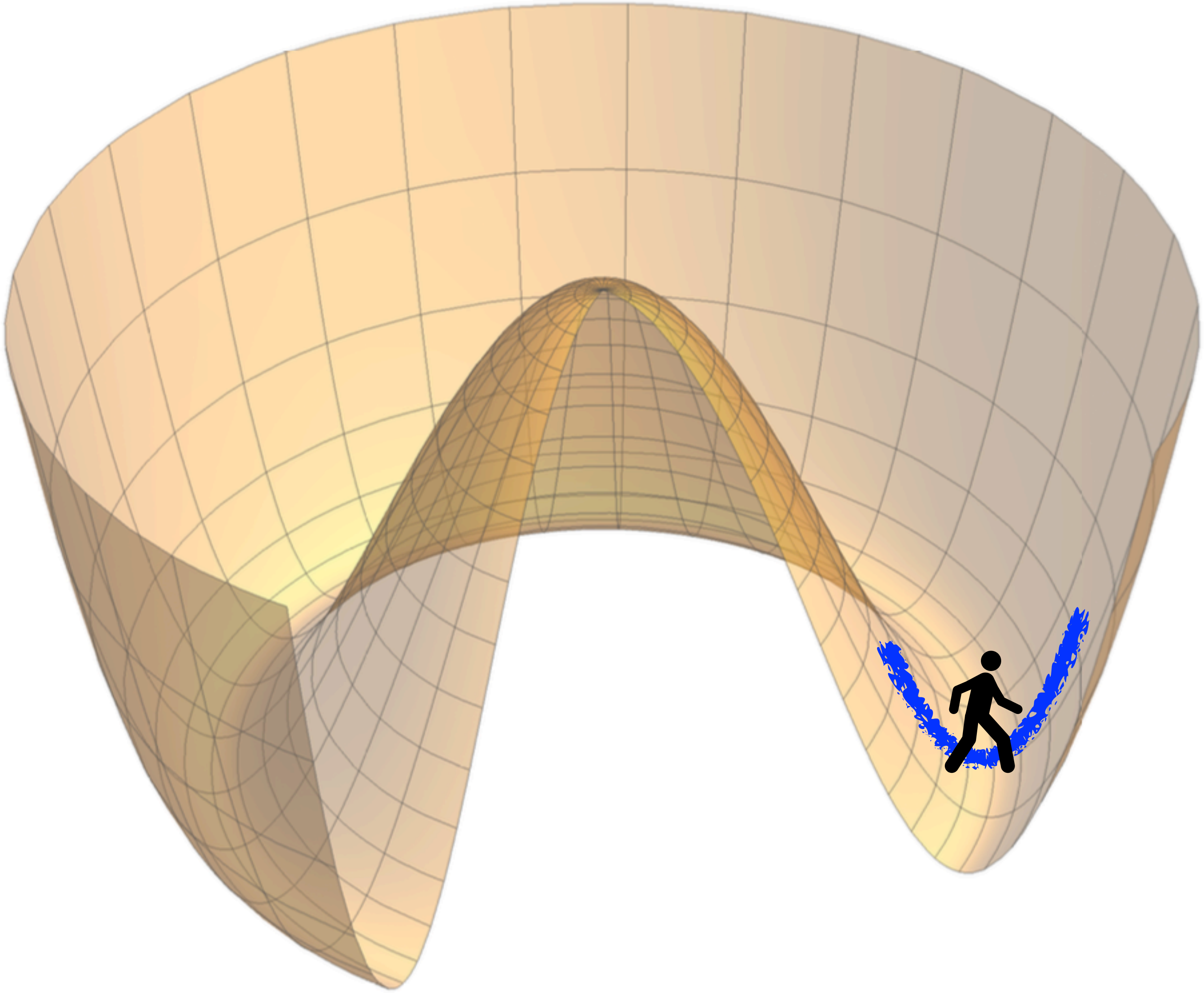
ヒッグス結合定数による新物理探索

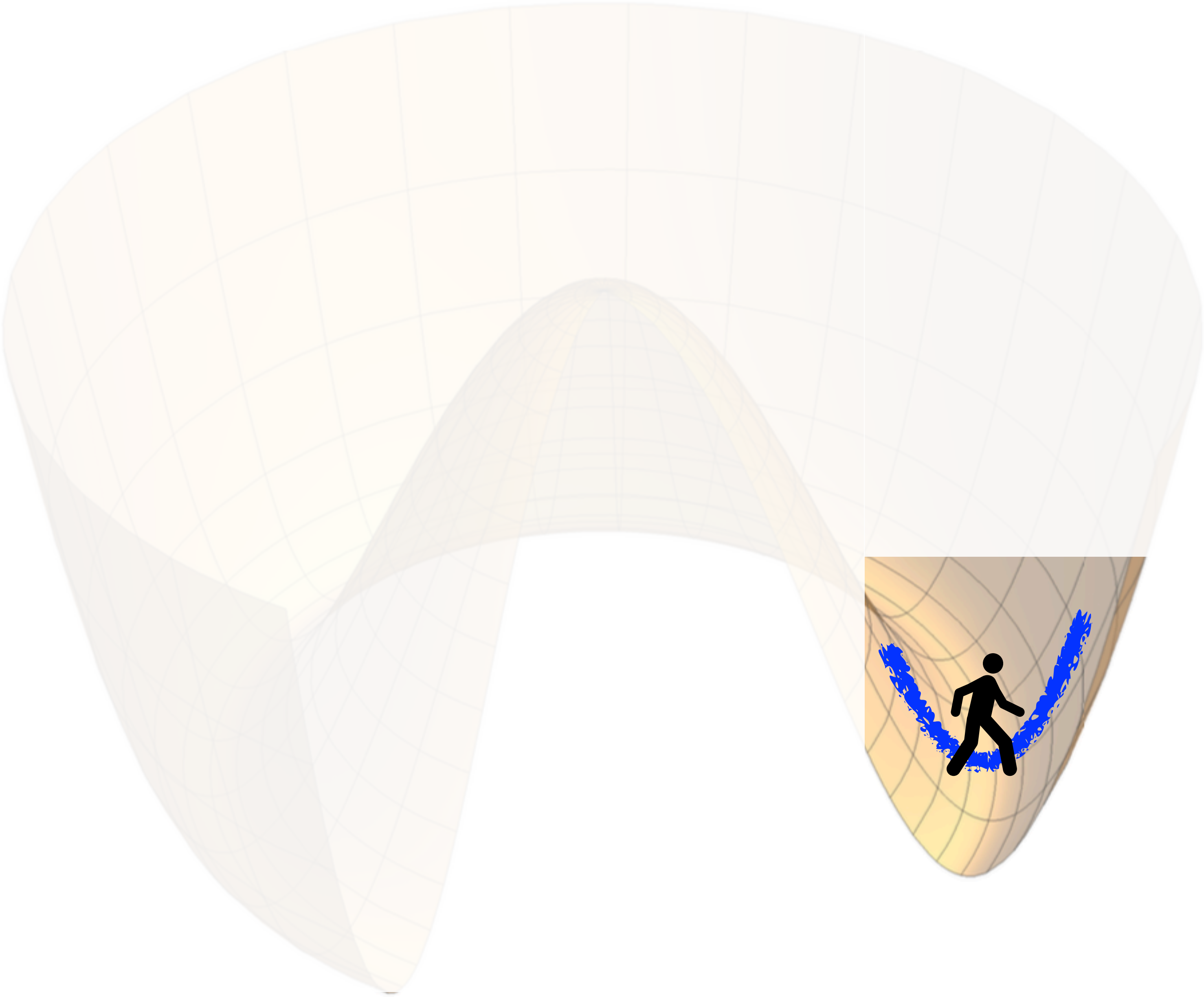
長井 遼 (大阪大)

共同研究者: 兼村 晋哉 (大阪大)

素粒子現象論研究会 2021

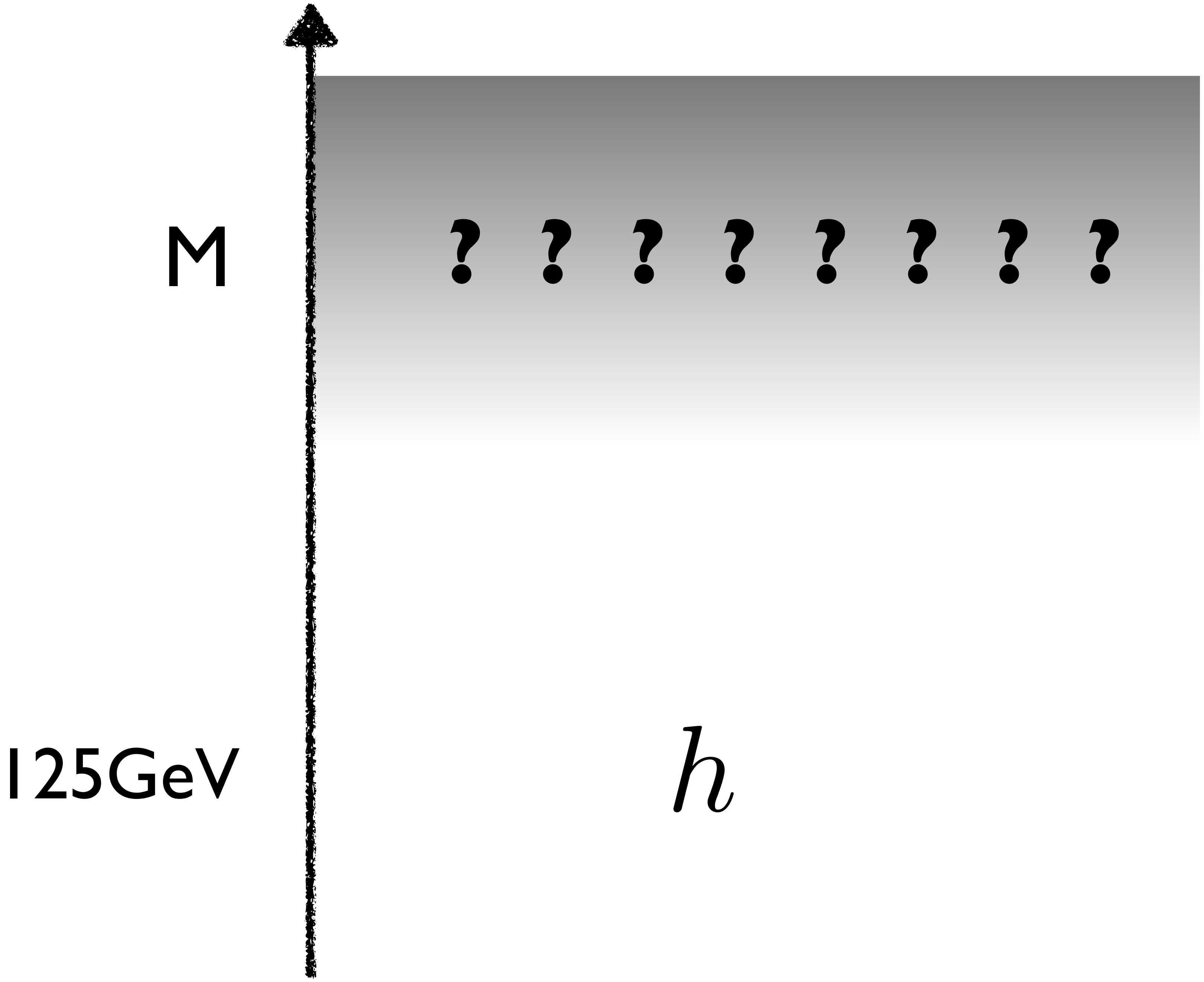


125GeV ヒッグス粒子発見！



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)

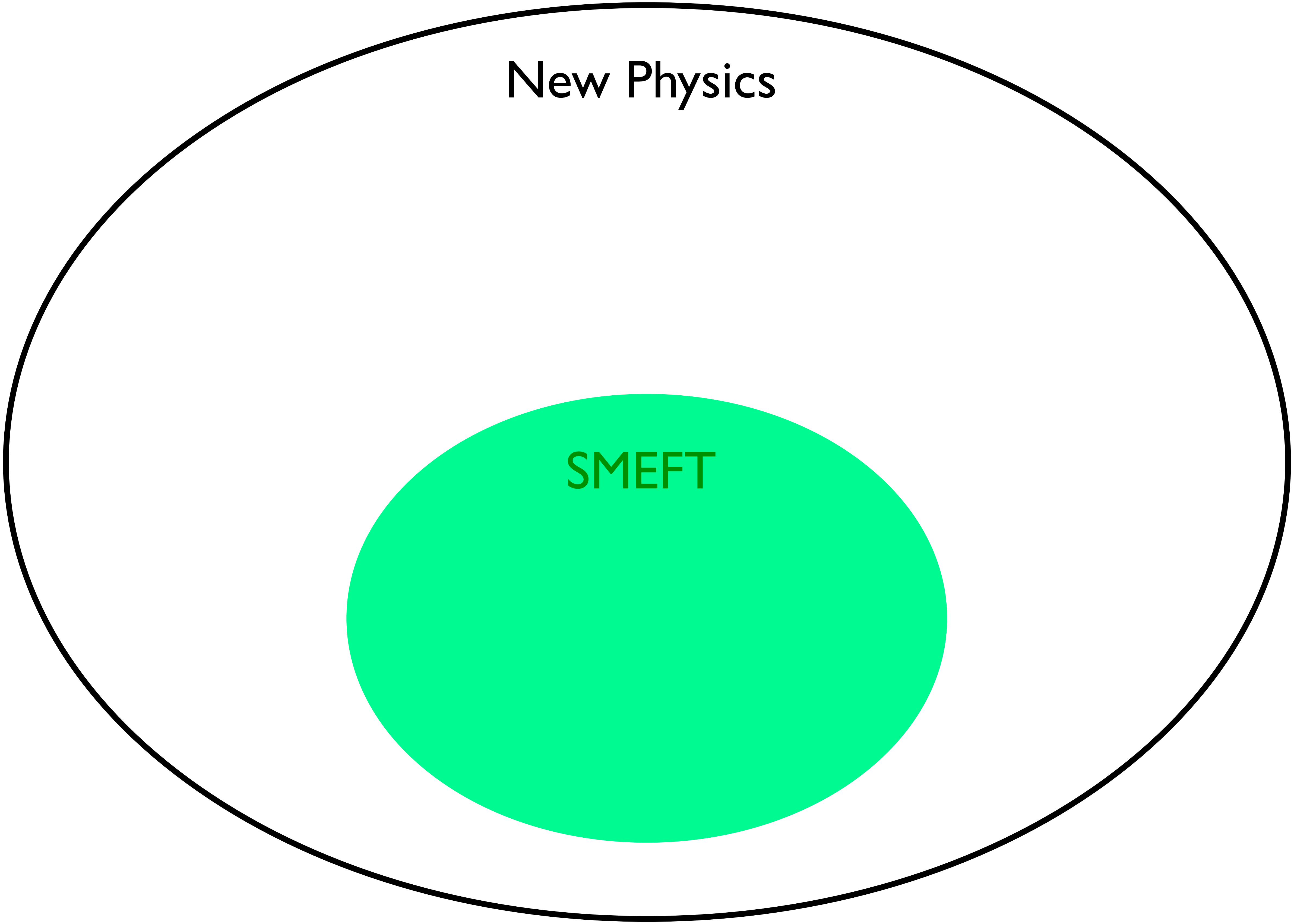
$$\mathcal{L}_{\rm EFT} \;=\; \mathcal{L}_{\rm SM} + c_6 \left|\Phi\right|^6 + c_8 \left|\Phi\right|^8 + \cdots$$

- 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

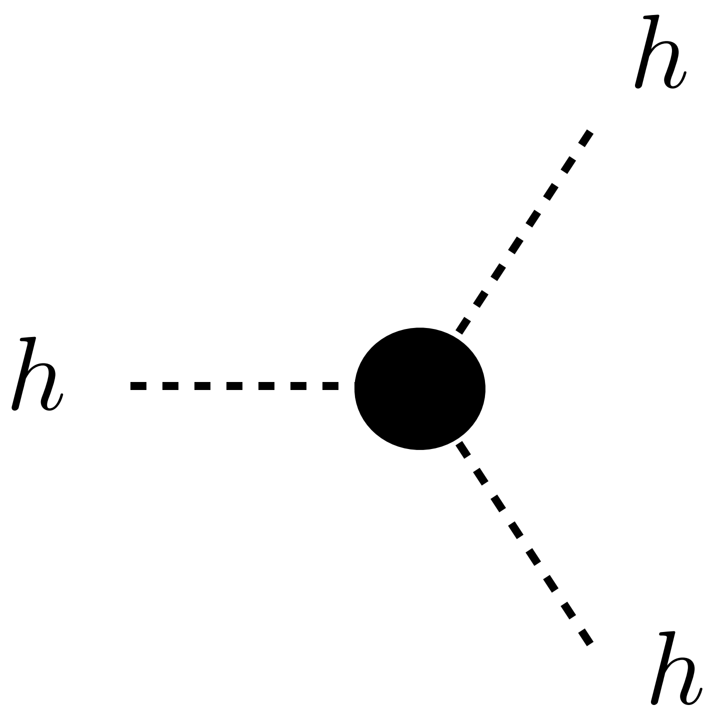
- (Dim 6) >> (Dim 8) とする



New Physics

SMEFT

hhh coupling



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

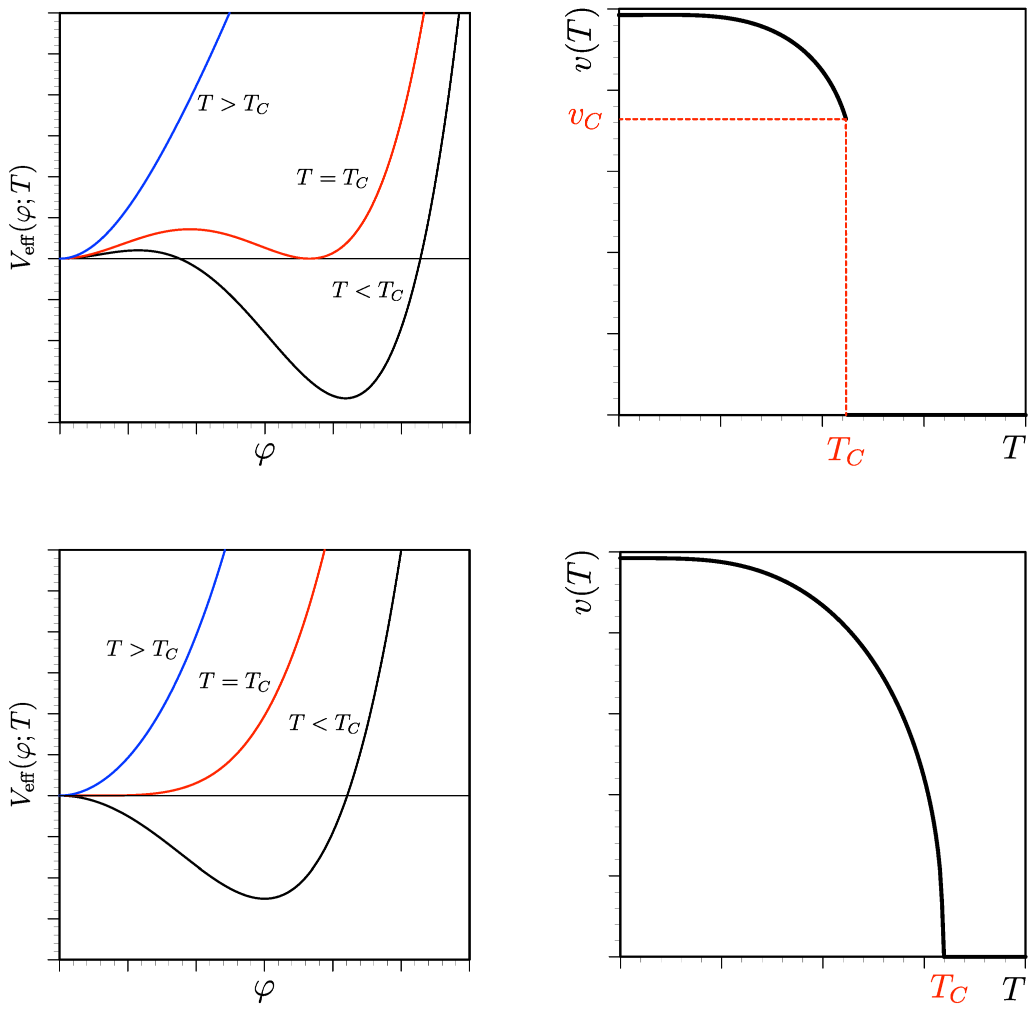
- 実験:　大きなずれは許されている。

e.g. CMS 2011.12373

$-3.3 < \kappa_3 < 8.5$

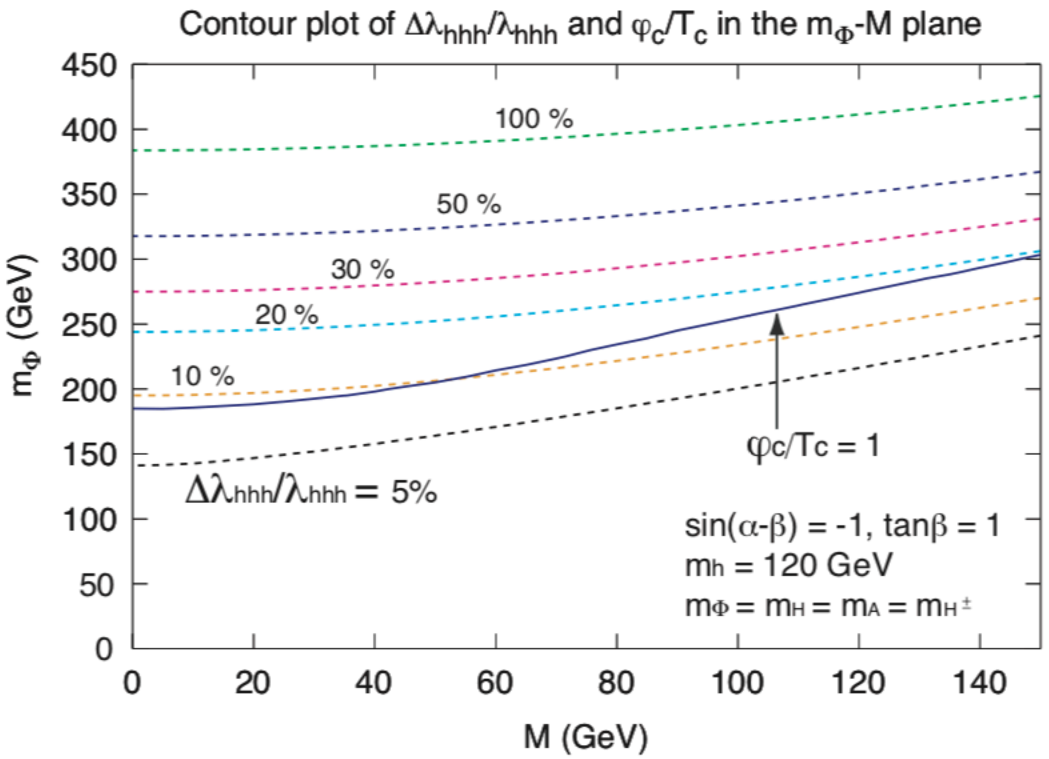
- 理論:　大きなずれが期待される。

Electroweak phase transition



[Senaha (2020)]

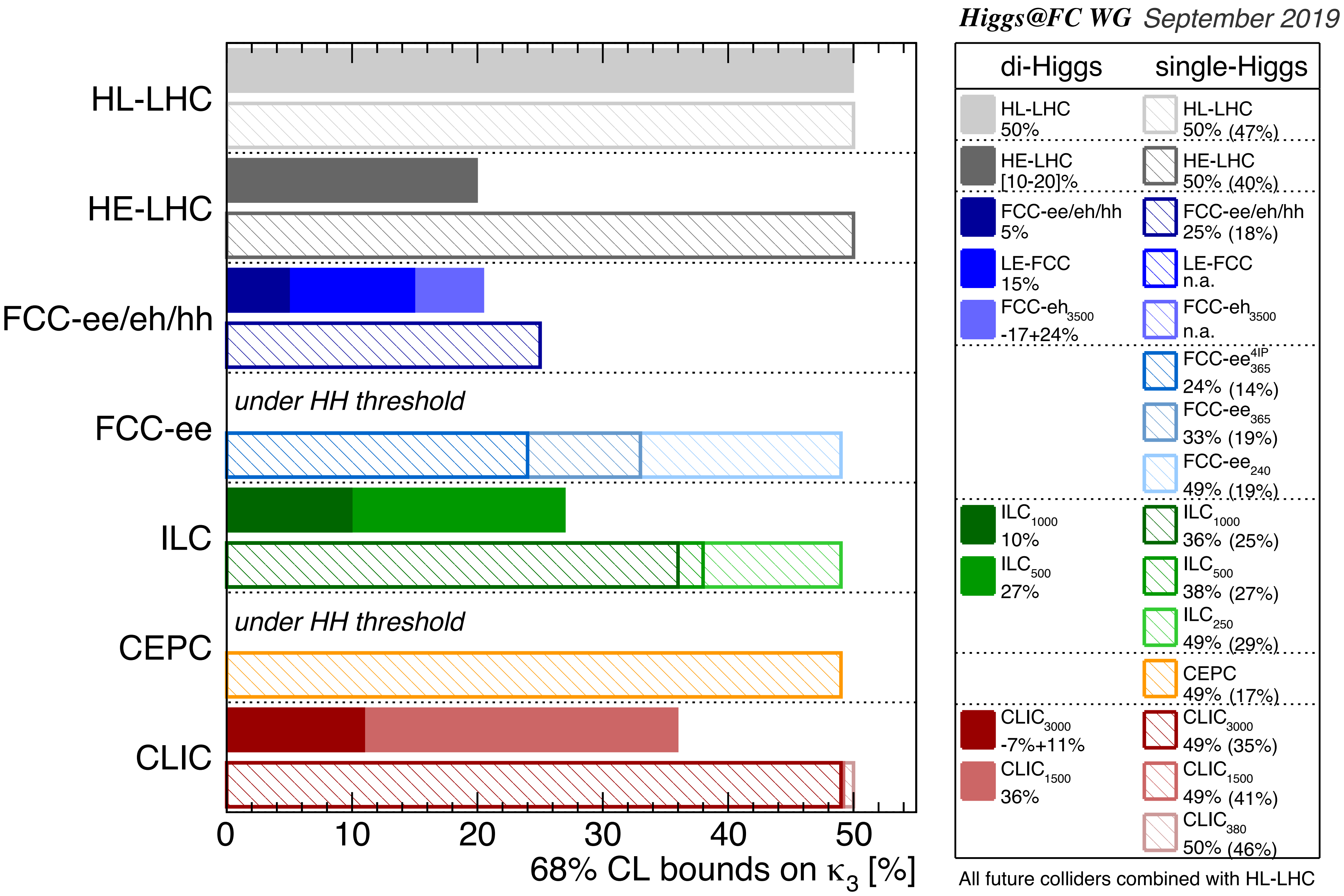
Two Higgs Doublet Model



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

[Kanemura, Okada, Senaha (2005)]

hhh measurement



[de Blas, et al (2020)]

$|\kappa_3| \gg 1$??

- *SM + real singlet scalar*
- No mixing → $\kappa_V\,, \kappa_f \simeq 1$
- 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

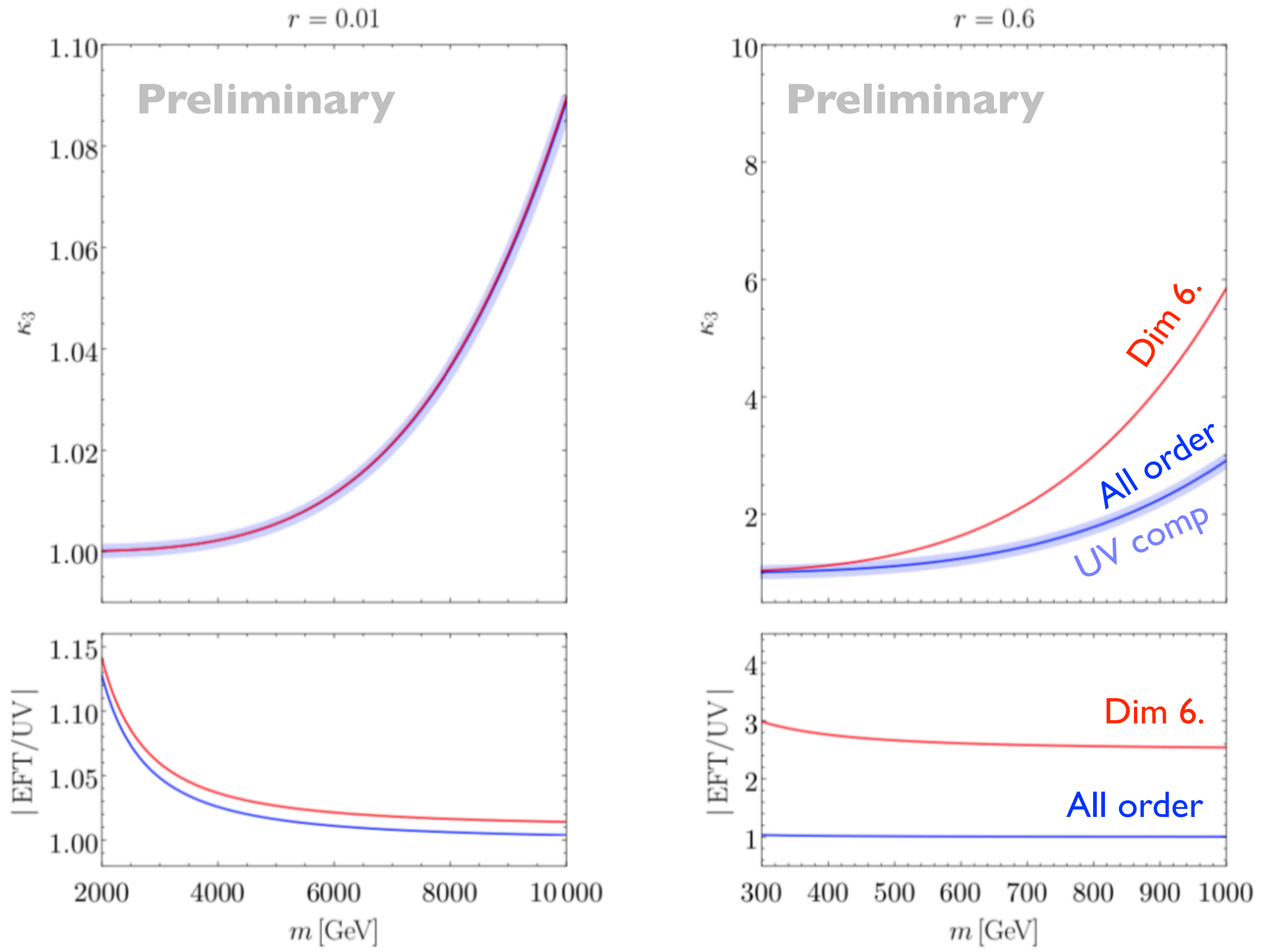
$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4(4\pi)^2}(M^2 + \kappa|\Phi|^2)^2 \ln \frac{M^2 + \kappa|\Phi|^2}{\mu^2} + \cdots$$

- $|\Phi|^2$ のべきに展開 (SMEFT form)

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

- M~0 のとき、**(Dim6) ~ (Dim8) になる！**

Validity of dim 6 SMEFT



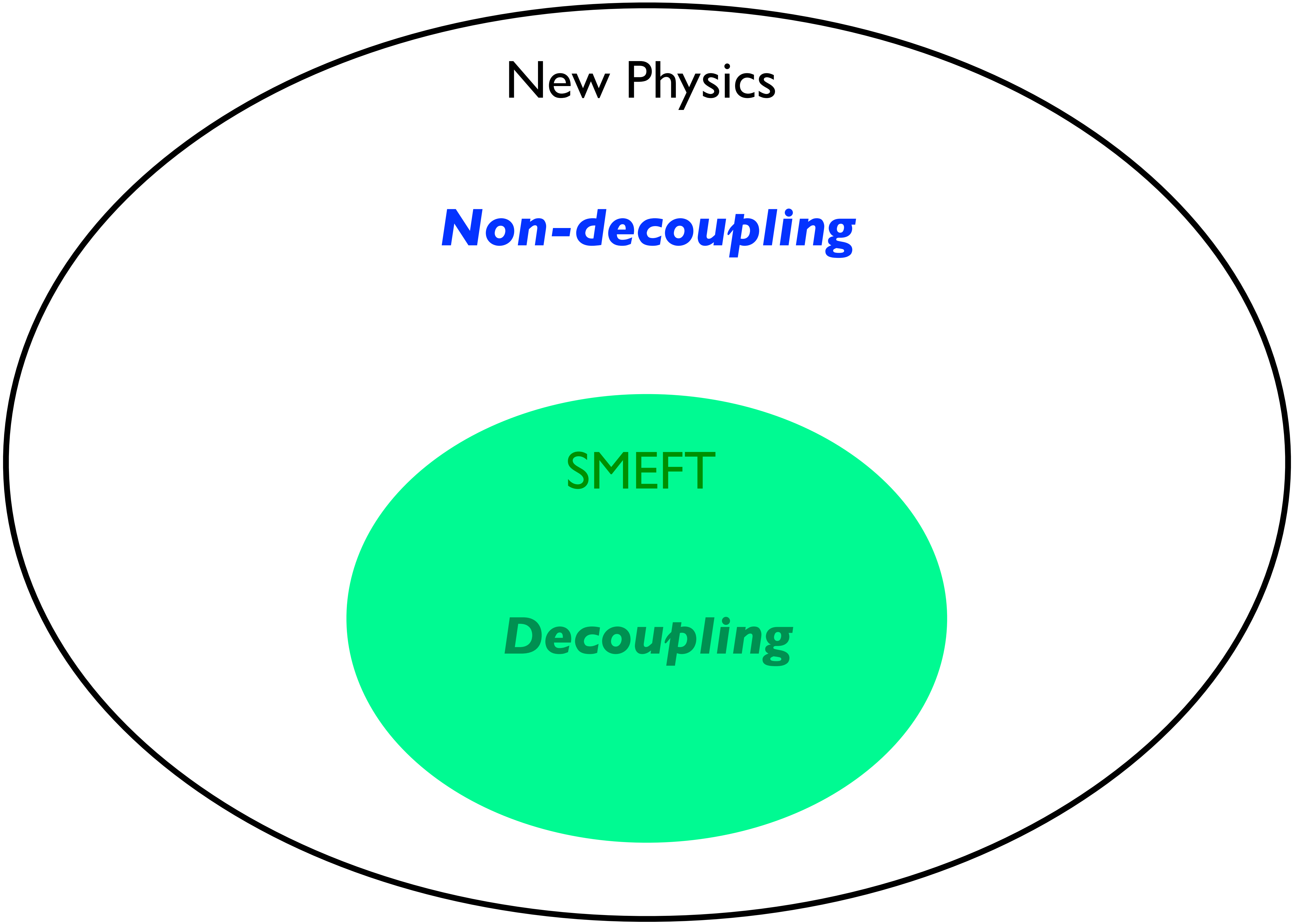
Decoupling

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!

d.o.m of BSM particle

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

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

- "Non-decouplingness" $r = \frac{\kappa_{\rm p}\langle\Phi\rangle^2}{\Lambda^2}$

- r ~ 0 のとき、SMEFTに帰着する。

How large “non-decouplingness” can be ?

$$r = \frac{\kappa_{\mathrm{p}} \left\langle \Phi \right\rangle^2}{\Lambda^2} \quad \sim \quad \text{“Non-decouplingness”}$$

- Vacuum stability
- Perturbative unitarity

Vacuum stability

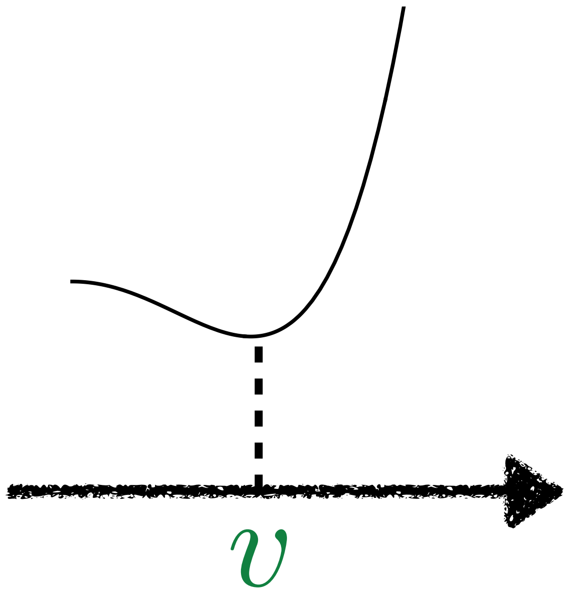
$$V = m^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{\kappa_0}{4(4\pi)^2}[\mathcal{M}^2(\Phi)]^2 \ln \frac{\mathcal{M}^2(\Phi)}{v^2}$$

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

$$r = \frac{\kappa_{\mathrm{p}}\langle\Phi\rangle^2}{\Lambda^2}$$

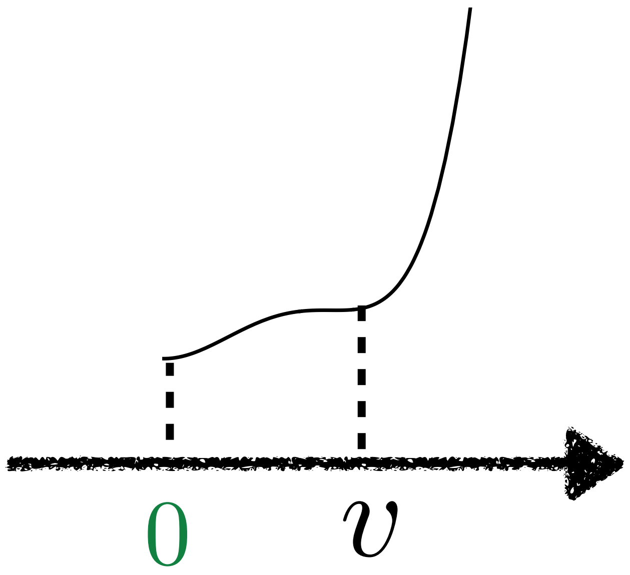
Decoupling

$$r \simeq 0$$

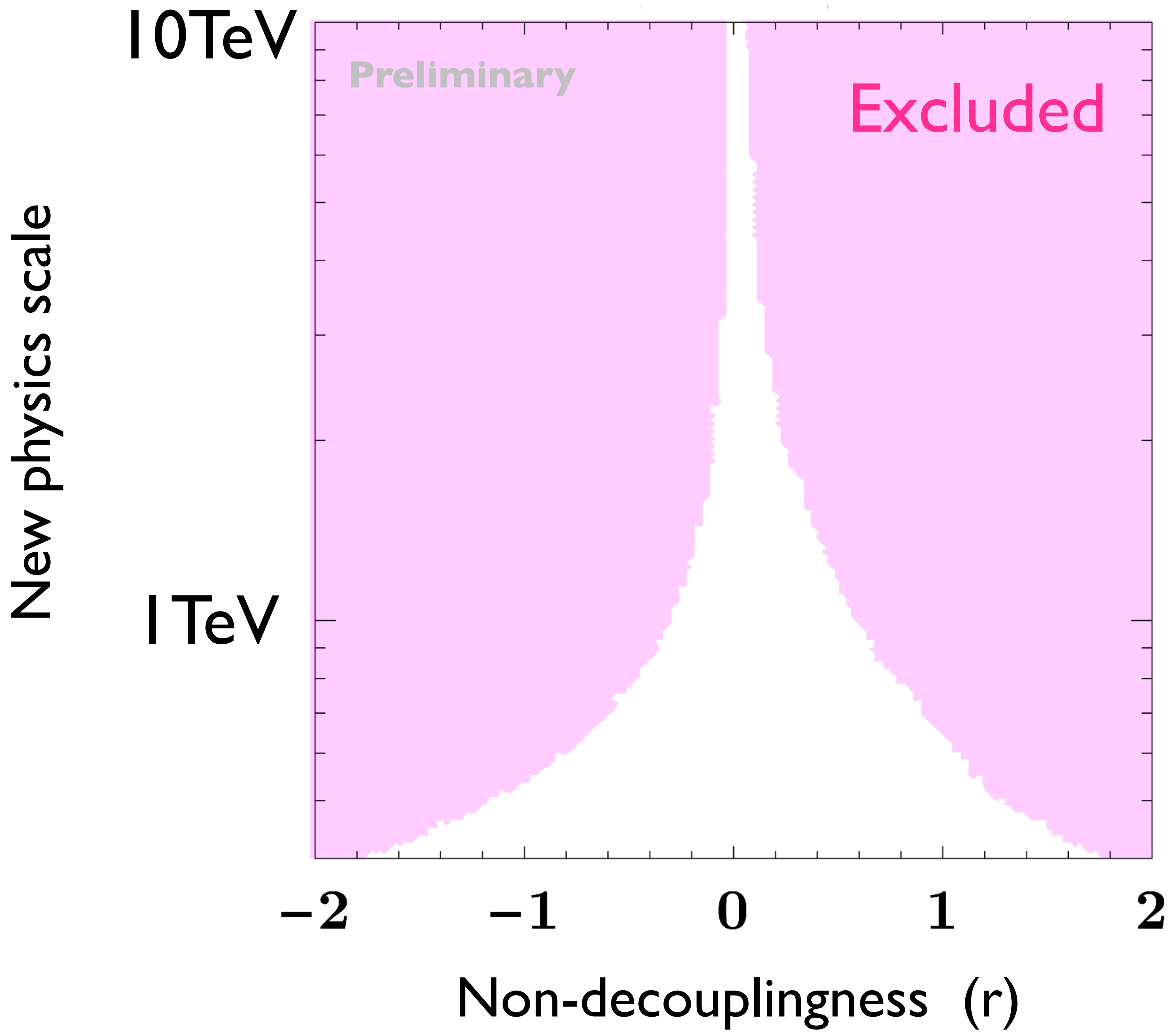


Non-Decoupling

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

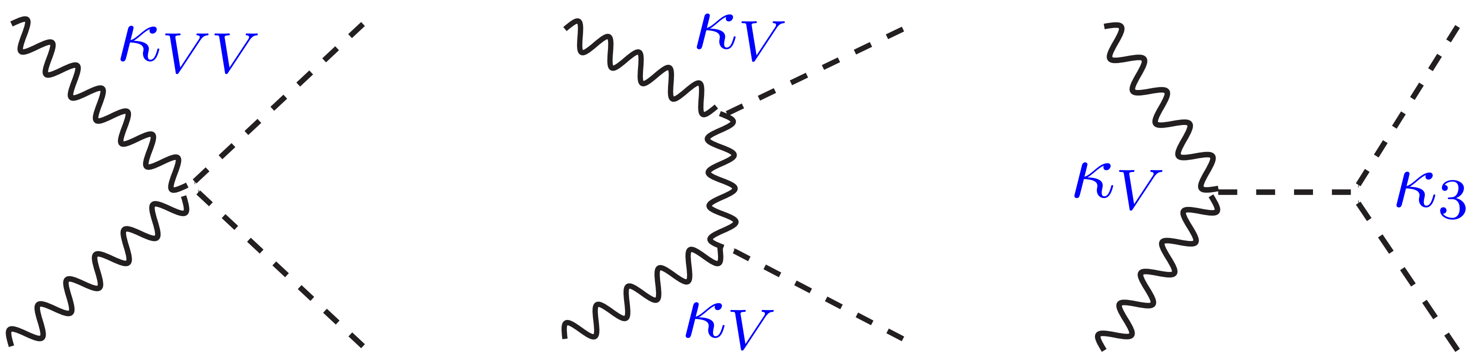


Vacuum stability



Perturbative unitarity

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



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

- ユニタリティ制限 $|\mathrm{Re}(a_0)| < \frac{1}{2}$ **at** $s = \Lambda^2$

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

Perturbative unitarity

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

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

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

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

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

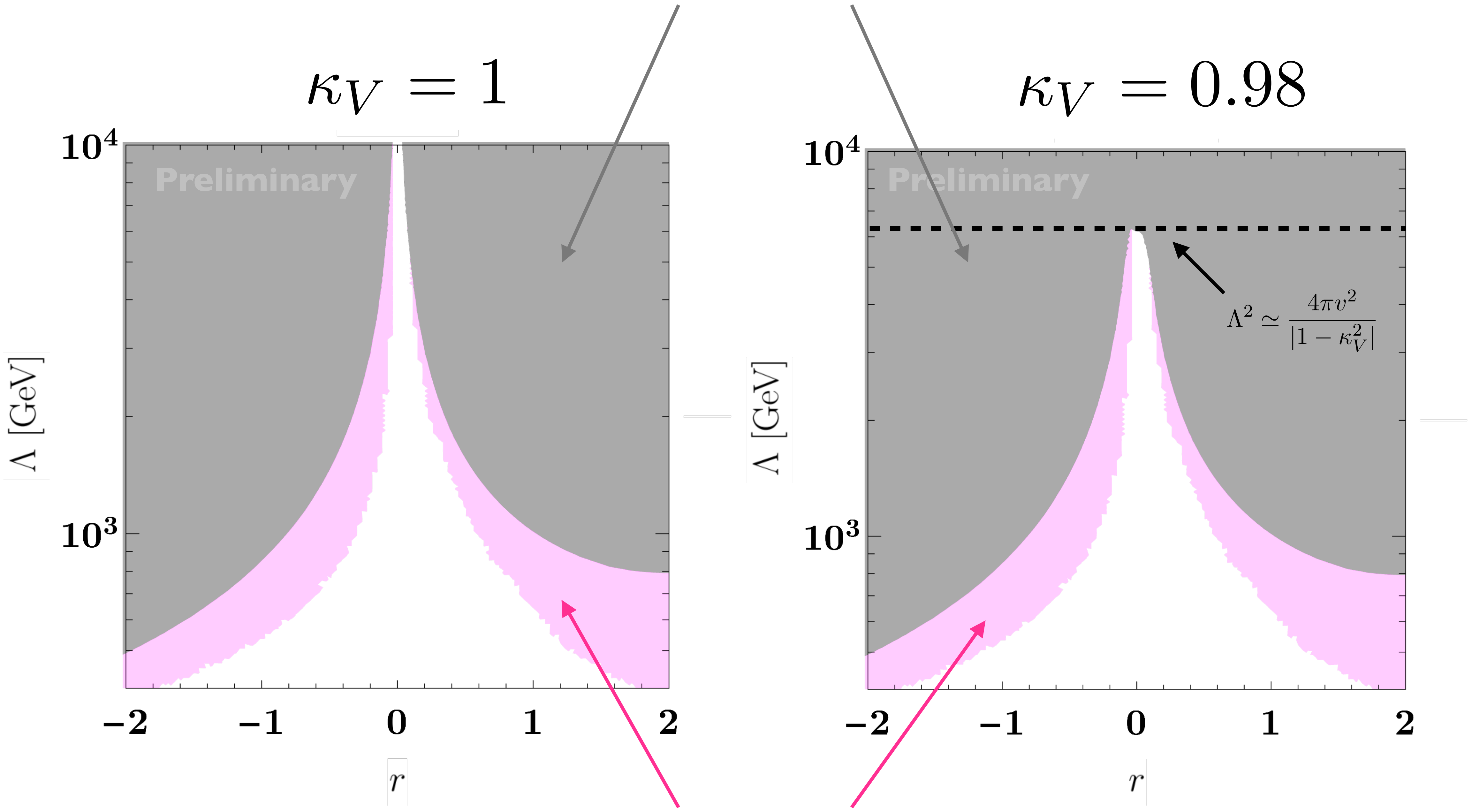
- ユニタリティ制限 $|{\rm Re}(a_0)| < \dfrac{1}{2}$ **at** $s = \Lambda^2$

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

Vacuum Stability + Unitarity

$\kappa_{VV} = 1$

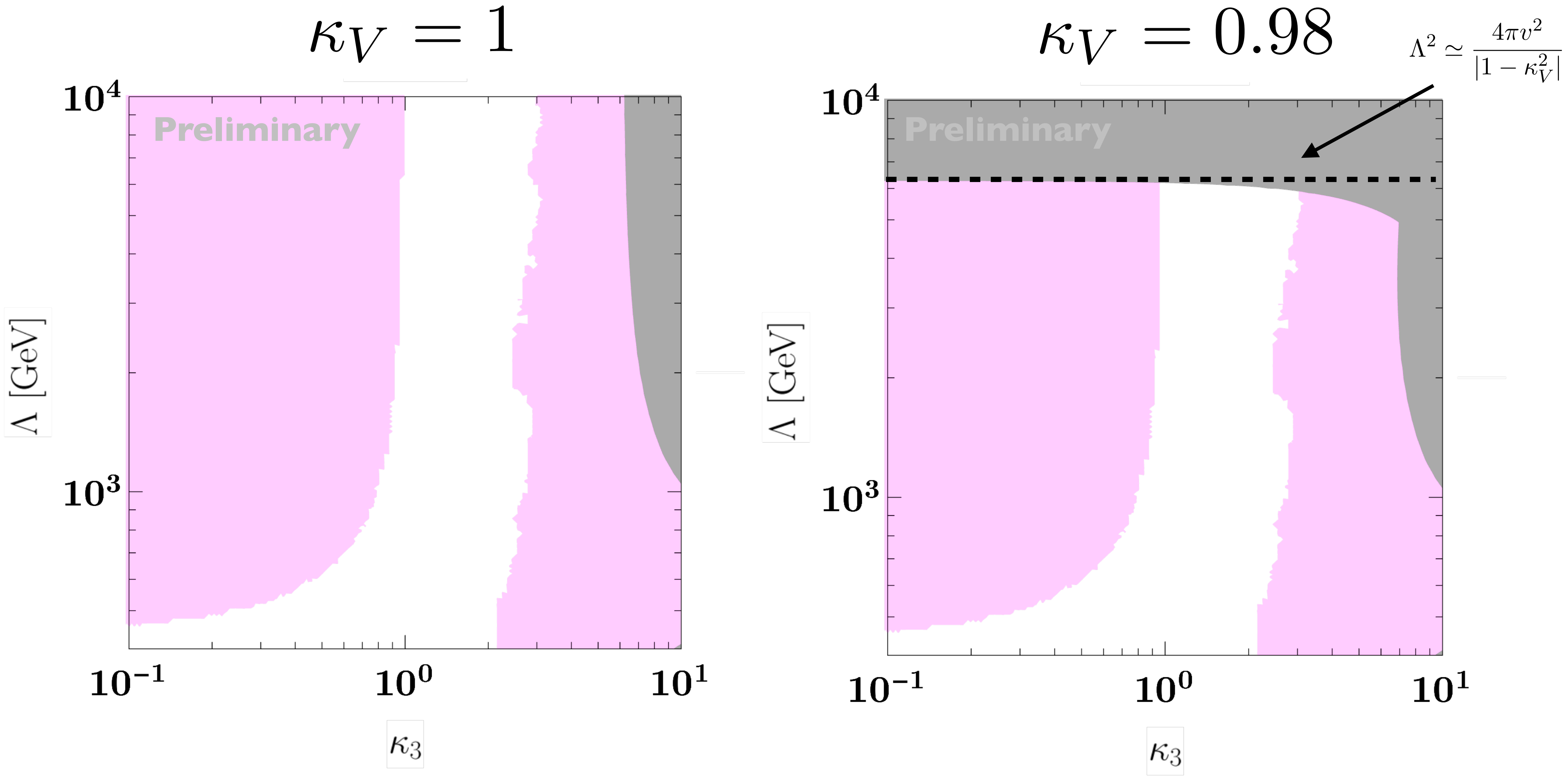
Perturbative unitarity bound



Vacuum stability bound

Vacuum Stability + Unitarity

$\kappa_{VV} = 1$



$$\Lambda^2 \simeq \frac{4\pi v^2}{|1-\kappa_V^2|}$$

Higgs coupling deviation → 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！