University of Glasgow

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Di-Higgs phenomenology at the LHC and beyond

Queen Mary University London

23/01/2020

di-Higgs = more of the same ?

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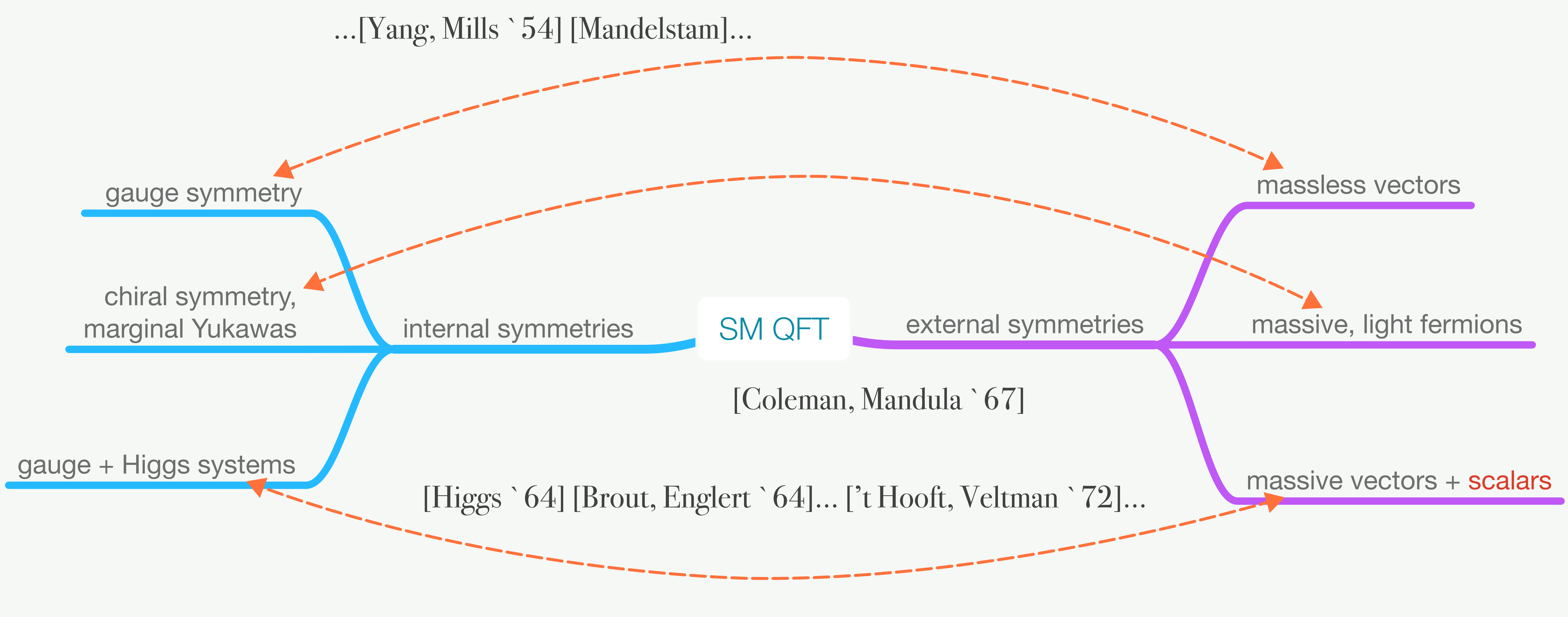

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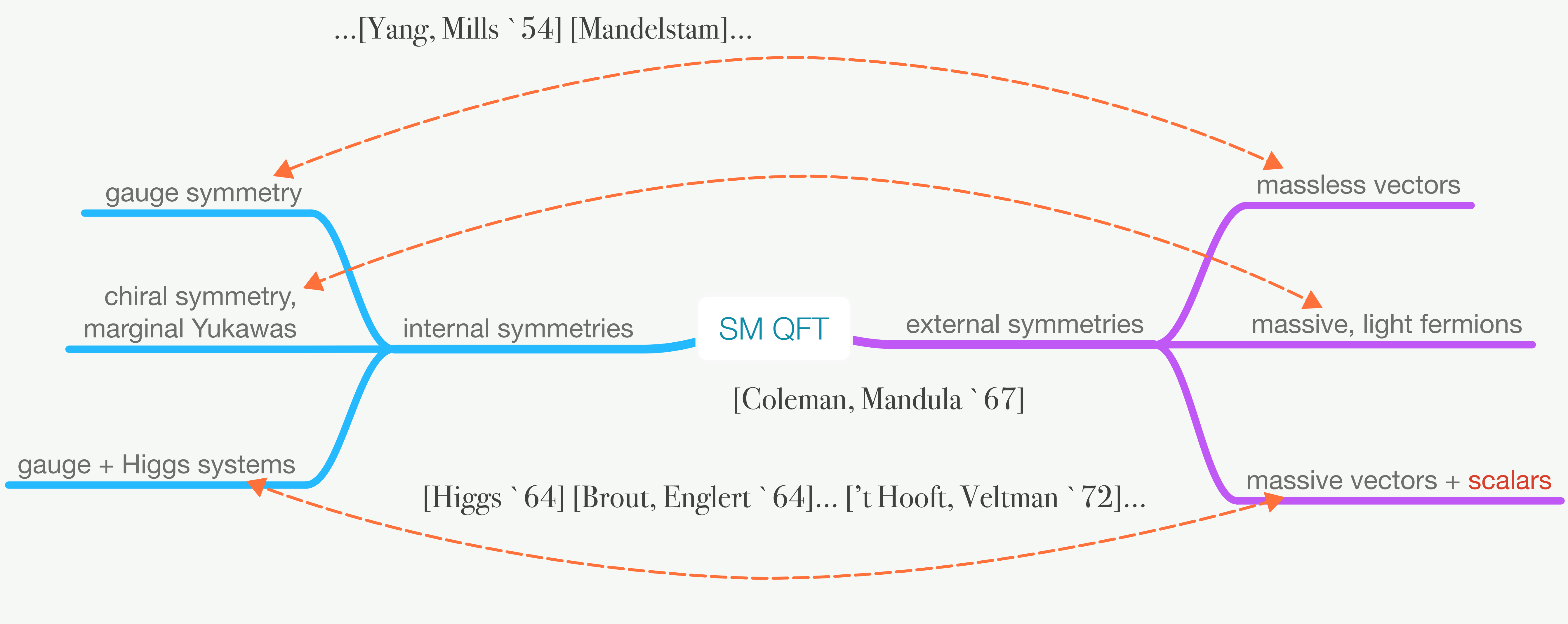
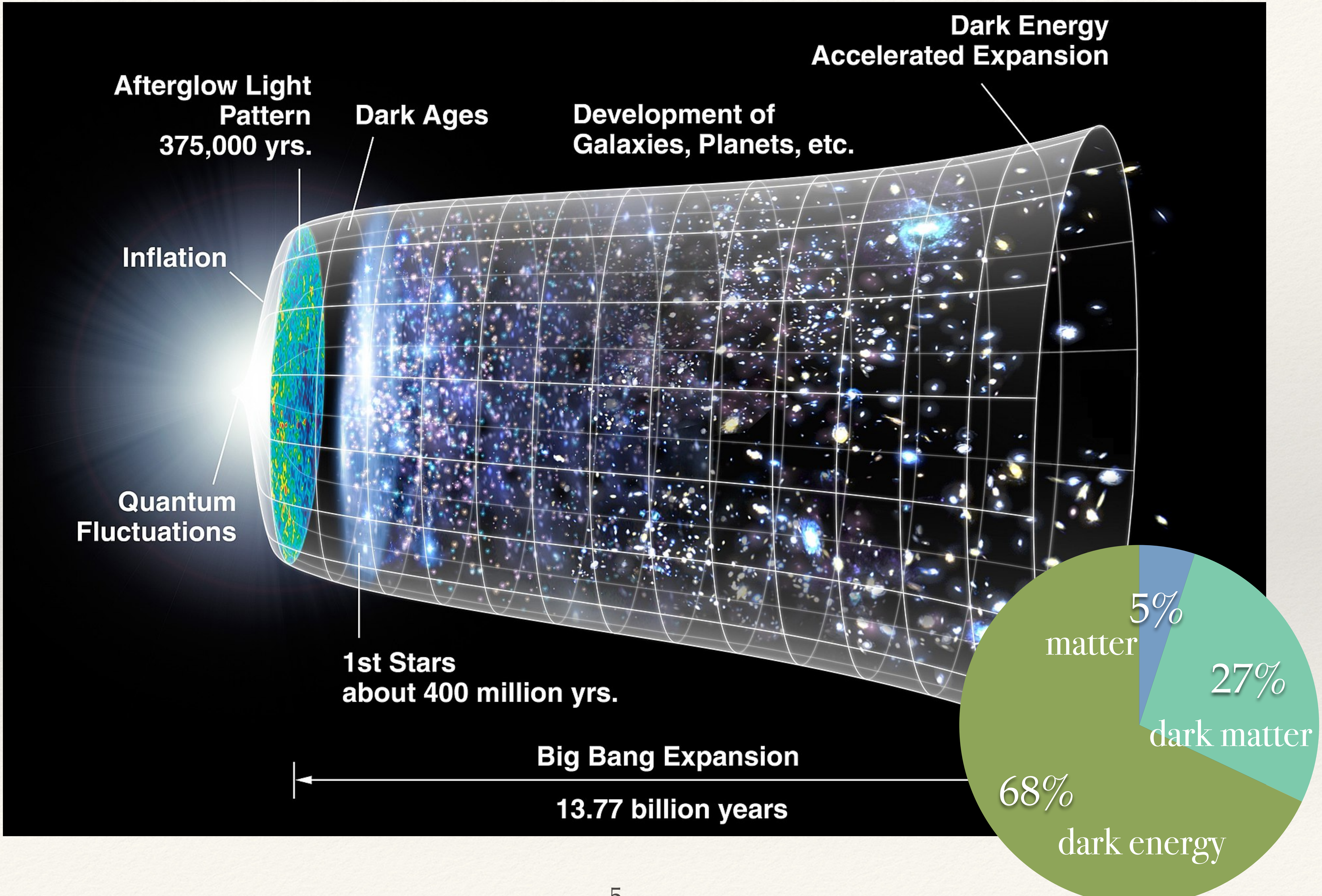


What is the precise mechanism that implements EW symmetry non-linearly?

di-Higgs = more of the same ?



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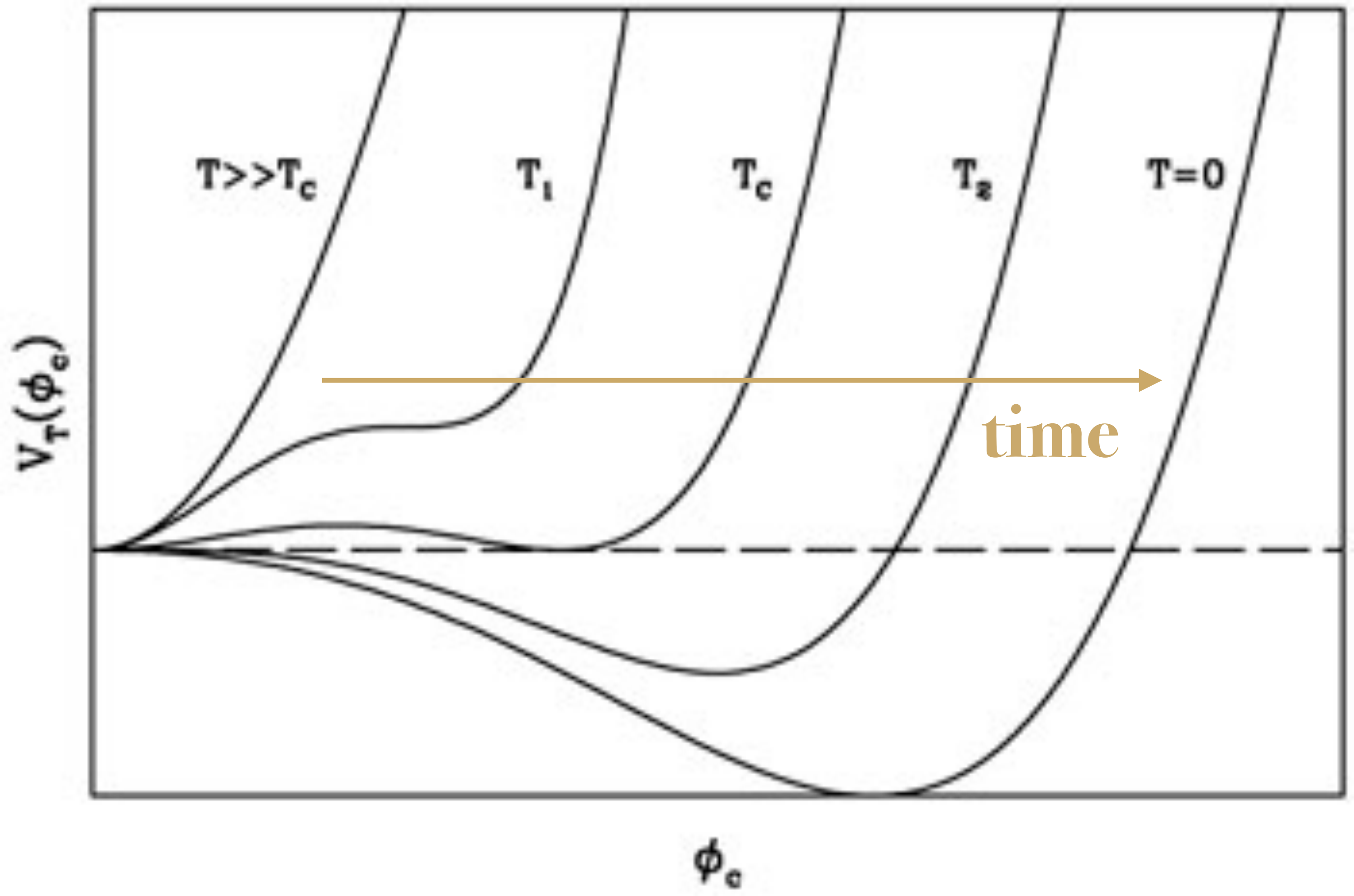

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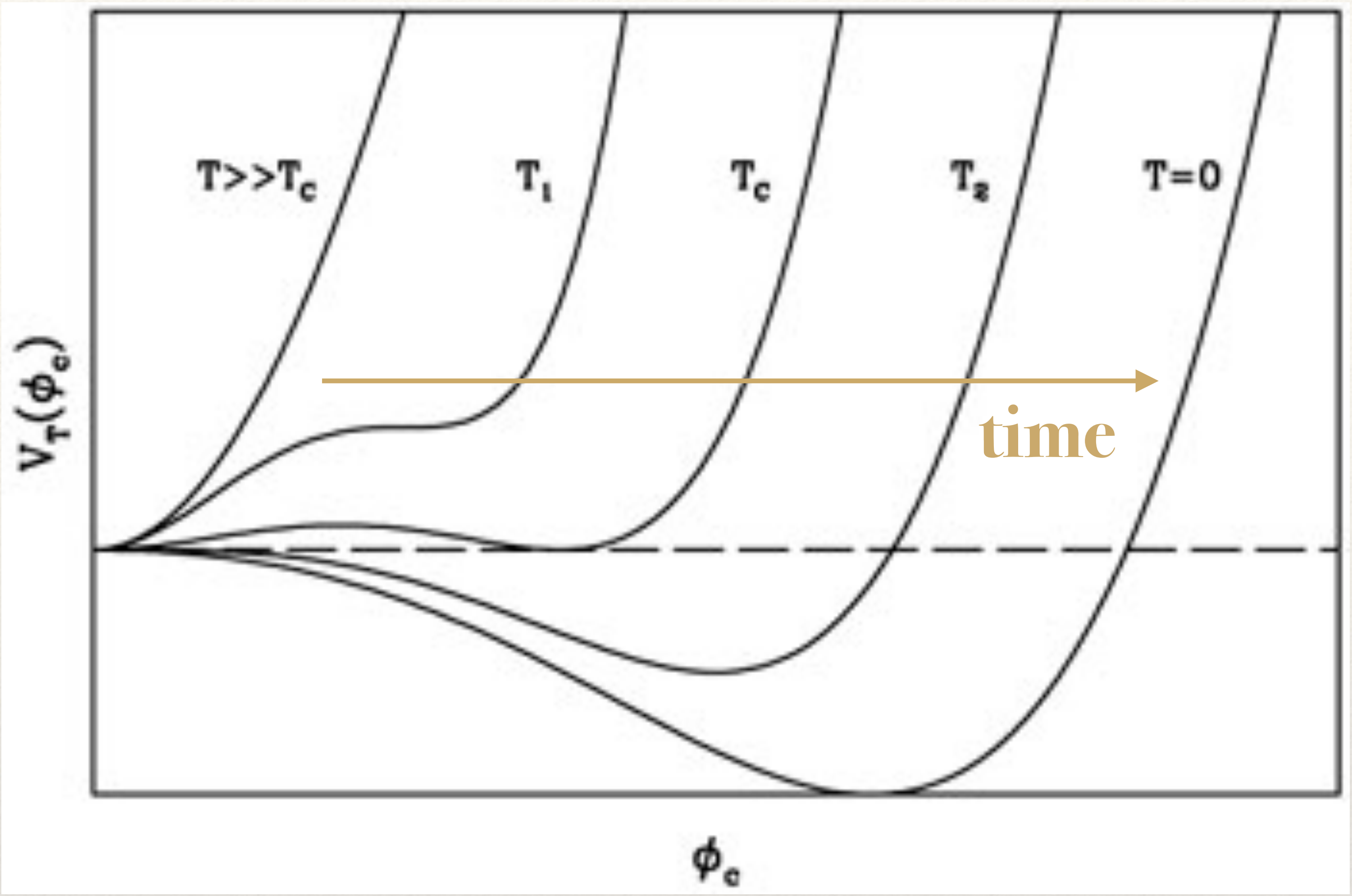
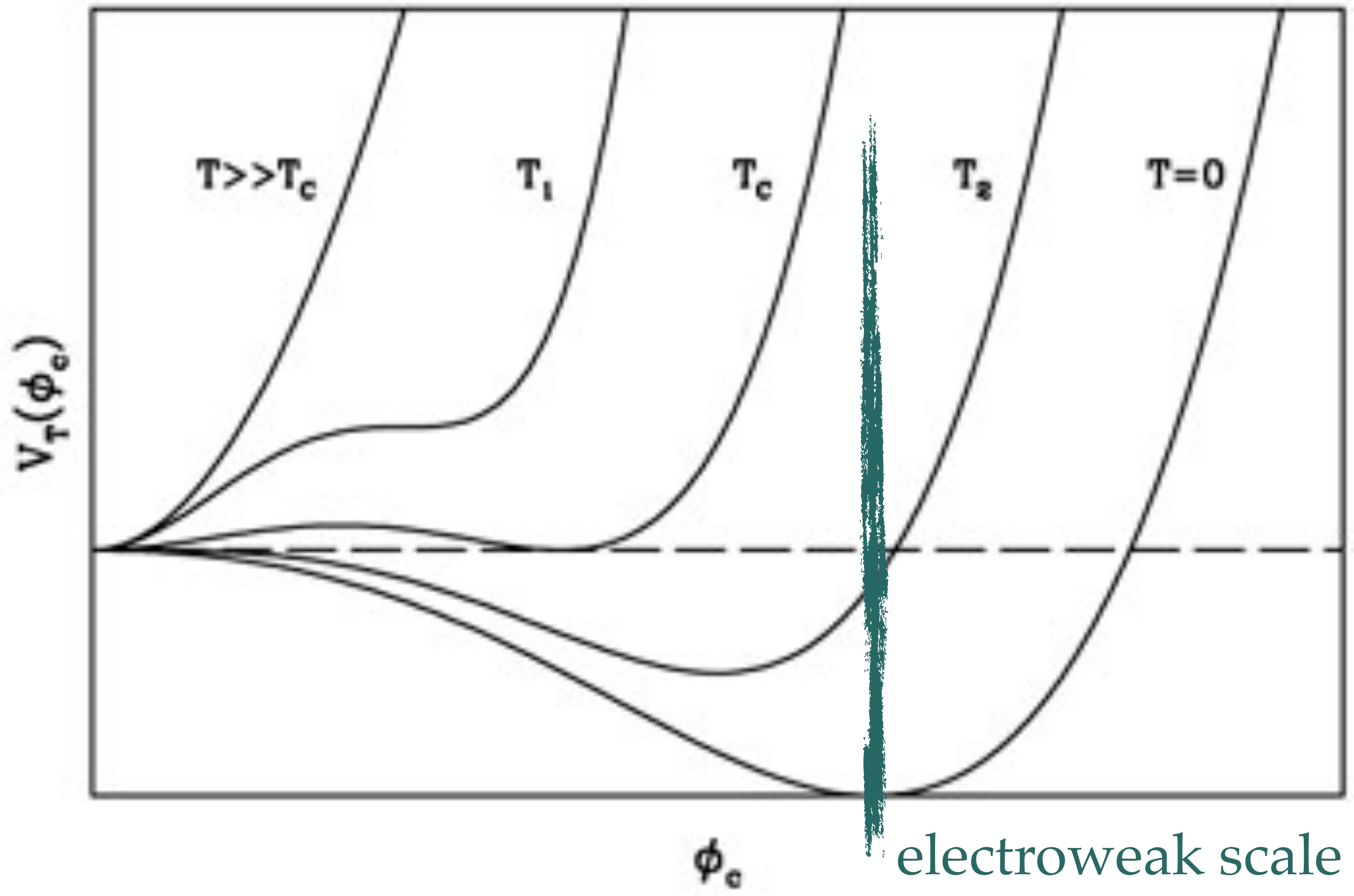


- early Universe: high temperature: symmetry intact (ϕ_{min}=0)
- Universe expands and cools: ϕ_{min}≠0 develops, ~~symmetry~~

di-Higgs = more of the same ?



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- Higgs physics fingerprints potential at low temperature

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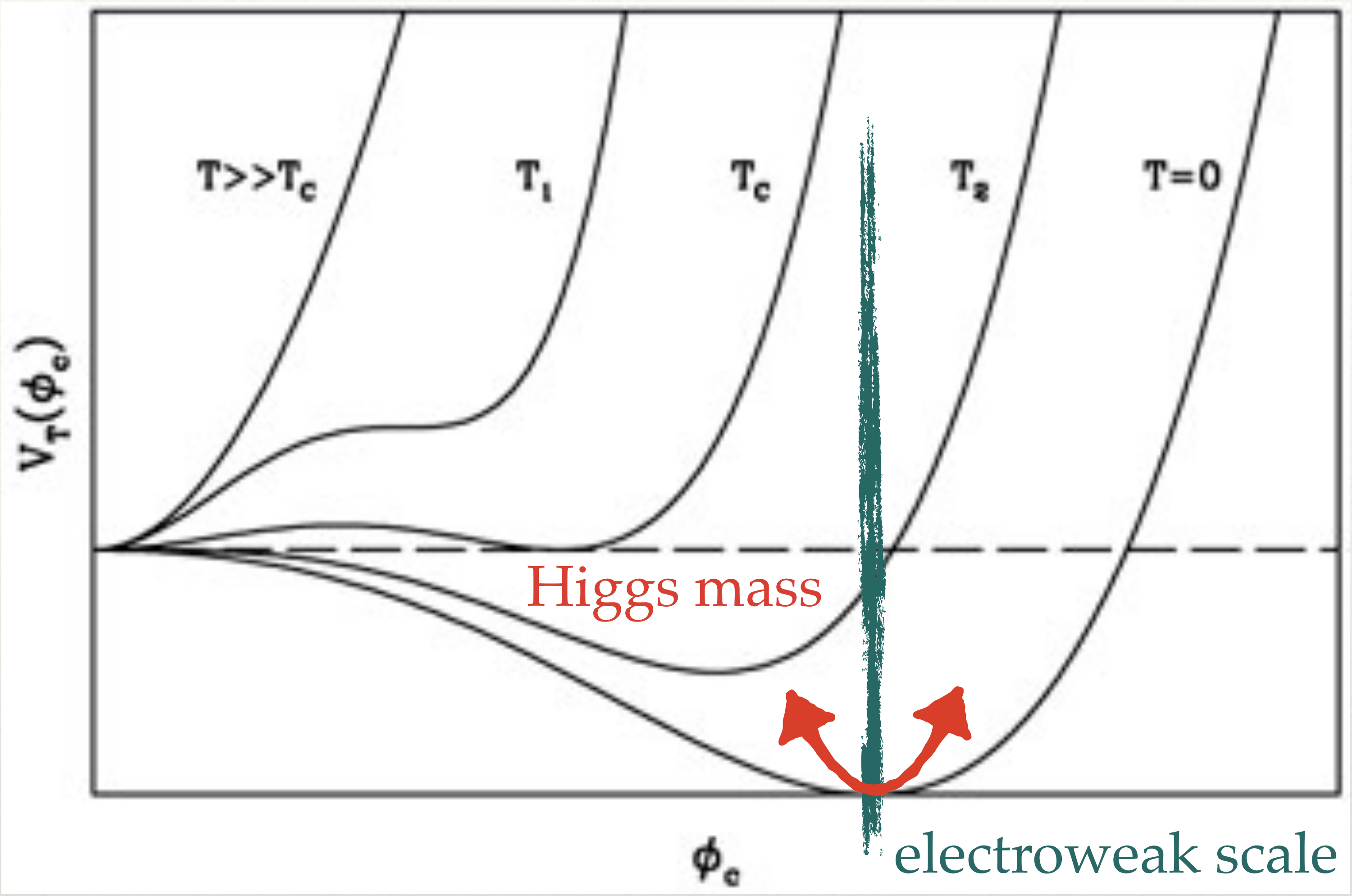

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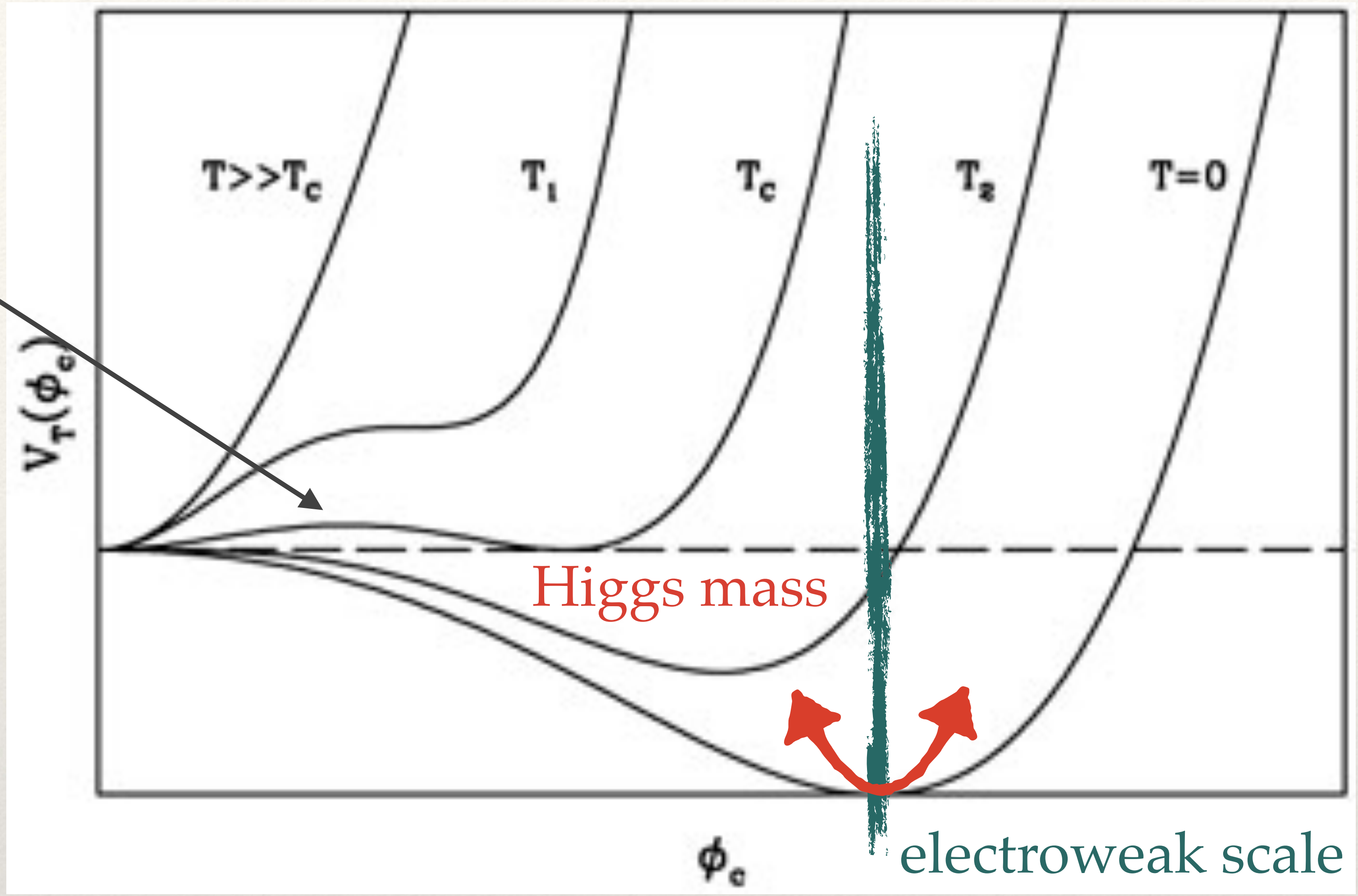
di-Higgs = more of the same ?

Sakharov

first order PT



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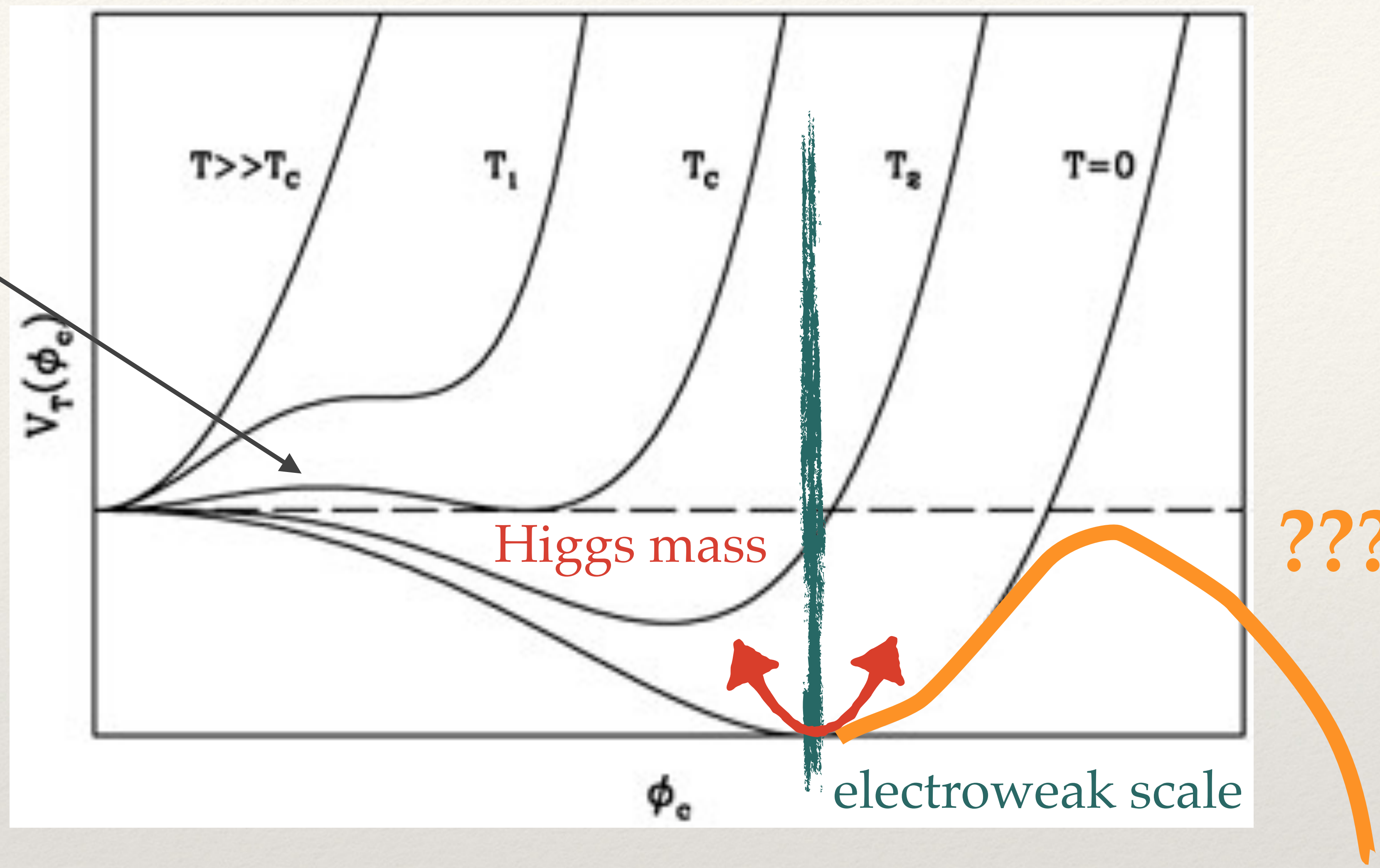

Higgs
self couplings…

- early Universe: high temperature: symmetry intact ($\phi_{min}=0$)
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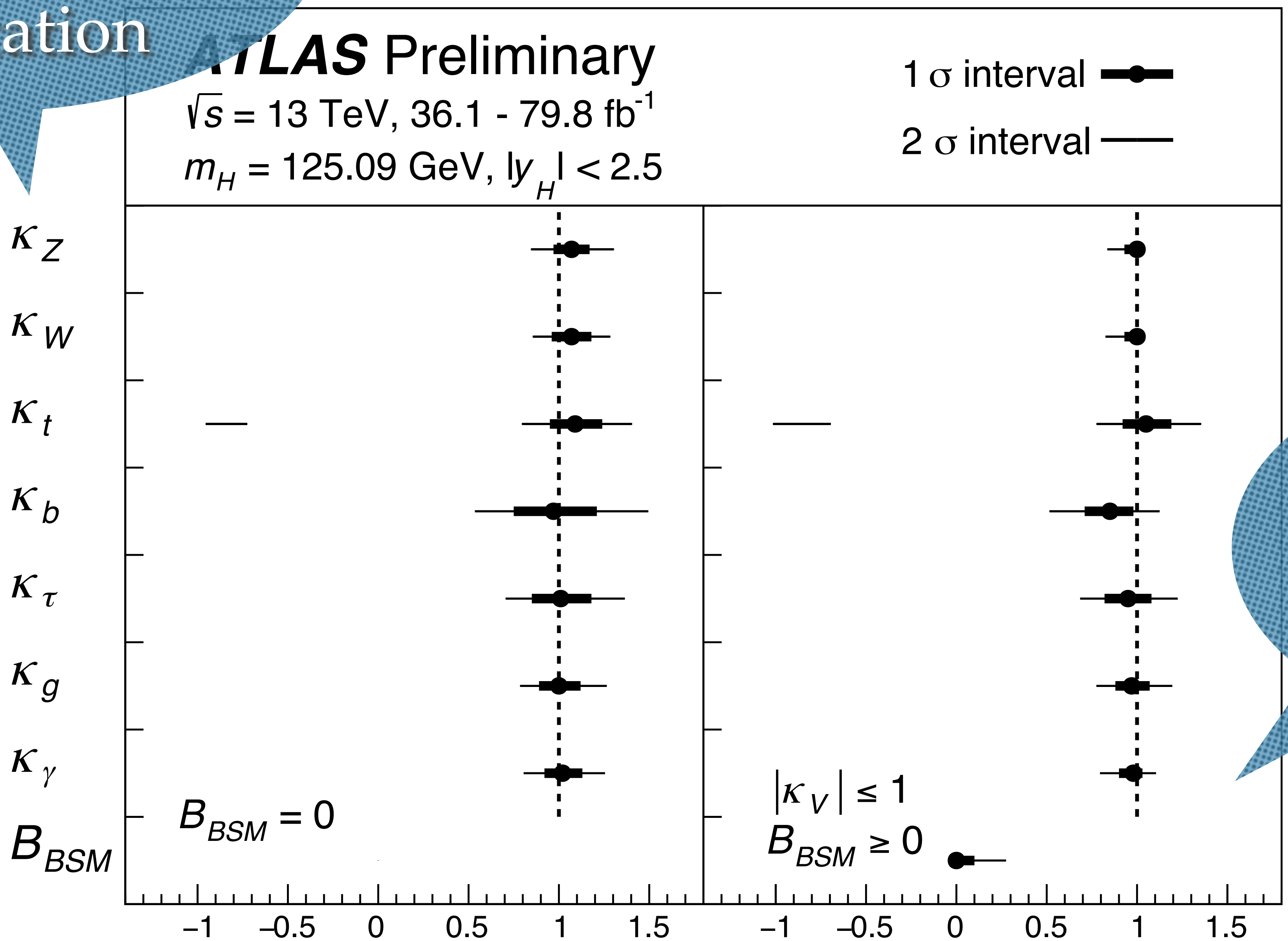
Higgs coupling/SM expectation



[ATLAS `18]

Higgs self-coupling missing…

☛ lack of CP violation, hierarchy,…. Where's the new physics?

- Can multi-Higgs phenomenology pinpoint BSM solutions?

Why have we not seen them yet?

What can be learned at 3/ab?

What about beyond the LHC?

- Can multi-Higgs phenomenology pinpoint BSM solutions?

Why have we not seen them yet?

What can be learned at 3/ab?

What about beyond the LHC?

In this talk:

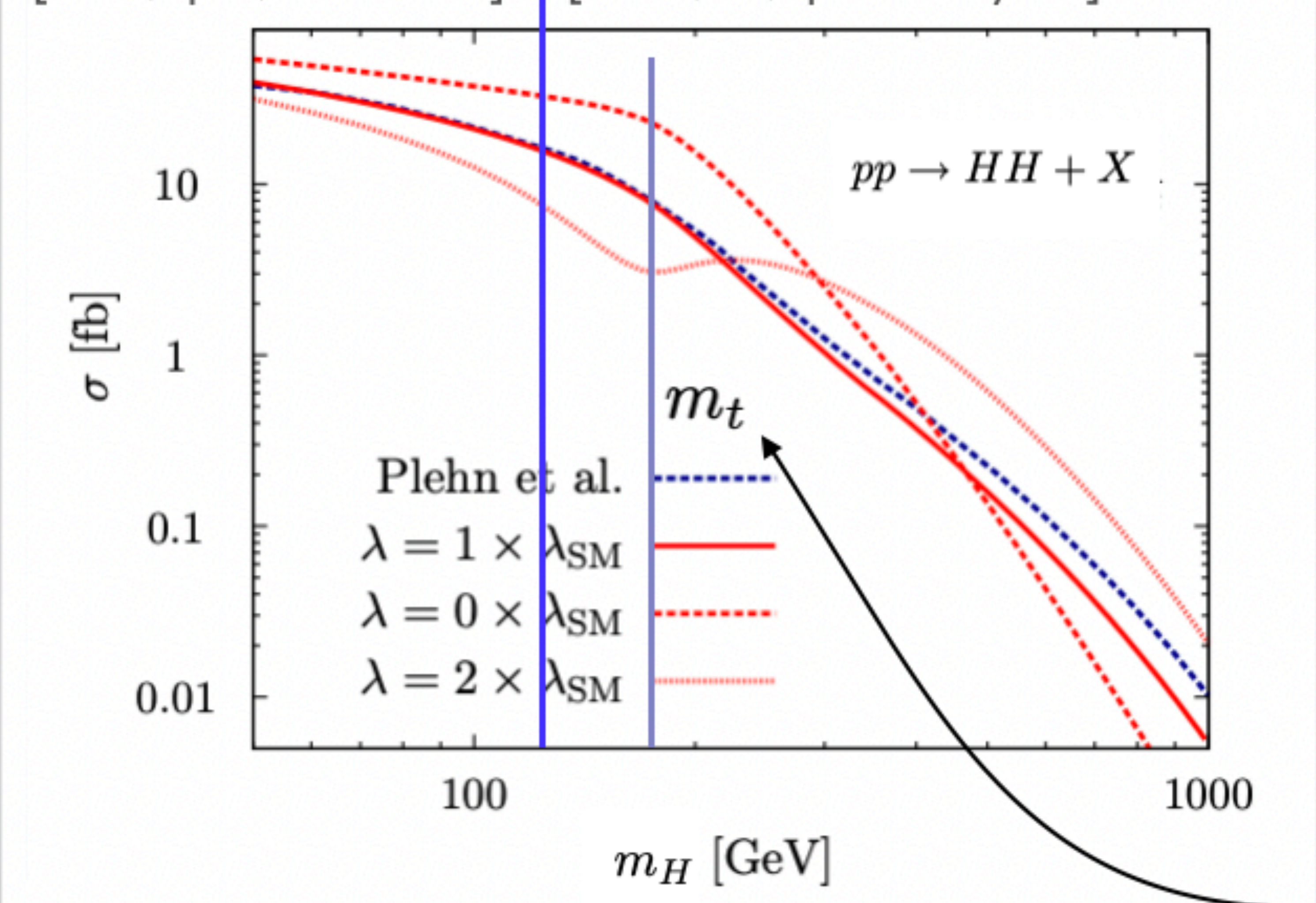
1. precision of Higgs self-coupling extraction
2. relevance of di-Higgs final states of exotics searches
3. sensitivity to weakly-coupled BSM, di-Higgs as a case for FCC-hh

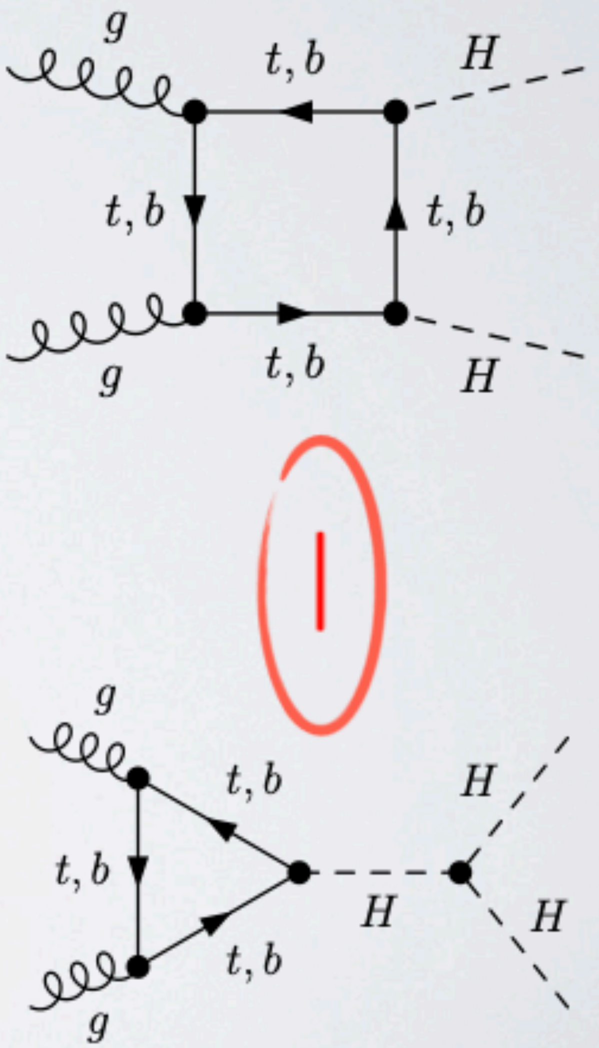
Electroweak symmetry breaking relies on self-interactions in the Higgs potential.

$$-\mathcal{L} \supset \frac{1}{2} m_H^2 H^2 + \overbrace{\sqrt{\frac{\eta}{2}}}^{=\lambda_{\rm SM}} m_H H^3 + \frac{\eta}{4} H^4 \longrightarrow$$

need at least di-Higgs production!

[Plehn, Spira, Zerwas `96] ... [Dolan, CE, Spannowsky `12] + on-going]





maximum at $m_H \sim m_t$

Electroweak symmetry breaking relies on self-interactions in the Higgs potential.

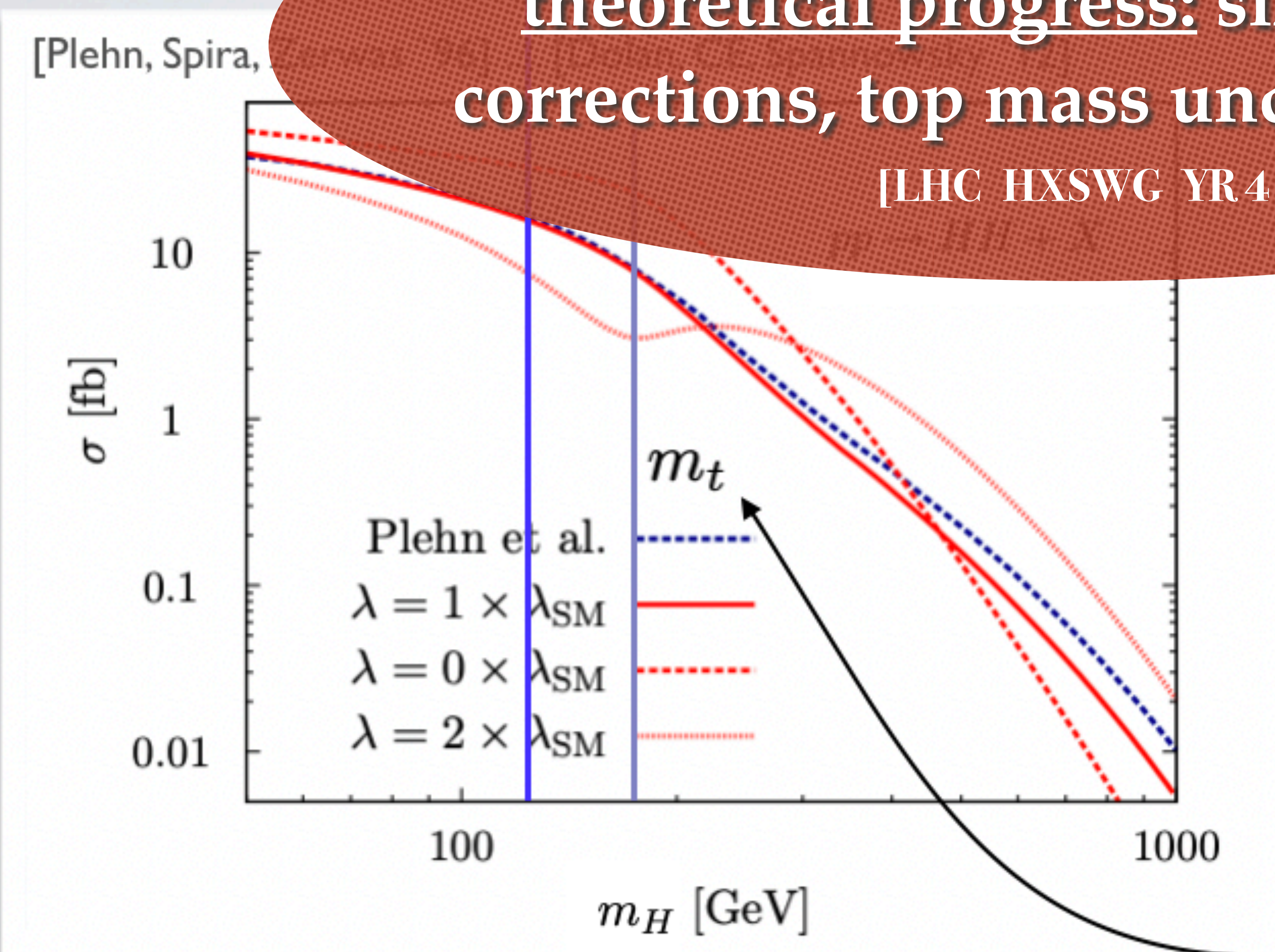
$-\mathcal{L} \supset \frac{1}{2} m_H^2 H^2 \ldots = \lambda_{\mathrm{SM}}$

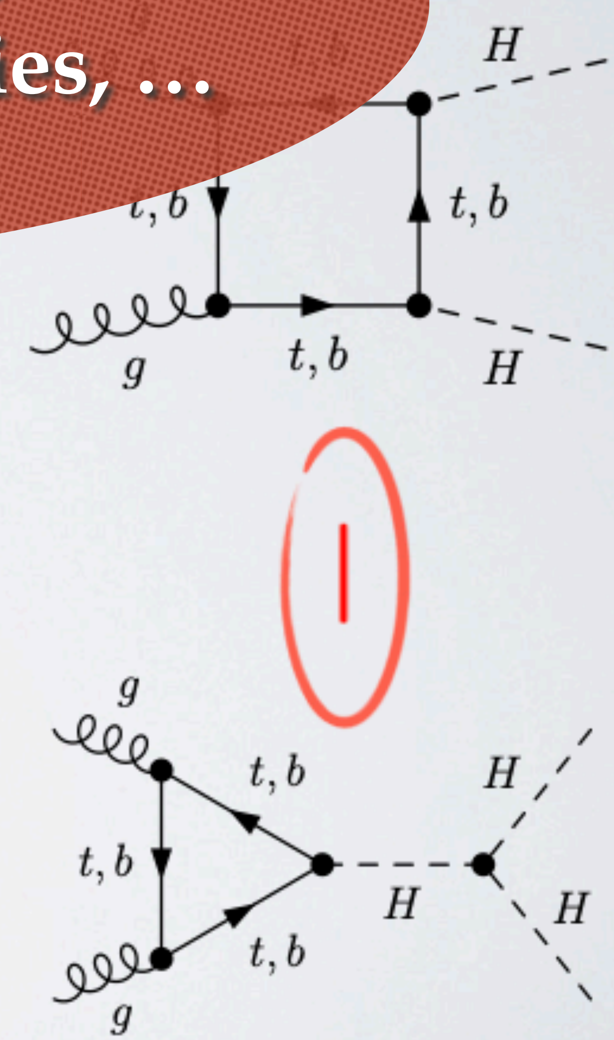
need at least <u>di-Higgs</u> production!

<u>theoretical progress:</u> sizable QCD corrections, top mass uncertainties, …

[LHC HXSWG YR 4 + on-going]

[Plehn, Spira, …]

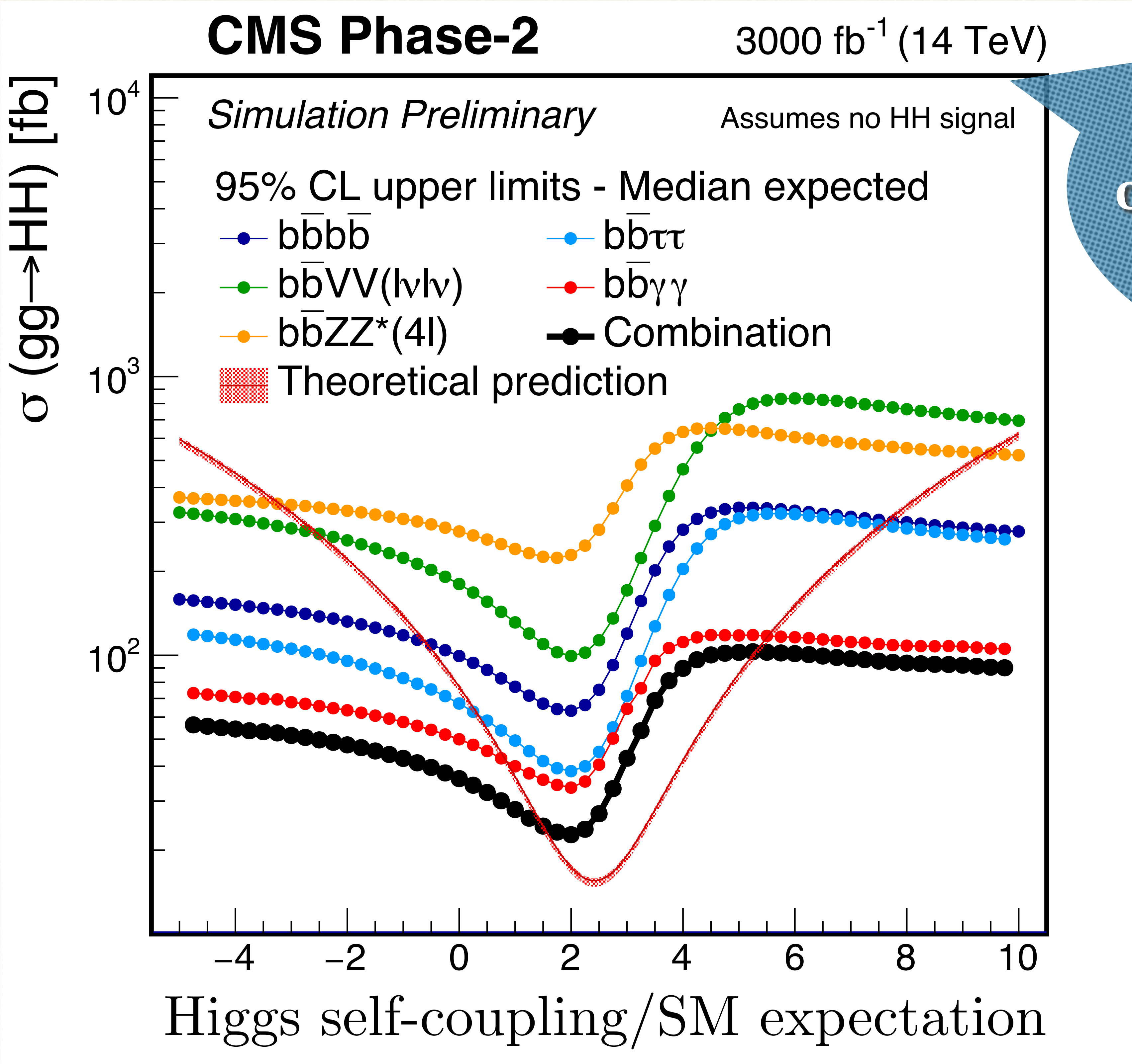




maximum at $m_H \sim m_t$

di-Higgs final states

rare final states = large statistics



we are in the domain of large (end-of-lifetime) LHC luminosity

$$\kappa_\lambda = [-0.18, 3.6]$$

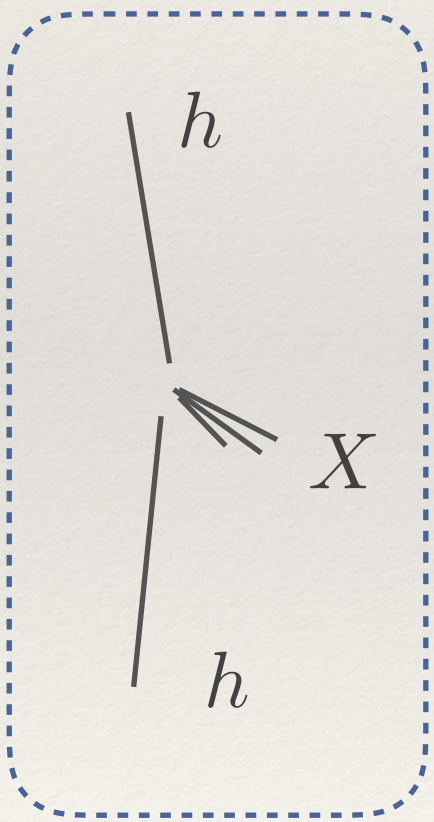
…only a factor 2 away from perturbative unitarity constraints…

LHC blind spot!

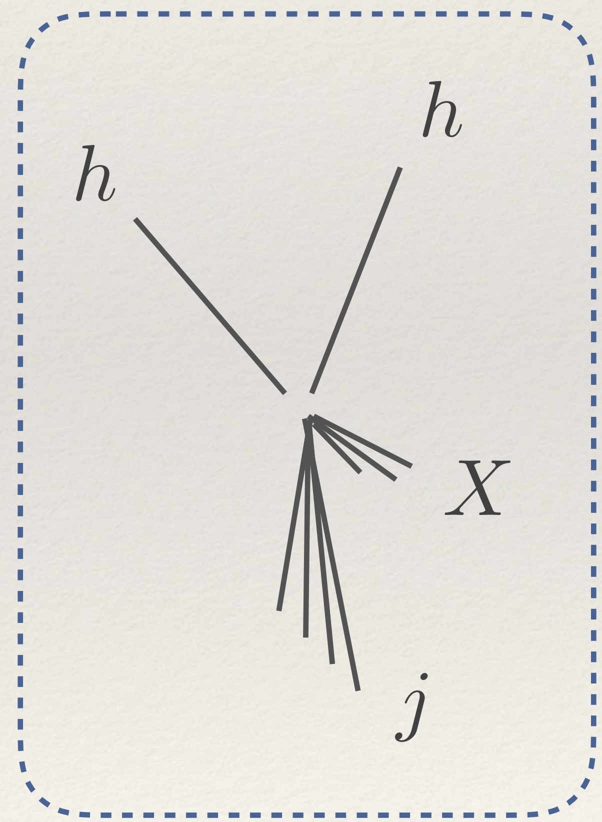
- sensitivity from small invariant mass: sensitive phase space in inclusive di-Higgs production is vastly limited

- open up the phase space by accessing small invariant masses in a collinear configuration

[Dolan, CE, Spannowsky ` 12]



vs



going beyond

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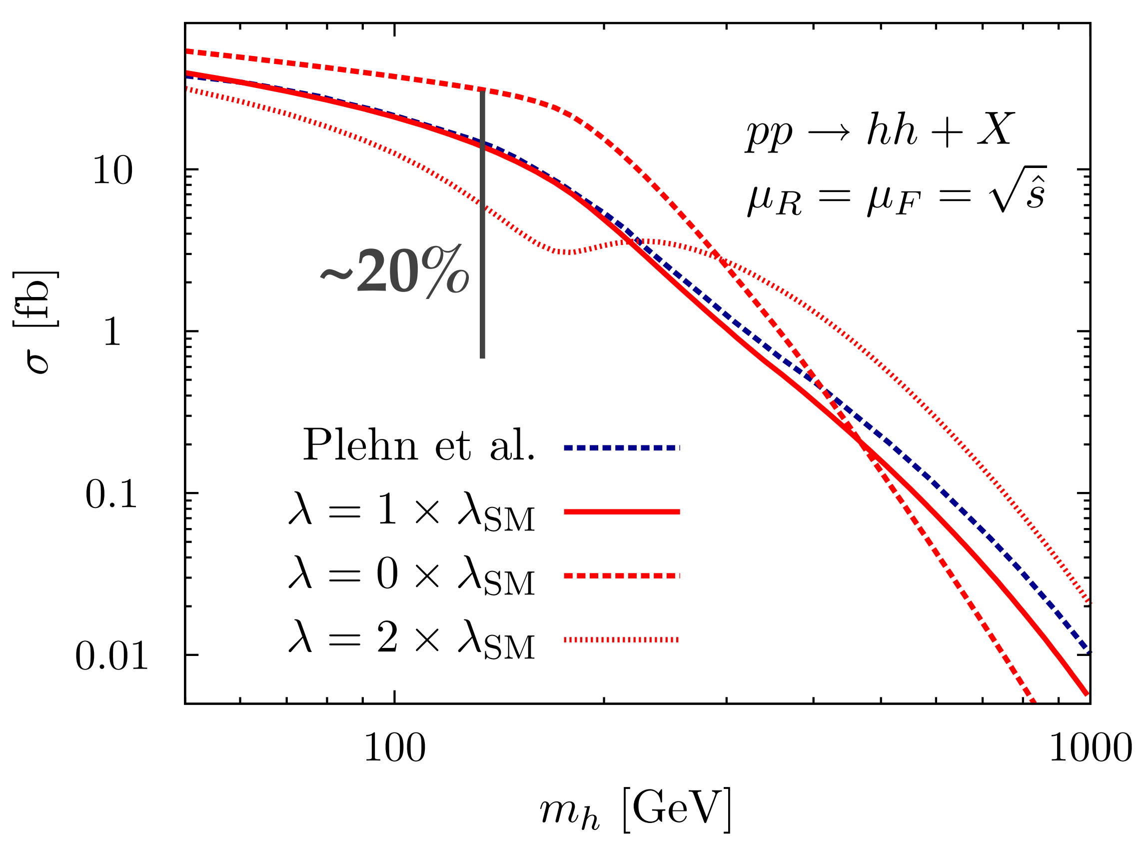
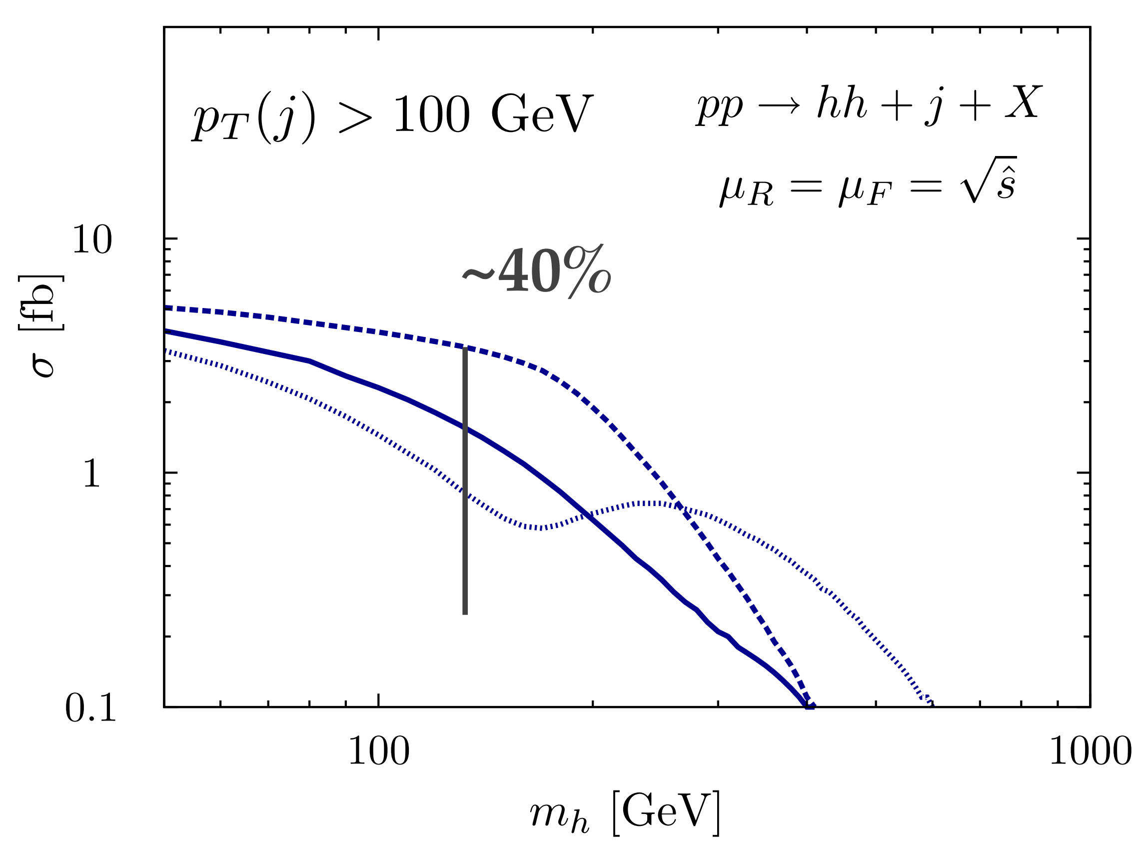




di-Higgs final states

going beyond

- sensitivity from small invariant mass: sensitive phase space in inclusive di-Higgs production is vastly limited

- open up the phase space by accessing small invariant masses in a collinear configuration

[Dolan, CE, Spannowsky ` 12]

- exploit this at FCC-hh: 8% accuracy on κ_λ in $b\bar{b}\tau\tau + j$ alone!

[Banerjee, CE, Mangano, Selvaggi, Spannowsky ` 12]

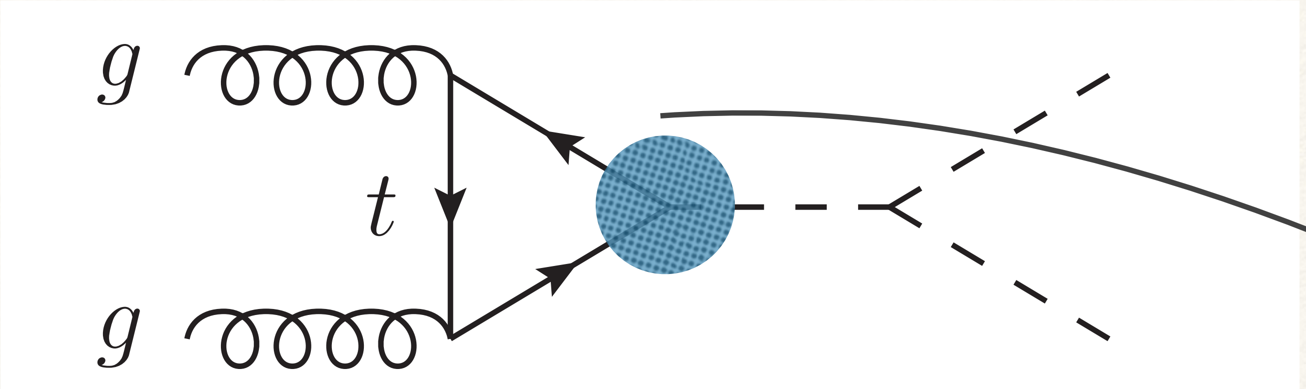
process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

$\mathcal{O}(\pm 3\%)$

FCC-hh @ 100 TeV

[Contino et al. CERN YR ` 16]

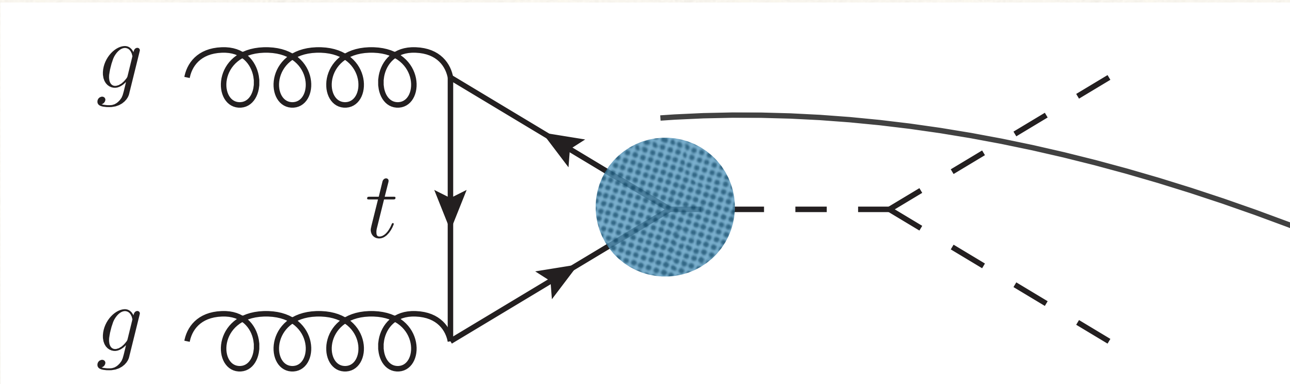
di-Higgs final states

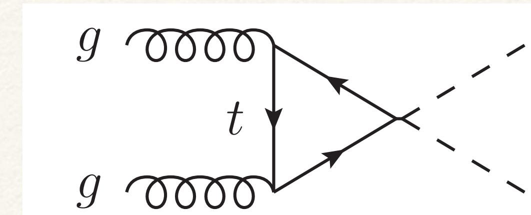


correlated with on-shell Higgs phenomenology

di-Higgs final states

going beyond the SM



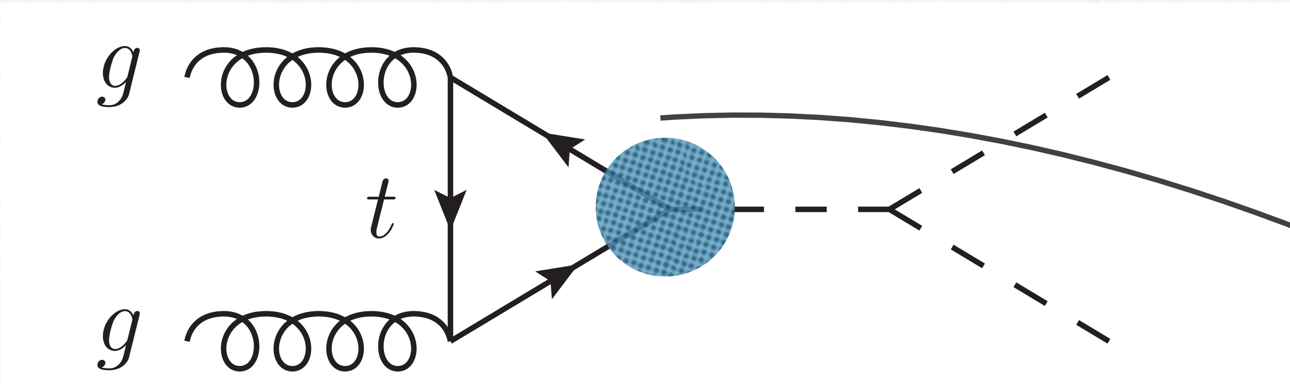


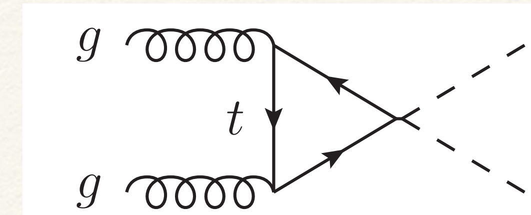
e.g. [Gröber, Mühlleitner `10]

correlated with on-shell Higgs phenomenology
broken by $\sim \bar{t}th^2/\Lambda$ ....

- easy to arrange ad-hoc EFT in a way to get spectacular rates, but casts doubt physical relevance of such limits ($\rightarrow$ matching)

going beyond the SM





e.g. [Gröber, Mühlleitner ` 10]

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- easy to arrange ad-hoc EFT in a way to get spectacular rates, but casts doubt physical relevance of such limits ($\longrightarrow$ matching)

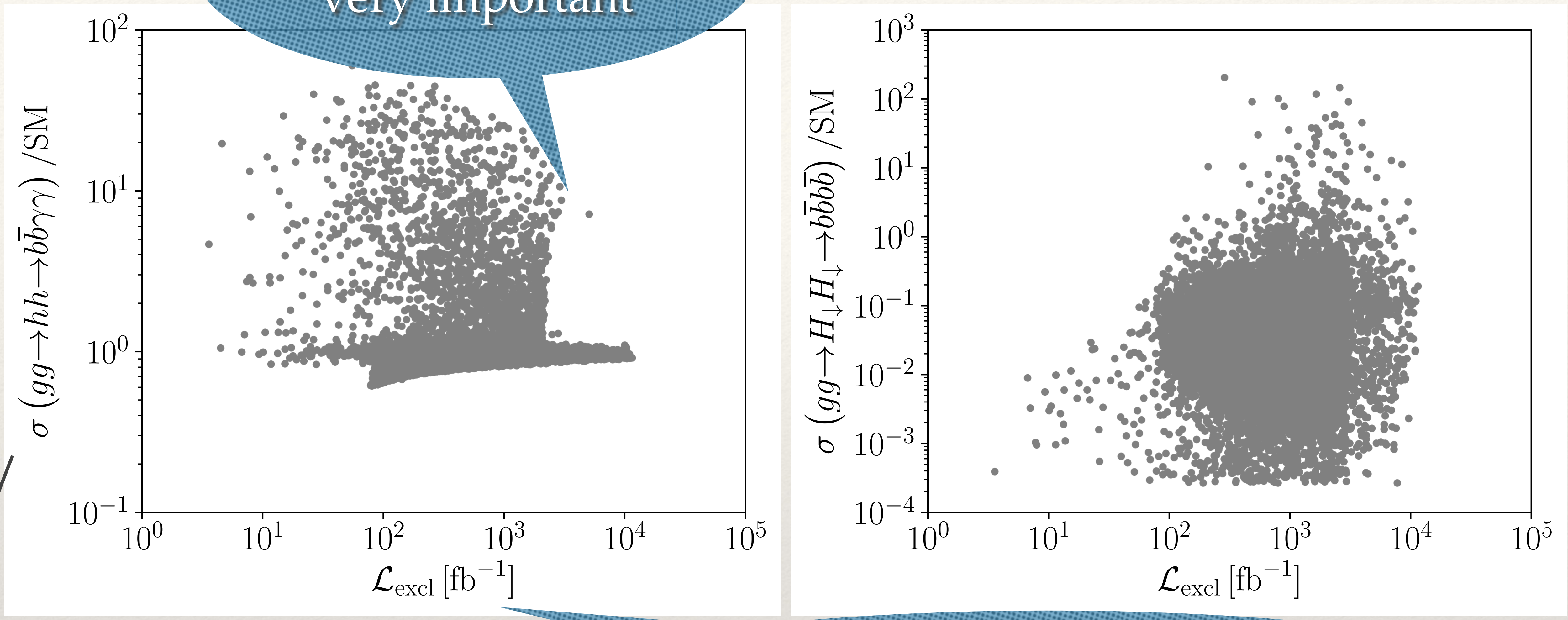
[Basler, Dawson, CE, Mühlleitner ` 18]

- use concrete Higgs sector extensions (C2HDM/CxSM/…)
  - extrapolate 125 GeV signal strengths
  - extrapolate exotic Higgs searches
  - more constraints (*electron EDMs, flavor, perturbativity, strong PS, CP viol.*)

What's left for di-Higgs?

e.g. C2HDM

tt resonance searches very important



[Basler,Dawson, CE, Mühlleitner ` 18]

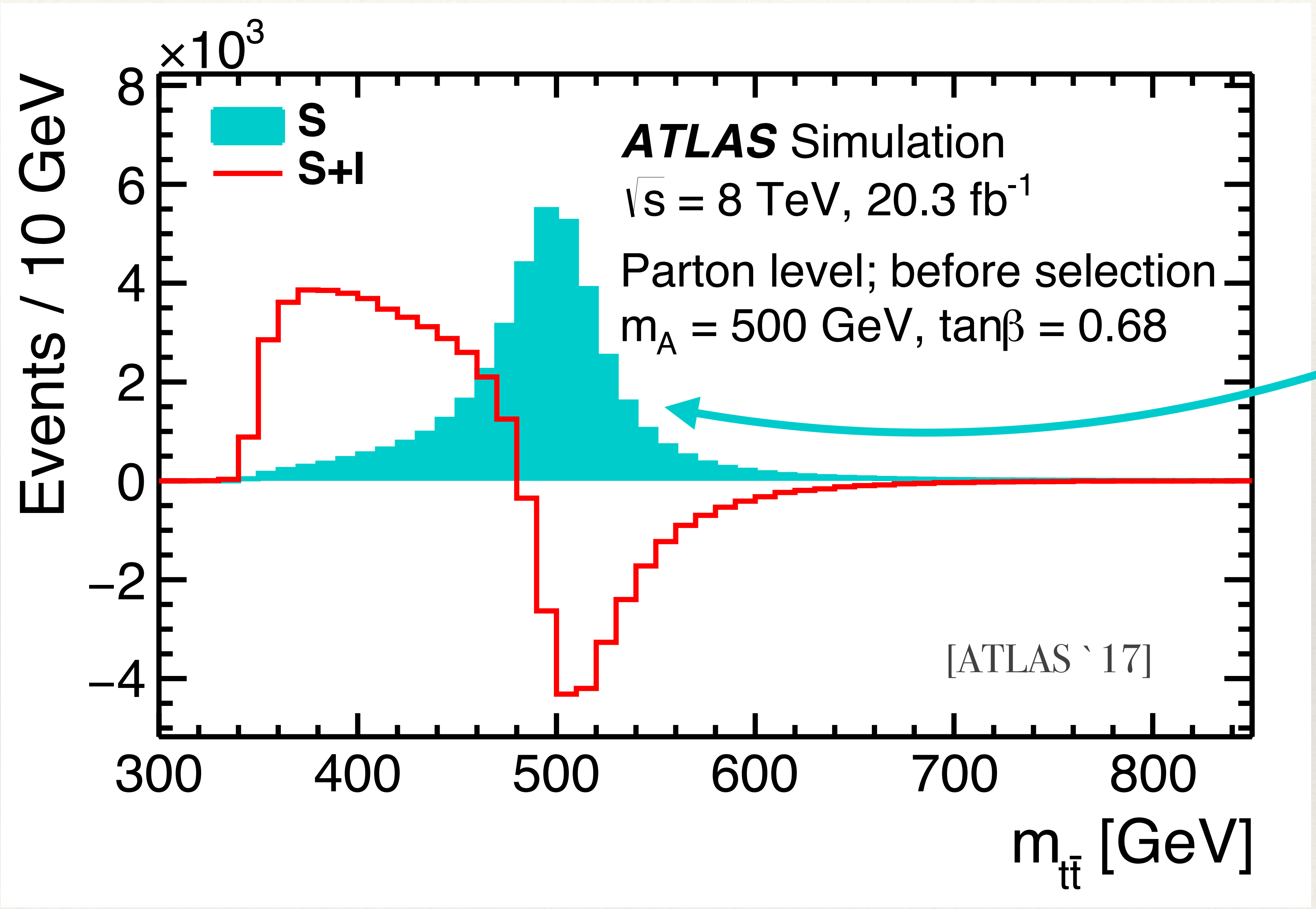
luminosity at which non-HH searches become sensitive

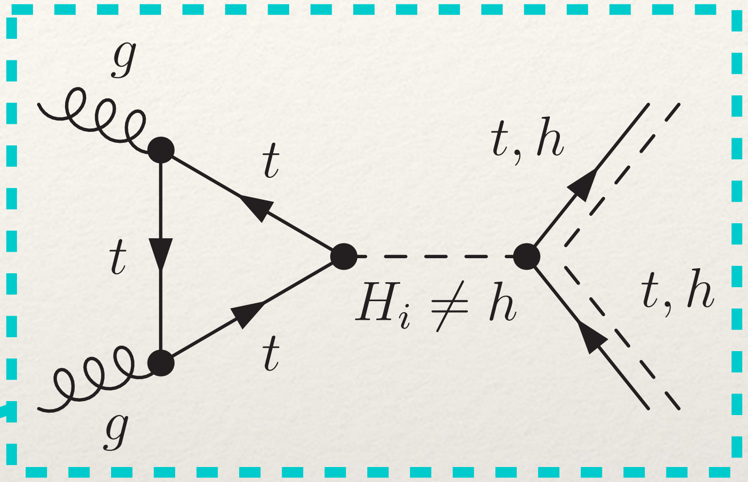
SM-like measurements can show a plethora resonant anomalies
diHiggs final states important for BSM discovery

special role of tops

- large interference effects of Higgs "signal" with QCD background

[Gaemers, Hoogeveen `84] [Dicus et al. `94]....





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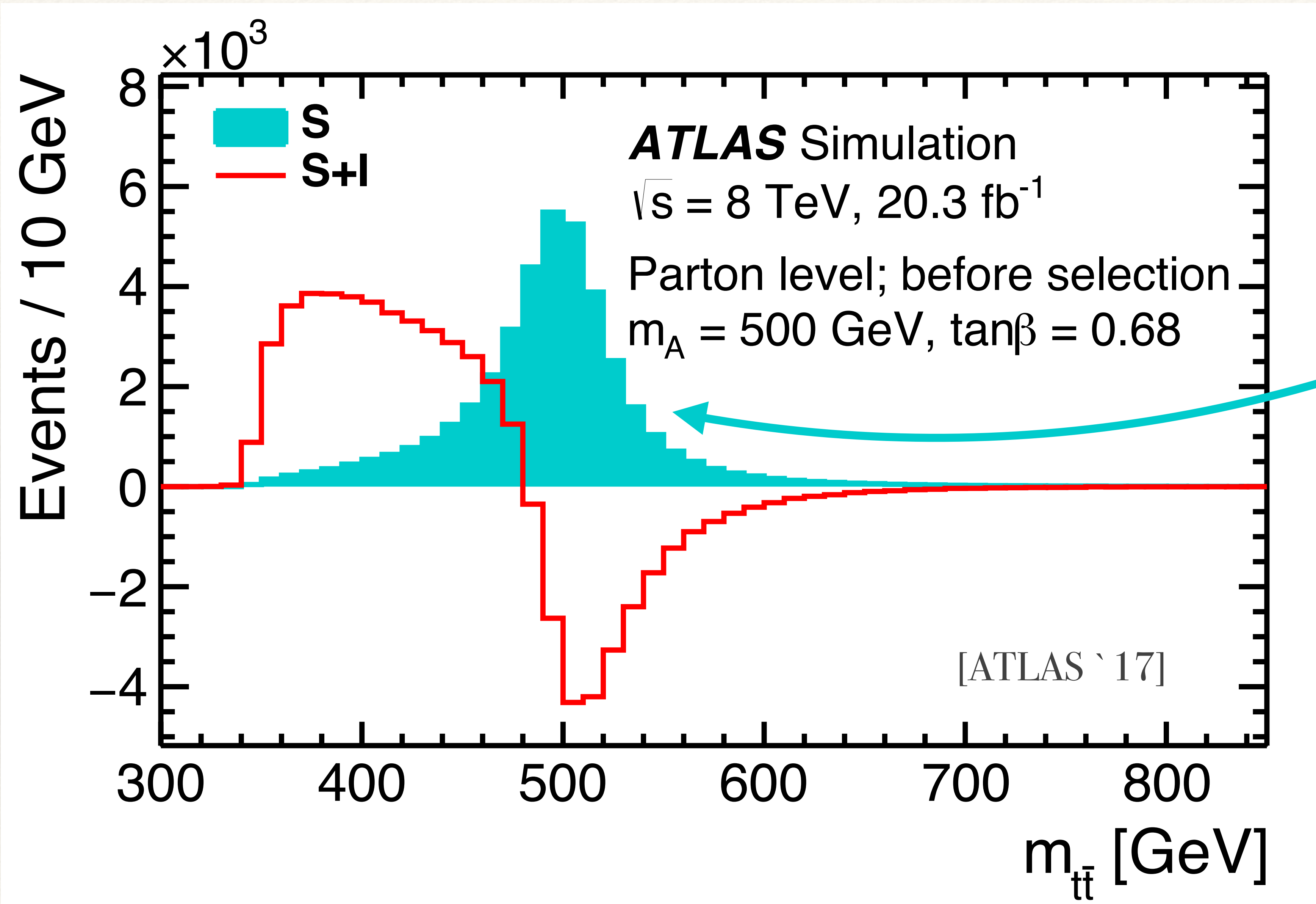
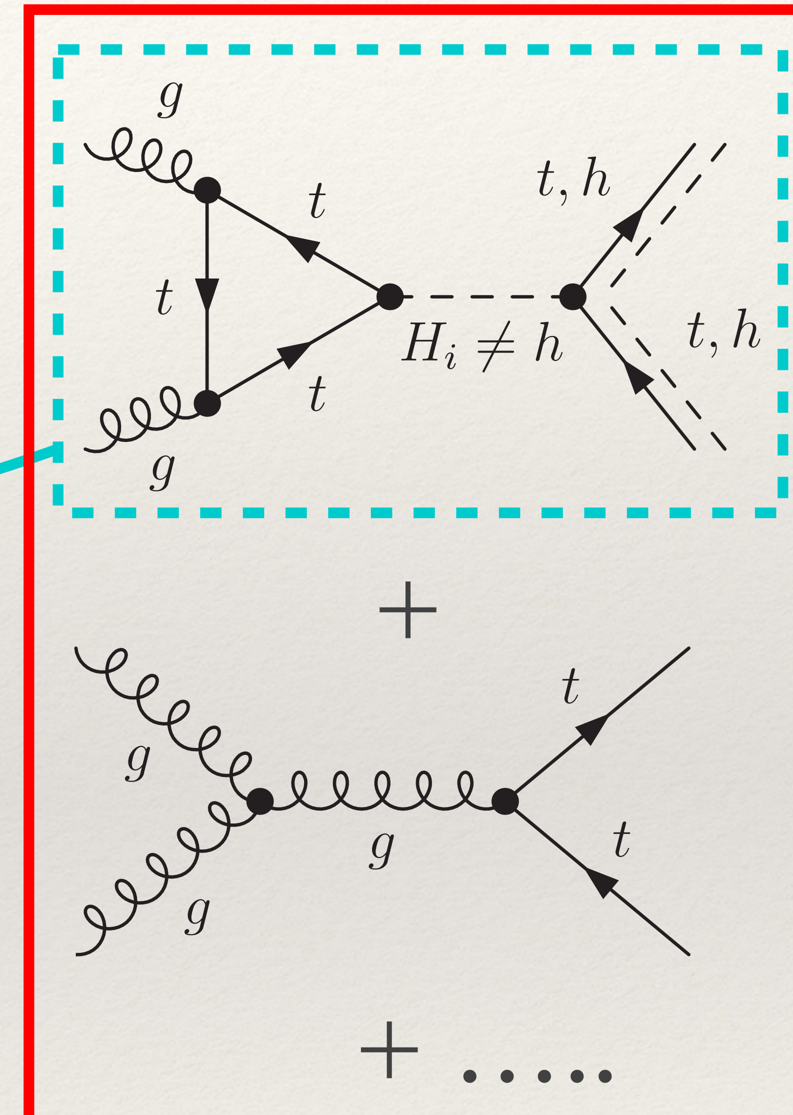
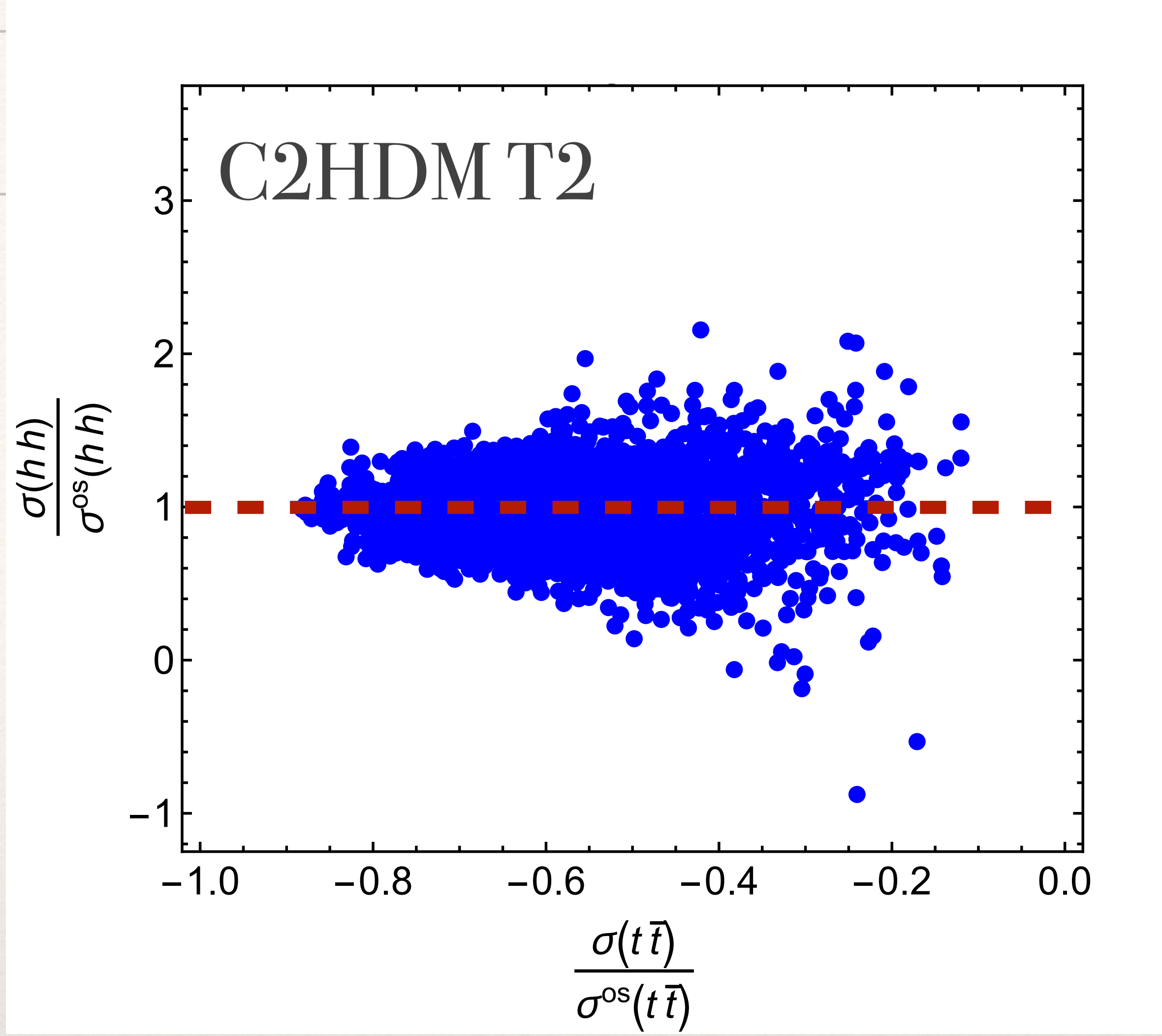




- top resonance searches in Higgs sector extensions with narrow width approximation is inadequate!

special role of tops

- destructive interference in top final states can be correlated with excess in HH - how ?



special role of tops

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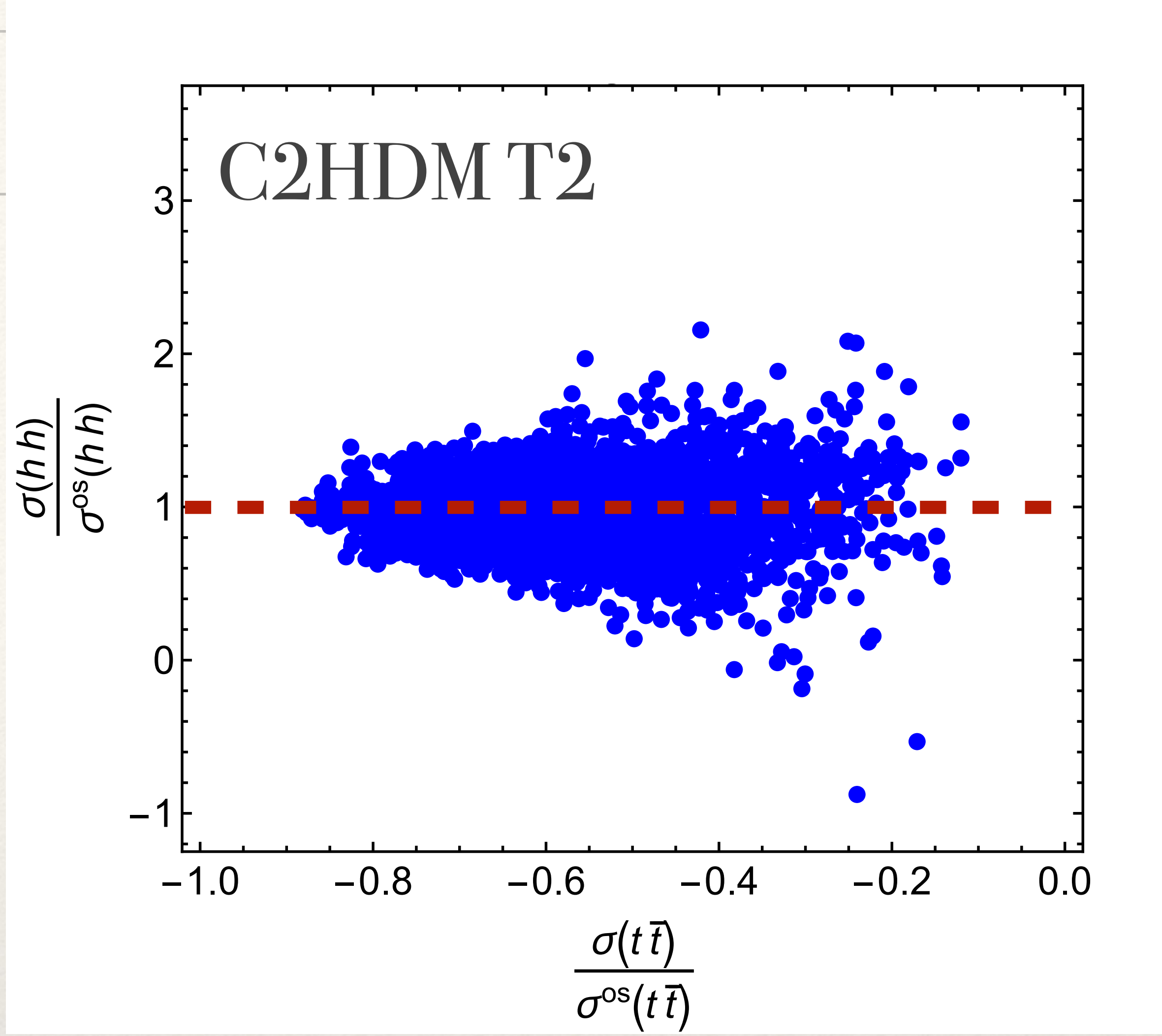
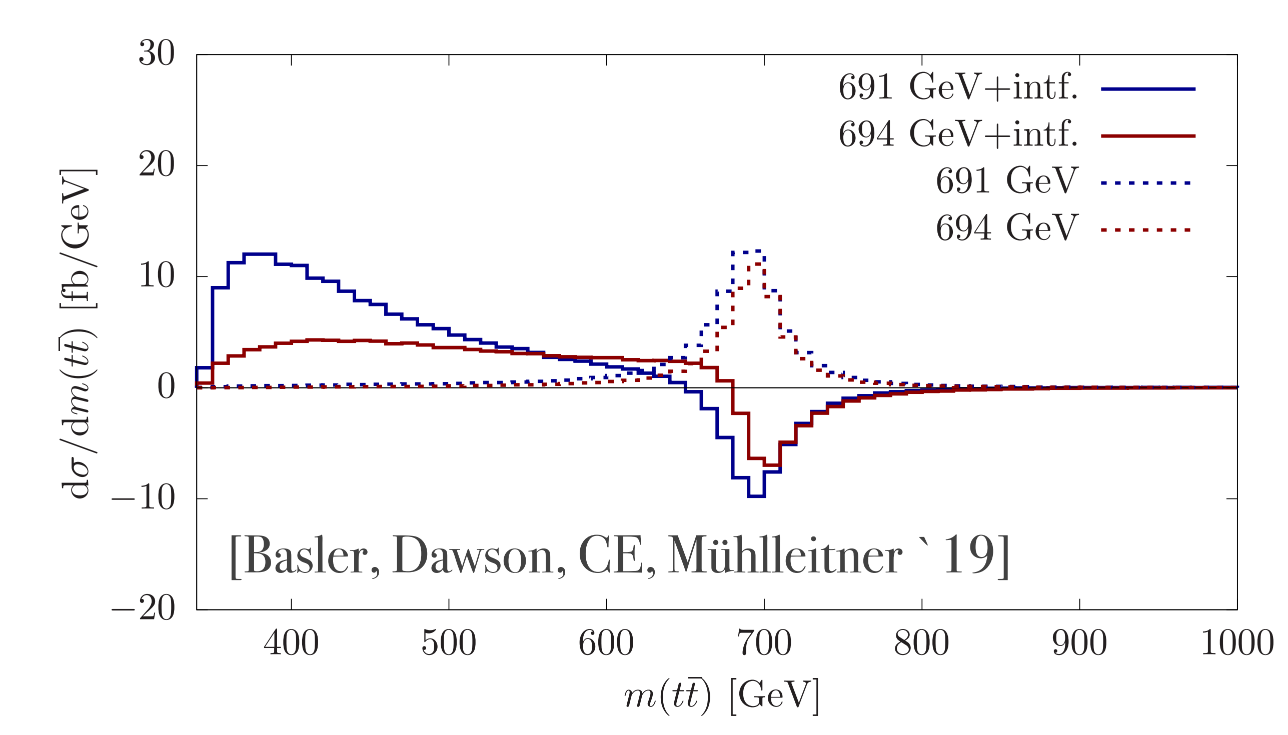
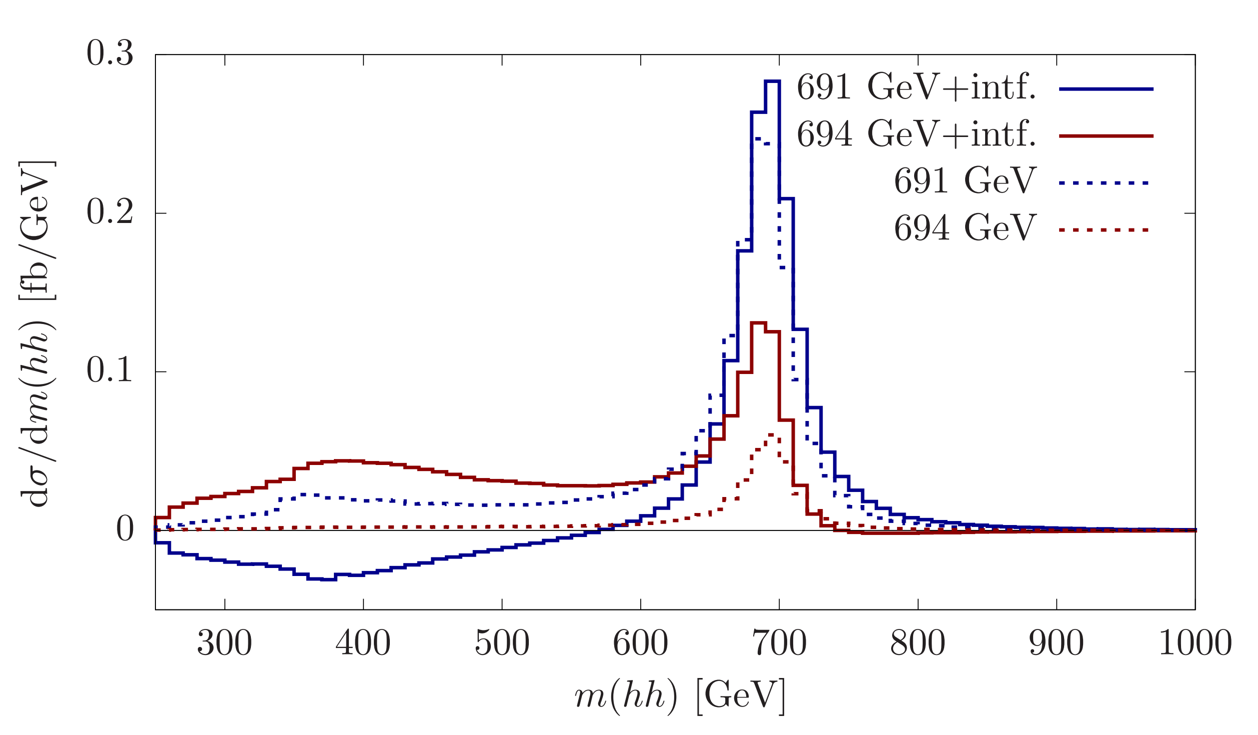
- phenomenologically viable regions exhibit compressed spectra: **signal-signal interference**







weakly coupled BSM

[CE, Jaeckel `19]

- weakly coupled BSM: the $\mathbb{Z}_2$-symmetric Higgs portal

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}(\partial_\mu S)^2 - \frac{m_S^2}{2}S^2 - \lambda S^2(\Phi^\dagger \Phi - v^2/2)$$

- for $m_S > m_H/2$ no direct SM Higgs decays
- Higgs physics modifications via loop- or kinematics-suppressed effects

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Trilinear Higgs coupling modifications

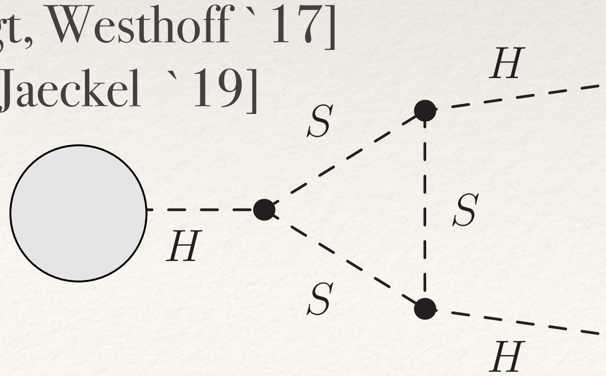
Higgs precision studies at colliders

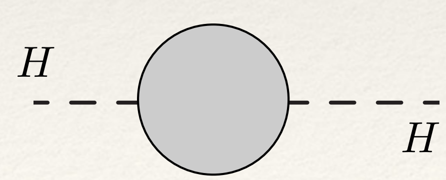
off-shell production

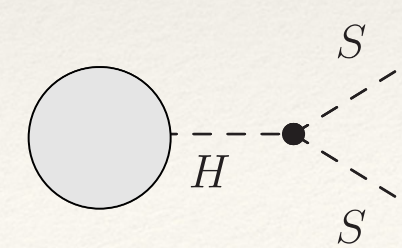
[Craig , Lou. et al.` 14]
[Ruhdorfer, Salvioni, Weiler ` 19]

[CE, McCullough ` 13]
[Craig, CE, McCullough ` 13]
[Goncalves, Han, Mukhopadhyay ` 18]

[He, Zhu ` 16]
[Voigt, Westhoff ` 17]
[CE, Jaeckel ` 19]

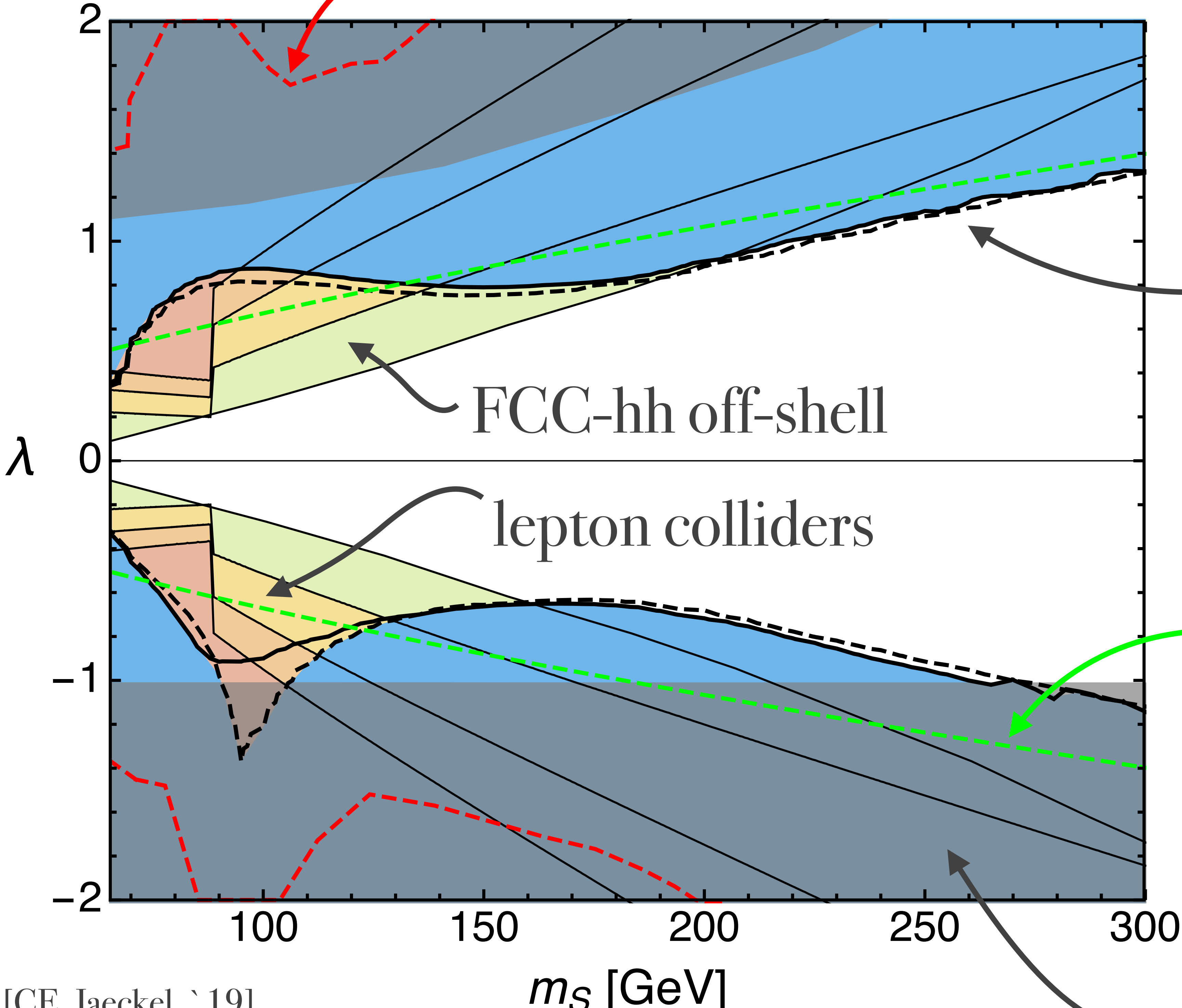






weakly coupled BSM

diHiggs @ LHC



[CE, Jaeckel `19]

FCC-hh off-shell

lepton colliders

diHiggs @ FCC-hh

[Contino et al. `17]

Coleman-Weinberg approximation for diHiggs

electroweak potential unstable

[Curtin , Meade. Yu` 14]

weakly coupled BSM

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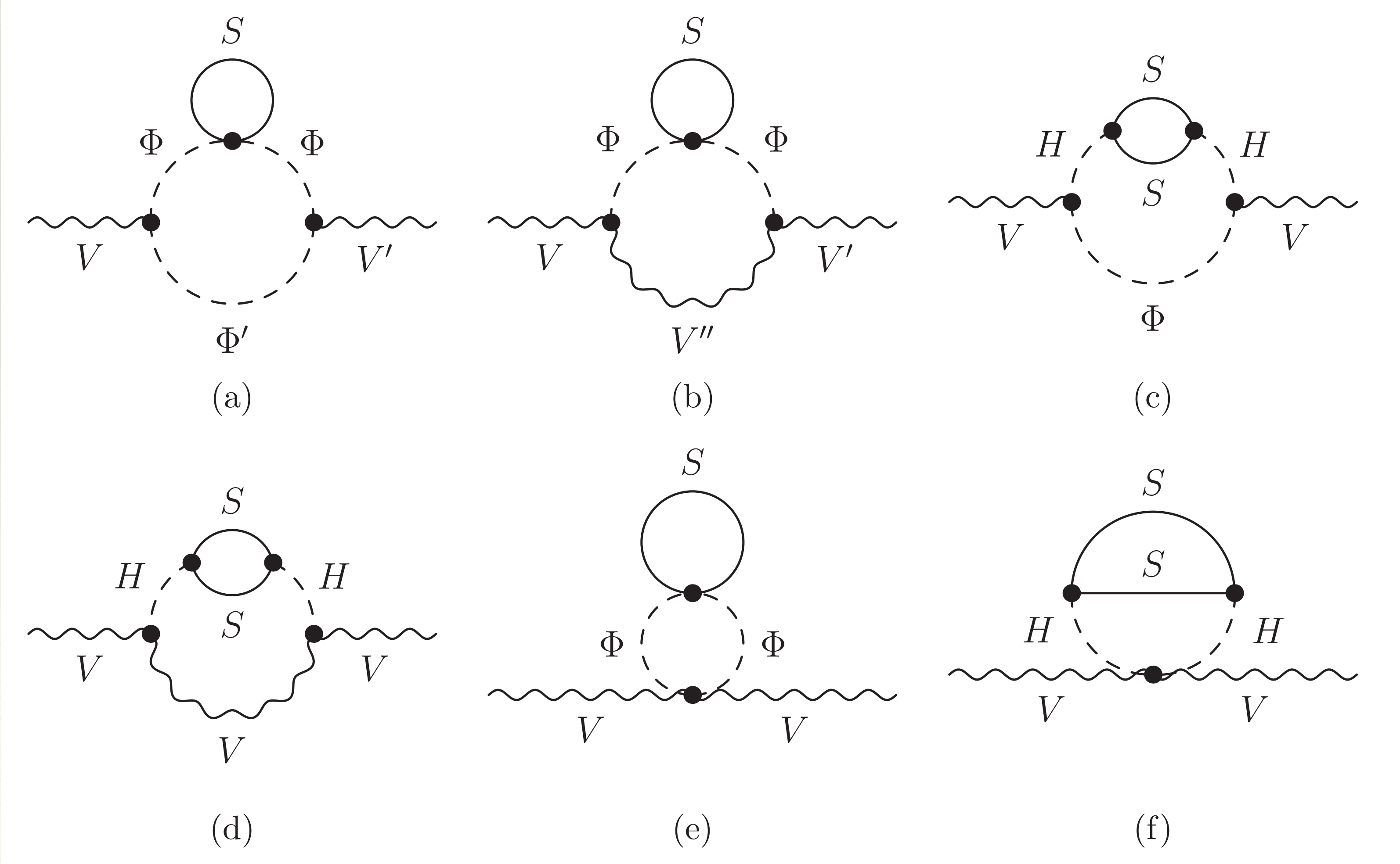
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{m_S^2}{2} S^2 - \lambda S^2 (\Phi^\dagger \Phi - v^2/2)$$

- high-precision physics on the Z pole (e.g. GigaZ)
- universal changes to four-fermion processes through loop contributions



S, T, U

[Peskin, Takeuchi`90]...

weakly coupled BSM

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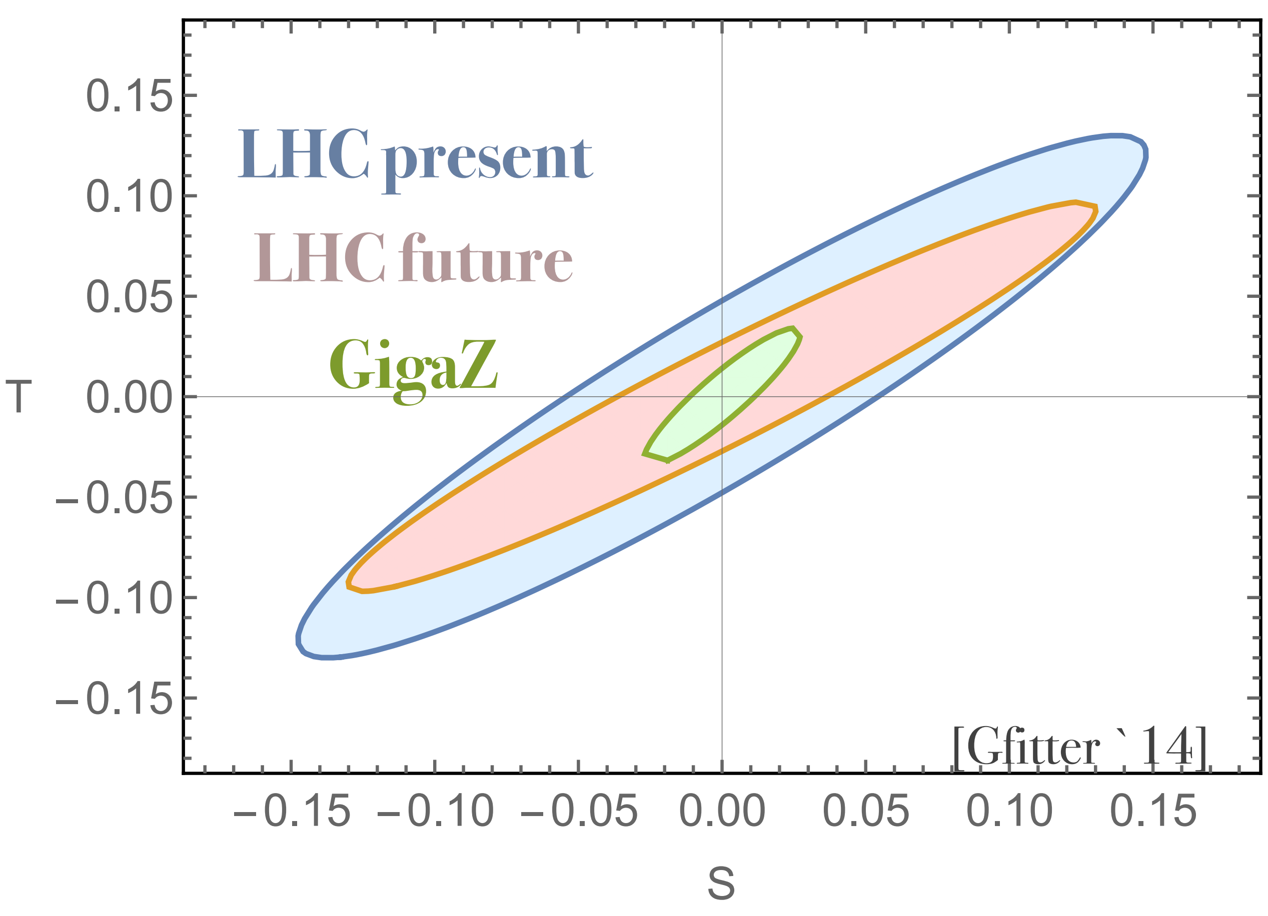
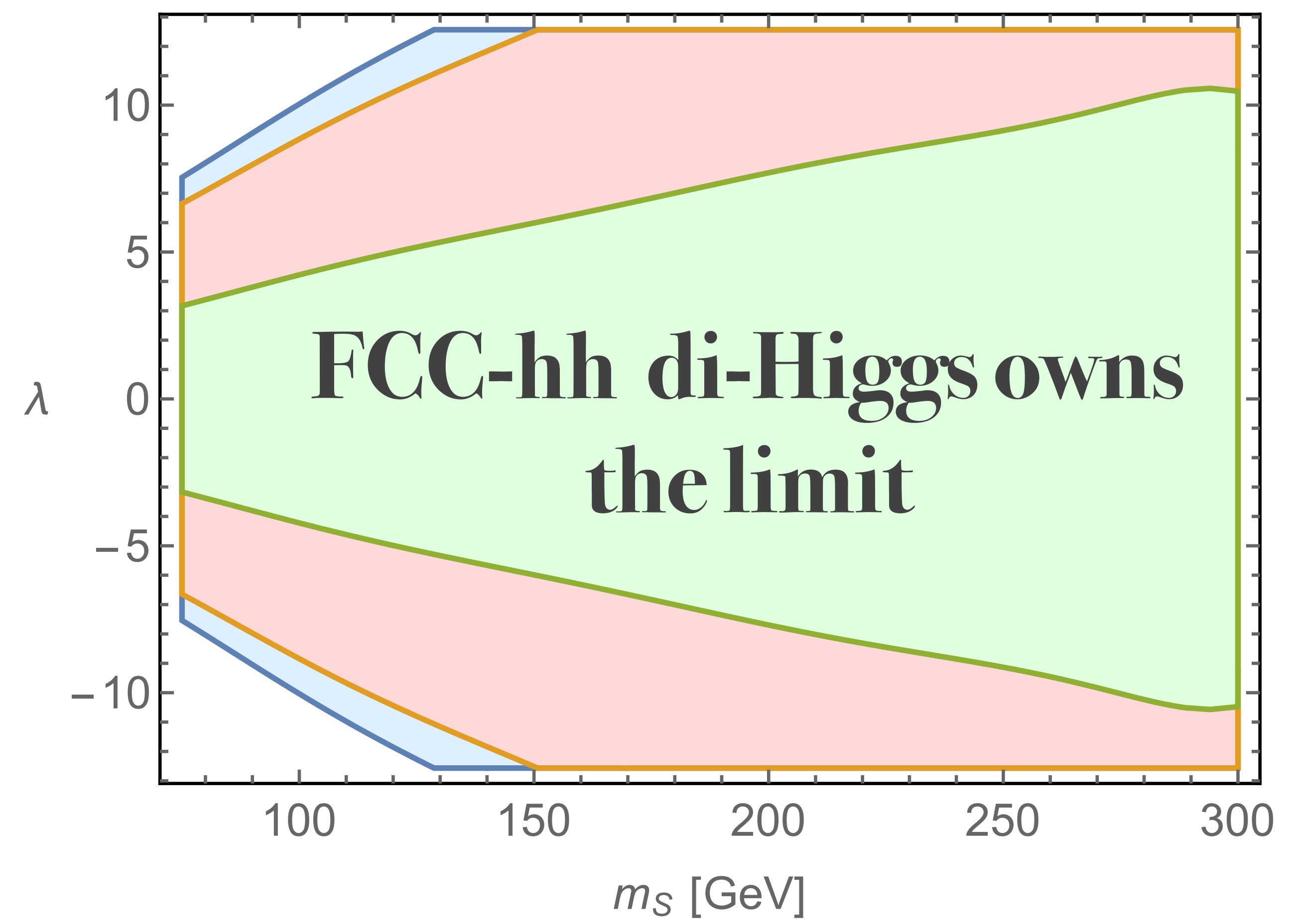


[CE, Jaeckel, Spannowsky, Stylianou in prep.]



weakly coupled BSM

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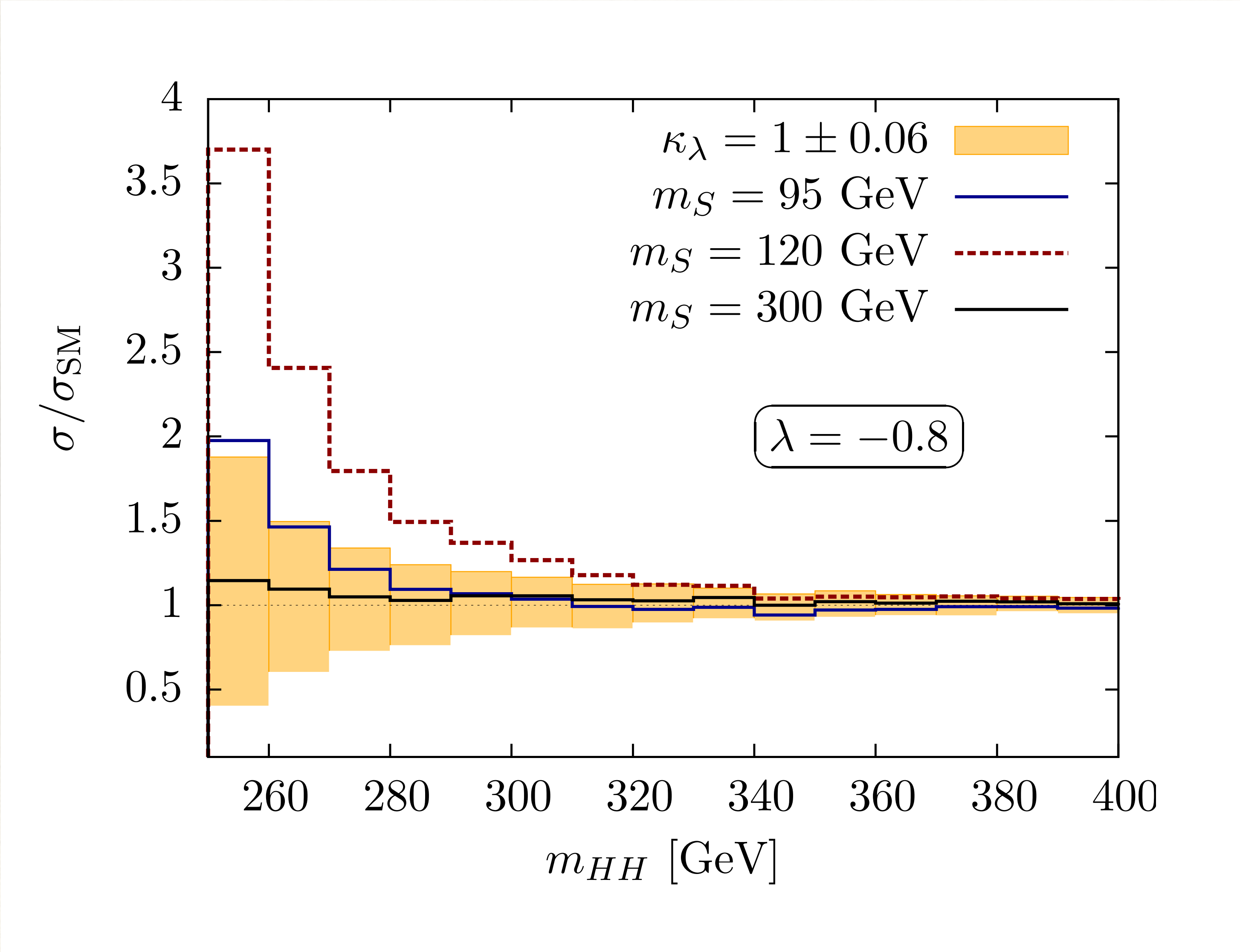
- why is di-Higgs the driving force here?



Combination of

- changed threshold behavior (cf. self-coupling)
- double sensitivity of Higgs coupling modification in the tail compared to single Higgs

- *Higgs physics sits at the heart of our BSM efforts*
  - enhancing theoretical predictions
  - limit setting tailored to minimise systematics polutions

Summary

- *multi-Higgs physics sits at the heart of our BSM efforts*
  - enhancing theoretical predictions
  - limit setting tailored to minimise systematics polutions

- *Opportunity to link the Higgs sector to new physics*
  - cure SM shortcomings (CP violation…)
  - multi-Higgs is a hard case for BSM sensitivity
  - new collider concepts can maximise precision vs energy reach in complementary ways