Higgs Pairs @ Dubrovnik

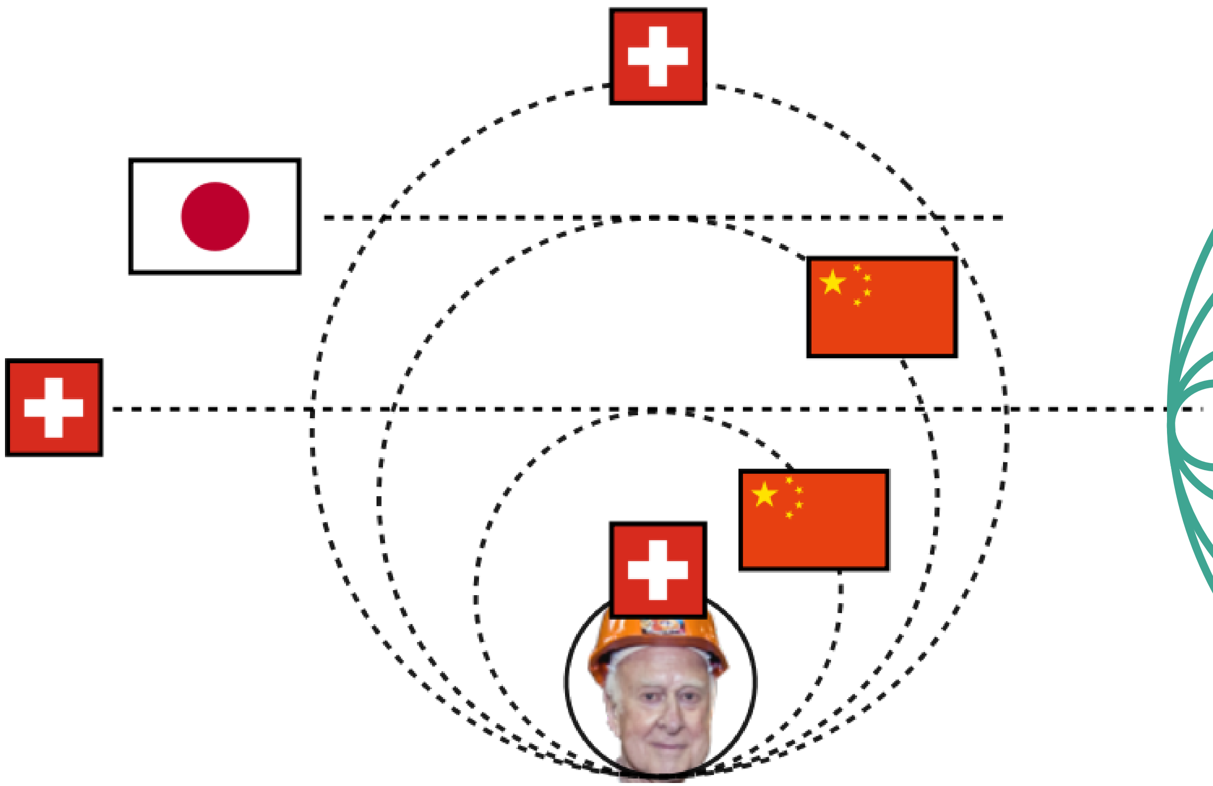
(HH at future colliders)
Theory Overview

Zhen Liu

U of Minnesota

Jun.2nd, 2022

Future Colliders: many rings



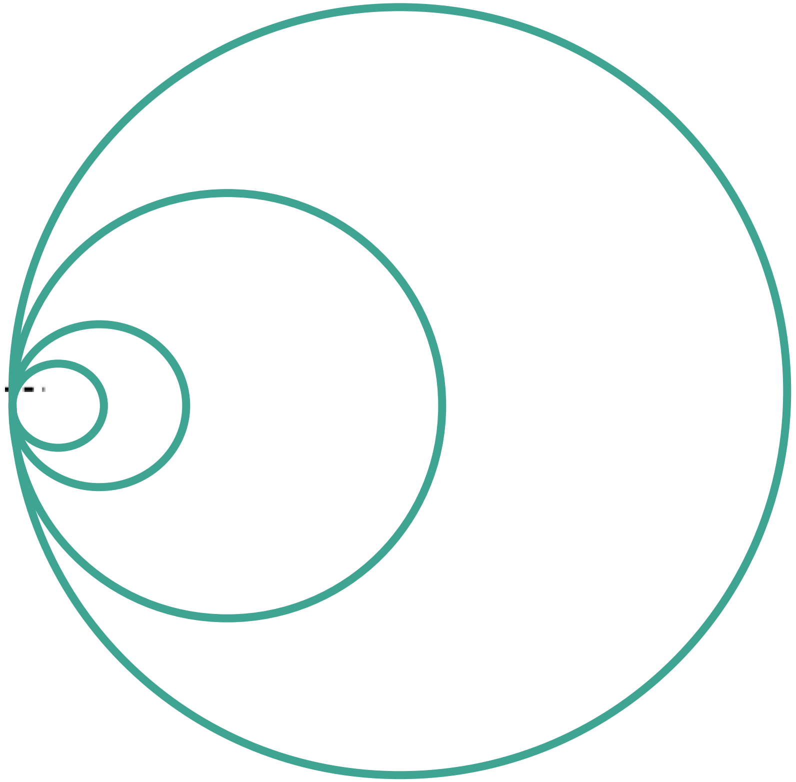
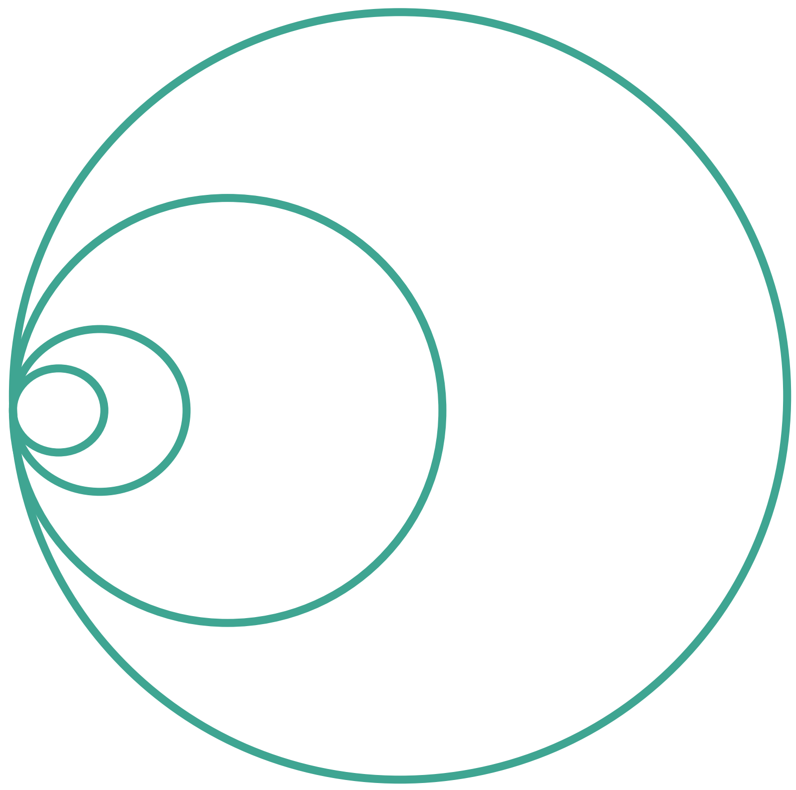


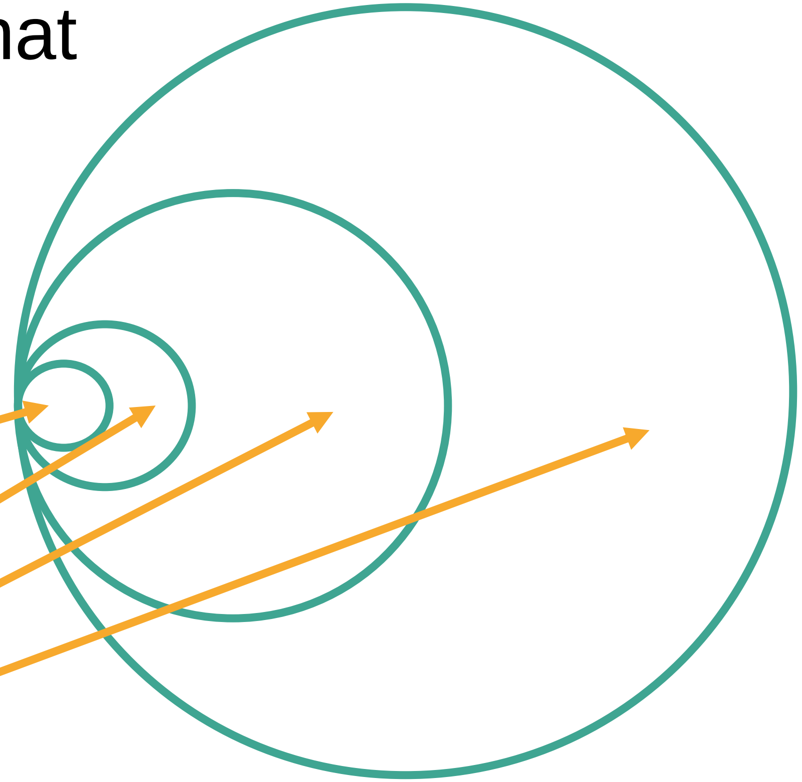
Fig. from C. Grojean.
For updated collider scope, see
Snowmass activities & updates.
See P. Meade's talk.

Rings inspired by the workshop discussion…



Rings inspired by the workshop discussion…

- There seems to be a consensus here…
- Cannot help asking is it true? In what sense?



- SM
- UV BSM
- SMEFT
- HEFT

Rings inspired by the workshop discussion…

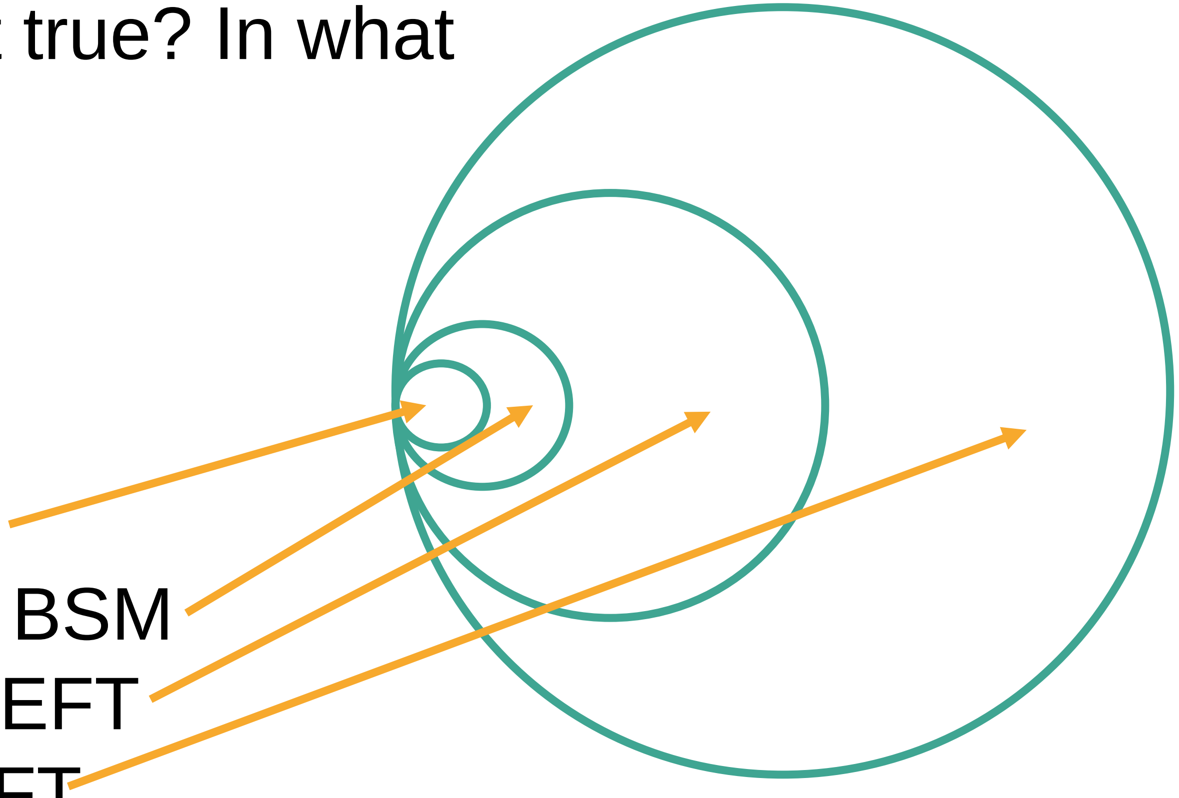
- There seems to be a consensus here…
- Cannot help asking is it true? In what sense?

- Fixed-order in mass-dim expansion
  HEFT⊃SMEFT

- Allowing all order (form factors)
  HEFT⊃UV BSM

…

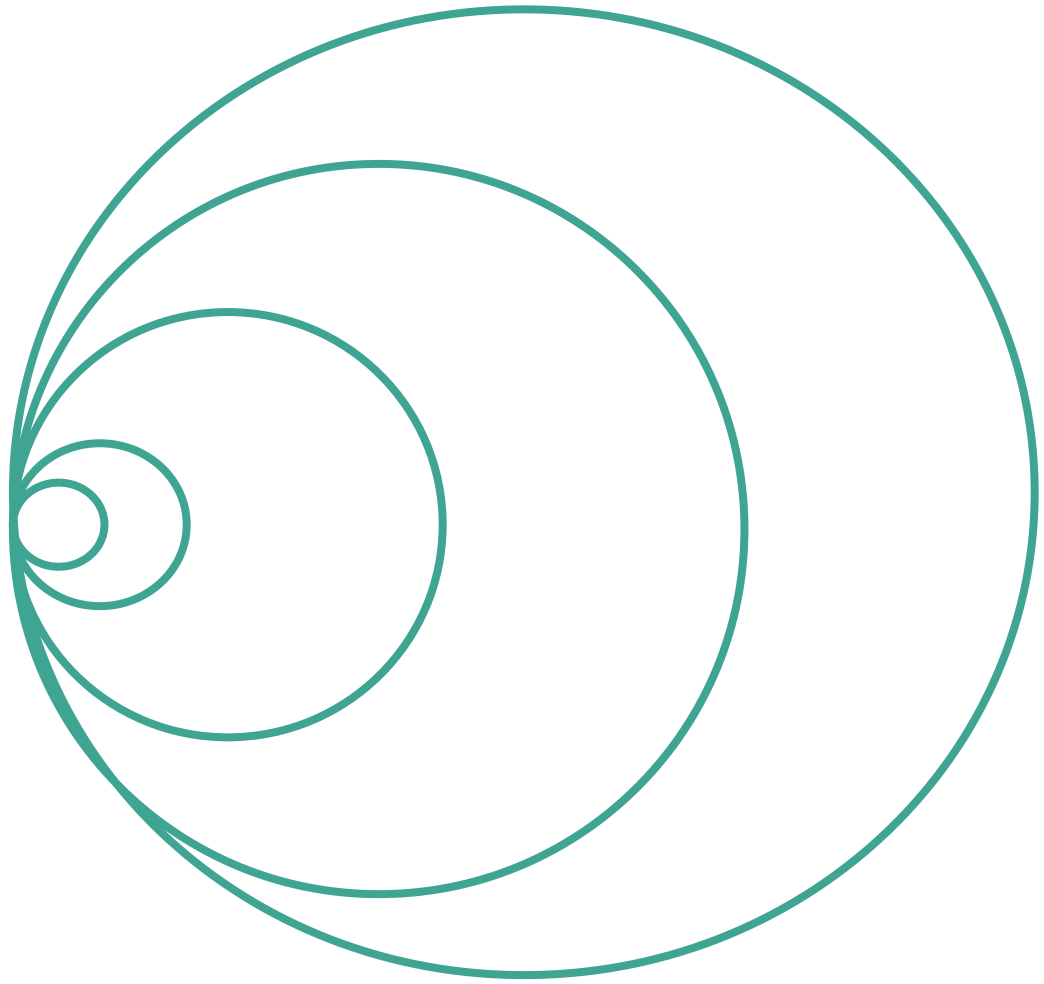
- SM
- UV BSM
- SMEFT
- HEFT



But more complex…

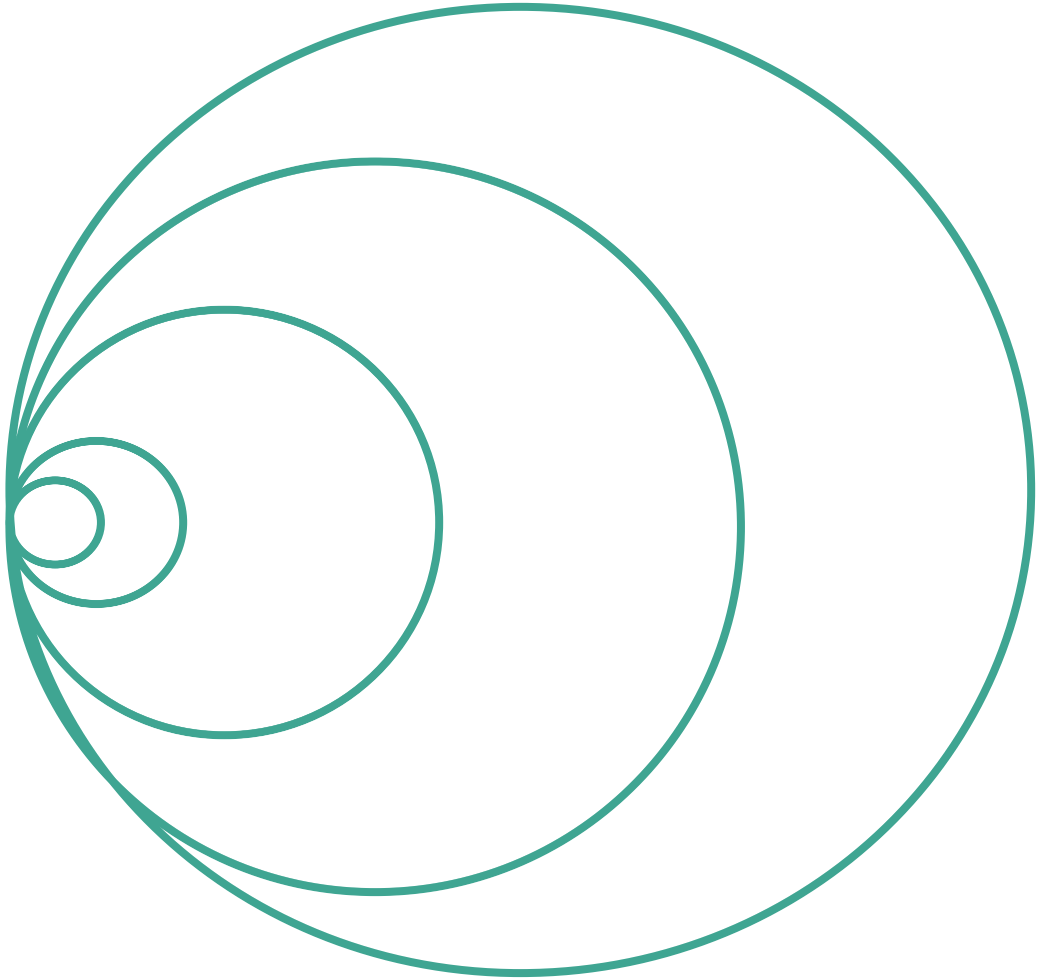
- Fixed-order HEFT $\subset$ All order HEFT
- Fixed-order SMEFT $\subset$ All order SMEFT
- Reasonable UV BSM $\subset$ All BSM

HEFT form factors are true momentum expansion…



There are many theory perspectives…

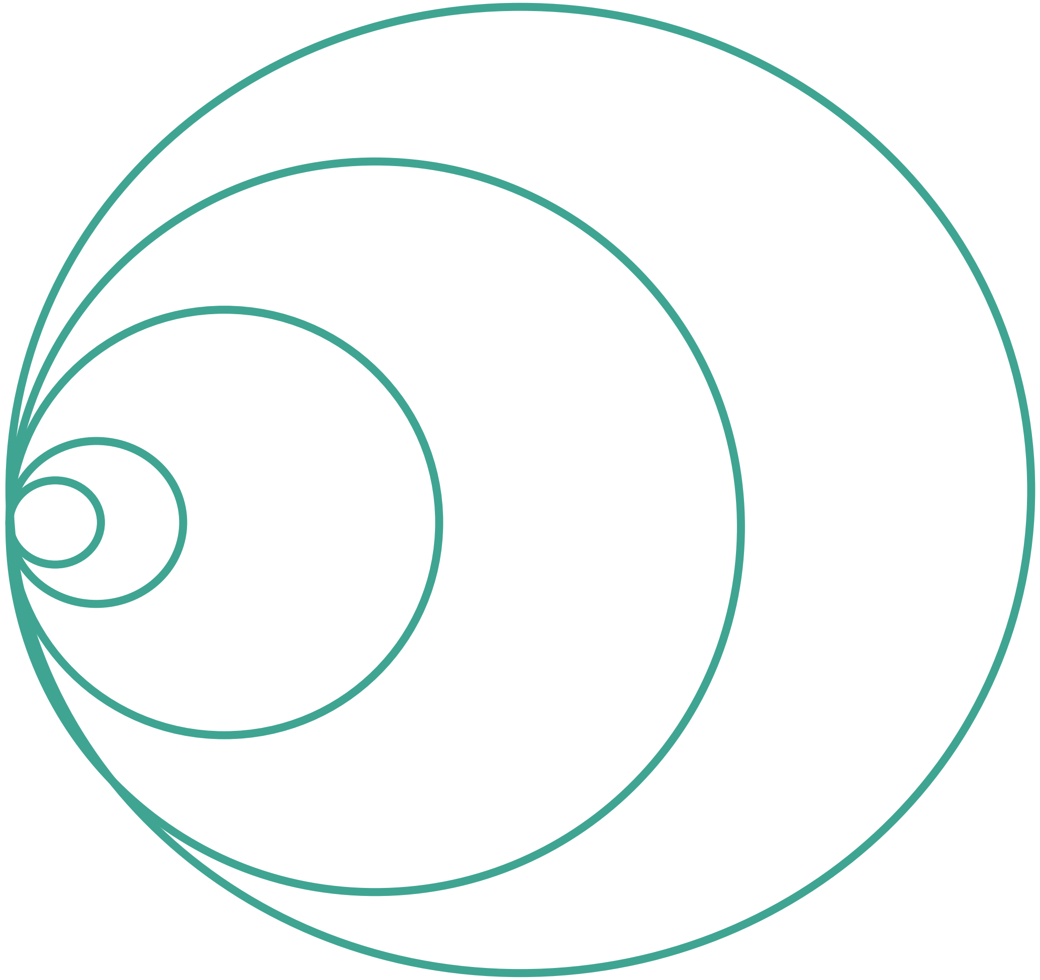
- {All order SMEFT} / {all order HEFT} (for analytic form factors)= 0, finite, or infinite? Conjecture1: finite.
- {All (including baroque and "ugly") UV BSM} / {all order SMEFT, HEFT} = 0, finite, or infinite? Conjecture2: 0 and part of them called Swampland.
- Conjecture3: it might be useless.



Our goal:

- ~~Most General~~
- ~~Interpreting Zeros~~

Explore & Discover



HEFT, SMEFT, and UV BSM, all are helping guide our explorations by providing benchmark directions!

Progress is in knowledge gain through measuring more independent quantities.

HH is exciting but not a single angle story

I am going to constantly change my theory language and contrast them in my talk.

I'll attempt to show cases w big picture in mind

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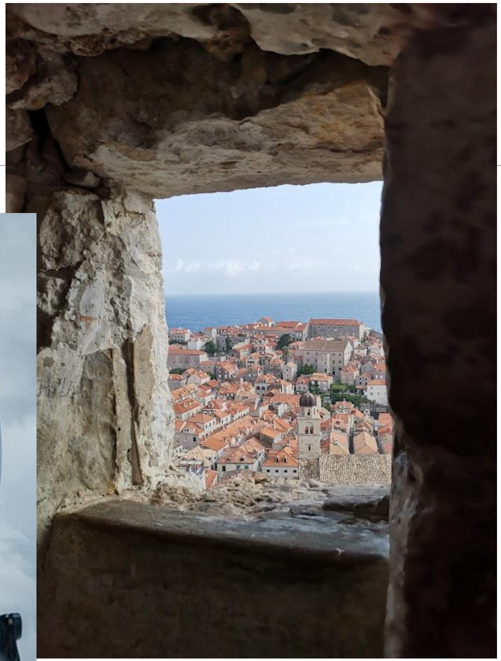

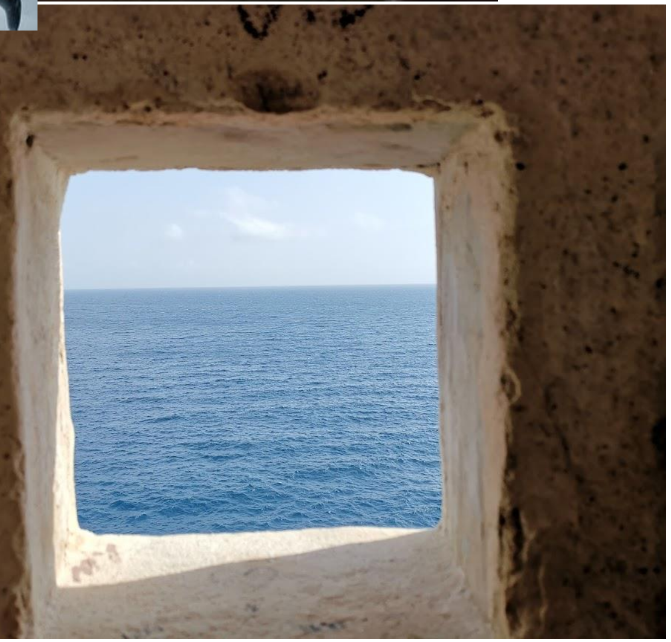

Higgs Pairs: probing a new force

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The only (trilinear) self-interaction between identical particles*

*w certain caveats

Higgs Pairs: probing a new force

The only (trilinear) self-interaction between identical particles*

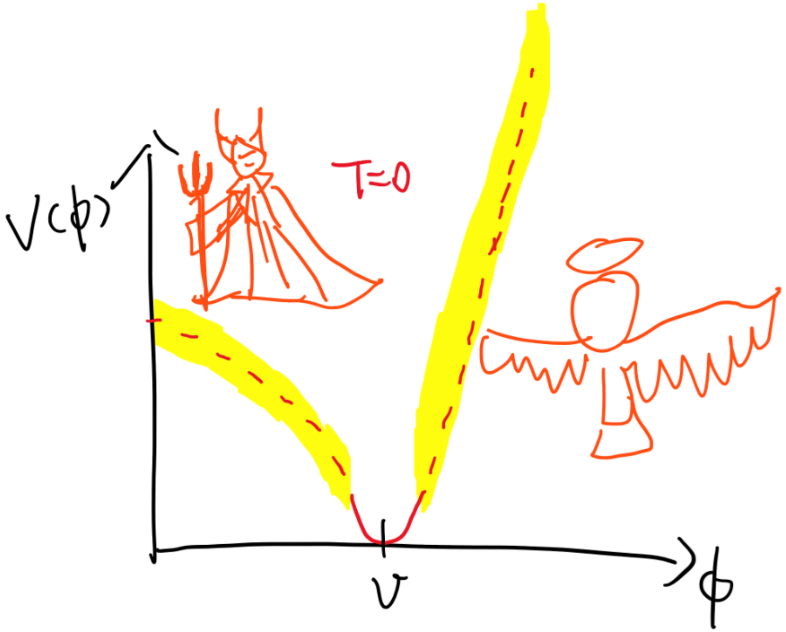
(If we want more motivations: concrete motivations need a clear context and many aspects.)

- Probing the Higgs potential
- Probing the nature of electroweak phase transition
- …

BSM Higgs Pairs

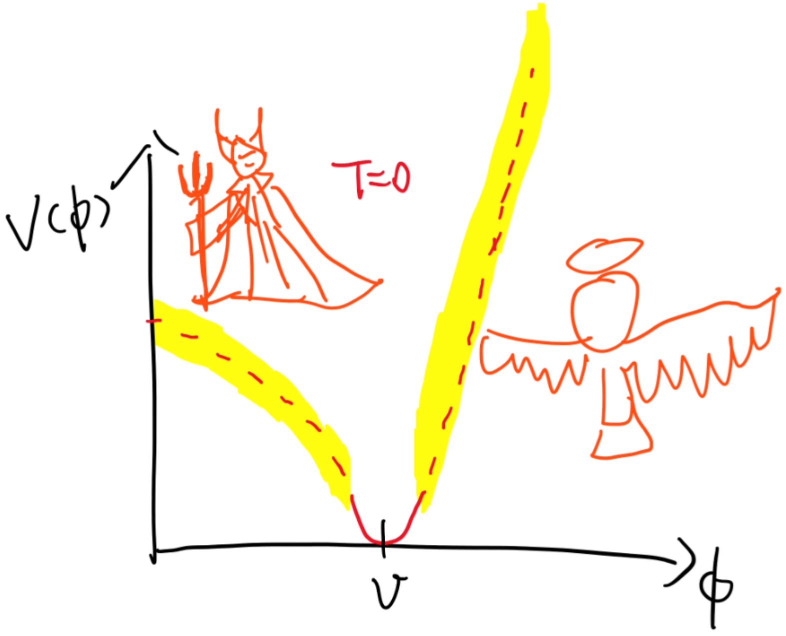
*w certain caveats

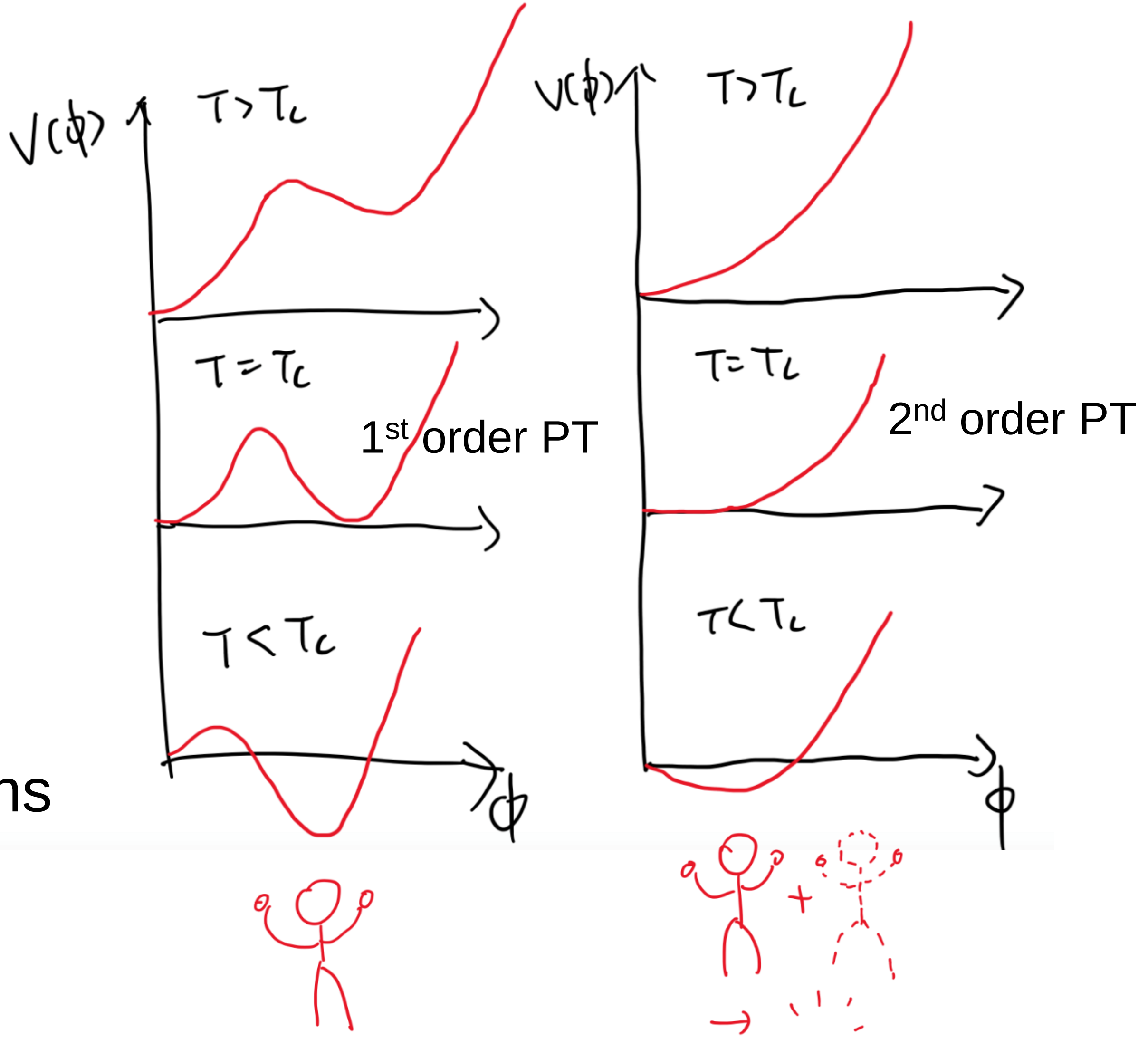
Higgs Precision and Electroweak Phase-Transition



What does the potential look like?
Is EWPT strong?
Higgs self-couplings determinations shed light.

Higgs Precision and Electroweak Phase-Transition





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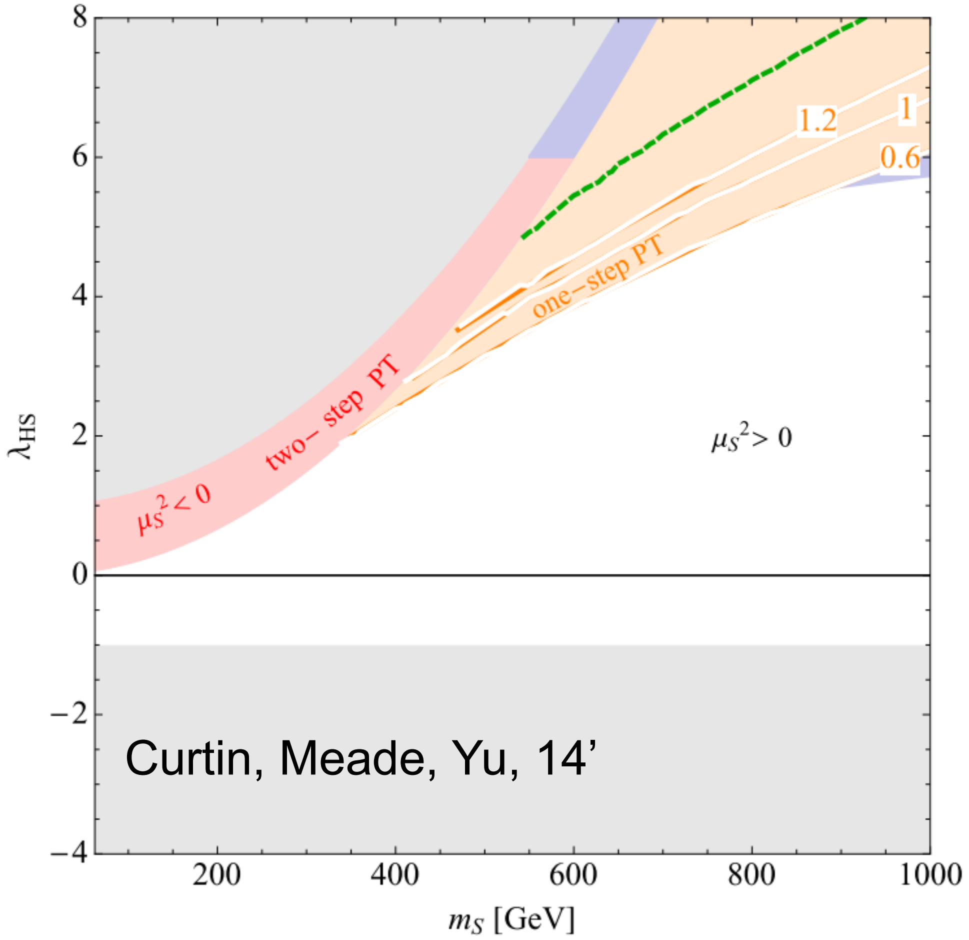
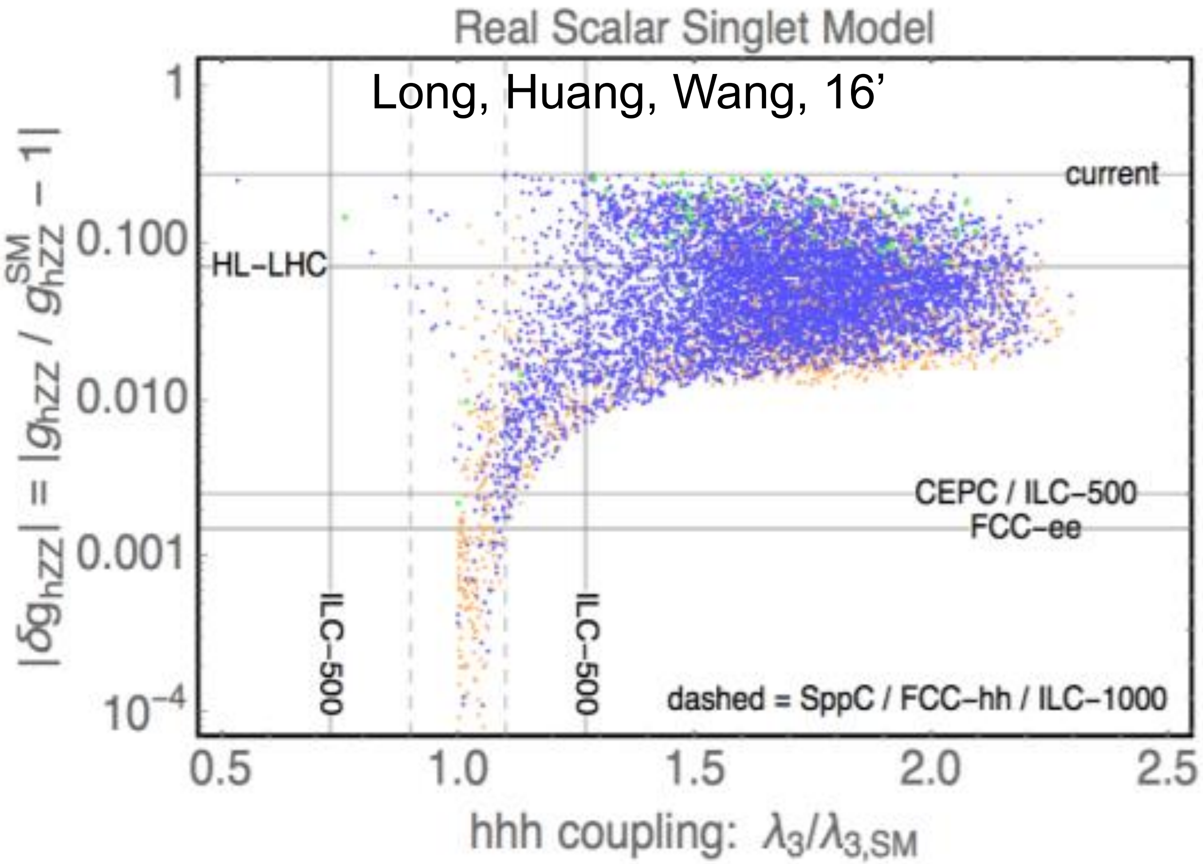
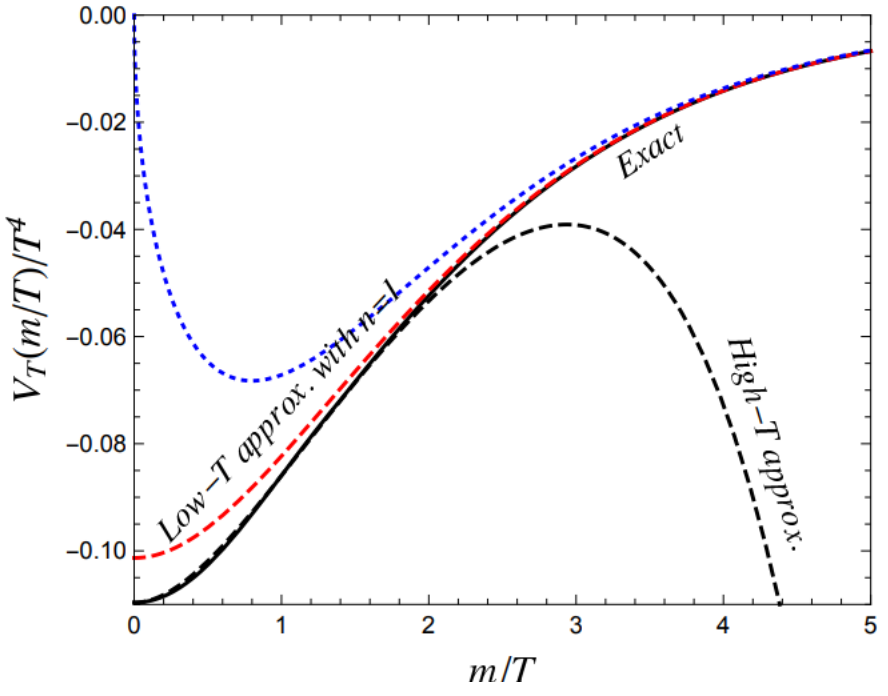
HH at future colliders





What’s the motivated parameter region (target)?



$$V_{tree} = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4 + \sum_{n=1}^{\infty} \frac{c_{4+2n}}{v^{2n}} \frac{m_h^2}{2v^2} \left(\frac{h^2}{2}\right)^{2+n}$$

$$V_{eff}(\phi, T) \equiv V_{tree}(\phi) + V_{CW}(m_i^2(\phi)) + V_T(m_i^2(\phi), T) + V_{ring}(m_i^2(\phi), T)$$

Jain, Lee, Son, 1709.03232

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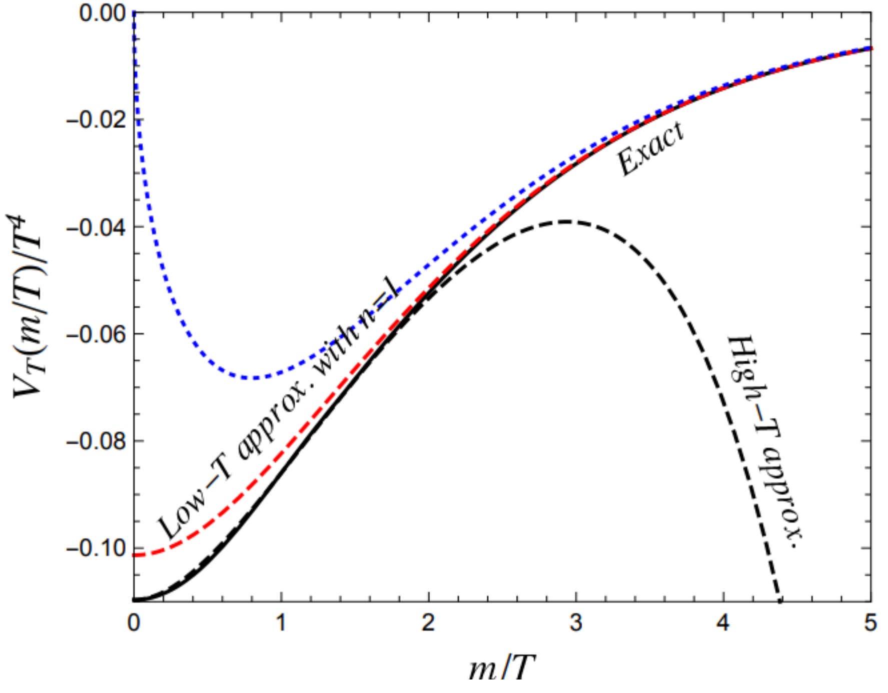

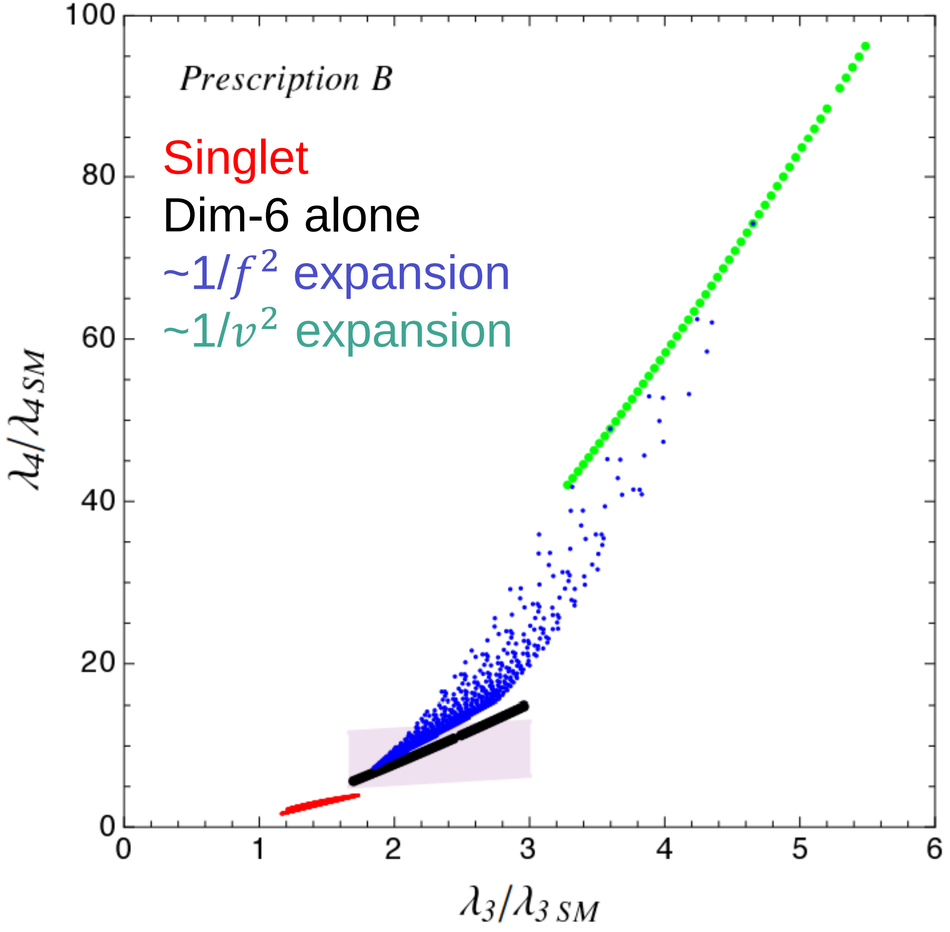

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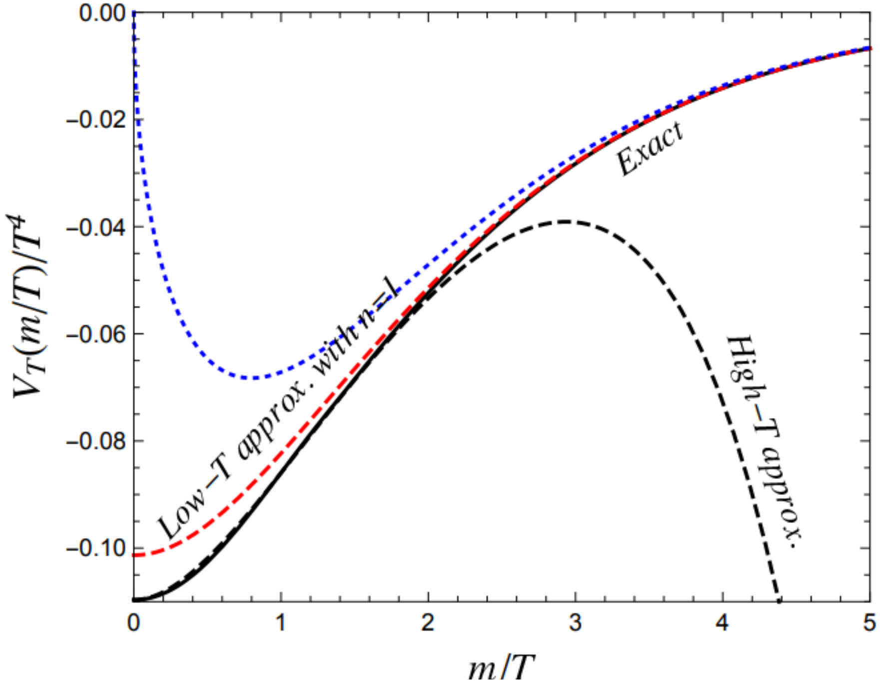

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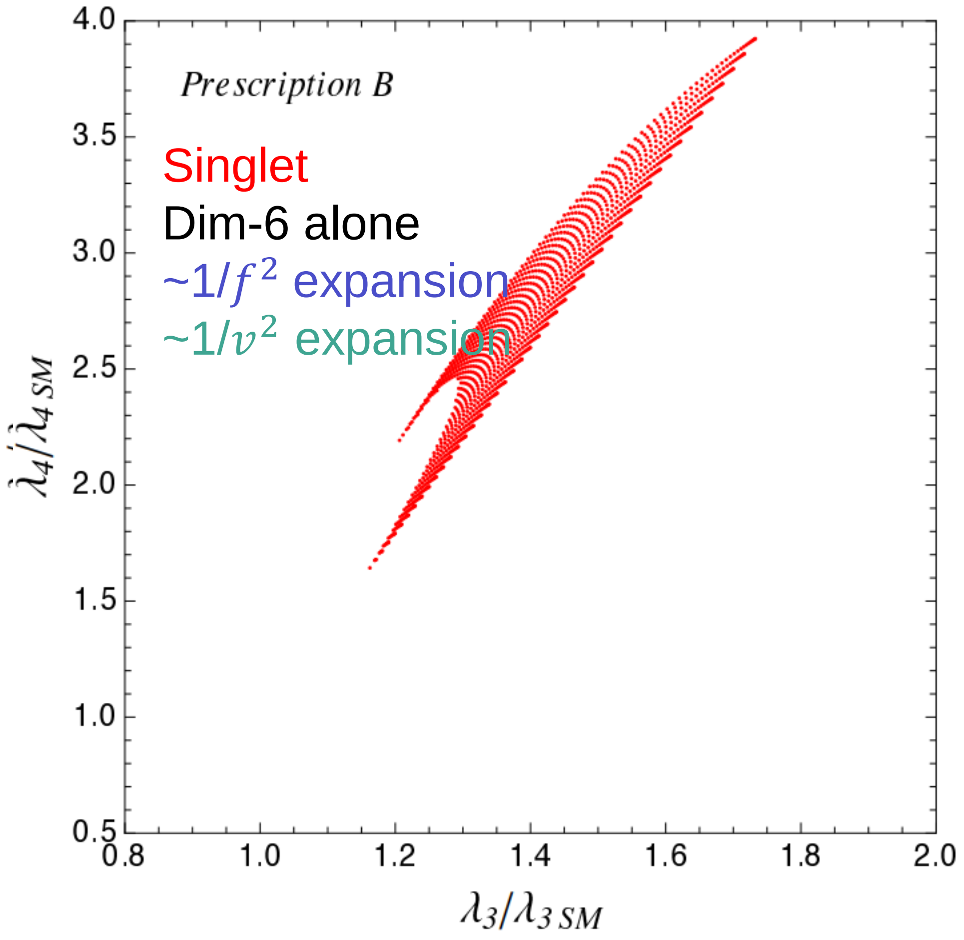

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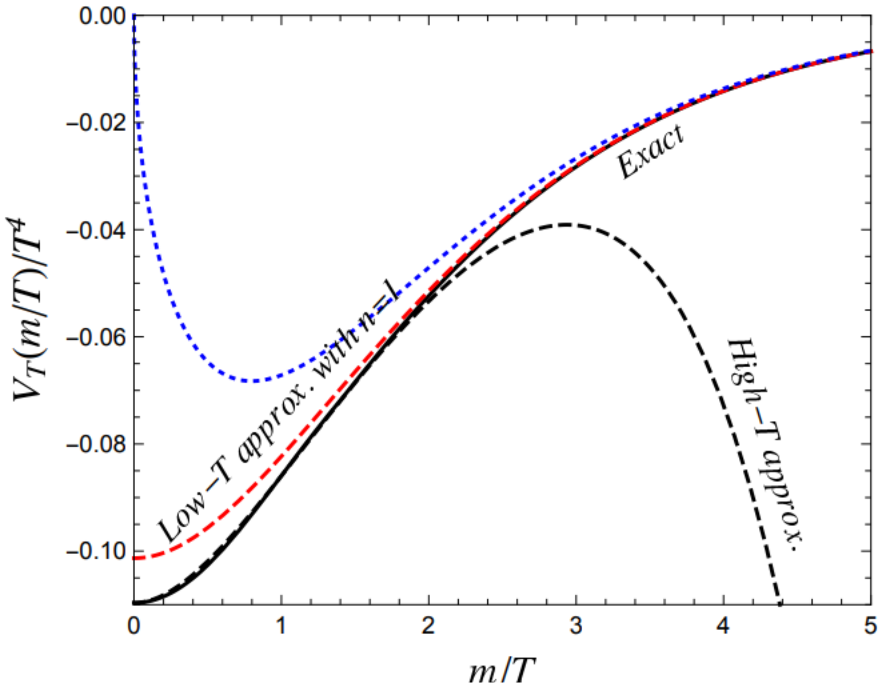

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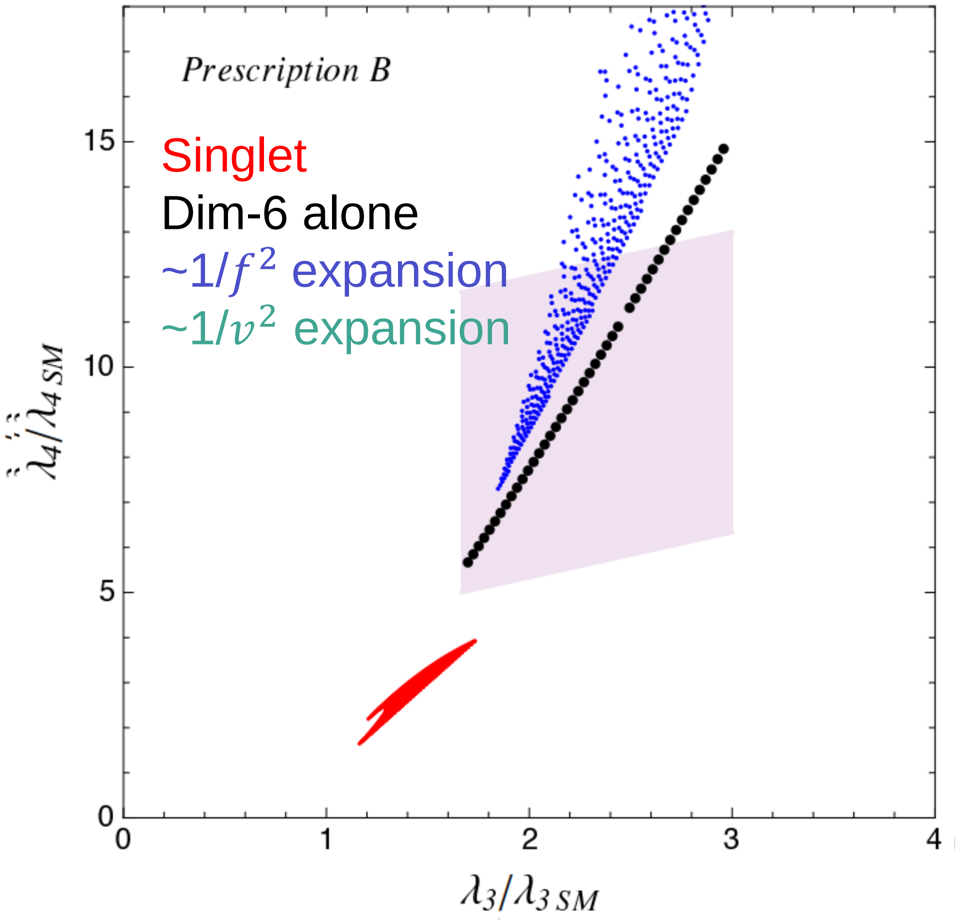
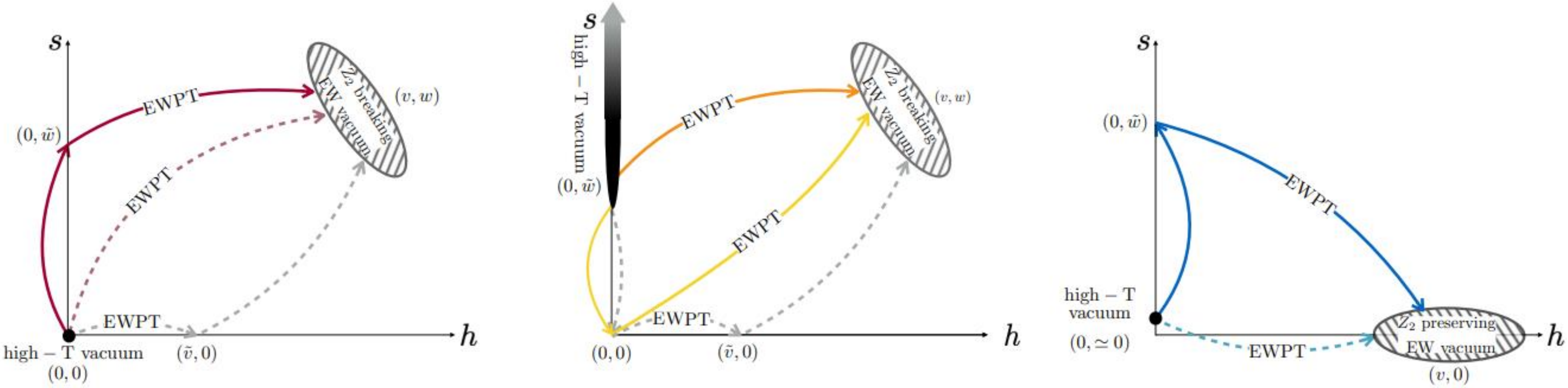


Jain, Lee, Son, 1709.03232

But EWPT is even more complex: phase patterns…



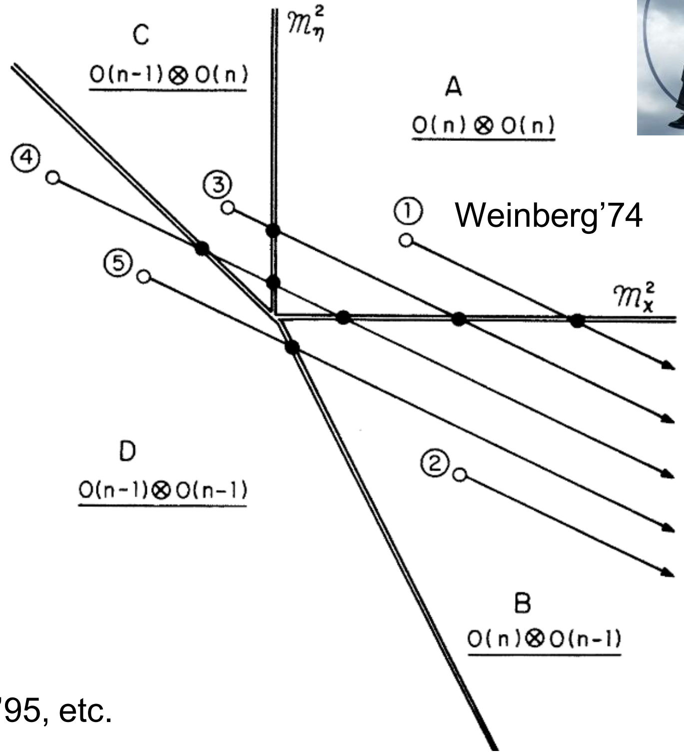
Carena, Kozaczuk, ZL, Ou, Ramsey-Musolf, Shelton, Wang, Xie, 2203.08206

Symmetry non-restoration

$$P(\chi,\eta)=\tfrac{1}{2}\mathfrak{M}_\chi{}^2\chi_A\chi_A+\tfrac{1}{2}\mathfrak{M}_\eta{}^2\eta_a\eta_a+\tfrac{1}{4}e_{\chi\chi}{}^2(\chi_A\chi_A)^2-\tfrac{1}{2}e_{\chi\eta}{}^2(\chi_A\chi_A)(\eta_a\eta_a)+\tfrac{1}{4}e_{\eta\eta}{}^2(\eta_a\eta_a)^2\,,$$

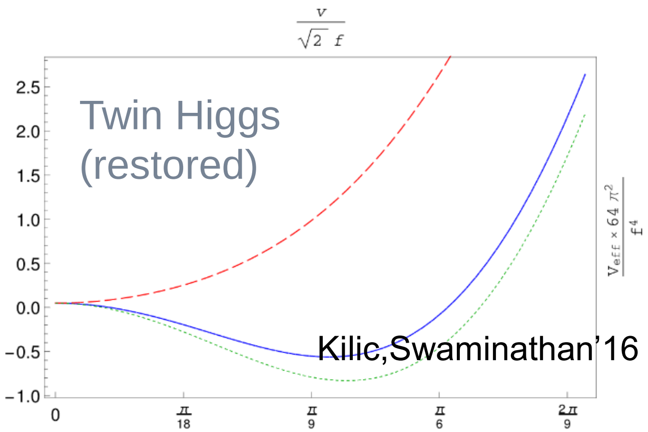
Symmetry non-restoration has be studied to discuss:

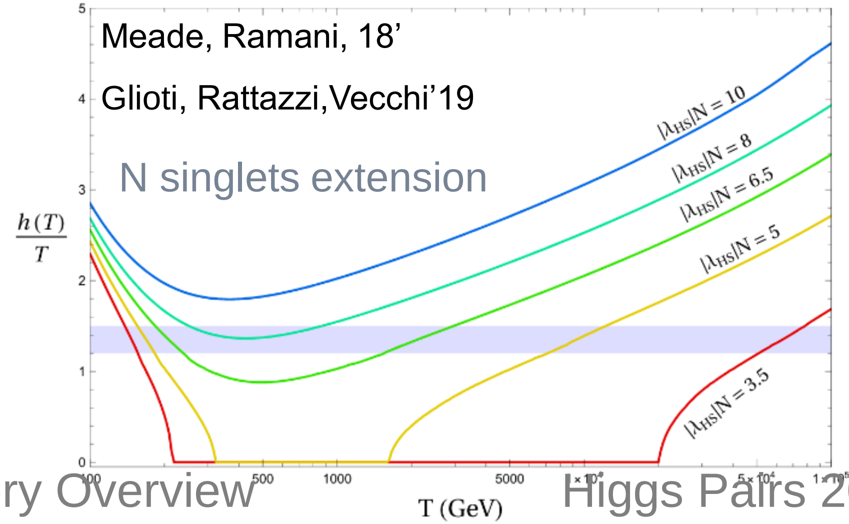
- High scale asymmetry creation;
- UV Model building has little dependence on EW scale physics;
- Avoid low scale constraints such as electron dipole moment on CP violation;

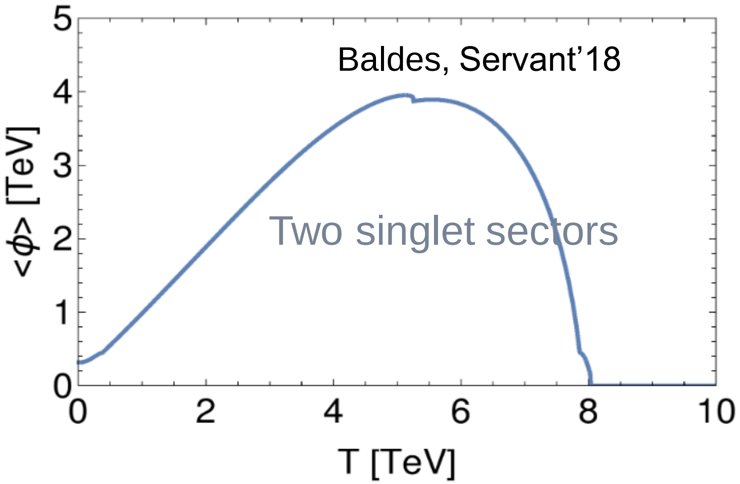


Mohapatra, Senjanov'79, Dvali , Senjanov'95, etc.

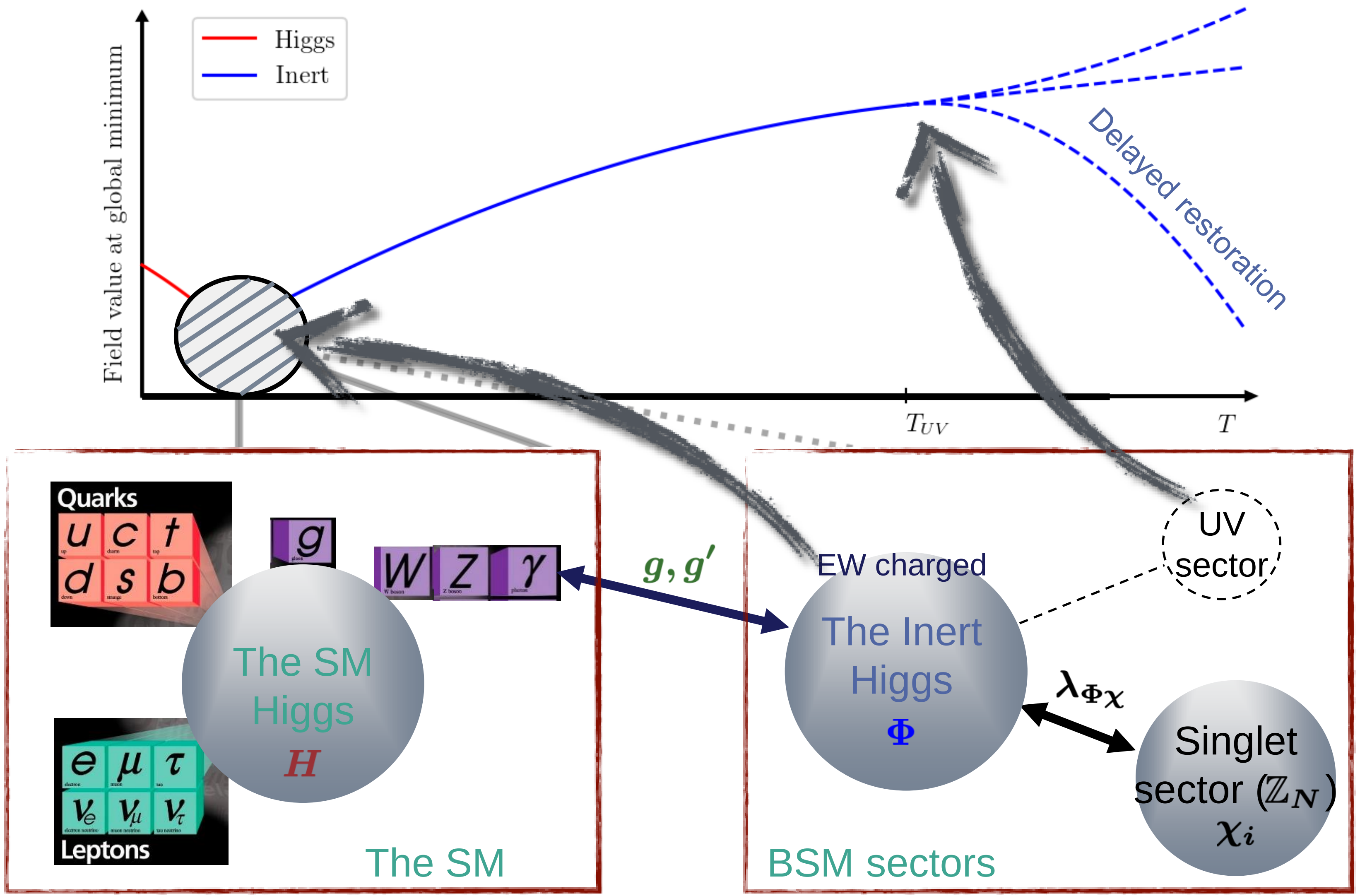
More recent development of EWNR







Even a rely of broken EW symmetry



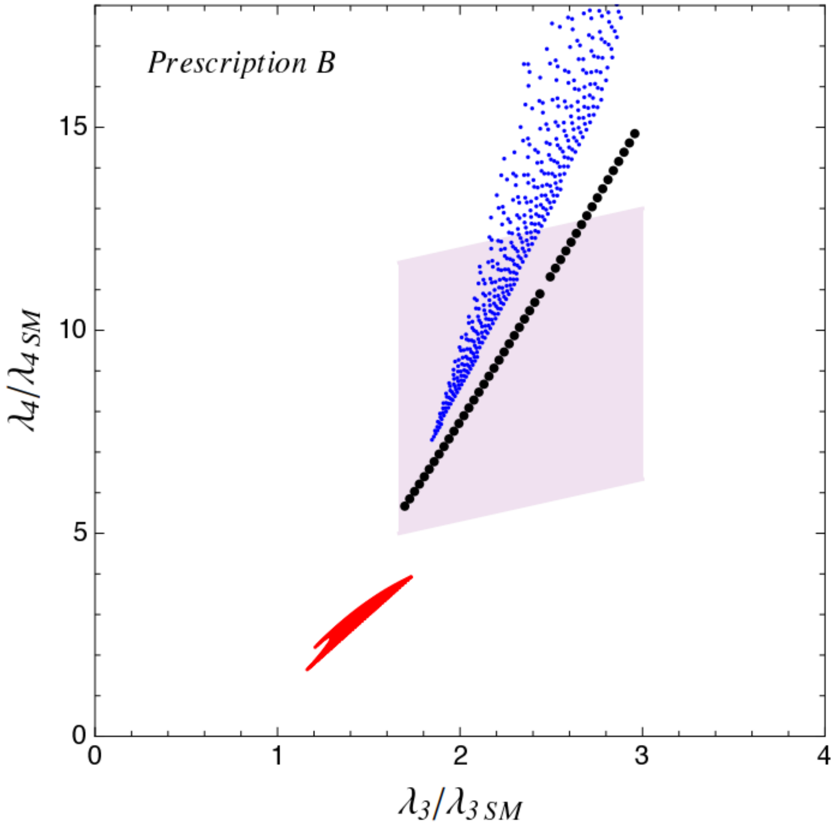
EW Symmetry Non-Restoration (EWNR)

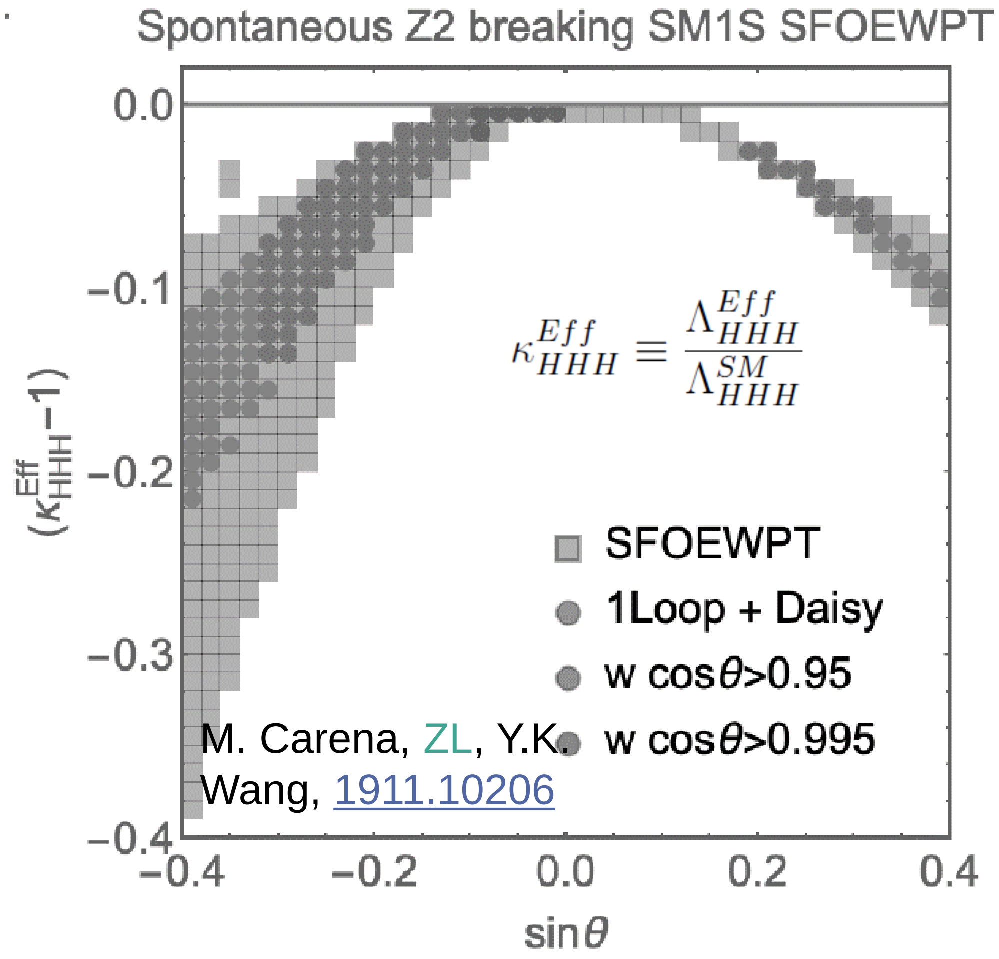
- High scale asymmetry creation;
- UV Model building has little dependence on EW scale physics;
- Avoid low scale constraints such as electron dipole moment on CP violation;

Carena, Krause, ZL, Wang, [2104.00638](2104.00638)

modified HH production

EWPT and EWBG will have imprints in the HH.
It is a direct, intuitive, and independent probe
that we are all excited to measure and discover.





M. Carena, ZL, Y.K. Wang, 1911.10206

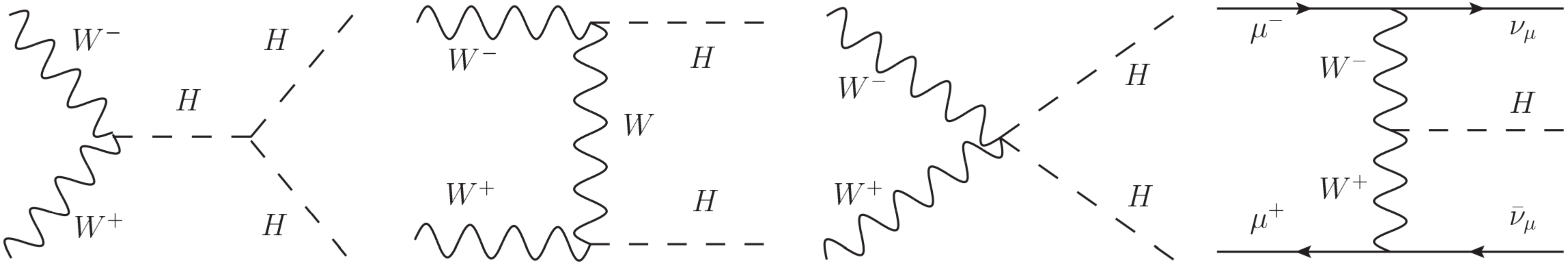
$$\Lambda^{\rm Eff}_{HHH} = \frac{2}{3}\sin\theta\frac{\hat{s}^2}{(\hat{s}-m_S^2)^2+i\Gamma_S m_S}\Lambda_{SHH} + \cos\theta\frac{\hat{s}^2}{(\hat{s}-m_H^2)^2+i\Gamma_H m_H}\Lambda_{HHH}$$
$$\simeq \frac{2}{3}\sin\theta\Lambda_{SHH} + \cos\theta\Lambda_{HHH}.$$

HH at Future Colliders

Multi-Higgs & Higgs Self-couplings

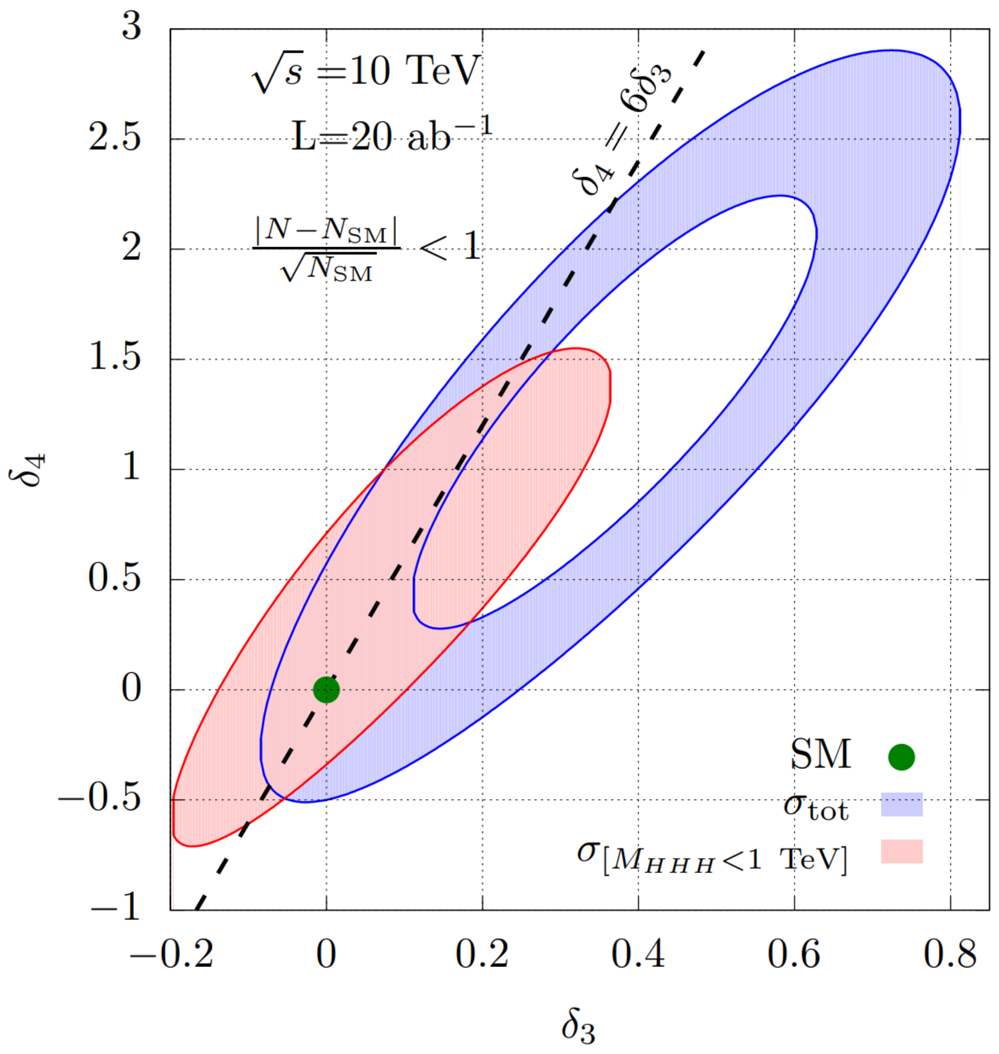
$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [41]
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2	3.6	5.3	(95% C.L.)
$WWHH$ ($\Delta\kappa_{W_2}$)	5.3%	1.3%	0.62%	0.41%	0.20%	5% [36]
$\Lambda/\sqrt{c_i}$ (TeV)	1.1	2.1	3.1	3.8	5.5	(68% C.L.)
HHH ($\Delta\kappa_3$)	25%	10%	5.6%	3.9%	2.0%	5% [22, 23]
$\Lambda/\sqrt{c_i}$ (TeV)	0.49	0.77	1.0	1.2	1.7	(68% C.L.)

Allow %-level trilinear Higgs measurements, and a consistent measurement between gauge boson-Higgs coupling measurements.



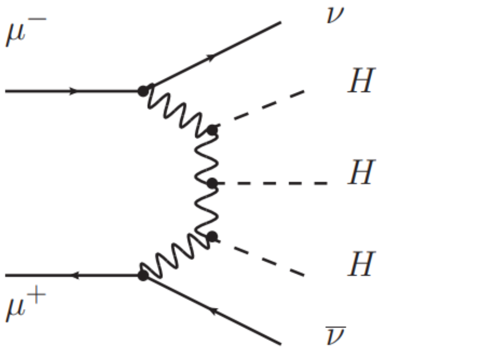
T. Han, D. Liu, I. Low, X. Wang, 2008.12204

Multi-Higgs & Higgs Self-couplings

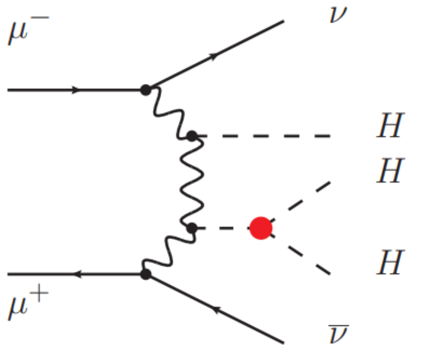


O(1) quartic determination possible.

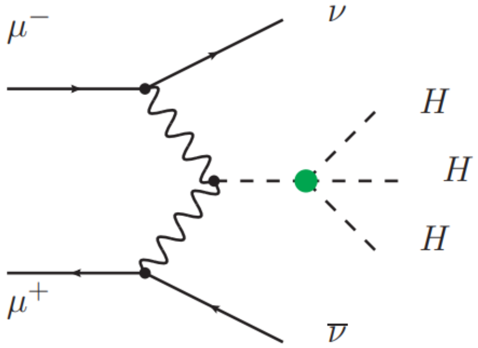
Chiesa, Maltoni, Mantani, Mele, Piccinini, 2003.13628



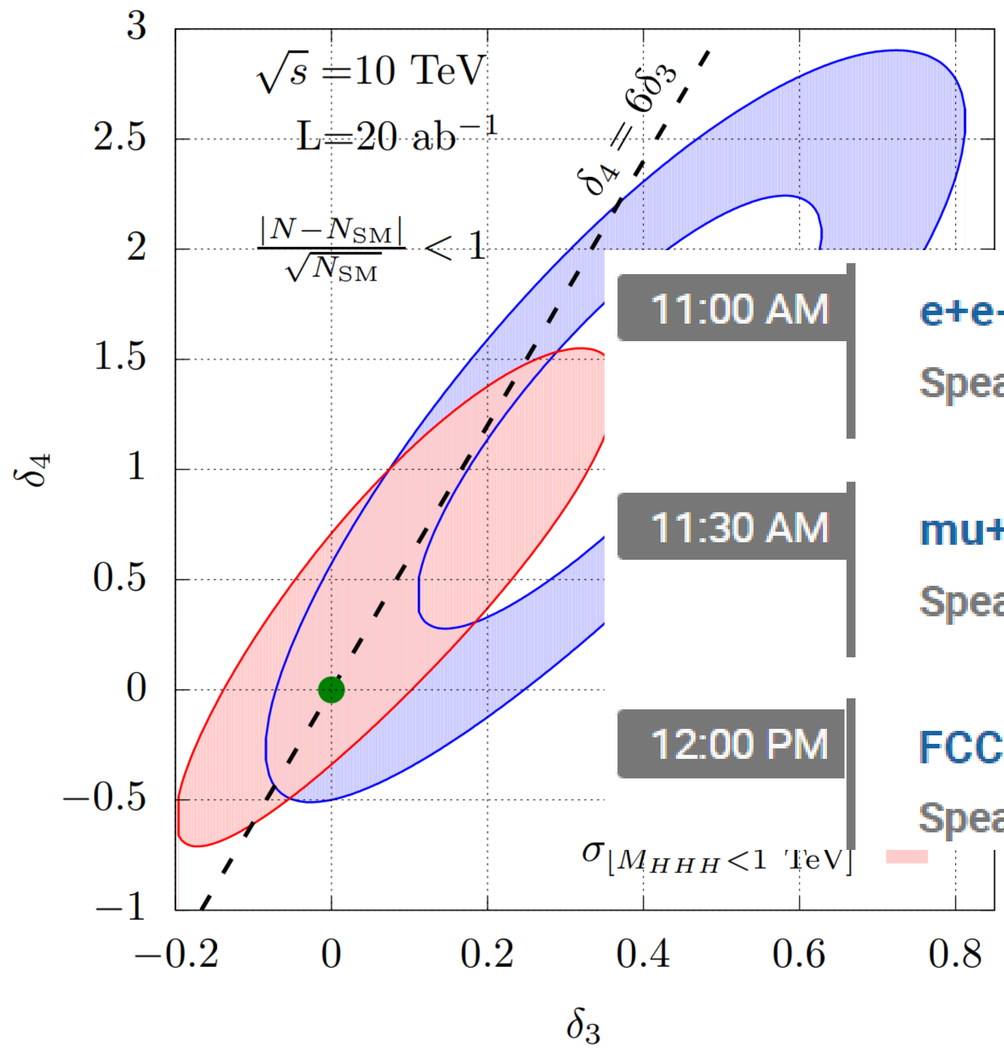
Correlated measurements of trilinear and quartic couplings reveals deep information about EFT and EWPT.



e.g, Huang, Joglekar, Wagner, 1512.00068, Falkowski, Gonzalez-Alonso, Grejio, Marzocca, M. Son, 1609.06312, Chang, Luty, 1902.05556,+Abu-Ajamieh, M. Chen, 2009.11293; DiHiggs review 1910.00012



Multi-Higgs & Higgs Self-couplings



O(1) quartic determination possible.

Chiesa, Maltoni, Mantani, Mele, Piccinini, 2003.12628

11:00 AM

e+e- colliders

Speaker: Aidan Robson (University of Glasgow (GB))

11:30 AM

mu+ mu- colliders

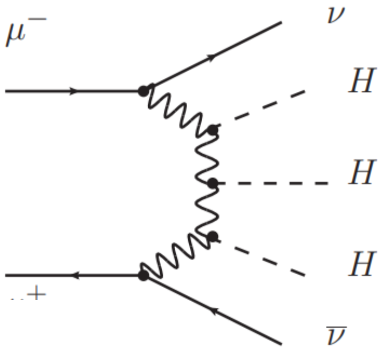
Speaker: Donatella Lucchesi (Universita e INFN, Padova (IT))

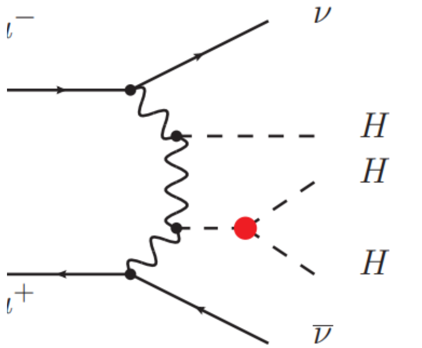
12:00 PM

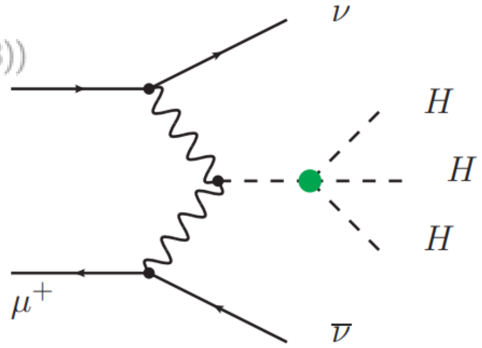
FCC-hh

Speaker: Matthew James Sullivan (University of Liverpool (GB))

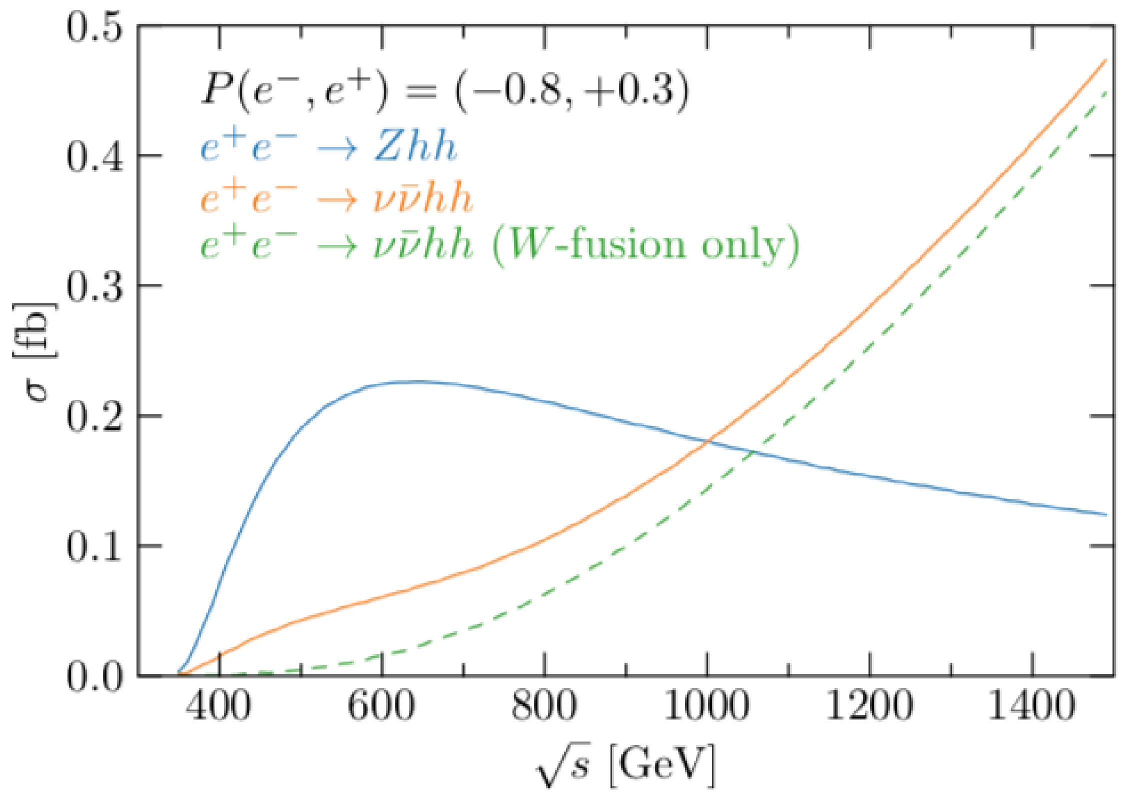
Grejio, Marzocca, M. Son, 1609.06312, Chang, Luty, 1902.05556,+Abu-Ajamieh, M. Chen, 2009.11293; DiHiggs review 1910.00012

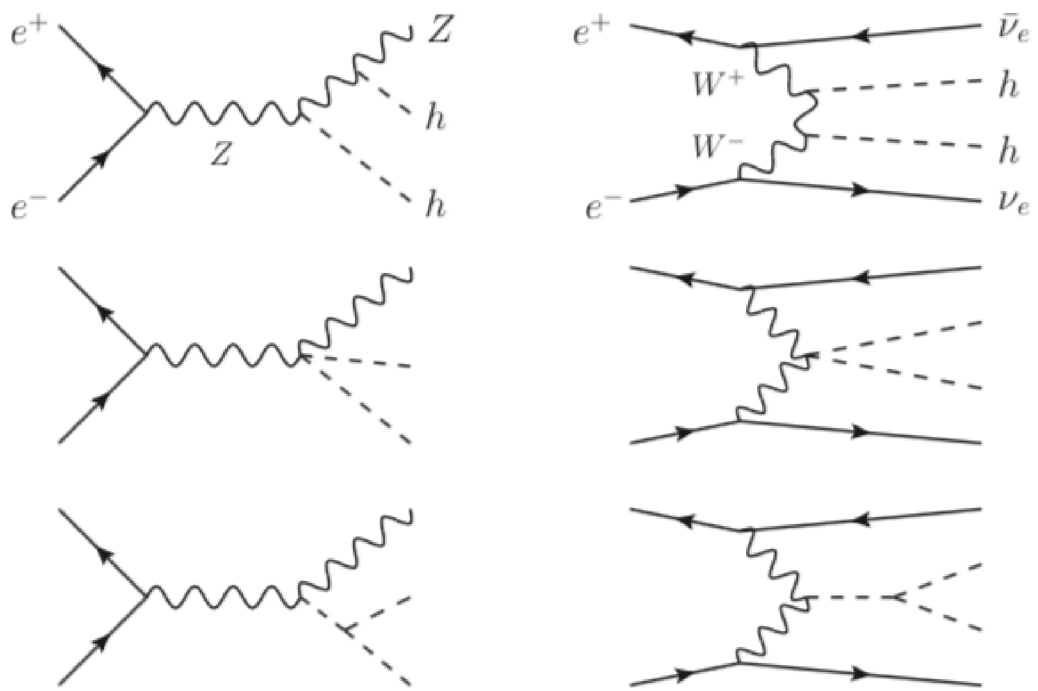






Identifying observables: 2H processes

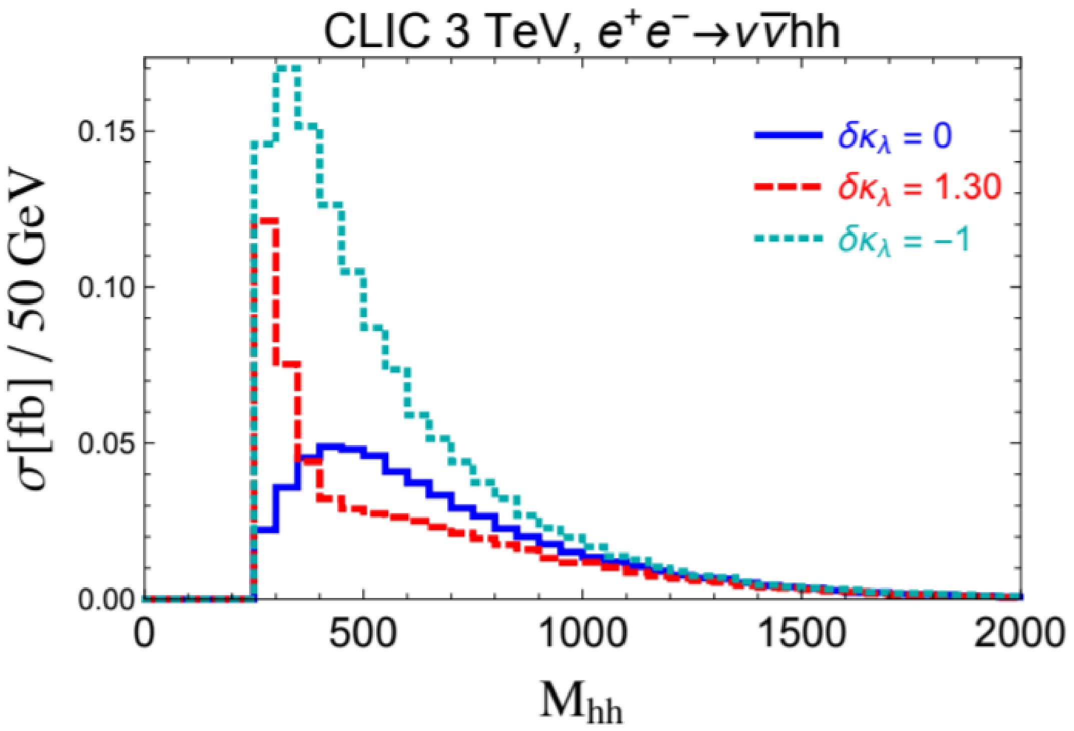


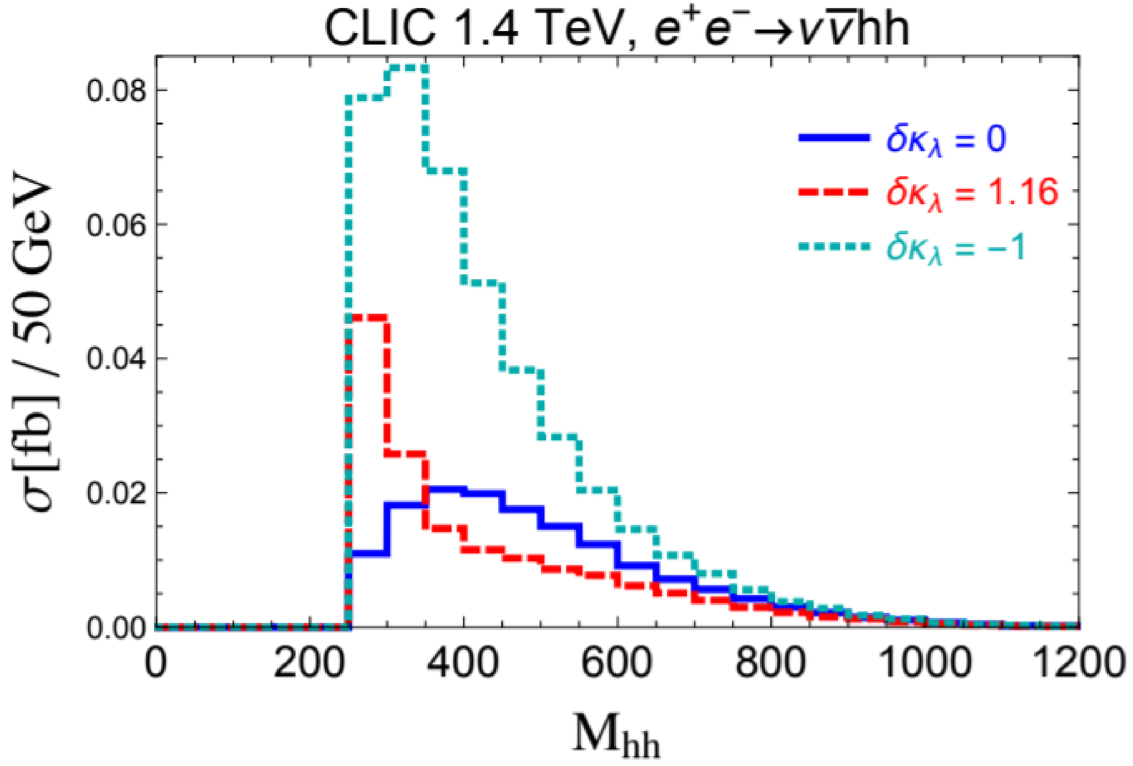


- Tree-level probes for the Higgs self-couplings are *NOT* kinematically accessible at their baseline running (250 GeV for ILC and 350 GeV for CLIC), we need to think about alternative probes.
- Help understanding the staging and complementarity between different running energies.

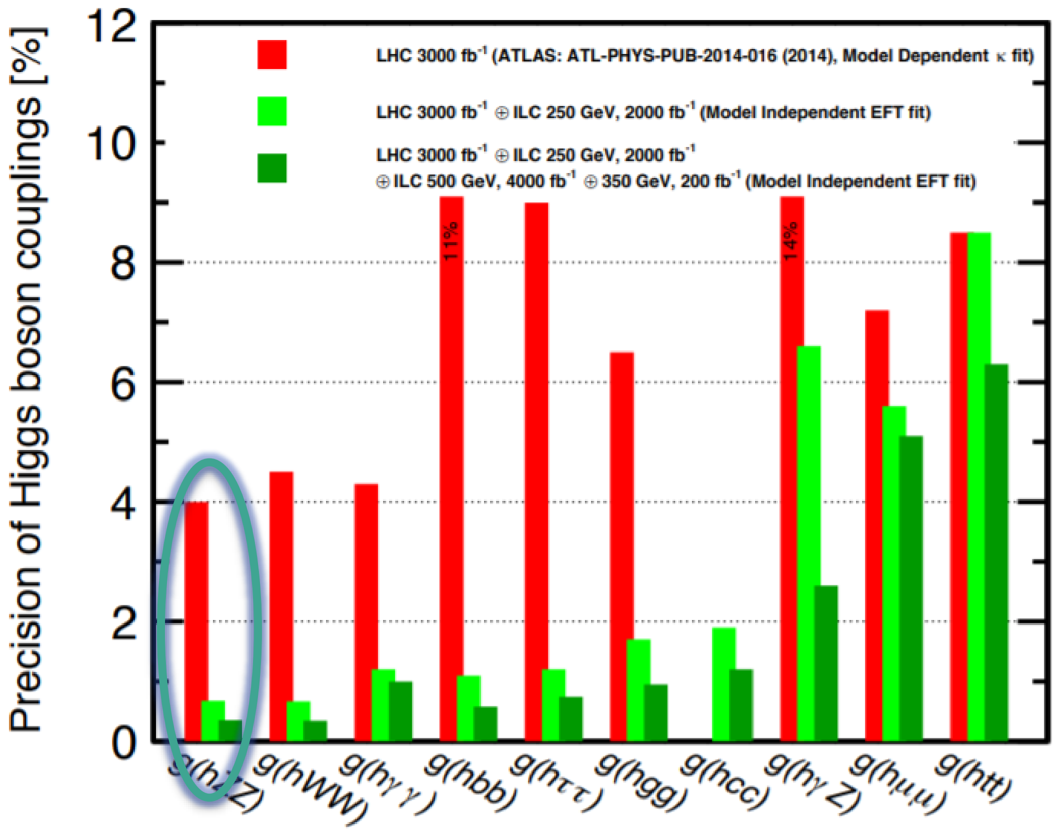
More observables in 2h

Differential observables help resolve interplays between different diagrams.





Finding probes for Higgs trilinear at Linear Colliders

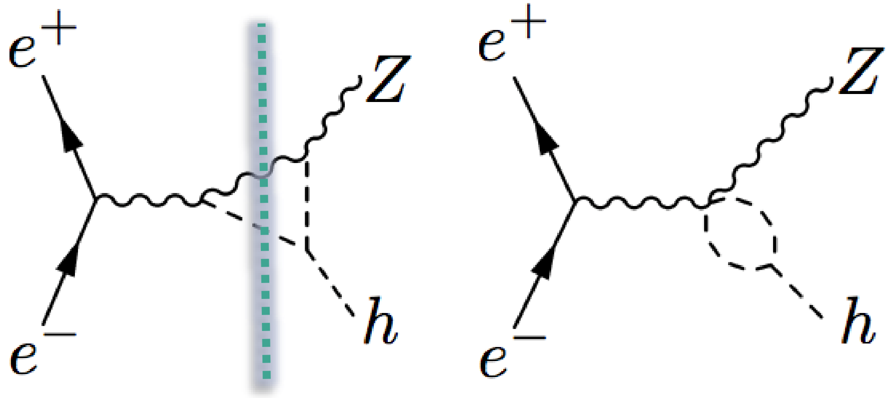


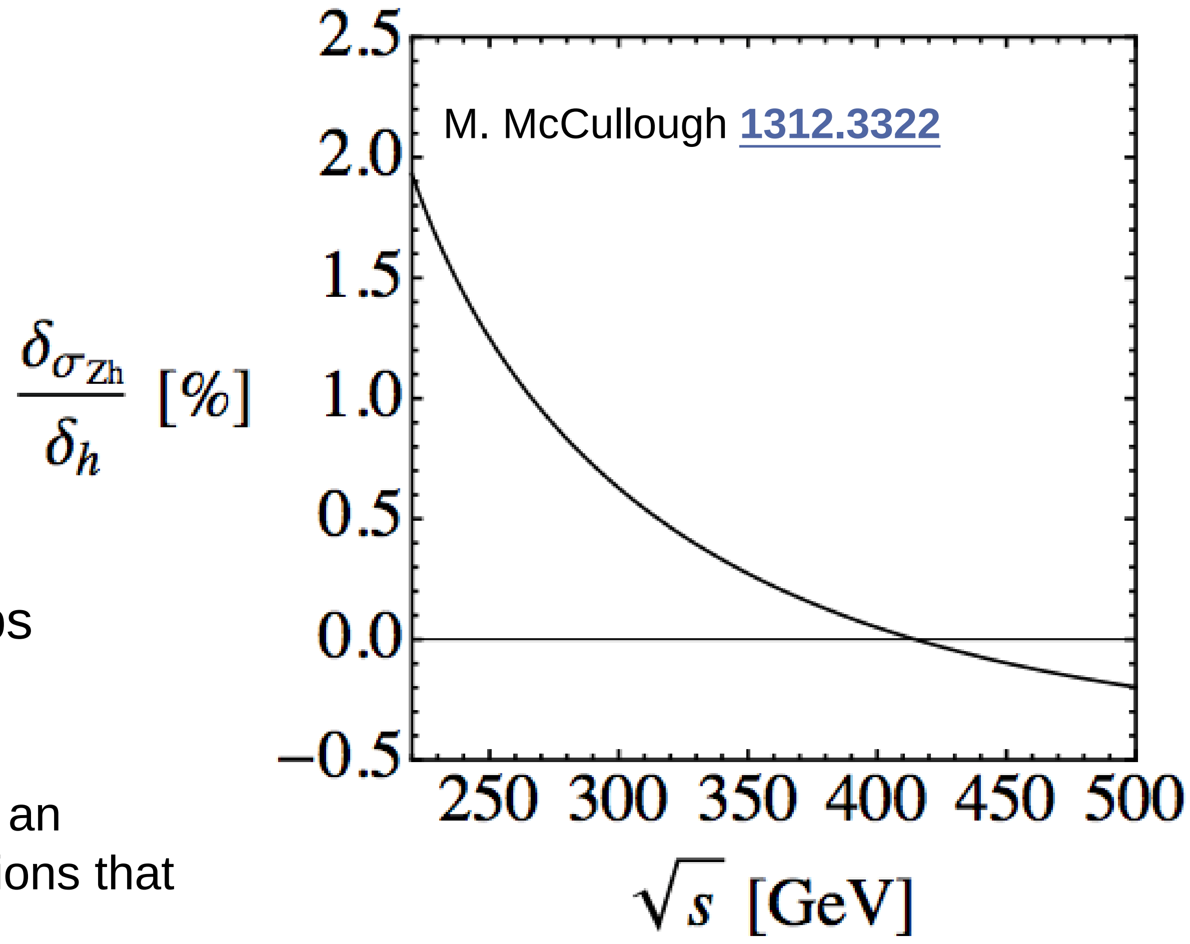
LCC Physics WG, arXiv: 1710.07621

$e^+e^- \to ZH$, the best determined process without dependence on the exclusive decay of the Higgs boson

Use precision to gain knowledge (directly) accessible at higher energy.

Constraints from $e^+e^- \to ZH$





A natural/free threshold enhancement helps enhance the sensitivity;

O(30%) precision achievable, at 5 ab^-1 for an unpolarized e+e- machine, with some assumptions that we will break down in the next few slides;

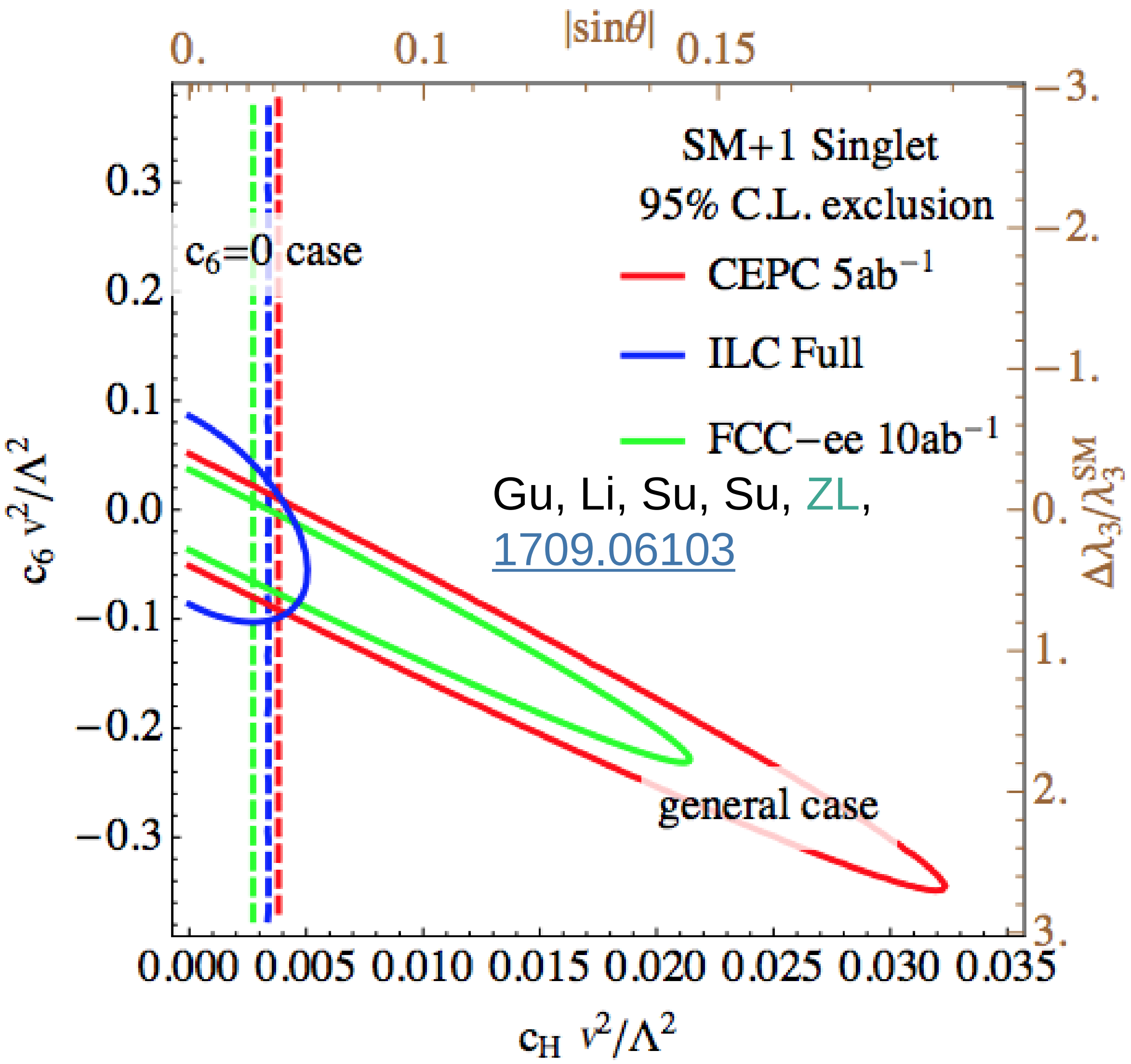
Hard to only generate h^3 (in SMEFT $|H^+H|^3$)

Singlet Extension of the SM,
EFT and UV Model

$$\Delta\mathcal{L}_{\text{eff,1-loop}} = \frac{1}{2(4\pi)^2}\frac{1}{m^2}\left[-\frac{1}{12}(P_\mu U)^2 - \frac{1}{6}U^3\right]$$
$$= \frac{1}{(4\pi)^2}\frac{1}{m^2}\left(\frac{k^2}{12}\mathcal{O}_H - \frac{k^3}{12}\mathcal{O}_6\right).$$

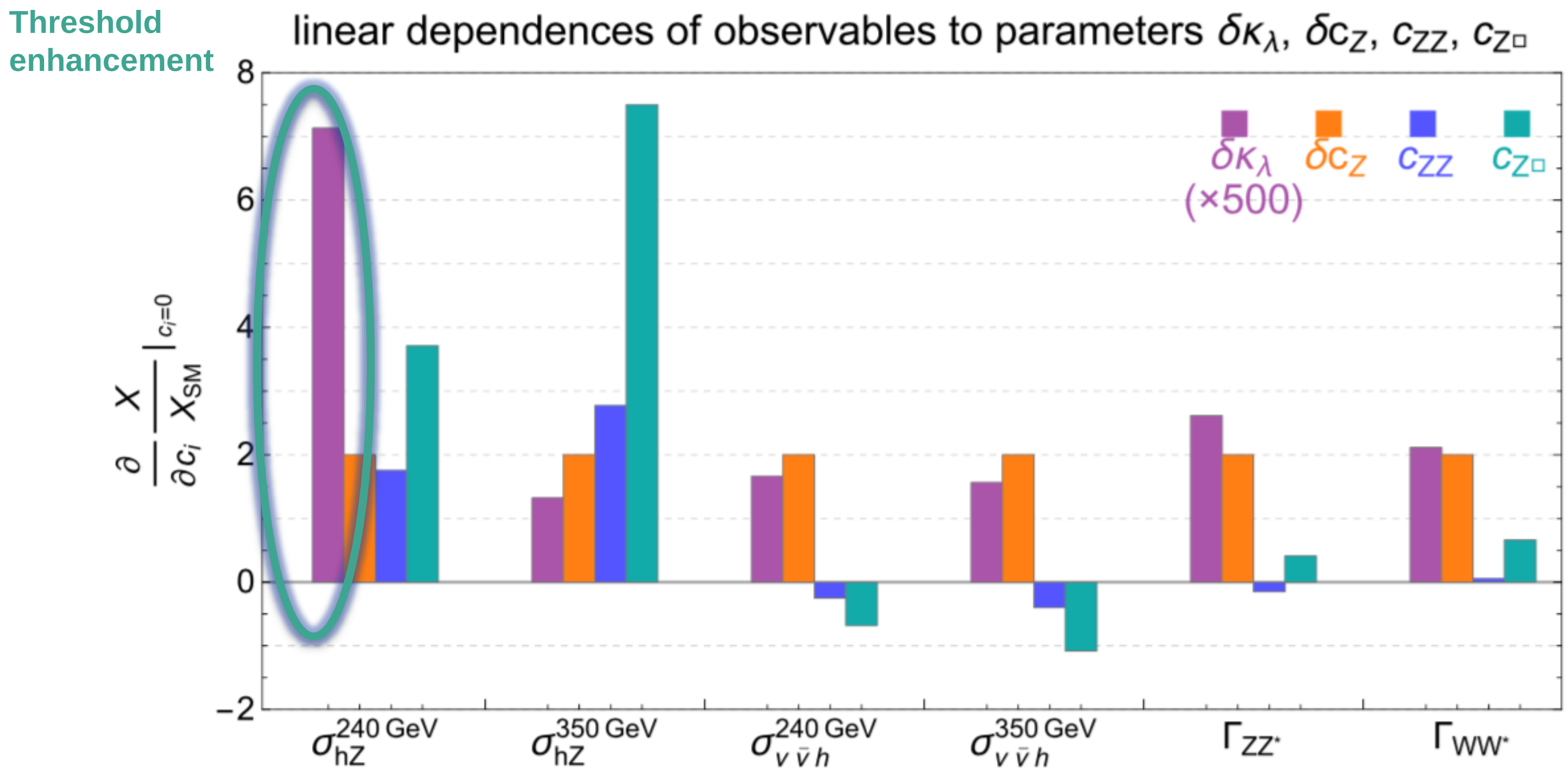
$$\Delta\mathcal{L}_{\text{eff,tree}} = -A|H|^2\Phi_c + \frac{1}{2}\Phi_c\left(-\partial^2 - m^2 - k|H|^2\right)\Phi_c - \frac{1}{3!}\mu\Phi_c^3 - \frac{1}{4!}\lambda_\Phi\Phi_c^4$$
$$\approx \frac{1}{2m^2}A^2|H|^4 + \frac{A^2}{m^4}\mathcal{O}_H + \left(-\frac{kA^2}{2m^4} + \frac{1}{3!}\frac{\mu A^3}{m^6}\right)\mathcal{O}_6.$$

$$\Delta\mathcal{L} = \frac{1}{2}(\partial_\mu\Phi)^2 - \frac{1}{2}m^2\Phi^2 - A|H|^2\Phi - \frac{1}{2}k|H|^2\Phi^2 - \frac{1}{3!}\mu\Phi^3 - \frac{1}{4!}\lambda_\Phi\Phi^4.$$



Gu, Li, Su, Su, ZL,
1709.06103

More observables (that are sensitive to Higgs trilinear)



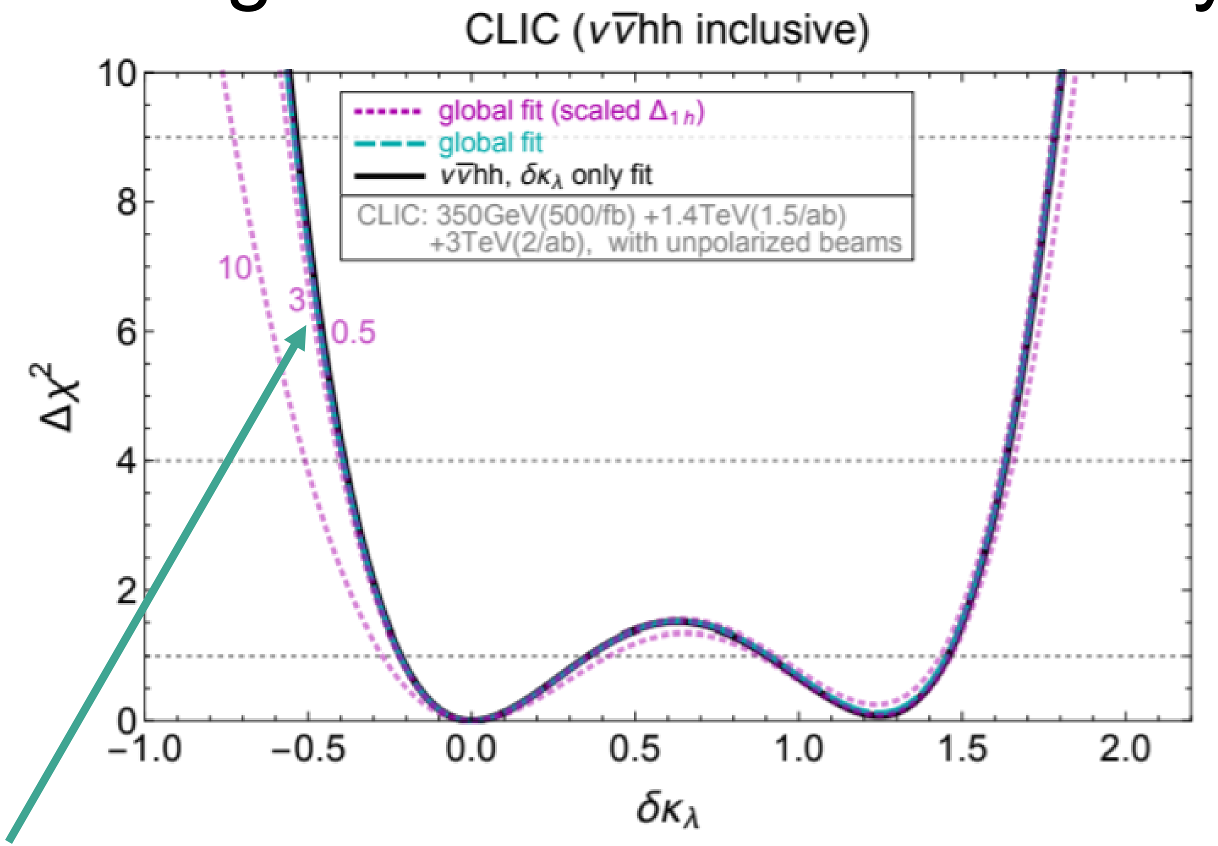
New probes:
Cross sections at different c.o.m. energies, 240 GeV & 350 GeV ;
Different production processes, ZH & WW-fusion;
Decay processes, WW^* and ZZ^*;

C_1	ZZ	WW	$\gamma\gamma$	gg	$f\bar{f}$
on-shell h decay	0.0083	0.0073	0.0049	0.0066	0

C_1 linear dependence on trilinear modifications
G. Degrassi, P. Giardino, F. Maltoni, D. Pagani, 1607.04251

Taking CLIC for example (also applies to 3 TeV μC)

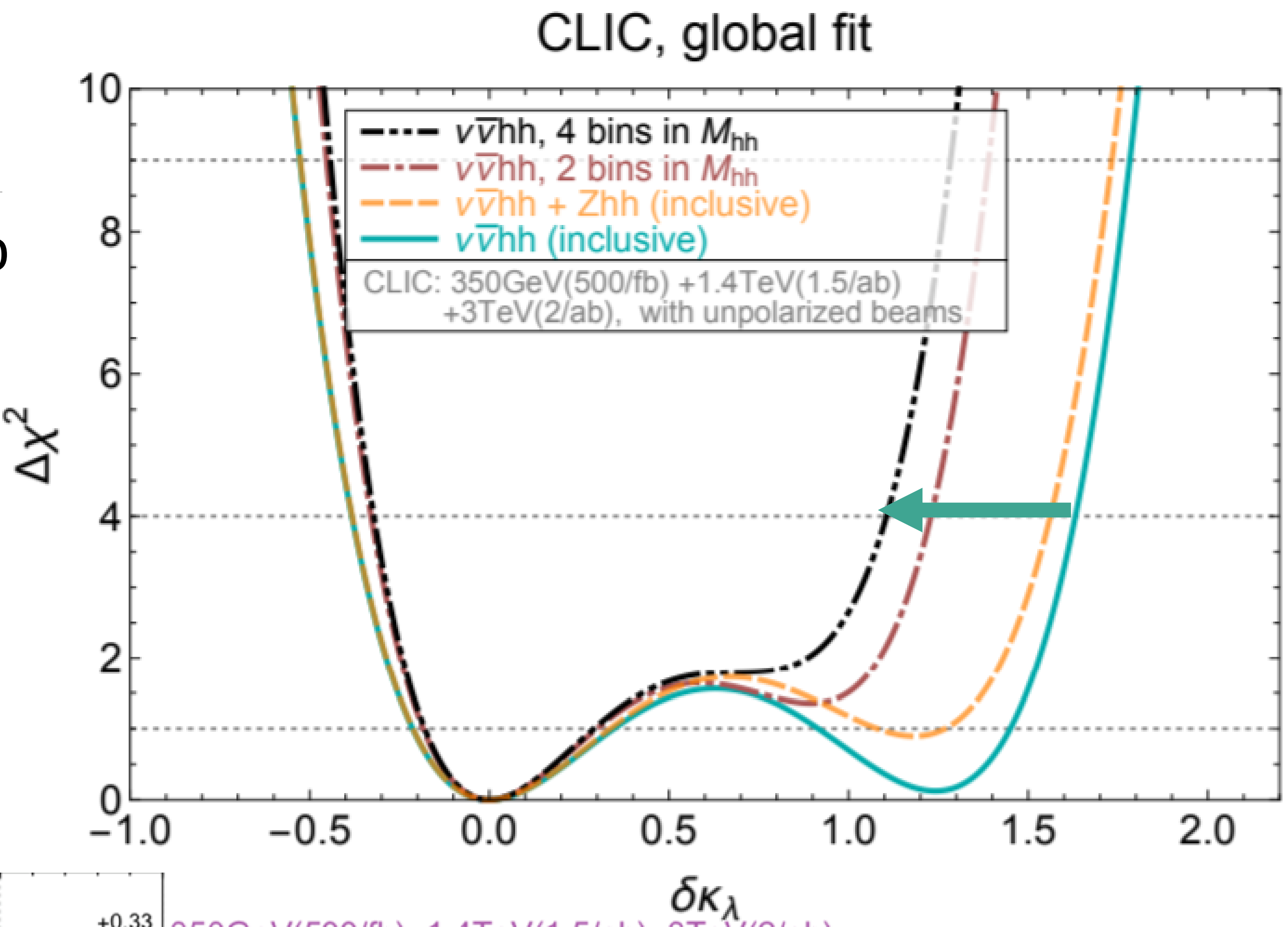
Single parameter fit and global fit doesn't diff visibly so only show global here.

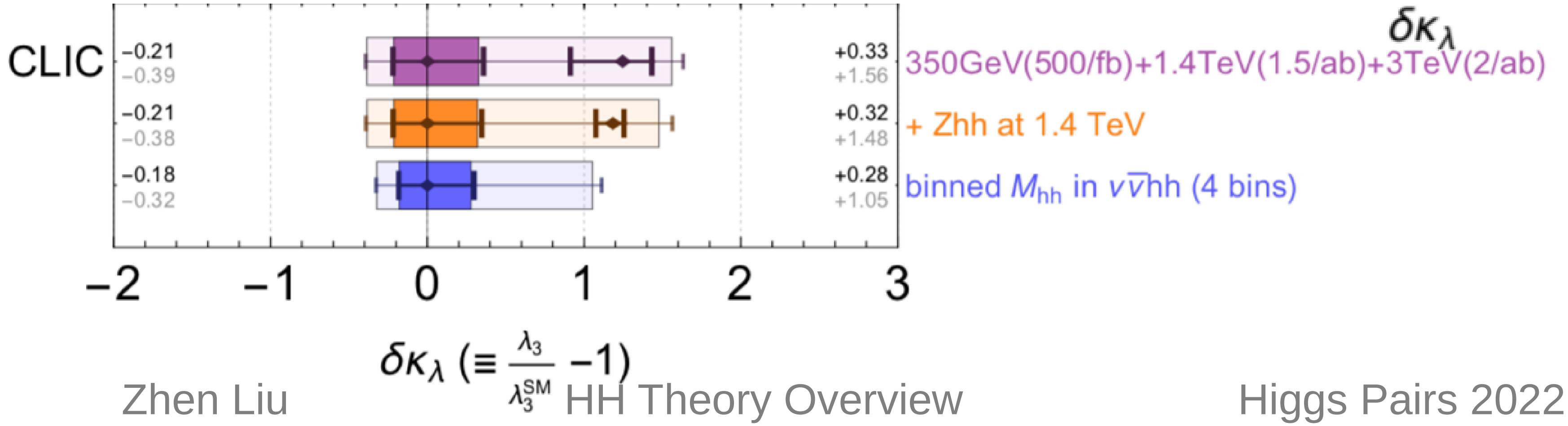


Varying 1H inputs between 0.5~3 do not change the result much: implying at CLIC 1H is not yet sensitive to trilinear but good enough to not affect the trilinear extrapolation from 2H processes

CLIC results

- 1H not good enough to derive trilinear limits, but also not limiting;
- More modes helps;
- Differential helps;

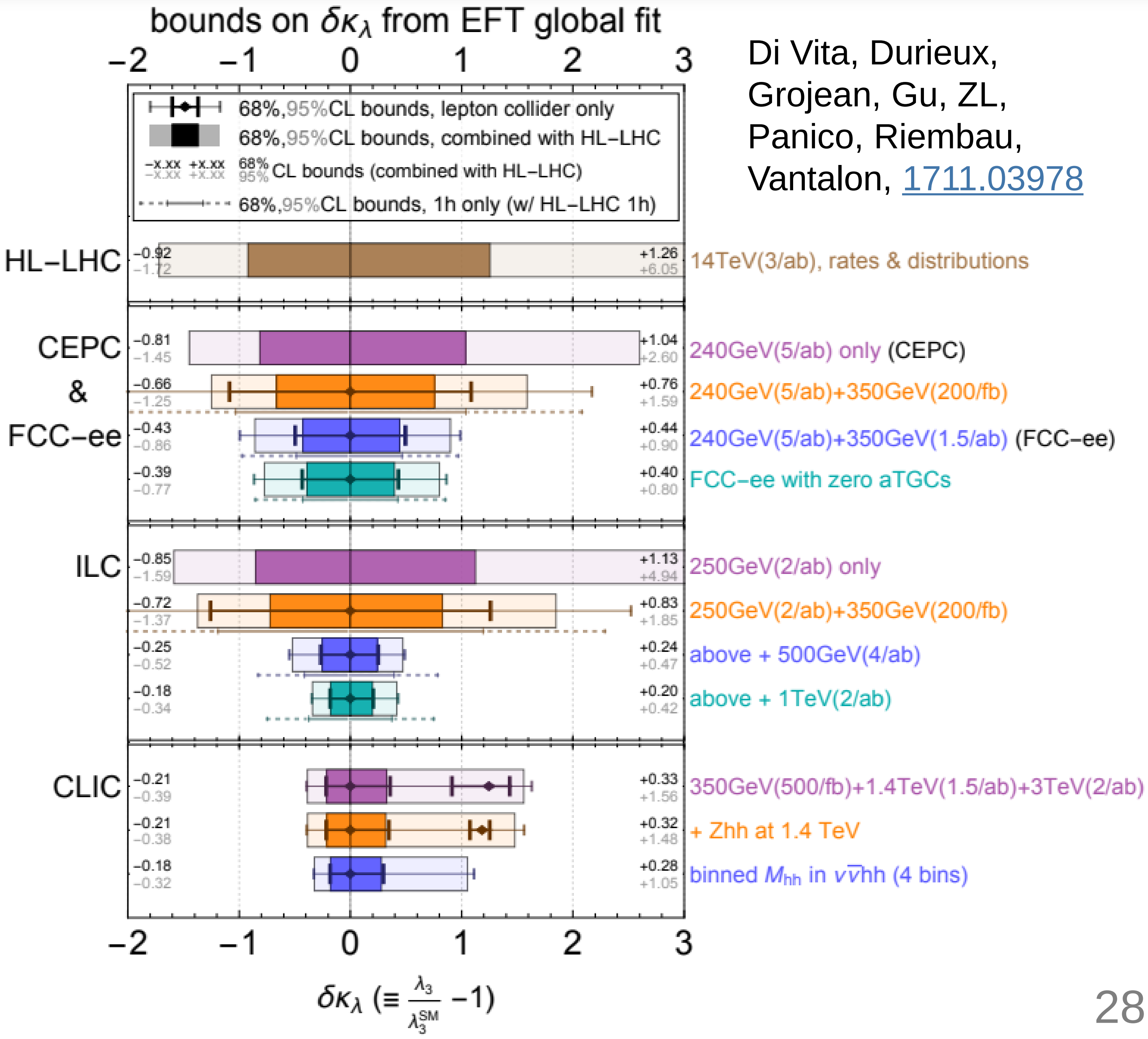




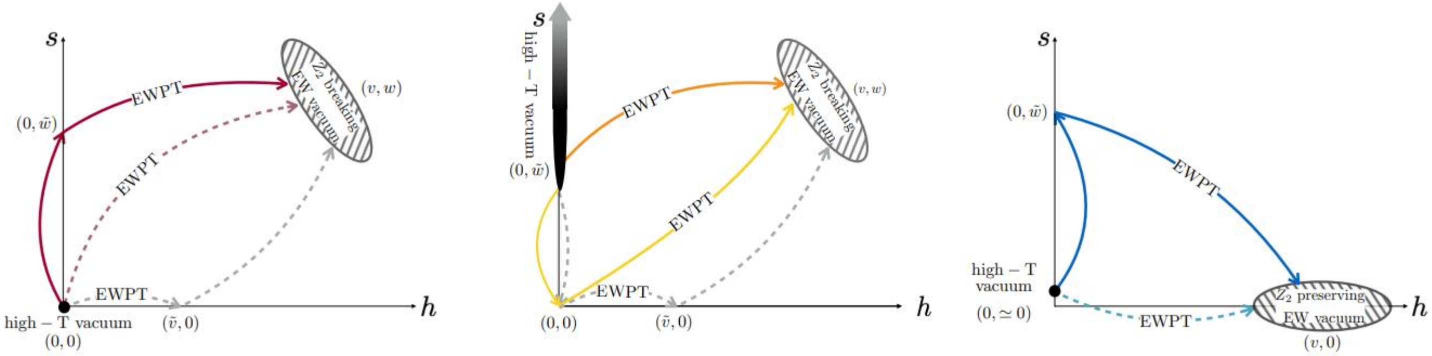
HH@
Future Colliders

- Other precision inputs and constraints are needed for trilinear extraction if one turns on a few couplings or with a given model;
- Single H allows consistent trilinear precision O(40%)
- Double H and differential crucial to reach O(10%)
- High Energy will do better (hopefully O(%) but studies are missing)

Di Vita, Durieux, Grojean, Gu, ZL, Panico, Riembau, Vantalon, 1711.03978

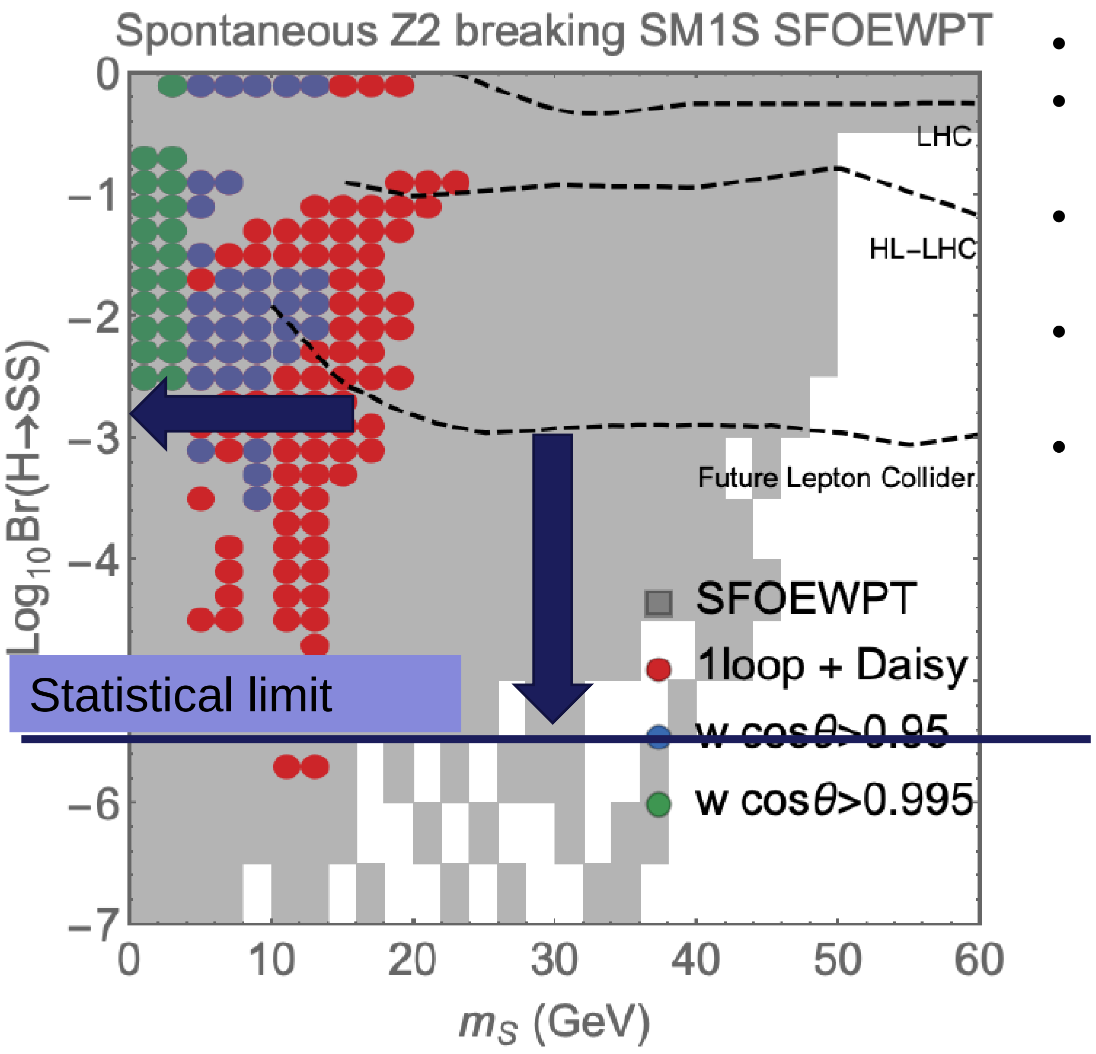


Beyond Higgs Precision



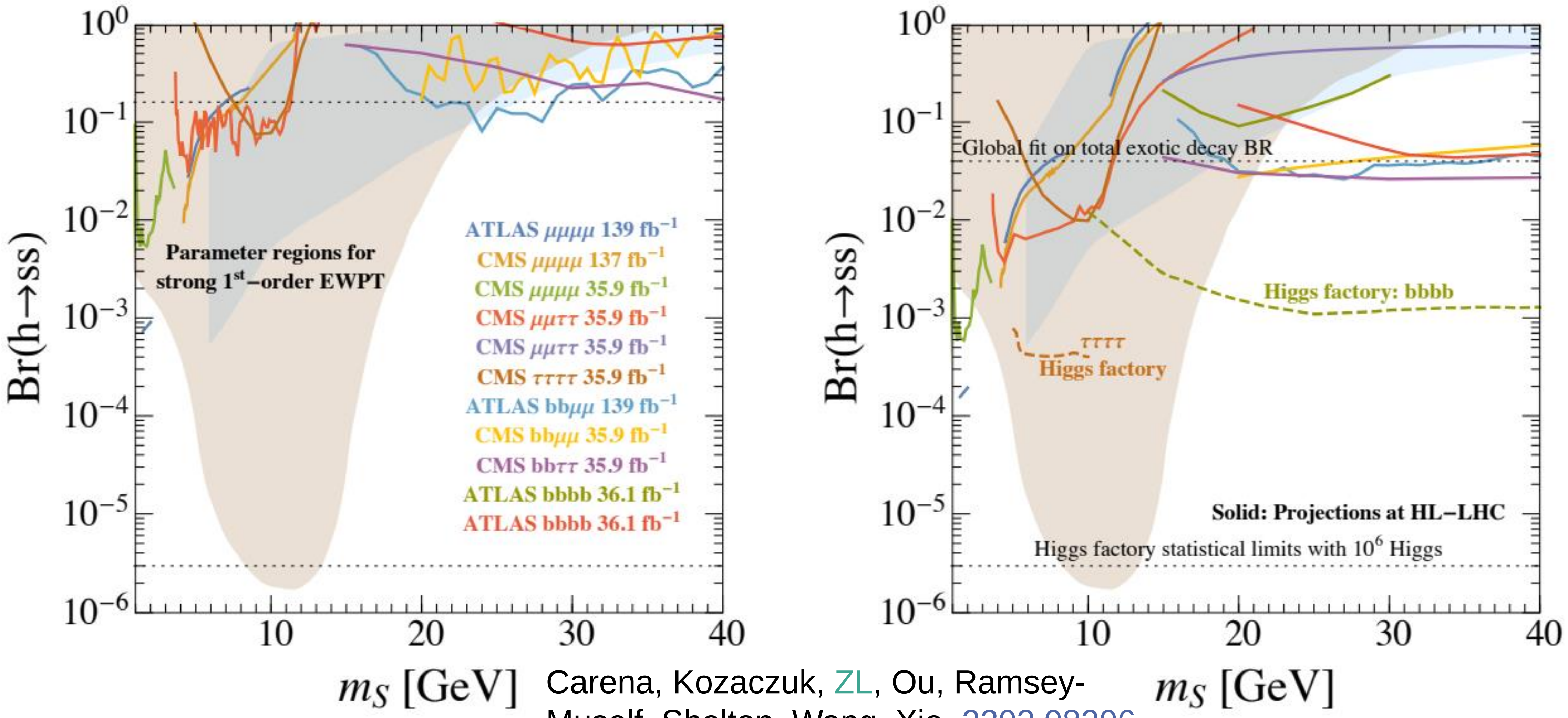
Higgs Exotic Decays

In the mass basis: $\frac{v_c}{T_c} = (\frac{v_c^{SM}}{T_c^{SM}})\frac{\lambda_h^{SM}}{\widetilde{\lambda}_h} = (\frac{v_c^{SM}}{T_c^{SM}})[1 + \sin^2\theta\ \frac{m_H^2 - m_S^2}{m_S^2}]$



- A firm prediction of a light scalar in this model;
- Higgs exotic decay into a pair of light scalars is a crucial probe;
- Higgs exotic decays complements the Higgs precision program;
- Higgs exotic decays requires further studies of **merged jets** for lighter singlet masses(Jung, ZL, Wang, Xie, 21');
- Also possible to have long-lived Higgs exotic decays in certain parameter space; (e.g., Craig et al, 18'; ZL, Liu, Wang, 18')

Higgs Exotic Decays to light Higgs pairs



Carena, Kozaczuk, ZL, Ou, Ramsey-Musolf, Shelton, Wang, Xie, 2203.08206

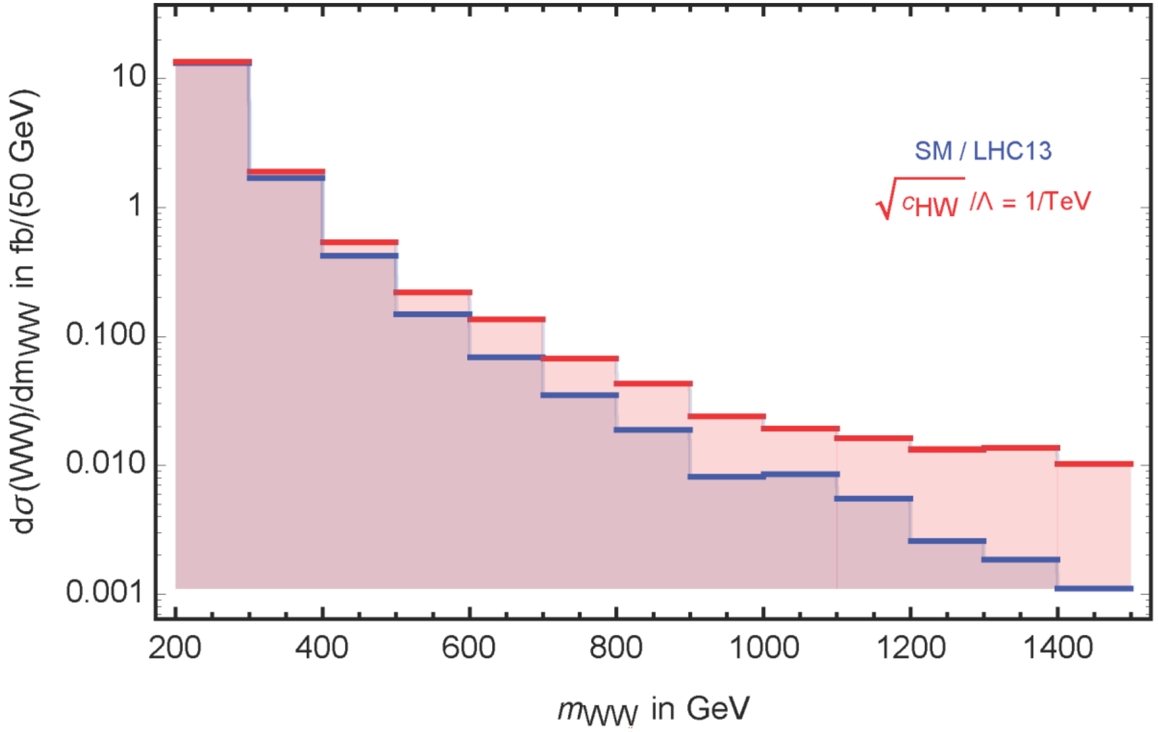
The other Higgs (e.g., the “eaten” Goldstones)

Generalize HH precision with high energy

- High Λ suppression ⇒ Needs precision measurements
- Typically associated with EWPO
$$\delta \lesssim \mathcal{O}(1\%)$$
- Does hadron collider play any rule?

Doable if
$$\frac{S}{B} \propto E^n, \qquad n \geq 1$$

Example: Diboson processes



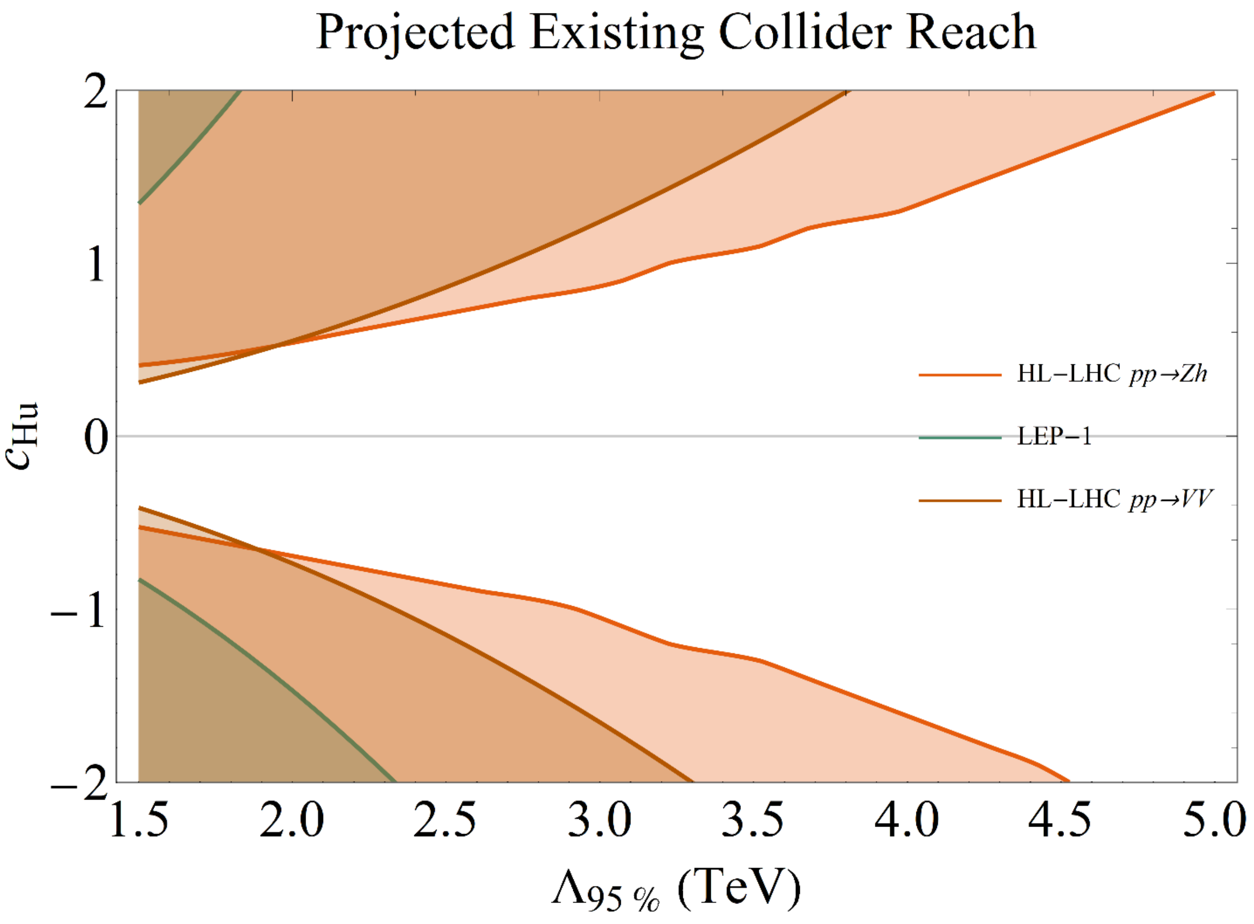
Operators	
$\mathcal{O}_{Hu}$	$\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{u}_R\gamma^\mu u_R)$
$\mathcal{O}_{Hd}$	$\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{d}_R\gamma^\mu d_R)$
$\mathcal{O}_{HQ}$	$\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{Q}_L\gamma^\mu Q_L)$
$\mathcal{O}_{HQ}^{(3)}$	$\left(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right)(\bar{Q}_L\gamma^\mu \sigma^a Q_L)$

Will show an example analysis with Zh→(ll)(bb).

W. Chiu, ZL, L. Wang, 1909.04549
R. Franceschini et at, 1712.01310, C. Grojean et al, 1810.05149 & S. Banerjee et al, 1807.01796, F. Bishara et al, 2004.06122, 2011.13941

High energy probes v.s. EWPO and flavor

- For Unity Wilson Coefficient, HL-LHC ZH process can probe up to 3 TeV
- Sensitivity extend beyond 4.5 TeV for stronger interactions
- One does obtain more sensitivity when compared to LEP
- In the first two-generation partial universal theories, covers more than flavor constraints



W.H. Chiu, ZL, L.-T. Wang, 1909.04549

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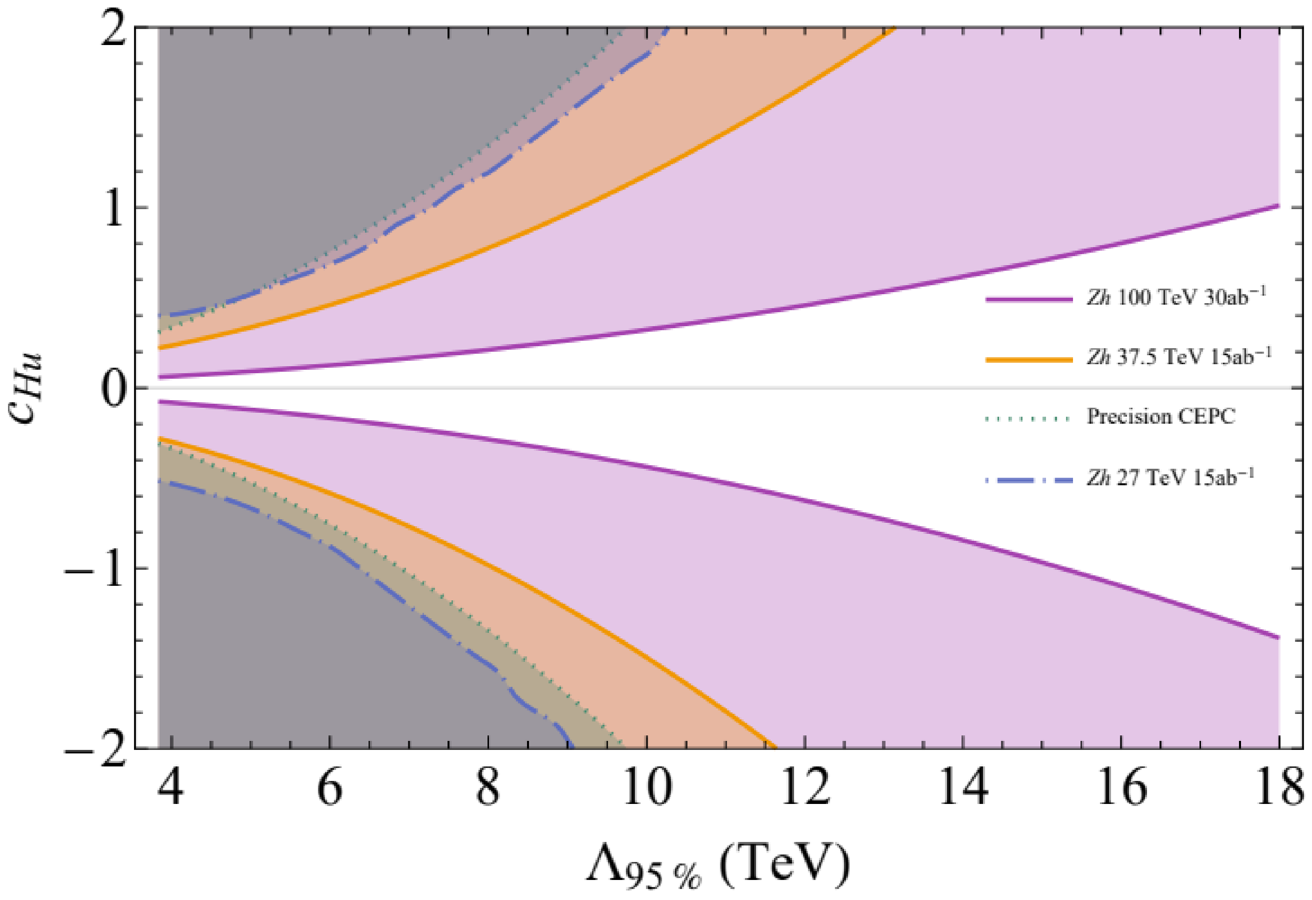
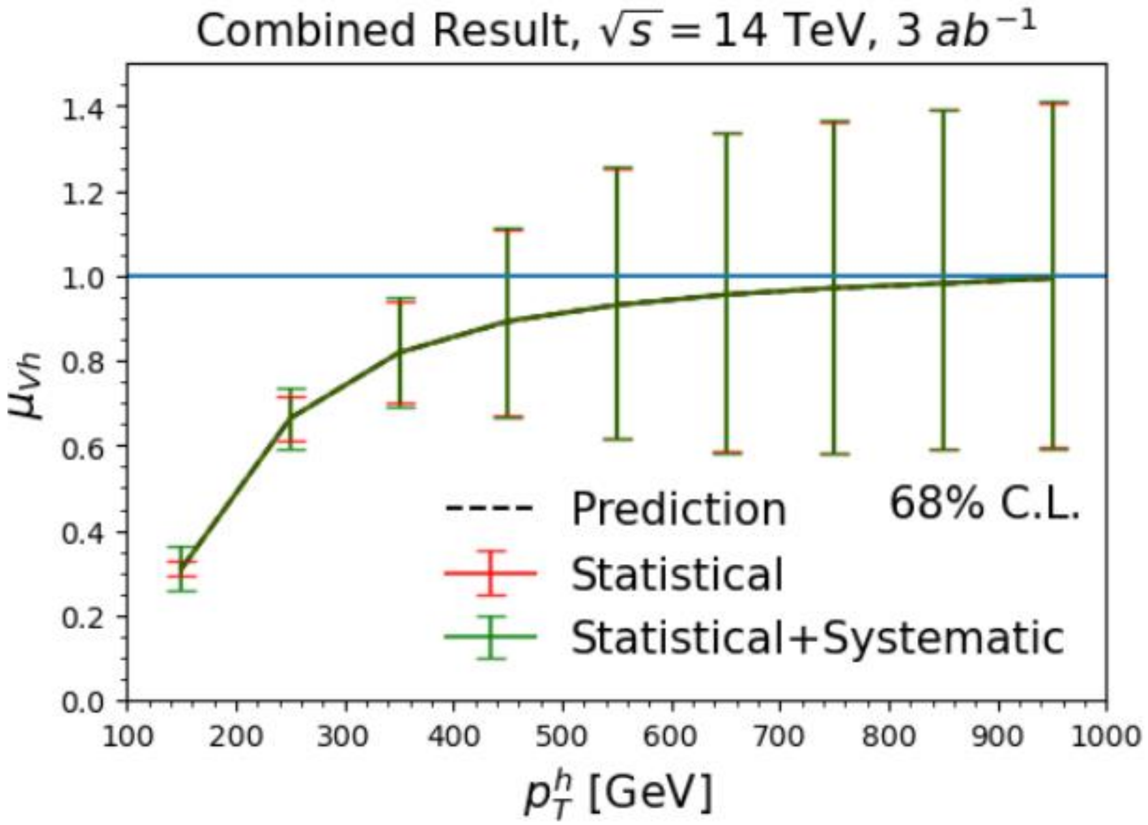
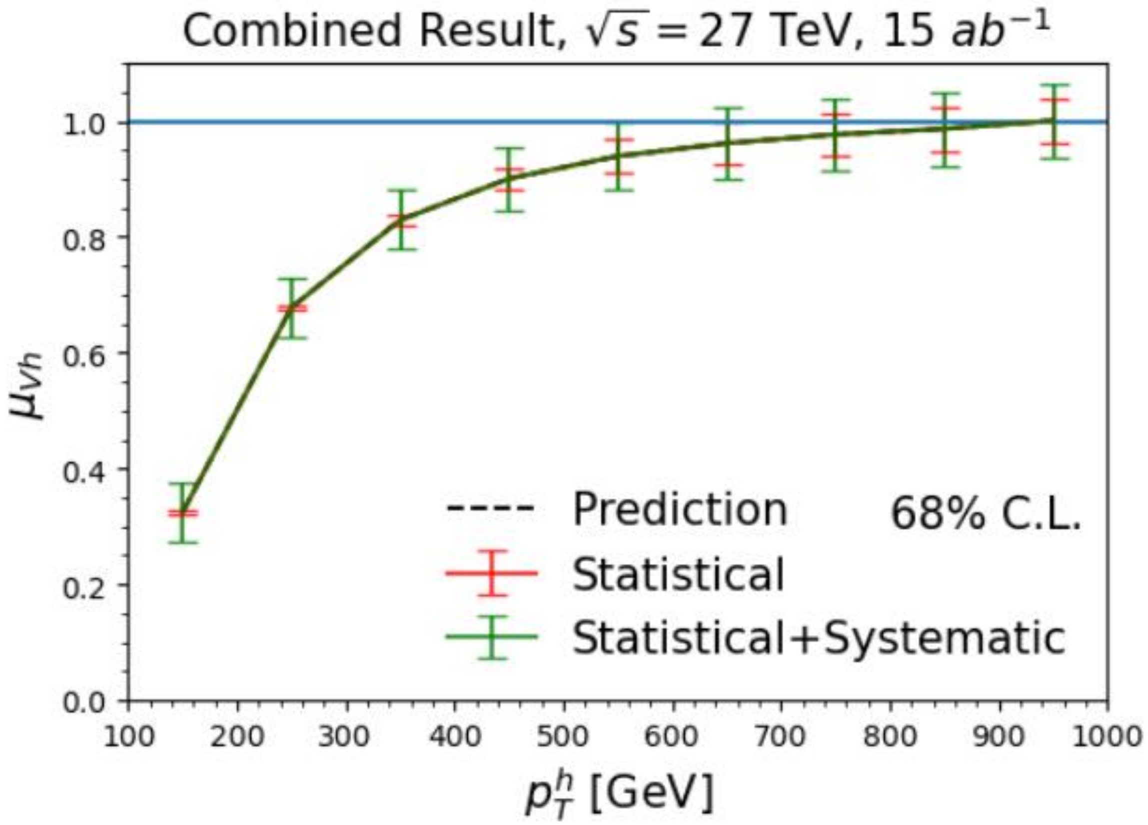


W.H. Chiu, ZL, L.-T. Wang, 1909.04549

“Seeing” Goldstone Equivalence Emerging





Huang, Lane, Lewis, ZL, 2012.00774

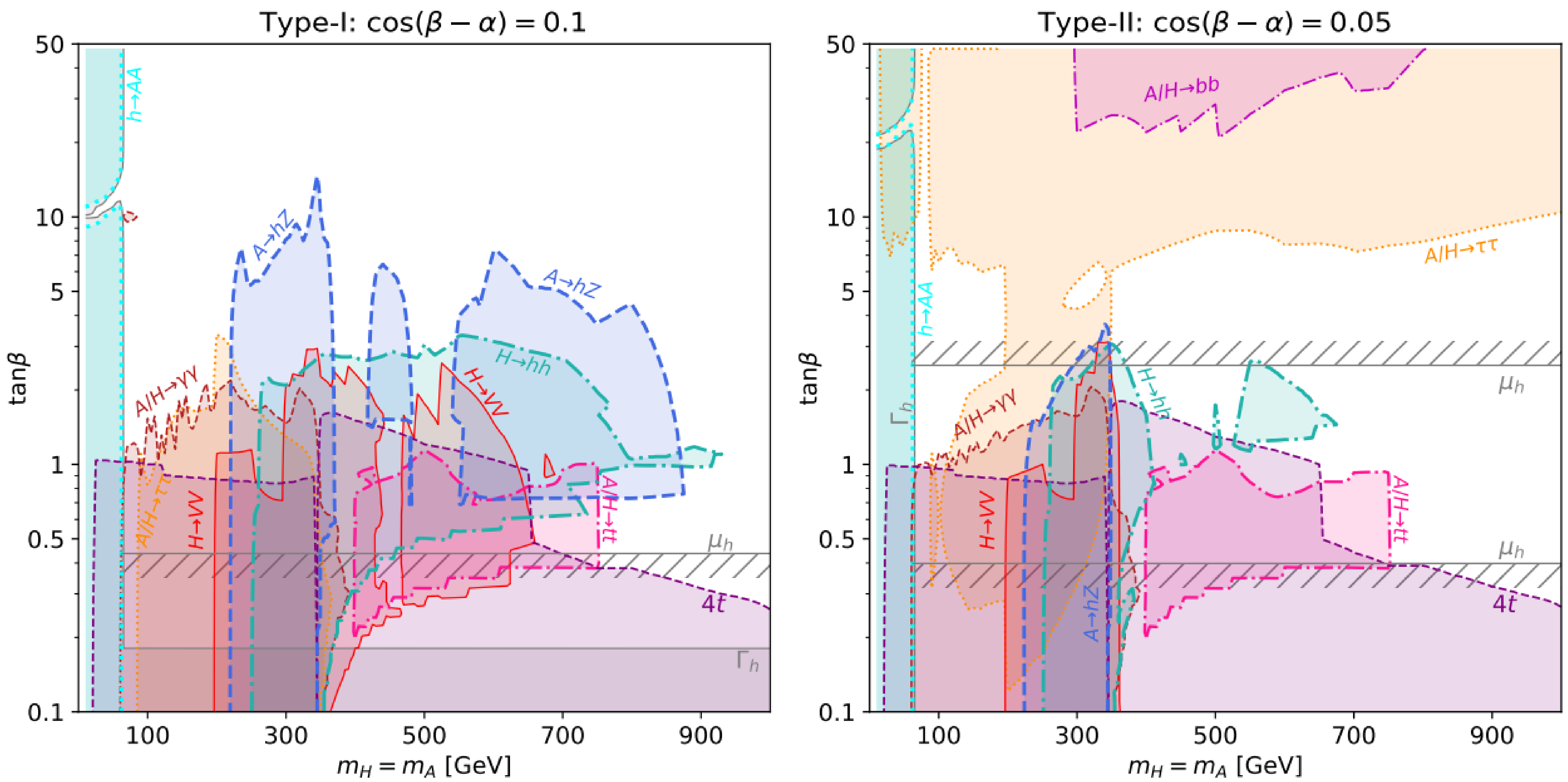
Beyond SM Higgs

Overview of resonant HH/HS/SS production

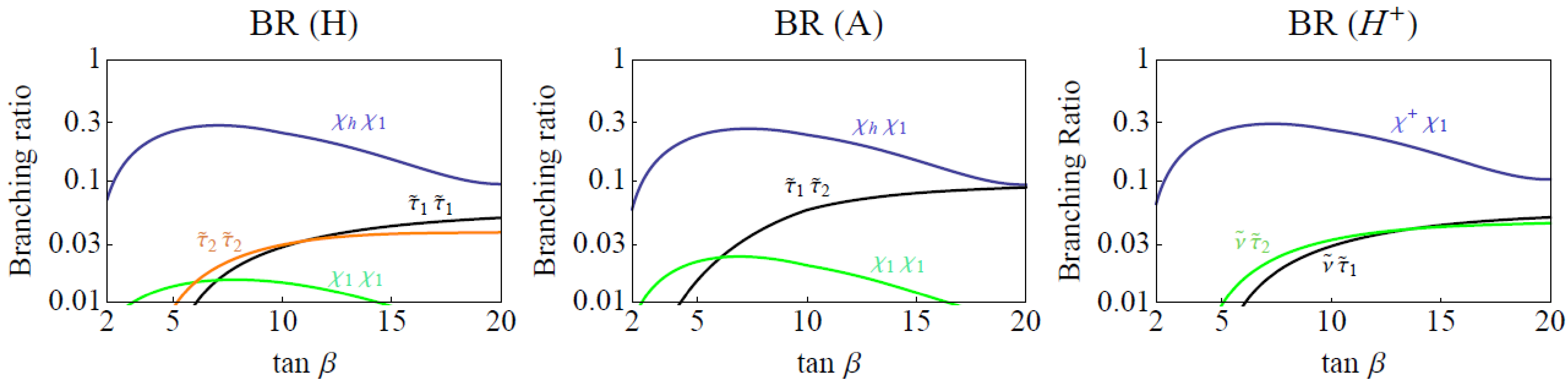
Rui Santos

	Model	Higgs Spectrum	In principle possible Higgs pair final states from resonant production
Singlet	RxSM SM+real singlet	'dark phase': H_{SM}, DM 'broken phase': H_{SM}, S	DMDM $H_{SM}H_{SM}$ SS
	TRSM SM+2real singlets	'broken phase': H_{SM},H_1,H_2	$H_{SM}H_{SM}$ H_1H_1 H_2H_2 H_1H_2 $H_{SM}H_1$
	CxSM SM+complex singlet	'dark phase': H_{SM},S,DM 'broken phase': H_{SM},H_1,H_2	$H_{SM}H_{SM}$ SS DMDM $H_{SM}H_{SM}$ H_1H_1 H_2H_2 H_1H_2 $H_{SM}H_1$
Doublet	2HDM 2 Higgs doublets	CP-conserving: H_{SM},H,A	$H_{SM}H_{SM}$ HH
	MSSM 2 Higgs doublets, SUSY!	CP-conserving: H_{SM},H,A	$H_{SM}H_{SM}$ no HH (due to constraints)
	C2HDM 2 doublets, 3 Higgses mix	CP-violating: H_{SM},H_1,H_2	$H_{SM}H_{SM}$ H_1H_1 H_2H_2 H_1H_2 $H_{SM}H_1$
Doublet+Singlet	N2HDM 2 doublets, 1 real singlet	H_{SM},H_1,H_2,A	$H_{SM}H_{SM}$ H_1H_1 H_2H_2 H_1H_2 $H_{SM}H_1$
	2HDM+S 2 doublets + 1 complex singlet	H_{SM},H_1,H_2,A_1,A_2	$H_{SM}H_{SM}$ H_1H_1 H_2H_2 $H_{SM}H_1$ $H_{SM}A_1$ H_1H_2 A_1H_1 A_1H_2
	NMSSM SUSY! 2 doublets + 1 complex singlet	H_{SM},H_1,H_2,A_1,A_2	$H_{SM}H_{SM}$ H_1H_1 $H_{SM}H_1$ $H_{SM}A_1$ A_1H_1 (no H_2H_2,A_1H_2,H_1H_2 ← constraints)

Various Higgs Pairs complements each other



Higgs can also portal into Higgs partners (Higgsinos*)



mA=800 GeV
mstau=mHiggsinos=350 GeV
mBino=150 GeV
Atau= 1 TeV

- coupling proportional to A_{tau}, constrained by vacuum stability
- BR(A/H->staus) can also be ~O(10)%; comparable/larger than BR(A/H->tau), scales similarly with tanbeta
- same final state in signal as A/H -> tau search channel, with more MET

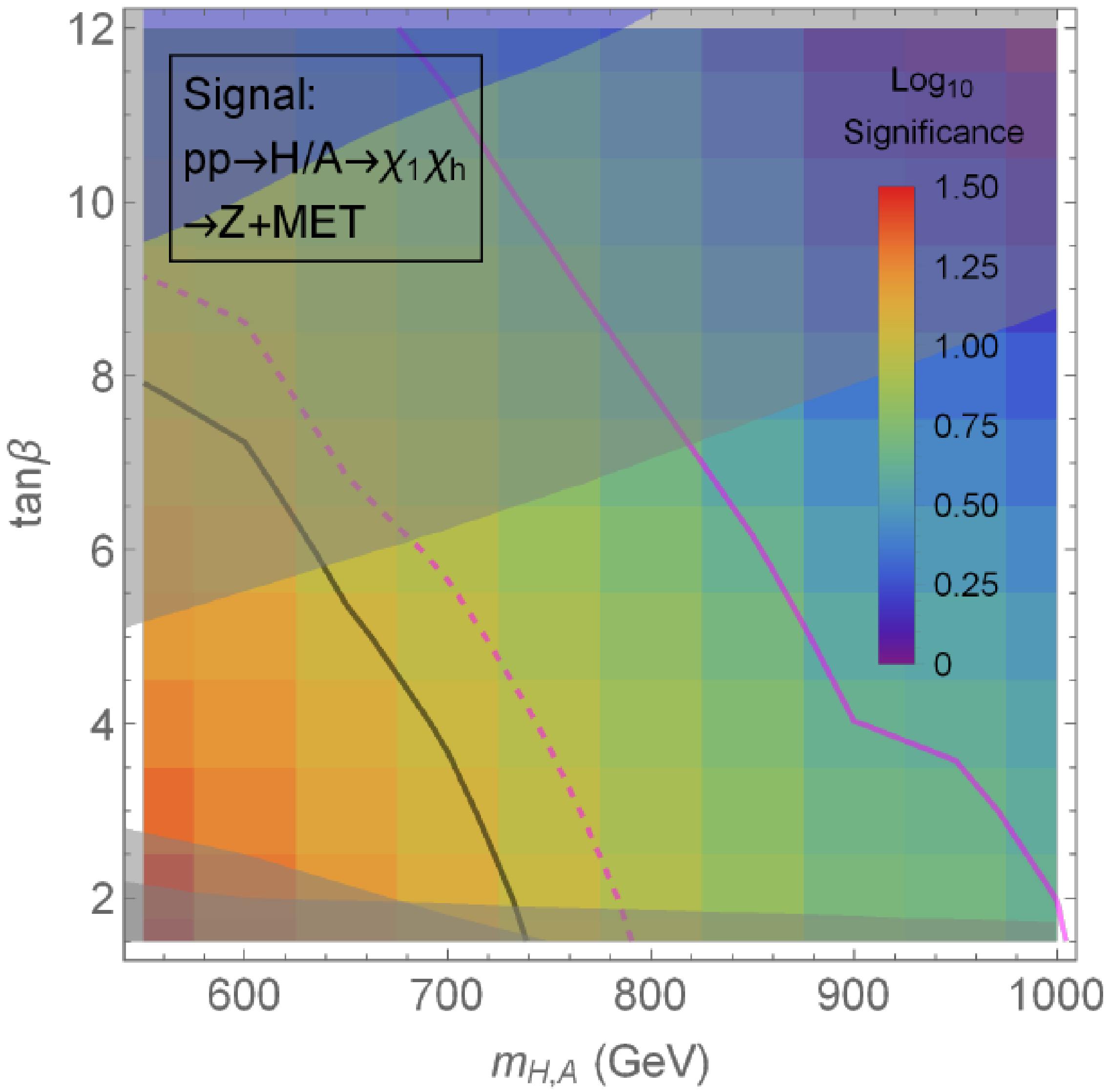
S. Gori, ZL, B. Shakya, 1811.11918

Competitive to direct searches

- Magenta lines: 95% exclusion at HL-LHC
- Magenta dashed: discovery at HL-LHC
- Black lines: 95% exclusion at LHC 300 fb^-1

In the mA-tan\beta plane:

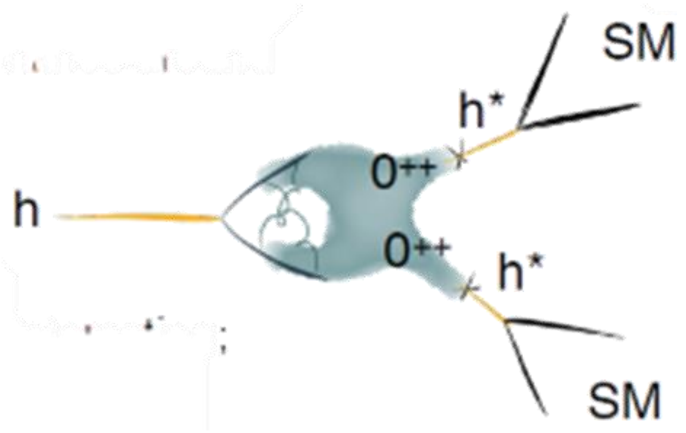
- Blue shades: current limits from H→$\tau\tau$
- Gray shades:
  - Upper: projections from H→$\tau\tau$
  - Lower: projections from gg→H→tt, and pp→ttH, H→tt
- Very interesting and nice coverage of the Wedge region; excellent discovery and exclusion potential



S. Gori, ZL, B. Shakya, 1811.11918

Model building: Chacko, Goh, Harnik, hep-ph/0506256, hep-ph/0512088, +Burdman hep-ph/0609152+many… **Pheno:** Craig, Katz, Strassler, Sundrum 1501.05310 +many…

Higgs to Long-lived light Higgs pairs



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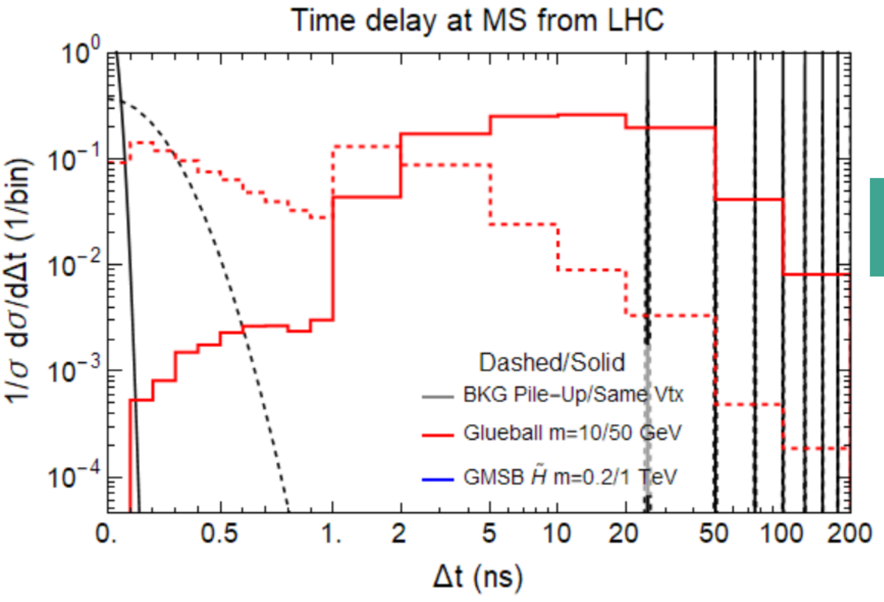

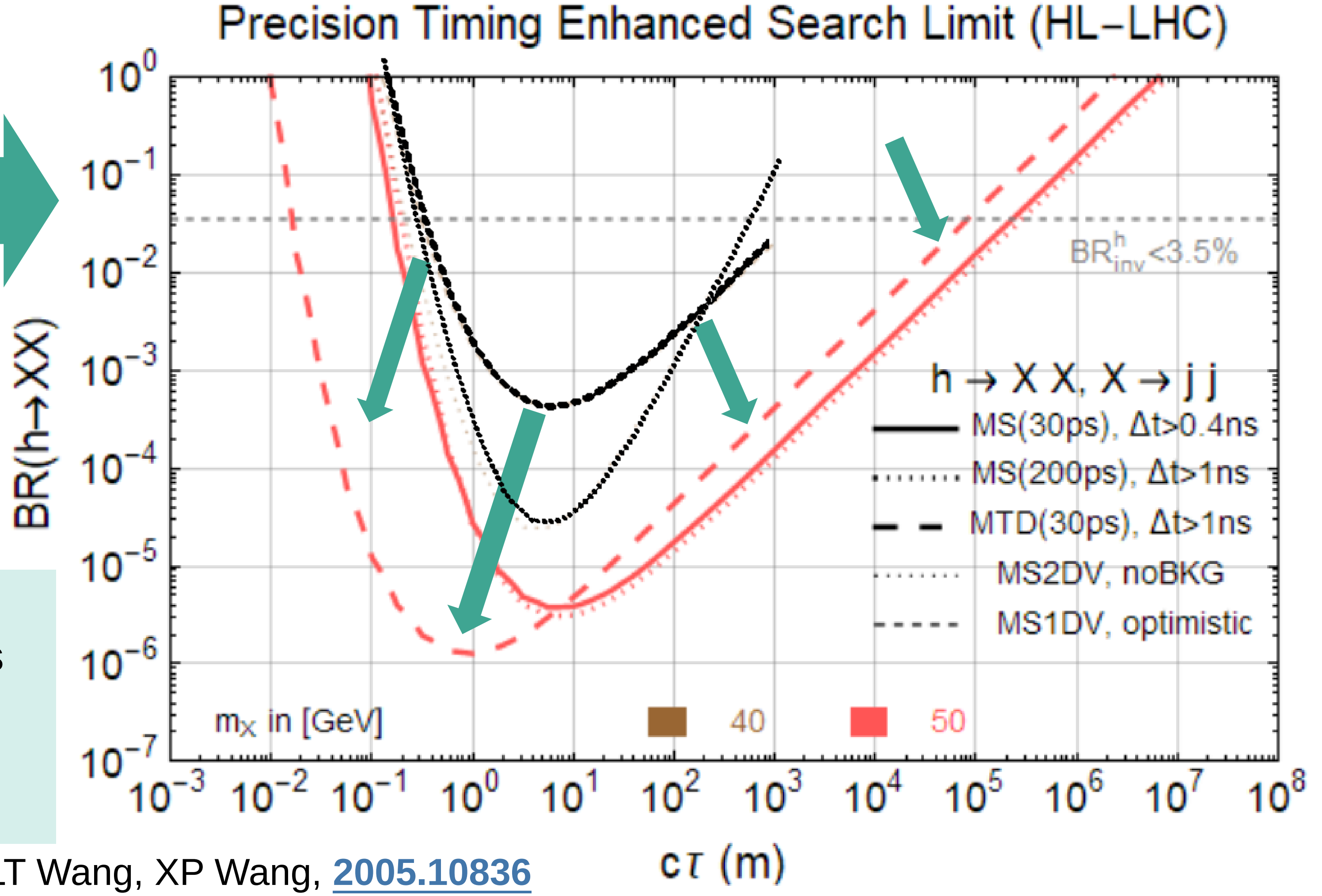

A lot new ideas and possibilities to improve the Higgs to long-lived particles searches; (see the llp11 workshop happening now https://indico.cern.ch/event/1128662/)

J. Liu, ZL, LT Wang, 1805.05957, J. Liu, ZL, LT Wang, XP Wang, 2005.10836

WH Chiu, ZL, M Low, LT Wang, 2109.01682

Summary and Outlook

- HH is well motivated
  - By many theory angles
  - HEFT, SMEFT, UV BSM
- HH at Future Colliders
  - 10%-1% precision achievable
  - In a SMEFT framework extracting h^3
- (Generalized) HH with lots of opportunities
  - W_L, Z_L
  - $H', a, A, s, \widetilde{H}$
  - …

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Thank you!