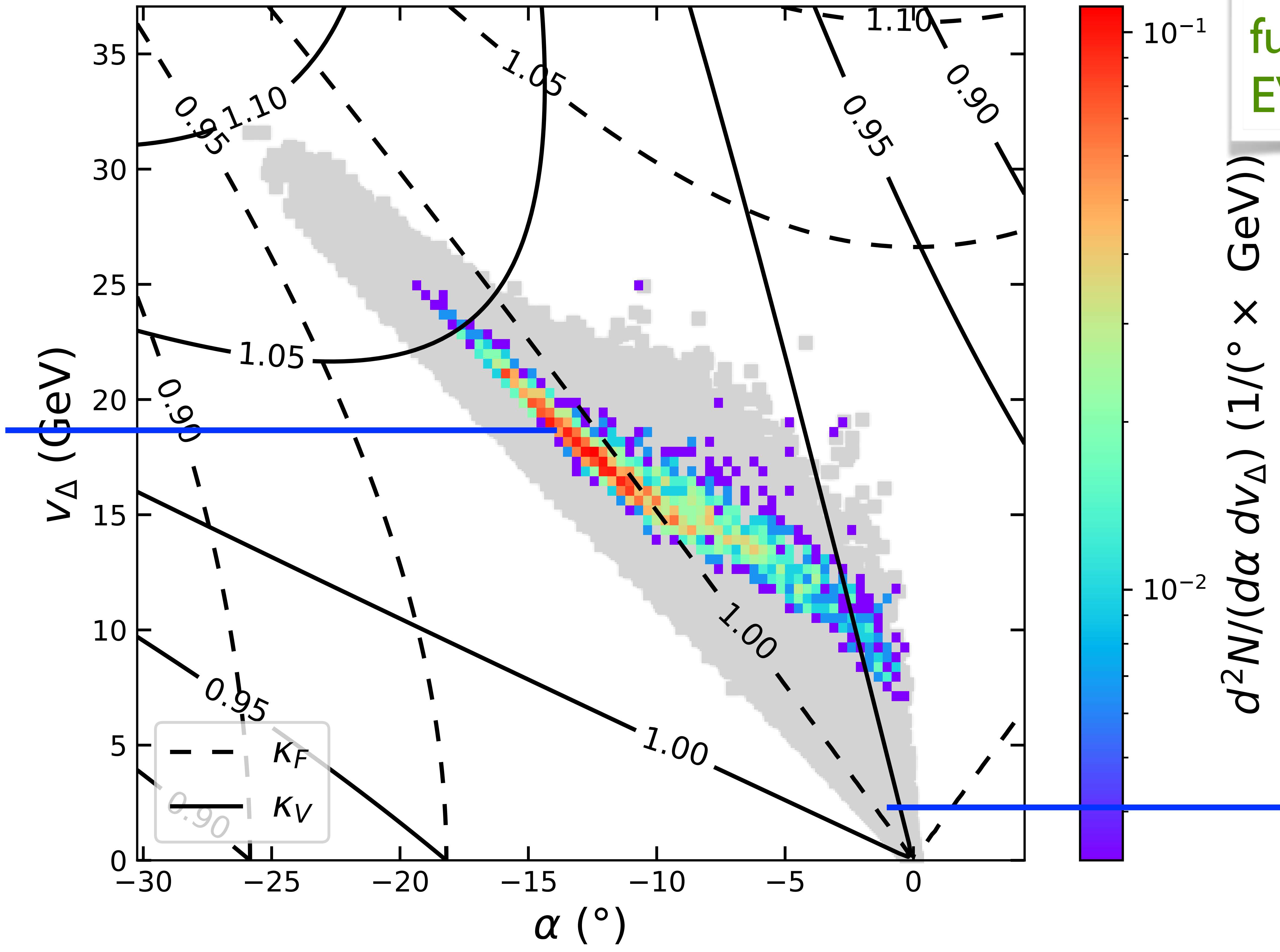
— Mark Twain

Distribution in the α-v_Δ Plane

- In the following, we make predictions based upon the parameter points that lead to sufficiently strong first-order phase transitions.

Grey dots are from the HEPfit global fit to theoretical bounds and collider data; colored dots further feature strong 1st-order EWPTs.

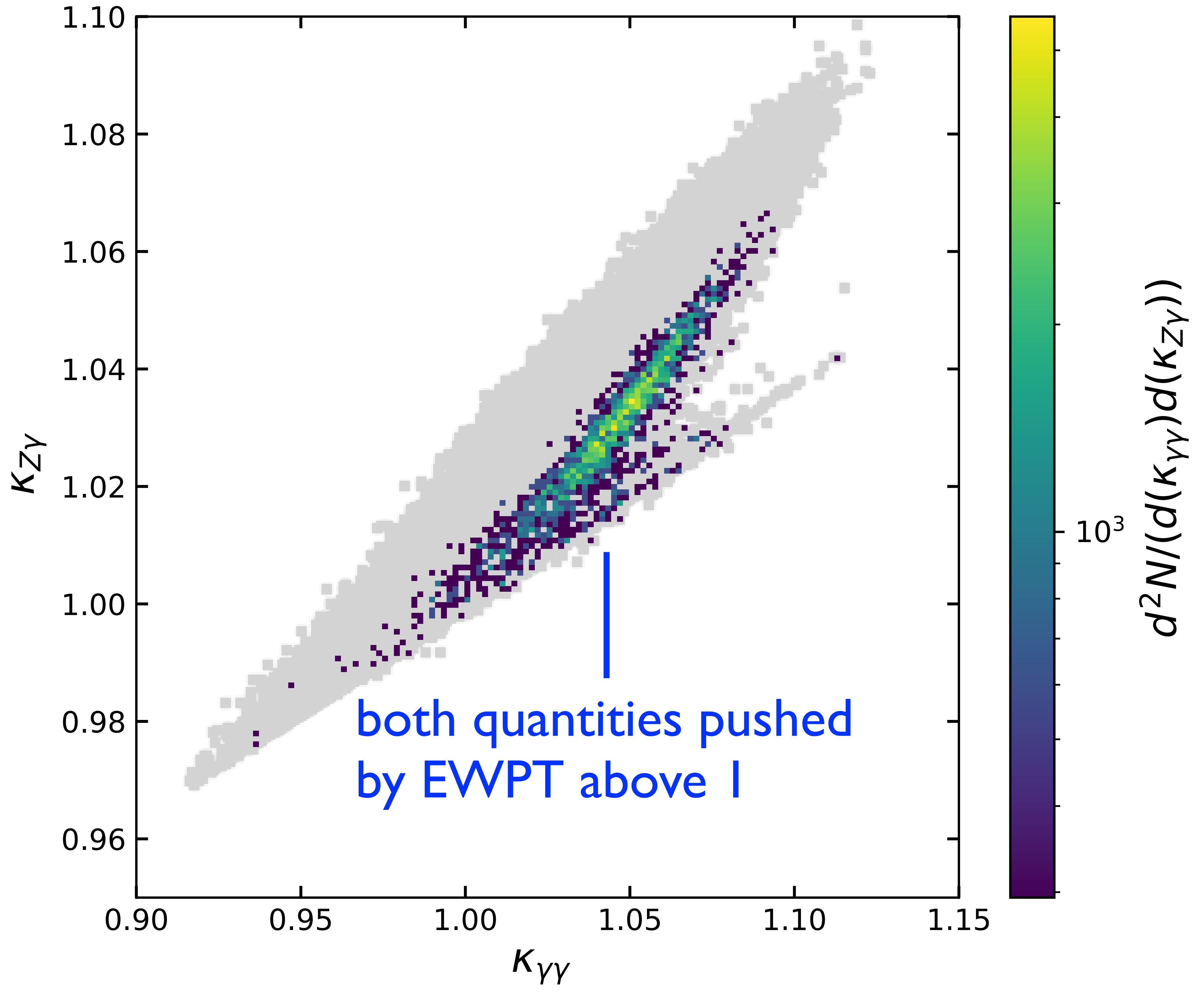
Most of the strong first-order EWPT data accumulate around $v_\Delta \in [15,20]$ GeV and $\alpha \in \left[-15^\circ, -10^\circ\right]$, corresponding to $\kappa_F \sim 1$, $\kappa_V \in (1.0, 1.05)$.



No data show up around the decoupling region because a SM-like potential could only induce a smooth crossover rather than strong first-order EWPTs.

The $hZ\gamma$ and $h\gamma\gamma$ Couplings

- $\kappa_{Z\gamma}$ and $\kappa_{\gamma\gamma}$ are the ratios of the loop-induced $hZ\gamma$ and $h\gamma\gamma$ couplings to the respective SM predictions.
- The two couplings are positively correlated and the peak in the $\kappa_{\gamma\gamma}$-$\kappa_{Z\gamma}$ plane is around (1.03,1.05) after we require strong first-order EWPTs.
- Thus, a more precise measurement of these couplings can be a good probe to the EWPT behavior of the GM model.



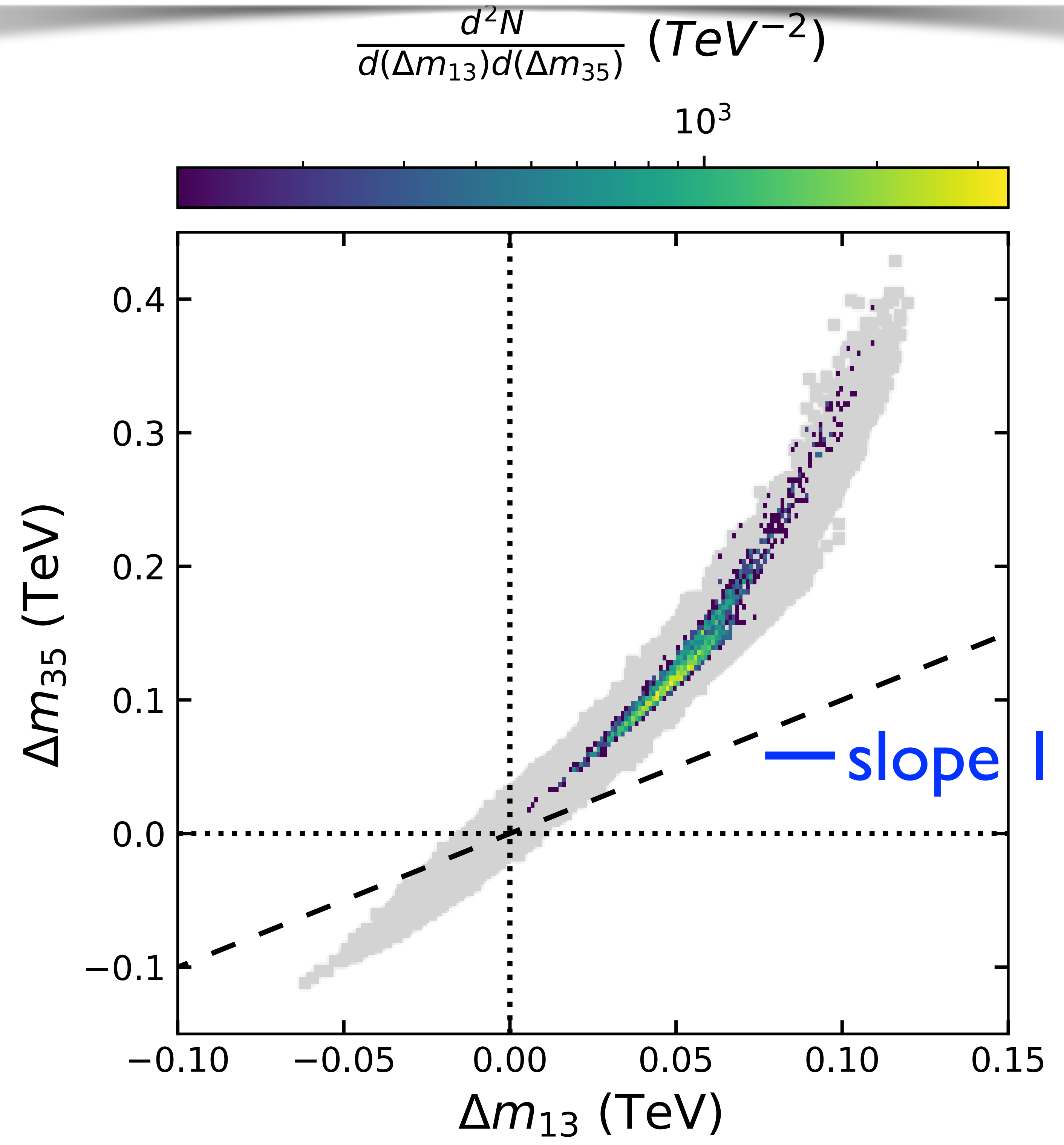
Exotic Higgs Masses

- Define $\Delta m_{ij} \equiv m_{H_i} - m_{H_j}$ and $\Delta m^2_{ij} \equiv m^2_{H_i} - m^2_{H_j}$ for $i, j = 1,3,5$.

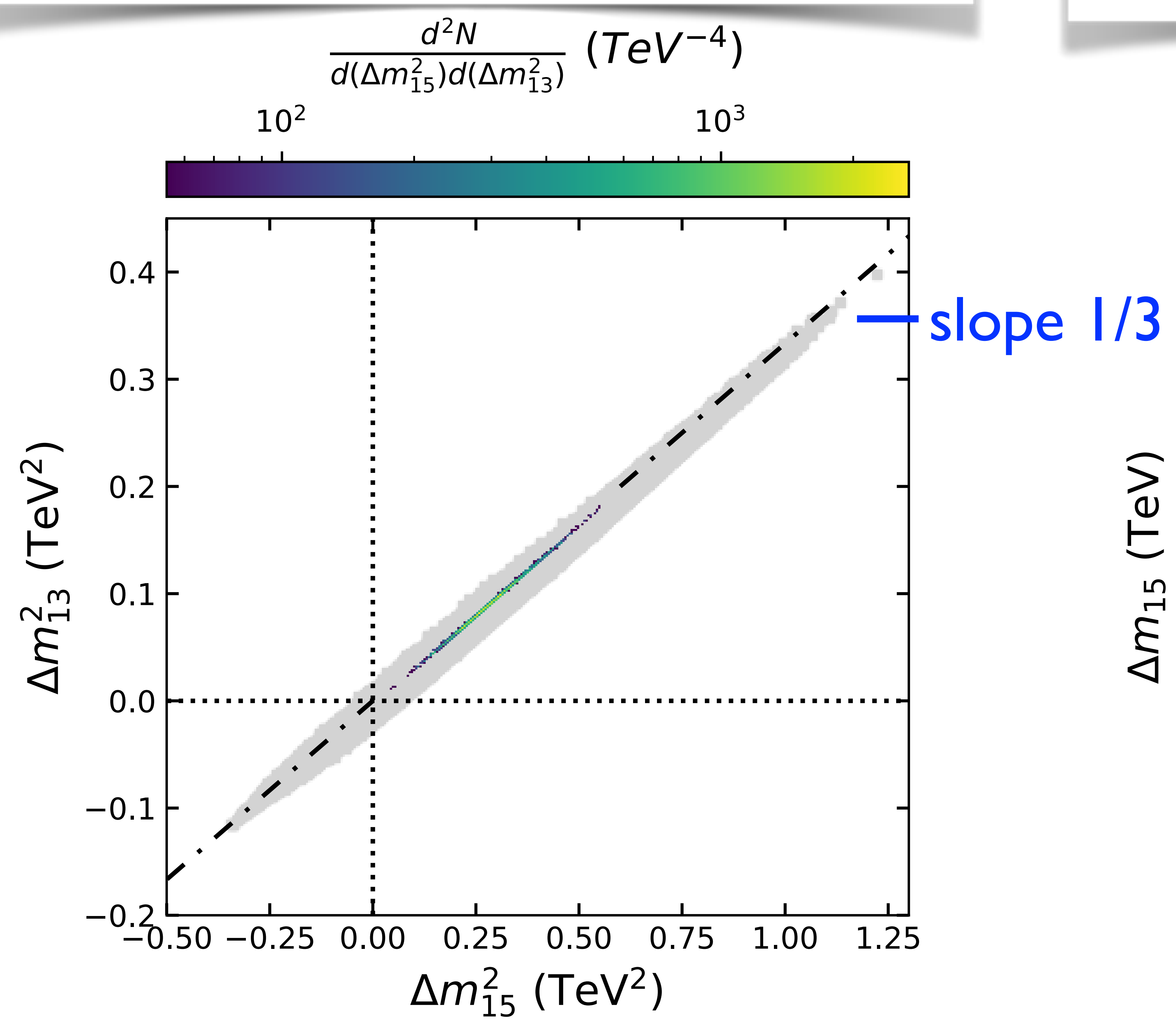
after imposing the strong EWPT requirement, all data predict $m_{H_1} > m_{H_3} > m_{H_5}$
➠ forbidding decays like $H_3^0 \to H_1^0 Z$

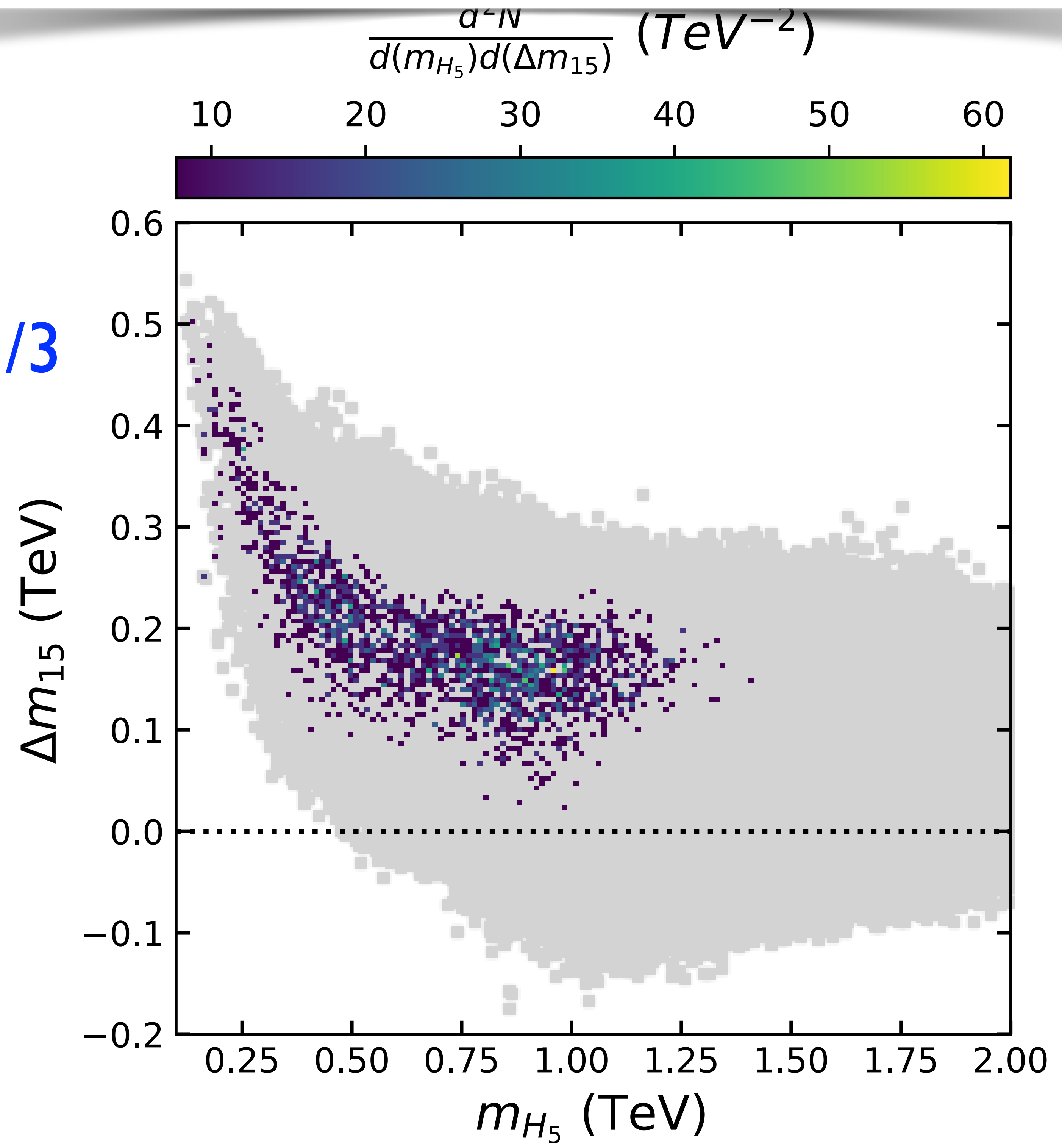
satisfy the mass relation $\Delta m^2_{13} = \frac{1}{3}\Delta m^2_{15}$ that is valid in the decoupling limit

after requiring strong EWPT, m_{H_5} falls in the range of [150, 1500] GeV and tends to have a larger gap with m_{H_1} as it gets smaller



smaller mass gap

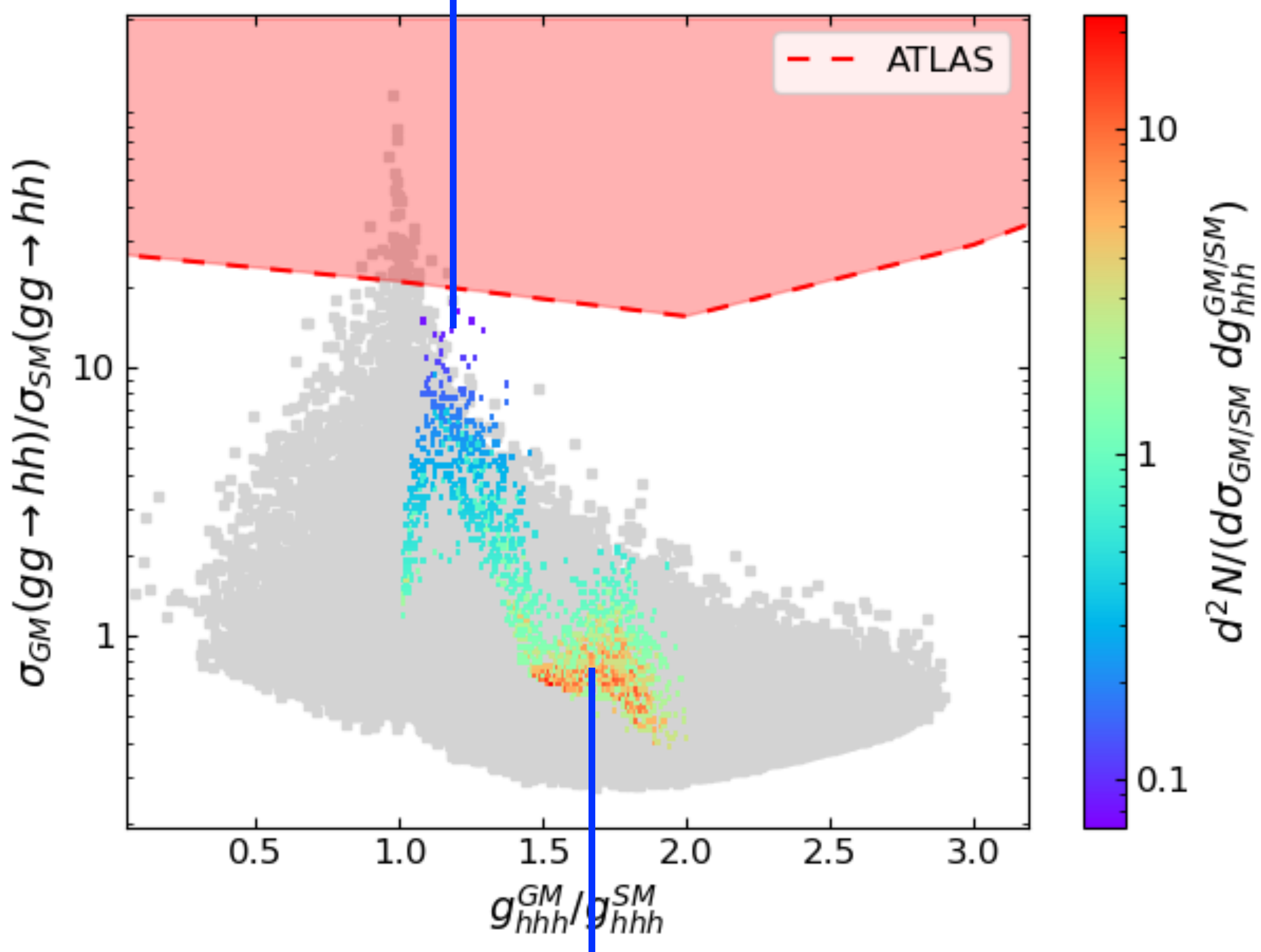




Di-Higgs Production at LHC

- The di-Higgs production cross sections are calculated with the `Hpair` package. Dawson, Dittmaier, Spira 1998
- At the leading order, the two triangle diagrams mediated by h and H_1, as well as the box diagram with the top quark running in the loop give the most dominant contributions.
- The strong EWPT samples prefer $g_{hhh}^{GM}/g_{hhh}^{SM} > 1$ and, due to constructive interference, have an enhancement in the production.

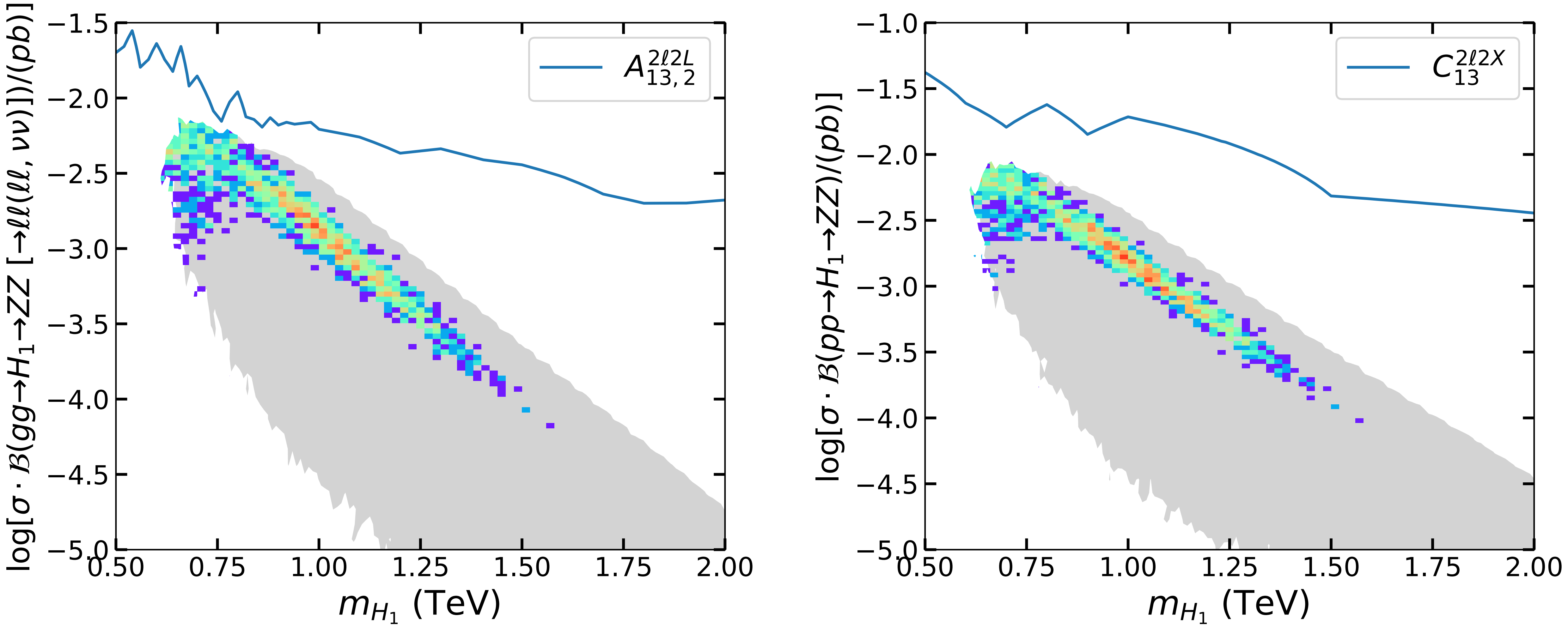
smaller m_{H_1} and larger constructive interference, close to current bound



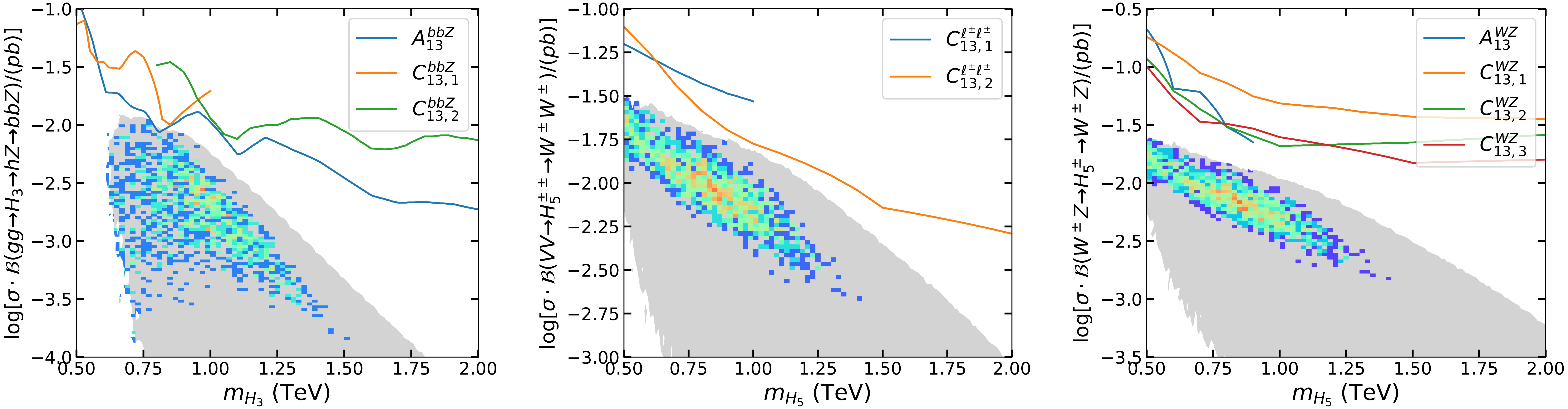
moving toward complete destructive between h triangle diagram and t square diagram

Most Constraining Direct Search Channels

- The following are direct search channels that are most promising to lead to a discovery or to constrain the GM model:



Such collider data serve as good probes to the EWPT behavior of the GM model, as the desired parameter space tend to predict larger production rates for these modes.



Summary

- We have performed a comprehensive global fit for the GM model to theoretical and experimental bounds, obtaining viable parameter samples.
  ➠ e.g., samples distribute around $\left(\kappa_F, \kappa_V\right) \sim (0.99, 1.03)$
- We have calculated under the high-T assumption and found samples that can lead to strong first-order EWPTs.
  ➠ e.g., only one-step transitions allowed
- We have computed the gravitational wave spectra associated with the EWPTs, with the peak frequency lying within $\left[10^{-2}, 1\right]$ Hz and an amplitude that could be probed by `Taji`, `DECIGO` and `BBO`, but not `LISA`.
- We have made further predictions based upon the scanned samples.
  ➠ e.g., the mass hierarchy $m_{H_1} > m_{H_3} > m_{H_5}$ is favored; $\kappa_{Z\gamma}$ and $\kappa_{\gamma\gamma}$ preferably slightly above 1; LHC di-Higgs production likely enhanced (within one order of magnitude); etc
- We have identified direct search channels that are most promising to probe the model.

Thank you for your attention!