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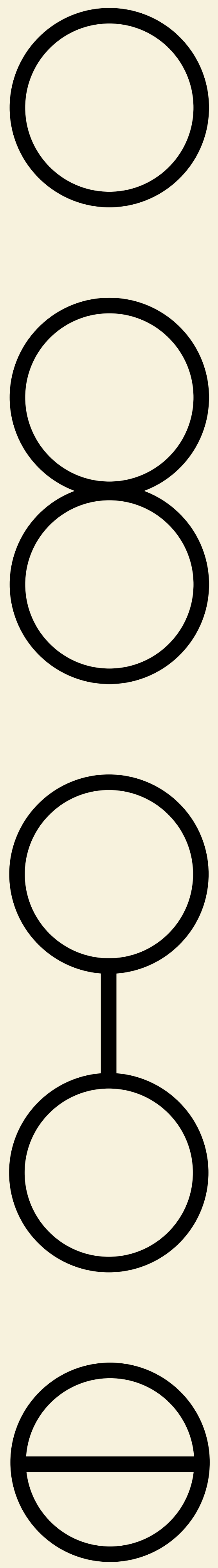
A Critical Look at the Electroweak Phase Transition

Based on work with Andreas Ekstedt
arXiv: 2006.12614



Johan Löfgren
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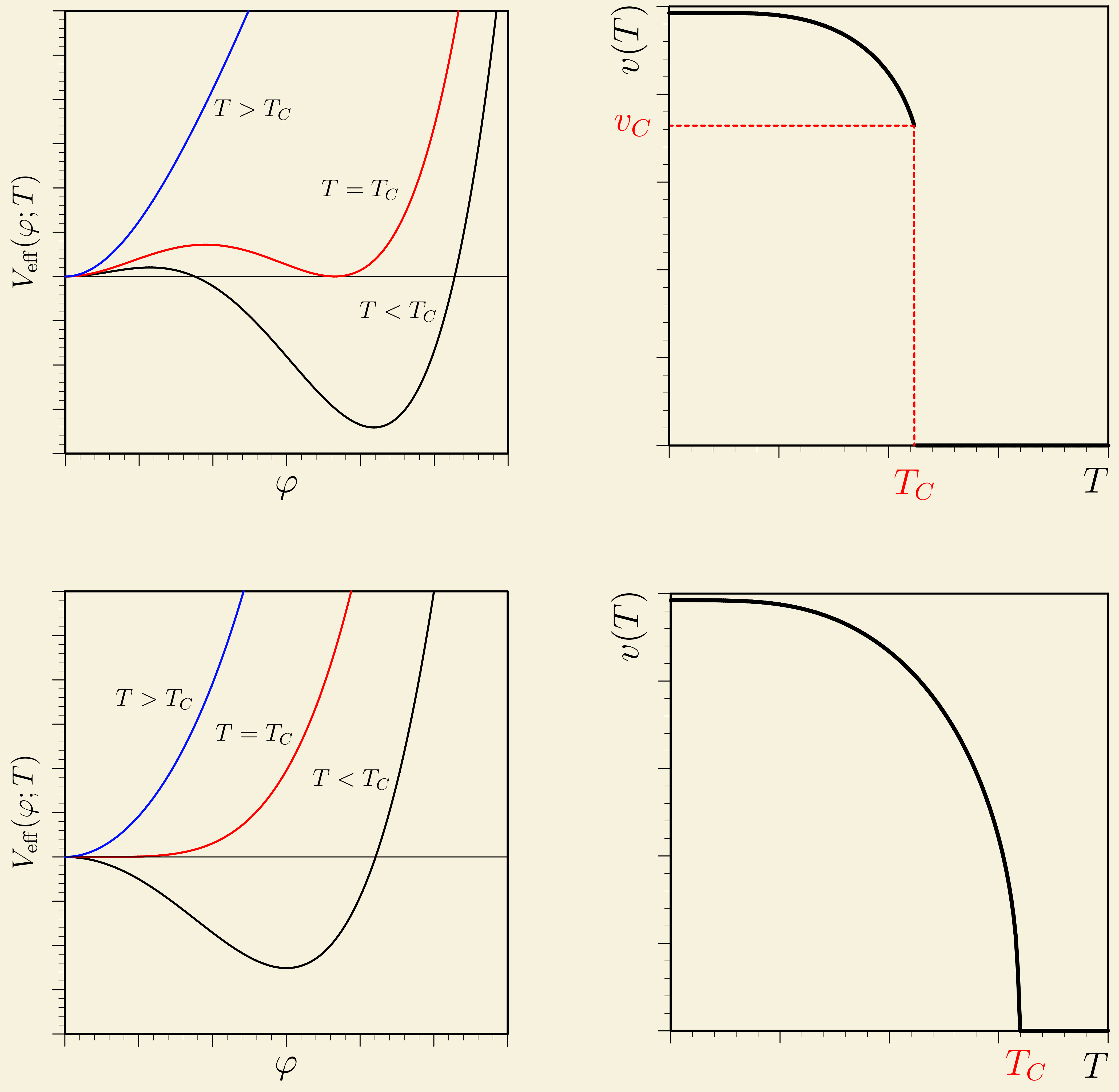
Phase transitions

Senaha (DOI: 10.3390/sym12050733)



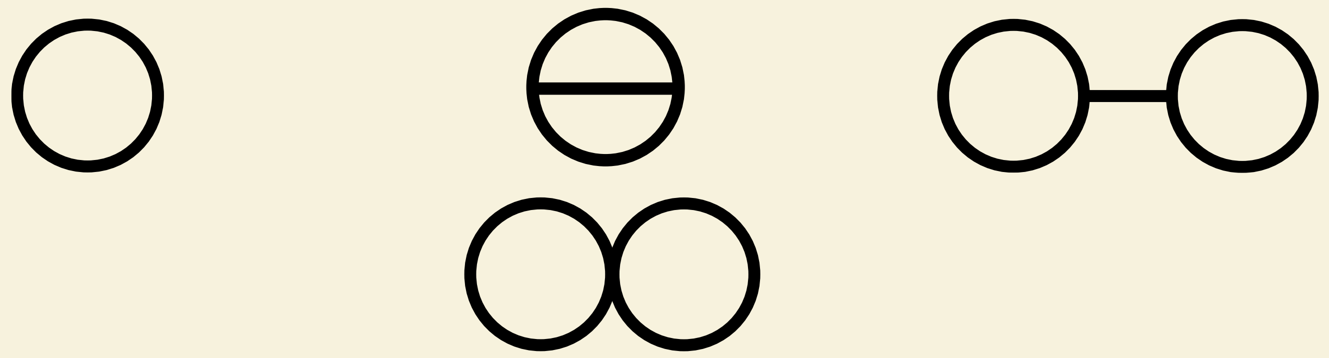
- Two different classes
- Electroweak phase transition might have detectable remnants
- **Two opposing problems**: gauge dependence and breakdown of the loop expansion

Gauge dependence

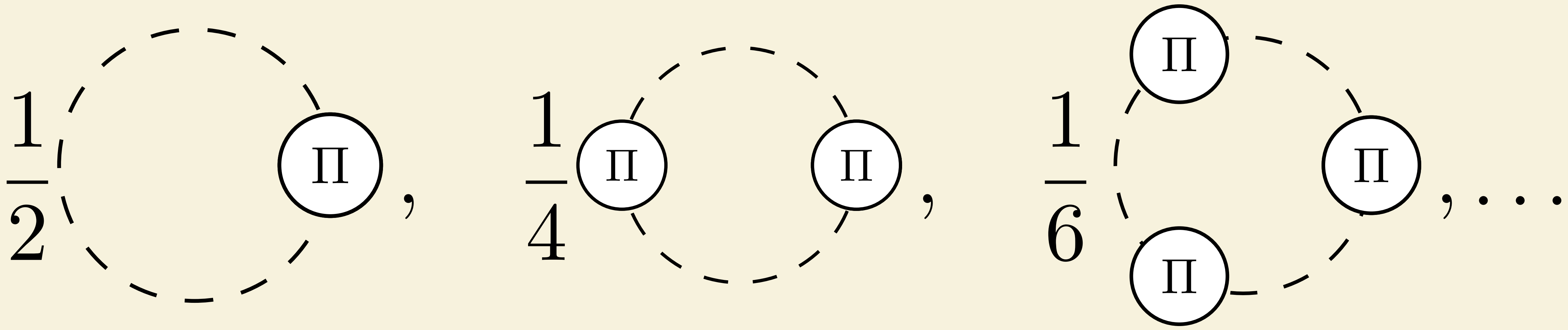
- The effective potential is gauge dependent
- Resolution: use the ħ-expansion ←
- Be pedantic about loop counting!

S. Weinberg (DOI: 10.1103/PhysRevD.7.2887)
Fukuda and Kugo, (DOI: 10.1103/PhysRevD.13.3469)
Laine (arXiv: 9411252)
Patel and Ramsey-Musolf (arXiv: 1101.4665)

$$V(\phi^{\mathrm{M}}) = V_0\big|_{\phi_0^{\mathrm{M}}} + \hbar\, V_1\big|_{\phi_0^{\mathrm{M}}} + \hbar^2 \left(V_2 - \frac{1}{2} \left(\phi_1^{\mathrm{M}}\right)^2 \partial^2 V_0 \right)\Bigg|_{\phi_0^{\mathrm{M}}} + \ldots$$



Resummation



$$\frac{d_n}{d_{n-1}} \sim \frac{e^2 T^2}{m^2}$$

- The perturbative expansion breaks down
- Cannot order by loops anymore: a resummation must be made
- Then what about gauge invariance?

Loop-induced symmetry breaking

$T = 0$: Coleman-Weinberg model

- Regular loop counting: **λ** ~ e^2
- Radiative symmetry breaking: **λ** ~ e^4 ← S. Coleman and E. Weinberg (DOI:10.1103/PhysRevD.7.1888) Andreassen, Frost, and Schwartz (1408.0287)

$$V^{\text{LO}} = \frac{\lambda}{24}\phi^4 + \frac{e^4}{16\pi^2}\phi^4\left(-\frac{5}{8} + \frac{3}{2}\ln\frac{e\phi}{\mu}\right)$$

- The new **power counting** "forces" a resummation.

e.g. the Higgs mass must be resummed

- Perturbative expansions ordered according to a consistent counting are gauge invariant.

Loop-induced barriers

$T > 0$: *Abelian-Higgs*

- For phase transitions, think hard about the **power counting**

- **λ** ~ e³ gives a barrier

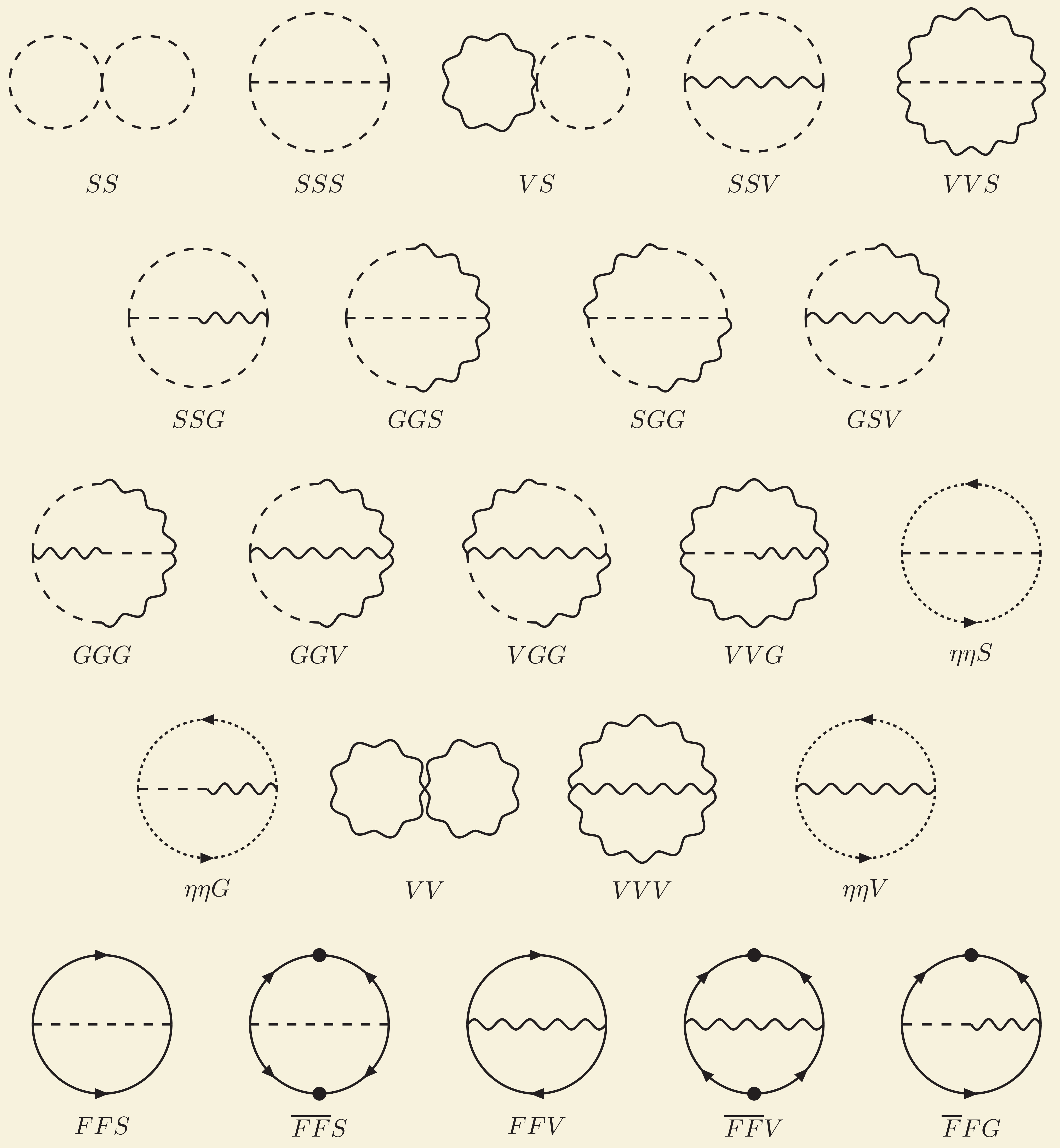
Arnold and Espinosa (9212235)
Konstandin and Garny (1205.3392)

$$V_{\rm LO}(\phi, T) = -\frac{1}{2}m_{\rm eff}^2(T)\phi^2 - e^3\frac{T}{12\pi}\phi^3 + \frac{\lambda}{8}\phi^4.$$

- Resummation and gauge invariance at the same time

Ekstedt, JL: 2006.12614

Martin and Patel (1808.07615)



Power-counting

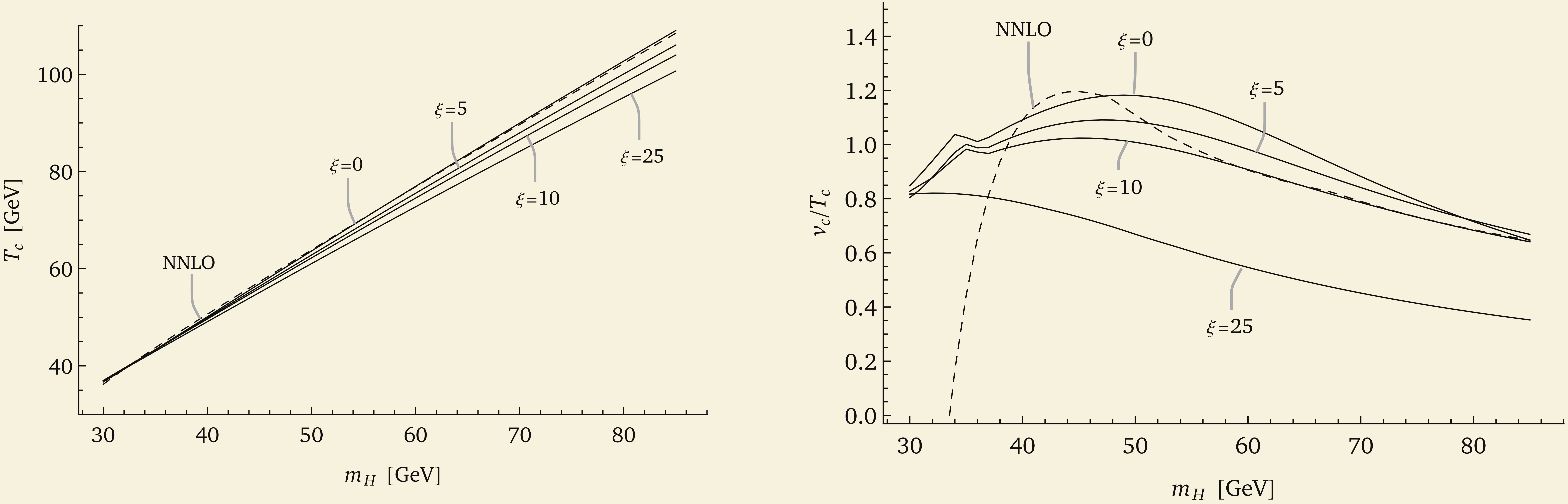
Ekstedt, JL: 2006.12614

$$V_{\min} = e^{-1} V_{\mathrm{LO}}\Big|_{\phi_{\mathrm{LO}}} + V_{\mathrm{NLO}}\Big|_{\phi_{\mathrm{LO}}} + e^{1/2} V_{\mathrm{NNLO}}\Big|_{\phi_{\mathrm{LO}}} + e\left(V_{\mathrm{N^3LO}} - \frac{1}{2}\phi_{\mathrm{NLO}}^2 \partial^2 V_{\mathrm{LO}}\right)\Big|_{\phi_{\mathrm{LO}}} + \ldots$$

$$\begin{aligned} V_{\mathrm{LO}}(\phi) &\sim V_0(\phi) + \kappa T^2 \phi^2 (e^2 + \lambda^2) + \kappa T (2Z^{3/2} + Z_L^{3/2}), \\ V_{\mathrm{NLO}}(\phi) &\sim \kappa Z^2 + \kappa^2 e^2 T^2 Z, \\ V_{\mathrm{NNLO}}(\phi) &\sim \kappa T (\overline{G}^{3/2} + \overline{H}^{3/2}), \\ V_{\mathrm{N^3LO}}(\phi) &\sim \kappa^2 e^2 T (Z^{3/2}) + \kappa^3 e^4 T^3 (Z^{1/2}) + \ \ldots, \end{aligned}$$

Results

Ekstedt, JL: 2006.12614



Comparisons of **power counting** method and standard approach (gauge dependent numerical minimization), for some various values of the gauge fixing parameter, in the SM. (JL, Ekstedt: 2006.12614)

Conclusions

- Gauge independence and resummation simultaneously with "ħ-expansions" that employ proper **power counting**

Future Work

- Further theoretical uncertainties

  Croon, Gould, Schicho, Tenkanen, White (2009.10080)

- Other observables related to tunneling
- Other models

  Camargo-Molina, Enberg, JL: 2103.14022