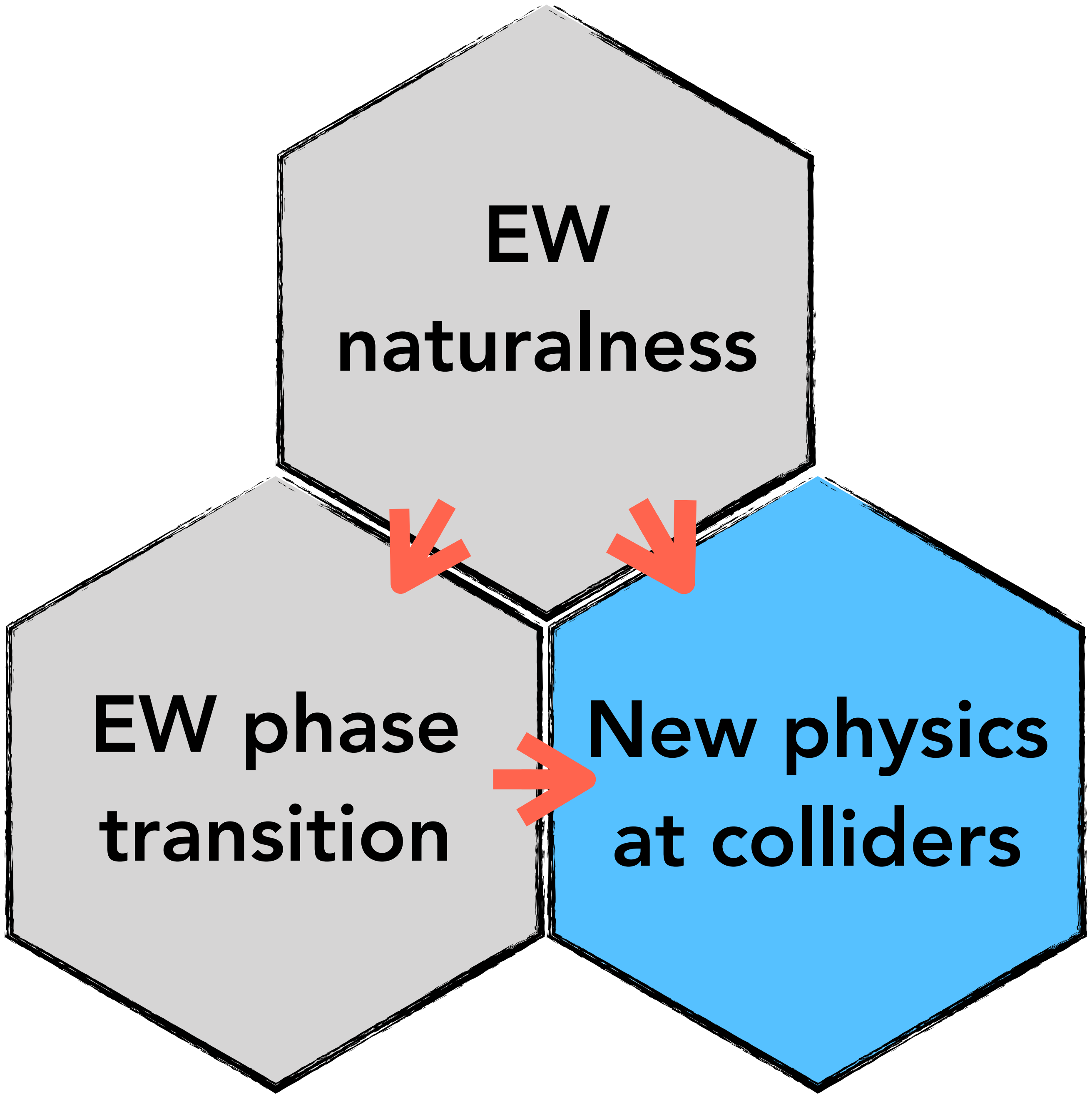
# Footprints of EW Phase Transition at Colliders

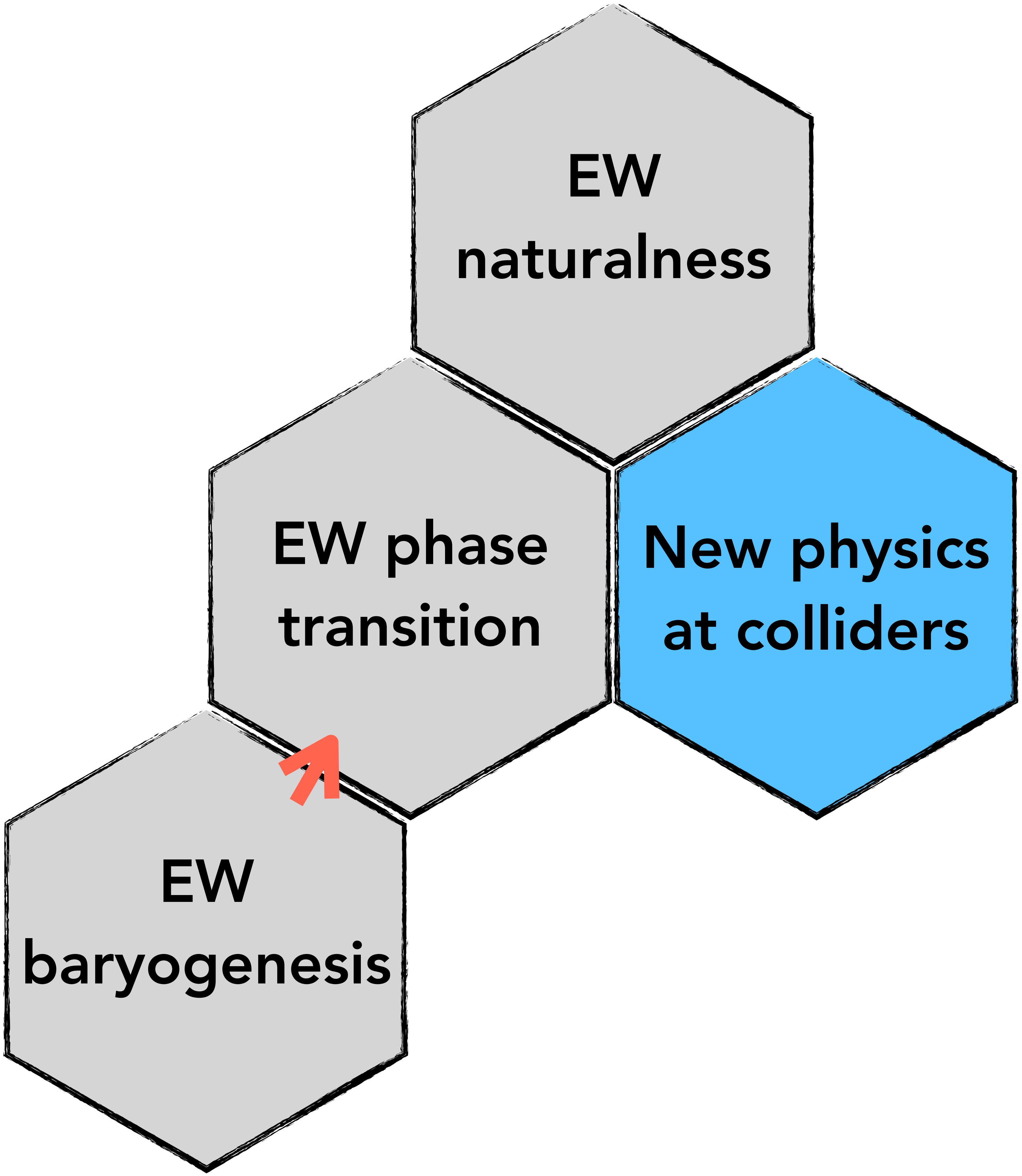
Oleksii Matsedonskyi

Technical University of Munich

*Higgs Hunting, 2025*

New physics at colliders


EW
naturalness
EW phase
transition
New physics
at colliders


EW
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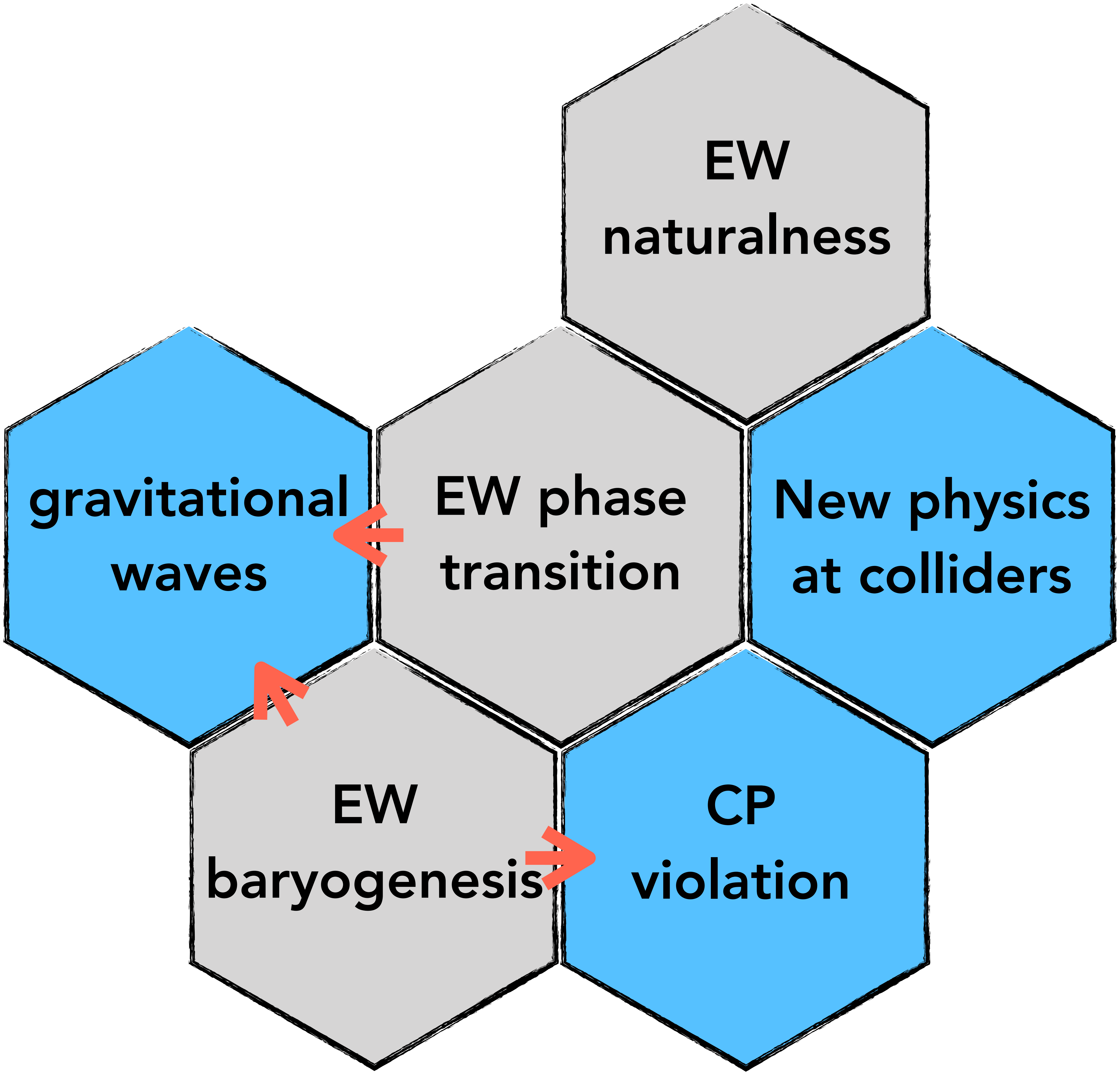
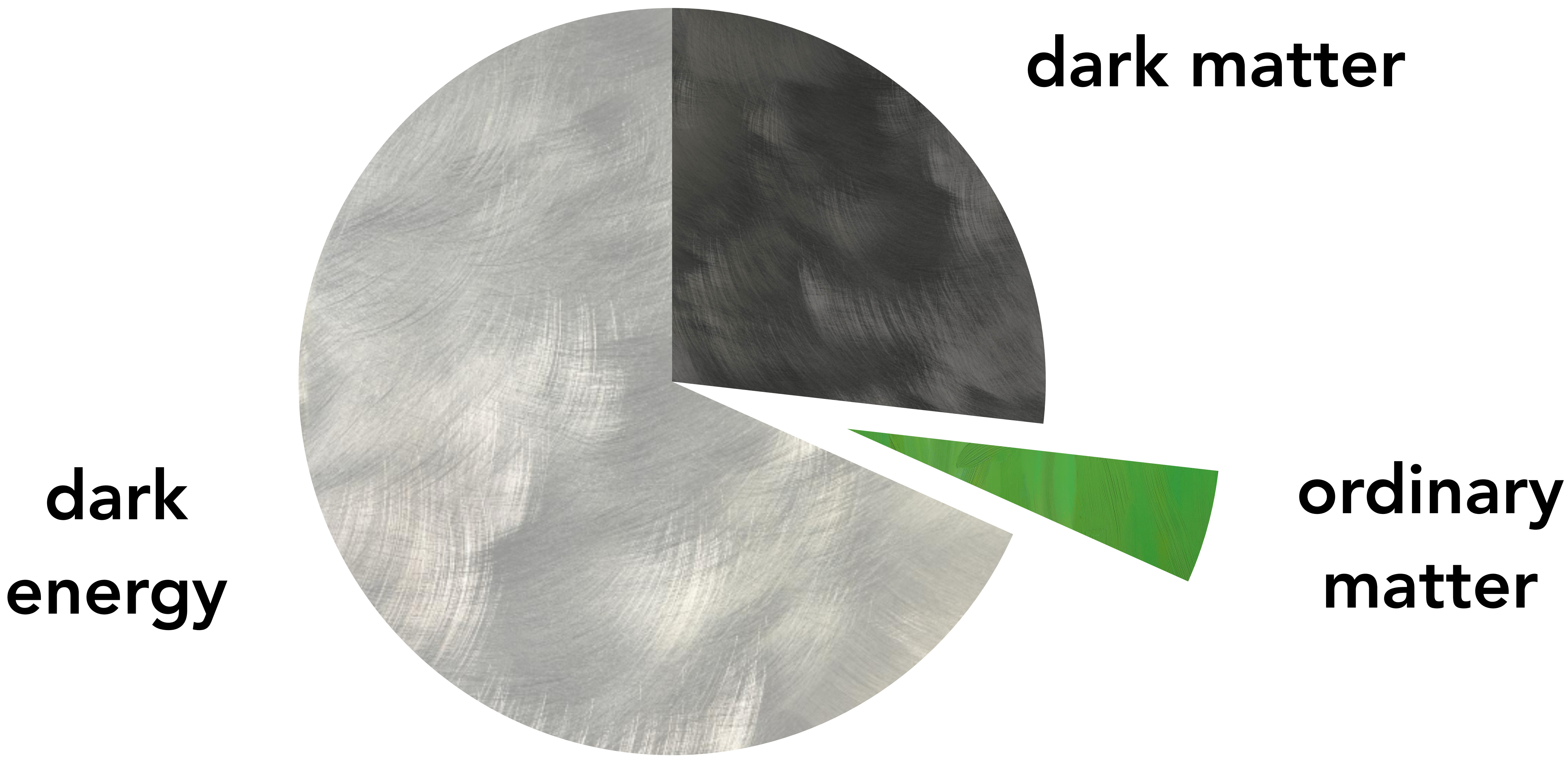
EW
baryogenesis



EW
naturalness
gravitational
waves
EW phase
transition
New physics
at colliders
EW
baryogenesis
CP
violation

# Matter-Antimatter Asymmetry


dark matter
ordinary matter
dark energy

- QFT predicts particles to have partners - antiparticles

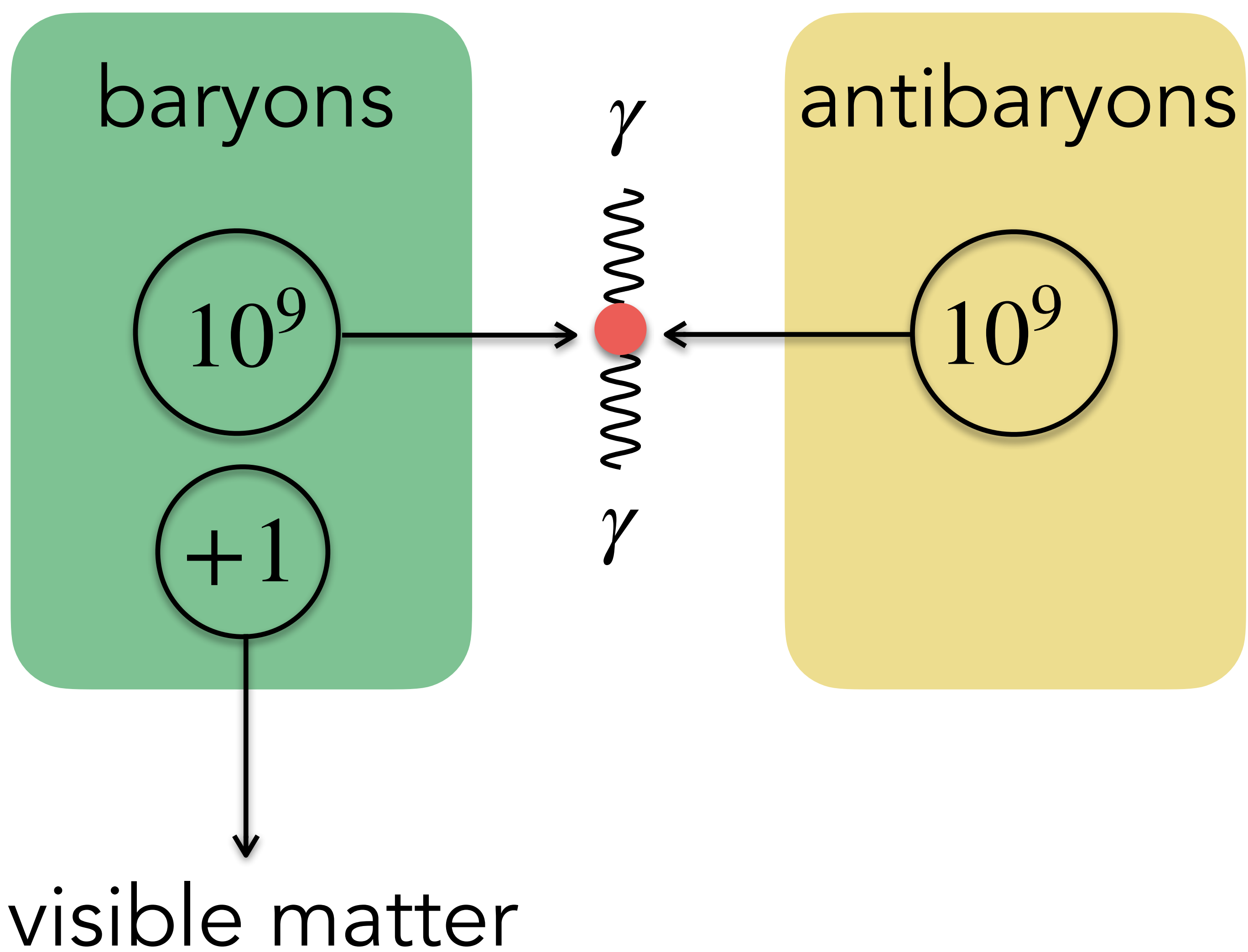
| | | |
|---|---|---|
| electron<br>proton<br>neutron | $\leftrightarrow$ | positron<br>antiproton<br>antineutron |

- But no such symmetry around us:
  - we are made of matter
  - in cosmic rays: $\bar{p}/p \sim 10^{-4}$

- cosmology: $\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$

| baryons | antibaryons |
| --- | --- |
| $10^9$ | $10^9$ |
| $+1$ | |

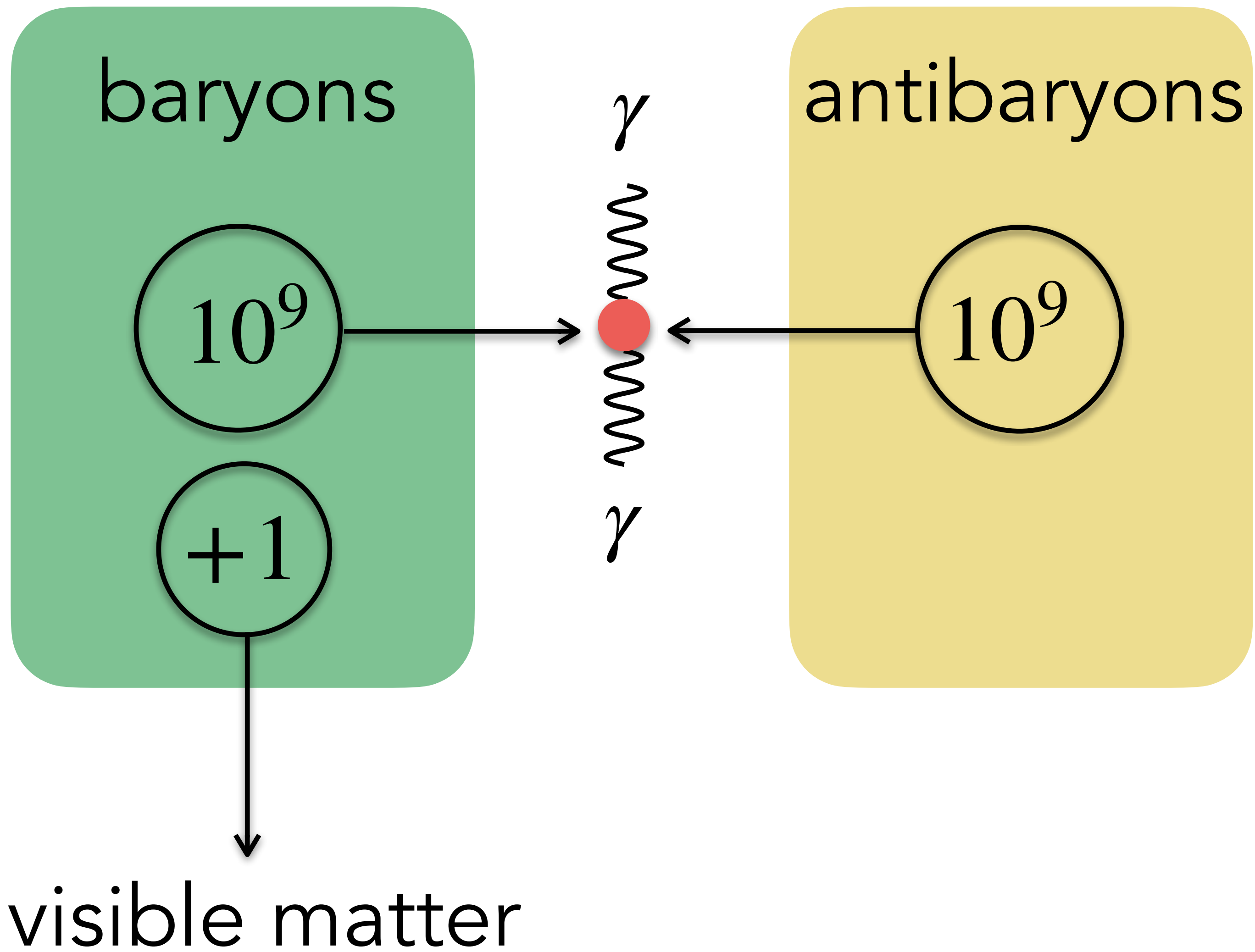
- cosmology: $$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$$



- cosmology: $\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$

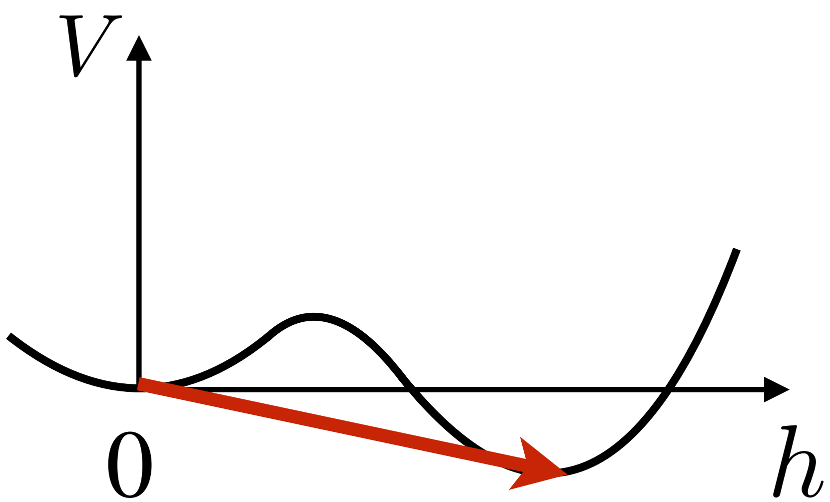
Which is … **too large.**

**No explanation within SM.**

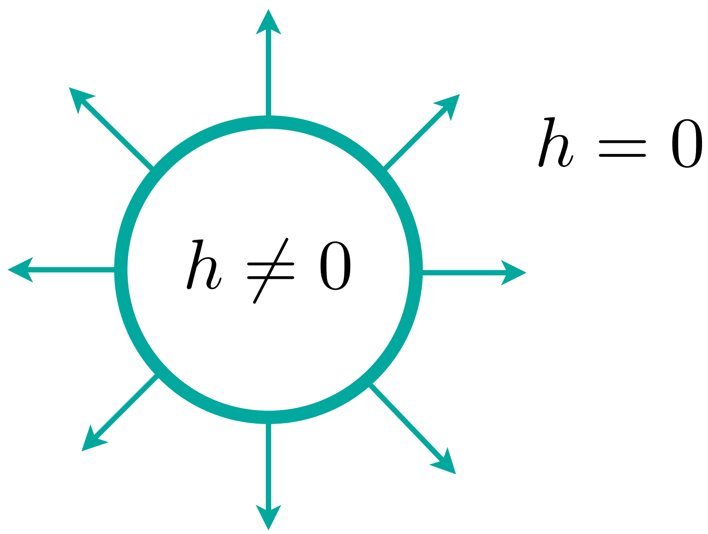


# Electroweak Baryogenesis

**First order EW phase transition proceeds through bubble nucleation:**



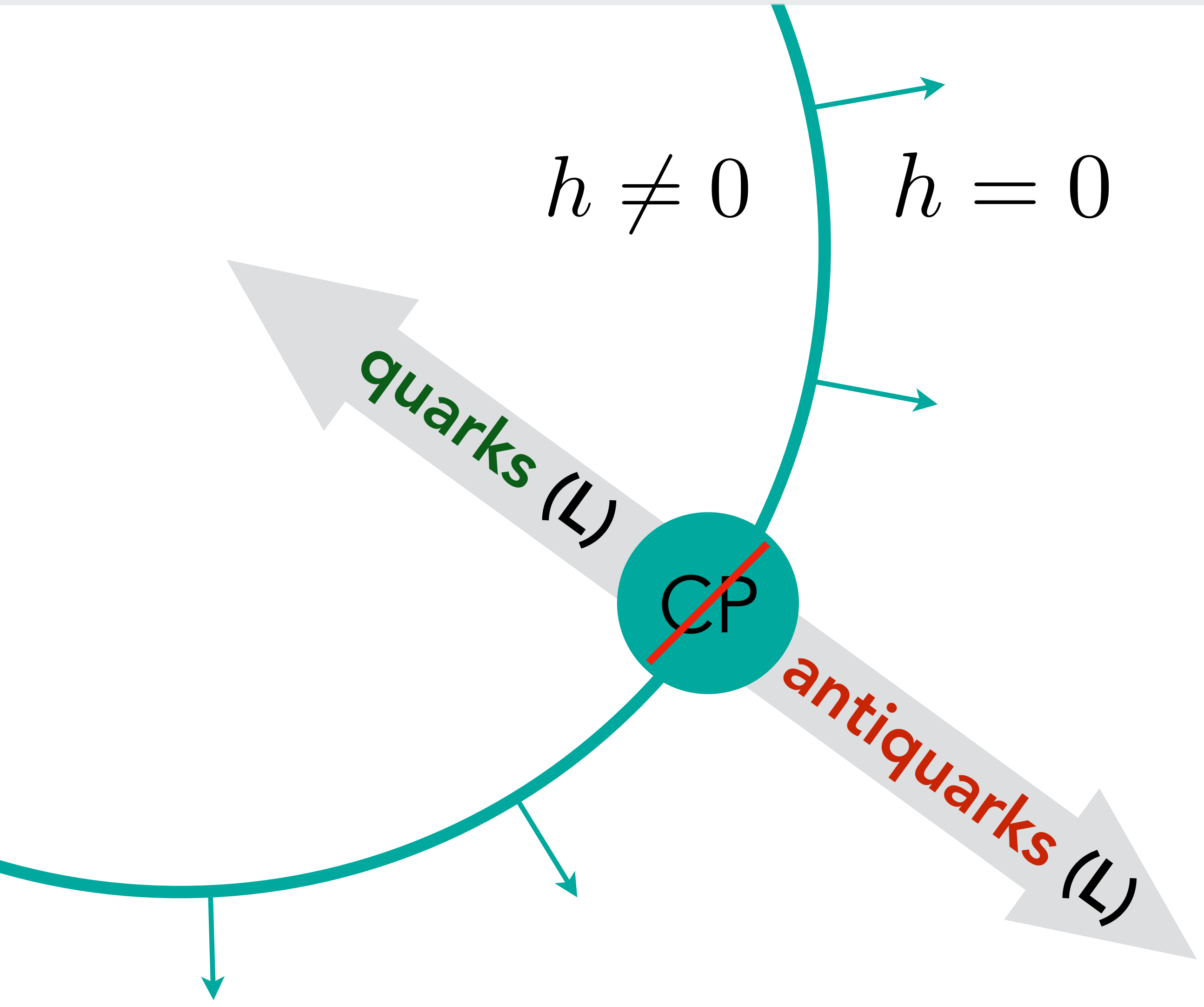

$\Longrightarrow$



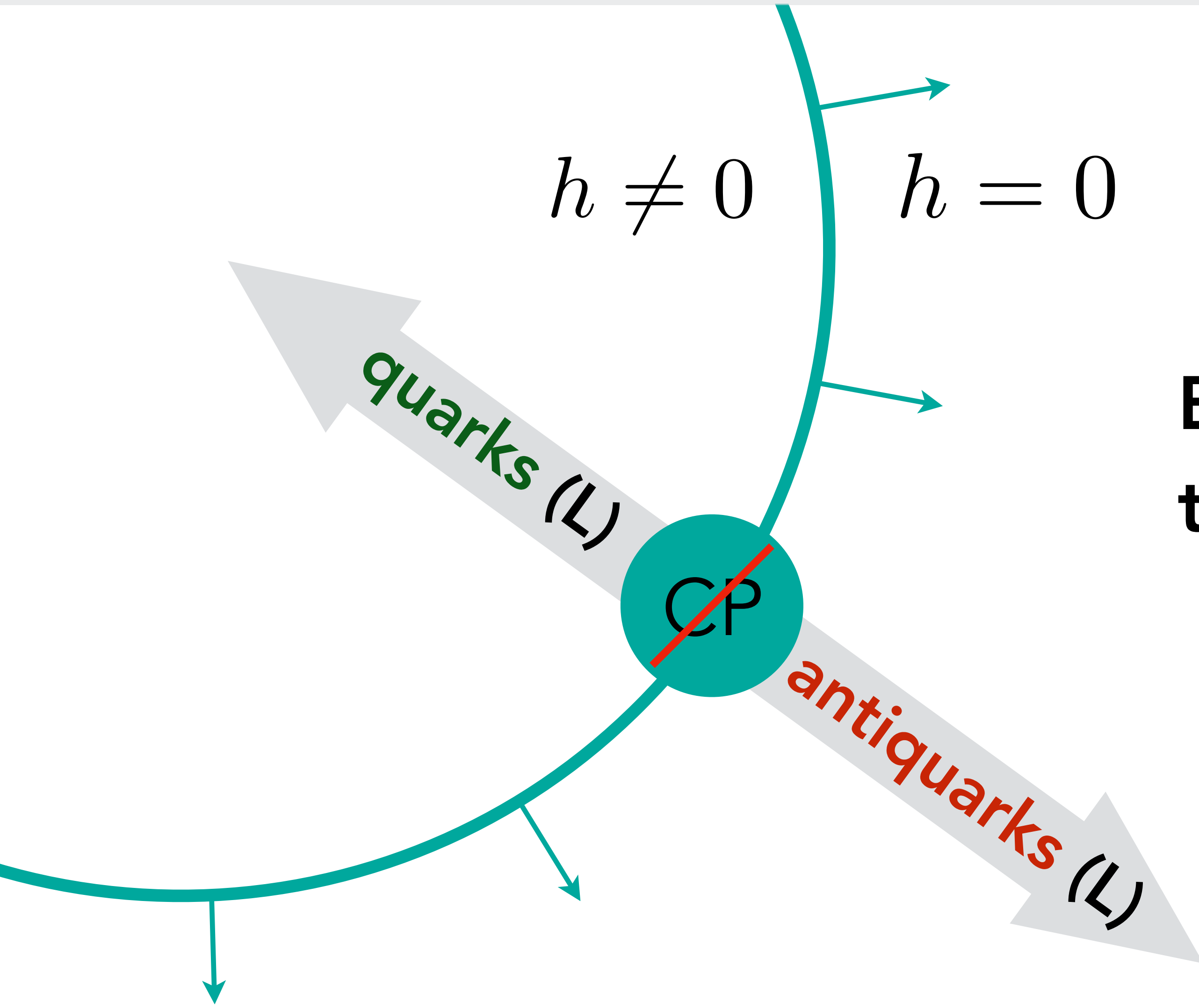

Shaposhnikov '87

Cohen,Kaplan,Nelson '91

$\sim$


$h \neq 0$
$h = 0$
quarks (L)
CP
antiquarks (L)

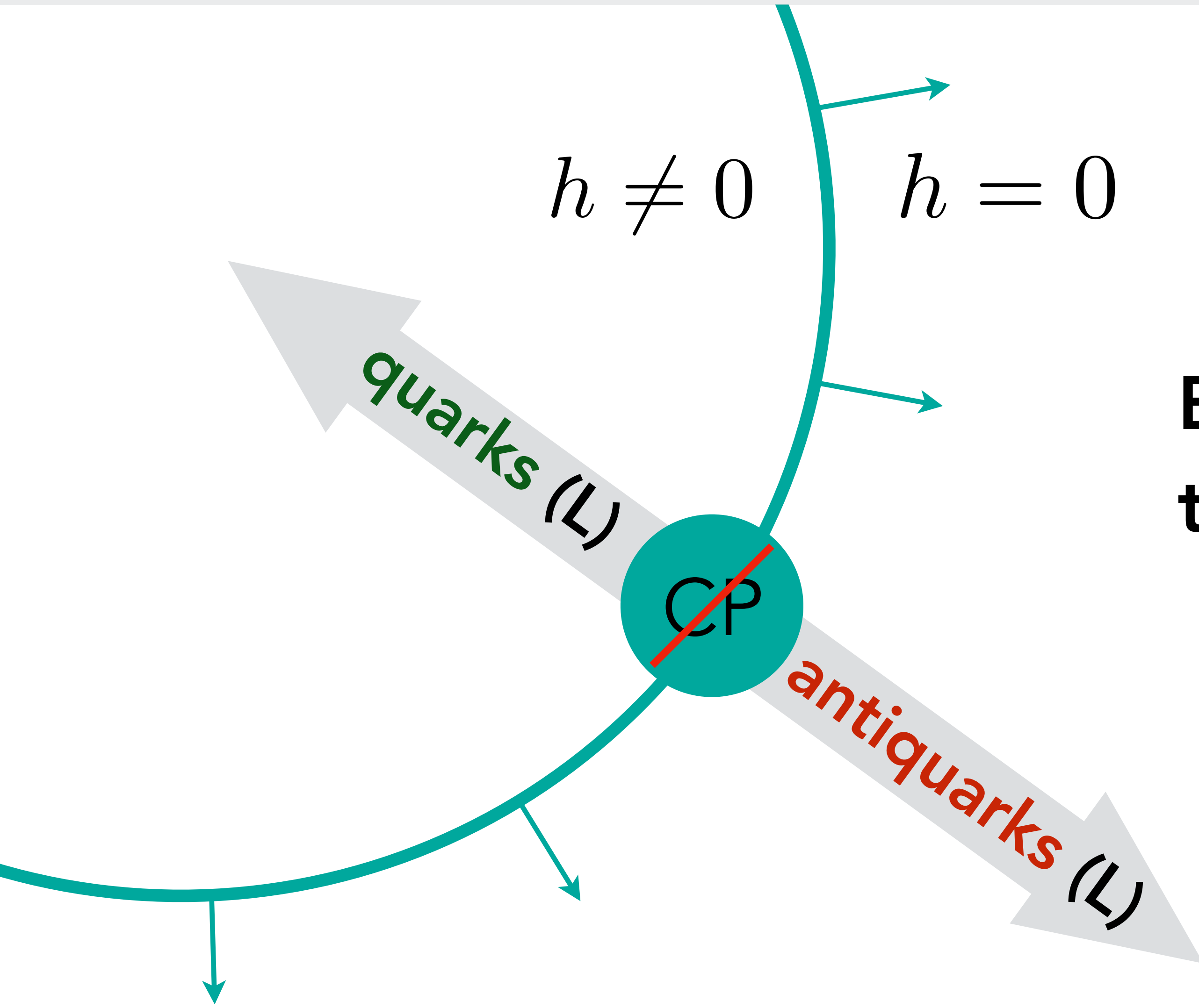
# Electroweak Baryogenesis




**Baryon asymmetry is created close to bubble walls:**

- B+L violation from EW sphalerons
- $$\partial_\mu j_B^\mu = \partial_\mu j_l^\mu = n_f \left( \frac{g^2}{32\pi^2} W^a_{\mu\nu} \tilde{W}^{a\mu\nu} - \frac{g'^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} \right)$$

# Electroweak Baryogenesis




**Baryon asymmetry is created close to bubble walls:**

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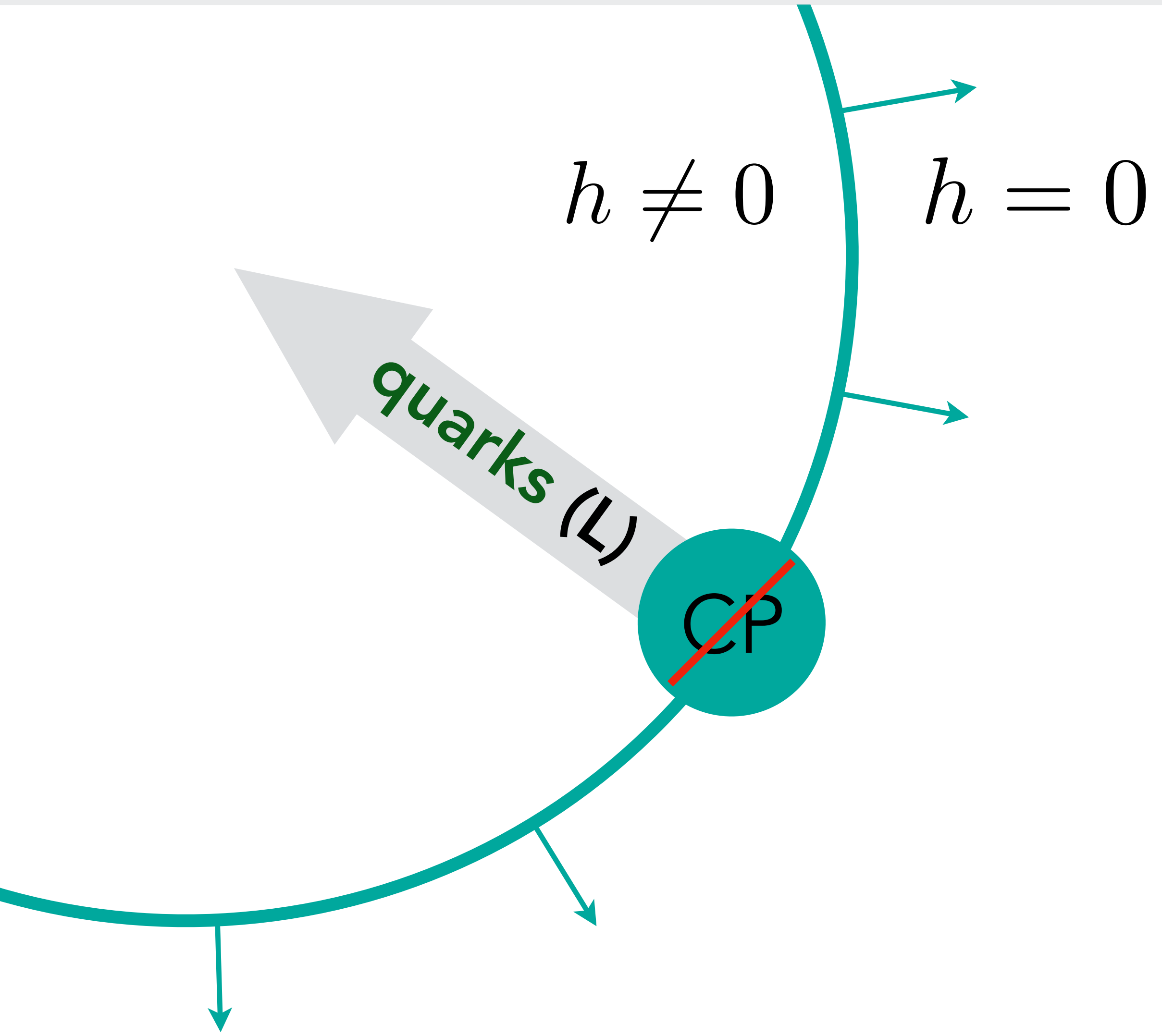
- rate is Boltzmann-suppressed:

$$\sim \exp[-\underbrace{E_{\rm sph}}_{\propto h}/T]$$

$\Rightarrow$ convert -B into L at $h/T < 1$

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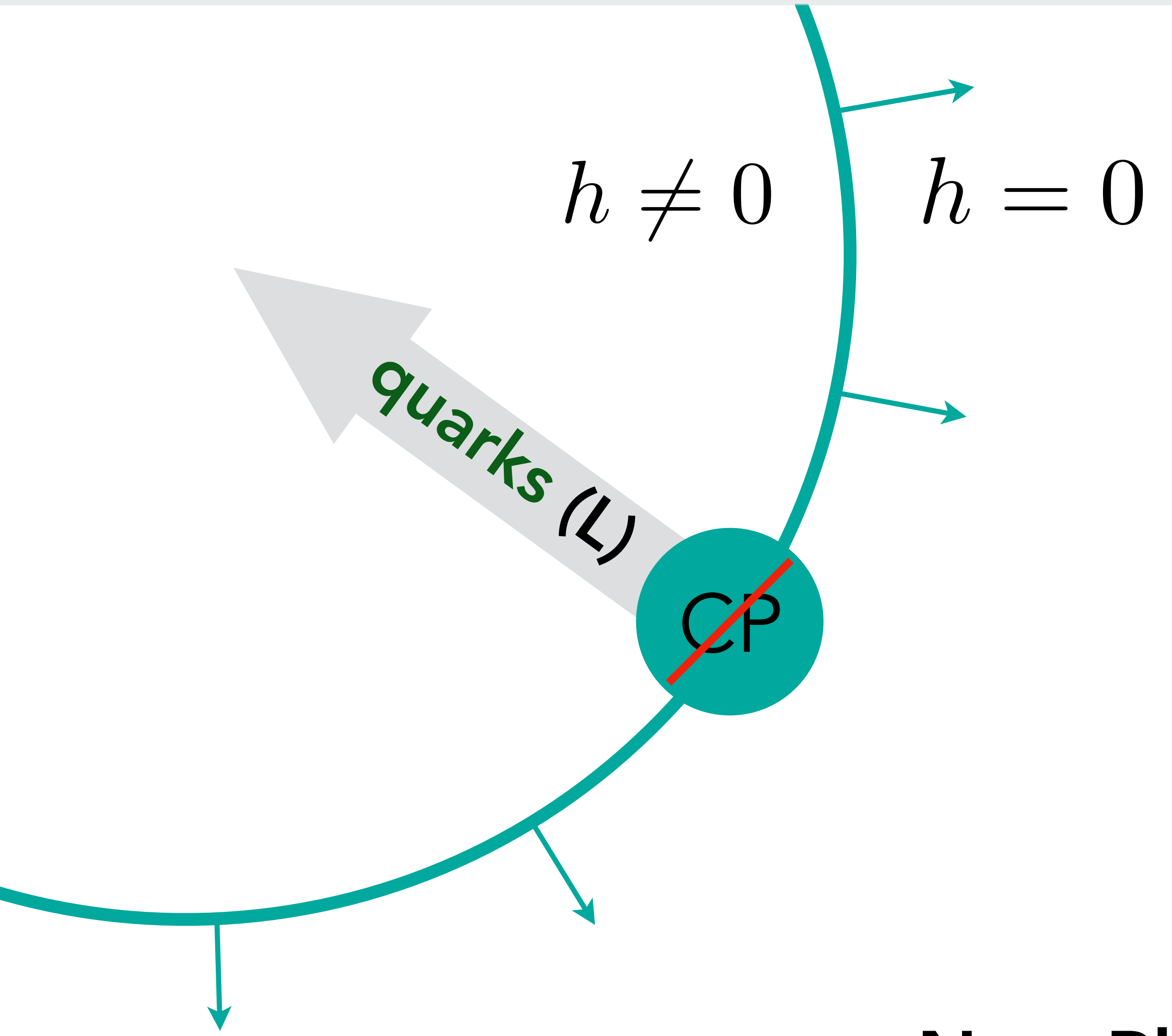


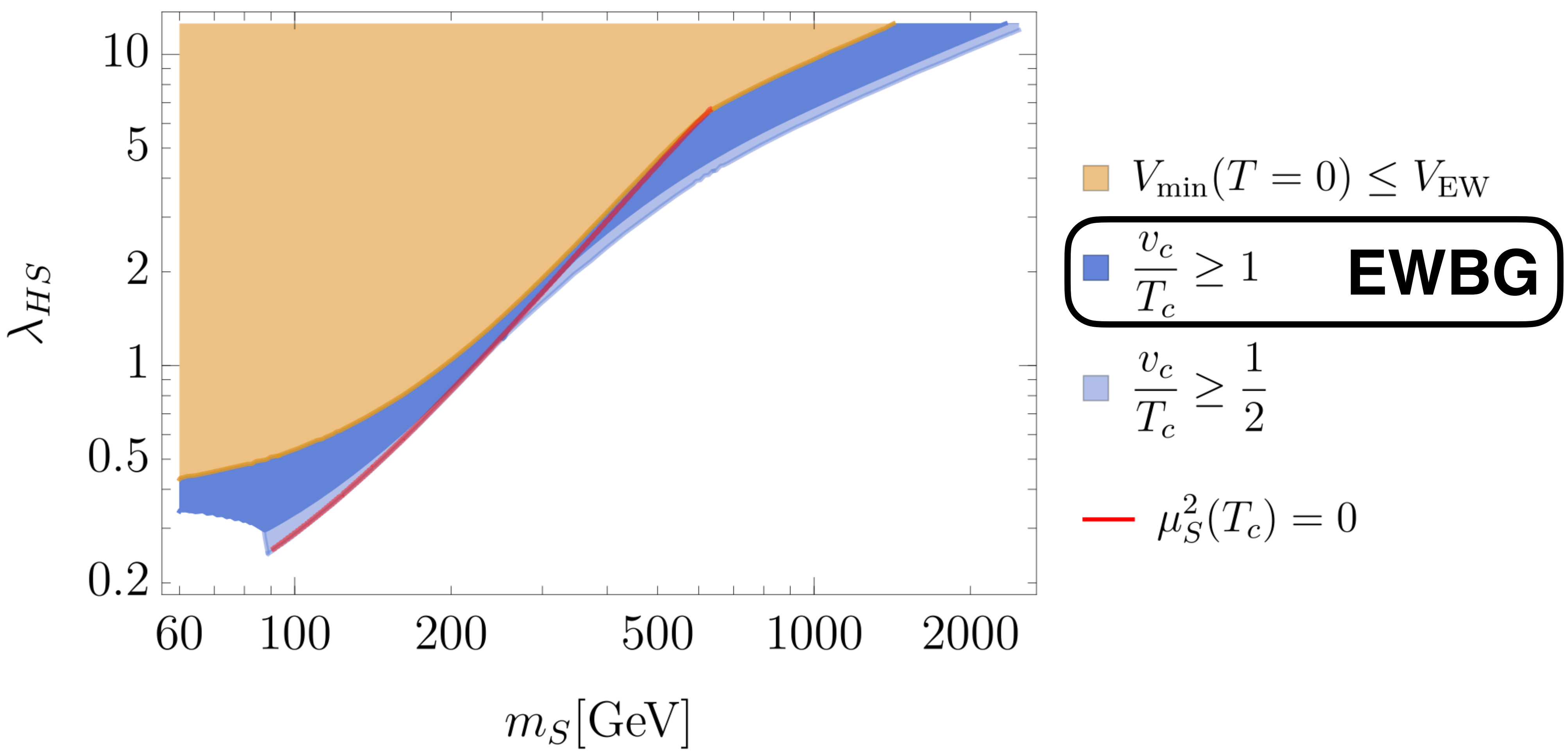

**New Physics needed for:**

- strongly first-order EW phase transition
  as compared to cross-over in SM
- CP-violation

# Minimal EWBG Model

# SM + Singlet

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




A.Benival et al, 1702.06124

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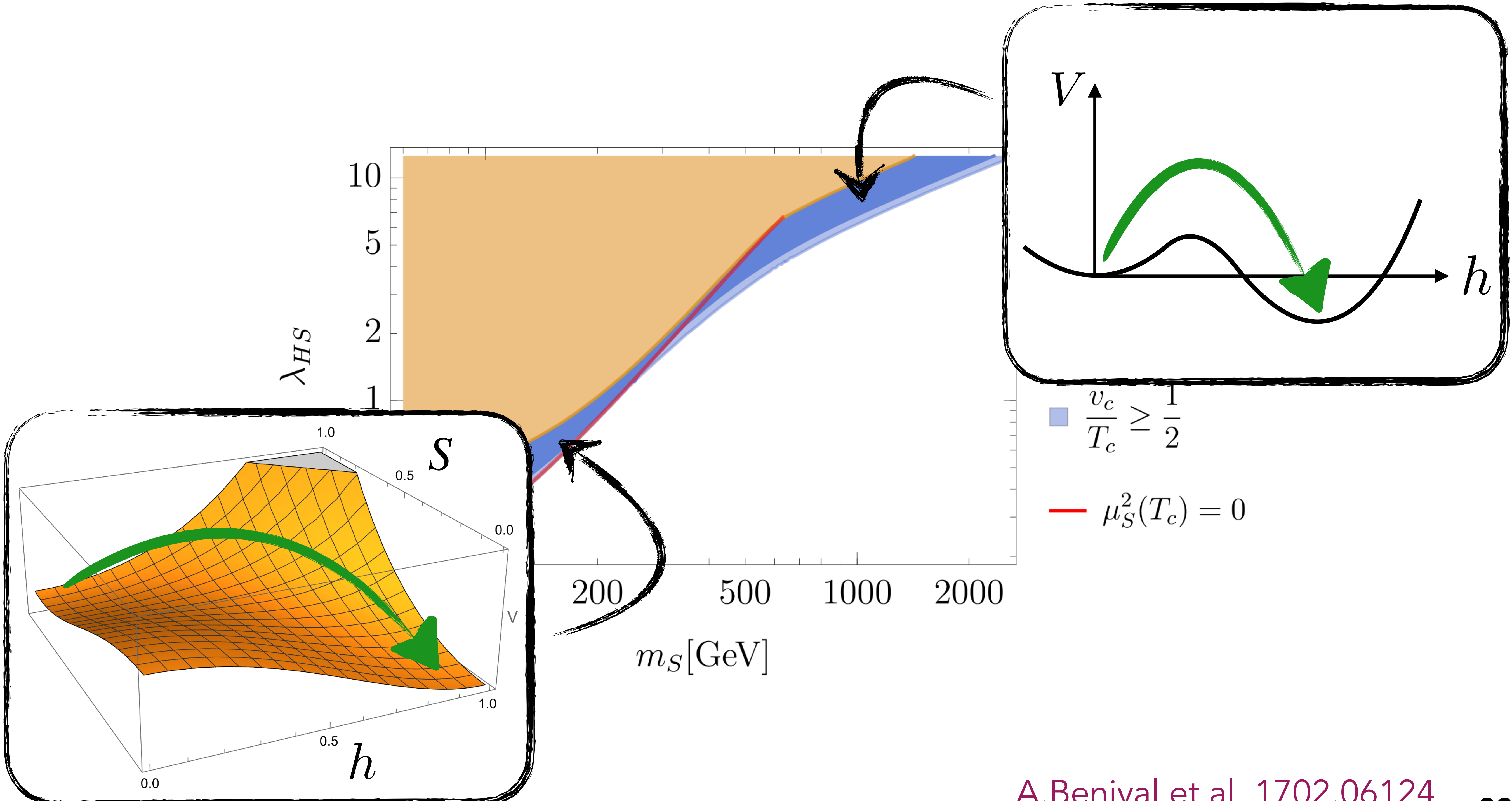



A.Benival et al, 1702.06124

# SM + Singlet

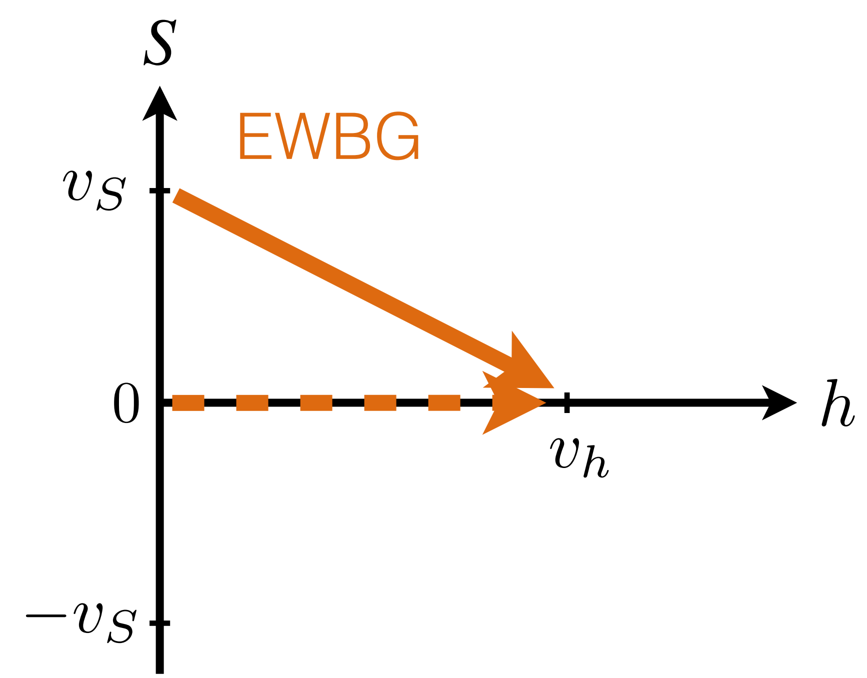
## Pheno: S-h mixing

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

- $S \to -S$ symmetry:

  $\Rightarrow$ no sizeable Higgs-S mixing

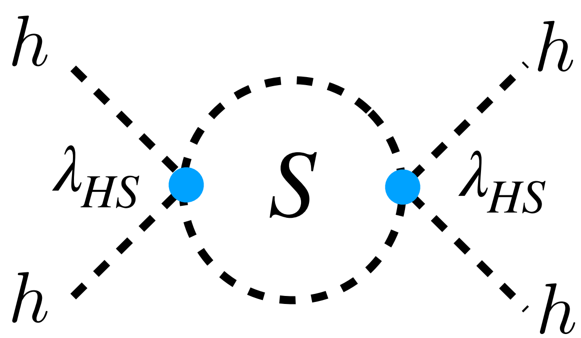
  $$\sin\theta \propto \lambda_{HS} \langle h \rangle \langle S \rangle$$




$\Rightarrow$ search for loop-induced effects of $\lambda_{HS}$

# SM + Singlet

## 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

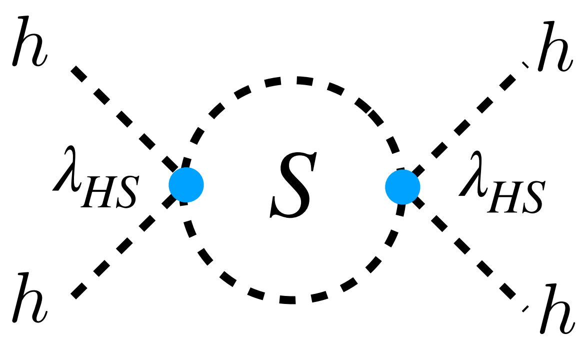
future sensitivities ($1\sigma$):

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*

# Pheno: $c_H$

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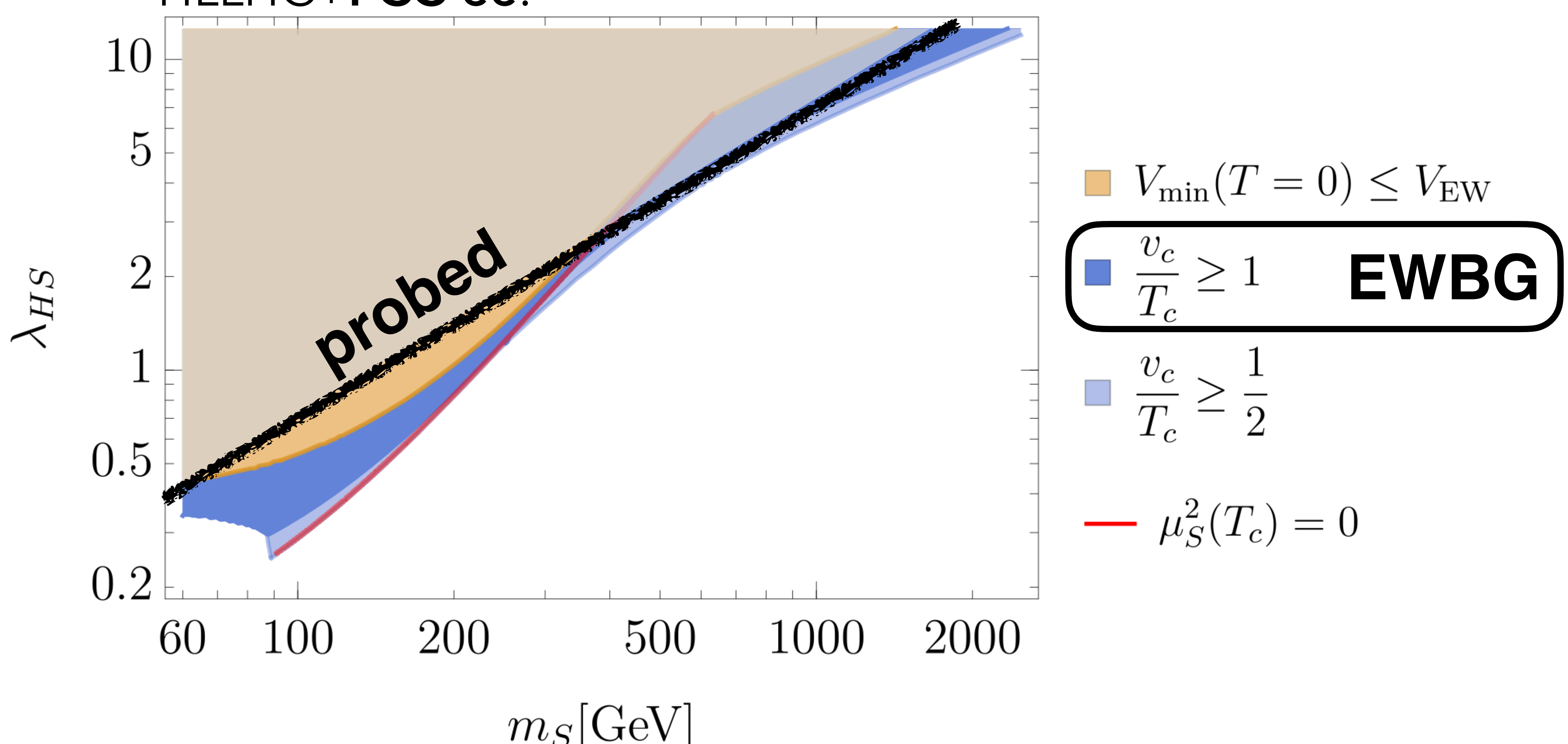
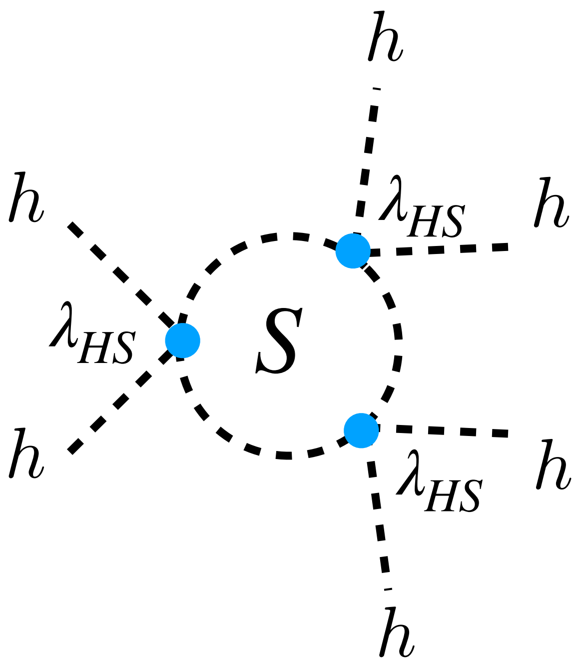
HLLHC+**FCC-ee**:



# SM + Singlet

## Pheno: $h^3$




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

A.Benival et al, 1702.06124

# SM + Singlet

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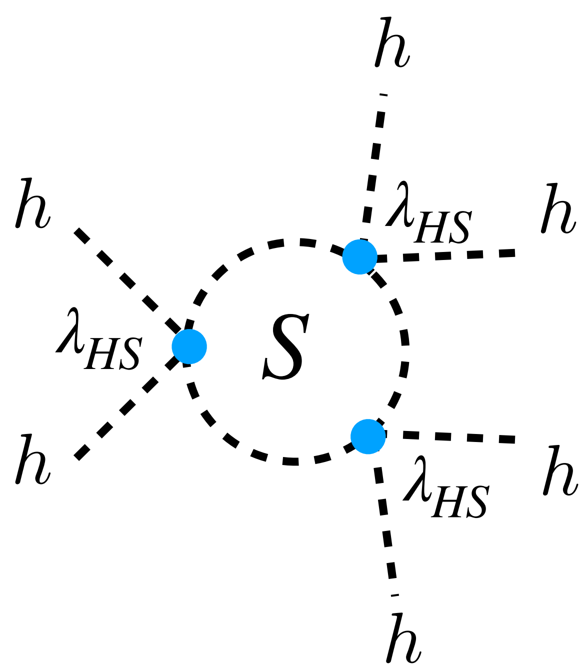


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A.Benival et al, 1702.06124

future sensitivities ($1\sigma$):

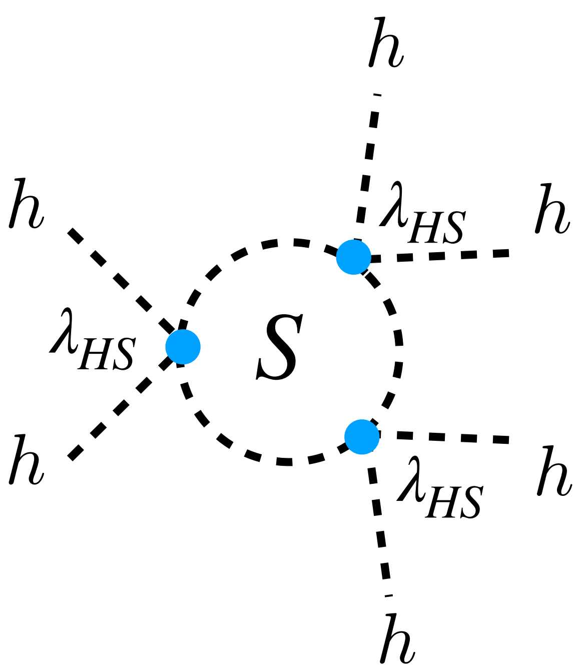
HL-LHC: $\delta\kappa \sim 0.5$

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

*J de Blas et al,1905.03764*

# SM + Singlet

## Pheno: $h^3$

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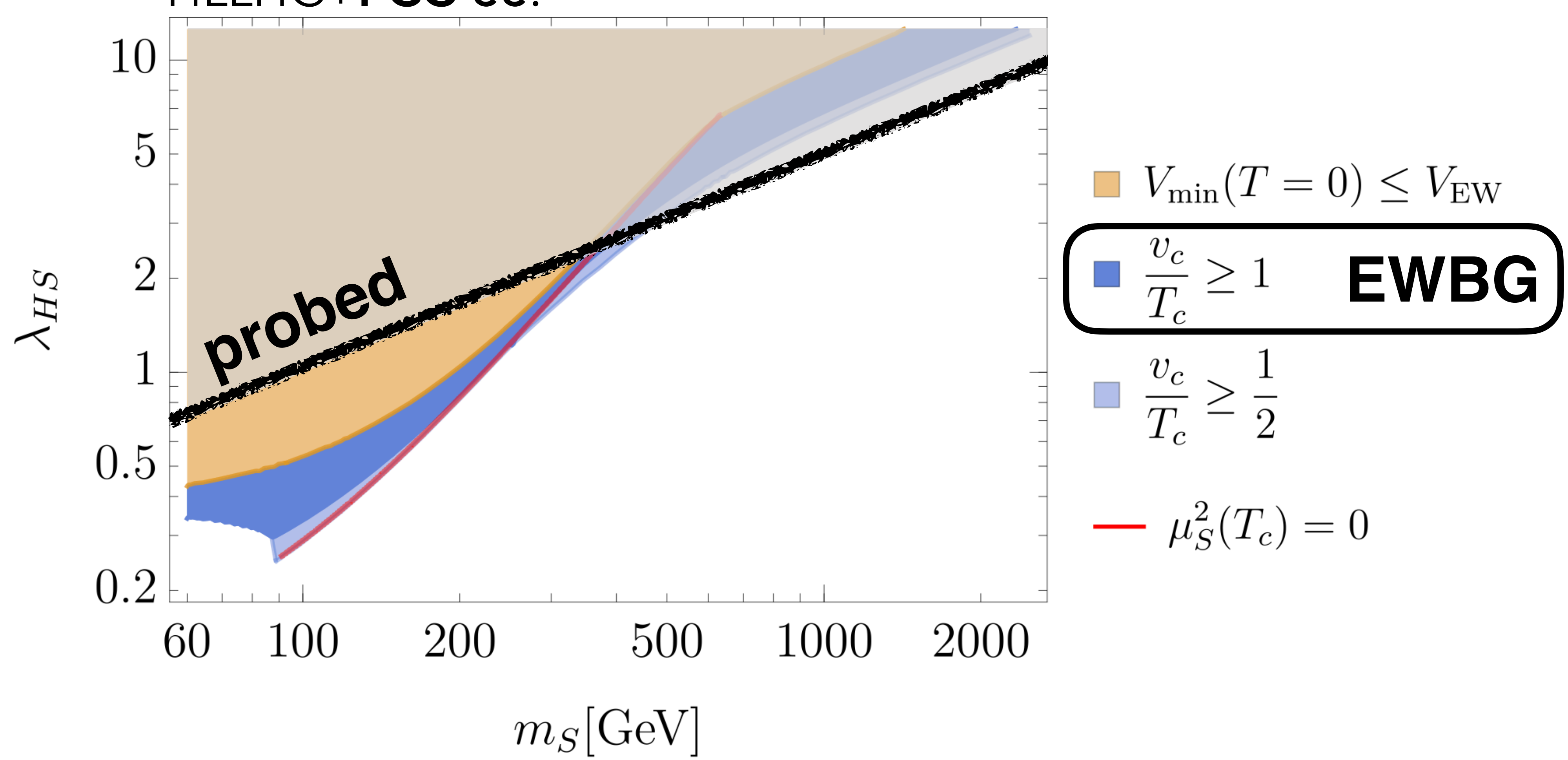
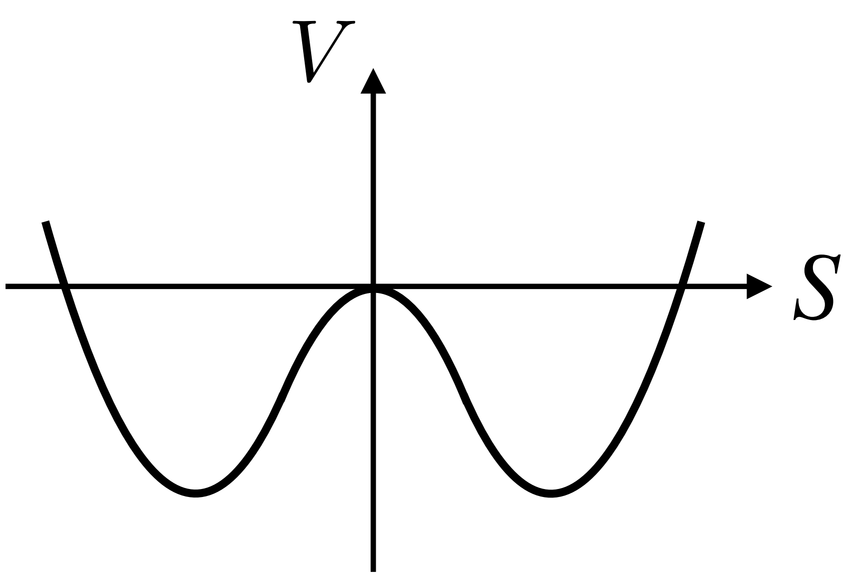


# Minimal
# *Defect-Mediated* EWBG Model

# SM + Singlet: EWBG via Domain Walls

- Brandenberger, Davis, Prokopec, Trodden Phys. Rev. D 53 (1996) 4257–4266
- J.Azzola,OM,A.Weiler JHEP 04 (2025)

discrete symmetry of vacuum manifold




$$S = v_S \tanh \frac{m_S z}{2}$$

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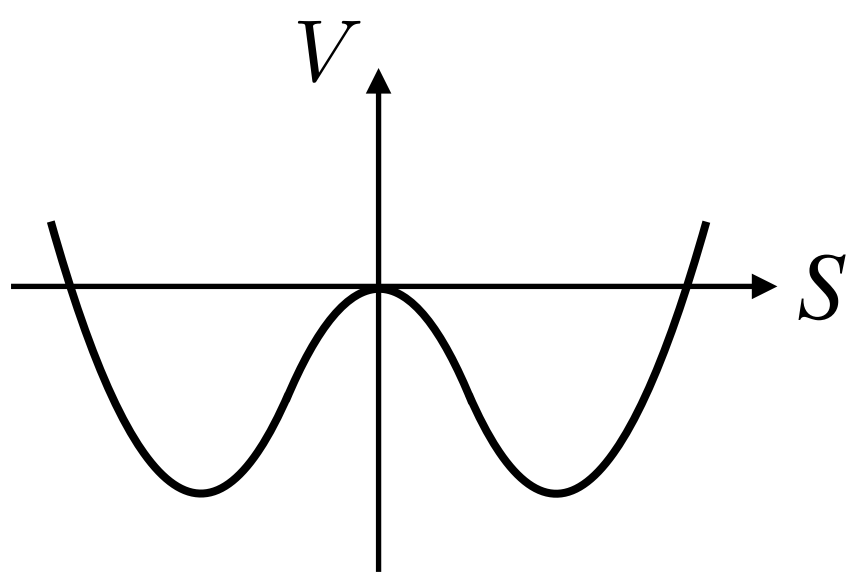
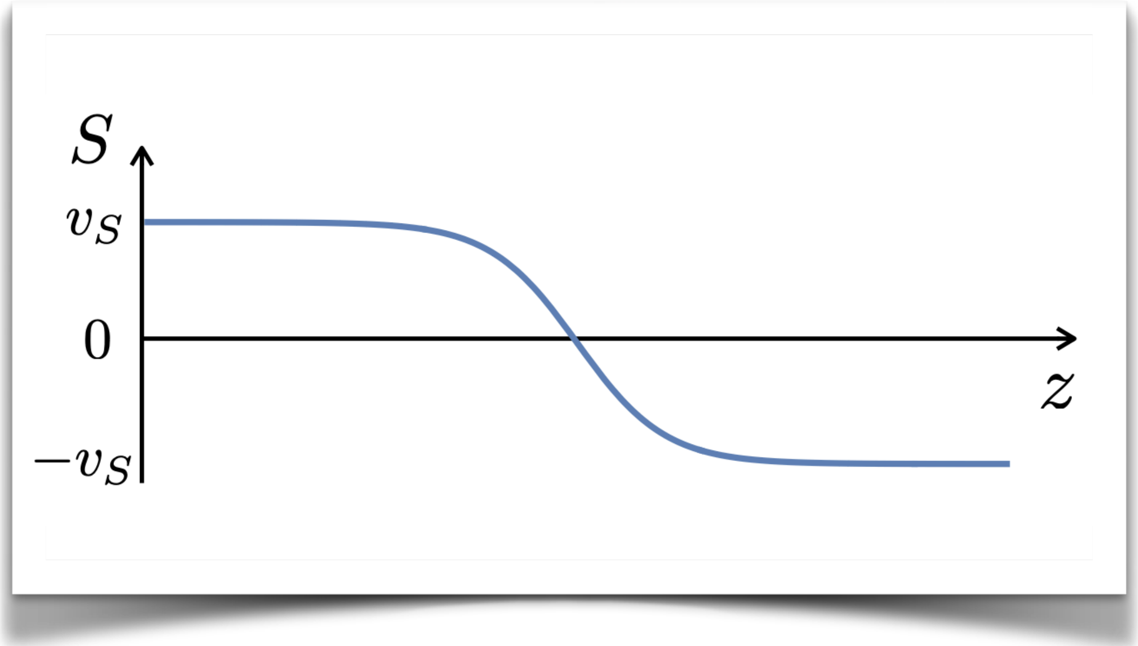



$\Rightarrow$

domain walls can be formed in Z2 breaking phase transition

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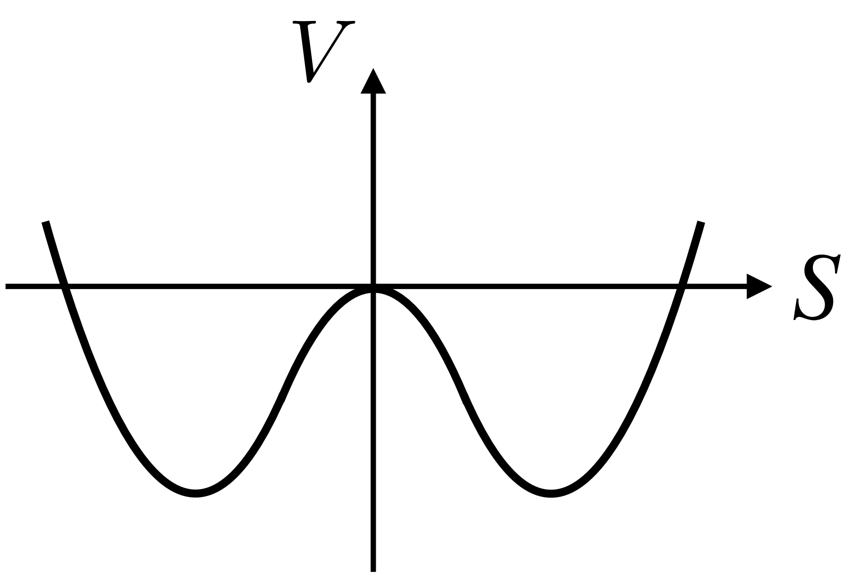


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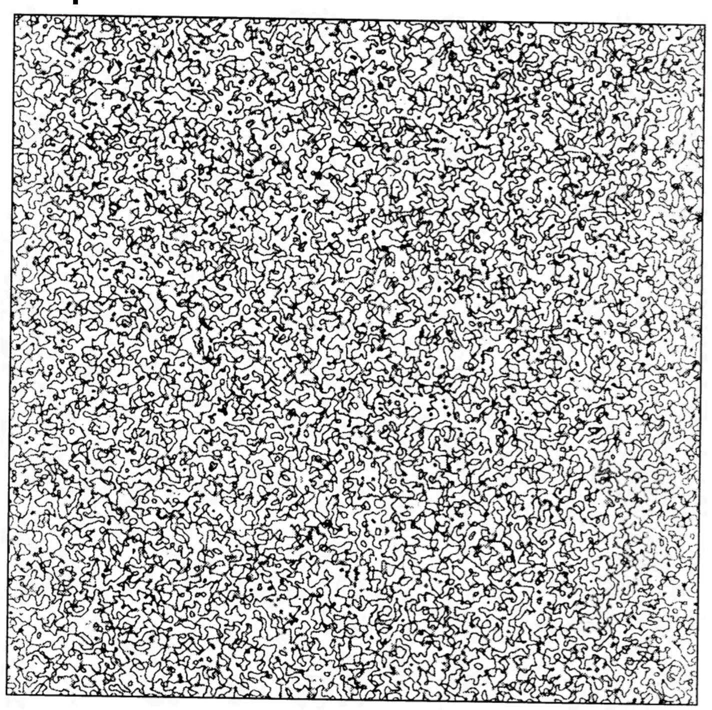

Press,Ryden,Spergel, Astrophys.J. 347 (1989)

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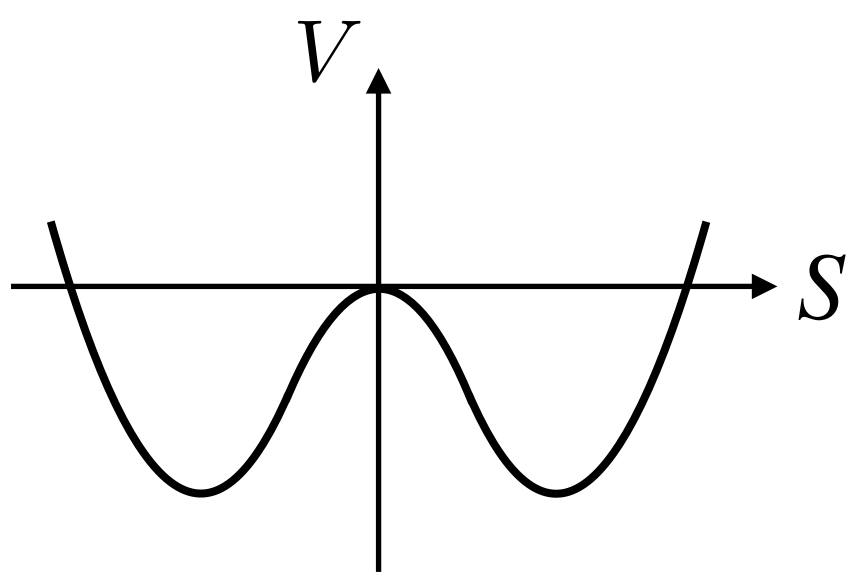


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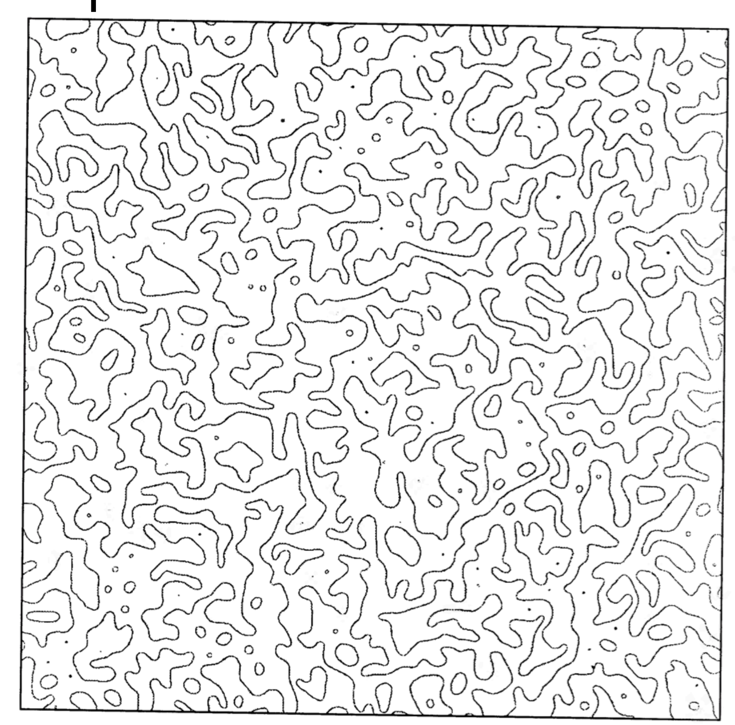

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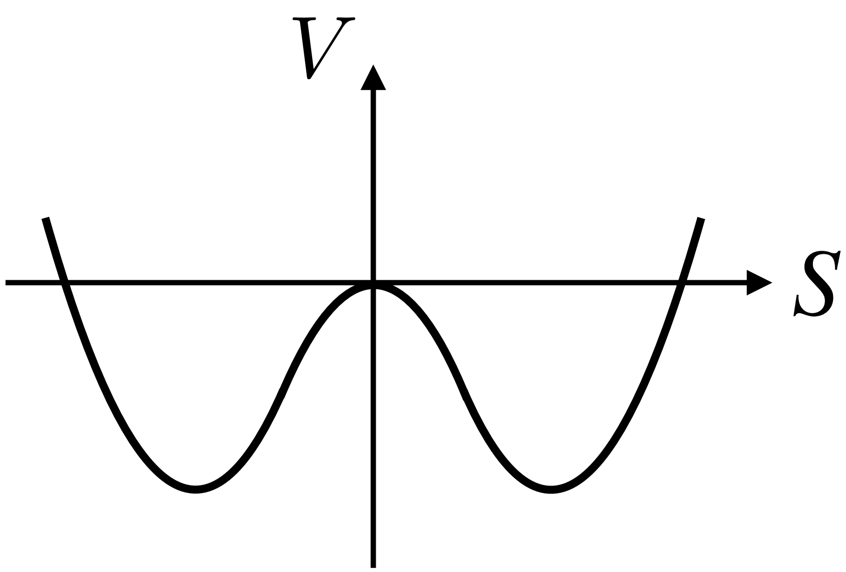


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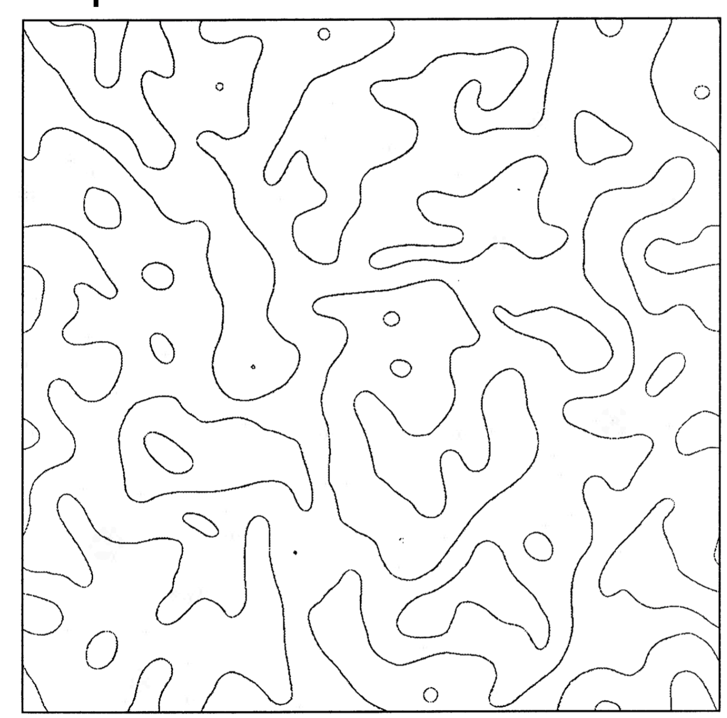

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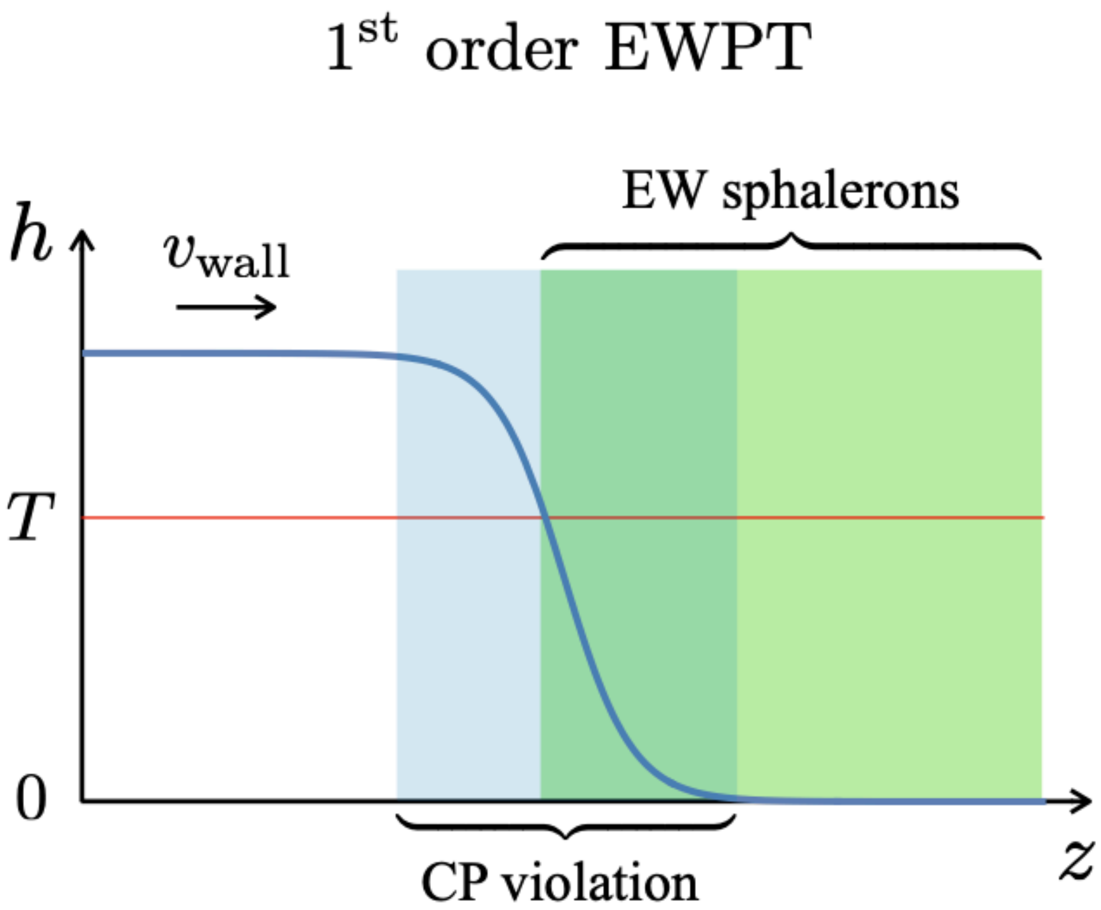
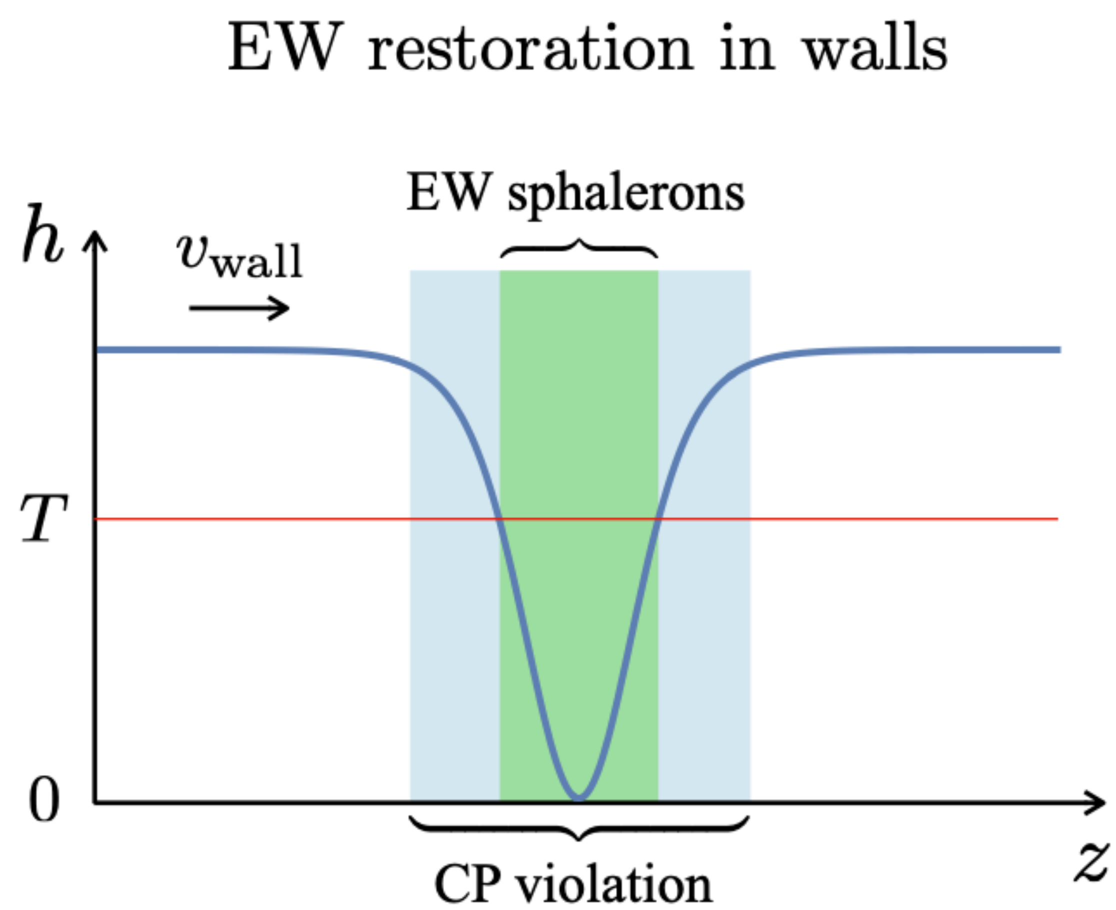
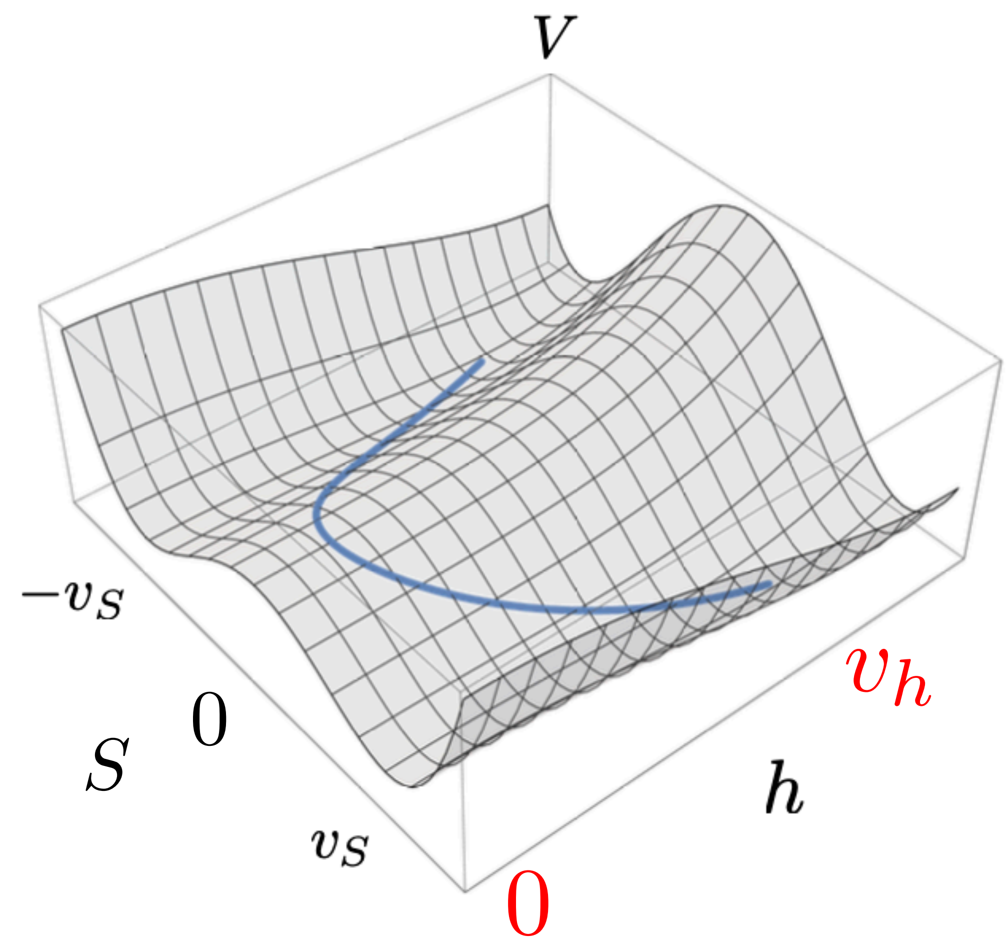


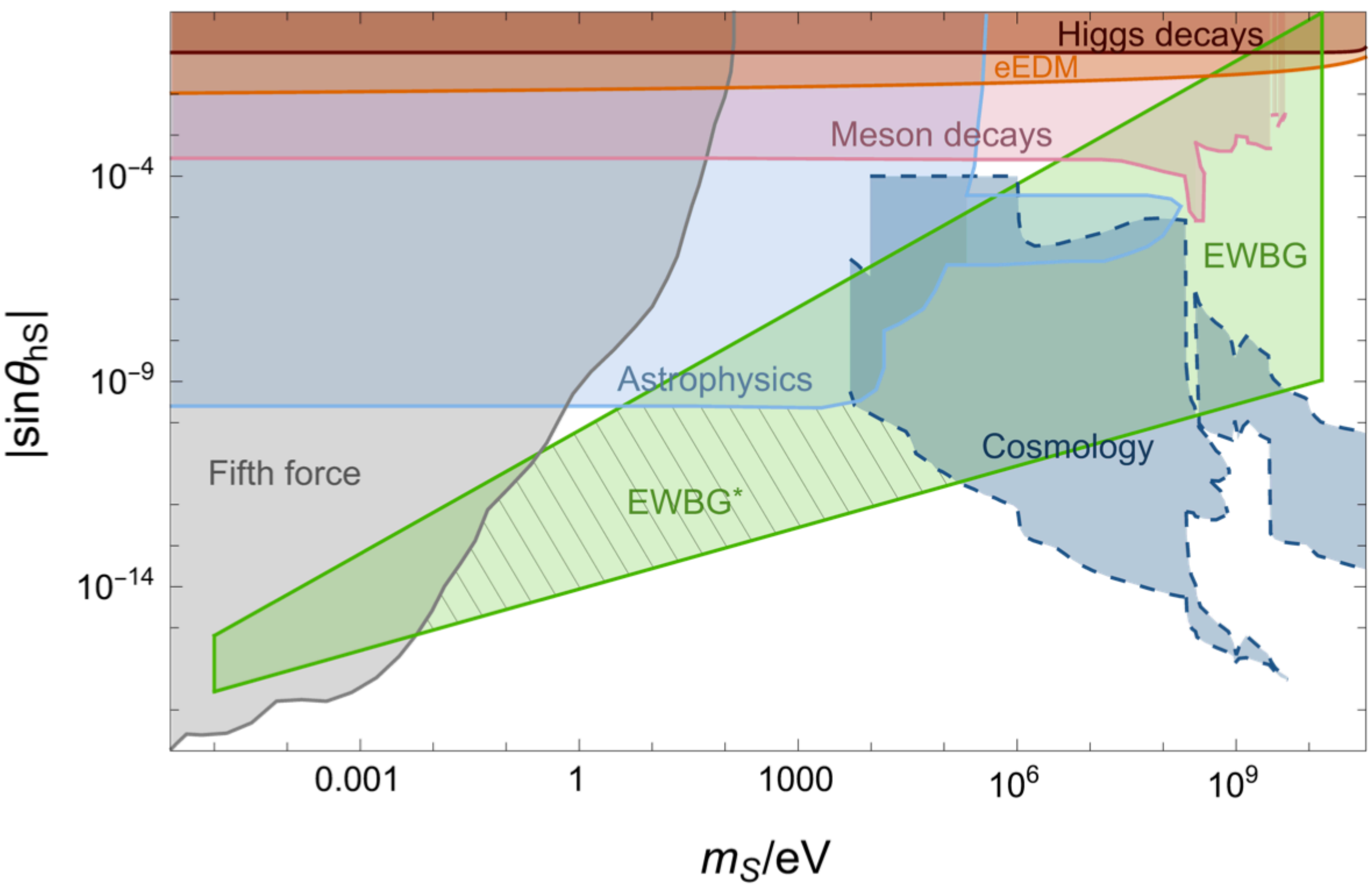
# SM + Singlet: EWBG via Domain Walls

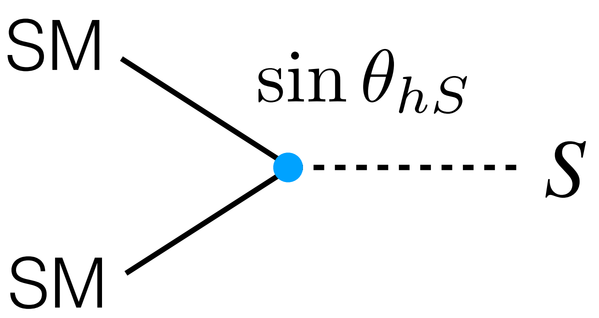
- h-S trajectory curved towards h=0

$$\mathscr{L} \supset -\frac{1}{2}|\lambda_{HS}||H|^2 S^2$$



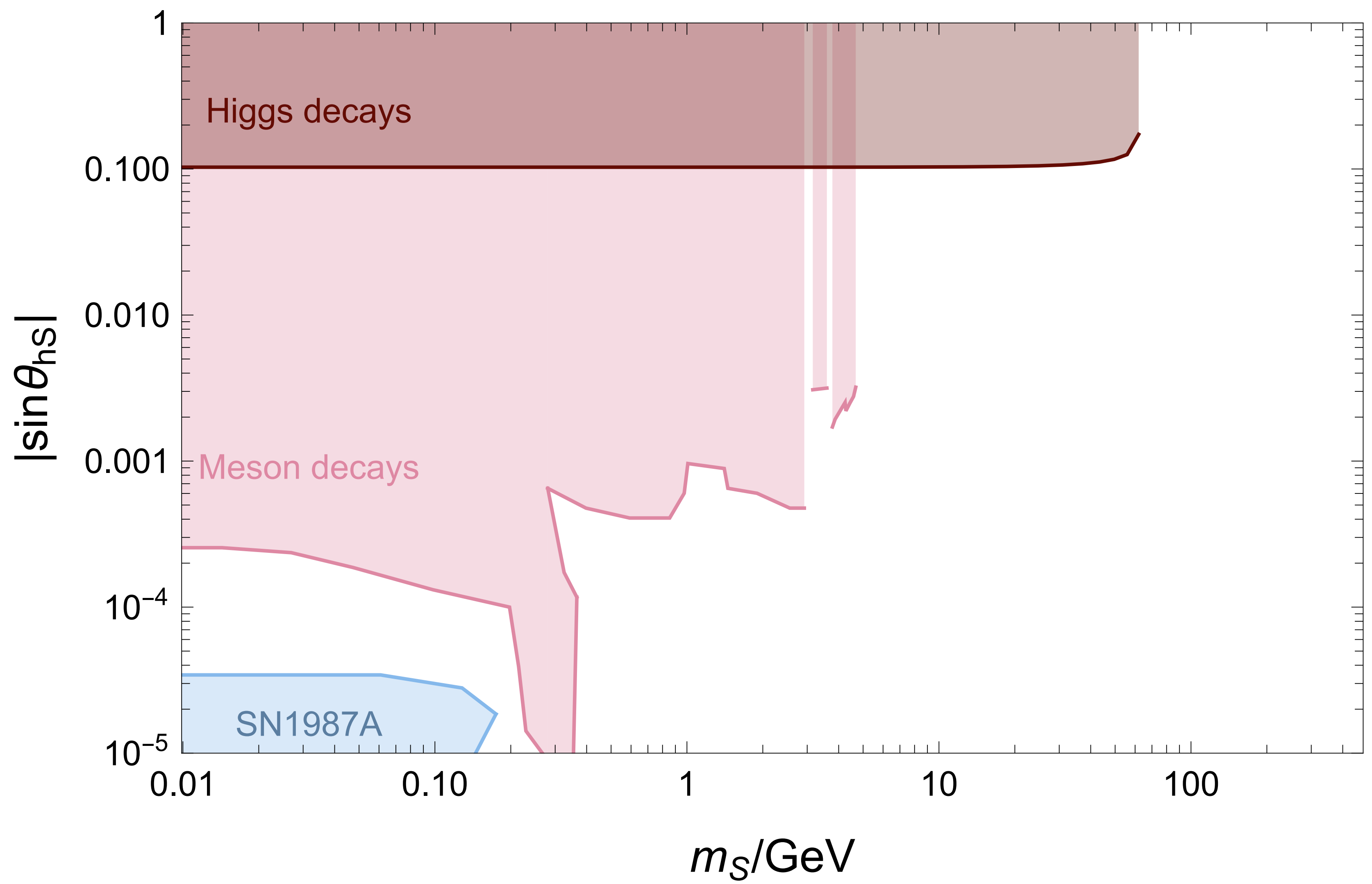
# Parameter Space



# Parameter Space

- High mass region:



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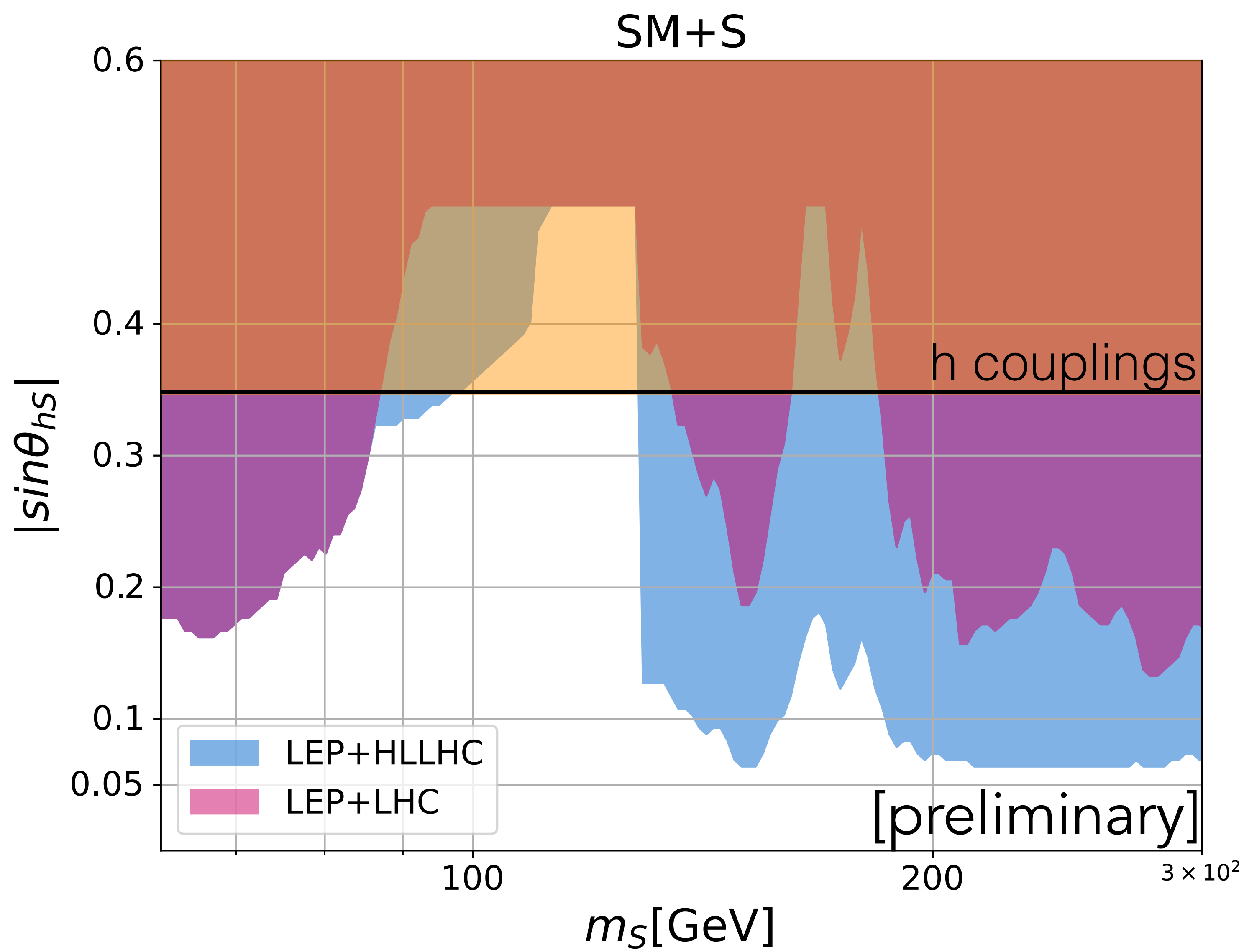
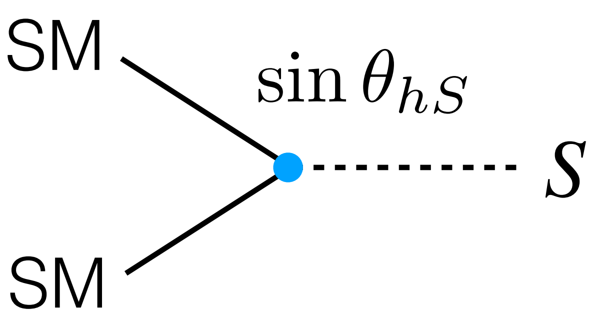



using HiggsBounds, 2210.09332

# Naturalness Perspective

**Gauge hierarchy problem:**

$$\delta m_h^2 \propto \Lambda^2 \quad \longleftarrow$$ any physics that Higgs interacts with

e.g. $$\frac{m_P^2}{m_h^2} \sim 10^{34}$$

**Traditional approaches:**

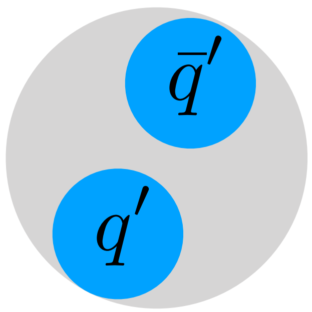
$$\delta m_h^2 = {\color{red}0}\,\Lambda^2 + \mathcal{O}(100GeV)$$

↑

supersymmetry
compositeness
extra dimensions

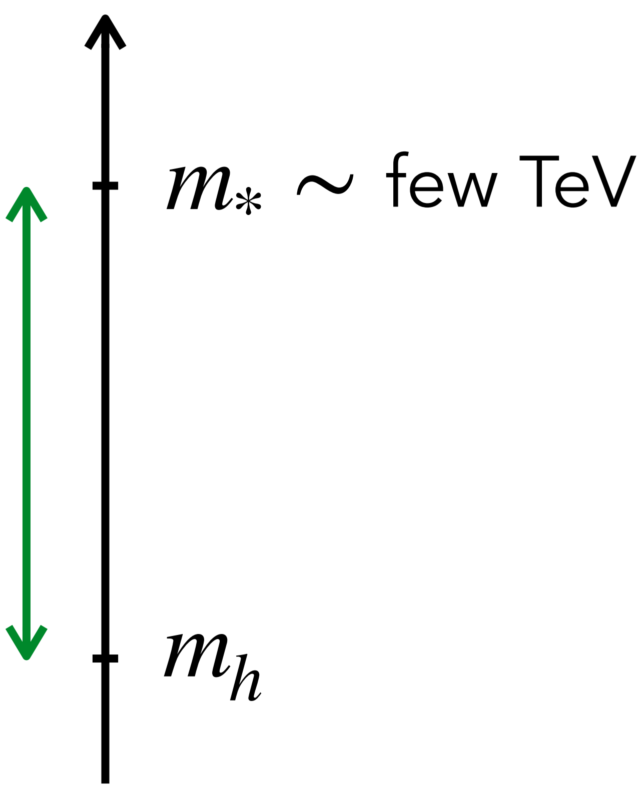
# Composite Higgs

Higgs is a bound state of new strong interactions confining at $f$ ~ 1TeV

$h =$ 


**spectrum:**

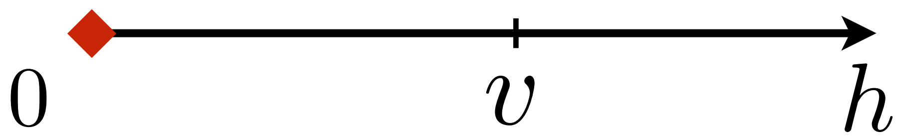
Higgs is pNGB similar to QCD pions




Kaplan,Georgi '84

Agashe,Contino,Pomarol '04

# Phase Transitions in CH models



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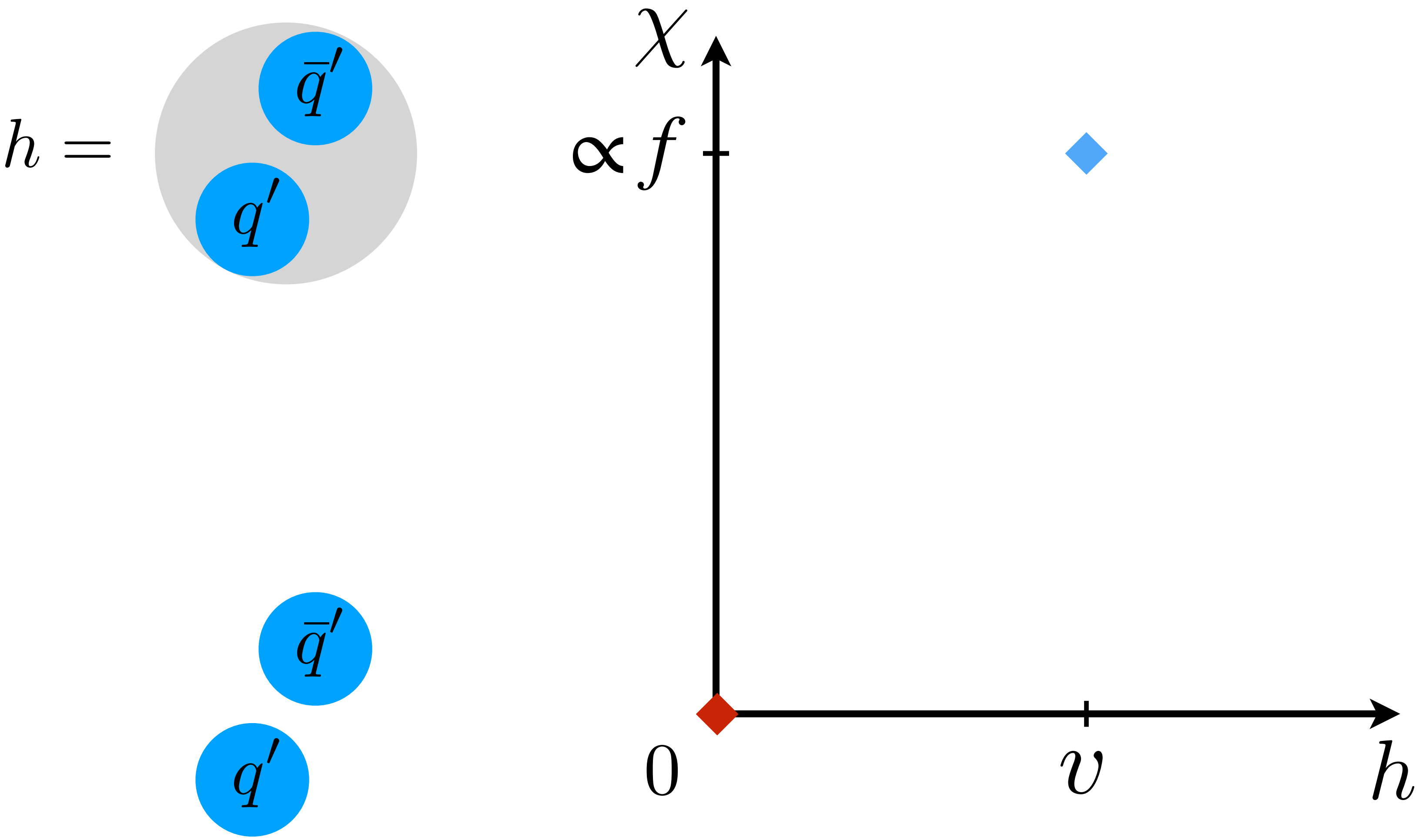
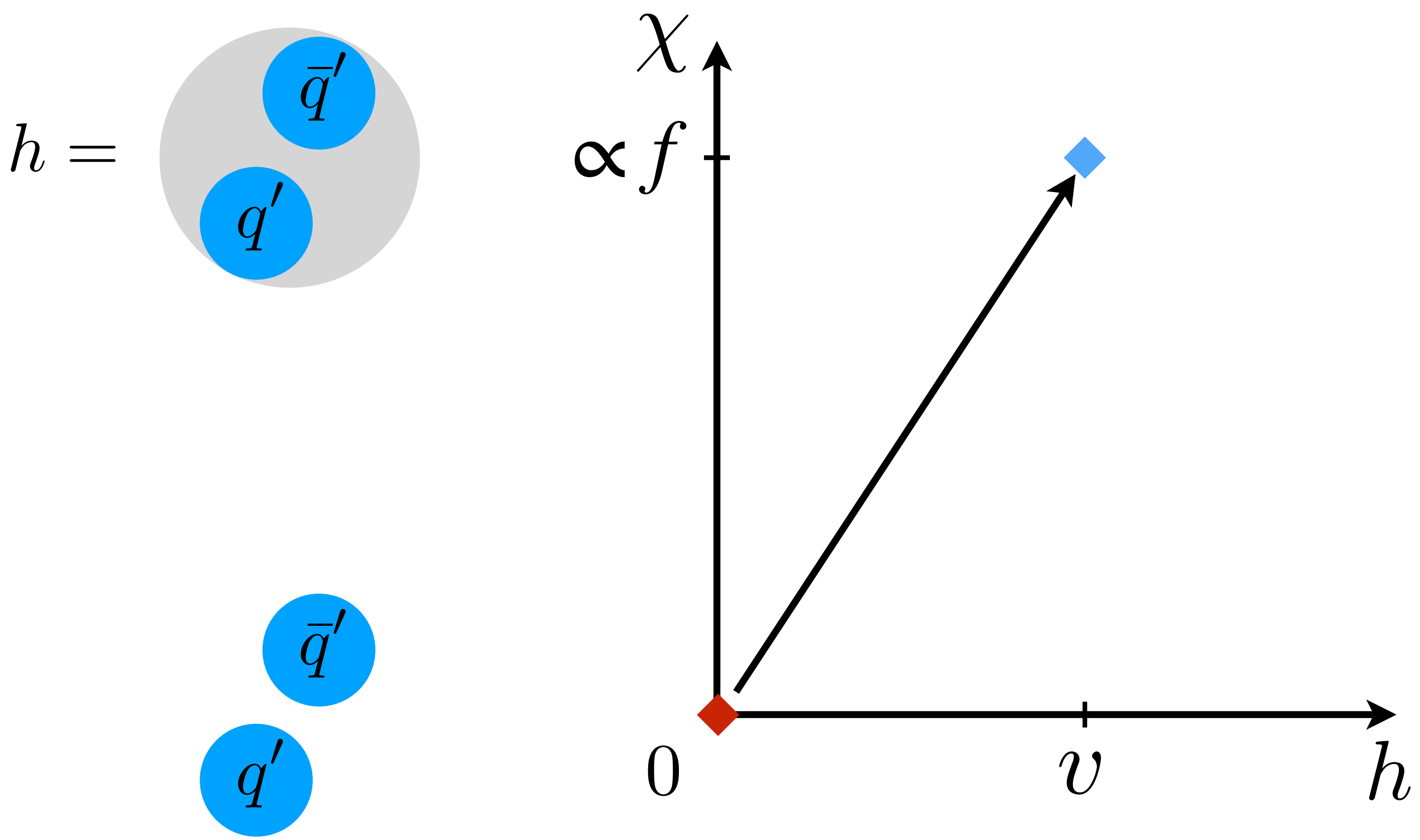


# Phase Transitions in CH models




**1-step**: if T(confinement) < T(EWSB)

$h \propto \chi$ and EWPT is 1st order if confinement PT is

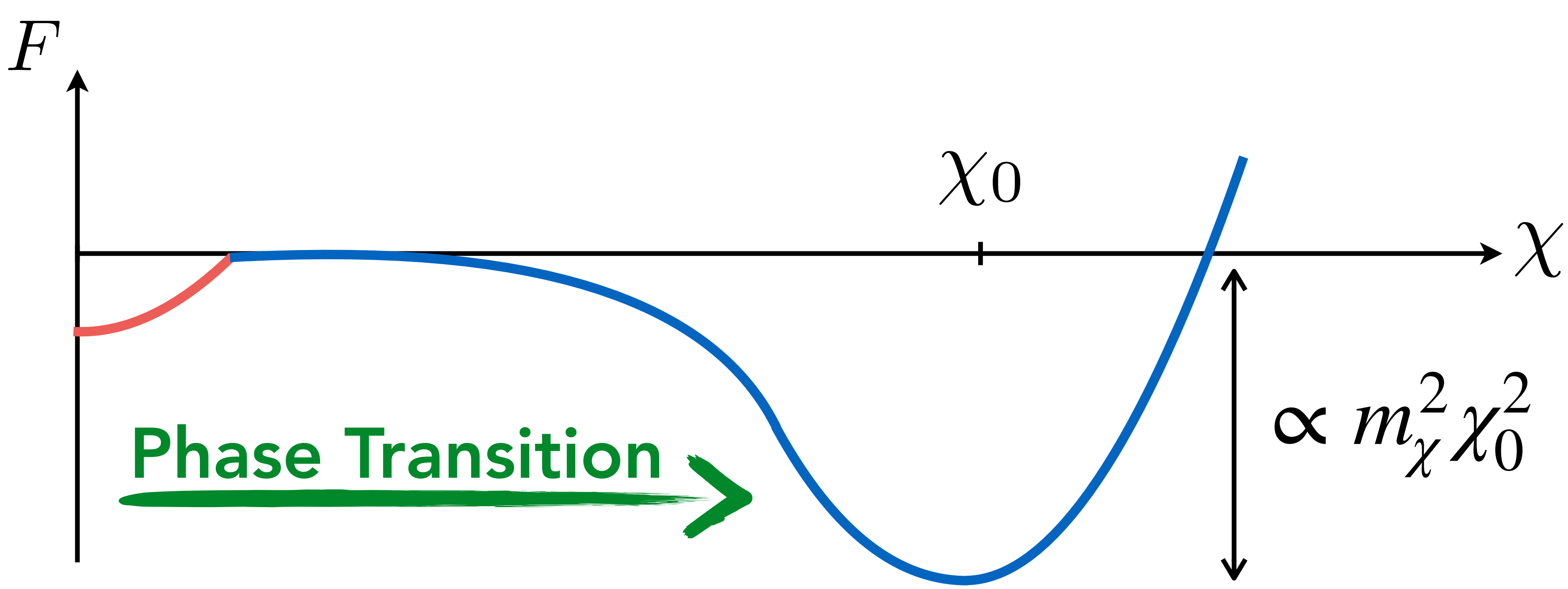
Bruggisser,vonHarling,OM,Servant,
1803.08546, 2212.11953

# Dilaton & Conformal Invariance

- Conformal invariance is often assumed for new strong interactions

- When broken spontaneously, a light PNGB - dilaton - can appear

- Dilaton mass and VEV are defining for the PT properties




Bruggisser,vonHarling,OM,Servant,
1803.08546, 2212.11953

# Dilaton at the LHC

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

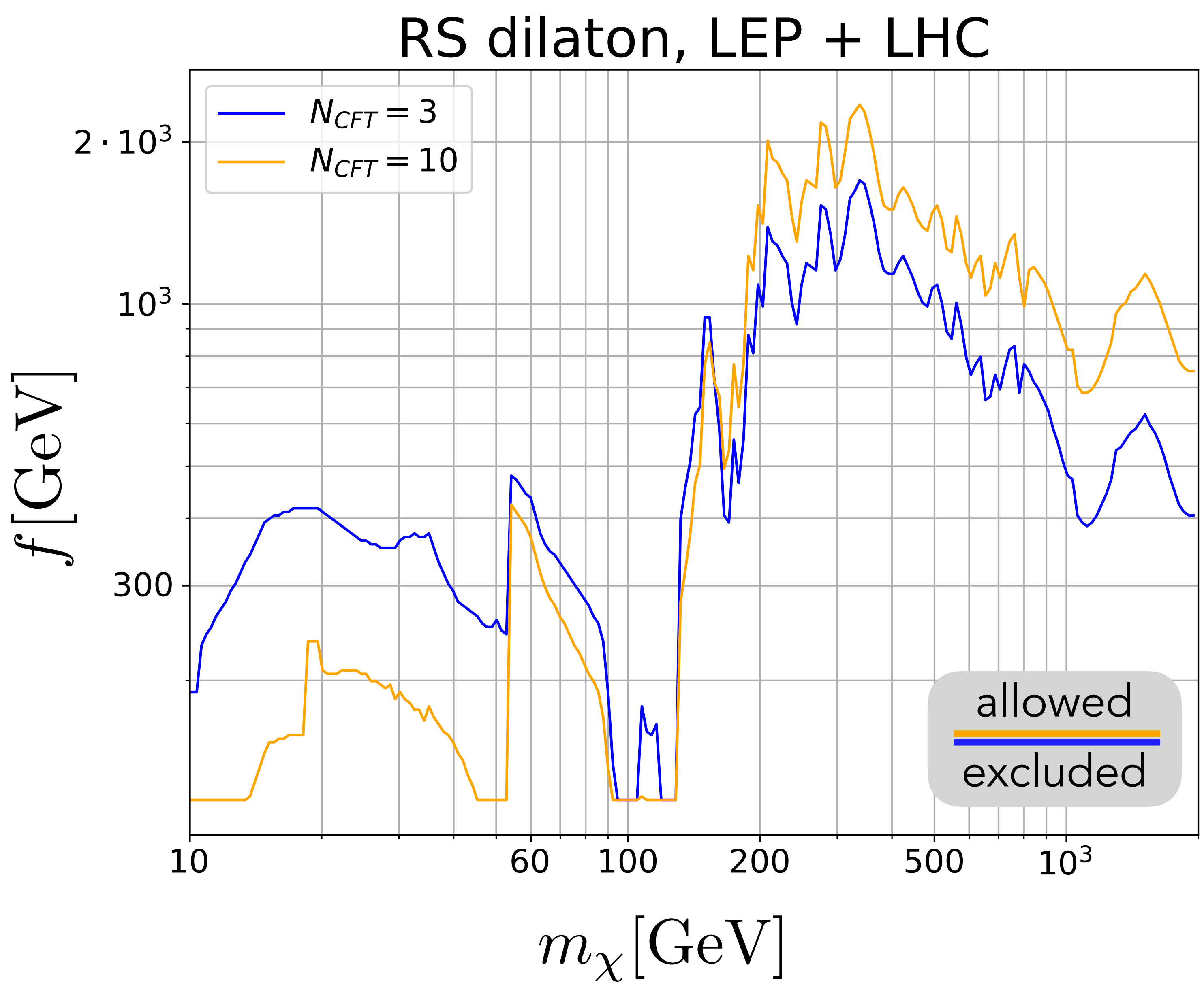
e.g. quark mass: $\underbrace{m_q}\,\bar{q}q$

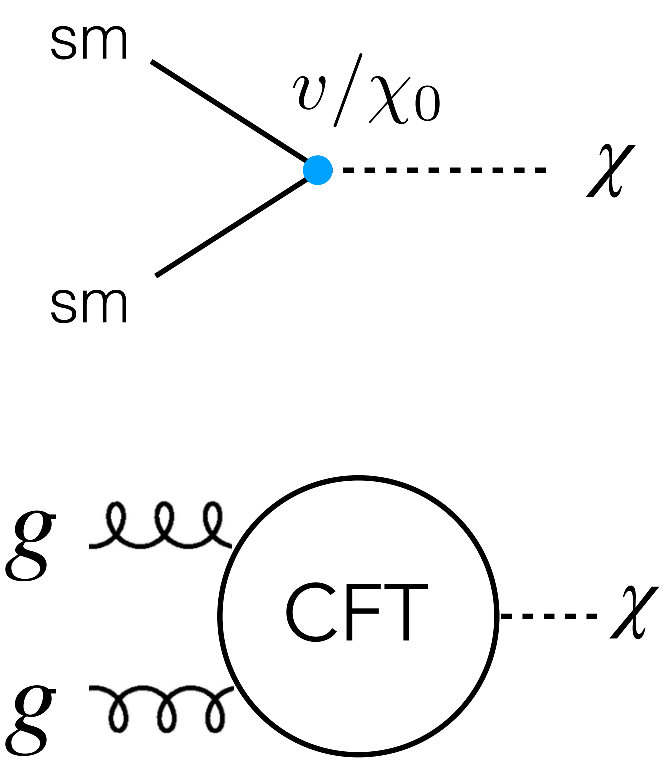
$$m_q \frac{\chi}{\chi_0} = \frac{y_q}{\sqrt{2}} \frac{v}{\chi_0} \chi \qquad \text{with} \qquad \chi_0 \propto f$$

- Hence similar to the Higgs couplings, up to a factor of $v/\chi_0$

Bruggisser,vonHarling,OM,Servant,2212.00056

- LHC bounds:

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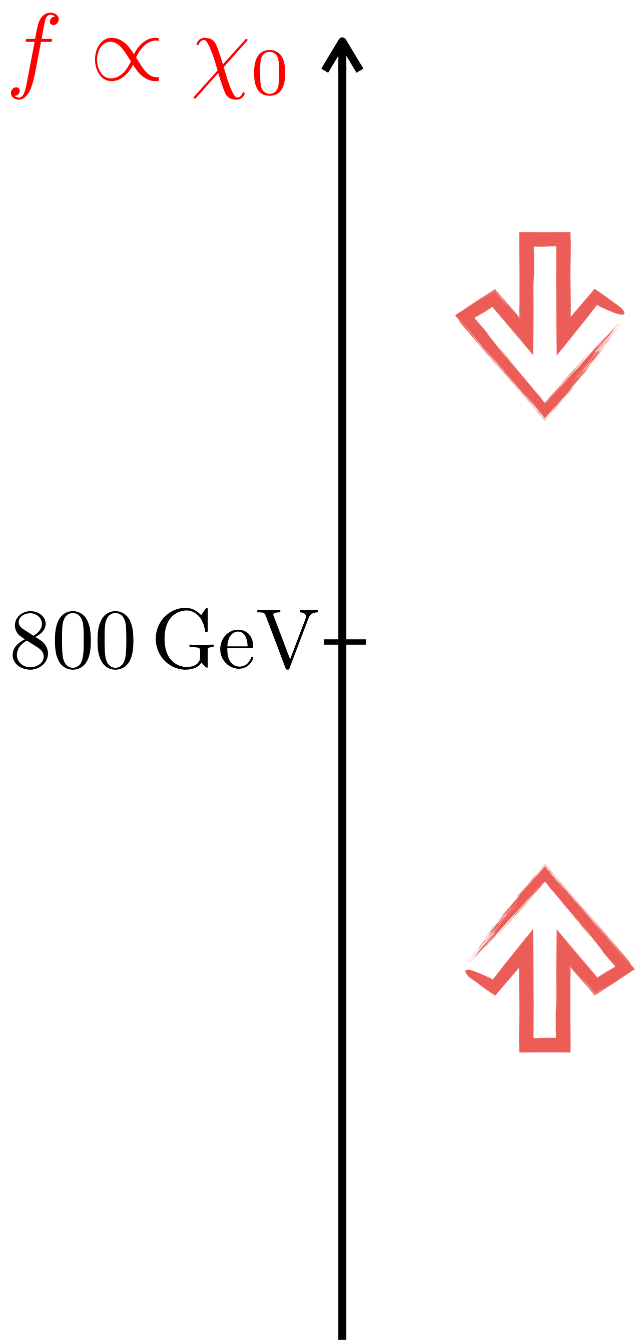
- Probing compositeness as a solution to the naturalness problem:




**Naturalness:**

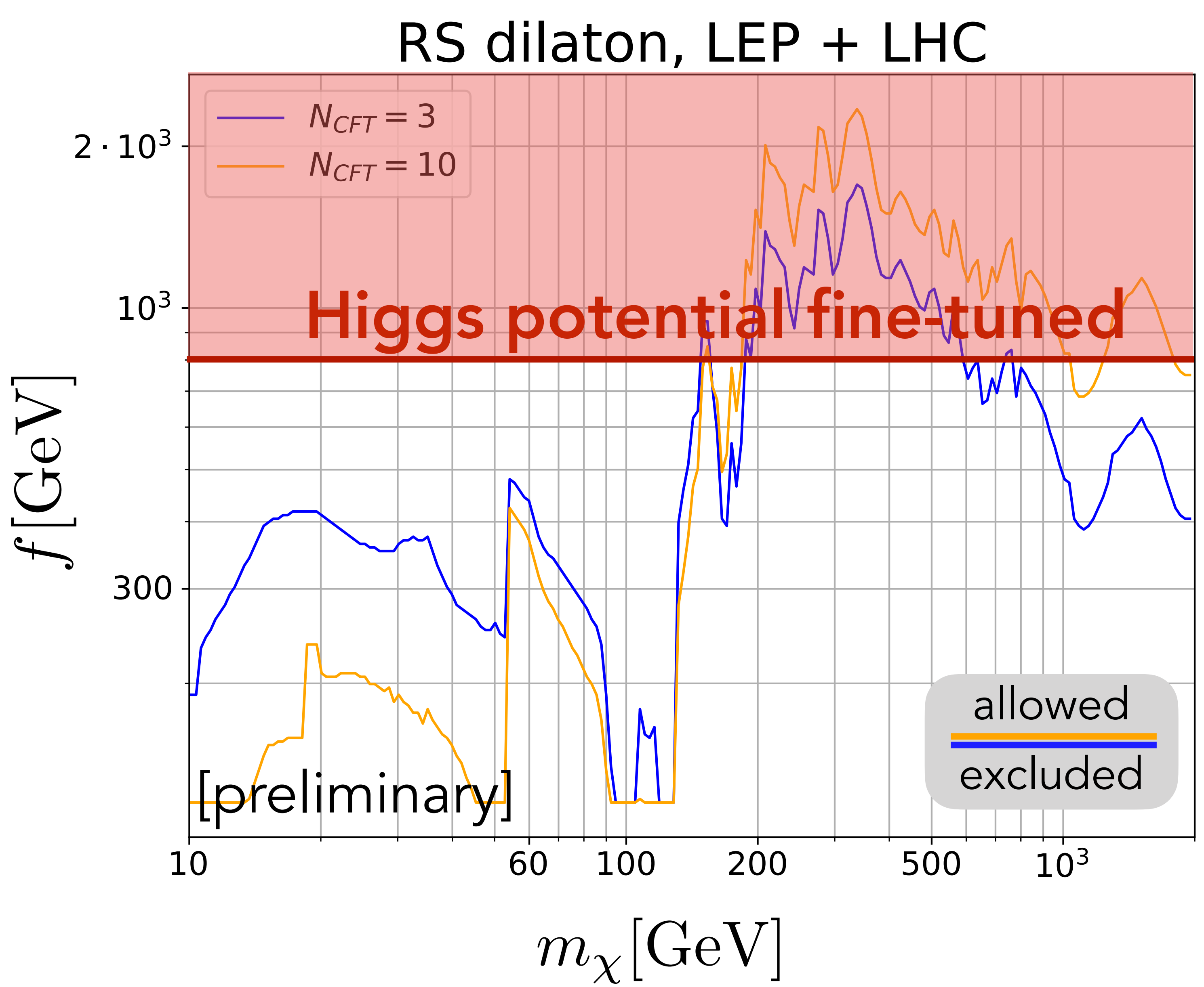
EW scale ~ **f** times **tuning**

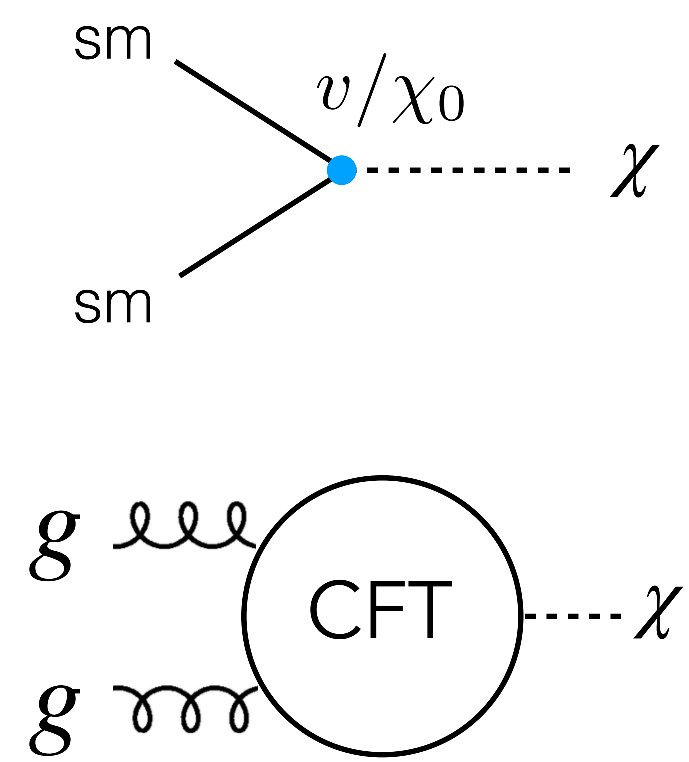
**Experimental bounds:**

e.g. $m_W^2 \propto \sin^2 h/f$

$g_{hWW} \propto (m^2)'_h \propto \cos v/f \simeq 1 - v^2/2f^2$

- LHC bounds:

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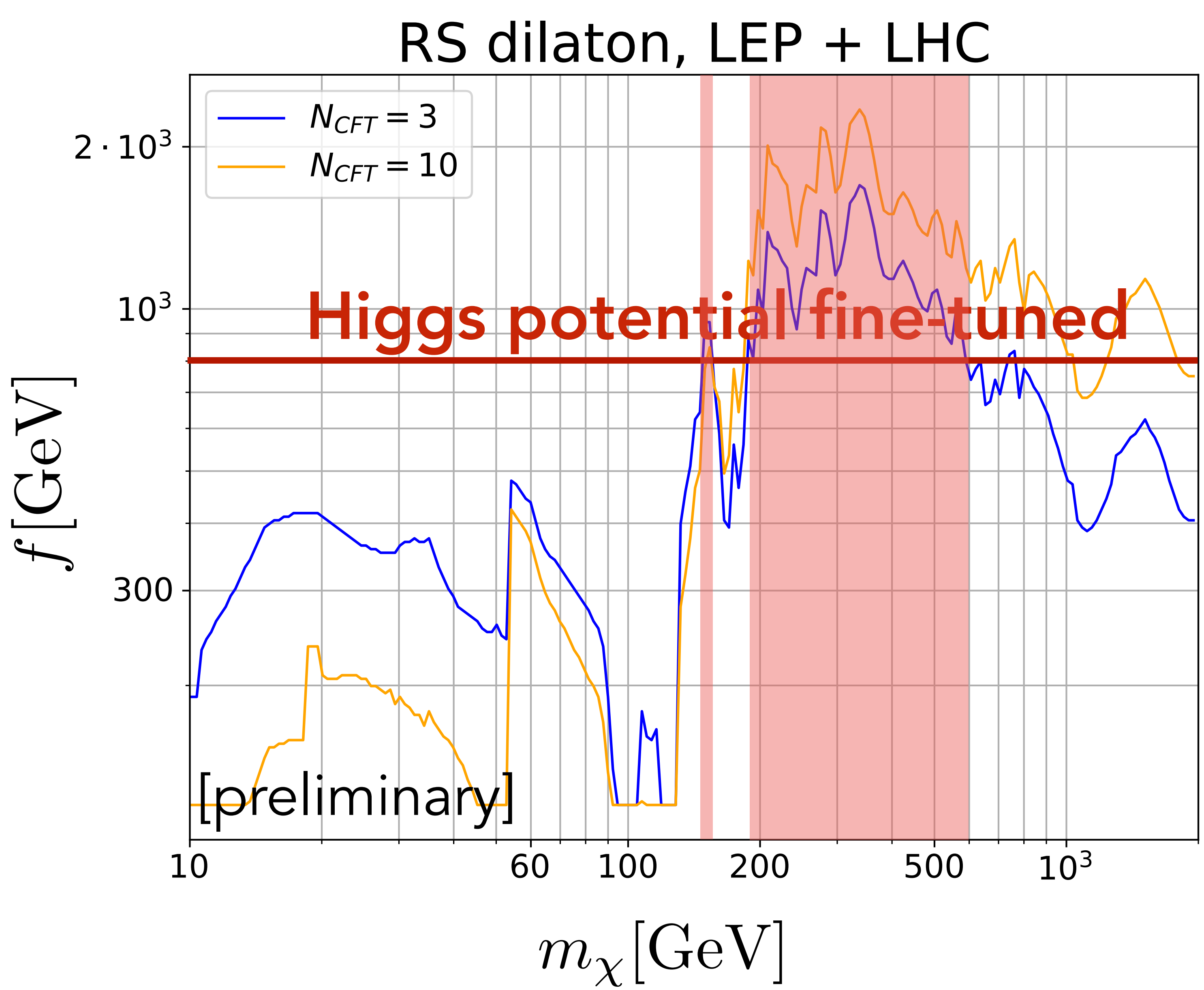
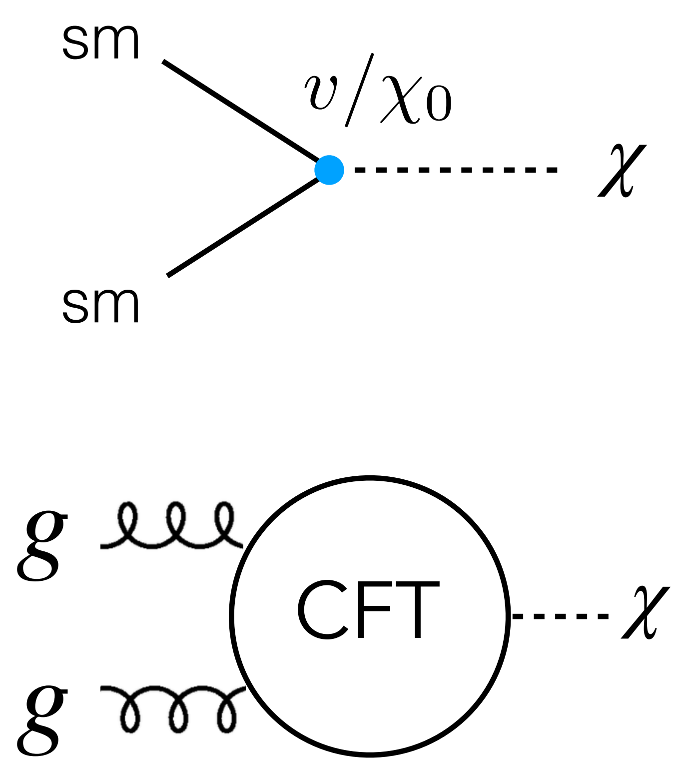
# Dilaton at the LHC

- LHC bounds:

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# Summary

# Summary

- Electroweak phase transition may be related to such fundamental particle physics problems as matter-antimatter asymmetry and gauge hierarchy problem

- EWPT can be tested at colliders

  such indirect tests require coherent combined treatment of all the available probes (colliders, EDM, GW, …)

  and hence models that could describe the correlations

- Minimal models for EWBG are not fully probed yet and provide a range of potential collider signals, from Higgs couplings modifications to new resonances

Thank you!