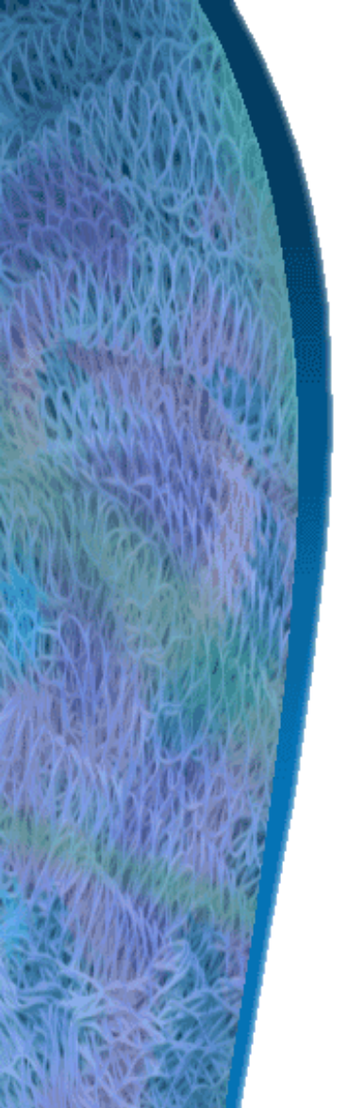
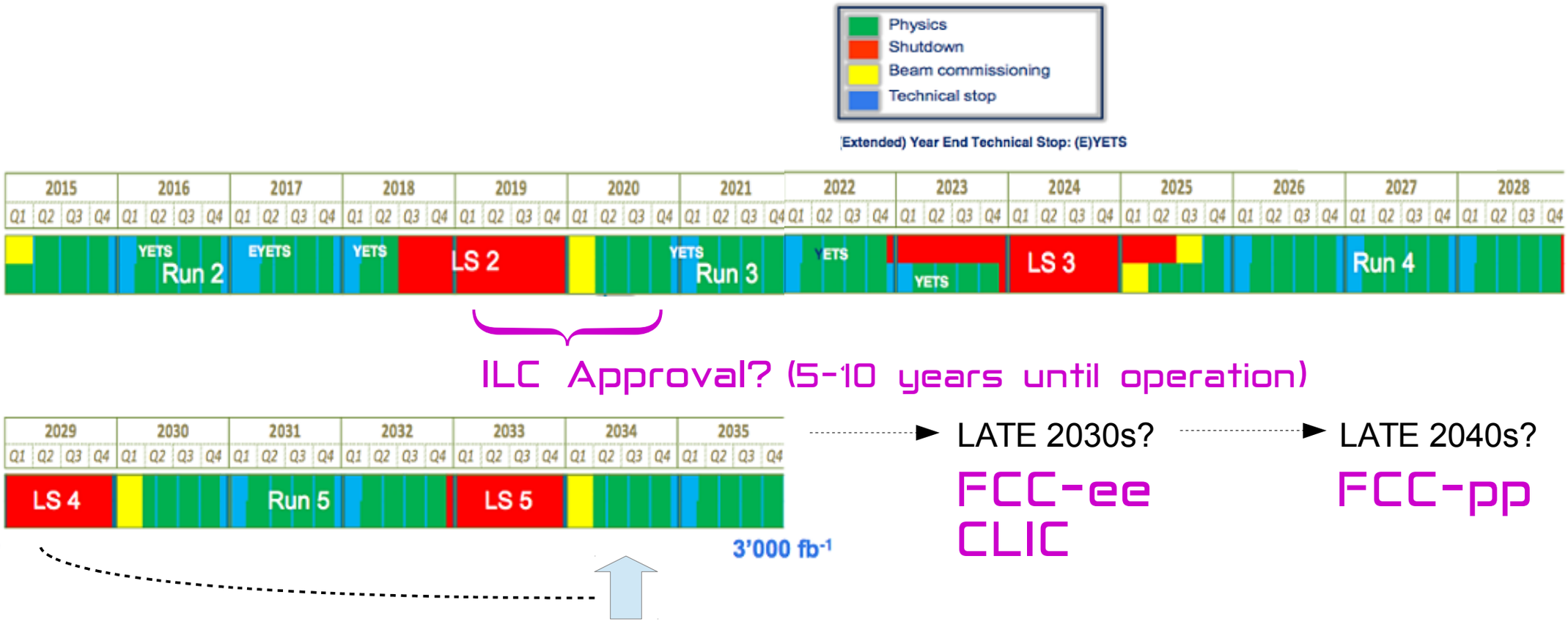


1st Order Phase Transitions: LISA-LHC Complementarity

Jose Miguel No
King's College London

MITP, LISA CosmoWG
16/10/2017

LISA in the Context of High-Energy Colliders Timeline



ILC Approval? (5-10 years until operation)

LATE 2030s? FCC-ee CLIC

LATE 2040s? FCC-pp

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

LISA & LHC

Let's Concentrate on ElectroWeak PT...

Models (broad classes) for a Strong 1st Order EWPT:

⇨ EWPT from Thermal Effects

MSSM (light stop scenario) $m_{\tilde{t}} < 150 - 160\ GeV$

*Carena, Nardini, Quiros, Wagner, Nucl. Phys. B**812** (2009) 243*
*Laine, Nardini, Rummukainen, JCAP **1301** (2013) 011*

⇨ EWPT from Vacuum Effects

Non-Minimal Higgs Sectors → Non-Singlets (e.g. 2HDM)

*Dorsch, Huber, Mimasu, No, Phys. Rev. Lett. **113** (2014) 211802*

⇨ EWPT from Tree-level (Barrier) Effects

New Scalar Singlets

SM + Singlet (xSM)

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

NMSSM

*Huber, Konstandin, Prokopec, Schmidt Nucl. Phys. B**757** (2006) 172*
*Kozaczuk, Profumo, Haskins, Wainwright, JHEP **1501** (2015) 144*

LISA & LHC

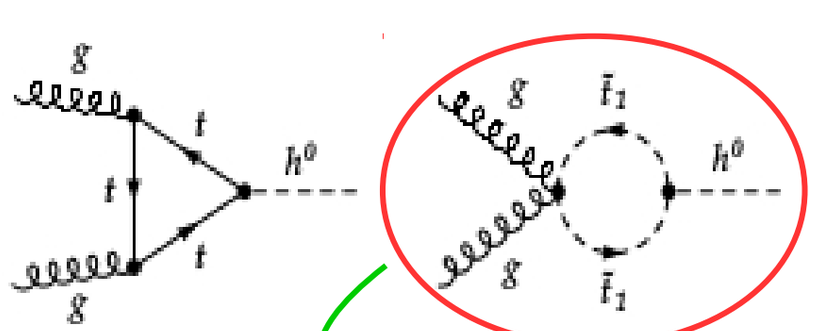
1) SCENARIOS/MODELS WITHIN LHC REACH...

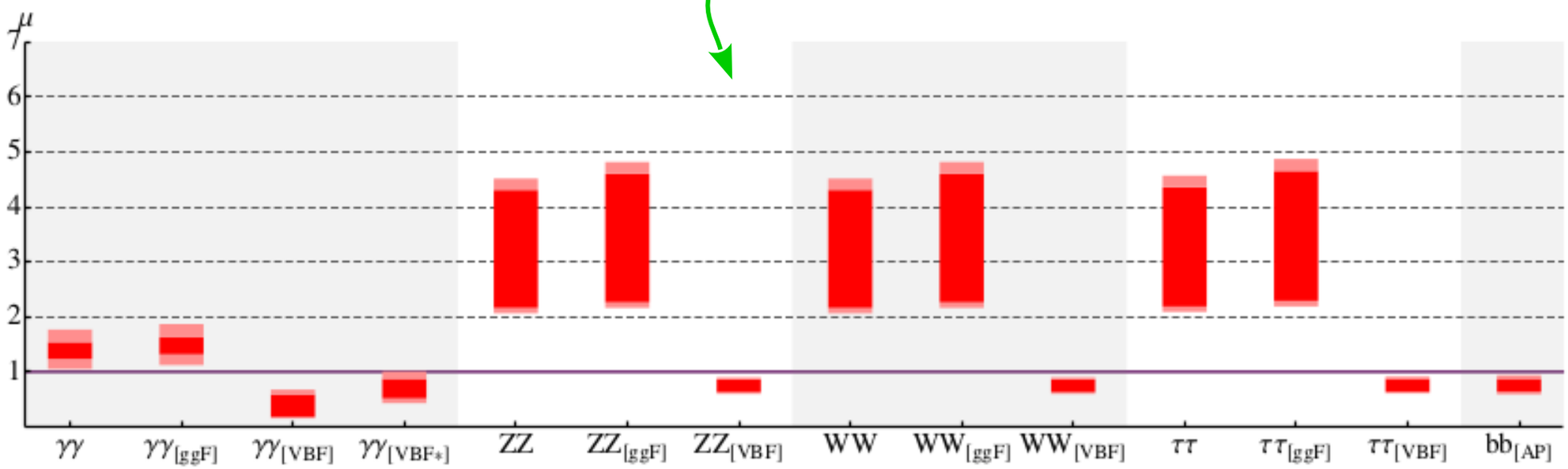
MSSM (light stop scenario)

(Generically, EWPT from new coloured states)

Deviations in Higgs Signal Strengths from SM @ LHC

due to Light Stops





*Curtin, Jaiswal, Meade, JHEP **1208** (2012) 005*

*Carena, Nardini, Quiros, Wagner, JHEP **1302** (2013) 001*

LISA & LHC

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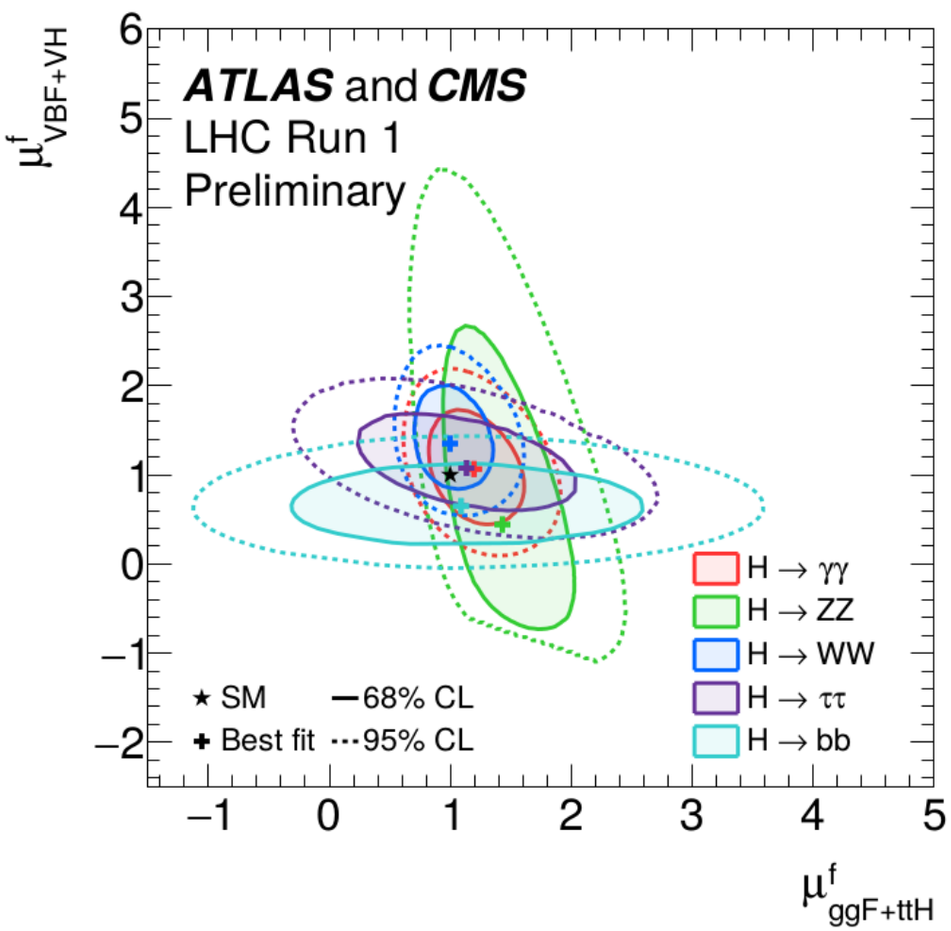

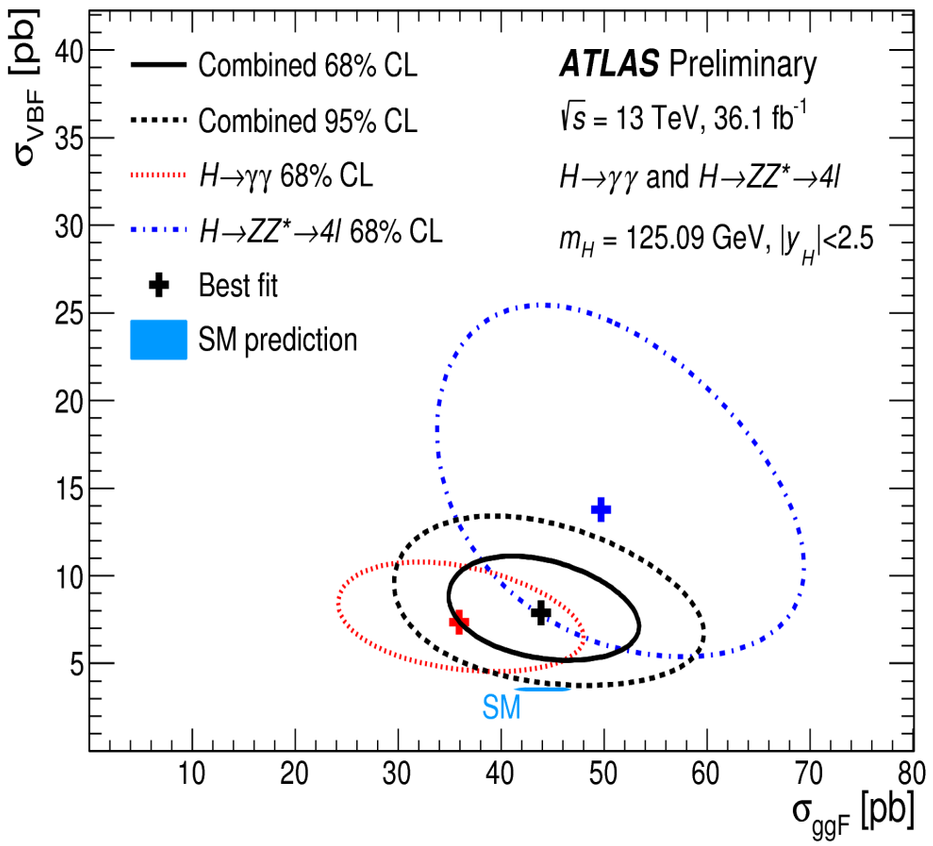

LISA & LHC

1) SCENARIOS/MODELS WITHIN  REACH...

2HDM

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

$$m_{H_0} \quad m_{A_0} \quad m_{H^\pm}$$

$$c_{\beta-\alpha} \quad \tan\beta$$

LISA & LHC

1) SCENARIOS/MODELS WITHIN LHC REACH...

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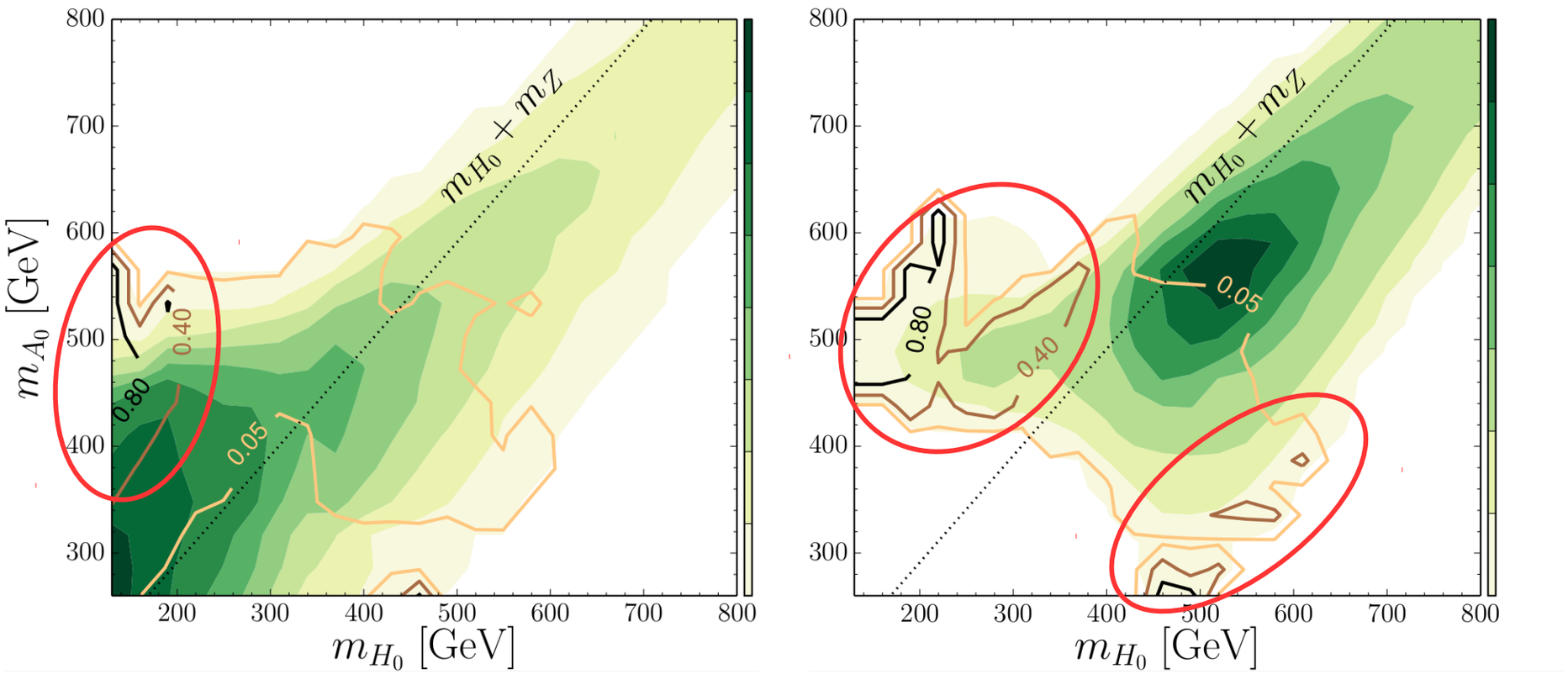
$$

m_{H_0} m_{A_0} $m_{H^\pm}$

$c_{\beta-\alpha}$ $\tan\beta$



Dorsch, Huber, Mimasu, No, Phys. Rev. Lett. ***113*** *(2014) 211802*
Dorsch, Huber, Mimasu, No, 1705.09186

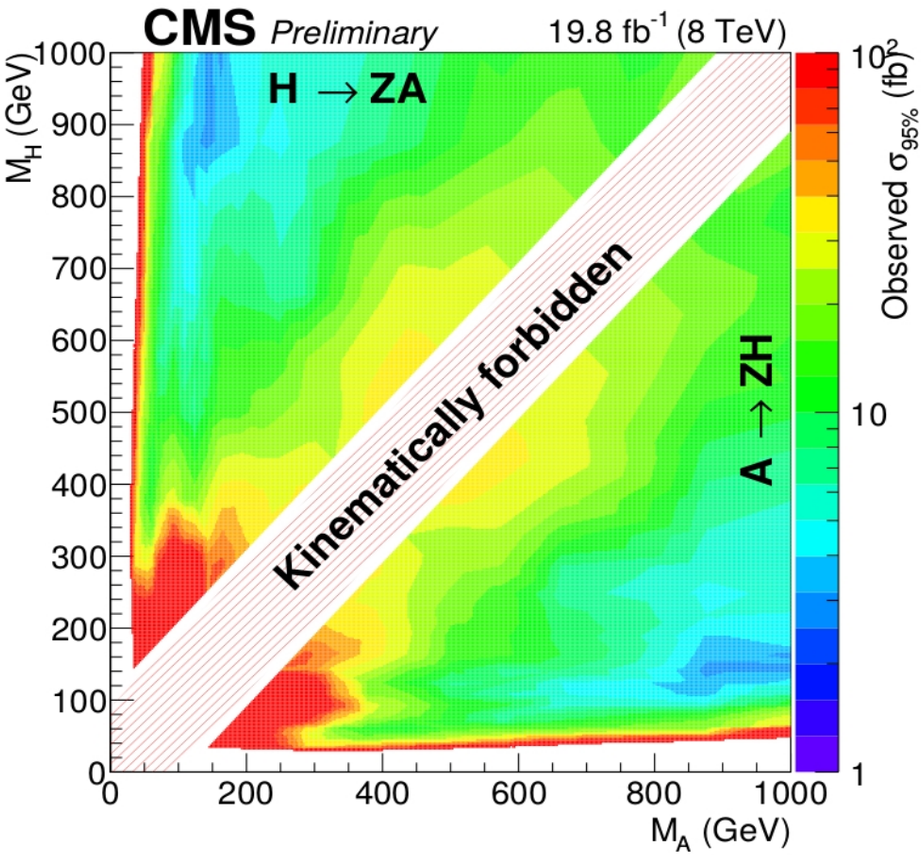
$|m_{A_0} - m_{H_0}| \sim v \quad (> m_z)$

LISA & LHC

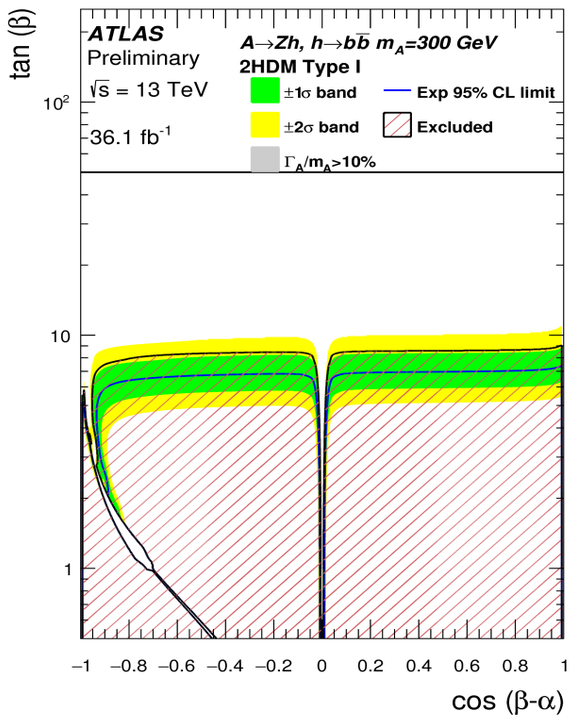
1) SCENARIOS/MODELS WITHIN LHC REACH...

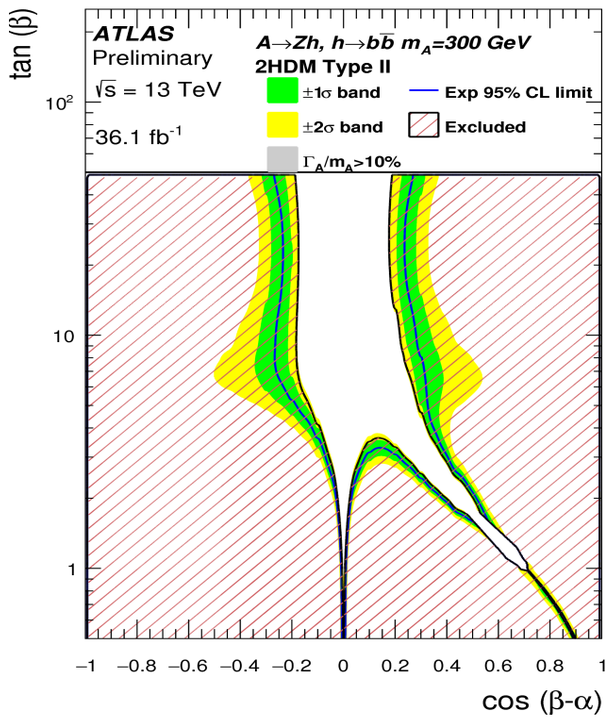
2HDM

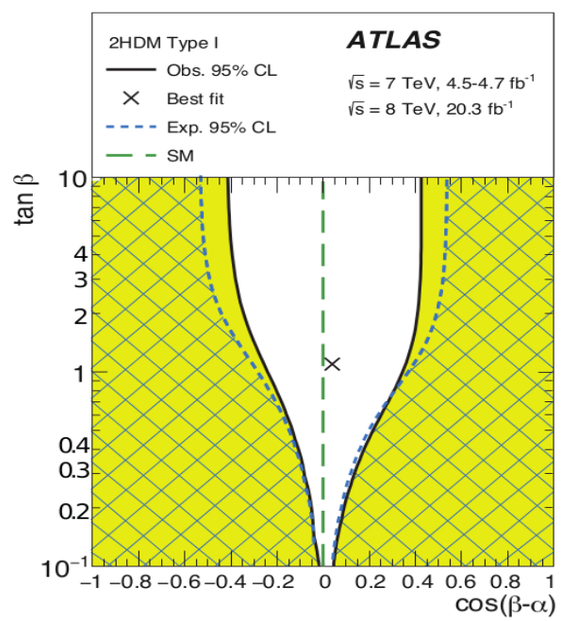
CMS-PAS-HIG-15-001 (1603.02991)

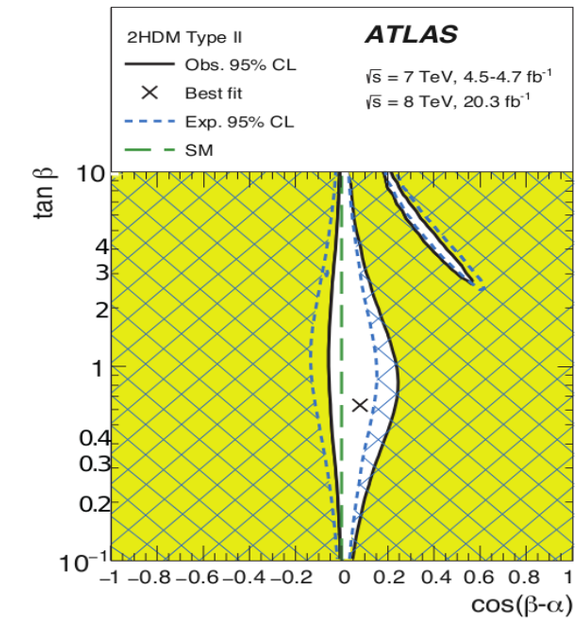


New LHC 13 TeV results expected end of 2017





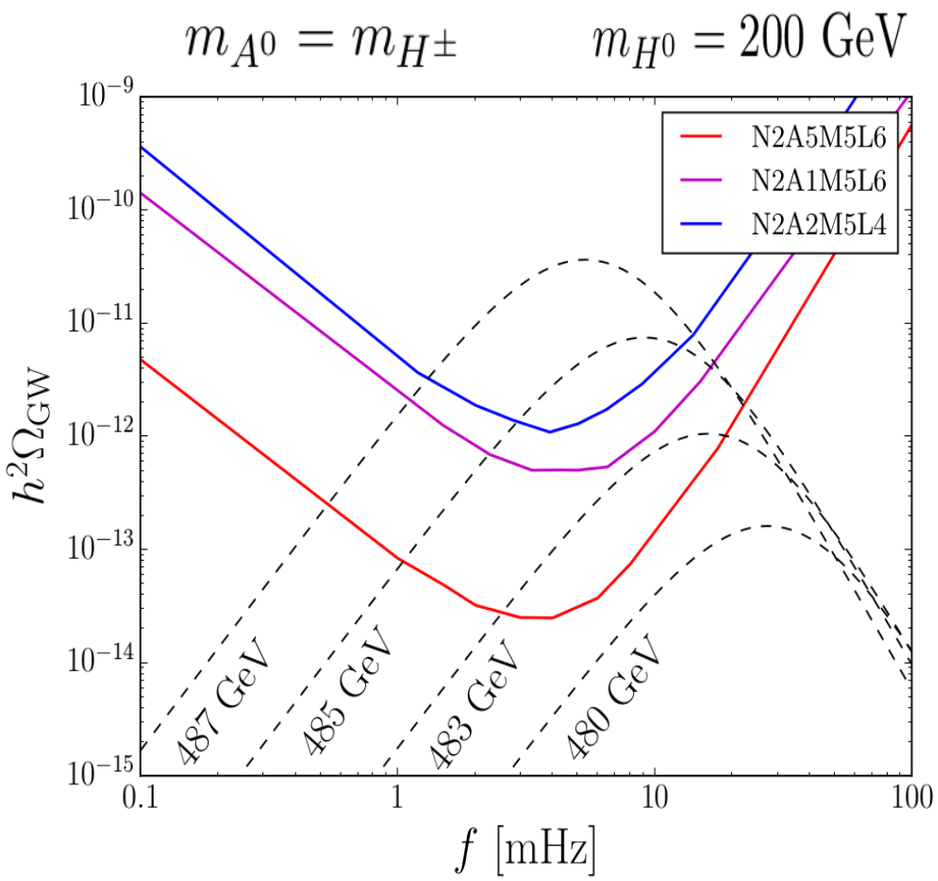




LISA & LHC

2HDM, PT & GW

m_{A^0} [GeV]	T_n	v_n/T_n	α_n	β/H_*	v_w
450	83.665	2.408	0.024	3273.41	0.15
460	76.510	2.770	0.035	2282.42	0.20
480	57.756	3.983	0.104	755.62	0.30
483	53.549	4.349	0.140	557.77	0.35
485	50.297	4.668	0.179	434.80	0.45
487	46.270	5.120	0.250	306.31	$\approx c_s$



Dorsch, Huber, Konstandin, No, JCAP ***1705*** *(2017) 052*

LISA & LHC

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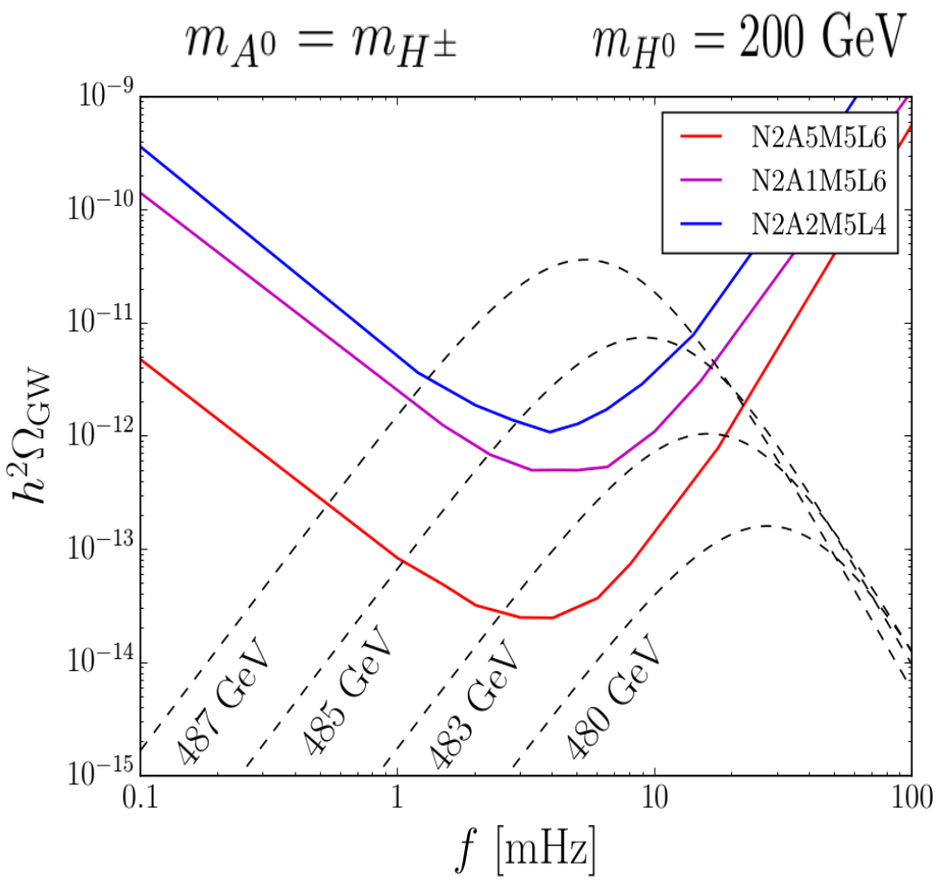


*Dorsch, Huber, Konstandin, No, JCAP **1705** (2017) 052*

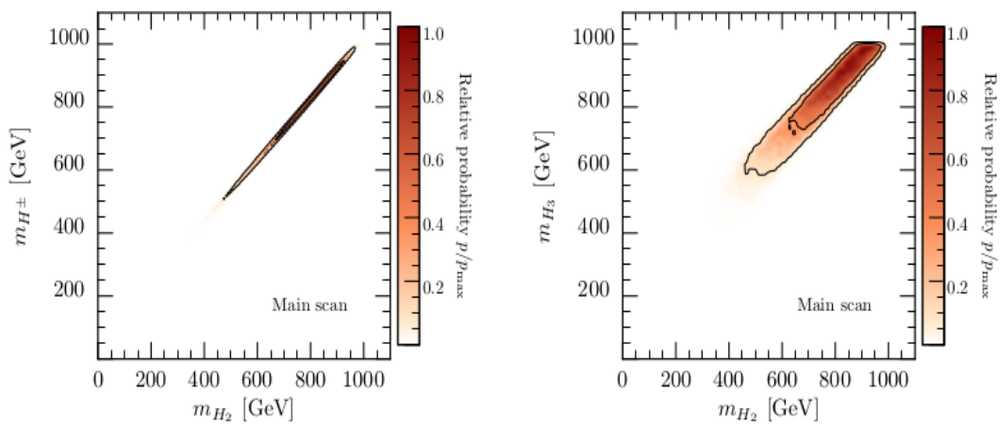
➔ 2HDM could yield observable GW signal @ LISA

➔ … yet LHC likely to probe viable region

➔ Further study needed & underway

2HDM Lattice Studies

Tenkanen, Weir, Work in Progress



Haarr, Kvellestad, Petersen, 1611.05757

LISA & LHC

2) SCENARIOS/MODELS FOR WHICH LHC STRUGGLES... BUT NOT SO LISA!

SINGLETS (e.g. NMSSM, Higgs Portal...)

LISA & LHC

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SINGLETS (e.g. NMSSM, Higgs Portal...)

The xSM

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

Higgs Portal

Higgs - Singlet Mixing

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

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

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

(m_1 = 125 GeV)

(h_1 couplings to SM as in SM)

h_2 inherits its couplings to SM via Mixing

LISA & LHC

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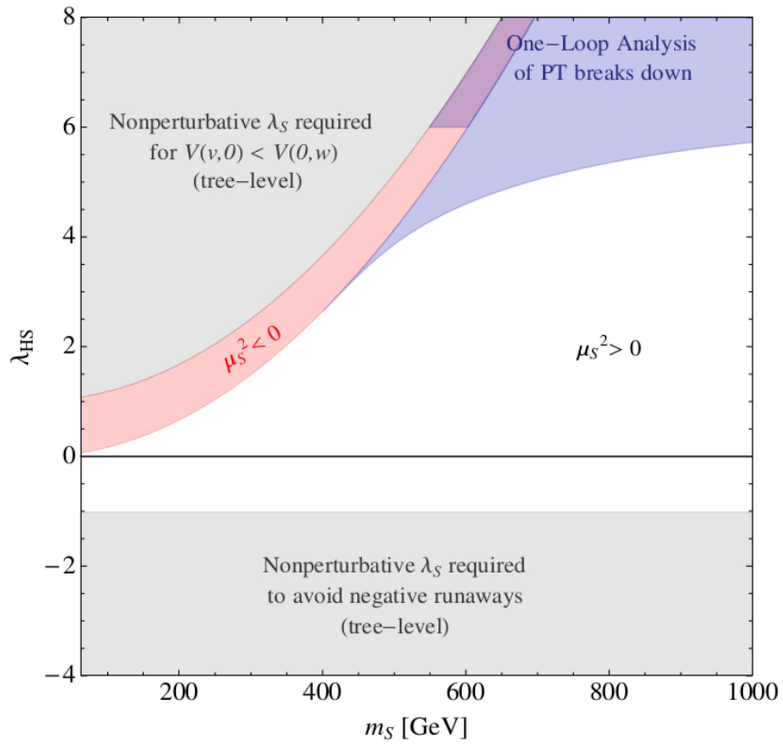
... But Strong EWPT Possible for No Mixing

Espinosa, Konstandin, Riva, Nucl. Phys. ***B854*** *(2012) 592*



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

LISA & LHC

2) SCENARIOS/MODELS FOR WHICH LHC STRUGGLES... BUT NOT SO LISA!

SINGLETS (e.g. NMSSM, Higgs Portal...)

What Can LHC Do?

⇨ Higgs Coupling Measurements $\sin\theta < 0.25$ (95% C.L.)
HL-LHC

(also, EW Precision Observables)

$(\sin\theta,\ m_2)$

LISA & LHC

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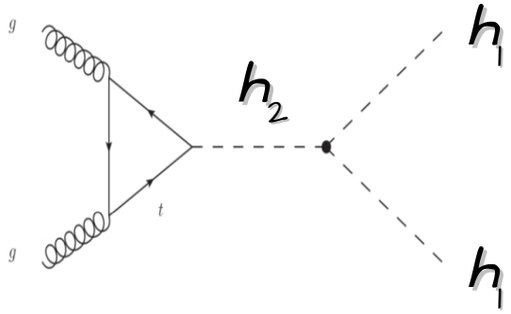
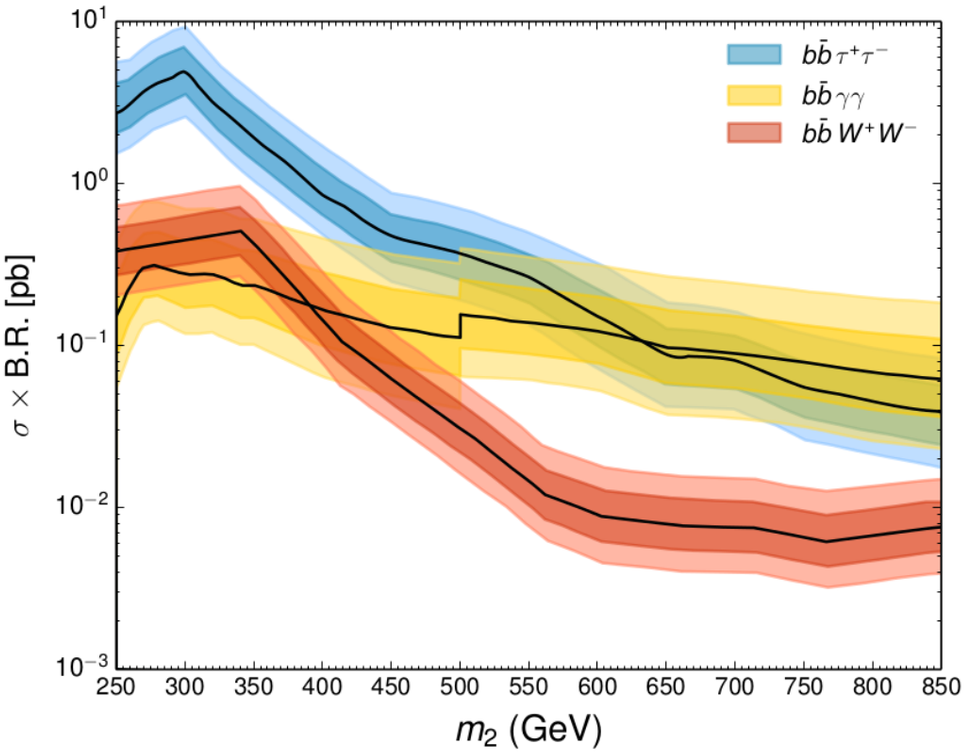


⇨ $m_2 > 250$ GeV ⇨ RESONANT HIGGS PAIR PRODUCTION

Dolan, Englert, Spannowsky, Phys. Rev. ***D87*** *(2013) 5, 055002*
No, Ramsey-Musolf, Phys. Rev. ***D89*** *(2014) 095031*
Chen, Dawson, Lewis, Phys. Rev. ***D91*** *(2015) 035015*

$$\lambda_{211} = \frac{s_\theta}{2}\left[c_\theta^4(m_2^2 - m_1^2)/v_0 + 2v_0(a_2 - 3\lambda)c_\theta^2 - (a_1 + 2a_2x_0 - 2b_3 - 6b_4x_0)c_\theta s_\theta - a_2v_0s_\theta^2\right]$$

$$\Gamma_{h_2\to h_1h_1} = \frac{\lambda_{211}^2\sqrt{1 - 4\,m_1^2/m_2^2}}{8\pi m_2}$$



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

LISA & LHC

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HL-LHC

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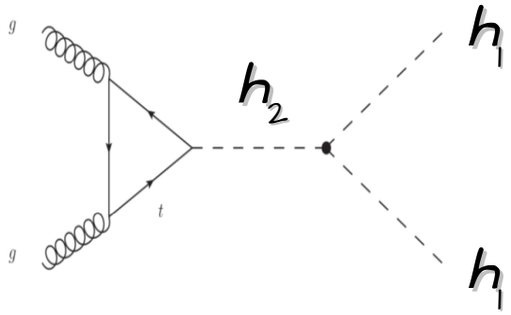
$(\sin\theta, m_2)$



*Dolan, Englert, Spannowsky, Phys. Rev. **D87** (2013) 5, 055002*
*No, Ramsey-Musolf, Phys. Rev. **D89** (2014) 095031*
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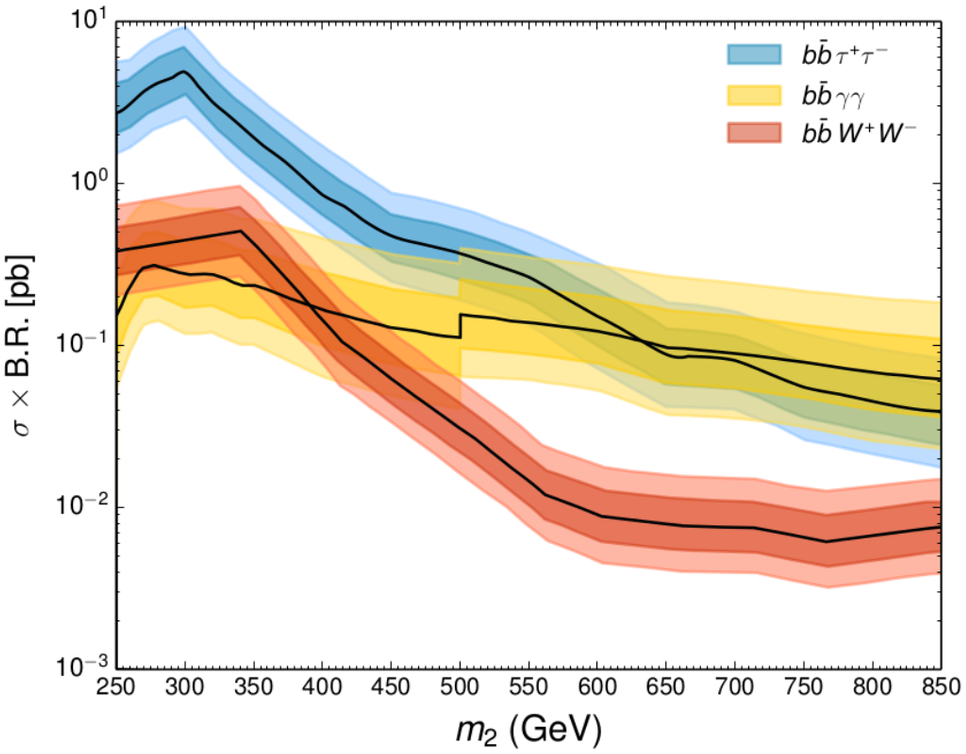

$$\lambda_{211} = \frac{s_\theta}{2}\left[c_\theta^4(m_2^2 - m_1^2)/v_0 + 2v_0(a_2 - 3\lambda)c_\theta^2 - (a_1 + 2a_2x_0 - 2b_3 - 6b_4x_0)c_\theta s_\theta - a_2v_0s_\theta^2\right]$$

$$\Gamma_{h_2\to h_1h_1} = \frac{\lambda_{211}^2\sqrt{1 - 4\,m_1^2/m_2^2}}{8\pi m_2}$$

But Not Yet Clear What Impact on PT and GW @ LISA Is

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

LISA & LHC

2) SCENARIOS/MODELS FOR WHICH LHC STRUGGLES... BUT NOT SO LISA!

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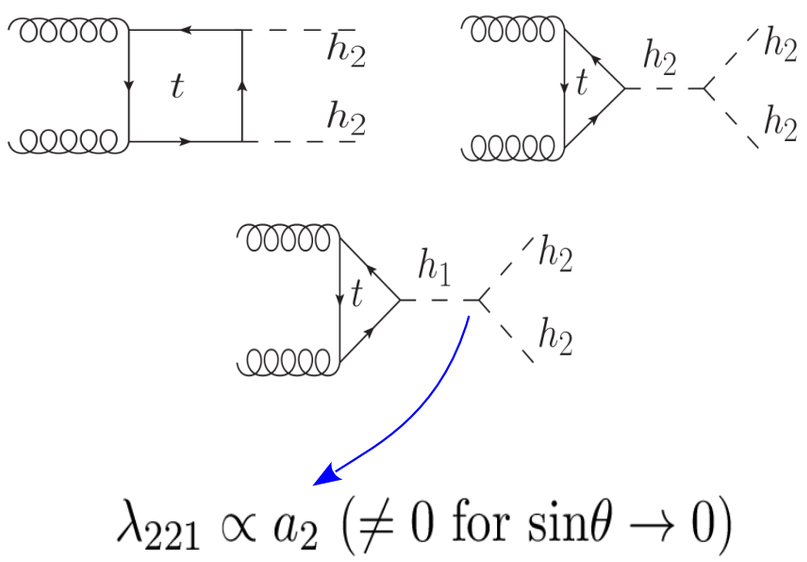
What Can LHC Do?

⇨ Higgs Coupling Measurements

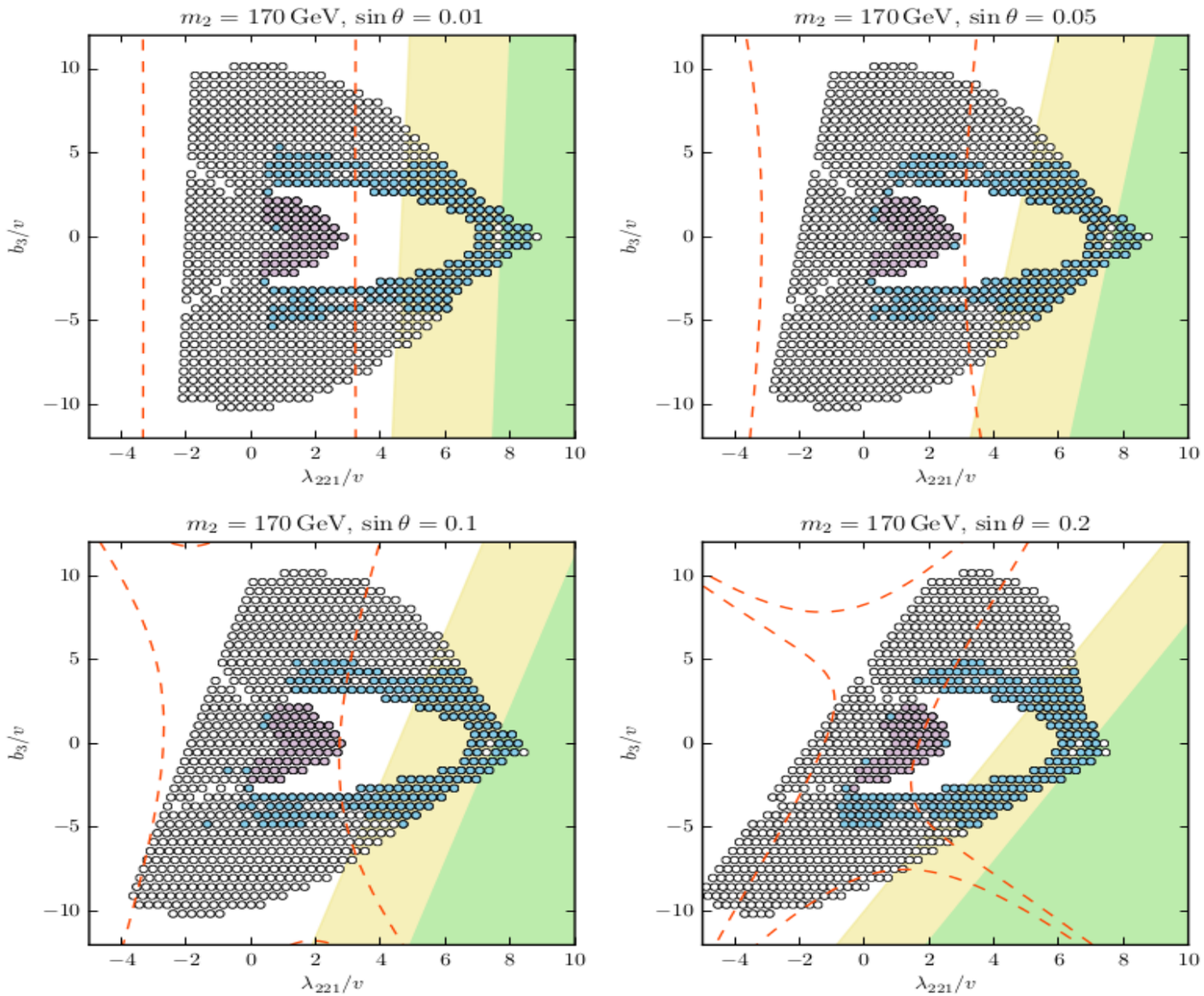
$$\sin\theta < 0.25 \ (95\%\ \text{C.L.})$$

⇨ $m_2 < 250$ GeV



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

First Step towards LHC Reach on Singlet PT



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

LISA & LHC

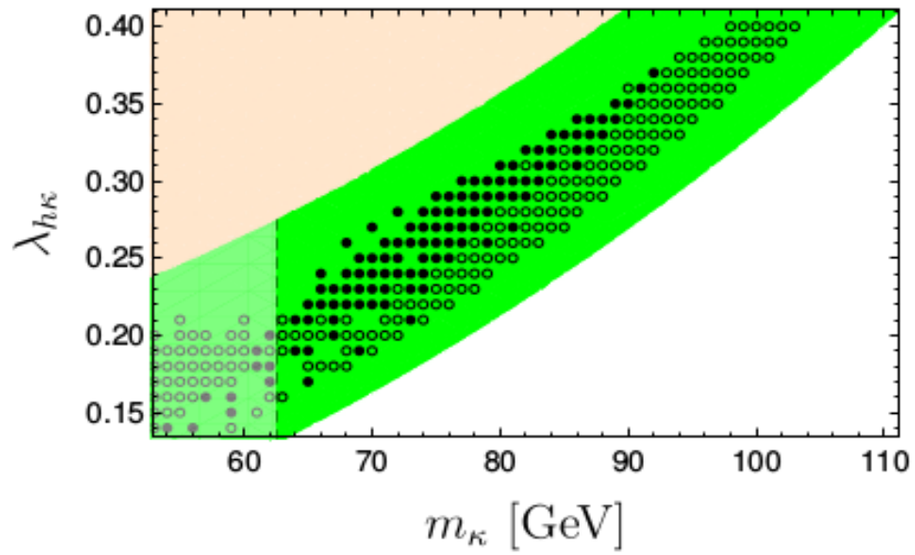
2) SCENARIOS/MODELS FOR WHICH LHC STRUGGLES... BUT NOT SO LISA!

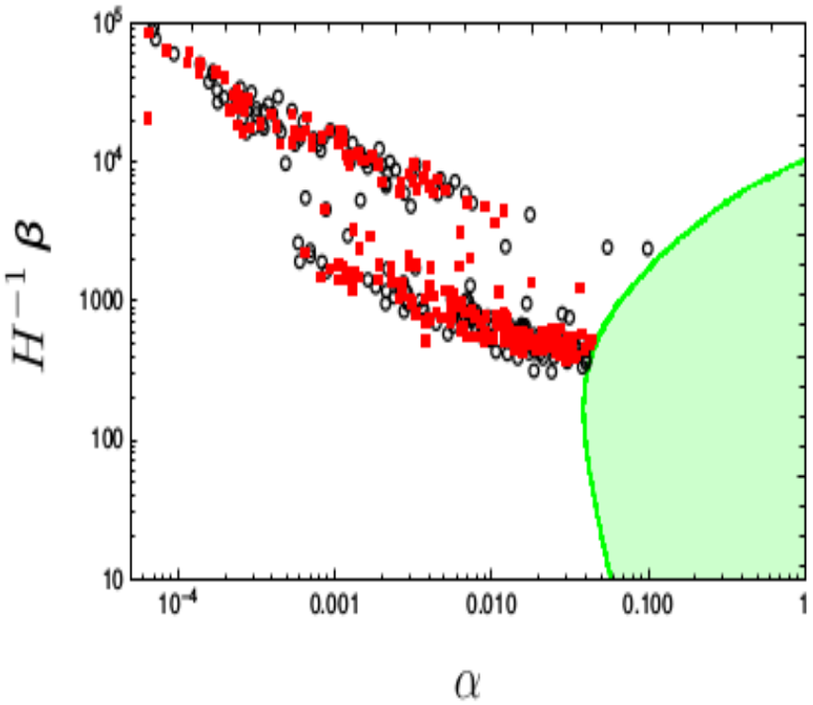
SINGLETS (e.g. NMSSM, Higgs Portal...)

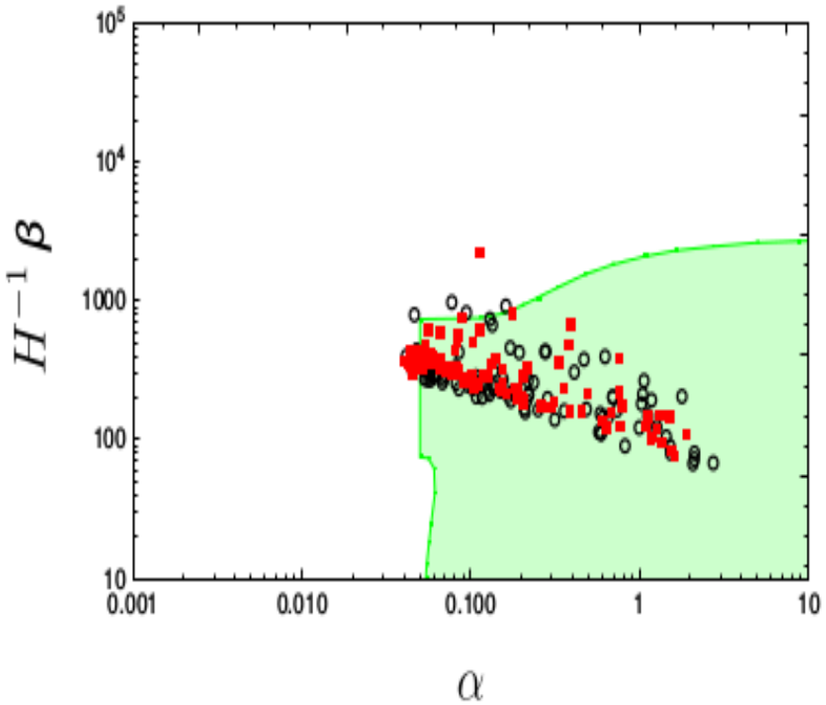
What Can LISA Do?

$$V = -\frac{1}{2}\mu_h^2 h^2 + \cancel{\frac{1}{2}\mu_\eta^2 \eta^2} + \frac{1}{2}\mu_\kappa^2 \kappa^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{4}\lambda_\kappa \kappa^4 + \cancel{\frac{1}{4}\lambda_{h\eta} h^2 \eta^2} + \frac{1}{4}\lambda_{h\kappa} h^2 \kappa^2$$

Chala, Nardini, Sobolev, Phys. Rev. ***D94*** *(2016) 055006*







LISA & LHC

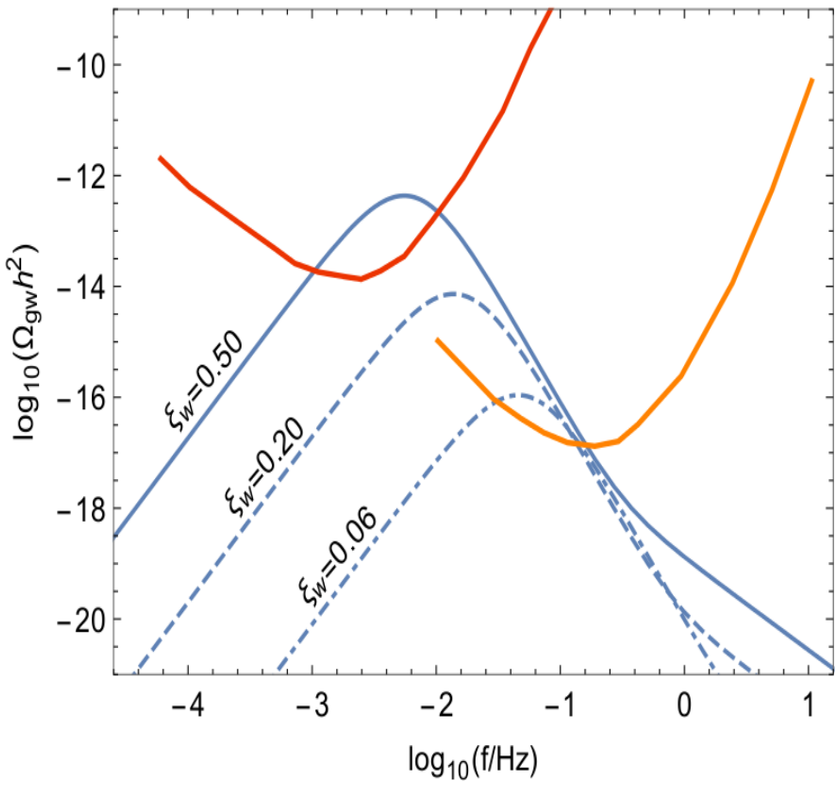
2) SCENARIOS/MODELS FOR WHICH LHC STRUGGLES... BUT NOT SO LISA!

SINGLETS (e.g. NMSSM, Higgs Portal...)

What Can LISA Do?

xSM

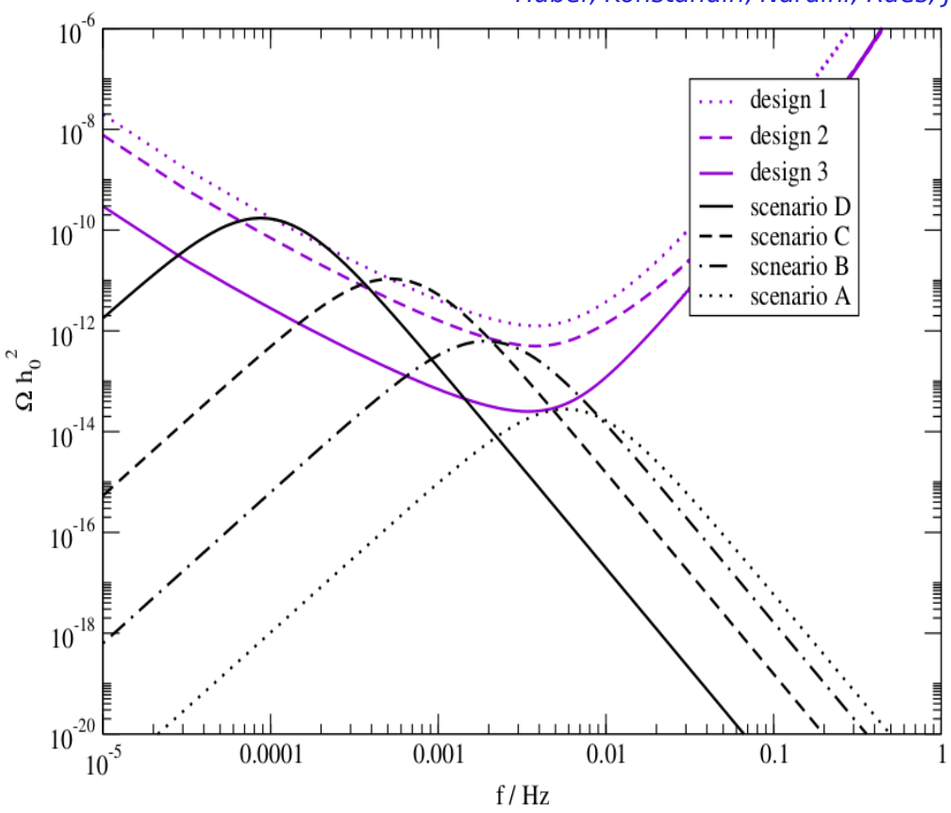
Vaskonen, Phys. Rev. ***D95*** *(2017) 123515*



$$\lambda_{hs} = 0.785 \quad m_s = 138.7 \text{ GeV}$$

NMSSM

Huber, Konstandin, Nardini, Rues, JCAP ***1603*** *(2016) 036*



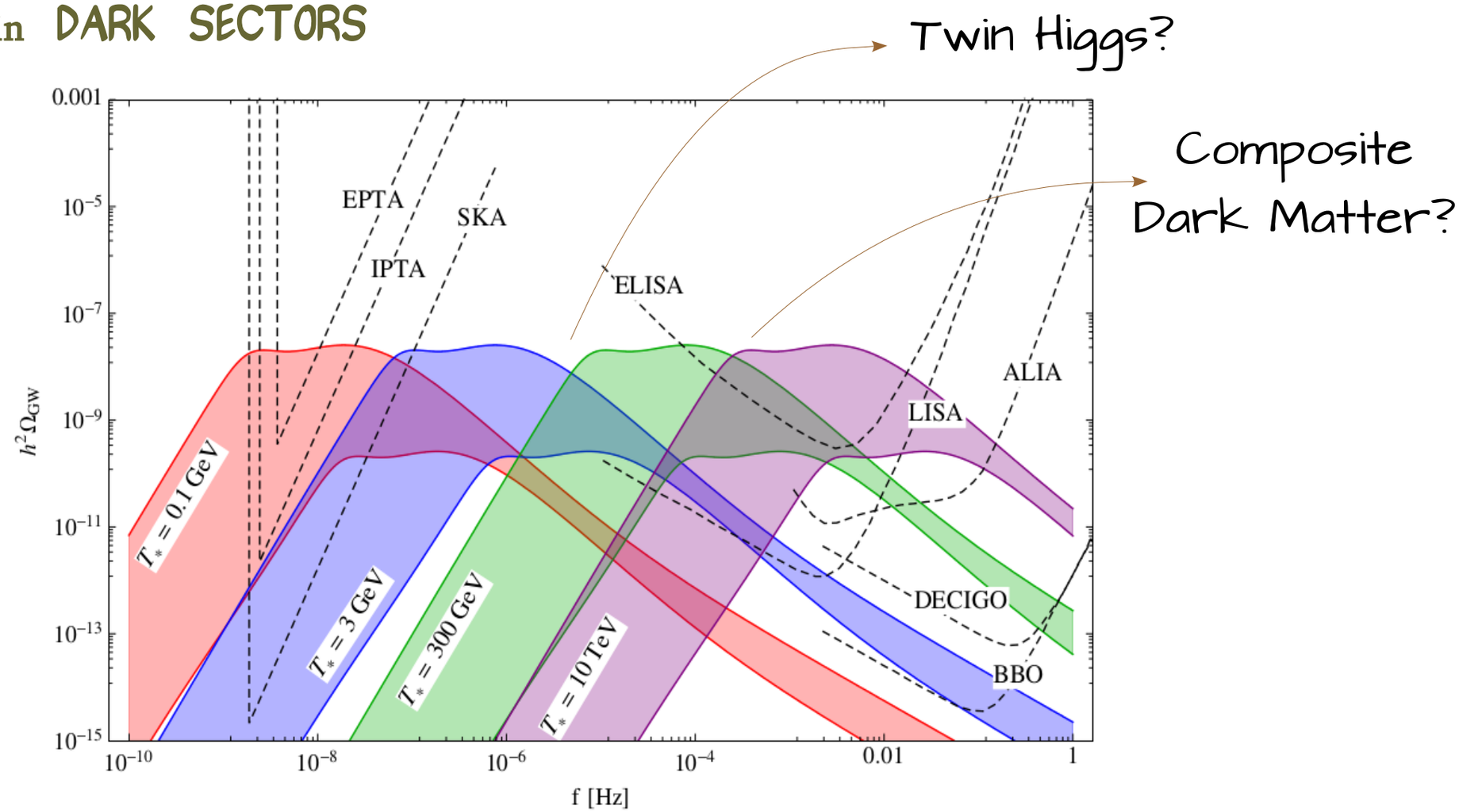
1-loop	A - D
m_{h_1}	91
m_{h_2}	125.6
$\sin^2\gamma$	10^{-3}

	A	B	C	D
T_n [GeV]	112.3	94.7	82.5	76.4
α	0.037	0.066	0.105	0.143
β/H	277	105.9	33.2	6.0
$v_h(T_n)/T_n$	1.89	2.40	2.83	3.12

LISA & LHC

3) SCENARIOS/MODELS "JUST" FOR LISA

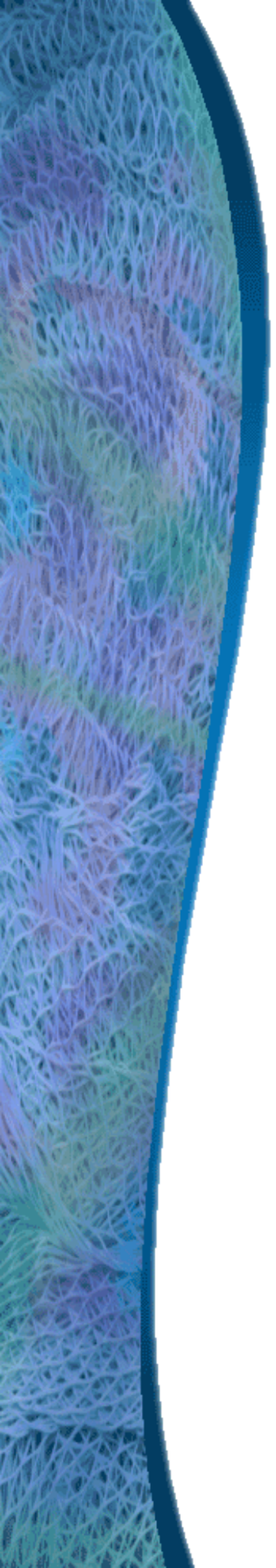
PT in DARK SECTORS



Schwaller, Phys. Rev. Lett. ***115*** *(2015) 181101*

Just to emphasize LISA could probe dynamics of sectors weakly/feebly coupled to SM


That's all Folks!




KEEP
CALM
AND
BACKUP

LISA & LHC

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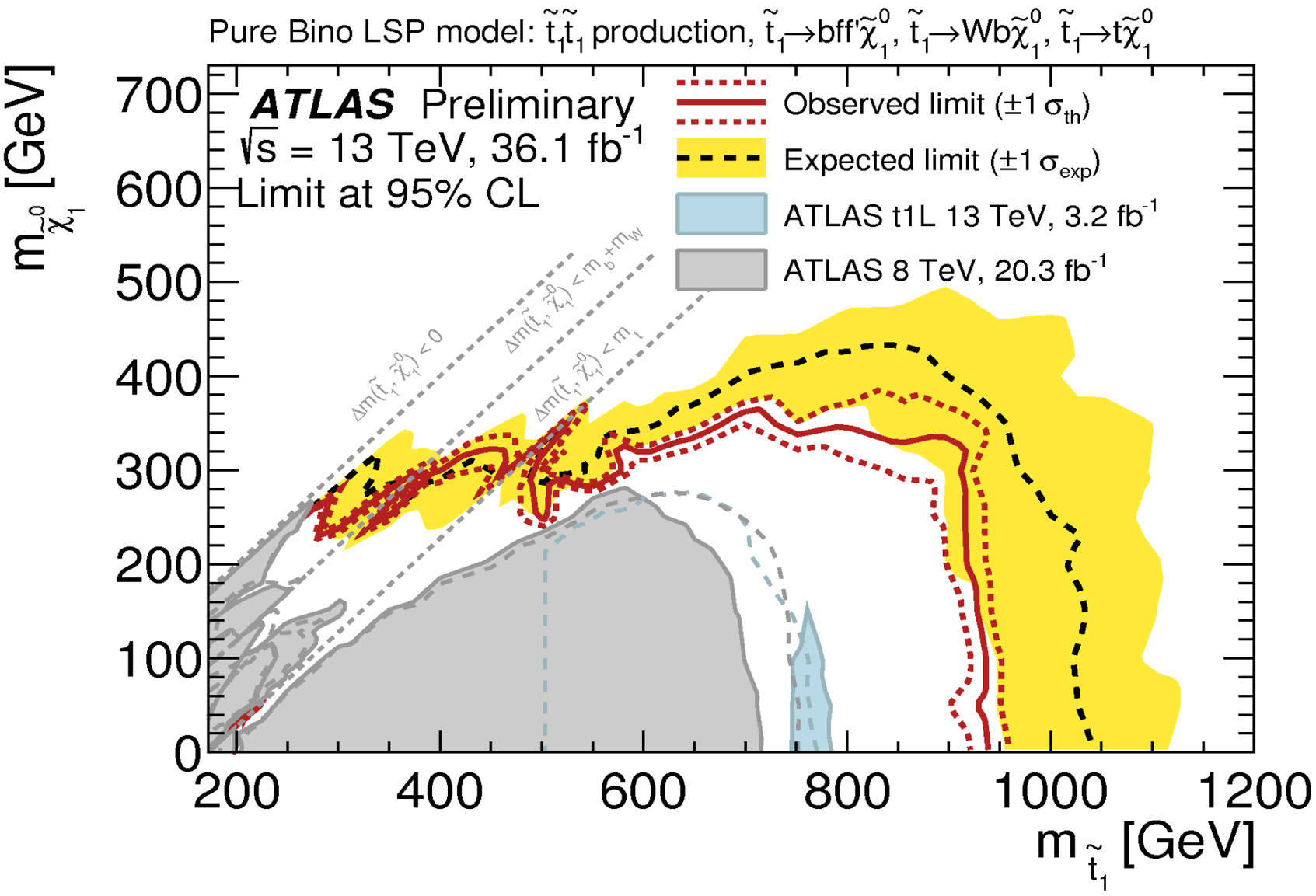
MSSM (light stop scenario)

(Generically, EWPT from new coloured states)

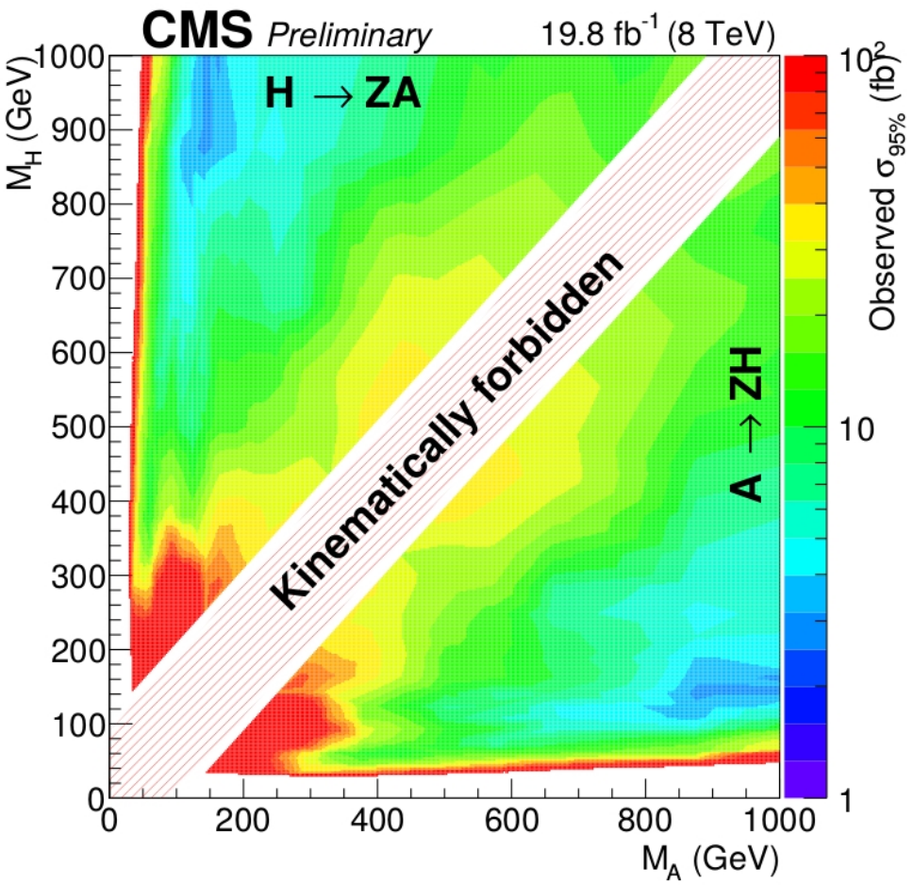
Direct Search for Light Stops

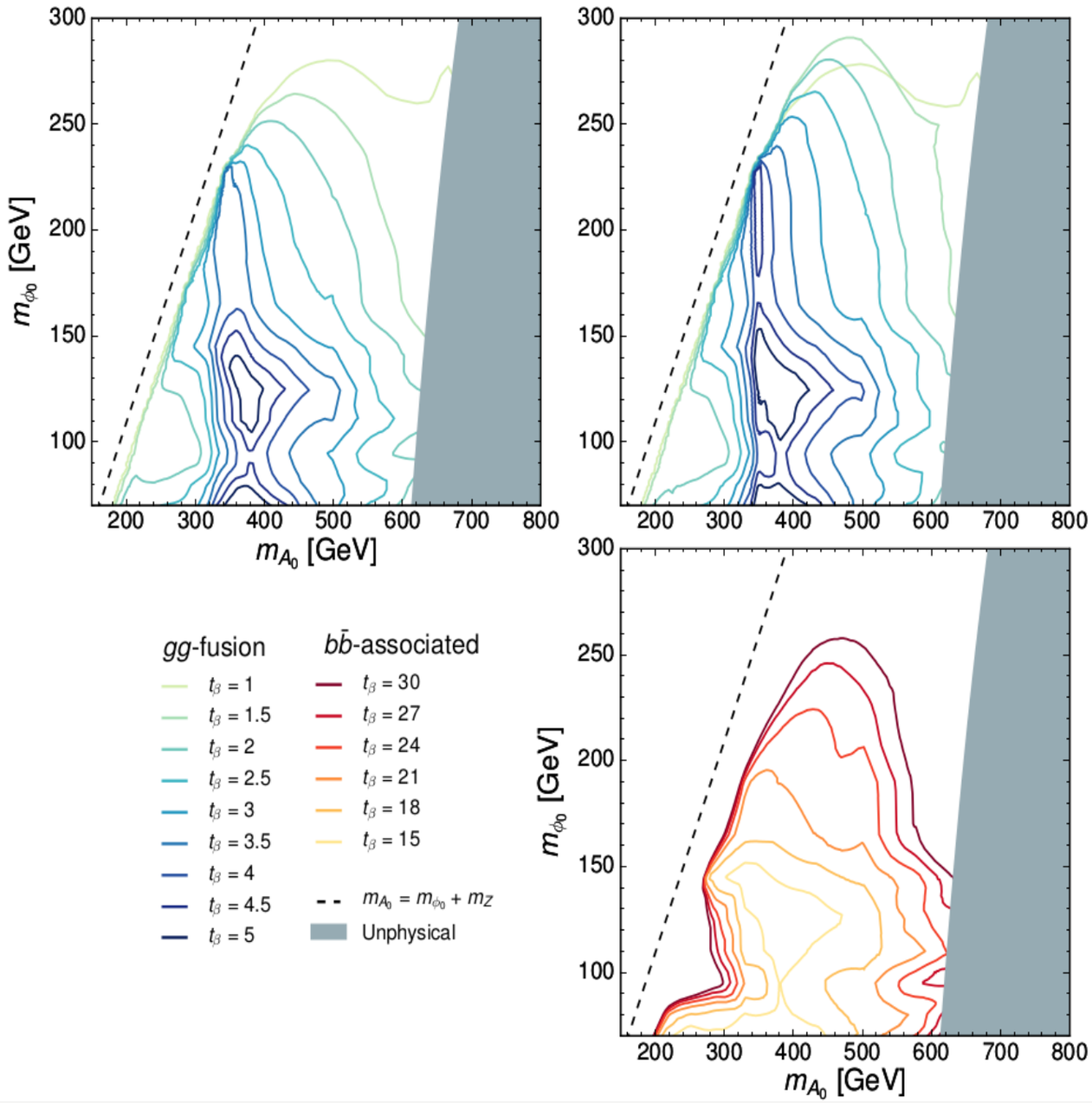


LISA & LHC

1) SCENARIOS/MODELS WITHIN LHC REACH...

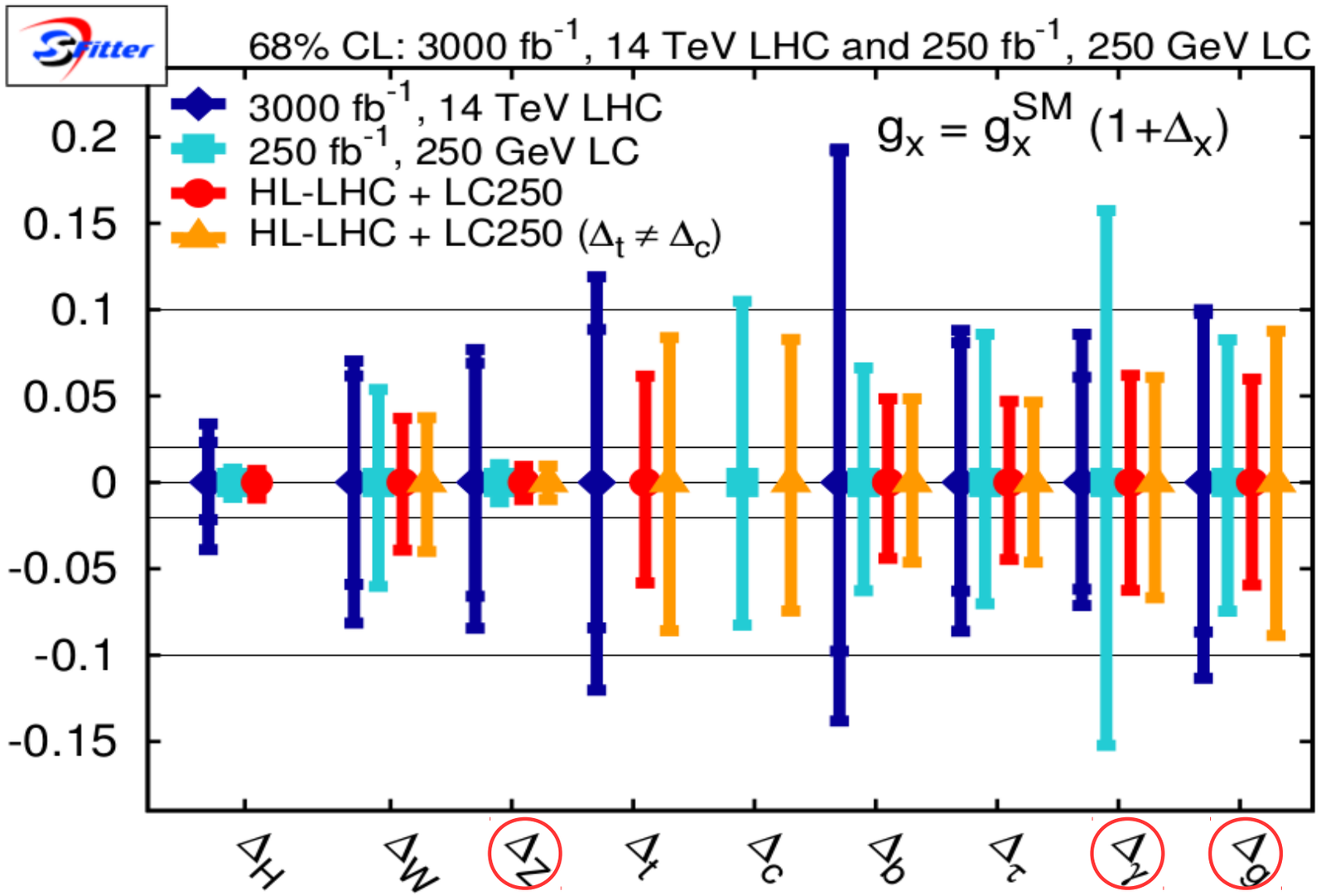
2HDM





Deviations in Higgs Couplings from SM

M. Klute, R. Lafaye, T. Plehn, M. Rauch, D. Zerwas, Europhys. Lett. ***101*** *(2013) 51001*



+ Higgs boson self-coupling $\lambda\, h^3$