Dark Matter and Baryogenesis with an Inert Doublet

Joint FMF-JSI high energy physics seminar

4.3.2021
Ljubljana

Fabian, FG, Jiang, 2012.12847

& in progress w/ Angelescu, Dias Astros, Fabian, Lozano Onrubia, Jiang

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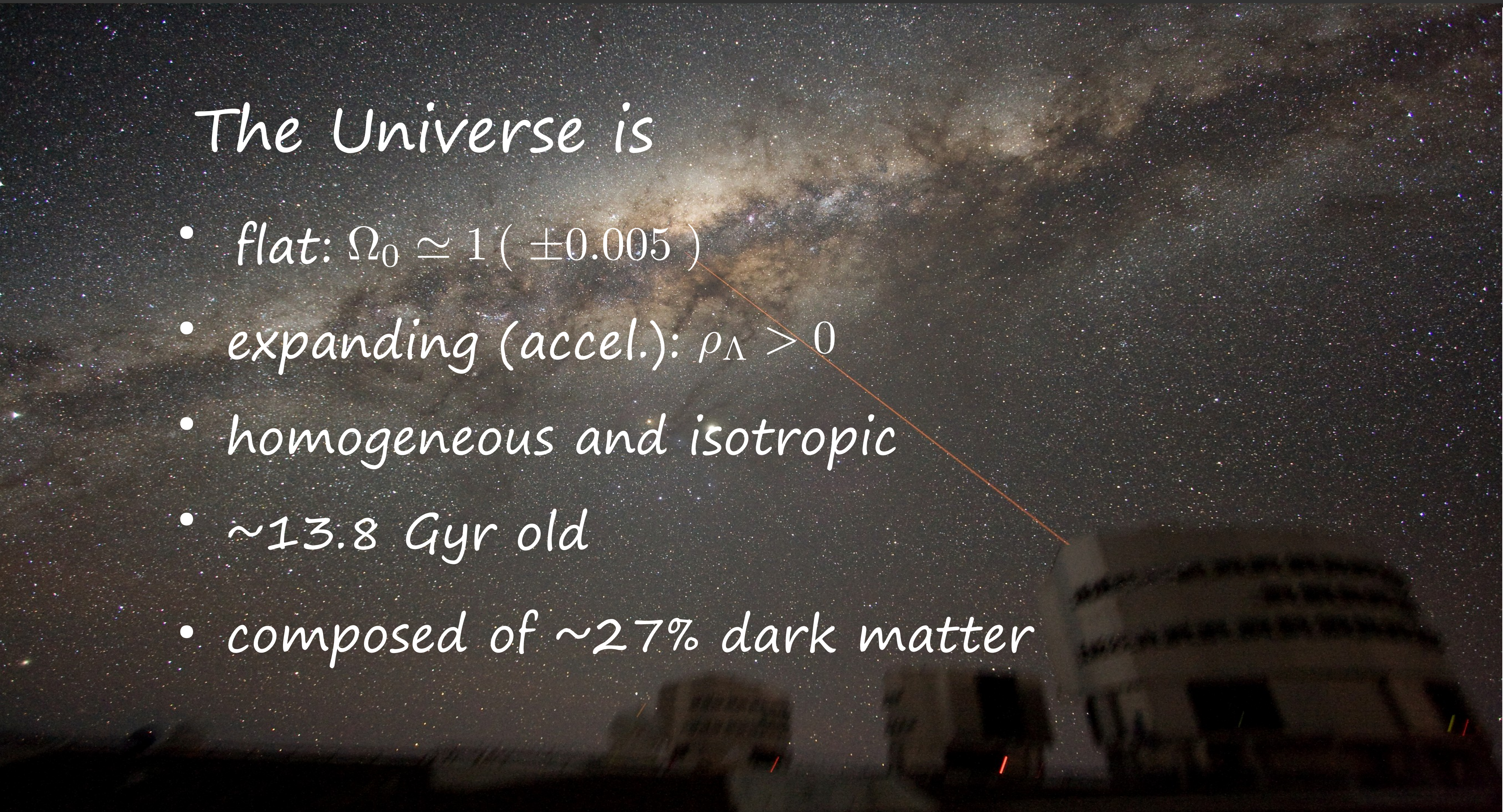
Cosmological Observations



The Universe is

- flat: $\Omega_0 \simeq 1\,(\pm 0.005)$
- expanding (accel.): $\rho_\Lambda > 0$
- homogeneous and isotropic
- ~13.8 Gyr old
- composed of ~27% dark matter

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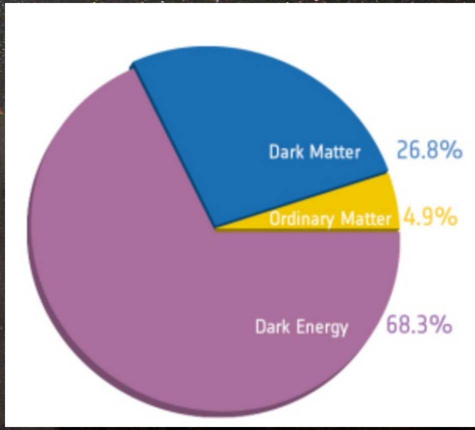
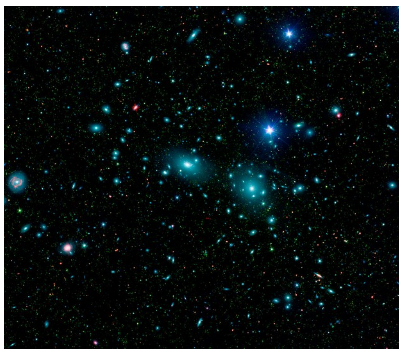


Dark Matter

- **Luminous matter cannot explain many observations**

- luminous matter not sufficient to keep clusters bound

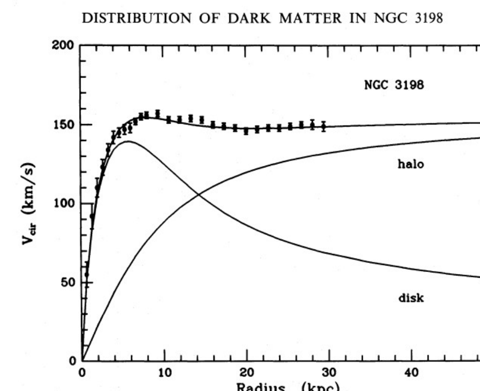


Coma Cluster, NASA, Zwicky

- Bullet Cluster:
  Optical observation (x-ray) vs. grav. lensing

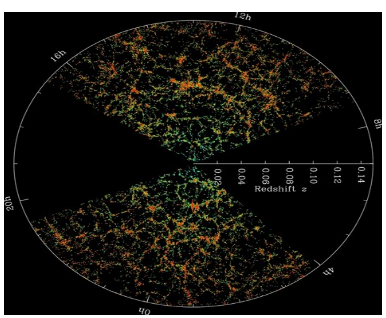
NASA, ...

- rotation curves of galaxies



Albada, Bahcall, Begeman, Sanscisi, APJ, 295, 305-313 (1985)

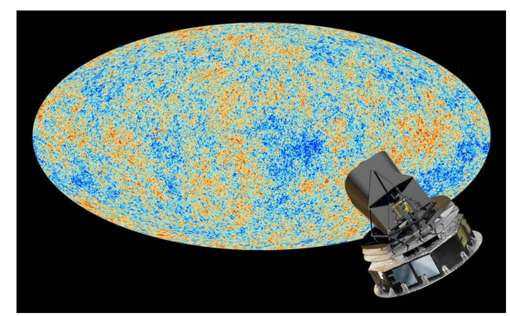
- large-scale structure formation



Sloan Digital Sky Survey

+ BBN, Lyman-α forest, ...

- CMB

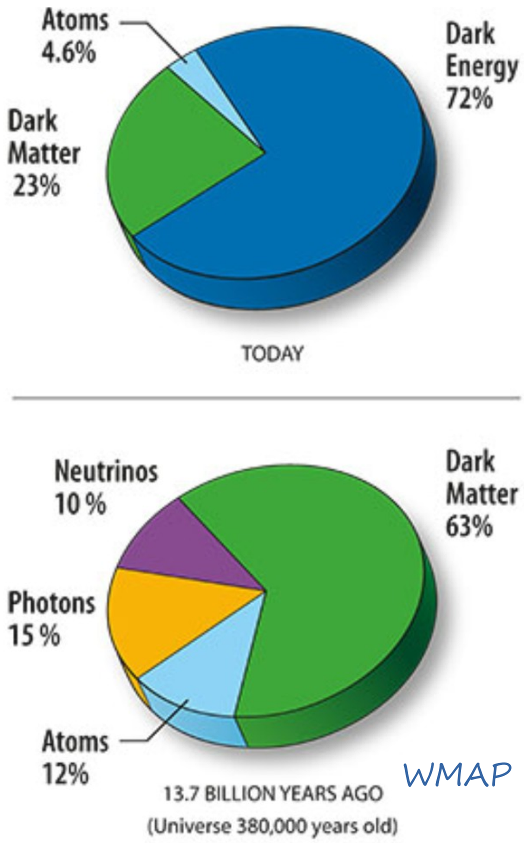


ESA

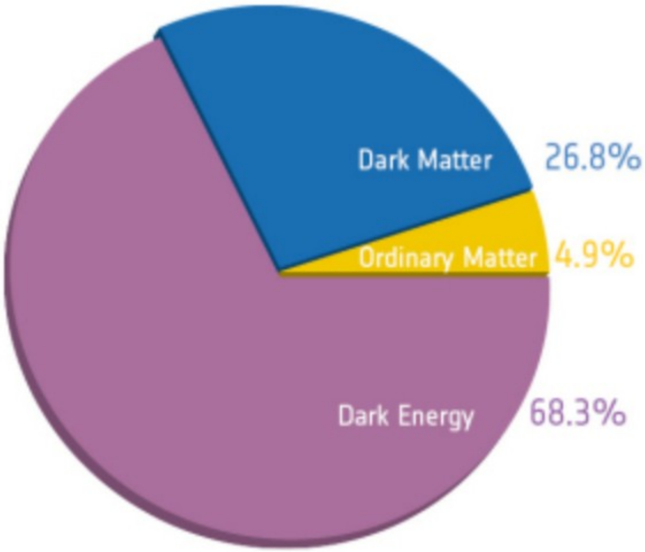
- All these observations can be explained by the presence of **Dark Matter**... What is its origin?

Dark Matter

ΛCDM Picture



WMAP



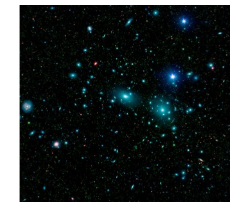
After Planck

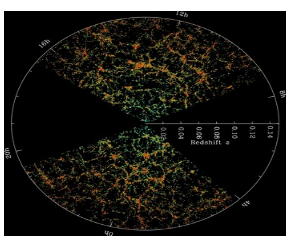
$\Omega_r \lesssim 10^{-4}$

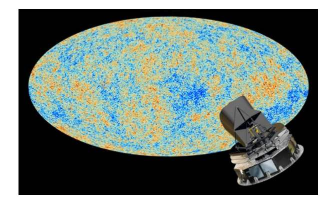
Dark Matter

- *Viable candidate for DM:*

electrically neutral,
cosmologically stable,
colorless particle,
with abundance in agreement with Ω_{DM}







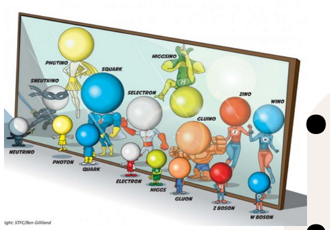
structure formation → cold (non-relativistic) dark matter preferred

↓

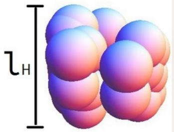
weakly interacting massive particle (WIMP),
...

Cosmology ↔ Particle Physics

Some Dark Matter Candidates



- Lightest SUSY partner (Neutralino…)
- Lightest Kaluza-Klein excitation (KK parity)



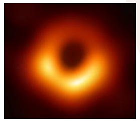
- Composite DM
- Higgs-Portal DM

www.photoshoptutorials.ws/

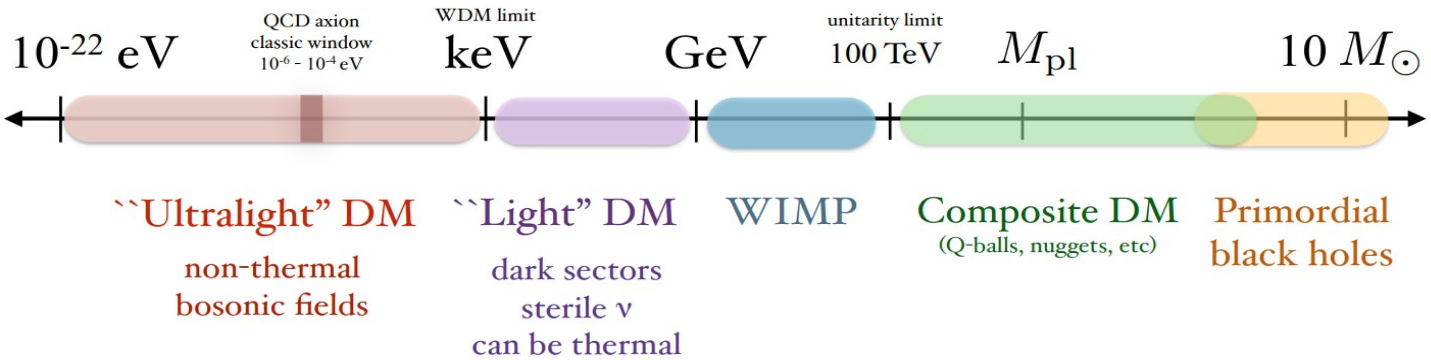
Sandbox Studio, Chicago, Ana Kova

- Sterile neutrinos
- Axions

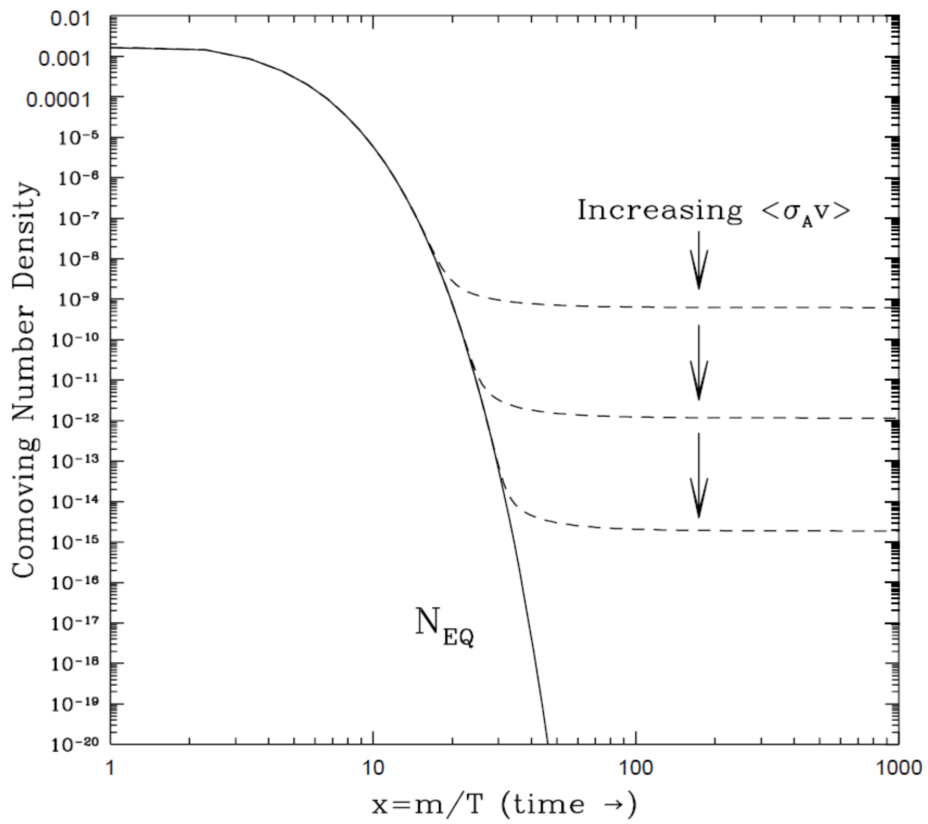
Economist



- Primordial BH, …



WIMP Miracle



$$< \sigma_{X\bar{X}}|v| >= a + b < v^2 > + \mathcal{O}(v^4)$$

$$x \equiv m_X/T$$

Weakly Interacting Massive Particle:

$m_X \sim \text{GeV} - \text{TeV}$, weak scale $< \sigma_{X\bar{X}}|v| >$

$x_{FO} \sim 20 - 30$ (freeze-out temperature)

→ Correct Relic Abundance $\Omega_X h^2 \approx 0.1 \underbrace{\left(\frac{x_{\rm FO}}{20}\right)\left(\frac{g_\star}{80}\right)^{-1/2}}_{\sim 1} \left(\frac{a + 3b/x_{\rm FO}}{3 \times 10^{-26} \text{cm}^3/\text{s}}\right)^{-1}$

Hooper, 0901.4090

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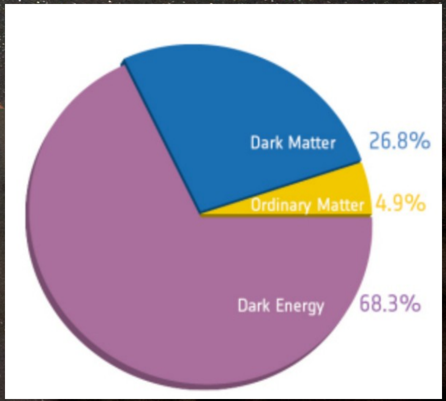

Physics Beyond the SM

Cosmological Observations

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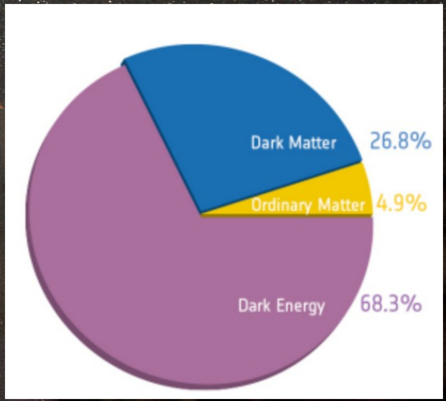
- composed of ~27% dark matter
- composed of matter at all!




Baryogenesis

Baryogenesis

→ Matter–Antimatter Asymmetry

Evidences:

- On Earth: No hints for significant amounts of antimatter
- Solar System: – particles from sun → made out of matter

  – space probes landed on many objects without annihilation

- Universe: – composition of cosmic rays → no antimatter

  – no γ-rays from annihilation between matter and antimatter regions

Universe seems not symmetric (with just regions of matter and antimatter separated)...

Baryogenesis

→ Matter-Antimatter Asymmetry

Quantitatively:

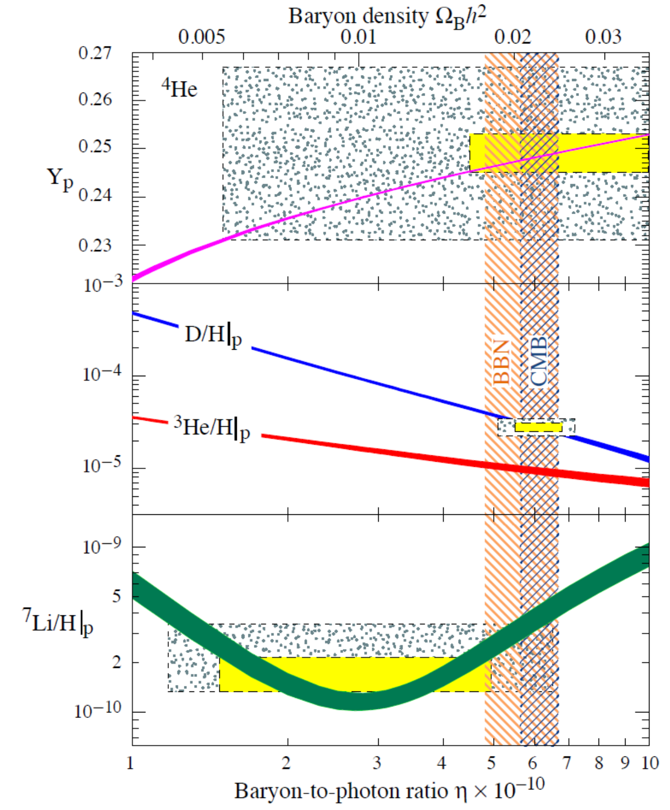
- Antimatter in cosmic rays: $\bar{p}/p \sim 10^{-4}$ → only secondary production
- Baryon-to-Photon ratio

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10}$$

BB-Nucleosynthesis:

abundances depend on η

+ CMB



5% uncertainty

Sakharov Conditions

Sakharov, 1967

Conditions for generation of baryon asymmetry

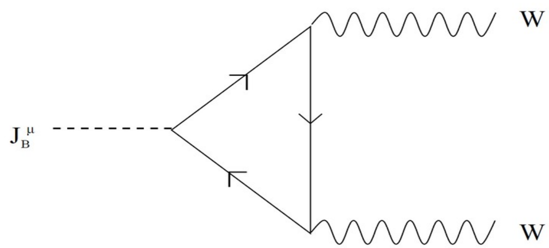
- Baryon Number (B) Violation
- C and CP violation
- Departure from Thermal Equilibrium

Within the SM?

Baryon Number Violation in SM

B violated through triangle anomaly

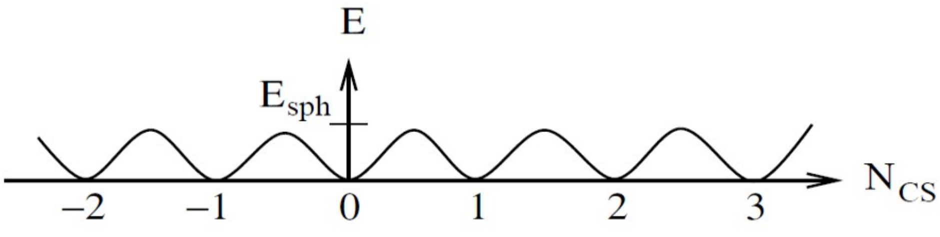
$$\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = \frac{N_{\rm gen}}{32\pi^2}\epsilon_{\alpha\beta\gamma\delta}(g^2 W_a^{\alpha\beta} W_a^{\gamma\delta} - g'^{\,2} B^{\alpha\beta} B^{\gamma\delta})$$



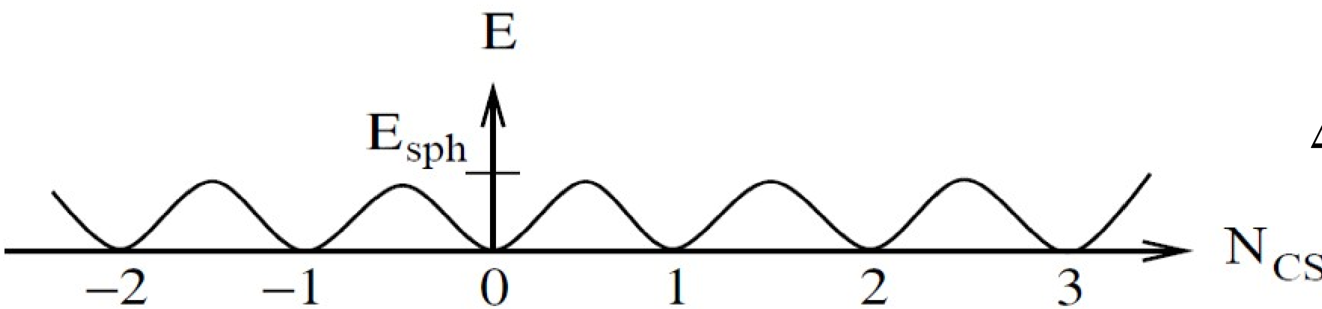
$$J^\mu_B = \frac{1}{3}\sum_q \bar{q}\gamma^\mu q$$

B-L conserved

- associated to degenerate vacuum structure of SU(N) gauge theories with SSB (transition between vacua non-perturbatively)



Baryon Number Violation in SM



$$\Delta B = \Delta L = N_{\rm gen}\, \Delta N_{CS}$$

- Can hop over barrier via thermal 'sphaleron' process $(T > 0)$
$$\to \Delta B \neq 0$$

- Height of barrier: $E_{\rm sph}(T) = \frac{g\langle\phi(T)\rangle}{\alpha_w} f\left(\frac{\lambda}{g^2}\right)$

- Electroweak Phase Transition (EWPhT)

$$\langle\phi(T)\rangle = 0\,,\quad T > T_c \quad \to \quad \text{sphaleron unsuppressed } (E_{\rm sph} = 0)$$
$$\langle\phi(T)\rangle > 0\,,\quad T < T_c \quad \to \quad \text{sphaleron suppressed } (E_{\rm sph} > 0)$$

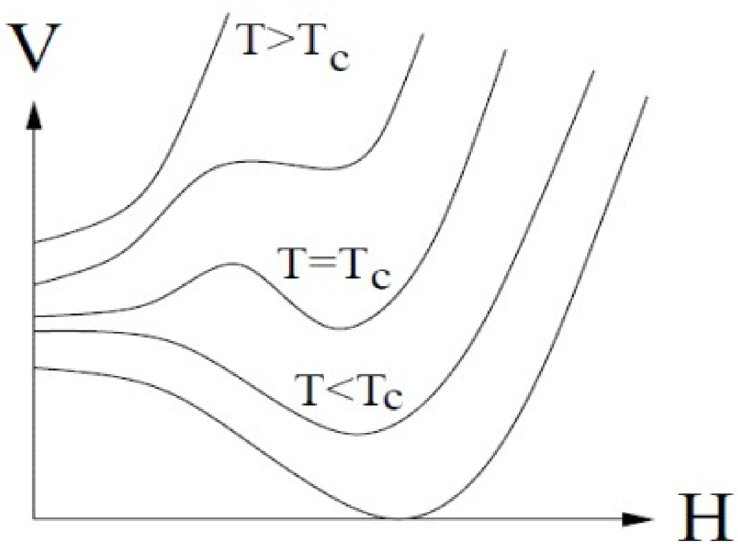
$$\Gamma_{\rm sph} \sim e^{-E_{\rm sph}/T}$$

Departure from Thermal Equilibrium in SM

- Should be out of thermal equilibrium before/when sphalerons become ineffective, otherwise asymmetry washed out

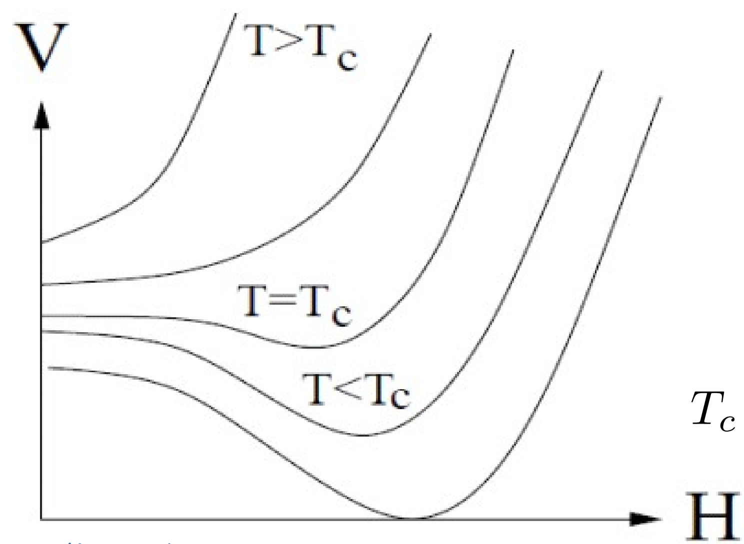
- Possible via EWPhT, if strong enough first order

1st order



$T_c : V(H^1_{\mathrm{min}}) = V(H^2_{\mathrm{min}})$

2nd order



$T_c : V''(0) = 0$

Cline, ph-0609145

Departure from Thermal Equilibrium in SM

- Strength of (1st order) PhT: v_c/T_c - sufficient?

$v_c \equiv \langle \phi(T_c) \rangle$

$$\Gamma_{\rm sph} \sim e^{-E_{\rm sph}/T} \qquad \frac{E_{\rm sph}}{T} \sim \frac{8\pi}{g}\frac{v}{T}$$

→ the stronger the PhT, the less the washout

→ require $\xi \equiv \dfrac{v_c}{T_c} \gtrsim 1$

- Calculate in finite-T QFT

SM: $\dfrac{v_c}{T_c} \cong \dfrac{3g^2}{16\pi\lambda} \Rightarrow \lambda < 3g^3/16\pi \quad \Rightarrow m_h < 32\,\mathrm{GeV}$

Departure from Thermal Equilibrium in SM

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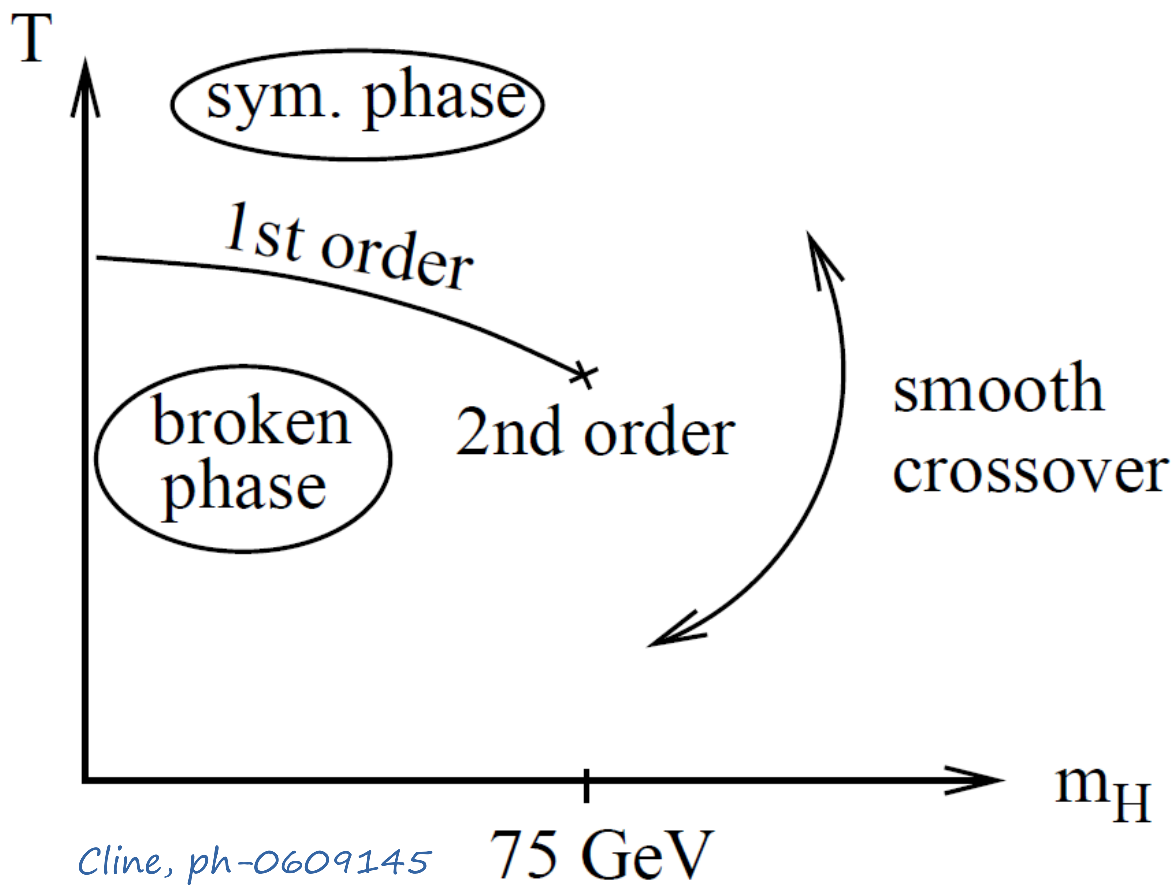


C and CP Violation in SM

- CKM mechanism (complex Yukawas) → CP violation

- quantitatively too small:

$$I_{\rm CP} = {\rm Im}\,\det[m_u^2, m_d^2] = 2 J_{\rm CKM} \prod (m_i^{u\,2} - m_j^{u\,2}) \prod (m_i^{d\,2} - m_j^{d\,2})$$

$$\mathrm{Im}\left[(V_{\rm CKM})_{ij}(V_{\rm CKM})_{kl}(V^*_{\rm CKM})_{il}(V^*_{\rm CKM})_{kj}\right] = J_{\rm CKM} \sum_{m,n=1}^{3} \epsilon_{ikm}\epsilon_{jln} \quad (i,j,k,l = 1,2,3)$$

- Jarlskog invariant $J_{\rm CKM} \sim 10^{-5} \ll 1$

Jarlskog, PRL 55 1039 (1985)

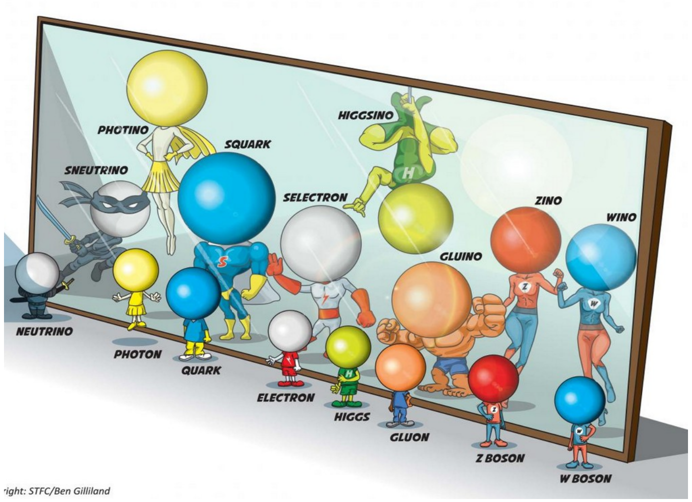
Electroweak Baryogenesis in SM...

... lacks enough CP violation and strong 1^{st} order PhT (SFOPhT)...

$\rightarrow$ Physics Beyond the SM!

Big "UV-Complete" Models

Supersymmetry



- New Scalars → SFOPhT ✓
- New CP violating Interactions ✓
- Tension with LHC Data… → nMMSM?

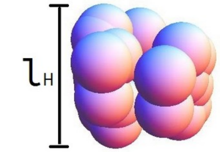
Pietroni, hep-ph/9207227
Menon, Morrissey, Wagner, hep-ph/0404184
Huber, Konstandin, Prokopec, Schmidt, hep-ph/0606298
Katz, Perelstein, Ramsey-Musolf, Winslow, 1509.02934
…

Composite Higgs Models

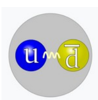
Kaplan, Georgi, Dimopoulos,. . .

- Higgs is composite at small distances

  ➡ m_H saturated in IR ➡ Hierarchy Problem solved

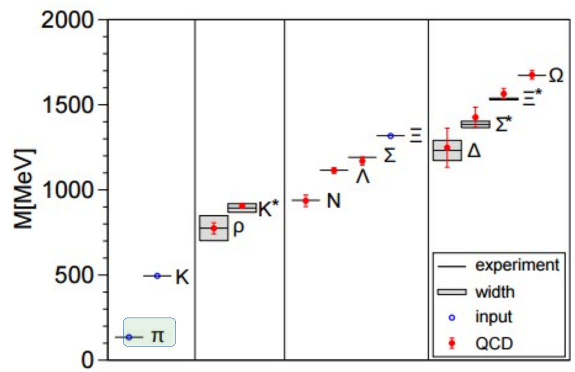


- Higgs = (pseudo) Goldstone Boson ➡ $m_H \ll m_\rho$

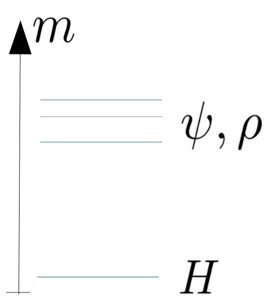


like pions in QCD

$$SU(2)_L \times SU(2)_R \xrightarrow{\langle \bar{q} q \rangle \neq 0} SU(2)_V$$



0906.3599



- Minimal models: SO(5)→SO(4) *Contino, Nomura, Pomarol, ph/0306259* *Agashe, Contino, Pomarol, ph/0412089*

→ 4 Goldstones, custodial symmetry $SO(4) \cong SU(2)_L \times SU(2)_R$

Naturally address

- Hierarchical Flavor Structure
- Dynamical EWSB
- Tiny Neutrino Masses

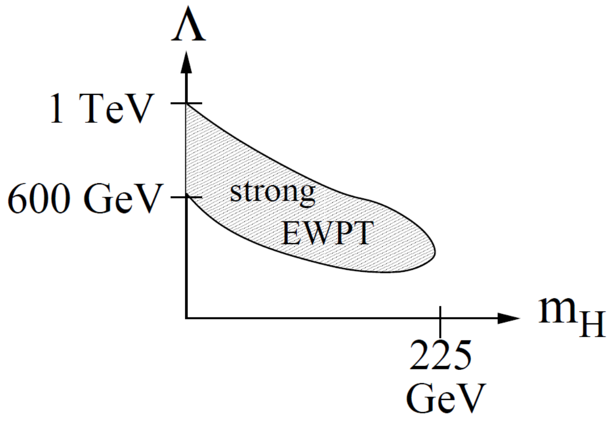
$\dim[SO(5)/SO(4)] = 4$ GB

Composite Higgs Models

- D=6 operator $V(H) = \mu^2 |H|^2 + \lambda |H|^4 + \frac{|H|^6}{\Lambda^2}$

can trigger SFOPhT

Grojean, Servant, Wells, hep-ph/0407019
Delaunay, Grojean, Wells, 0711.2511
Grinstein, Trott, 0806.1971
Goertz, 1504.00355
...

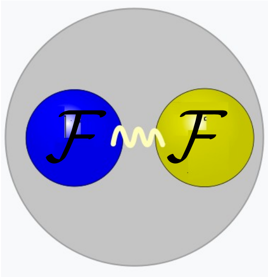


Emerges in minimal composite Higgs, however not completely straightforward to obtain viable parameters, low f...

→ scalar extension?!

Minimal "4D-Complete" Composite Higgs

- New confining force breaks $G \to H$ spontaneously via condensation of charged fermions $\langle \bar{\mathcal{F}}\mathcal{F} \rangle \neq 0$



→ Goldstone Higgs

- *Minimal example:* confining $G_{\mathrm{TC}} = Sp(N)_{\mathrm{TC}}$, with $N_F = 4$ TC-charged Weyl fermions

Barnard, Gherghetta, Ray 1311.6562
Ferretti, Karateev, 1312.5330
Cacciapaglia, Sannino 1402.0233
Vecchi, 1506.00623
Ma, Cacciapaglia, 1508.07014
Cacciapaglia, Pica, Sannino, 2002.04914

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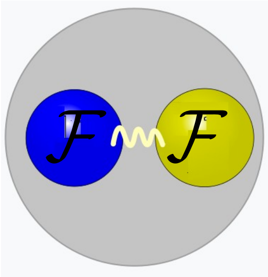

→ Goldstone Higgs

- Minimal example: confining $G_{\rm TC} = Sp(N)_{\rm TC}$, with $N_F = 4$ TC-charged Weyl fermions

- Condensate $\langle \mathcal{F}^a \epsilon_{\rm TC} \mathcal{F}^b \rangle = \Lambda_c f^2 \Sigma_\theta^{ab}$ $\to$ $SO(6) \to SO(5)$

Σ_θ matrix: alignment of vacuum with $\mathrm{Sp}(4) \cong SO(5)$

⇒ No $SO(5) \to SO(4)$!

→ 5 Goldstons: Higgs + EW Singlet $\eta \equiv \Pi_5$

$$\Sigma(x) = \exp\left[i \frac{2\sqrt{2}}{f} \Pi_{\hat{a}}(x) T_\theta^{\hat{a}} \right] \Sigma_\theta$$

Barnard, Gherghetta, Ray 1311.6562
Ferretti, Karateev, 1312.5330
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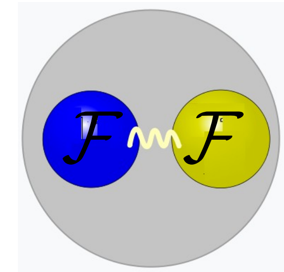
Minimal "4D-Complete" SO(6)/SO(5)



- Interesting Model-Building opportunities due to additionally emerging singlet pNGB η:

- Could be (naturally light) **Dark Matter**

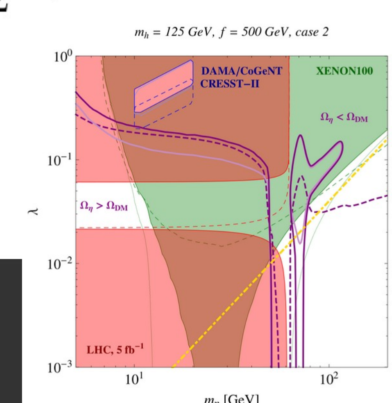
  $SO(6) \to SO(5)$ + preserved parity $P_\eta : \eta -> -\eta$

  Frigerioa, Pomarol, Riva, Urbano, 1204.2808

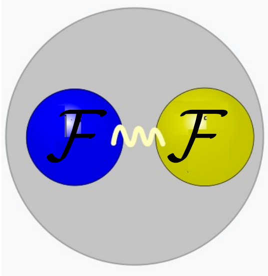
- Interesting Interactions beyond standard scalar portal $H^2 S^2$

$$\mathcal{L}_\eta = \frac{1}{2}(\partial_\mu \eta)^2 - V(\eta, H) + \frac{1}{2f^2}\left(\partial_\mu |H|^2 + \frac{1}{2}\partial_\mu \eta^2\right)^2 \qquad V(\eta, H) = \frac{1}{2}\mu_\eta^2 \eta^2 + \lambda |H|^2 \eta^2 + \cdots$$

$$+ \frac{\eta^2}{f^2}\left(c_t y_t \, \overline{q_L} \tilde{H} t_R + \cdots\right)$$



Minimal "4D-Complete" SO(6)/SO(5)



- Interesting Model-Building opportunities due to additionally emerging singlet pNGB η:

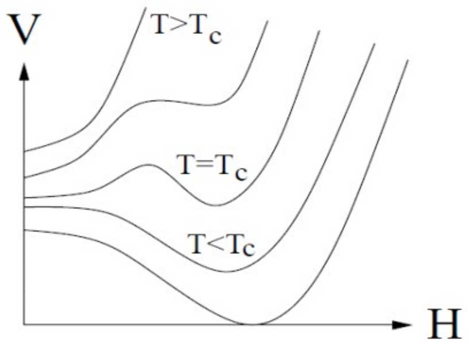
- Could trigger Strong First Order Electroweak Phase Transition and induce new sources of CP violation

$$\frac{s}{f} H \bar{Q}_3 (a + i b \gamma_5) t$$

- Combined 2-field evolution, can lead to SFOEWPhT..

$$V(h,s,T) = \frac{\lambda_h}{4}\left[h^2 - v_c^2 + \frac{v_c^2}{w_c^2} s^2\right]^2 + \frac{\kappa}{4} s^2 h^2 + \frac{1}{2}(T^2 - T_c^2)(c_h\, h^2 + c_s\, s^2)\ ,$$

Espinosa, Gripaios, Konstandi
Riva, 1110.2876



$\eta \equiv s$

$w \equiv \langle s \rangle \qquad \kappa \equiv \lambda_m - 2\lambda_h \frac{v_c^2}{w_c^2}$

The Inert Doublet Model

https://www.facebook.com/getirelandactive

https://tips4tech.wordpress.com/2012/07/02/summer-online-security/

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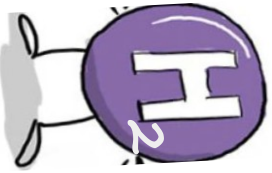

The Inert Doublet Model

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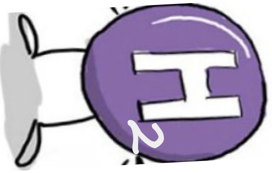
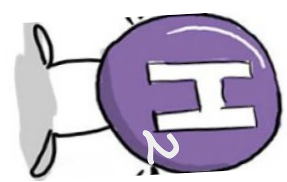


- **Minimal** SM Extension with various interesting features
- Offers a simple, predictive, yet versatile playground
- Can already do a lot concerning open questions of SM

The Inert Doublet Model

https://www.facebook.com/getirelandactive

https://tips4tech.wordpress.com/2012/07/02/summer-online-security/



Z_2	even	odd
vev [GeV] (T=0)	246	0
Yukawa int.	$Y_{u,SM}$, $Y_{d,SM}$	x
	SM-like	DM candidate

Deshpande, Ma, Phys. Rev. D 18
Barbieri, Hall, Rychkov, hep-ph/0603188
Lopez Honorez, Nezri, Oliver, Tytgat, hep-ph/0612275

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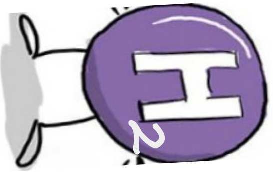

$$H_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ h + i\phi \end{pmatrix} \qquad H_2 = \begin{pmatrix} H^+ \\ (H + iA)/\sqrt{2} \end{pmatrix}$$

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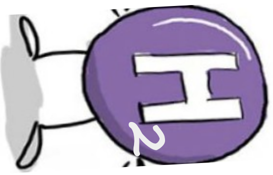
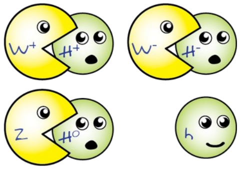


$$H_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ h + i\phi \end{pmatrix} \qquad H_2 = \begin{pmatrix} H^+ \\ (H + iA)/\sqrt{2} \end{pmatrix}$$

$\langle h \rangle \equiv v \approx 246$

→ EWSB


quantumdiaries.org

5 physical scalars: $\{h, H^\pm, H, A\}$

The Inert Doublet Model

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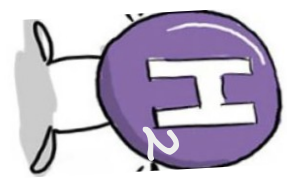

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$$H_2 = \begin{pmatrix} H^+ \\ (H + iA)/\sqrt{2} \end{pmatrix}$$

DM

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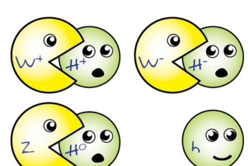
→ EWSB



quantumdiaries.org

$$\text{5 physical scalars: } \{h, H^\pm, H, A\}$$

The Inert Doublet Model

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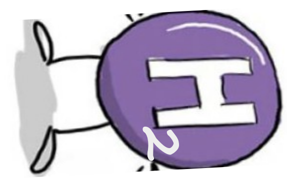


$$\mathcal{L} = \mathcal{L}_{\text{SM}} \;+\; (D_\mu H_2)^\dagger D^\mu H_2$$

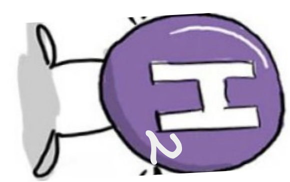
$$V(H) \to V(H_1, H_2) = \mu_1^2 \left|H_1\right|^2 + \mu_2^2 \left|H_2\right|^2 + \lambda_1 \left|H_1\right|^4 + \lambda_2 \left|H_2\right|^4 + \lambda_3 \left|H_1\right|^2 \left|H_2\right|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]$$

$\to$ 5 new, real paramters, no $\cancel{C}$P

Masses

https://www.facebook.com/getirelandactive

https://tips4tech.wordpress.com/2012/07/02/summer-online-security/



$$M_S^2 = \begin{pmatrix} \overset{m_h}{\boxed{2\lambda_1 v^2}} & 0 \\ 0 & \underset{m_H}{\boxed{\lambda_{345} v^2/2 + \mu_2^2}} \end{pmatrix}, \quad M_P^2 = \frac{1}{2}\begin{pmatrix} 0 & 0 \\ 0 & \underset{m_A}{\boxed{\bar{\lambda}_{345} v^2 + 2\mu_2^2}} \end{pmatrix}, \quad M_\pm^2 = \frac{1}{2}\begin{pmatrix} 0 & 0 \\ 0 & \underset{m_H^\pm}{\boxed{\lambda_3 v^2 + 2\mu_2^2}} \end{pmatrix}$$

$$\lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5$$

$$\bar{\lambda}_{345} \equiv \lambda_3 + \lambda_4 - \lambda_5 = \lambda_{345} - 2\lambda_5$$

$$\xi = 0$$

Masses

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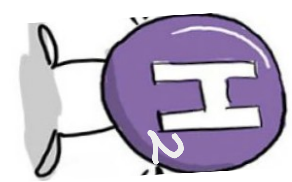

m_h

$$M_S^2 = \begin{pmatrix} 2\lambda_1 v^2 & 0 \\ 0 & \lambda_{345} v^2/2 + \mu_2^2 \end{pmatrix}, \quad M_P^2 = \frac{1}{2}\begin{pmatrix} 0 & 0 \\ 0 & \bar{\lambda}_{345} v^2 + 2\mu_2^2 \end{pmatrix}, \quad M_\pm^2 = \frac{1}{2}\begin{pmatrix} 0 & 0 \\ 0 & \lambda_3 v^2 + 2\mu_2^2 \end{pmatrix}$$

m_H m_A $m_H^{\pm}$

$$\lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5$$

$$\bar{\lambda}_{345} = \lambda_{345} - 2\lambda_5$$

$$\lambda_3 = \lambda_{345} + 2\frac{m_{H^\pm}^2 - m_H^2}{v^2}, \quad \lambda_4 = \frac{m_A^2 + m_H^2 - 2m_{H^\pm}^2}{v^2}, \quad \lambda_5 = \frac{m_H^2 - m_A^2}{v^2}$$

The Inert Doublet Model

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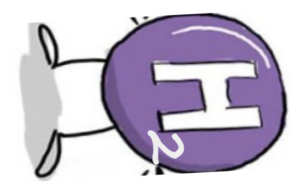

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5 free parameters: $\{\lambda_2, \lambda_{345}, m_{H\pm}, m_H, m_A\}$

The Inert Doublet Model

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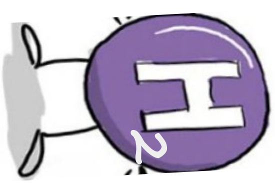


(incomplete) list of relevant recent literature:

Dolle, Su, 0906.1609
Chowdhury, Nemevsek, Senjanovic, Zhang, 1110.5334
Borah, Cline, 1204.4722,
Gil, Chankowski, Krawczyk, 1207.0084
Cline, Kainulainen, 1302.2614
Blinov, Profumo, Stefaniak, 1504.05949,
Ilnicka, Krawczyk, Robens, 1508.01671
Belyaev, Cacciapaglia, Ivanov, Rojas-Abatte, Thomas, 1612.00511
Banerjee, Boudjema, Chakrabarty, Sun, 2101.02165, 2101.02166, 2101.02167, 2101.02170

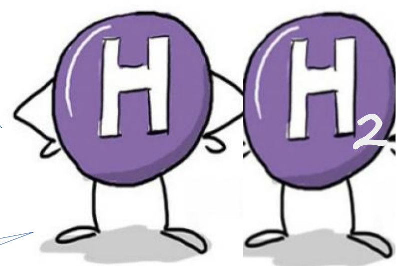
5 free parameters: $\{\lambda_2, \lambda_{345}, m_{H^\pm}, m_H, m_A\}$

Theoretical Constraints

Vacuum Stability

$$\lambda_1 > 0\,, \quad \lambda_2 > 0\,, \quad \lambda_3 > -2\sqrt{\lambda_1 \lambda_2}$$

$$\lambda_3 + \lambda_4 - |\lambda_5| > -2\sqrt{\lambda_1 \lambda_2}$$



Perturbative Unitarity

$$c_{1,2} = \lambda_3 \pm \lambda_4$$

$$c_{3,4} = -3\lambda_1 - 3\lambda_2 \pm \sqrt{9\left(\lambda_1 - \lambda_2\right)^2 + \left(2\lambda_3 + \lambda_4\right)^2}$$

$$c_{5,6} = \lambda_3 \pm \lambda_5$$

$$c_{7,8} = -\lambda_1 - \lambda_2 \pm \sqrt{\left(\lambda_1 - \lambda_2\right)^2 + \lambda_5^2}$$

$$c_{9,10} = \lambda_3 + 2\lambda_4 \pm 3\lambda_5$$

$$c_{11,12} = -\lambda_1 - \lambda_2 \pm \sqrt{\left(\lambda_1 - \lambda_2\right)^2 + \lambda_4^2}$$

$$|c_i| < 8\pi$$

Charge-Conserving Vacuum

$$\lambda_4 - |\lambda_5| < 0$$

→ Implement in Numerical Analysis

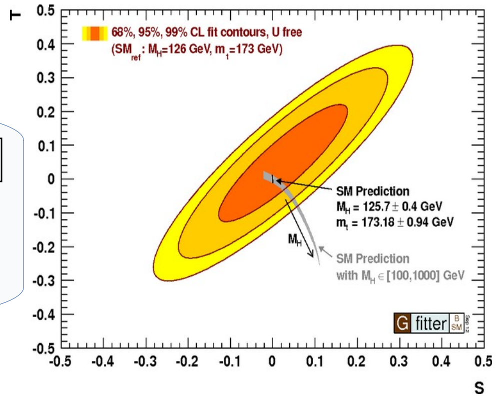
Precision Tests, ...

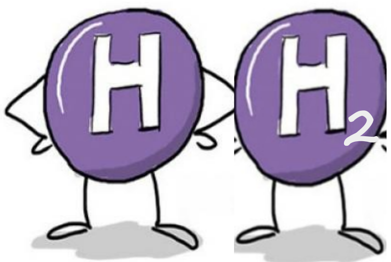
$$S=\frac{1}{72\pi\left(x_2^2-x_1^2\right)^3}\left[x_2^6 f_a\left(x_2\right)-x_1^6 f_a\left(x_1\right)+9x_1^2x_2^2\left(x_2^2 f_b\left(x_2\right)-x_1^2 f_b\left(x_1\right)\right)\right]$$

$$T=\frac{1}{32\pi^2\alpha v^2}\left[f_c\left(m_{H^\pm}^2,m_A^2\right)+f_c\left(m_{H^\pm}^2,m_H^2\right)-f_c\left(m_A^2,m_H^2\right)\right]$$

$$f_a\left(x\right)\equiv-5+12\ln x \qquad f_b\left(x\right)\equiv 3-4\ln x \qquad x_1\equiv\frac{m_H}{m_{H^\pm}},\; x_2\equiv\frac{m_A}{m_{H^\pm}}$$

$$f_c\left(x,y\right)\equiv\begin{cases}\frac{x+y}{2}-\frac{xy}{x-y}\ln\frac{x}{y} & \text{for } x\neq y\\ 0 & \text{for } x=y\end{cases}$$





$$W^\pm\to H^\pm H,\ldots$$

$$\Gamma\left(h\to\text{inv.}\right)=\frac{\left(\lambda_{345}m_W\right)^2}{8\pi g^2 m_h}\sqrt{1-4\left(\frac{m_H}{m_h}\right)^2}$$

$$\text{BR}\left(h\to\text{inv.}\right)<\begin{cases}0.26 \text{ from ATLAS}\\ 0.19 \text{ from CMS}\end{cases}$$

W,Z decay widths

$$m_H+m_{H^\pm}>m_{W^\pm}$$
$$m_A+m_{H^\pm}>m_{W^\pm}$$
$$m_H+m_A>m_Z$$
$$2m_{H^\pm}>m_Z$$

→ Implement in Numerical Analysis

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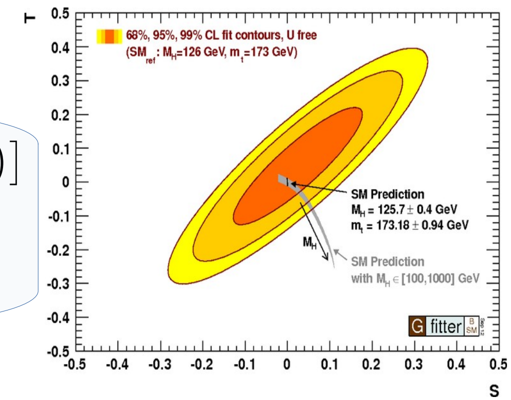
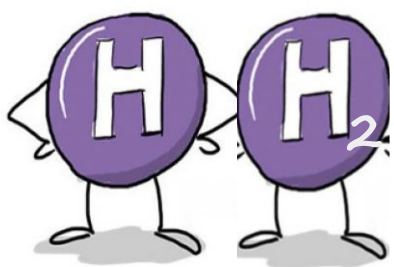
$$T = \frac{1}{24\pi^2 \alpha v^2}(m_{H^\pm} - m_H)(m_{H^\pm} - m_A) \xrightarrow{m_{H^\pm} \to m_A} 0$$





$$W^\pm \to H^\pm H, \ldots$$

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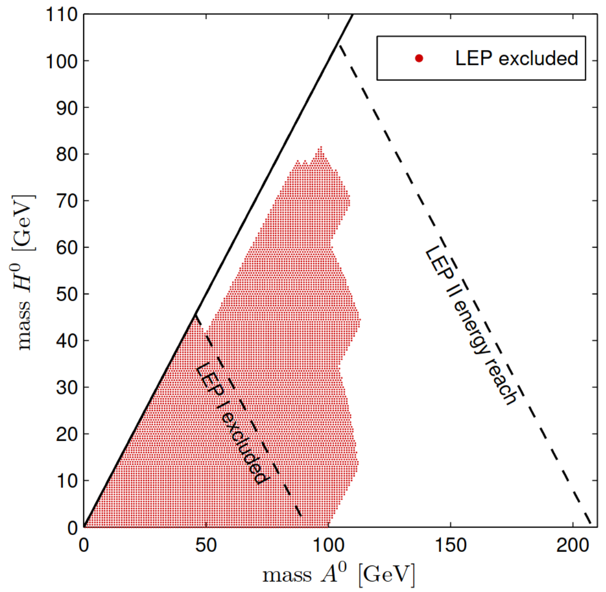
$\longrightarrow$ Implement in Numerical Analysis

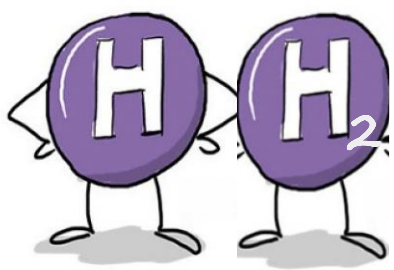
LEPII recast

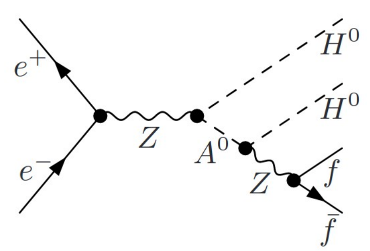


Lundstrom, Gustafsson, Edsjo, 0810.3924

$m_{H^\pm} > 70$

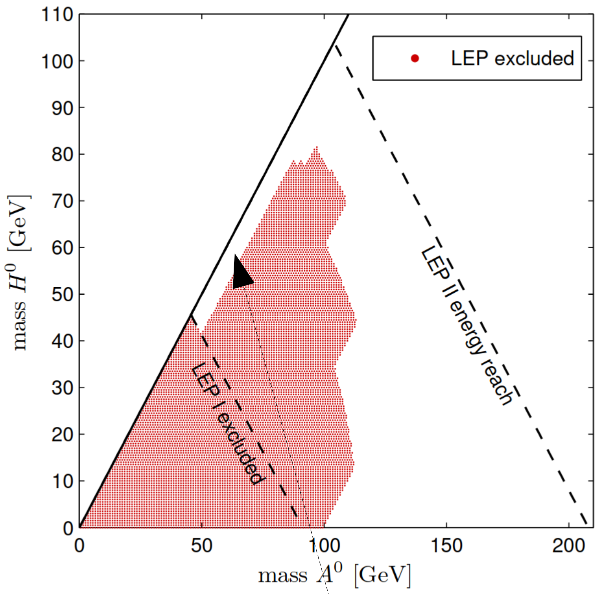
$m_H > 80\,\text{GeV} \;\cup\; m_A > 100\,\text{GeV} \;\cup\; m_A - m_H < 8\,\text{GeV}$





→ Implement in Numerical Analysis

LEPII recast



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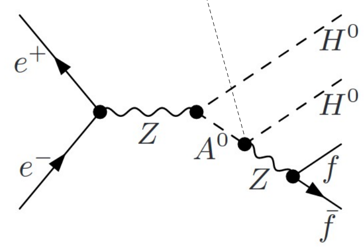

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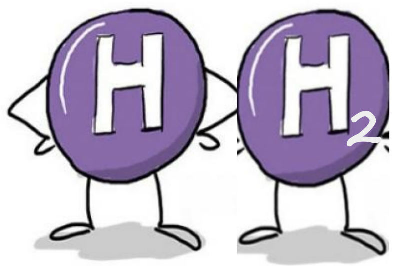

→ Implement in Numerical Analysis

IDM

IDM Dark Matter

IDM Dark Matter

$$H_2 = \begin{pmatrix} H^+ \\ (H + iA)/\sqrt{2} \end{pmatrix}$$

same with $\lambda_{345} \leftrightarrow \bar{\lambda}_{345}$

IDM Dark Matter

$$H_2 = \begin{pmatrix} H^+ \\ (H + iA)/\sqrt{2} \end{pmatrix}$$

Boltzman Equation

$$\frac{dn_H}{dt} = -3Hn_H - \langle\sigma_{\rm eff}v\rangle\left[n_H^2 - (n_H^{\rm eq})^2\right]$$

$$\langle\sigma_{\rm eff}v\rangle \equiv \sum_{j=1}^{N}\langle\sigma v\rangle_{Hj}\frac{n_H^{\rm eq}n_j^{\rm eq}}{(n^{\rm eq})^2}$$

co-annihilations

(quite natural for weak multiplets)

$$n^{\rm eq} = \sum_i n_i^{\rm eq} = \frac{T}{2\pi^2}\sum_i g_i m_i^2 K_2\left(\frac{m_i}{T}\right)$$

Relic Abundance (w/ co-annihilations)

Boltzman Equation

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co-annihilations
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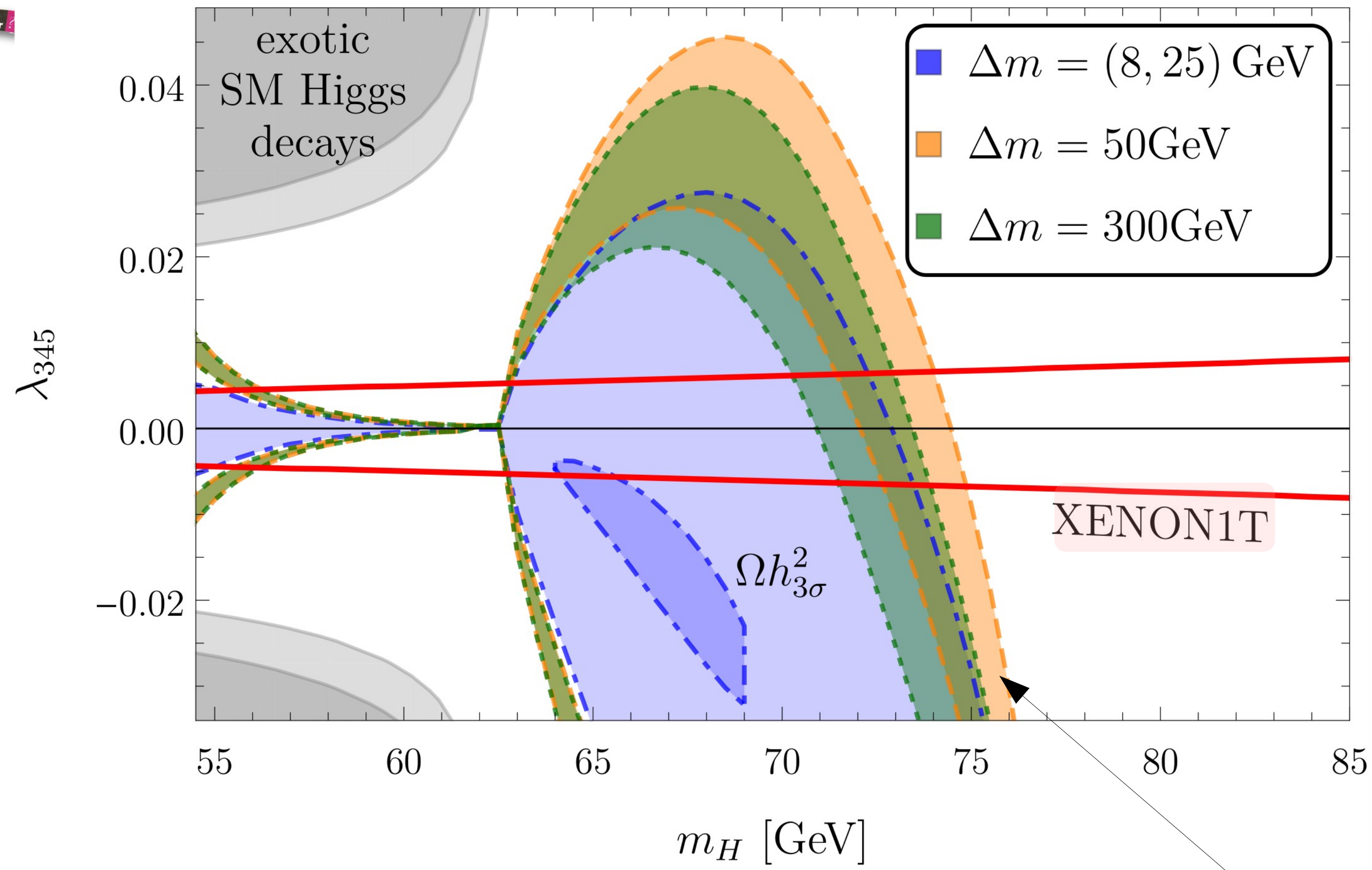
CalcHEP
Micromegas

Relic Abundance (w/ co-annihilations)

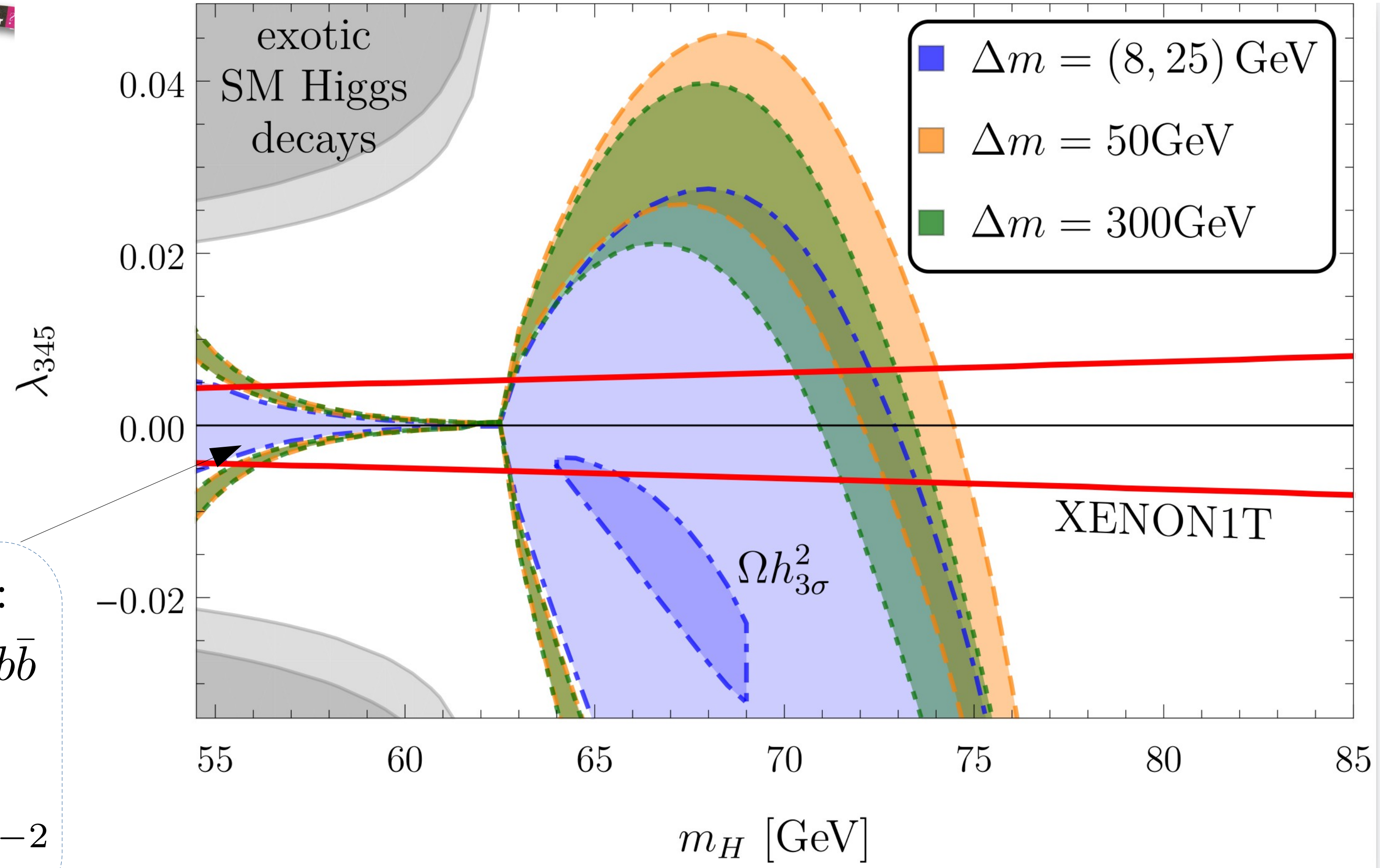
$\Delta m \equiv m_{A,H^\pm} - m_H$



$\Omega h^2_{\rm best} = 0.1200(12)$

$0.6\Omega h^2_{\rm best} < \Omega h^2 < \Omega h^2_{\rm best} + 3\sigma$

Relic Abundance (w/ co-annihilations)



$m_{\rm DM} < m_h/2$:

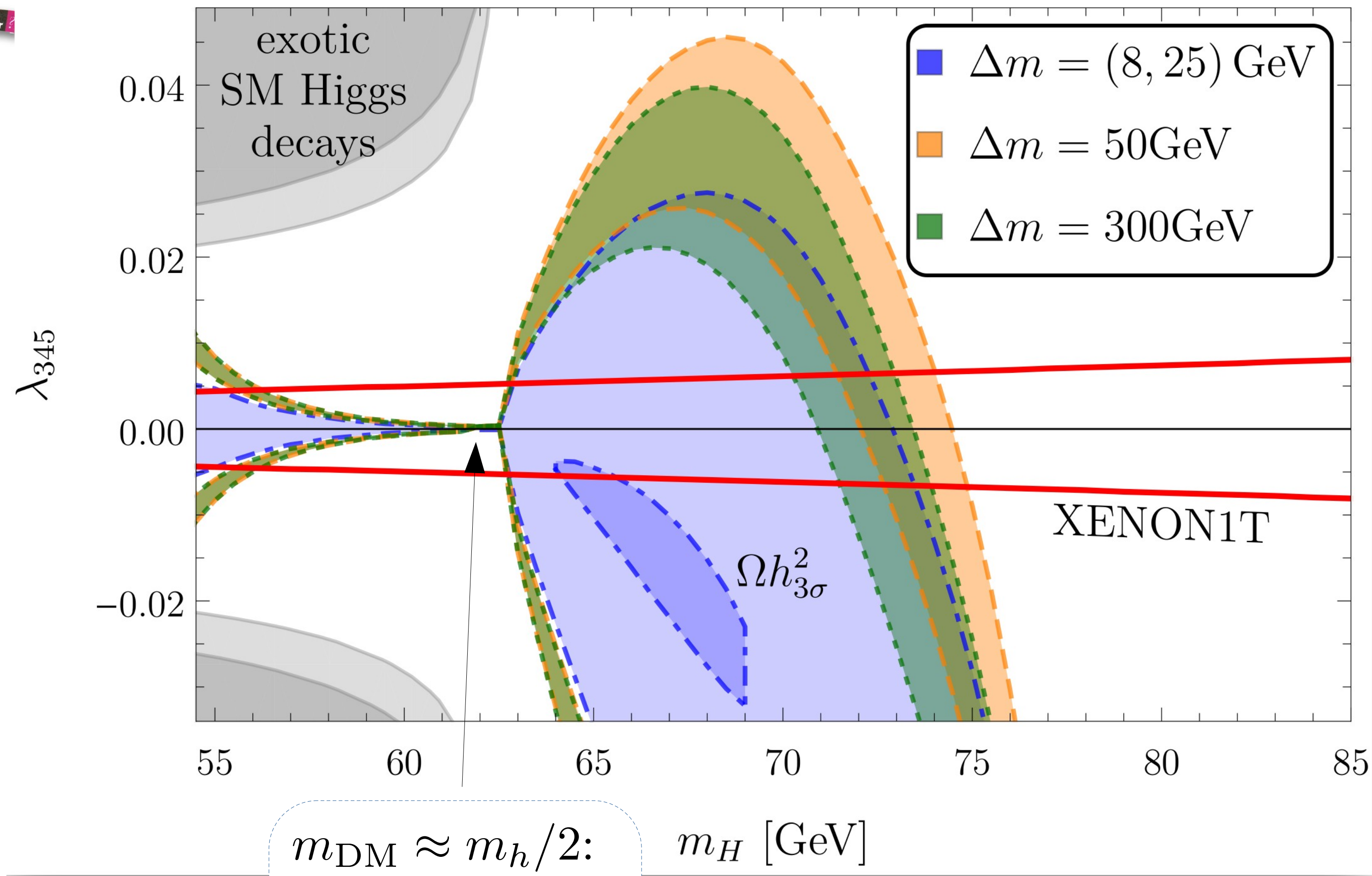
$HH \to h^* \to b\bar{b}$

$g_{HHh} \sim v\lambda_{345}$

$\Omega h^2 \propto |\lambda_{345}|^{-2}$

$0.6\Omega h^2_{\rm best} < \Omega h^2 < \Omega h^2_{\rm best} + 3\sigma$

Relic Abundance (w/ co-annihilations)



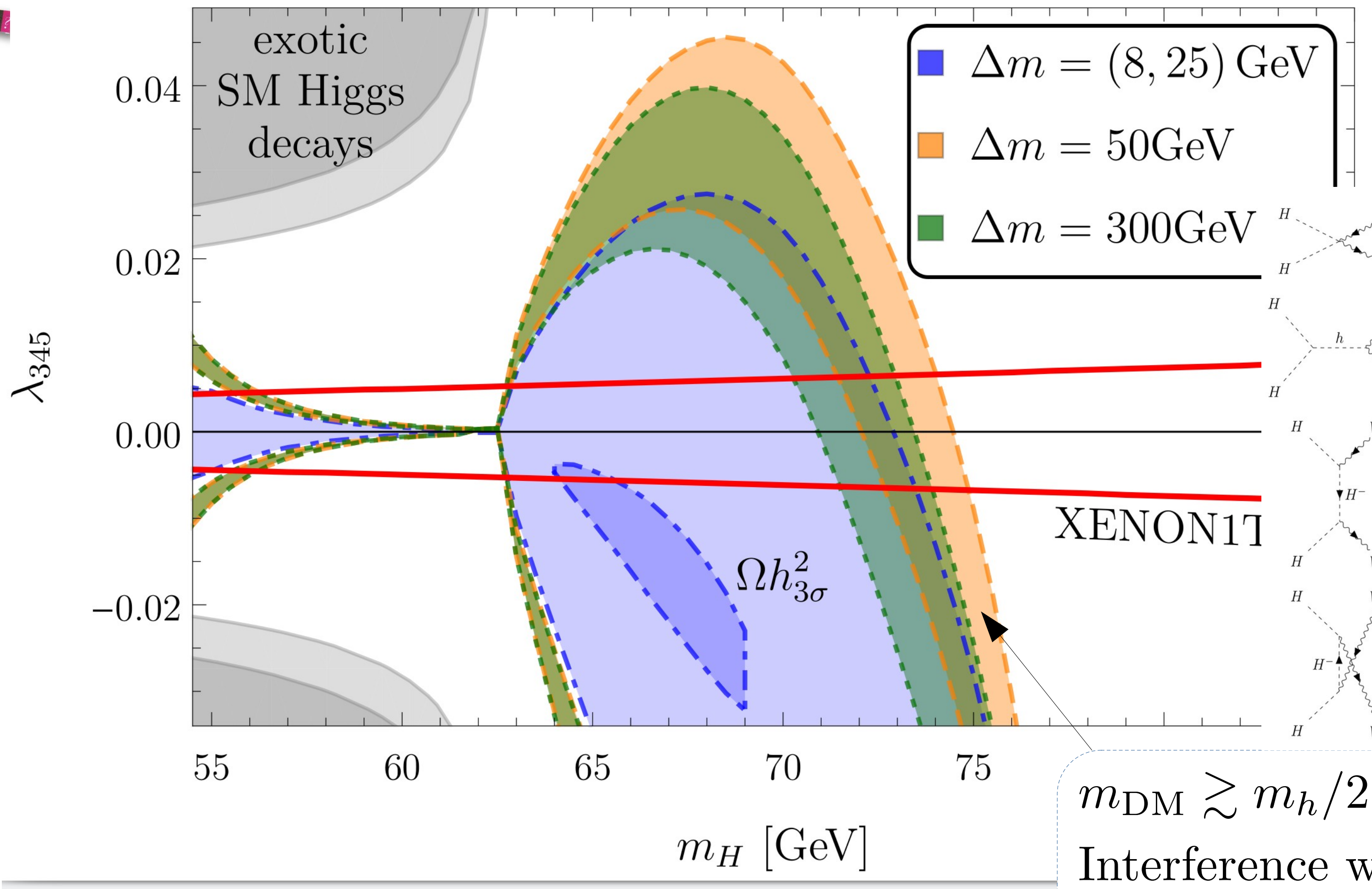
$m_{\rm DM} \approx m_h/2$:

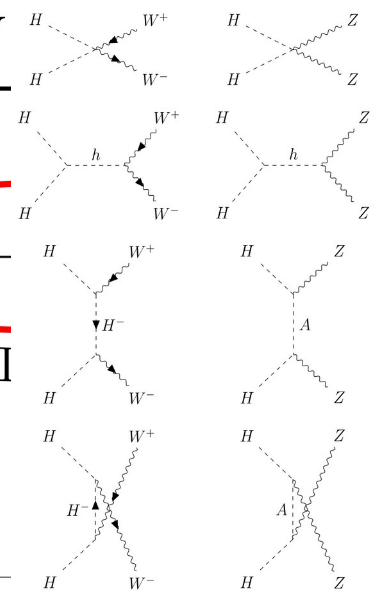
$HH \to h^* \to b\bar{b}$

Resonant Enhancement

$0.6\Omega h^2_{\rm best} < \Omega h^2 < \Omega h^2_{\rm best} + 3\sigma$

Relic Abundance (w/ co-annihilations)

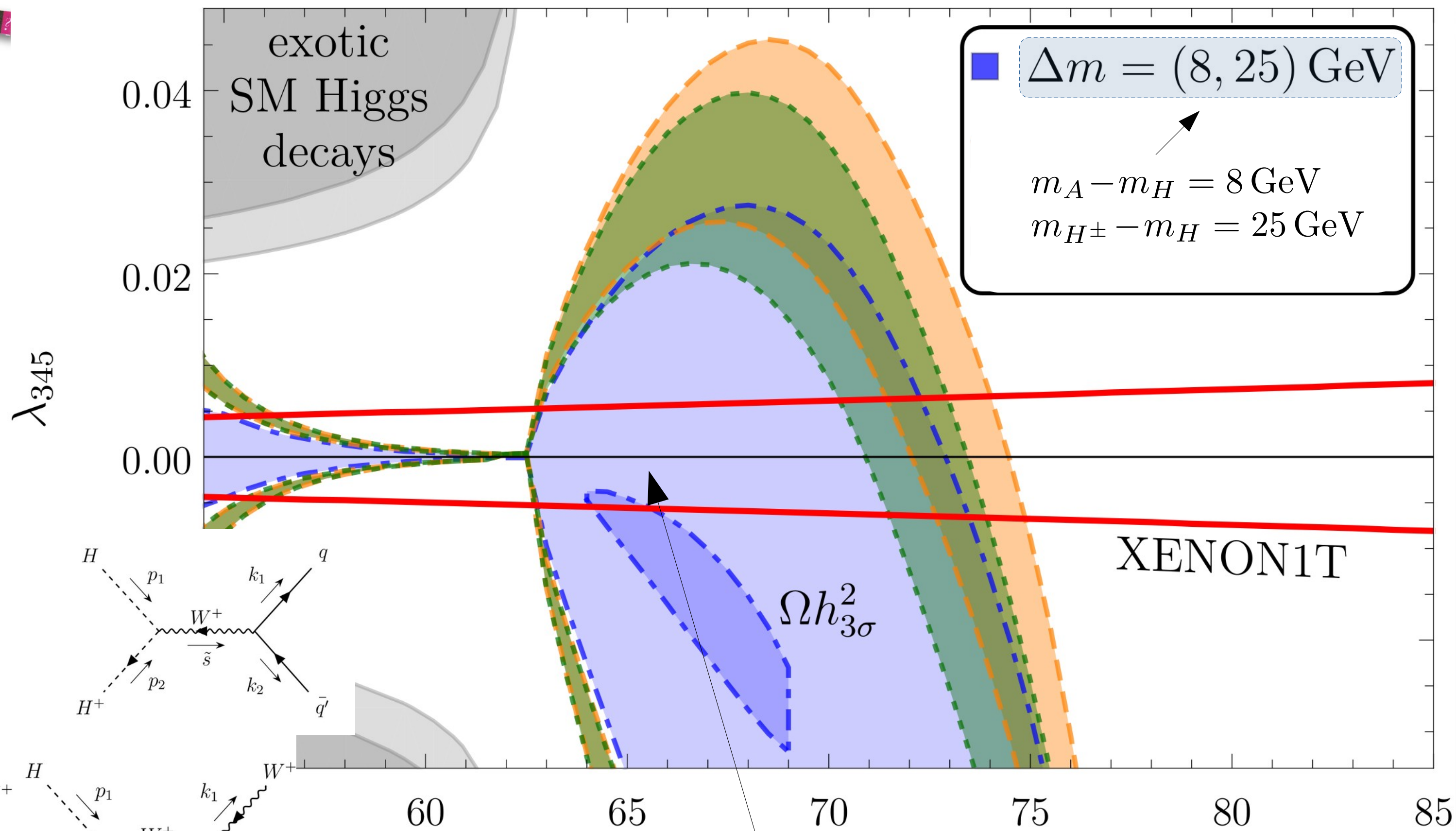


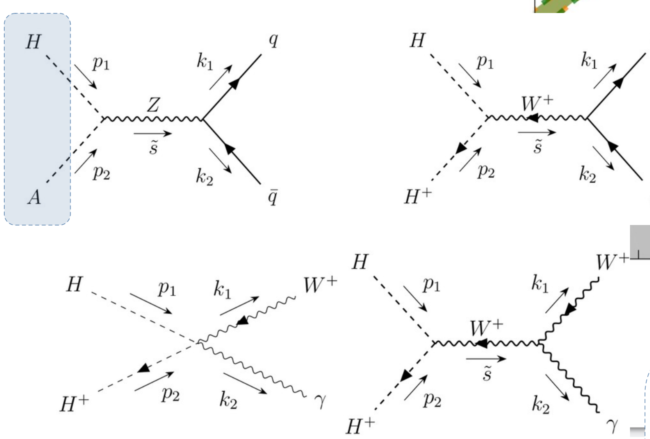


$m_{\mathrm{DM}} \gtrsim m_h/2$:
Interference with
$HH \to W^{-*}W^+$
$HH \to Z^*Z$

Small Splittings -> Co-annihilations

LEPII: $m_H > 80\,\mathrm{GeV} \,\cup\, m_A > 100\,\mathrm{GeV} \,\cup\, m_A - m_H < 8\,\mathrm{GeV}$





S. Fabian, master's thesis

<u>Co-annihilations</u>:

Sizable new region in agreement with DD!
Evade LEPII constraints
& too strong co-annih.
via *non-trivial* splitting

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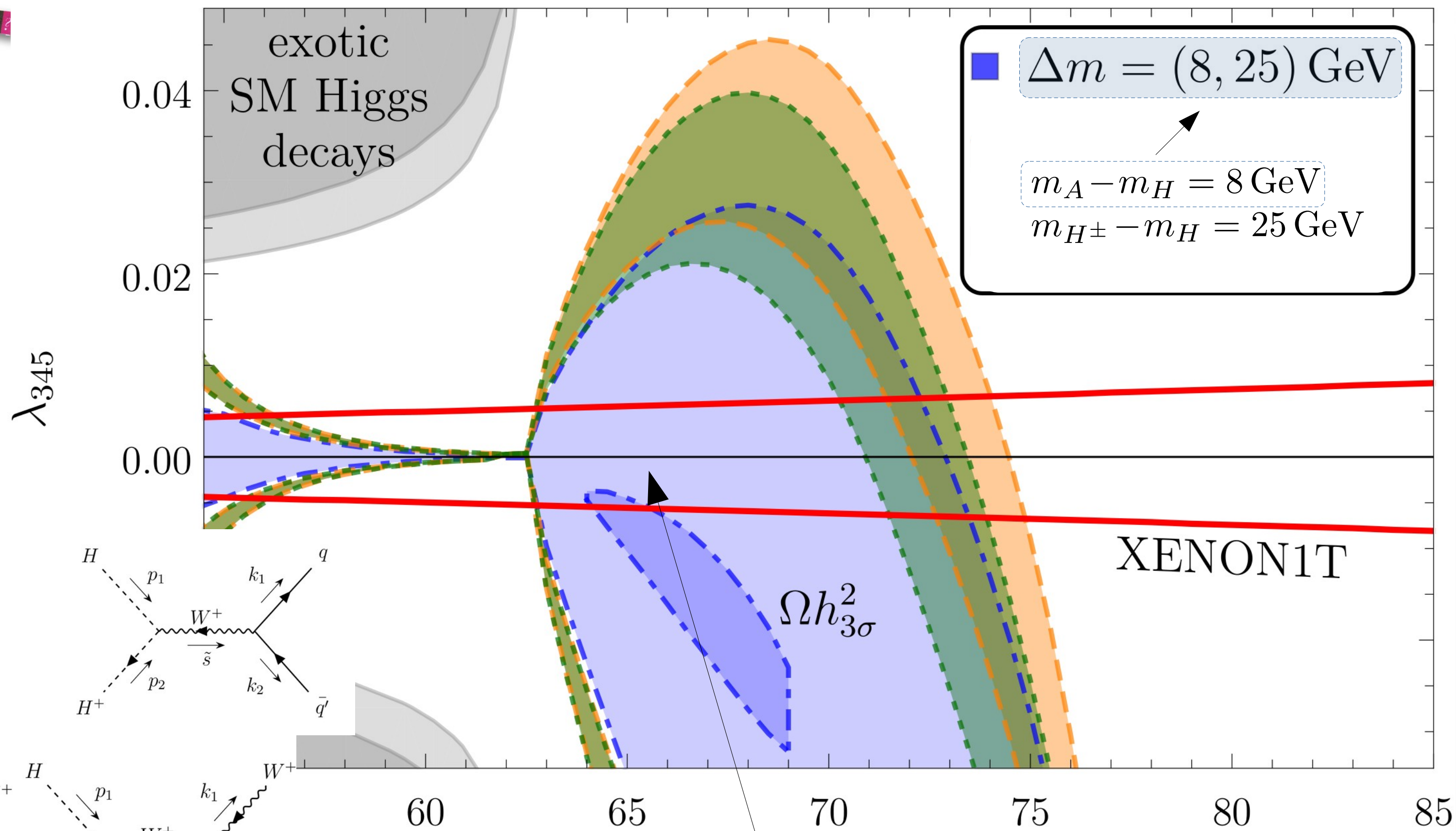

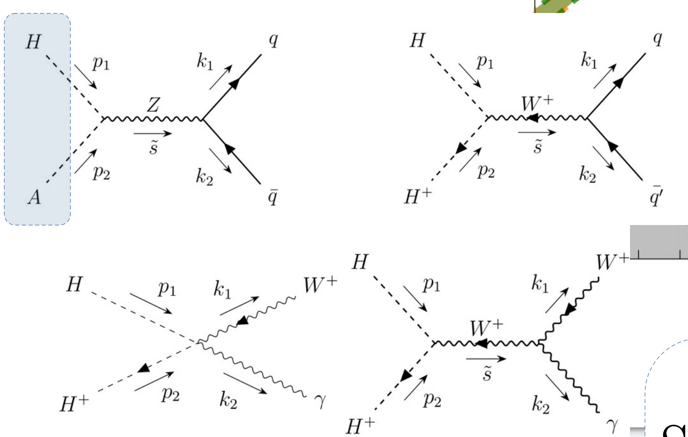

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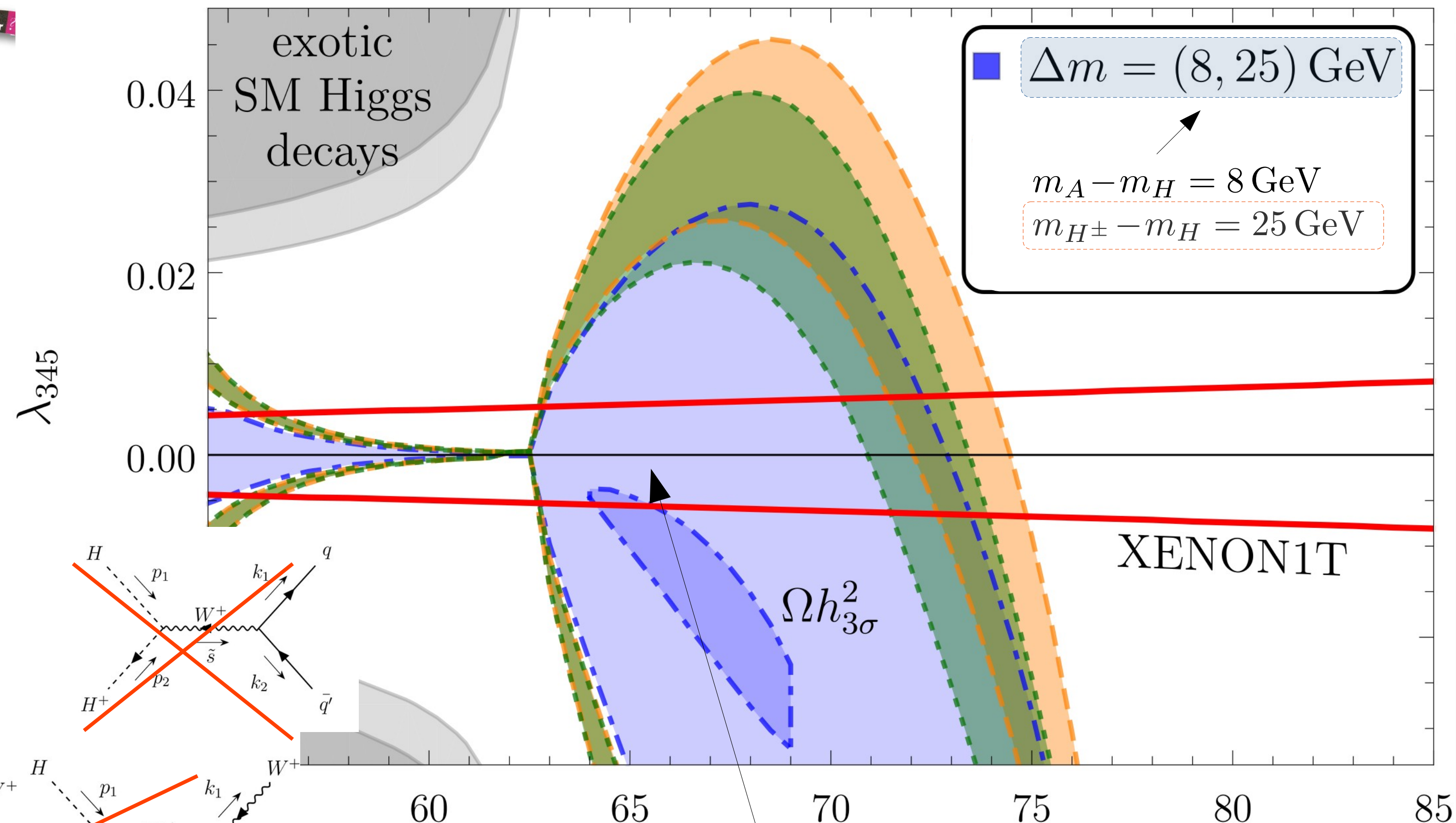
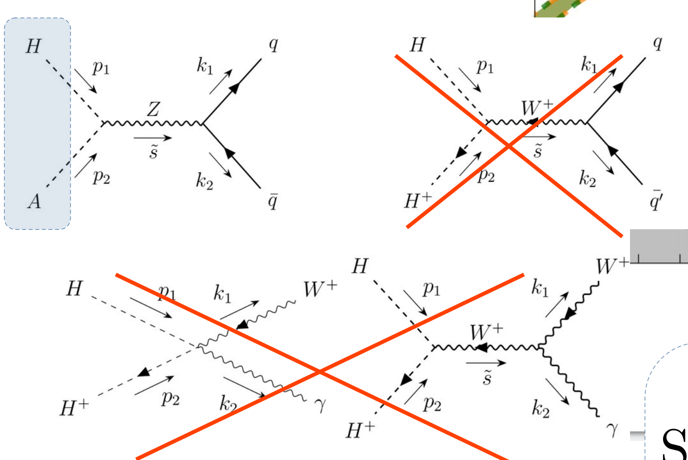
LEPII: $m_H > 80\,\mathrm{GeV} \,\cup\, m_A > 100\,\mathrm{GeV} \,\cup\, m_A - m_H < 8\,\mathrm{GeV}$





S. Fabian, master's thesis

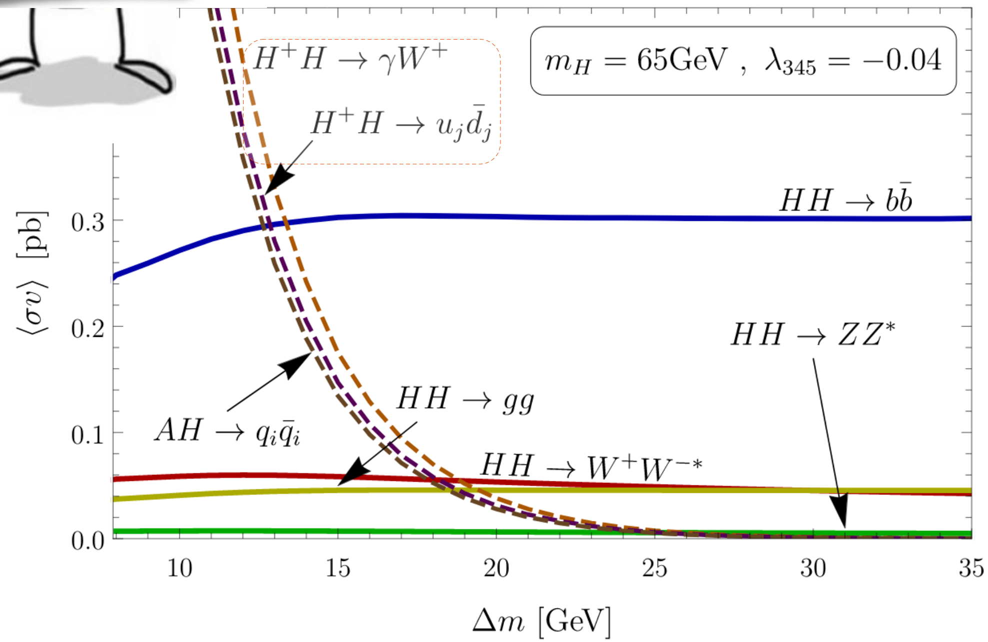
Co-annihilations:

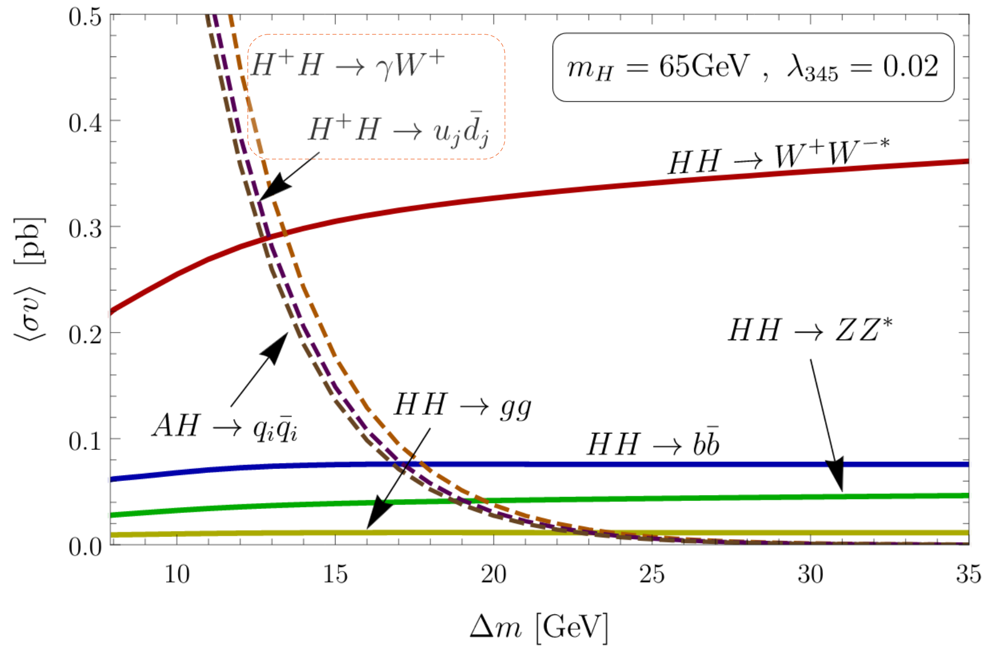
Sizable new region in agreement with DD!
Evade LEPII constraints
& too strong co-annih.
via *non-trivial* splitting

Small Splittings -> Co-annihilations

$m_A - m_H = 8\,\mathrm{GeV}$

$m_{H^\pm} - m_H = 25\,\mathrm{GeV}$





Co-annihilations:

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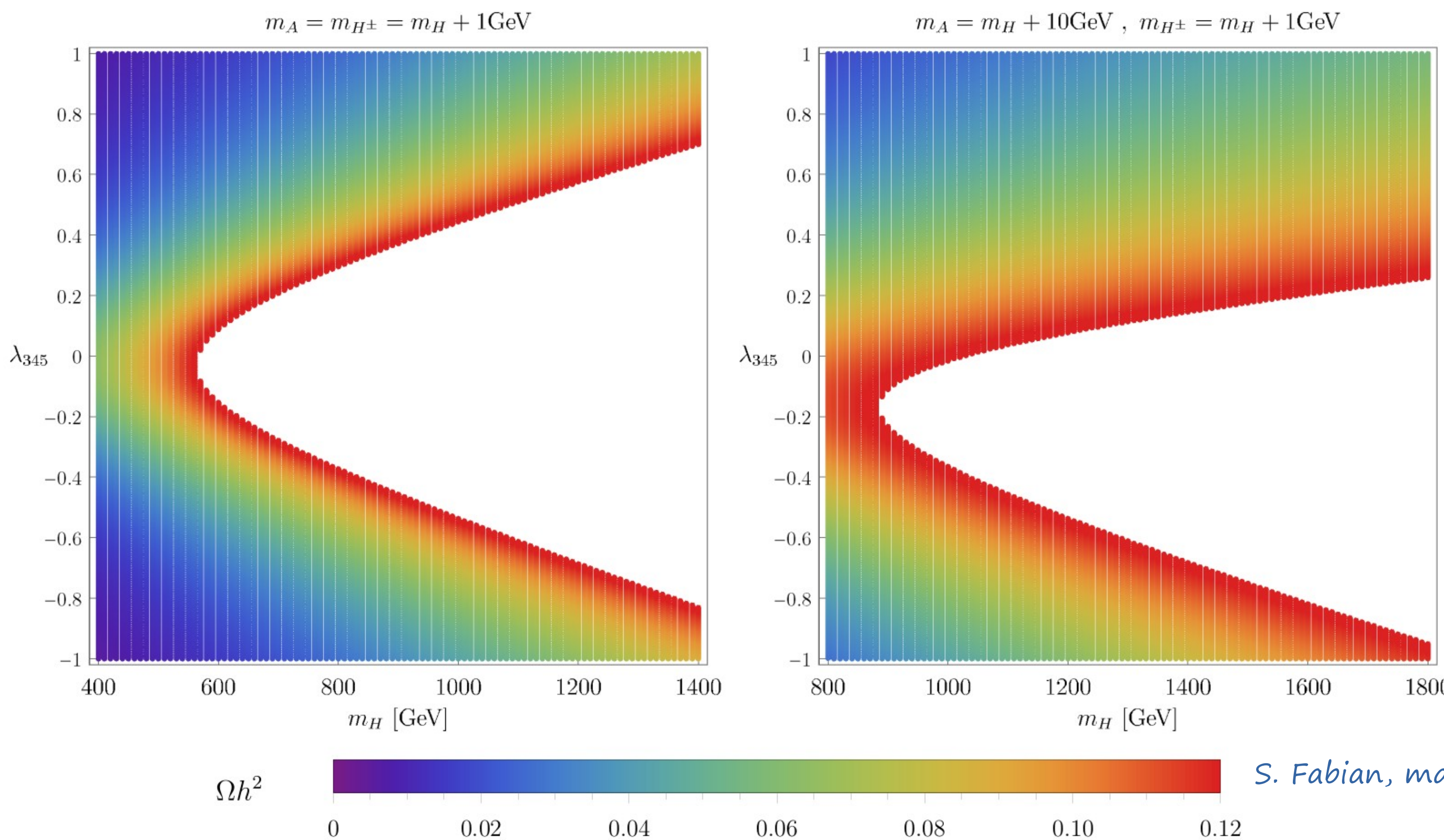
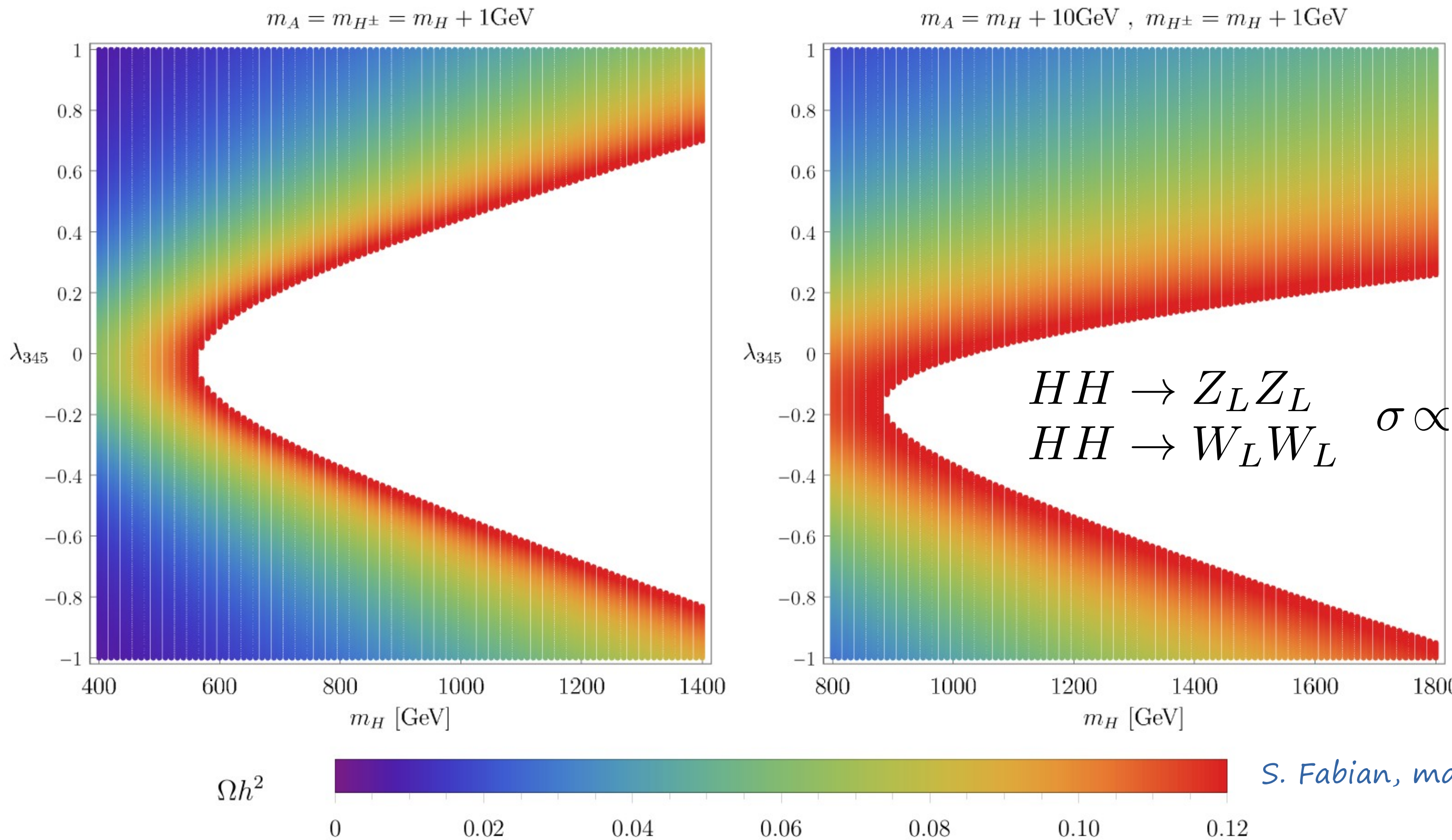
High Mass Regieme



S. Fabian, master's thesis

High Mass Regieme

small $\lambda_3, \bar{\lambda}_{345}$



$\sigma \propto \bar{\lambda}_{345}^2, \lambda_3^2$

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$$\lambda_3 = \lambda_{345} + 2\frac{m_{H^\pm}^2 - m_H^2}{v^2}\ ,\ \lambda_4 = \frac{m_A^2 + m_H^2 - 2m_{H^\pm}^2}{v^2}\ ,\ \lambda_5 = \frac{m_H^2 - m_A^2}{v^2} \qquad \bar{\lambda}_{345} = \lambda_{345} - 2\lambda_5$$


Baryogenesis

Electroweak Phase Transition

→ Finite-T Coleman-Weinberg Potential

$$V^{(1)}(T,h,H) = V(h,H) + V_{\rm CW}(h,H) + V_{\rm CT}(h,H) + V_T(h,H)$$

tree-level (v.s.)

Electroweak Phase Transition

→ Finite-T Coleman-Weinberg Potential

$$V^{(1)}(T,h,H) = V(h,H) + V_{\rm CW}(h,H) + V_{\rm CT}(h,H) + V_T(h,H)$$

T=0: $$V_{\rm CW}(h,H) = \sum_i \frac{n_i}{64\pi^2}\hat{m}_i^4(h,H)\left[\ln\left(\frac{\hat{m}_i^2}{Q^2}\right) - C_i\right]$$

Electroweak Phase Transition

→ Finite-T Coleman-Weinberg Potential

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$$i = W^\pm, Z, t, h, H, \phi, A, \phi^\pm, H^\pm$$

$$n_W = 6,\ n_Z = 3,\ n_t = -12,\ n_\Phi = 1,\ n_{\Phi^\pm} = 2$$
$$C_W = C_Z = 5/6,\ C_t = C_\Phi = C_{\Phi^\pm} = 3/2$$

$$\Phi = h, H, A, \phi\ ,\ \Phi^\pm = H^\pm, \phi^\pm$$

Electroweak Phase Transition

→ Finite-T Coleman-Weinberg Potential

$$V^{(1)}(T,h,H) = V(h,H) + V_{\mathrm{CW}}(h,H) + V_{\mathrm{CT}}(h,H) + V_T(h,H)$$

T=0: $$V_{\mathrm{CW}}(h,H) = \sum_i \frac{n_i}{64\pi^2}\hat{m}_i^4(h,H)\left[\ln\left(\frac{\hat{m}_i^2}{Q^2}\right) - C_i\right]$$

$$\hat{m}_V^2(h,H) = \frac{h^2+H^2}{v^2}m_V^2\,, \quad \hat{m}_f^2(h) = \frac{h^2}{2}y_f^2$$

$$\widehat{M}_S^2 = \frac{1}{2}\begin{pmatrix} 6\lambda_1 h^2 - 2\lambda_1 v^2 + \lambda_{345}H^2 & 2hH\lambda_{345} \\ 2hH\lambda_{345} & 6\lambda_2 H^2 + \lambda_{345}h^2 + 2\mu_2^2 \end{pmatrix}$$

$$\widehat{M}_P^2 = \frac{1}{2}\begin{pmatrix} 2\lambda_1 h^2 - 2\lambda_1 v^2 + \bar{\lambda}_{345}H^2 & 2hH\lambda_5 \\ 2hH\lambda_5 & 2\lambda_2 H^2 + \bar{\lambda}_{345}h^2 + 2\mu_2^2 \end{pmatrix}$$

$$\widehat{M}_\pm^2 = \frac{1}{2}\begin{pmatrix} 2\lambda_1 h^2 - 2\lambda_1 v^2 + \lambda_3 H^2 & hH(\lambda_4+\lambda_5) \\ hH(\lambda_4+\lambda_5) & 2\lambda_2 H^2 + \lambda_3 h^2 + 2\mu_2^2 \end{pmatrix},$$

Electroweak Phase Transition

→ Finite-T Coleman-Weinberg Potential

$$V^{(1)}(T,h,H) = V(h,H) + V_{\mathrm{CW}}(h,H) + V_{\mathrm{CT}}(h,H) + V_T(h,H)$$

$$\boxed{V_{\mathrm{CT}}\left(h,H\right) = \delta m_h^2 h^2 + \delta m_H^2 H^2 + \delta\lambda_1 h^4}$$

$$\left.\frac{\partial V_{\mathrm{CT}}}{\partial h}\right|_{\mathrm{vev}} = -\left.\frac{\partial V_{\mathrm{CW}}}{\partial h}\right|_{\mathrm{vev}}$$

$$\left.\frac{\partial^2 V_{\mathrm{CT}}}{\partial h^2}\right|_{\mathrm{vev}} = -\left.\left(\frac{\partial^2 \left.V_{\mathrm{CW}}\right|_{n_{\phi(\pm)}=0}}{\partial h^2} + \frac{1}{32\pi^2}\sum_{i=\phi,\phi^\pm} n_i \left(\frac{\partial \hat{m}_i^2\left(h,H\right)}{\partial h}\right)^2 \ln\frac{m_{\mathrm{IR}}^2}{Q^2}\right)\right|_{\mathrm{vev}}$$

$$\left.\frac{\partial^2 V_{\mathrm{CT}}}{\partial H^2}\right|_{\mathrm{vev}} = -\left.\left(\frac{\partial^2 \left.V_{\mathrm{CW}}\right|_{n_{\phi(\pm)}=0}}{\partial H^2} + \frac{1}{32\pi^2}\sum_{i=\phi,\phi^\pm} n_i \left(\frac{\partial \hat{m}_i^2\left(h,H\right)}{\partial H}\right)^2 \ln\frac{m_{\mathrm{IR}}^2}{Q^2}\right)\right|_{\mathrm{vev}}$$

$\lambda_2, \lambda_{345} : \overline{\mathrm{MS}}$

massless Goldstones → IR divergences
→ subtract, add regularized

$\xi = 0$

Electroweak Phase Transition

→ Finite-T Coleman-Weinberg Potential

$$V^{(1)}(T,h,H) = V(h,H) + V_{\mathrm{CW}}(h,H) + V_{\mathrm{CT}}(h,H) + V_T(h,H)$$

$$V_T\left(h,H\right) = \frac{T^4}{2\pi^2}\left[\sum_i n_i^{\mathrm{B}} J_{\mathrm{B}}\left(\frac{\tilde{m}_i^2\left(h,H,T\right)}{T^2}\right) + \sum_i n_i^{\mathrm{F}} J_{\mathrm{F}}\left(\frac{\tilde{m}_i^2\left(h,H,T\right)}{T^2}\right)\right]$$

Thermal corrections to n-point functions

Electroweak Phase Transition

→ Finite-T Coleman-Weinberg Potential

$$V^{(1)}(T,h,H) = V(h,H) + V_{\mathrm{CW}}(h,H) + V_{\mathrm{CT}}(h,H) + V_T(h,H)$$

$$V_T(h,H) = \frac{T^4}{2\pi^2}\left[\sum_i n_i^{\mathrm{B}} J_{\mathrm{B}}\left(\frac{\tilde{m}_i^2(h,H,T)}{T^2}\right) + \sum_i n_i^{\mathrm{F}} J_{\mathrm{F}}\left(\frac{\tilde{m}_i^2(h,H,T)}{T^2}\right)\right]$$

Thermal corrections to n-point functions

$$J_{\mathrm{B/F}}(x) \equiv \pm\int_0^\infty dt\ t^2 \ln\left[1 \mp e^{-\sqrt{t^2+x}}\right] = \lim_{N\to\infty} \mp \sum_{l=1}^{N} \frac{(\pm 1)^l x}{l^2} K_2\left(\sqrt{x}l\right)$$

truncate at N $\gtrsim$ 5

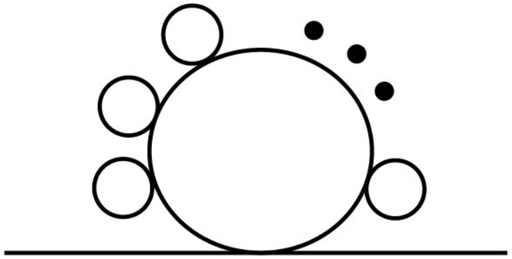
Bernon, Bian, Jiang, 1712.08430

Electroweak Phase Transition

→ Finite-T Coleman-Weinberg Potential

$$V^{(1)}(T,h,H) = V(h,H) + V_{\mathrm{CW}}(h,H) + V_{\mathrm{CT}}(h,H) + V_T(h,H)$$

$$V_T\left(h,H\right) = \frac{T^4}{2\pi^2}\left[\sum_i n_i^{\mathrm{B}} J_{\mathrm{B}}\left(\frac{\tilde{m}_i^2\left(h,H,T\right)}{T^2}\right) + \sum_i n_i^{\mathrm{F}} J_{\mathrm{F}}\left(\frac{\tilde{m}_i^2\left(h,H,T\right)}{T^2}\right)\right]$$



resummation of T-enhanced contributions (backup)

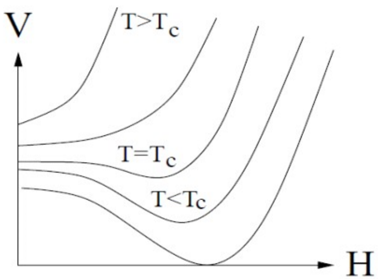
$$\hat{m}_i^2\left(h,H\right) \to \tilde{m}_i^2\left(h,H,T\right)$$

Parwani, hep-ph/9204216, Gross, Pisarski, Yaffe, Rev.Mod. Phys.53, Quiros, hep-ph/9901312

Numerics

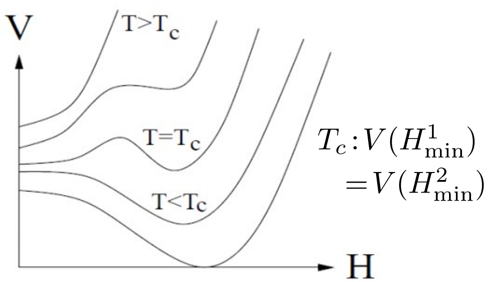
→ Trace T-dependent Potential $V^{(1)}(T,h,H)$:
determine Minimum for evolving T

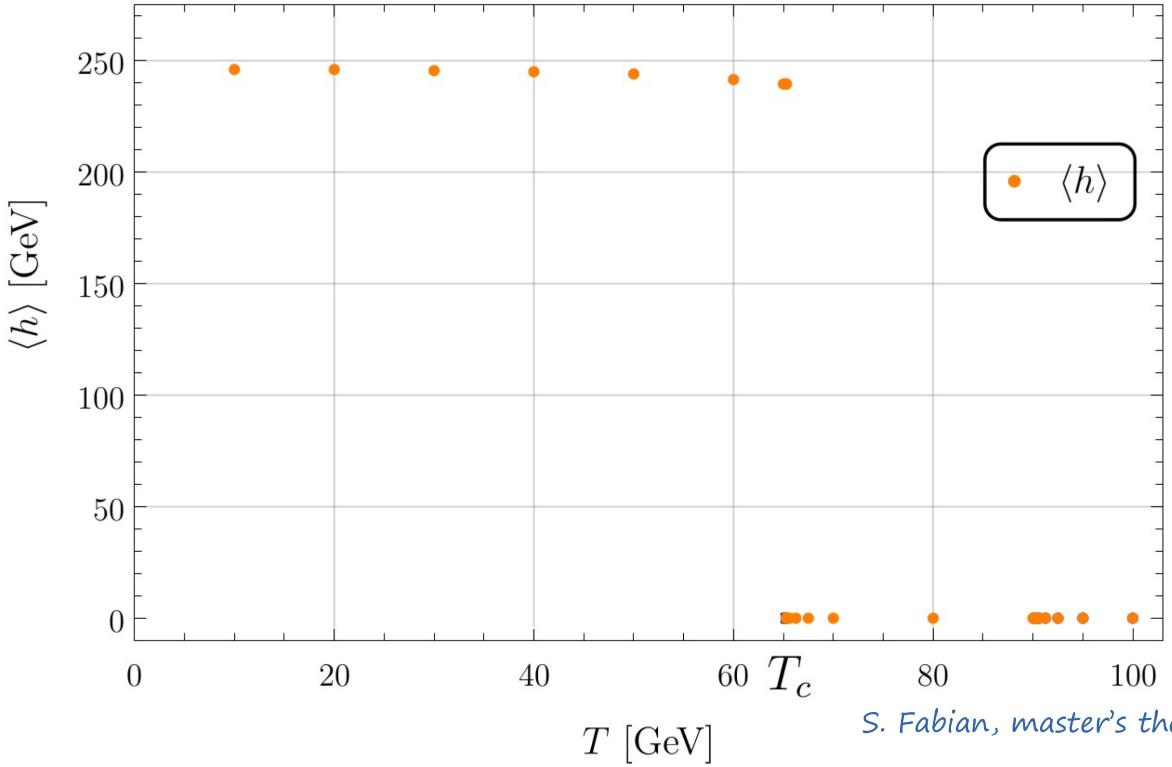
2nd order



Cline, ph/0609145

1st order





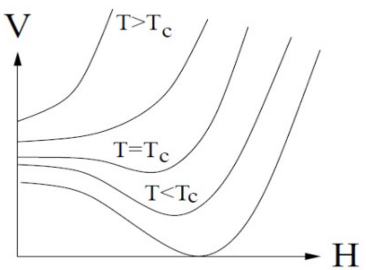
S. Fabian, master's thesis

→ Determine Type (and strength) of PhT

Numerics

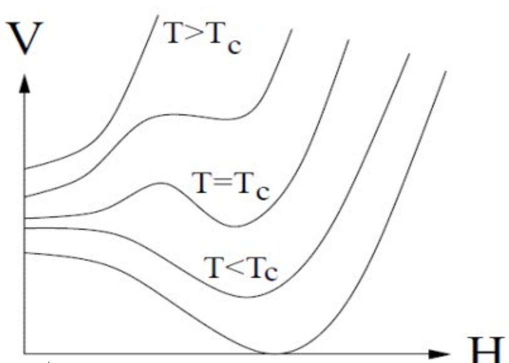
→ Trace T-dependent Potential $V^{(1)}(T, h, H)$:
determine Minimum for evolving T

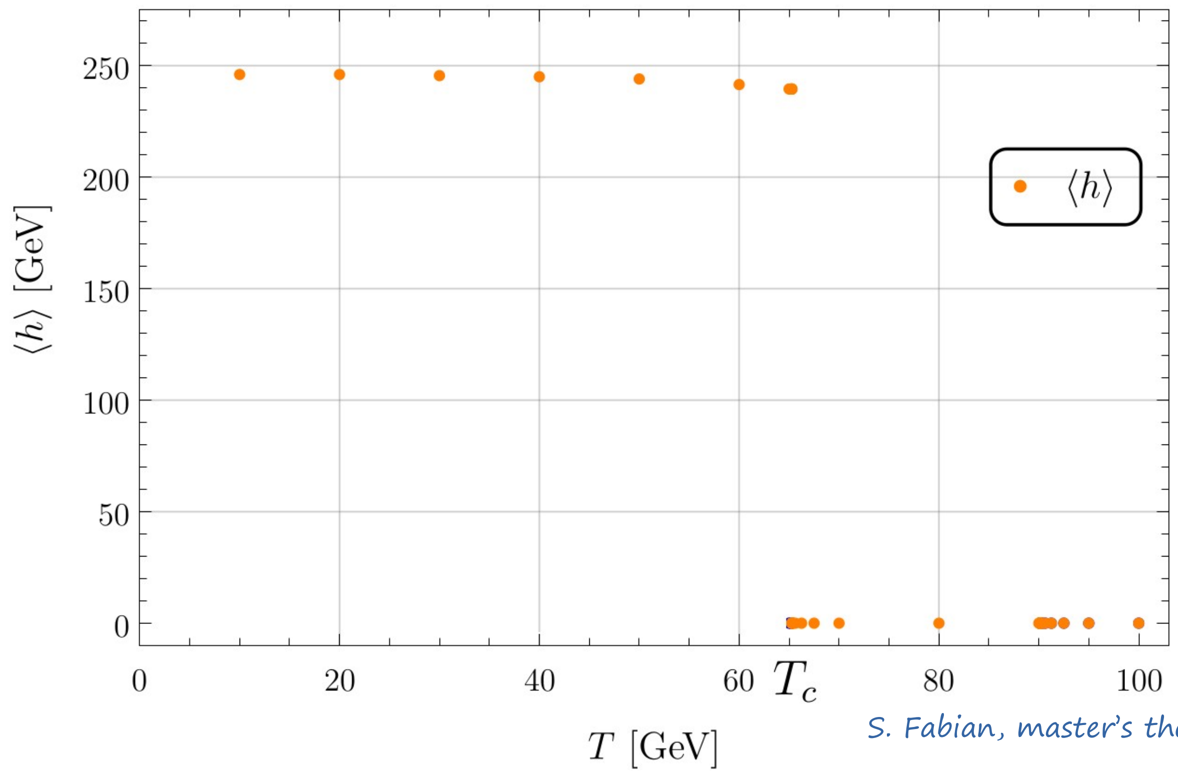
2nd order



Cline, ph-0609145

1st order





S. Fabian, master's thesis

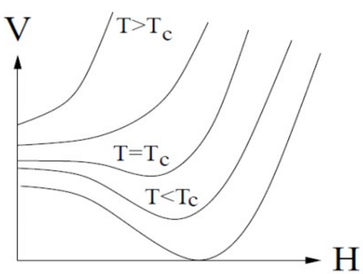
$v_c \equiv \langle h\rangle(T = T_c)$

$T_c : V(H^1_{\min}) = V(H^2_{\min})$ → Strength $\boxed{\xi \equiv \frac{v_c}{T_c}}$

Numerics

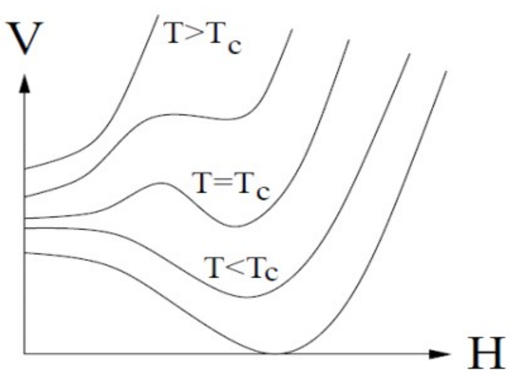
→ Trace T-dependent Potential $V^{(1)}(T,h,H)$:
determine Minimum for evolving T

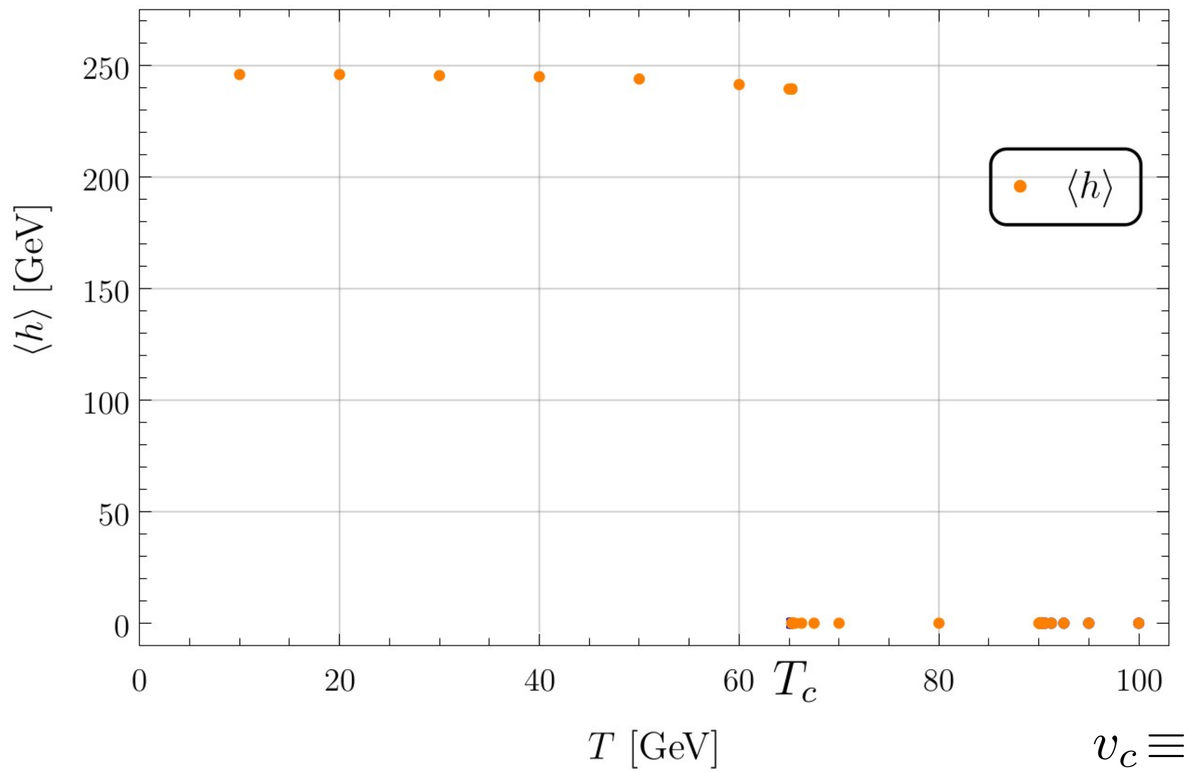
2^{nd} order



Cline, ph-0609145

1^{st} order

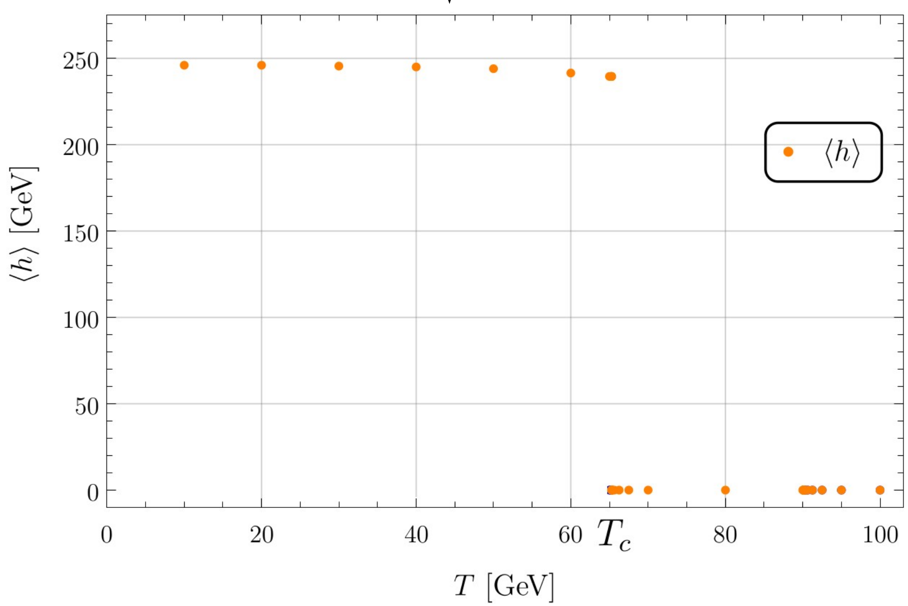


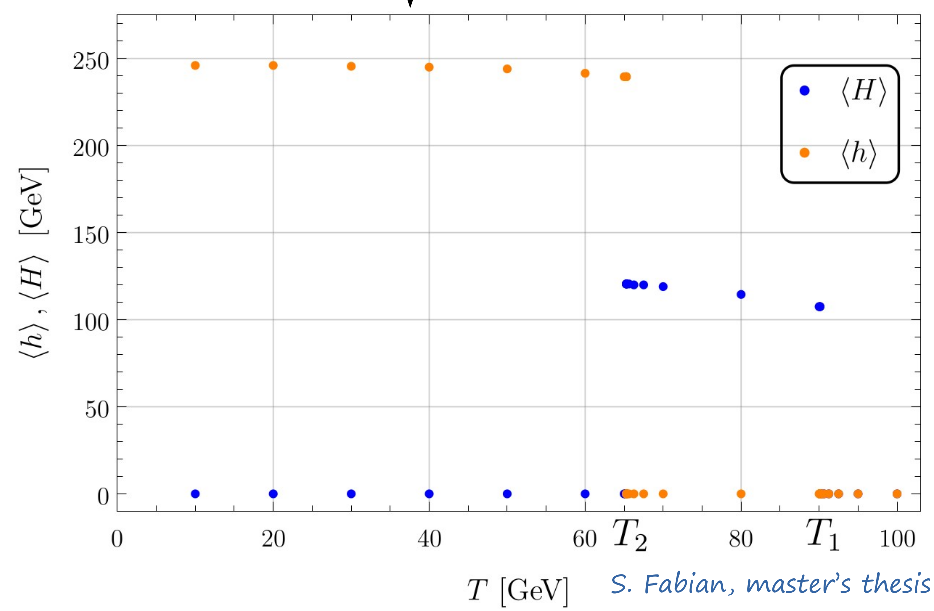


$v_c \equiv \langle h \rangle (T = T_c)$

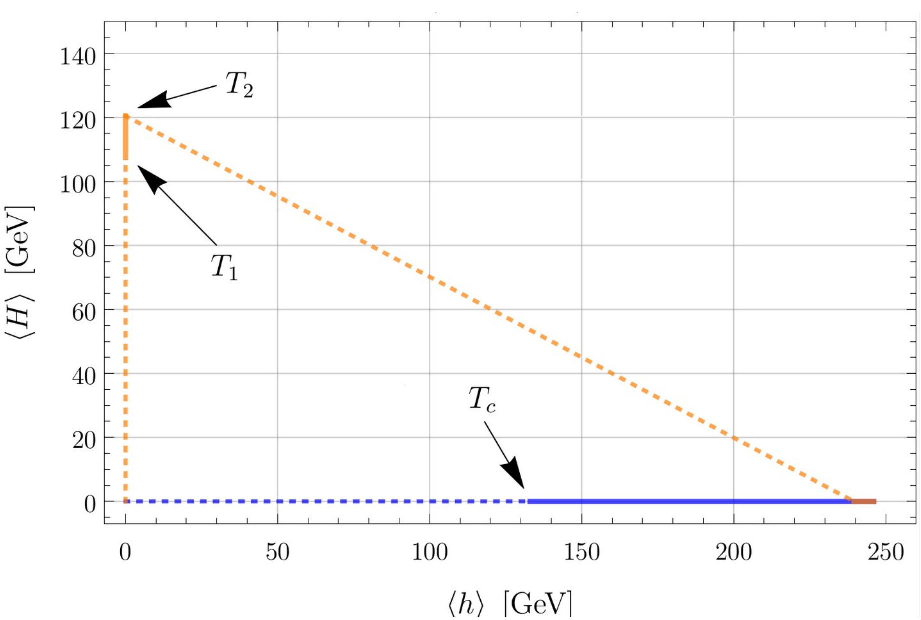
$T_c : V(H^1_{\text{min}}) = V(H^2_{\text{min}})$ ⟶ Strength $\boxed{\xi \equiv \frac{v_c}{T_c}} > 1$ ⟶ strong 1^{st}OPhT

One-Step vs. Two-Step EWPhT





S. Fabian, master's thesis



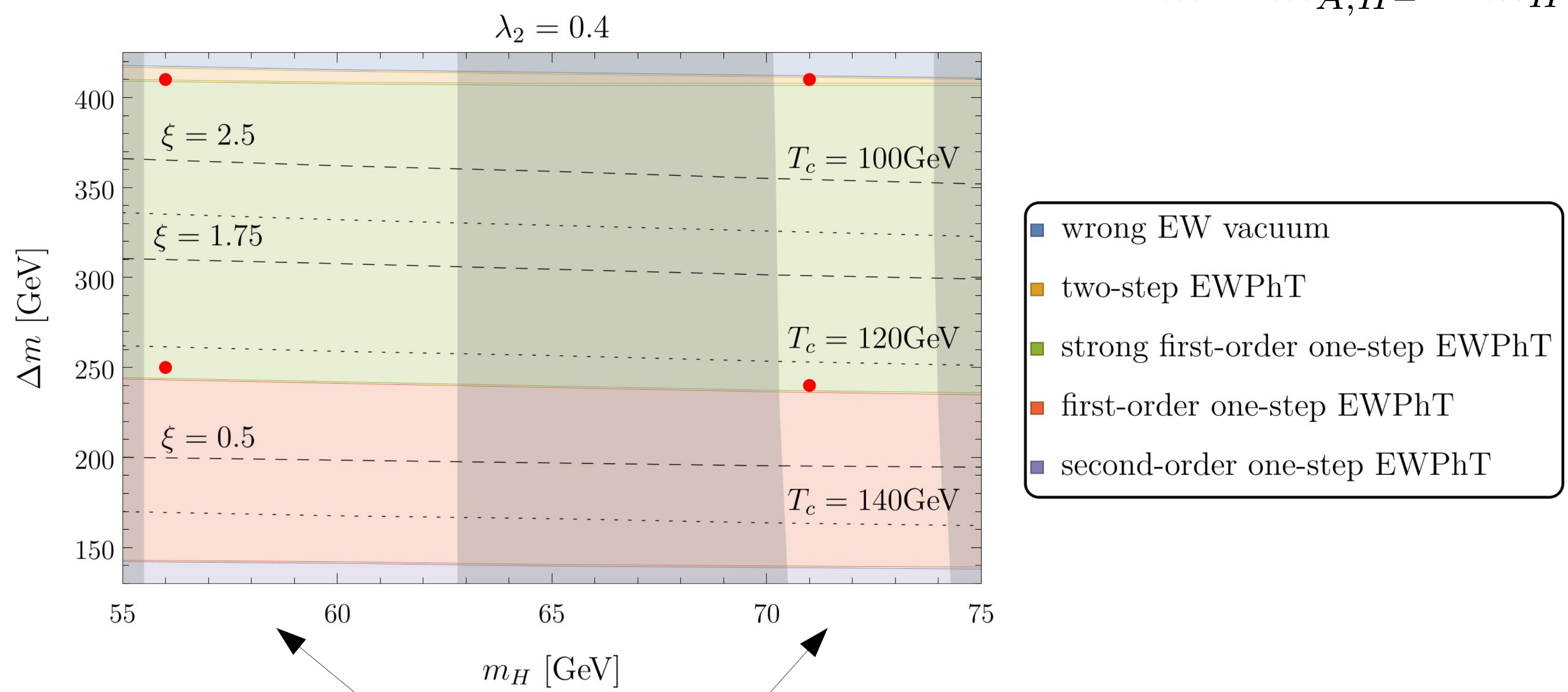
multi-step transition

$$\xi_j \equiv \frac{\sqrt{\langle h\rangle_j^2 + \langle H\rangle_j^2}}{T_j}$$

$\xi_j > 1$: sphalerons suppressed

EWPhT & DM in IDM I: Low Mass

$$\Delta m \equiv m_{A,H^\pm} - m_H$$



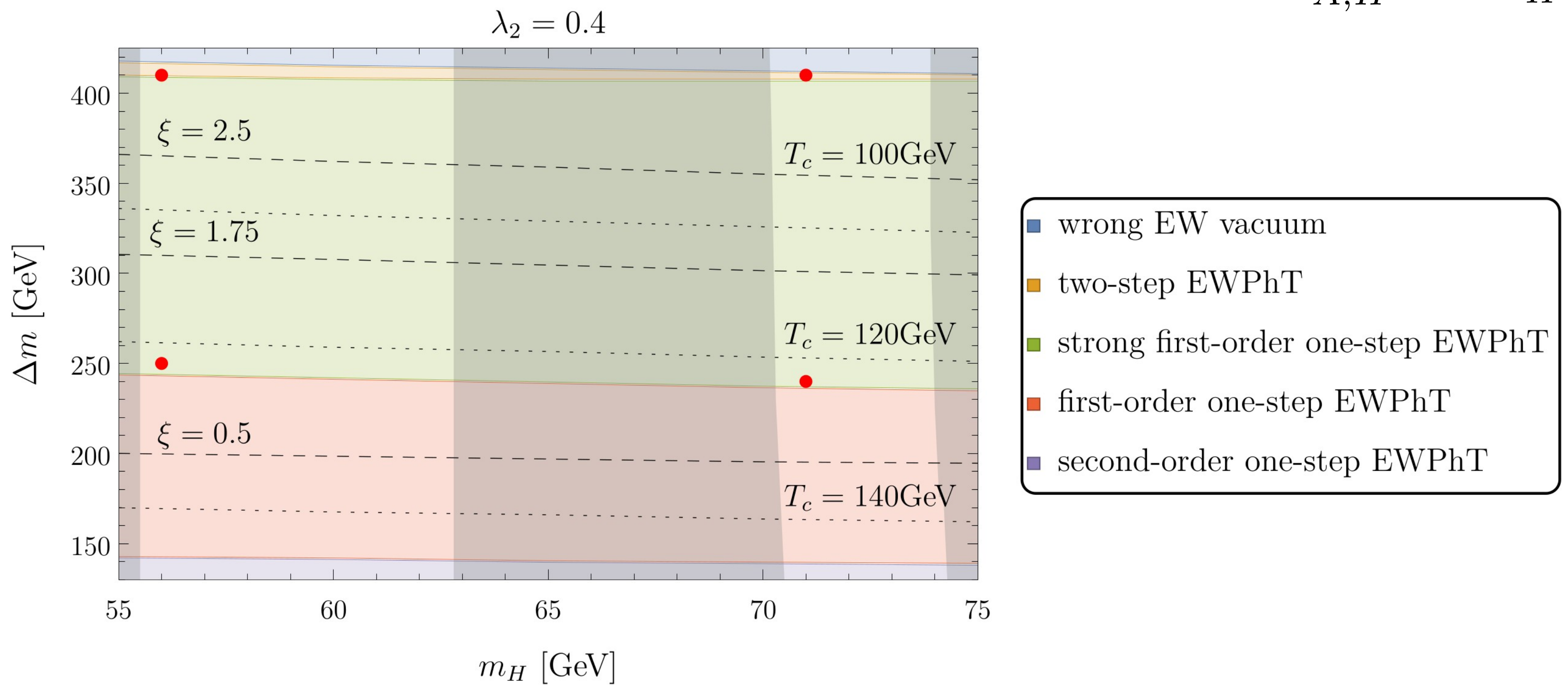
$0.6\Omega h^2_{\text{best}} \leq \Omega h^2 \leq \Omega h^2_{\text{best}} + 3\sigma$ +XENON1T ✓ $(\lambda_{345} \lesssim 0.005)$

EWPhT & DM in IDM I: Low Mass

$$\Delta m \equiv m_{A,H^\pm} - m_H$$

$\lambda_{3,4,5} \gtrsim 1$
large effects

$\lambda_{3,4,5} \ll 1$
"decoupling"



$$\lambda_3 = \lambda_{345} + 2\frac{m_{H^\pm}^2 - m_H^2}{v^2}\,,\quad \lambda_4 = \frac{m_A^2 + m_H^2 - 2m_{H^\pm}^2}{v^2}\,,\quad \lambda_5 = \frac{m_H^2 - m_A^2}{v^2} \qquad (\lambda_{345} \lesssim 0.005)$$

$$V(H_1,H_2) = \mu_1^2\,|H_1|^2 + \mu_2^2\,|H_2|^2 + \lambda_1\,|H_1|^4 + \lambda_2\,|H_2|^4 + \lambda_3\,|H_1|^2\,|H_2|^2 + \lambda_4\,\left|H_1^\dagger H_2\right|^2 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]$$

EWPhT & DM in IDM I: Low Mass

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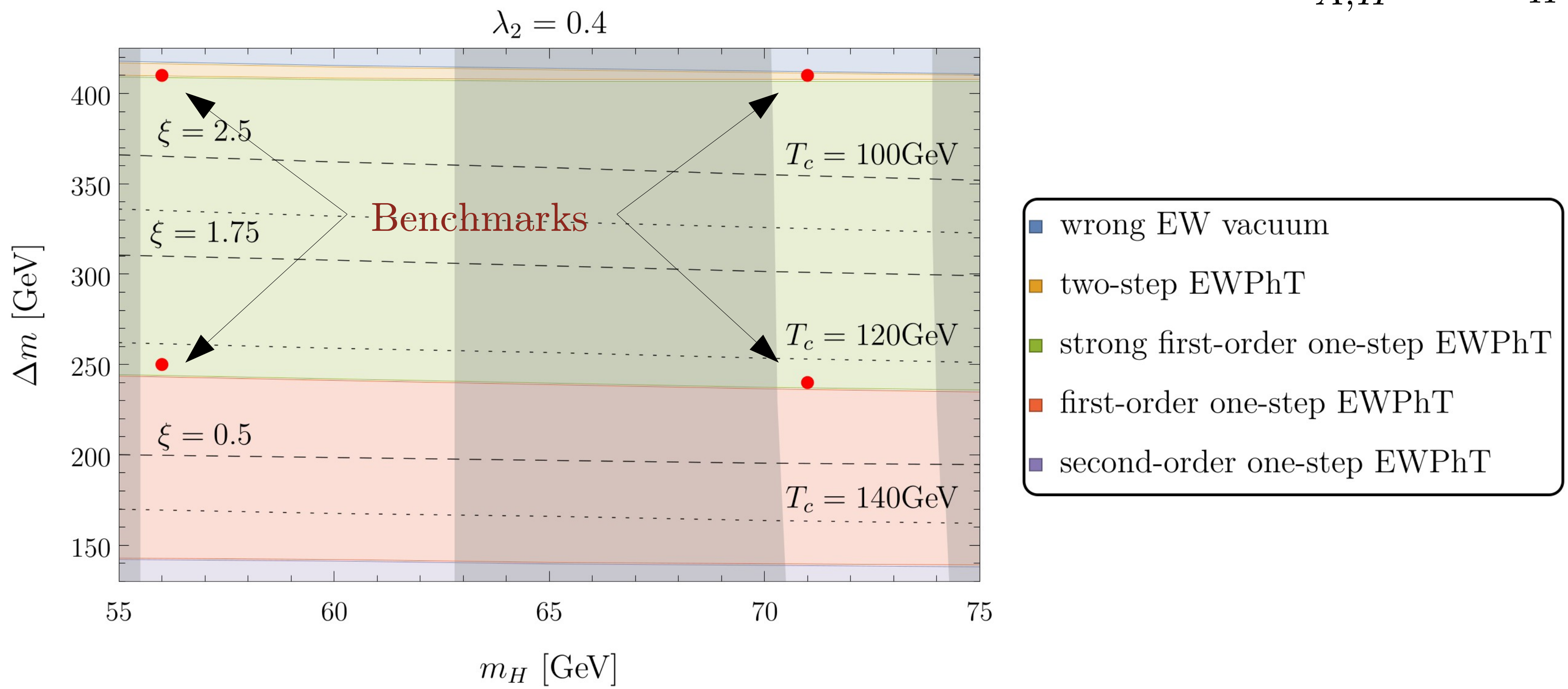

$$\lambda_3 = \lambda_{345} + 2\frac{m_{H^\pm}^2 - m_H^2}{v^2}\,,\quad \lambda_4 = \frac{m_A^2 + m_H^2 - 2m_{H^\pm}^2}{v^2}\,,\quad \lambda_5 = \frac{m_H^2 - m_A^2}{v^2} \qquad (\lambda_{345} \lesssim 0.005)$$

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Benchmarks for Further Study

BM	m_H [GeV]	$m_{A,H^\pm}$ [GeV]	λ_{345}	Ωh^2	σ_n $[10^{-13}\text{pb}]$	σ_p $[10^{-13}\text{pb}]$
1	56	306	0.0037	0.1188	379.7	372.2
2	56	466	0.0037	0.1188	379.7	372.2
3	71	311	0.0020	0.1210	69.5	68.1
4	71	481	0.0020	0.1177	69.5	68.1

SFOPhT

Two-Step

Correct Relic

OK with recent XENON1T

Benchmarks for Further Study

BM	m_H [GeV]	$m_{A,H^\pm}$ [GeV]	λ_{345}	Ωh^2	σ_n $[10^{-13}\text{pb}]$	σ_p $[10^{-13}\text{pb}]$
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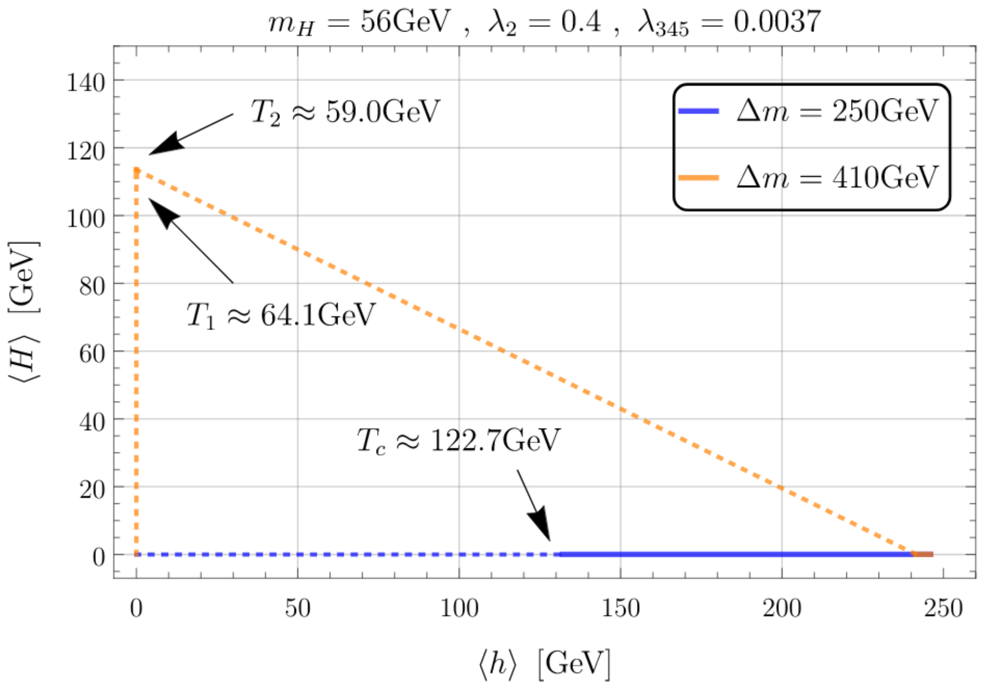
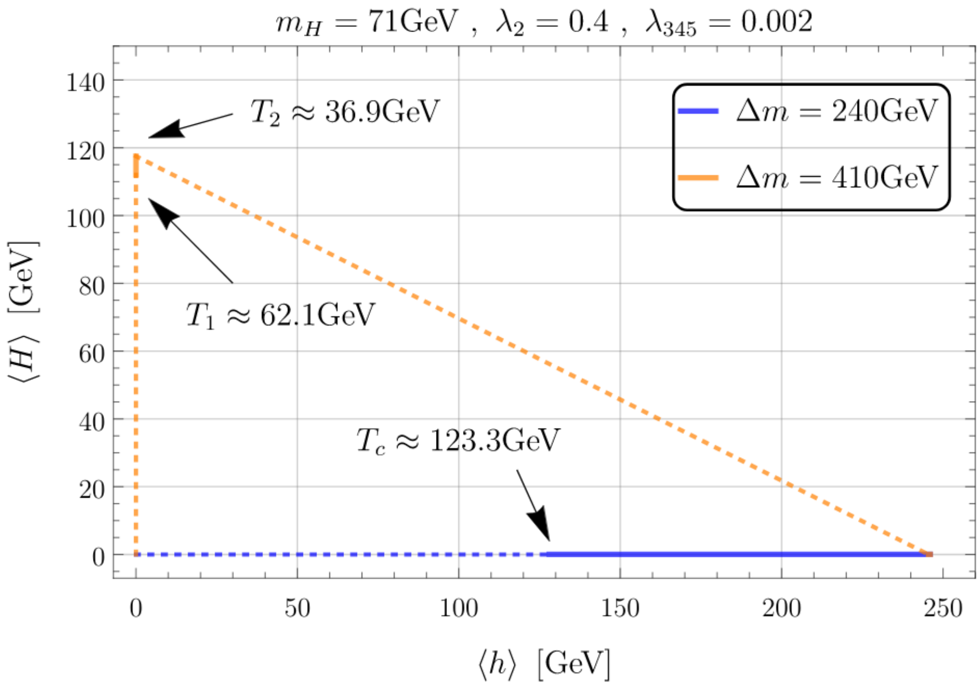
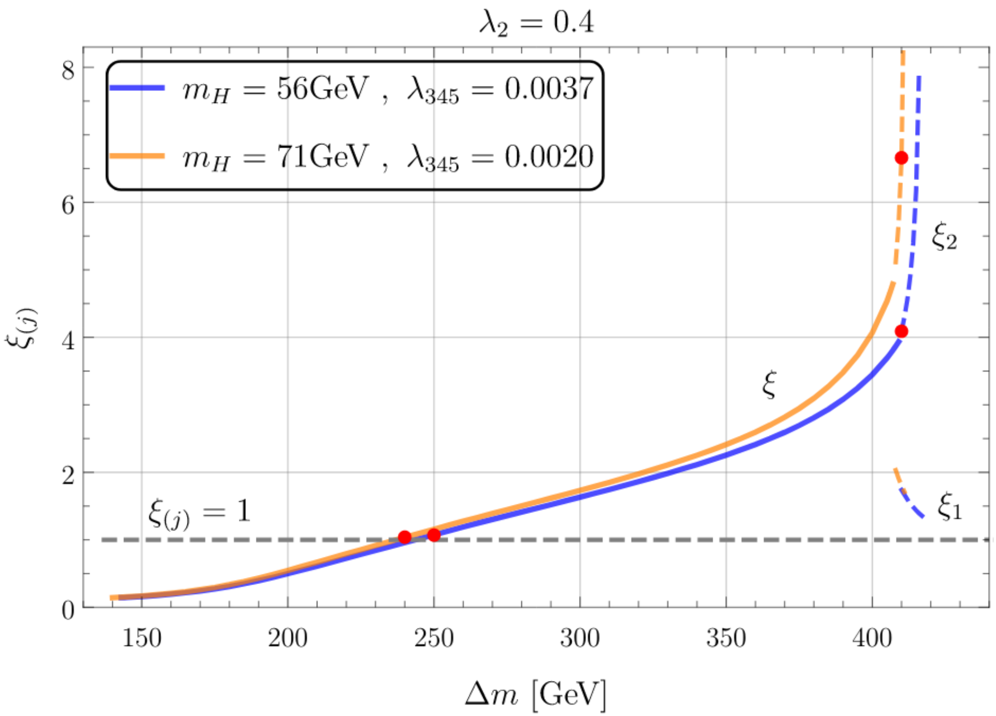
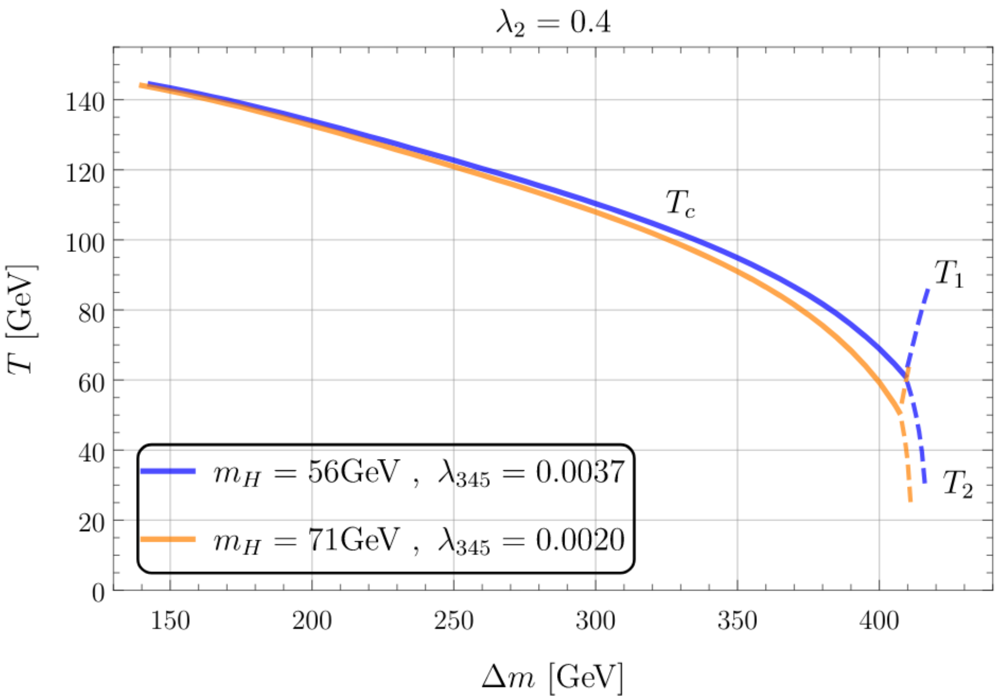




Benchmarks for Further Study

BM	m_H [GeV]	$m_{A,H^\pm}$ [GeV]	λ_{345}	EWPhT type	$\xi_{(1)}$	ξ_2
1	56	306	0.0037	strong first-order one-step	1.07	–
2	56	466	0.0037	two-step	1.74	4.09
3	71	311	0.0020	strong first-order one-step	1.04	–
4	71	481	0.0020	two-step	1.80	6.66





Benchmarks for Further Study

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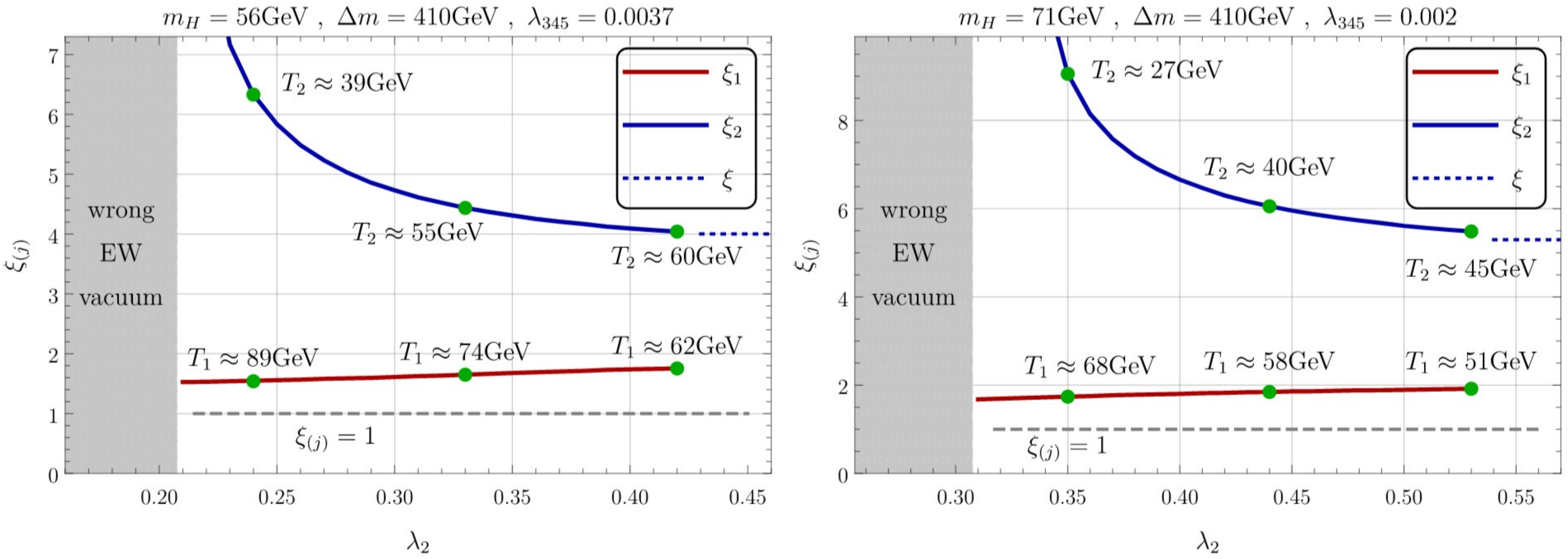

Benchmarks for Further Study

BM	m_H [GeV]	$m_{A,H^\pm}$ [GeV]	λ_{345}	EWPhT type	$\xi_{(1)}$	ξ_2
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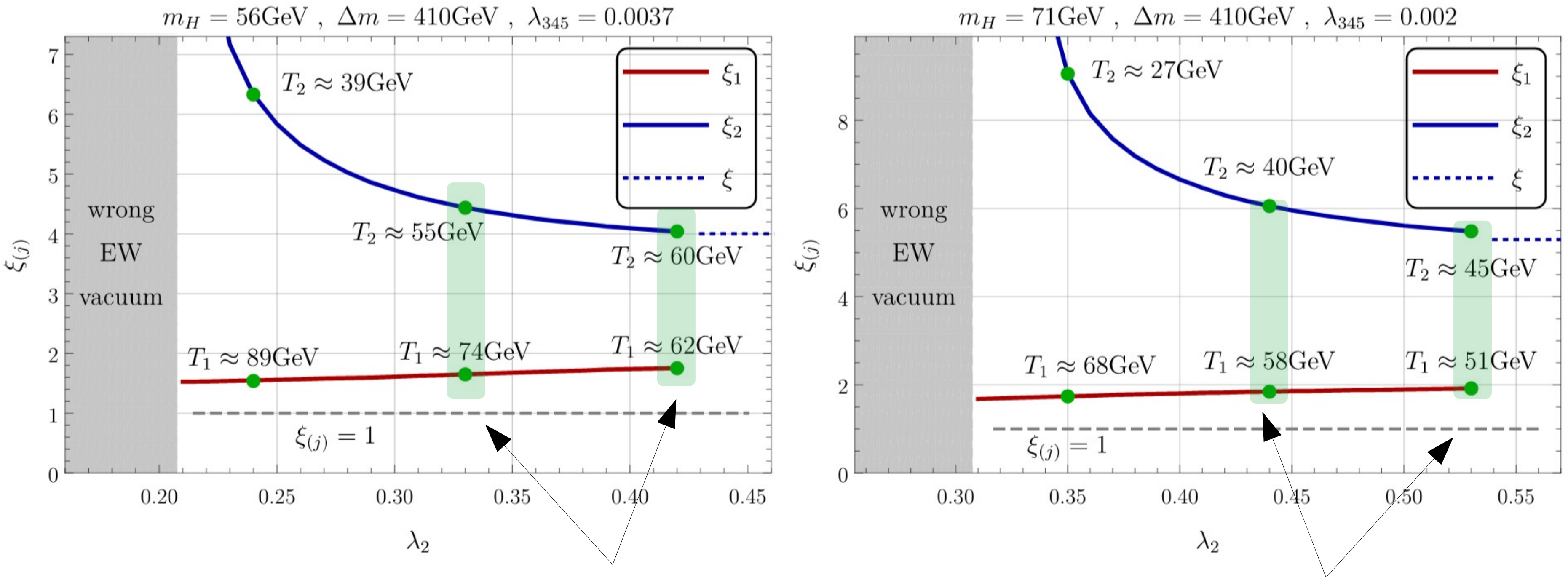
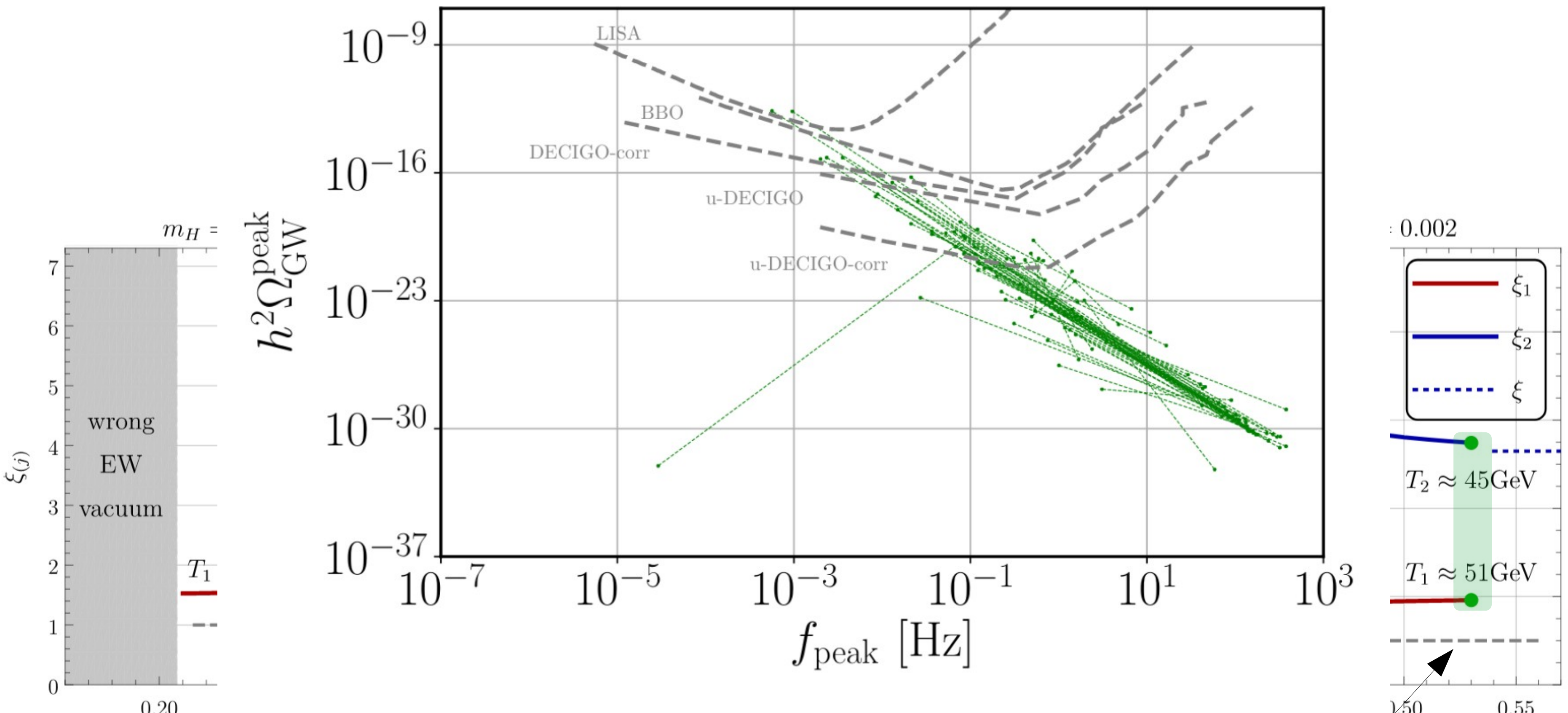


Interesting targets for Gravitational Wave studies: multi peaked spectra...

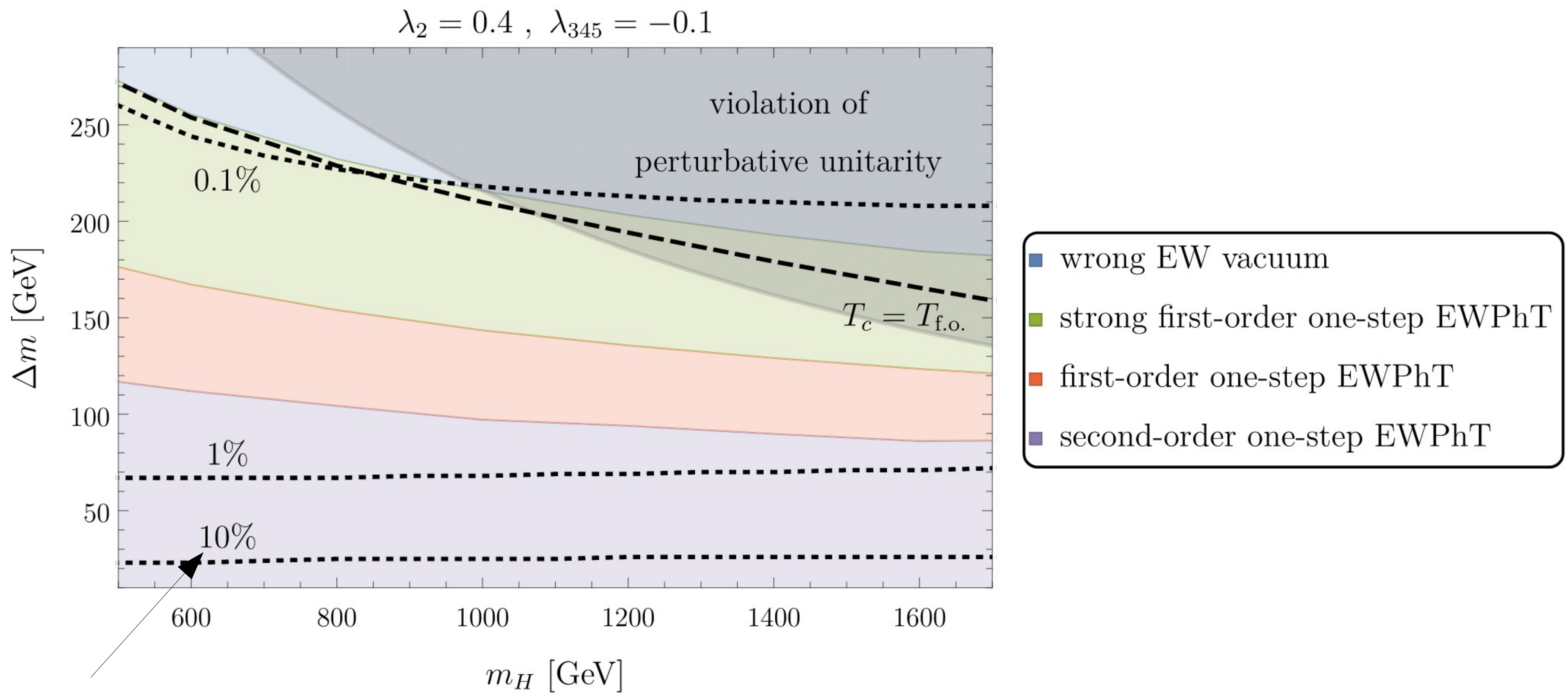
Benchmarks for Further Study



Like in Morais, Pasechnik, 1910.00717

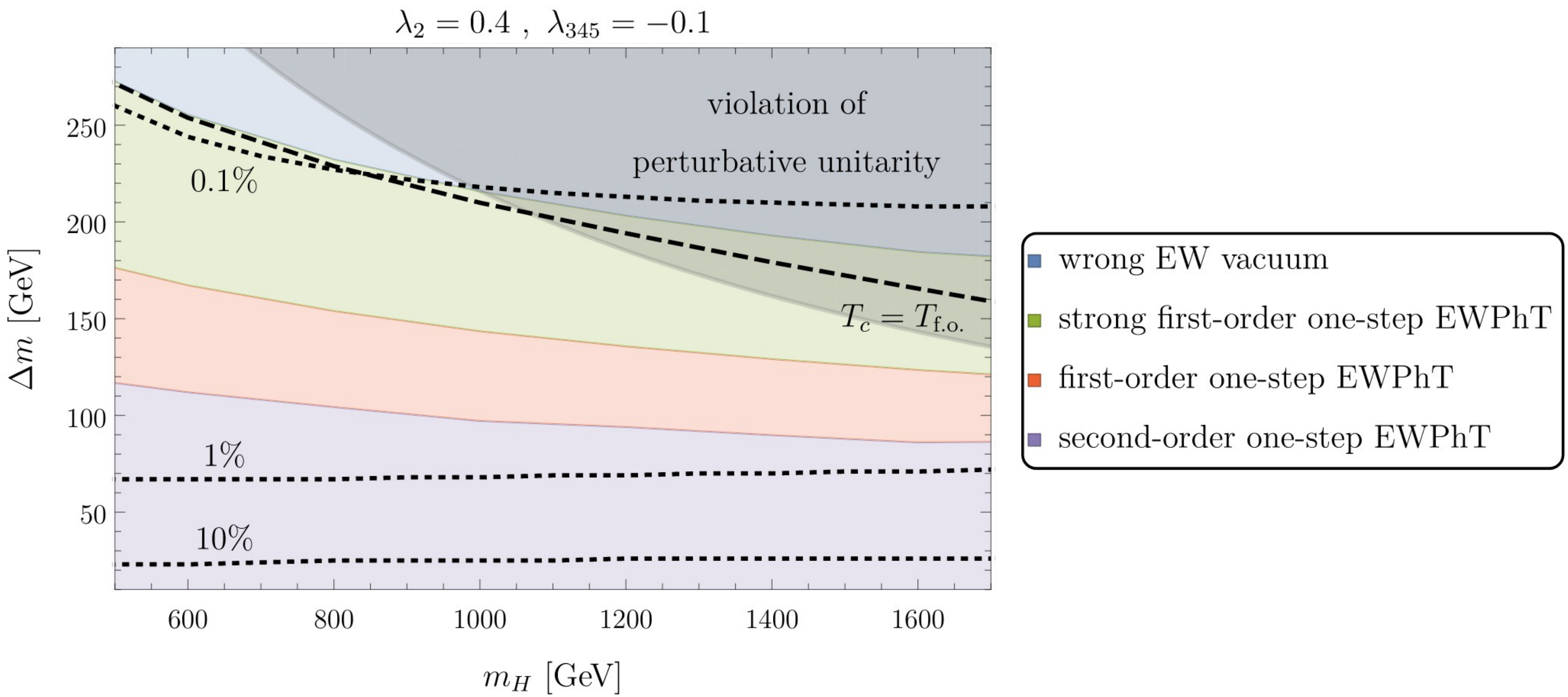
Interesting targets for Gravitational Wave studies: multi peaked spectra...

EWPhT & DM in IDM II: High Mass



DM fraction

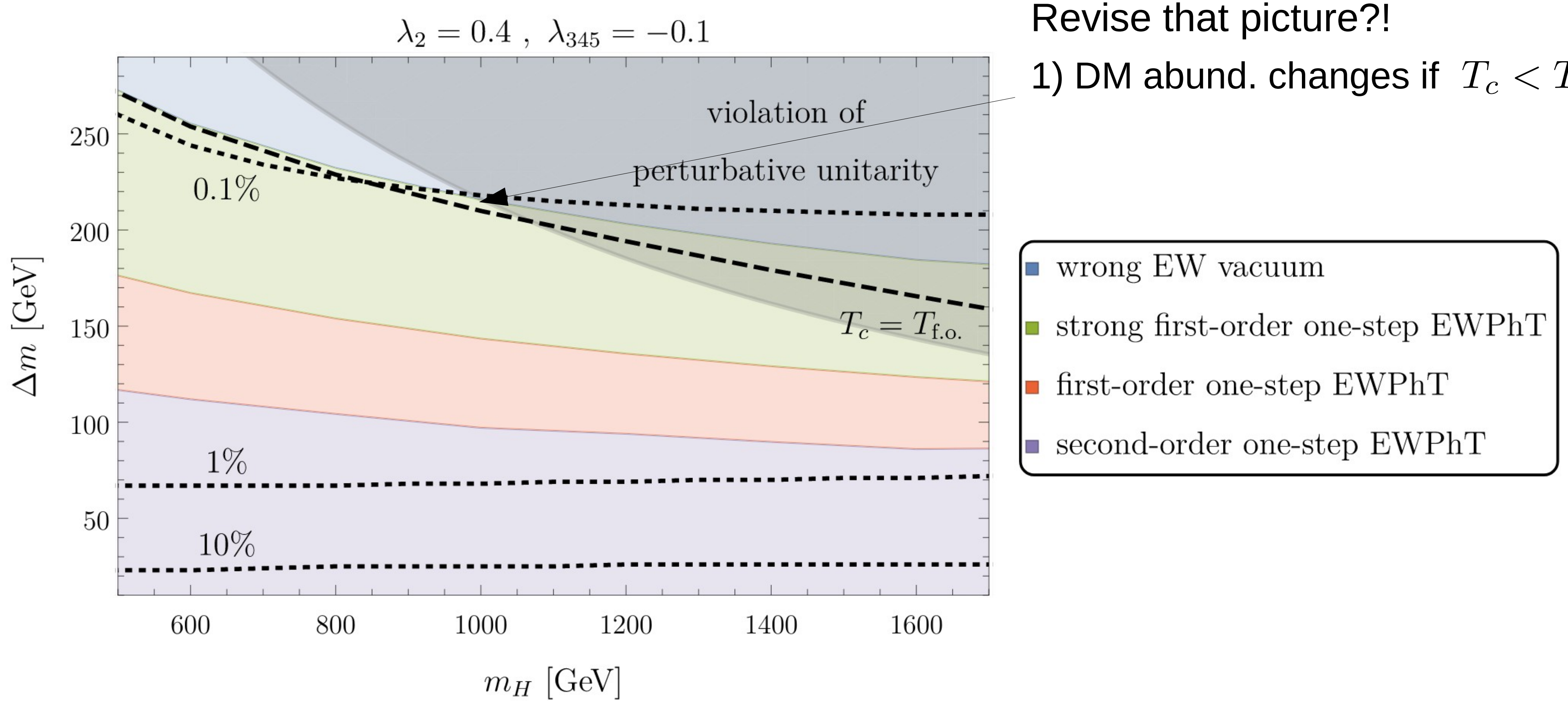
EWPhT & DM in IDM II: High Mass



→ Tension between full abundance: small splitting / small $\lambda_3, \bar{\lambda}_{345}$ and SFOPhT

→ Still could (in principle) look in DM DD for agent of EWBG

Current Directions



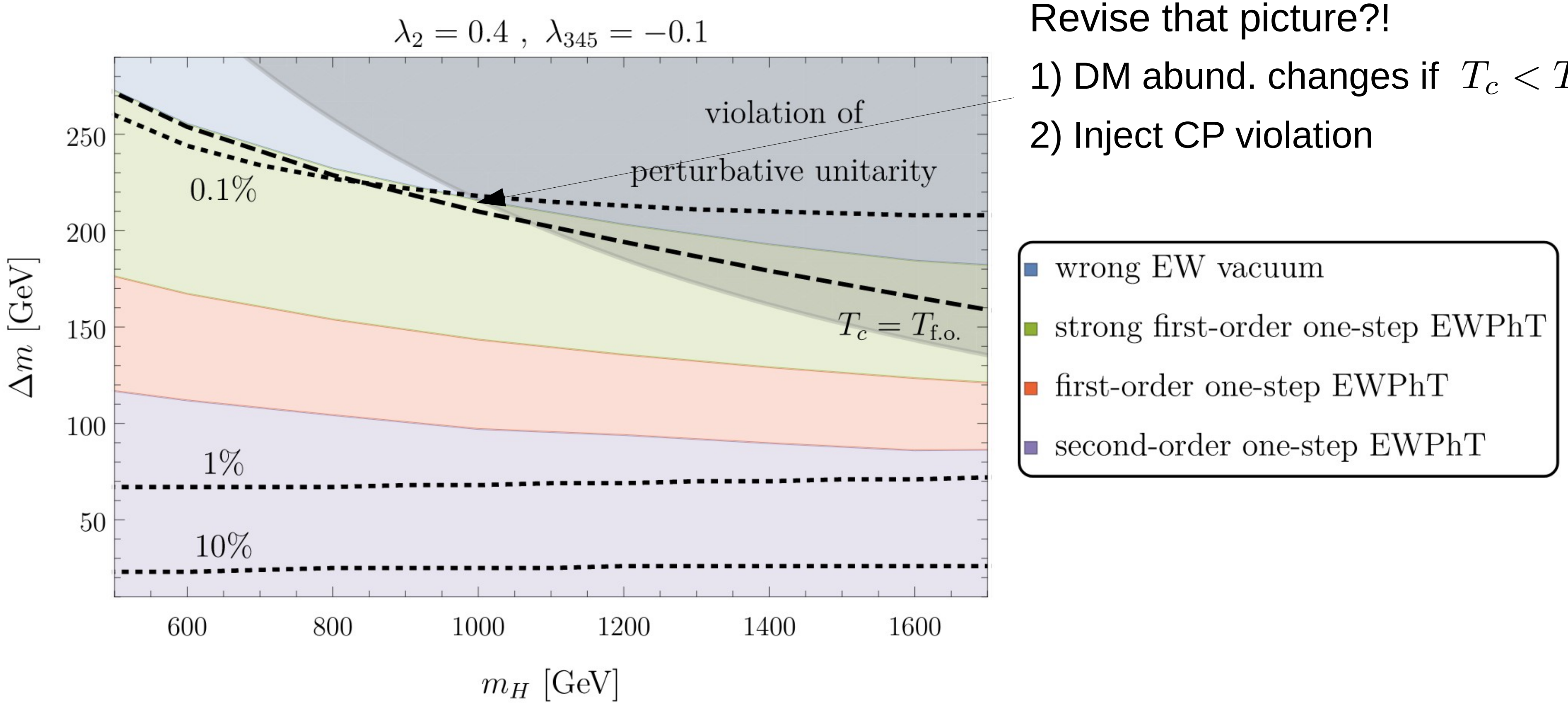
Revise that picture?!

1) DM abund. changes if $T_c < T_{\rm f.o.}$

→ Tension between full abundance: small splitting / small $\lambda_3, \bar{\lambda}_{345}$ and SFOPhT

→ Still could (in principle) look in DM DD for agent of EWBG

Current Directions



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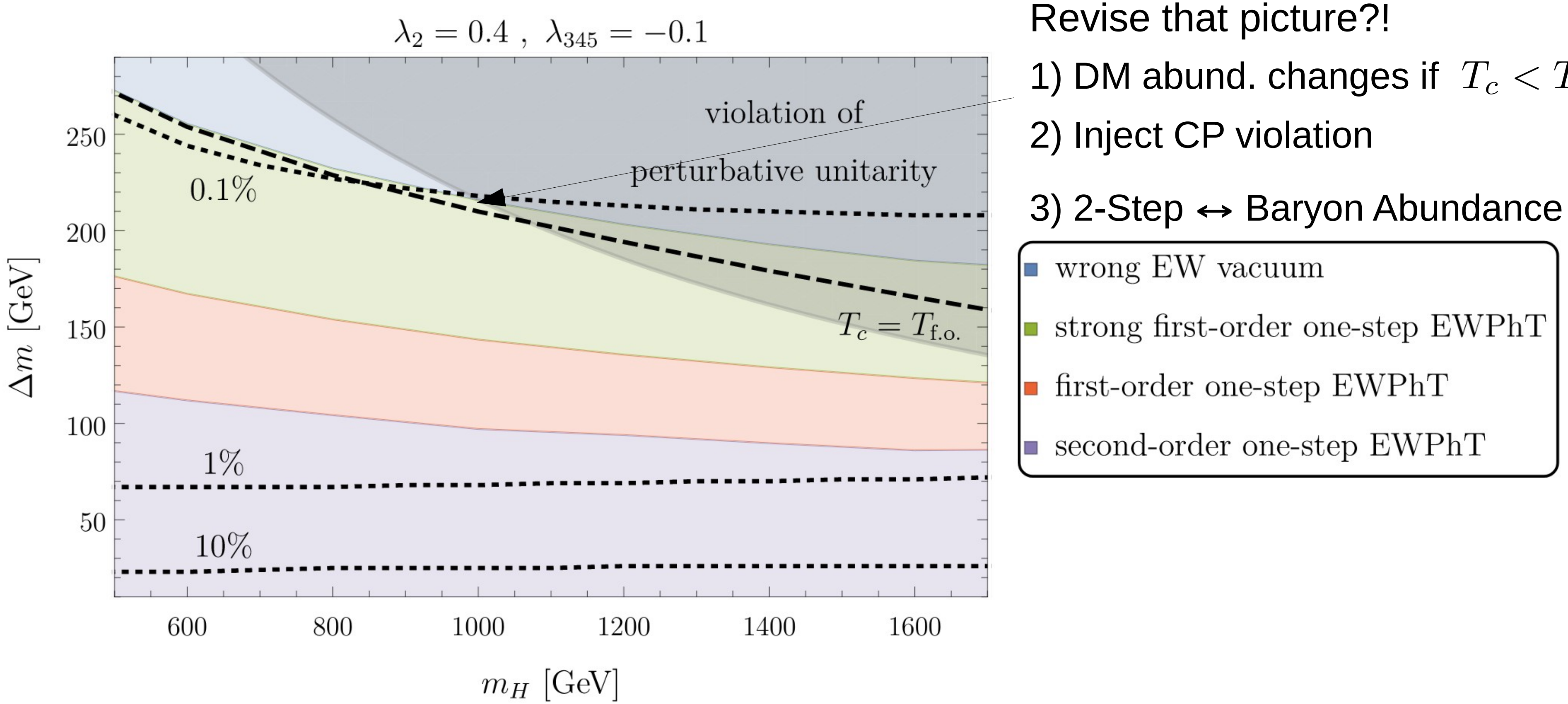

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1) DM abund. changes if $T_c < T_{\rm f.o.}$

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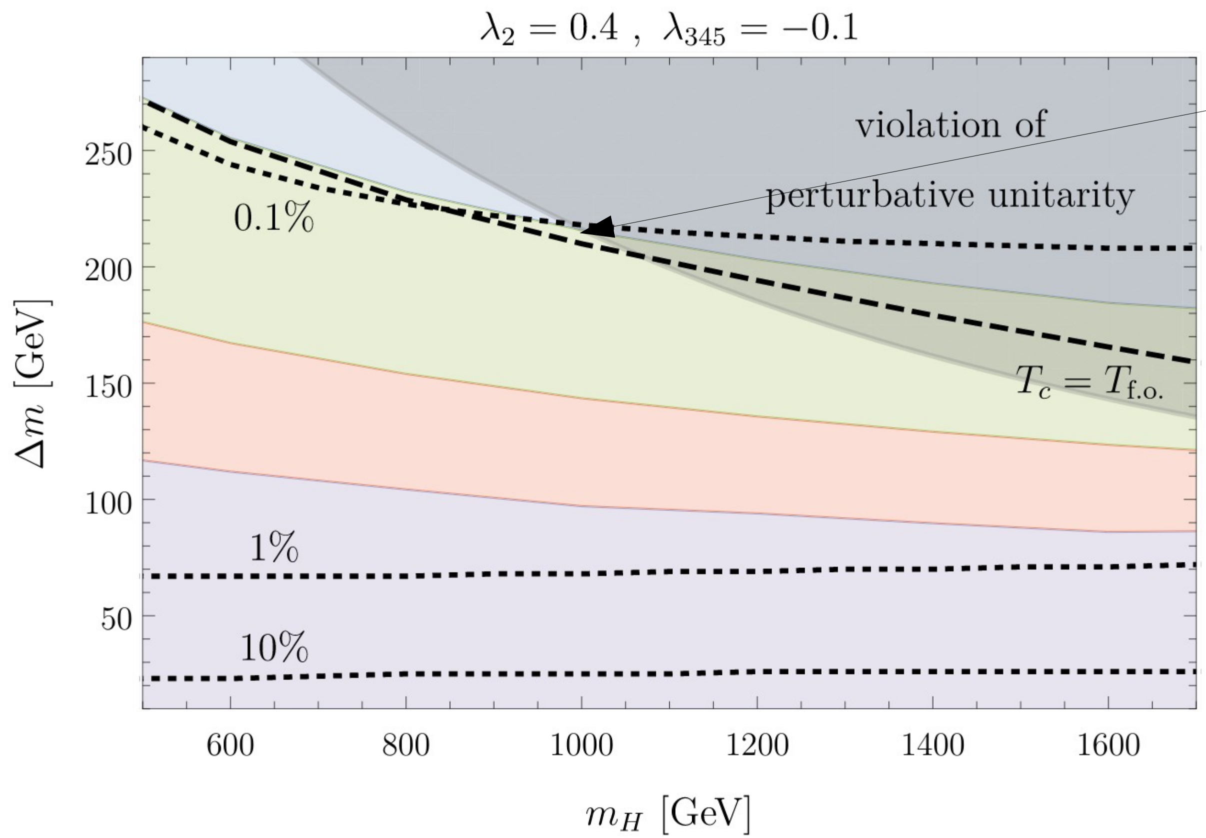

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CP Violation

Agnostic EFT approach, sticking to given field content

$$\mathcal{L}_{\not{\mathrm{CP}}} \supset C_{H_1\tilde{F}}\,|H_1|^2\,\tilde{F}^I_{\mu\nu}F^{I\,\mu\nu} + C_{qH_1}\,|H_1|^2\,\bar{q}_L H_1 q_R + C_{H_2\tilde{F}}|H_2|^2\tilde{F}^I_{\mu\nu}F^{I\,\mu\nu}$$

...

EW gauge bosons

CP Violation

Agnostic EFT approach, sticking to given field content

$$\mathcal{L}_{\not{CP}} \supset C_{H_1\tilde{F}} |H_1|^2 \tilde{F}^I_{\mu\nu} F^{I\,\mu\nu} + C_{qH_1} |H_1|^2 \bar{q}_L H_1 q_R + C_{H_2\tilde{F}} |H_2|^2 \tilde{F}^I_{\mu\nu} F^{I\,\mu\nu}$$

...

studied a lot, but....

Dine, Huet, Singleton, Susskind, Phys. Lett. B257(1991)

Dine, Huet, Singleton, Nucl.Phys. B375(1992)

Balazs, White, Yue, 1612.01270

Ferreira, Fuks, Sanz, Sengupta, 1612.01808

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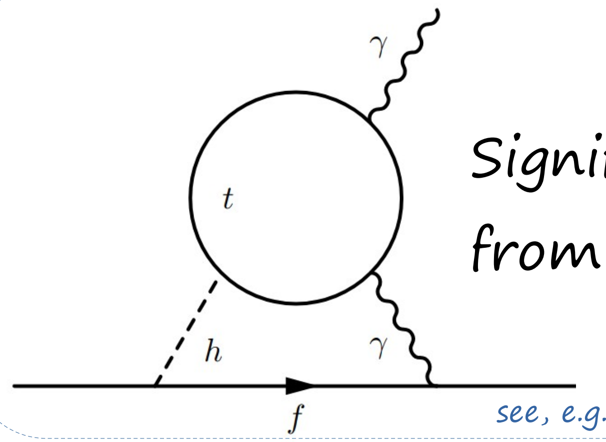
...



Significantly constrained from EDM limits

see, e.g., Balazs, White, Yue, 1612.01270

CP Violation

Agnostic EFT approach, sticking to given field content

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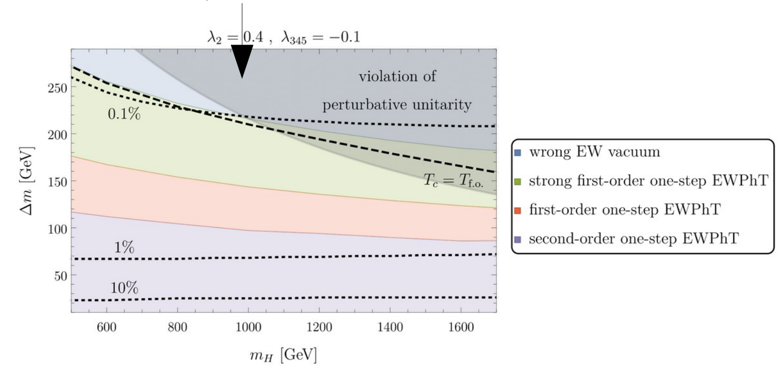
explore

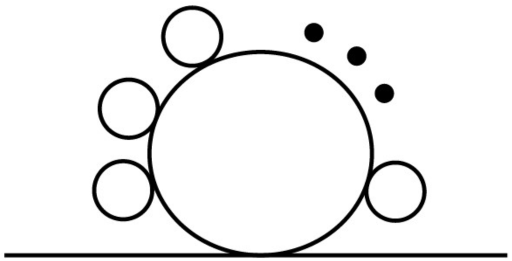


Conclusions

- The Nature of DM and origin of Baryon Asymmetry are among the most pressing questions in physics
- IDM as simple, predictive & versatile SM Extension with various interesting features: can address major open questions of SM
- Low mass regime leaves several opportunities to simultaneously realize DM (new region with small splitting) and SFOPhT
- 2-step PhT in viable region, potentially interesting signatures
- More things to explore…

THANK YOU!

Backup: Daisy Resummation



Resummation of T-enhanced contributions

$$\hat{m}_i^2\left(h,H\right)\rightarrow\tilde{m}_i^2\left(h,H,T\right)$$

Parwani, hep-ph/9204216, Gross, Pisarski, Yaffe, Rev.Mod. Phys.53, Quiros, hep-ph/9901312

$$\boxed{\widetilde{M}_X^2\equiv\widehat{M}_X^2+\widehat{\Pi}(T),\ X=S,P,\pm}$$

$$\widehat{\Pi}_{11}\left(T\right)=\frac{T^2}{24}\left(6y_t^2+6y_b^2+2y_\tau^2+\frac{9}{2}g^2+\frac{3}{2}g'^2+12\lambda_1+4\lambda_3+2\lambda_4\right)$$

$$\widehat{\Pi}_{22}\left(T\right)=\frac{T^2}{24}\left(\frac{9}{2}g^2+\frac{3}{2}g'^2+12\lambda_2+4\lambda_3+2\lambda_4\right)$$

$$\boxed{\tilde{m}_{W_L}^2=\frac{h^2+H^2}{v^2}m_W^2+2g^2T^2,\quad\tilde{m}_{Z_L,\gamma_L}^2=\frac{h^2+H^2}{8}\left(g^2+g'^2\right)+\left(g^2+g'^2\right)T^2\pm\Delta}$$

$$\Delta^2\equiv\frac{\left(h^2+H^2+8T^2\right)^2}{64}\left(g^2+g'^2\right)^2-g^2g'^2T^2\left(h^2+H^2+4T^2\right)$$

Backup: Baryon Number Violation

B conserved → $n_B - n_{\bar{B}} = \text{const.}$

→ no asymmetry can be generated

Backup: C and CP Violation

- Universe initially matter-antimatter symmetric, without preferred direction of time

  → described by C and CP invariant state $|\phi_0\rangle$, with $B|\phi_0\rangle = 0$

- C or CP conserved → $[C, H] = 0$ v $[CP, H] = 0$

$$|\phi(t)\rangle = e^{iHt}|\phi_0\rangle \;\rightarrow\; C|\phi(t)\rangle = |\phi(t)\rangle \;\; \mathrm{v} \;\; CP|\phi(t)\rangle = |\phi(t)\rangle$$

$$B|\phi(t)\rangle = B(\mathcal{C}|\phi(t)\rangle) = -B|\phi(t)\rangle\,, \;\; \mathcal{C} = C, CP$$

$$\rightarrow \boxed{B|\phi(t)\rangle = 0}$$

Backup: Departure from Thermal Equilibrium

- Thermal Equilibrium Average:

$$\begin{aligned}\langle B\rangle_T &= \mathrm{Tr}[e^{-\beta H}B] \\ &= \mathrm{Tr}[(CPT)(CPT)^{-1}e^{-\beta H}B] \\ &= \mathrm{Tr}[e^{-\beta H}(CPT)^{-1}B(CPT)] \\ &= -\mathrm{Tr}[e^{-\beta H}B]\end{aligned}$$

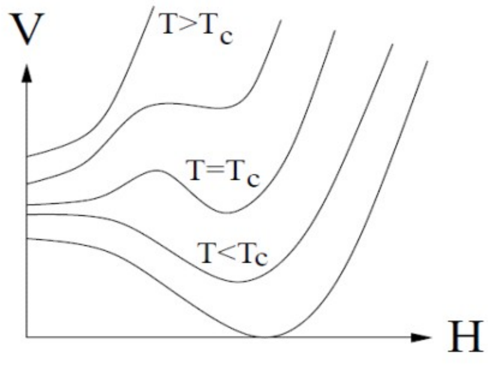
$\rightarrow \langle B\rangle_T = 0$ → no net B asymmetry although B violated

Thermal Equilibrium:
reaction rates Γ >> expansion of universe H

$\beta = 1/(k_B T)$

Backup: Departure from Thermal Equilibrium

- First Order PT → Bubble Nucleation: bubbles with $\langle H \rangle > 0$ form inside regions of symmetric phase ($\langle H \rangle = 0$)



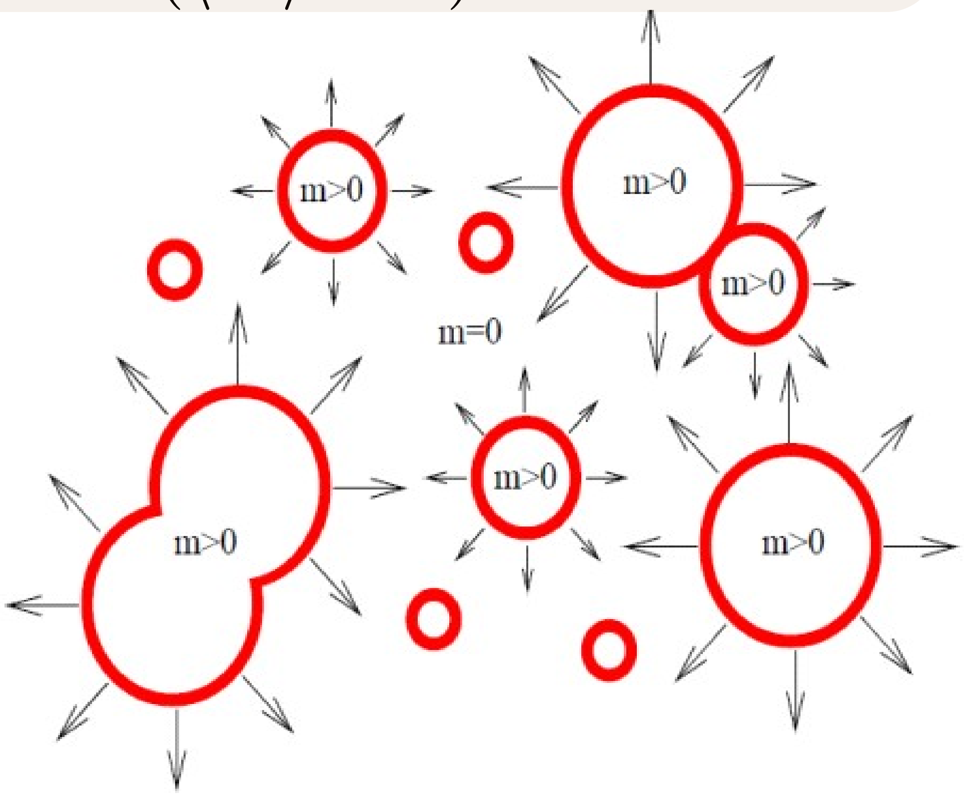
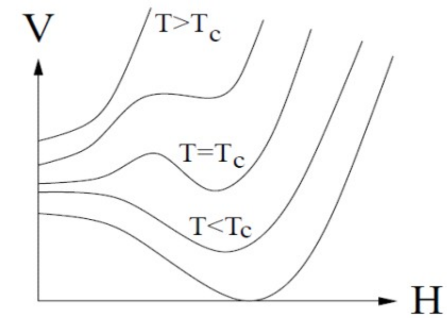


Fig. 11. Bubble nucleation during a first-order EWPT. Cline, ph-0609145

Backup: Departure from Thermal Equilibrium

- First Order PT → Bubble Nucleation: bubbles with $\langle H \rangle > 0$ form inside regions of symmetric phase ($\langle H \rangle = 0$)

- Moving bubbles, C and CP violation $\rightarrow$ different ammounts of $q_L, q_R, \bar{q}_L, ..$ reflected



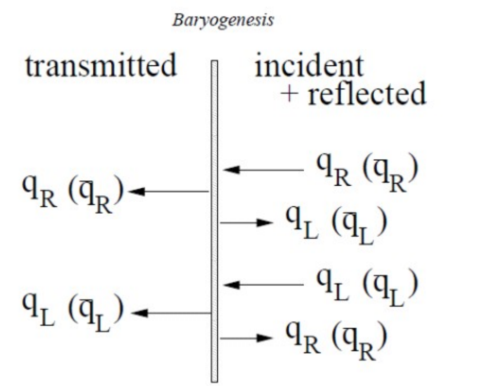


Fig. 12. CP-violating reflection and transmission of quarks at the moving bubble wall

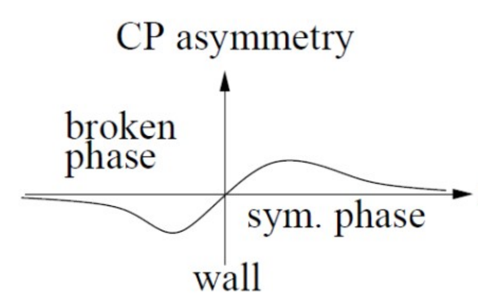


Fig. 13. The CP asymmetry which develops near the bubble wall.

Cline, ph-0609145

Backup: Departure from Thermal Equilibrium

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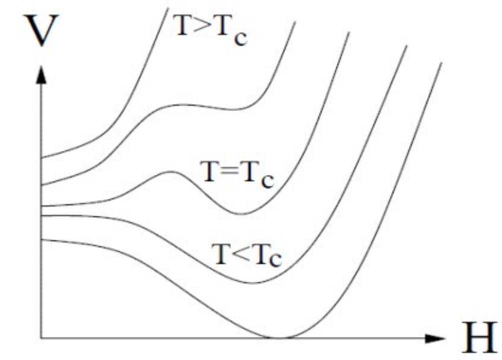
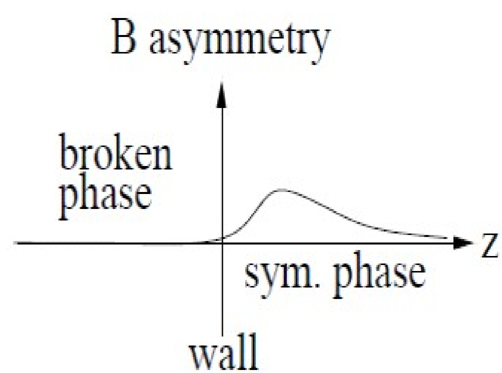


- Moving bubbles, C and CP violation $\rightarrow$ different ammounts of $q_L, q_R, \bar{q}_L, ..$ reflected

- CP asymmetry converted to B asymmetry through unsuppressed sphalerons outside bubbles → transmitted into moving bubbles



- Sphalerons out of equilibrium inside bubbles: Γ_{sph} suppressed due to $E_{\text{sph}} > 0$ → no washout