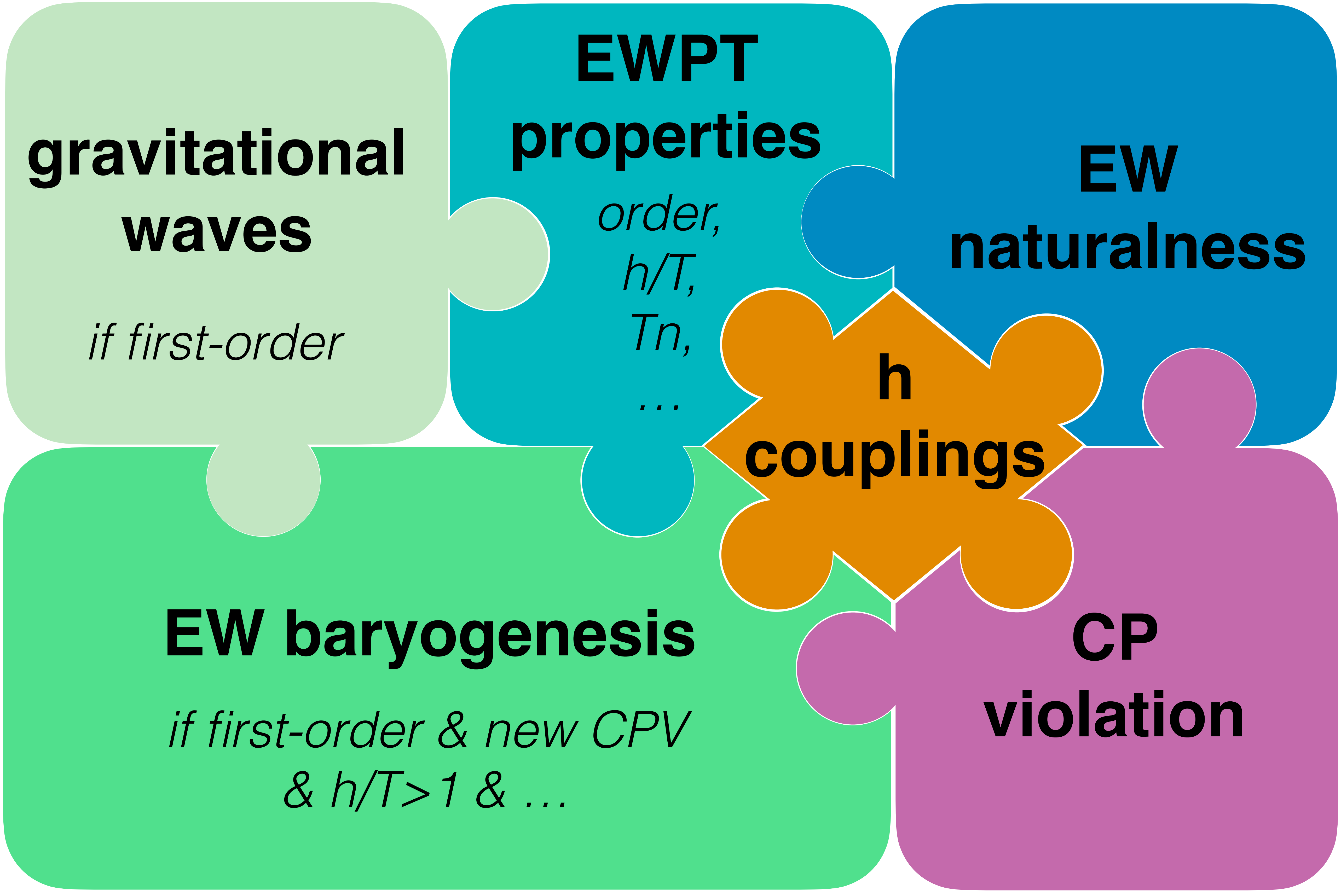
Higgs Couplings
and
ElectroWeak Phase Transition

Oleksii Matsedonskyi

TUM

FCC Physics Workshop


gravitational waves
if first-order
EWPT properties
order, h/T, Tn, …
EW naturalness
h couplings
EW baryogenesis
if first-order & new CPV & h/T>1 & …
CP violation

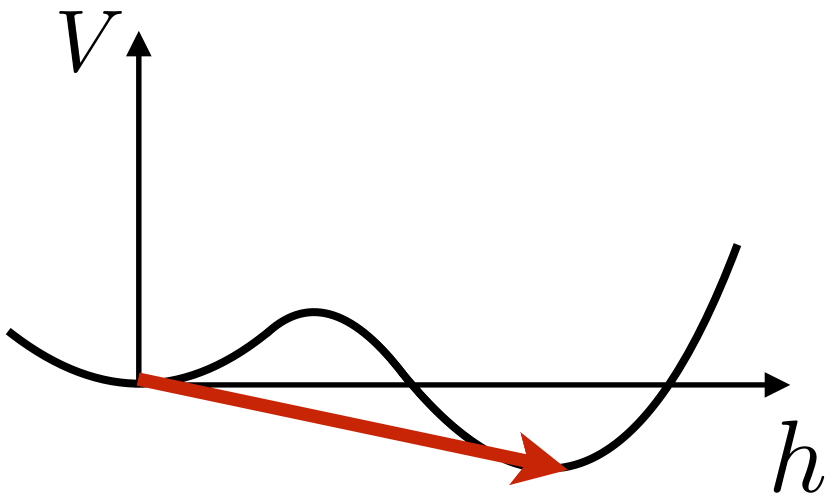
- All aspects of Higgs couplings - EWPhT connection is a broad topic with a lot of model dependence.

- The most interesting aspect is the signatures of first-order EWPhT, potentially leading to GW and EWBG.

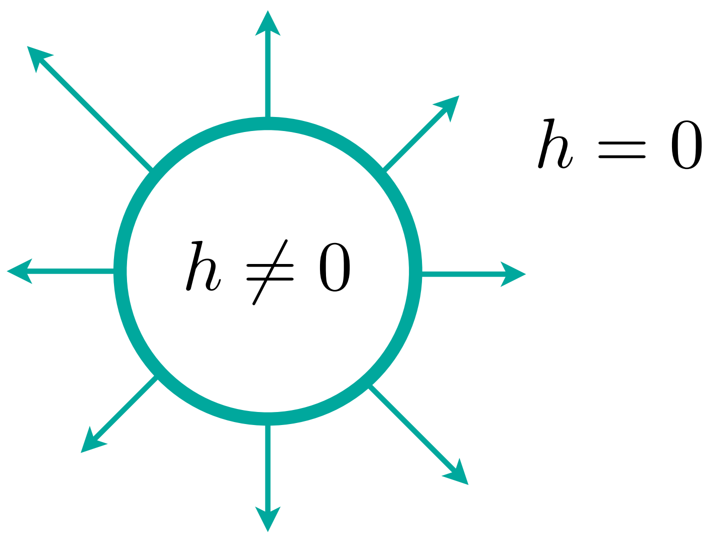
- I'll discuss several examples of connection between Higgs couplings and properties of EWPhT/EWBG.

Why first-order EWPT?

First order EW phase transition proceeds through bubble nucleation:



$\Longrightarrow$



Electroweak Baryogenesis

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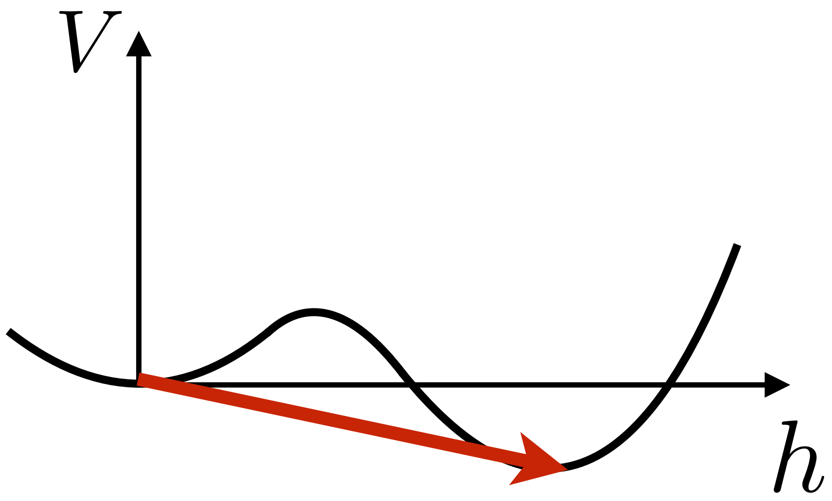

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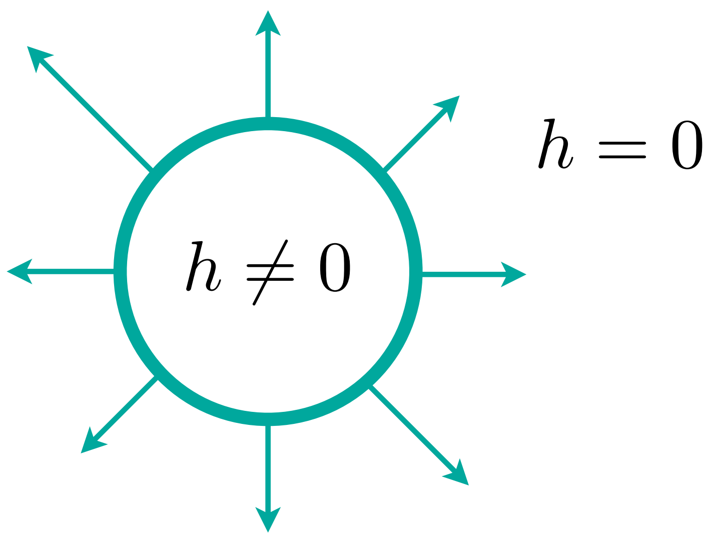
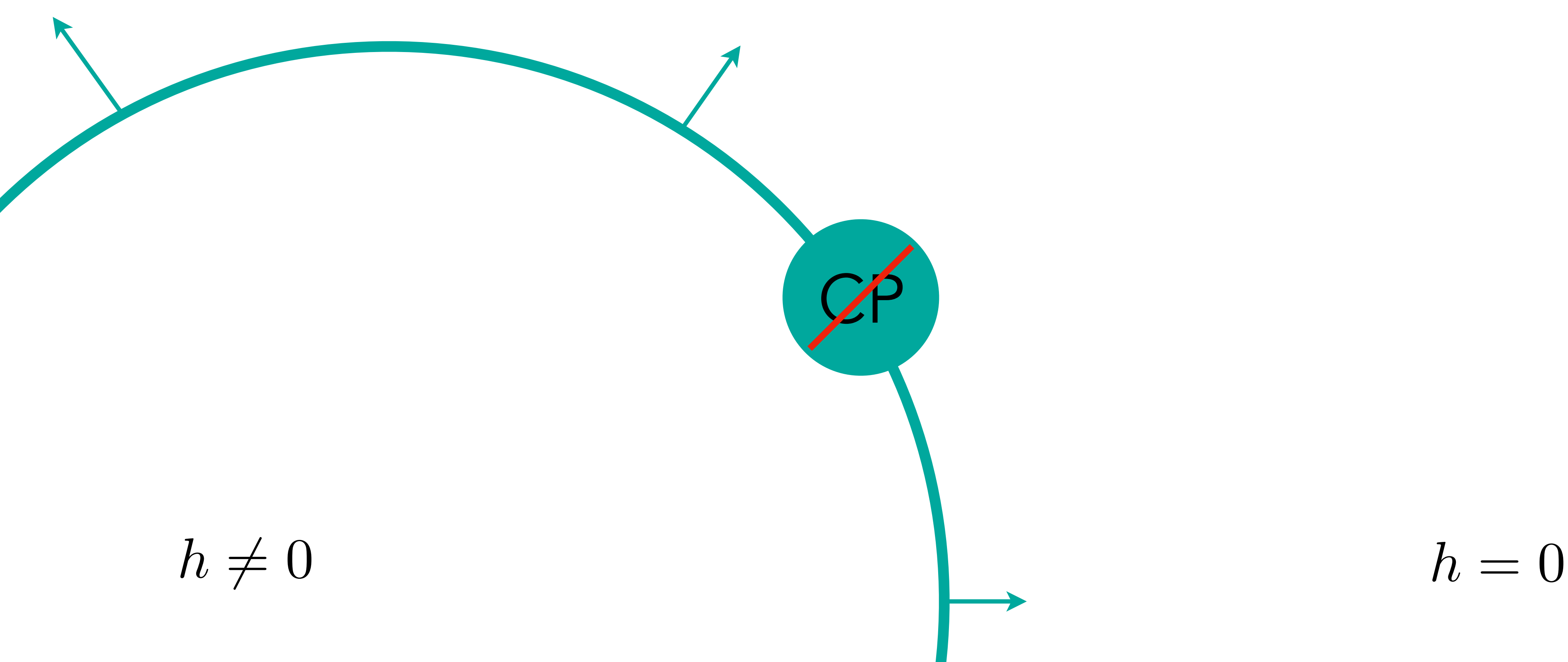


Baryon asymmetry is created close to bubble walls:



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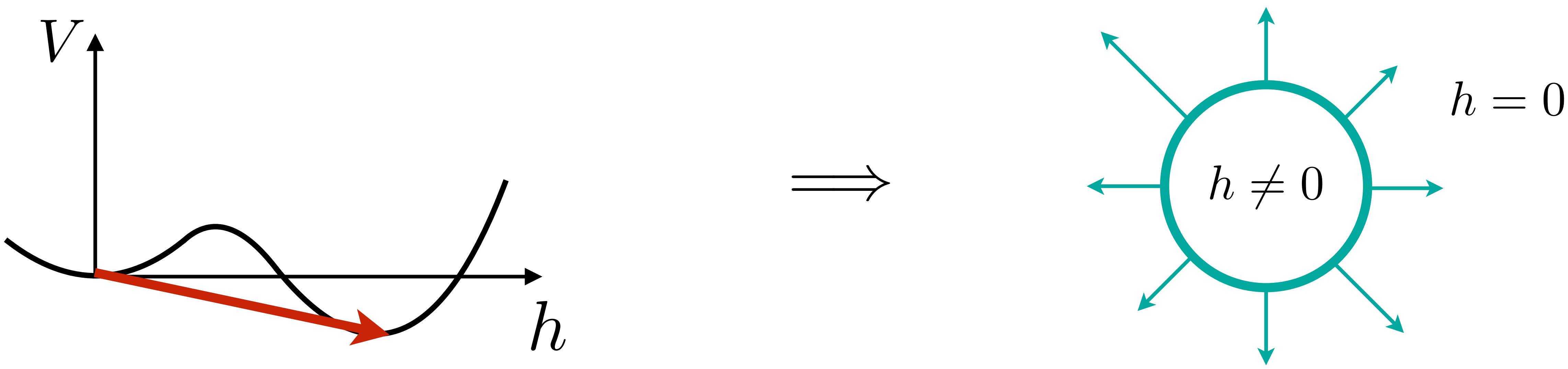

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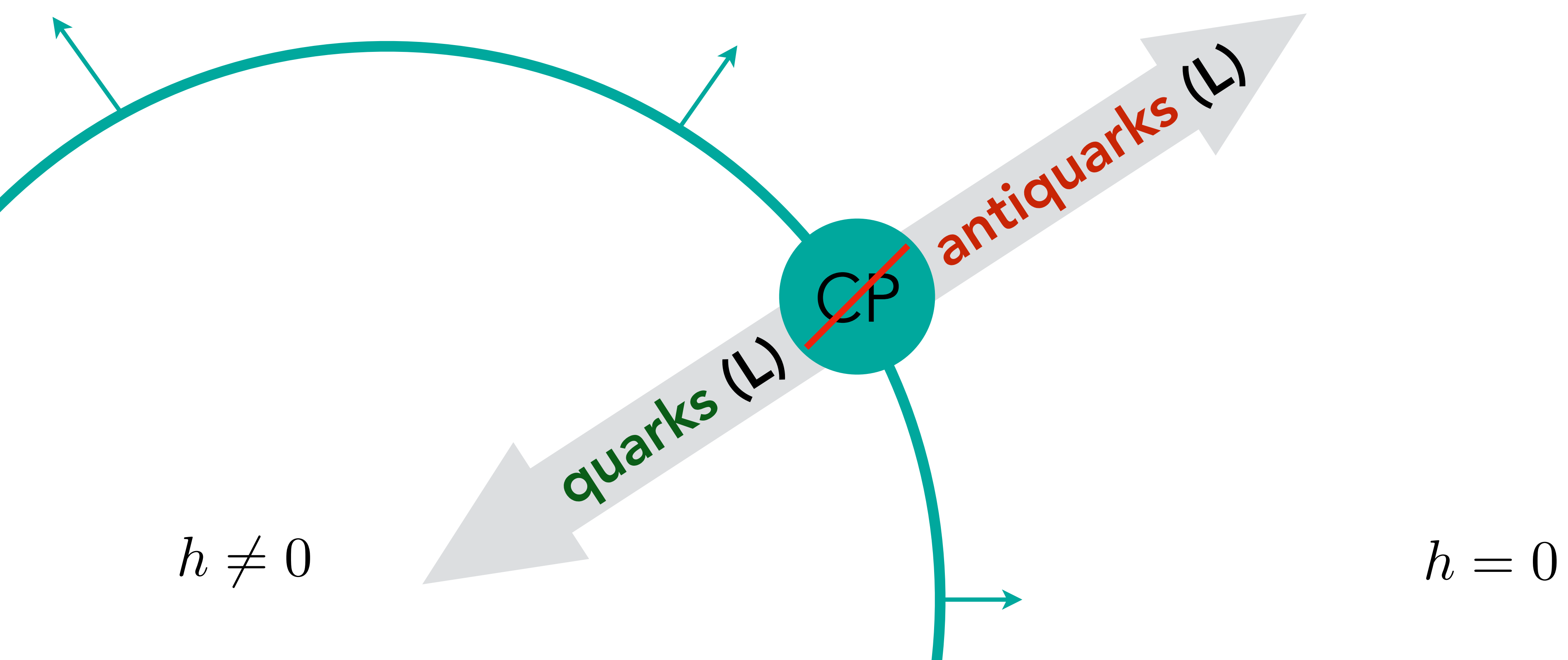

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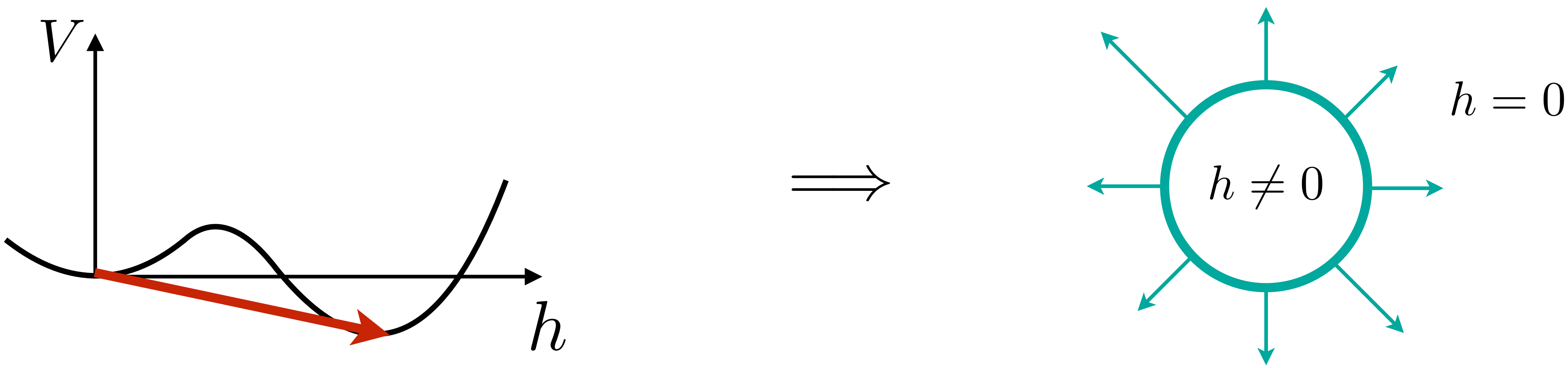

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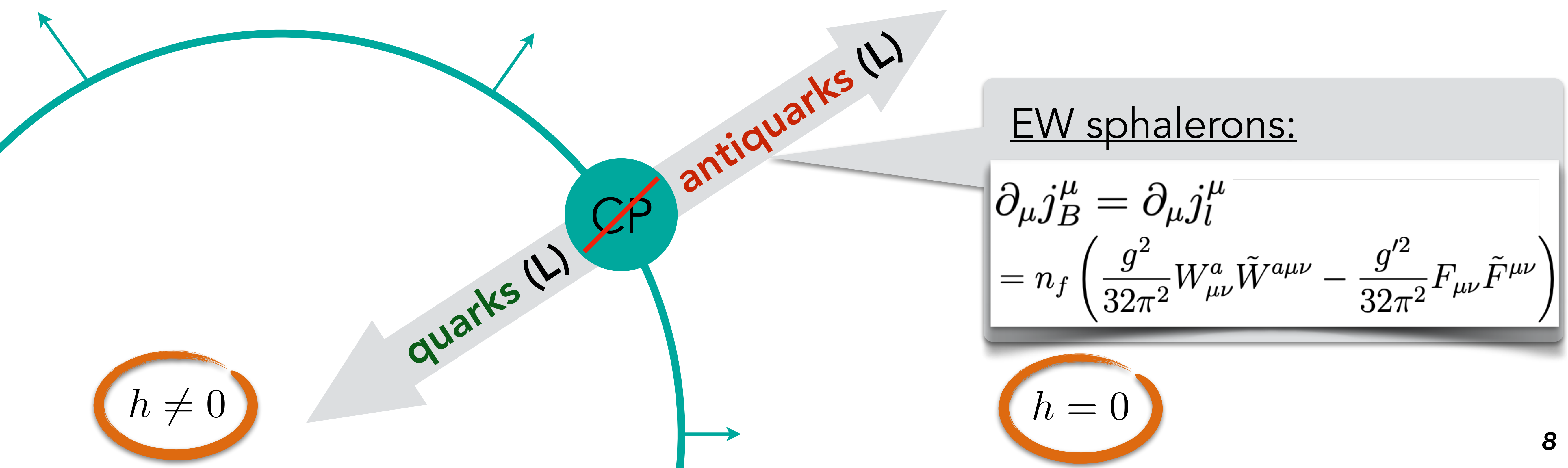

$$\partial_\mu j_B^\mu = \partial_\mu j_l^\mu = n_f \left(\frac{g^2}{32\pi^2} W_{\mu\nu}^a \tilde{W}^{a\mu\nu} - \frac{g'^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} \right)$$

Electroweak Baryogenesis

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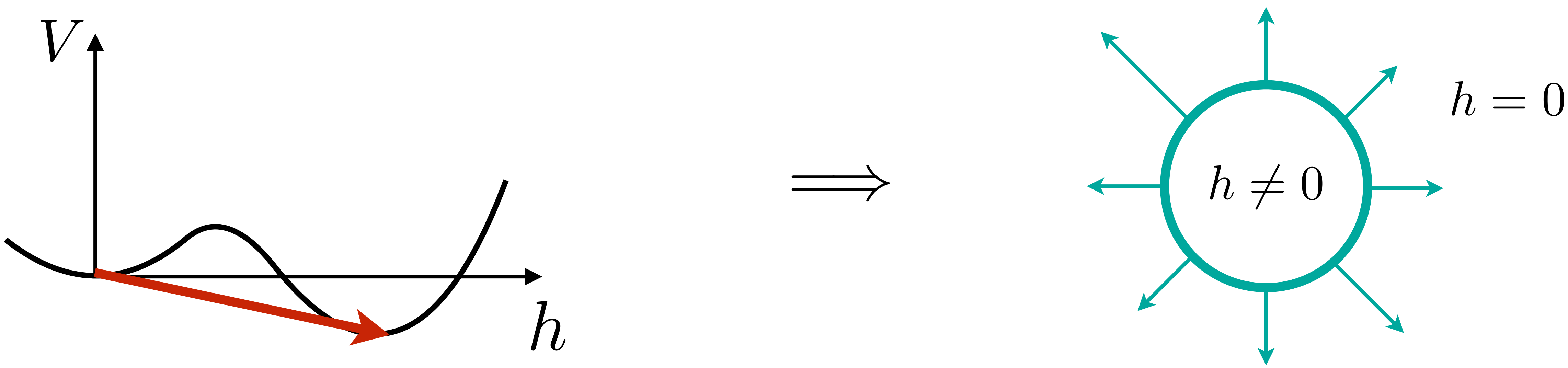

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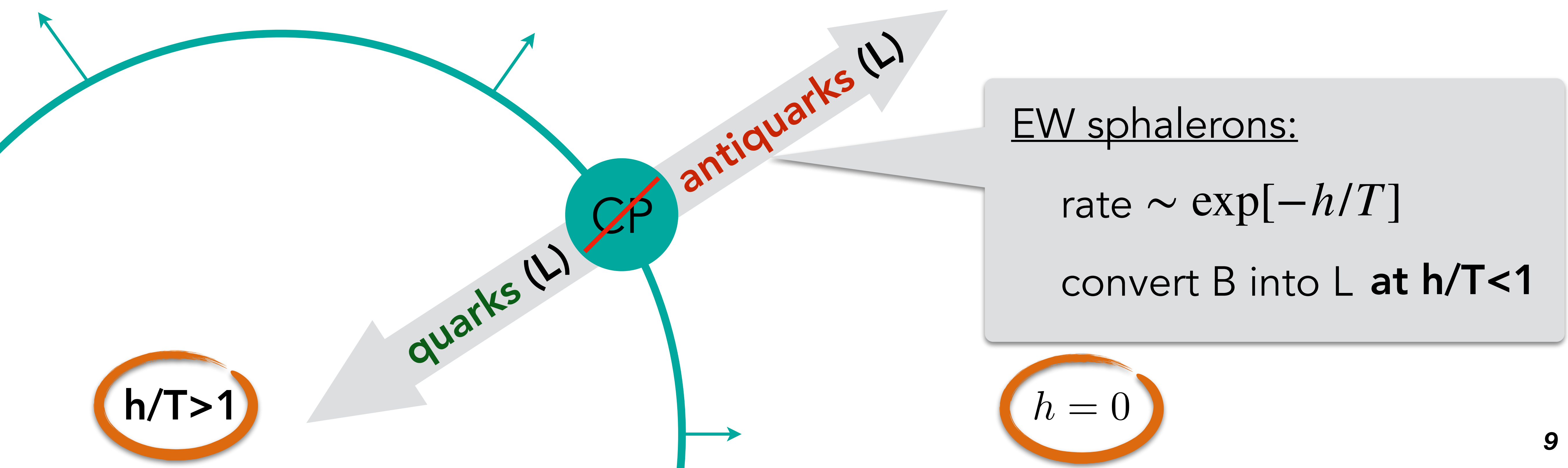

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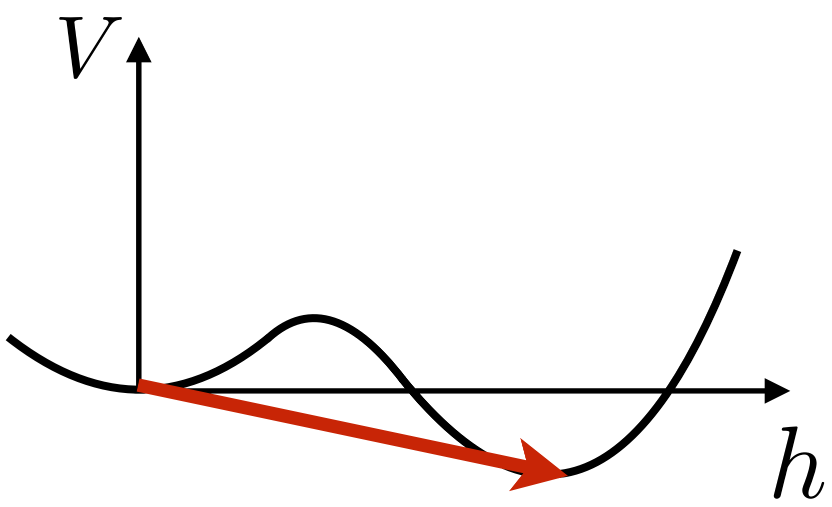

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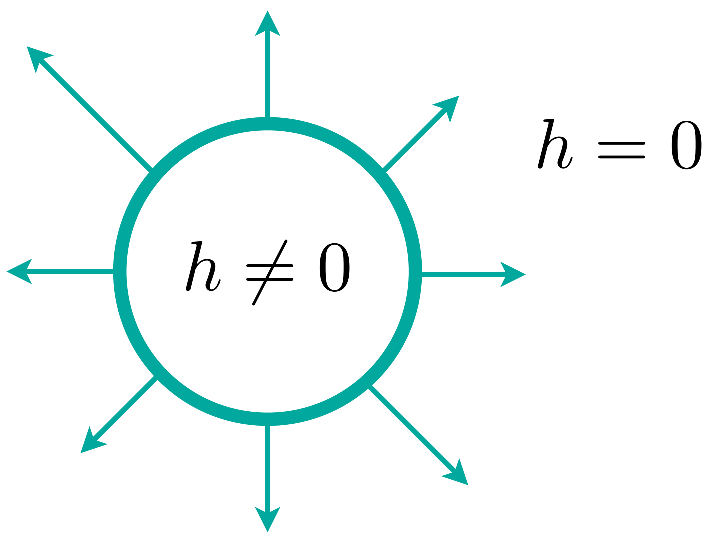

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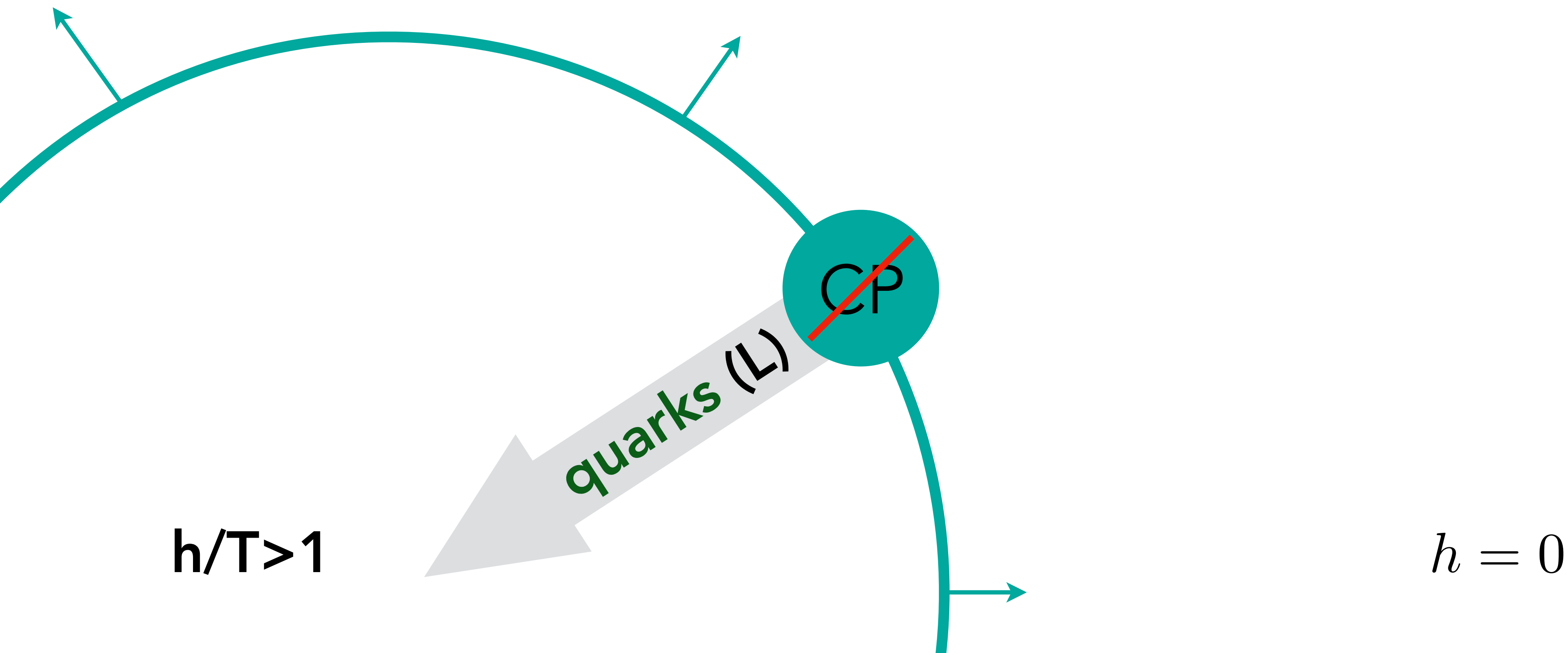

Electroweak Baryogenesis

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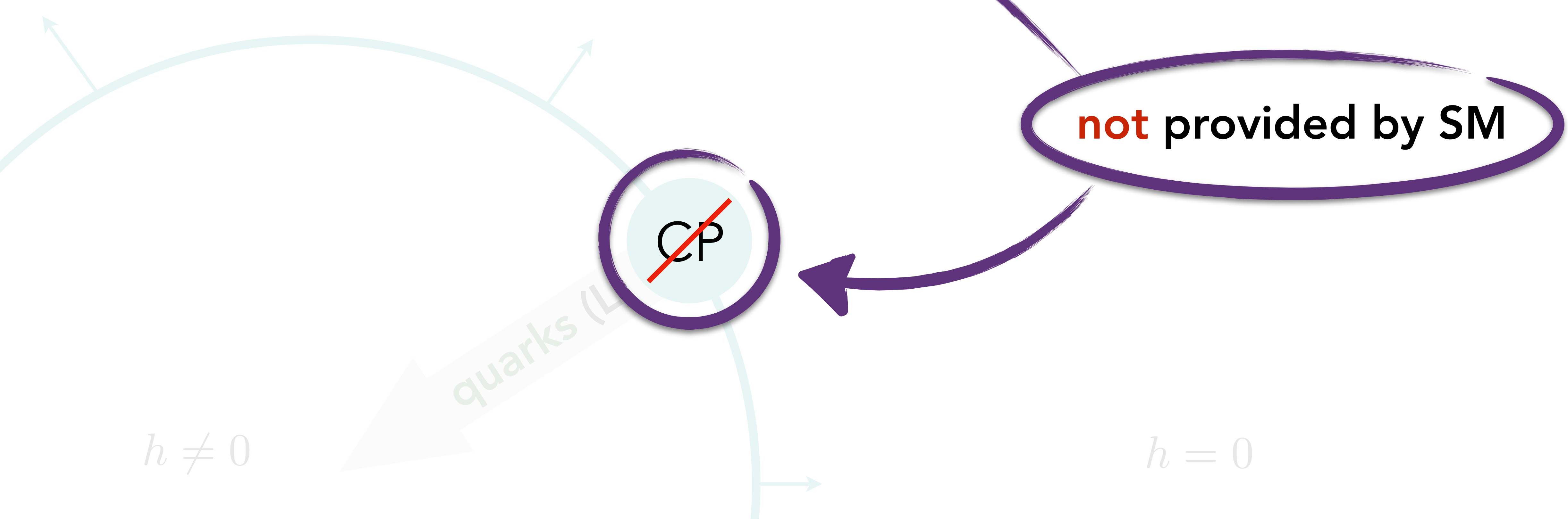
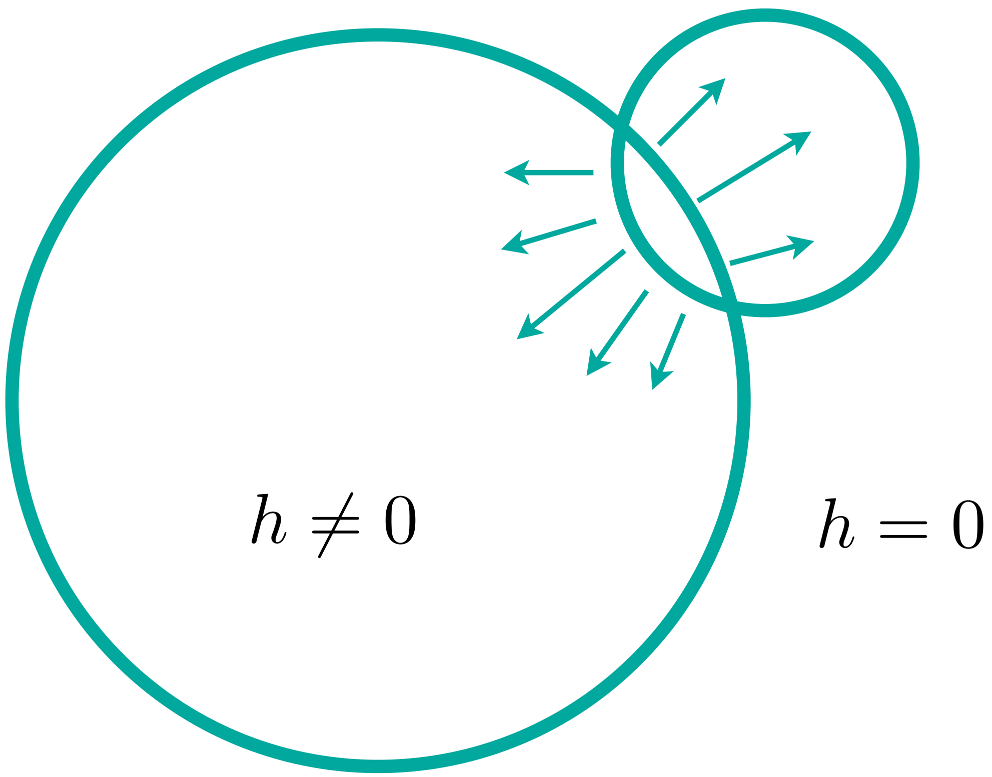
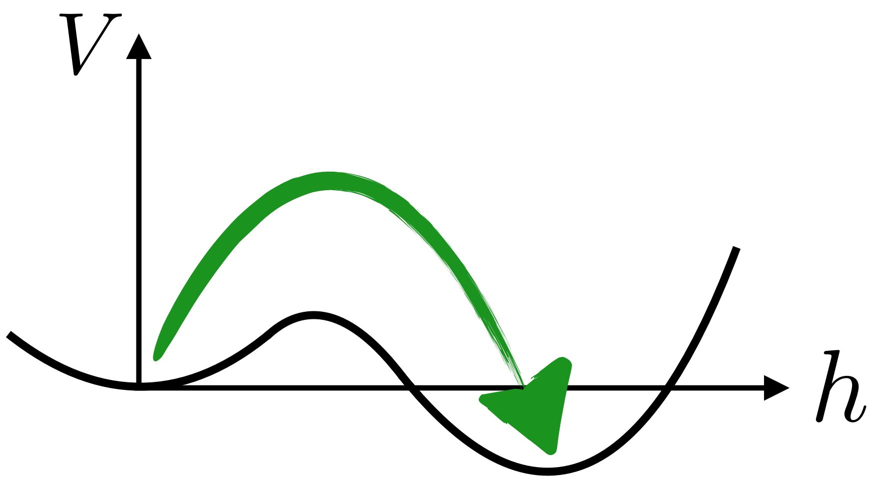



$h \neq 0$
$h = 0$

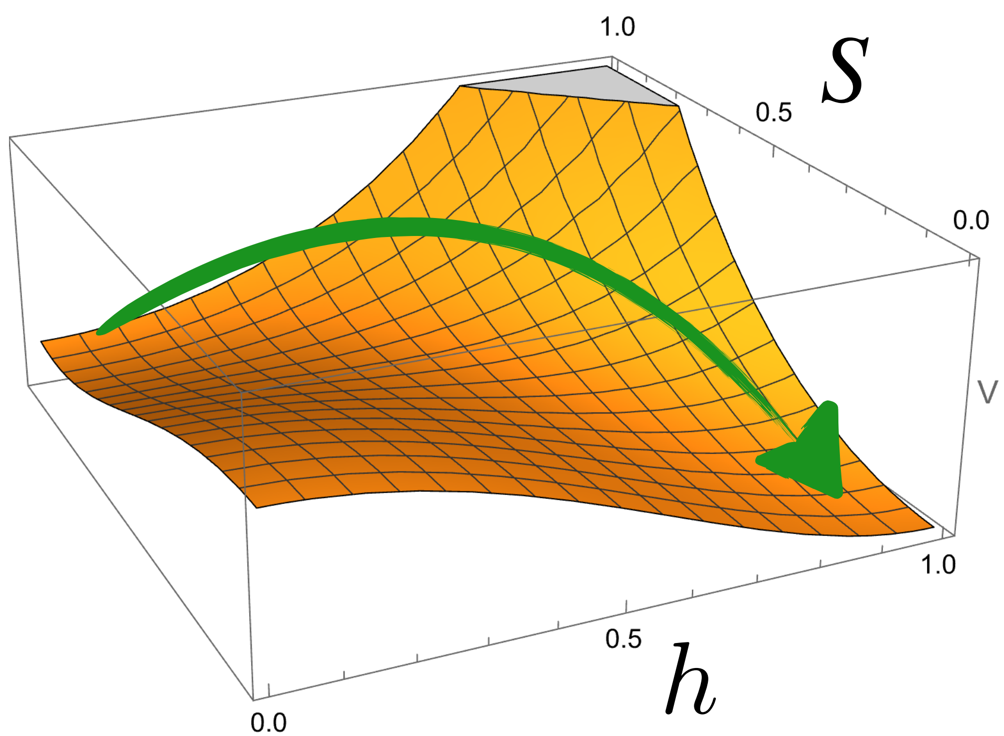
How to get first-order EWPT?

How to get first-order EWPT?

- New particles s.t. thermal/quantum corrections modify SM Higgs potential



- New field directions



SM + Singlet

$$V_{\rm tree}(h,S) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}\lambda_{HS} h^2 S^2 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4$$

- Only an extremely small explicit $S \to -S$ breaking is needed to get B asymmetry and remove domain walls. Espinosa et al, 1110.2876

- Consider the case with $S \to -S$ respected by the EWSB minimum

(For models with spontaneous or sizeable explicit breaking see 2210.16305,1911.10206)

SM + Singlet

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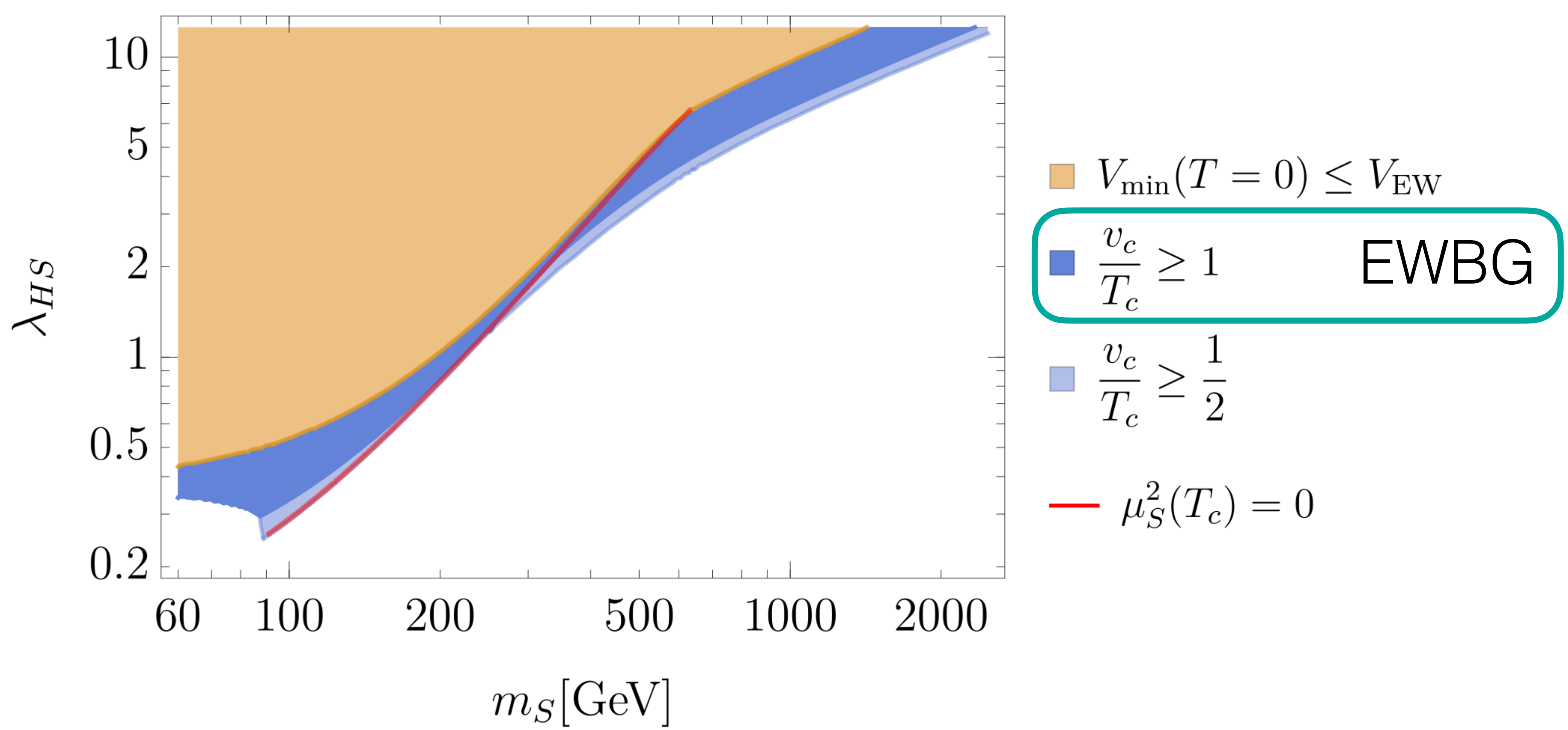

A.Benival et al, 1702.06124

* may be affected by Agrawal et al, 2312.06749

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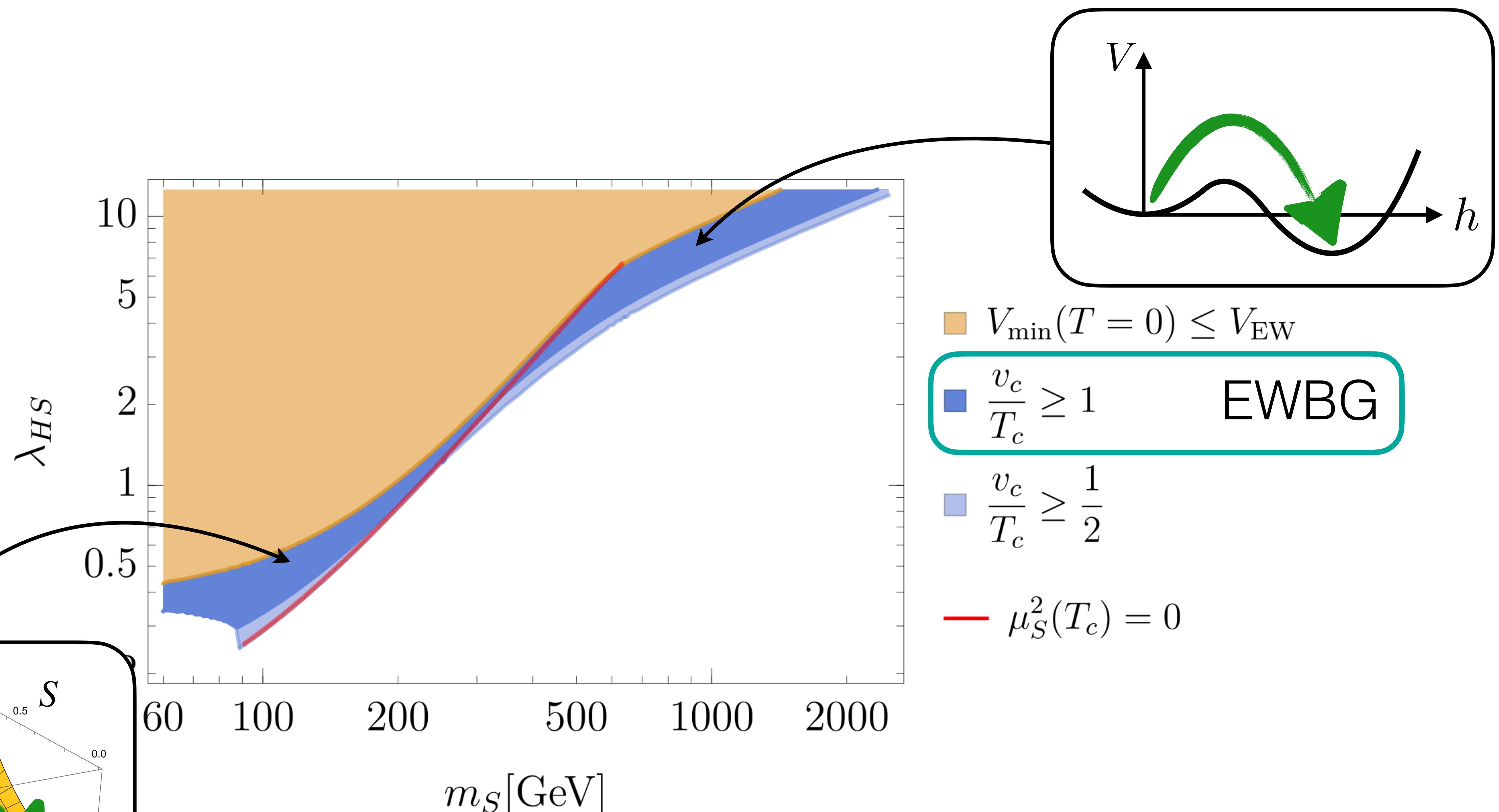

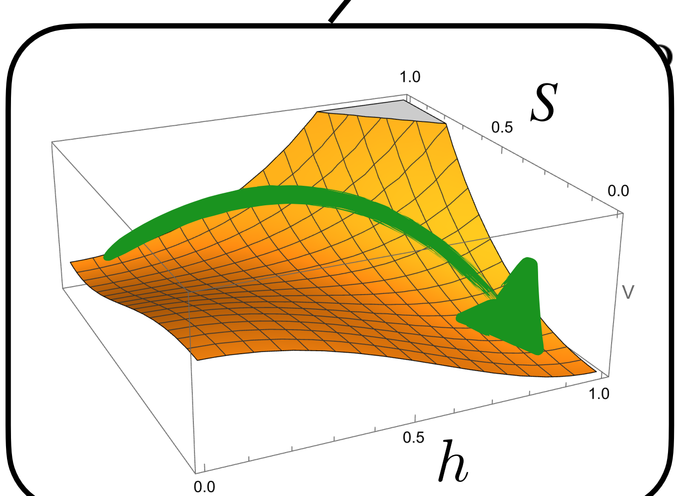

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Pheno: S-h mixing

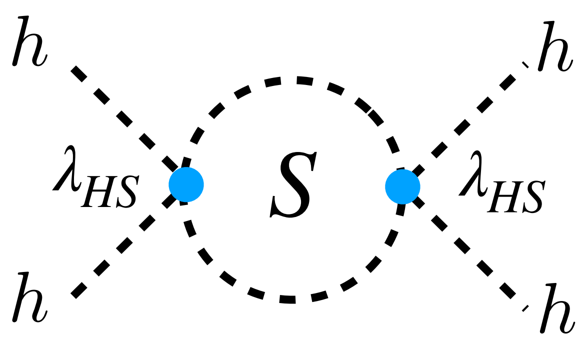
$$V_{\text{tree}}(h,S) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}\lambda_{HS} h^2 S^2 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4$$

- $S \to -S$ symmetry:

$\Rightarrow$ no sizeable Higgs-S mixing

$\Rightarrow$ loop-induced effects of λ_{HS}

Pheno: c_H



$$\mathscr{L} \ni \frac{c_H}{\Lambda^2}\mathcal{O}_H \quad \text{where} \quad \mathcal{O}_H = \frac{1}{2}(\partial_\mu |H|^2)^2$$

$$\frac{c_H}{\Lambda^2} = \frac{\lambda_{HS}^2}{48\pi^2}\frac{1}{m_S^2}$$

M.Carena et al, 2104.00638

future sensitivities (1σ):

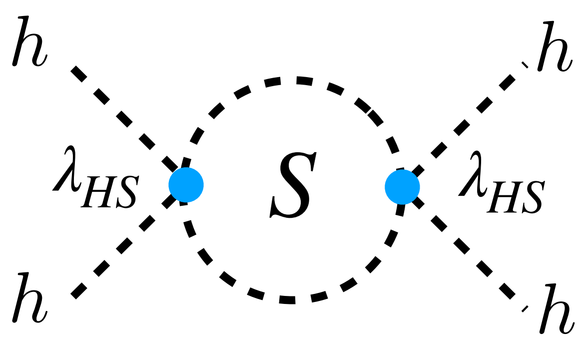
HL-LHC: $\Lambda/\sqrt{|c_H|} < 1.4(1.8)\, TeV$

+**FCC-ee**: $\Lambda/\sqrt{|c_H|} < 3.2(5)\, TeV$

J de Blas, Eur. Phys. J. Plus (2021) 136:897

SM + Singlet

Pheno: c_H



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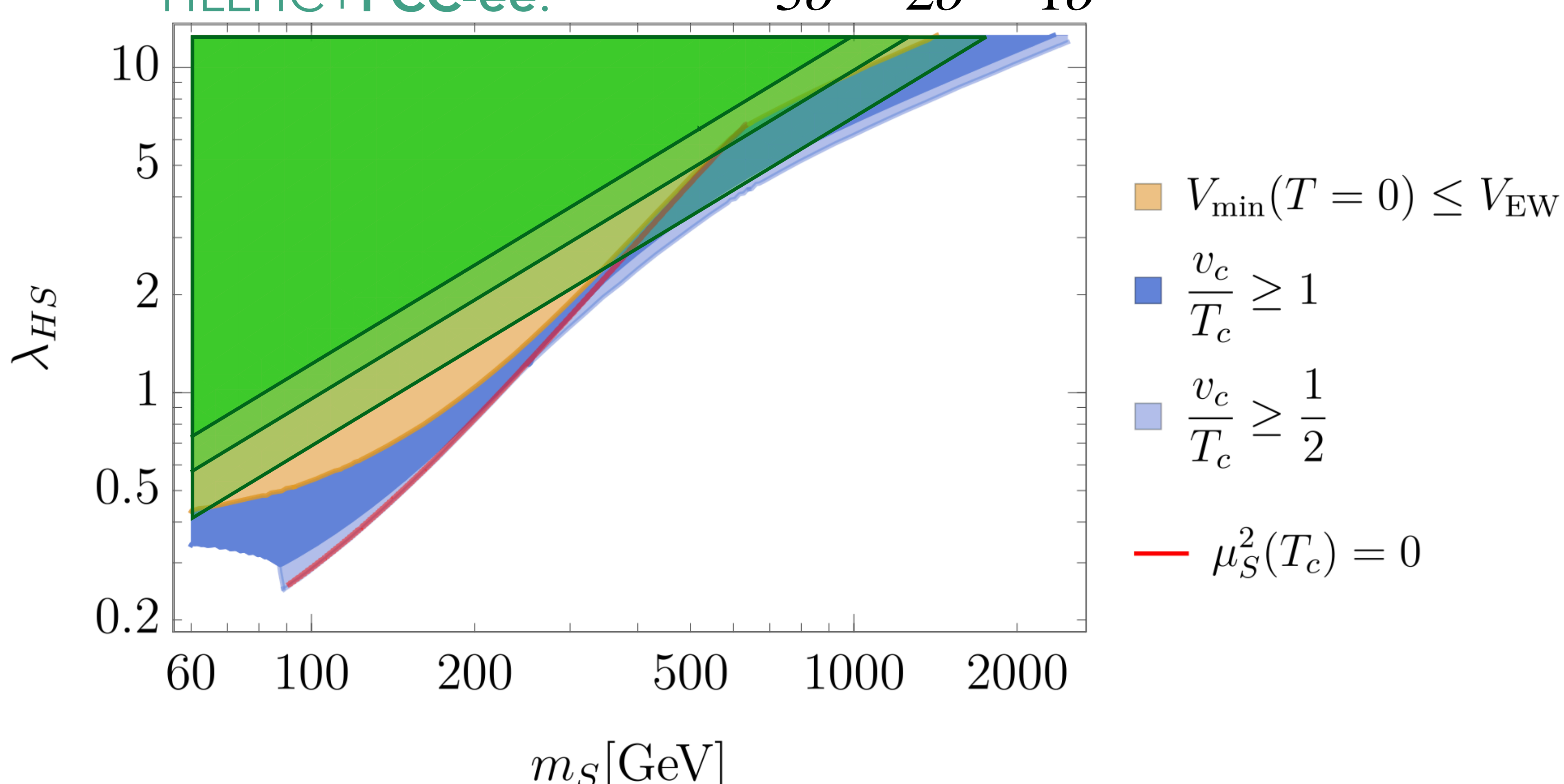
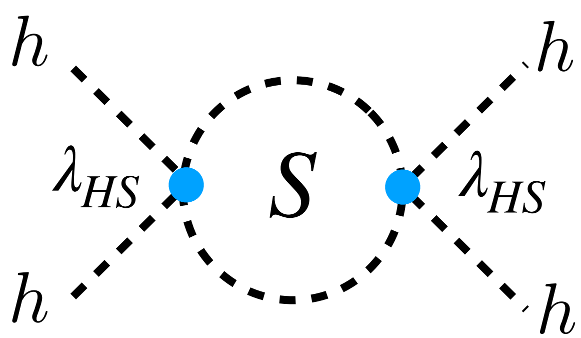
HLLHC+**FCC-ee**: $3\sigma - 2\sigma - 1\sigma$



SM + Singlet

Pheno: c_H



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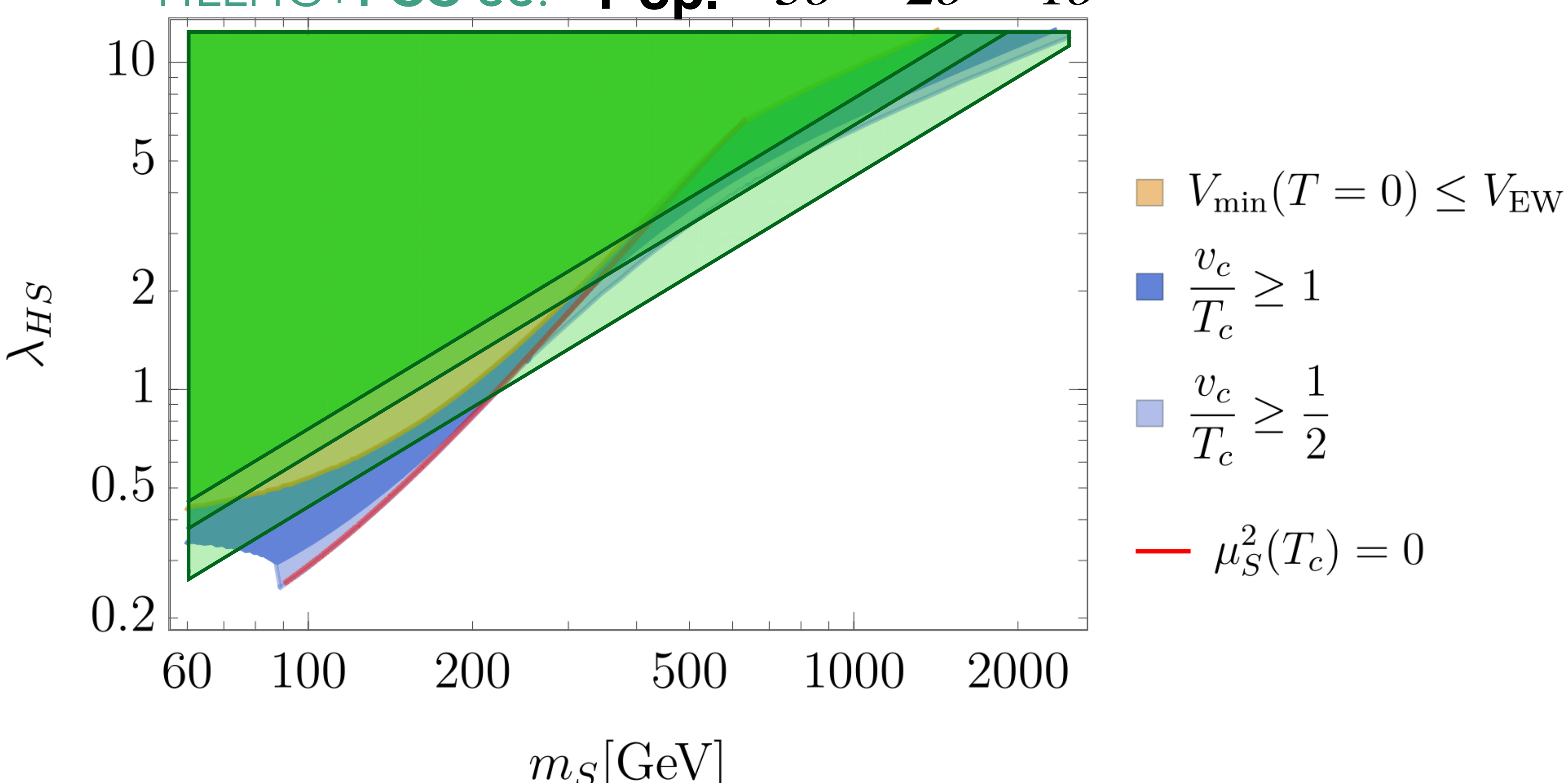
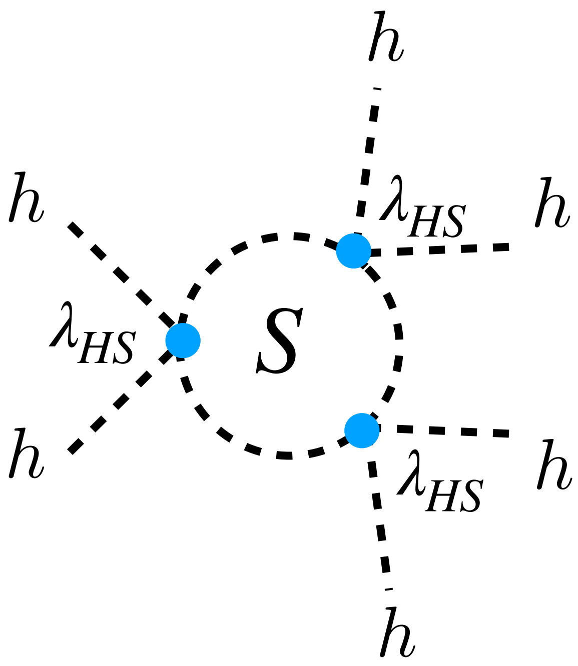
HLLHC+**FCC-ee**: **1-op.** $3\sigma - 2\sigma - 1\sigma$



SM + Singlet

Pheno: h^3



$$\lambda_3 = \frac{1}{6}\frac{\partial^3 V(h, S=0, T=0)}{\partial h^3}\bigg|_{h=v_0} \approx \frac{m_h^2}{2v_0} + \frac{\lambda_{HS}^3 v_0^3}{24\pi^2 m_S^2}$$

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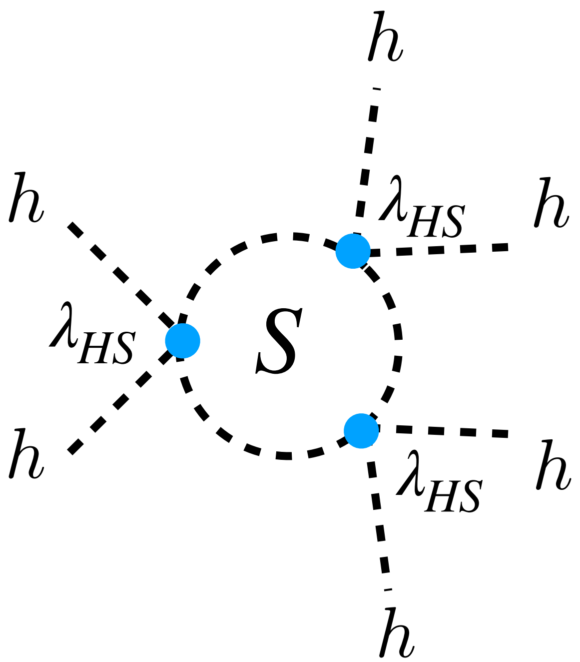
SM + Singlet

Pheno: h^3



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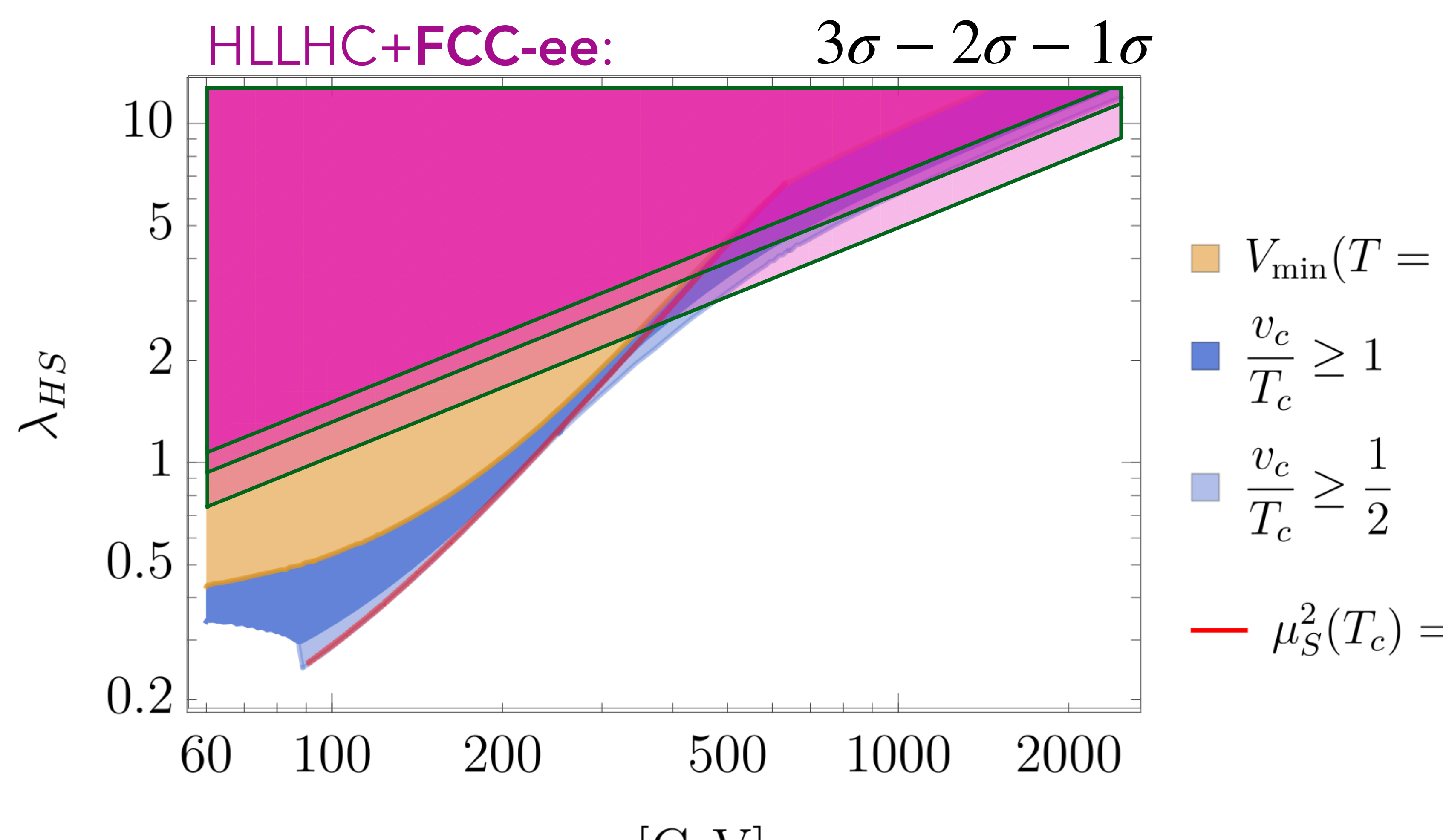
A.Benival et al, 1702.06124

future sensitivities (1σ):

HL-LHC: $\delta\kappa \sim 0.5$

+**FCC-ee**: $\delta\kappa \sim 0.2 - 0.3$

J de Blas et al,1905.03764



Naturalness Perspective

SM + “Singlet”: Naturalness Perspective

- Naturalness-motivated models can provide ingredients for 1st-order EWPT/EWBG

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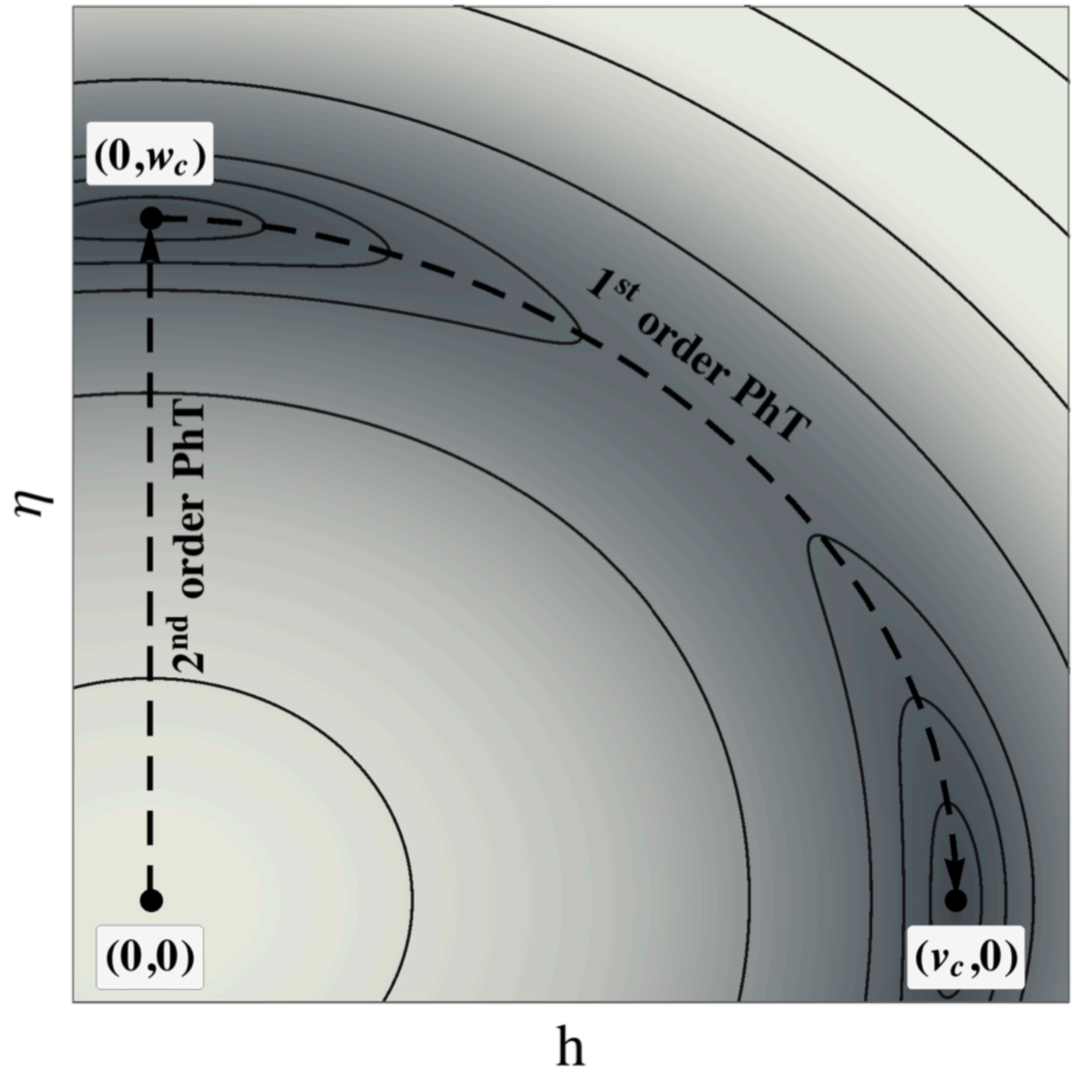
  e.g. composite Higgs + singlet pNGB   Espinosa et al, 1110.2876



DeCurtis,DelleRose,Panico, 1909.07894

SM + "Singlet": Naturalness Perspective

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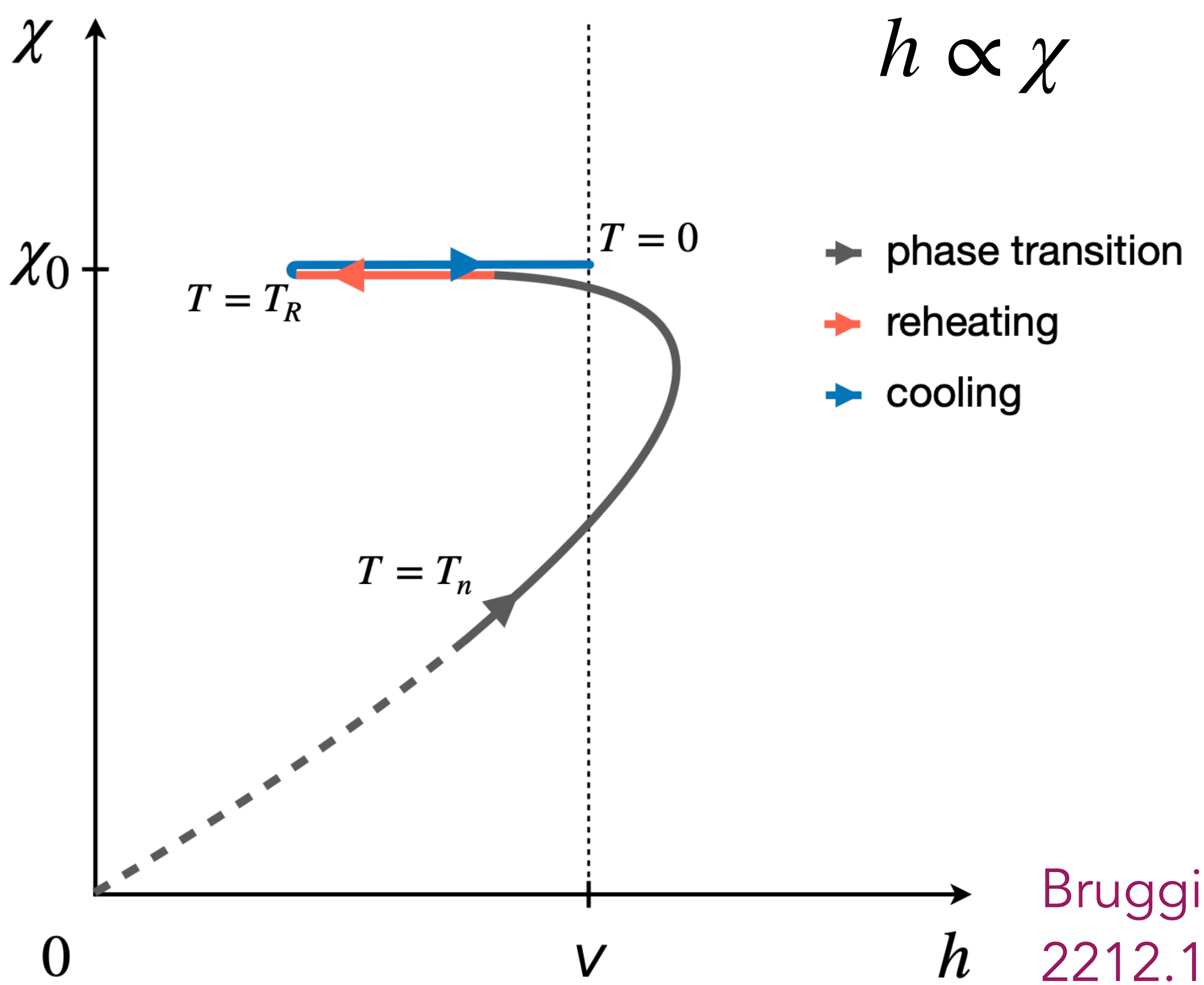
  e.g. composite Higgs + dilaton χ



Bruggisser, vonHarling,OM,Servant, 2212.11953

SM + “Singlet”: Naturalness Perspective

- Naturalness-motivated models can provide ingredients for 1st-order EWPT/EWBG
- Main source of h couplings deviations may be independent of EWPT

generic CH corrections:

coefficient	operator	power counting
$c_W \frac{g}{m_W^2}$	$\frac{1}{2}(\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi)\, D^\nu W^a_{\mu\nu}$	$\frac{g}{m_\star^2}$
$c_B \frac{g'}{m_W^2}$	$\frac{1}{2}(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)\, \partial^\nu B_{\mu\nu}$	$\frac{g'}{m_\star^2}$
$c_\gamma \frac{g'^2}{m_W^2}$	$\phi^\dagger \phi\, B_{\mu\nu} B^{\mu\nu}$	$\frac{g'^2}{m_\star^2} \frac{\lambda_t^2}{16\pi^2} N_c$
$c_{HB} \frac{g'}{m_W^2}$	$i(D^\mu \phi)^\dagger (D^\nu \phi) B_{\mu\nu}$	$\frac{g'}{m_\star^2} \frac{g_\star^2}{16\pi^2}$
$c_{HW} \frac{g}{m_W^2}$	$i(D^\mu \phi)^\dagger \tau^a (D^\nu \phi) W^a_{\mu\nu}$	$\frac{g}{m_\star^2} \frac{g_\star^2}{16\pi^2}$
$c_H \frac{1}{v^2}$	$\frac{1}{2}(\partial_\mu \lvert\phi\rvert^2)^2$	$\frac{g_\star^2}{m_\star^2}$
$c_g \frac{g_S^2}{m_W^2}$	$\lvert\phi\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\frac{g_S^2}{m_\star^2} \frac{\lambda_t^2}{16\pi^2}$
$c_u \frac{\lambda_u}{v^2}$	$\bar{q}\tilde{\phi} u\, \lvert\phi\rvert^2$	$\frac{\lambda_u g_\star^2}{m_\star^2}$
$c_d \frac{\lambda_d}{v^2}$	$\bar{q}\phi d\, \lvert\phi\rvert^2$	$\frac{\lambda_d g_\star^2}{m_\star^2}$
$c_e \frac{\lambda_e}{v^2}$	$\bar{l}\phi e\, \lvert\phi\rvert^2$	$\frac{\lambda_e g_\star^2}{m_\star^2}$
$c_6 \frac{\lambda}{v^2}$	$-\lvert\phi\rvert^6$	$\frac{g_\star^4}{m_\star^2} \frac{\lambda}{g_\star^2}$
$c_{3W} \frac{g}{3! m_W^2}$	$\epsilon_{abc} W^{a\nu}_\mu W^b_{\nu\rho} W^{c\rho\mu}$	$\frac{g^3}{g_\star^2 m_\star^2} \frac{g_\star^2}{16\pi^2}$

e.g. *OM, Durieux, 1807.10273*

SM + "Singlet": Naturalness Perspective

- Naturalness-motivated models can provide ingredients for 1st-order EWPT/EWBG
- Main source of h couplings deviations may be independent of EWPT

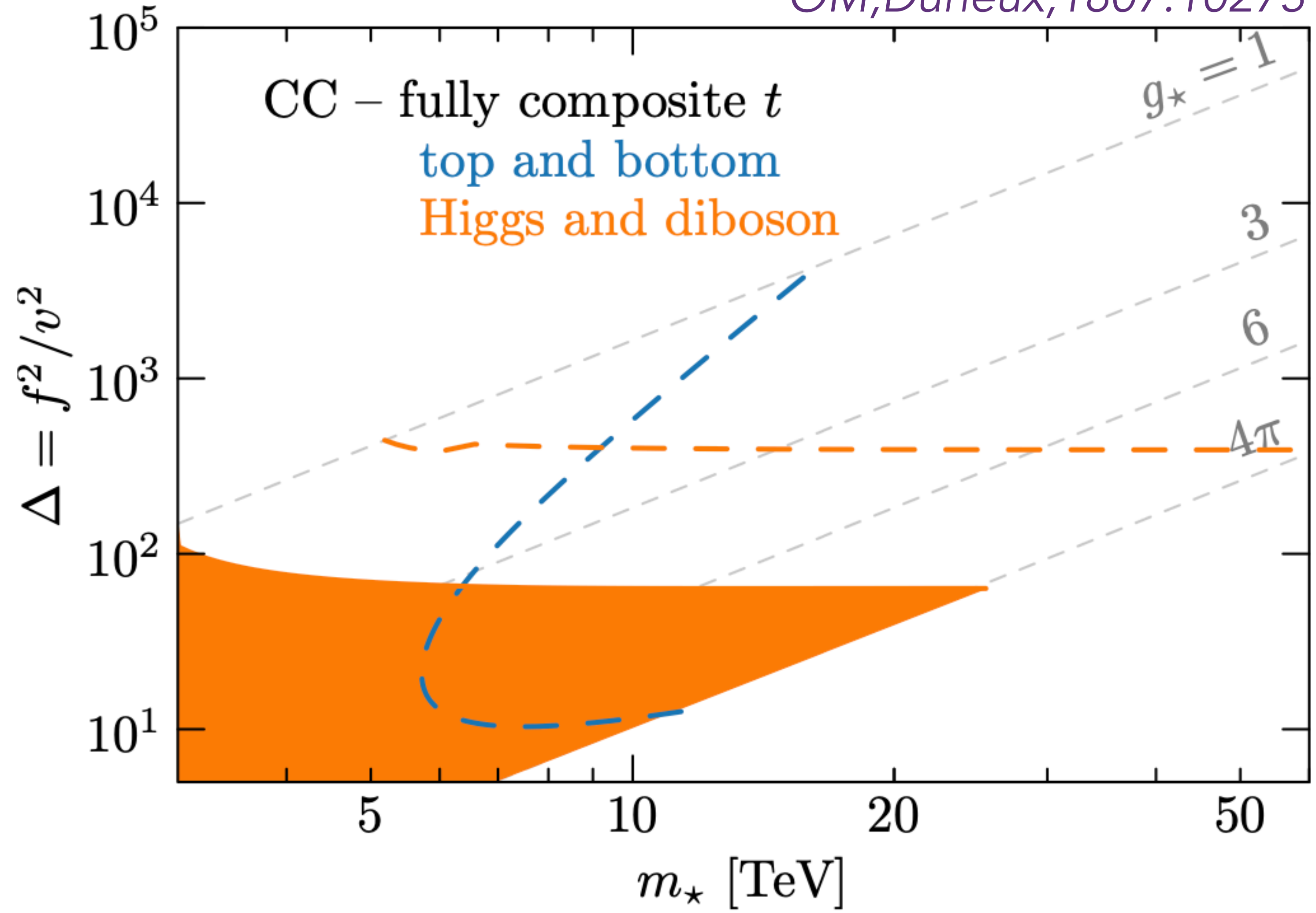
SM: $m_V^2 \propto h^2$

CH: $m_V^2 \propto \sin^2 h/f$

$$\kappa_v^h = \cos v/f \simeq 1 - \frac{v^2}{2f^2}$$

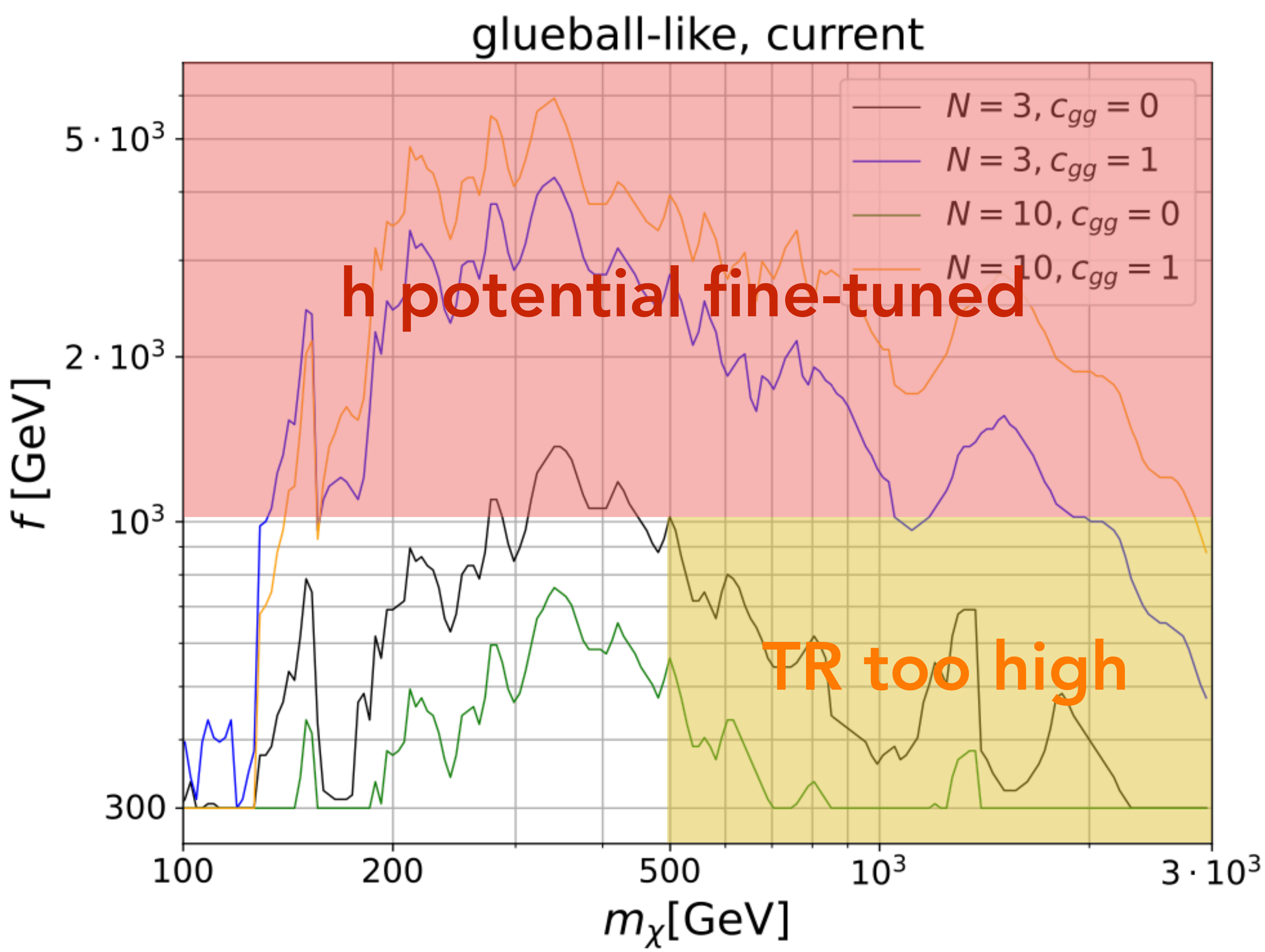
$$c_H \sim \frac{v^2}{f^2}$$

OM,Durieux,1807.10273



SM + "Singlet": Naturalness Perspective

- While the primary EWPT probe can be e.g. the search for the dilaton



Bruggisser, vonHarling,OM,Servant, 2212.00056

SM + "Singlet": Naturalness Perspective

- However one can also search for correlations. E.g:

$$m_V^2 \propto \chi^2 \sin^2 h/f$$

dilaton-Higgs mixing s_θ is tied to CPV

$$\kappa_V^h = c_\theta \cos\frac{v_{\rm CH}}{f} - s_\theta \frac{g_\chi}{g_*} \sin\frac{v_{\rm CH}}{f}$$

$$g_\chi = g_* \quad \Rightarrow \quad \kappa_V^h = \cos\left(\theta + \frac{v_{\rm CH}}{f}\right)$$

(to get an idea)

SM + "Singlet": Naturalness Perspective

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(to get an idea)

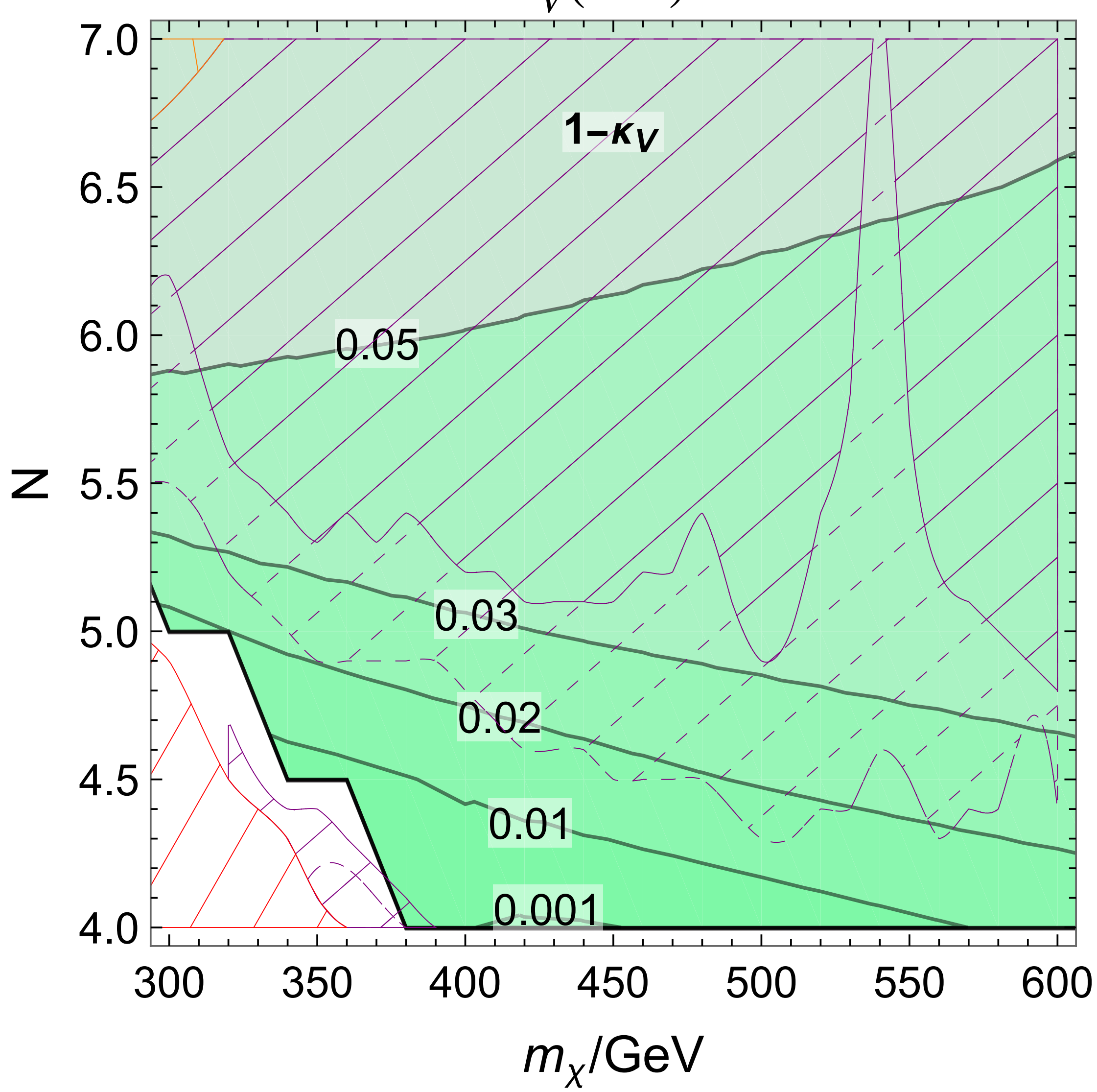
future sensitivities (1σ):

HL-LHC: $\delta\kappa_Z \sim 0.015$

+**FCC-ee**: $\delta\kappa_Z \sim 0.0017$

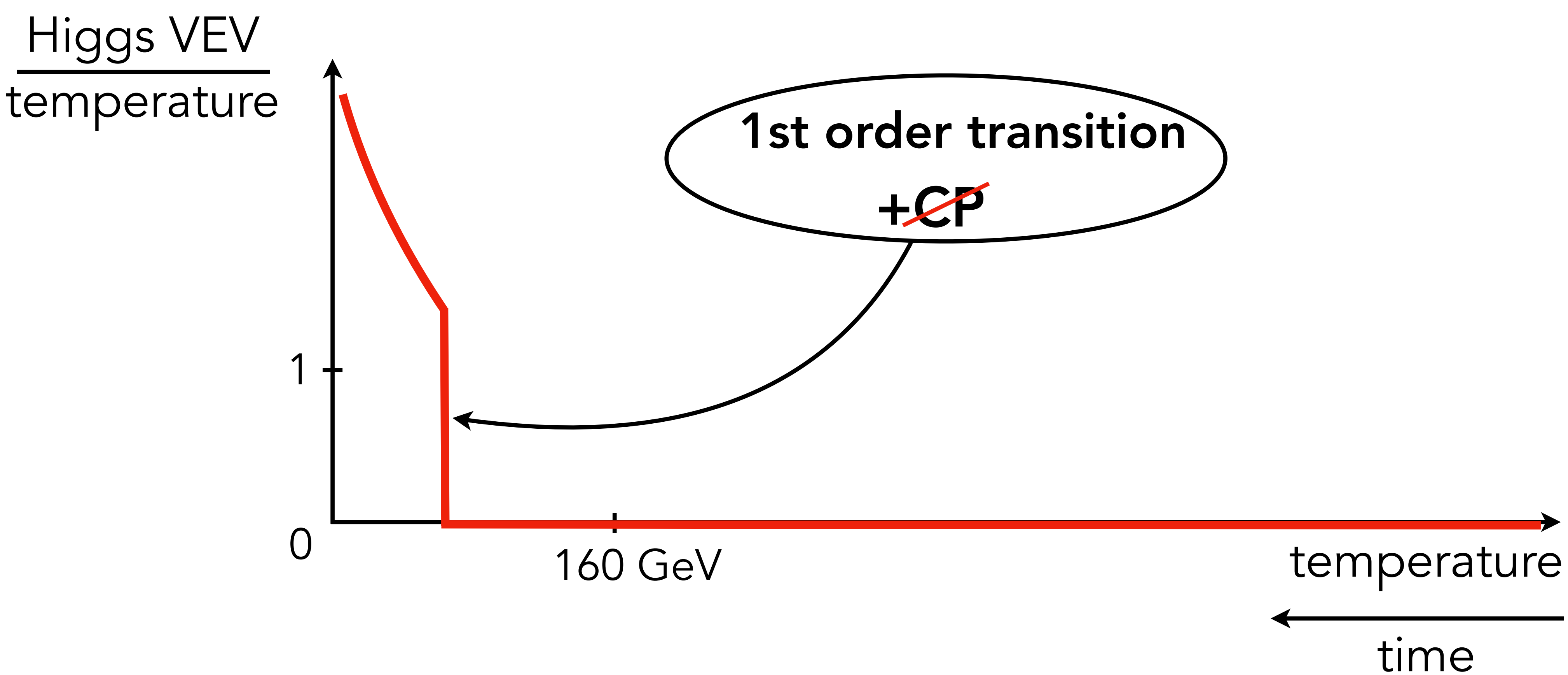
J de Blas et al, 1905.03764

$1 - \kappa_V(\mathrm{CH}) = 0.05$



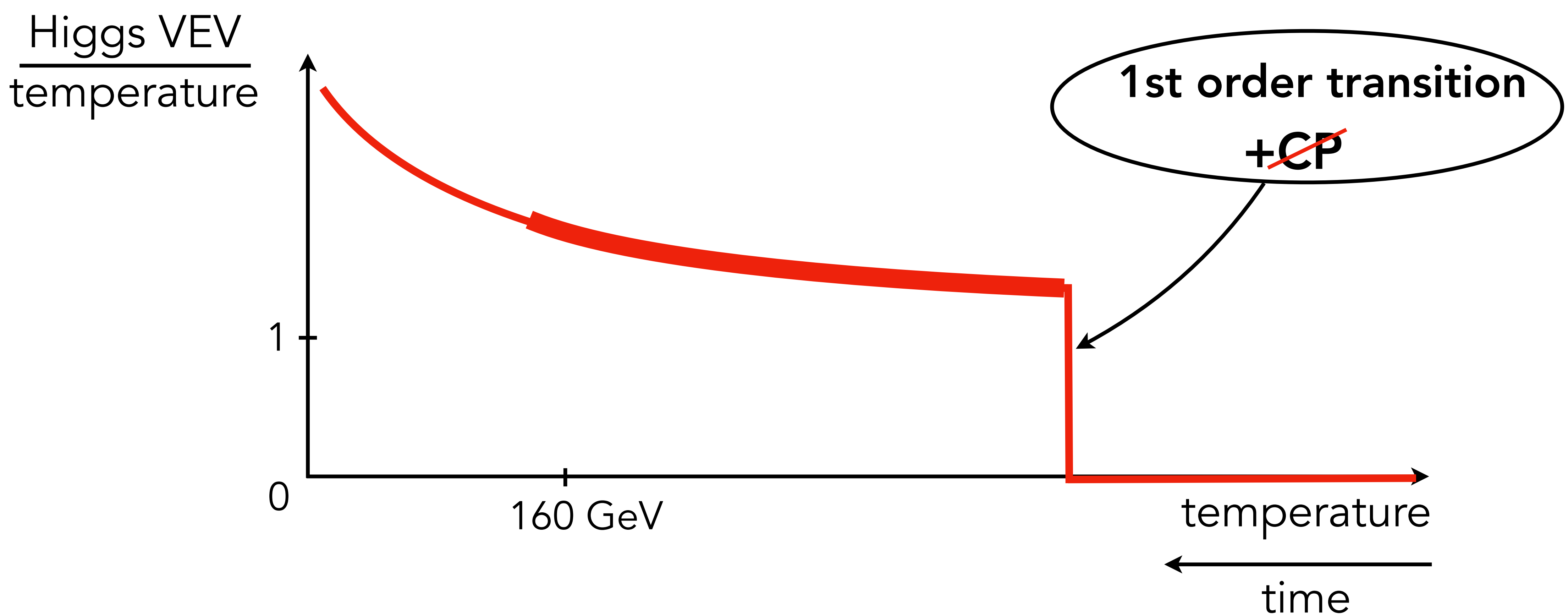
High-Temperature EWPT

Electroweak Baryogenesis



- new physics responsible for CP violation and first-order phase transition is tied to 100 GeV scale

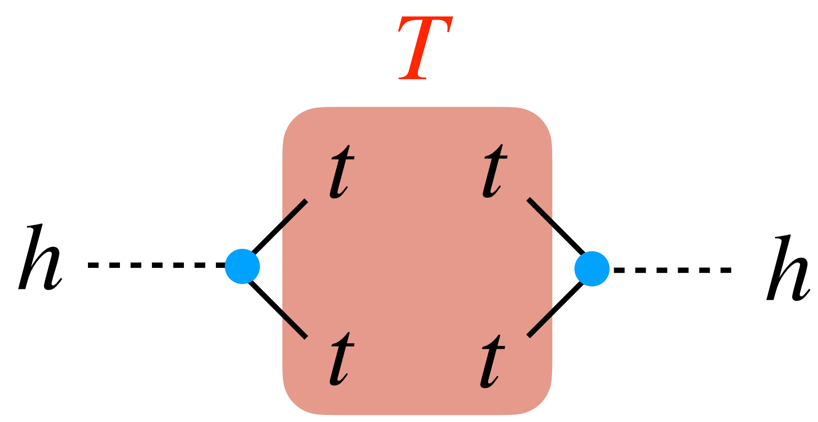
EWBG with Symmetry Non-Restoration



- GW spectrum changed
- new physics responsible for CP violation and first-order phase transition is above 100 GeV scale
- one can search for traces of new physics responsible for SNR

- what prevents SNR:

$$\frac{\lambda_t}{\sqrt{2}}\bar{t}th \quad \Rightarrow$$

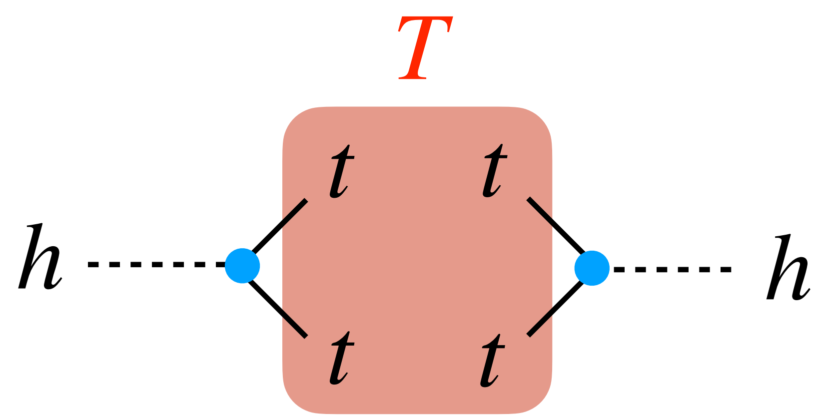


$$\Rightarrow \quad \delta V_h = \frac{1}{8}\lambda_t^2 T^2 h^2$$

High-temperature EWPT

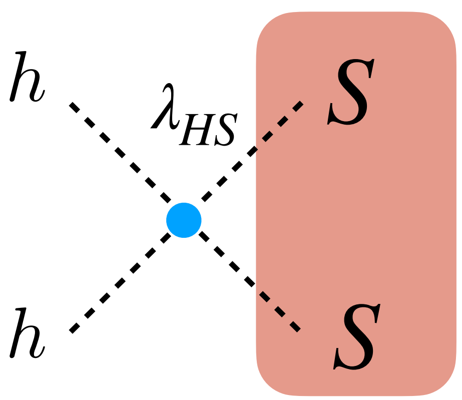
- what prevents SNR:

$$\frac{\lambda_t}{\sqrt{2}}\bar{t}th \quad \Rightarrow$$



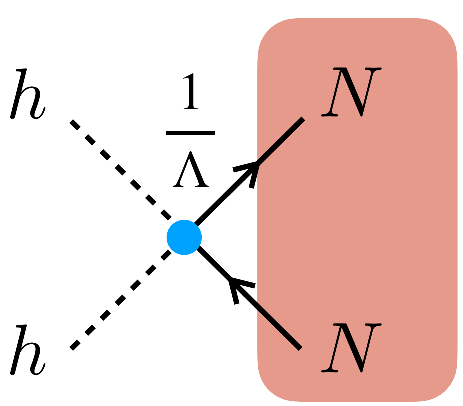
$$\Rightarrow \quad \delta V_h = \frac{1}{8}\lambda_t^2 T^2 h^2$$

- can be countered by, e.g.:



$$\Rightarrow \quad \delta V_h \sim -n_\chi |\lambda_{HS}| T^2 h^2$$

Weinberg '74 (toy model)
Meade, Ramani, 1807.07578
Baldes, Servant, 1807.08770
Glioti, Rattazzi, Vecchi, 1811.11740

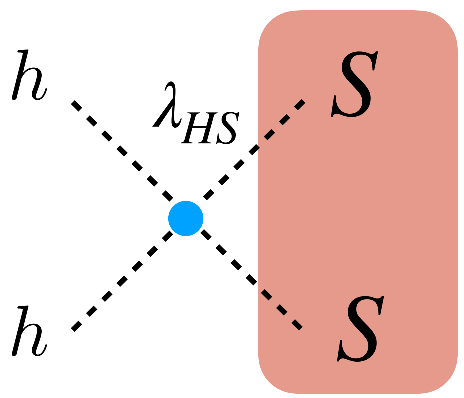


$$\Rightarrow \quad \delta V_h \sim -n_N \frac{m_N}{\Lambda} T^2 h^2$$

OM, Servant, 2020.05174

High-temperature EWPT

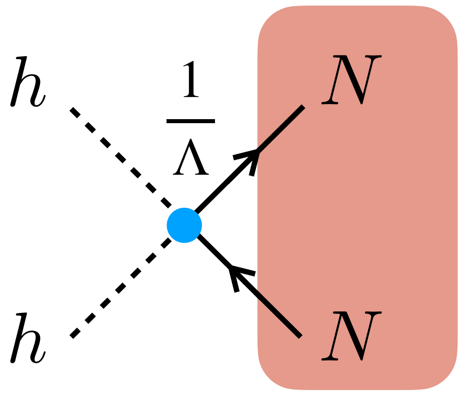
Pheno: h to invisible



Glioti, Rattazzi, Vecchi, 1811.11740

$$\mathrm{BR}(h \to \mathrm{inv}) = \frac{v^2 (n\lambda_{HS})^2}{8\pi m_h \Gamma_{\mathrm{tot}}} \frac{1}{n} \qquad \propto 1/n$$

SNR: $n|\lambda_{HS}| \sim 10$



OM, Servant, 2020.05174

$$\mathrm{BR}_{h\to NN} \sim \frac{1}{n}\left(n\lambda_N \frac{m_N}{\Lambda}\right)^2 \frac{v_{\mathrm{SM}}^2}{m_h \Gamma_h} \qquad \propto 1/n$$

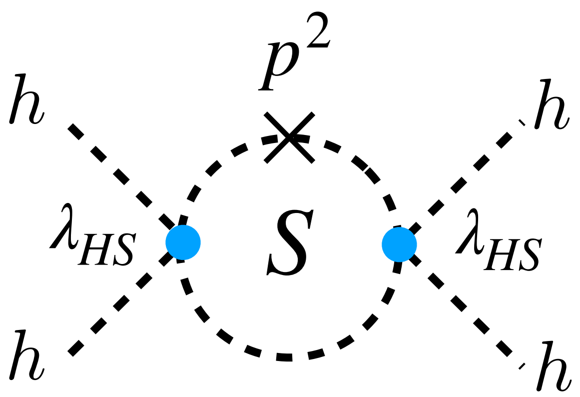
SNR: $nm_N/\Lambda \sim 1$

currently: $\mathrm{BR}_{h\to XX} \lesssim 0.1 \quad \Rightarrow \quad n \gtrsim 10^6$

$\Rightarrow$ more plausible, $m_{S,N} < m_h/2$

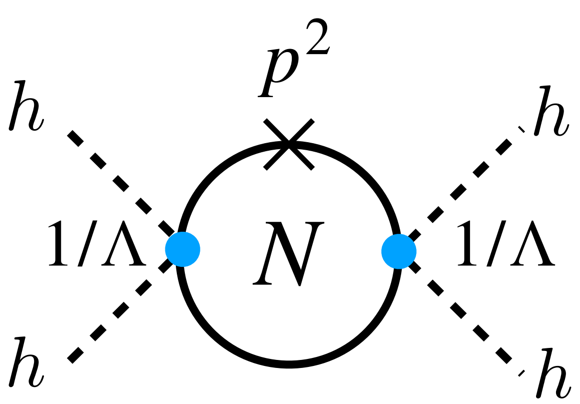
High-temperature EWPT

Pheno: c_H



$$\frac{c_H}{\Lambda^2} = n\frac{\lambda_{HS}^2}{48\pi^2}\frac{1}{\mu_\chi^2}$$

Glioti, Rattazzi, Vecchi, 1811.11740
M.Carena,C.Krause,Z.Liu,Y.Wang 2104.00638



$$\frac{c_H}{\Lambda^2} \sim n\frac{4}{16\pi^2}\frac{1}{\Lambda^2}$$

future sensitivities (1σ):

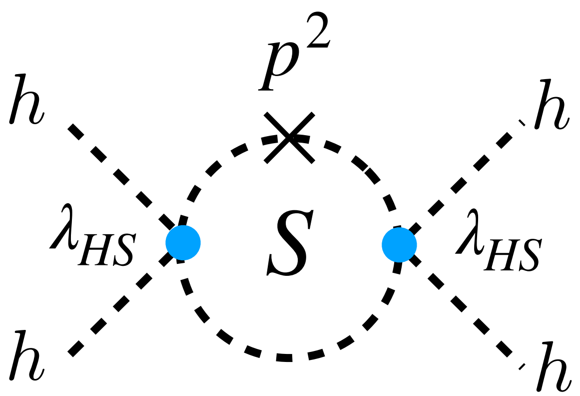
HL-LHC: $\Lambda/\sqrt{|c_H|} < 1.4(1.8)\, TeV$

+**FCC-ee**: $\Lambda/\sqrt{|c_H|} < 3.2(5)\, TeV$

J de Blas, Eur. Phys. J. Plus (2021) 136:897

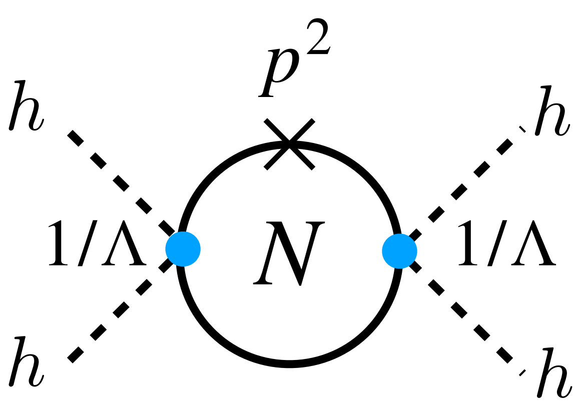
High-temperature EWPT

Pheno: c_H



$$\frac{c_H}{\Lambda^2} = n\frac{\lambda_{HS}^2}{48\pi^2}\frac{1}{\mu_\chi^2}$$

Glioti, Rattazzi, Vecchi, 1811.11740
M.Carena,C.Krause,Z.Liu,Y.Wang 2104.00638



$$\frac{c_H}{\Lambda^2} \sim n\frac{4}{16\pi^2}\frac{1}{\Lambda^2}$$

perturbativity

$$n\frac{\lambda_{HS}^2}{16\pi^2} \ll \lambda_h(\mu)$$

$$n\frac{T^2}{\Lambda^2} \ll 1$$

$$\Lambda/\sqrt{|c_H|} \gtrsim 3\,TeV$$

future sensitivities (1σ):

HL-LHC: $\Lambda/\sqrt{|c_H|} < 1.4(1.8)\,TeV$

+**FCC-ee**: $\Lambda/\sqrt{|c_H|} < 3.2(5)\,TeV$

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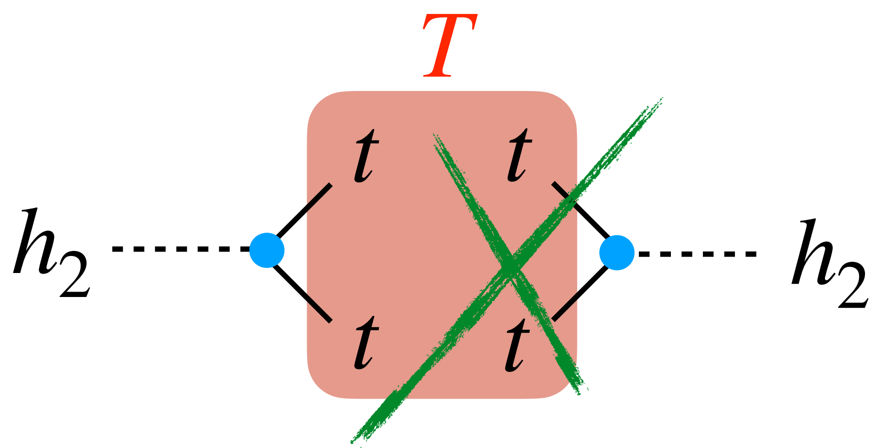
2HDM with inert H2

$$\frac{\lambda_t}{\sqrt{2}}\bar{t}th_2 \quad \Rightarrow$$

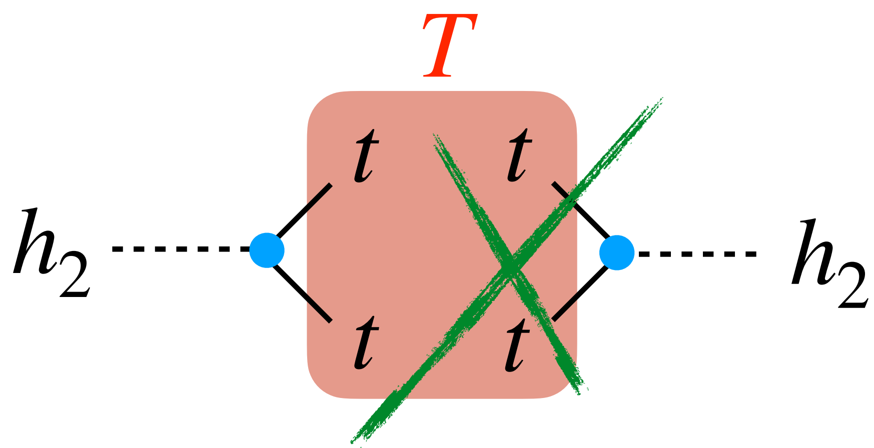


$$\Rightarrow \quad \delta V_h = \frac{1}{8}\lambda_t^2 T^2 h_2^2$$

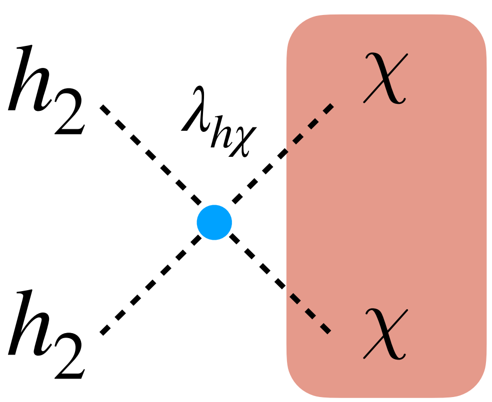
High-temperature EWPT

2HDM with inert H2

$$\frac{\lambda_t}{\sqrt{2}} t t h_2 \Rightarrow$$



$$\Rightarrow \delta V_h = \frac{1}{8}\lambda_t^2 T^2 h_2^2$$



$$\Rightarrow \delta V_h \sim -n_\chi |\lambda_{h\chi}| T^2 h_2^2$$

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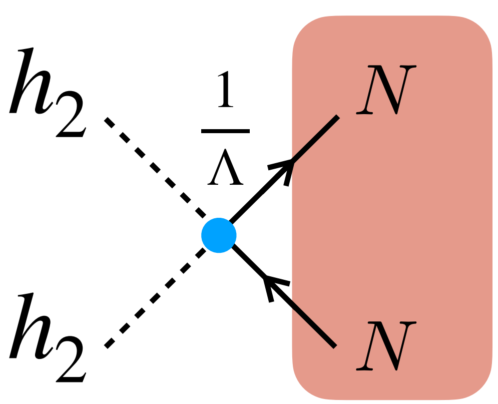

$$\Rightarrow \delta V_h \sim -n_N \frac{m_N}{\Lambda} T^2 h_2^2$$

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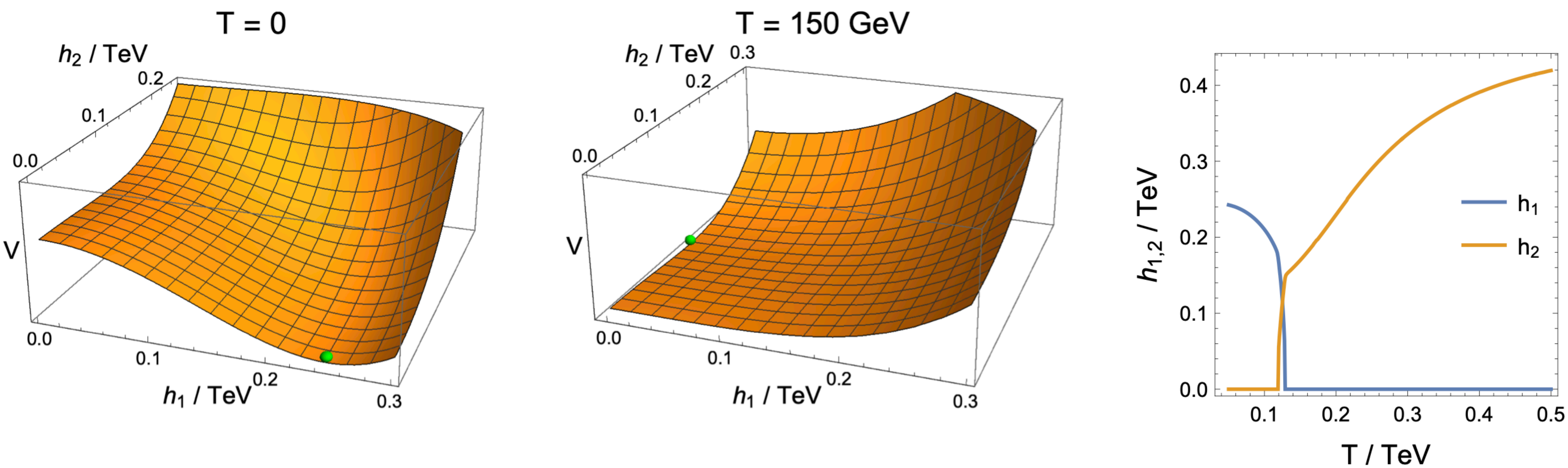
$\Rightarrow$ lower n needed

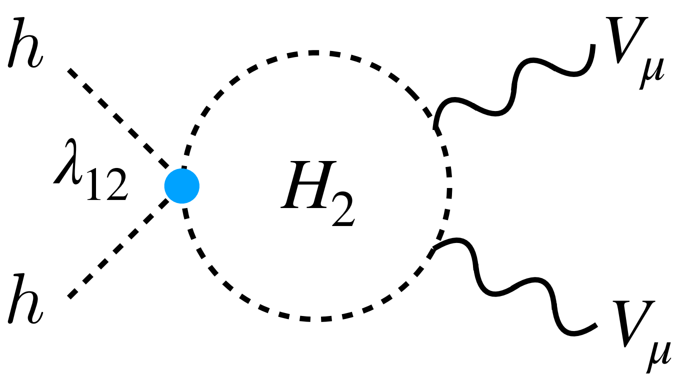
High-temperature EWPT

2HDM with inert H2



- ~5 less d.o.f. and SNR states can be DM candidates

2HDM with inert H2: $h \to \gamma\gamma$



$$\mathcal{O}_{BB} = g'^2 |H|^2 BB$$
$$\mathcal{O}_{WW} = g^2 |H|^2 WW$$

$$\frac{c_{BB}}{\Lambda^2} = \frac{c_{WW}}{\Lambda^2} = \frac{\lambda_{12}}{384\pi^2}\frac{1}{\mu_{h_2}^2}$$

$$\Rightarrow \quad 1 - \kappa_\gamma \simeq 10\pi^2 v^2 (c_{BB} + c_{WW})$$

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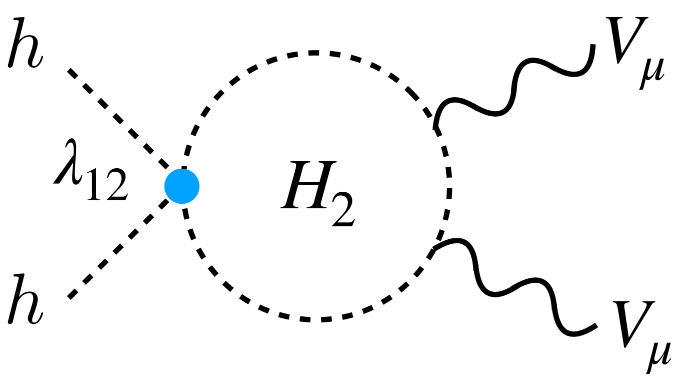
2104.00638

High-temperature EWPT

2HDM with inert H2: $h \to \gamma\gamma$



$$\mathcal{O}_{BB} = g'^2 |H|^2 BB$$
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$$\frac{c_{BB}}{\Lambda^2} = \frac{c_{WW}}{\Lambda^2} = \frac{\lambda_{12}}{384\pi^2}\frac{1}{\mu_{h_2}^2}$$

$$\Rightarrow \quad 1 - \kappa_\gamma \simeq 10\pi^2 v^2 (c_{BB} + c_{WW})$$

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2104.00638

current bound (1σ): $\kappa_\gamma = 0.97 \pm 0.07$ → $\lambda_{12} \lesssim 0.12$

J de Blas et al, 1803.00939

future sensitivities (1σ):

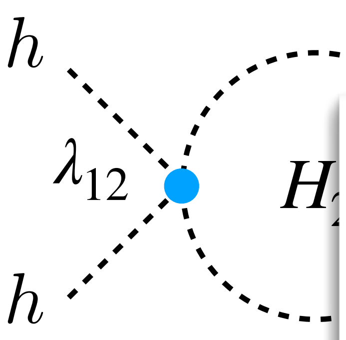
HL-LHC: $\delta\kappa_\gamma = \pm 0.019$ → $\lambda_{12} > 0.024$

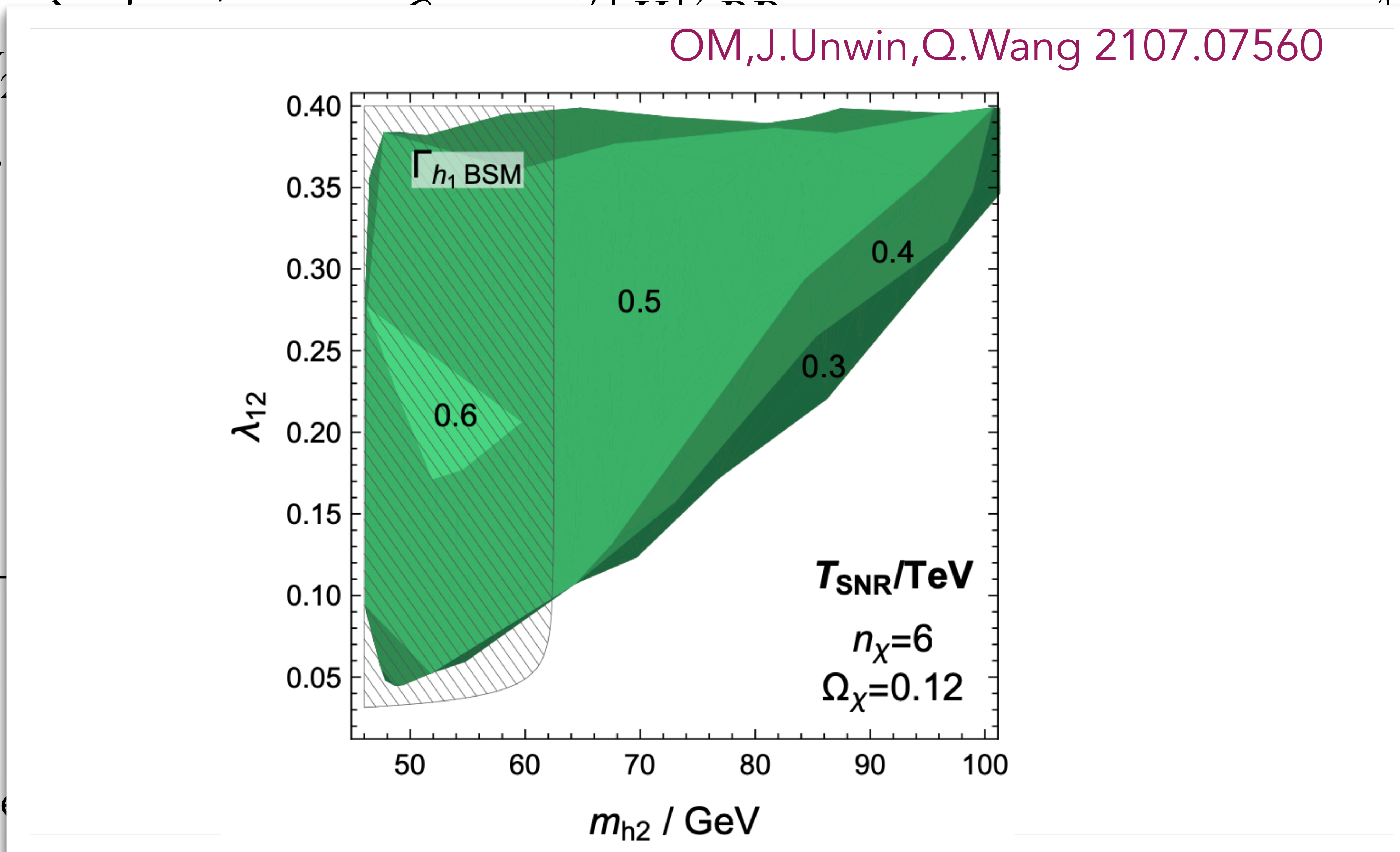
+**FCC-ee**: $\delta\kappa_\gamma = \pm 0.013$ → $\lambda_{12} > 0.016$

J de Blas et al, 1905.03764

High-temperature EWPT

2HDM with inert H2: $h \to \gamma\gamma$





current

future s

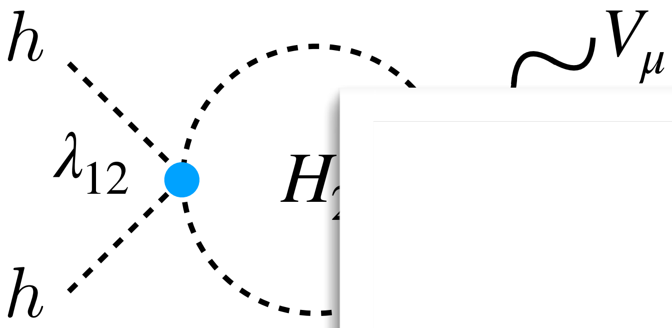
HL-LHC: $\delta\kappa_\gamma = \pm 0.019$ → $\lambda_{12} > 0.024$

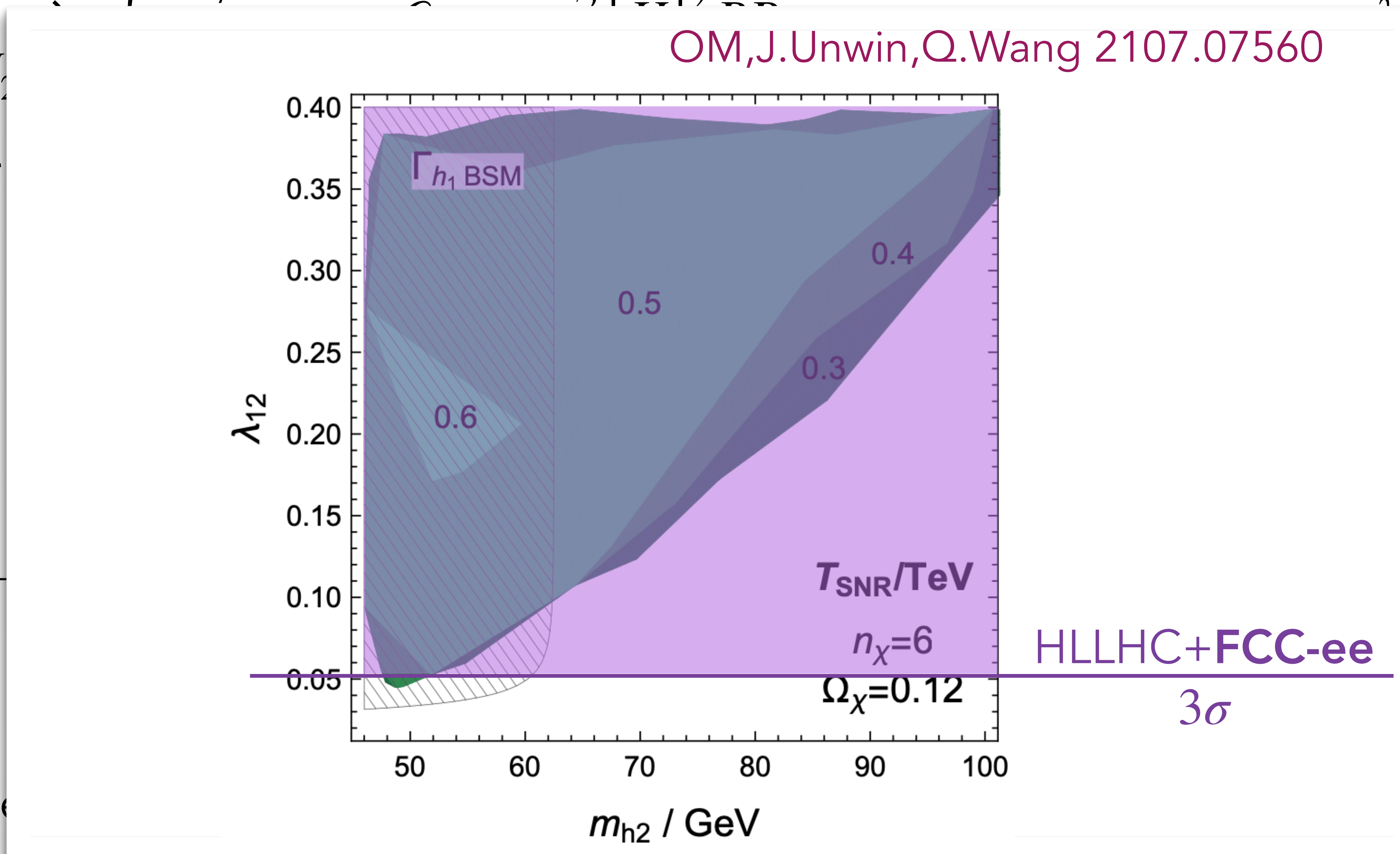
+**FCC-ee**: $\delta\kappa_\gamma = \pm 0.013$ → $\lambda_{12} > 0.016$

J de Blas et al, 1905.03764

High-temperature EWPT

2HDM with inert H2: $h \to \gamma\gamma$





$\frac{1}{\mu_{h_2}^2}$

$c_{WW})$

.Wang

current

future se

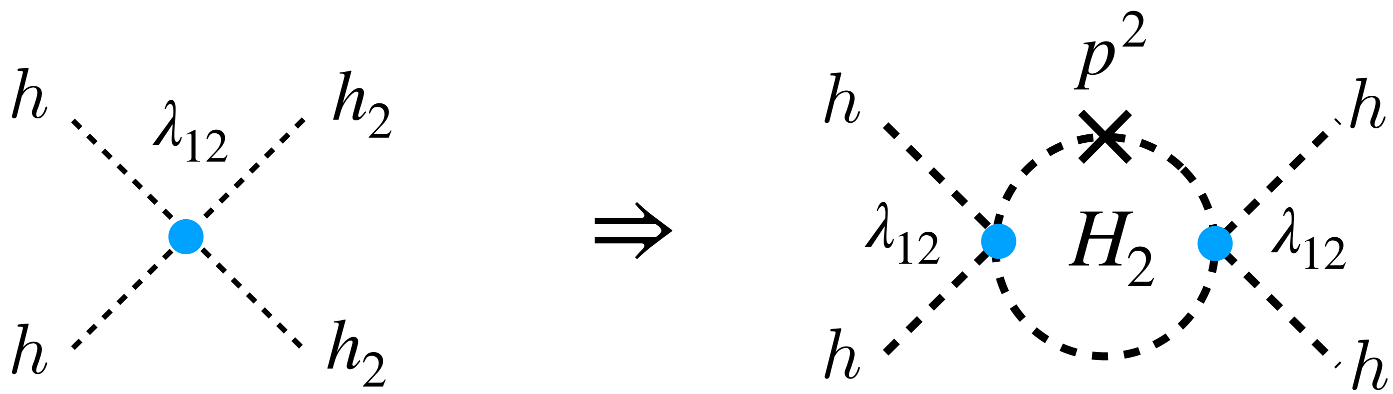
HL-LHC: $\delta\kappa_\gamma = \pm 0.019$ ⟶ $\lambda_{12} > 0.024$

+**FCC-ee**: $\delta\kappa_\gamma = \pm 0.013$ ⟶ $\lambda_{12} > 0.016$

J de Blas et al, 1905.03764

High-temperature EWPT

2HDM with inert H2: c_H



$\Rightarrow$

$$\frac{c_H}{\Lambda^2} = \frac{\lambda_{12}^2}{48\pi^2}\frac{1}{m_{h_2}^2}$$

$\Downarrow$

$$\Lambda/\sqrt{|c_H|} \lesssim 3.4\,TeV$$

currently allowed by $h \to \gamma\gamma$ and $h \to$ BSM

future sensitivities (1σ):

HL-LHC: $\Lambda/\sqrt{|c_H|} < 1.4(1.8)\,TeV$

+**FCC-ee**: $\Lambda/\sqrt{|c_H|} < 3.2(5)\,TeV$

J de Blas, Eur. Phys. J. Plus (2021) 136:897

Conclusions

- EWSB is both important, and potentially within our grasp (GW, EDMs, colliders)

- Higgs physics, together with other experimental data can allow to “triangulate” the right description of EWSB

- Higgs physics already puts significant bounds on NP potentially involved in EWPT, and FCCee sensitivities would provide here a significant step forward in constraining or finding it

Thank you!

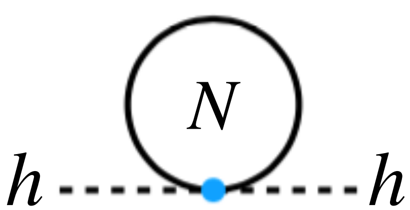
Back-up slides

SNR with **fermions**

OM, Servant, 2020.05174

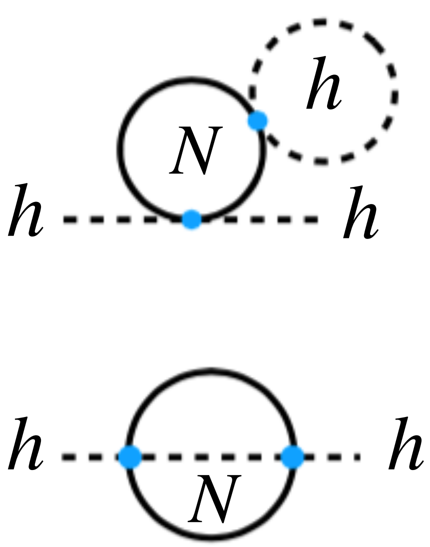
- High-T perturbativity implies $T_{\rm SNR}^{\rm max} \sim \sqrt{n}\, m_N$

calculable 1-loop (negative mass):

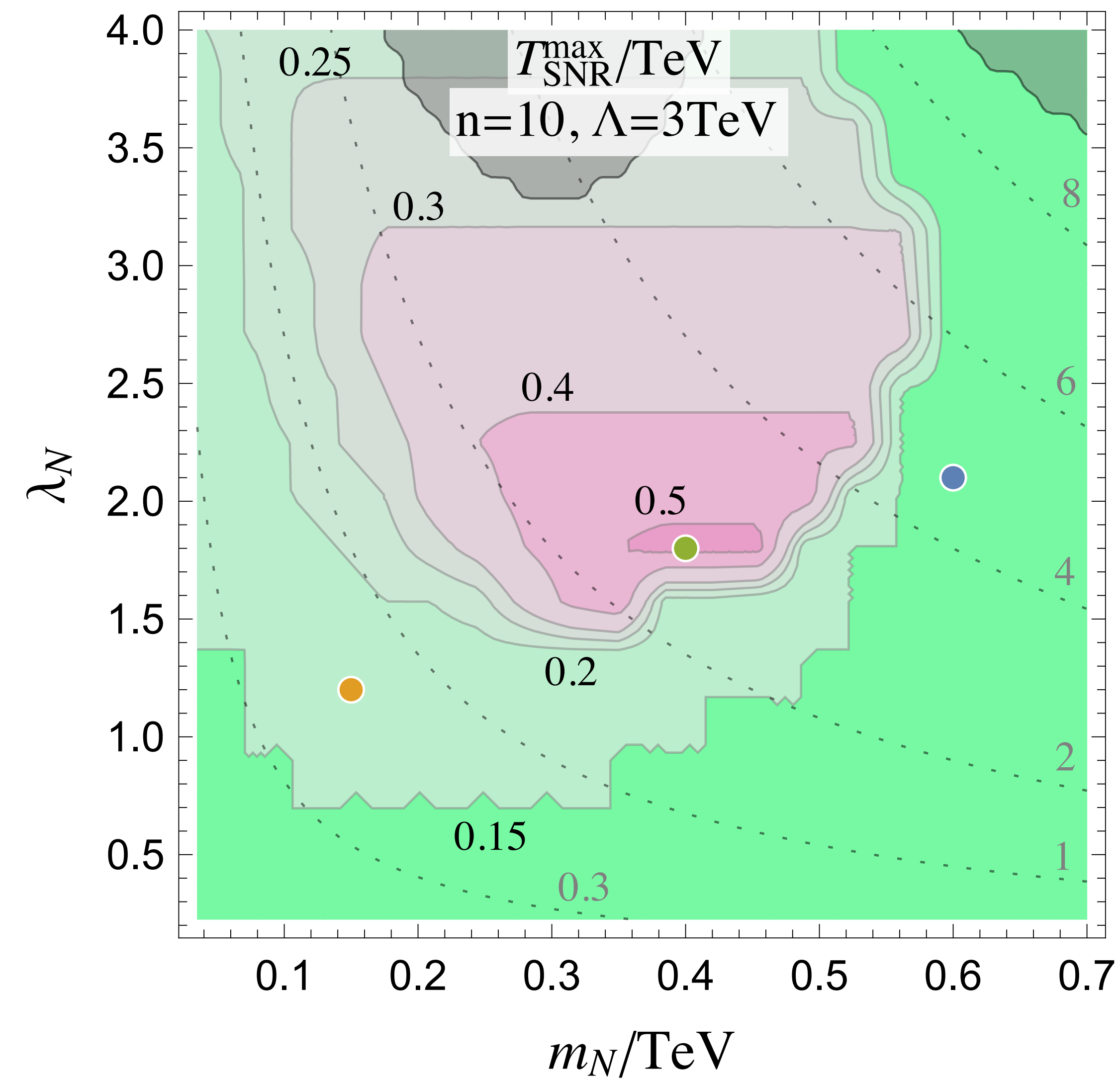


$\propto n\lambda_N \frac{m_N}{\Lambda} \simeq 1$

higher loops (out of control):



$\beta = n\lambda_N^2 \frac{T^2}{\Lambda^2} < 1$



SNR with **scalars**

- Putting all together:

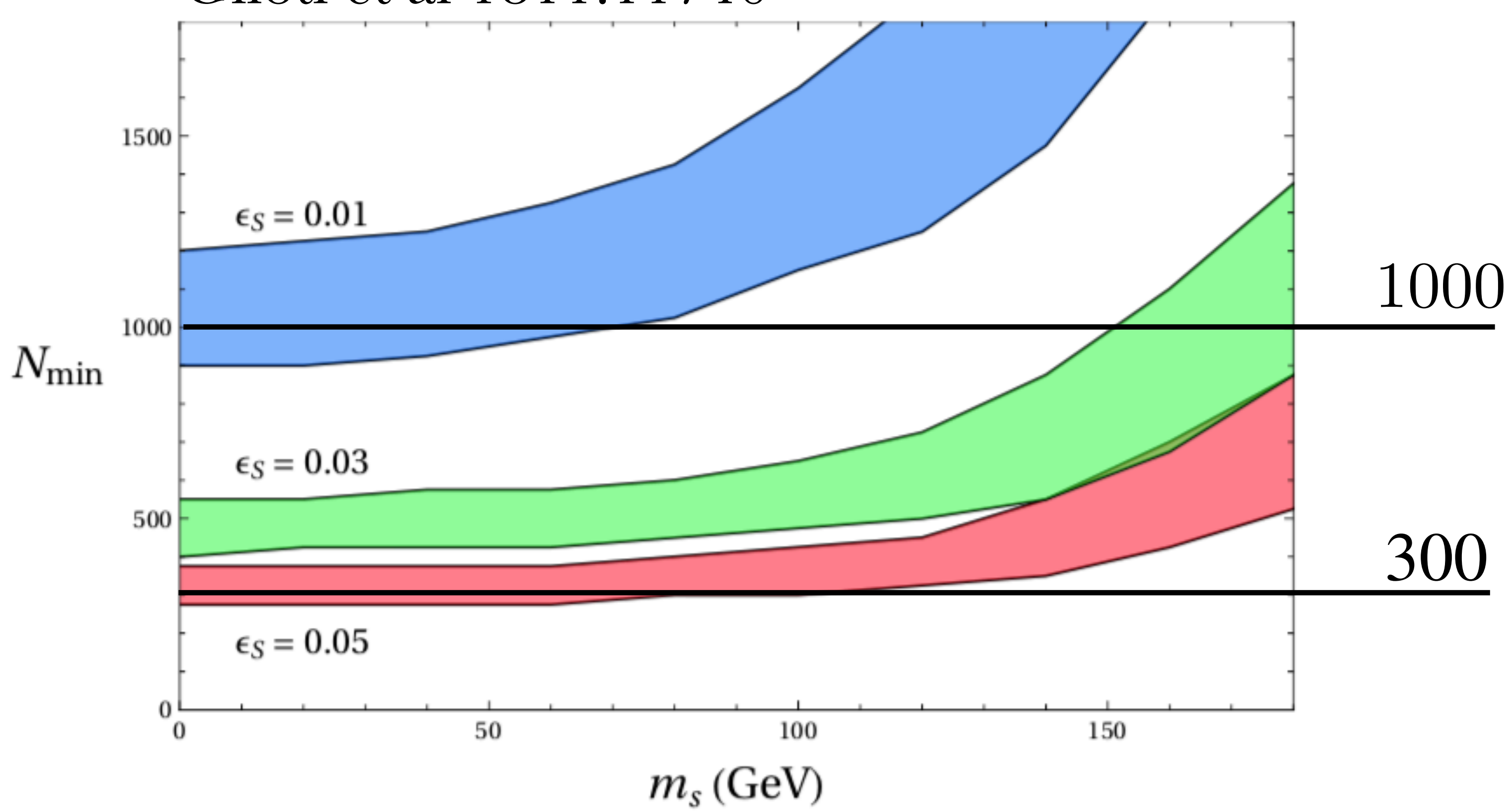
$$8/n \;<\; \lambda_{\chi h} \;<\; \sqrt{\lambda_\chi \lambda_h} \;\ll\; \frac{4\pi}{\sqrt{n}}\sqrt{\lambda_h(\mu)} \qquad \Rightarrow \qquad n \gg 10$$

SNR

V bounded

perturbativity

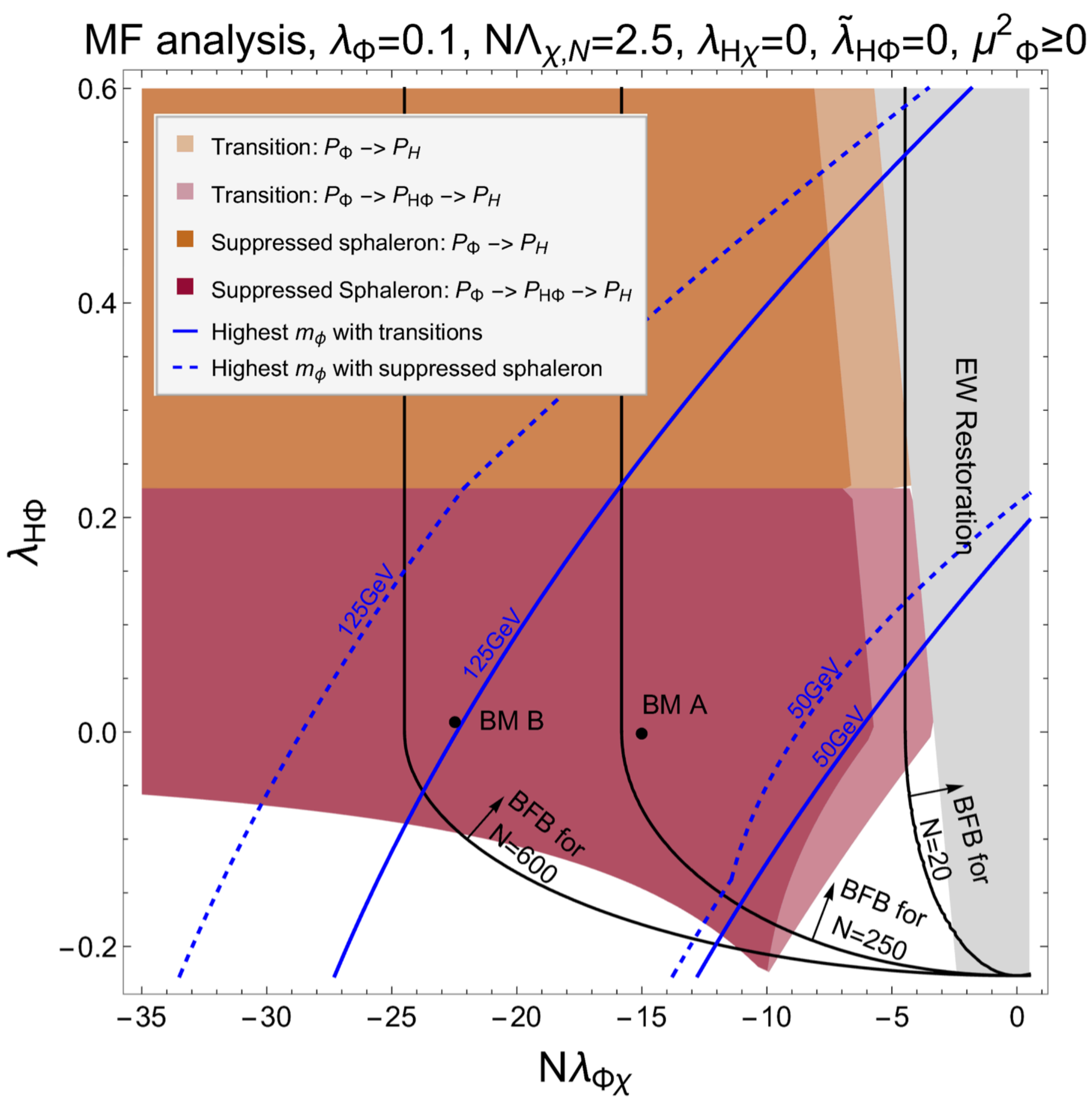
Glioti et al 1811.11740

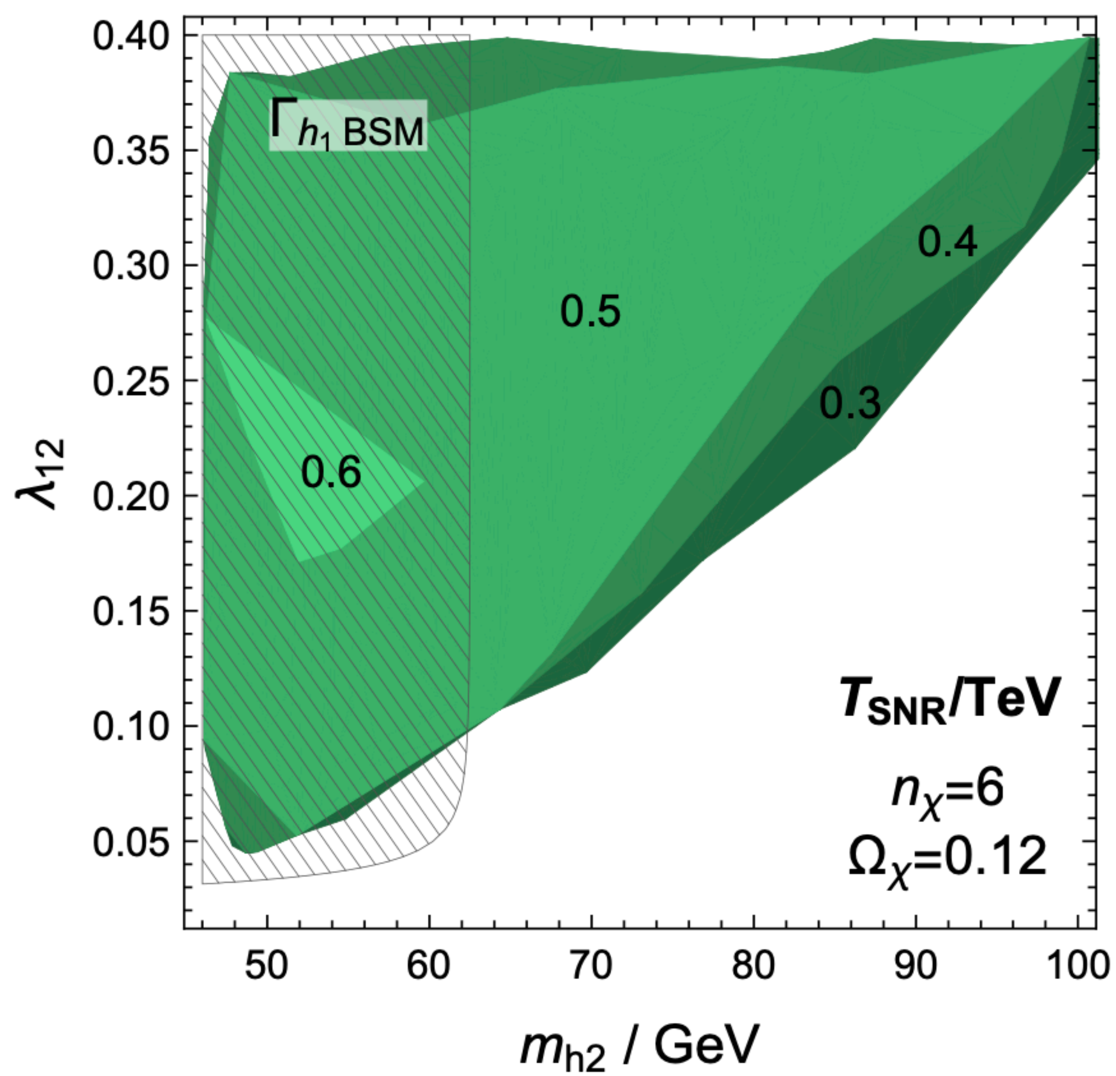


$$\epsilon_S \equiv \frac{n\lambda_\chi}{16\pi^2}$$

High-temperature EWPT

2HDM with inert H2: tests





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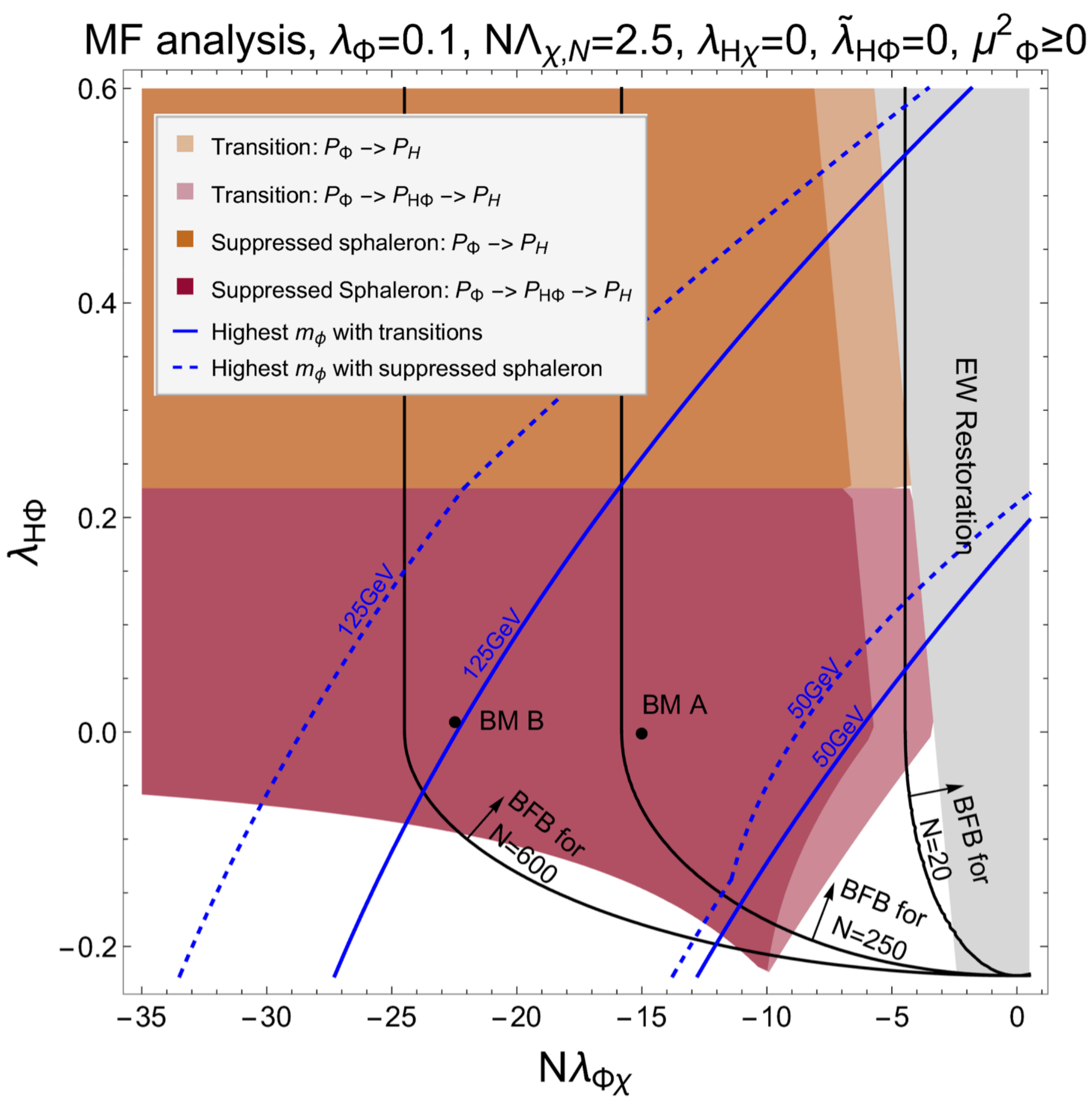
2107.07560

High-temperature EWPT

2HDM with inert H2: tests



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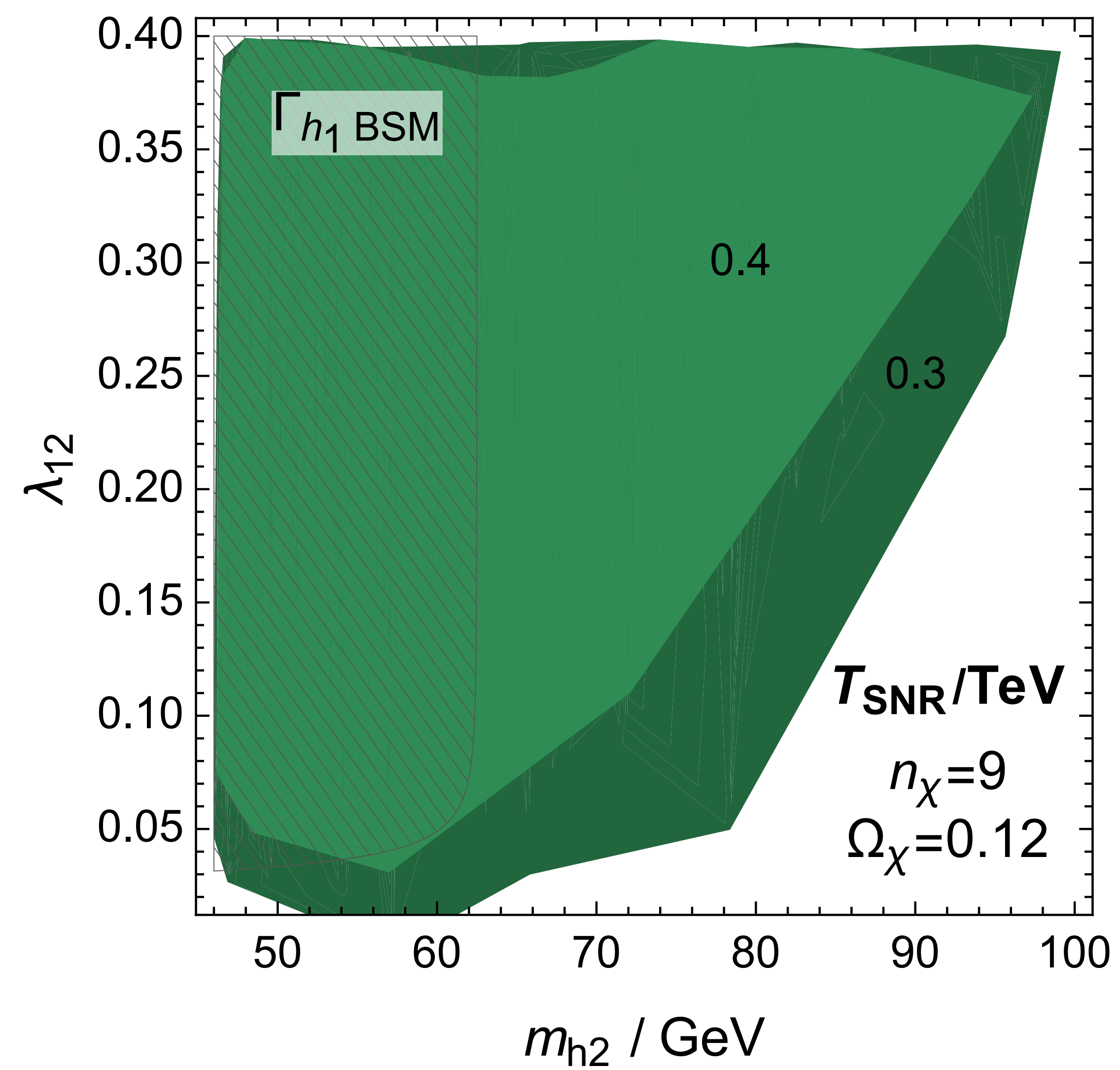

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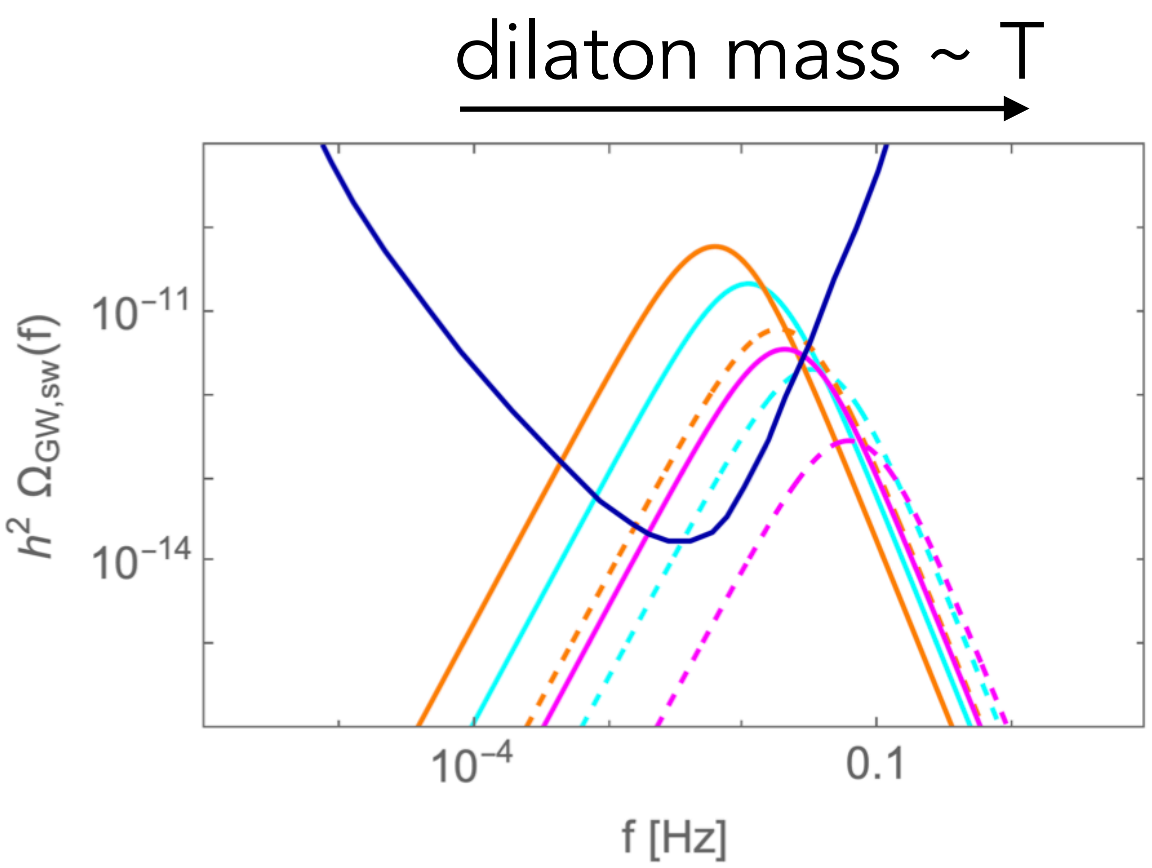
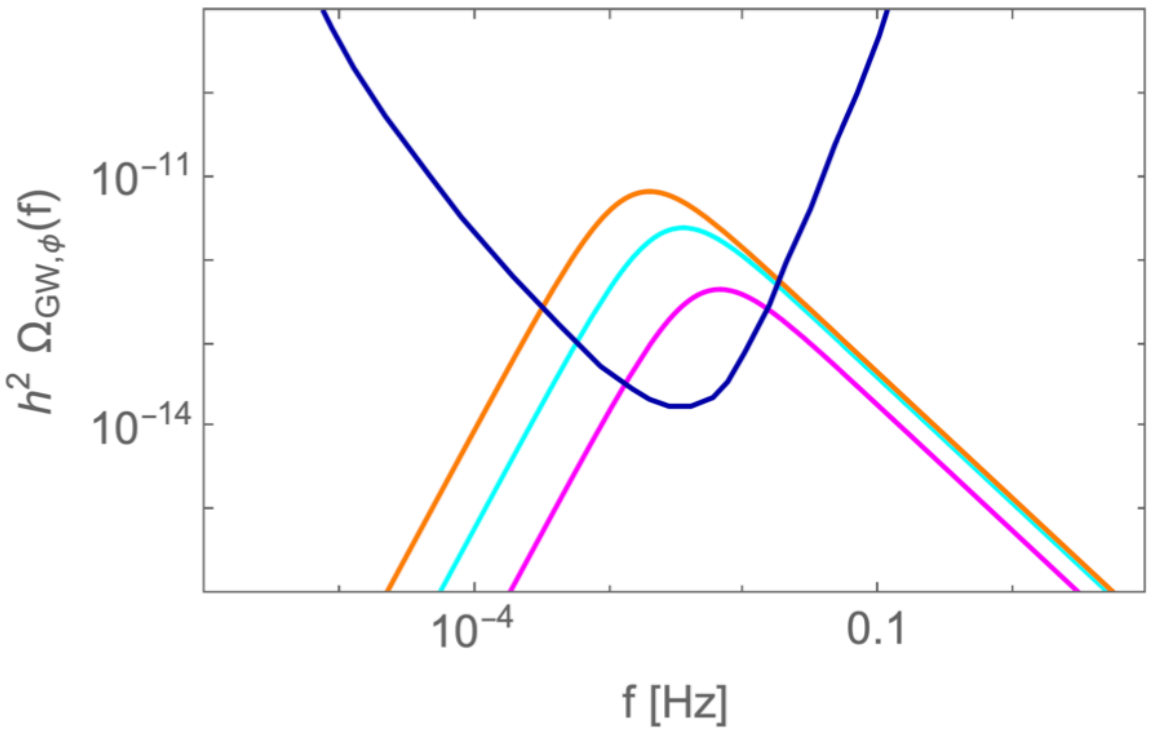
2107.07560

High-temperature EWPT

GW in dilaton-assisted EWBG





OM,vonHarling,Servant 2307.14426

LHC bounds

- Dilaton value sets all SM mass terms, and also the renormalization scales for the running induced by the new strong dynamics.

$$m_q \bar{q} q \; = \; m_q \bar{q} q \frac{\chi}{\chi_0} \; = \; m_q \bar{q} q \frac{\chi_0 + \delta\chi}{\chi_0} \; \supset \; m_q \bar{q} q \frac{\delta\chi}{\chi_0}$$

- Hence similar* to the Higgs couplings, up to a factor of v/χ_0

- What is χ_0 ?

LHC bounds

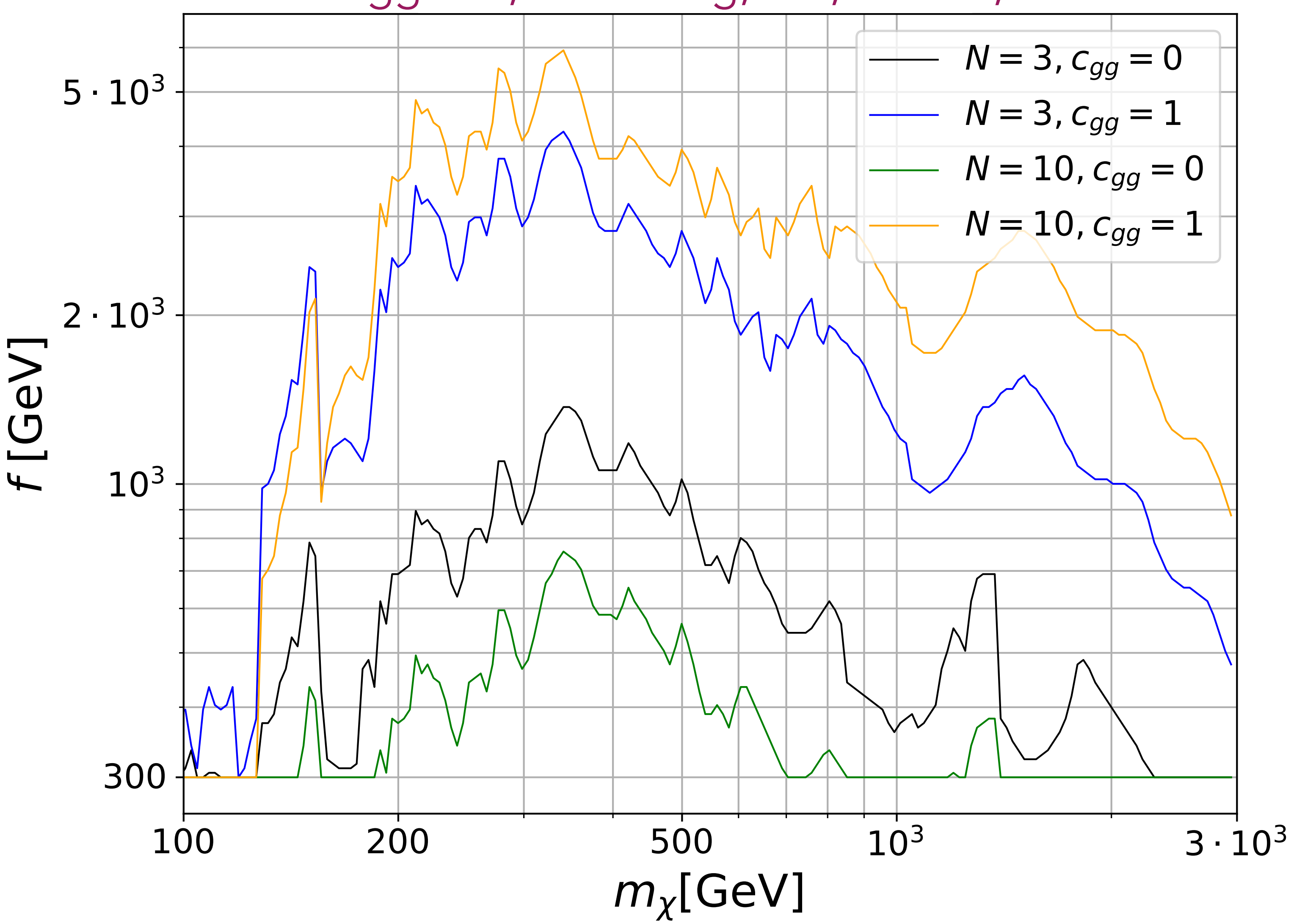
- $\chi_0 \neq f$

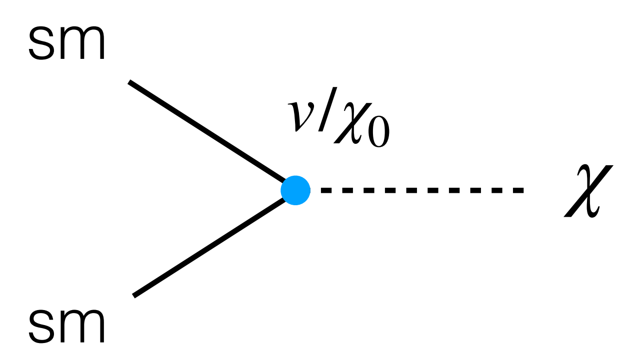
$$\frac{\chi_0}{f} \sim \frac{m_{\text{glue}}/g_{\text{glue}}}{m_{\text{mes}}/g_{\text{mes}}} \sim \sqrt{N}$$

N - number of colors of underlying strong dynamics

LHC bounds

Bruggisser,vonHarling,OM,Servant,2212.00056





*extra N for $gg\chi$