

Singlet-Catalyzed Electroweak Phase Transitions in the 100 TeV Frontier

Peter Winslow

In Collaboration with:

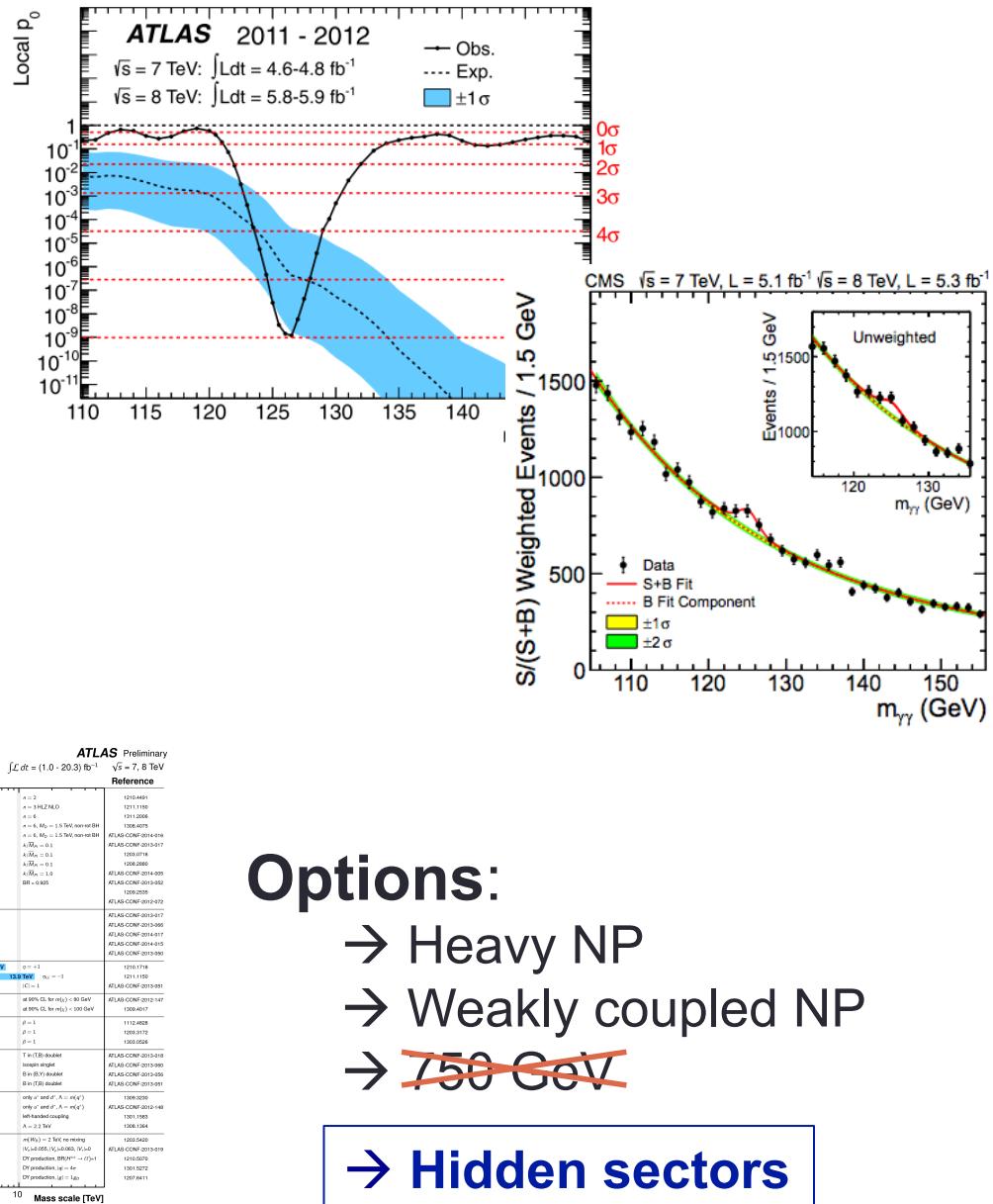
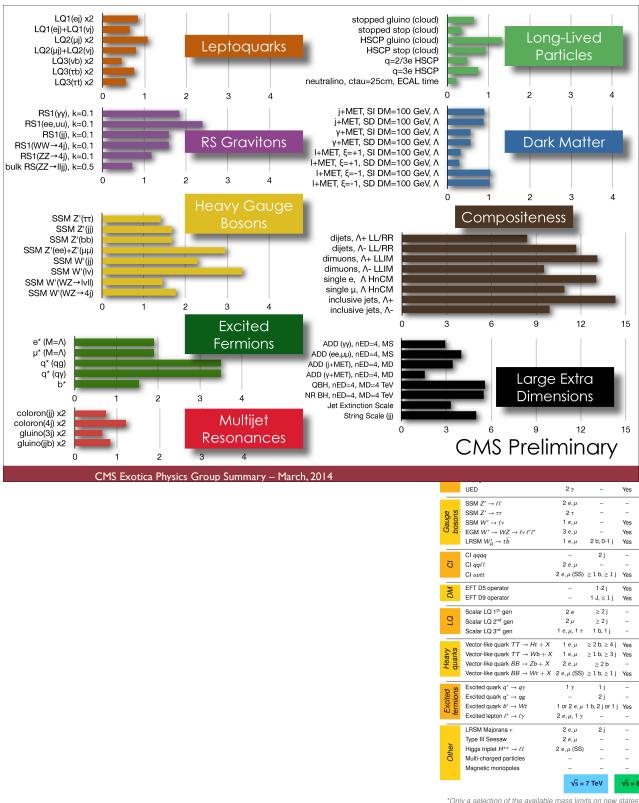
A. Kotwal, M. Ramsey-Musolf, J. No

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LHC has thrown open the door to the scalar sector of the SM!

... but where's all the NP?



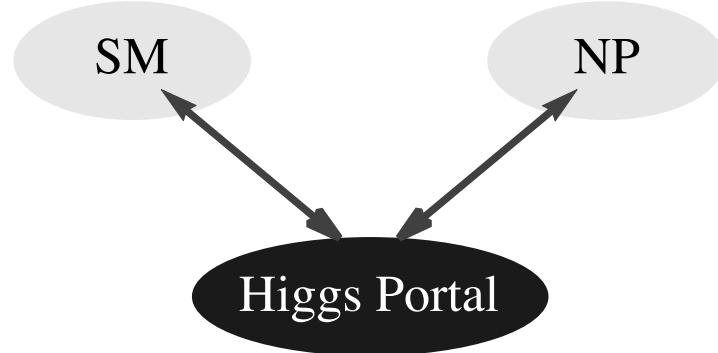
Options:

- Heavy NP
- Weakly coupled NP
- ~~750 GeV~~

→ Hidden sectors

Hidden Sectors

- Less constrained (possibly still weak scale)
- Typically still couple to SM via portals
 - Interesting collider signatures
- Also motivated by real cosmological problems
 - Baryon asymmetry of the Universe
- Can modify character of EWPT to give
 - Strongly 1st order EWPT
 - Required for successful EWBG



$$\Delta\mathcal{L} \supset \mathcal{O}_{NP}|H|^2$$

Requirement of a SFOEWPT identifies a preferred parameter space
→ ***Cosmological motivation for collider searches***

Motivation:

Can we discover these models at next-generation colliders?

The xSM

$$V_{xSM}(H, S) = V_{SM}(H) + \underbrace{\left(\frac{a_1}{2}S + \frac{a_2}{2}S^2 \right) |H|^2}_{Higgs\ Portal} + \overbrace{\frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4}^{Secluded\ Self-Interactions}$$

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v_0 + h + iG^0) \end{pmatrix}, \quad S = x_0 + s$$

Higgs Mixing

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

$$\sin 2\theta = \frac{(a_1 + 2a_2 x_0)v_0}{(m_1^2 - m_2^2)}$$

1. Assume h_1 is previously observed scalar
 $m_{h_1} = 125$ GeV

2. Scalar sector involves new tri-linear couplings that enable new processes, e.g.,

$$h_2 \rightarrow h_1 h_1$$

3. h_2 inherits interactions with SM fermions and gauge fields from mixing

$$hXX \rightarrow (h_1 \cos \theta - h_2 \sin \theta) XX$$

Which measurements will yield more sensitivity?
 Di-Higgs or mixing angle

Constraints and projected sensitivities to mixing angle

Oblique parameters:
Perform full fit to current best-fit
values from Gfitter group

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Dedicated heavy SM-like Higgs
searches aren't competitive

Future Higgs coupling measurements:

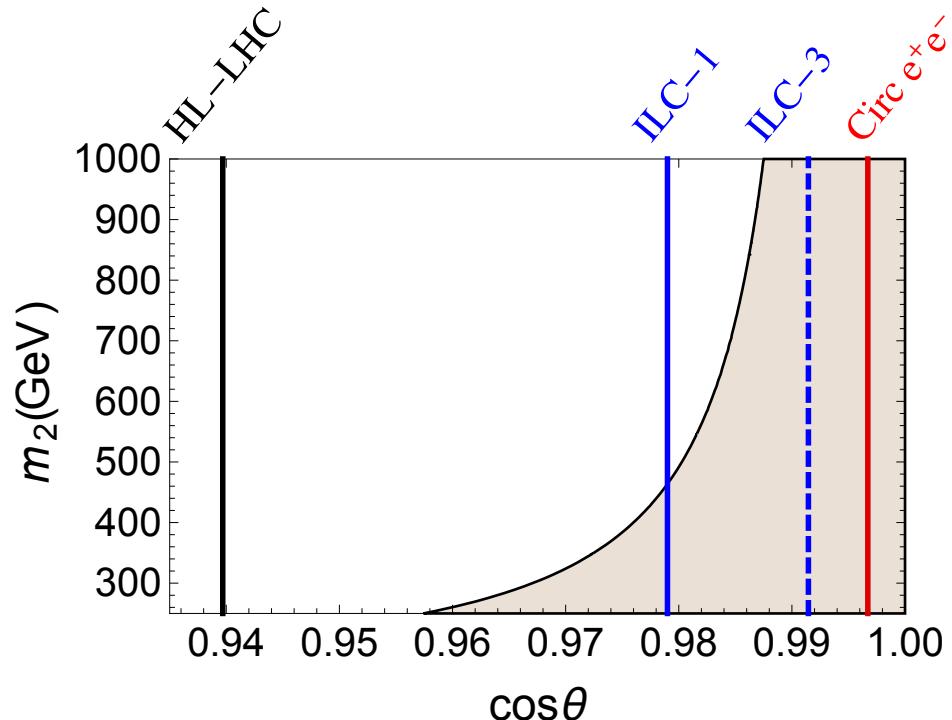
HL-LHC:
 $\sqrt{s} = 14 \text{ TeV}, 3 \text{ ab}^{-1}$
ATL-PHYS-PUB-2013-014, CMS-NOTE-13-002

ILC-1:
 $\sqrt{s} = 250 \text{ GeV}, 250 \text{ fb}^{-1}$

ILC-3:
 $\sqrt{s} = 1 \text{ TeV}, 1 \text{ ab}^{-1}$

ILC Higgs White Paper

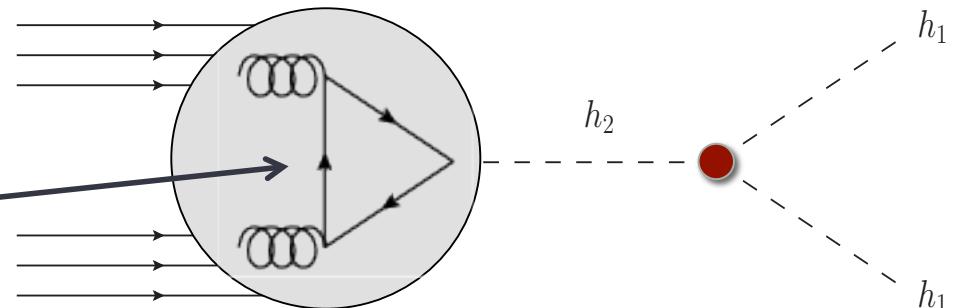
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arXiv:1305.6498



Di-Higgs production at next-generation pp colliders

Assumptions:

- $m_2 > 2 m_1$
- In the resonance region



$$\lambda_{211} = \sin \theta f(\lambda, x_0, a_1, b_3, b_4)$$

Can we discover SFOEWPT-viable models via di-Higgs production?

Strategy:

Map boundaries of parameter space by determining a set of benchmark points based on largest/smallest σ BR

→ Concentrate on ggF

$$\sigma_{LO}(pp(gg) \rightarrow h_2) = \sin^2 \theta \sigma_0^{ggF} m_2^2 \frac{d\mathcal{L}}{dm_2^2}$$

Higgs XSWG
at 100 TeV

$$BR(h_2 \rightarrow h_1 h_1) = \left(1 + \frac{8\pi \sin^2 \theta m_2 \Gamma_{h_1}^{SM}(m_2)}{\lambda_{211}^2 \sqrt{1 - \frac{4m_1^2}{m_2^2}}} \right)^{-1}$$

Benchmarks for discovery prospects

Perform MC scans over xSM space

$$a_1/\text{TeV}, b_3/\text{TeV} \in [-1, 1], \quad x_0/\text{TeV} \in [0, 1], \\ b_4, \lambda \in [0, 1]$$

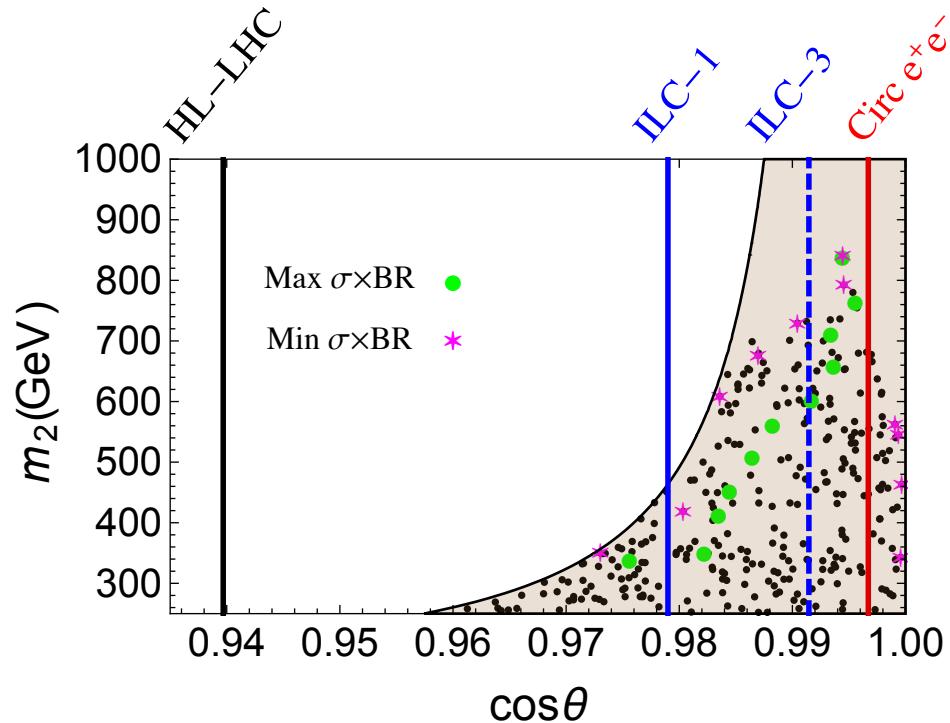
Max/Min benchmarks are chosen for each 50 GeV window in $2m_1 < m_2 < 1$ TeV

Requirements:

SFOEWPT

CosmoTransitions

Sufficient tunnelling



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Should future precision studies constrain $|\theta| \leq 0.08$, xSM **can still yield SFOEWPT**.

Can 100 TeV colliders do better?

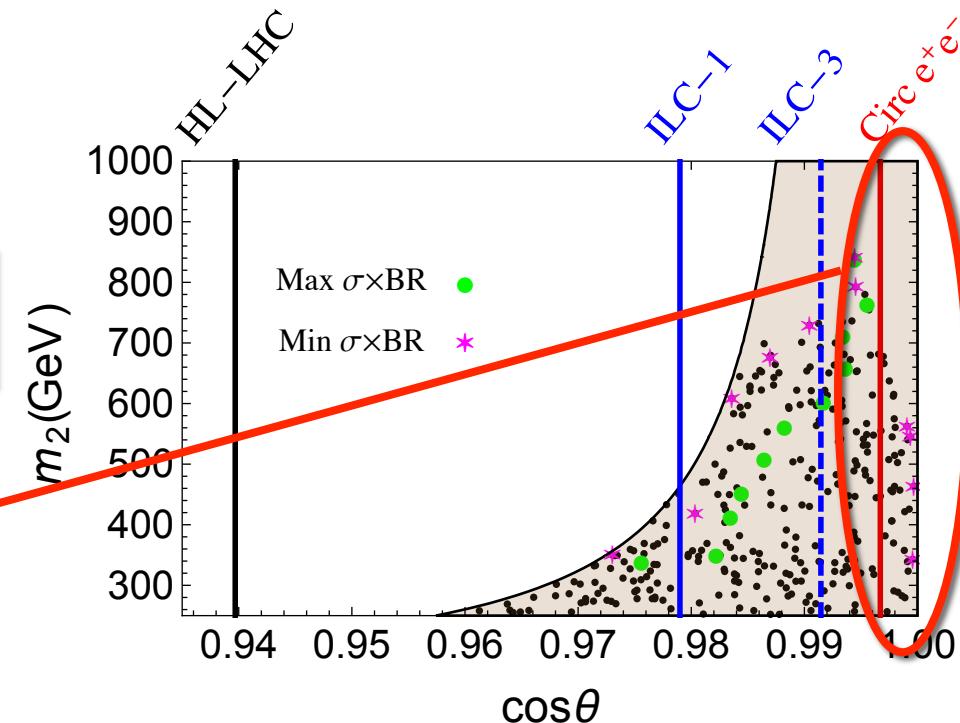
→ A question of significance...

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SFOEWPT

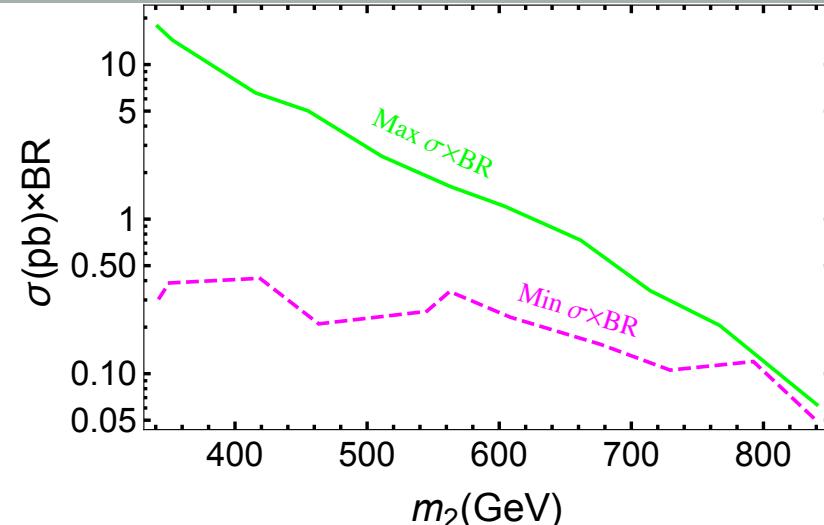
Sufficient tunnelling

CosmoTransitions



Simulate signal + BG σBR with MG5+Pythia for each benchmark.

Strategy: Explore ideal case and ask what is optimal combination of \sqrt{s} and \mathcal{L}



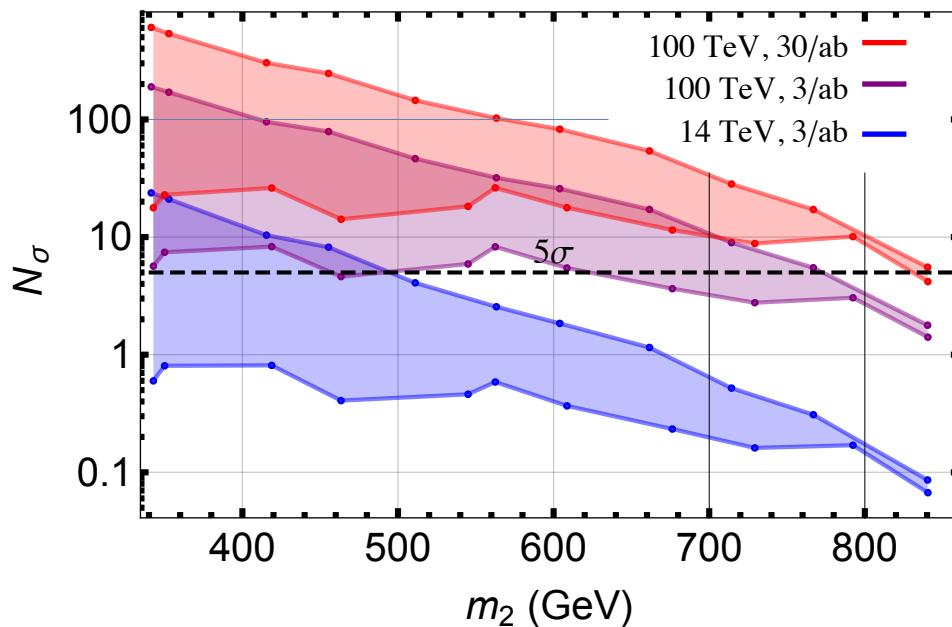
Event selection		
Final State	$bb\gamma\gamma$	$\tau\tau\tau\tau$
Backgrounds	$(b\bar{b}\gamma\gamma)_{SM}, t\bar{t}\gamma\gamma$	$(\tau\tau\tau\tau)_{SM}$
	$ \eta(\gamma), \eta(b) < 4 $	$ \eta(\tau) < 4 $
	$p_T(\gamma), p_T(b) > 20$ GeV	$p_T(\tau) > 20$ GeV
	$p_T^{\text{leading}}(\gamma), p_T^{\text{leading}}(b) > 40$ GeV	$p_T^{\text{leading}}(\tau) > 40$ GeV
	$120 < m(\gamma\gamma) < 130$ GeV, $40 < m(bb) < 200$ GeV	

For each benchmark:

- Optimize signal and BG separation with boosted decision tree (BDT) classifier
- Perform optimized multivariate cut on BDT score
- Estimate significance as

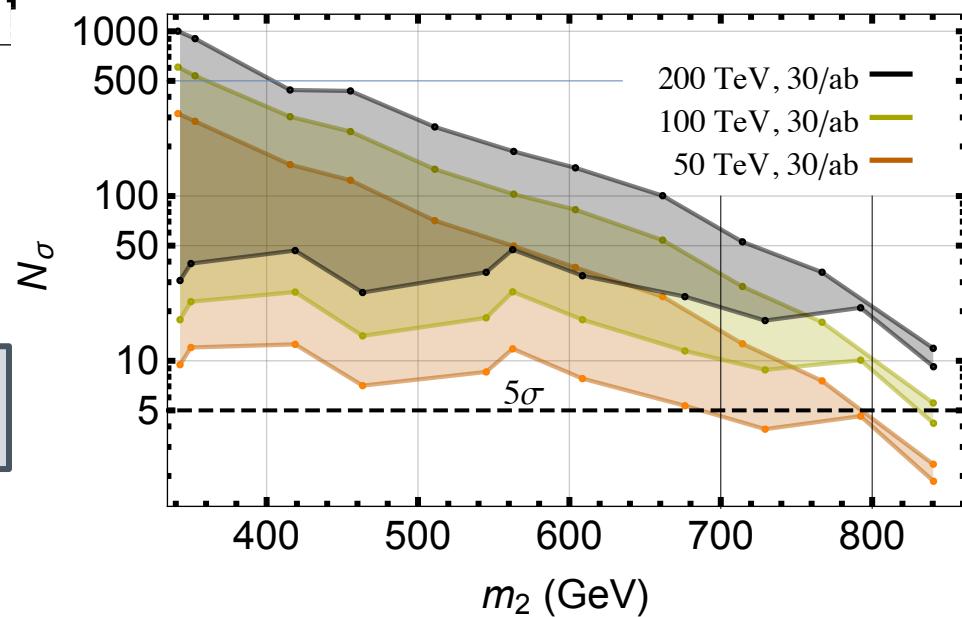
$$N_\sigma(S, B) = \sqrt{2((S + B) \ln(1 + S/B) - S)}$$

For each benchmark, combine maximal significances for each final state



There exists interesting discovery potential for HL-LHC for $m_2 \leq 500$ GeV

50 TeV at same L significantly extends reach but remains limited in high m_2 region



A 100 (200) TeV pp collider with 30 ab $^{-1}$ could probe nearly all (all) of SFOEWPT-viable space

Conclusions

xSM: a simple framework linking EWPT dynamics to mixing phenomenology, allowing EWPT-preferred parameter space to act as a guide for collider searches

Measurements of Di-Higgs production in the O(100) TeV frontier have the potential to

- Provide a more powerful probe than indirect mixing angle measurements from ILC and Circ e+e-
- Render the entire xSM SFOEWPT-viable space fully discoverable

Reach displayed here may be enhanced by including other final states, features, etc.
→ Opportunities to probe (and potentially discover!!) new dynamics during
the EWPT in the 100 TeV frontier appear quite promising

Thank you!

Appendix slide with (1) table listing efficiencies and (2) table listing BDT features

Where are strong 1st order EWPTs likely?

Connecting to EWPT requires finite temperature effective potential

$$V_{eff}(\phi, T) = V_0(\phi) + V_{CW}(\phi) + V^{T \neq 0}(\phi, T) + V^{\text{Ring-sum}}(\phi, T)$$

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Connecting to EWPT requires finite temperature effective potential

$$V_{eff}(\phi, T) = V_0(\phi) + \cancel{V_{CW}(\phi)} + \cancel{V^{T \neq 0}(\phi, T)} + \cancel{V^{\text{Ring-sum}}(\phi, T)}$$

→ Gauge dependent!! JHEP 1107 (2011) 029

→ Independence restored at high temperature

$$\begin{aligned} V_{eff}(\phi, \alpha, T)^{xSM} &\xrightarrow{\text{High T}} \bar{D}(T^2 - T_0^2)\phi^2 + \color{red}e\phi^3 + \frac{\bar{\lambda}}{4}\phi^4 \\ v(T)/\sqrt{2} &= \phi(T) \cos \alpha(T), \quad x(T) = \phi(T) \sin \alpha(T) \end{aligned}$$

Condition for SFOEWPT

$$\begin{aligned} \cos \alpha(T_c) \frac{\Delta \phi(T_c)}{T_c} &\gtrsim 1 \\ \implies -\cos \alpha(T_c) \frac{\color{red}e}{2T_c \bar{\lambda}} &\gtrsim 1 \end{aligned}$$

SFOEWPT driven by tree-level parameters

$$\begin{aligned} \color{red}e &= \left(\frac{a_1}{2} \cos^2 \alpha + \frac{b_3}{3} \sin^2 \alpha \right) \sin \alpha \\ \bar{\lambda} &= \lambda \cos^4 \alpha + \frac{a_2}{2} \cos^2 \alpha \sin^2 \alpha + \frac{b_4}{4} \sin^4 \alpha \end{aligned}$$

Projected sensitivities to mixing angle: Higgs-like couplings

All relevant couplings rescaled by $\cos\theta$

$$\mu_{h_1 \rightarrow XX} = \frac{\sigma \cdot \text{BR}}{\sigma^{SM} \cdot \text{BR}^{SM}} = \cos^2 \theta$$

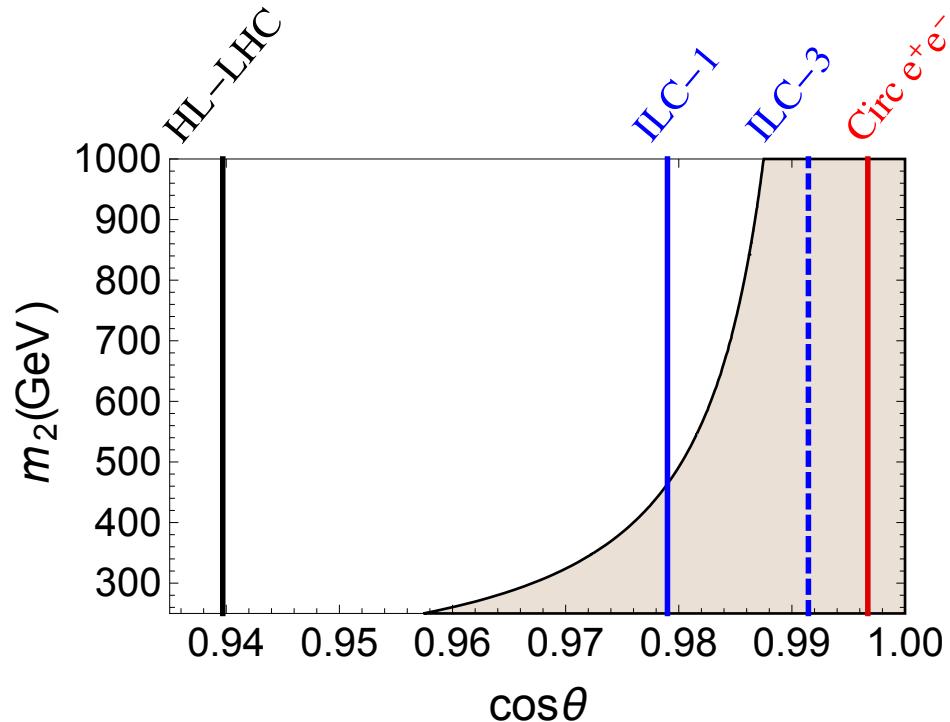
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Sensitivity from projected uncertainties

$$\chi^2(\theta) = \sum_i \left(\frac{1 - \cos^2 \theta}{\Delta \mu_i^{proj}} \right)^2$$



Current constraints: Oblique Parameters

Effects are simple to calculate

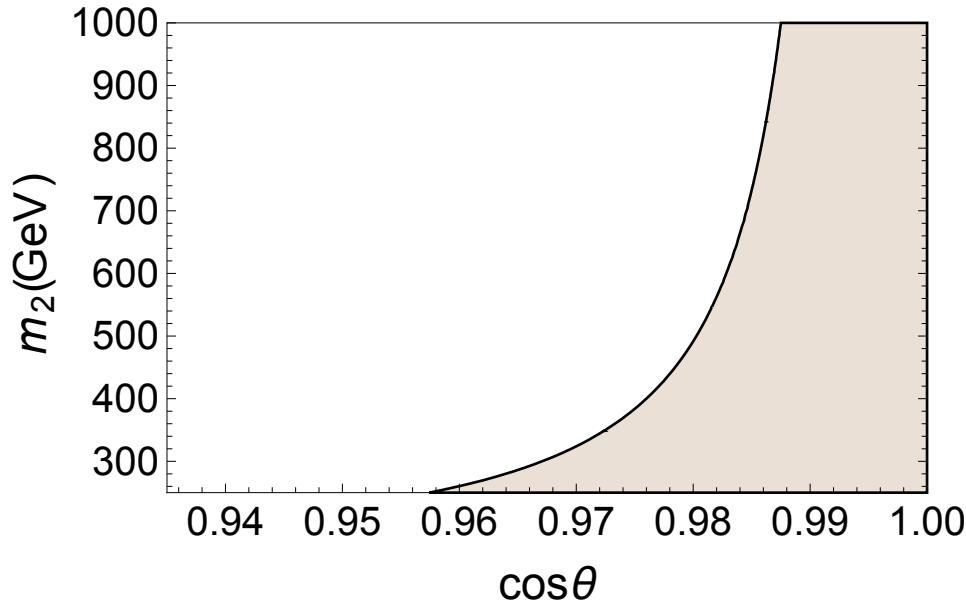
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$$\mathcal{O} = S, T, U$$

Perform full fit to current best-fit values from Gfitter

$$\Delta \chi^2 = \sum_{i,j} (\Delta \mathcal{O}_i - \Delta \mathcal{O}_i^0) (\sigma^2)_{ij}^{-1} (\Delta \mathcal{O}_j - \Delta \mathcal{O}_j^0)$$

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