Understanding the EW Phase Transition @ LHC and Beyond

Jose Miguel No
IFT-UAM/CSIC, Madrid

Opportunities at Future Colliders
Madrid, 11/06/19

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Understanding the EW Epoch

Why?

- ➔ Yield Precise knowledge of EWSB in Early Universe
- ➔ **(Possible) Cosmological Relics from the EW Epoch**

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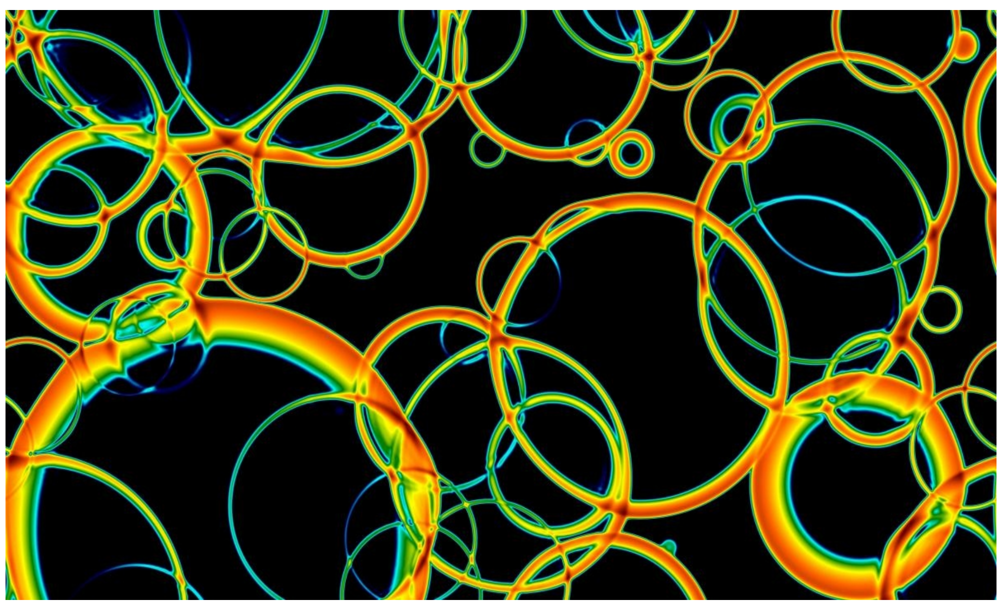
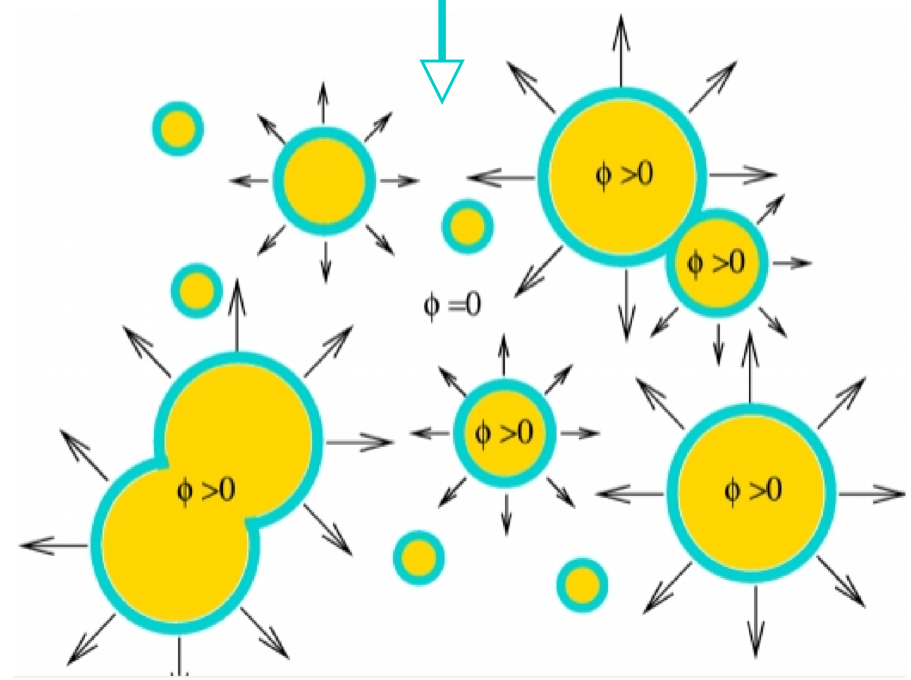
Gravitational Wave Signal



[courtesy of David Weir]

*Hindmarsh, Huber, Rummukainen, Weir, PRD **96** (2017) 103520*

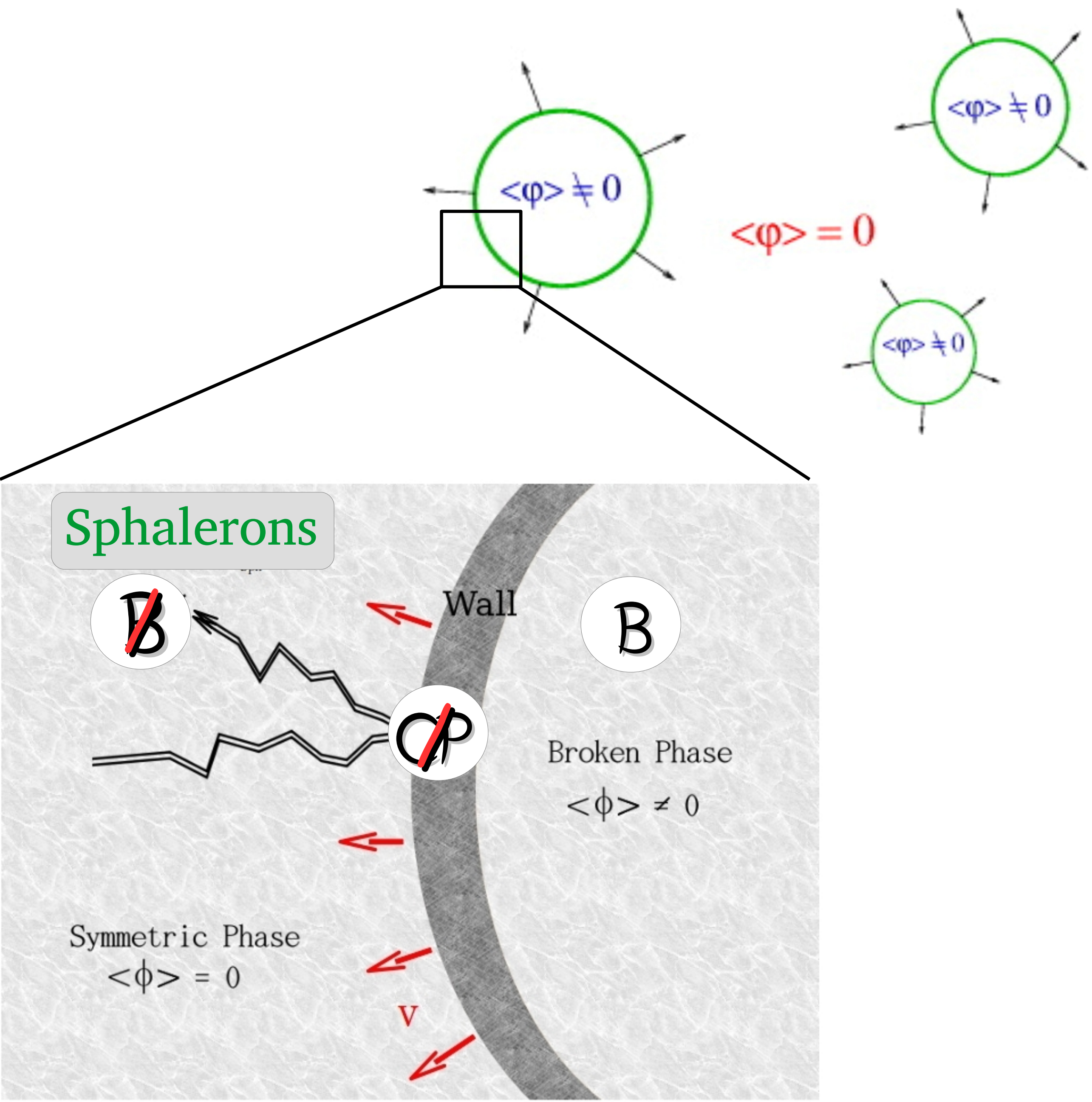


Sourced by bubble Collisions & subsequent plasma motions

Understanding the EW Epoch

Why?

- ➔ Yield Precise knowledge of EWSB in Early Universe
- ➔ (Possible) Cosmological Relics from the EW Epoch
- ➔ (Possible) Answer to Open Mysteries at Interface Particle Physics Cosmology



Matter-Antimatter Asymmetry

▶ Baryogenesis

<u>SAKHAROV CONDITIONS</u> *(for dynamical generation of baryon asymmetry)*

B Violation Sphalerons

C/CP Violation

Departure from Thermal Equilibrium

EW Phase Transition

Higgs Evolution in Early Universe → FINITE-TEMPERATURE EFFECTIVE POTENTIAL

$$\boxed{V_{\text{eff}}(h,T) = \underbrace{V_0(h)}_{\text{Tree-level potential}} + \underbrace{V_0^{\text{loop}}(h)}_{\text{Loop corrections}} + \underbrace{V_T(h,T)}_{\text{Thermal corrections}}}$$

(Perturbative) Nature of EWPT

Higgs Evolution in Early Universe ➔ FINITE-TEMPERATURE EFFECTIVE POTENTIAL

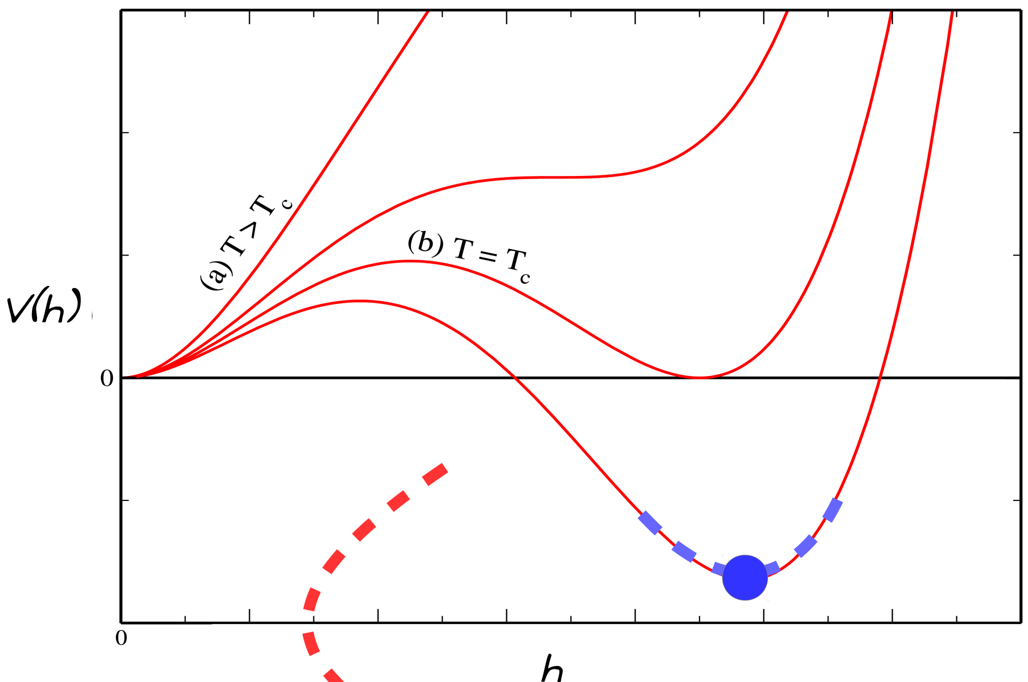
$$V_{\rm eff}(h,T) = V_0(h) + V_0^{\rm loop}(h) + V_T(h,T)$$

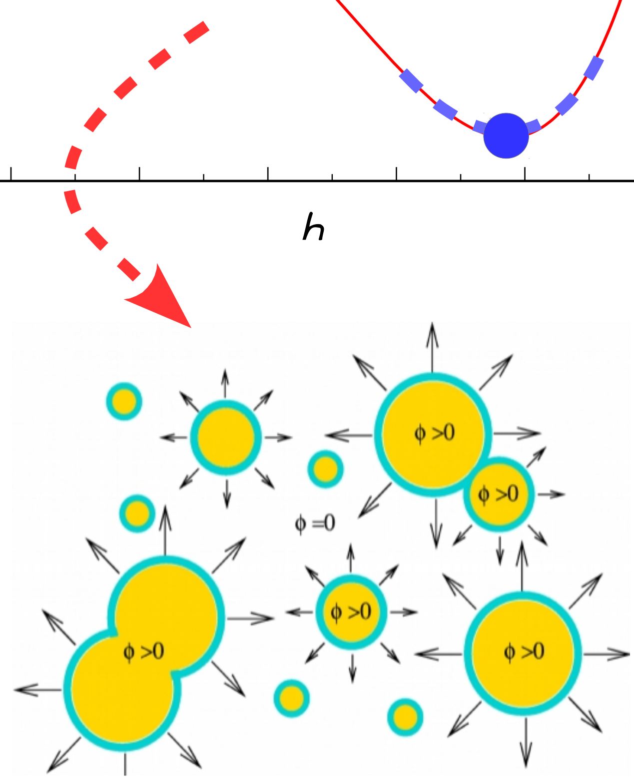
Tree-level potential | Loop corrections | Thermal corrections

(Perturbative) Nature of EWPT

1st Order:

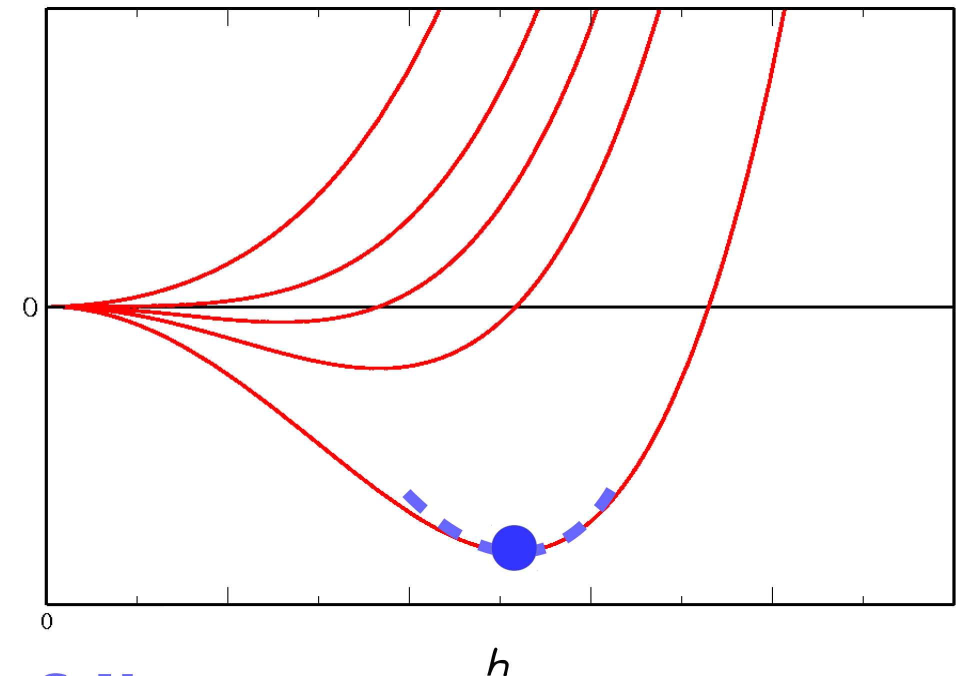
$\langle h \rangle = 0 \rightarrow \langle h \rangle = h(T)$ Discontinuous





2nd Order:

$\langle h \rangle = 0 \rightarrow \langle h \rangle = h(T)$ Continuous



v = 246 GeV

m_h = 125 GeV

Higgs Evolution in Early Universe → FINITE-TEMPERATURE EFFECTIVE POTENTIAL

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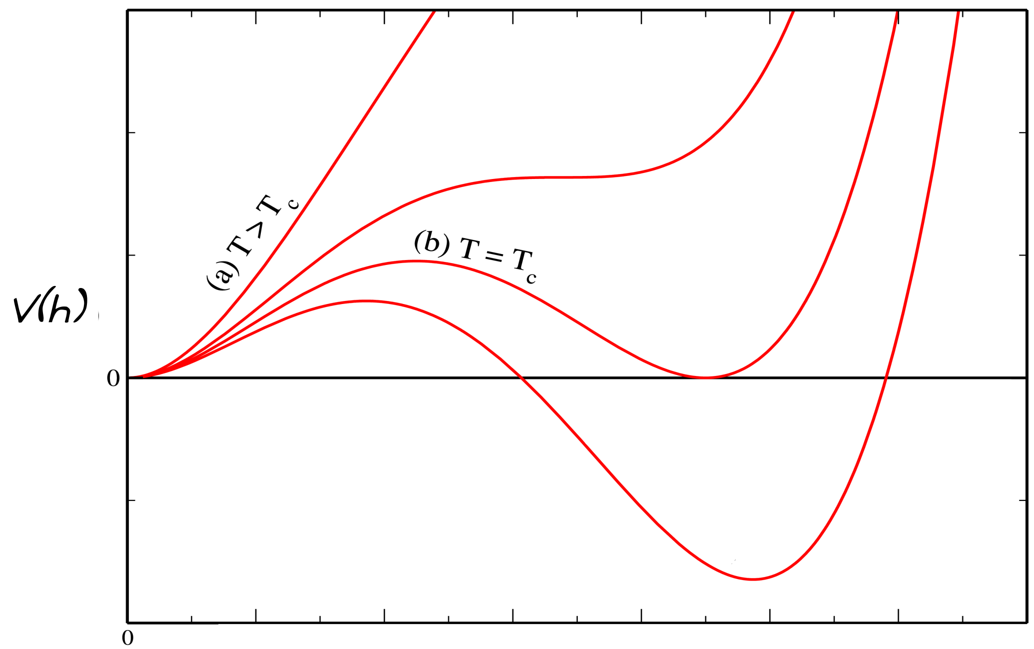

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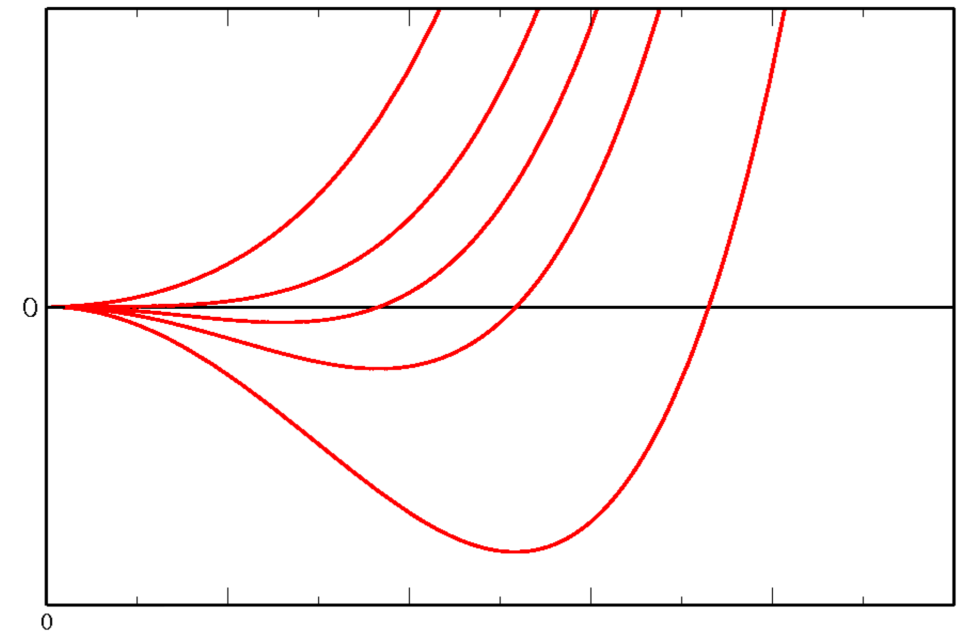

SM: EWPT (non-perturbatively) is Smooth Cross-Over

Kajantie, Laine, Rummukainen, Shaposhnikov, Phys. Rev. Lett. ***77*** *(1996) 2887*

Higgs Evolution in Early Universe → FINITE-TEMPERATURE EFFECTIVE POTENTIAL

$$V_{\mathrm{eff}}(h,T) = V_0(h) + V_0^{\mathrm{loop}}(h) + V_T(h,T)$$

Tree-level potential

Loop corrections

Thermal corrections

Non-analytic term $(m^2)^{3/2}$ in $V(h,T)$ from Matsubara Zero-modes

(only present for bosons)

(Perturbative) Nature of EWPT

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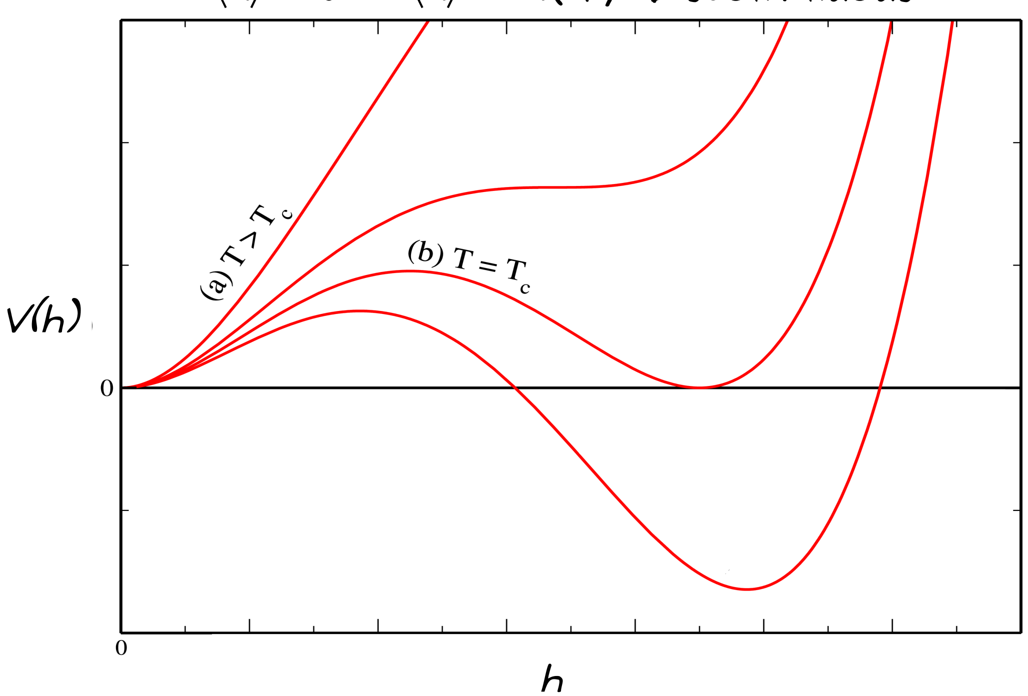
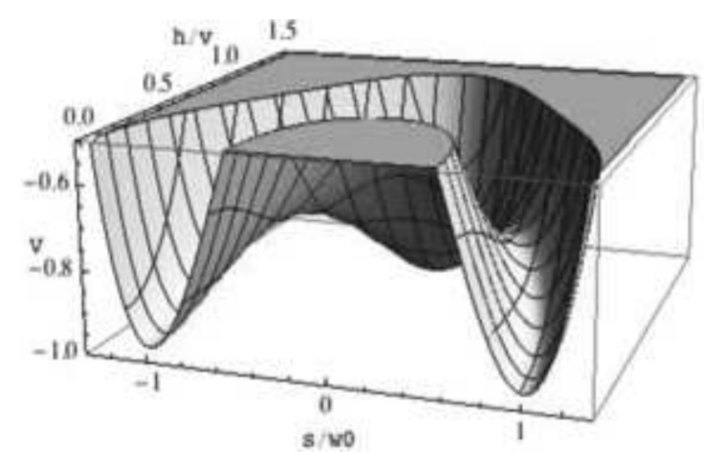


Multiple fields involved in the EWPT may allow for tree-level potential barrier



BSM: New Physics sizeably coupled to Higgs can drastically change the EWPT nature

Higgs Evolution in Early Universe ➔ FINITE-TEMPERATURE EFFECTIVE POTENTIAL

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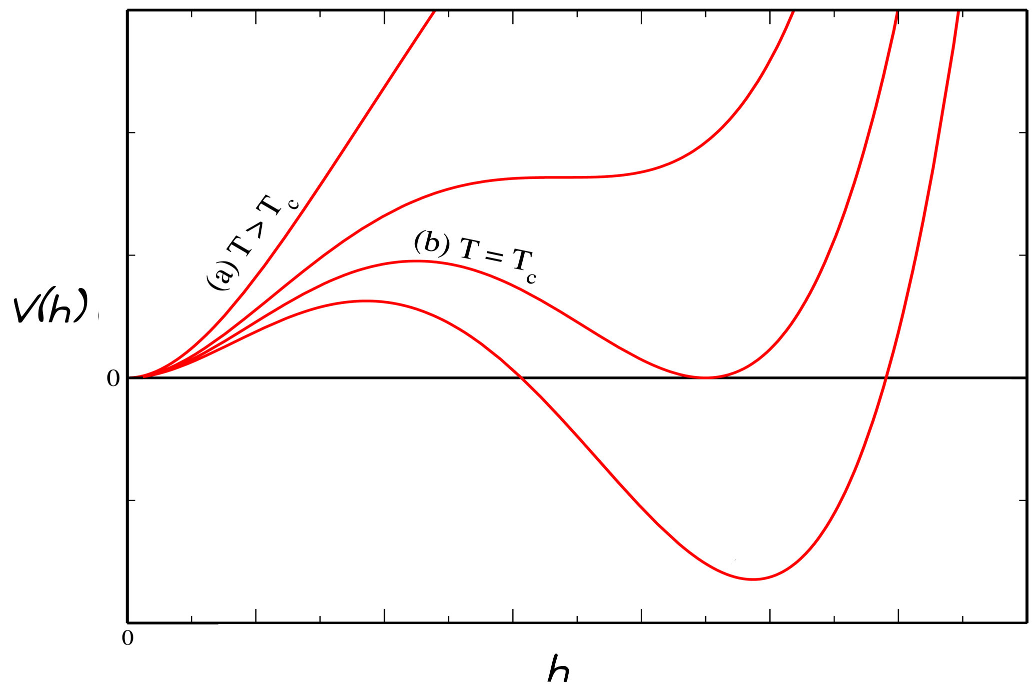

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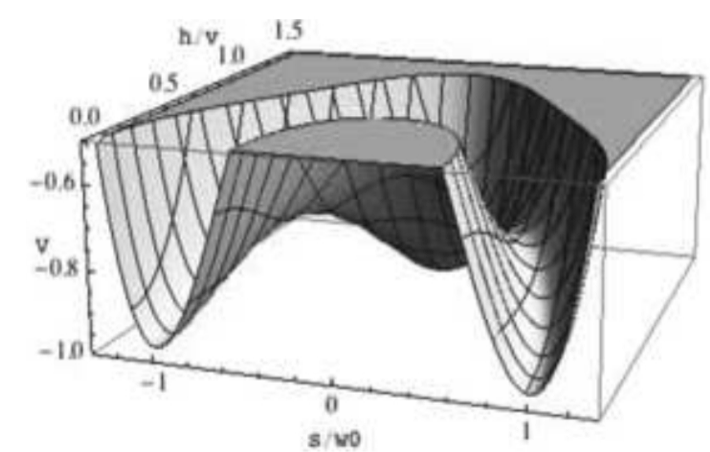

BSM: New Physics sizeably coupled to Higgs can drastically change the EWPT nature

- New Physics will induce deviations in Higgs couplings
- New Physics needed close to EW scale

What BSM Scenarios?

Chung, Long, Wang, PRD **87** (2013) 023509

NO Systematic approach for BSM
yielding 1st Order EW Phase Transition

⊕

Collider Phenomenology

❶ EFT not possible in general

➔ New Particles Present in Thermal plasma → EW Scale

➔ New Particles get mass from EWSB

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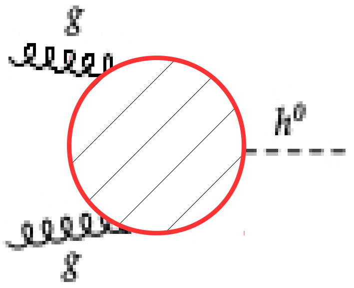
❷ Models with same EWPT Dynamics & Very Different Collider Phenomenology

e.g. Colored vs Uncolored BSM

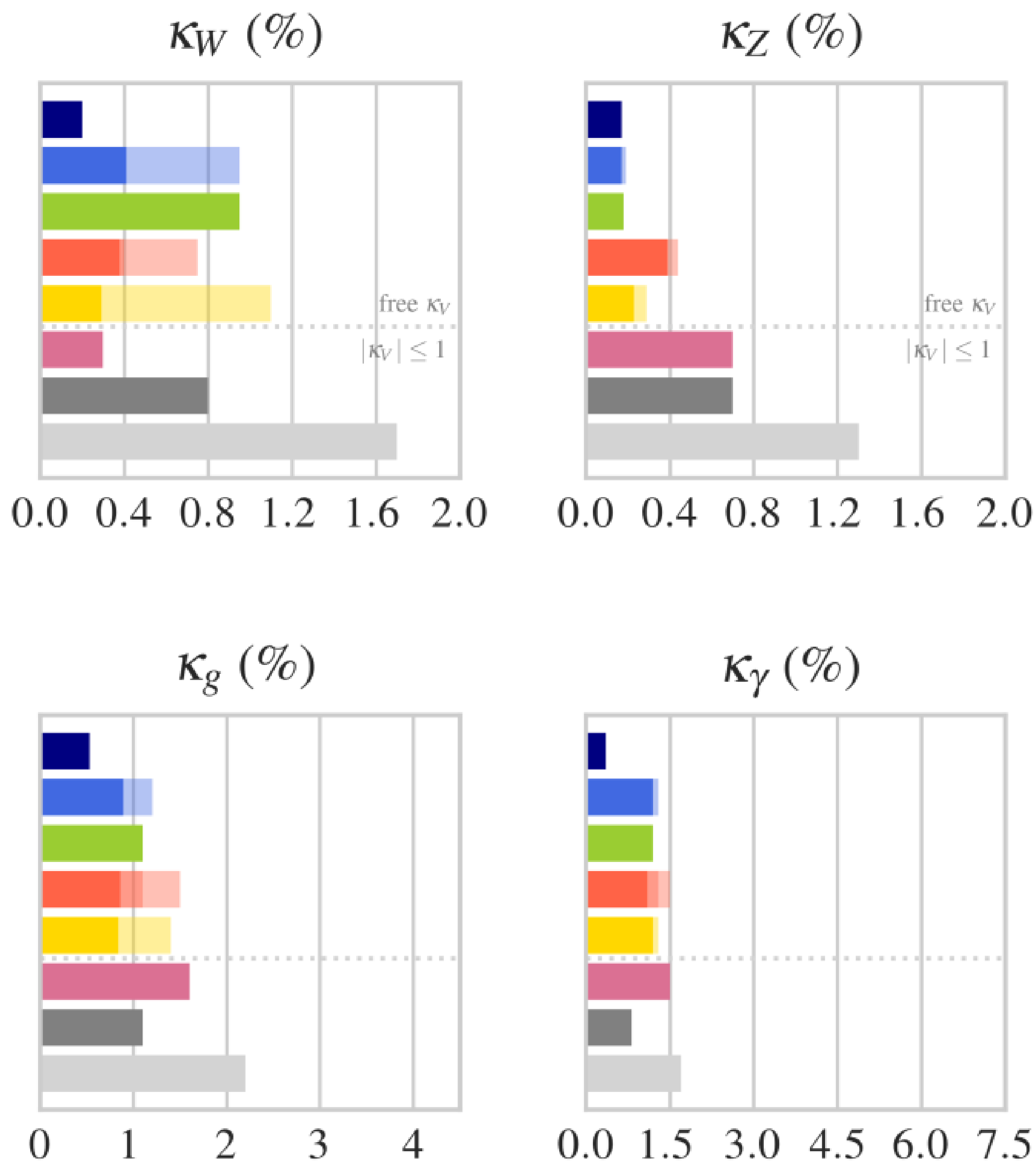


What BSM Scenarios?

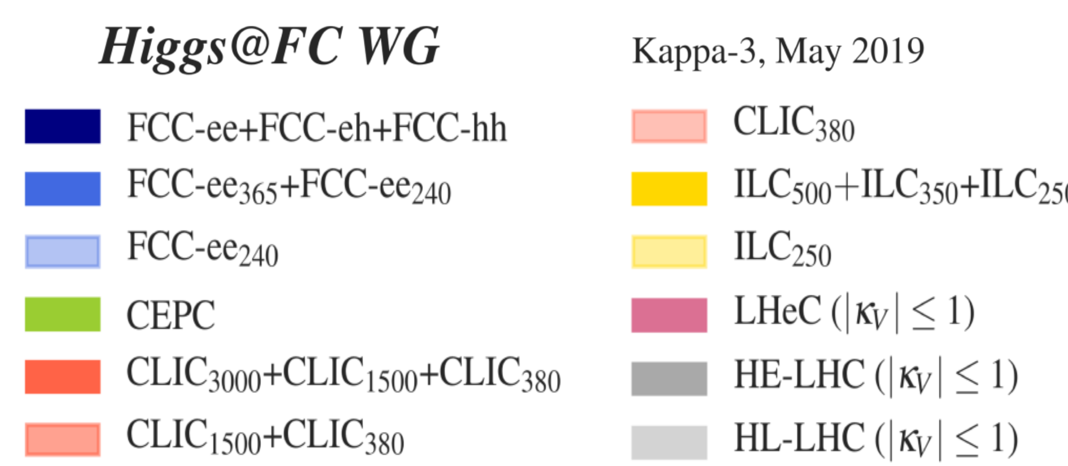
SM + Scalar Singlet	Espinosa, Quiros 93, Benson 93, Choi, Volkas 93, Vergara 96, Branco, Delepine, Emmanuel-Costa, Gonzalez 98, Ham, Jeong, Oh 04, Ahriche 07, Espinosa, Quiros 07, Profumo, Ramsey-Musolf, Shaughnessy 07, Noble, Perelstein 07, Espinosa, Konstandin, No, Quiros 08, Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy 09, Ashoorioon, Konstandin 09, Das, Fox, Kumar, Weiner 09, Espinosa, Konstandin, Riva 11, Chung, Long 11, Barger, Chung, Long, Wang 12, Huang, Shu, Zhang 12, Fairbairn, Hogan 13, Katz, Perelstein 14, Profumo, Ramsey-Musolf, Wainwright, Winslow 14, Jiang, Bian, Huang, Shu 15, Kozaczuk 15, Cline, Kainulainen, Tucker-Smith 17, Kurup, Perelstein 17, Chen, Kozaczuk, Lewis 17, Gould, Kozaczuk, Niemi, Ramsey-Musolf, Tenkanen, Weir 19...
SM + Scalar Doublet (2HDM)	Turok, Zadrozny 92, Davies, Froggatt, Jenkins, Moorhouse 94, Cline, Lemieux 97, Huber 06, Froome, Huber, Seniuch 06, Cline, Kainulainen, Trott 11, Dorsch, Huber, No 13, Dorsch, Huber, Mimasu, No 14, Basler, Krause, Muhlleitner, Wittbrodt, Wlotzka 16, Dorsch, Huber, Mimasu, No 17, Bernon, Bian, Jiang 17, Andersen, Gorda, Helset, Niemi, Tenkanen, Tranberg, Vuorinen, Weir 18...
SM + Scalar Triplet	Patel, Ramsey-Musolf 12, Niemi, Patel, Ramsey-Musolf, Tenkanen, Weir 18 ...
MSSM	Carena, Quiros, Wagner 96, Delepine, Gerard, Gonzalez Felipe, Weyers 96, Cline, Kainulainen 96, Laine, Rummukainen 98, Carena, Nardini, Quiros, Wagner 09, Cohen, Morrissey, Pierce 12, Curtin, Jaiswal, Meade 12, Carena, Nardini, Quiros, Wagner 13, Katz, Perelstein, Ramsey-Musolf, Winslow 14...
NMSSM...	Pietroni 93, Davies, Froggatt, Moorhouse 95, Huber, Schmidt 01, Ham, Oh, Kim, Yoo, Son 04, Menon, Morrissey, Wagner 04, Funakubo, Tao, Yokoda 05, Huber, Konstandin, Prokopec, Schmidt 07, Chung, Long 10, Kozaczuk, Profumo, Stephenson Haskins, Wainwright 15...
EFT Approach (H^6)	Grojean, Servant, Wells 05, Bodeker, Froome, Huber, Seniuch 05, Huang, Joglekar, Li, Wagner 15...

What BSM Signatures?

Indirect Probes (Higgs couplings)



ECFA Higgs Study Group, 2019
(for the ESPP Update)



[courtesy of Christophe Grojean]

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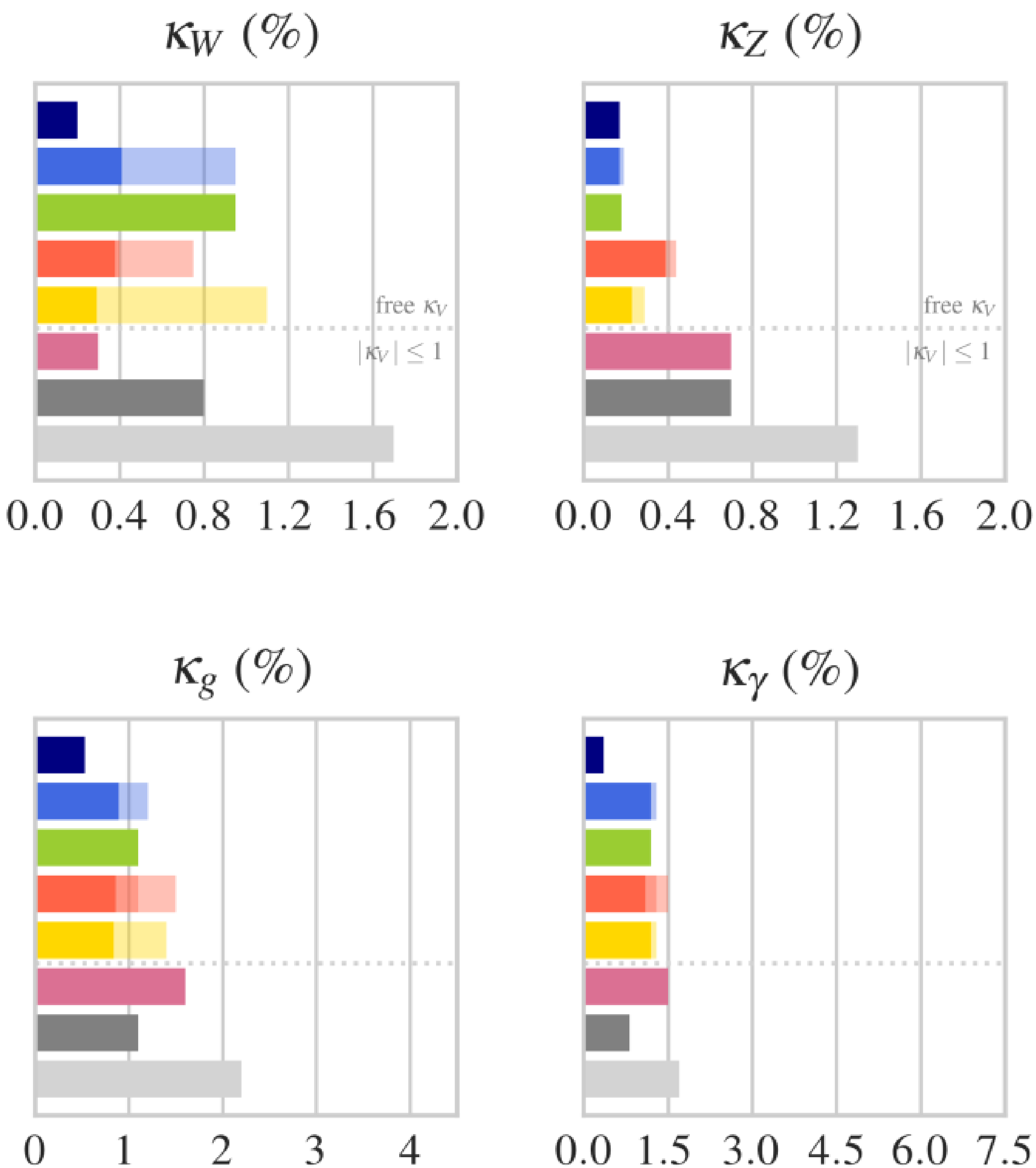

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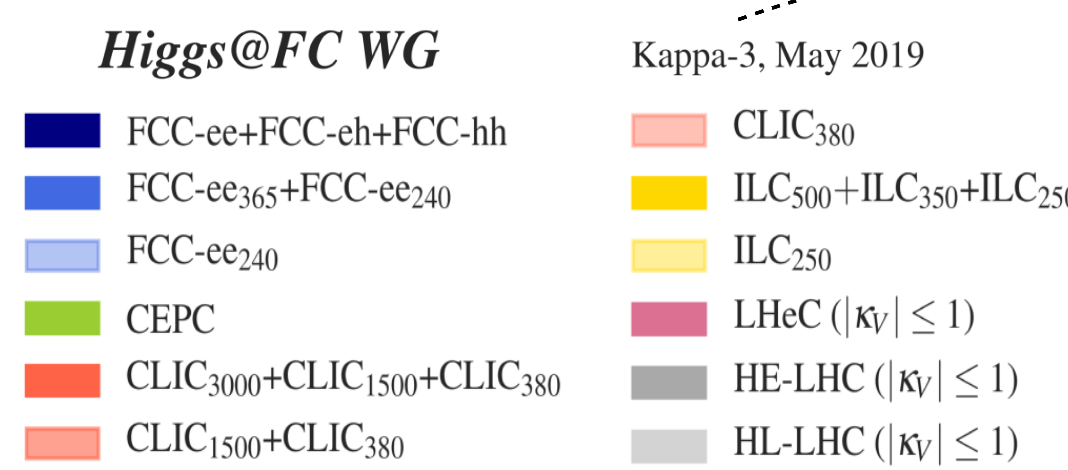

[courtesy of Christophe Grojean]

Scenario	BR_{inv}	BR_{unt}	include HL-LHC
kappa-3	measured	measured	yes

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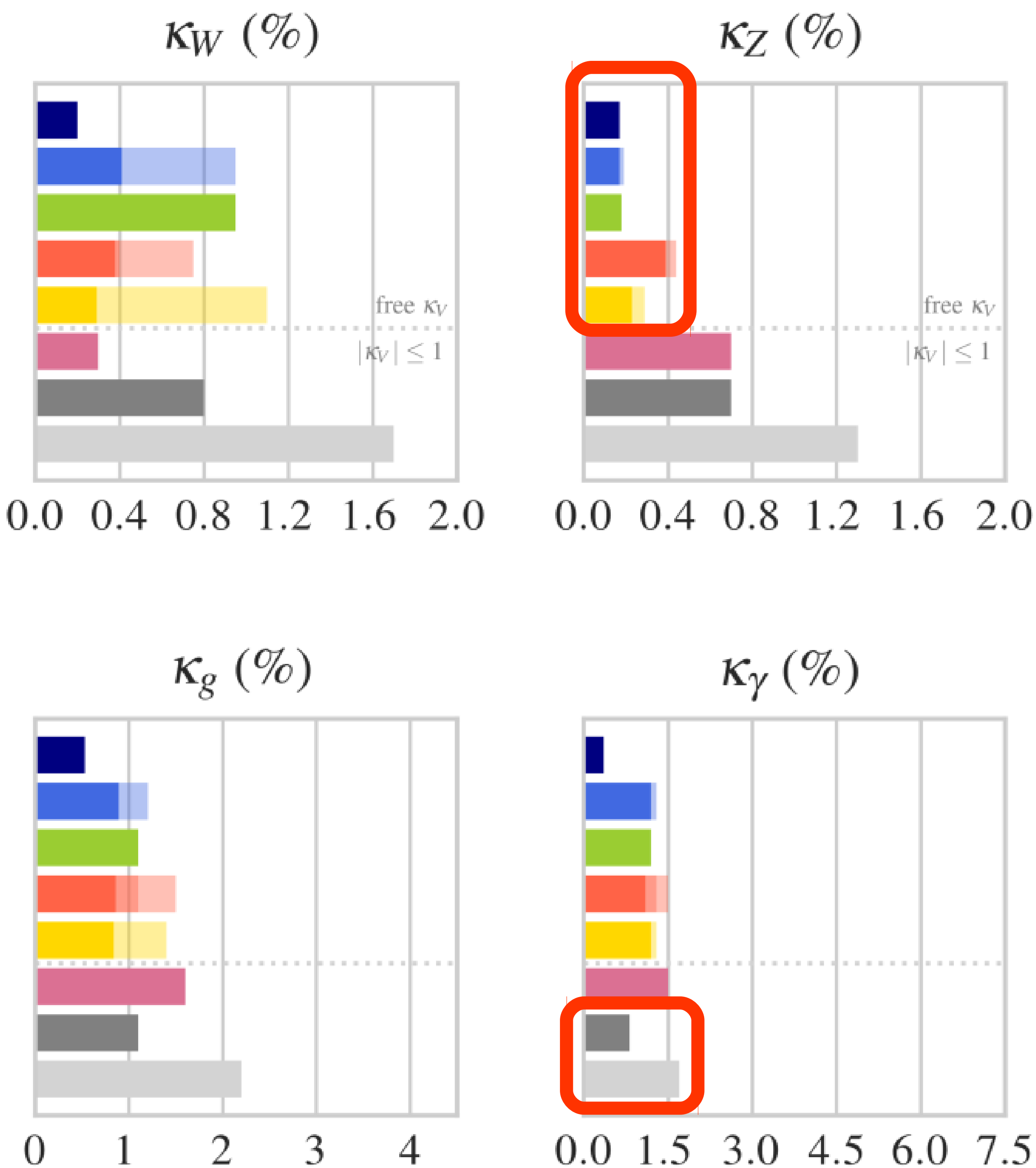

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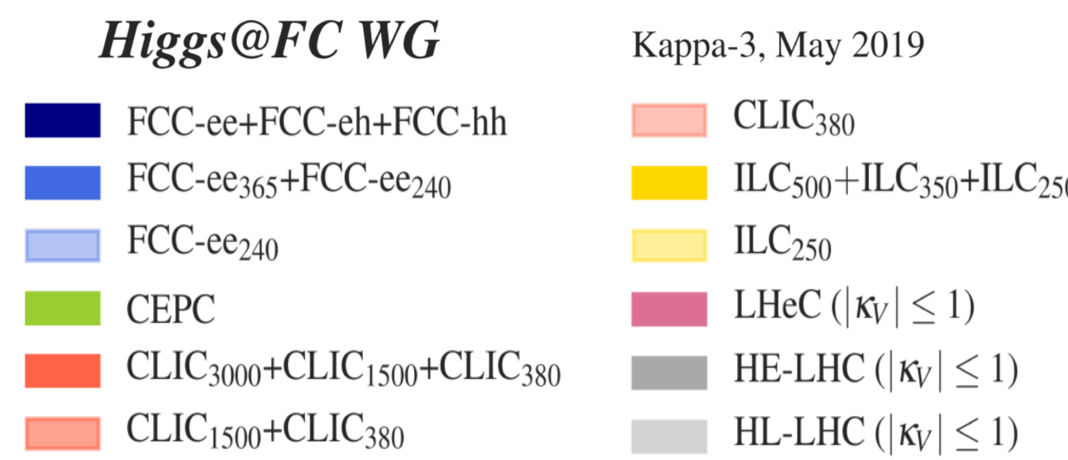

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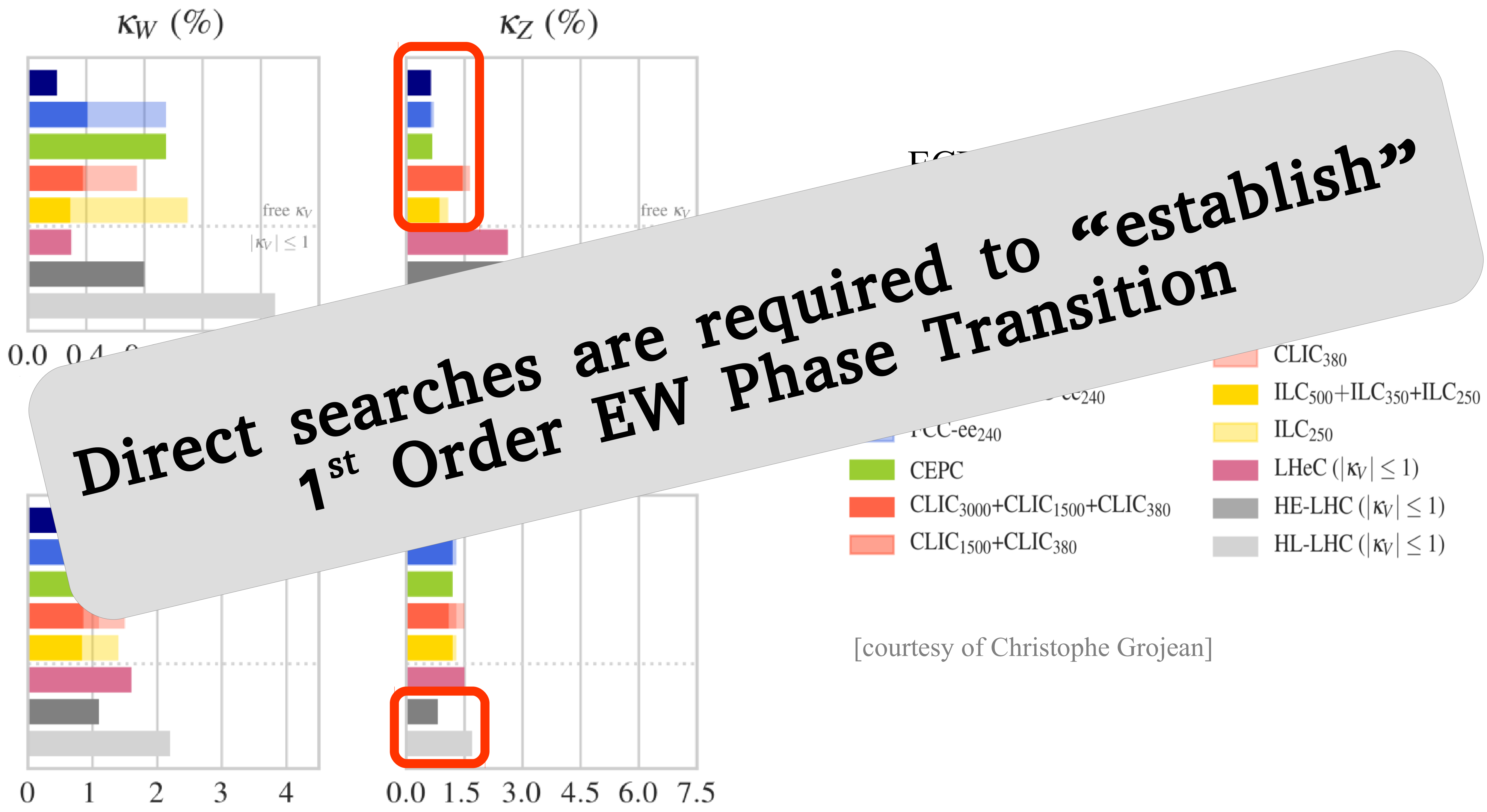

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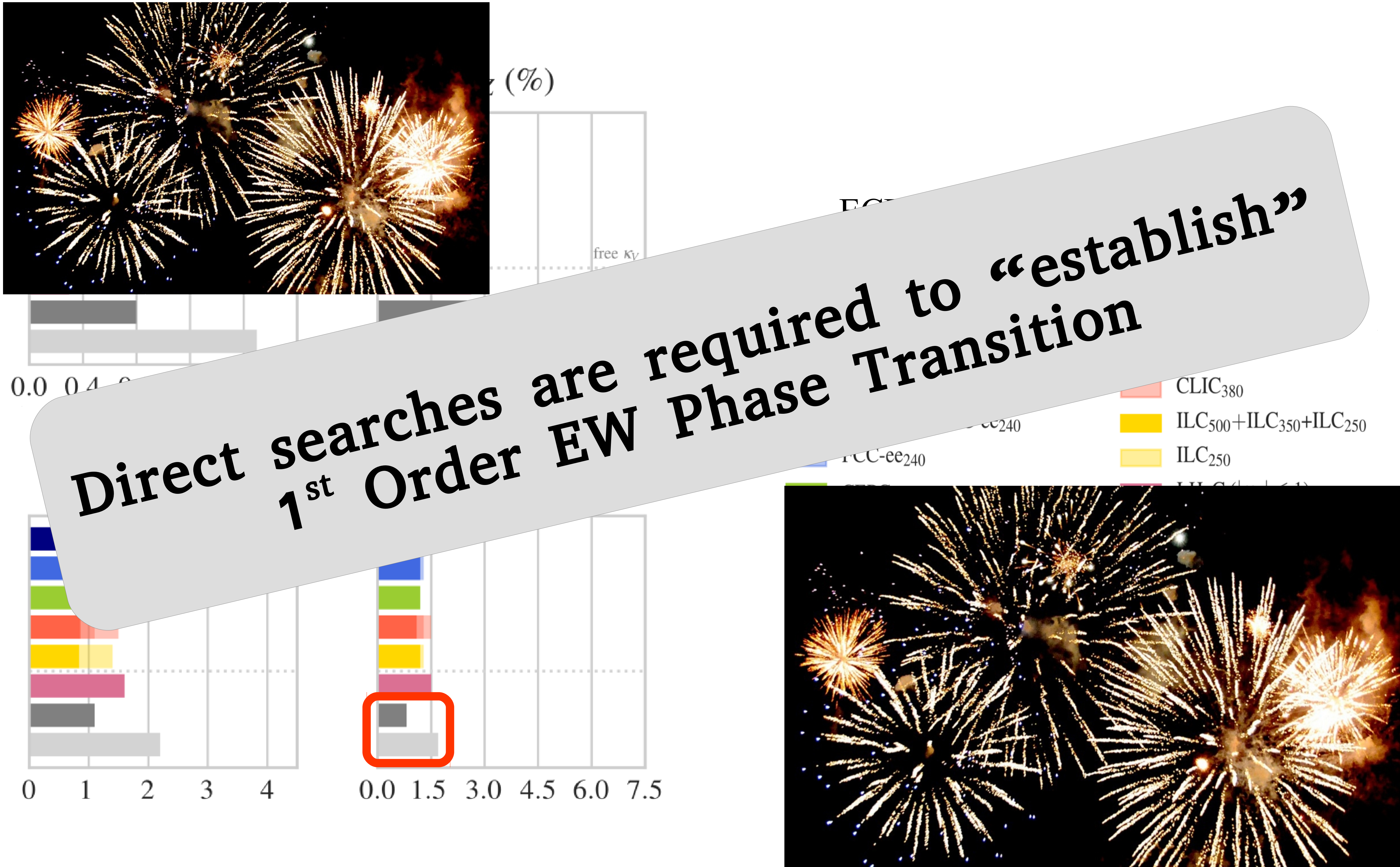
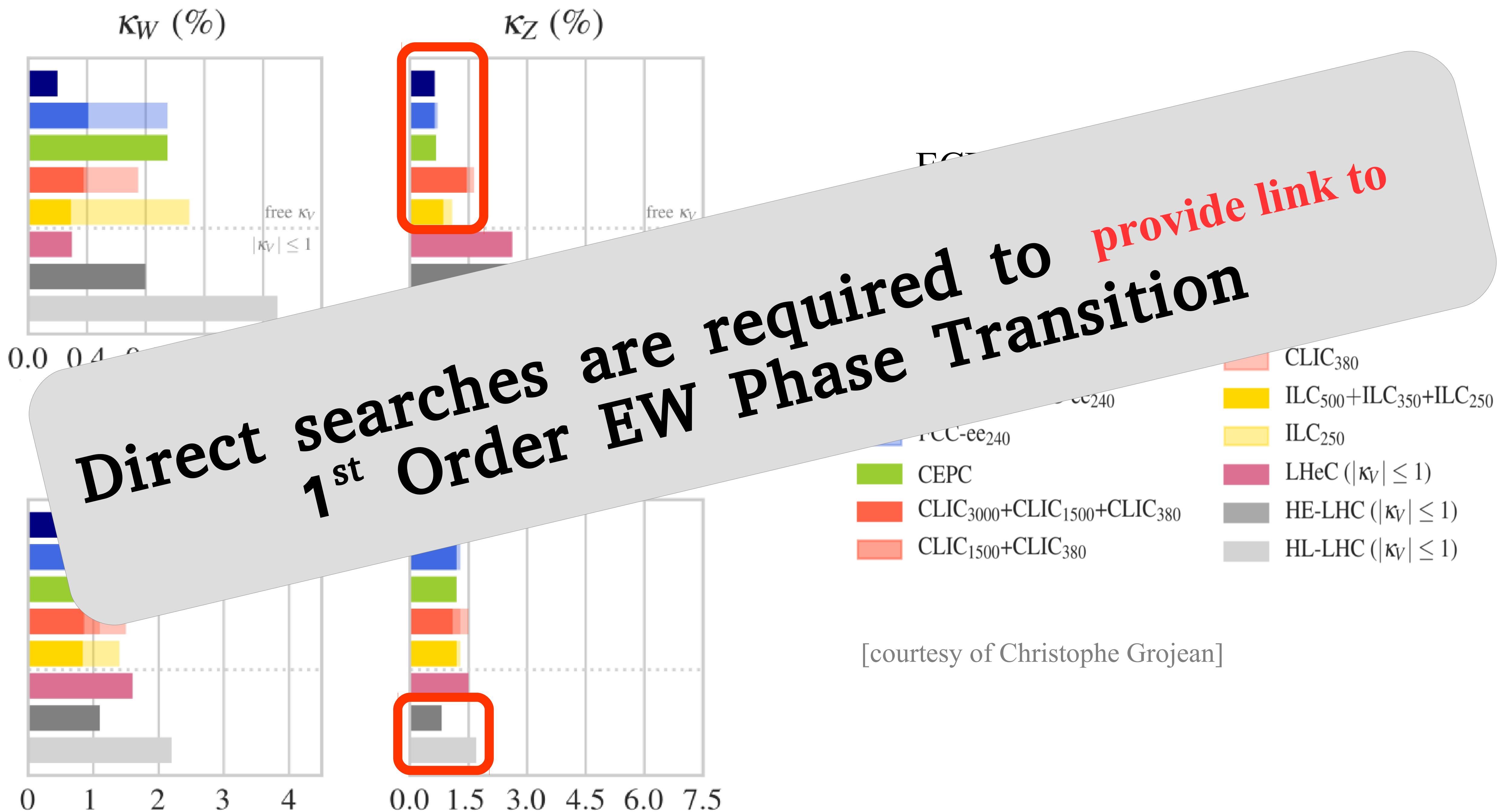


Direct searches are required to “establish” 1st Order EW Phase Transition

What BSM Signatures?

Indirect Probes (Higgs couplings)



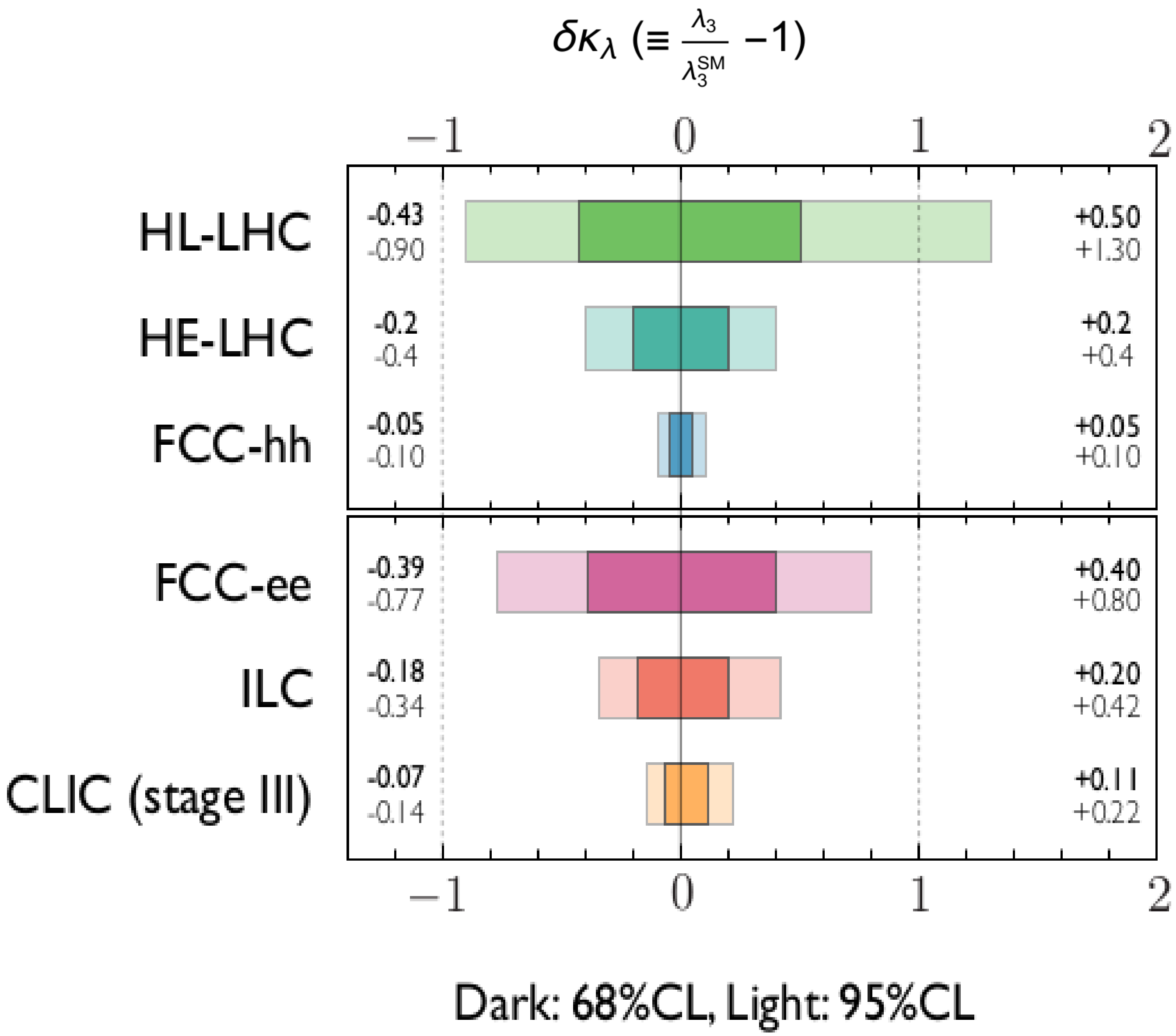
[courtesy of Christophe Grojean]

Direct searches are required to provide link to 1st Order EW Phase Transition

What BSM Signatures?

"Indirect" Probe: **Higgs self-coupling**

ECFA Higgs Study Group, 2019
(for the ESPP Update)



*Di Vita, Durieux, Grojean, Gu. Liu, Panico, Riembau, Vantalon, JHEP **1802** (2018) 178*

What BSM Signatures?

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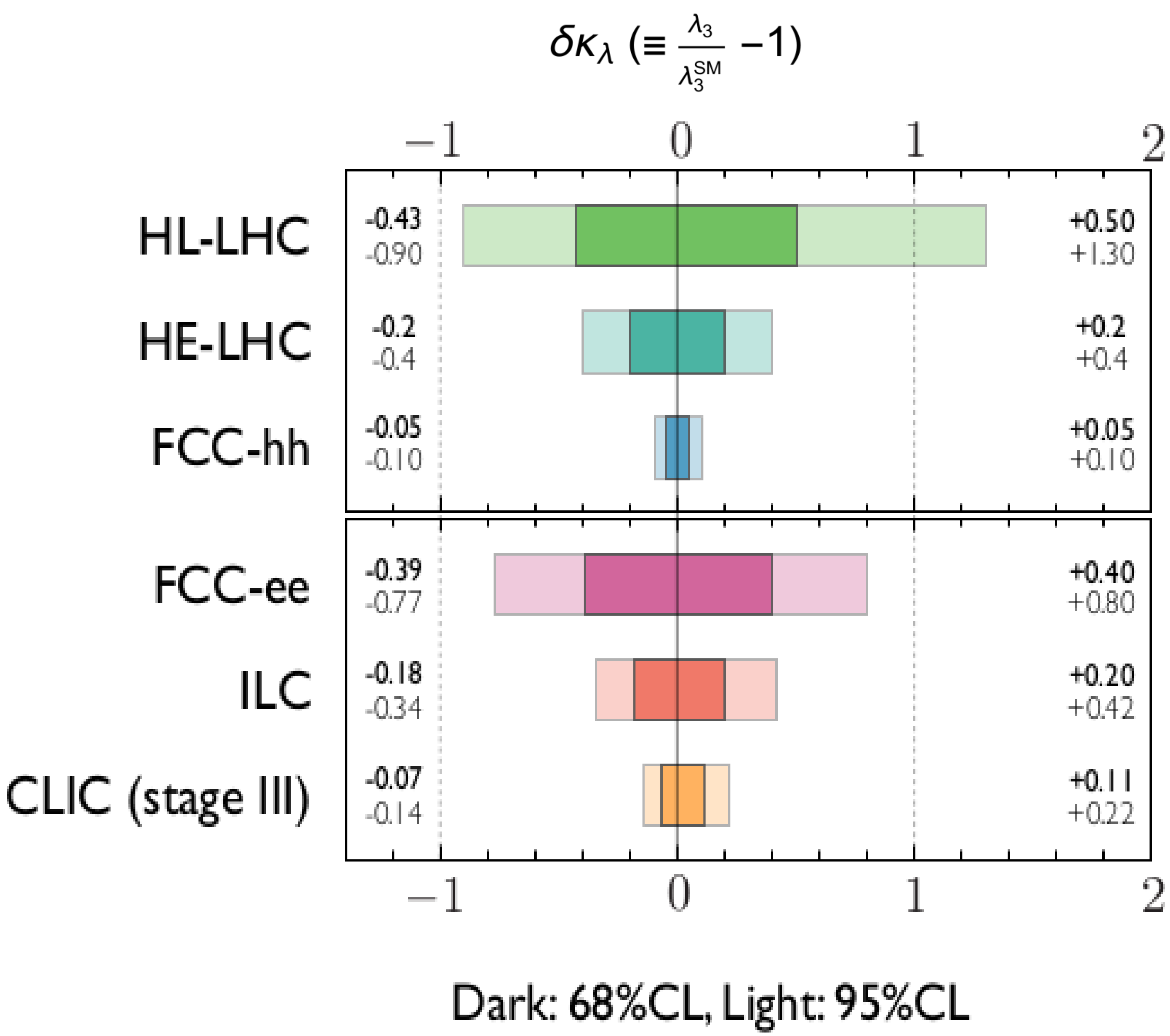

Also in this case, NP may manifest itself via direct signatures!

Di Vita, Durieux, Grojean, Gu. Liu, Panico, Riembau, Vantalon, JHEP ***1802*** *(2018) 178*

EWPT Scenarios within LHC Reach

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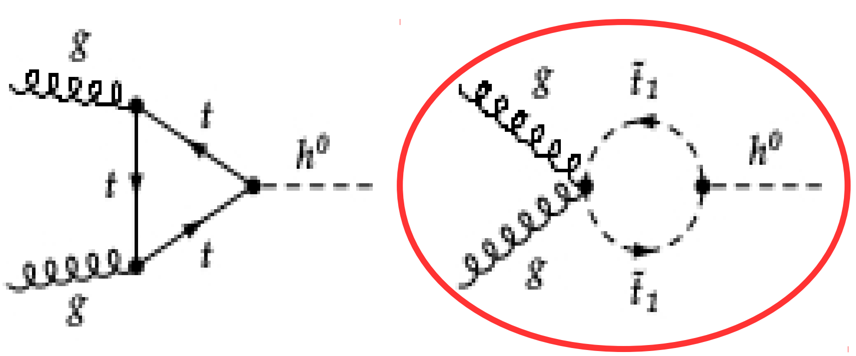
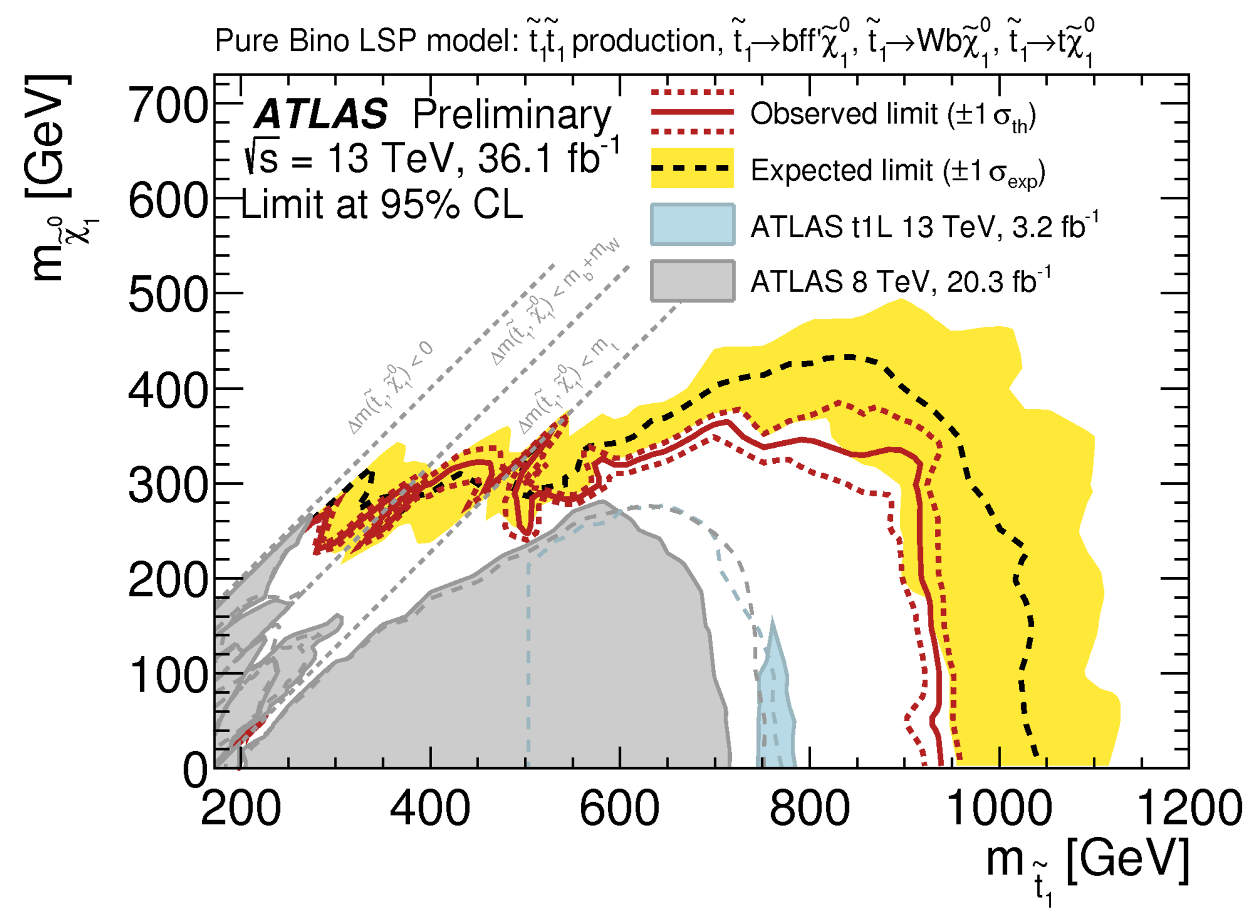
▷ **MSSM** (light stop scenario)

[courtesy of Kimmo Kainulainen]

Large Deviations from SM Higgs Signal Strengths due to light stops





EWPT Scenarios within LHC Reach

▷ NON-MINIMAL HIGGS SECTOR

e.g. **2HDM**

$$
\begin{aligned}
V(H_1, H_2) &= \mu_1^2 \left|H_1\right|^2 + \mu_2^2 \left|H_2\right|^2 - \mu^2 \left[H_1^\dagger H_2 + \text{h.c.}\right] \\
&+ \frac{\lambda_1}{2} \left|H_1\right|^4 + \frac{\lambda_2}{2} \left|H_2\right|^4 + \lambda_3 \left|H_1\right|^2 \left|H_2\right|^2 \\
&+ \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{\lambda_5}{2} \left[\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]
\end{aligned}
$$

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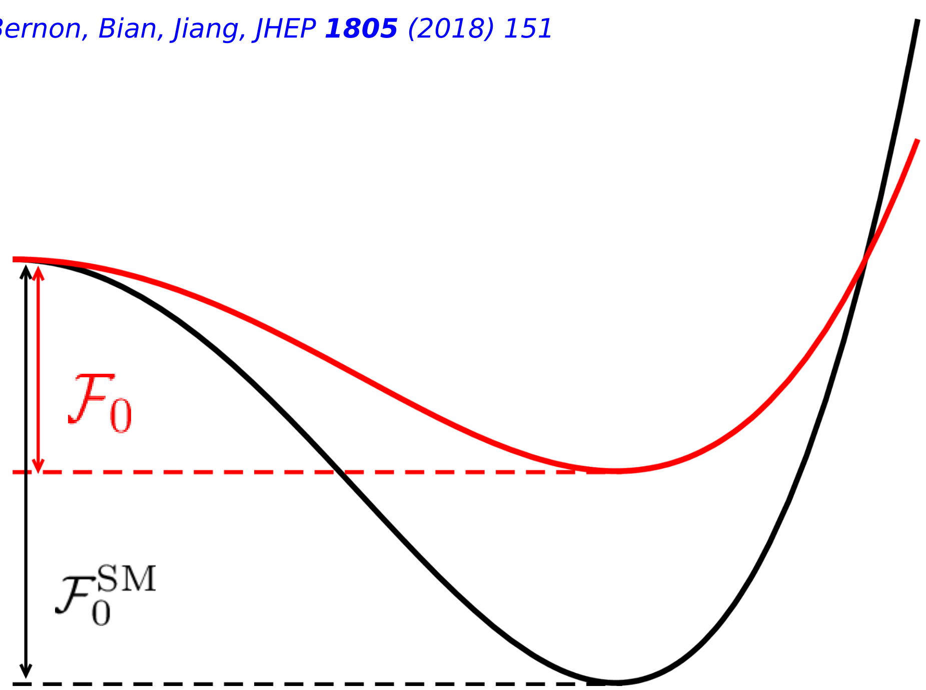
Nature of EWPT dominantly controlled by
T=0 Vacuum energy difference

*Dorsch, Huber, Mimasu, JMN, JHEP **1712** (2017) 086*

*Bernon, Bian, Jiang, JHEP **1805** (2018) 151*



$$\begin{aligned} \Delta\mathcal{F} \equiv \mathcal{F}_0-\mathcal{F}_0^{\rm SM} &= -\frac{v^2}{8}\cos(\beta-\alpha)^2(m_{H_0}^2-m_h^2) \\ &+ \left[\sum_s \frac{m_s^4}{64\pi^2}\left(\log\frac{|m_s^2|}{Q^2}-\frac{1}{2}\right)\right]\Bigg|_v - \left[\sum_s \frac{m_s^4}{64\pi^2}\left(\log\frac{|m_s^2|}{Q^2}-\frac{1}{2}\right)\right]\Bigg|_0 \end{aligned}$$

Broken Symmetric

1-loop (Coleman-Weinberg)

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$$m^2_{H_0,A_0,H^\pm} = \mu^2 + \lambda_i v^2$$

Difference between Synmetric - Broken phase in CW piece guaranteed for large BSM mass splitting!

$$m_{A_0} - m_{H_0}$$

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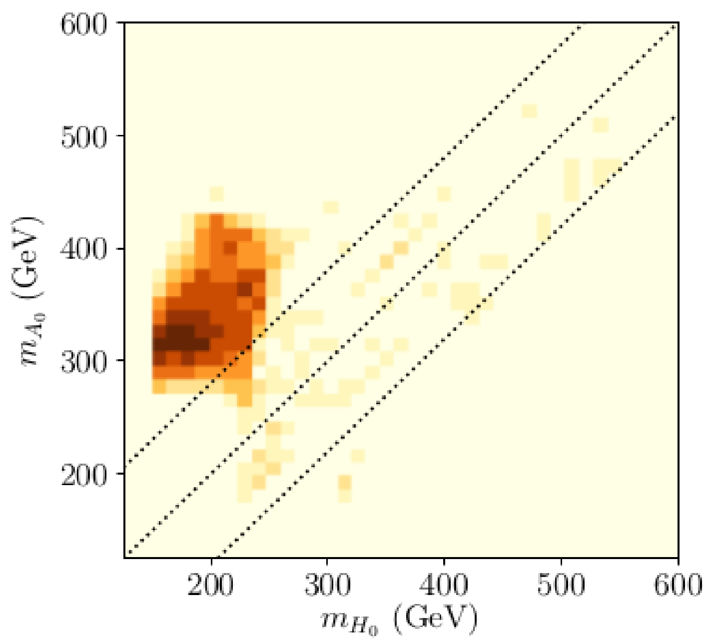
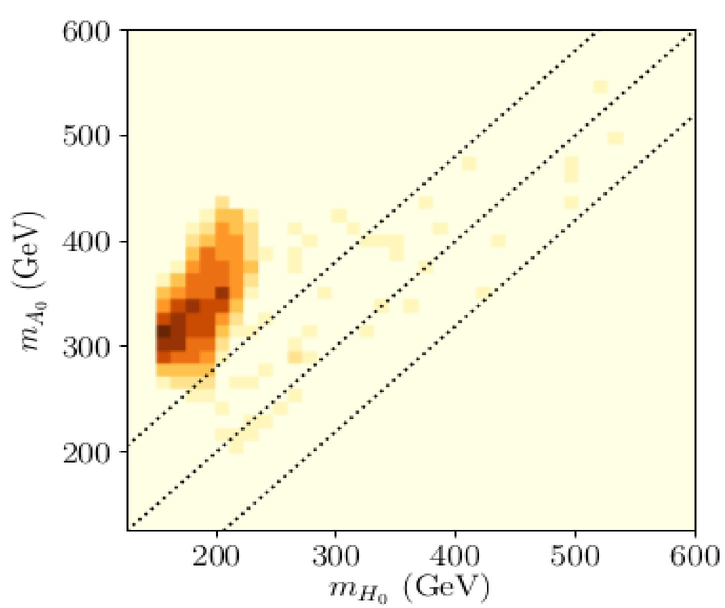


(b) $\tan(\beta) = 2.0$



(c) $\tan(\beta) = 2.5$

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Broken Symmetric

1-loop (Coleman-Weinberg)

Andersen, Gorda, Helset, Niemi, Tenkanen, Tranberg, Vuorinen,Weir, Phys. Rev. Lett. ***121*** *(2018) 191802*

EWPT Scenarios within LHC Reach

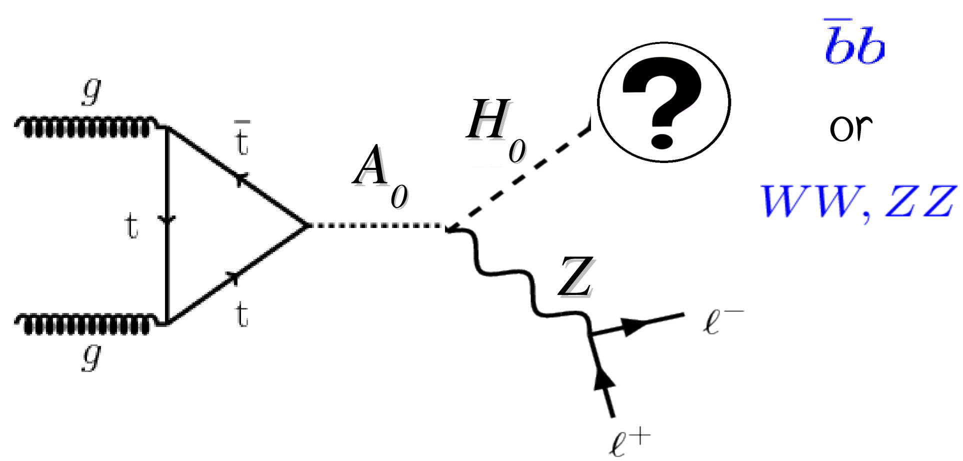
▷ NON-MINIMAL HIGGS SECTOR

e.g. **2HDM**

$$\boxed{m_{A_0} - m_{H_0} \sim v}$$

Search for 2HDM 1st Order EWPT region via $A_0 \to H_0\, Z$

Dorsch, Huber, Mimasu, JMN, Phys. Rev. Lett. ***113*** *(2014) 211802*



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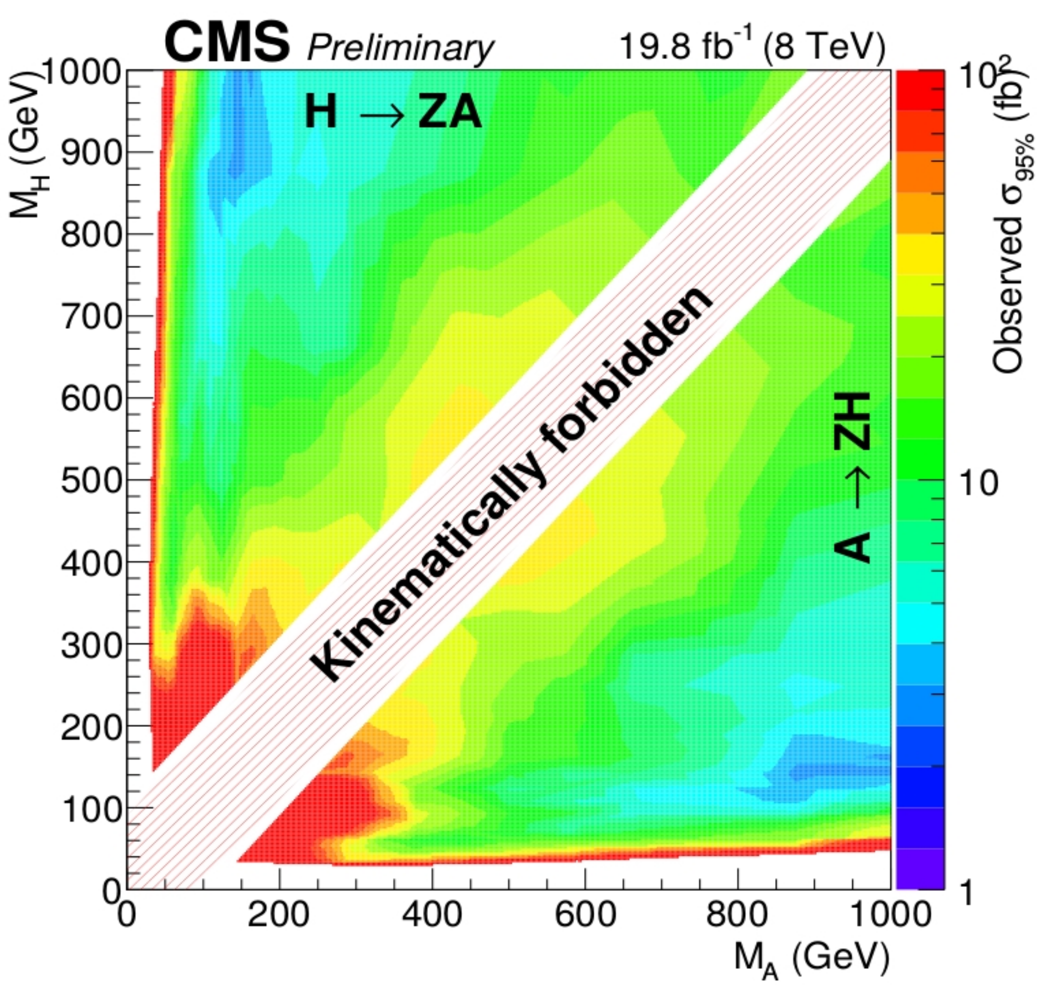
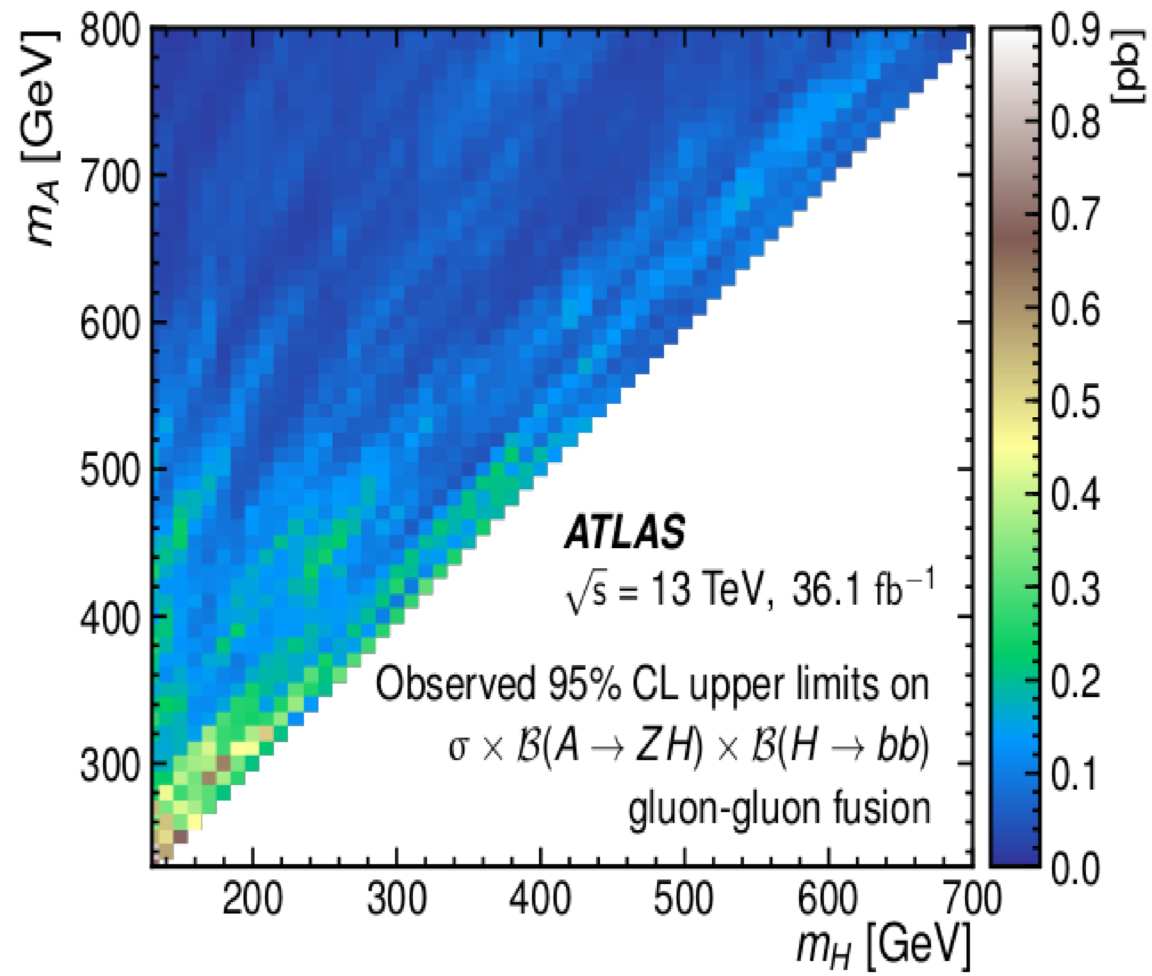
CMS-PAS-HIG-15-001 (1603.02991)

Search for H/A decaying into Z and A/H, with Z→ $\ell\ell$ and A/H→ bb or A/H→ $\tau\tau$



ATLAS-PHYS-EXO-16-034 (1804.01126)



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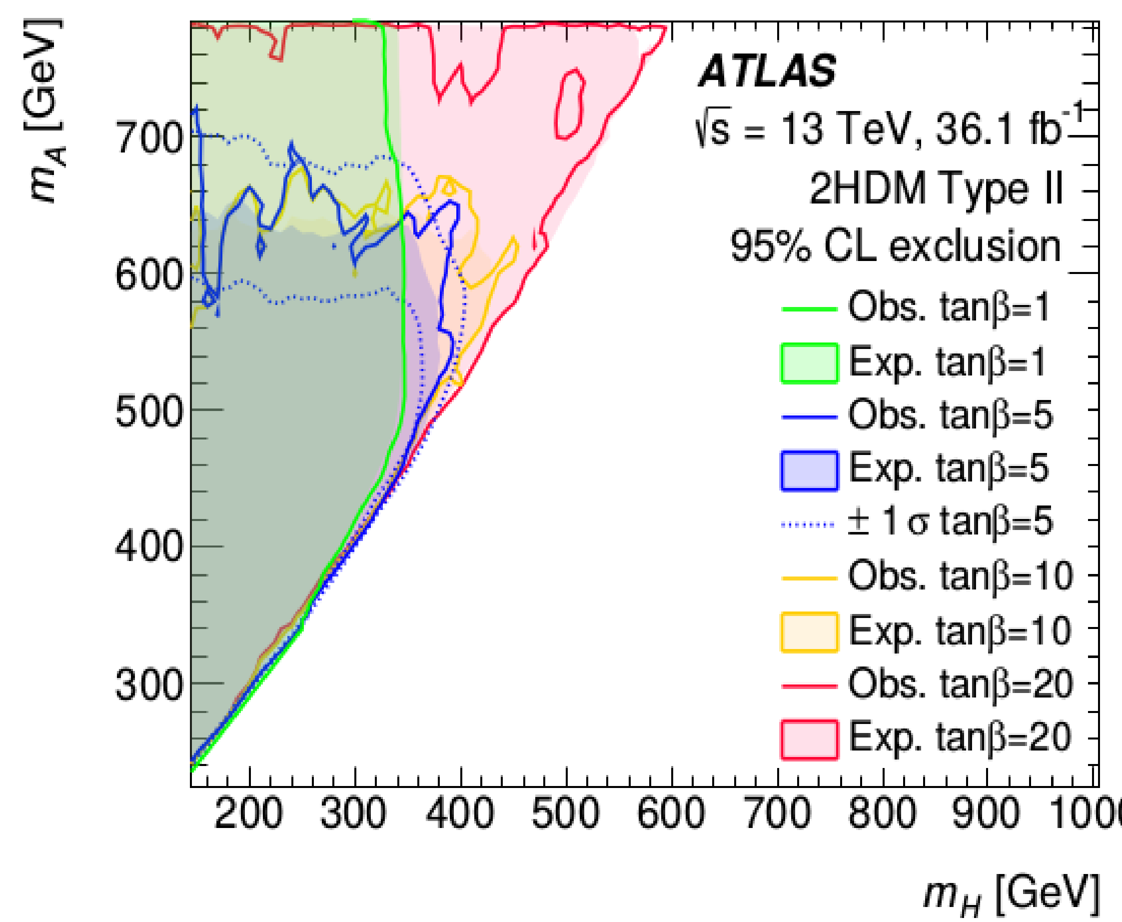
*Dorsch, Huber, Mimasu, JMN, Phys. Rev. Lett. **113** (2014) 211802*

Very strong LHC 13 TeV limits on 2HDM EWPT!

[courtesy of Kimmo Kainulainen]



EWPT Scenarios within LHC Reach

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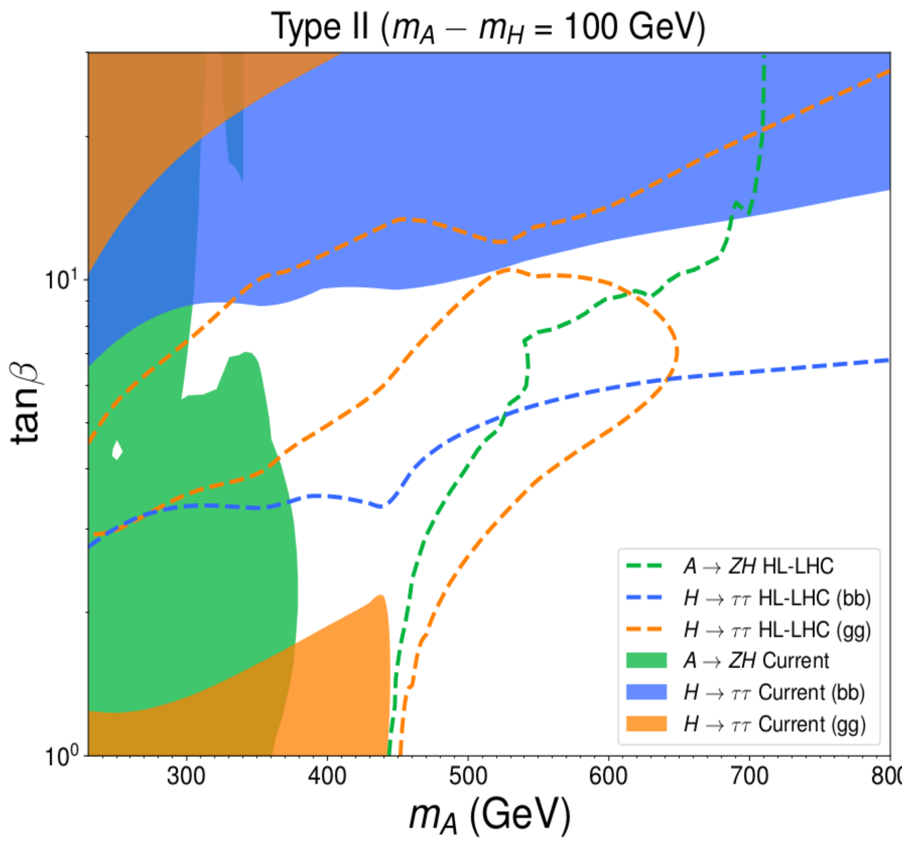
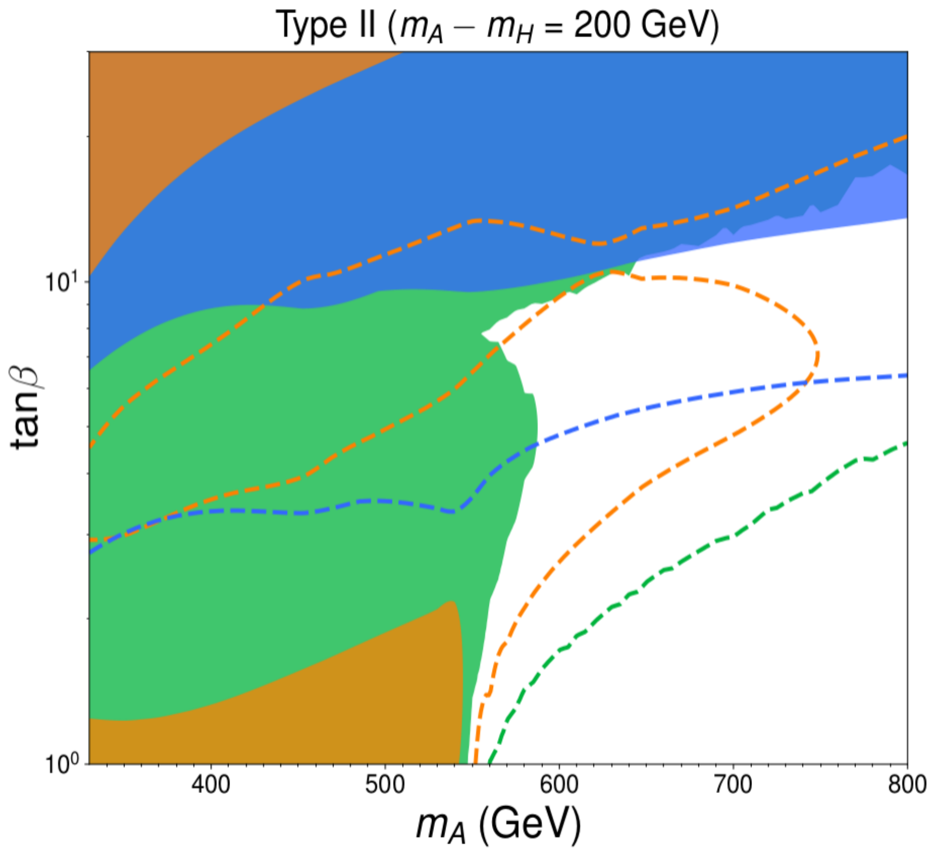
e.g. **2HDM**

HL-LHC will fully explore 2HDM EWPT

for *Higgs Physics at HL-LHC & HE-LHC* Report, 2019 (by K.Mimasu, JMN)





EWPT Scenarios within LHC Reach?

▷ SM + SCALAR EW MULTIPLET

e.g. **EW Triplet**

*Fileviez Perez, Patel, Ramsey-Musolf, Wang, PRD **79** (2009) 055024*

*Patel, Ramsey-Musolf, PRD **88** (2013) 035013*

$$V_{H\Sigma} = \frac{a_1}{2} H^\dagger \Sigma H + \frac{a_2}{2} H^\dagger H \, \mathrm{Tr}\, \Sigma^2$$

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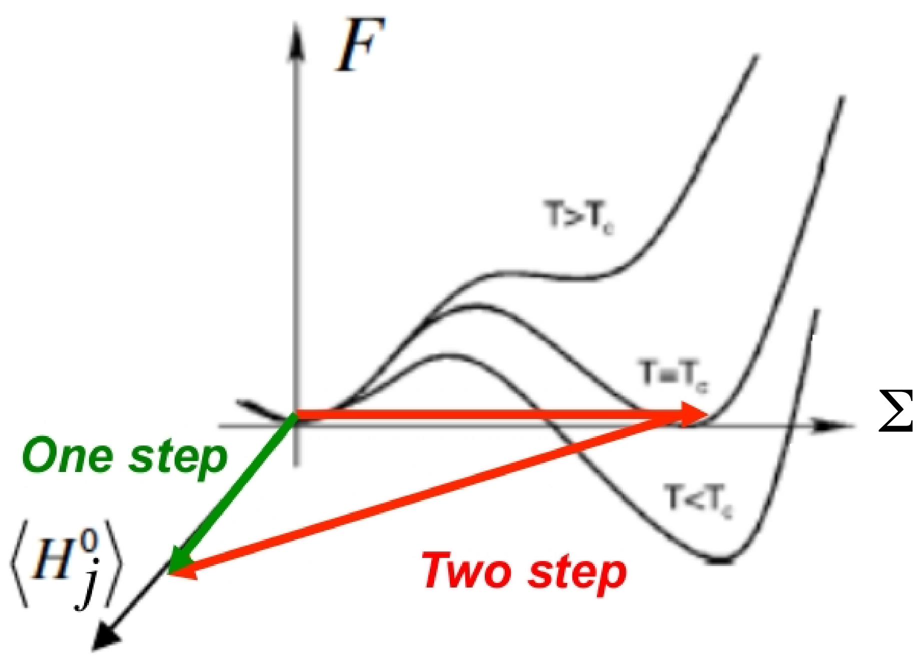
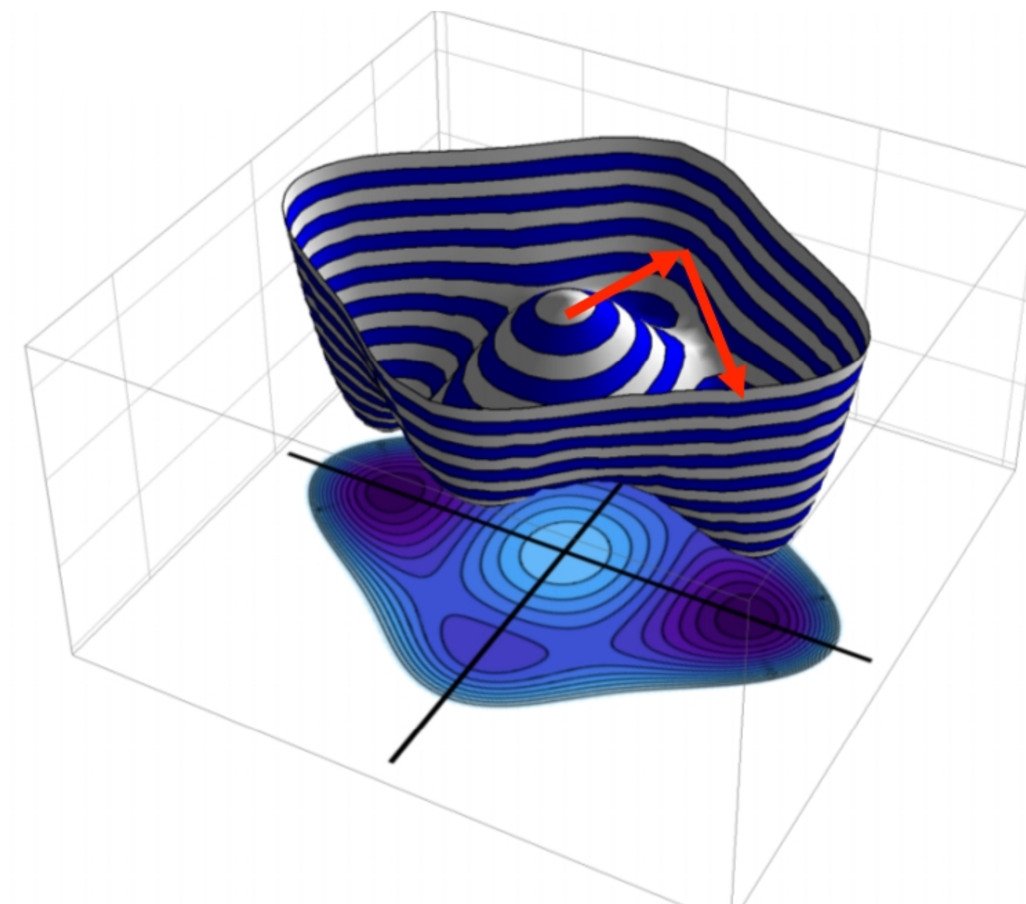
Possible multi-step EWPT





[courtesy of Michael Ramsey-Musolf]

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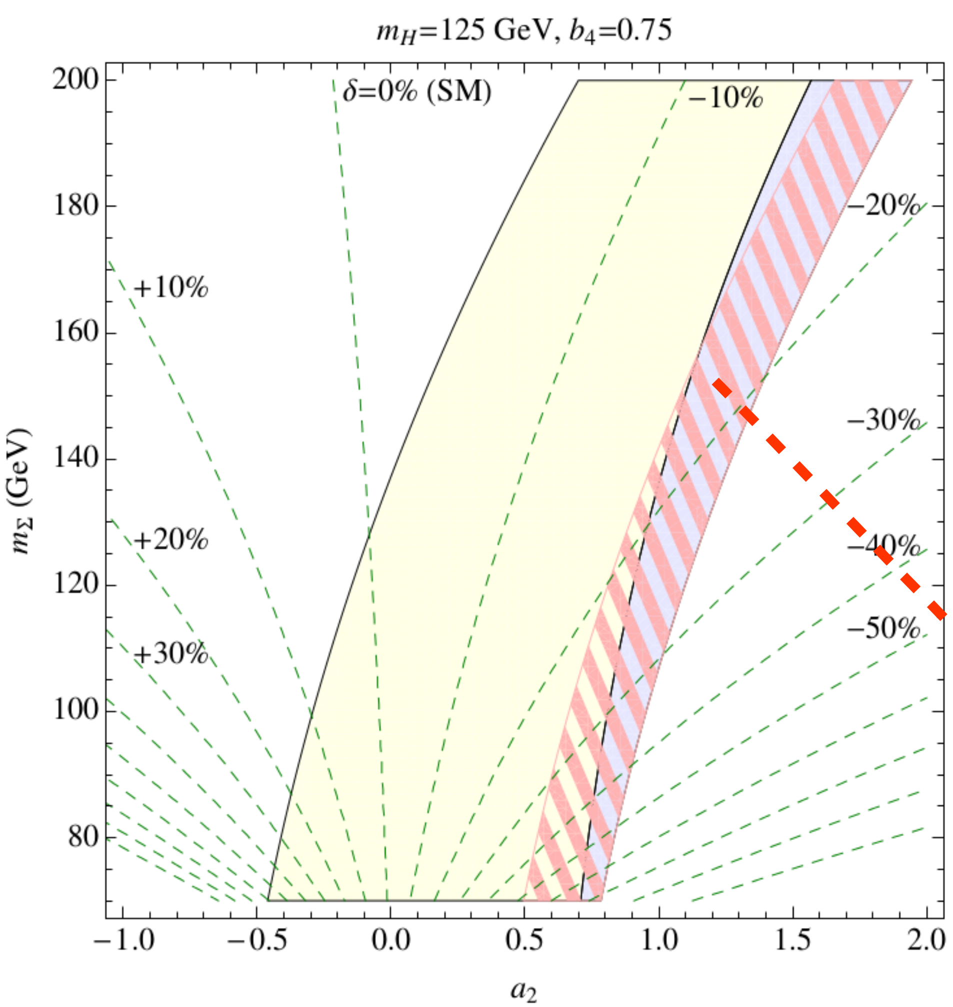

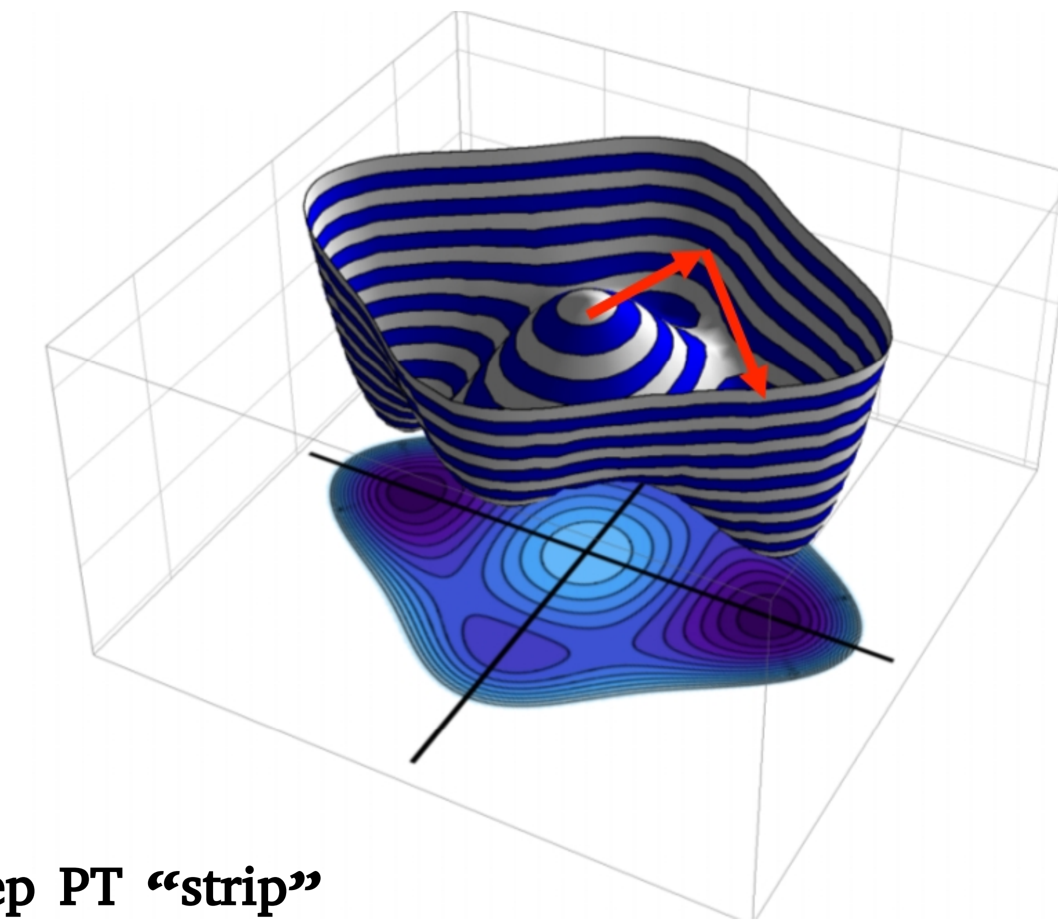

Two-step PT "strip"
(a_2 vs m_Σ relation)

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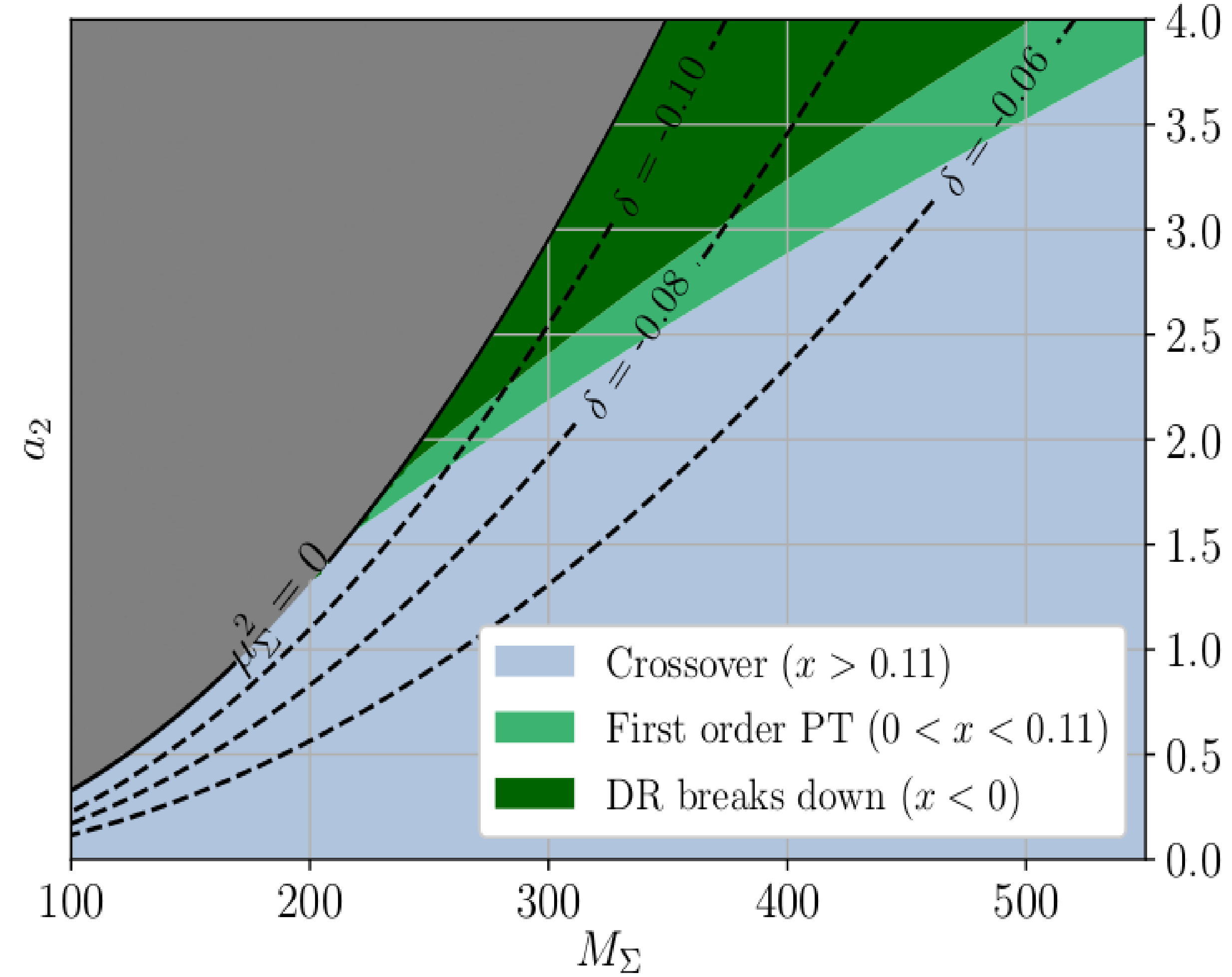
Non-Perturbative EWPT Study

Niemi, Patel, Ramsey-Musolf, Tenkanen, Weir, arXiv:1802.10500



Dim. Reduction
(3D Eff. Theory)

$$\boxed{\bar{V}_3(H) = \bar{\mu}_3^2 H^\dagger H + \bar{\lambda}_3 (H^\dagger H)^2 \qquad x = \frac{\bar{\lambda}_3}{\bar{g}_3^2}, \quad y = \frac{\bar{\mu}_3^2}{\bar{g}_3^4}}$$

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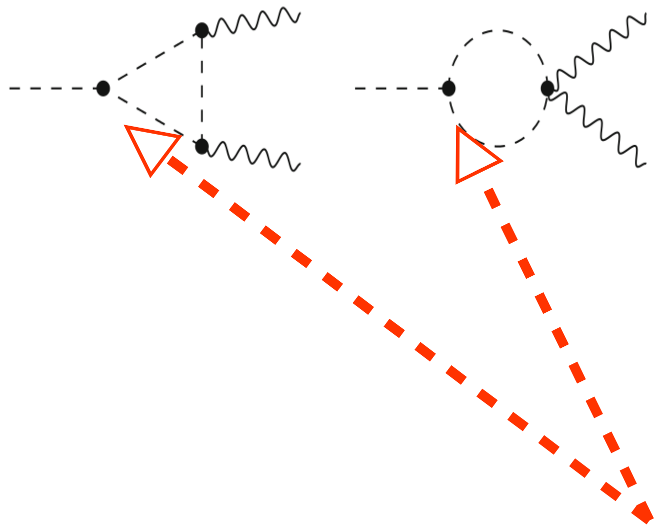

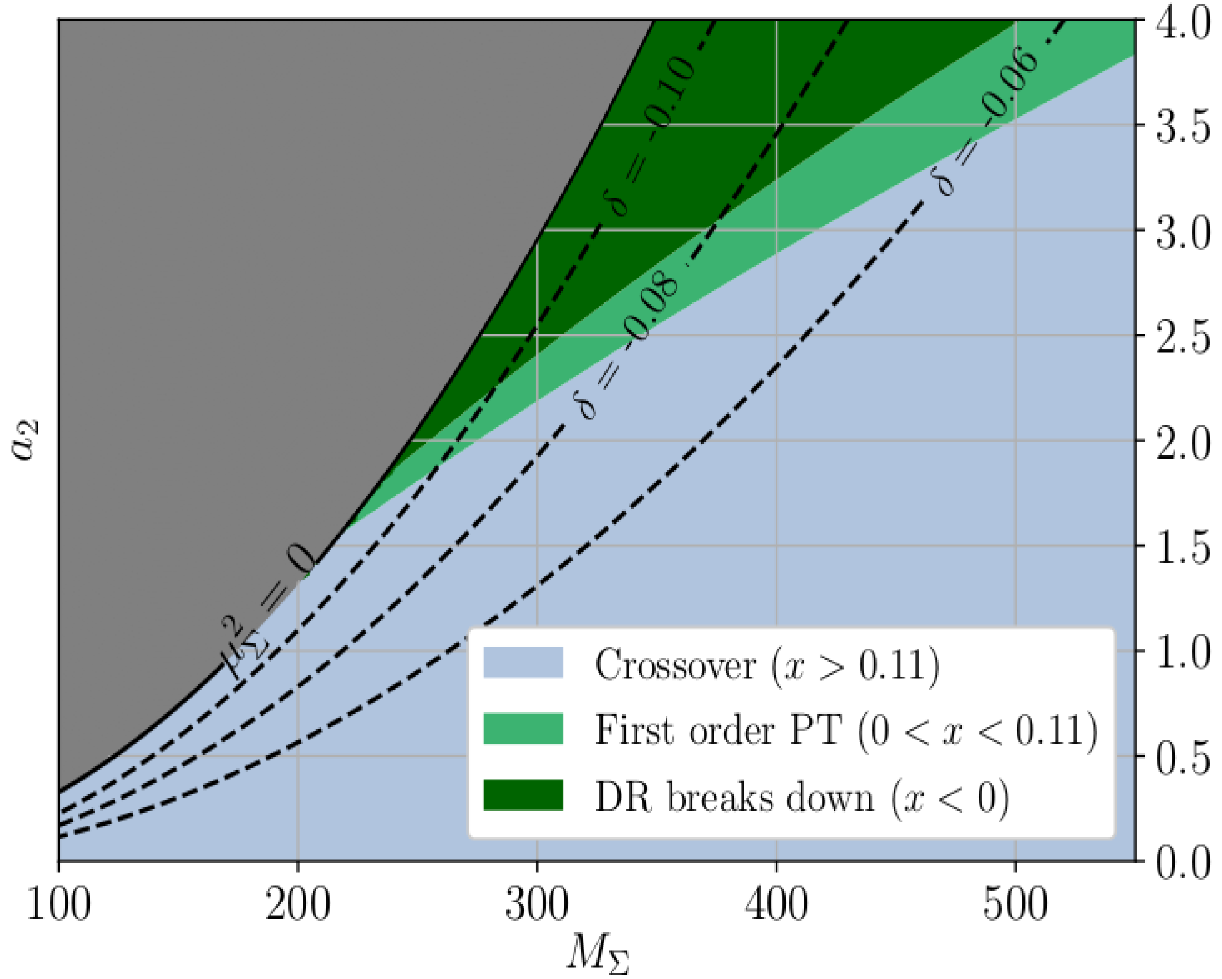

Charged component of triplet modifies h → γγ

$$\delta = \frac{\Gamma^{\Sigma SM}(h\to\gamma\gamma) - \Gamma^{SM}(h\to\gamma\gamma)}{\Gamma^{SM}(h\to\gamma\gamma)}$$

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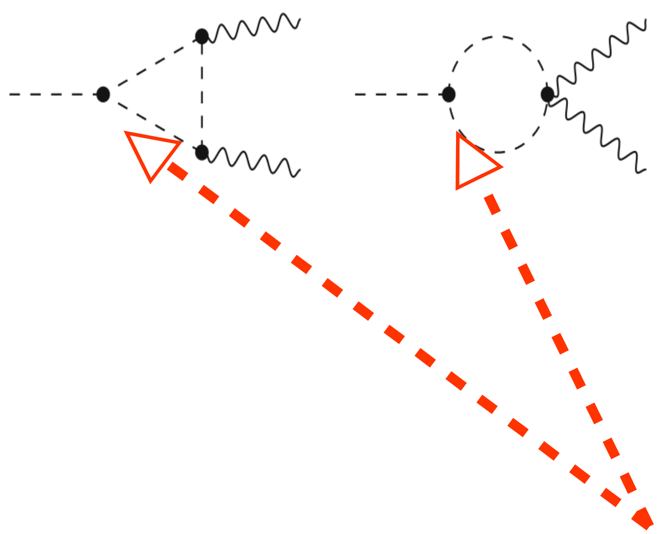

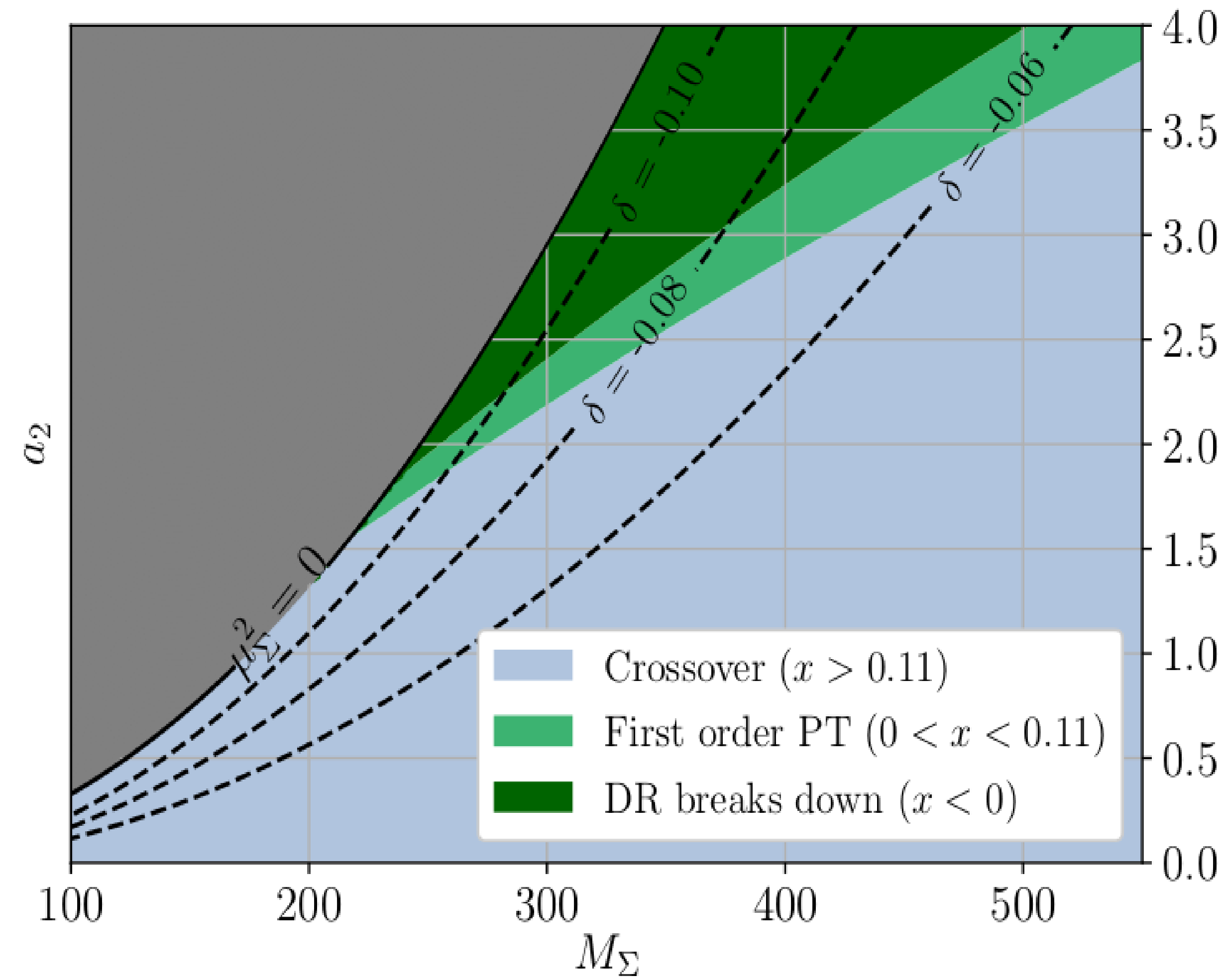

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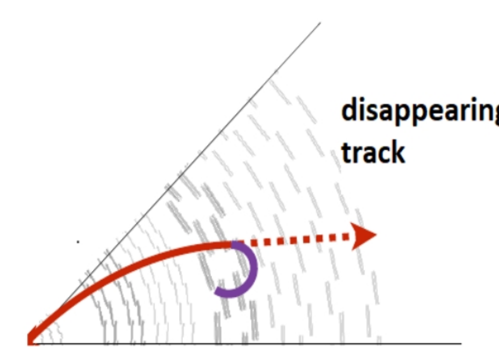
very small (radiative) mass splitting between charged-neutral triplet states

$\delta M_\Sigma \sim$ 100 - 300 MeV

Disappearing Track Signature!



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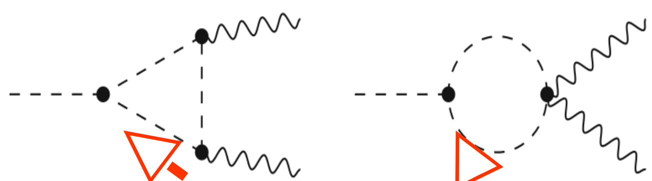

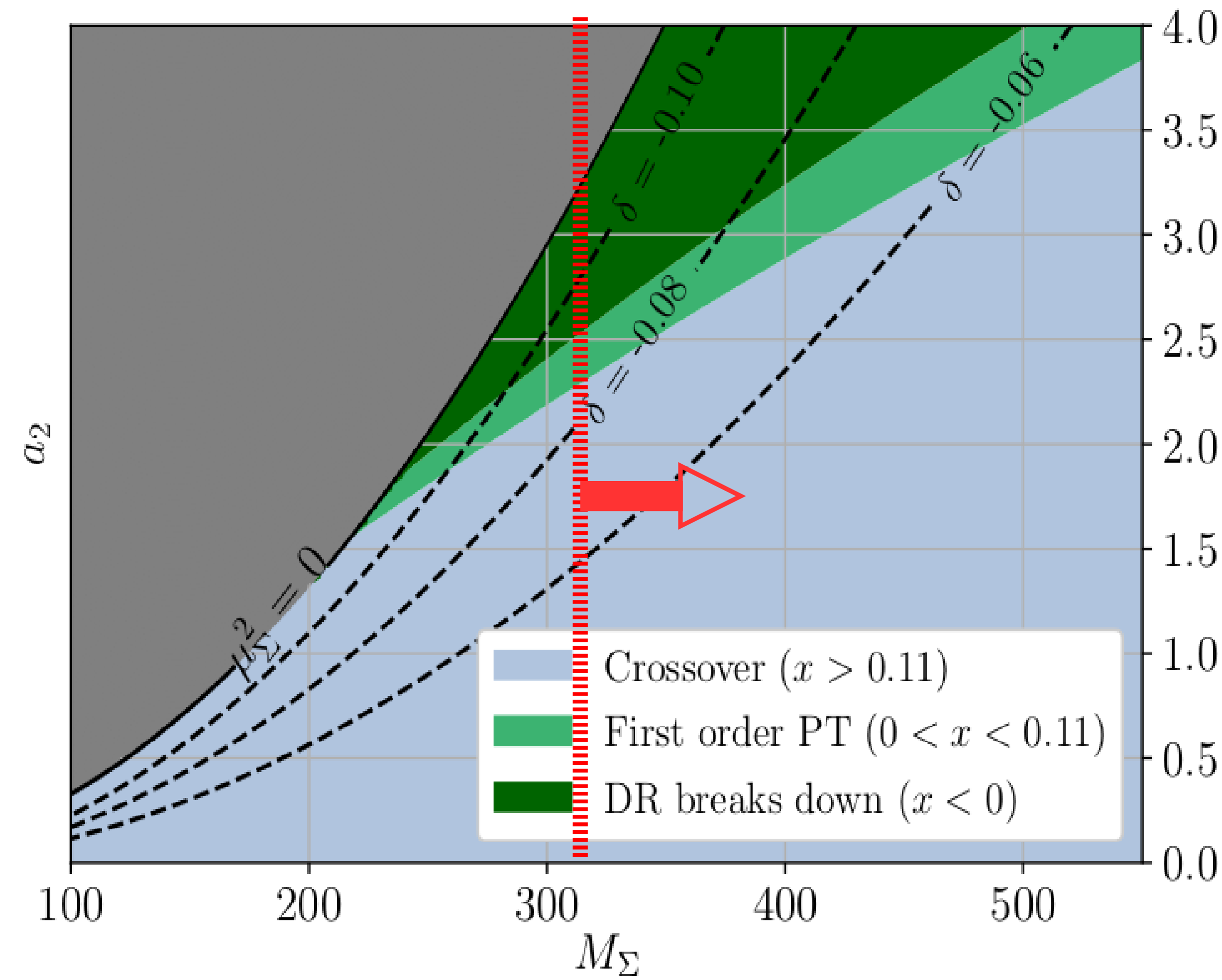

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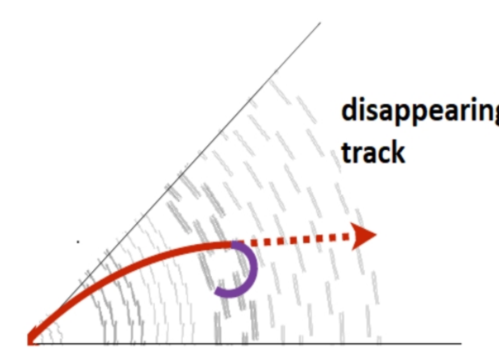

EWPT Scenarios for Future Colliders!

Singlet Driven EW Phase Transition

(lots of) Motivation

⇒ Neutral Naturalness

⇒ Higgs Portal (Dark Sectors)

⇒ Non-minimal SUSY (e.g. NMSSM)

⇒ Warped Extra Dim (dilaton...)

...

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EWPT Scenarios for Future Colliders

The xSM (singlet scalar extension of the SM)

5 BSM Parameters

*Profumo, Ramsey-Musolf, Shaughnessy, JHEP **0708** (2007) 010*
*Espinosa, Konstandin, Riva, Nucl. Phys. **B854** (2012) 592*

$$\boxed{V(H,S) = -\mu^2\,|H|^2+\lambda\,|H|^4+\underbrace{\frac{a_1}{2}S|H|^2+\frac{a_2}{2}S^2|H|^2}_{\text{Higgs Portal (Higgs - Singlet Mixing)}}+\frac{b_2}{2}S^2+\frac{b_3}{3}S^3+\frac{b_4}{4}S^4}$$

EWPT Scenarios for Future Colliders

Simplest case

The xSM with Z_2

3 BSM Parameters

$$V(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \cancel{\frac{a_1}{2} S |H|^2} + \frac{a_2}{2} S^2 |H|^2 + \frac{b_2}{2} S^2 + \cancel{\frac{b_3}{3} S^3} + \frac{b_4}{4} S^4$$

Higgs Portal

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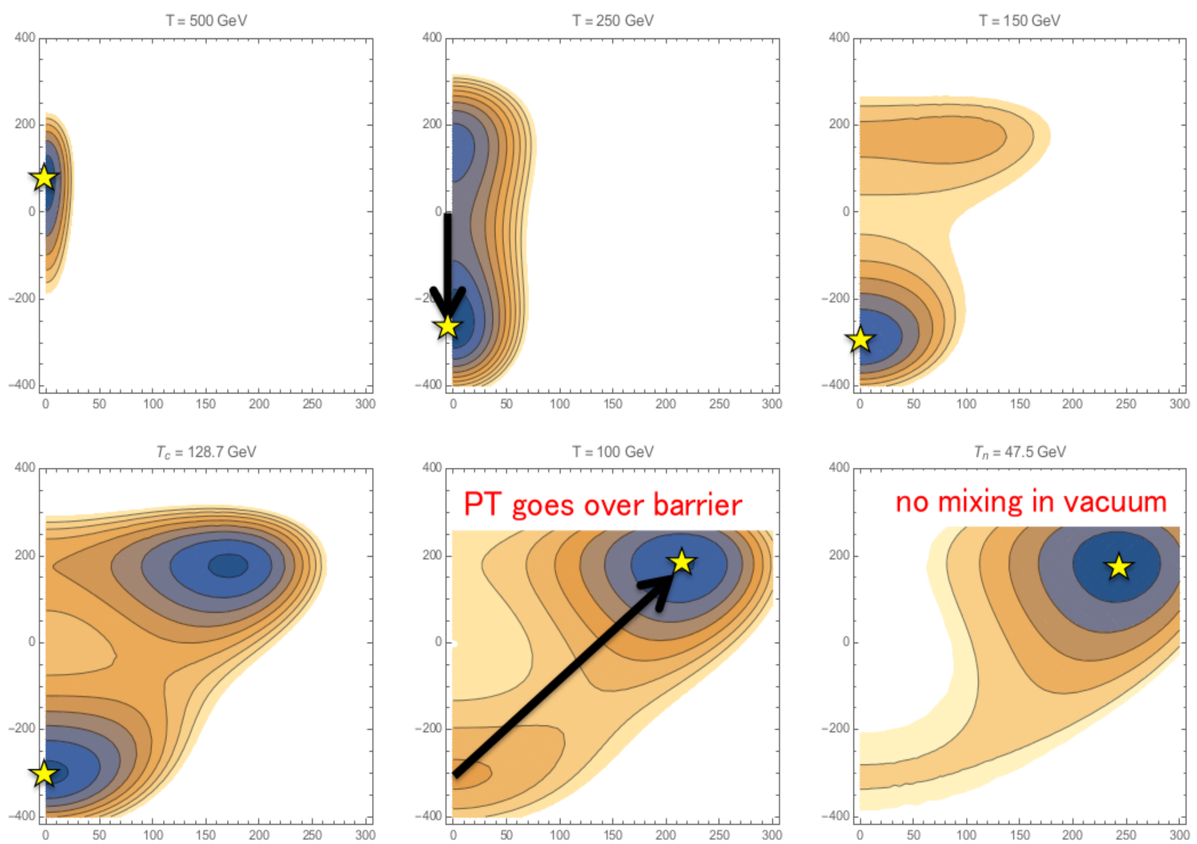
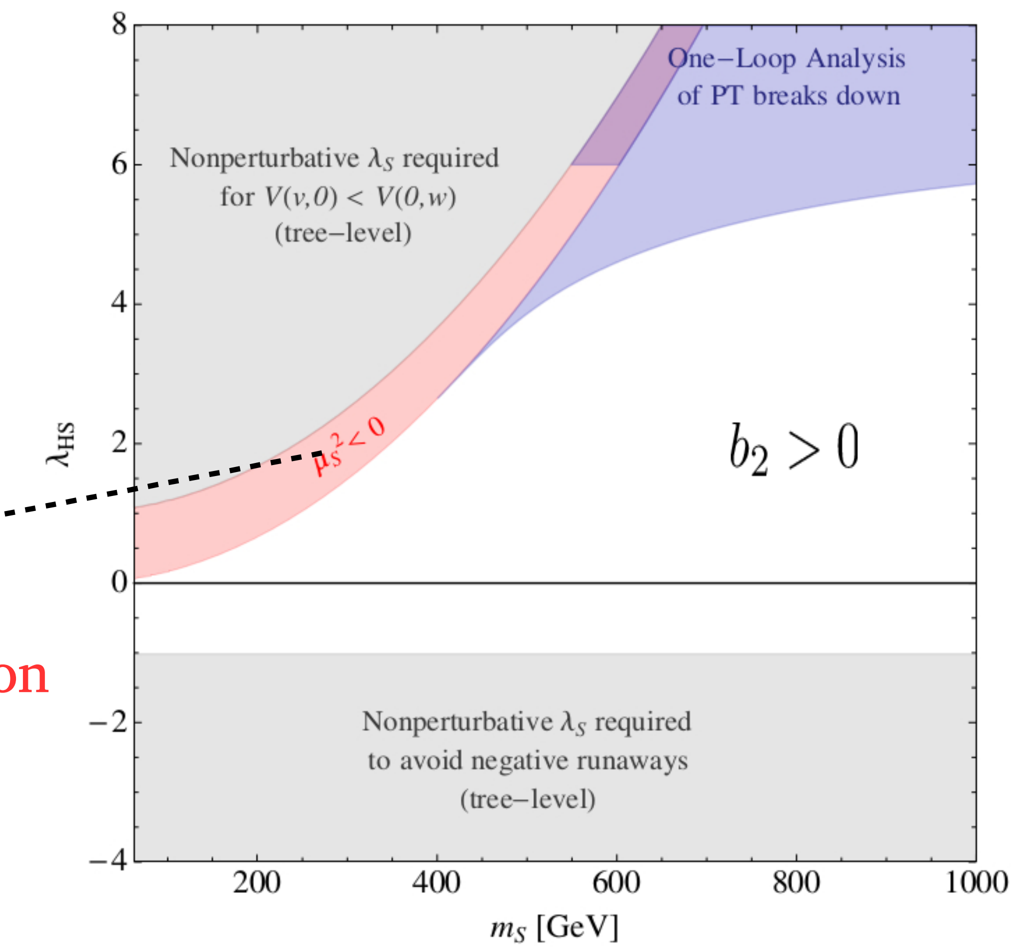
Higgs Portal



[courtesy of Andrew Long]

$b_2 < 0$

Two-Step Phase Transition



Curtin, Meade, Yu, JHEP **1411** (2014) 127

EWPT Scenarios for Future Colliders
(FCC-ee, hh, CLIC)

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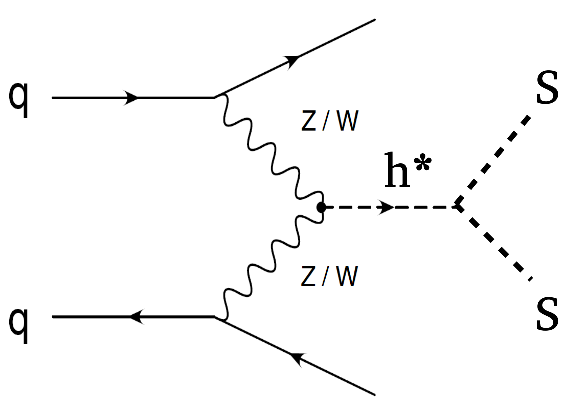
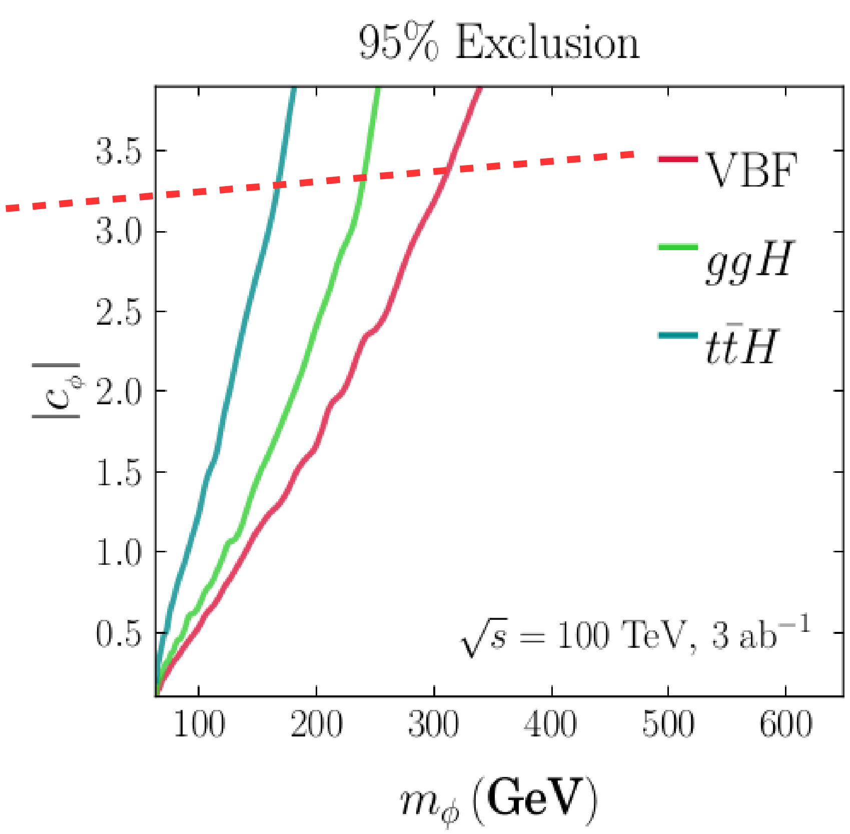
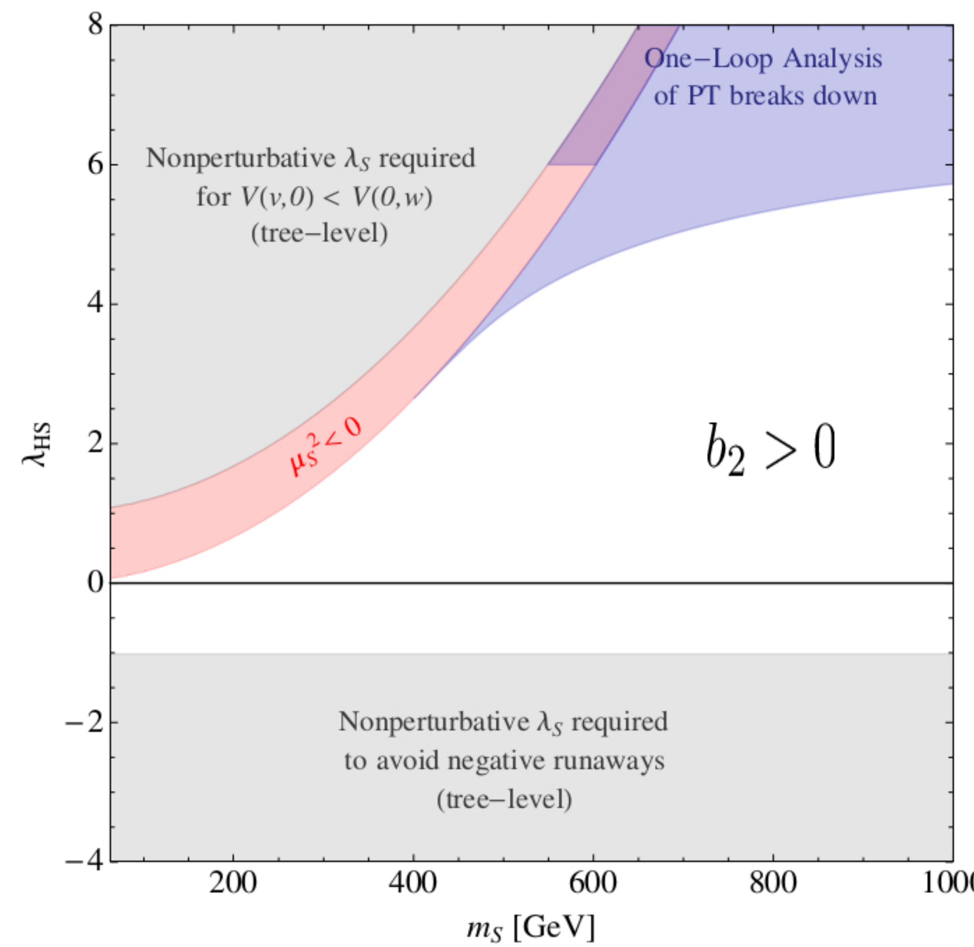
Direct Searches ("Higgs portal above threshold")





*Craig, Lou, McCullough Thalapillil JHEP **1602** (2016) 127*



*Curtin, Meade, Yu, JHEP **1411** (2014) 127*

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(**FCC**-ee, **hh**, CLIC)

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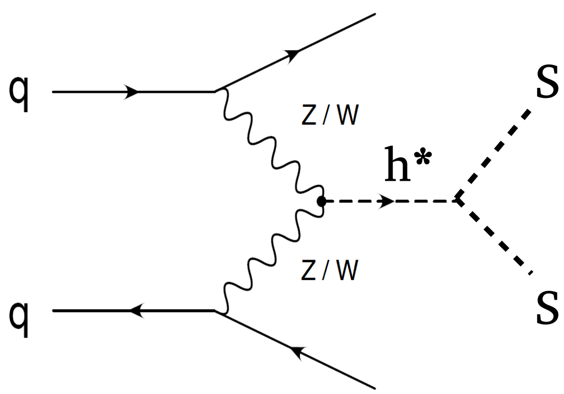

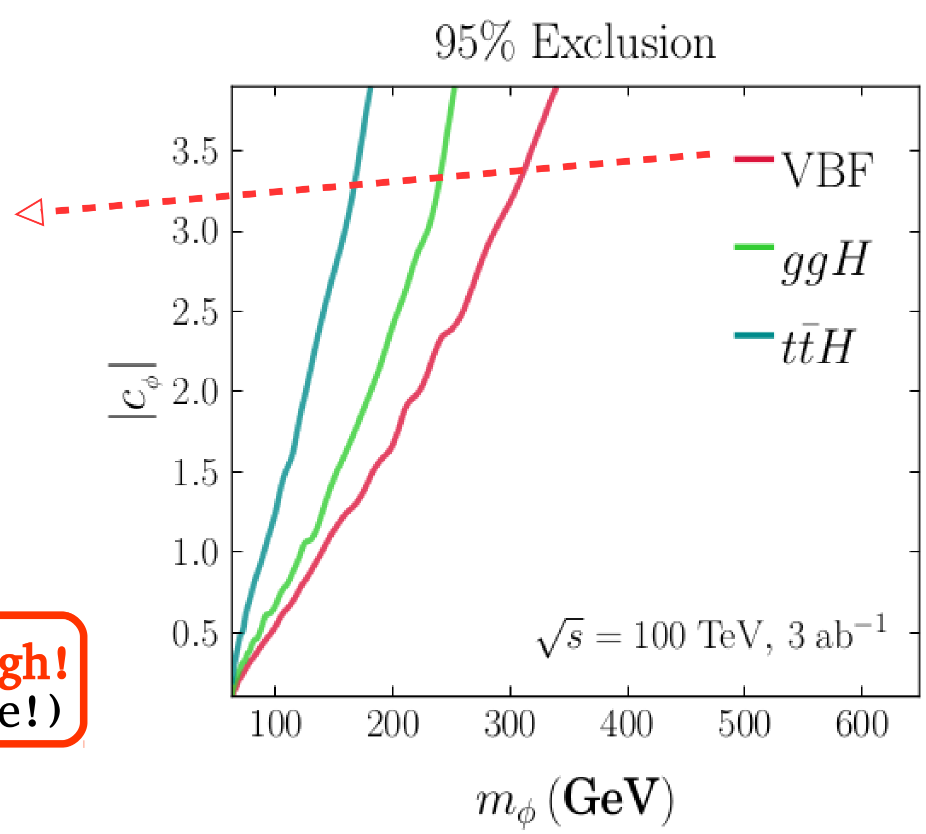

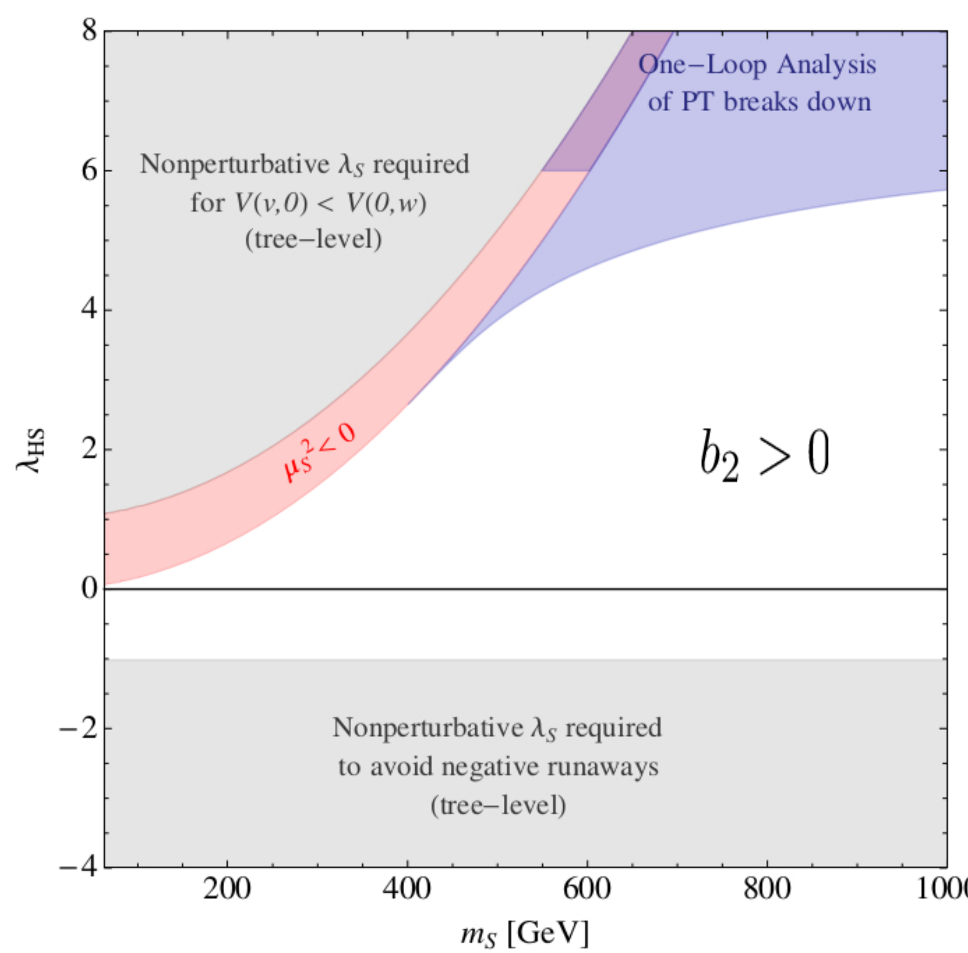

direct searches very tough!
(with a caveat... ask me!)

Garcia-Abenza, JMN, To Appear

*Craig, Lou, McCullough Thalapillil JHEP **1602** (2016) 127*

*Curtin, Meade, Yu, JHEP **1411** (2014) 127*

EWPT Scenarios for Future Colliders

(**FCC-ee**, hh, **CLIC**)

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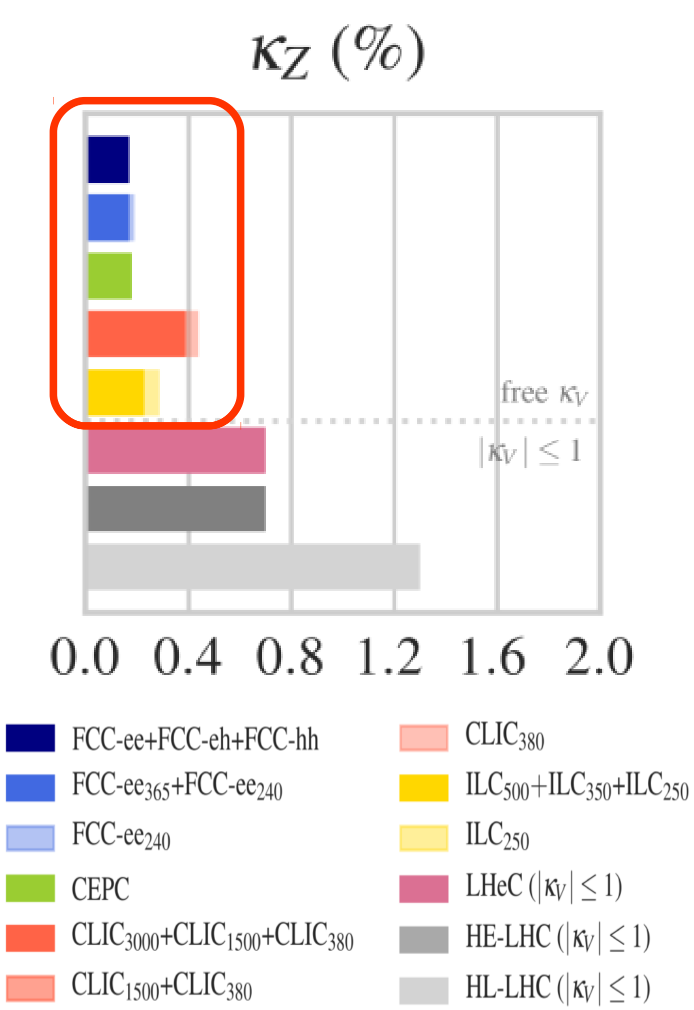
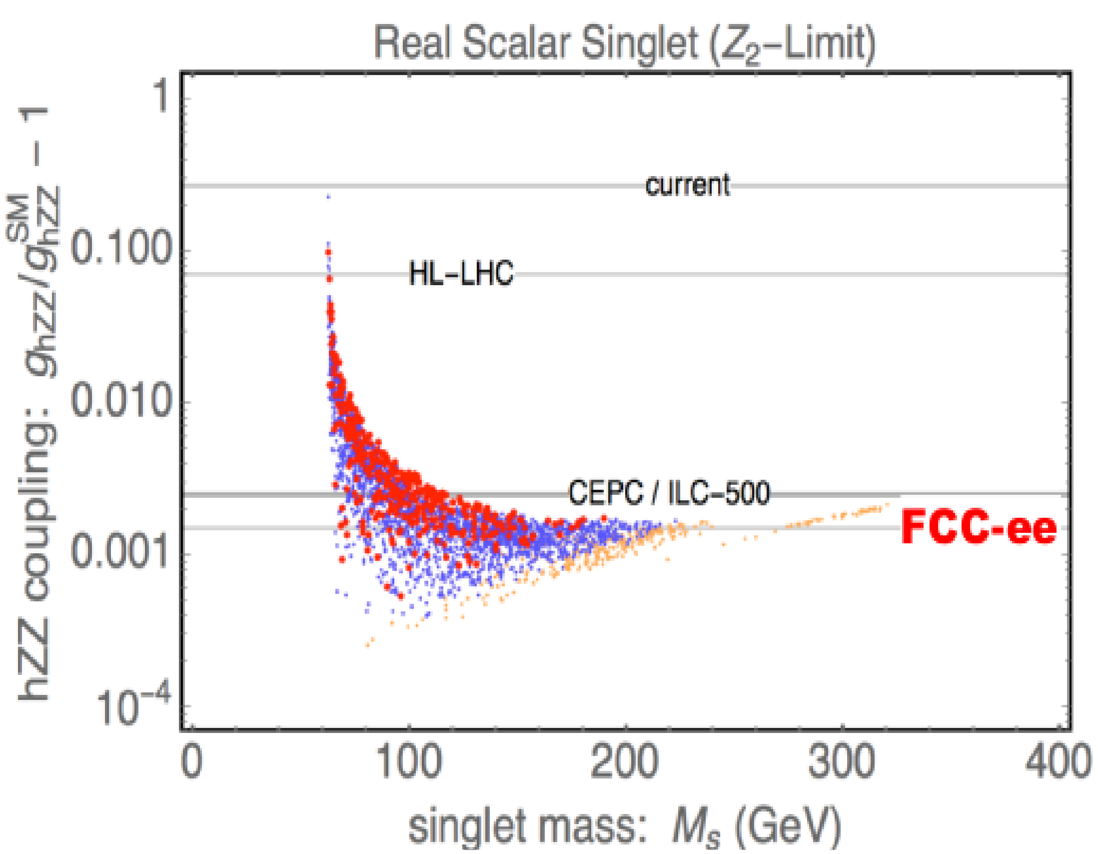
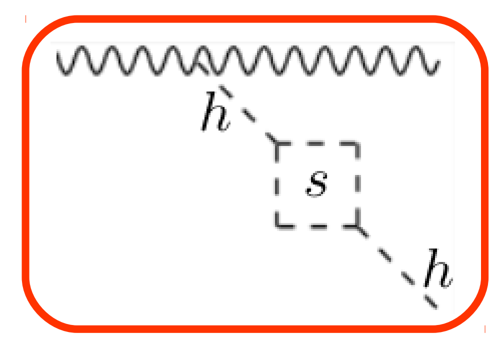
Indirect Searches





*Huang, Long, Wang PRD **94** (2016) 075008*

Precision to probe loop corrections!



EWPT Scenarios for Future Colliders

The General xSM Case

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h_2 inherits its couplings to SM via Higgs Mixing

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

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

m_{h1} = 125 GeV

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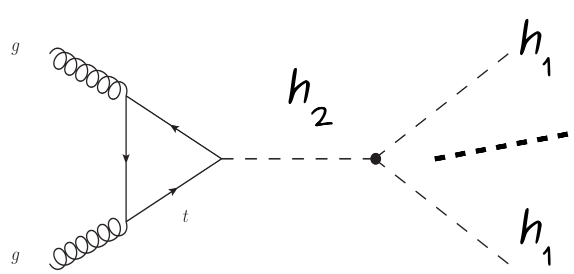
$\boxed{m_2 > 250 \text{ GeV} \quad \textbf{Resonant Higgs Pair Production}}$

Dolan, Englert, Spannowsky, Phys. Rev. ***D87*** *(2013) 5, 055002*
JMN, Ramsey-Musolf, Phys. Rev. ***D89*** *(2014) 095031*
Chen, Dawson, Lewis, Phys. Rev. ***D91*** *(2015) 035015*



$$\begin{aligned}\lambda_{211} \quad = \quad & \frac{s_\theta}{2}\left[c_\theta^4(m_2^2 - m_1^2)/v_0 + 2v_0(a_2 - 3\lambda)c_\theta^2\right. \\ & \left. - (a_1 + 2a_2 x_0 - 2b_3 - 6b_4 x_0)c_\theta s_\theta - a_2 v_0 s_\theta^2\right]\end{aligned}$$

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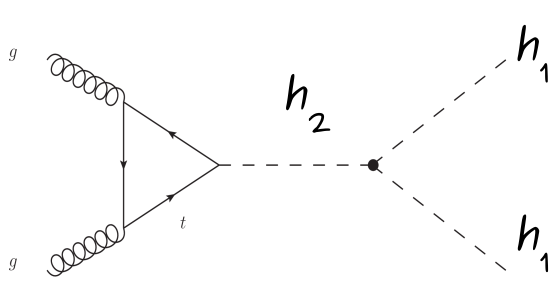
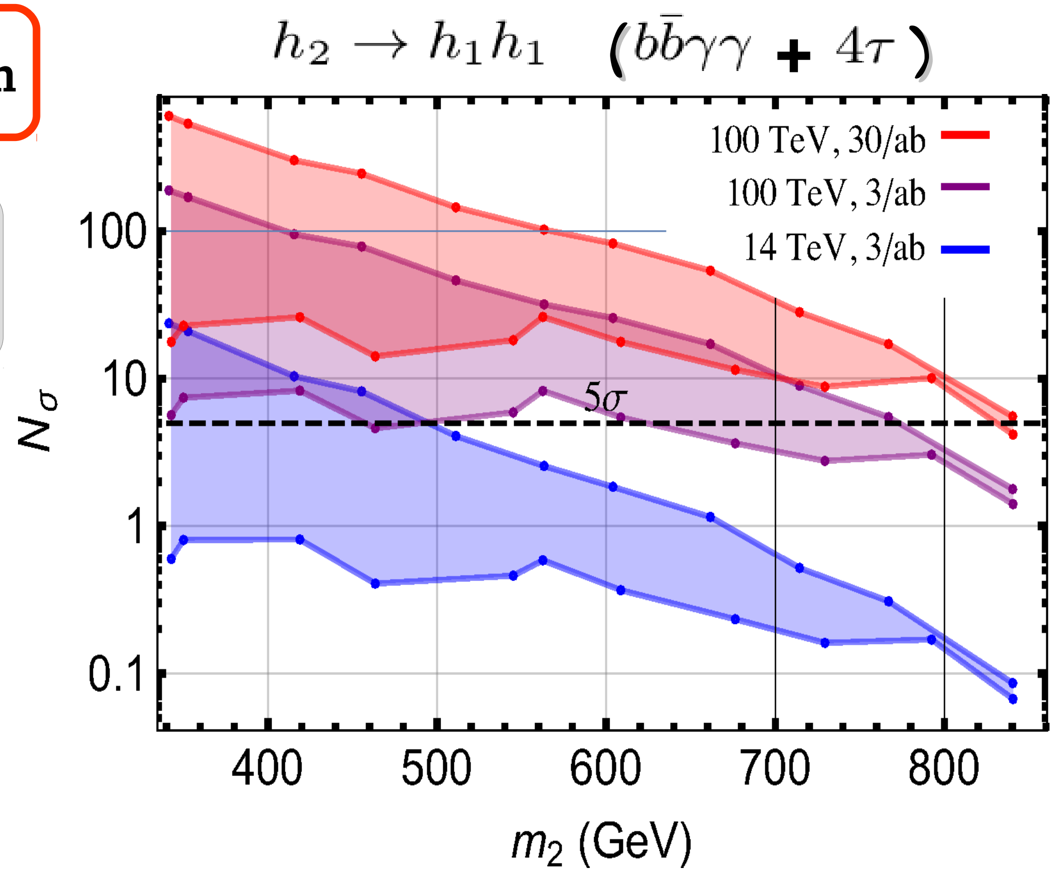
m_2 > 250 GeV **Resonant Higgs Pair Production**

FCC-hh largely **probes** 1st Order EW Phase Transition parameter space **via** $h_2 \to h_1 h_1$





Kotwal, JMN, Ramsey-Musolf, Winslow, PRD **94** (2016) 035022

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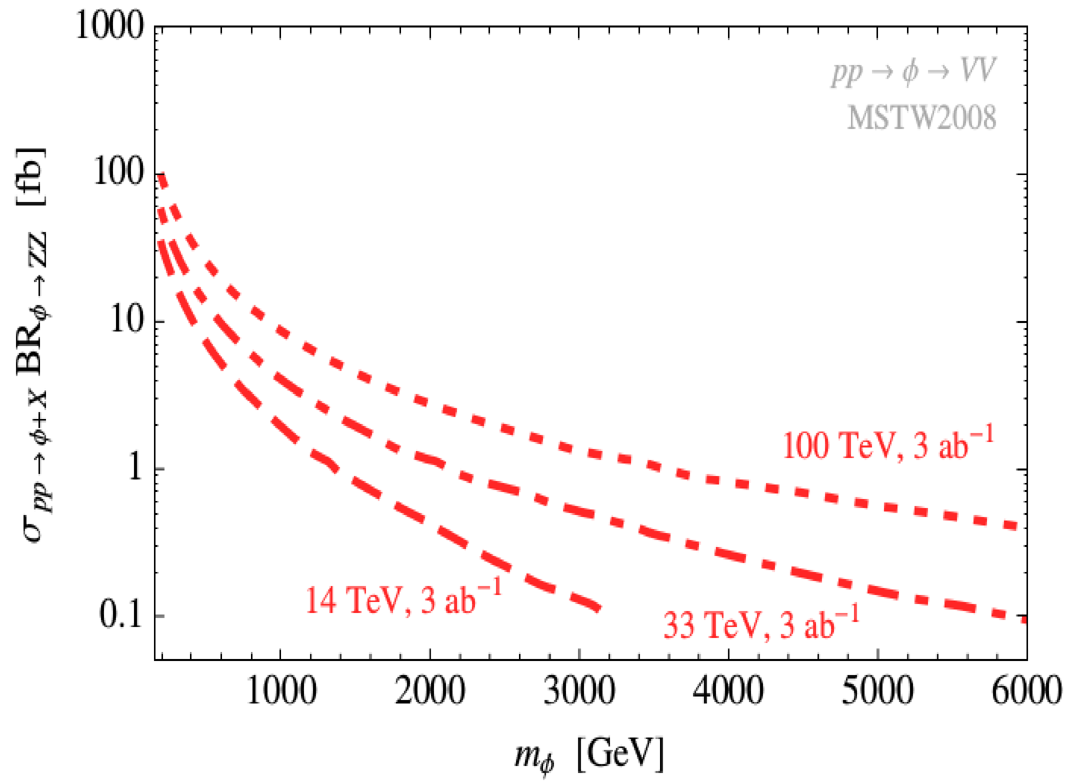
m_{h1} = 125 GeV

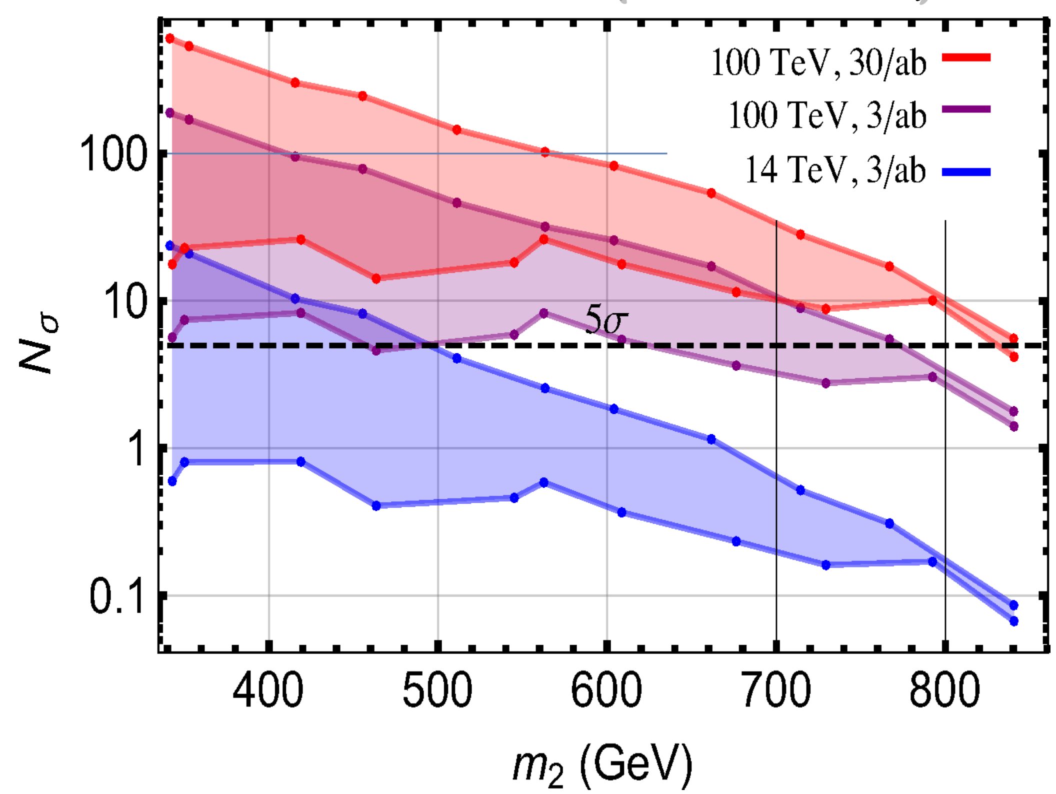
Interplay with $h_2 \to VV$ searches

Crucial for Higgs + Singlet parameter extraction



Buttazzo, Sala, Tesi, JHEP **1511** (2015) 158

$h_2 \to h_1 h_1$ ($b\bar{b}\gamma\gamma$ + 4τ)



Kotwal, JMN, Ramsey-Musolf, Winslow, PRD **94** (2016) 035022

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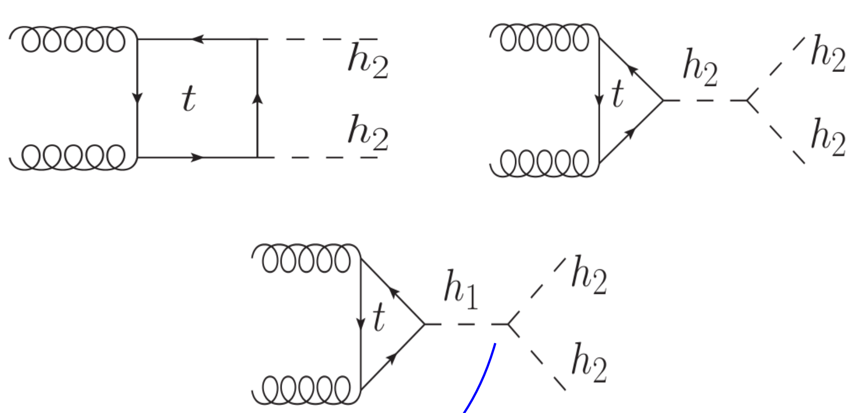
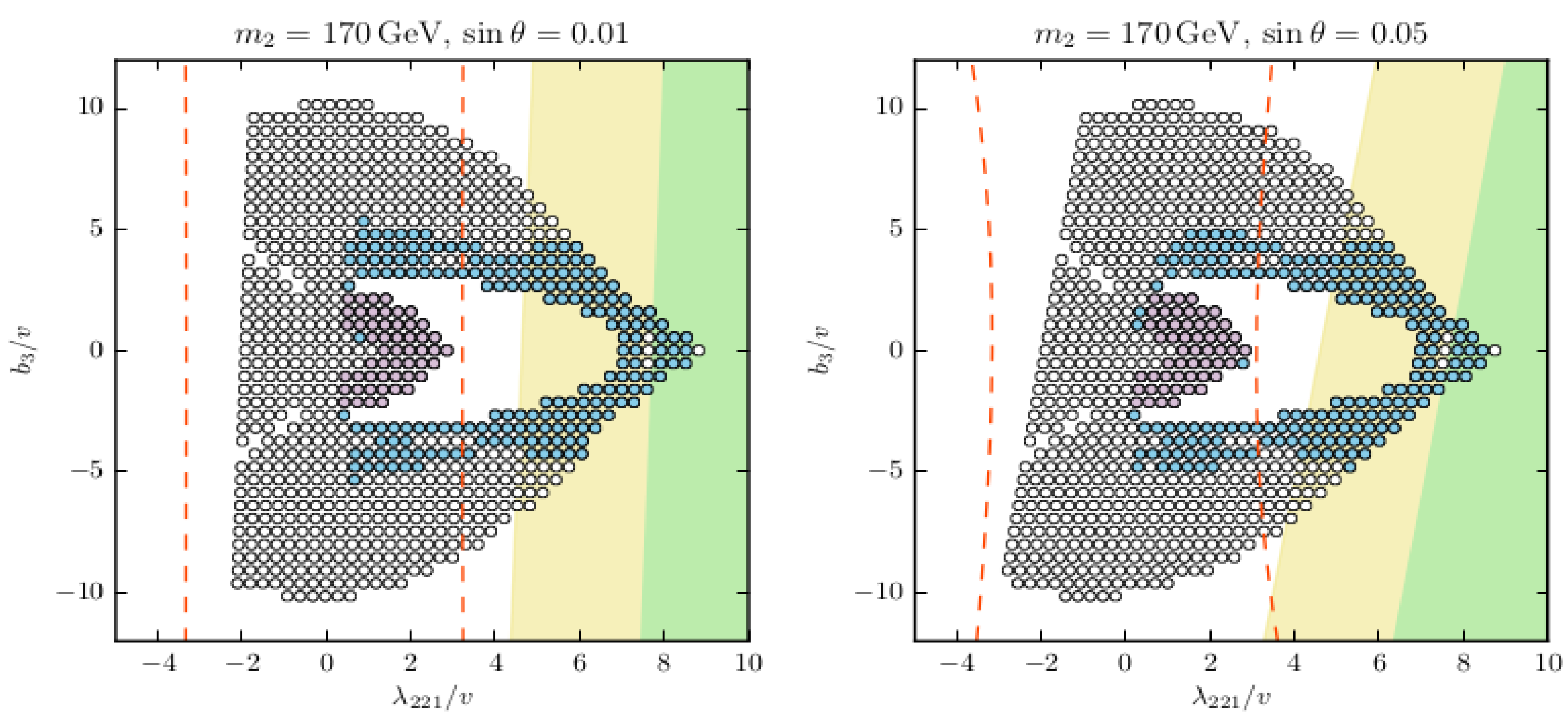
m_2 < 250 GeV



$\lambda_{221} \propto a_2$ ($\neq 0$ for $\sin\theta \to 0$)



Chen, Kozaczuk, Lewis, JHEP ***1708*** *(2017) 096*

HL-LHC

EWPT Scenarios for Future Colliders

The General xSM Case

$$V(H,S) = -\mu^2\,|H|^2 + \lambda\,|H|^4 + \frac{a_1}{2}S|H|^2 + \frac{a_2}{2}S^2|H|^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

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

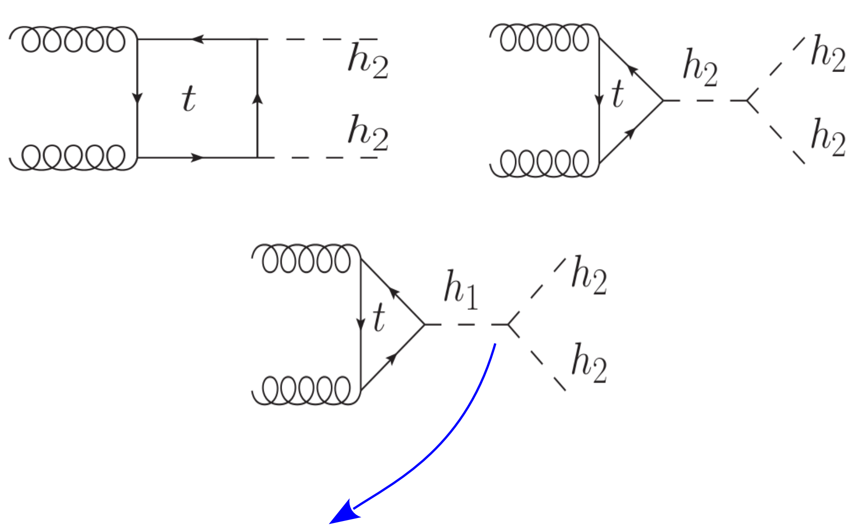
h_2 inherits its couplings to SM via Higgs Mixing

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

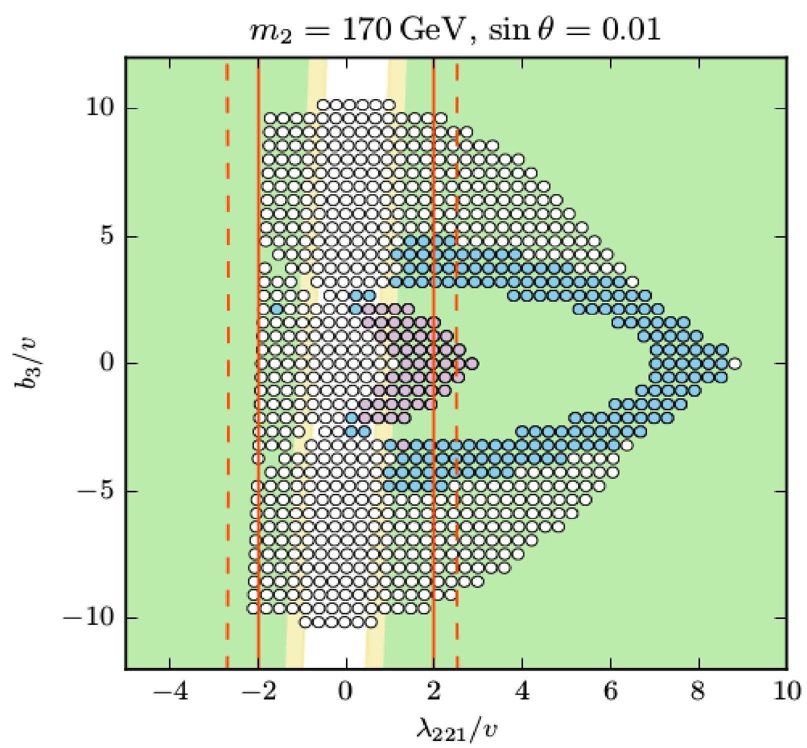
$$\sin 2\theta = \frac{(a_1 + 2a_2 x_0)v_0}{(m_1^2 - m_2^2)}$$

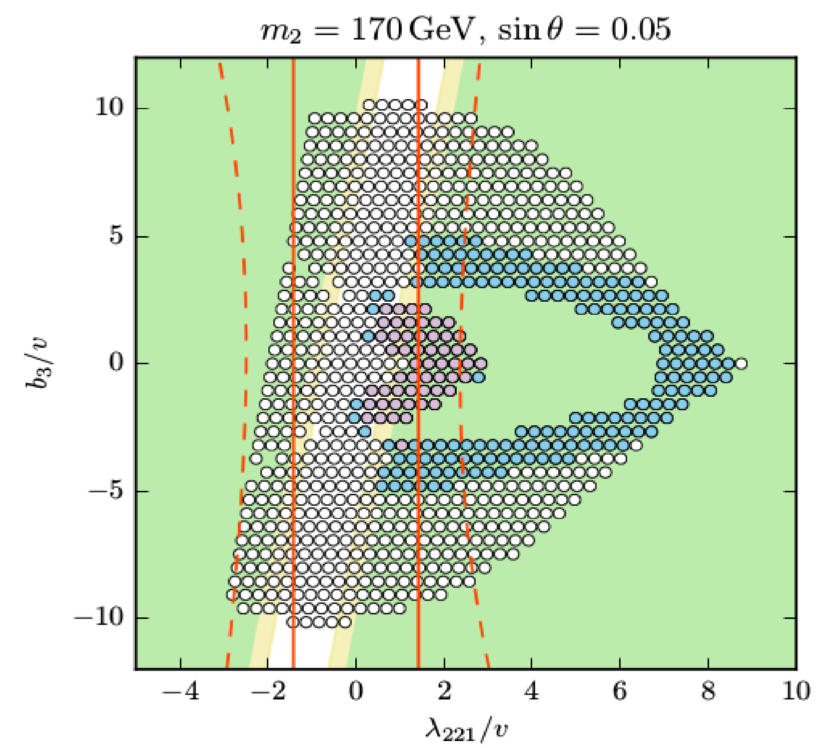
m_{h1} = 125 GeV

m_2 < 250 GeV



$\lambda_{221} \propto a_2$ ($\neq 0$ for $\sin\theta \to 0$)





*Chen, Kozaczuk, Lewis, JHEP **1708** (2017) 096*

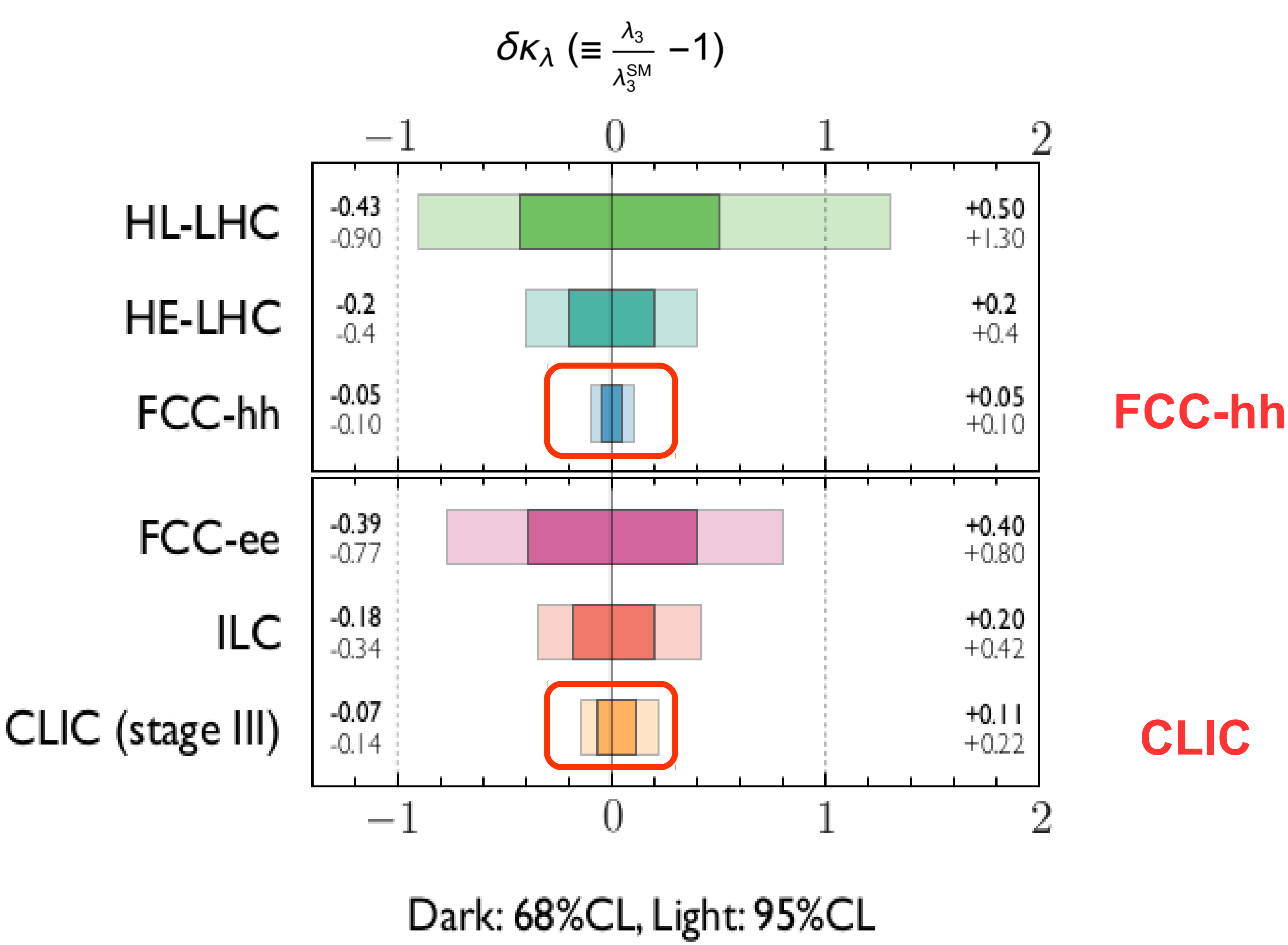
FCC-hh

EWPT Scenarios for Future Colliders

The General xSM Case

$$V(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{a_1}{2} S |H|^2 + \frac{a_2}{2} S^2 |H|^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

+ Higgs self-coupling!



*Di Vita, Durieux, Grojean, Gu. Liu, Panico, Riembau, Vantalon, JHEP **1802** (2018) 178*

EWPT Scenarios for Future Colliders

CLIC

The General xSM Case

$$\boxed{V(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{a_1}{2} S|H|^2 + \frac{a_2}{2} S^2|H|^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4}$$

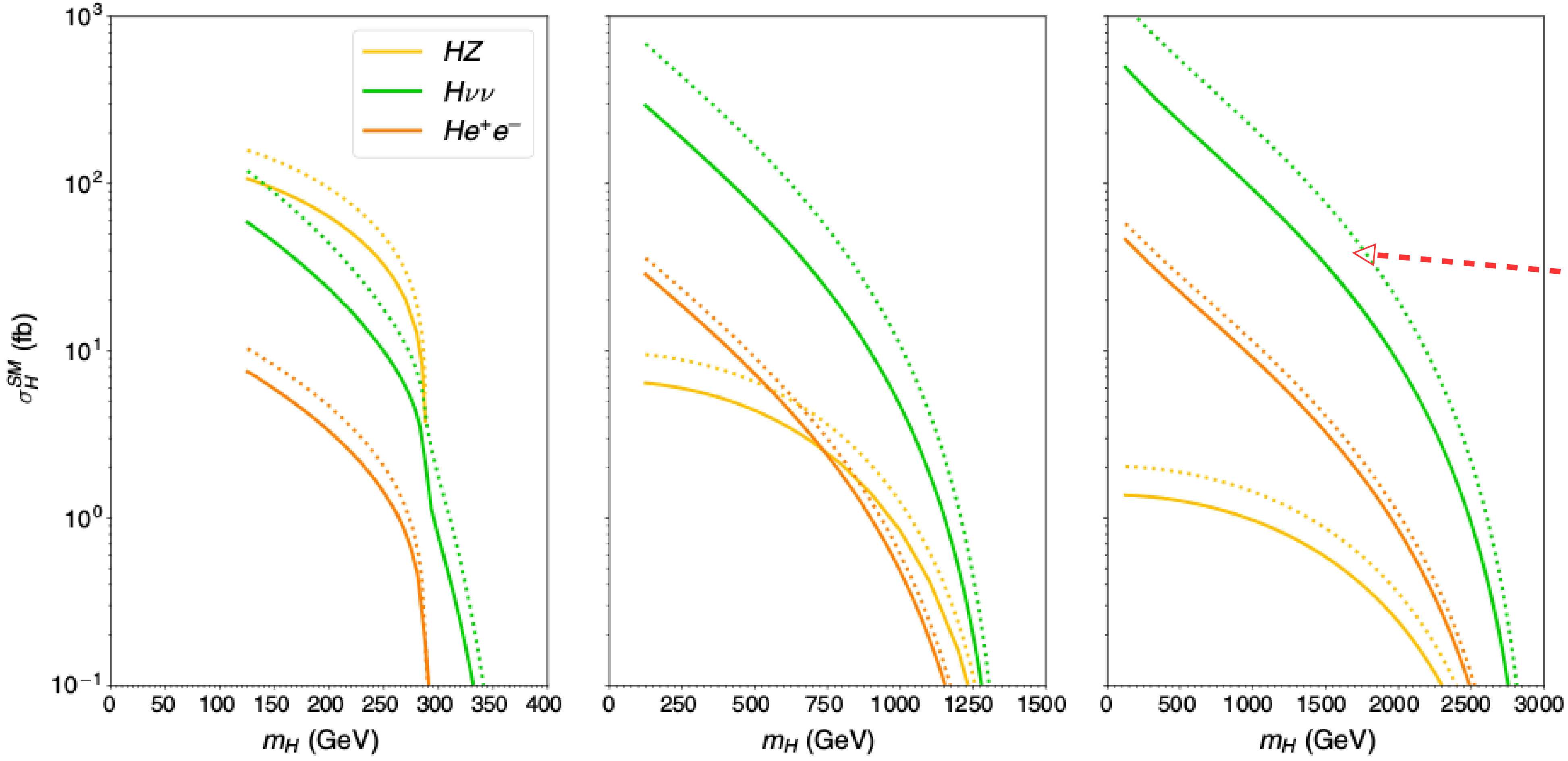
EWPT Scenarios for Future Colliders

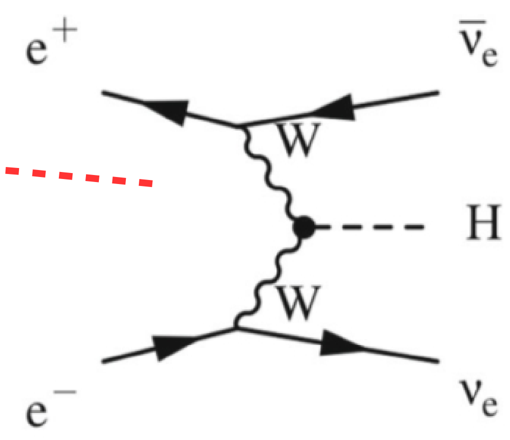
CLIC

The General xSM Case

$$V(H,S) = -\mu^2\,|H|^2 + \lambda\,|H|^4 + \frac{a_1}{2}S|H|^2 + \frac{a_2}{2}S^2|H|^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

Large VBF (heavy) Higgs production XS





*JMN, Spannowsky, Eur. Phys J. C**79** (2019) 467*

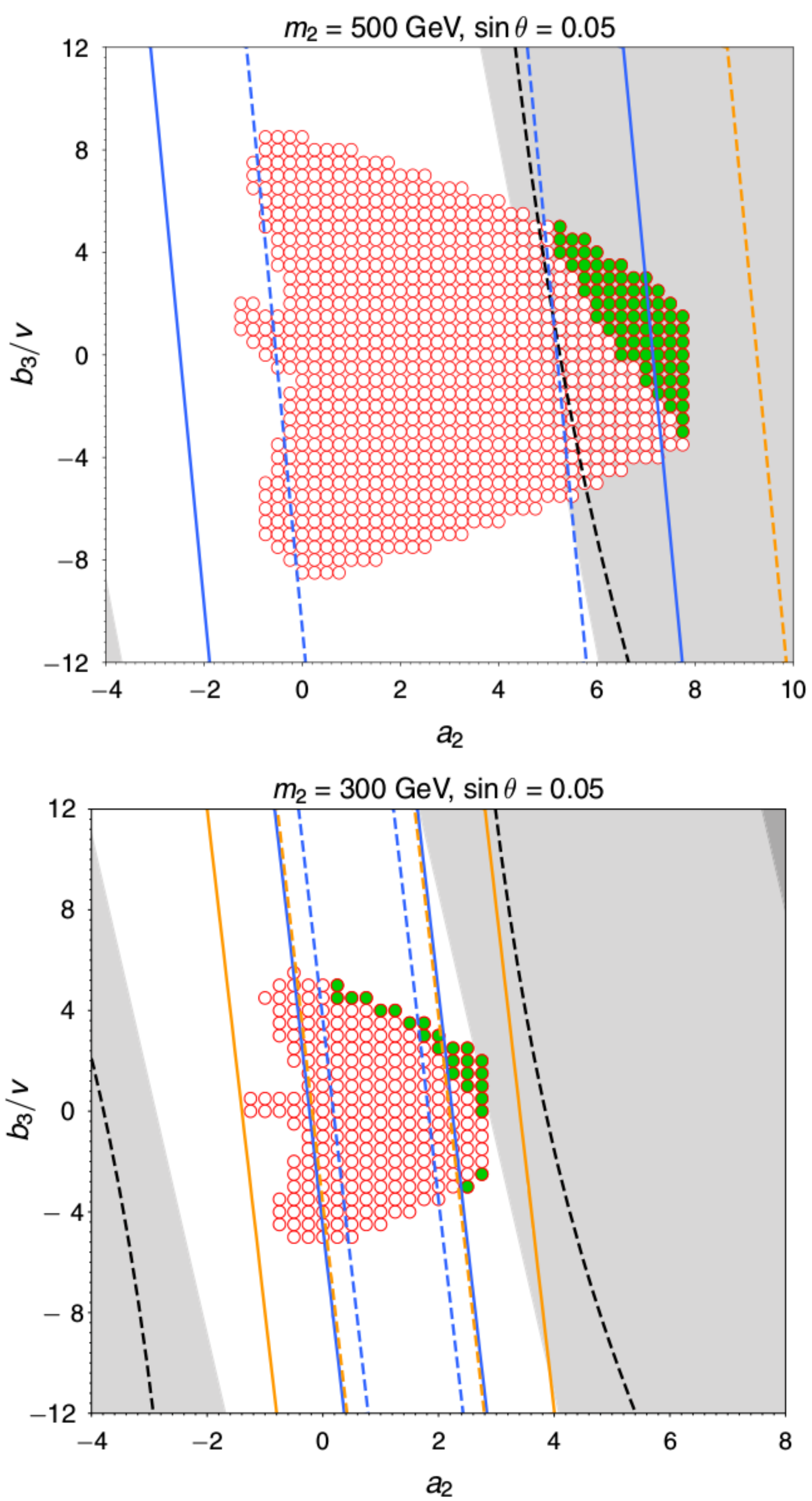
EWPT Scenarios for Future Colliders

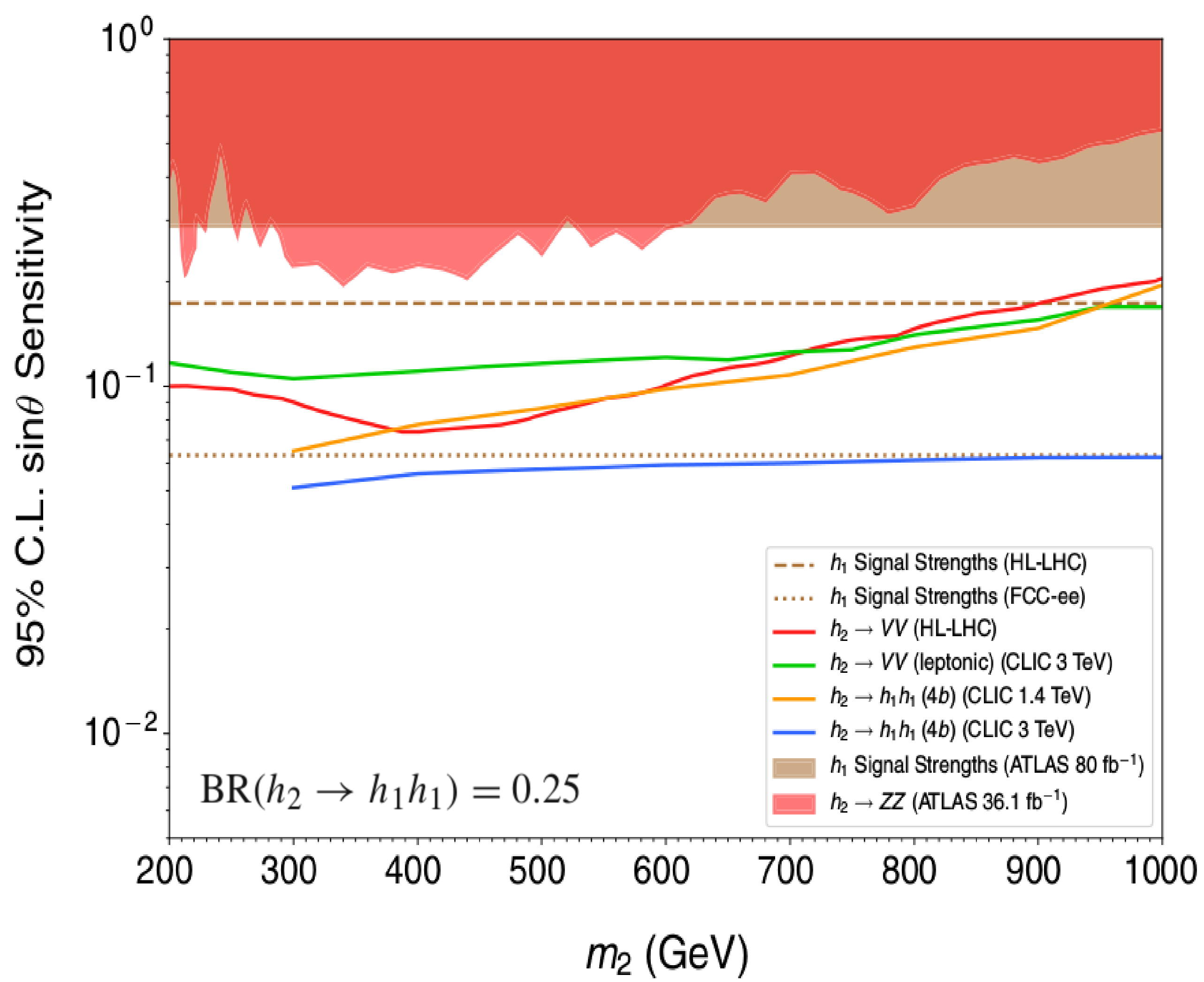
CLIC

The General xSM Case

$$V(H,S) = -\mu^2\,|H|^2 + \lambda\,|H|^4 + \frac{a_1}{2}S|H|^2 + \frac{a_2}{2}S^2|H|^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

$$H \to hh \to b\bar{b}b\bar{b}$$





*JMN, Spannowsky, Eur. Phys J. C **79** (2019) 467*

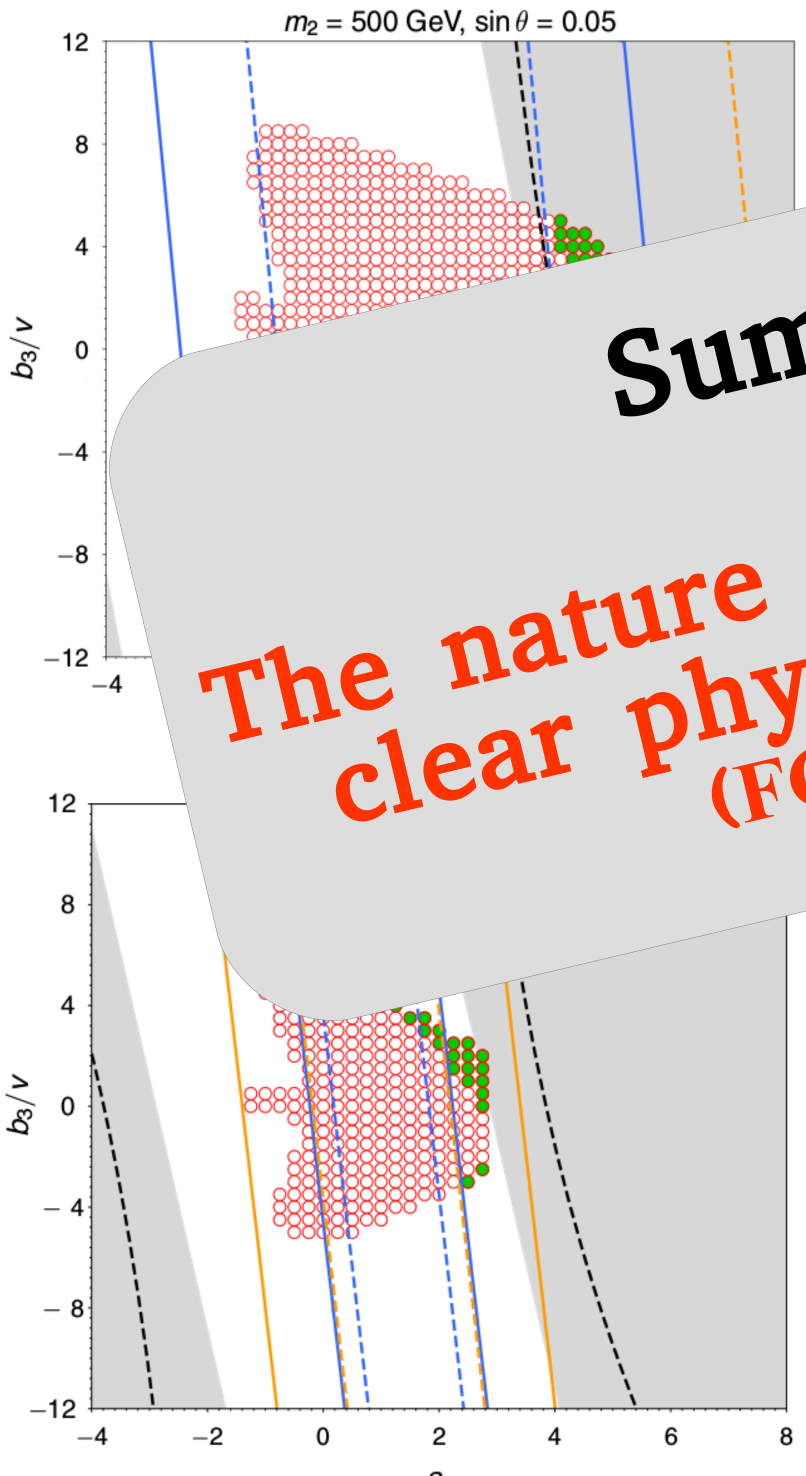
EWPT Scenarios for Future Colliders

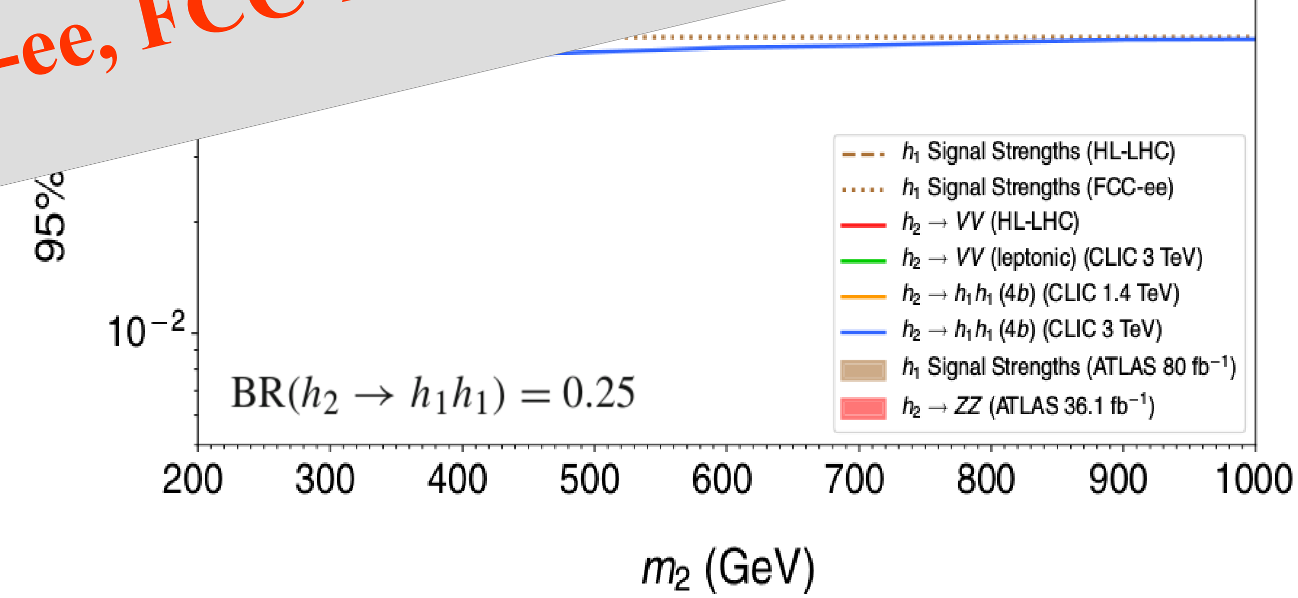
CLIC

The General xSM Case

$$V(H,S) = -\mu^2\,|H|^2 + \lambda\,|H|^4 + \frac{a_1}{2} S|H|^2 + \frac{a_2}{2} S^2|H|^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

$H \to hh$



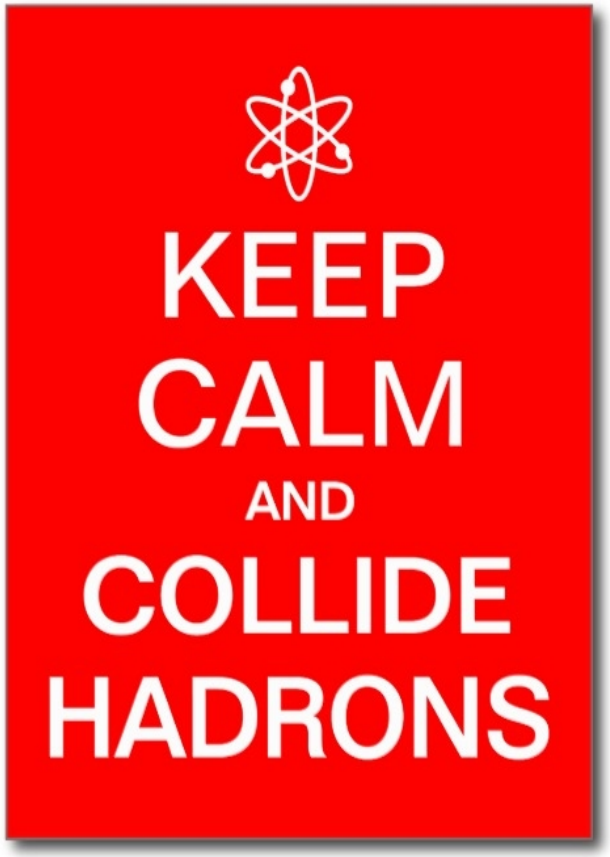


JMN, Spannowsky, Eur. Phys J. C**79** (2019) 467

Summary & Conclusions

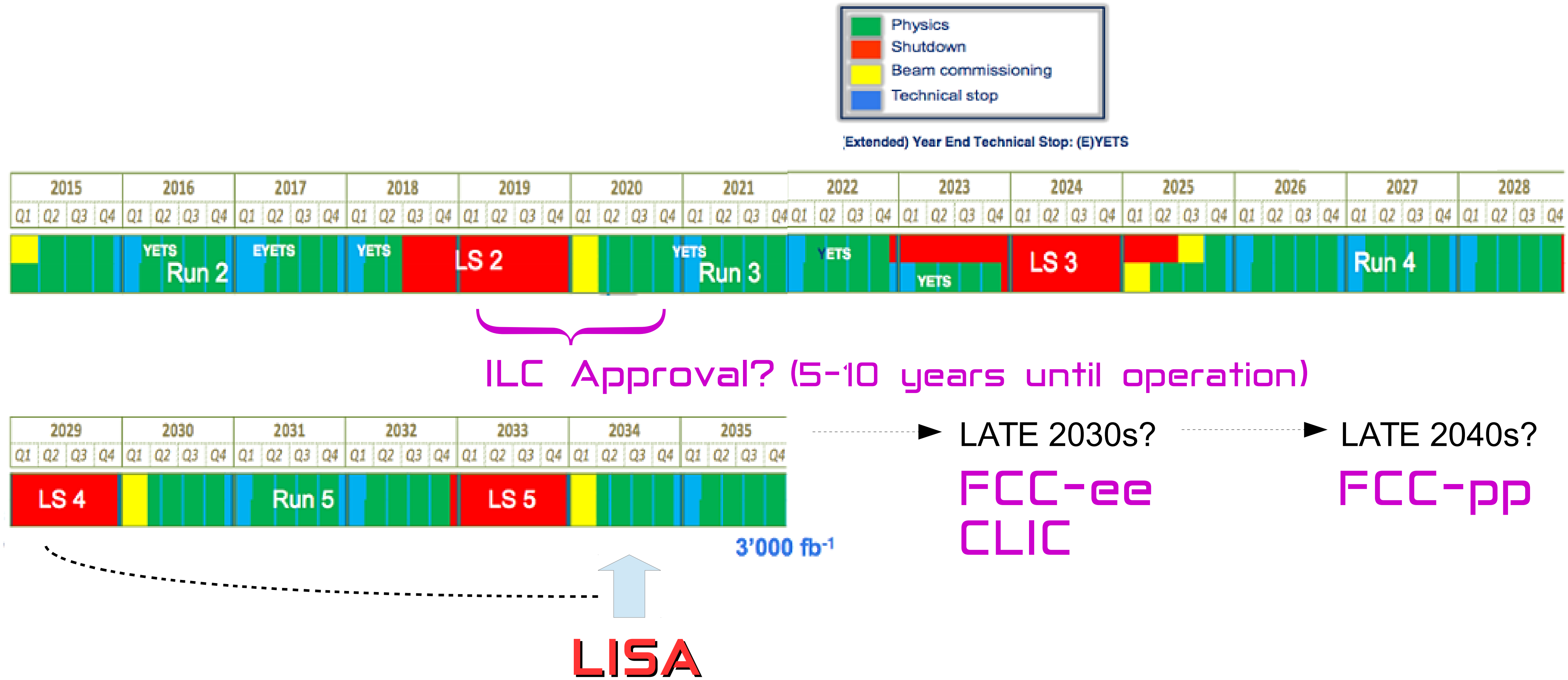
The nature of the EW Phase Transition is a clear physics target for Future Colliders (FCC-ee, FCC-hh, ILC, CLIC, CEPC)

Thank you!




KEEP
CALM
AND
BACKUP
YOUR
WORK

LISA in the Context of High-Energy Colliders Timeline



After LHC, LISA may be Next Step in Exploration of ElectroWeak Scale Physics

Indirect Probes

	current	HL-LHC	CEPC	ILC	FCC-ee	FCC-hh
hZZ	27%	7%	0.25%	0.25%	0.15%	-
$\Gamma(h \to \gamma\gamma)$	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)

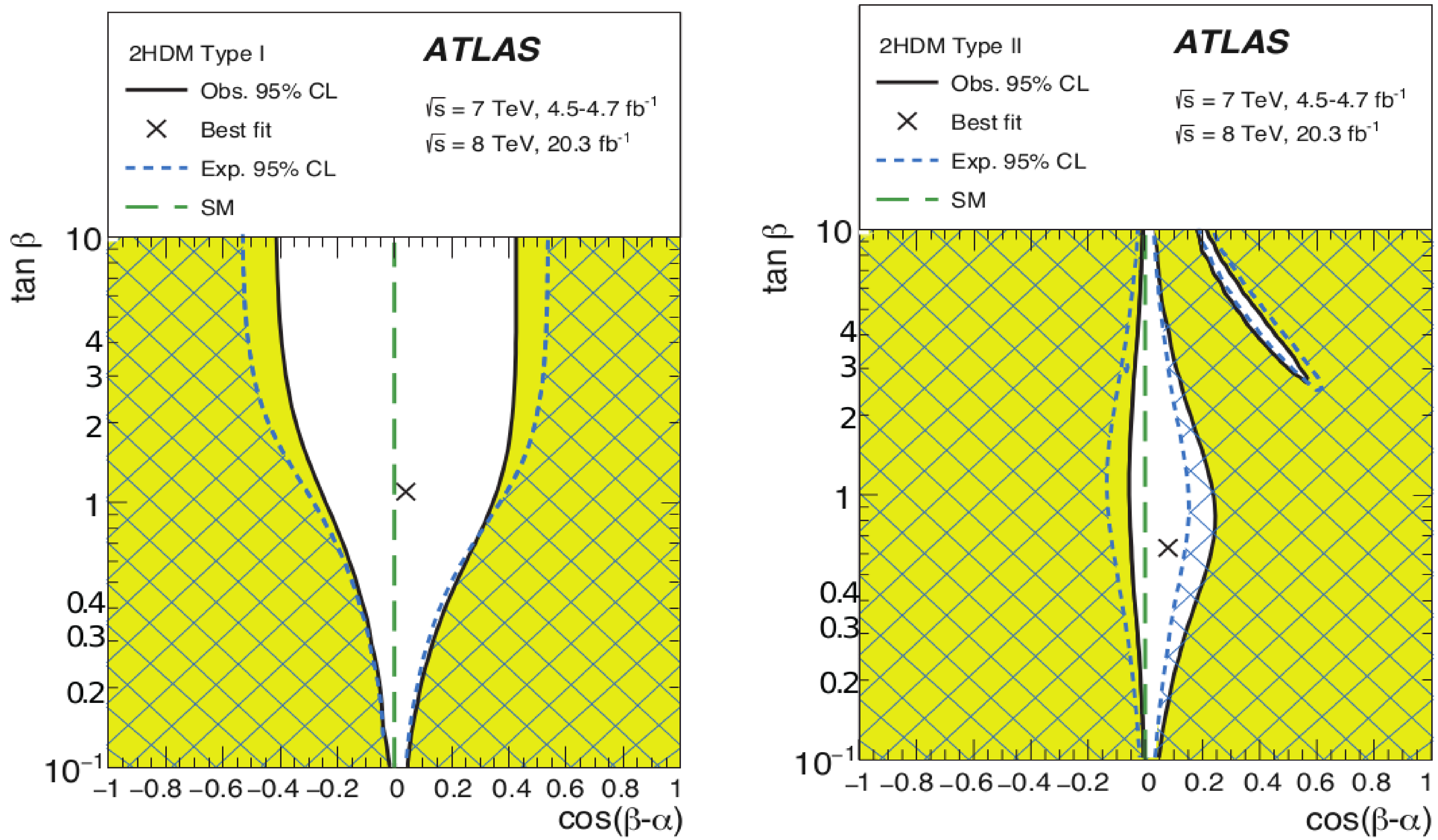
hhh @ HL-LHC = 3000 fb^{-1} at $\sqrt{s}$ = 14 TeV (ATL-PHYS-PUB-2017-001, hh->bb$\gamma\gamma$)

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)

2HDM


2HDM Type I
ATLAS
Obs. 95% CL
Best fit
Exp. 95% CL
SM
√s = 7 TeV, 4.5-4.7 fb-1
√s = 8 TeV, 20.3 fb-1
tan β
cos(β-α)
2HDM Type II
ATLAS
Obs. 95% CL
Best fit
Exp. 95% CL
SM
√s = 7 TeV, 4.5-4.7 fb-1
√s = 8 TeV, 20.3 fb-1
tan β
cos(β-α)

2HDM

CMS-PAS-HIG-15-001

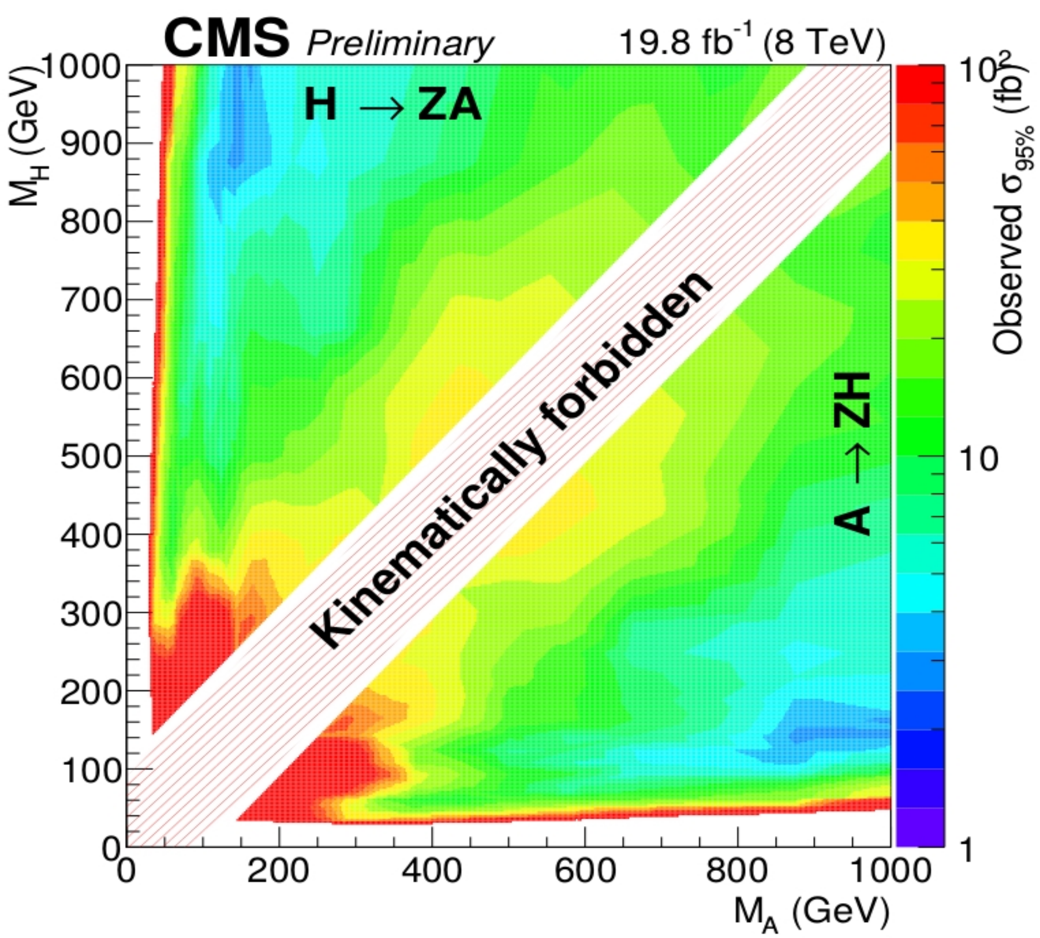
Phys. Lett. B759 (2016) 369 (ArXiv:1603.02991)

Search for H/A decaying into Z and A/H, with Z$\rightarrow \ell\ell$ and A/H$\rightarrow$ bb or A/H$\rightarrow \tau\tau$

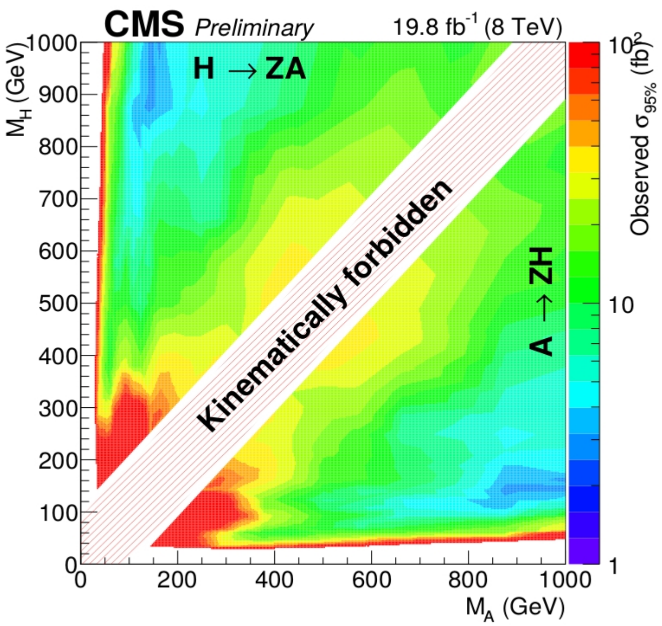
The CMS Collaboration

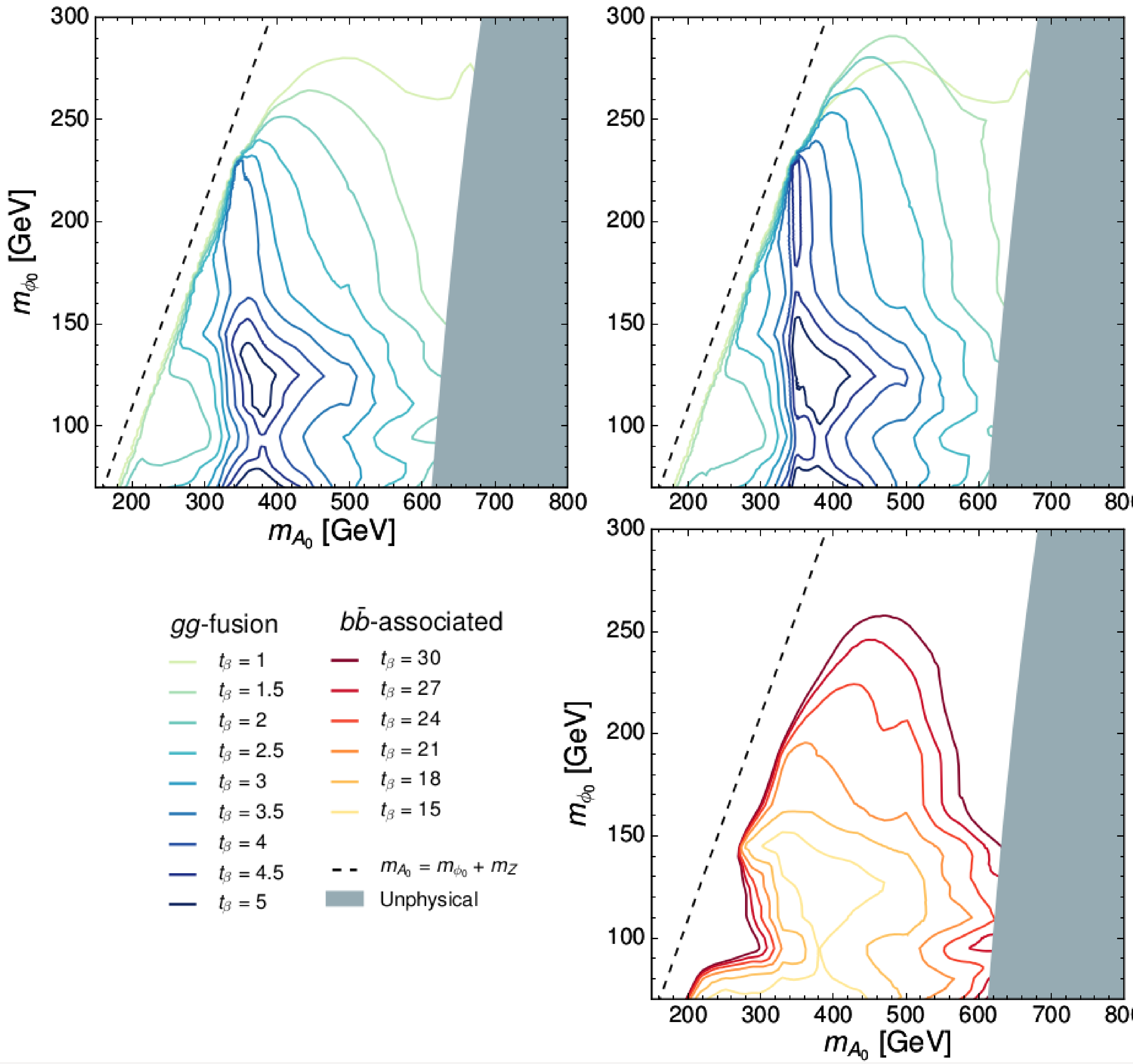
One important motivation for 2HDMs is that these models provide a way to explain the asymmetry between matter and anti-matter observed in the Universe [4, 5]. Another important motivation is Supersymmetry [6], which is a theory that falls in the broad class of 2HDMs. Axion models [7], which would explain how the strong interaction does not violate the CP symmetry, would give rise to an effective low-energy theory with two Higgs doublets. Finally, it has also been recently noted [8] that certain realizations of 2HDMs can accommodate the muon $g-2$ anomaly [9] without violating the present theoretical and experimental constraints.

In the most general case 14 parameters are necessary to describe the scalar sector in a 2HDM. However, only 6 free parameters remain once the so-called Z_2 symmetry is imposed to suppress flavor changing neutral currents, in agreement with experimental observations, and the values of the mass of the recently discovered Higgs boson (125 GeV) and the electroweak vacuum expectation value (246 GeV) are assumed. The compatibility of a 125 GeV SM-like Higgs boson with 2HDMs is possible in the so-called alignment limit. In such a limit, one of the CP-even scalars, h or H, is identified with the 125 GeV Higgs boson and the condition $cos(\beta-\alpha) \approx 0$ or $sin(\beta-\alpha) \approx 0$ is satisfied, where tan β and α are, respectively, the ratio of the vacuum expectation values, and the mixing angle of the two Higgs doublets. A recent theoretical study [5] has shown that, in this limit, a large mass splitting (>100 GeV) between the A and H bosons would favor the electroweak phase transition that would be at the origin of the baryogenesis process in the early Universe, thus explaining the currently observed matter-antimatter asymmetry in the Universe. In such a scenario, the most frequent decay mode of the pseudoscalar A boson would be A$\rightarrow$ZH.



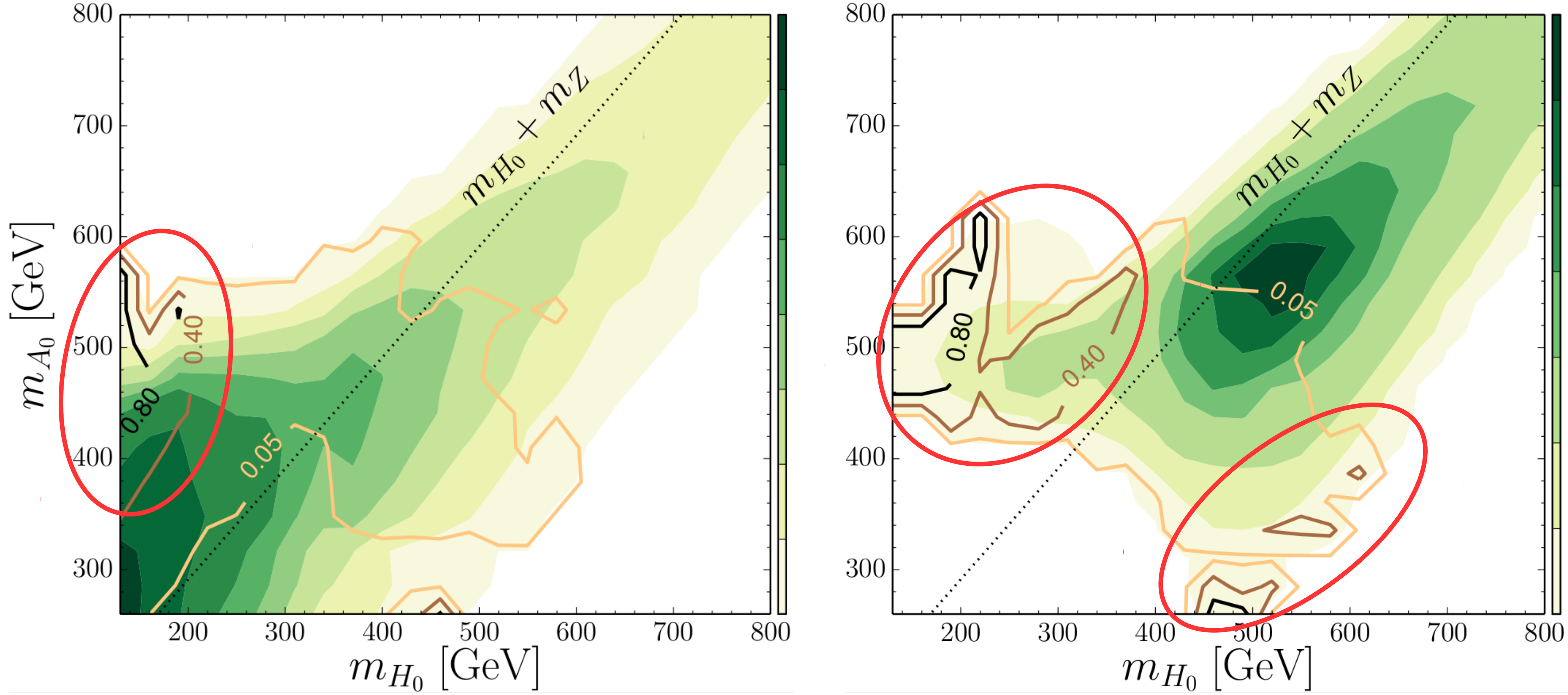
2HDM





Dorsch, Huber, Mimasu, No, PRD **93** (2016) 115033

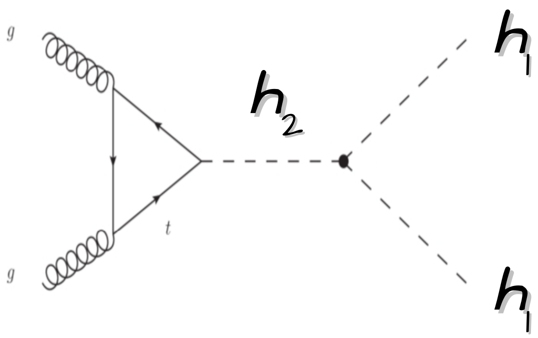
2HDM

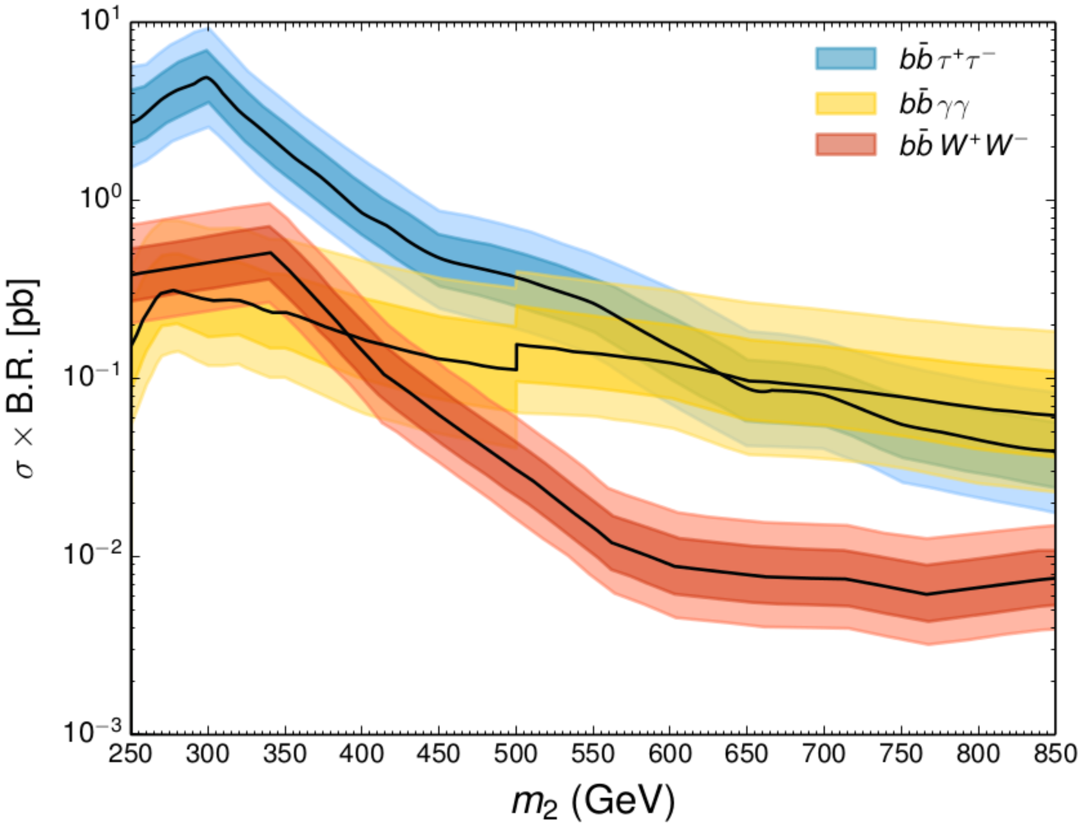


Dorsch, Huber, Mimasu, No, JHEP **1712** (2017) 086

Singlet

RESONANT HIGGS PAIR PRODUCTION



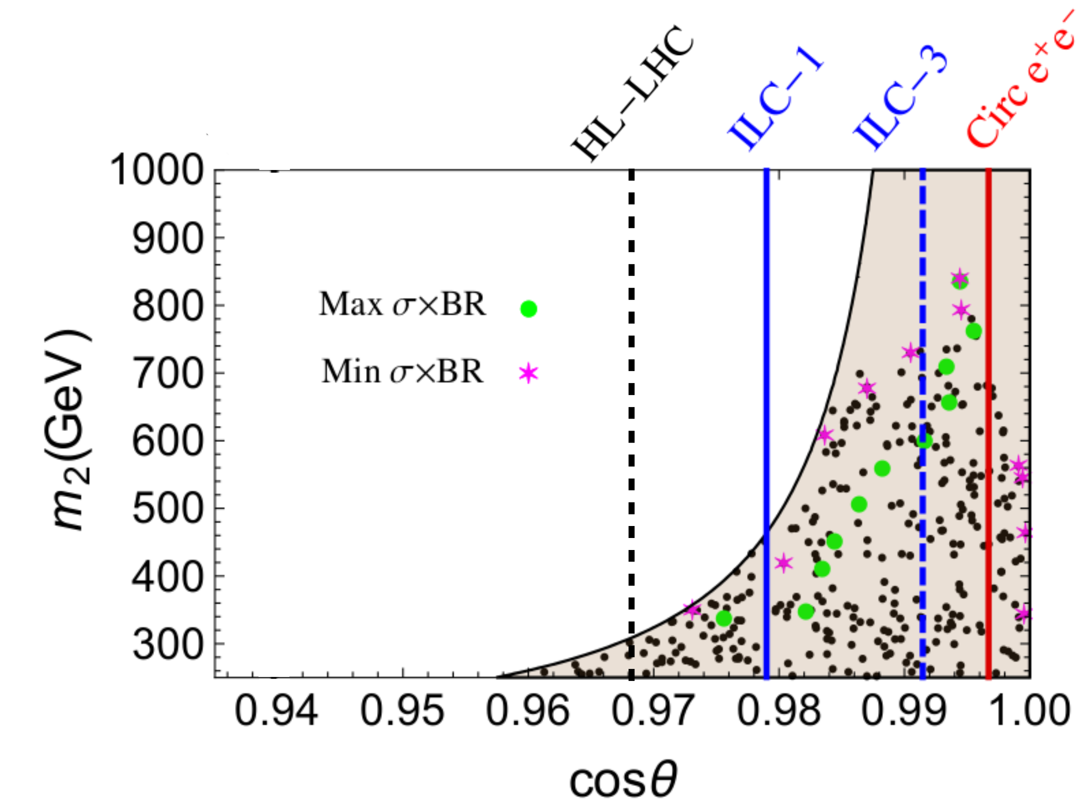


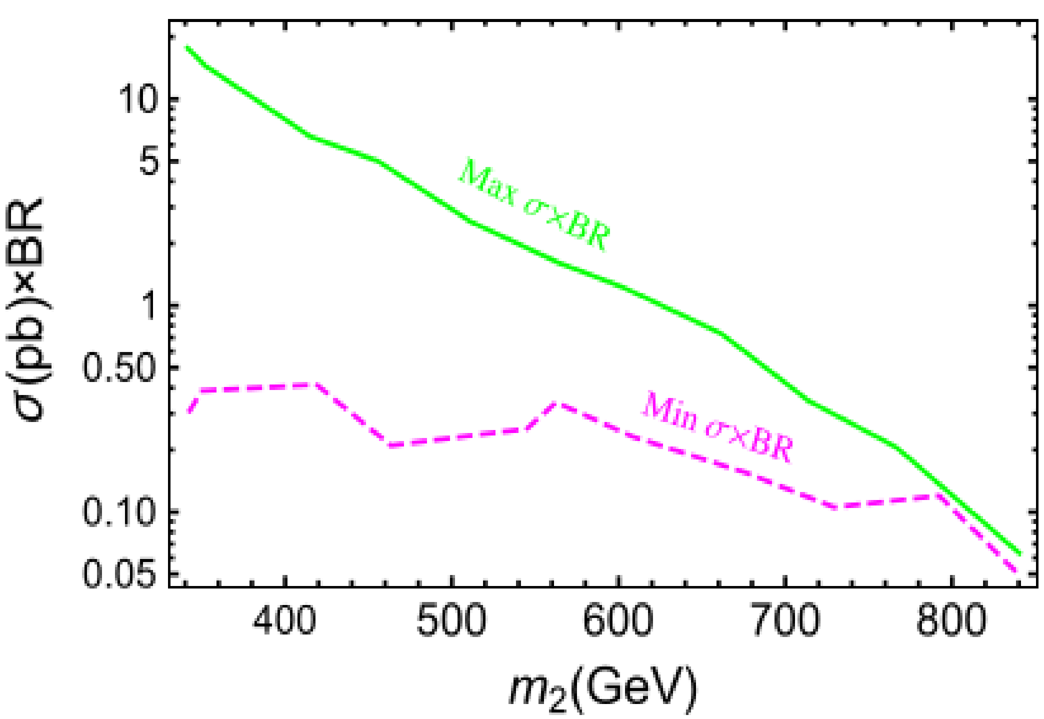
$$\Gamma_{h_2 \to h_1 h_1} = \frac{\lambda_{211}^2 \sqrt{1 - 4\, m_1^2/m_2^2}}{8\pi m_2}$$

Huang, No, Pernie, Ramsey-Musolf, Safonov, Spannowsky, Winslow, Phys. Rev. ***D96*** *(2017) 035007*

- Scan of 1^{st} Order EWPT Parameter Space
- Project Scan into m_2, $\sigma(h_2)$ x $\text{BR}(h_2 \to h_1\, h_1)$ @ 100 TeV

*Kotwal, No, Ramsey-Musolf, Winslow, PRD **94** (2016) 035022*





Benchmark	$\cos\theta$	$\sin\theta$	m_2 (GeV)	σ (pb)	BR
B1	0.976	0.220	341	23.9	0.74
B2	0.982	0.188	353	19.0	0.76
B3	0.983	0.181	415	20.1	0.33
B4	0.984	0.176	455	16.3	0.31
B5	0.986	0.164	511	10.8	0.24
B6	0.988	0.153	563	6.96	0.23
B7	0.992	0.129	604	4.01	0.30
B8	0.994	0.113	662	2.23	0.33
B9	0.993	0.115	714	1.73	0.20
B10	0.996	0.094	767	0.918	0.22
B11	0.994	0.105	840	0.802	0.079

~ 17 pb

BMmax

~ 50 fb

Benchmark	$\cos\theta$	$\sin\theta$	m_2 (GeV)	σ (pb)	BR
B1	0.999	0.029	343	0.428	0.72
B2	0.973	0.231	350	27.8	0.014
B3	0.980	0.197	419	23.5	0.018
B4	0.999	0.026	463	0.334	0.63
B5	0.999	0.035	545	0.408	0.62
B6	0.999	0.043	563	0.553	0.62
B7	0.984	0.180	609	7.67	0.030
B8	0.987	0.161	676	4.17	0.037
B9	0.990	0.138	729	2.33	0.045
B10	0.995	0.104	792	0.991	0.12
B11	0.994	0.105	841	0.801	0.062

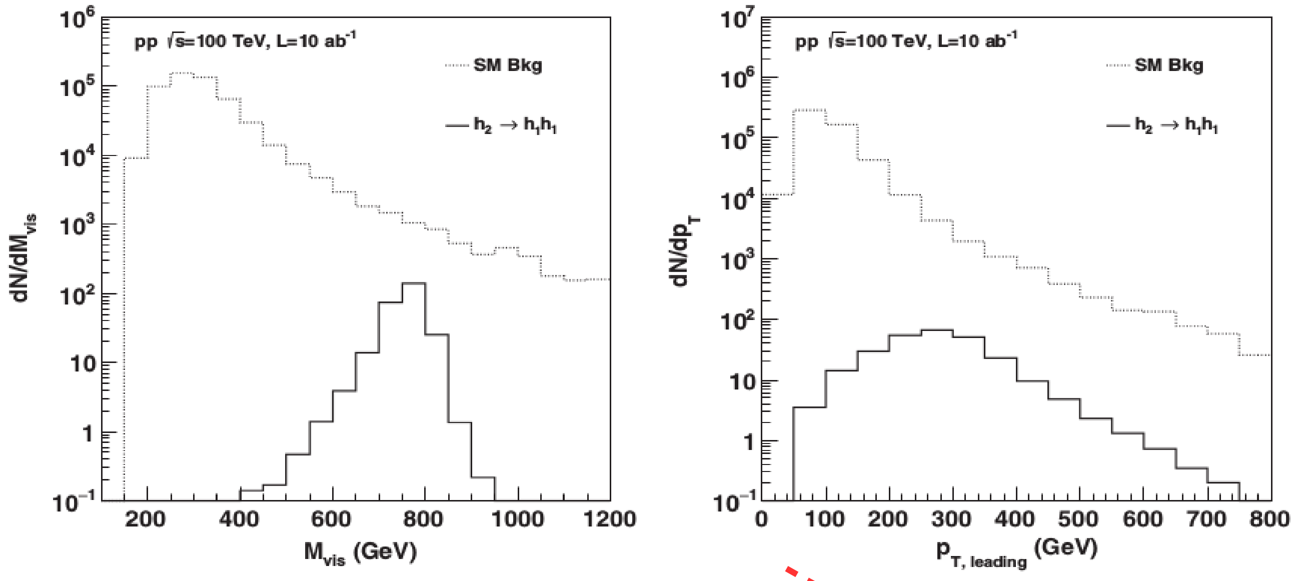
~ 0.3 pb

BMmin

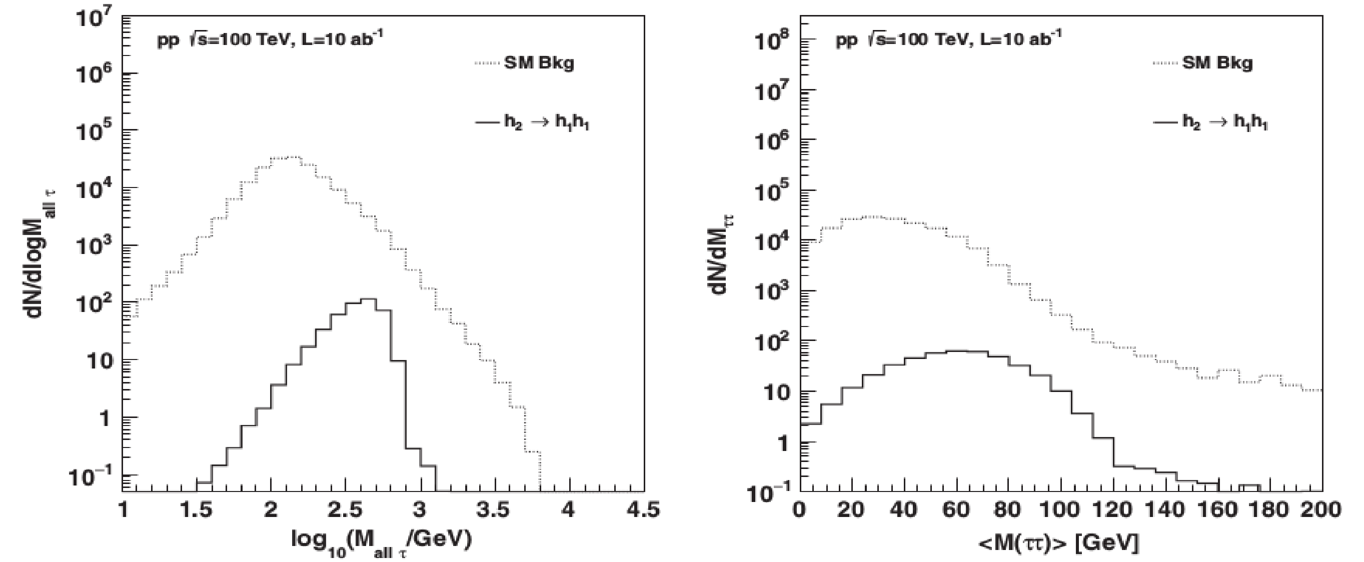
~ 50 fb

Decay channel	Branching ratio
$b\bar{b}b\bar{b}$	3.33×10^{-1}
$\tau\tau b\bar{b}$	7.29×10^{-2}
$W^+(\to l\nu)W^-(\to l\nu)b\bar{b}$	1.09×10^{-2}
$\tau\tau\tau\tau$	3.99×10^{-3}
$\gamma\gamma b\bar{b}$	2.63×10^{-3}
$W^+(\to l\nu)W^-(\to l\nu)\tau\tau$	1.20×10^{-3}
$\gamma\gamma\tau\tau$	2.88×10^{-4}
$b\bar{b}\mu^+\mu^-$	2.53×10^{-4}
$Z(\to l^+l^-)Z(\to l^+l^-)b\bar{b}$	1.41×10^{-4}
$b\bar{b}Z(\to l^+l^-)\gamma$	1.21×10^{-4}

$b\bar{b}\gamma\gamma$



4τ

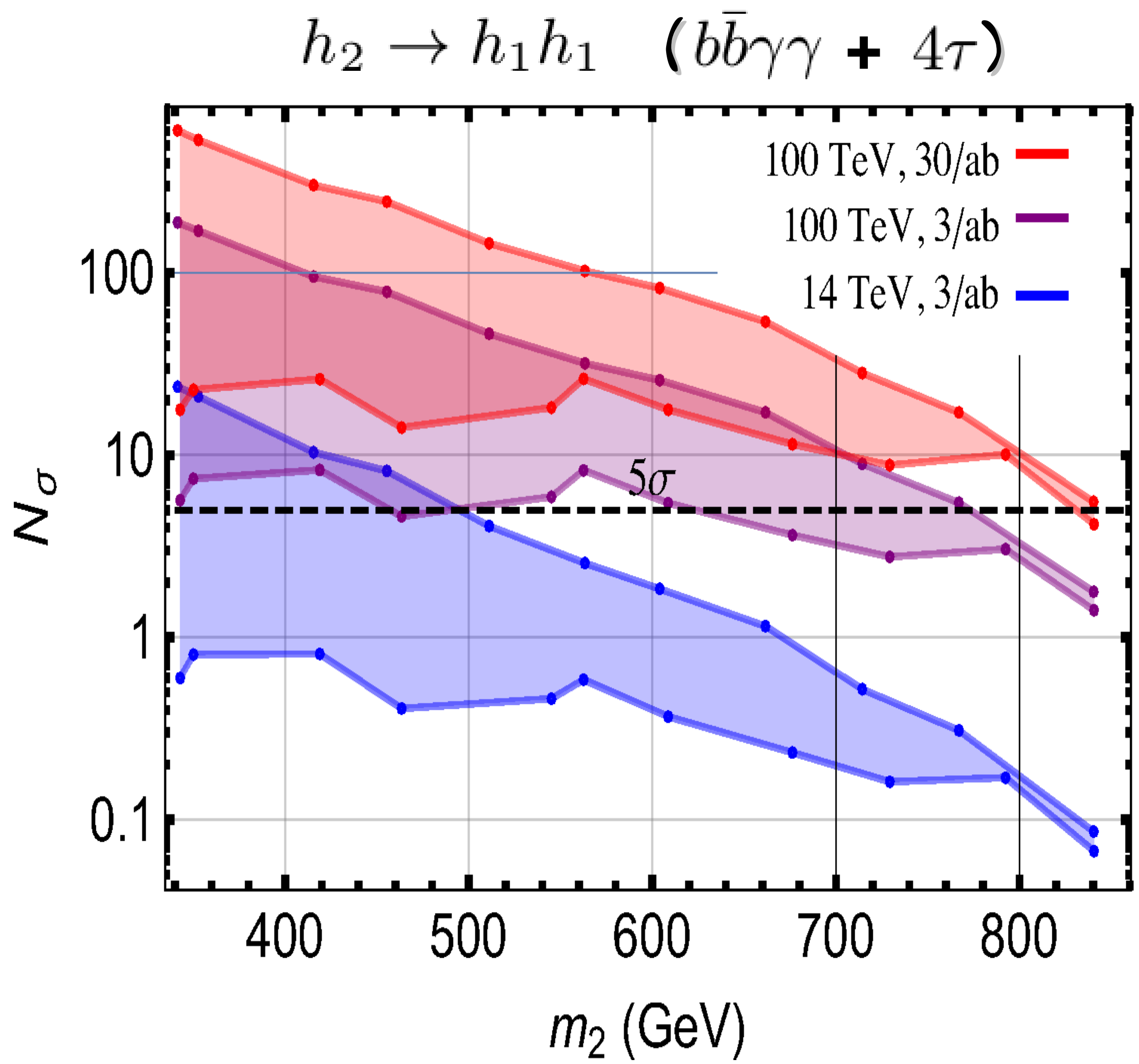


BDT analysis

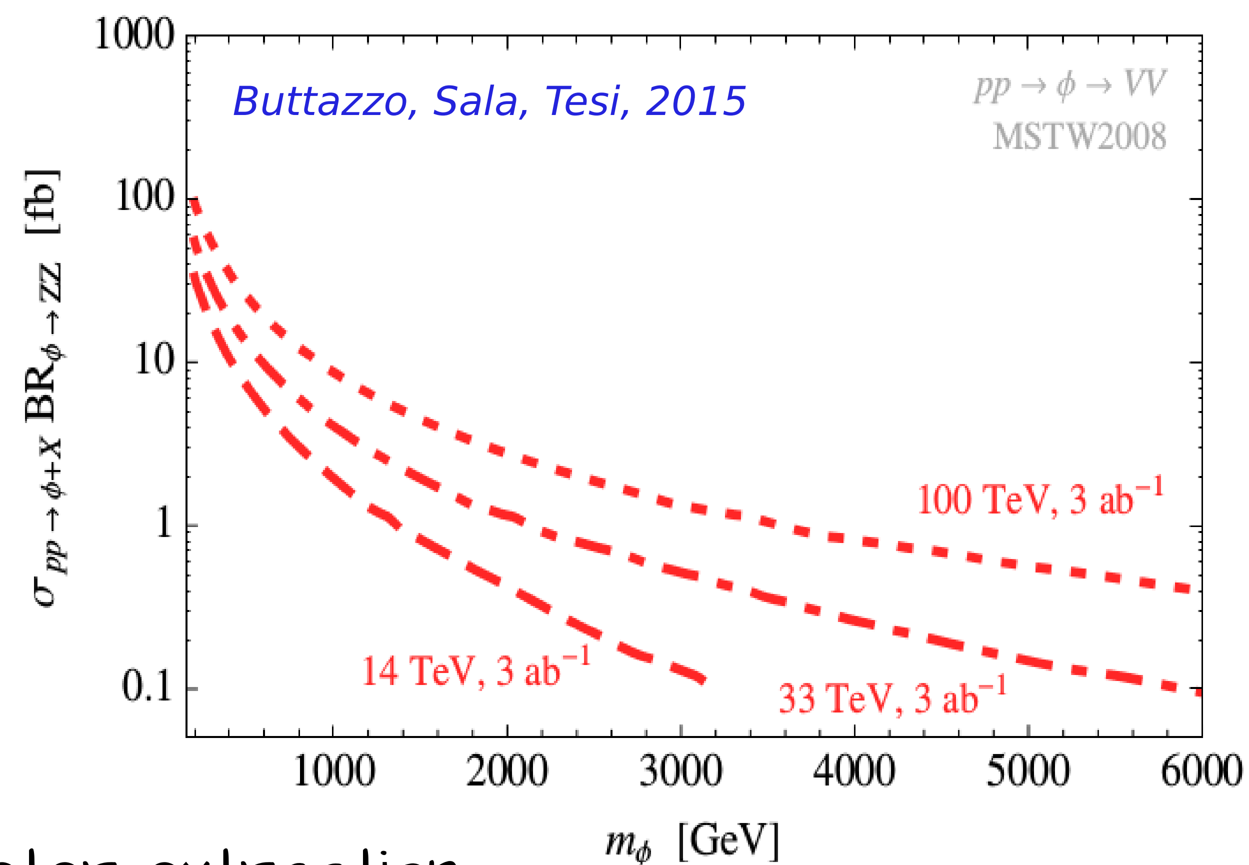
(e.g. BM10)

$b\bar{b}\gamma\gamma$ and 4τ end-up yielding similar BSM sensitivity

$b\bar{b}\gamma\gamma$ better than 4τ for parameter (m_2) extraction



FCC hh (30 ab^{-1}) largely probes 1st Order EWPT parameter space via $h_2 \to h_1 h_1$



- Interplay with $h_2 \to VV$ searches

  Crucial for Higgs + Singlet parameter extraction

  $\cos\theta$ vs λ_{211}

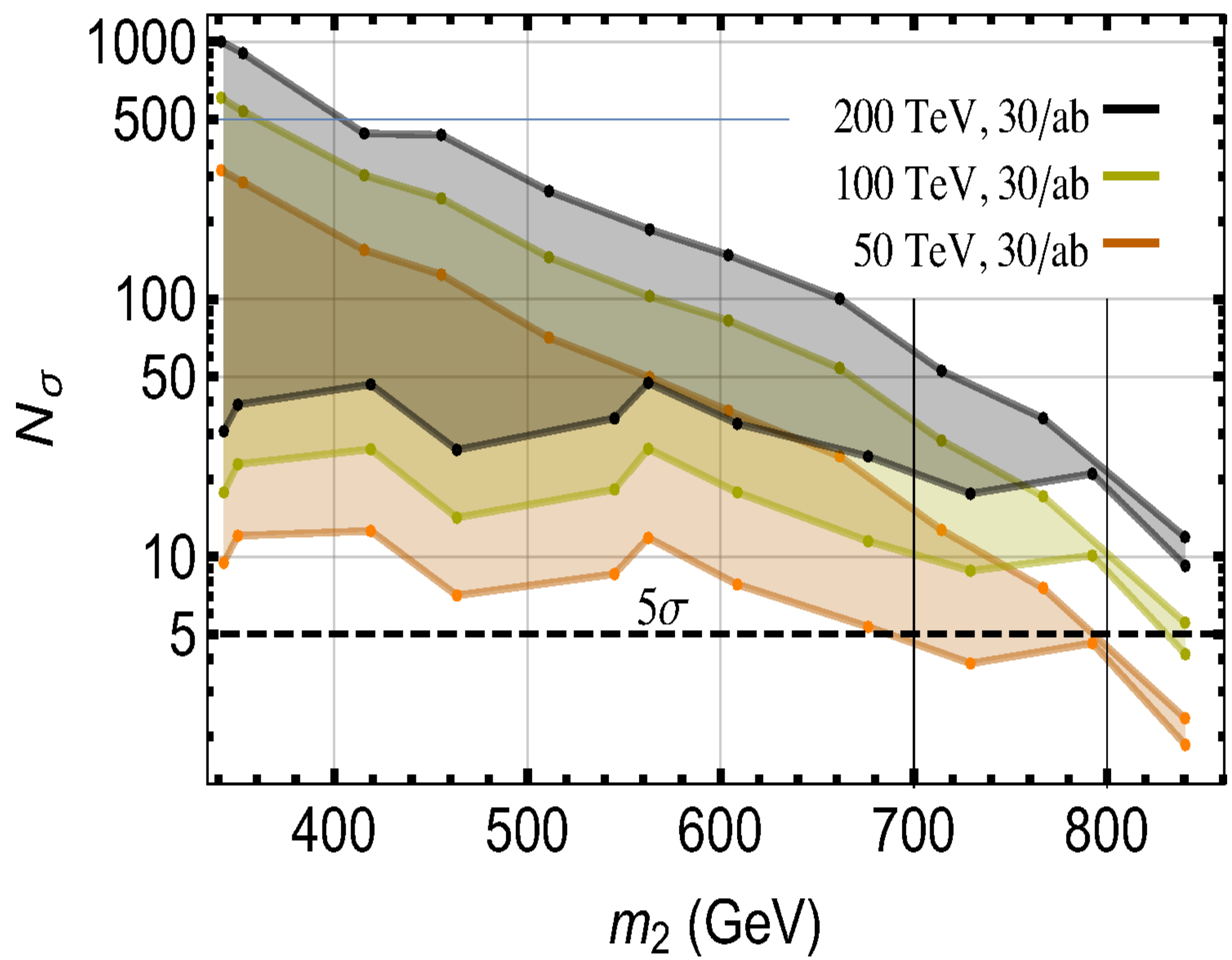
- Impact of Resonant Di-Higgs on Higgs self-coupling extraction at FCC hh

- Go beyond EWPT numerical Scan . . .

How Sensitivity scales with C.O.M. Energy?

What C.O.M. Energy Needed to Quantitatively Study Singlet-Driven EWPT?

$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$



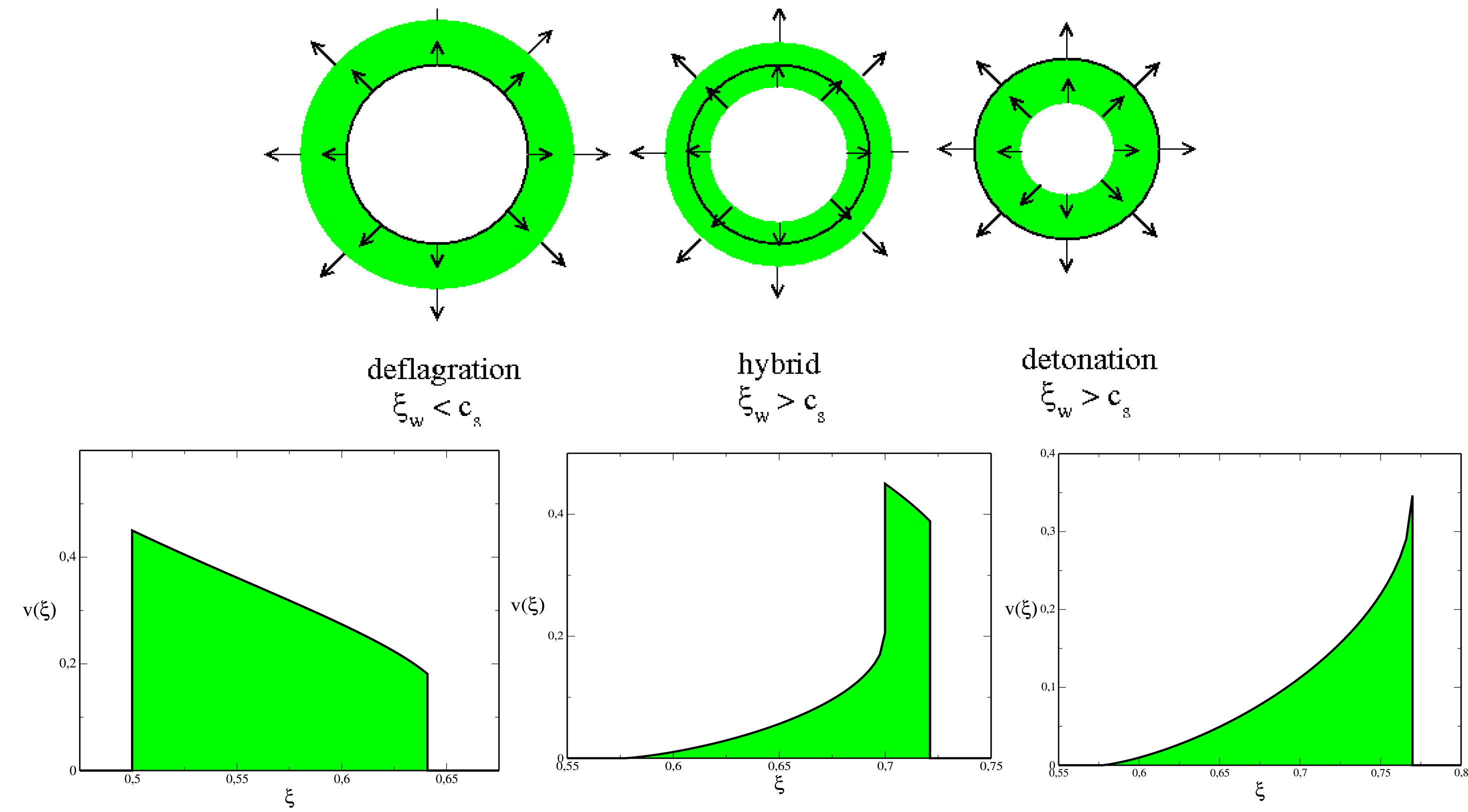
Bubble Dynamics

Laine, Phys. Rev. D**49** (1994) 3847
Kurki-Suonio, Laine, Phys. Rev. D**51** (1995) 5431
Espinosa, Konstandin, No, Servant, JCAP **1006** (2010) 028

$$\partial_\mu T^{\mu\nu}_{Plasma} = 0 \qquad v(r,t) = v(\xi = r/t)$$

$$\frac{1-\xi v(\xi)}{1-v^2(\xi)}\left[\frac{\mu^2}{c_s^2} - 1\right]\partial_\xi v = 2\frac{v(\xi)}{\xi}$$

$$w(\xi) = w_0 \exp\left[\left(1+\frac{1}{c_s^2}\right)\int_{v_0}^{v(\xi)} \gamma^2 \mu \, dv\right]$$



Available PT Energy → Fluid Shells (shock waves)

$\boxed{\text{Kinetic}}$ + Thermal E

ENERGY BUDGET

Kamionkowski, Kosowsky, Turner, Phys. Rev. D**49** (1994) 2837
Espinosa, Konstandin, No, Servant, JCAP **1006** (2010) 028

$$\int T(r)\, r^2 dr = \kappa \frac{\epsilon}{3} R^3_{Bubble} \qquad (\Delta V = \epsilon)$$

GW Source Efficiency

$$\kappa = \frac{3}{\epsilon\, v_W^3}\int w(\xi)\, v(\xi)^2\, \gamma(\xi)^2\, \xi^2\, d\xi < 1$$