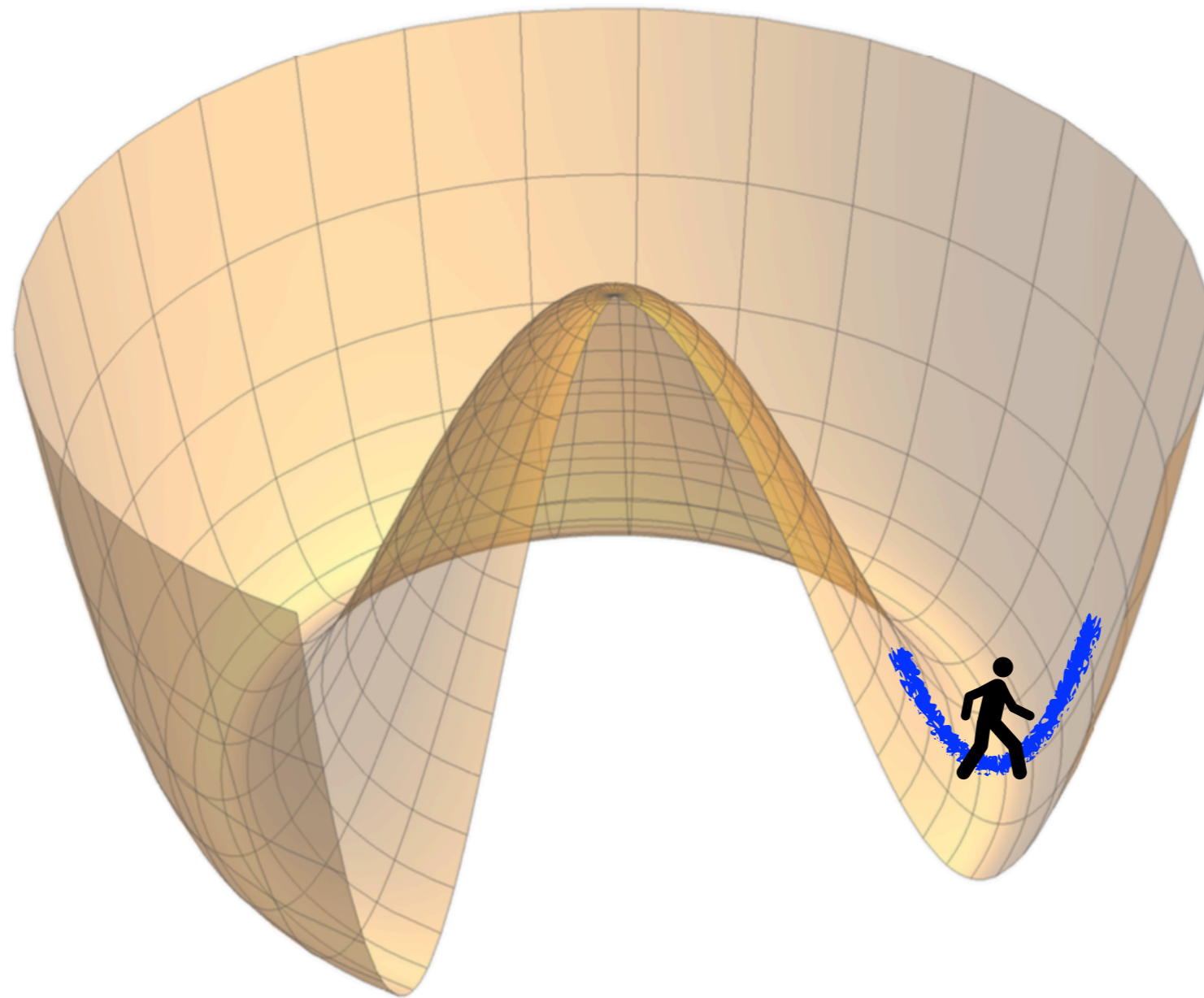


ヒッグス結合定数による新物理探索

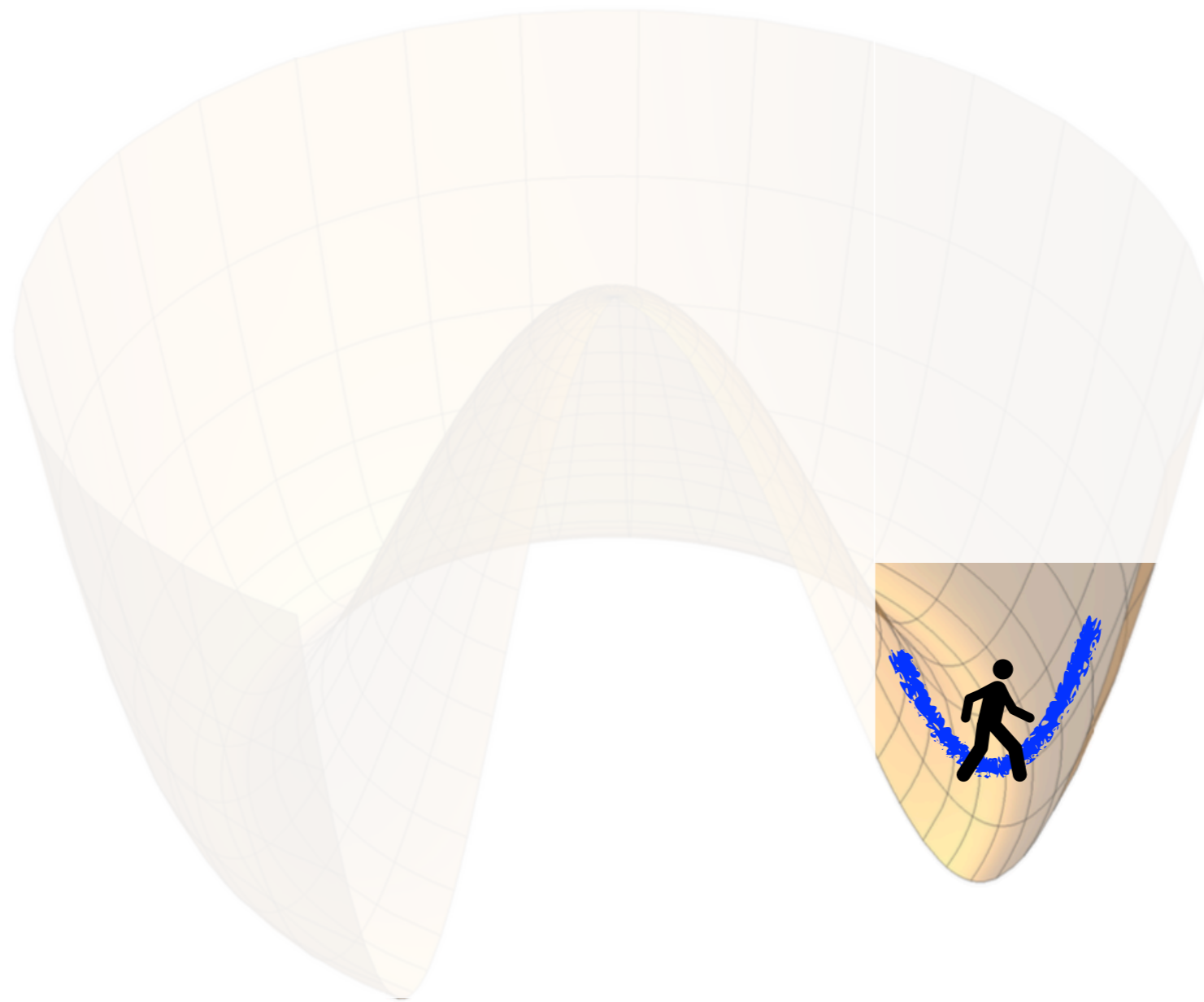
長井 遼 (大阪大)

共同研究者: 兼村 晋哉 (大阪大)

素粒子現象論研究会 2021

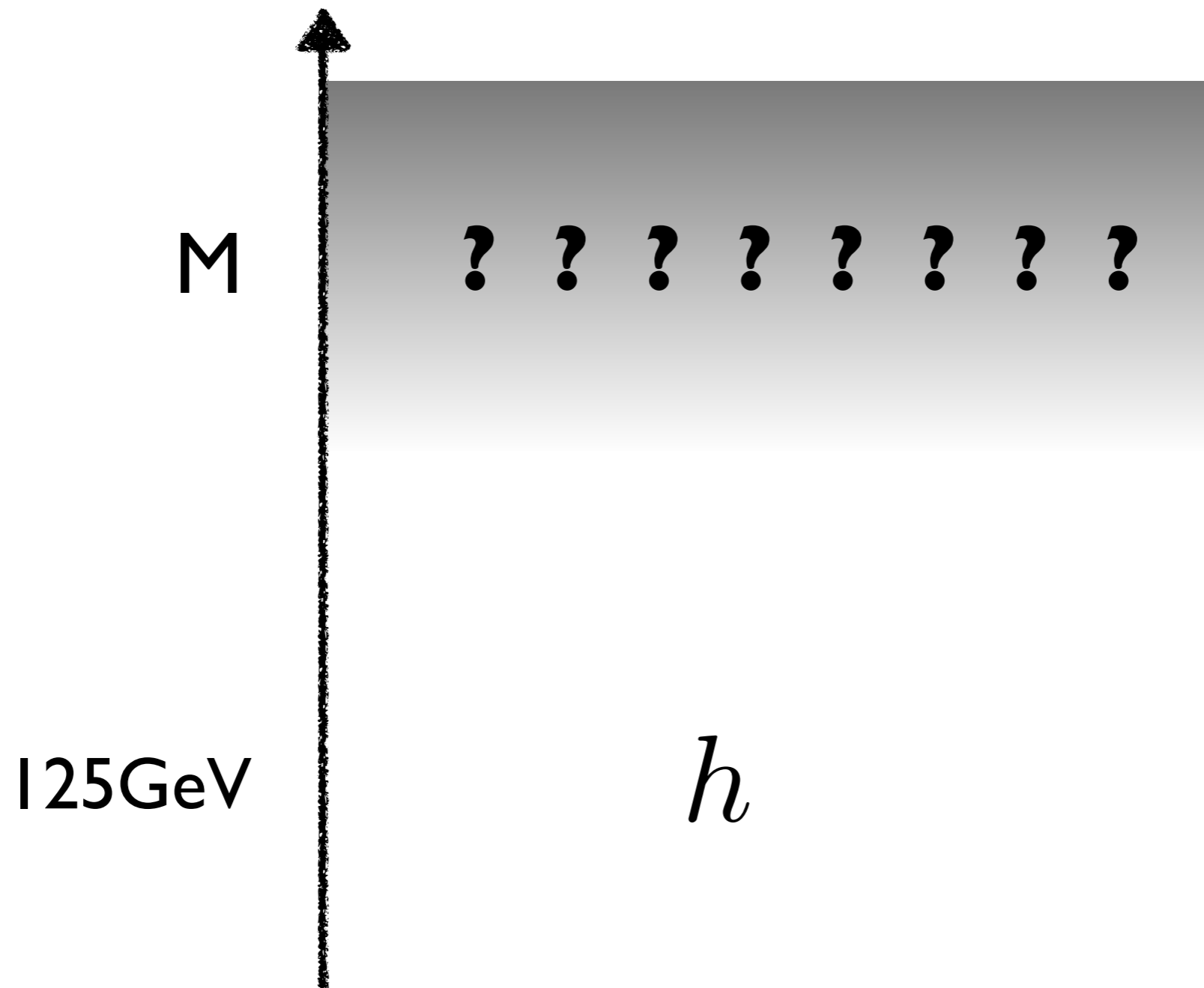


125GeV ヒッグス粒子発見！



けど、電弱対称性の破れの起源は謎

有効理論による記述



有効理論による記述

Standard Model EFT (SMEFT)

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + c_6 |\Phi|^6 + c_8 |\Phi|^8 + \dots$$

- ヒッグスポテンシャルのずれを $|\Phi|^2$ の多項式で表す。

$$|\Phi|^2 = (v + h)^2$$

125GeV Higgs boson



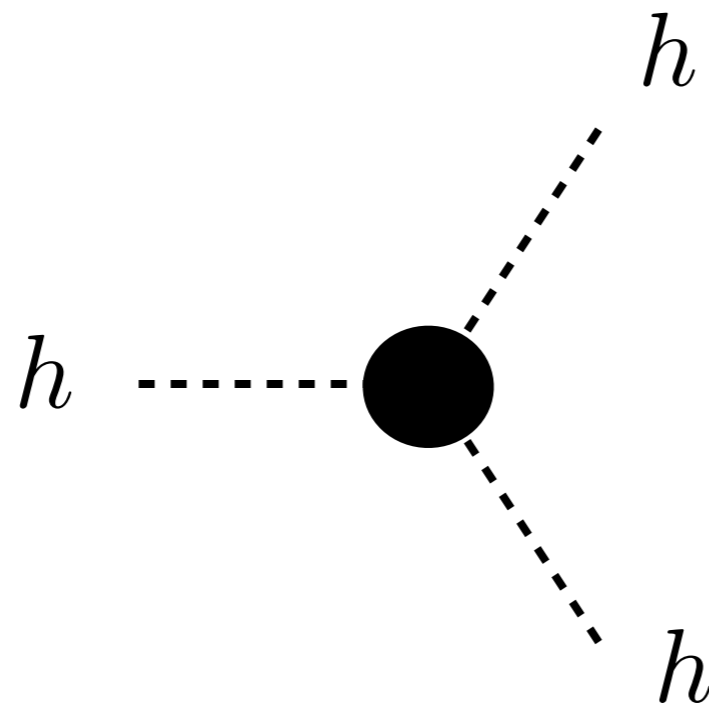
- (Dim 6) \gg (Dim 8) とする

The diagram consists of a large black-outlined oval containing the text 'New Physics' at the top. Inside this oval, there is a smaller, solid green oval containing the text 'SMEFT' in green. This visualizes SMEFT as a specific subset or framework within the broader field of New Physics.

New Physics

SMEFT

hhh coupling



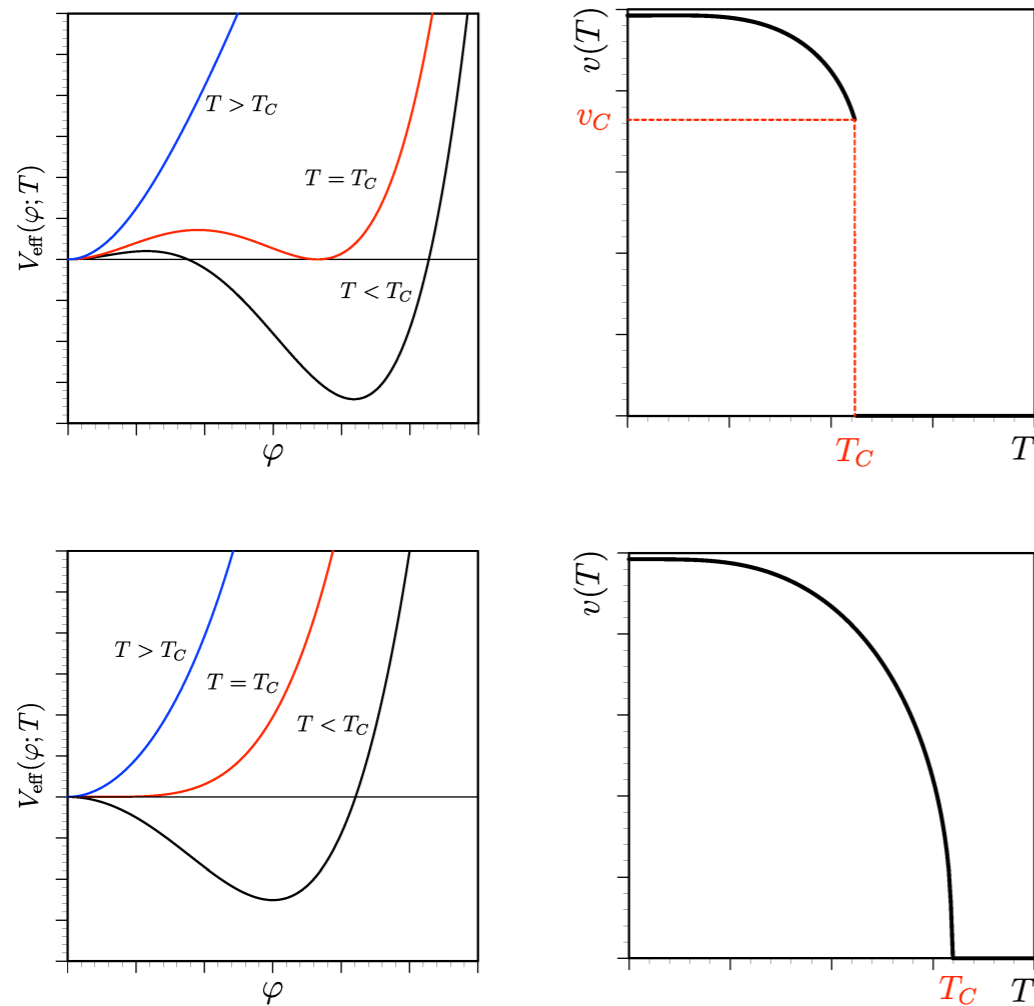
A Feynman diagram showing a central black circle vertex with three dashed lines extending outwards, each labeled with the letter 'h'. The lines are positioned at approximately 9, 1, and 5 o'clock.

$$\approx \left. \frac{\partial^3 V}{\partial h^3} \right|_{h=0} = \lambda_{hhh}^{\text{SM}} \kappa_3$$

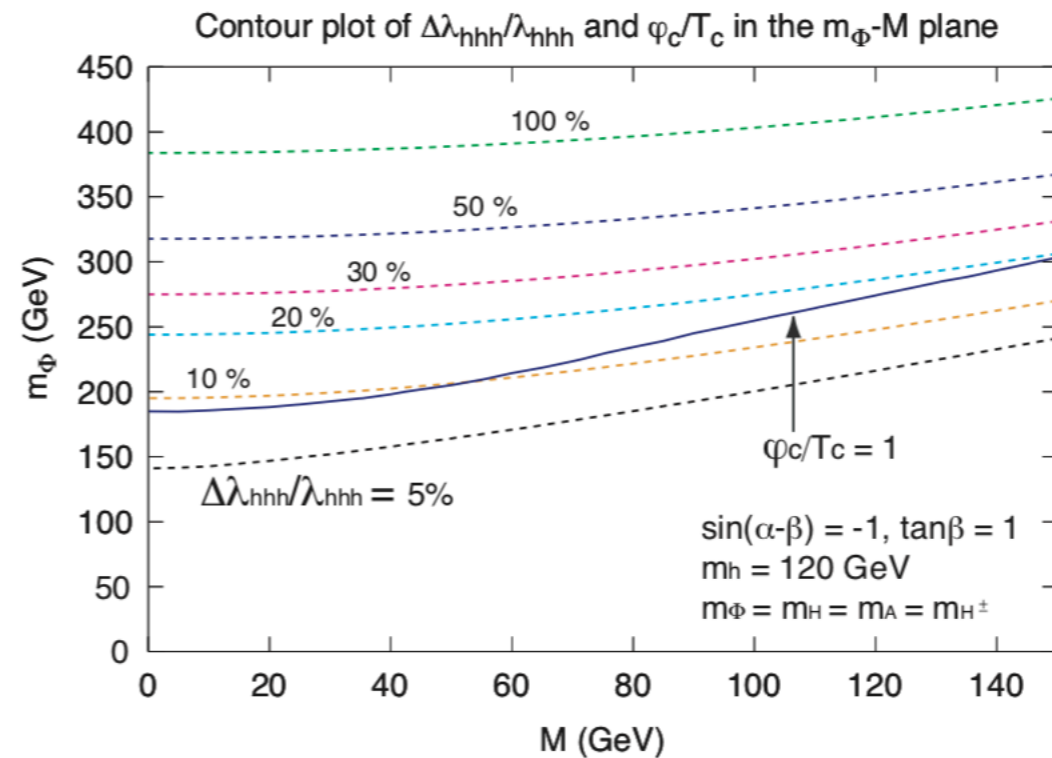
- 実験: 大きなずれは許されている。 e.g. CMS 2011.12373
 $-3.3 < \kappa_3 < 8.5$
- 理論: 大きなずれが期待される。

Electroweak phase transition

Two Higgs Doublet Model



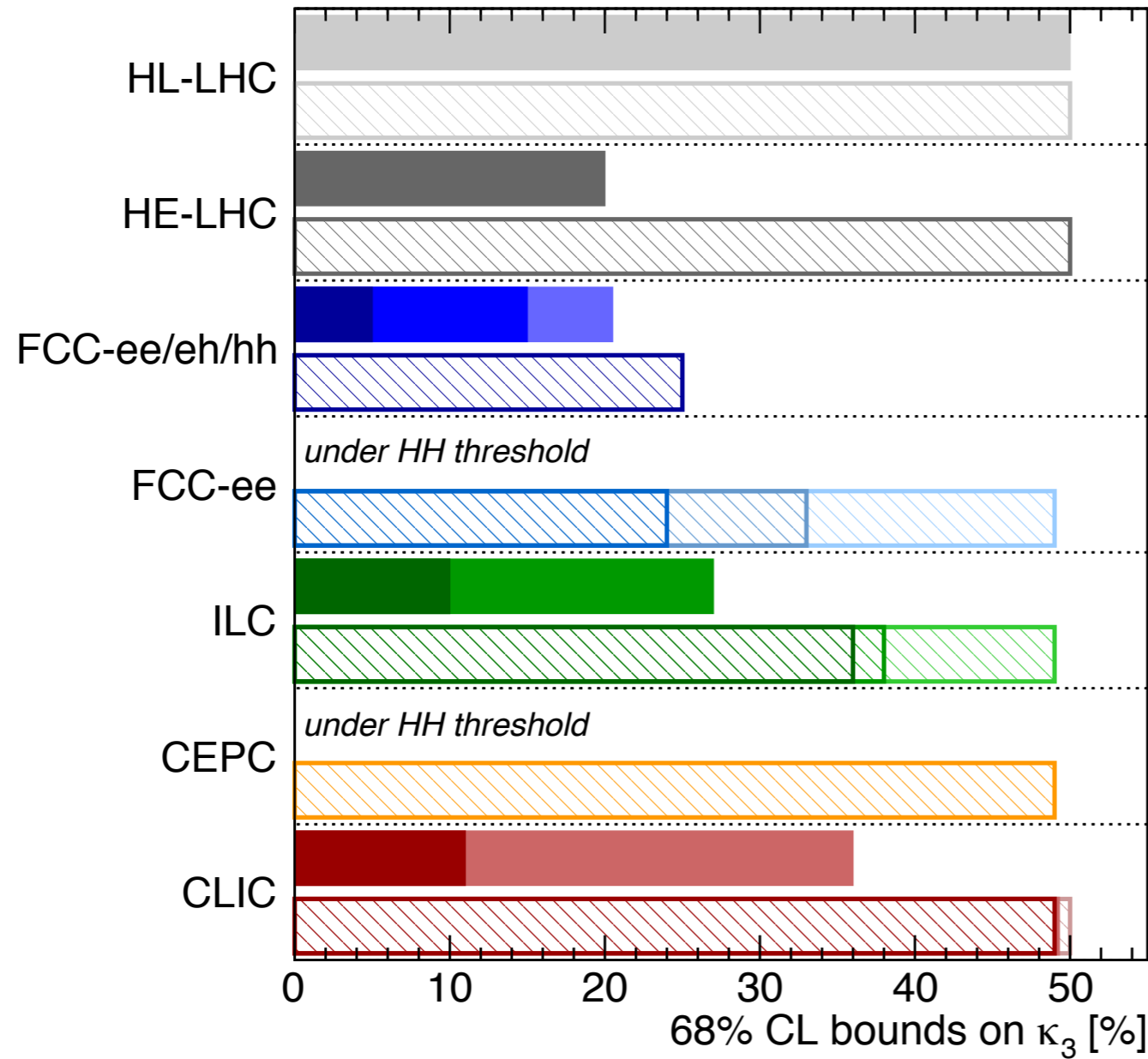
[Senaha (2020)]



$$\kappa_3 - 1 \gtrsim \mathcal{O}(10\%)$$

[Kanemura, Okada, Senaha (2005)]

hhh measurement



Higgs@FC WG September 2019

di-Higgs	single-Higgs
HL-LHC 50%	HL-LHC 50% (47%)
HE-LHC [10-20]%	HE-LHC 50% (40%)
FCC-ee/eh/hh 5%	FCC-ee/eh/hh 25% (18%)
LE-FCC 15%	LE-FCC n.a.
FCC-eh ₃₅₀₀ -17+24%	FCC-eh ₃₅₀₀ n.a.
	FCC-ee ^{4IP} ₃₆₅ 24% (14%)
	FCC-ee ₃₆₅ 33% (19%)
	FCC-ee ₂₄₀ 49% (19%)
ILC ₁₀₀₀ 10%	ILC ₁₀₀₀ 36% (25%)
ILC ₅₀₀ 27%	ILC ₅₀₀ 38% (27%)
	ILC ₂₅₀ 49% (29%)
	CEPC 49% (17%)
CLIC ₃₀₀₀ -7%+11%	CLIC ₃₀₀₀ 49% (35%)
CLIC ₁₅₀₀ 36%	CLIC ₁₅₀₀ 49% (41%)
	CLIC ₃₈₀ 50% (46%)

All future colliders combined with HL-LHC

[de Blas, et al (2020)]

$$|\kappa_3| \gg 1 ??$$

- *SM + real singlet scalar*

- No mixing $\rightarrow \kappa_V, \kappa_f \simeq 1$

- Mass $m^2 = M^2 + \kappa \langle \Phi \rangle^2$ $r = \frac{\kappa \langle \Phi \rangle^2}{m^2}$

$$\kappa_3 \simeq 1 + \frac{4}{3(4\pi)^2} \frac{m^4}{M_h^2 v^2} r^3$$

[Kakizaki, Kanemura, Matsui (2015)]

- $r \simeq 1$: **Non-decoupling** even for $m \gg M_h$

EFT point of view

- 余分なスカラーを積分すると

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} - \frac{1}{4(4\pi)^2} (M^2 + \kappa|\Phi|^2)^2 \ln \frac{M^2 + \kappa|\Phi|^2}{\mu^2} + \dots$$

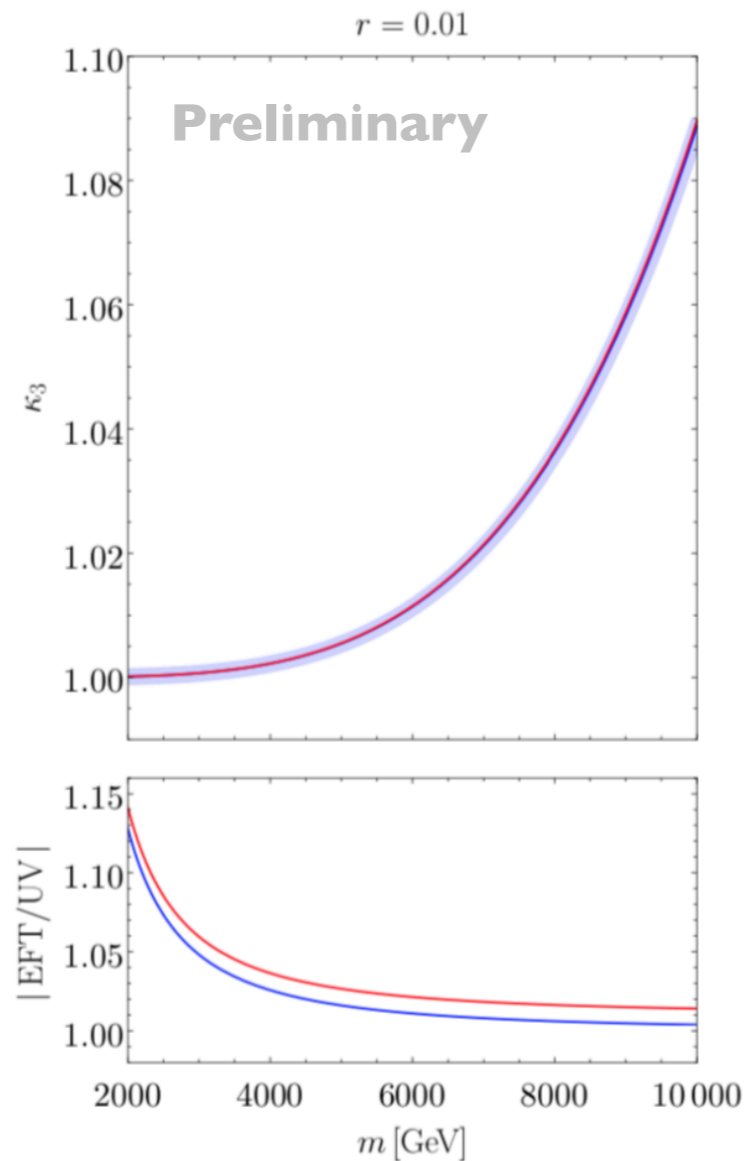
- $|\Phi|^2$ のべきに展開 (SMEFT form)

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} - \frac{1}{6(4\pi)^2} \frac{\kappa^3}{M^2} |\Phi|^6 + \dots$$

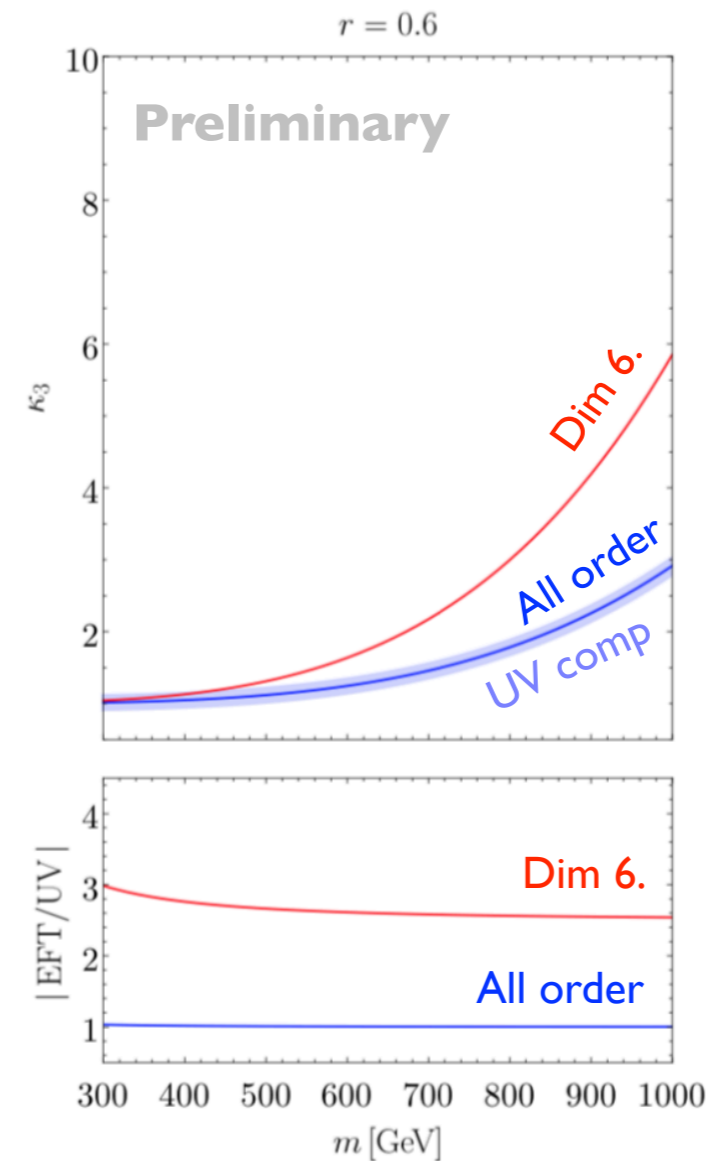
- $M \sim 0$ のとき、**(Dim6) ~ (Dim8)** になる！

Validity of dim 6 SMEFT

Decoupling



Non-Decoupling



$$r = \frac{\kappa \langle \Phi \rangle^2}{m^2}$$

Non-decoupling のとき、(Dim6) ~ (Dim8) になる !

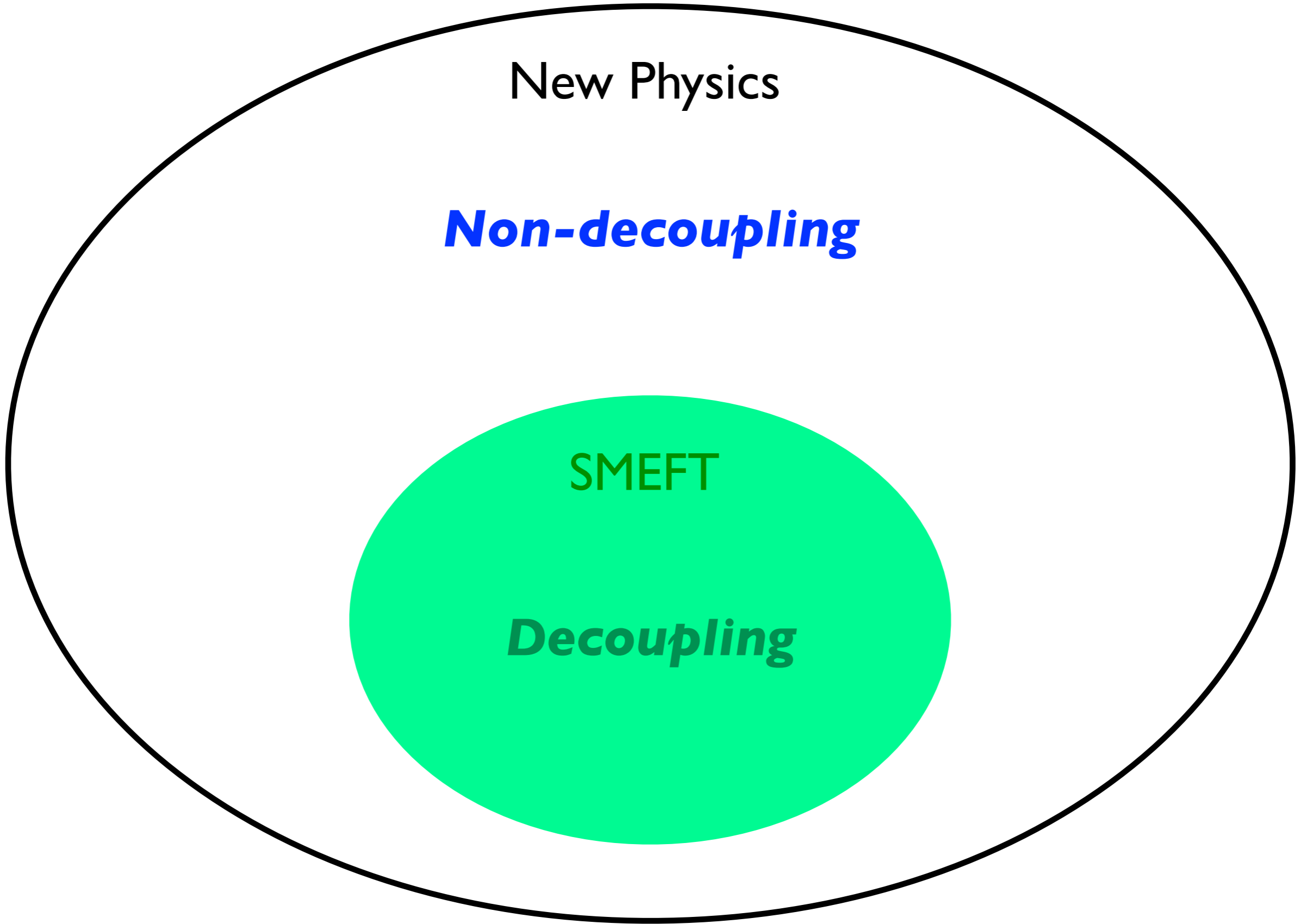
[Falkowski, Rattazzi (2019)]
[Cohen, Craig, Lu, Sutherland (2020)]

New Physics

Non-decoupling

SMEFT

Decoupling



Beyond EFT

- Non-decoupling 効果を記述する新たなEFTを提案します。

NEW!

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} - \frac{1}{(4\pi)^2} \frac{\kappa_0}{4} [\mathcal{M}^2(\Phi)]^2 \ln \frac{\mathcal{M}^2(\Phi)}{v^2}$$

d.o.m of BSM particle

$$\mathcal{M}^2(\Phi) = \Lambda^2 + \kappa_p \left(|\Phi|^2 - \frac{v^2}{2} \right)$$

- “Non-decouplingness” $r = \frac{\kappa_p \langle \Phi \rangle^2}{\Lambda^2}$
- $r \sim 0$ のとき、SMEFTに帰着する。

How large “non-decouplingness” can be ?

$$r = \frac{\kappa_p \langle \Phi \rangle^2}{\Lambda^2} \sim \text{“Non-decouplingness”}$$

- Vacuum stability
- Perturbative unitarity

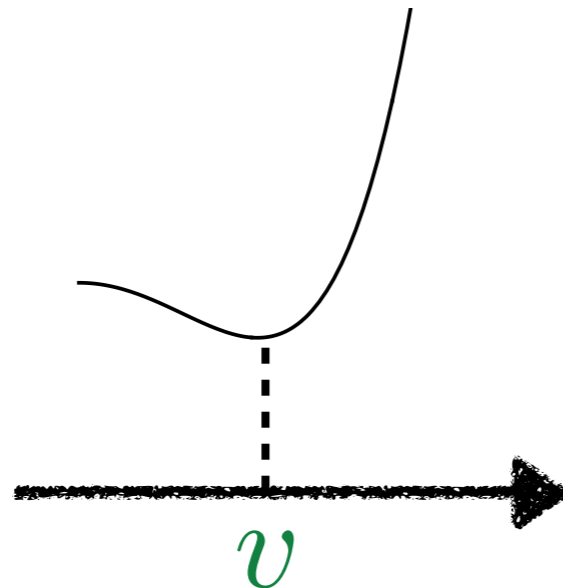
Vacuum stability

$$V = m^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{\kappa_0}{4(4\pi)^2} [\mathcal{M}^2(\Phi)]^2 \ln \frac{\mathcal{M}^2(\Phi)}{v^2}$$

$$\mathcal{M}^2(\Phi) = \Lambda^2 + \kappa_p \left(|\Phi|^2 - \frac{v^2}{2} \right)$$
$$r = \frac{\kappa_p \langle \Phi \rangle^2}{\Lambda^2}$$

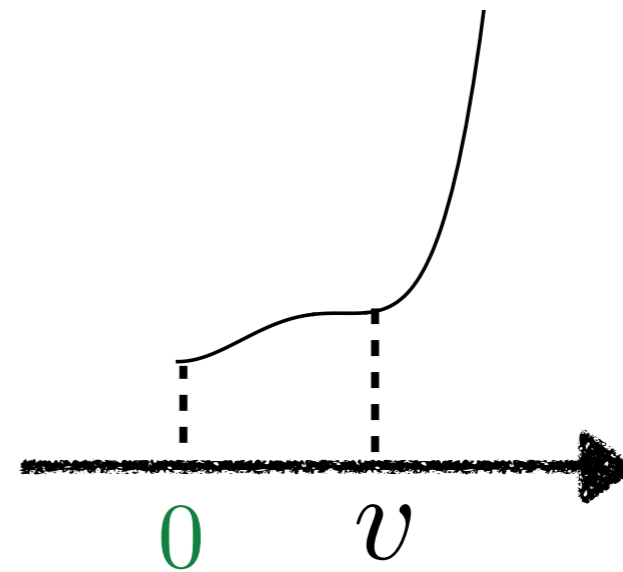
Decoupling

$$r \simeq 0$$

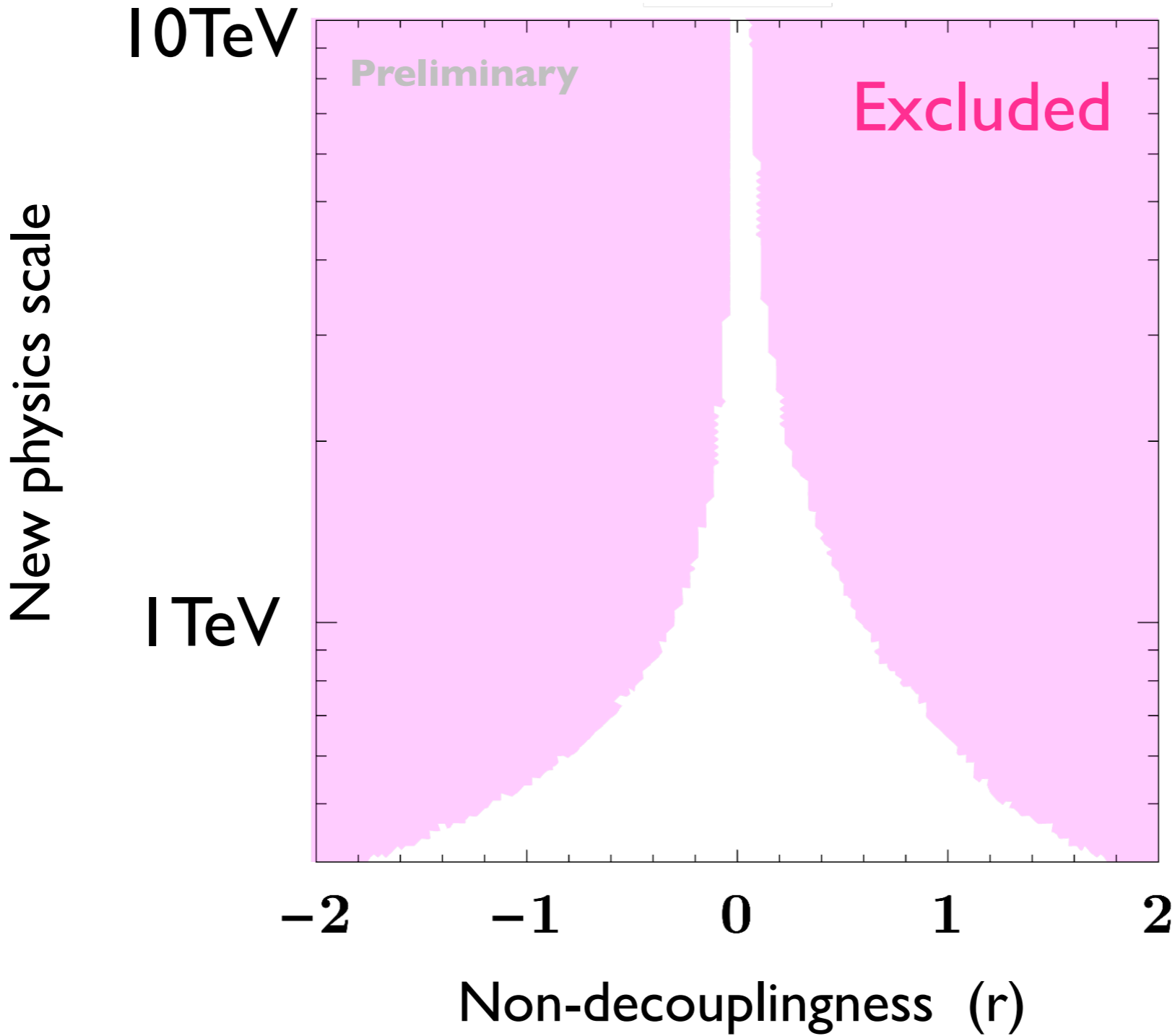


Non-Decoupling

$$r \simeq \mathcal{O}(1)$$

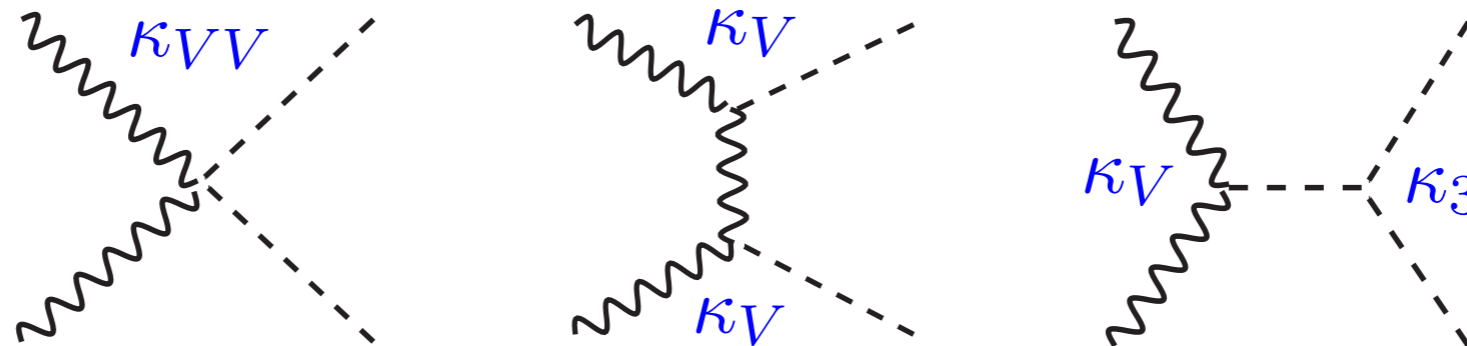


Vacuum stability



Perturbative unitarity

- e.g. $Z_L Z_L \rightarrow hh$



$$A \simeq (\kappa_V^2 - \kappa_{VV}) \frac{s}{v^2} + \kappa_V \kappa_3 \frac{M_h^2}{v^2}$$

- ユニタリテイ制限 $|\text{Re}(a_0)| < \frac{1}{2}$ at $s = \Lambda^2$

Maximum eigenvalue of $2 \rightarrow 2$ S-wave Higgs/Gauge scattering matrix

Perturbative unitarity

- e.g. $Z_L Z_L \rightarrow hh$

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} - \frac{1}{(4\pi)^2} \frac{\kappa_0}{4} [\mathcal{M}^2(\Phi)]^2 \ln \frac{\mathcal{M}^2(\Phi)}{v^2}$$

$$\mathcal{M}^2(\Phi) = \Lambda^2 + \kappa_p \left(|\Phi|^2 - \frac{v^2}{2} \right) \quad r = \frac{\kappa_p \langle \Phi \rangle^2}{\Lambda^2}$$

$$\kappa_3 \simeq 1 + \frac{4}{3(4\pi)^2} \frac{\Lambda^4}{M_h^2 v^2} r^3$$

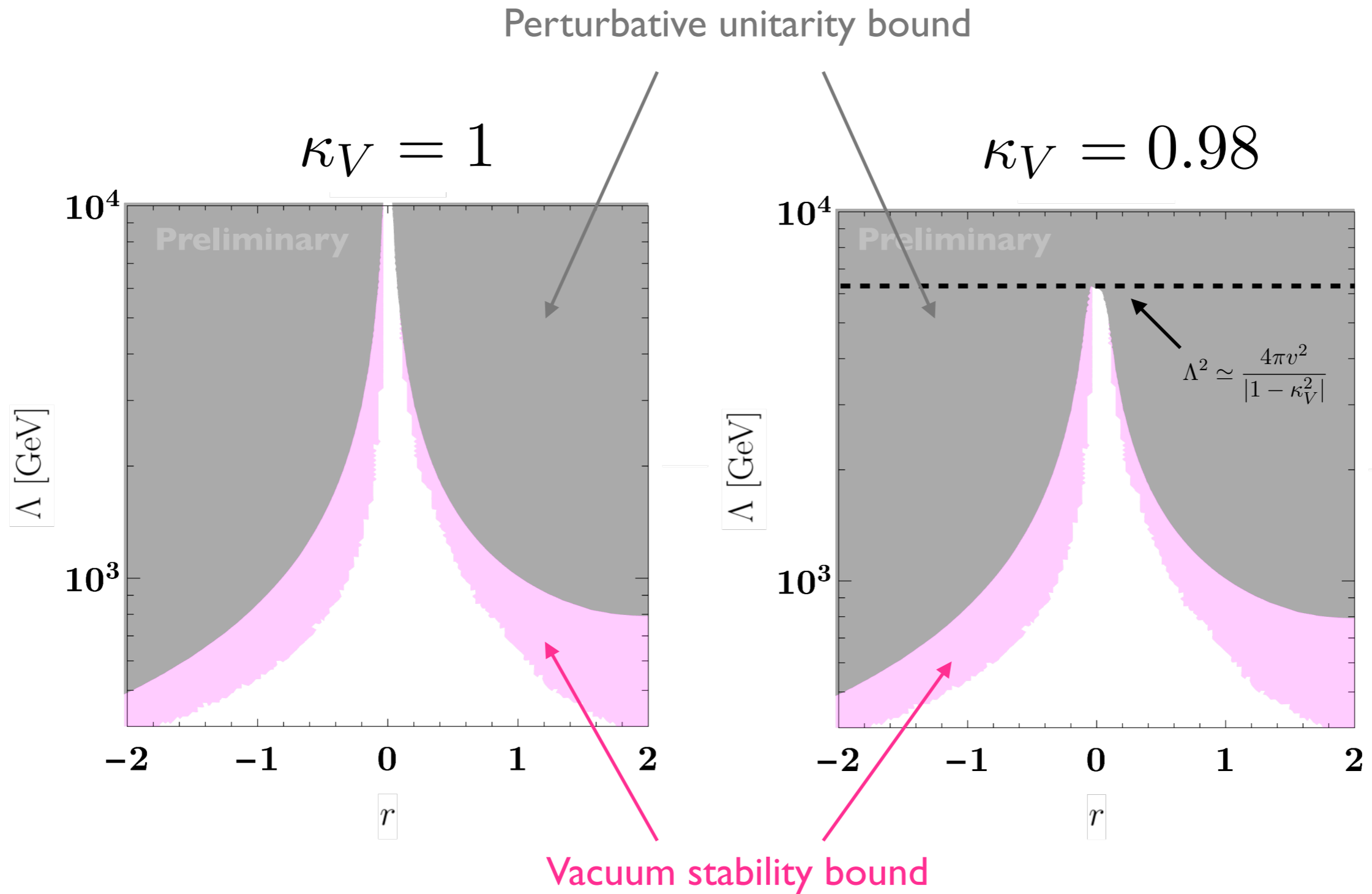
$$\mathcal{A} \simeq (\kappa_V^2 - \kappa_{VV}) \frac{s}{v^2} + \kappa_V \kappa_3 \frac{M_h^2}{v^2}$$

- ユニタリテイ制限 $|\text{Re}(a_0)| < \frac{1}{2}$ at $s = \Lambda^2$

Maximum eigenvalue of 2→2 S-wave
Higgs/Gauge scattering matrix

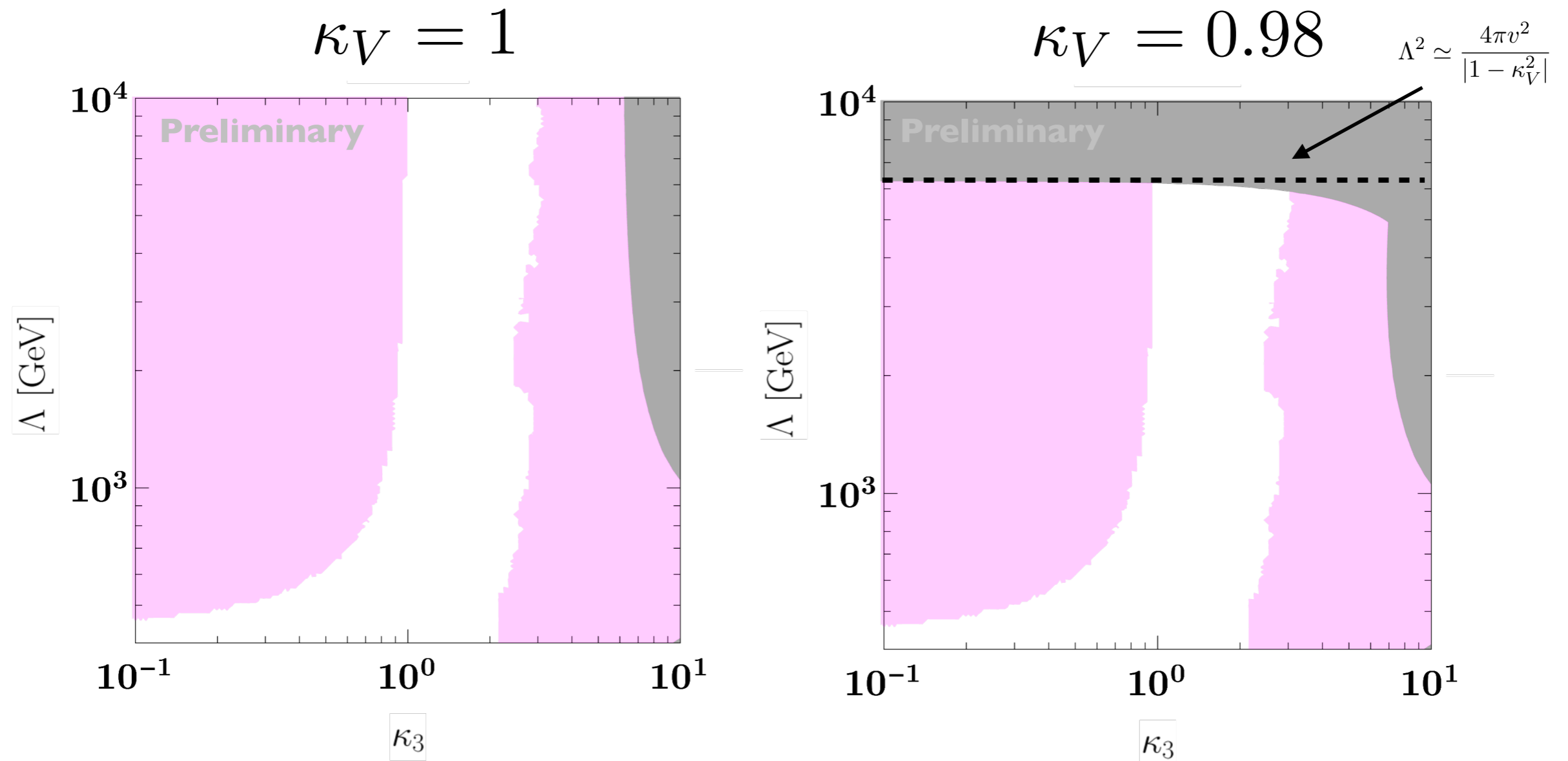
Vacuum Stability + Unitarity

$$\kappa_{VV} = 1$$



Vacuum Stability + Unitarity

$$\kappa_{VV} = 1$$



Higgs coupling deviation \rightarrow New physics must appear

“No Lose theorem”

Summary

- “SMEFT” は、non-decoupling 効果を記述できない。
- この弱点を克服した、**新たな EFT** を提案します。
- Vacuum stability + Unitarity = No Lose theorem
- **ヒッグス結合のずれ**から、**新物理スケール**を見積もれる！