Search for the endpoint of first order phase transition in many-flavor lattice QCD

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in collaboration with

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Based on PRL110, 172001 (2013) + α

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Introduction

- EW baryogenesis in Technicolor models

  Appelquist, Schwetz and Selipsky, PRD52, 4741 (1995);
  Kikukawa, Kohda and Yasuda, PRD77 (2008) 015014

  ⇒ 1st order chiral transition

  ⇒ Techni-fermion masses must be lighter than m_h^{crit}

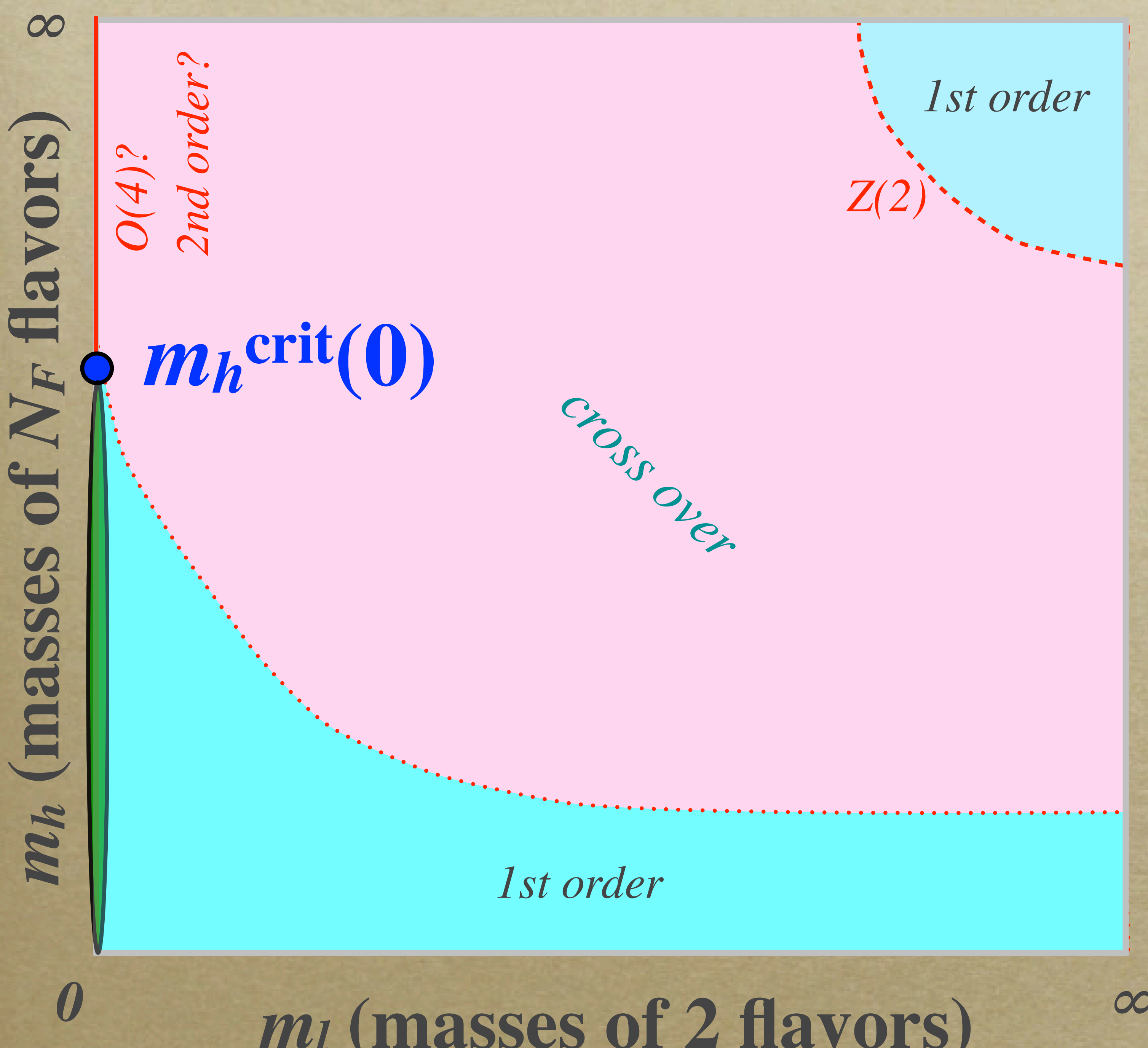
  Pisarski & Wilczek(1984)

  ⇒ m_h^{crit} gives upper bound on techni-pion mass

  ⇒ compare with LHC

We consider 2(light) + N_f (heavy) flavor QCD as TC.

Expected Colombia plot for 2+N_f QCD



Define $m_h^{crit}(m_l)$ as the boundary between 1st and corssover.

1st order $\Leftrightarrow m_h < m_h^{crit}$

First goal: Identify $m_h^{crit}(m_l)$

$m_h^{crit}(0) \Leftrightarrow m_h^{TCP}$

In other words, search for tricritical point

Tricritical point

Mean field analysis:

$$m_l \sim [m_h^{TCP} - m_h^{crit}(m_l)]^{5/2}$$

The power 5/2 is independent of N_f.

⇒ Able to test this universal scaling with $2+N_f$-flavor QCD (Larger N_f has a great advantage.)

⇒ Feedback on real (2+1) QCD

Strategy I: Re-weighting

- Starting from 2(light)-flavor configurations, incorporate the determinant of N_f (heavy) flavors by re-weighting.

$$Z(\beta, m_f, \mu_f) = \int \mathcal{D}U \; e^{6\beta N_{\rm site}\hat{P}} \; (\det M(m_{\rm l}, 0))^2 \prod_{h=1}^{N_{\rm f}} \left(\frac{\det M(m_{\rm h}, 0)}{\det M(\infty, 0)} \right)$$

M:quark matrix
P :plaquette
Ω:Re[Polyakov loop]

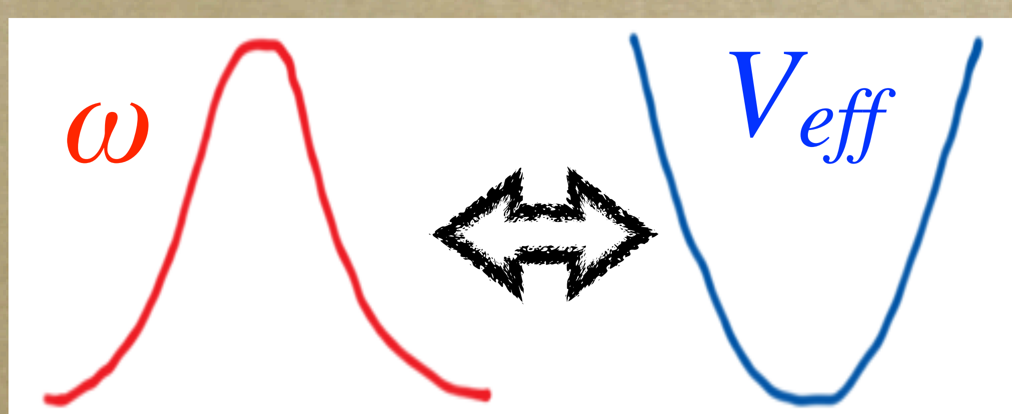
Re-weighting with HPE

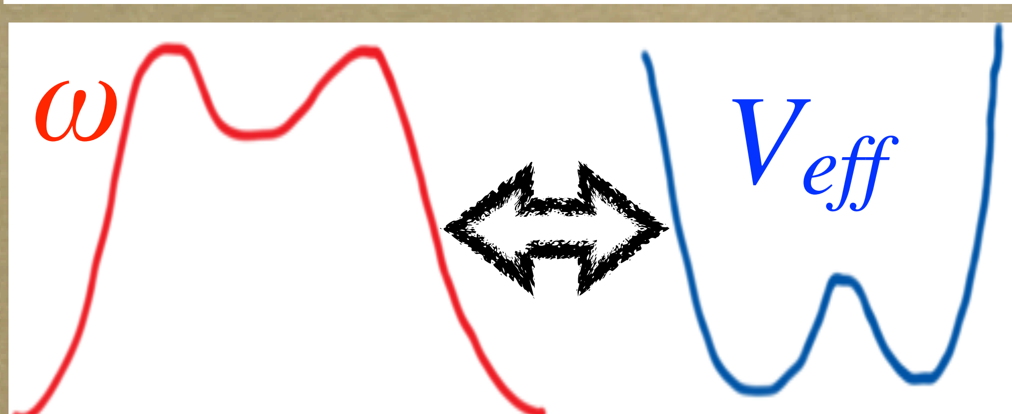
$$\ln \left[\frac{\det M(\kappa_{\rm h}, 0)}{\det M(0, 0)} \right] = 288 N_{\rm site} \kappa_{\rm h}^4 P + 12 N_s^3 (2\kappa_{\rm h})^{N_t} \Omega + \cdots$$

Strategy II: Histogram Method

- Define Effective Potential of (generalized) plaquette through plaquette histogram

$$
\begin{aligned}
w(P,\beta) &= \langle \delta(P-\hat{P}) \rangle_\beta \\
V_{\text{eff}}(P,\beta) &= -\ln w(P,\beta)
\end{aligned}
$$





At T_c,

if single-well ⇔ crossover

if double-well ⇔ 1st

Re-weighted V_{eff}

Combining two methods ⇒ V_{eff} for (2+N_f)-flavor QCD

$$V_{\rm eff}(P;\beta,\kappa_l,\kappa_h)$$

$$= \quad V_{\rm eff}(P,\beta_0,\kappa_l,0) - \ln \frac{\left\langle \delta(P'-P)\exp\left[6N_s^3 h \times {\rm Re}\Omega\right]\right\rangle_{{\rm two},\beta_0,\kappa_l}}{\left\langle \delta(P'-P)\right\rangle_{{\rm two},\beta_0,\kappa_l}} + \ldots$$

Two-flavor part
Always single well

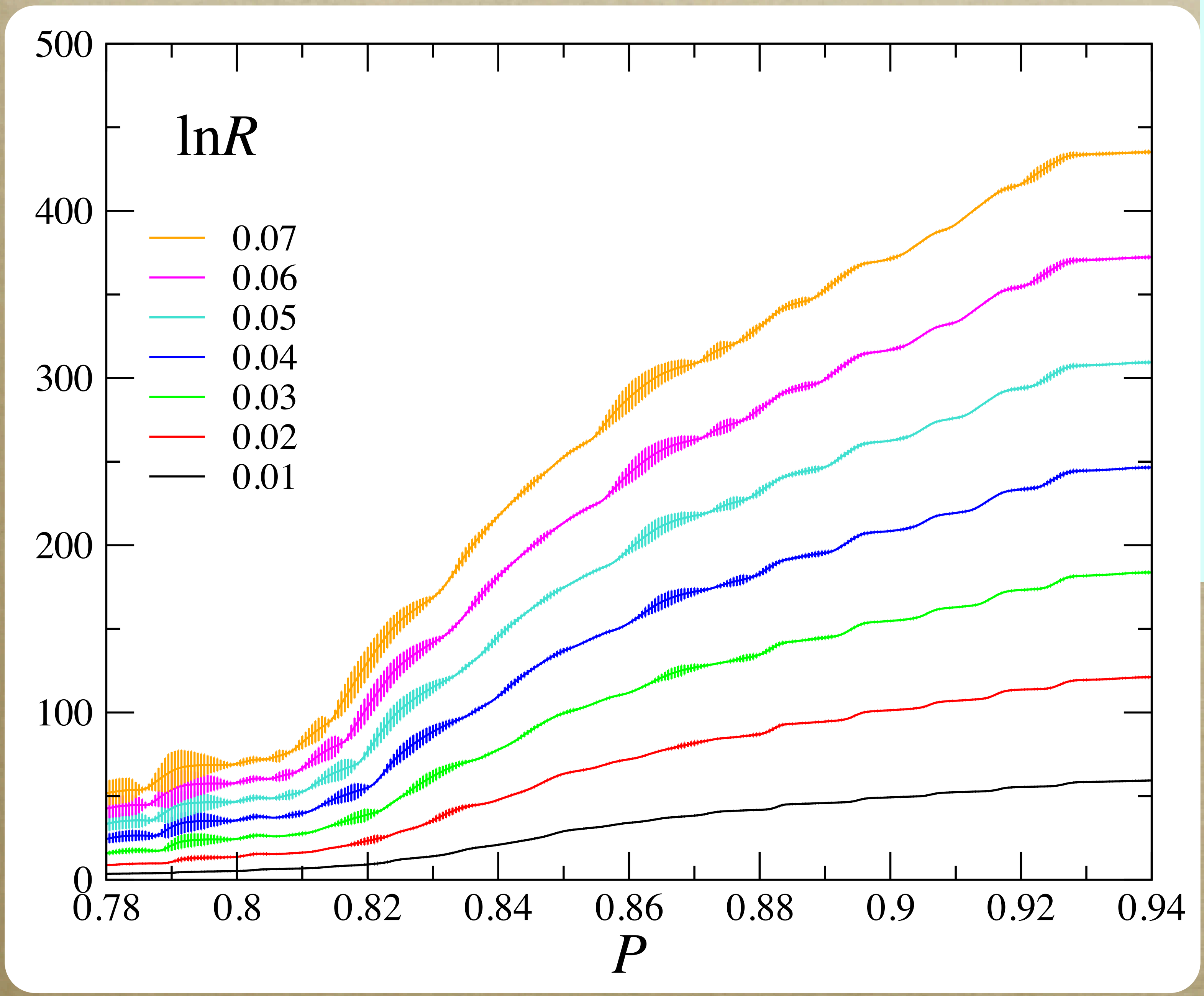
→ $\ln R$ Heavy flavors contribution

Note: hopping parameter is in $h = 2N_{\rm f}(2\kappa_{\rm h})^{N_t}$

In the following,

- look at the curvature of potential (2_{nd} deriv. wrt P)
- determine $h^{\rm crit}$ above which transition is 1st order ⇔ $m_h^{\rm crit}$

Heavy flavors contribution to V_{eff}



2-flavor configurations:

p4-improved staggered quark

the standard plaquette gauge

$a\, m_l = 0.1$,

10,000-40,000 trajs.

$V=16^3\times 4$,

$\beta = [3.52, 4.00]$ (16 values),

$T/T_c = [0.76, 1.98]$,

$M_{PS}/M_V \sim 0.7$

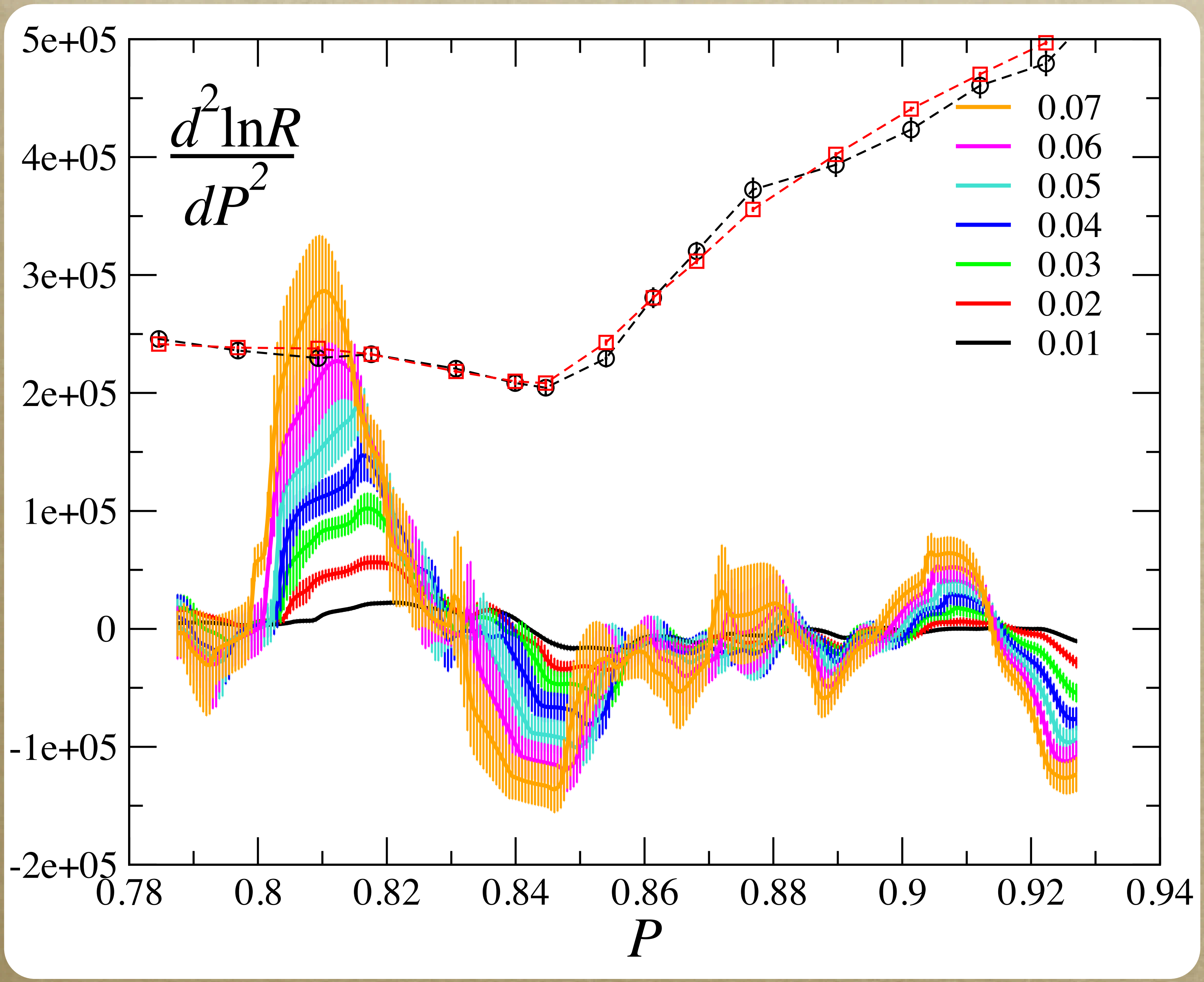
[C.R. Allton, et al., PRD71,054508 (2005)]

Calculated with $h = [0.01, 0.07]$

- ln$R$ increases with h.
- Rapid increase@$P\sim 0.81$

⇒large curvature

$\partial^2 V_{\text{eff}}/\partial P^2 = \partial^2 V_0/\partial P^2 - \partial^2(\ln R)/\partial P^2$



Maximum of the 2nd term exceeds 1st term at P~0.81 for $h \gtrsim 0.06$, where $\partial^2 V_{\text{eff}}/\partial P^2$ is negative.

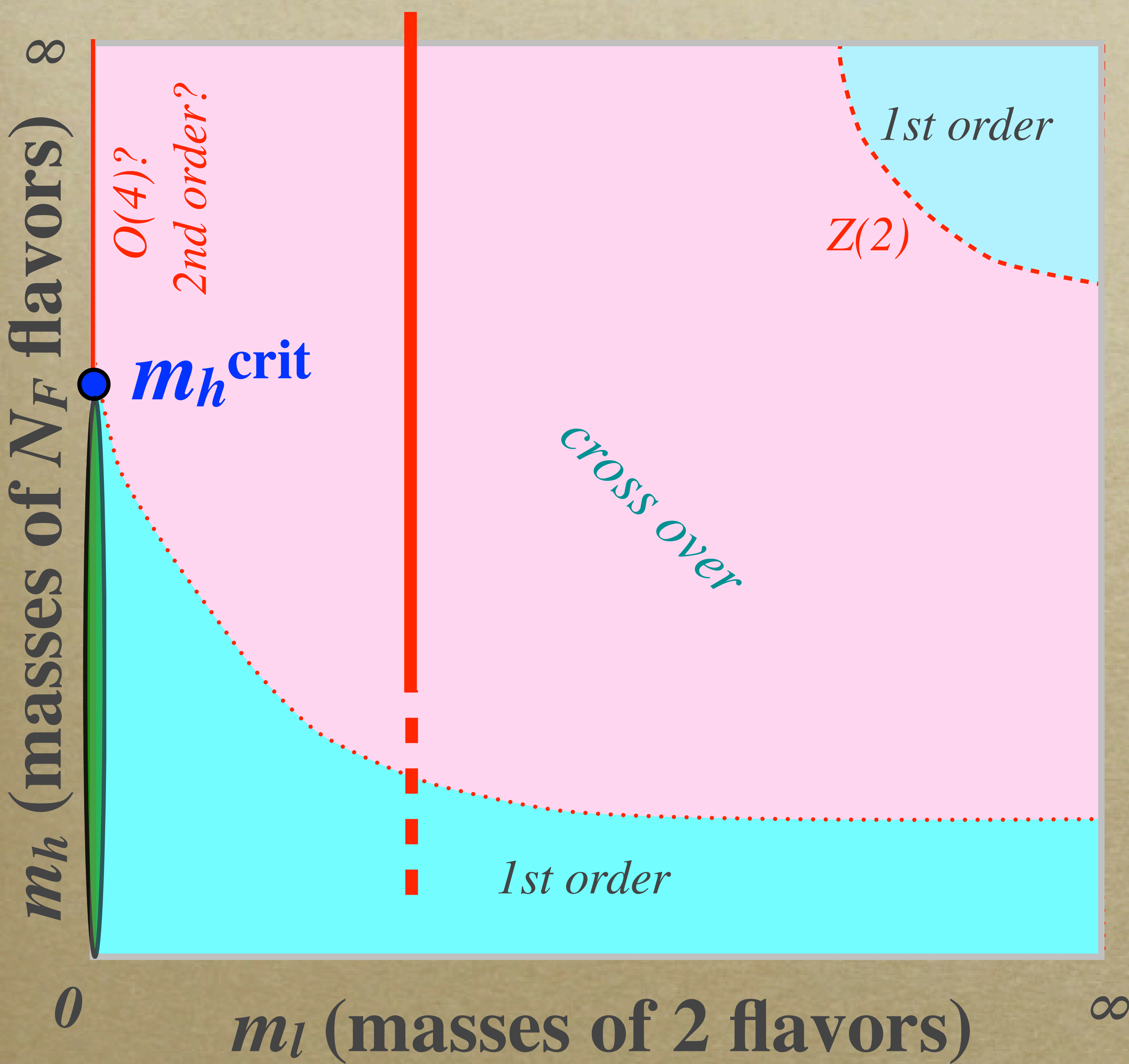
⇒ **1st order phase transition**

$h_c = 0.0614(69)$

$@M_{PS}/M_V \sim 0.7$

S. Ejiri and N. Yamada, PRL110, 172001 (2013)

Comments



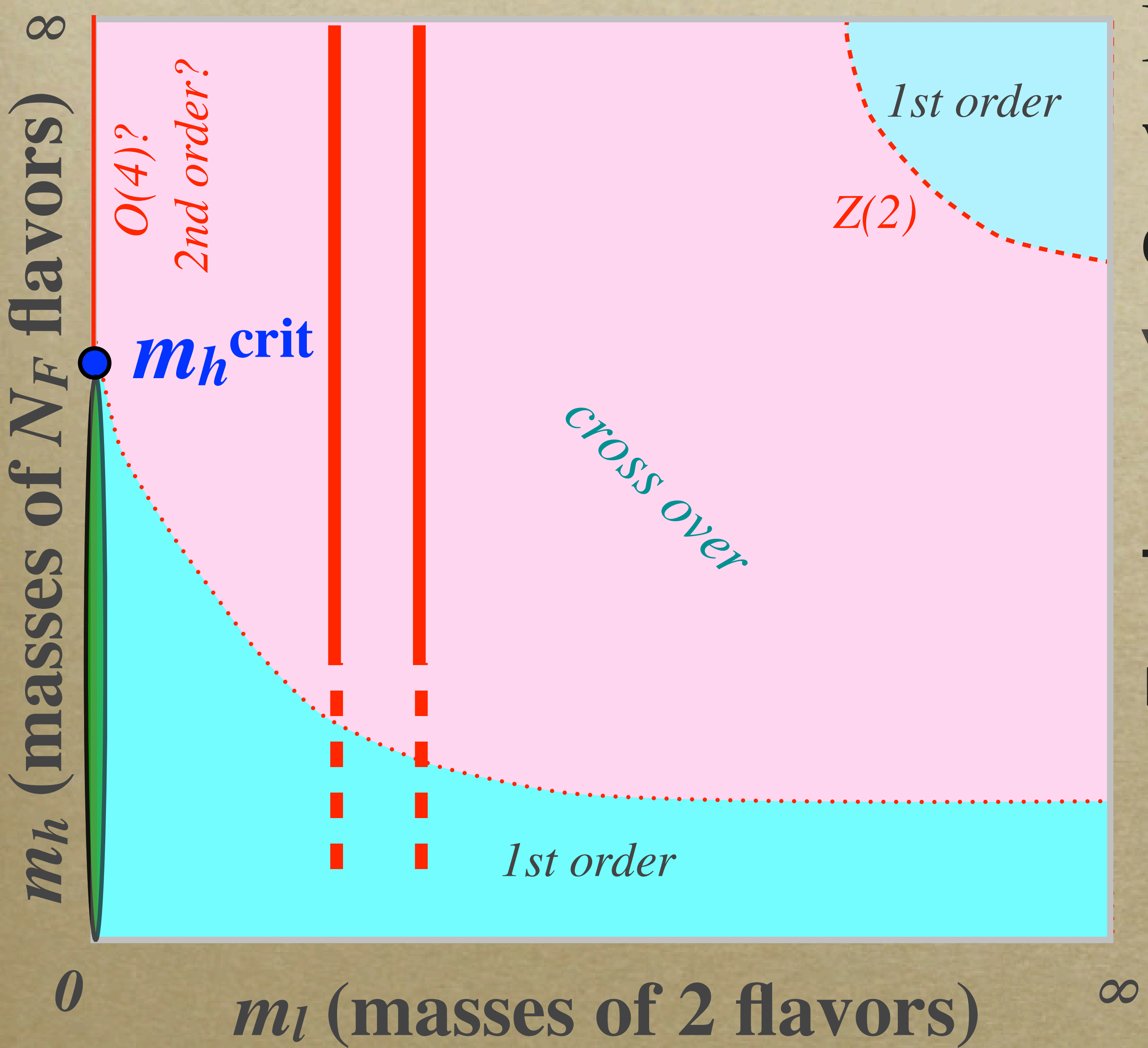
The order of the transition was studied along the red line.

- $h_c = 0.0614(69) = 2\,N_{\rm f}\,(2K_{\rm hc})^{Nt}$
- $K_{\rm hc}$ gets small as $N_{\rm f}$ increases.
- E.g., for $N_{\rm f}$ =10, $K_{\rm hc} \sim 0.118$.
- (LO)~(NLO) @$K_{\rm h} \sim 0.18$.

  [Ejiri et al. in preparation]

For large N_f, endpoint is in the region where HPE is valid.

Varying m_l



In order to determine m_h^{TCP}, **we have started to determine m_h^{crit}** for various m_l.

The following is progress report.

Summary and outlooks

- ✓ Successful EWBG in TC may put upper bound on techni-hadron masses.
- ✓ In general, parameter search of many flavor theories is computationally demanding. We proposed an easy-to-use approach and demonstrated that it works by determining the critical kappa.
- ✓ On-going calculation and Future plan:
  - Test for the existence of TCP through the universal power behavior.
  - Quantify the strength of 1st order transition to see whether EWBG is possible.