Student lectures November - December 2021

Higgs pair production - searches at the LHC

PLAN:

Lecture 1: Theory motivation

Lecture 2: Status of the di-Higgs at the LHC

Lecture 3: Challenge - background estimation in the $HH \to 4b$ analysis

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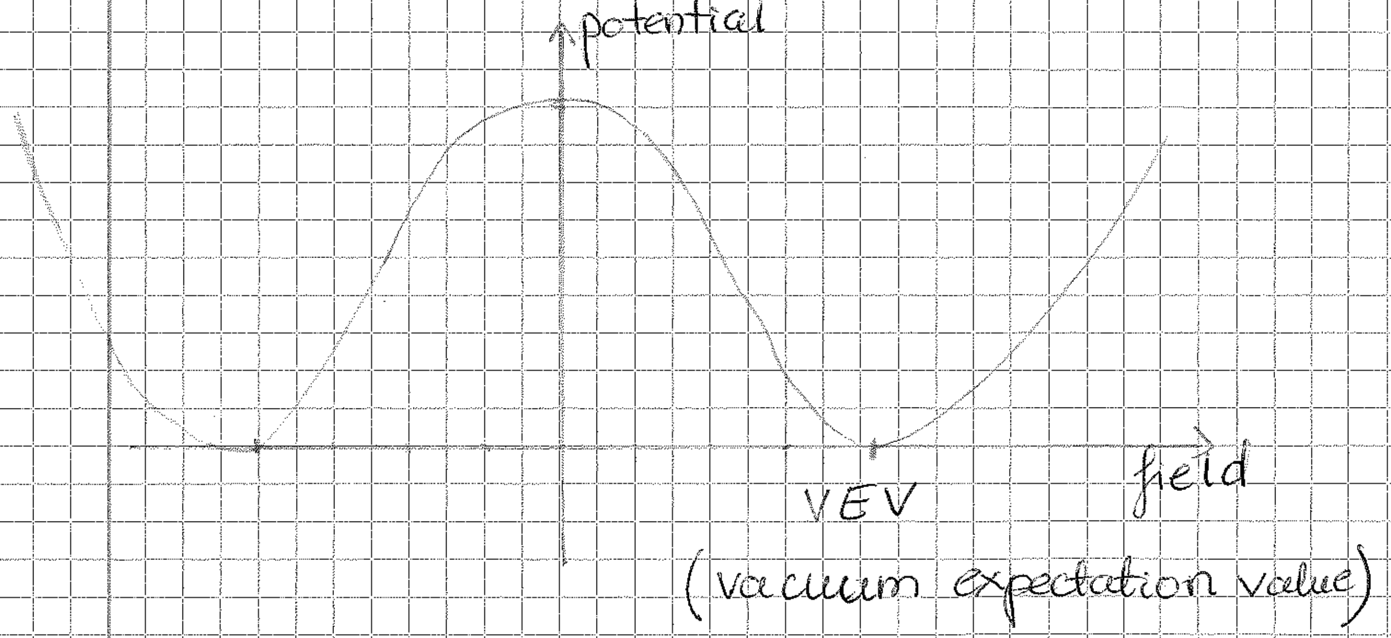
The Higgs potential

→ in the SM: $V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$

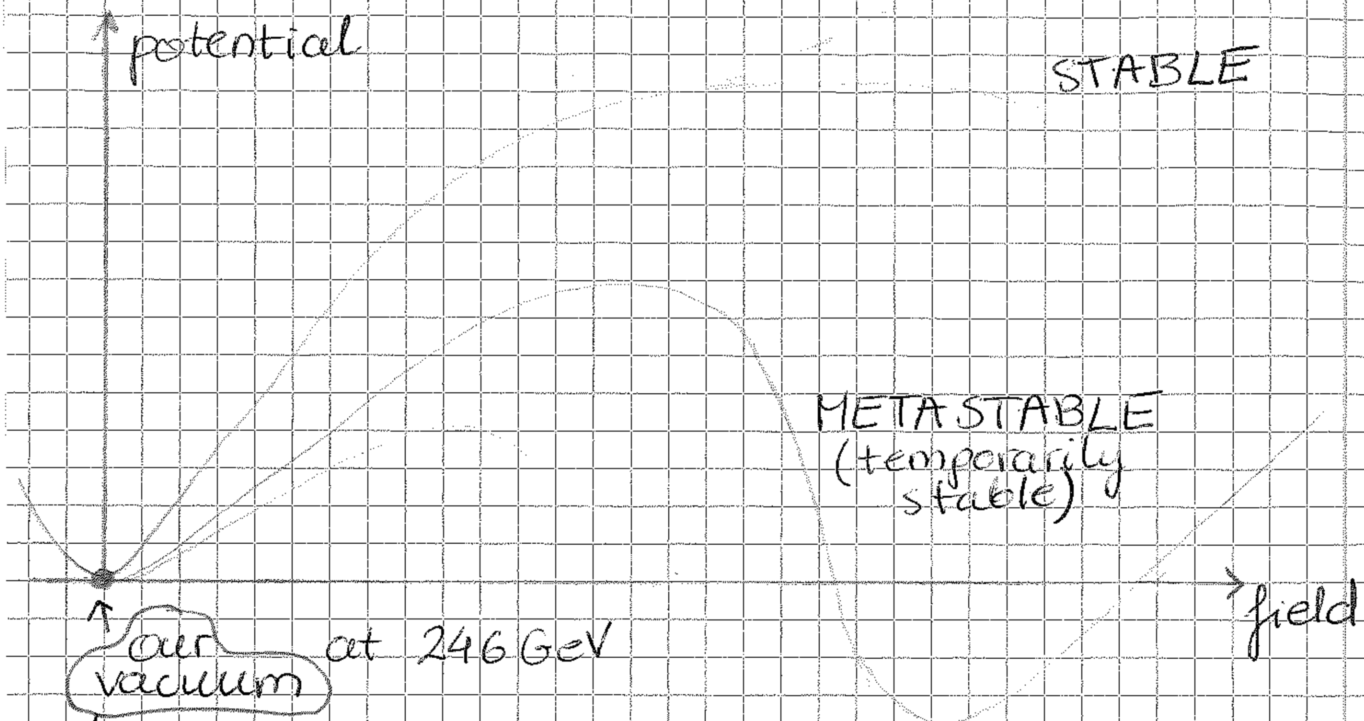


→ when the field is at the minimum → the symmetry is broken
(SU(2) and U(1) hypercharges mix)

Q: Is this effect only possible with the SM potential?

⇒ No, we only know about some of the properties of the Higgs potential, we <u>don't know</u> its <u>shape</u>

Possible scenarios

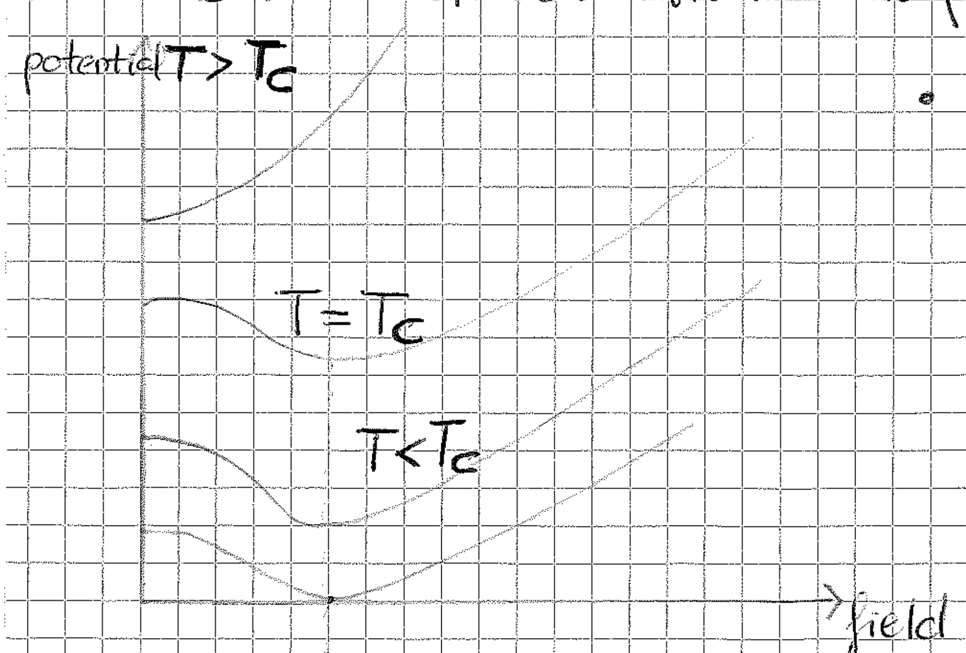


↳ Q: Is it a true minimum or only a local minimum?

↑ a deeper minimum could exist

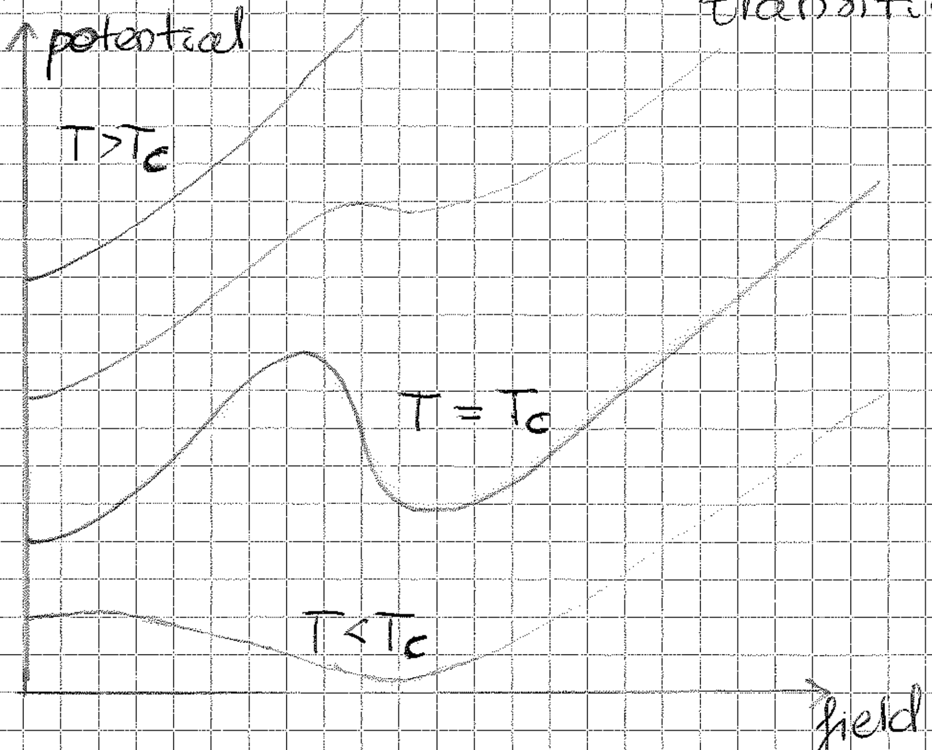
Main motivation for other models
↳ explain electroweak baryogenesis
→ symmetry breaking in the early universe proceeds through a phase transition

the SM case – smooth transition (no explanation of baryogenesis)

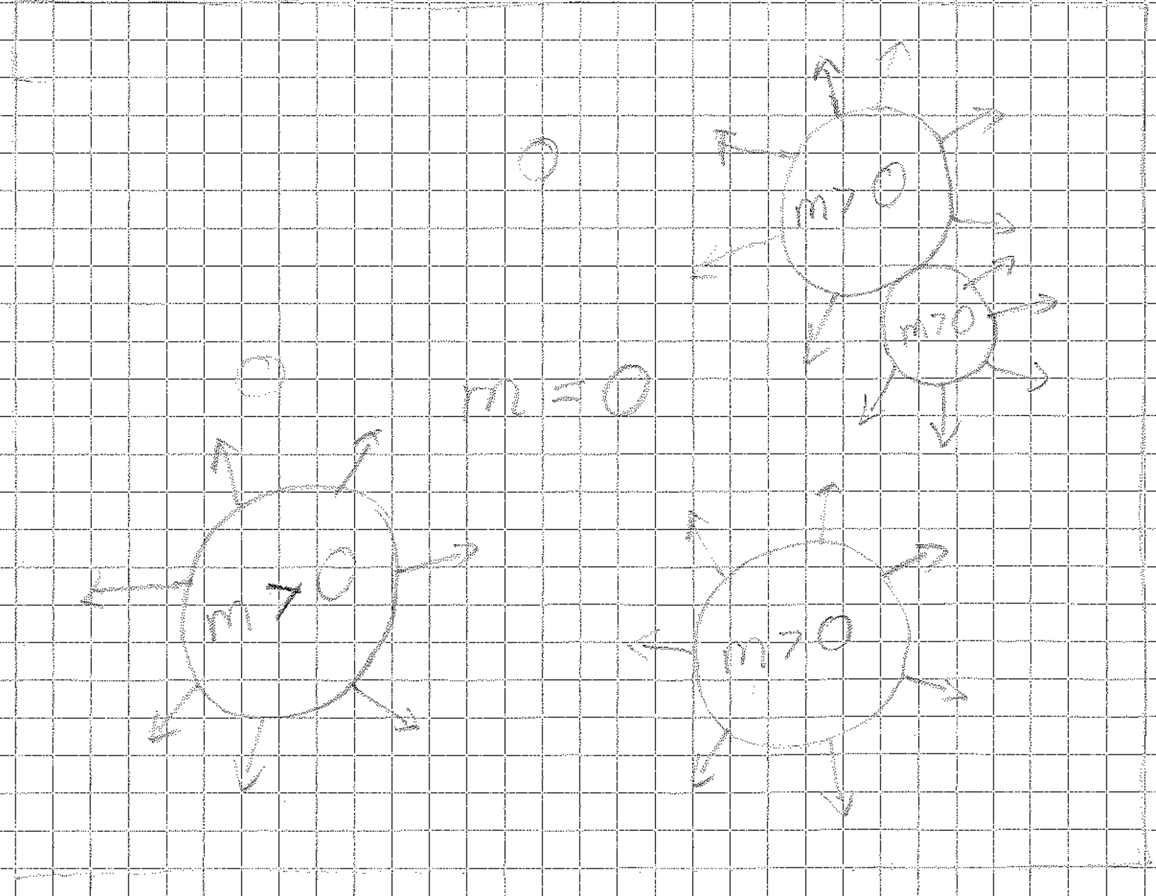


- smooth transition between the initial minimum and the 2-nd minimum

Other possibilities → first order phase transition



Q: What happens at $T = T_c$?
BUBBLE NUCLEATION



- at $T = T_c$ there are coexisting minima

→ inside the bubble: symmetry is broken, VEV=246 GeV)
m>0

→ outside of bubbles: electroweak symmetry is unbroken, everything is massless

→ at the point of thermal non-equilibrium: quarks and fermions move from outside to inside the bubbles and get the mass (baryon number is violated inside the bubbles, but violation is suppressed outside the bubbles)

→ matter-antimatter assymetry could be generated in this "bubbling" transition

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How can we explore the shape of the Higgs potential?

→ the SM Higgs potential:

$$V(\phi) = -\mu^2 \phi^2 + \lambda \phi^4$$

→ expanding around the minimum

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 +$$

$$= V_0 + \frac{1}{2} m_H^2 h^2 + \frac{m_H^2}{2v^2} v h^3 + \frac{1}{4} \frac{m_H^2}{2v^2} h^4$$

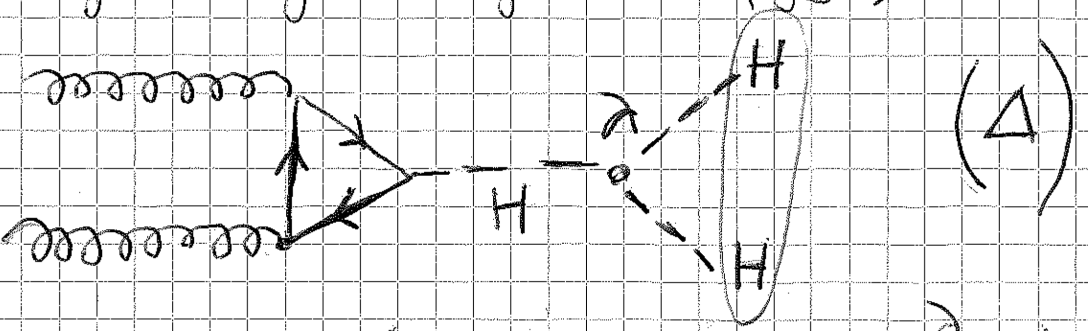
$\frac{1}{2} m_H^2 h^2$ → mass term ↓ well measured at the LHC, $m_H \approx 125$ GeV

$\frac{m_H^2}{2v^2}$ → Higgs self-coupling λ ↳ not measured but fixed in the SM by m_H and v

v → $v = \frac{\mu}{\lambda}$ ↳ measured in muon decays (246 GeV)

How to measure Higgs self-coupling?

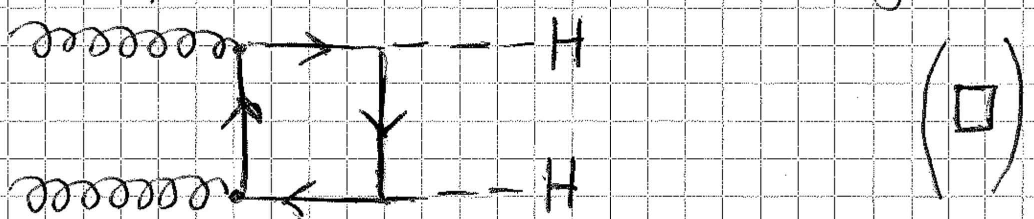
→ easiest: Higgs pair production via gluon-gluon fusion (ggF)



→ measure λ (in terms of $\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$)

↳ if the value deviates from the SM, the BSM framework is needed to explain the physics

→ measurement challenge: di-Higgs can also be produced via a box diagram



→ Δ and □ interact destructively in the SM

→ result: very low cross-section in the SM (~30 fb at 13 TeV c.f. WWW production ~ 800 fb)

→ potential BSM scenarios enhance this cross-section → another motivation to look at them

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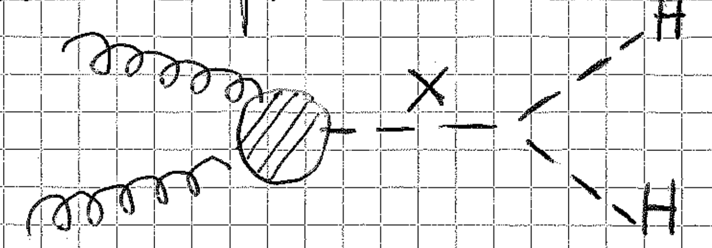
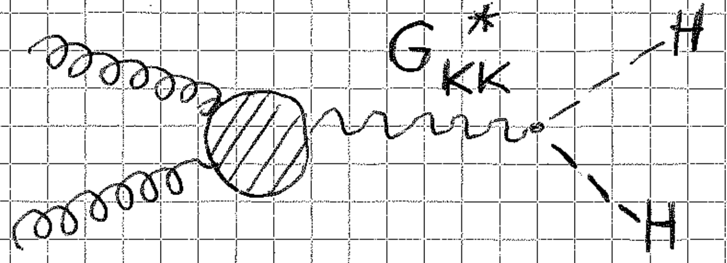
Note: resonant vs non-resonant production

- above diagrams → non-resonant production
- measuring/setting limits on κ_λ, could be either an SM or BSM process

- resonant production → explore BSM physics

1) 

via Scalar boson (e.g. two Higgs doublet model)

2) 

via Spin-2 boson

- set limits on masses of the resonances
- set limits on κ_λ values as well

Example of a non-resonant BSM benchmark scenario

↳ Dimension-6 EFT extension to the SM

- it gives modification to the Higgs potential
- possible to derive model-independent constraints on new physics

How?

$$V(H) = \mu^2 |H|^2 + \lambda |H|^4 + \frac{c_6}{\Lambda^2} \lambda |H|^6$$

↳ $\frac{c_6}{\Lambda^2}$ makes Baryogenesis possible

expanding the potential:

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_{3H} v H^3 + \frac{\lambda_{4H}}{4} H^4 + \mathcal{O}(H^5)$$

$$\lambda_{3H} = \frac{m_H^2}{2v^2} \underbrace{\left[1 + \frac{c_6 v^2}{\Lambda^2} \right]}_{\kappa_\lambda}$$