Electroweak Symmetry Breaking & CEPC

Andrew J. Long
University of Michigan – LCTP

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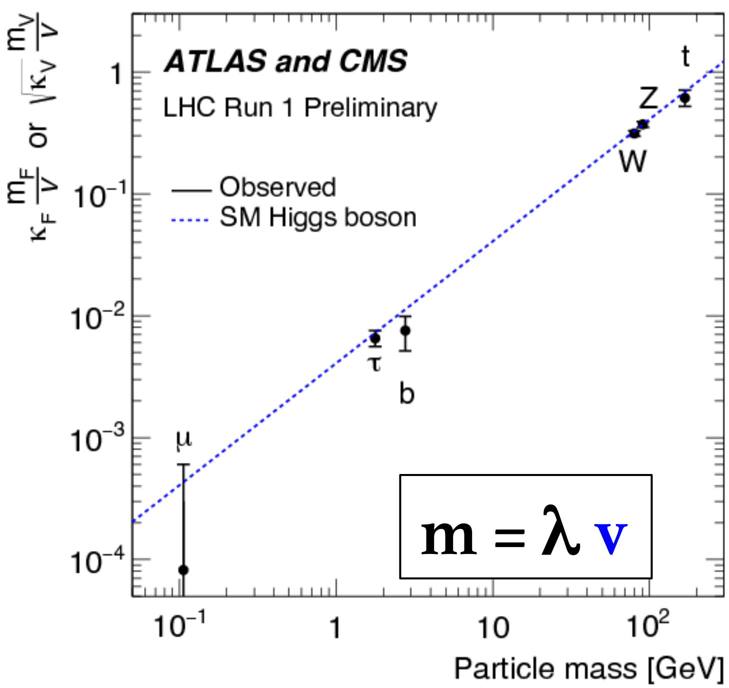
What we know and what we don't know about the Higgs

Large Hadron Collider experiment

$$m_h \simeq 125.09 \pm 0.24\, \mathrm{GeV}/c^2$$



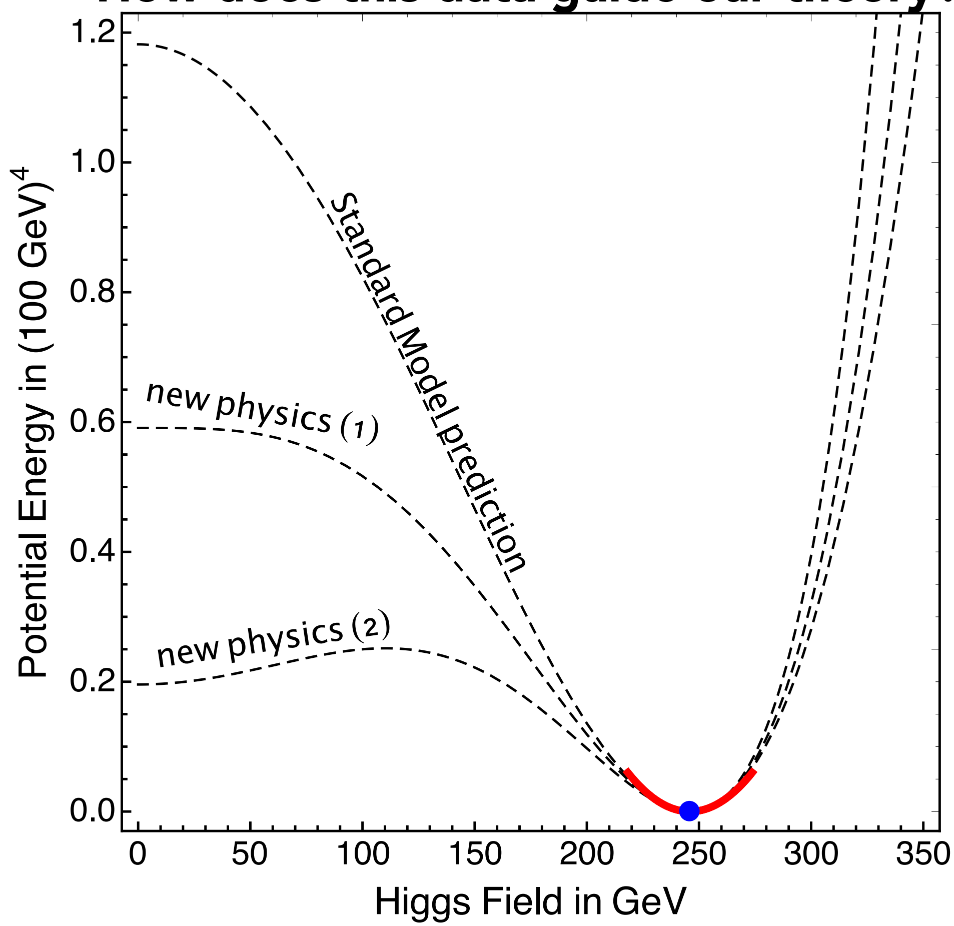
$$\mathbf{m_h \simeq 125.09 \pm 0.24\,GeV/c^2}$$

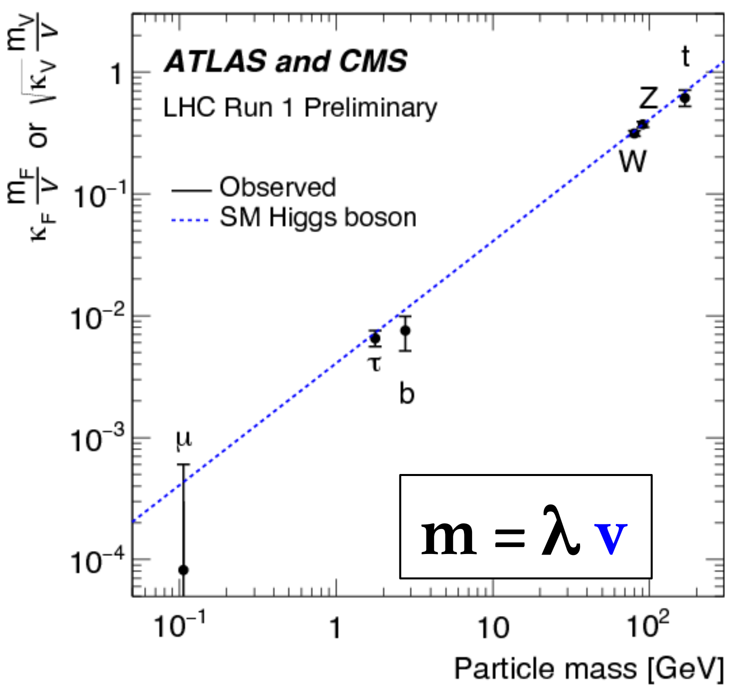
$$\text{SM)} \quad V = \frac{1}{2}m^2h^2 + \frac{1}{4}\lambda h^4$$

$$\text{NP 1)} \quad V = \frac{1}{4}\lambda h^4 \log\frac{h^2}{\Lambda^2}$$

$$\text{NP 2)} \quad V = \frac{1}{2}m^2h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{8\Lambda^2}h^6$$

How does this data guide our theory?





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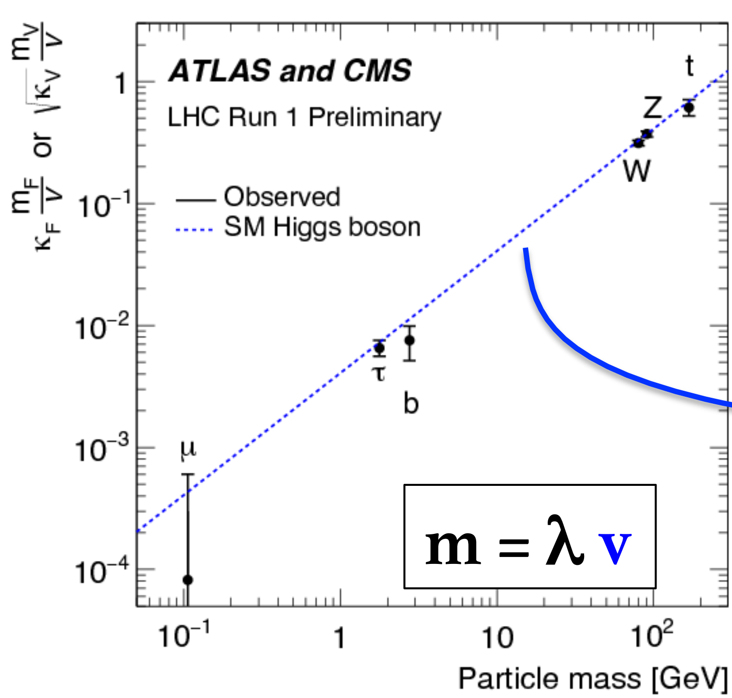
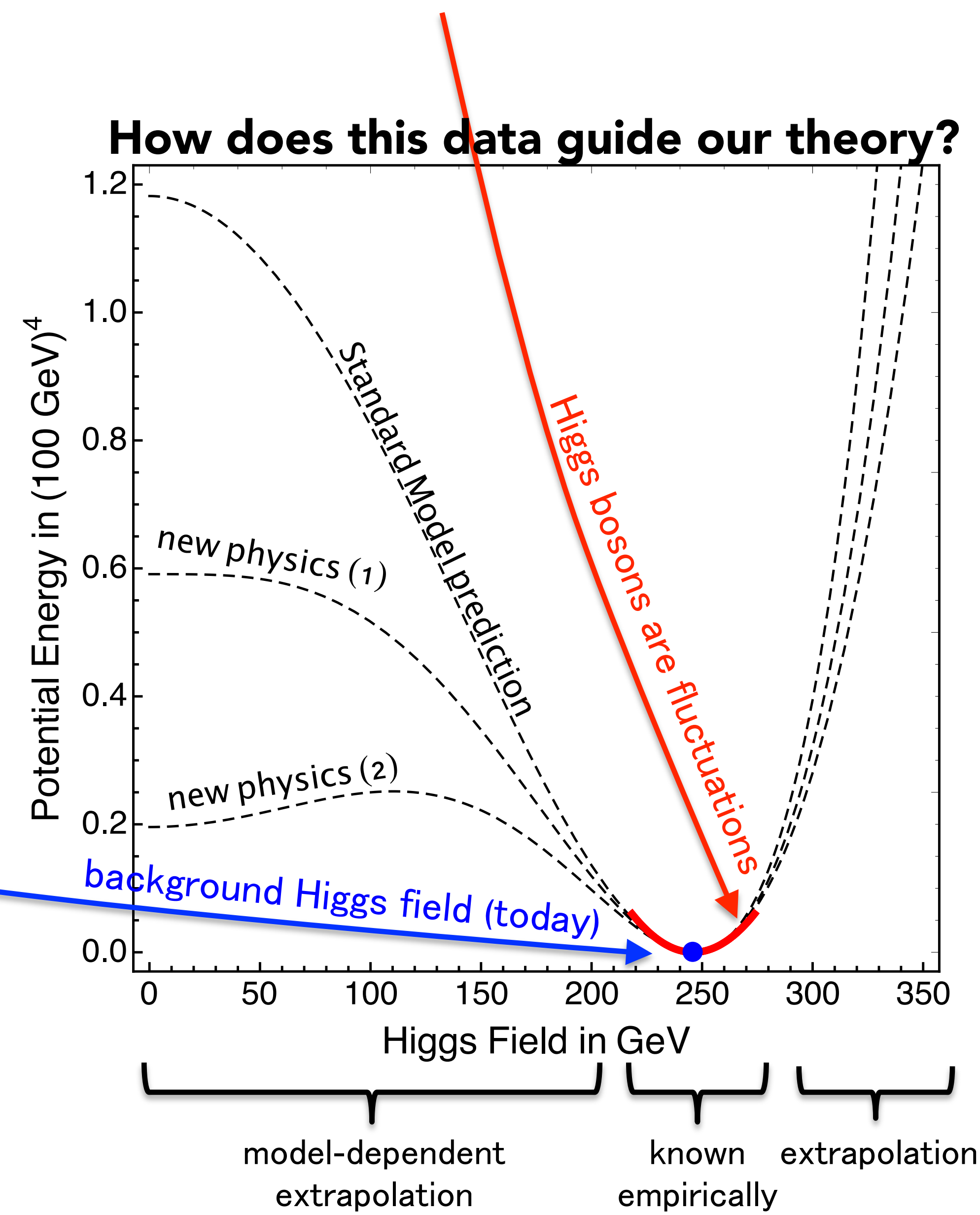
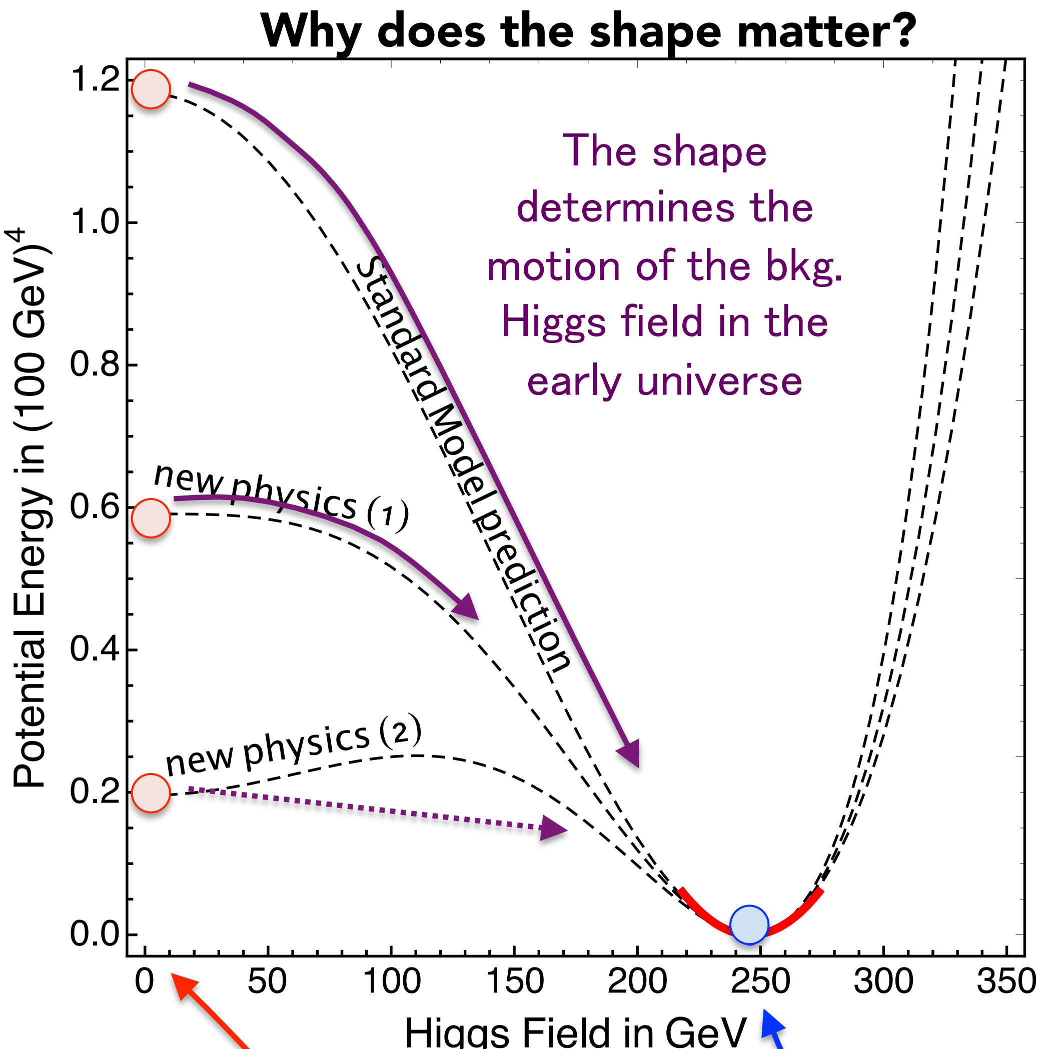




Why does the shape matter?

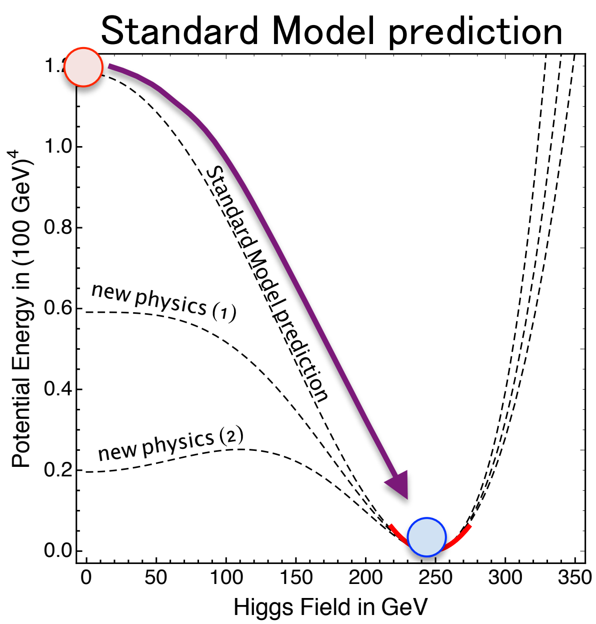


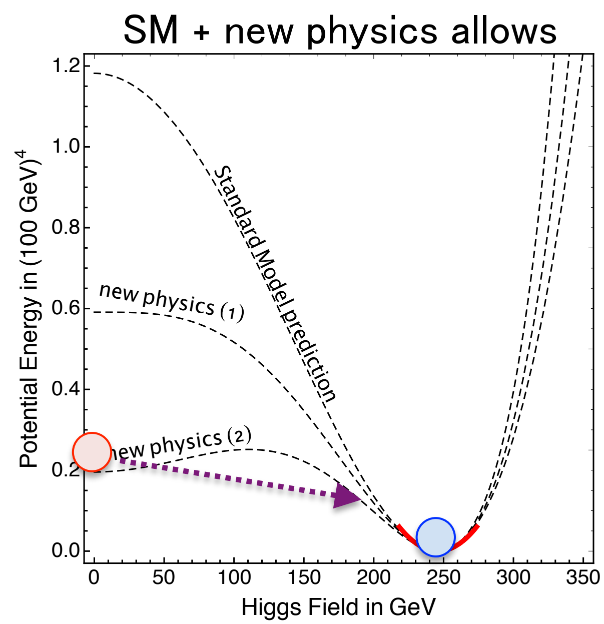
background Higgs field was here in the early universe (T > 100 GeV)

recall: F = E - TS ➔ min[F] = max[S]

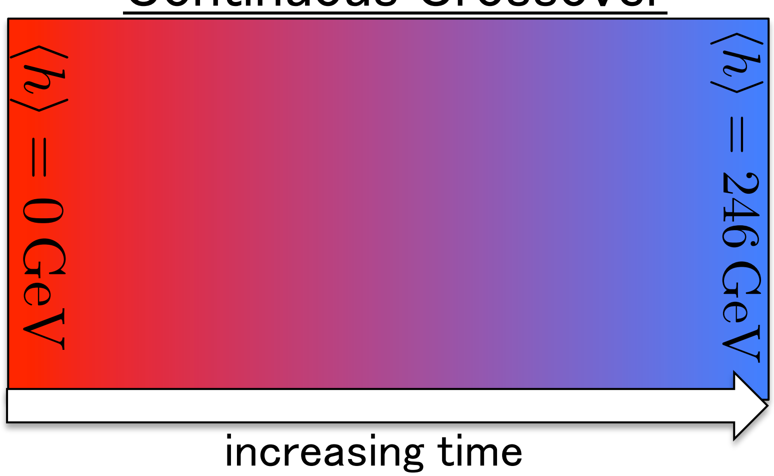
background Higgs field is here today … gives mass to SM particles

Electroweak Phase Transition. How does the background Higgs field move from zero in the early universe to its nonzero value today? (T ~ 100 GeV, t ~ 10 ps)

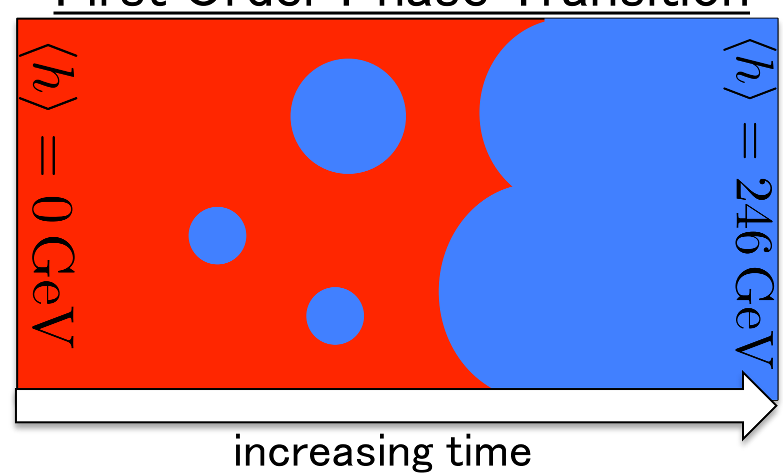




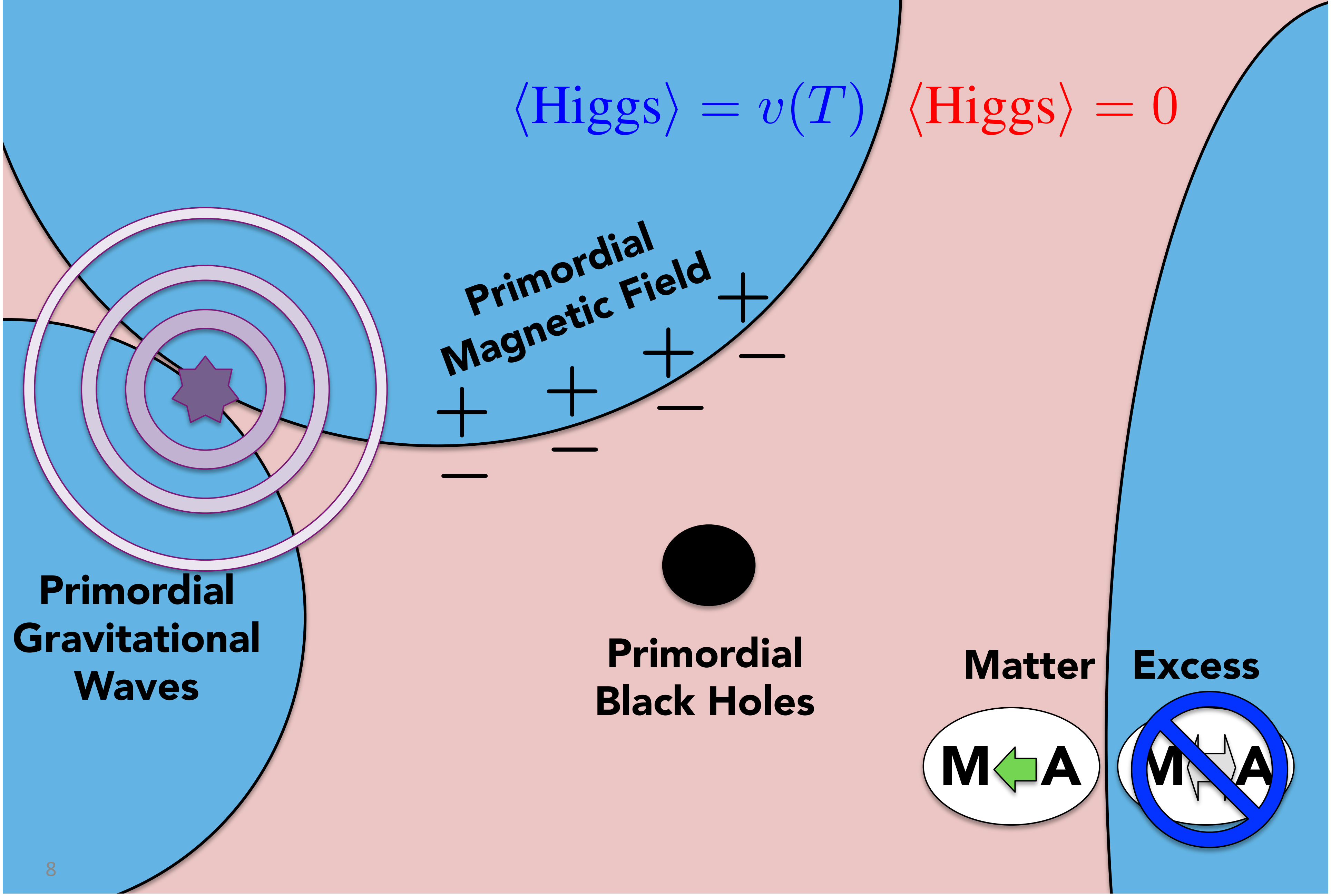
Continuous Crossover



First Order Phase Transition

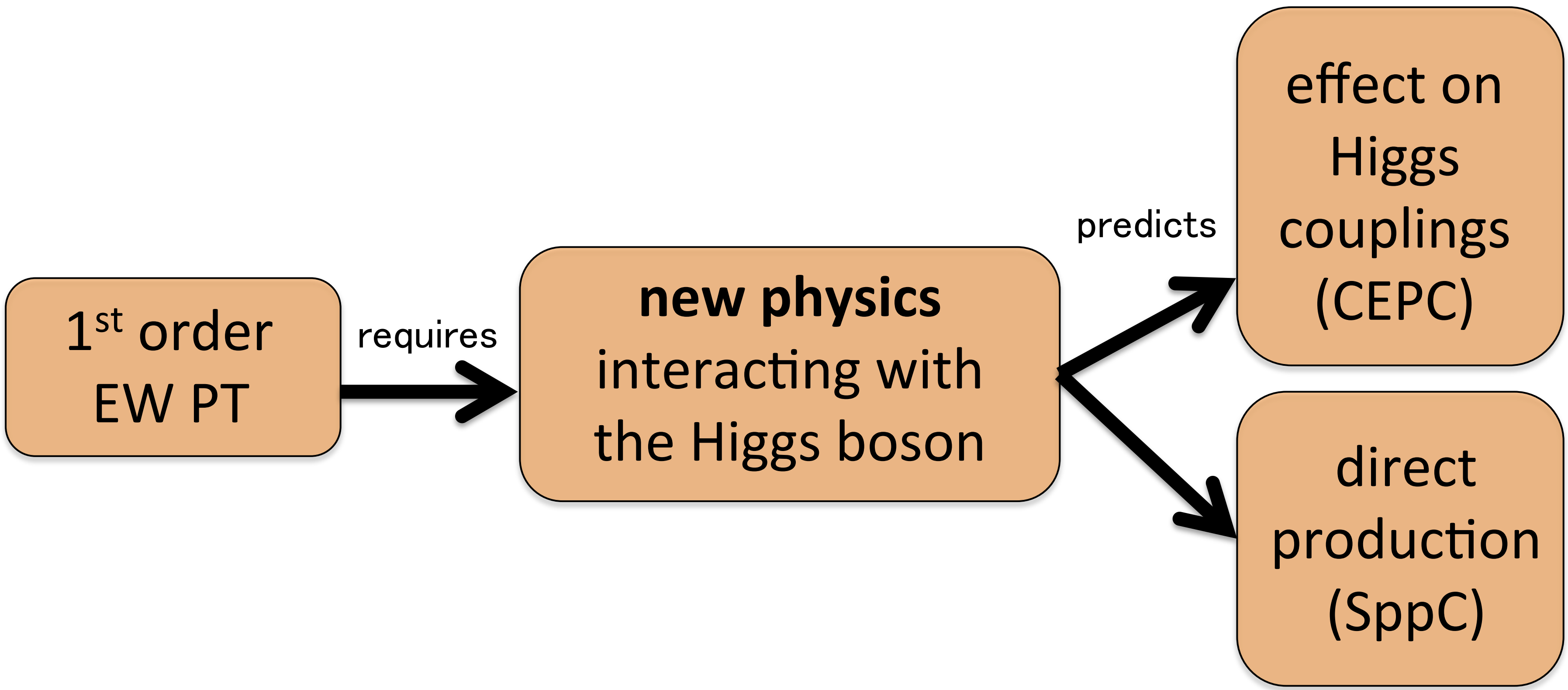


1st Order EWPT has profound implications for cosmology



Studying the Higgs @ CEPC

How can we learn about the electroweak phase transition?

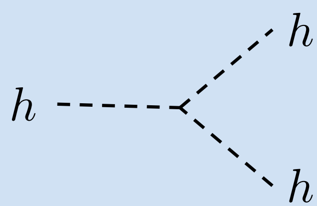


[Noble & Perelstein (2007)]
[Katz & Perelstein (2014)]

Effect on Higgs couplings

Higgs cubic self-coupling (hhh)

$\lambda_3 =$

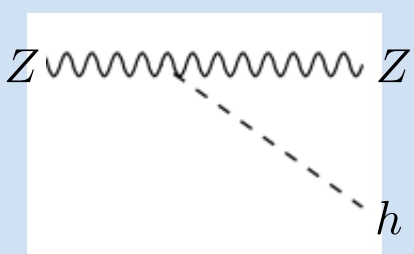


PRO:
Directly related to the shape of the Higgs potential (V‴).

CON:
Very challenging to measure. Target of FCC-hh & SppC.

Higgs coupling to Z-boson (hZZ)

$g_{hZZ} =$



CON:
An indirect probe of new physics & the EWPT.

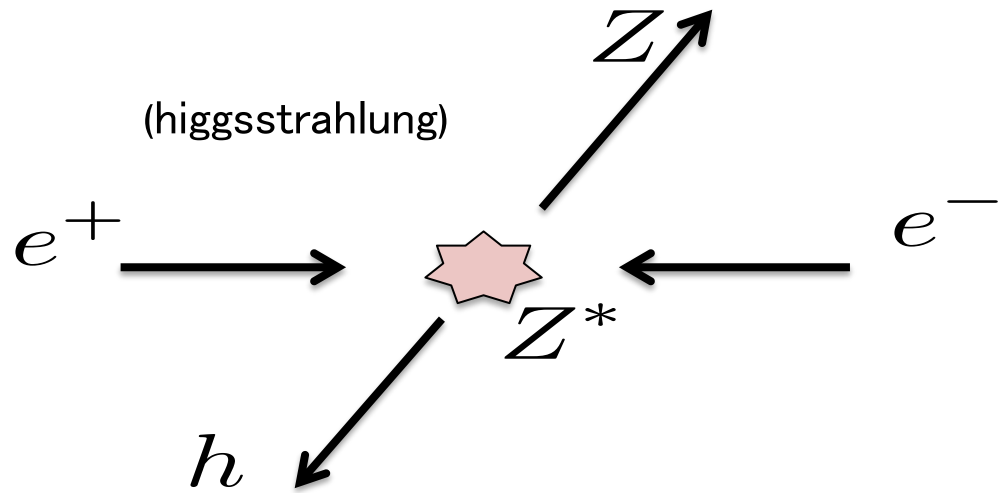
PRO:
It can be measured very precisely. Target of Higgs factories: FCC-ee, CEPC, & ILC.

Higgs Factories – precision Higgs measurements

Lepton colliders provide "clean" environment to study Higgs physics.

At E = 250 GeV, the production of Higgs + Z-boson is optimized.

Precision measurements of Higgs-Z-Z coupling at the sub-percent level!



Proposed Higgs factories:

- ➔ FCC-ee (Europe / CERN)
- ➔ CEPC (China)
- ➔ ILC (Japan)

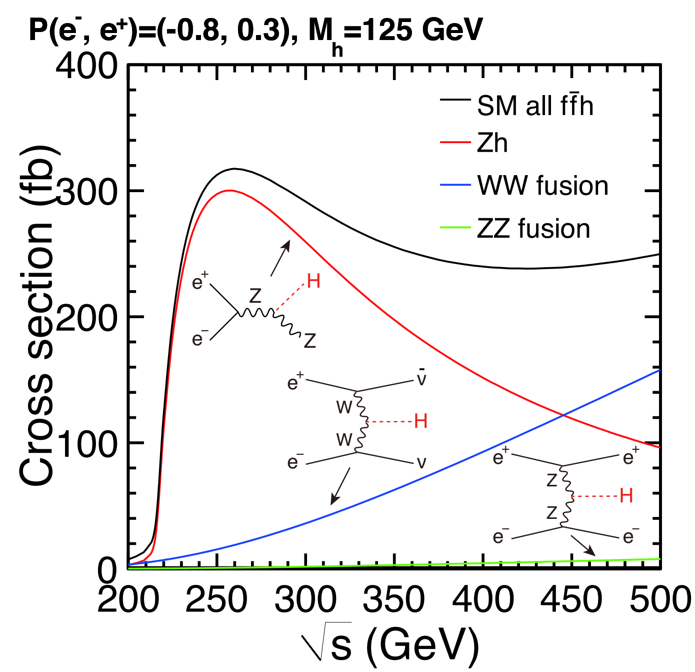


figure: ILC TDR, 1306.6352

Precision Higgs measurements

Projected sensitivities to various Higgs couplings at current & future colliders:

	current	HL-LHC	CEPC	ILC	FCC-ee	FCC-hh
hZZ	27%	7%	0.25%	0.25%	0.15%	-
$\Gamma(h \rightarrow \gamma\gamma)$	20%	8%	4%	-	1.5%	-
hhh	-	[-0.8 , 7.7] 95% CL	43%	27%	43%	10%

Assumptions & references:

hZZ current = 5 fb^{-1} at $\sqrt{s}$ = 7 TeV & 20 fb^{-1} at 8 TeV (1606.02266)

hZZ @ HL-LHC = 3000 fb^{-1} at $\sqrt{s}$ = 14 TeV (1307.7135, CMS)

hZZ @ CEPC = 5000 fb^{-1} at $\sqrt{s}$ = 250 GeV (pre-CDR)

hZZ @ ILC = 2000 fb^{-1} at $\sqrt{s}$ = 250 GeV (1506.05992)

hZZ @ FCC-ee = 2600 fb^{-1} at $\sqrt{s}$ = 250 GeV (1601.0640)

hhh @ HL-LHC = 3000 fb^{-1} at $\sqrt{s}$ = 14 TeV (ATL-PHYS-PUB-2017-001, hh->bb$\gamma\gamma$)

hhh @ ILC = 4000 fb^{-1} at $\sqrt{s}$ = 500 GeV (1506.05992, e^+e^->Zhh, hh->bbbb & bbWW)

hhh @ FCC-hh = 30000 fb^{-1} at $\sqrt{s}$ = 100 TeV (1606.09408)

hhh @ CEPC/FCC-ee = 5000 fb^{-1} at $\sqrt{s}$ = 240 GeV + 1700 fb^{-1} at $\sqrt{s}$ = 350 GeV (1711.03978)

Time to reach design sensitivity depends on run plan (not yet determined).

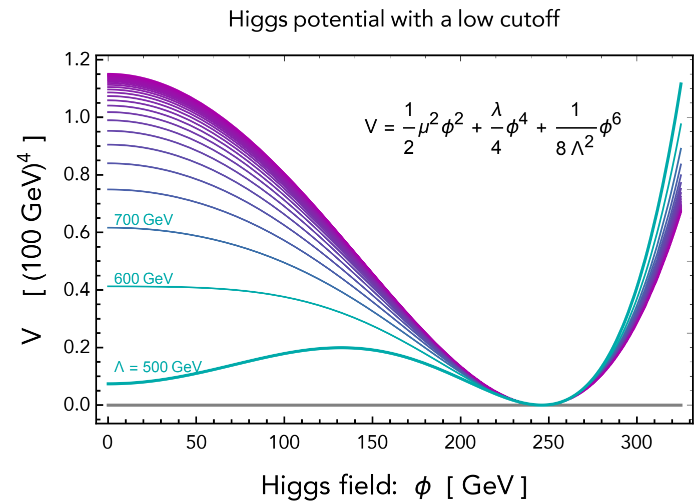
New physics coupled to the Higgs

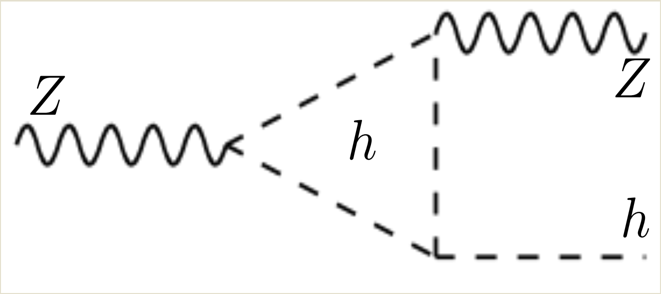
[Grojean, Servant, & Wells (2005)]
[Grinstein & Trott (2008)]
[Delaunay, Grojean, & Well (2008)]

Effective field theory description

Consider the SM with a low cutoff

$$-\mathscr{L} \supset \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \Lambda^{-2} (H^\dagger H)^3$$





$$\delta g_{hhh} \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} - 1 \simeq 70\% \left(\frac{\Lambda}{1\ {\rm TeV}}\right)^{-2}$$

$$\delta g_{hZZ} \simeq 0.006\, \delta g_{hhh} \simeq 0.4\% \left(\frac{\Lambda}{1\ {\rm TeV}}\right)^{-2}$$

A low cutoff can be probed at CEPC though its effect on the hZZ coupling.

[Katz & Perelstein (2014)]

Simplified models (with a new scalar)

Let the SM be extended by a new scalar field

$$V_\Phi = m_0^2|\Phi|^2 + \kappa|\Phi|^2|H|^2 + \eta|H|^4$$

Model	$(SU(3), SU(2))_{U(1)}$	g_Φ	C_3	C_2	$\frac{\Pi_W}{g^2T^2}$	$\frac{\Pi_B}{g'^2T^2}$	$\frac{\Delta\Pi_h}{\kappa T^2}$
"RH stop"	$(\bar{3},1)_{-2/3}$	6	4/3	0	11/6	107/54	1/4
Exotic triplet	$(3,1)_{-4/3}$	6	4/3	0	11/6	131/54	1/4
Exotic sextet	$(\bar{6},1)_{8/3}$	12	10/3	0	11/6	227/54	1/2
"LH stau"	$(1,2)_{-1/2}$	4	0	3/4	2	23/12	1/6
"RH stau"	$(1,1)_1$	2	0	0	11/6	13/6	1/12
Singlet	$(1,1)_0$	2	0	0	11/6	11/6	1/12

The phase transition doesn't "care about" quantum numbers.
→ only depends on mass and couplings

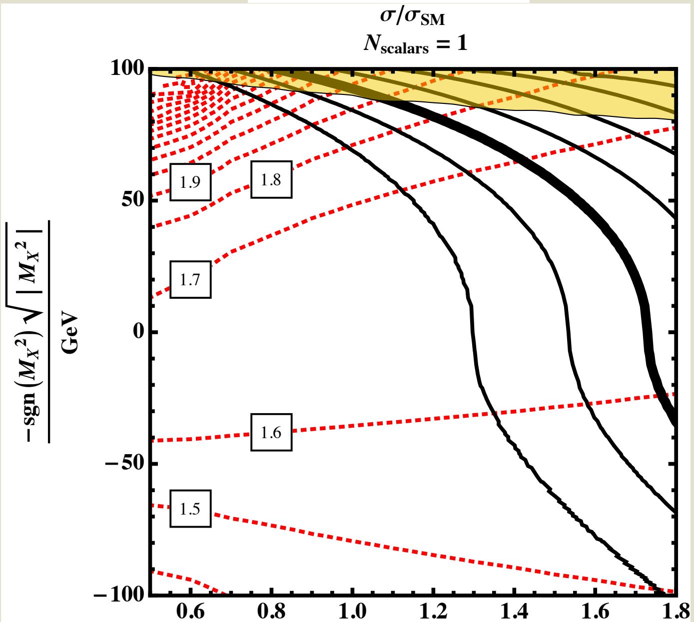
[Cohen, Morrissey, & Pierce (2012)]

(1) A colored scalar: strongly constrained

Let the SM be extended by a new scalar field

$$V_\Phi = m_0^2 |\Phi|^2 + \kappa |\Phi|^2 |H|^2 + \eta |H|^4 \qquad \text{with} \qquad \Phi \sim (\mathbf{3}\,,\,\mathbf{1}\,,\,0)$$

gluon fusion



Higgs portal coupling: κ

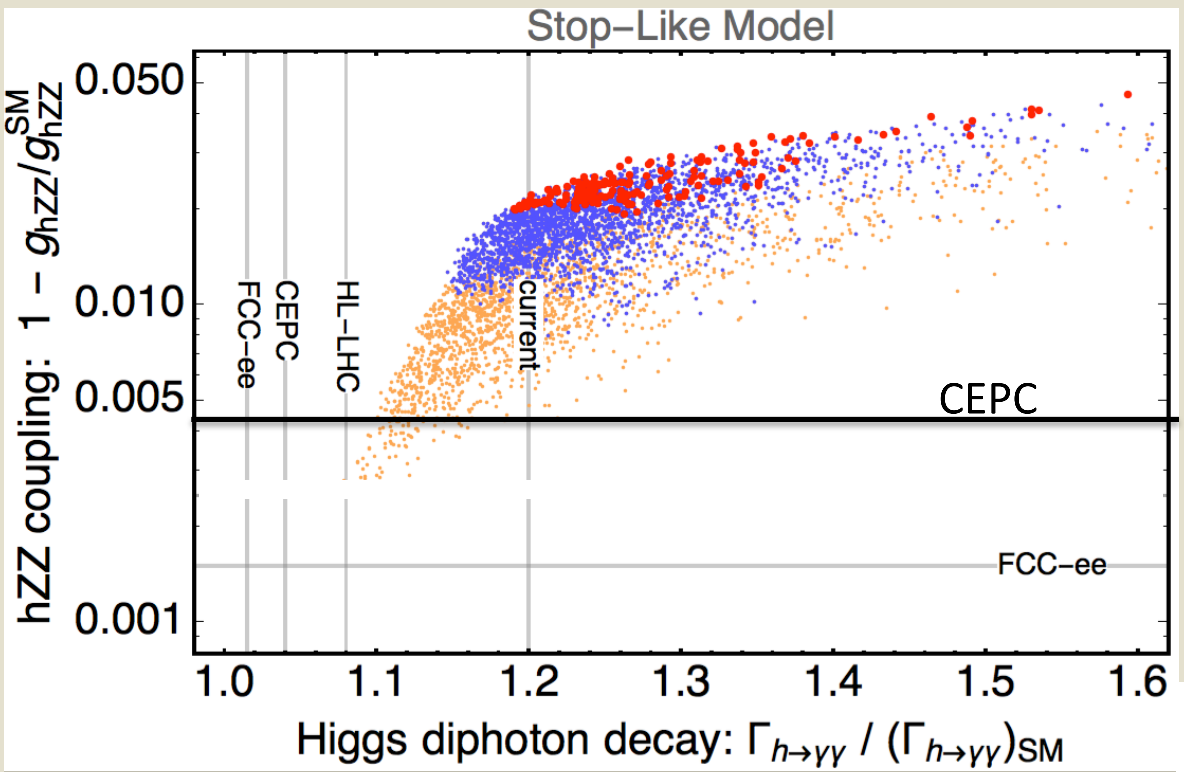
light colored particles are already strongly constrained by Higgs measurements at the LHC

black = strength of EW phase transition
red = enhancement to gg->h production

(2) A charged scalar: tested at HL-LHC & CEPC

Let the SM be extended by a new scalar field

$$V_\Phi = m_0^2 |\Phi|^2 + \kappa |\Phi|^2 |H|^2 + \eta |H|^4 + \cdots \qquad \text{with} \qquad \Phi \sim (\mathbf{1}\,,\, \mathbf{2}\,,\, q_Y)$$



light charged particles are constrained by Higgs diphoton decay at LHC & HL-LHC

complementary to CEPC

orange = 1st order EWPT
blue = also viable baryogenesis
red = also detectable GWs

(3) A singlet scalar: requires CEPC to test

Consider the theory:

SM + spin-0, colorless, uncharged particle **(aka., real scalar singlet)**

The new particle does not interact via the SM forces (strong, weak, EM)

➔ difficult to produce and detect at colliders

➔ (dark matter candidate if stable)

The new particle interacts with the Higgs boson

➔ induces 1st order phase transition

➔ affects Higgs couplings

Interactions:

five model parameters

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial\phi_s)^2 - \frac{m_s^2}{2}\phi_s^2 - \frac{a_s}{3}\phi_s^3 - \frac{\lambda_s}{4}\phi_s^4 - \lambda_{hs}H^\dagger H\phi_s^2 - 2a_{hs}H^\dagger H\phi_s$$

real scalar singlet

Higgs portal

Higgs-singlet mixing:

$$\langle H\rangle = (0\,,\ v/\sqrt{2}) \qquad \text{and} \qquad \langle\phi_s\rangle = v_s$$

$$\sin 2\theta = \frac{4v(a_{hs} + \lambda_{hs}v_s)}{M_h^2 - M_s^2}$$

hhh coupling (see e.g., Profumo, Ramsey-Musolf, Wainwright, & Winslow, 2014)

$$\lambda_3 \equiv g_{hhh} = \left(6\lambda_h v\right)\cos^3\theta + \left(6a_{hs} + 6\lambda_{hs}v_s\right)\sin\theta\cos^2\theta + \left(6\lambda_{hs}v\right)\sin^2\theta\cos\theta + \left(2a_s + 6\lambda_s v_s\right)\sin^3\theta$$

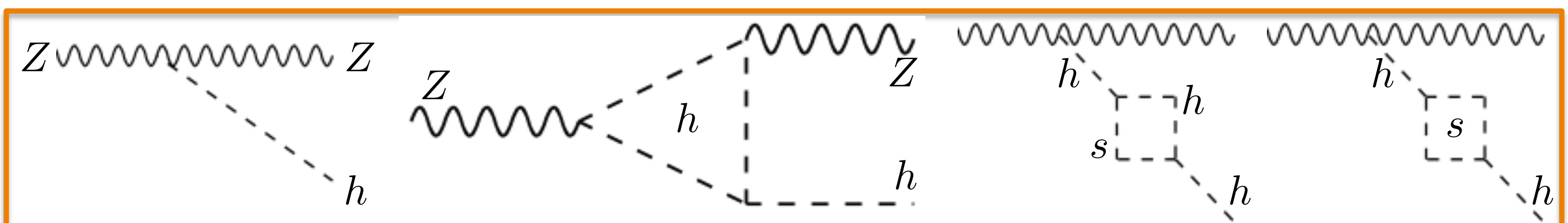
hZZ coupling (adapted from: Craig, Englert, & McCullough 2013; McCullough, 2014; Curtin, Meade, & Yu, 2014)

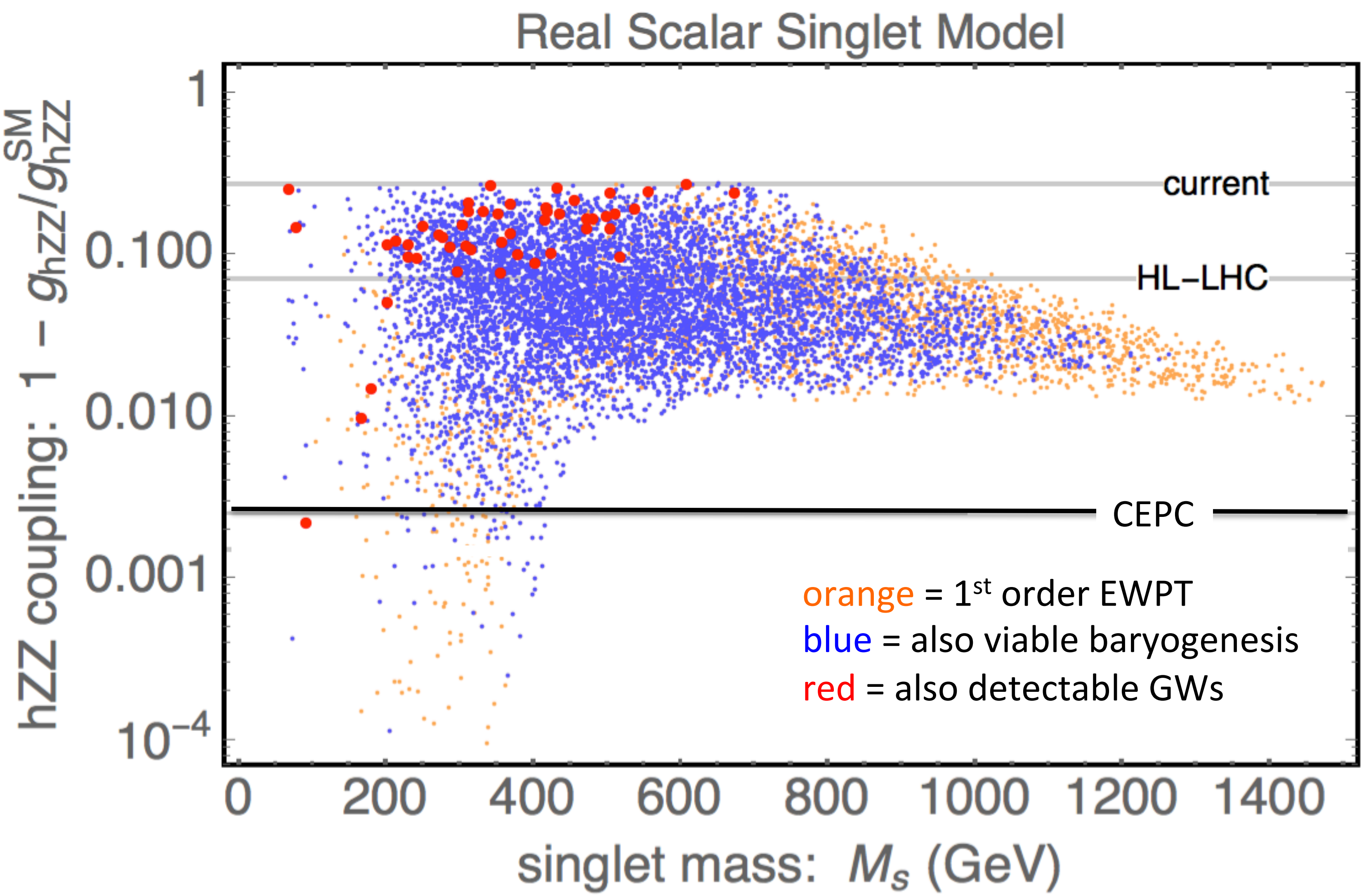
$$\frac{g_{hZZ}}{g_{hZZ,\mathrm{SM}}} \approx \cos\theta + 0.006\left(\frac{\lambda_3}{\lambda_{3,\mathrm{SM}}} - 1\right) - 2\frac{|a_{hs} + \lambda_{hs}v_s|^2}{16\pi^2} I_B(M_h^2; M_h^2, M_s^2) - \frac{|\lambda_{hs}|^2 v^2}{16\pi^2} I_B(M_h^2; M_s^2, M_s^2)\,.$$

(leading effect is from mixing)

(triangle probes self-coupling)

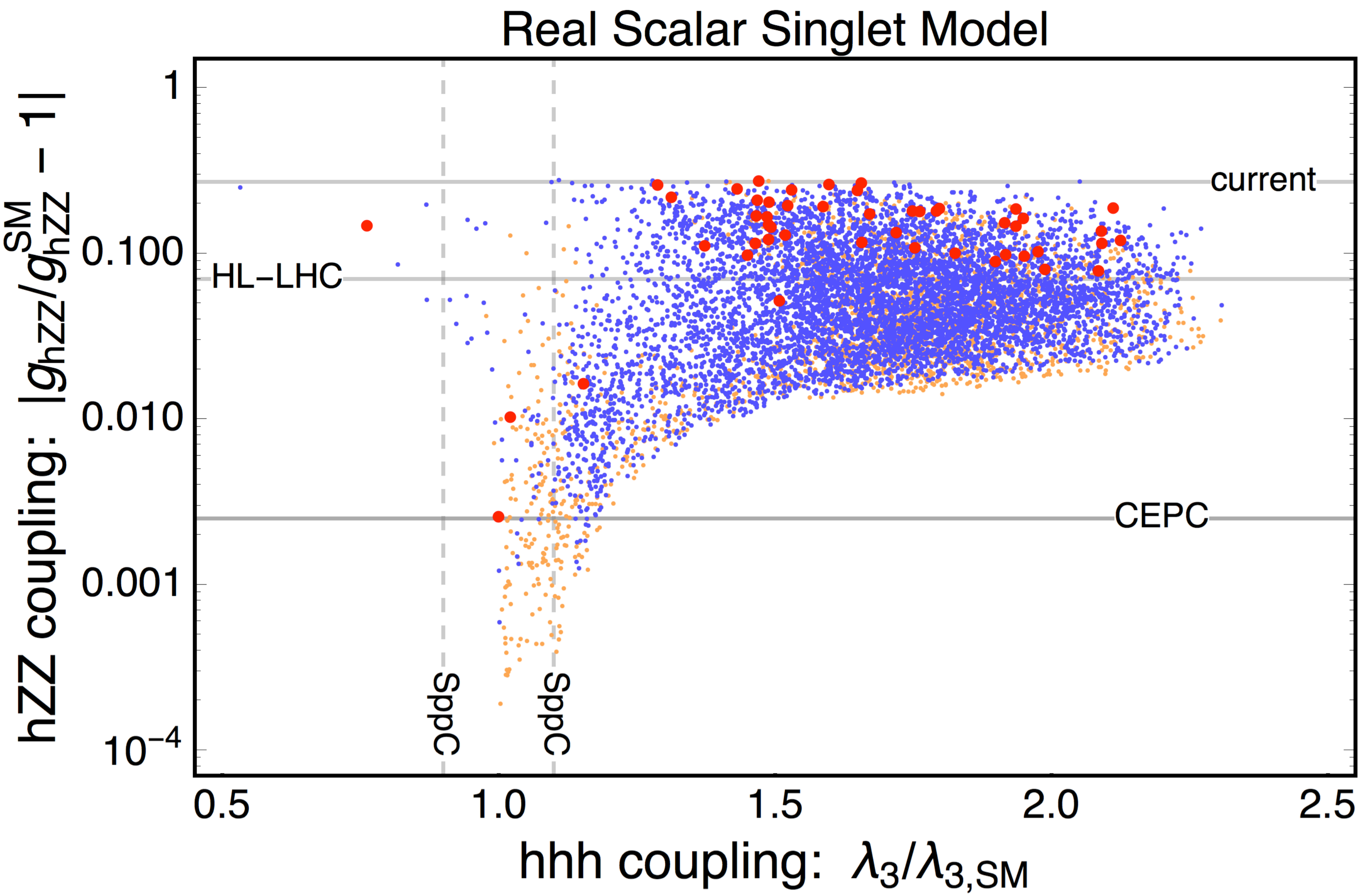
(Higgs wfcn. renorm.)





even hZZ measurements alone are a powerful test of PT!

[Huang, AL, & Wang (2016)]

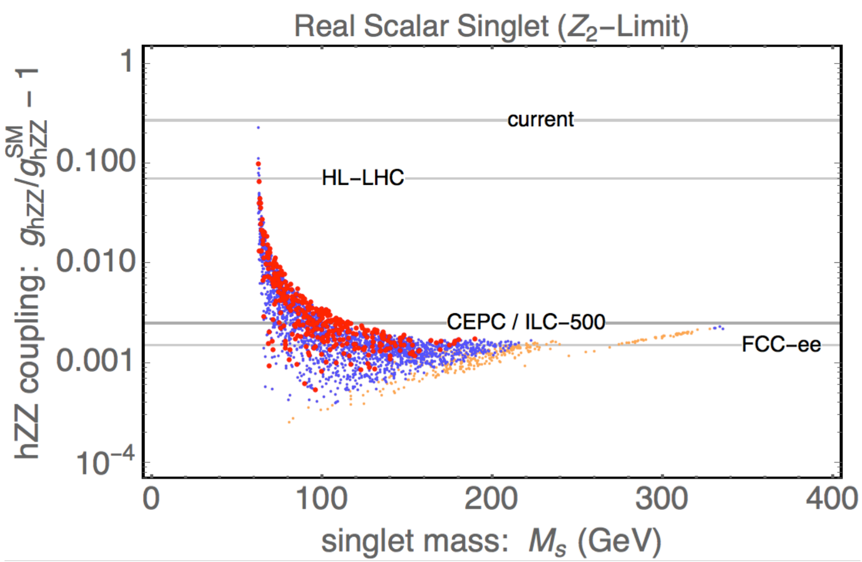


even hZZ measurements alone are a powerful test of PT!
(including also hhh is better)

Poking into the dusty corners (of parameter space)

Z2-Symmetric

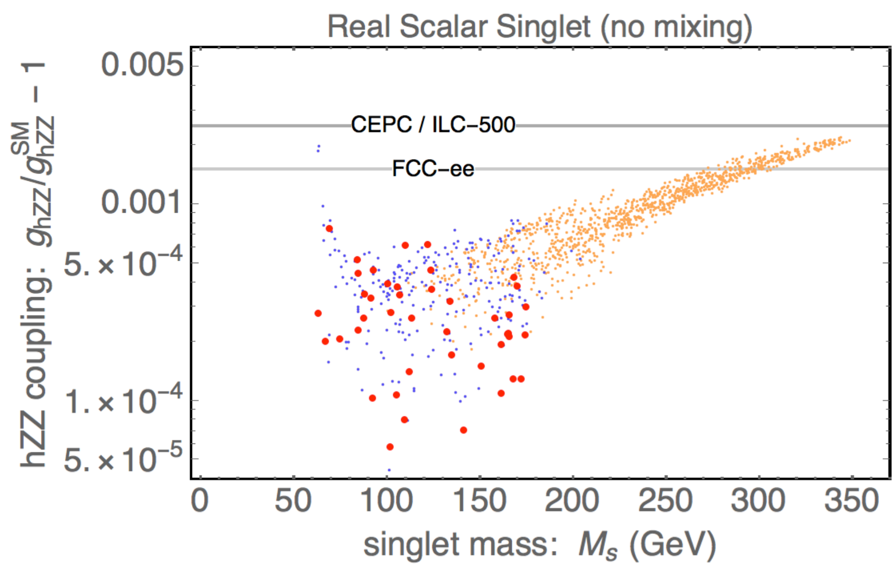
$$a_s = a_{hs} = v_s = 0$$



- aka, Z2xSM (Gonderinger, Li, Patel, Ramsey-Musolf)
- dubbed, "nightmare scenario" (Curtin, Meade, Yu)
- No Higgs-singlet mixing ➔ hard to test.
- Singlet is stable. Dark matter candidate.

Tuned Zero Mixing

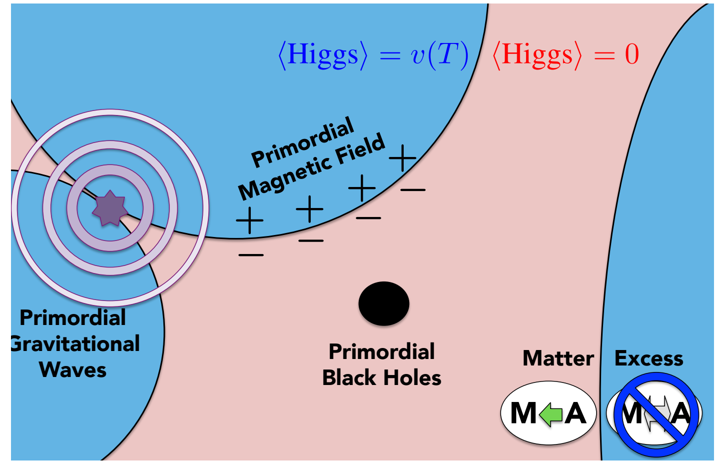
$$a_{hs} + \lambda_{hs} v_s = 0$$

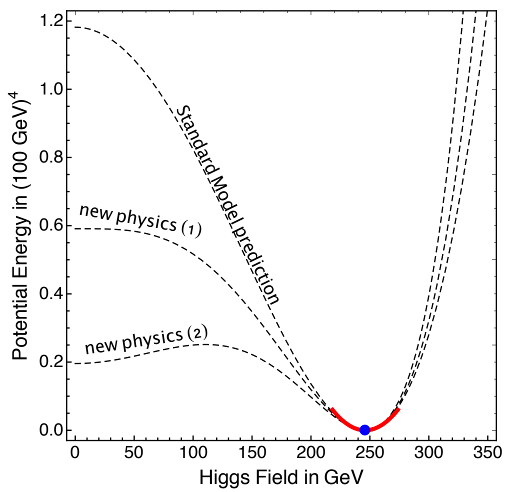


- A new "nightmare scenario" / "blind spot"
- Probed by non-resonant pair production pp → ss and s → visible. (Chen, Kozaczuk, Lewis, 2017)

Conclusions

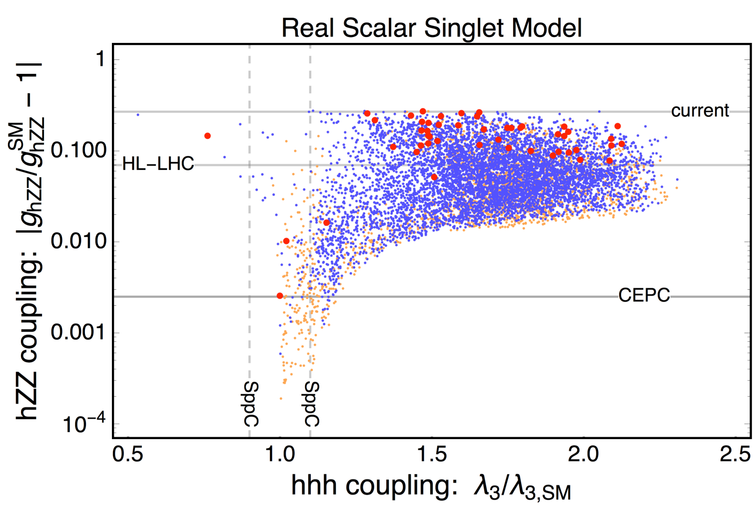
Cosmologists are asking:
What are the implications of the electroweak phase transition?





Particle physicists are asking:
Is there new physics coupled to the Higgs?

A Higgs factory like CEPC is ideally suited to probe the kind of new physics that leads to 1st order phase transition.



BACKUP SLIDES

(2) A charged scalar: tested at HL-LHC & CEPC

new particles: **inert doublet + singlet**

$$\tilde{Q} \sim (\mathbf{1}, \mathbf{2}, 1/3) \times 3 \text{ flavor}$$
$$\tilde{U} \sim (\mathbf{1}, \mathbf{1}, 4/3) \times 3 \text{ flavor}$$

$$\langle \tilde{Q} \rangle = (0\,,\,0) \qquad \text{and} \qquad \langle \tilde{U} \rangle = 0$$

interactions

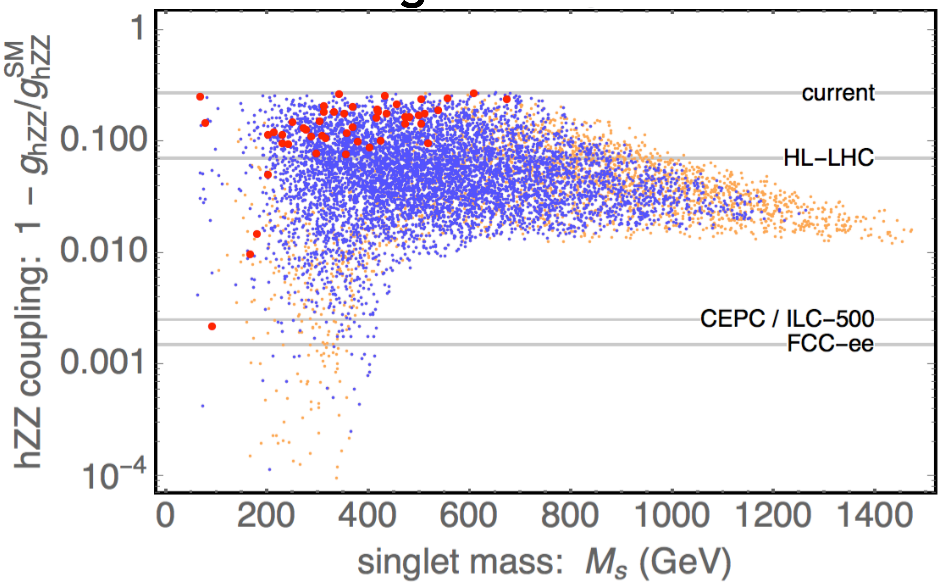
$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\rm SM} &+ \left(D_\mu \tilde{Q}\right)^\dagger \left(D^\mu \tilde{Q}\right) + \left(D_\mu \tilde{U}\right)^* \left(D^\mu \tilde{U}\right) - \left[a_{hQU} \tilde{Q} \cdot H \tilde{U}^* + \text{h.c.}\right] \\ &- m_Q^2 \tilde{Q}^\dagger \tilde{Q} - m_U^2 \tilde{U}^* \tilde{U} - \lambda_Q \left(\tilde{Q}^\dagger \tilde{Q}\right)^2 - \lambda_U \left(\tilde{U}^* \tilde{U}\right)^2 \\ &- \lambda_{QU} \left(\tilde{Q}^\dagger \tilde{Q}\right)\left(\tilde{U}^* \tilde{U}\right) - \lambda_{hU} \left(H^\dagger H\right)\left(\tilde{U}^* \tilde{U}\right) \\ &- \lambda_{hQ} \left(H^\dagger H\right)\left(\tilde{Q}^\dagger \tilde{Q}\right) - \lambda'_{hQ} \left(\tilde{Q} \cdot H\right)^* \left(\tilde{Q} \cdot H\right) - \lambda''_{hQ} \left(\tilde{Q}^\dagger H\right)^* \left(\tilde{Q}^\dagger H\right)\end{aligned}$$

four model parameters

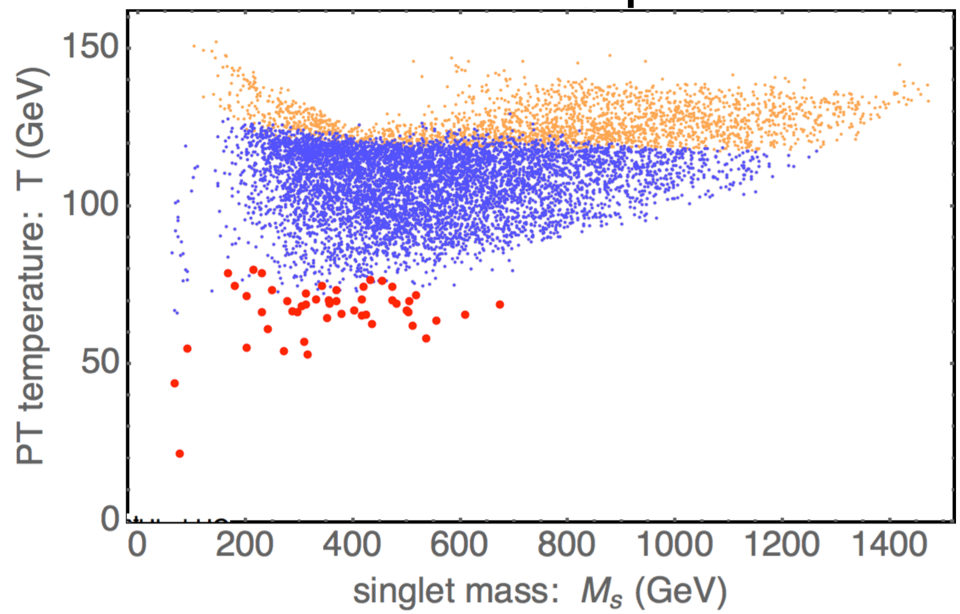
simplifying assumption

$$\lambda_Q = \lambda_U = \lambda_{QU} = \lambda_{hU} = \lambda_{hQ} = \lambda'_{hQ} = \lambda''_{hQ} \equiv \lambda$$

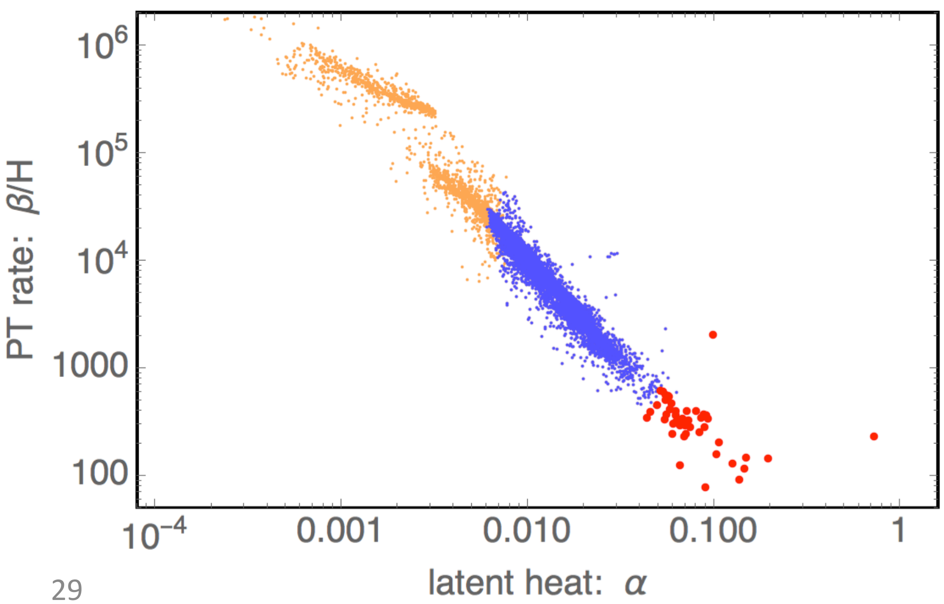
singlet mass scale



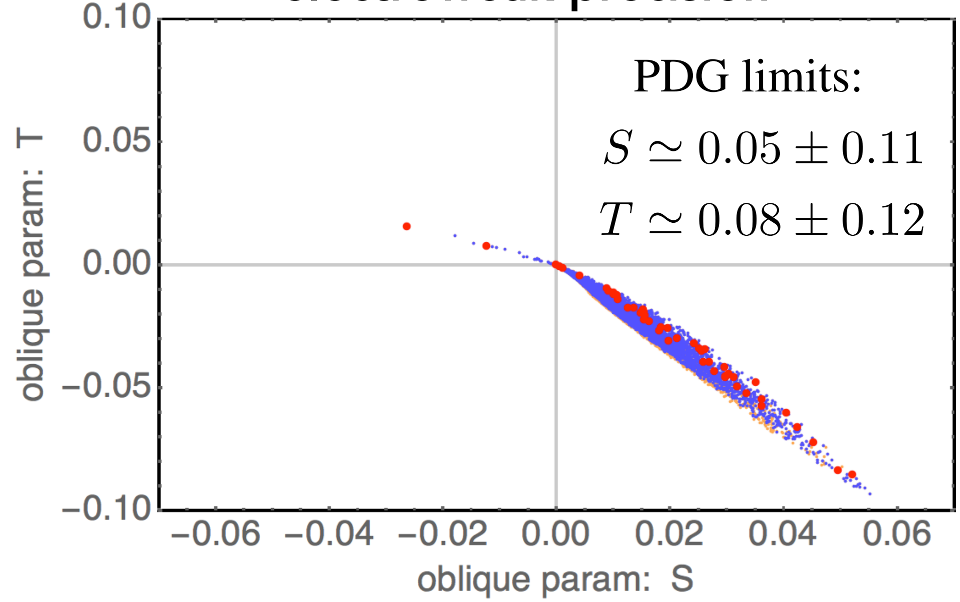
nucleation temperature



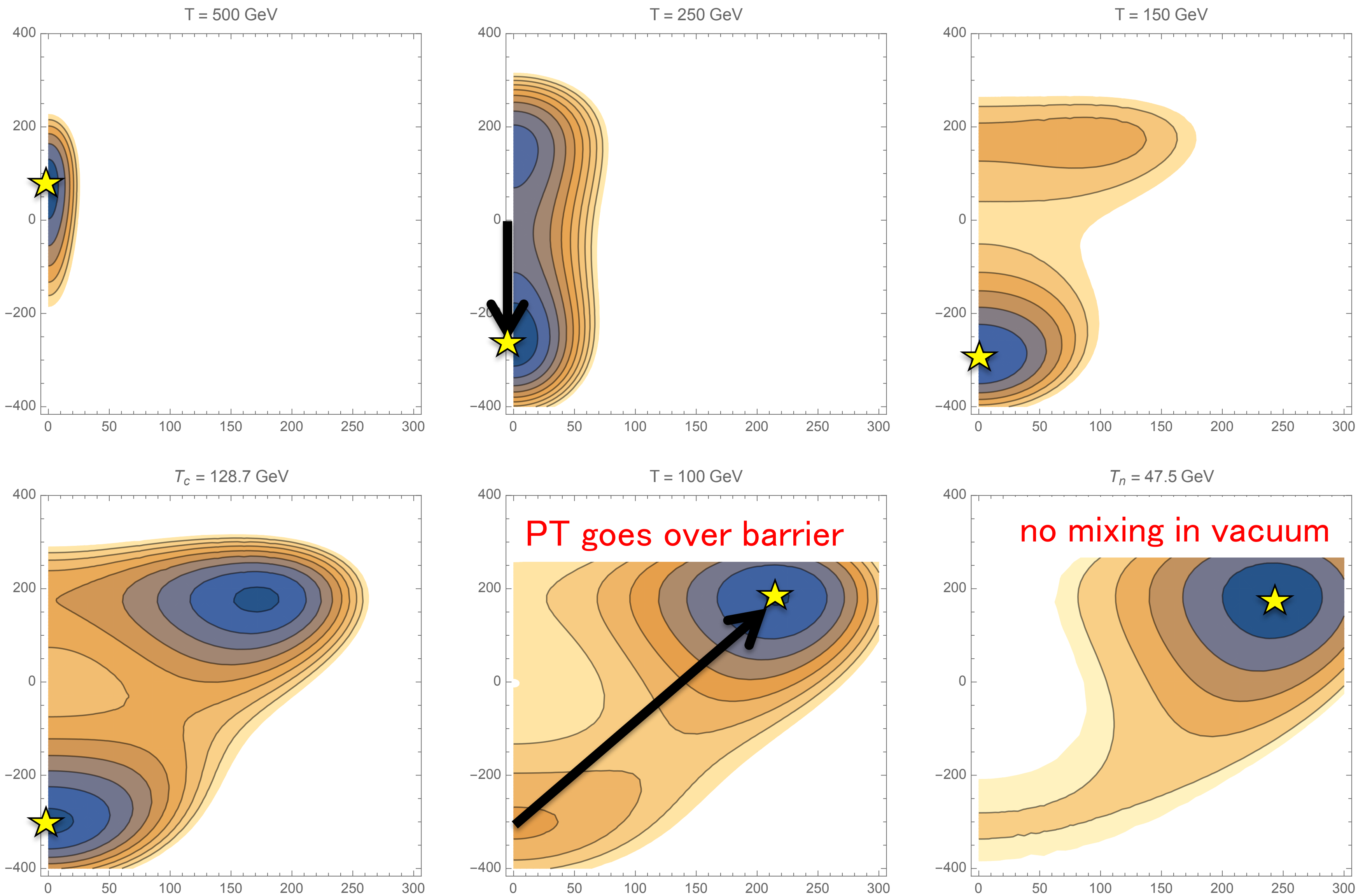
latent heat & PT duration



electroweak precision



E.g., the "tuned zero mixing" limit



THE LAST SLIDE