Higgs physics

Ryo Nagai
(Osaka U.)

Summer camp on ILC accelerator,
physics and detectors 2021

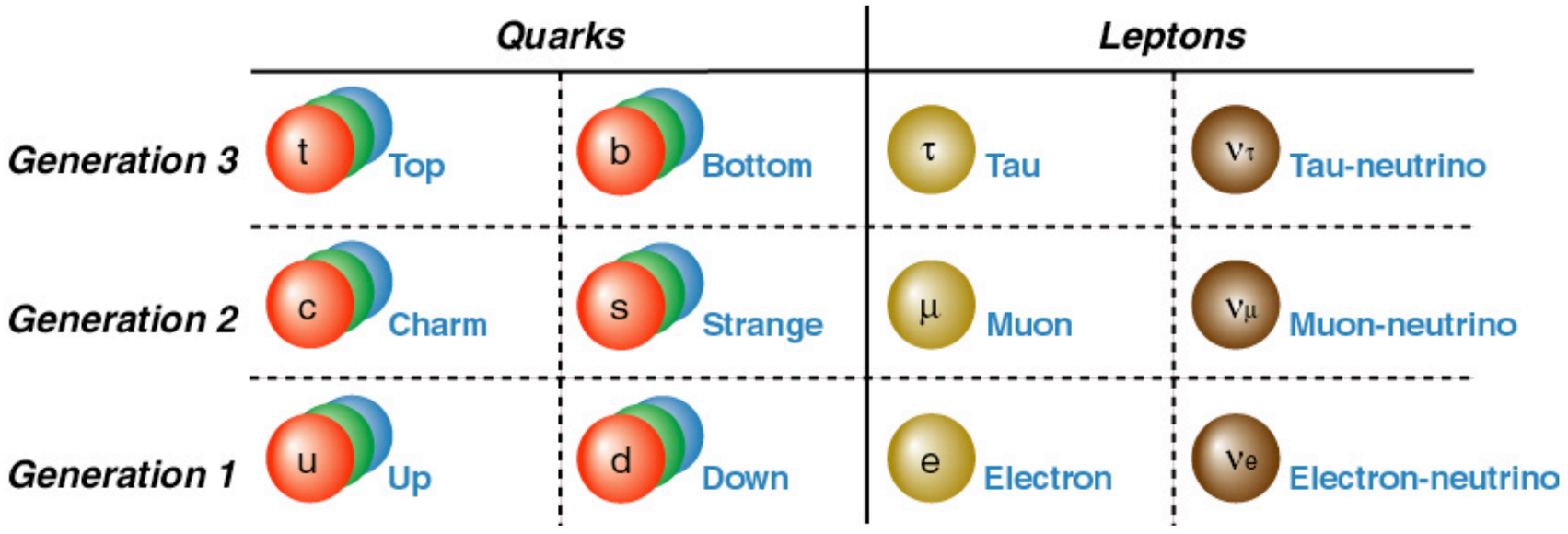
2021/9/24

Talk plan

- What is the *Higgs mechanism* ?
- What we know
- Next to do

Particle physics

"What are things made of ? "



https://physicsmasterclasses.org/exercises/keyhole/en/projects/number_of_families.html

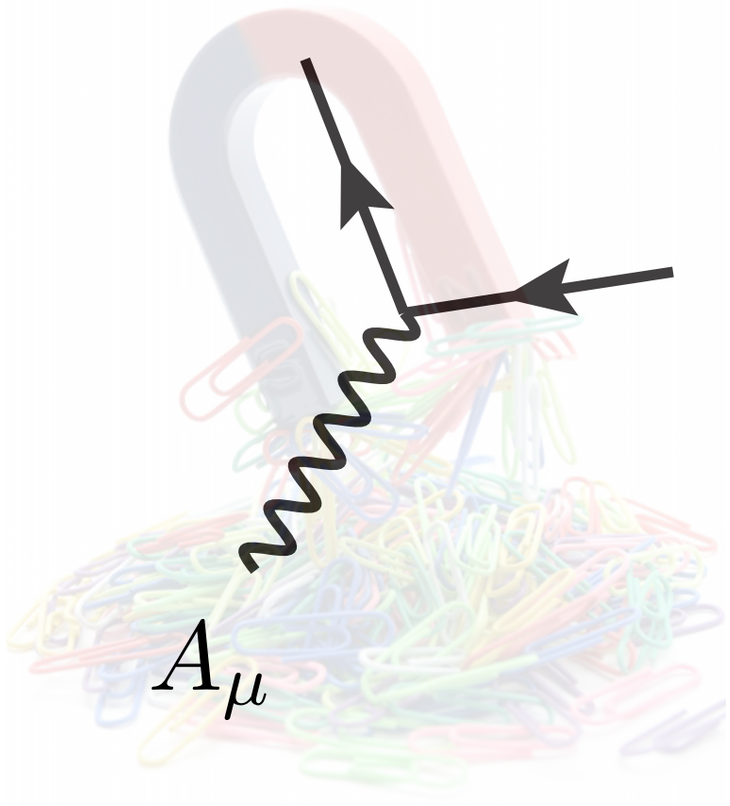
"What are the fundamental forces among them?"

Electromagnetic force

- Electromagnetic field

$$A_\mu = (\phi, \vec{A})$$

Electromagnetic force



- Electromagnetic field

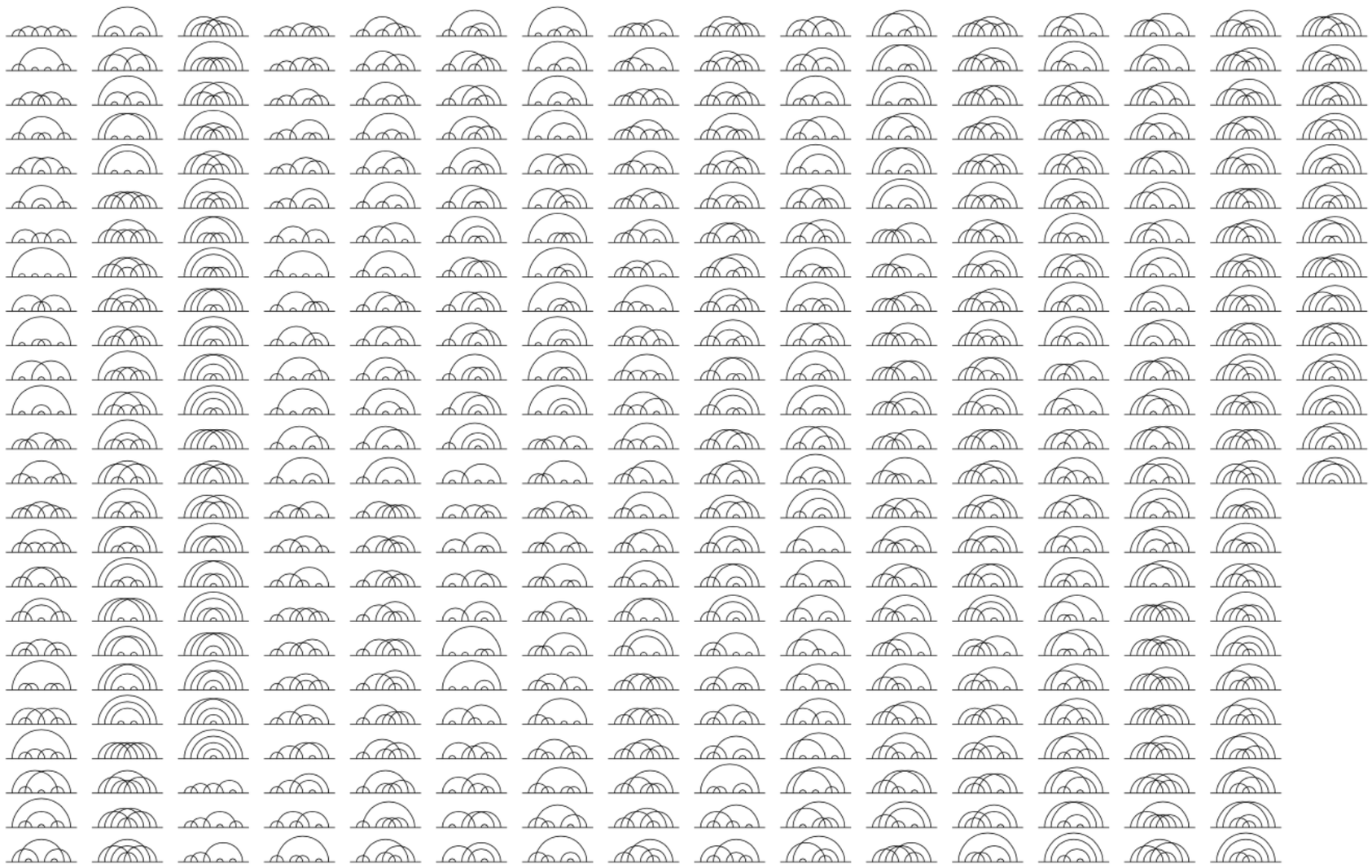
$$A_\mu = (\phi, \vec{A})$$

- *Gauge symmetry*

$$A_\mu(x) \to A_\mu(x) + \partial_\mu \theta(x)$$

- Long-range force $V \sim 1/r$

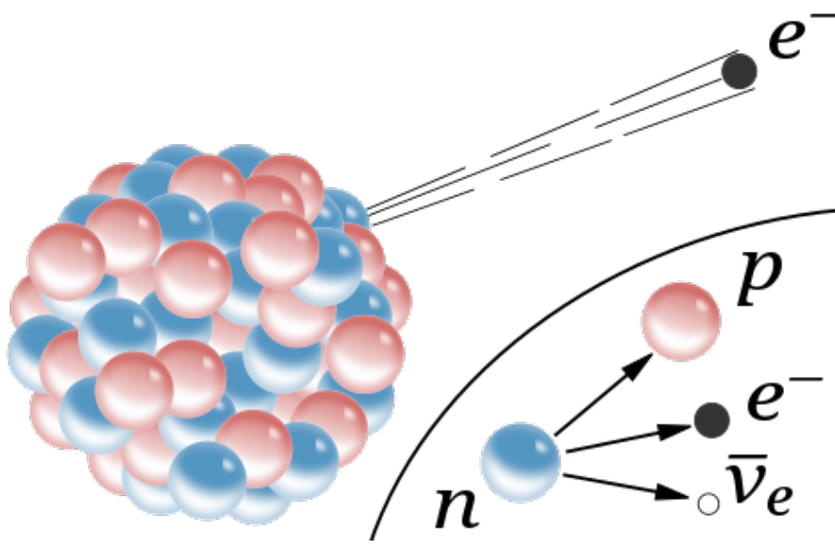
Predictive power



$$a_e(\text{experiment}) - a_e(\text{theory}) = -0.91\ (0.82) \times 10^{-12}.$$

[Aoyama, Hayasaka, Kinoshita, Nio (2015)]

Weak force



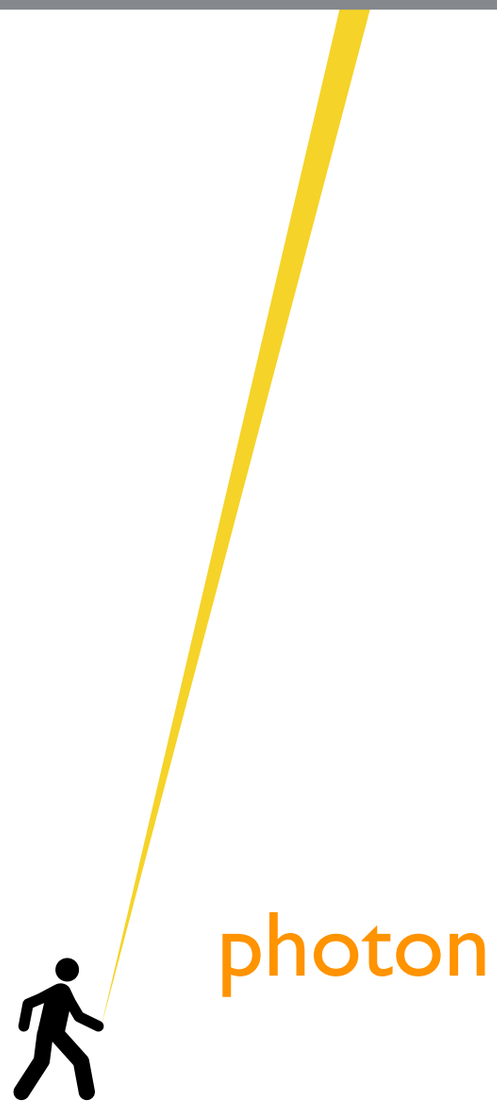
[Wikipedia]

- β-decay
- Short-range force

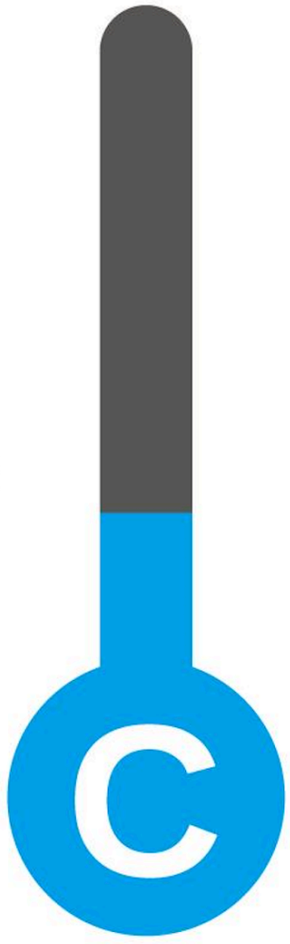
$$V \sim e^{-Mr}/r$$

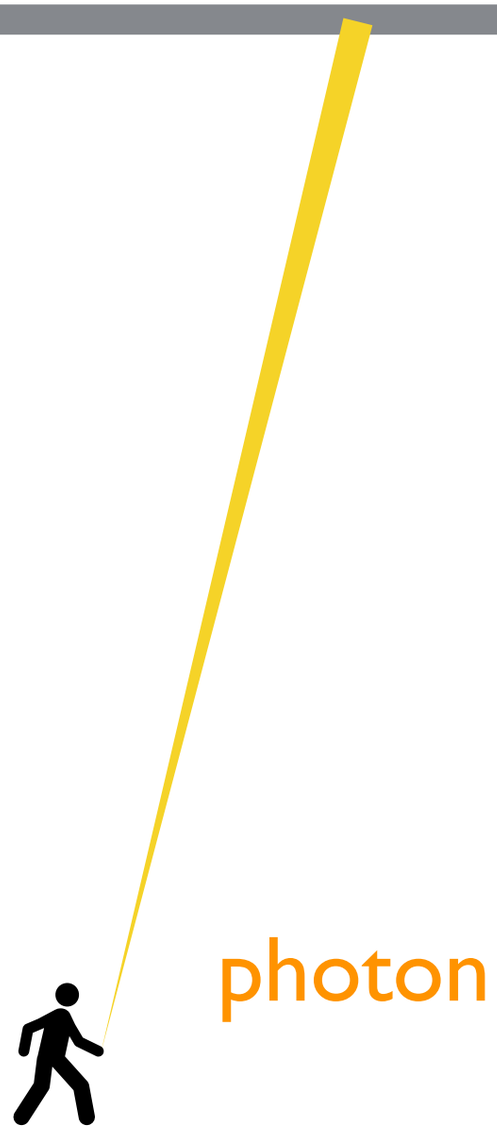
$$M \simeq (10^{-18}\mathrm{m})^{-1}$$

- Incompatible with gauge symmetry ??

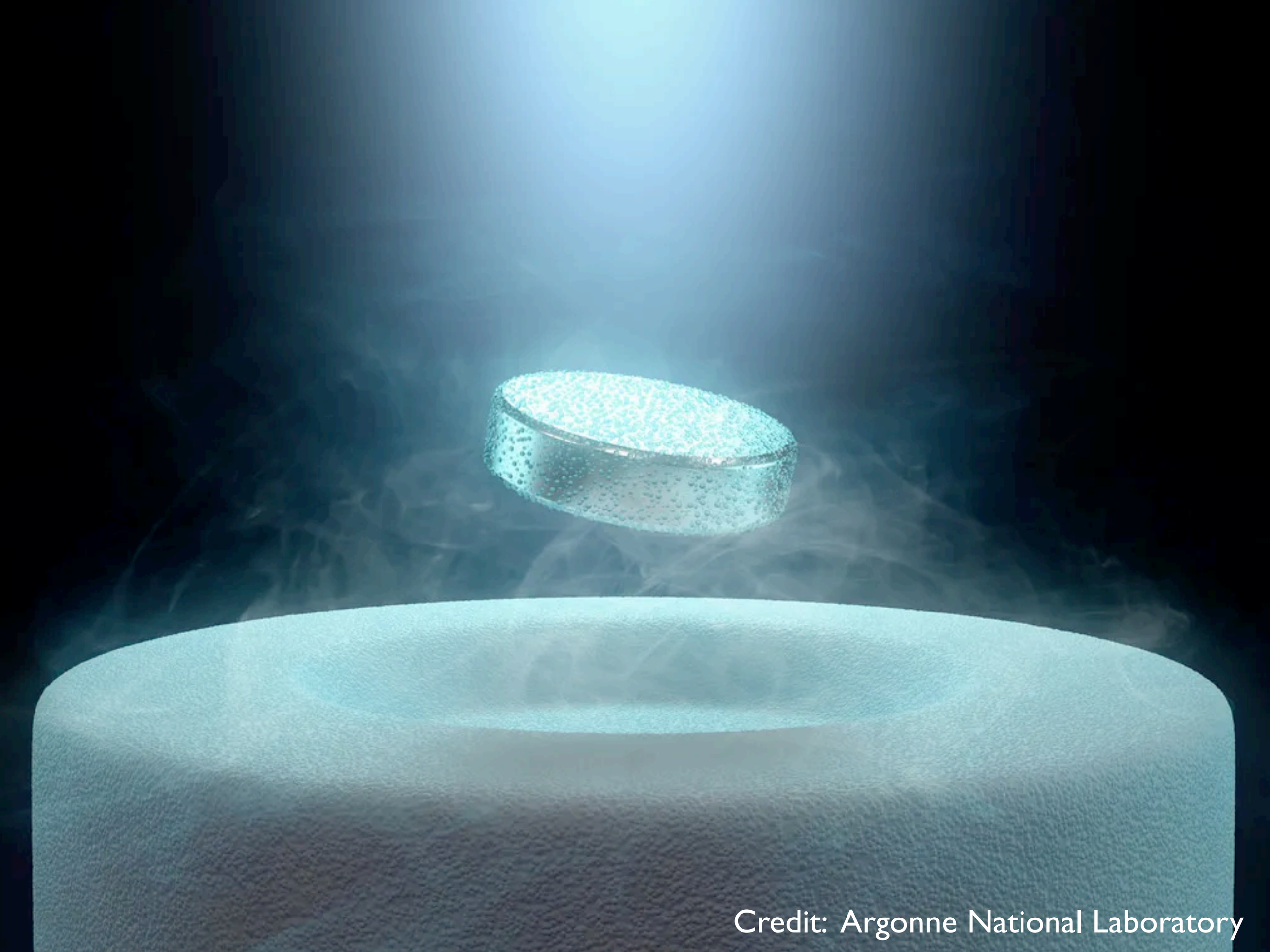


Superconductor

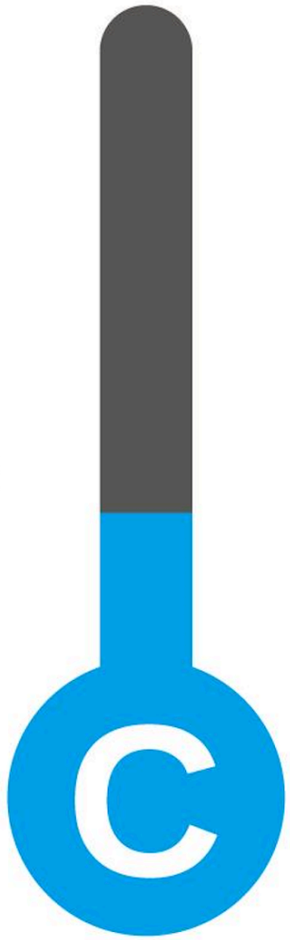




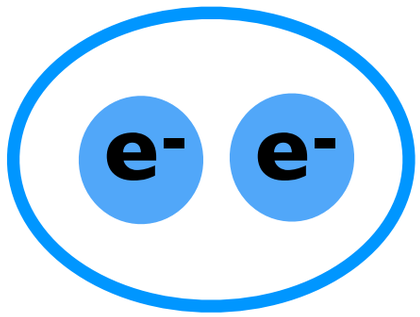
Superconductor



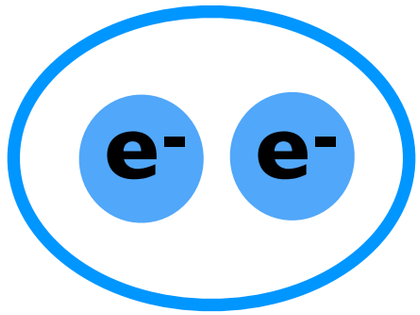
Credit: Argonne National Laboratory



Cooper pair



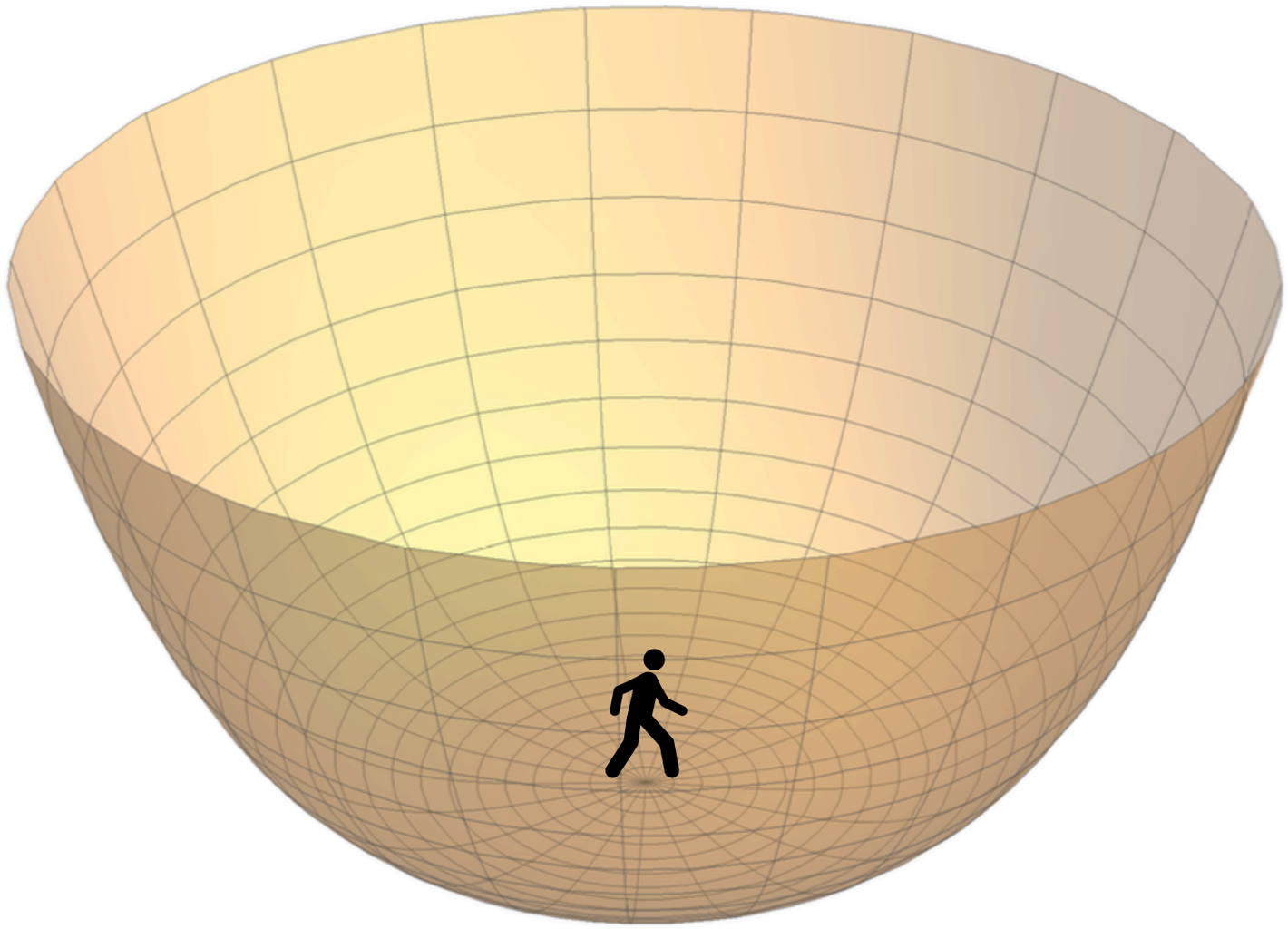
Cooper pair



"Meissner effect"

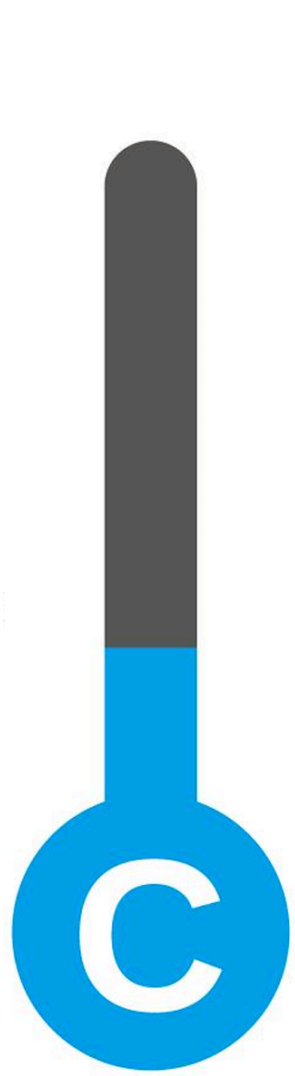
Superconductor

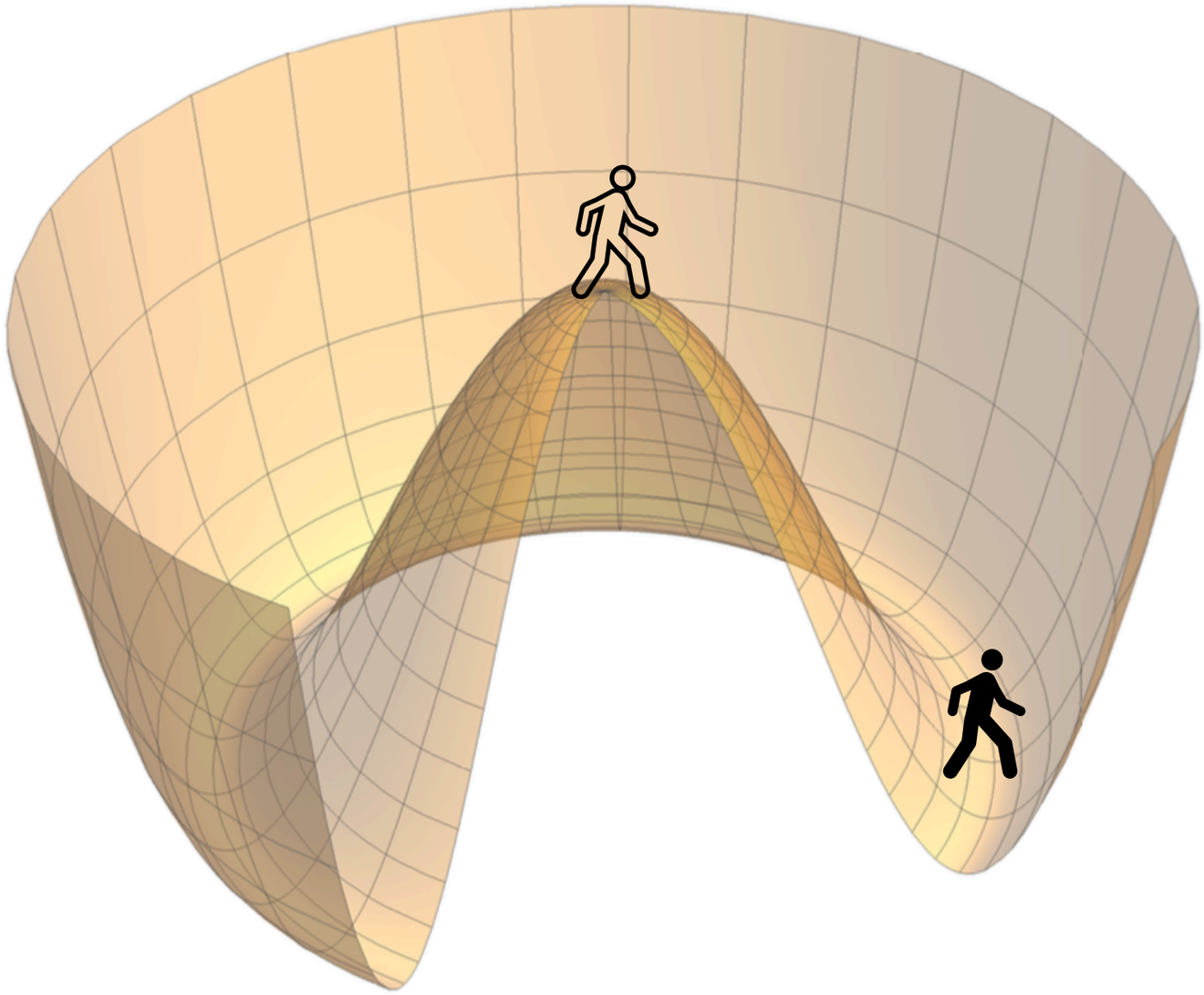
Spontaneous symmetry breaking



Potential energy

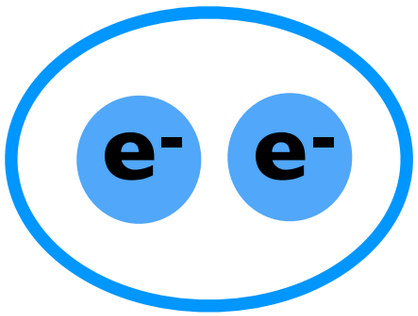
Spontaneous symmetry breaking

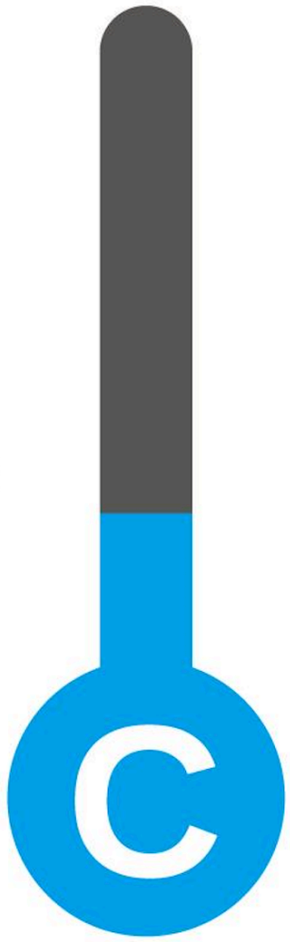




Potential energy

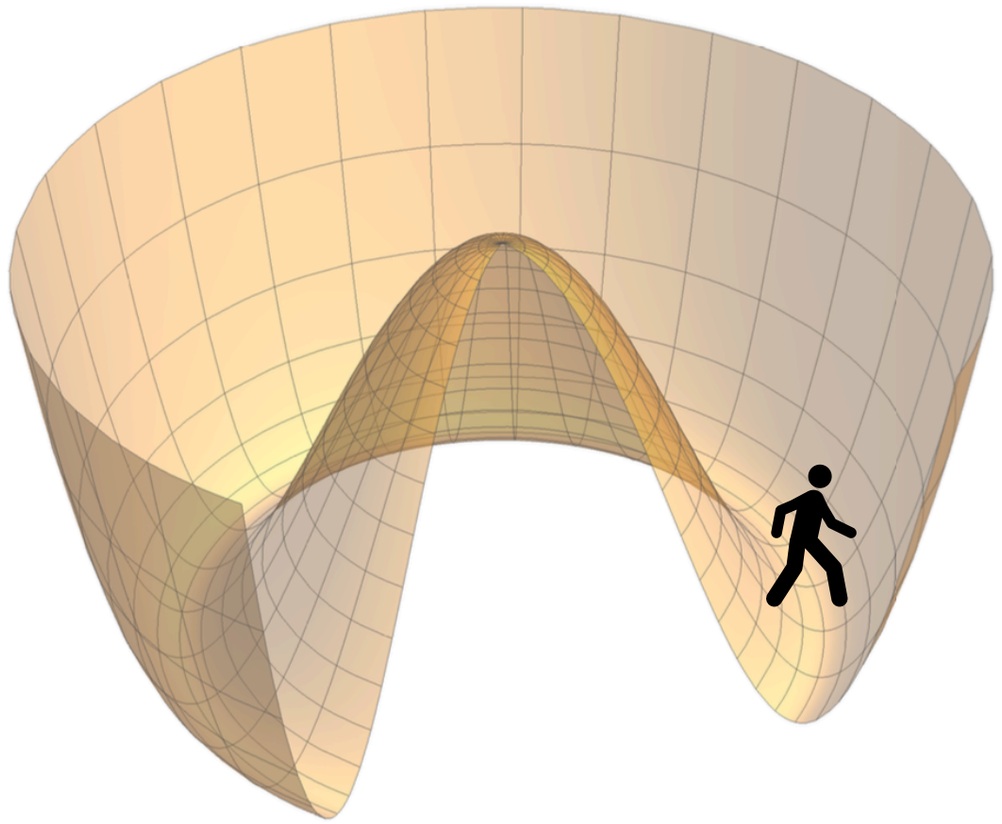
Cooper pair





EM force

Superconductor



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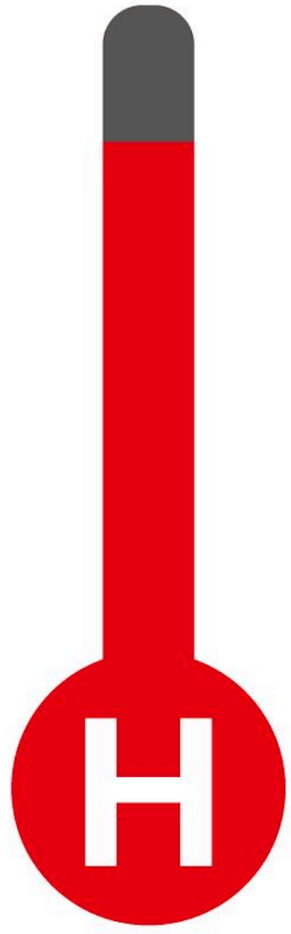
U(1)

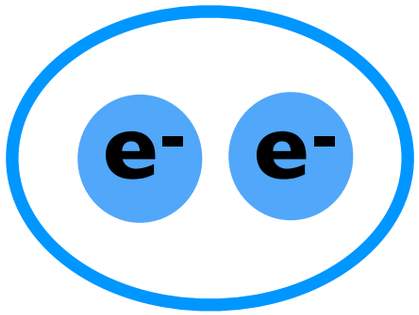
Superconductor

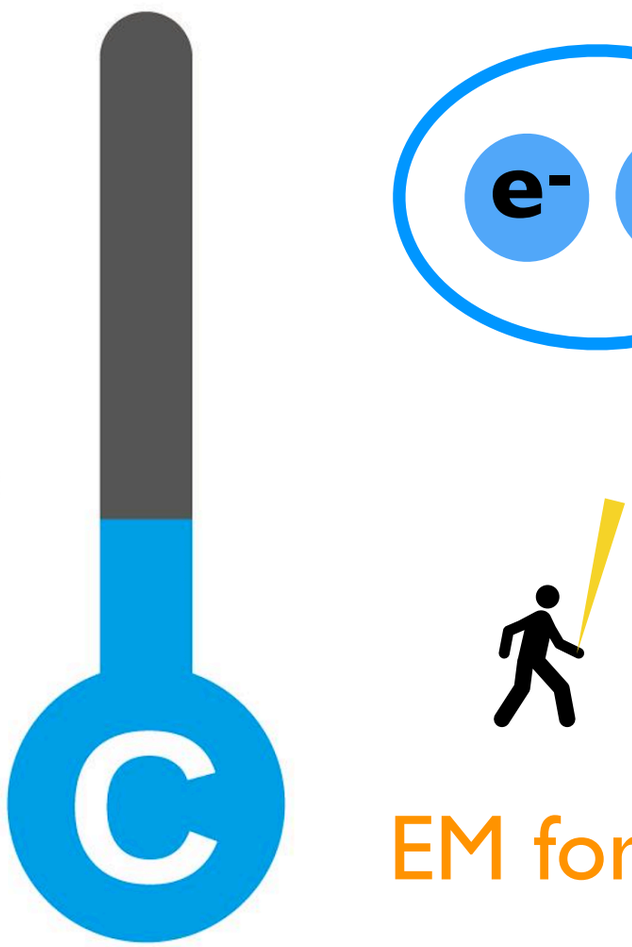


SU(2)×U(1)

Universe

Cooper pair

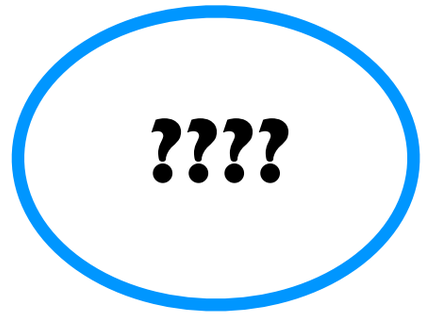


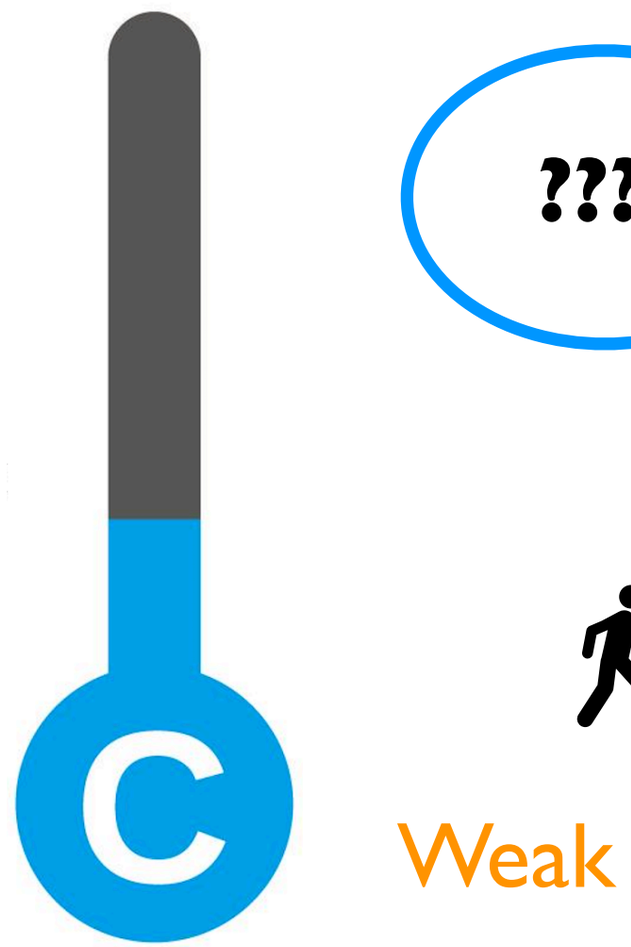


EM force

Superconductor

Higgs field

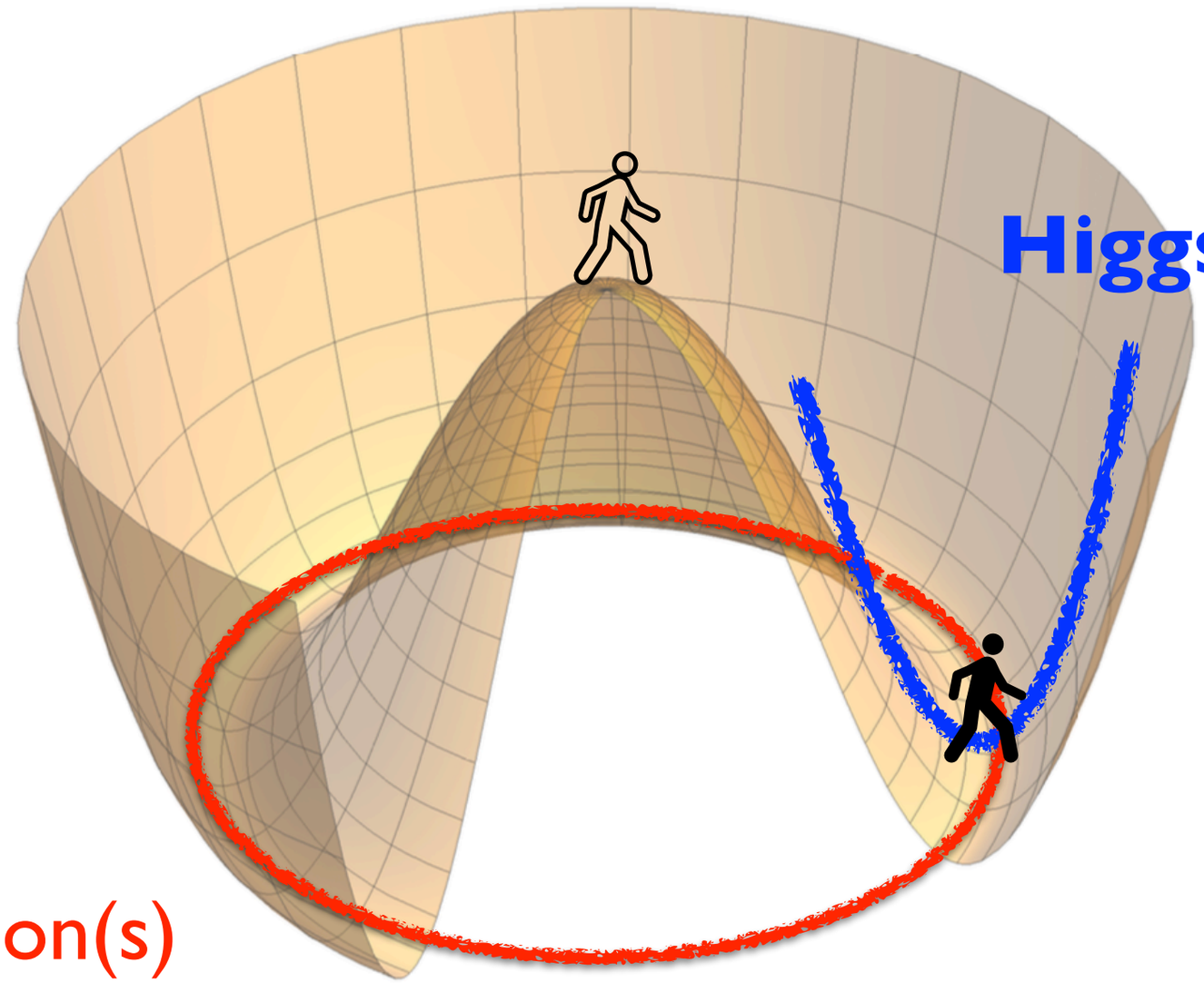




Weak force

Universe

Fluctuation around vacuum



$$V = -\mu^2 |\Phi|^2 + \lambda |\Phi|^4$$

Anderson-**B**rout-**E**nglert-**G**uralnik-**H**agen-**H**iggs-**K**ibble-**t'H**ooft mechanism

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

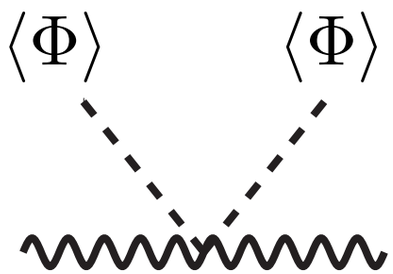
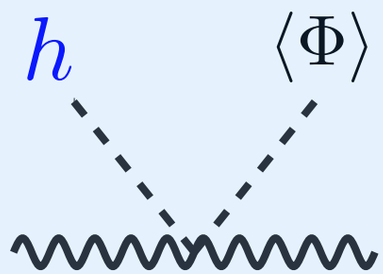
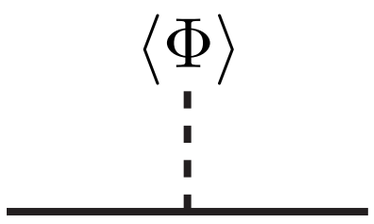
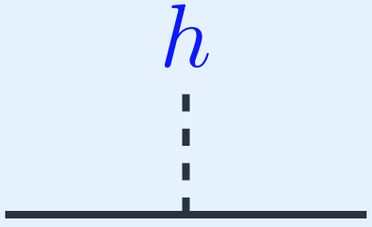
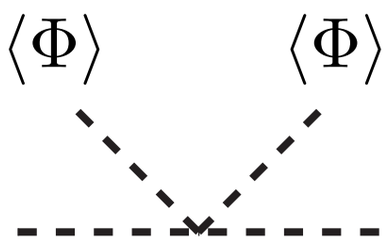
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

Last paragraph

It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8] It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields.[9]

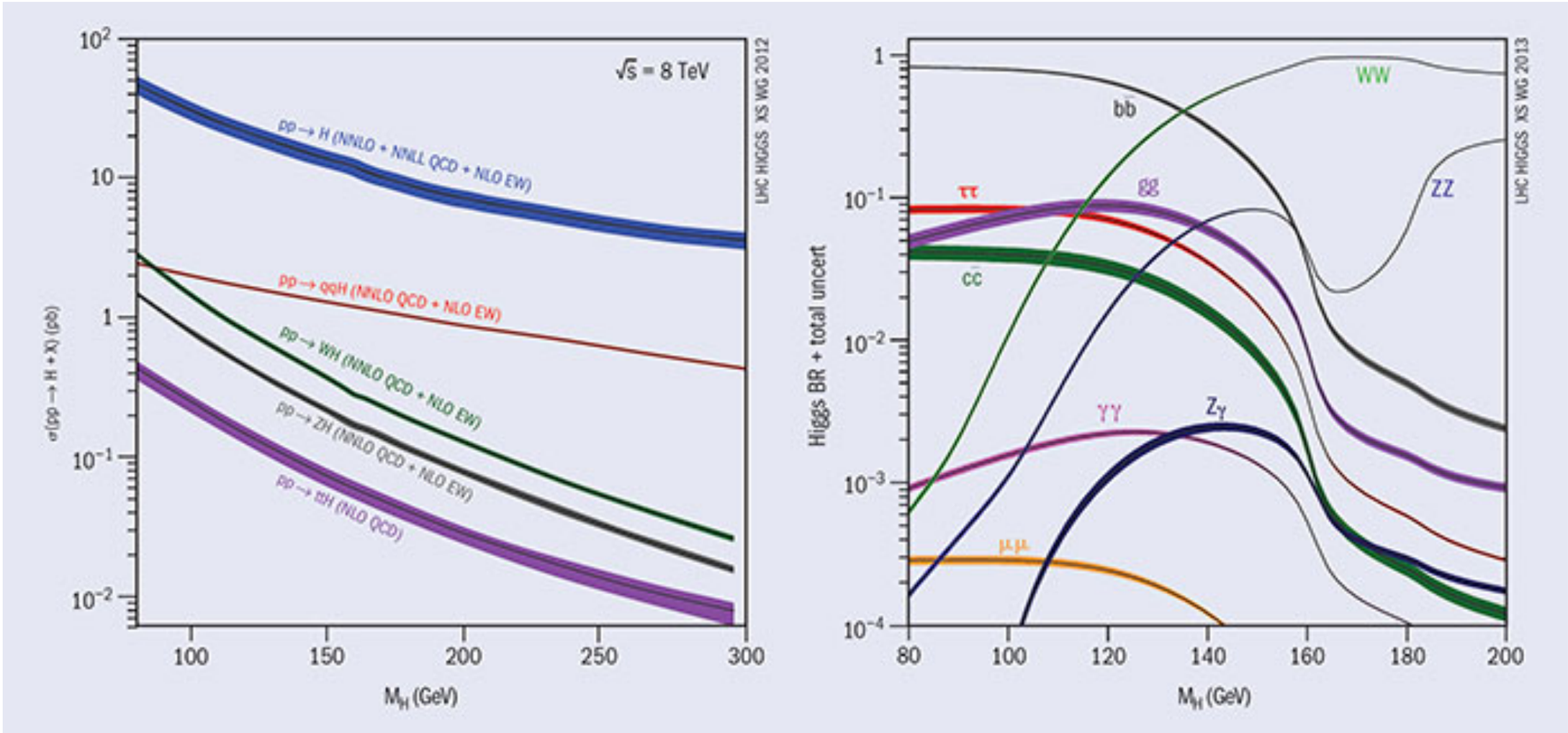
Higgs interactions

	Mass	Interaction
W/Z		
Quark/Lepton		
Higgs		

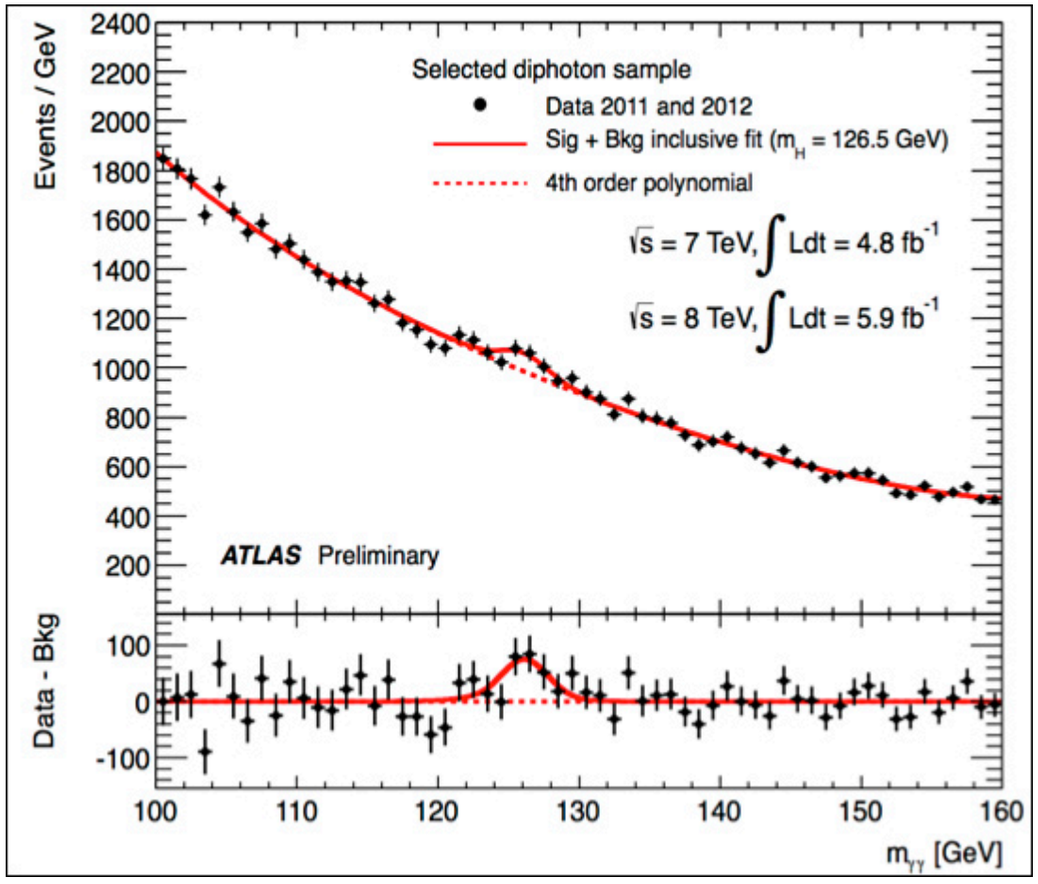
Higgs at LHC

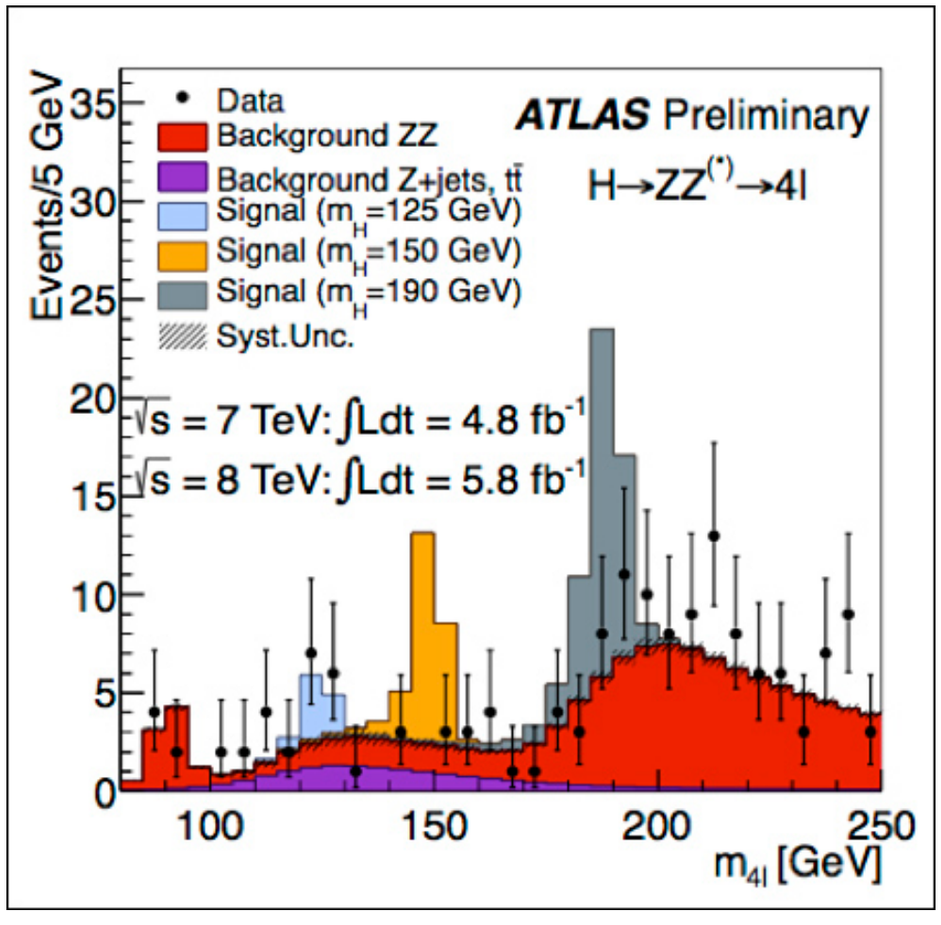
Production

Decay

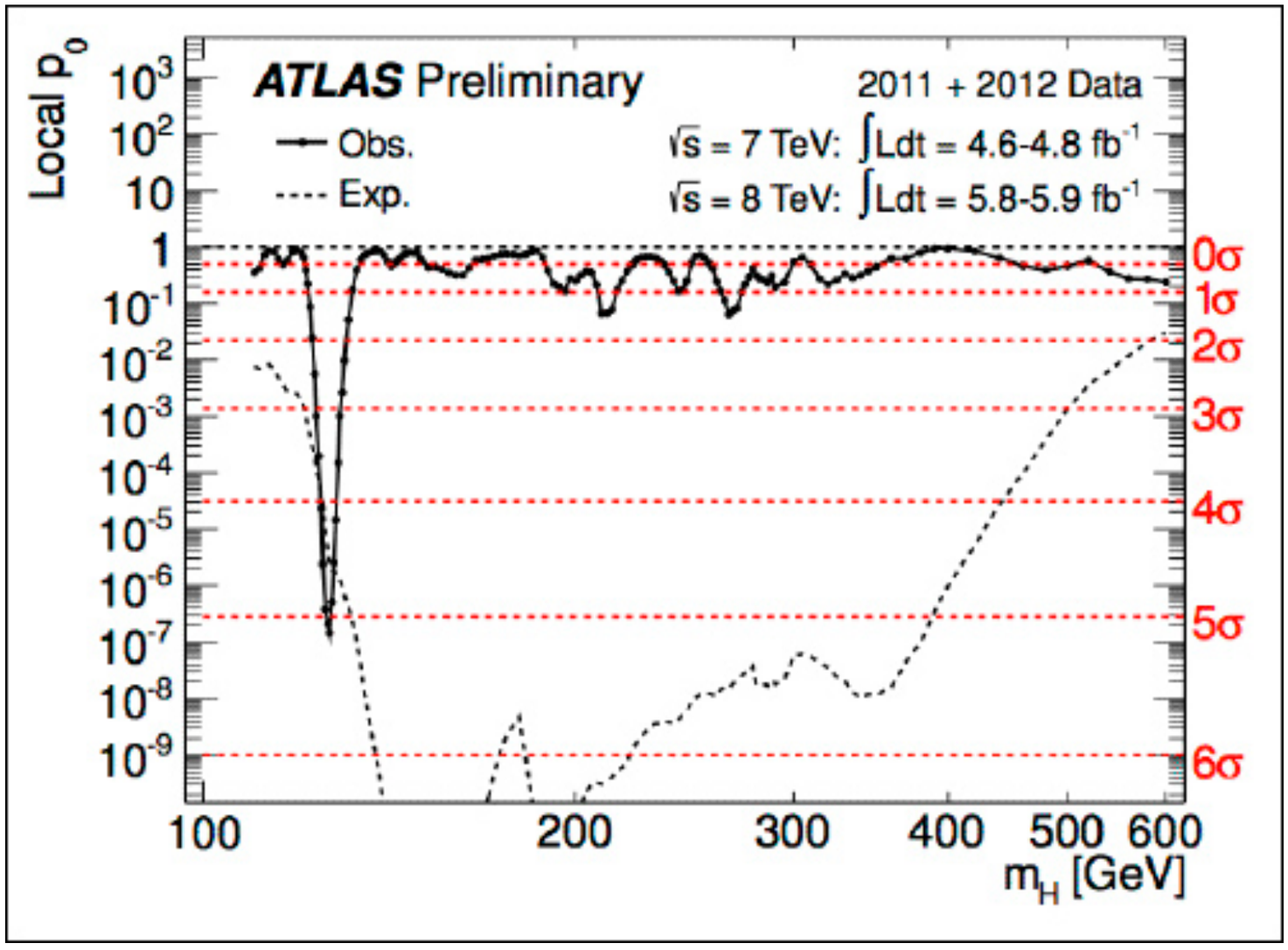


2012 / 7 / 4


Selected diphoton sample
Data 2011 and 2012
Sig + Bkg inclusive fit (m_H = 126.5 GeV)
4th order polynomial
√s = 7 TeV, ∫Ldt = 4.8 fb-1
√s = 8 TeV, ∫Ldt = 5.9 fb-1
ATLAS Preliminary
Events / GeV
Data - Bkg
m_γγ [GeV]


ATLAS Preliminary
H→ZZ(*)→4l
Data
Background ZZ
Background Z+jets, tt̄
Signal (m_H=125 GeV)
Signal (m_H=150 GeV)
Signal (m_H=190 GeV)
Syst.Unc.
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Events/5 GeV
m_4l [GeV]

2012 / 7 / 4


ATLAS Preliminary
2011 + 2012 Data
Obs.
Exp.
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8-5.9 fb-1
Local p0
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
0σ
1σ
2σ
3σ
4σ
5σ
6σ
100
200
300
400
500
600
mH [GeV]

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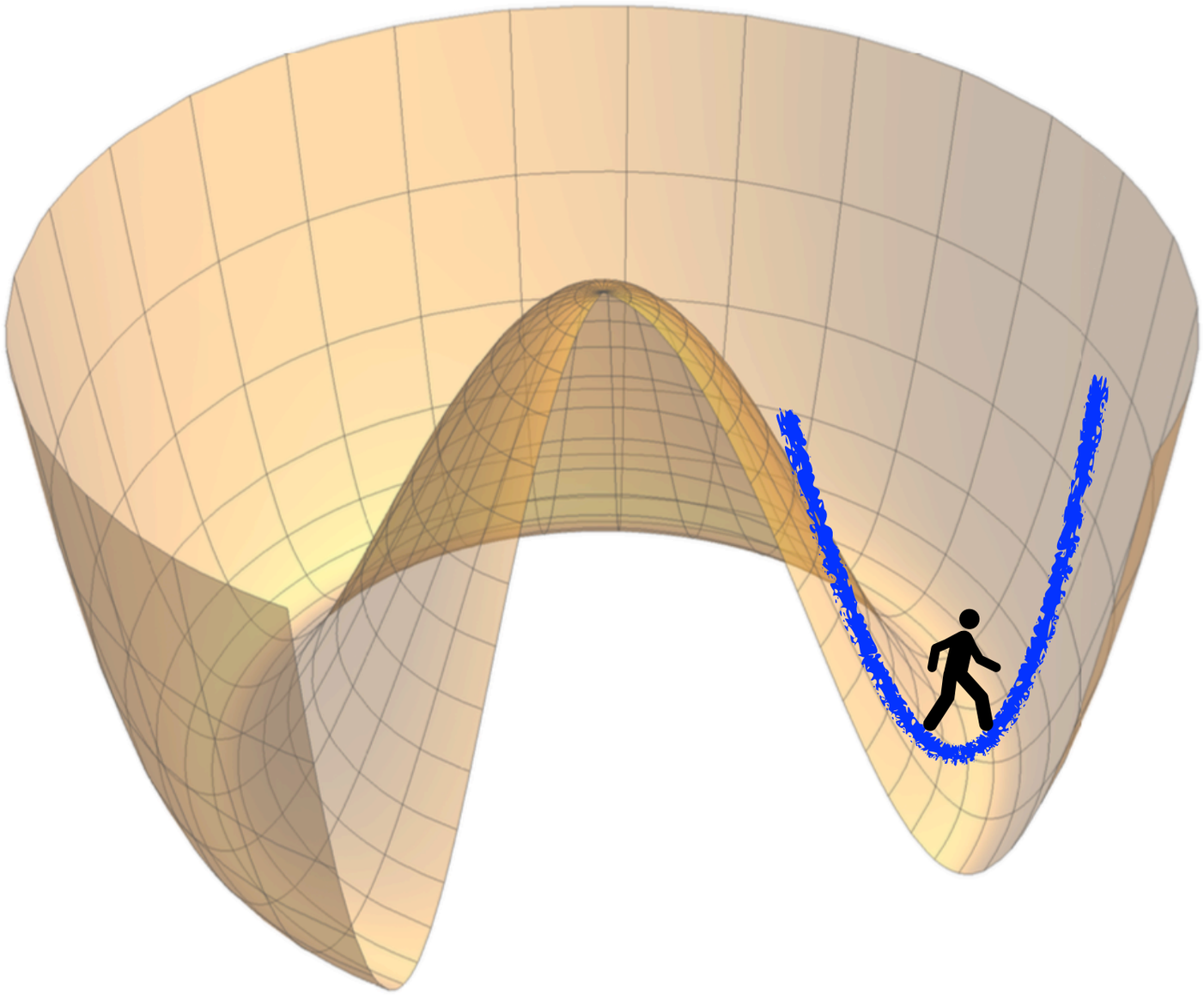
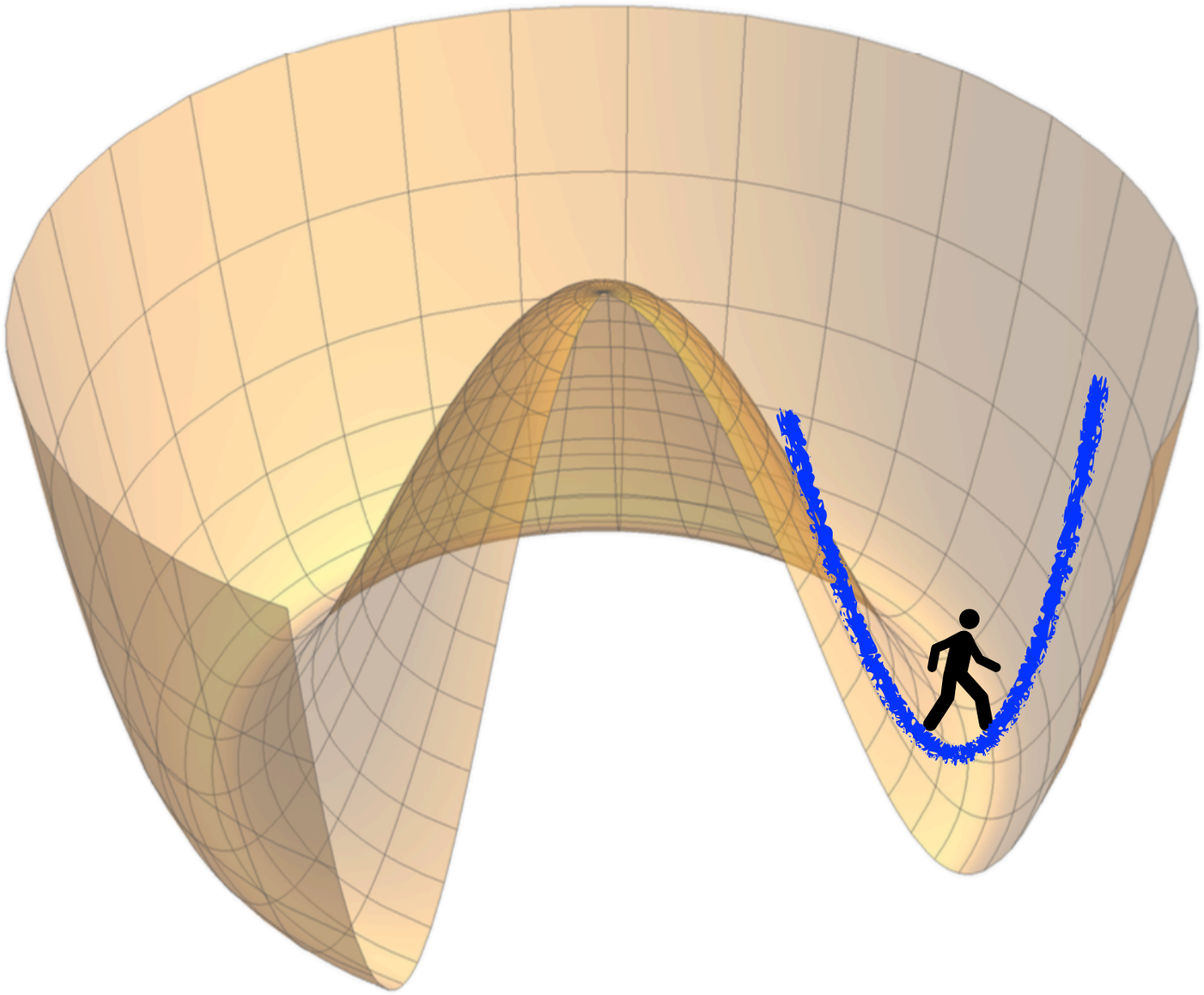
E·LINDBERG 1902

!!!!!



We observed "Higgs particle" !!

!!!!! ….. wait

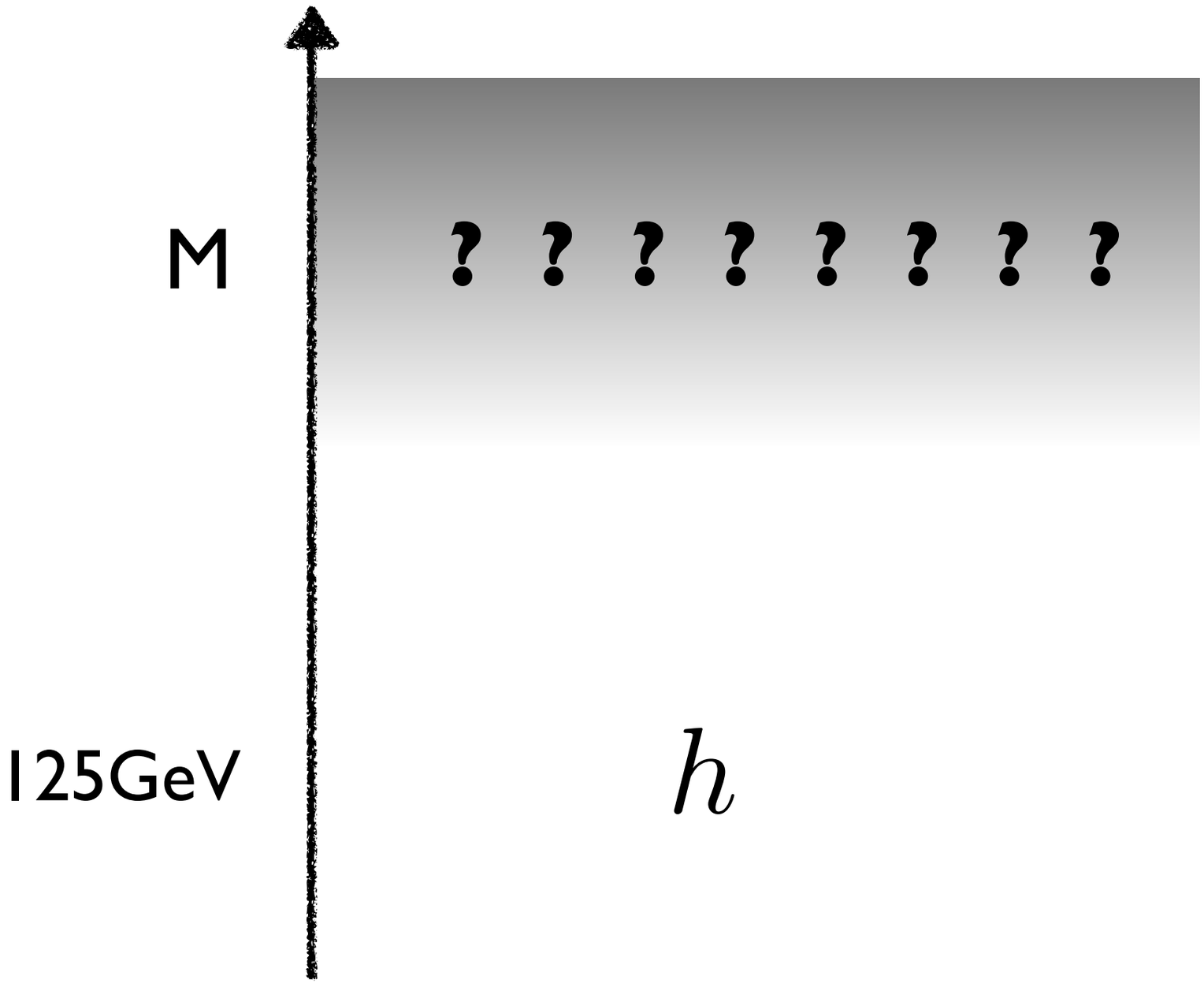


"What is the origin of EWSB ?"

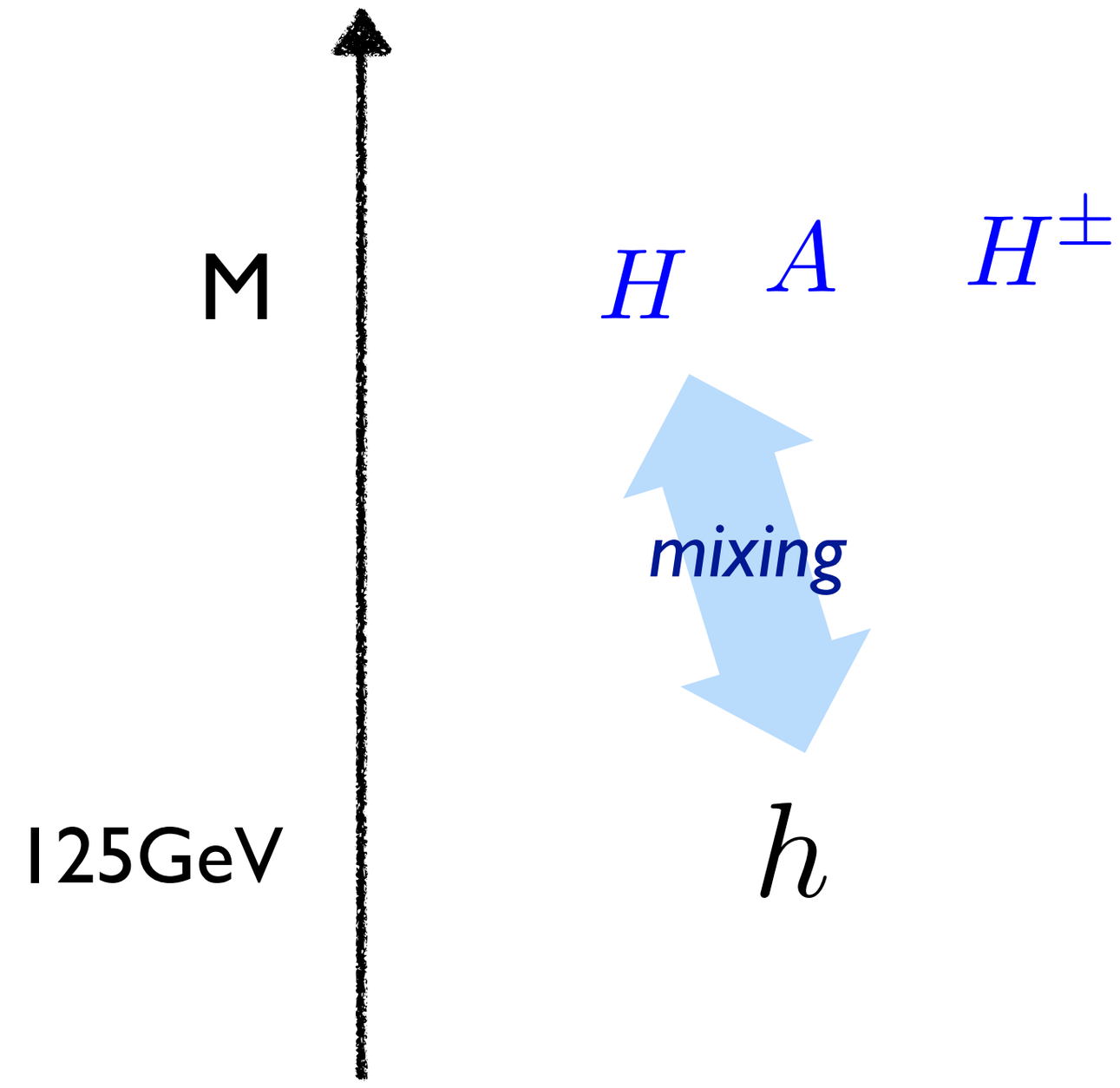
We are opening the door to new physics !!!

Credit: PIXTA

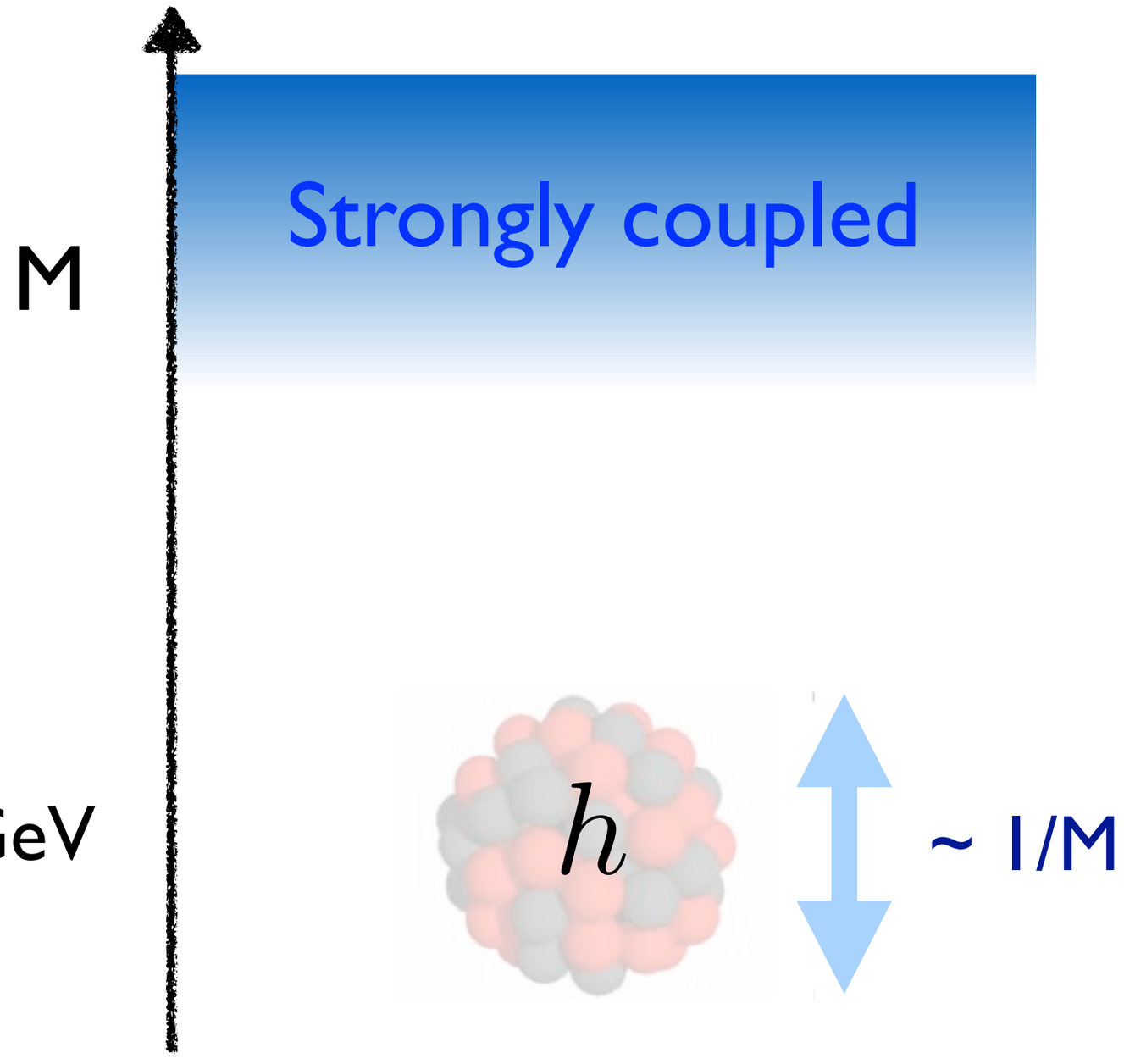
Higgs as a probe of new physics



Higgs as a probe of new physics



Higgs as a probe of new physics



EFT point of view

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \frac{c}{\Lambda^2}\left(\partial|\Phi|^2\right)^2 + \cdots$$

Mixed case

$$\Lambda \simeq \frac{v}{(\text{mixing})}$$

Composite case

$$\Lambda \simeq f$$

Composite scale ~ $4\pi f$

EFT point of view

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \frac{c}{\Lambda^2}\left(\partial|\Phi|^2\right)^2 + \cdots$$

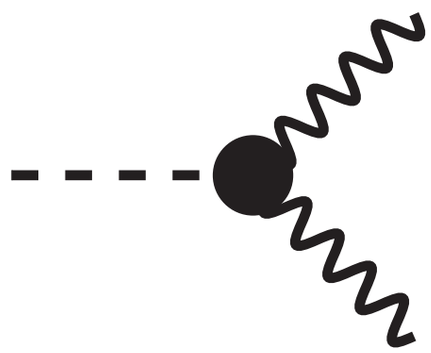
$$= \frac{1}{2}\left(1 + 2c\,\frac{v^2}{\Lambda^2}\right)(\partial h)^2 + \cdots$$

→ Modification of the Higgs wave function

→ (Universal) *Higgs coupling deviation*

EFT point of view

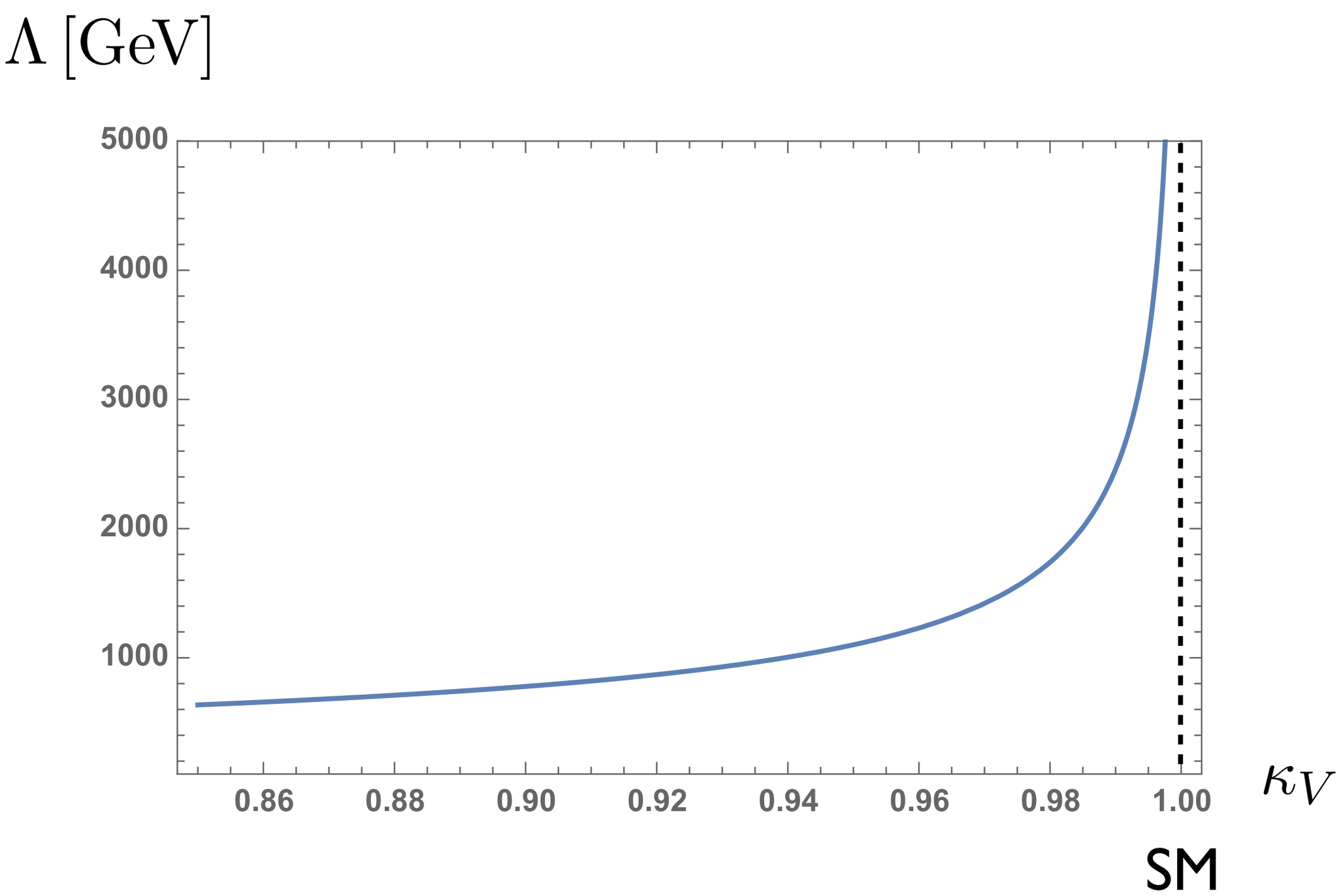
$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \frac{c}{\Lambda^2}\left(\partial|\Phi|^2\right)^2 + \cdots$$



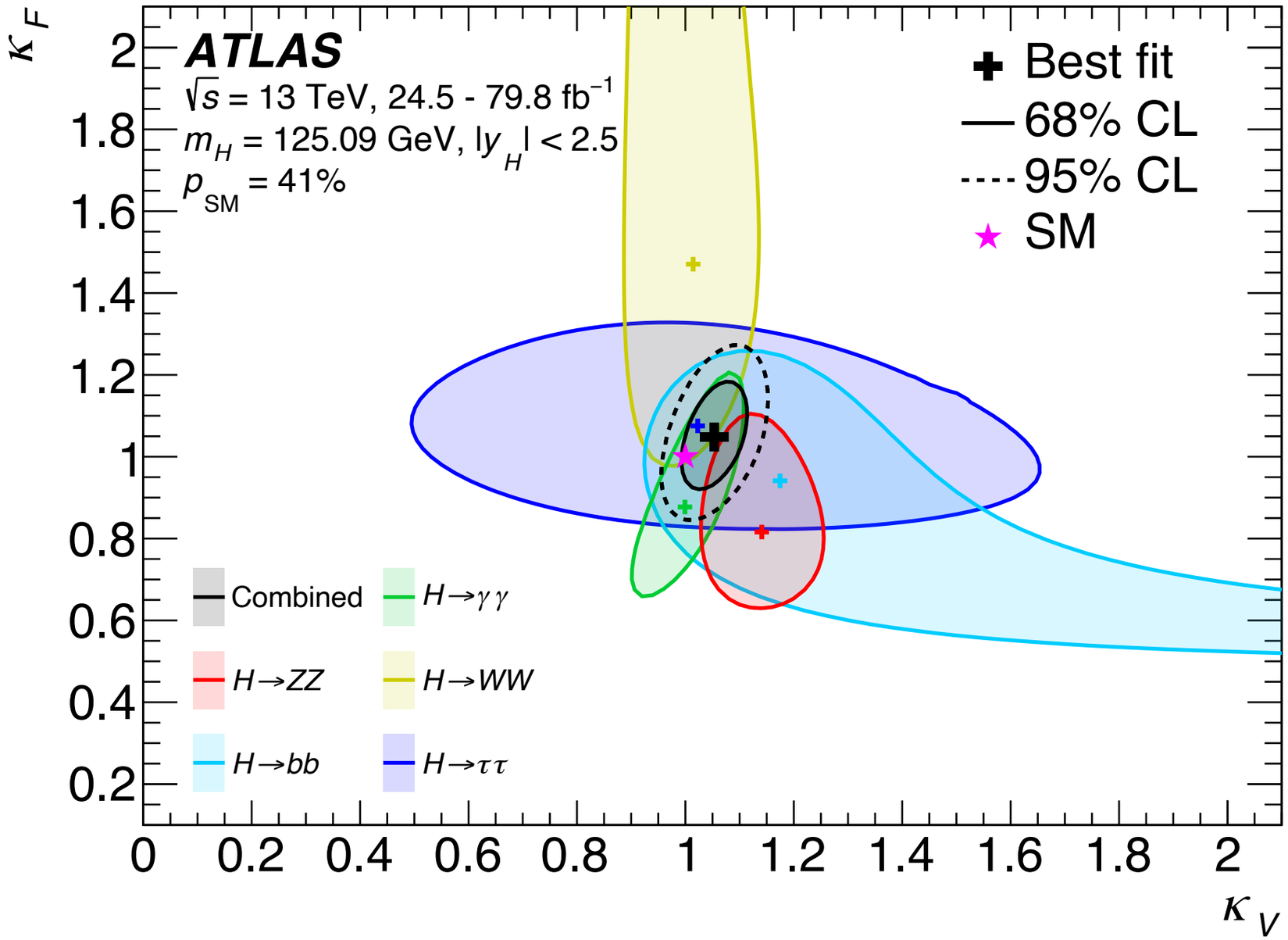
$$= \quad g_{hVV}^{(\rm SM)}\left(1 - c\,\frac{v^2}{\Lambda^2}\right)$$

$$\kappa_V$$

Higgs coupling measurement

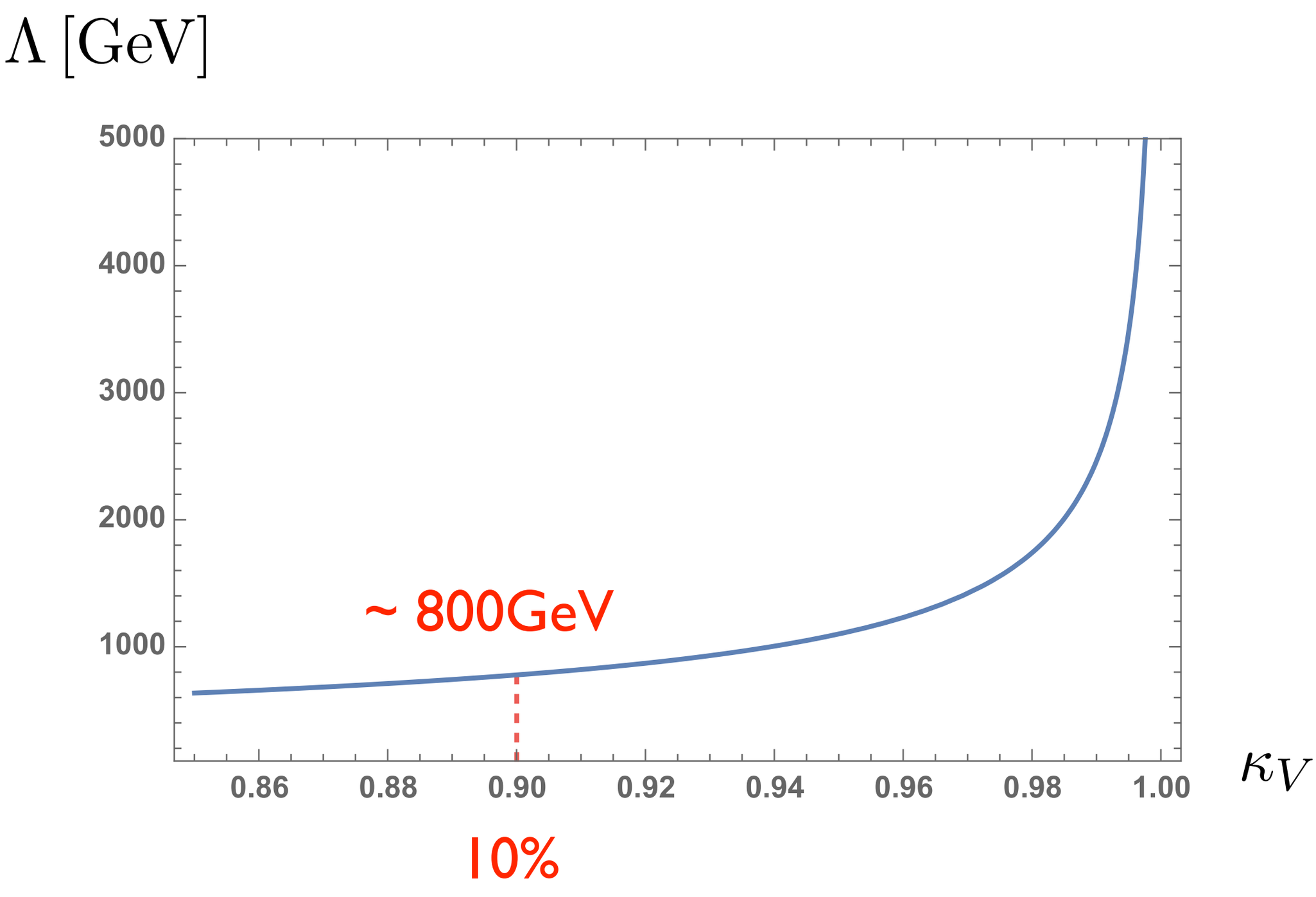


Higgs coupling measurement



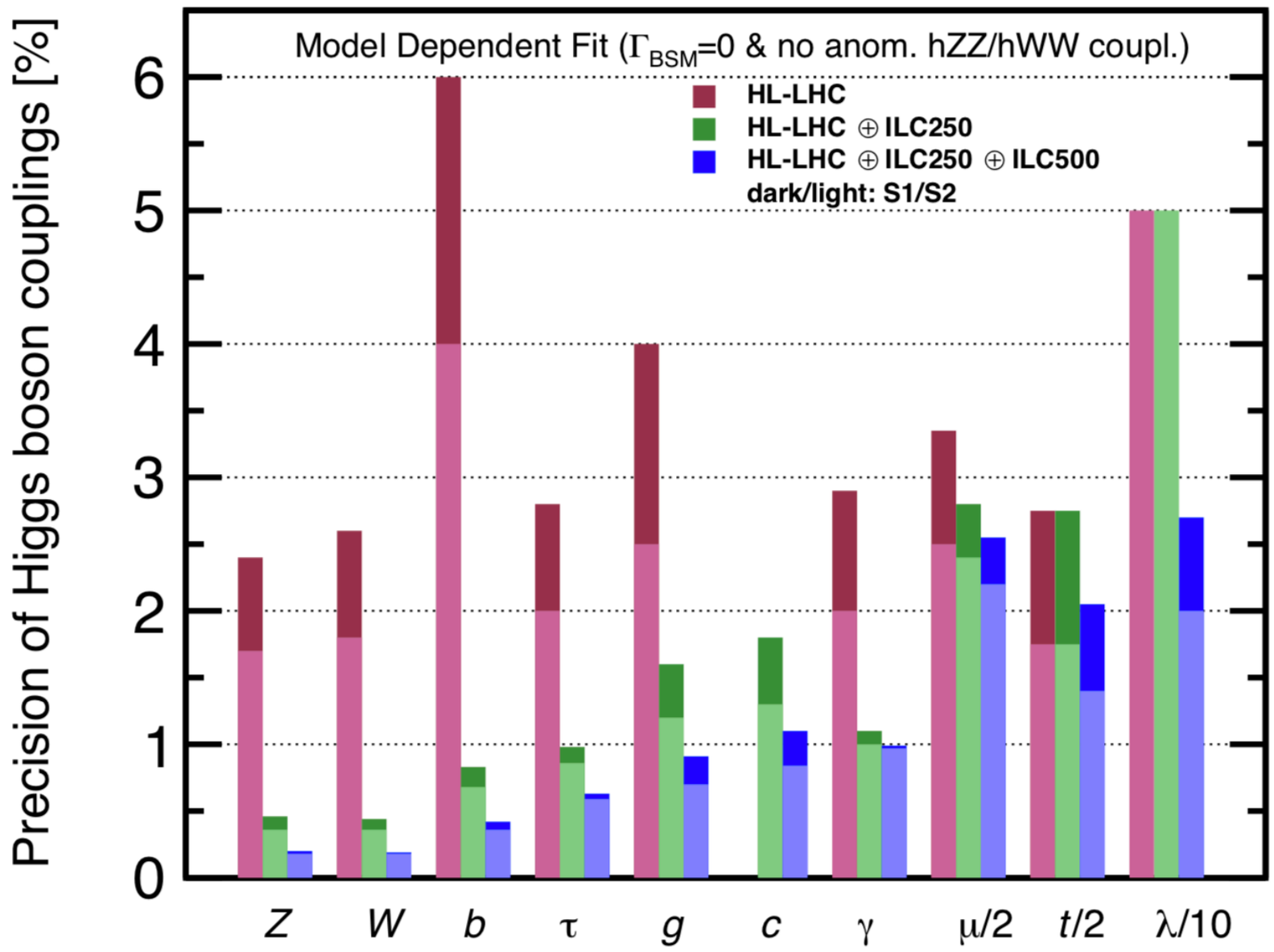
PRD 101 (2020) 012002

Higgs coupling measurement

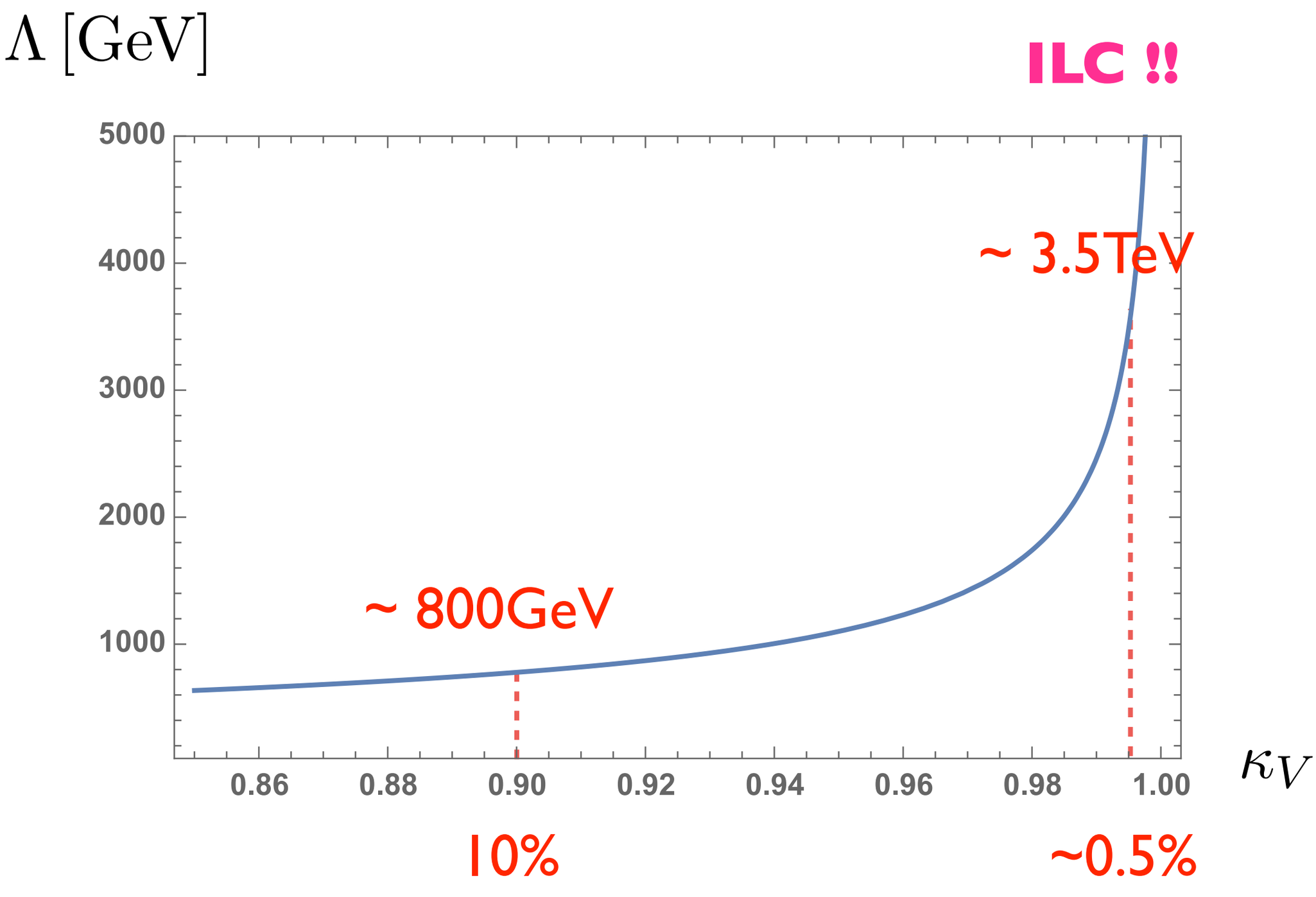


10%

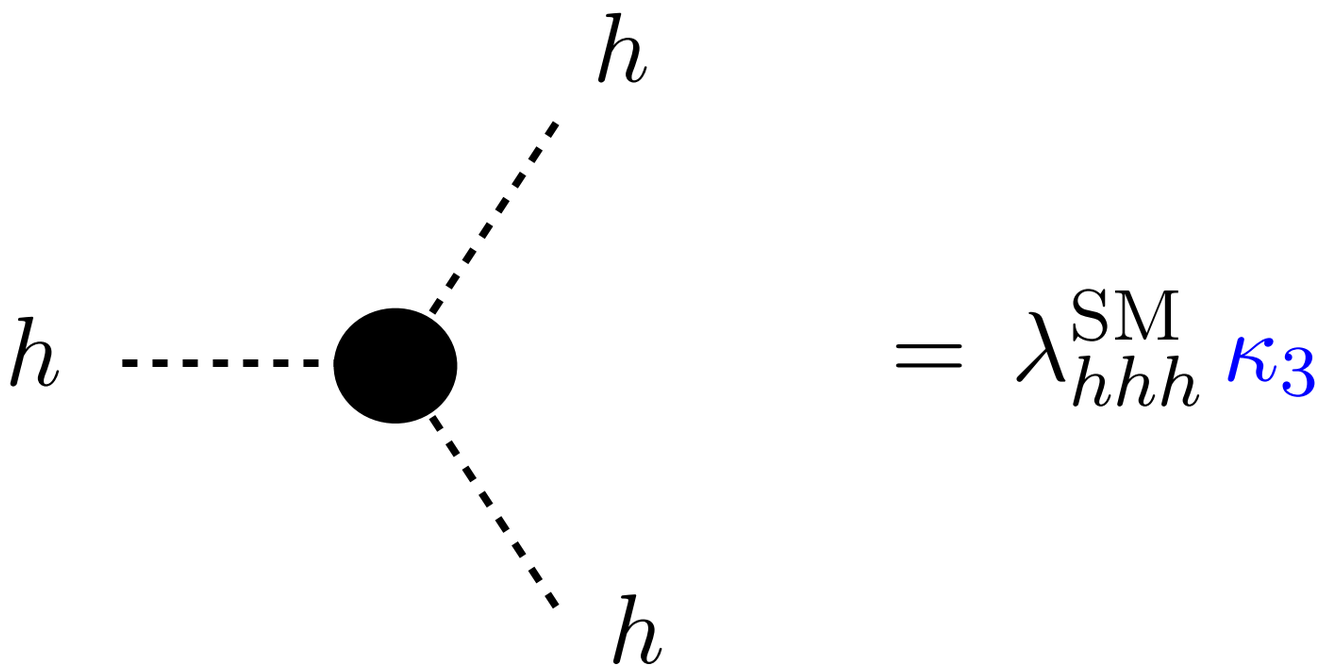
Higgs coupling measurement



Higgs coupling measurement



Higgs selfcoupling



$$= \lambda_{hhh}^{\rm SM}\, \kappa_3$$

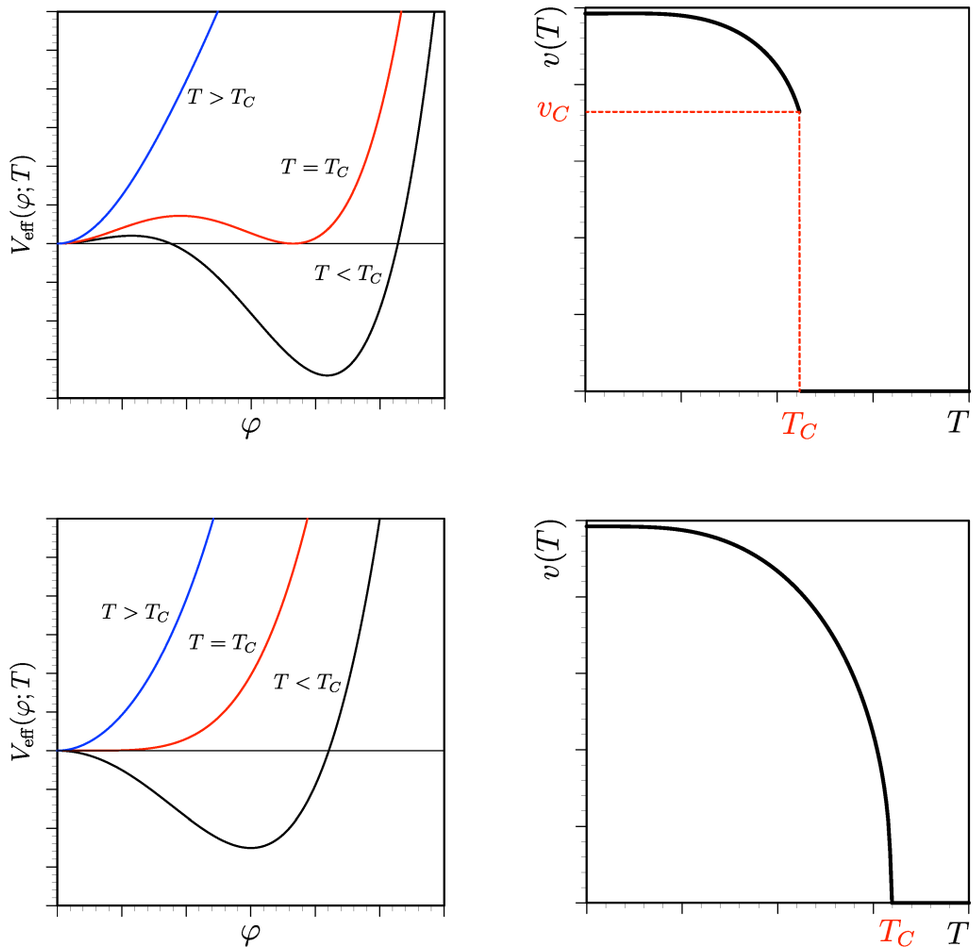
- Large deviation is still allowed.

e.g. CMS 2011.12373

$-3.3 < \kappa_3 < 8.5$

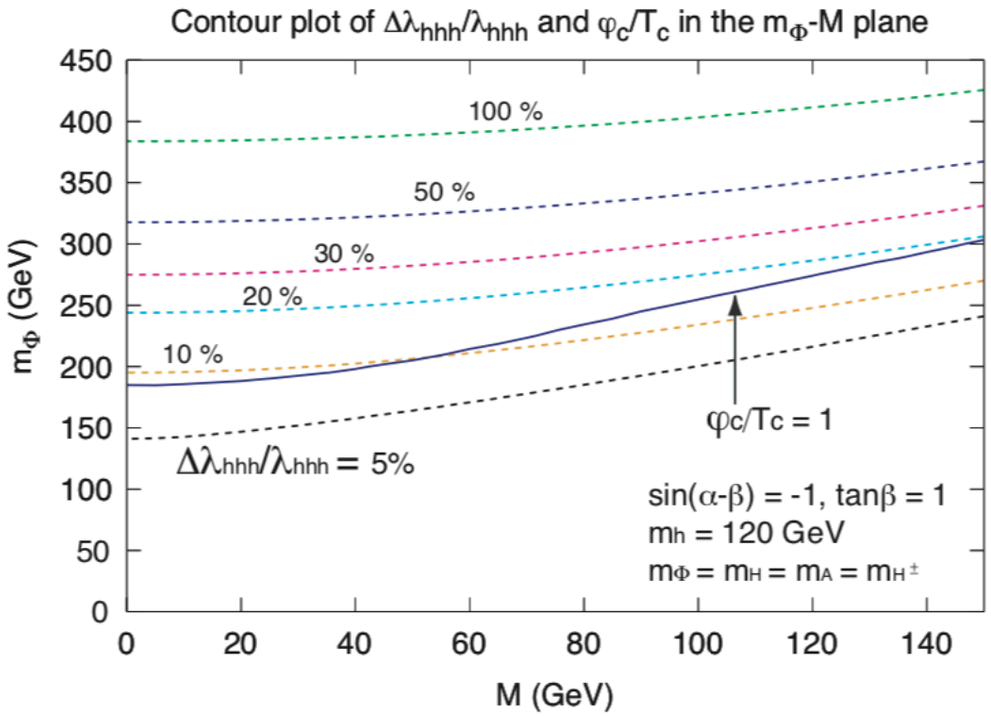
- Large deviation is *expected* (Next page)

Electroweak phase transition



[Senaha (2020)]

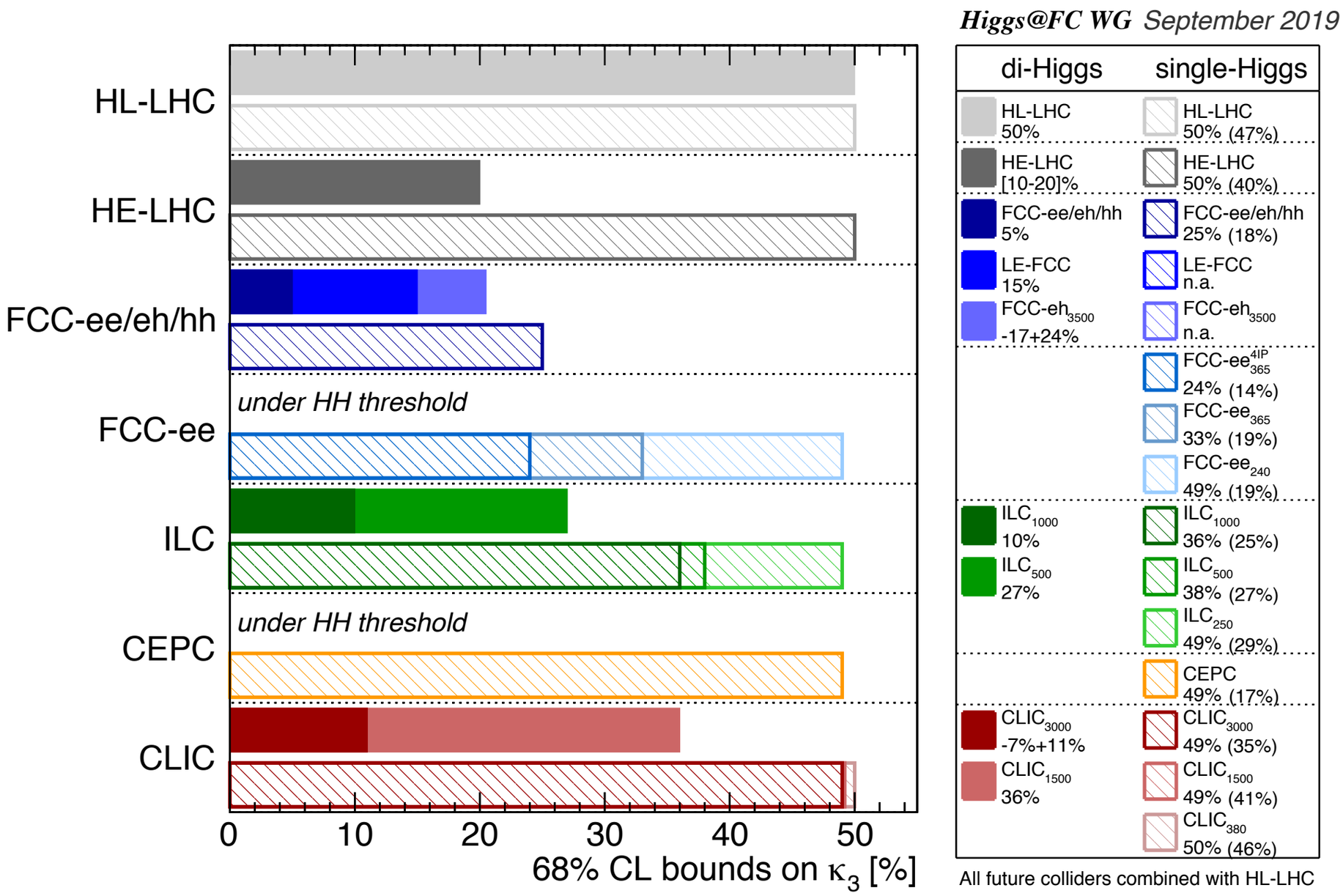
Two Higgs Doublet Model



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

[Kanemura, Okada, Senaha (2005)]
+ 田中さん(21日)、村さん(24日)のトーク

Higgs selfcoupling measurement



[de Blas, et al (2020)]

$\kappa_3 \gg 1$ with $\kappa_V \simeq 1$?

- Consider *SM + n_S real singlet scalars*
- No mixing → $\kappa_V \simeq 1$
- Mass $m^2 = M^2 + \kappa \langle \Phi \rangle^2$

$$\kappa_3 = 1 + \frac{4n_S}{3(4\pi)^2} \frac{m^4}{m_h^2 v^2} \left(1 - \frac{M^2}{m^2}\right)^3$$

[Kakizaki, Kanemura, Matsui (2015)]

- $M^2 \simeq 0$: *Non-decoupling* even for $m \gg m_h$

EFT point of view

- Integrating out extra scalars

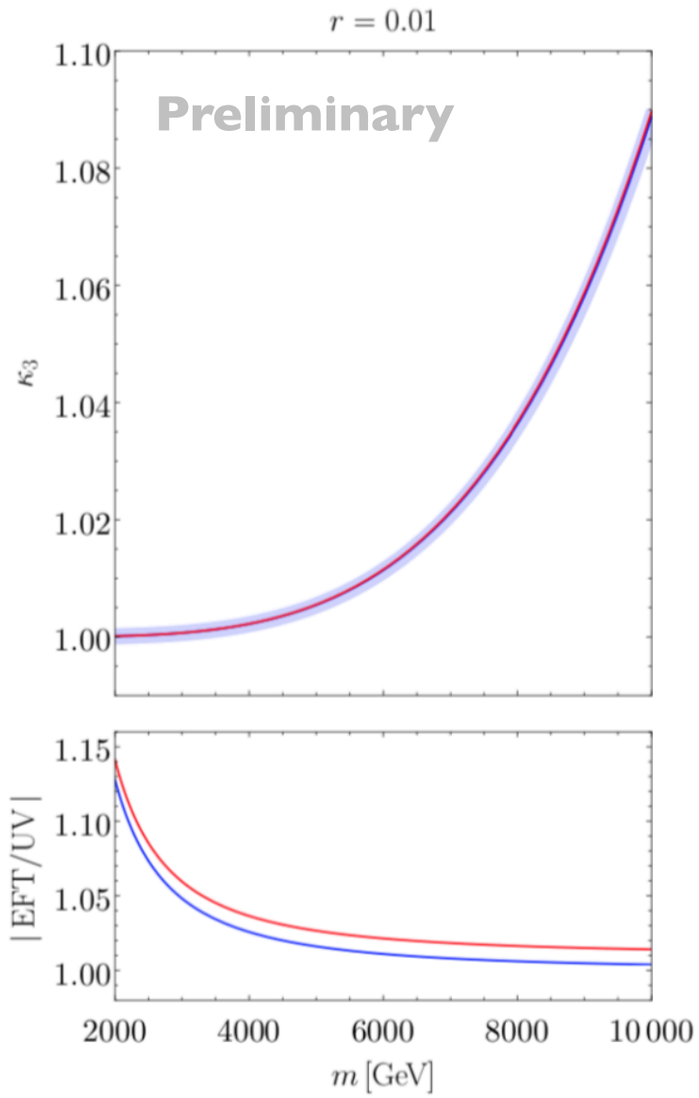
$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} - \frac{n_S}{4(4\pi)^2}(M^2+\kappa|\Phi|^2)^2 \ln\frac{M^2+\kappa|\Phi|^2}{\mu^2} + \cdots$$

- "SMEFT" expansion (up to dim 6)

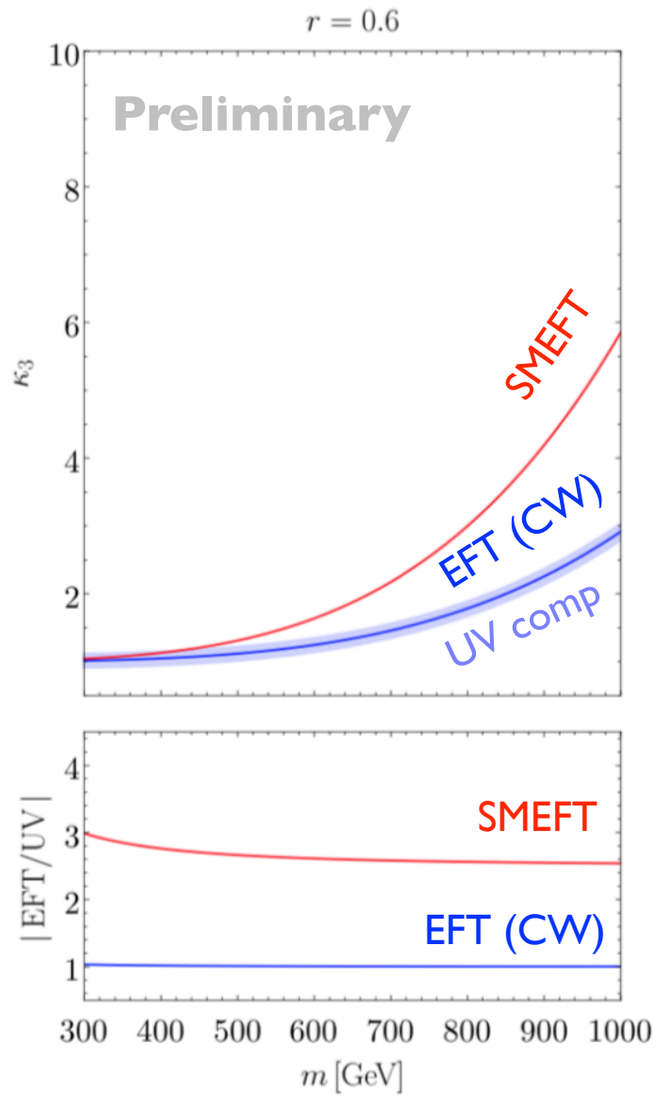
$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} - \frac{n_S}{6(4\pi)^2}\frac{\kappa^3}{M^2}|\Phi|^6 + \cdots$$

Beyond SMEFT

Decoupling



Non-Decoupling



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

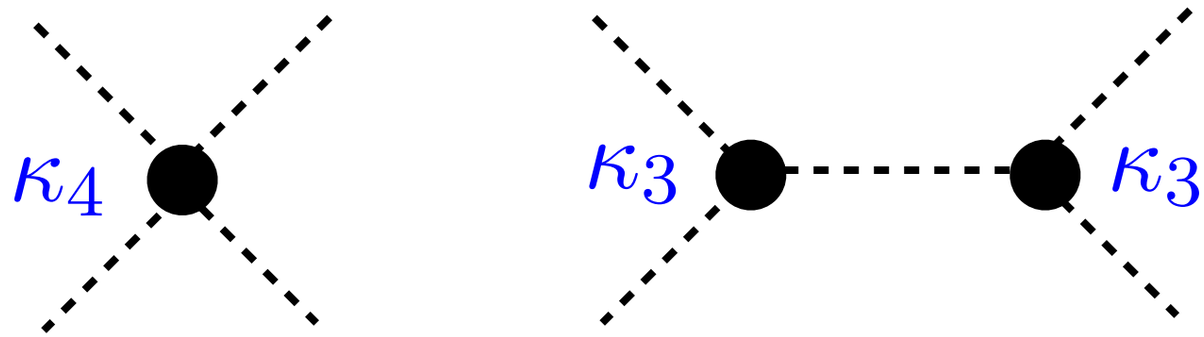
[Nagai-Kanemura (On-going)]

- SMEFT cannot be applied for non-decoupling case !

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

How large *hhh* / *hhhh* can be ?

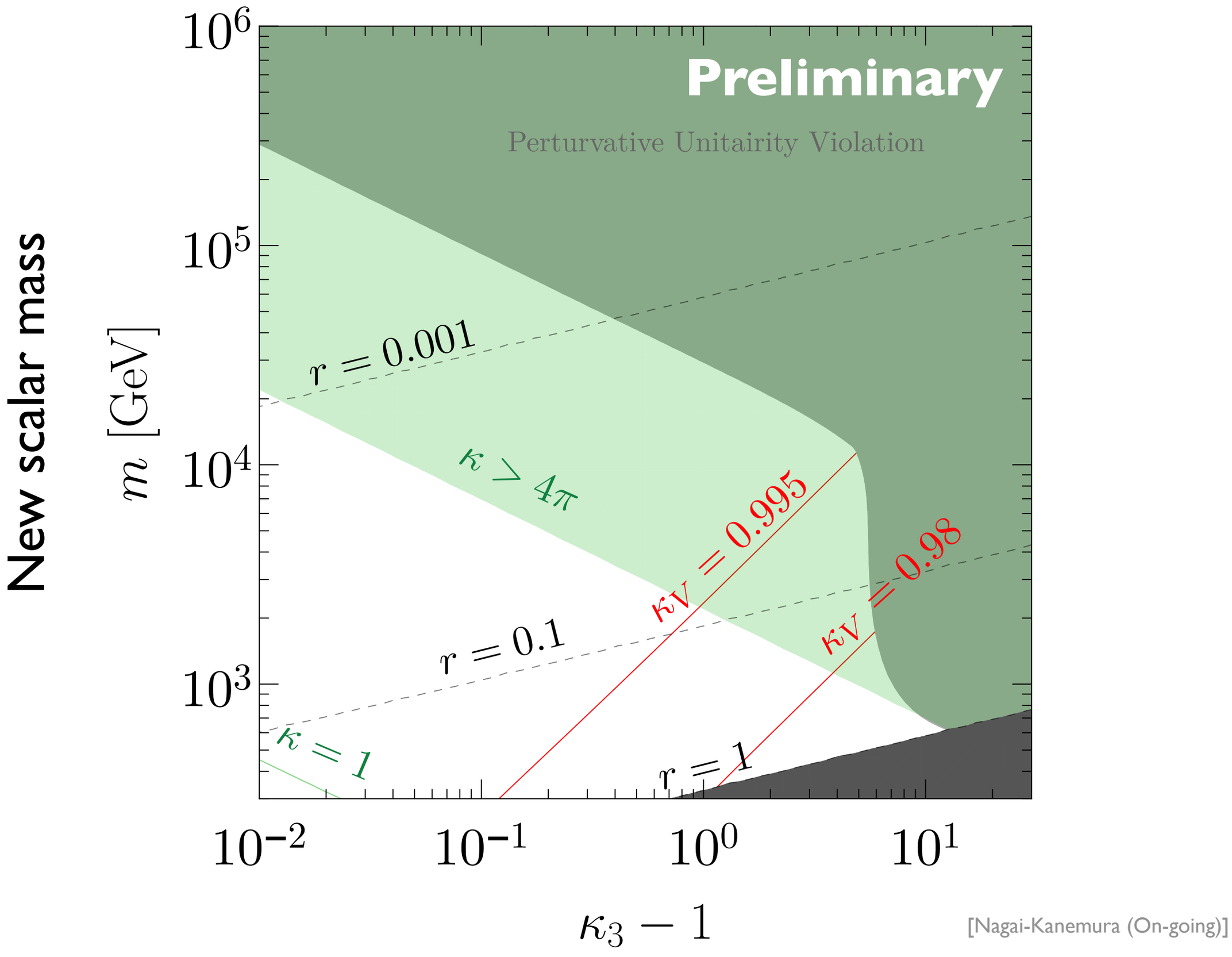
- Perturbative unitarity violation in hh → hh ?



- Upper bound : [Lee-Quigg-Thacker (1977)] [Nagai-Kanemura (On-going)]

$$\frac{1}{16\pi}\frac{3\kappa_4+4\sqrt{K}+5}{4}\frac{M_h^2}{v^2}<\frac{1}{2}$$

$$K=\frac{1}{16}\left(9\kappa_4^2+73-144\kappa_3+108\kappa_3^2-30\kappa_4\right)$$



[Nagai-Kanemura (On-going)]

Summary

- Big question : *"What is the origin of EWSB ?"*
- Higgs couplings imprint the clue.
- Non-decoupling effect in Higgs potential ? (Beyond SMEFT!)
- **We need ILC !!**