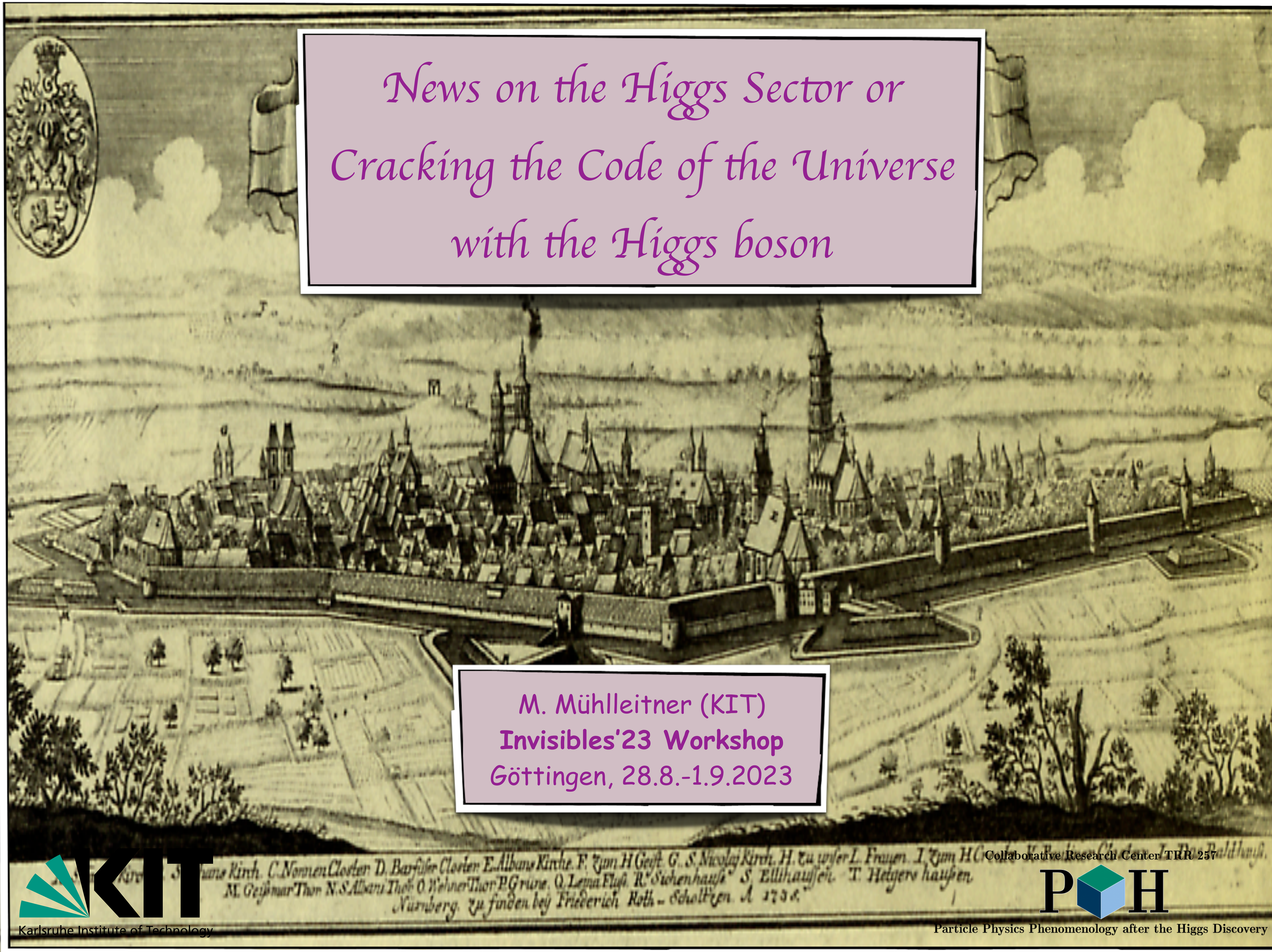
News on the Higgs Sector or Cracking the Code of the Universe with the Higgs boson



M. Mühlleitner (KIT)

Invisibles'23 Workshop

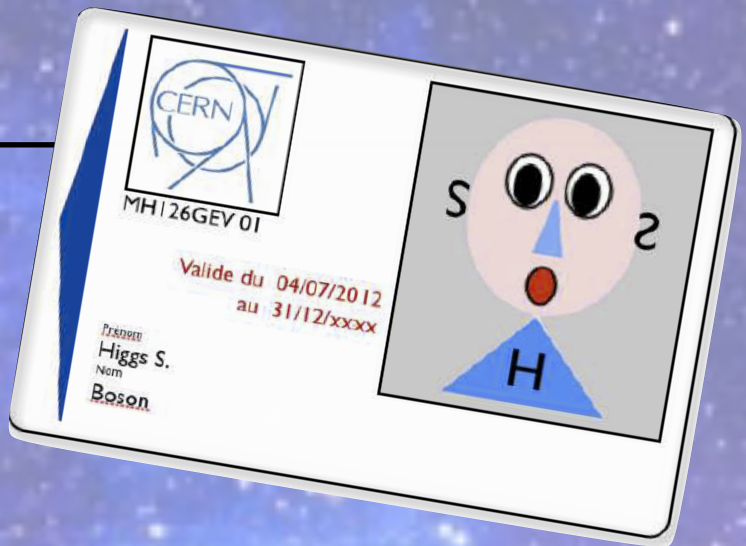
Göttingen, 28.8.-1.9.2023

Karlsruhe Institute of Technology

Collaborative Research Center TRR 257

Particle Physics Phenomenology after the Higgs Discovery

Outline



- ✦ Introduction
- ✦ Potential Parameters
  - Higgs Masses
  - Higgs Self-Couplings
- ✦ More on Precision: Higgs Decays
- ✦ Higgs Pair Production
  - Precision & Phenomenology
- ✦ HH-SFOEWPT-grav. waves
- ✦ Higgs Portal to Dark Matter
- ✦ Conclusions

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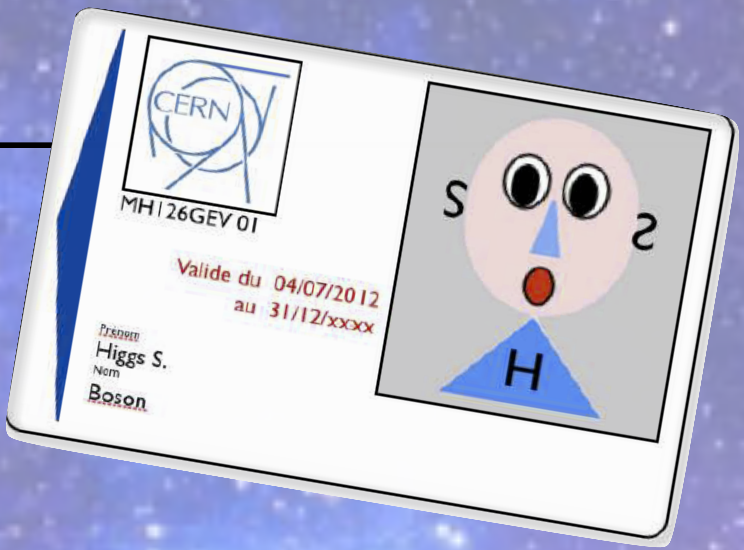

Disclaimer: Focus on Beyond-Standard-Model Theories & Phenomenology

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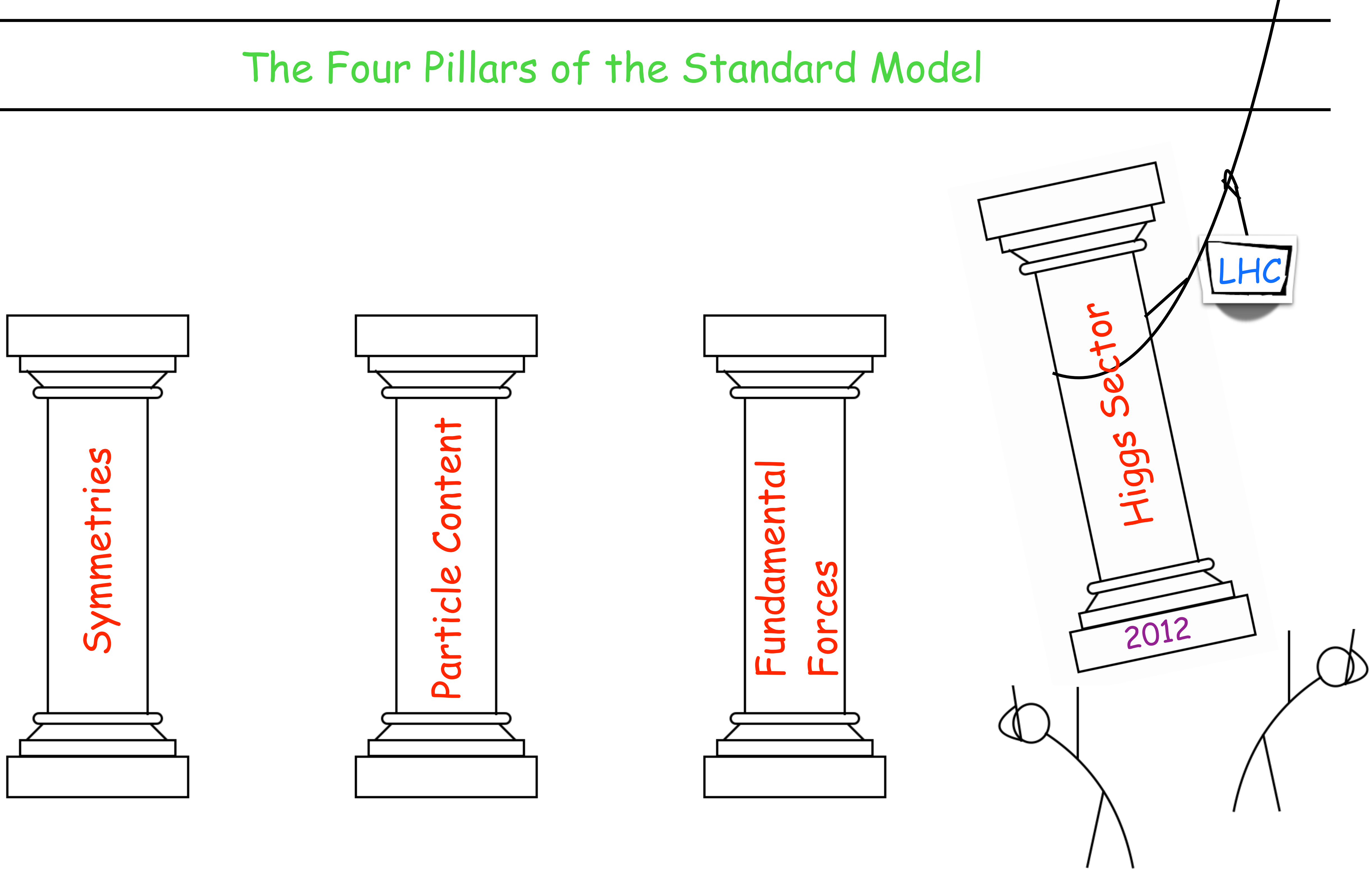
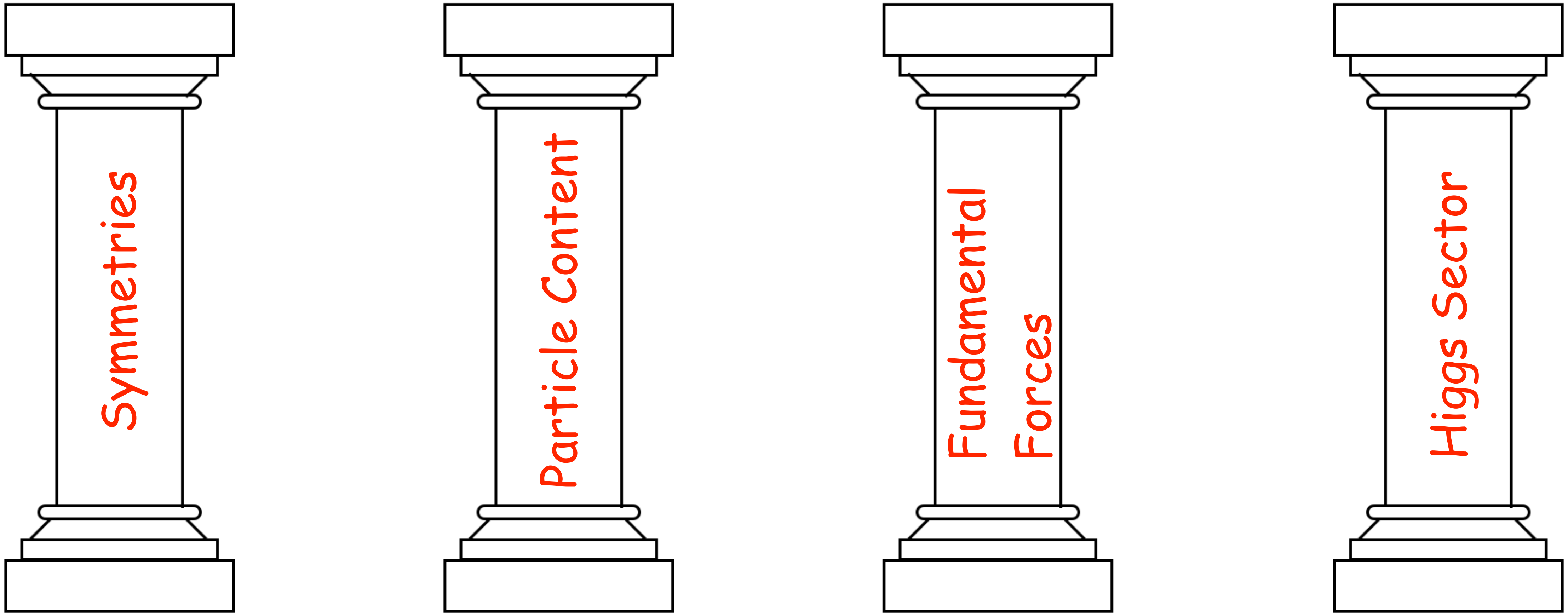
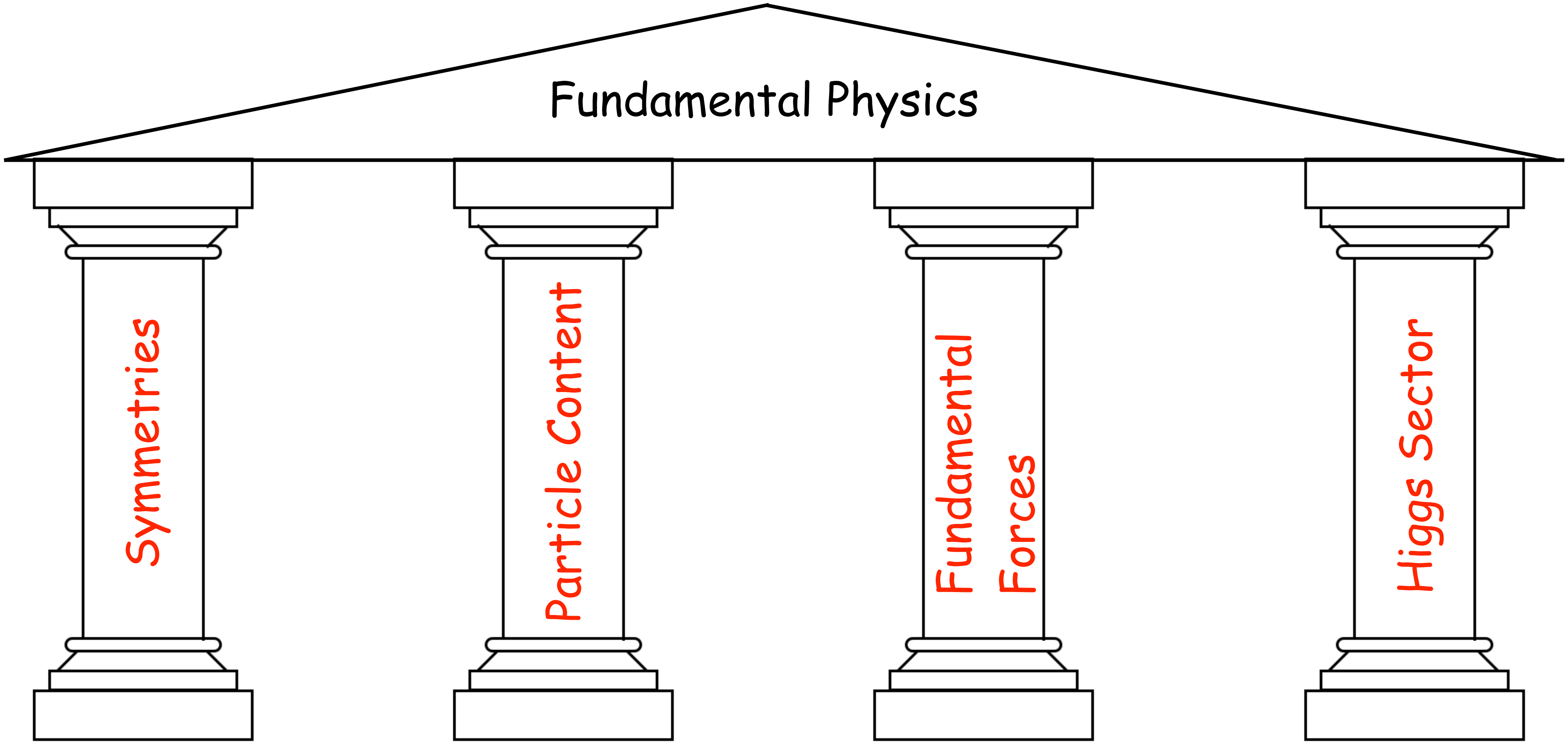
The Four Pillars of the Standard Model



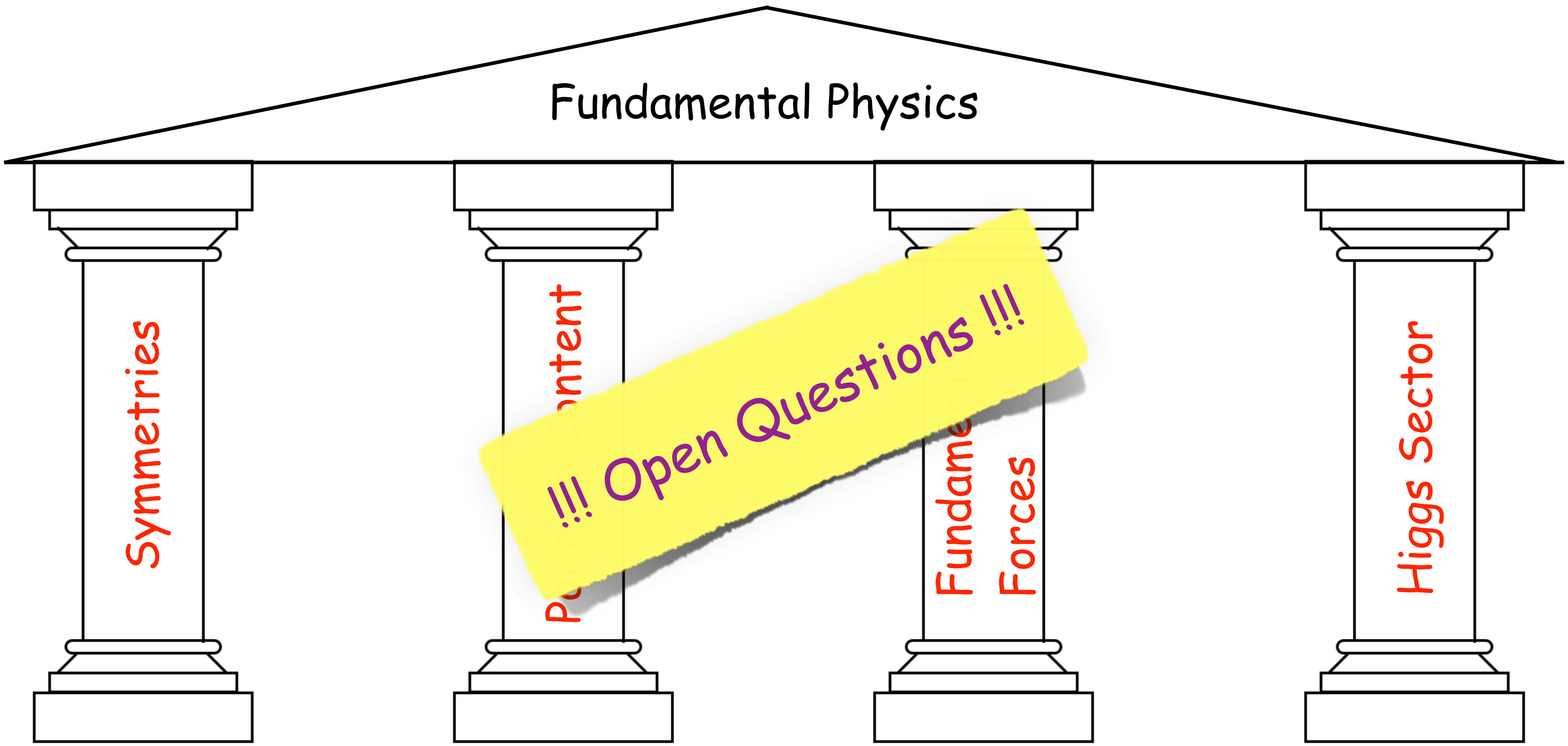
The Four Pillars of the Standard Model

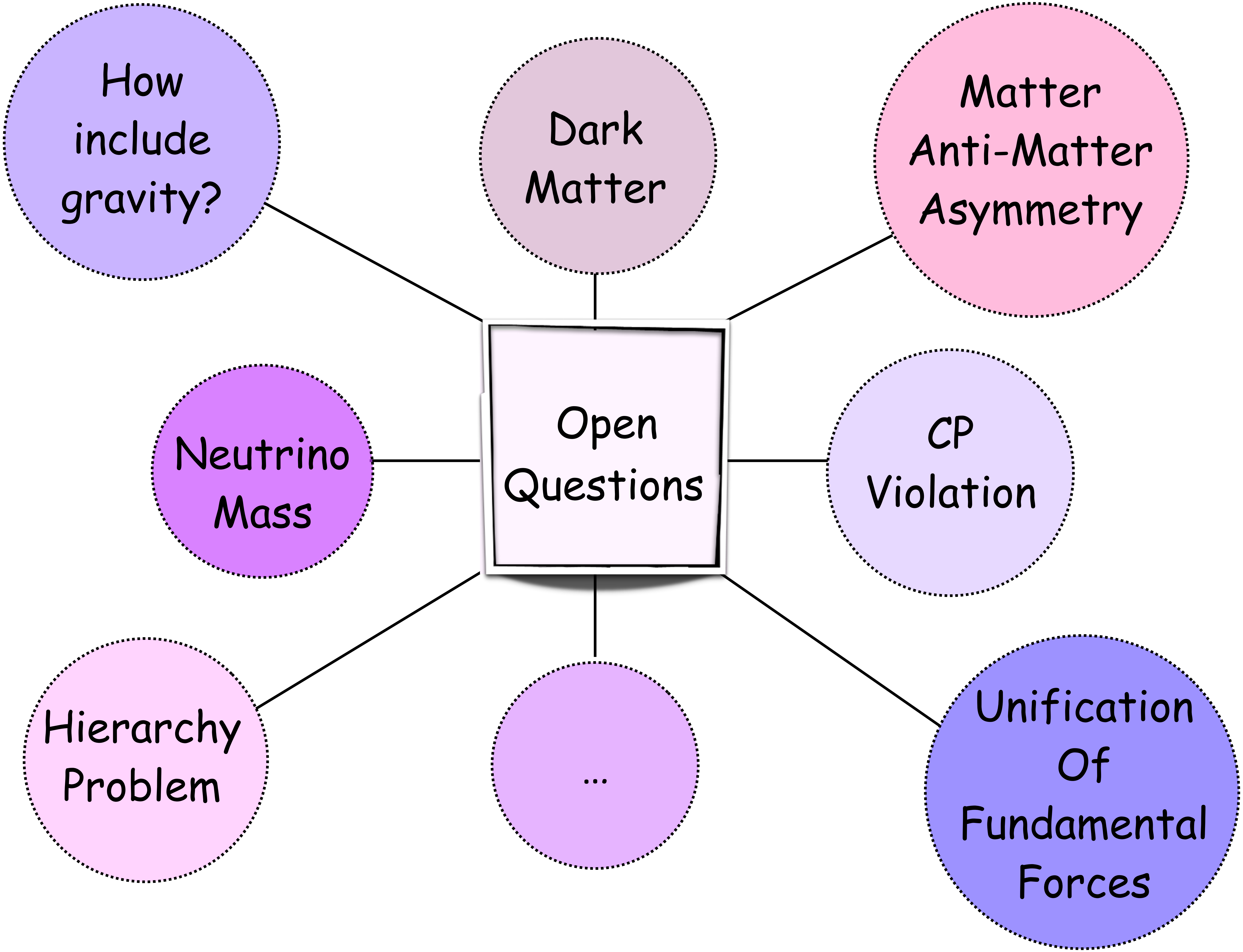


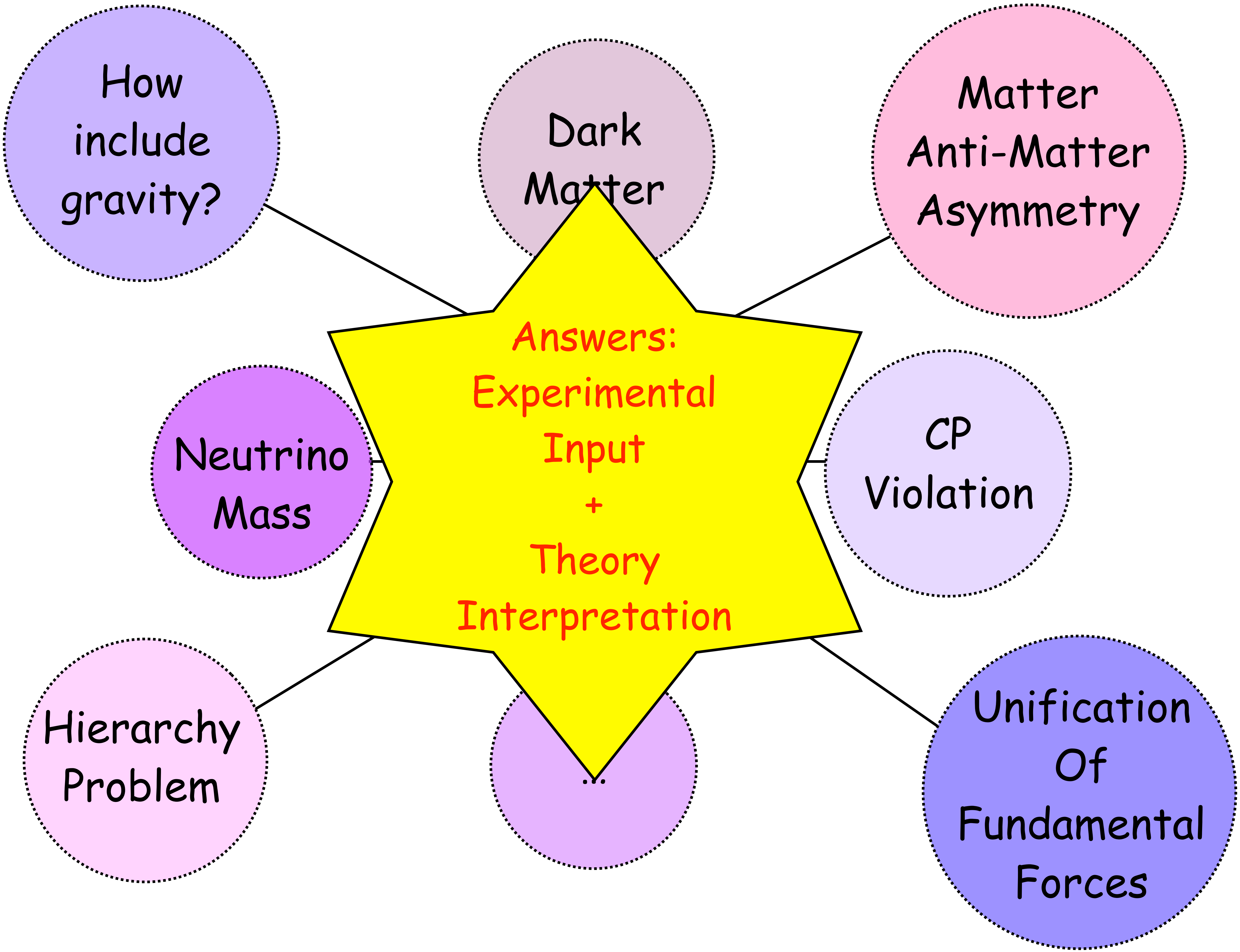
The Standard Model is Structurally Complete



The Standard Model is Structurally Complete - But

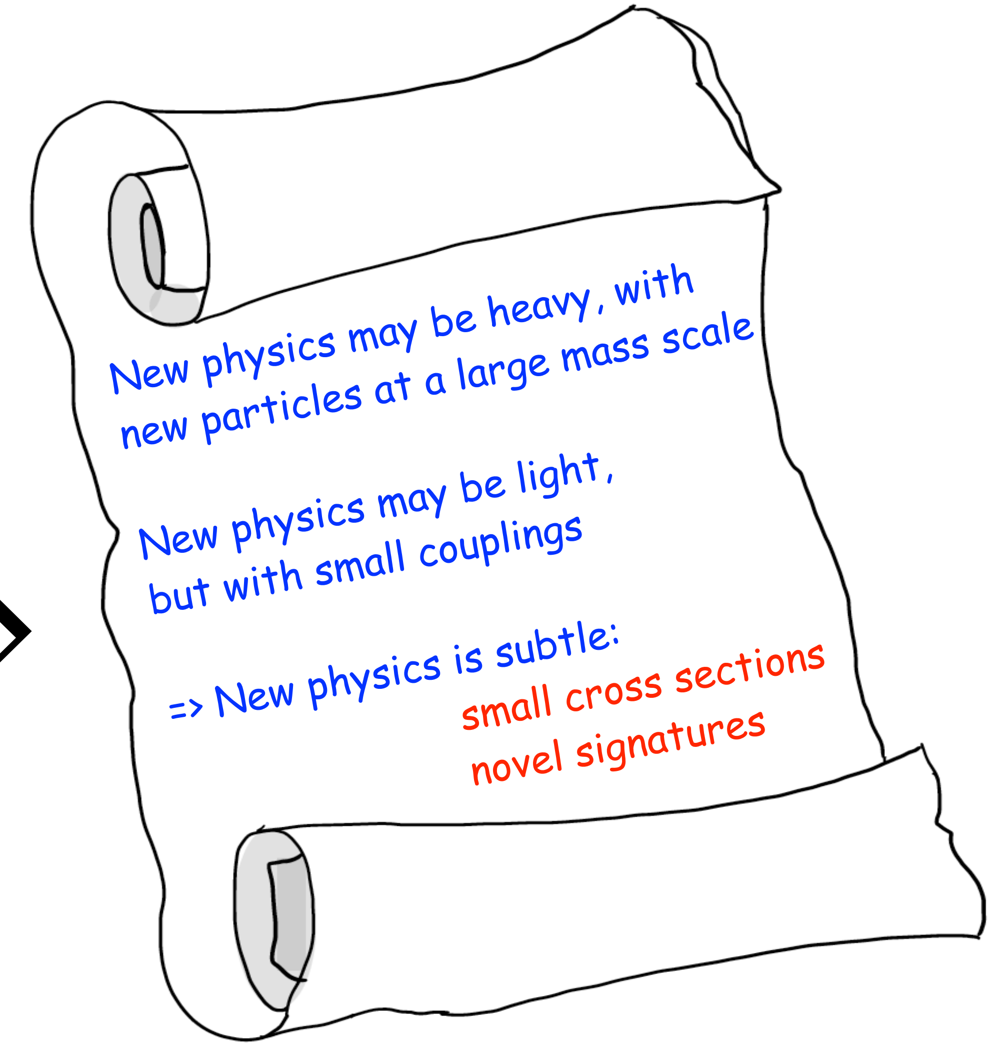



How include gravity?
Dark Matter
Matter Anti-Matter Asymmetry
Neutrino Mass
Open Questions
CP Violation
Hierarchy Problem
...
Unification Of Fundamental Forces


How include gravity?
Dark Matter
Matter Anti-Matter Asymmetry
Neutrino Mass
Answers: Experimental Input + Theory Interpretation
CP Violation
Hierarchy Problem
...
Unification Of Fundamental Forces

Status

Discovered Higgs Boson behaves very SM-like
Consistency Test of the SM at the quantum level
No direct discovery of New Physics so far

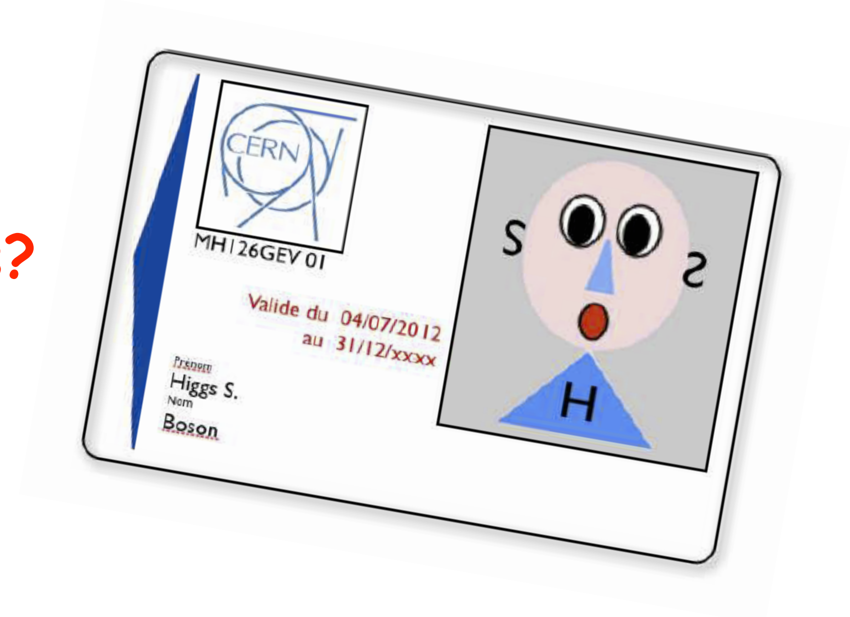


New physics may be heavy, with new particles at a large mass scale
New physics may be light, but with small couplings
=> New physics is subtle:
small cross sections
novel signatures

How to corner New Physics?

- **Experimental reality:** No Beyond the Standard Model Physics discovered so far!
  Guido Altarelli, 16/1/12, KIT: „The situation is depressing, but not desperate."

- We have the SM-like Higgs boson
  What can we learn from Higgs physics?



- Corner new physics:

  Combination of all available information from different sectors and experiments:
  Higgs physics, Dark Matter searches, baryogenesis, astrophysics, cosmology, …

  Experiment: **Precision analyses** - new analysis techniques, ML, …

  Theory: **Precision predictions** for observables for SM, BSM (specific models, EFT)

Higgs Potential Parameters

The Role of the Higgs Boson Mass

✦ Present Accuracy: [ATLAS,CMS]

$$M_H = 125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})\ \text{GeV}$$

✦ Why precision?

* Self-consistency test of SM at quantum level
  (e.g.: Higgs loop corrections to W boson mass)

* $M_H \leftrightarrow$ stability of the electroweak vacuum [Degrassi eal;Bednyakov eal]

* Higgs mass uncertainty feeds back in uncertainty on Higgs observables

* Test parameter relations in beyond-SM theories

  $\Rightarrow$ indirect constraint of viable BSM parameter space!

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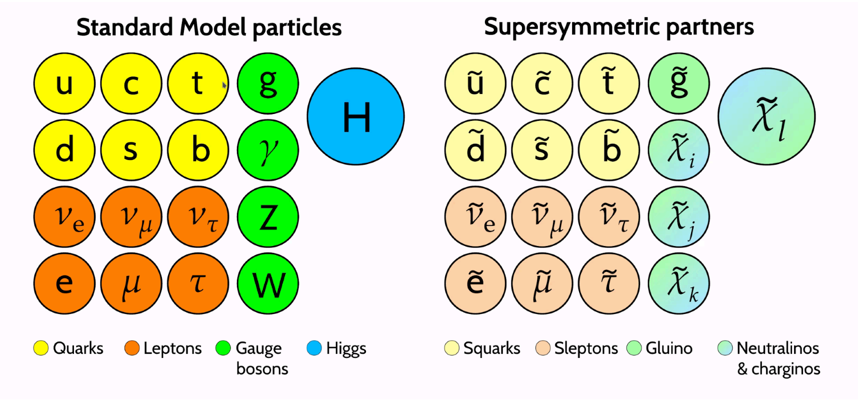


- **Supersymmetry:**
  - enlarged particle spectrum: each SM particle has SUSY partner
  - enlarged Higgs sector: requires at least 2 complex Higgs doublets

- **Minimal Supersymmetric extension (MSSM):** 2 complex Higgs doublets

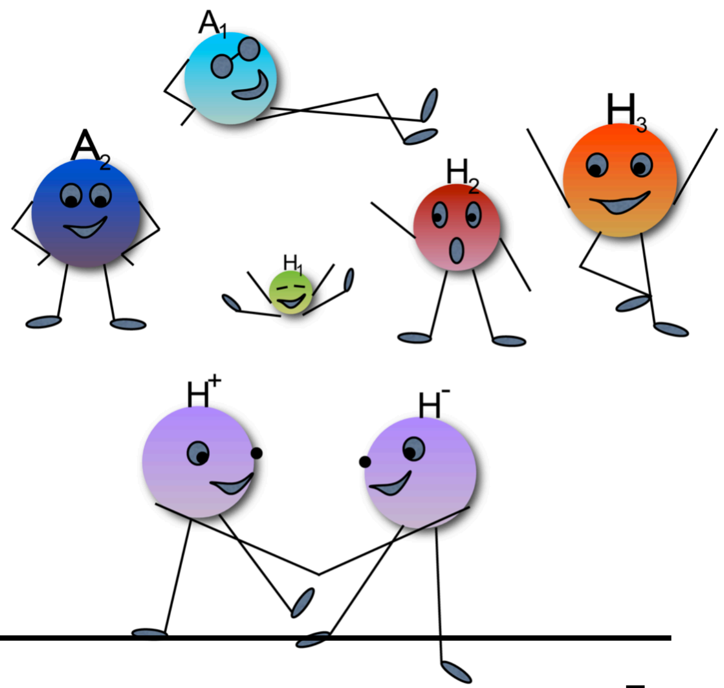
5 Higgs bosons: h, H, A, H^+, H^-

4 neutralinos: $\tilde{\chi}_i^0 \ (i = 1, ..., 4)$

- **Next-to-MSSM (NMSSM):** 2 complex Higgs doublets plus complex singlet field
  - enlarged Higgs and neutralino sector

7 Higgs bosons: $H_1, H_2, H_3, A_1, A_2, H^+, H^-$

5 neutralinos: $\tilde{\chi}_i^0 \ (i = 1, ..., 5)$



  - solves mu problem, interesting phenomenology

Higgs Mass in New Physics Extensions - Supersymmetry

Higgs boson mass:

* SM: fundamental parameter, not predicted by the theory
* Supersymmetry: calculable from input parameters;
  quantum corrections Δm^2_H are important!

$$\text{MSSM:} \quad m_H^2 \approx M_Z^2 \cos^2 2\beta \quad + \Delta m_H^2 \quad \leftarrow (85 \text{ GeV})^2\,!$$

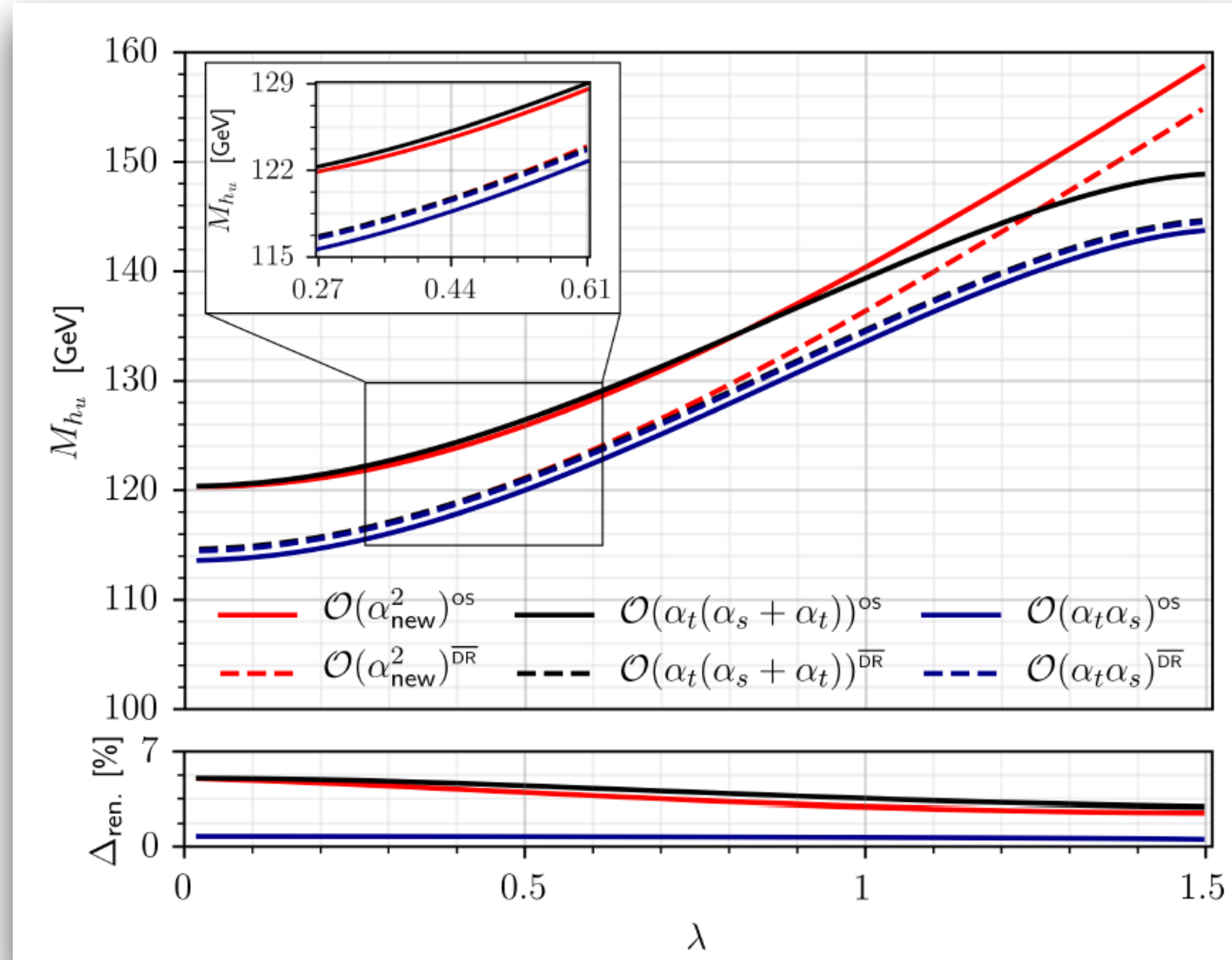
$$\text{NMSSM:} \quad m_H^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \quad + \Delta m_H^2 \quad \leftarrow (55 \text{ GeV})^2$$

NMSSM:

* less important loop corrections needed compared to the MSSM

$\mathcal{O}(\alpha_{new}{}^2) \equiv \mathcal{O}((\alpha_\lambda+\alpha_\kappa+\alpha_t)^2)$ Mass Corrections in the CP-Violating NMSSM

Corrections to h_u-like Higgs ($\triangleq$ SM-like Higgs) [Dao,Gabelmann,MM,Rzehak,'21]



$$\Delta_{\text{ren}} = \frac{\left|\lambda^{m_t(\overline{\text{DR}})} - \lambda^{m_t(\text{OS})}\right|}{\lambda^{m_t(\overline{\text{DR}})}}$$

: remaining theoretical error: $\mathcal{O}$(few%)

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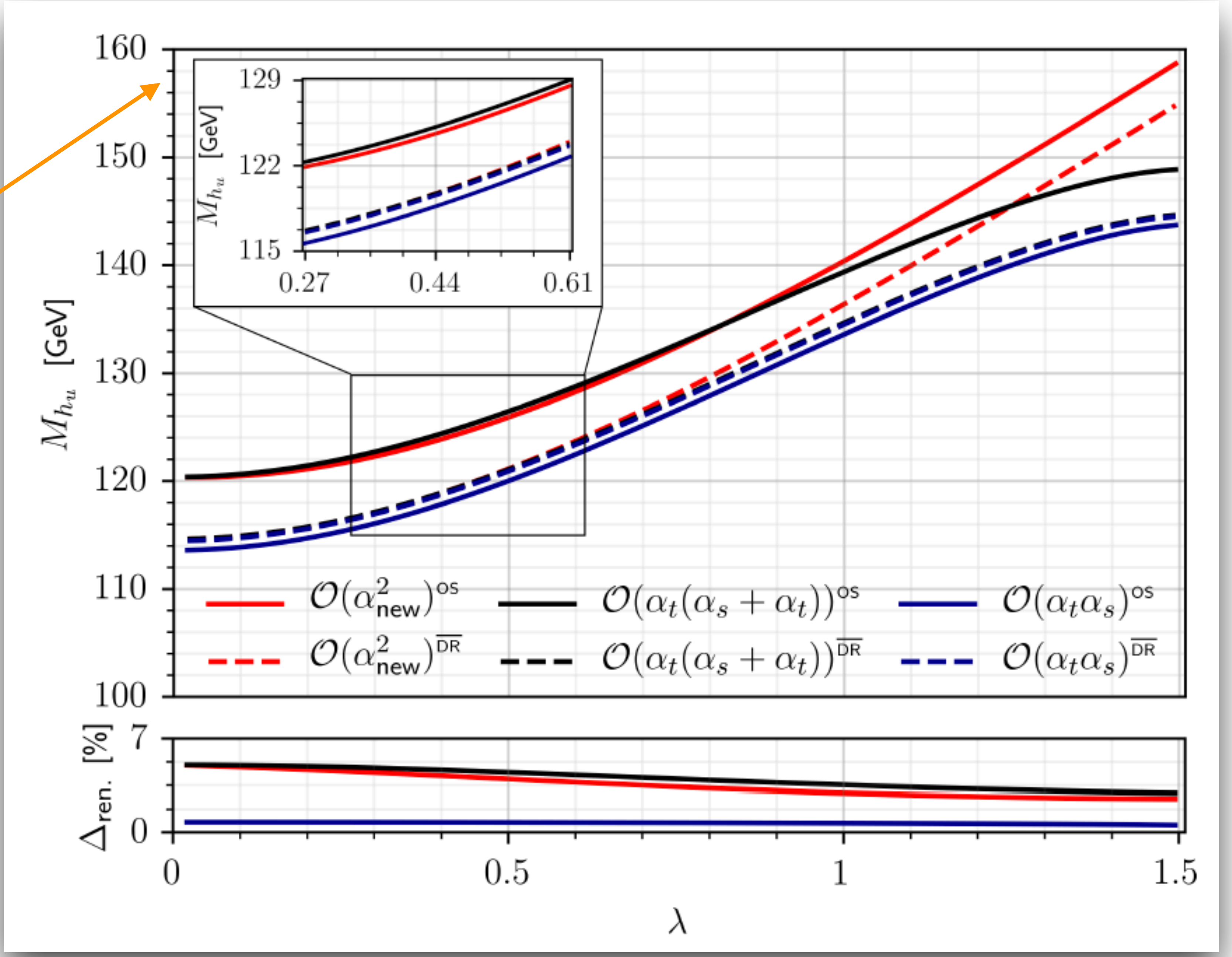
Corrections to h_u-like Higgs ($\triangleq$SM-like Higgs) [Dao,Gabelmann,MM,Rzehak,'21]

Zoomed: compatible w/ HiggsSignals after including the new correction



$$\Delta_{ren} = \frac{\left|\lambda^{m_t(\overline{DR})} - \lambda^{m_t(OS)}\right|}{\lambda^{m_t(\overline{DR})}}$$

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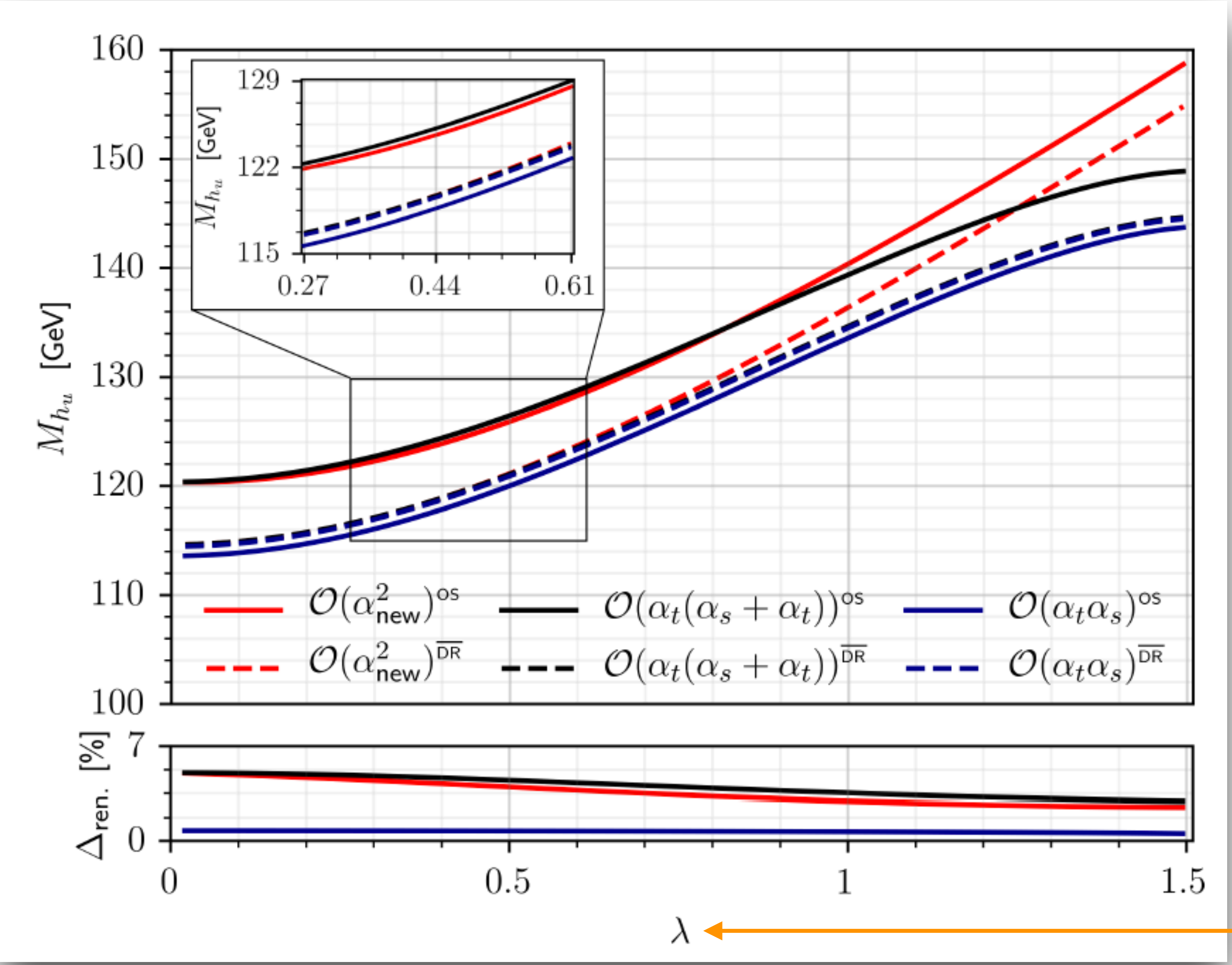

NMSSM specific couplings λ, κ related to new singlet field in superpotential

$$\Delta_{\text{ren}} = \frac{\left|\lambda^{m_t(\overline{\text{DR}})} - \lambda^{m_t(\text{OS})}\right|}{\lambda^{m_t(\overline{\text{DR}})}}$$

: remaining theoretical error: $\mathcal{O}$(few%)

Loop Corrected Trilinear Higgs Self-Couplings at $\mathcal{O}(\alpha_t(\alpha_s+\alpha_t))$

- Masses $M_{ij}=(\partial^2 V_H/\phi_i\,\phi_j)|_{\phi=0}$ and Higgs self-couplings $\lambda_{ijk}=(\partial^3 V_H/\phi_i\,\phi_j\,\phi_k)|_{\phi=0}$ **related through Higgs potential** V_H => catch up in precision w/ masses

Trilinear Higgs self-coupling:
- very sensitive to physics beyond the SM (BSM)
- important input for:
  - di-Higgs production,
  - Higgs-to-Higgs decays
  - electroweak phase transitions

- Available in NMSSM:
  full 1-loop [Dao,MM,Streicher,Walz,'13]
  2-loop $\mathcal{O}(\alpha_t\alpha_s)$ [Dao,MM,Ziesche,'15]
  2-loop $\mathcal{O}(\alpha_t(\alpha_t+\alpha_s))$ [Borschensky,Dao,Gabelmann,MM,Rzehak,'22]

Loop Corrected Trilinear Higgs Self-Couplings at $\mathcal{O}(\alpha_t(\alpha_s+\alpha_t))$

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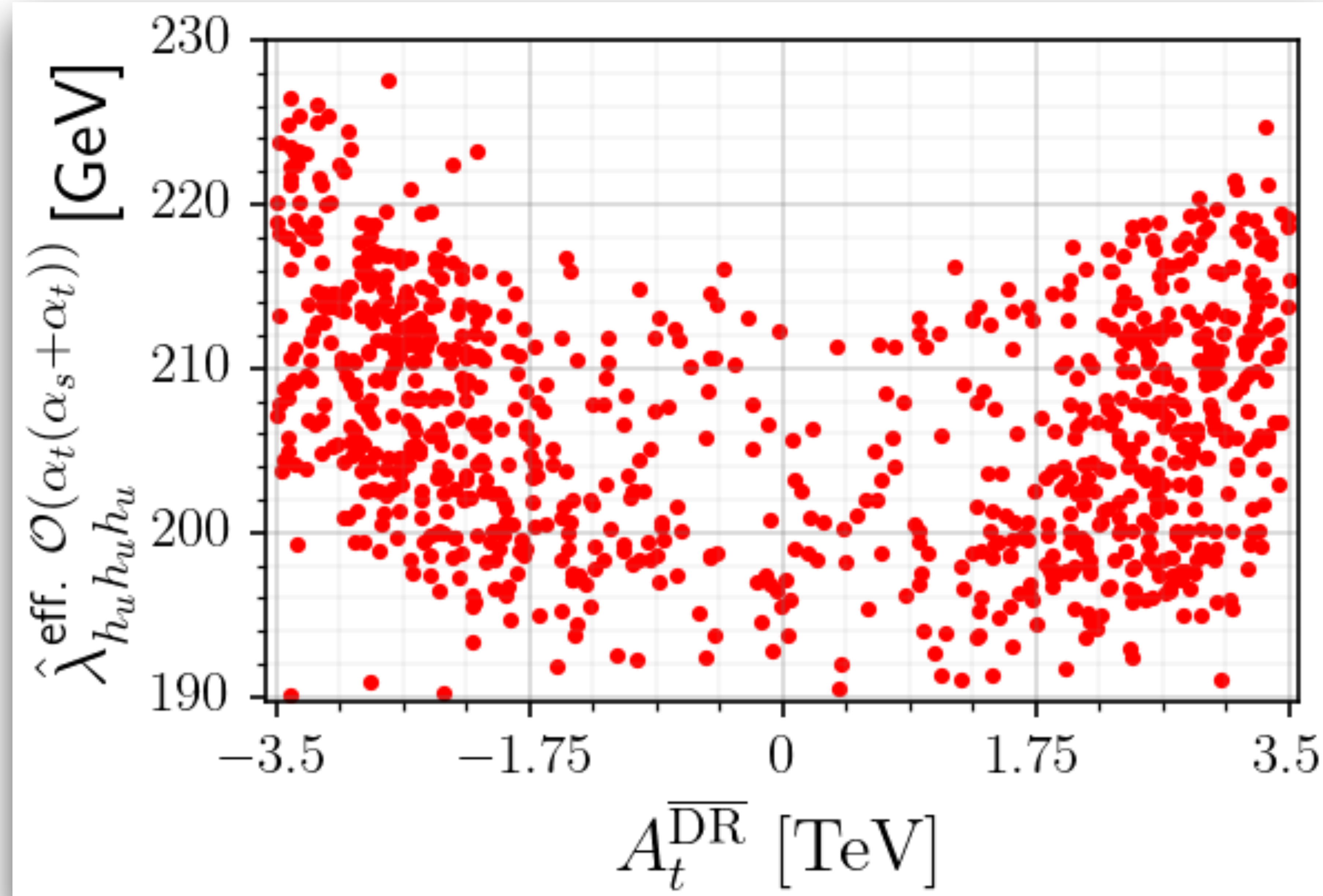


Theoretical & single Higgss data constraints => trilinear coupling values are SM-like,

$\lambda^{\text{SM}}_{HHH} = \frac{3M_H^2}{v} = 191\ \text{GeV}$, within theoretical uncertainty


More on Precision:
Higgs Decays

Status Standard Model Decays

[Taken from talk by M. Spira]

Partial Width	QCD	Electroweak	Total	on-shell Higgs
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$\sim 0.5\%$	$\sim 0.5\%$	NNNNLO / NLO
$H \to \tau^+\tau^-/\mu^+\mu^-$		$\sim 0.5\%$	$\sim 0.5\%$	NLO
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$	NNNLO approx. / NLO
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$	NLO / NLO
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$	(N)LO / LO
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$	$\sim 0.5\%$	(N)NLO

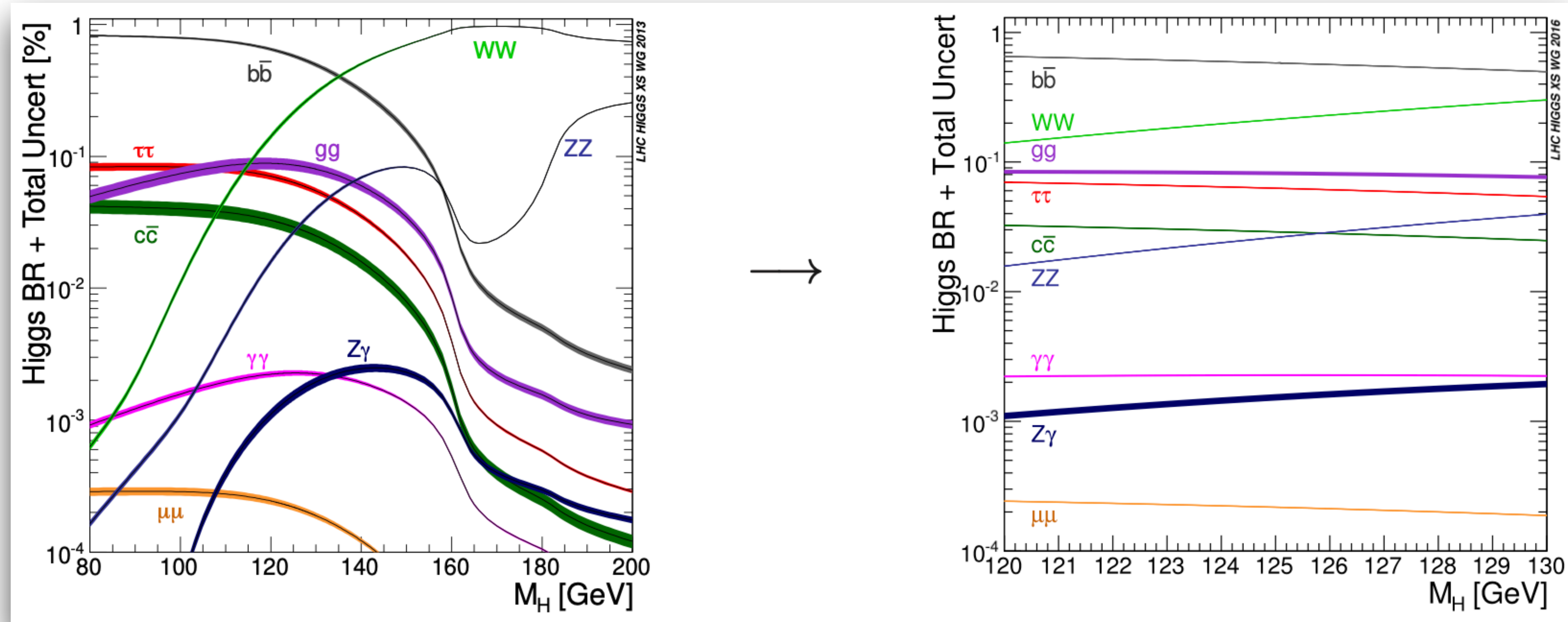
Impact of EW corrections on SM Higgs branching ratios $\Delta\mathrm{BR} = \frac{\mathrm{BR}^{\mathrm{QCD\&EW}} - \mathrm{BR}^{\mathrm{QCD}}}{\mathrm{BR}^{\mathrm{QCD}}}$ [HDECAY]

ΔBR	$b\bar{b}$	$\tau^+\tau^-$	$\mu^+\mu^-$	$s\bar{s}$	$c\bar{c}$	gg	$\gamma\gamma$	$Z\gamma$	W^+W^-	ZZ
	-1.76%	-1.59%	-3.52%	2.24%	-3.81%	4.34%	-2.29%	-0.71%	3.68%	1.61%

Standard Model Branching Ratios

[HDECAY & Prophecy4f]
[Denner,Heinemeyer,Puljak,Rebuzzi,Spira]

YR3 YR4



- Total uncertainties: parametric & theory uncertainties added linearly

- Refinements of input parameters, full NLO EW corrs. to H->ff, NLO quark-mass effects in H->gg

Higher-Order Impact in Beyond-SM Theories (BSM)

Impact of EW corrections on SM Higgs branching ratios $\Delta\mathrm{BR} = \dfrac{\mathrm{BR}^{\mathrm{QCD\&EW}} - \mathrm{BR}^{\mathrm{QCD}}}{\mathrm{BR}^{\mathrm{QCD}}}$ [HDECAY]

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Example: Impact of EW corrections on branching ratios of SM-like 2HDM Higgs boson

[Krause,MM,'19]

Type	$\Delta\mathrm{BR}^{S_1}_{hb\bar{b}}$	$\Delta\mathrm{BR}^{S_2}_{hb\bar{b}}$	$\Delta\mathrm{BR}^{S_3}_{hb\bar{b}}$	$\Delta\mathrm{BR}^{\mathrm{OS2}}_{hb\bar{b}}$	$\Delta\mathrm{BR}^{\overline{\mathrm{MS}}}_{hb\bar{b}}$
I	$\lesssim 2.5\,\%$ (96 %)	$\lesssim 5.0\,\%$ (98 %)	$\lesssim 2.5\,\%$ (90 %)	$\lesssim 2.5\,\%$ (94 %)	$\lesssim 10.0\,\%$ (50 %)
	$\lesssim 5.0\,\%$ (100 %)	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (12 %)
II	$\lesssim 2.5\,\%$ (99 %)	$\lesssim 2.5\,\%$ (54 %)	$\lesssim 2.5\,\%$ (98 %)	$\lesssim 2.5\,\%$ (81 %)	$\lesssim 40.0\,\%$ (50 %)
	$\lesssim 5.0\,\%$ (100 %)	$\lesssim 7.5\,\%$ (96 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (36 %)
LS	$\lesssim 2.5\,\%$ (96 %)	$\lesssim 2.5\,\%$ (54 %)	$\lesssim 2.5\,\%$ (75 %)	$\lesssim 2.5\,\%$ (94 %)	$\lesssim 17.5\,\%$ (50 %)
	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (97 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (14 %)
FL	$\lesssim 2.5\,\%$ (96 %)	$\lesssim 2.5\,\%$ (54 %)	$\lesssim 2.5\,\%$ (75 %)	$\lesssim 2.5\,\%$ (94 %)	$\lesssim 17.5\,\%$ (50 %)
	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (97 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (12 %)

Type	$\Delta\mathrm{BR}^{S_1}_{h\gamma\gamma/hZZ}$	$\Delta\mathrm{BR}^{S_2}_{h\gamma\gamma/hZZ}$	$\Delta\mathrm{BR}^{S_3}_{h\gamma\gamma/hZZ}$	$\Delta\mathrm{BR}^{\mathrm{OS2}}_{h\gamma\gamma/hZZ}$	$\Delta\mathrm{BR}^{\overline{\mathrm{MS}}}_{h\gamma\gamma/hZZ}$
I	$\lesssim 5.0\,\%$ (97 %)	$\lesssim 5.0\,\%$ (90 %)	$\lesssim 5.0\,\%$ (90 %)	$\lesssim 5.0\,\%$ (94 %)	$\lesssim 20.0\,\%$ (50 %)
	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 10.0\,\%$ (98 %)	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 7.5\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (21 %)
II	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (60 %)	$\lesssim 2.5\,\%$ (96 %)	$\lesssim 5.0\,\%$ (82 %)	$\lesssim 62.0\,\%$ (50 %)
	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 12.5\,\%$ (96 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 7.5\,\%$ (97 %)	$\gtrsim 100.0\,\%$ (47 %)
LS	$\lesssim 5.0\,\%$ (97 %)	$\lesssim 5.0\,\%$ (75 %)	$\lesssim 2.5\,\%$ (88 %)	$\lesssim 5.0\,\%$ (95 %)	$\lesssim 12.5\,\%$ (50 %)
	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 10.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 7.5\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (13 %)
FL	$\lesssim 5.0\,\%$ (97 %)	$\lesssim 5.0\,\%$ (75 %)	$\lesssim 2.5\,\%$ (88 %)	$\lesssim 5.0\,\%$ (95 %)	$\lesssim 15.0\,\%$ (50 %)
	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 10.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 7.5\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (11 %)

Type	$\Delta\mathrm{BR}^{S_1}_{h\tau^+\tau^-}$	$\Delta\mathrm{BR}^{S_2}_{h\tau^+\tau^-}$	$\Delta\mathrm{BR}^{S_3}_{h\tau^+\tau^-}$	$\Delta\mathrm{BR}^{\mathrm{OS2}}_{h\tau^+\tau^-}$	$\Delta\mathrm{BR}^{\overline{\mathrm{MS}}}_{h\tau^+\tau^-}$
I	$\lesssim 2.5\,\%$ (98 %)	$\lesssim 2.5\,\%$ (88 %)	$\lesssim 2.5\,\%$ (97 %)	$\lesssim 2.5\,\%$ (98 %)	$\lesssim 7.5\,\%$ (50 %)
	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (12 %)

Higher-Order Impact in Beyond-SM Theories (BSM)

Impact of EW corrections on SM Higgs branching ratios $\Delta\text{BR} = \dfrac{\text{BR}^{\text{QCD\&EW}} - \text{BR}^{\text{QCD}}}{\text{BR}^{\text{QCD}}}$ [HDECAY]

ΔBR	$b\bar{b}$	$\tau^+\tau^-$	$\mu^+\mu^-$	$s\bar{s}$	$c\bar{c}$	gg	$\gamma\gamma$	$Z\gamma$	W^+W^-	ZZ
	-1.76%	-1.59%	-3.52%	2.24%	-3.81%	4.34%	-2.29%	-0.71%	3.68%	1.61%

Example: Impact of EW corrections on branching ratios of non-SM-like 2HDM Higgs boson

[Krause,MM,'19]

Type	$\Delta\text{BR}^{S_1}_{H\tau^+\tau^-}$	$\Delta\text{BR}^{S_2}_{H\tau^+\tau^-}$	$\Delta\text{BR}^{S_3}_{H\tau^+\tau^-}$	$\Delta\text{BR}^{S_4}_{H\tau^+\tau^-}$	$\Delta\text{BR}^{\overline{\text{MS}}}_{H\tau^+\tau^-}$
I	$\lesssim$ 15.0 % (49 %)	$\lesssim$ 15.0 % (51 %)	$\lesssim$ 15.0 % (48 %)	$\lesssim$ 15.0 % (55 %)	$\lesssim$ 60.0 % (50 %)
	$\lesssim$ 35.0 % (88 %)	$\lesssim$ 35.0 % (88 %)	$\lesssim$ 35.0 % (77 %)	$\lesssim$ 35.0 % (88 %)	$\gtrsim$ 100.0 % (40 %)
II	$\lesssim$ 15.0 % (54 %)	$\lesssim$ 20.0 % (53 %)	$\lesssim$ 10.0 % (51 %)	$\lesssim$ 25.0 % (47 %)	$\lesssim$ 85.0 % (14 %)
	$\lesssim$ 25.0 % (91 %)	$\lesssim$ 30.0 % (90 %)	$\lesssim$ 35.0 % (90 %)	$\lesssim$ 40.0 % (86 %)	$\gtrsim$ 100.0 % (84 %)
LS	$\lesssim$ 15.0 % (54 %)	$\lesssim$ 17.5 % (48 %)	$\lesssim$ 7.5 % (46 %)	$\lesssim$ 25.0 % (46 %)	$\lesssim$ 77.5 % (15 %)
	$\lesssim$ 27.5 % (90 %)	$\lesssim$ 30.0 % (88 %)	$\lesssim$ 30.0 % (88 %)	$\lesssim$ 40.0 % (85 %)	$\gtrsim$ 100.0 % (81 %)
FL	$\lesssim$ 15.0 % (55 %)	$\lesssim$ 17.5 % (48 %)	$\lesssim$ 7.5 % (46 %)	$\lesssim$ 25.0 % (46 %)	$\lesssim$ 77.5 % (15 %)
	$\lesssim$ 27.5 % (90 %)	$\lesssim$ 30.0 % (88 %)	$\lesssim$ 30.0 % (88 %)	$\lesssim$ 40.0 % (85 %)	$\gtrsim$ 100.0 % (81 %)

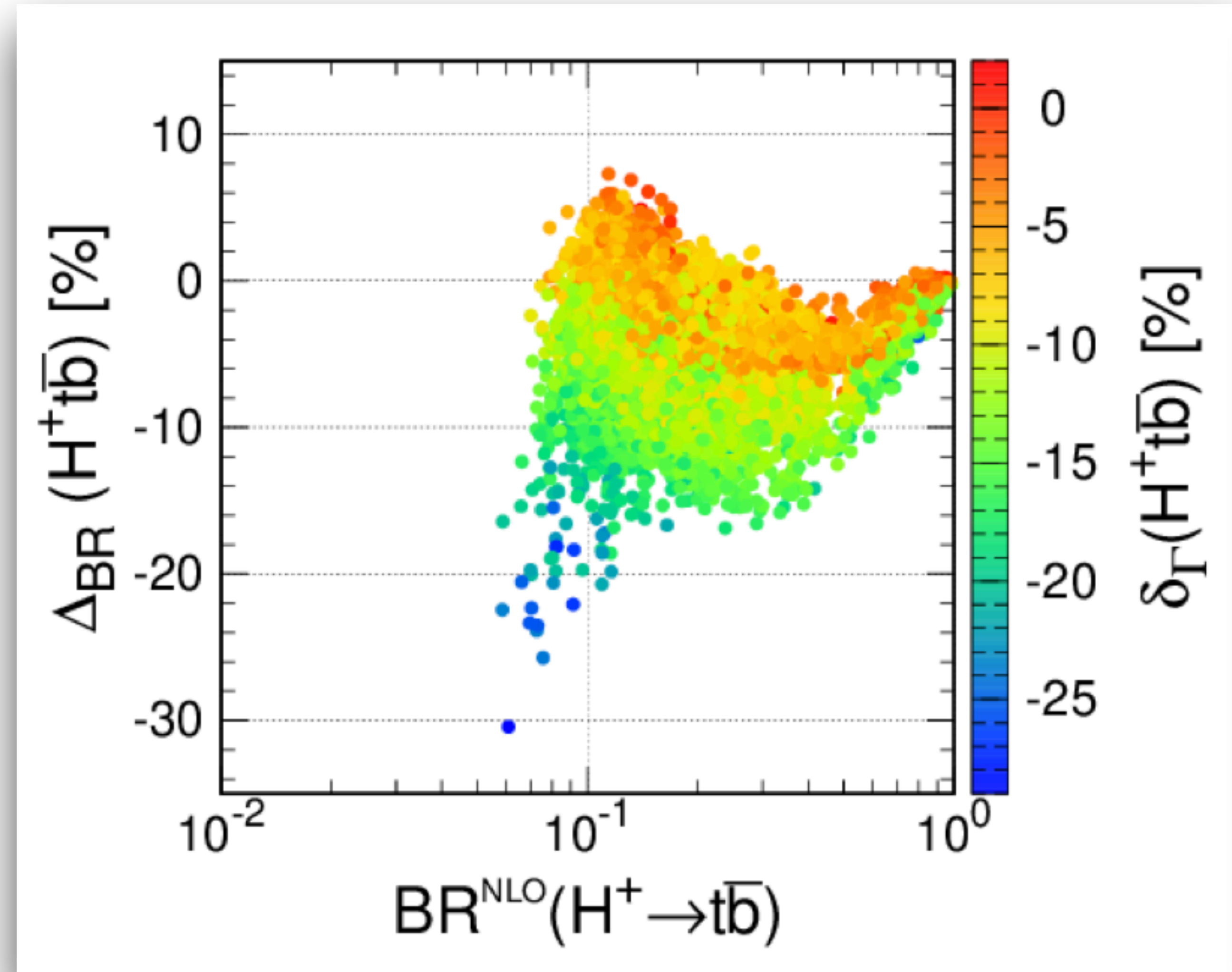
Type	$\Delta\text{BR}^{S_1}_{HZA}$	$\Delta\text{BR}^{S_2}_{HZA}$	$\Delta\text{BR}^{S_3}_{HZA}$	$\Delta\text{BR}^{S_4}_{HZA}$	$\Delta\text{BR}^{\overline{\text{MS}}}_{HZA}$
I	$\lesssim$ 5.0 % (51 %)	$\lesssim$ 5.0 % (51 %)	$\lesssim$ 10.0 % (46 %)	$\lesssim$ 10.0 % (53 %)	$\lesssim$ 80.0 % (26 %)
	$\lesssim$ 15.0 % (80 %)	$\lesssim$ 15.0 % (80 %)	$\lesssim$ 30.0 % (80 %)	$\lesssim$ 22.5 % (83 %)	$\gtrsim$ 100.0 % (52 %)
II	$\lesssim$ 5.0 % (68 %)	$\lesssim$ 5.0 % (69 %)	$\lesssim$ 10.0 % (50 %)	$\lesssim$ 7.5 % (73 %)	$\lesssim$ 85.0 % (20 %)
	$\lesssim$ 10.0 % (91 %)	$\lesssim$ 12.5 % (94 %)	$\lesssim$ 25.0 % (81 %)	$\lesssim$ 10.0 % (90 %)	$\gtrsim$ 100.0 % (56 %)
LS	$\lesssim$ 5.0 % (65 %)	$\lesssim$ 5.0 % (65 %)	$\lesssim$ 10.0 % (48 %)	$\lesssim$ 7.5 % (41 %)	$\lesssim$ 85.0 % (29 %)
	$\lesssim$ 10.0 % (86 %)	$\lesssim$ 10.0 % (86 %)	$\lesssim$ 27.5 % (80 %)	$\lesssim$ 15.0 % (90 %)	$\gtrsim$ 100.0 % (44 %)
FL	$\lesssim$ 5.0 % (65 %)	$\lesssim$ 5.0 % (63 %)	$\lesssim$ 10.0 % (53 %)	$\lesssim$ 7.5 % (51 %)	$\lesssim$ 82.5 % (20 %)
	$\lesssim$ 10.0 % (88 %)	$\lesssim$ 10.0 % (88 %)	$\lesssim$ 15.0 % (83 %)	$\lesssim$ 10.0 % (84 %)	$\gtrsim$ 100.0 % (30 %)

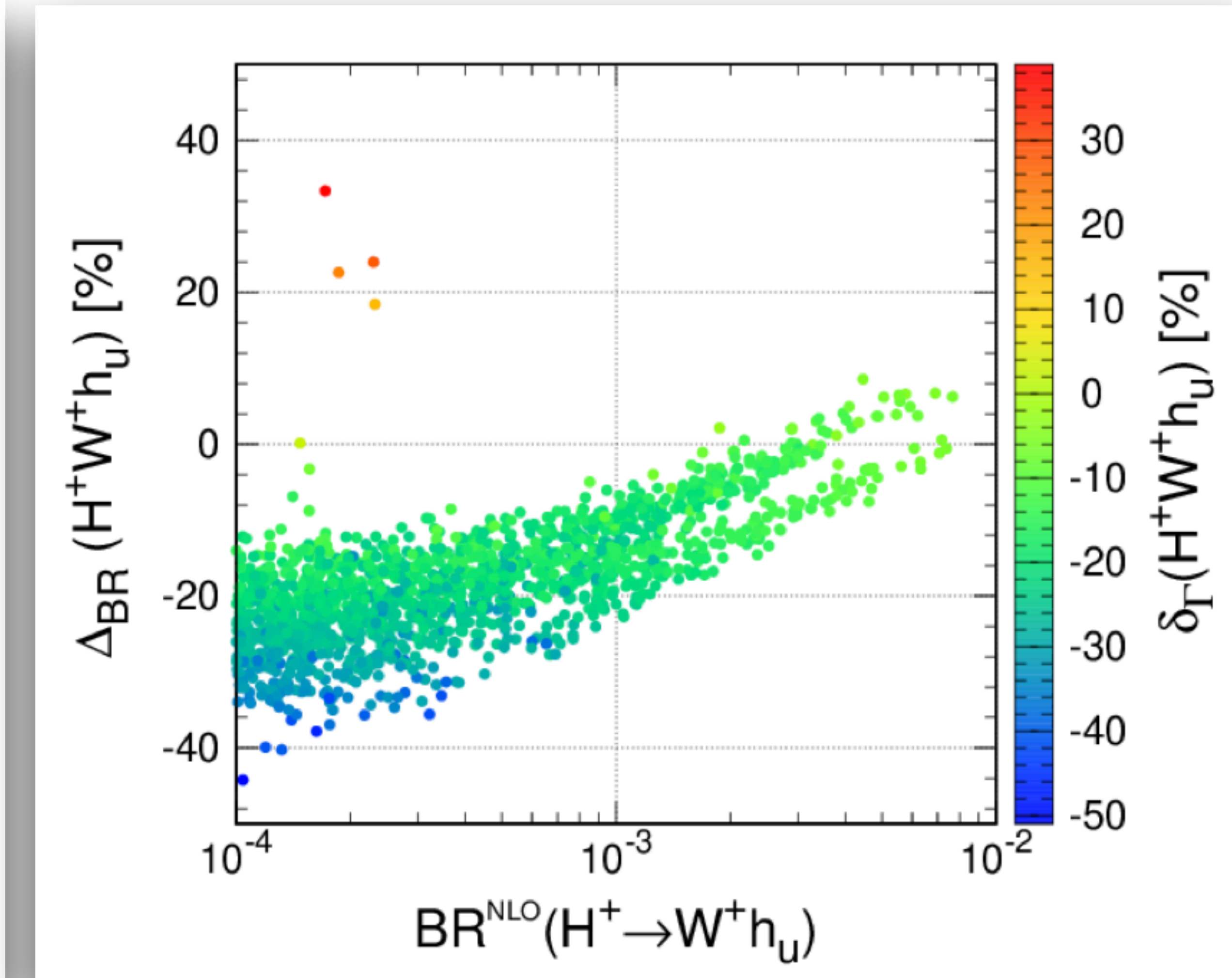
Type	$\Delta\text{BR}^{S_1}_{HW^\pm H^\mp}$	$\Delta\text{BR}^{S_2}_{HW^\pm H^\mp}$	$\Delta\text{BR}^{S_3}_{HW^\pm H^\mp}$	$\Delta\text{BR}^{S_4}_{HW^\pm H^\mp}$	$\Delta\text{BR}^{\overline{\text{MS}}}_{HW^\pm H^\mp}$
I	$\lesssim$ 5.0 % (56 %)	$\lesssim$ 5.0 % (55 %)	$\lesssim$ 10.0 % (49 %)	$\lesssim$ 10.0 % (57 %)	$\lesssim$ 70.0 % (25 %)
	$\lesssim$ 17.5 % (81 %)	$\lesssim$ 17.5 % (81 %)	$\lesssim$ 30.0 % (78 %)	$\lesssim$ 25.0 % (82 %)	$\gtrsim$ 100.0 % (52 %)

SUSY-EW & SUSY-QCD Corrected Charged Higgs Decays

Scan points compatible w/ Higgs data
[HiggsSignals,HiggsBounds]

[Dao,Fritz,Krause,MM,Patel,'19]
[Dao,MM,Patel,Sakurai,'21]



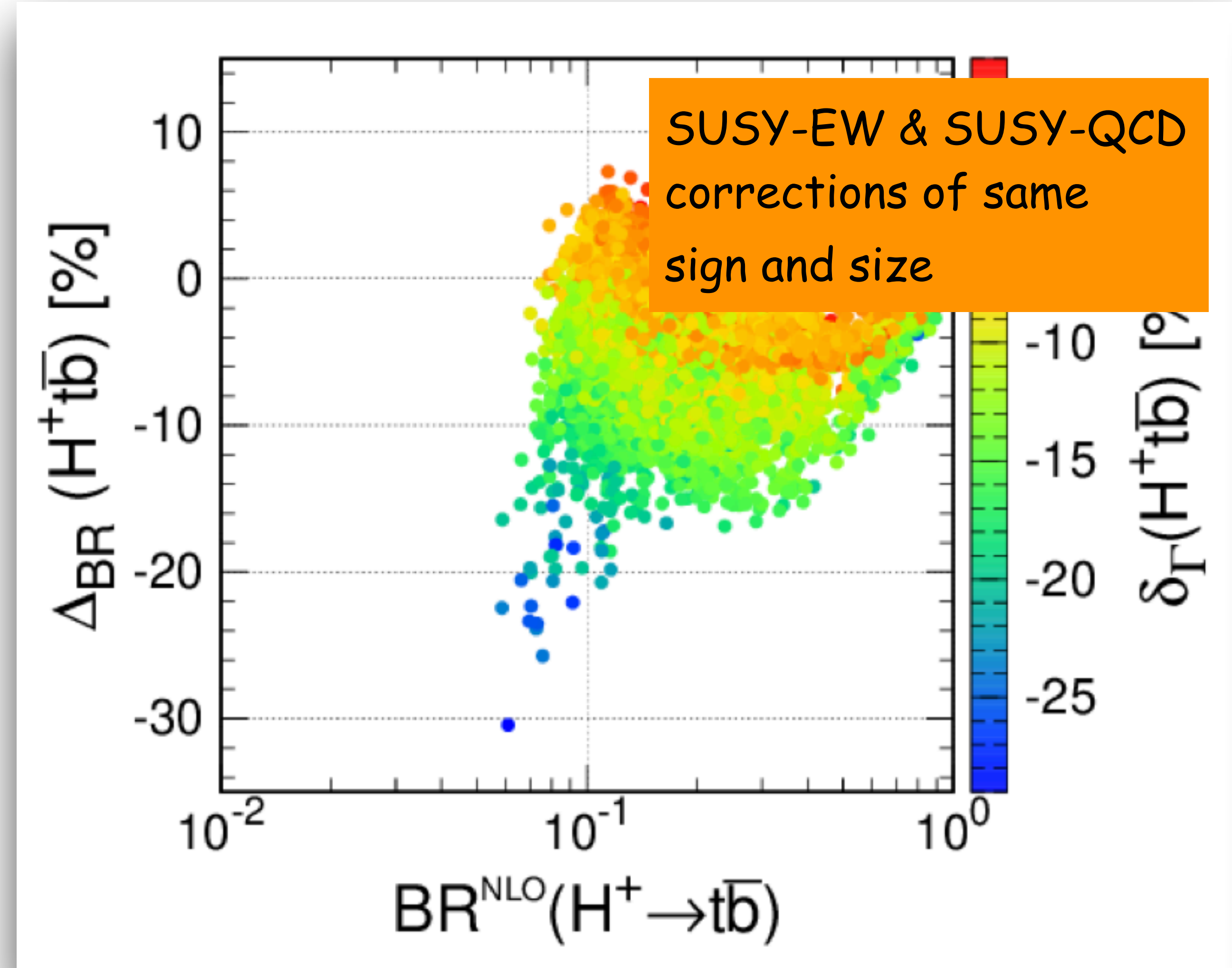


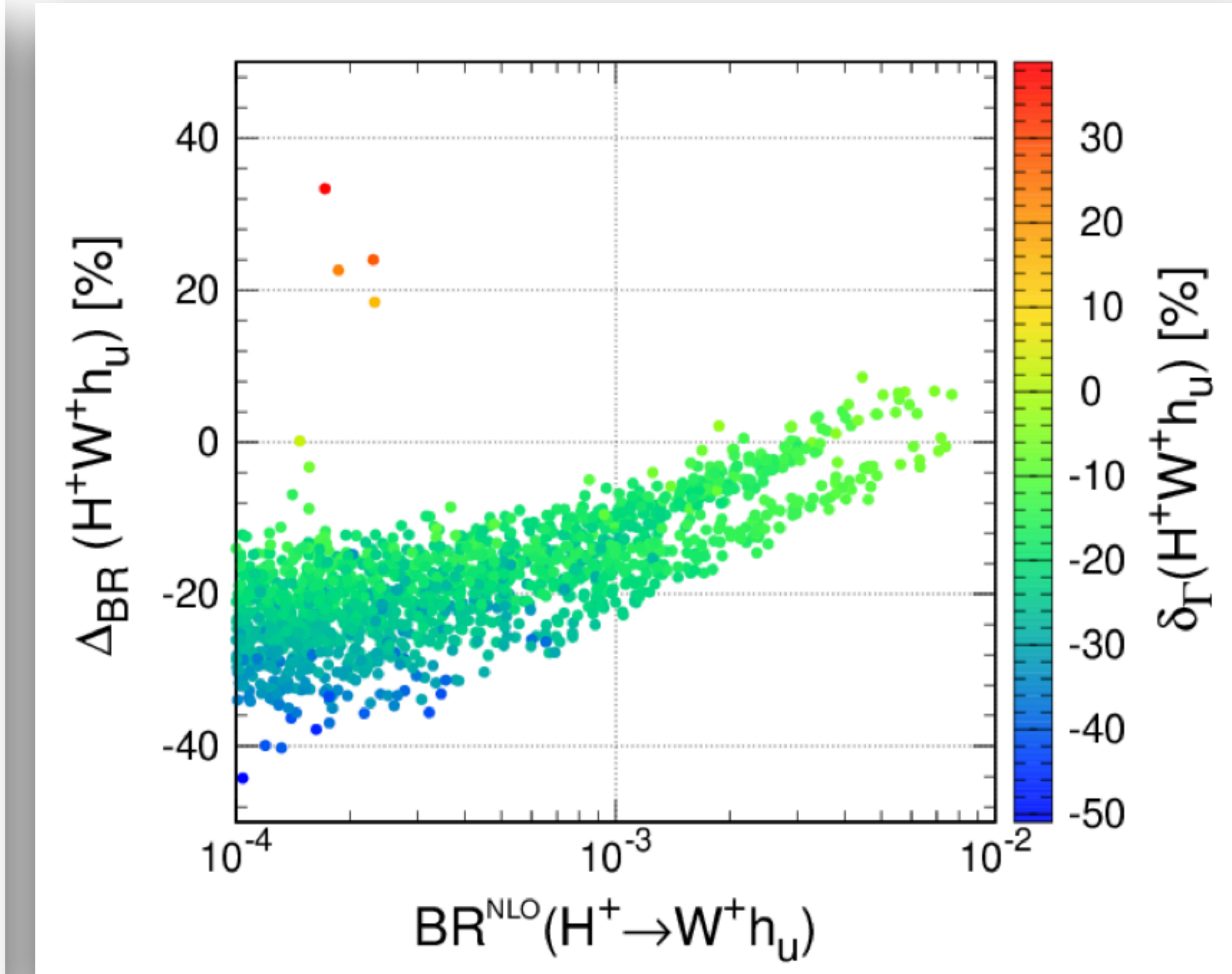
- Corrections to charged Higgs decays:
  Δ_{BR}: NLO impact on branching ratio, δ_Γ: NLO impact on partial width
- Implemented in NMSSMCALCEW, includes also NLO neutral Higgs decays
  [Dao,Baglio,MM,Patel,Sakurai]

SUSY-EW & SUSY-QCD Corrected Charged Higgs Decays

Scan points compatible w/ Higgs data
[HiggsSignals,HiggsBounds]

[Dao,Fritz,Krause,MM,Patel,'19]
[Dao,MM,Patel,Sakurai,'21]





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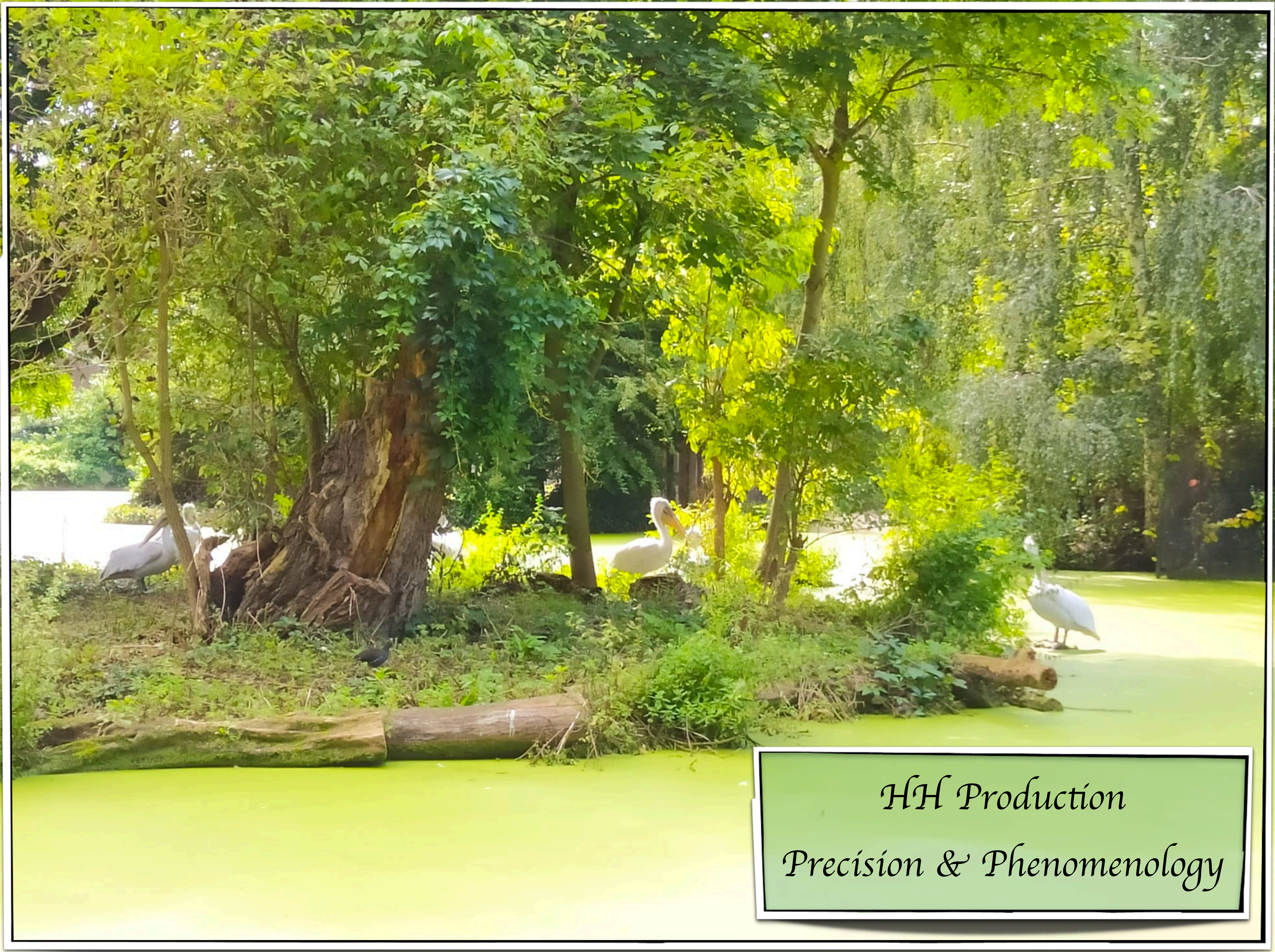
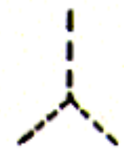

HH Production
Precision & Phenomenology

Ultimate Test of the Higgs Mechanism

$$V(H) = \frac{1}{2} M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

Higgs mass : $M_H = \sqrt{2\lambda}\, v$

trilinear Higg self-coupling : $\lambda_{HHH} = 3 M_H^2 / M_Z^2$



quadrilinear Higgs self-coupling : $\lambda_{HHHH} = 3 M_H^2 / M_Z^4$

(units $\lambda_0 = 33.8\,\mathrm{GeV}/\lambda_0^2$)

(a) trilinear coupling : via Higgs pair production

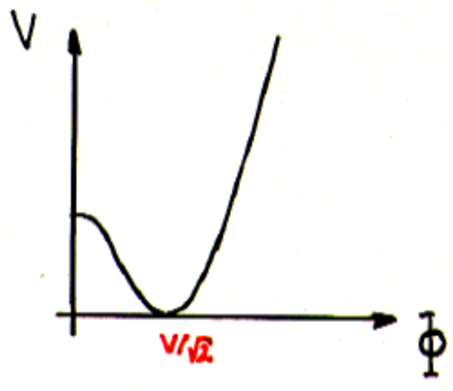
(b) quadrilinear coupling : via triple Higgs production

measurement of the Higgs self-couplings and reconstruction of the Higgs potential $\Big\} \Rightarrow$ establish the scalar sector of the Higgs mechanism experimentally

$$V(\Phi) = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2}\right)^2$$

$v = 246$ GeV

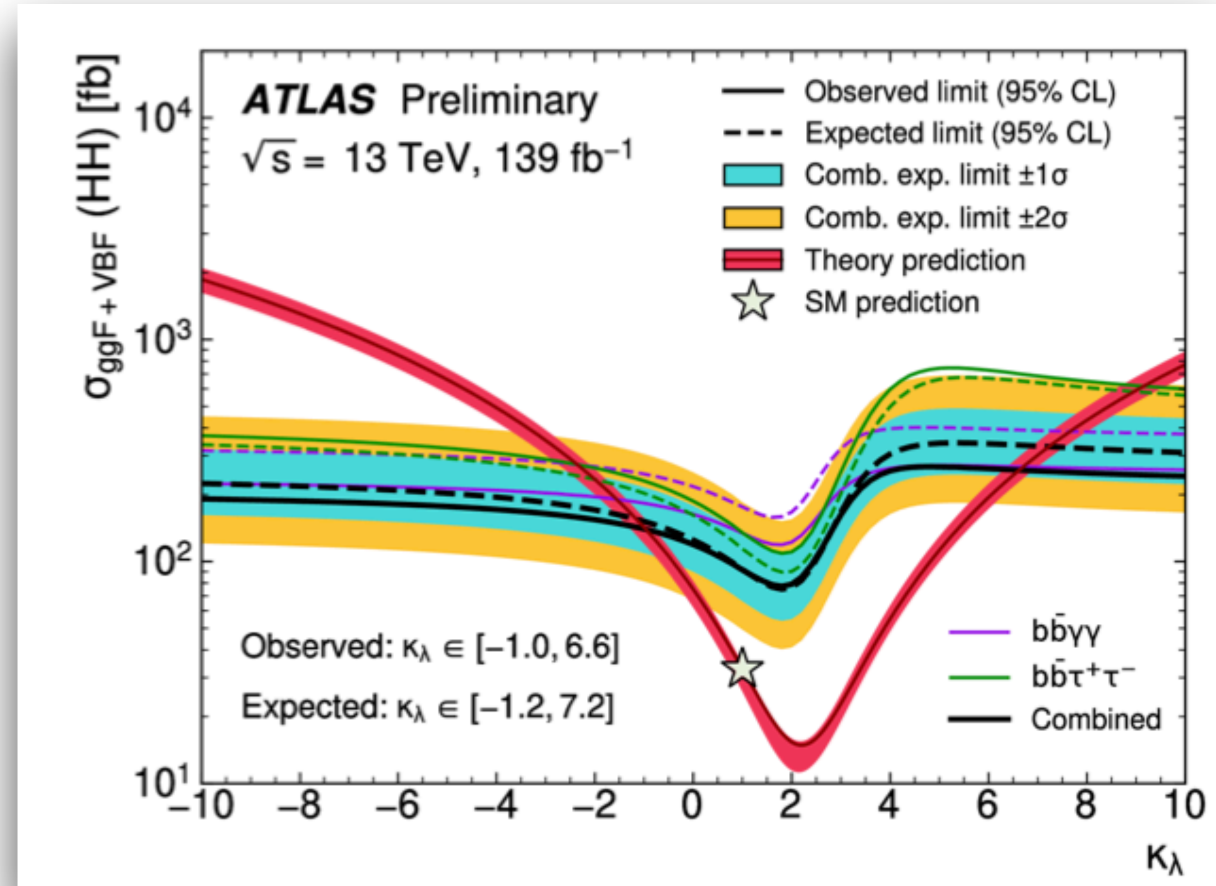
$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+H \end{pmatrix} \rightsquigarrow$$



Slides from LCWS, Fermilab, 10/2000

[Djouadi,Kilian,MM,Zerwas,03/99,04/99]

Experimental Results - Limits on Trilinear Higgs Self-Coupling

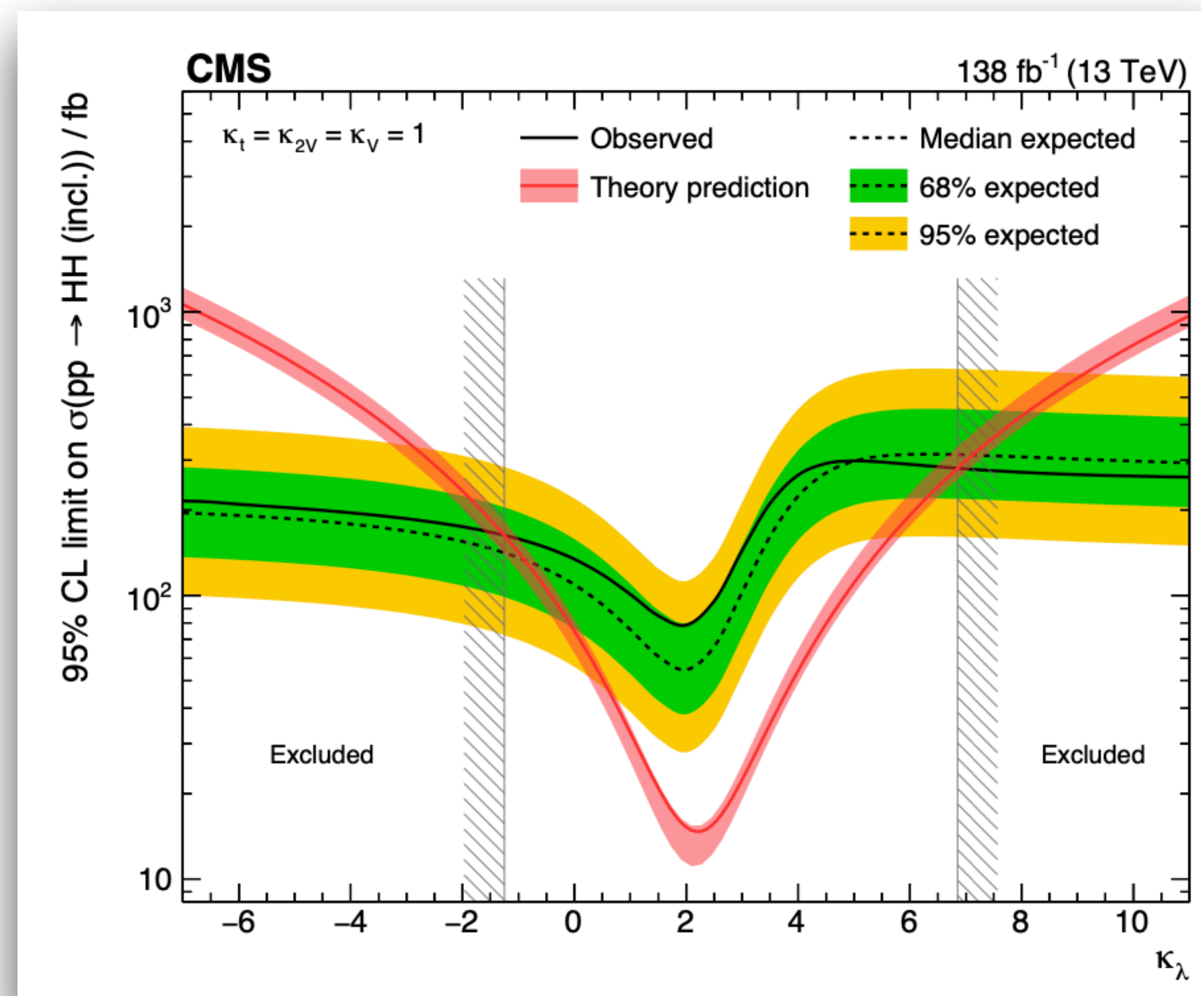


[Rui Zhang, ATLAS, HH Workshop´22]

Observed: $\kappa_\lambda \in [-1.0, 6.6]$

Expected: $\kappa_\lambda \in [-1.2, 7.2]$

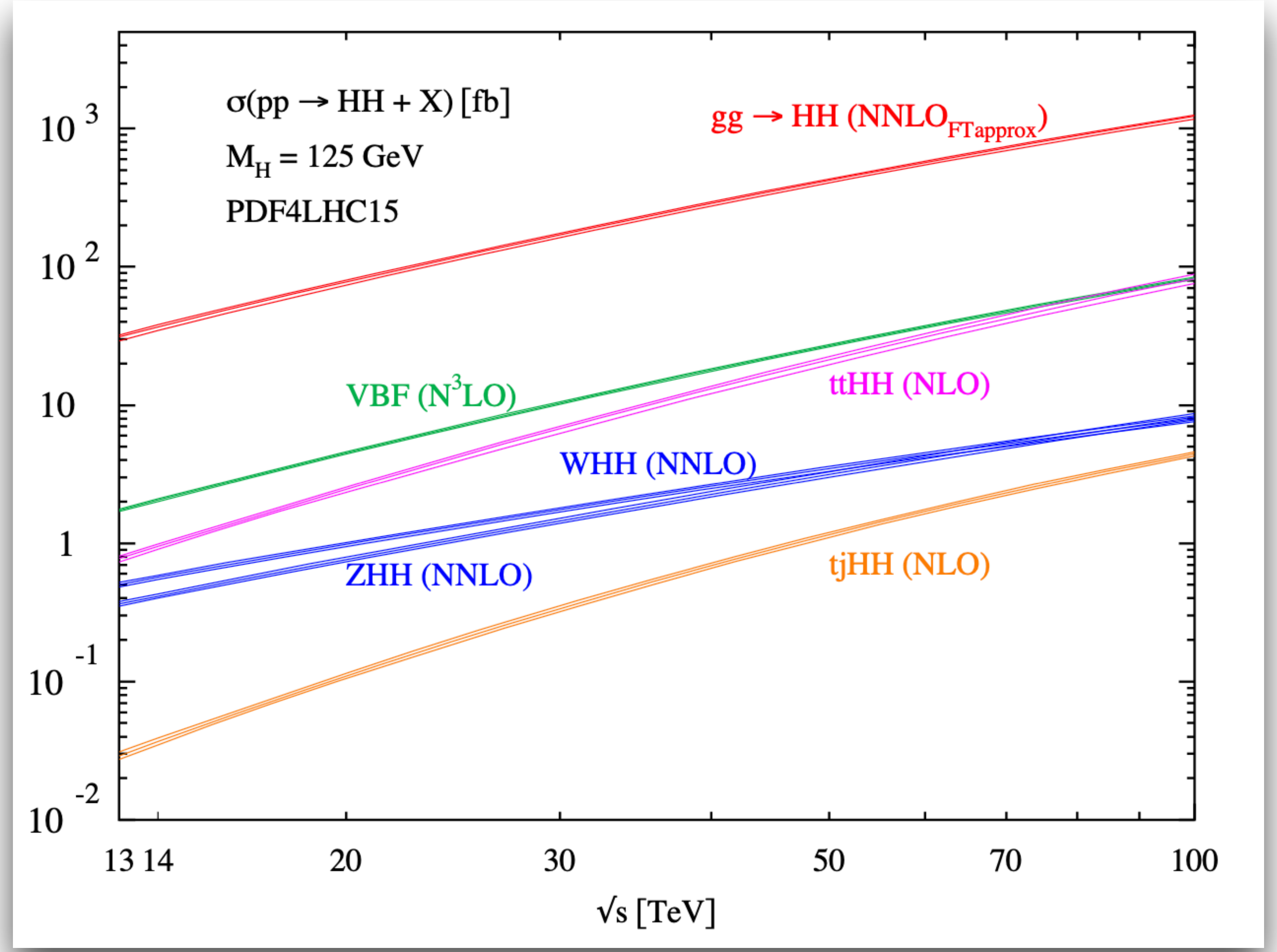
[CMS,2207.00043]



$-1.24 \leq \boldsymbol{\kappa_\lambda} \leq 6.49$

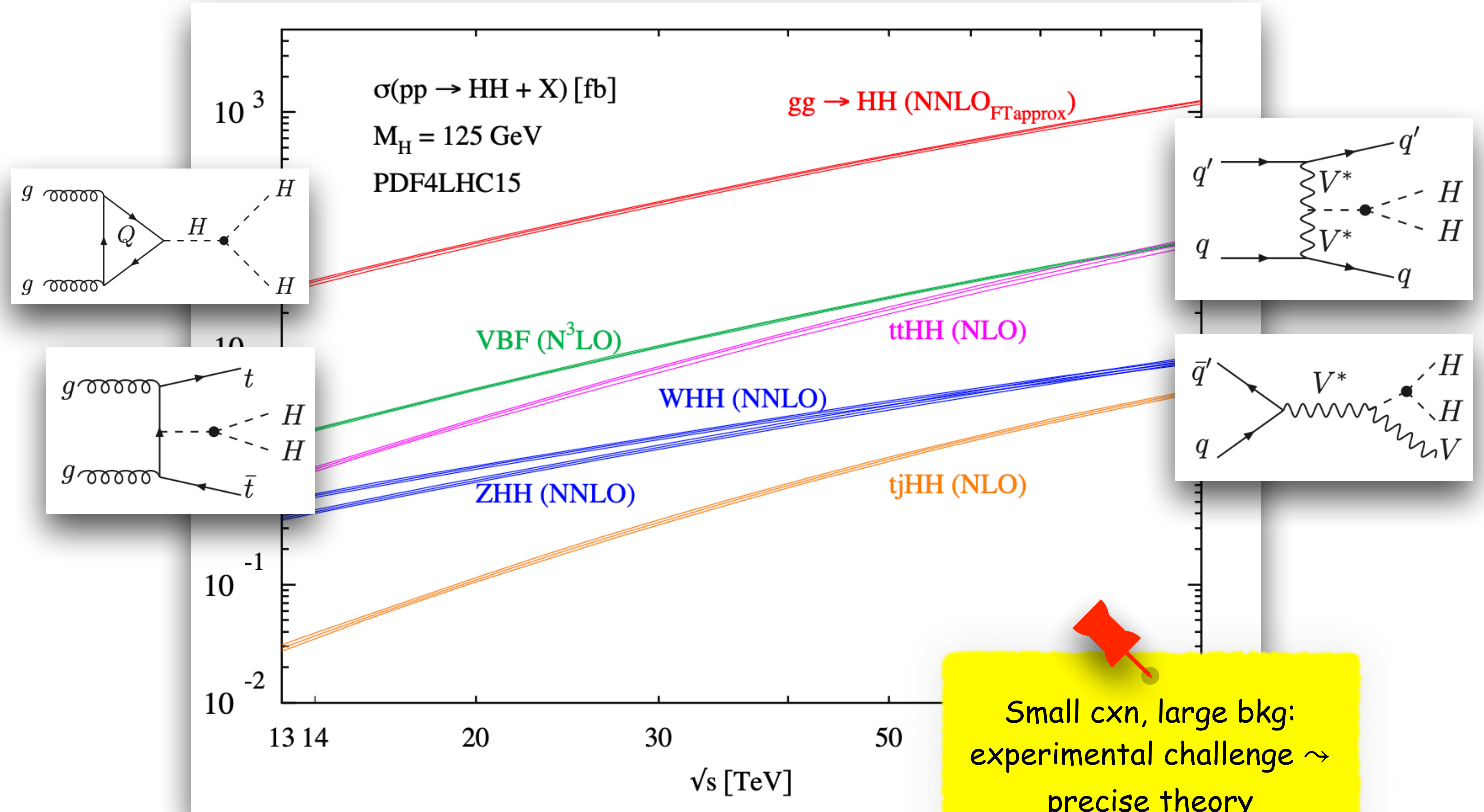
Double Higgs Production Processes

[HH, White paper]



Double Higgs Production Processes

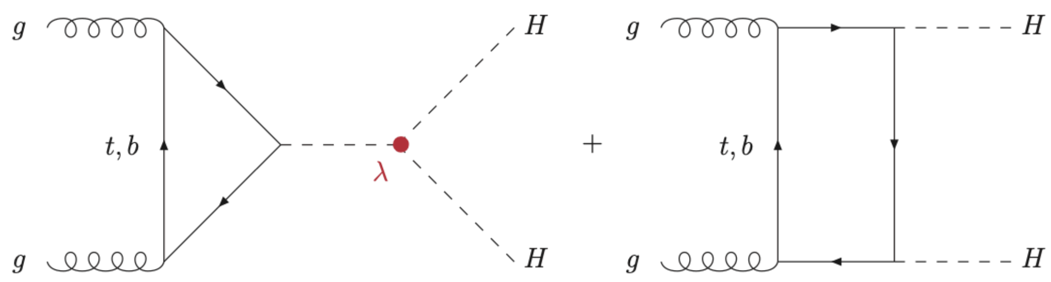
[HH, White paper]



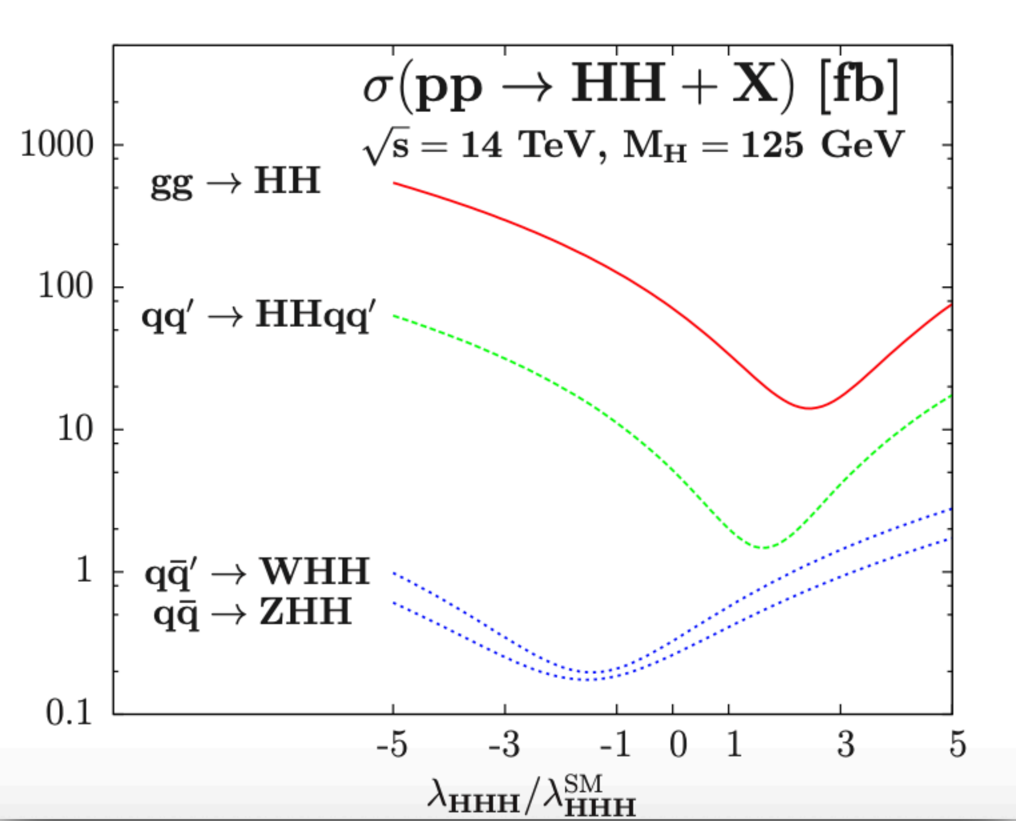
Small cxn, large bkg: experimental challenge ⇝ precise theory predictions required

Higgs Pair Production through Gluon Fusion

- Loop mediated at leading order - SM: third generation dominant



- Threshold region sensitive to λ; large M_{HH}: sensitive to new physics effects in loops



[Baglio,Djouadi,Gröber,MM,Quévillon,Spira]

$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

decreasing with M_{HH}

Higher-Order QCD Corrections to Higgs Pair Production

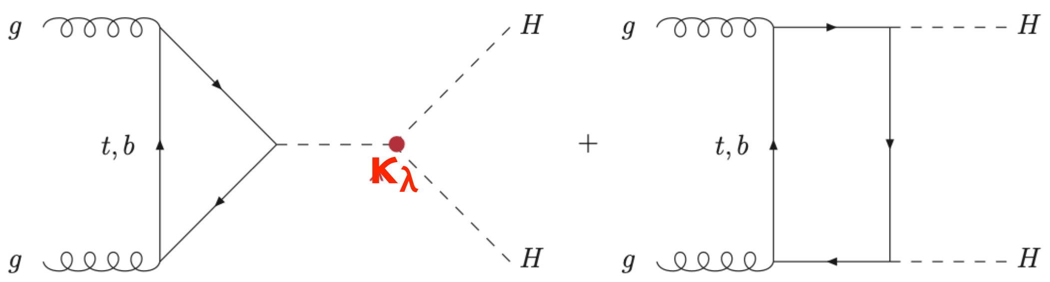
- 2-loop QCD corrections: $\lesssim$ 70% [HTL, $\mu = M_{HH}/2$] [Dawson,Dittmaier,Spira]
- 2-loop QCD corrections: $\sigma = \sigma_0 + \sigma_1/m_t^2 + \ldots + \sigma_4/m_t^8$
  [refinement: full LO at differential level] [Grigo,Hoff,Melnikov,Steinhauser]
- Mass effects @ NLO in real corrections: ~ - 10%
  [Frederix,Frixione,Hirschi,Maltoni,Mattelaer,Torrielli,Vryonidou,Zaro]
- NNLO QCD corrections: ~ 20% [HTL] [de Florian,Mazzitelli; Grigo,Melnikov,Steinhauser]
- N^3LO QCD corrections: ~ 5% [HTL] [Chen,Li,Shao,Wang]
- NNLO Monte Carlo: inclusion of full top-mass effects @ NLO [partly at NNLO]
  [Grazzini,Heinrich,Jones,Kallweit,Kerner,Lindert,Mazzitelli]
- NLO: matching to parton showers [Heinrich,Jones,Kerner,Luisoni,Vryonidou]
- New expansion/extrapolation methods:
  (i) $1/m_t^2$ expansion + conformal mapping + Padé approximants [Gröber,Maier,Rauh]
  (ii) p_T^2 expansion [Bonciani,Degassi,Giardino,Gröber]
- NLO: small mass expansion [$Q^2 \gg m_t^2$] [Davies,Mishima,Steinhauser,Wellmann]
- Combination of full NLO and small mass expansion [Davies,Heinrich,Jones,Kerner, Mishima,Steinhauser,Wellmann]
- Light fermionic 3-loop corrections [Davies,Schönwald,Steinhauser]

Higher-Order QCD, EW Corrections to Higgs Pair Production

- Complete list, see e.g. twiki of LHC Higgs Working Subgroup HH and recent reviews

  -> recommendations for cross sections to be used given for
    - different c.m. energies
    - different coupling modifiers κ_λ

  -> uncertainties on di-Higgs cross sections



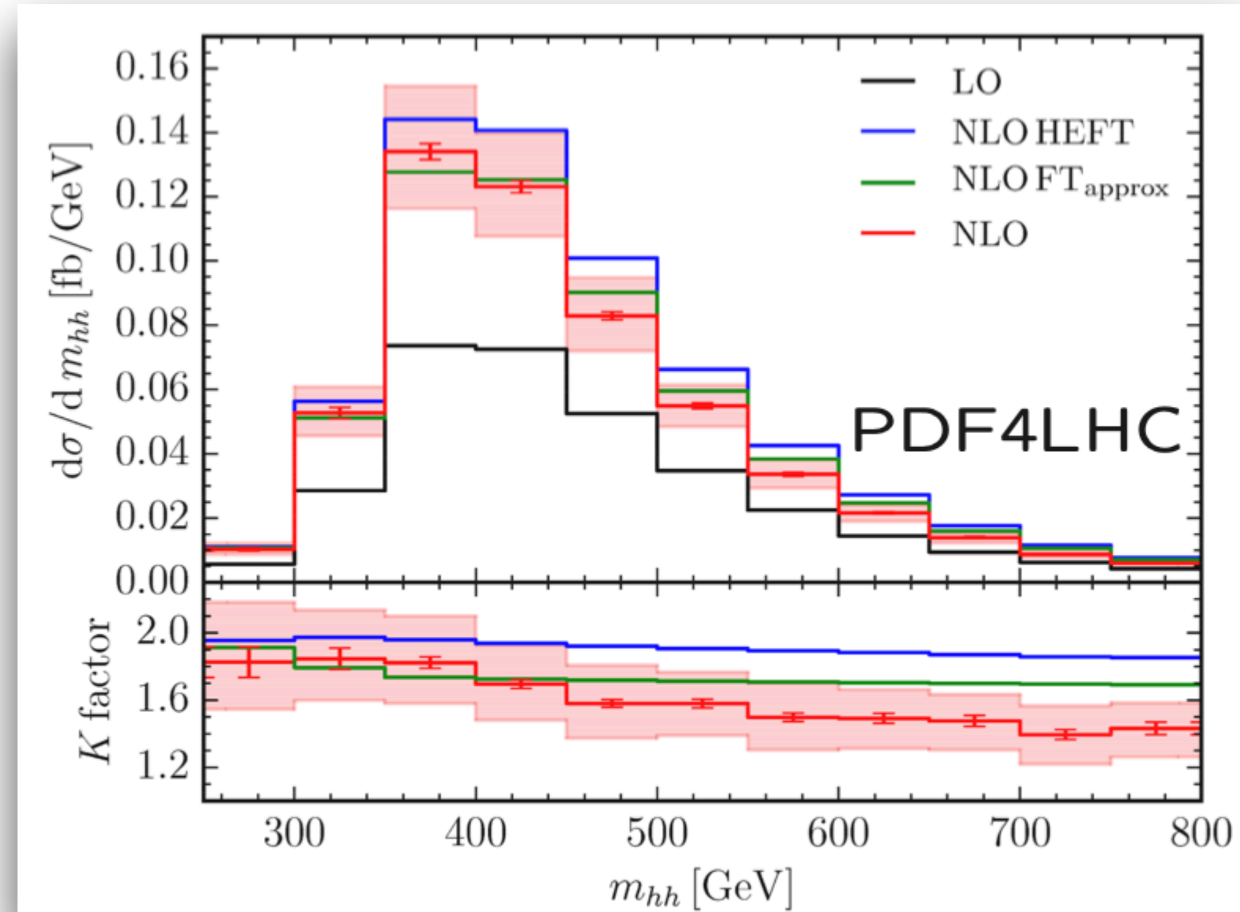
- First results on EW corrections:

✦ top-Yukawa induced corrections: 0.2%, not absorbable in effective trilinear coupling [MM,Schlenk,Spira,'22]

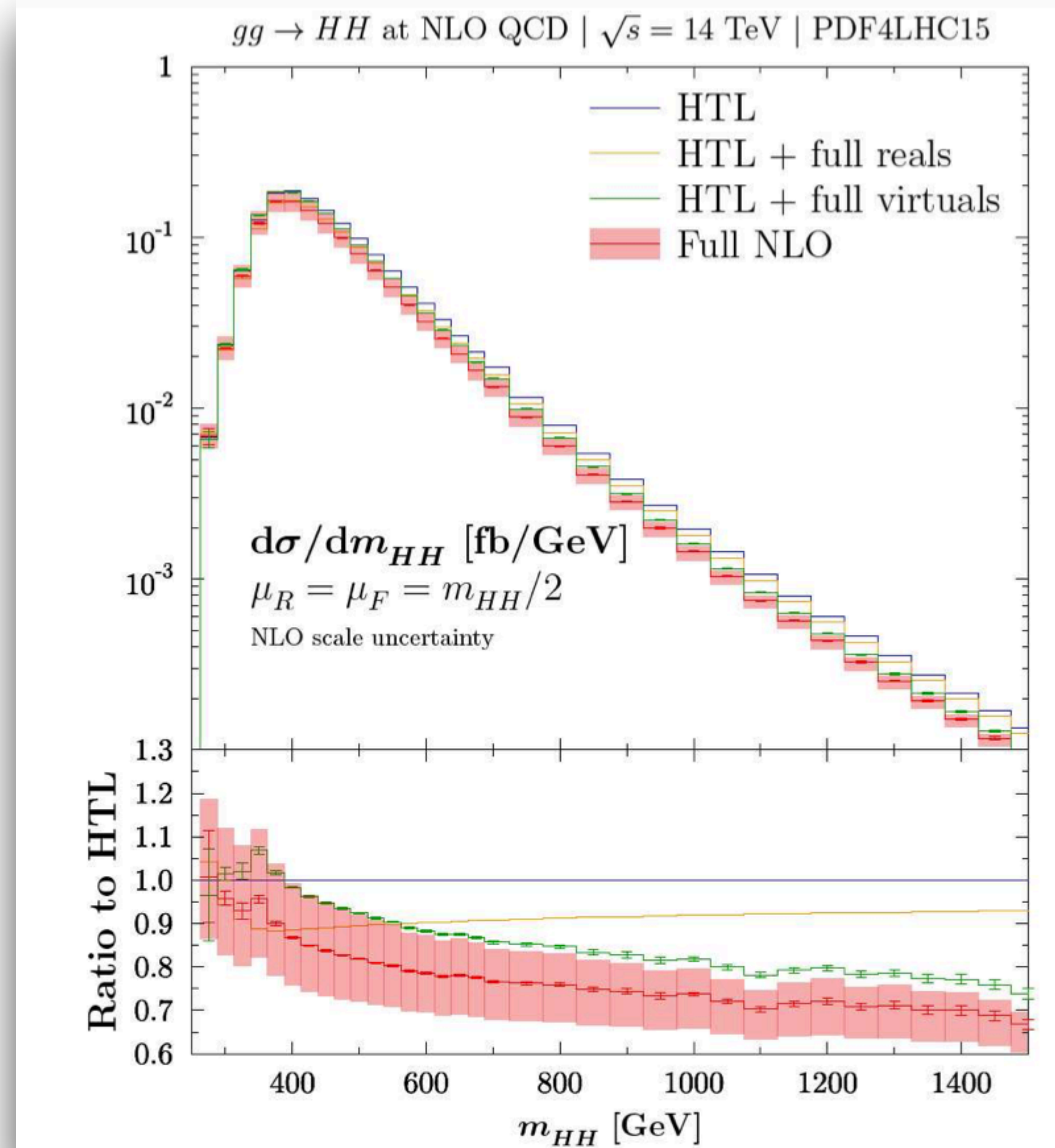
✦ top Yukawa corrections in the high-energy limit [Davies,Mishima,Schönwald,Steinhauser,Zhang,'22]
large top mass expansion up to $1/m_t^8$ or more [Davies,Schönwald,Steinhauser,Zhang,'23]

Full NLO QCD Calculation

[Borowka,Greiner,Heinrich,Jones,Kerner, Schlenk,Schubert,Zirke]



[Baglio,Campanario,Glaus,MM,Ronca,Spira,Streicher]



$\sigma_{NLO} =$	$32.91(10)^{+13.8\%}_{-12.8\%}\ fb$	$32.81(7)^{+13.5\%}_{-12.5\%}\ fb$
$\sigma^{HTL}_{NLO} =$	$38.75^{+18\%}_{-15\%}\ fb$	$38.66^{+18\%}_{-15\%}\ fb$
$m_t =$	173 GeV	172.5 GeV

⇒ -15% mass effects on top of LO 20-30% for distributions

Uncertainties at NLO QCD

- Renormalization and factorization scale uncertainties at NLO:

$$\begin{aligned}
\sqrt{s} = 13\ \text{TeV}: &\quad \sigma_{tot} = 27.73(7)^{+13.8\%}_{-12.8\%}\ \text{fb} \\
\sqrt{s} = 14\ \text{TeV}: &\quad \sigma_{tot} = 32.81(7)^{+13.5\%}_{-12.5\%}\ \text{fb} \\
\sqrt{s} = 27\ \text{TeV}: &\quad \sigma_{tot} = 127.0(2)^{+11.7\%}_{-10.7\%}\ \text{fb} \\
\sqrt{s} = 100\ \text{TeV}: &\quad \sigma_{tot} = 1140(2)^{+10.7\%}_{-10.0\%}\ \text{fb}
\end{aligned}$$

- m_t scale/scheme uncertainties at NLO:

$$\begin{aligned}
\sqrt{s} = 13\ \text{TeV}: &\quad \sigma_{tot} = 27.73(7)^{+4\%}_{-18\%}\ \text{fb} \\
\sqrt{s} = 14\ \text{TeV}: &\quad \sigma_{tot} = 32.81(7)^{+4\%}_{-18\%}\ \text{fb} \\
\sqrt{s} = 27\ \text{TeV}: &\quad \sigma_{tot} = 127.8(2)^{+4\%}_{-18\%}\ \text{fb} \\
\sqrt{s} = 100\ \text{TeV}: &\quad \sigma_{tot} = 1140(2)^{+3\%}_{-18\%}\ \text{fb}
\end{aligned}$$

- Linear sum of uncertainties ~>

Final Uncertainties at FT_{approx}

- Final combined renormalization/factorization scale and m_t scale/scheme uncertainties at $NNLO_{FTapprox}$*:

$$\sqrt{s} = 13\ \text{TeV}: \quad \sigma_{tot} = 31.05^{+6\%}_{-23\%}\ \text{fb}$$

$$\sqrt{s} = 14\ \text{TeV}: \quad \sigma_{tot} = 36.69^{+6\%}_{-23\%}\ \text{fb}$$

$$\sqrt{s} = 27\ \text{TeV}: \quad \sigma_{tot} = 139.9^{+5\%}_{-22\%}\ \text{fb}$$

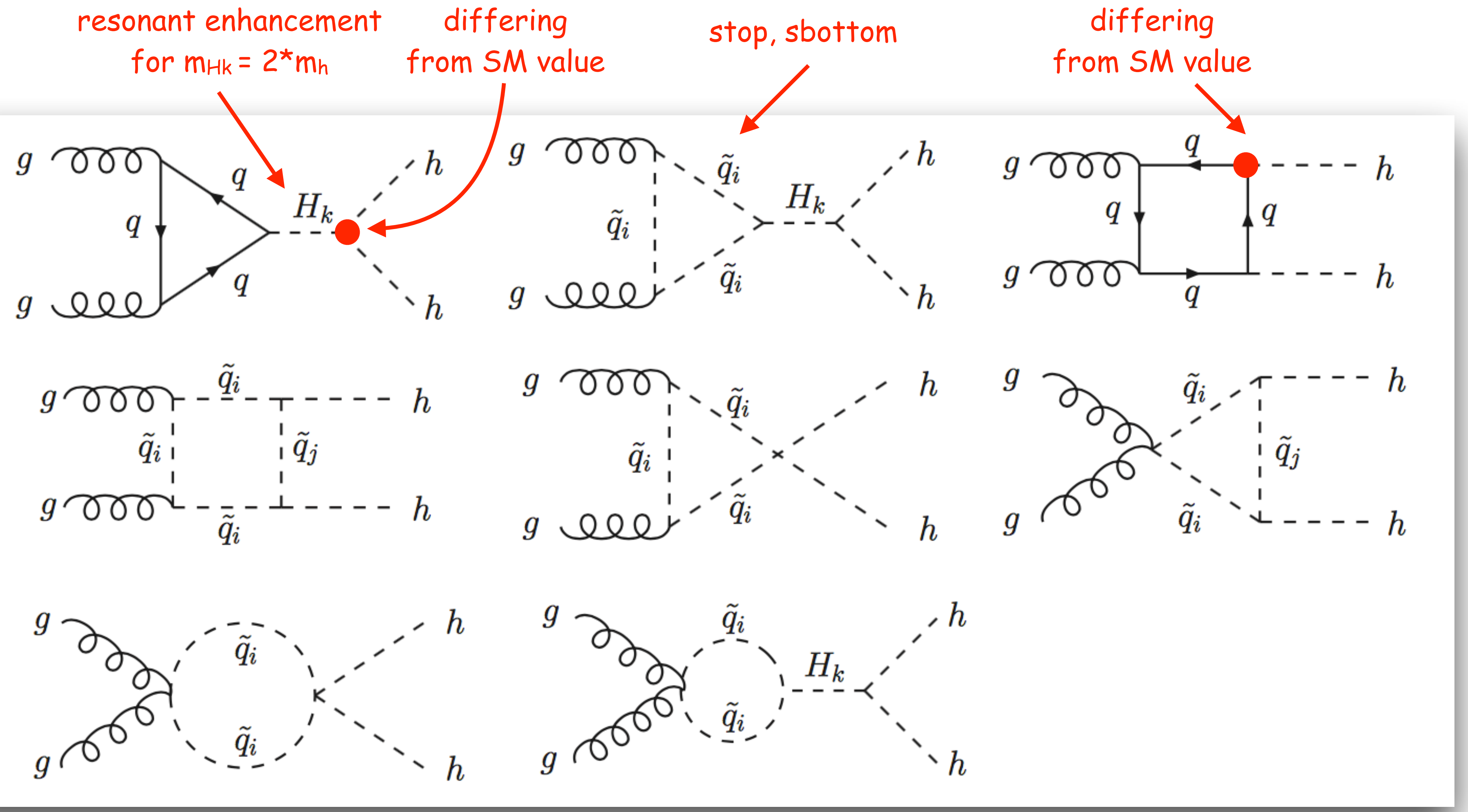
$$\sqrt{s} = 100\ \text{TeV}: \quad \sigma_{tot} = 1224^{+4\%}_{-21\%}\ \text{fb}$$

*FT_{approx}: full NNLO QCD in the heavy-top-limit with full LO and NLO mass effects and full mass dependence in the one-loop double real corrections at NNLO QCD

New Physics Effects in Higgs Pair Production

- **Cross section:** - different trilinear couplings - different Yukawa couplings - novel particles in the loops - resonant enhancement - novel couplings

- **Example NMSSM:** [taken from Dao,MM,Streicher,Walz,´13]



2HDM | C2HDM | N2HDM | NMSSM

2 Higgs doublets

h, H, A, H^+, H^-

SFOEWPT, DM, plus charged Higgs

CP-violating

$H1, H2, H3, H^+, H^-$

plus CP violation baryogenesis

Singlet extension

$H1, H2, H3, H^+, H^-$

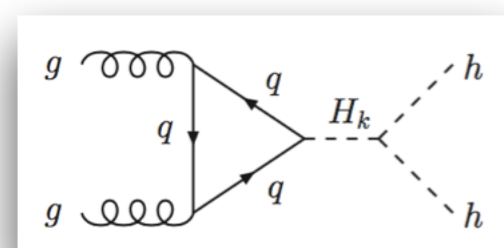
rich pheno, DM

Supersymmetry

$H1, H2, H3, A, H^+, H^-$

a lot (DM, CPviol, Hierarychy, ...)

Resonant Enhancement



Higgs-to-Higgs Cascade decays

- Following results based on:

  Abouabid, Arhrib, Azevedo, El Falaki, Ferreira, MMM, Santos, „Benchmarking Di-Higgs Production in Extended Higgs Sectors", JHEP 09 (2022) 011

Parameter Point Samples

✦ Scans in parameter spaces of the models w/ ScannerS:

take into account all relevant theoretical and experimental constraints
+ limits from di-Higgs searches

4b: [ATLAS-CONF-Note-2021-030, ATLAS,1804.06174], WWγγ: [ATLAS,1807.08567]; bbγγ: [ATLAS,1807.04873]; bbWW: [ATLAS,1811.04671, bbZZ: [CMS,2006.06391] bbττ: [ATLAS,1808.00336;ATLAS-CONF-Note-2021-035; ATLAS,2007.14811], 4W: [ATLAS,1811.11028]

Resonant and non-resonant di-Higgs limits start cutting in parameter space of the models

✦ Computation of Higgs pair production cxn:

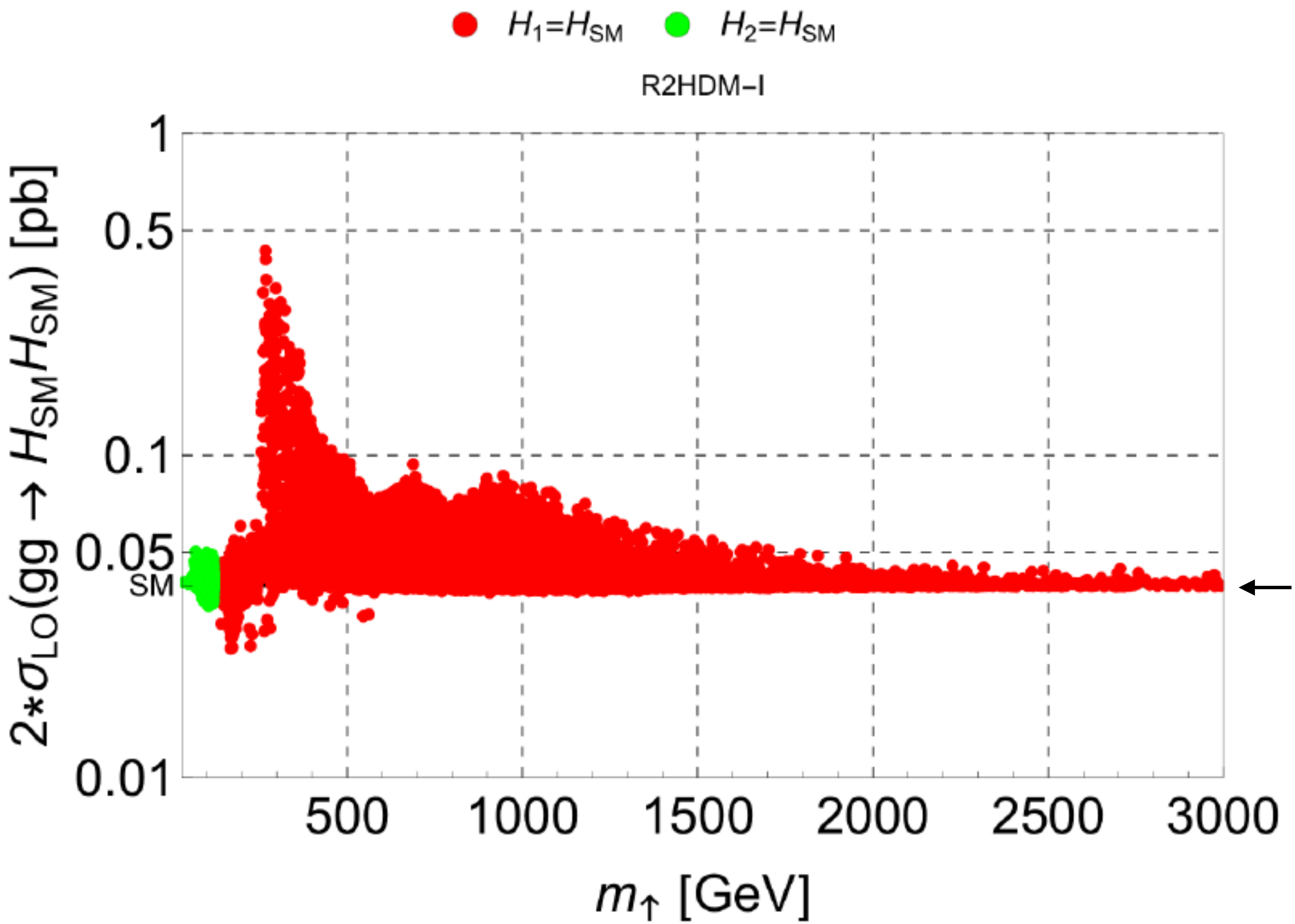
HPAIR [Spira] for C2HDM [Gröber,MM,Spira,'17], NMSSM [Dao,MM,Streicher,Walz,'13], 2HDM [MM], N2HDM [MM]: Born-improved HTL cxn; K-factors 1.4-2.1

✦ Scatter plots:

LO cxn times factor 2 (to approx. account for NLO QCD), benchmark points include NLO QCD calculated w/ HPAIR

2-Higgs Doublet Model: SM-like Higgs Pair Production

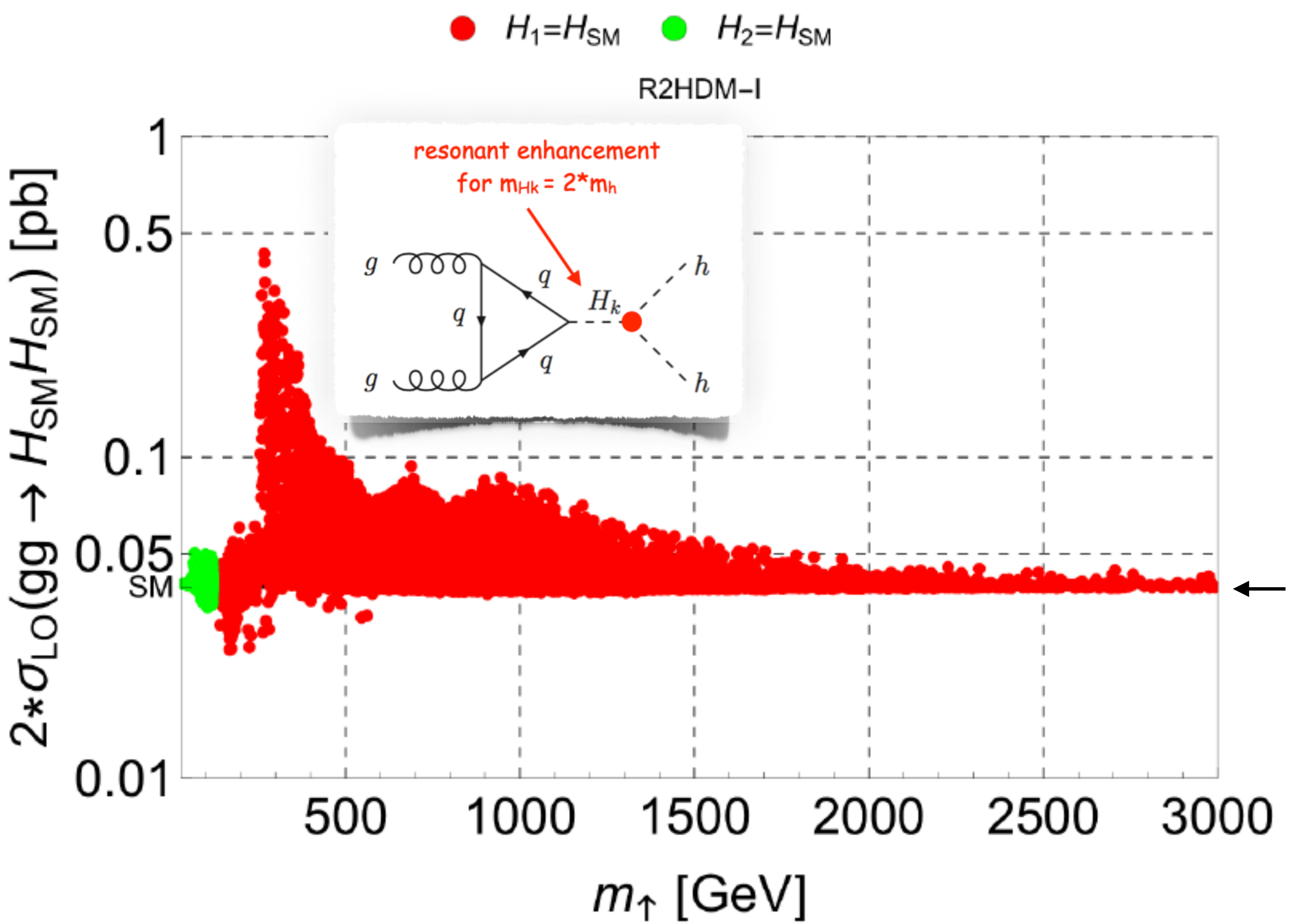
[Abouabid,Arhrib,Azevedo,El Falaki,Ferreira,MM,Santos,'21]



← SM result @NLO QCD

2-Higgs Doublet Model: SM-like Higgs Pair Production

[Abouabid,Arhrib,Azevedo,El Falaki,Ferreira,MM,Santos,'21]



SM result @NLO QCD

Resonant/Non-Resonant Maximum SM-Like Higgs Pair Production

[Abouabid,Arhrib,Azevedo,El Falaki,Ferreira,MM,Santos,'21]

Resonant production
at NLO QCD in fb

	H_1	H_2
R2HDM-I	444	n.a.
R2HDM-II	81	n.a.
C2HDM-I	387	47
C2HDM-II	130	–
N2HDM-I	376	344
N2HDM-II	188	63
NMSSM	183	65

Non-Resonant production
at NLO QCD in fb

	H_1	H_2
R2HDM-I	92	–
R2HDM-II	59	–
C2HDM-I	98	42
C2HDM-II	75	–
N2HDM-I	151	96
N2HDM-II	112	48
NMSSM	73	65

SM value at NLO QCD 38 fb

Di-Higgs Beats Single-Higgs

- Singlet extended N2HDM, NMSSM: non-SM-like Higgs is singlet-like and/or more down-than up-type like => suppressed direct production rate

- Sample parameter point N2HDM T1:

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$
125.09	281.54	441.25	386.98	421.81	1.990
α_1	α_2	α_3	v_s [GeV]	$\text{Re}(m_{12}^2)$ [GeV^2]	
1.153	0.159	0.989	9639	29769	

Final state:

6b: $\sigma^{\text{NLO}}_{H_1H_2} \times \text{BR}(H_2 \to H_1H_1) \times \text{BR}(H_1 \to b\bar{b})^3 = 509 \cdot 0.37 \cdot 0.60^3 \text{ fb} = 40 \text{ fb}$

4b: $\sigma^{\text{NNLO}}(H_2) \times \text{BR}(H_2 \to H_1H_1) \times \text{BR}(H_1 \to b\bar{b})^2 = 161 \cdot 0.37 \cdot 0.60^2 \text{ fb} = 21 \text{ fb}$

H_2 has tiny couplings to b-quarks => better chances to be discovered in di-Higgs than single Higgs channels

HH and Strong First Order EWPT
SFOEWPT and Gravitational Waves

- **Electroweak Baryogenesis (EWBG):** generation of the observed baryon-antibaryon asymmetry in the electroweak phase transition (EWPT) [Riemer-Sorensen, Jenssen '17]

$$5.8 \cdot 10^{-10} < \frac{n_B - n_{\bar{B}}}{n_\gamma} < 6.6 \cdot 10^{-10}$$

- **Sakharov Conditions:** [Sakharov '67]
  - (i) B number violaton (sphaleron processes)
  - (ii) C and CP violation
  - (iii) Departure from thermal equilibrium

- **Additional constraint:** EW phase transition must be strong first order PT [Quiros '94; Moore '99]

$$\xi_c \equiv \frac{\langle \Phi_c \rangle}{T_c} \geq 1$$

$\langle \Phi_c \rangle$ and T_c field configuration and temperature at phase transition

Higgs Pair Production and a 2HDM-EFT [Anisha,Biermann,Englert,MM,'22]

- 2HDM type II struggles to reach SFOEWPT (compared to type I)

  [see e.g. Basler,Krause,MM,Wittbrodt,Wlotzka,'16]

- For 2HDM type II points with $\xi_c < 1$:

  What extra dynamics is required to achieve SFOEWPT?

- Our model: CP-conserving 2HDM with softly broken discrete Z_2 symmetry

$$V_{\text{tree}}(\Phi_1,\Phi_2) = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2]$$

- Extended by (purely scalar) dim-6 EFT contributions to the Higgs potential [Anisha eal,´19]

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{2HDM}} + \sum_i \frac{C_6^i}{\Lambda^2} O_6^i \quad \Rightarrow \quad V_{\text{dim-6}} = -\sum_i \frac{C_6^i}{\Lambda^2} O_6^i$$

- Higgs pair production: a tool for fingerprinting an SFOEWPT?

Higgs Pair Production and a 2HDM-EFT [Anisha,Biermann,Englert,MM,'22]

O_6^{111111}	$(\Phi_1^\dagger \Phi_1)^3$	O_6^{222222}	$(\Phi_2^\dagger \Phi_2)^3$
O_6^{111122}	$(\Phi_1^\dagger \Phi_1)^2(\Phi_2^\dagger \Phi_2)$	O_6^{112222}	$(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)^2$
O_6^{122111}	$(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_1)$	O_6^{122122}	$(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)$
O_6^{121211}	$(\Phi_1^\dagger \Phi_2)^2(\Phi_1^\dagger \Phi_1)$ + h.c.	O_6^{121222}	$(\Phi_1^\dagger \Phi_2)^2(\Phi_2^\dagger \Phi_2)$ + h.c.

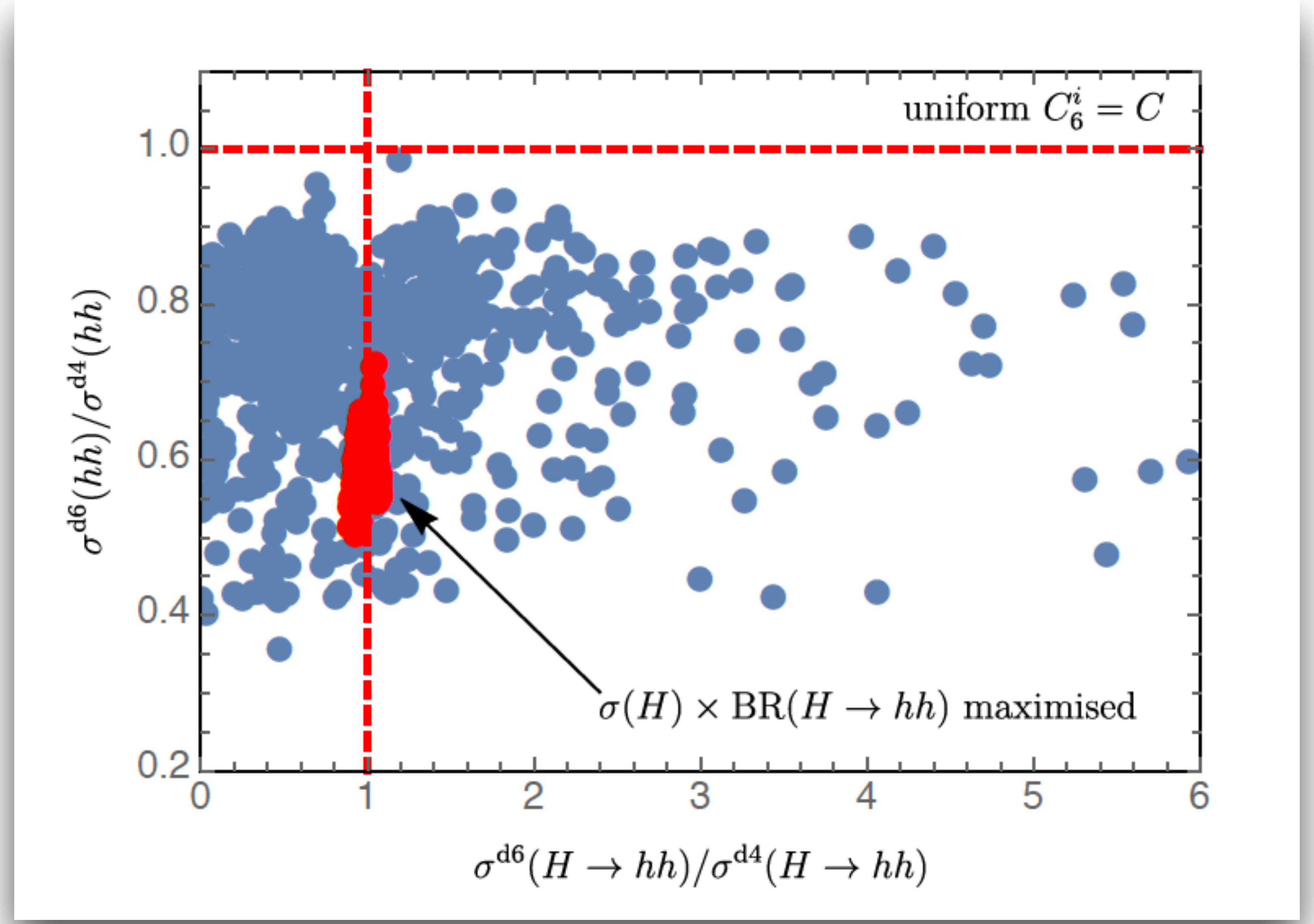
- absorb dim-6 contributions (to scalar masses) in shifts $\lambda_i \to \lambda_i + \delta\lambda_i$, $m_{12}^2 \to m_{12}^2 + \delta m_{12}^2$

$\Rightarrow$ scalar mass spectrum same as for dim-4 @ LO
$\Rightarrow$ shift EFT effects into **Higgs self-couplings & multi-Higgs final states**

- Computation of ξ_c with BSMPT [Basler,Biermann,Mühlleitner,Müller]:
  Loop-corrected effective potential at finite temperature including daisy resummation of bosonic masses; „OS" renormalization

Correlation of ξ_c^{d4}, continuum and resonant hh production

[Anisha,Biermann,Englert,MM,'22]



- Points with $\xi_c^{d6} \cong 1$ for $\xi_c^{d4} \geqq 0.3$ (red Higgs-philic points: $\xi_c^{d4} > 0.15$)
- Higgs-philic points: resonance contribution modified by ~5-10%, continuum production modified by ~50%

STATUS QUO: CODES ON THE MARKET

taken from Lisa Biermann

Available codes to calculate the bounce solution:

- `CosmoTransitions` [Wainwright, 2011]: via path deformation
- `AnyBubble` [Masoumi, 2017]: via a multiple shooting algorithm
- `BubbleProfiler` [Athron et al., 2019]: via a semi-analytic algorithm [Akula et al., 2016]
- `SimpleBounce` [Sato, 2019]: via gradient flow method
- `FindBounce` [Guada et al., 2018/20]: via polygonal multifield method
- `OptiBounce` [Bardsley, 2021]: via solving the 'reduced' minimization problem [Coleman, 1977]

$\Rightarrow$ [coming 2023]: `BSMPTv3`
[BSMPTv1:Basler,MM,Müller]
[BSMPTv2:Basler,Biermann,MM,Müller]
[BMPTv3:Biermann,MM,Santos,Viana]

WHY BSMPTV3?

taken from Lisa Biermann

→ optimized *minimum tracing* and tracking of temperature-dependent coexisiting minimum phases over any temperature interval

→ numerical derivation of the *bounce solution* for any number of field dimensions

→ more precise calculation of *nucleation temperature* (than implemented in `CosmoTransitions`)

→ calculation of *percolation temperature* (not implemented in `CosmoTransitions`)

→ calculation of *GW parameters* α, β/H

→ derivation of f^{peak}, $h^2\Omega_{\text{GW}}^{\text{peak}}$ of (acoustic) gravitational wave spectrum

→ calculation of *signal-to-noise ratio* at LISA

→ ...for all models implemented (singlet-, doublet-, singlet+doublet-extensions)

→ ...embedded into the framework of the existing `BSMPT`-code

- easy-to-use interface to implement your own model of choice
- designed to use input from `ScannerS`

Additional Remark: Gravitational Waves from FOEWPT

- Model CP in the Dark: N2HDM scalar sector with one discrete Z_2 symmetry

$$\Phi_1 \to +\Phi_1 \,, \quad \Phi_2 \to -\Phi_2 \,, \quad \Phi_S \to -\Phi_S$$

$$\begin{aligned} V^{(0)} = & \; m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 + \frac{m_S^2}{2}\Phi_S^2 + \left(A\Phi_1^\dagger\Phi_2\Phi_S + h.c.\right) + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 \\ & + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right] + \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}|\Phi_1|^2\Phi_S^2 + \frac{\lambda_8}{2}|\Phi_2|^2\Phi_S^2 \end{aligned}$$

- Spectrum: Visible SM Higgs, Dark Sector with h_1,h_2,h_3,$H^\pm$

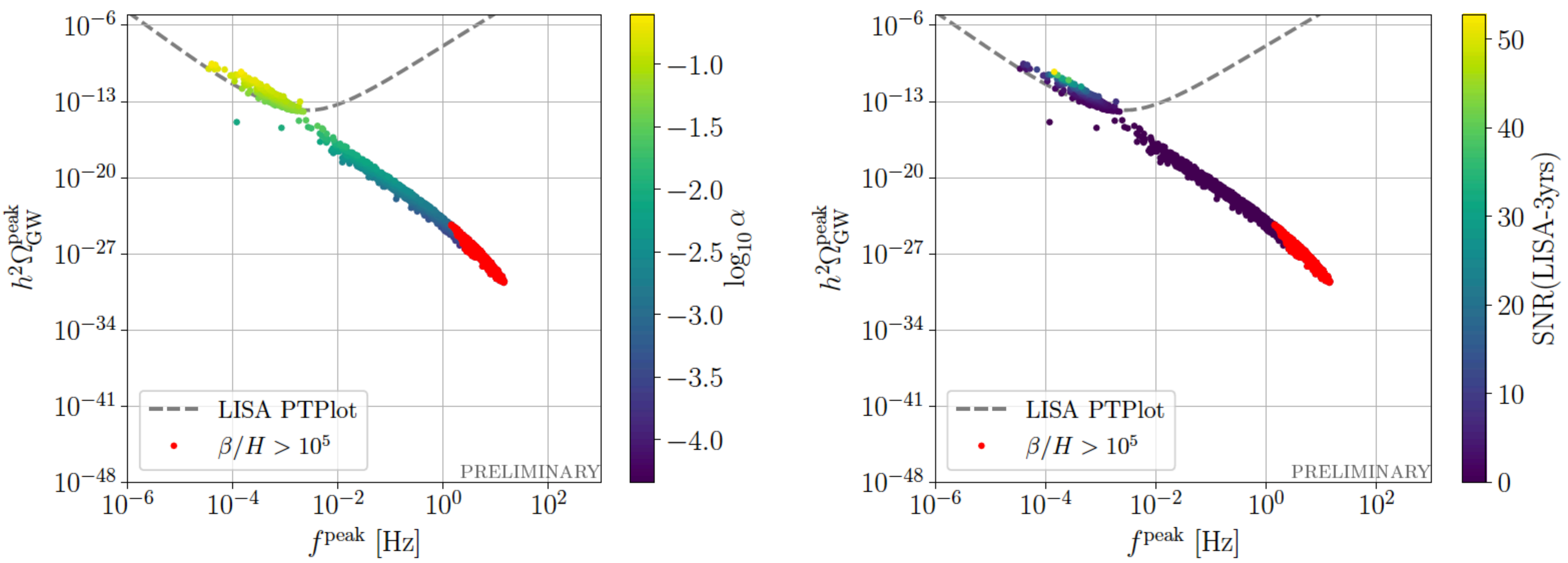
- Im(A) ≠ 0 => explicit CP violation in Dark Sector

Gravitational Waves from FOEWPT

[Biermann,MM,Santos,Viana,to appear]

PRELIMINARY

$$\text{signal-to-noise ratio SNR} = \sqrt{\mathcal{T} \int_{f_{\min}}^{f_{\max}} df \left[\frac{h^2 \Omega_{\rm GW}(f)}{h^2 \Omega_{\rm Sens}(f)} \right]^2}$$



SNR(LISA-3yrs) >10 compatible w/ collider, DM, theor. constraints and have SFOEWPT


Higgs Portal
to Dark Matter

The Higgs Boson as Portal to Dark Matter

- Higgs sector extensions with discrete symmetries:

Dark Matter candidate

- Example CxSM: SM extended by complex singlet field

$$V = \frac{m^2}{2}\Phi^\dagger\Phi + \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2 + \frac{\delta_2}{2}\Phi^\dagger\Phi|\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{b_1}{4}\mathbb{S}^2 + c.c.\right)$$

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + H + iG^0\right) \end{pmatrix}, \quad \mathbb{S} = \frac{1}{\sqrt{2}}(v_S + S + i(v_A + A))$$

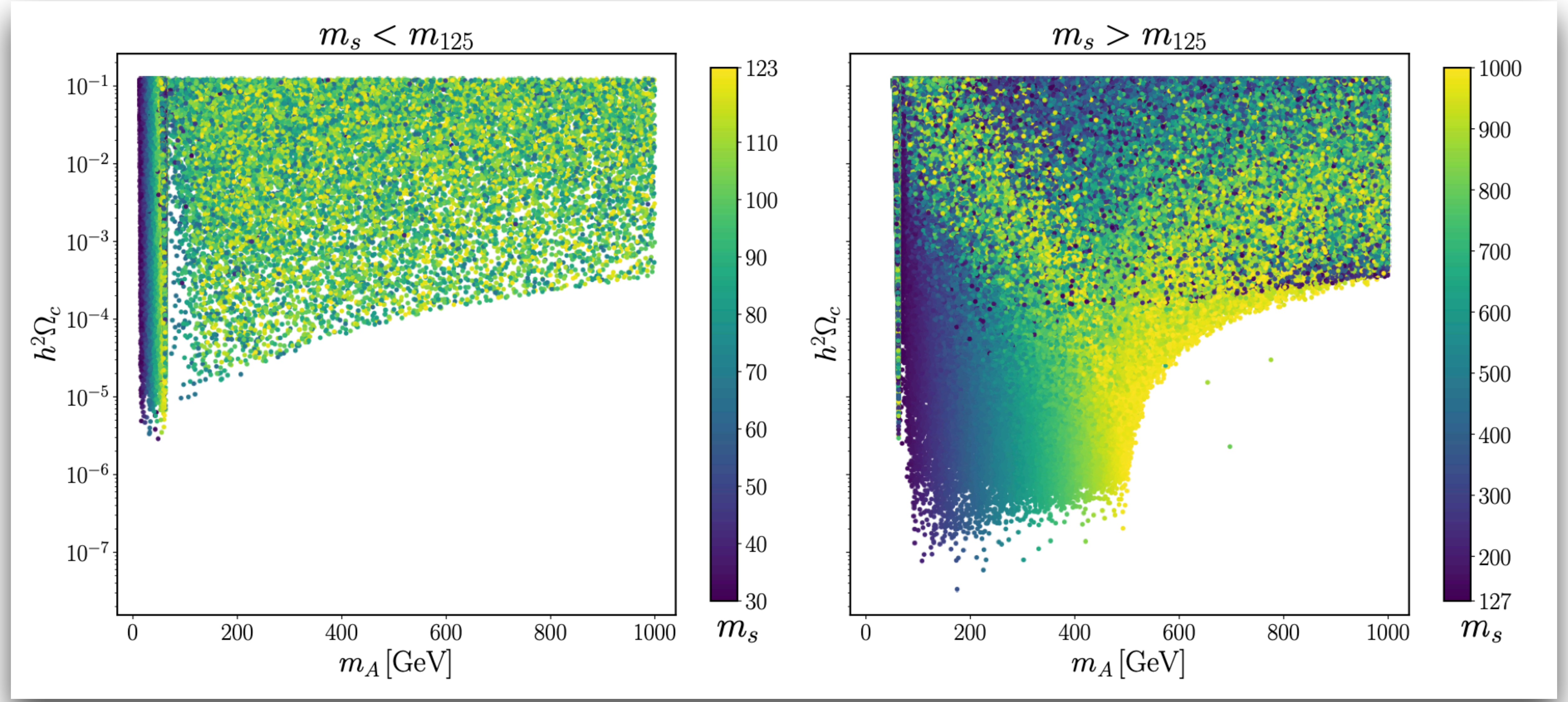
impose two separate discrete symmetries: S -> -S and A -> -A
v_A=0 => A-> -A symmetry unbroken, **A is stable => the Dark Matter candidate**

Spectrum: h_1, h_2, A; one of the $h_{1,2}$ is the h_{125}

- Scan in parameter space of the model: keep only points compatible with relevant theoretical and experimental constraints (H&HH data, EWPT, DM observables)

Relic Density For Allowed Parameter Points

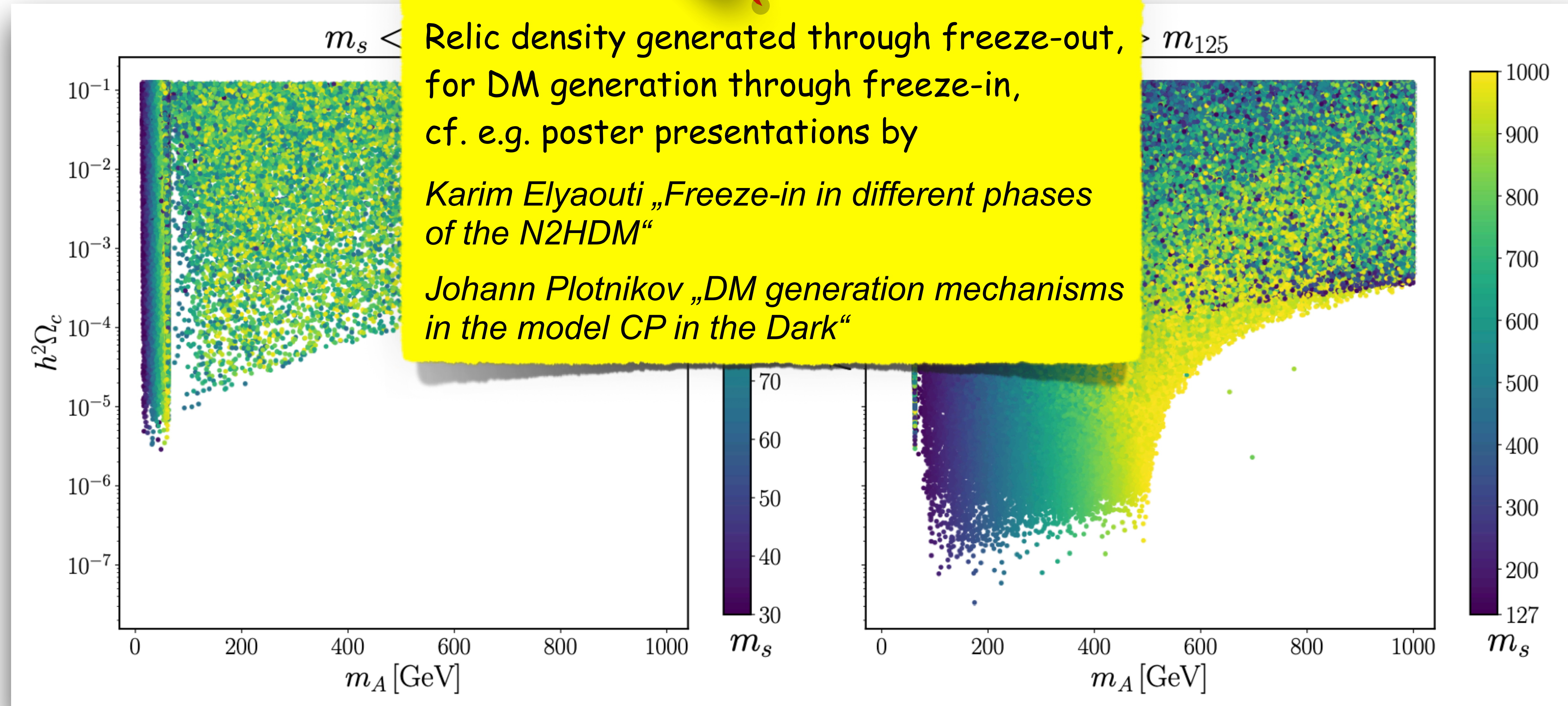
[Egle,MM,Santos,Viana,'23]



In whole scanned m_A region: allowed parameter scenarios exist saturating the relic density

Relic Density For Allowed Parameter Points

[Egle,MM,Santos,Viana,'23]



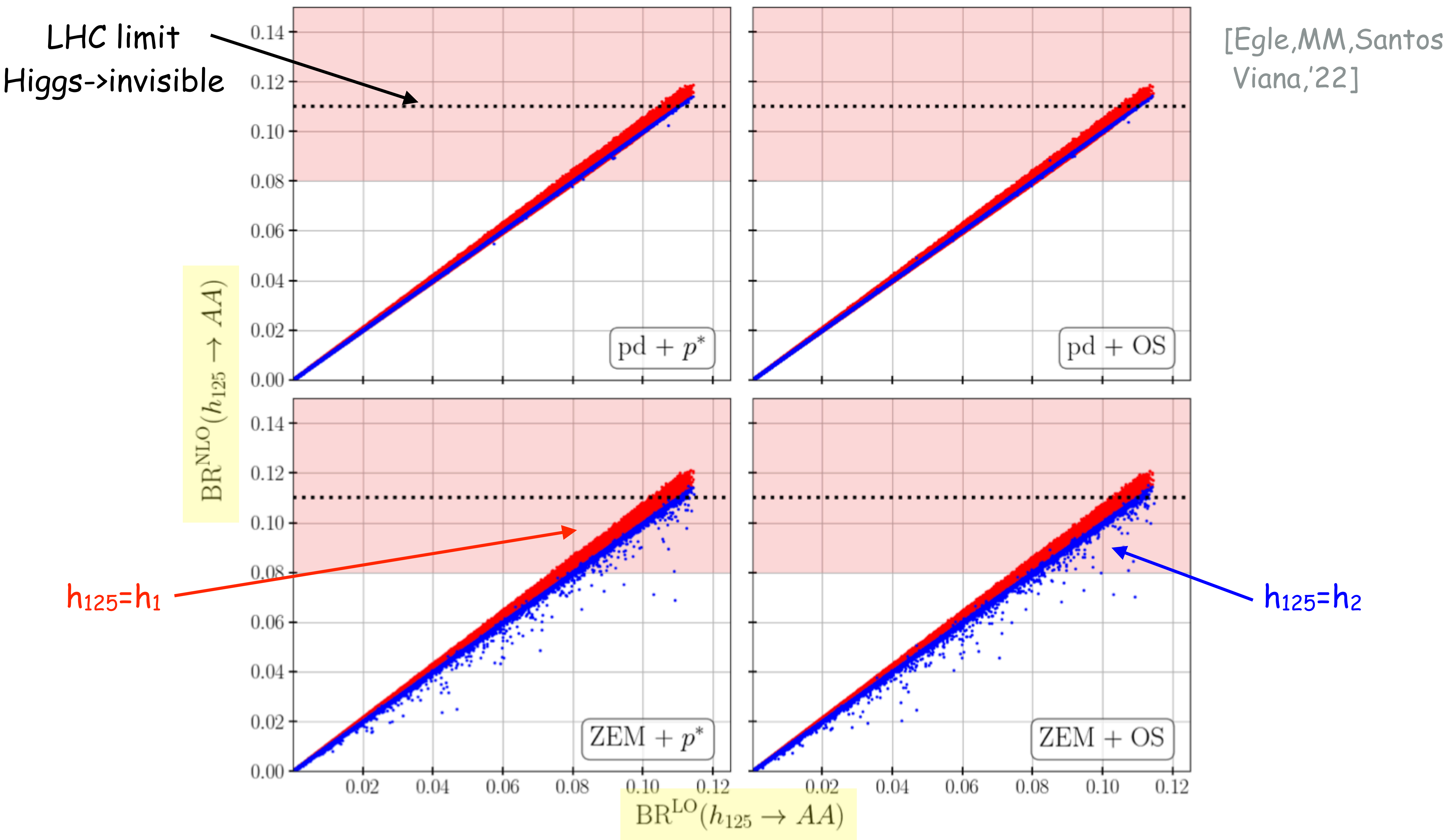
Relic density generated through freeze-out, for DM generation through freeze-in, cf. e.g. poster presentations by

Karim Elyaouti „Freeze-in in different phases of the N2HDM"

Johann Plotnikov „DM generation mechanisms in the model CP in the Dark"

In whole scanned m_A region: allowed parameter scenarios exist saturating the relic density

LHC Test: Higgs Decay into two DM Particles, $h_{125} \to AA$



Parameter point allowed at leading order may be excluded at next-to-leading order and vice versa

Conclusions

- **Flaws of SM** call for new physics; no direct signs of new physics => Higgs boson
- **Combine results** of all available observables, precision important => constrain BSM parameter space
- **Both QCD&EW corrections** are important; corrections can be more important in BSM models
- **Higgs pair production** => insights in mechanism of EWSB
  Precision slowly catching up w/ H production
  NLO QCD mass effects important: -15% (inclusive), -30-40% (distribution at large M_{HH})
  uncertainties from top mass scale and scheme choice are significant
- **HH in extended Higgs sectors**
  large cross sections due to resonant enhancement possible
  non-resonant&resonant searches start testing BSM models in HH
  interesting effects in singlet models: di-Higgs can beat single Higgs
- **Strong First Order EWPT (required for baryogenesis)**
  extension of 2HDM by scalar dim-6 operators can lead to SFOEWPT, relation to LHC pheno
  LISA sensitive to grav. waves from SMFOEWPT in CP in the Dark incl. exp (H) & theor constraints
- **Higgs Portal to DM**
  CxSM: compatible w/ DM constraints, testable at LHC, EW corrections important

Higgs boson can give many insights in BSM physics
Interesting times ahead!

Thank you for your attention!

Uncertainties for Different Higgs Self-Coupling Values

- Final combined uncertainties at $NNLO_{FTapprox}$:

$$\kappa_\lambda = -10: \quad \sigma_{tot} = 1680^{+13\%}_{-14\%}\ \text{fb}$$

$$\kappa_\lambda = -5: \quad \sigma_{tot} = 598.9^{+13\%}_{-15\%}\ \text{fb}$$

$$\kappa_\lambda = -1: \quad \sigma_{tot} = 131.9^{+11\%}_{-16\%}\ \text{fb}$$

$$\kappa_\lambda = 0: \quad \sigma_{tot} = 70.38^{+8\%}_{-18\%}\ \text{fb}$$

$$\kappa_\lambda = 1: \quad \sigma_{tot} = 31.05^{+6\%}_{-23\%}\ \text{fb}$$

$$\kappa_\lambda = 2: \quad \sigma_{tot} = 13.81^{+3\%}_{-28\%}\ \text{fb}$$

$$\kappa_\lambda = 2.4: \quad \sigma_{tot} = 13.10^{+6\%}_{-27\%}\ \text{fb}$$

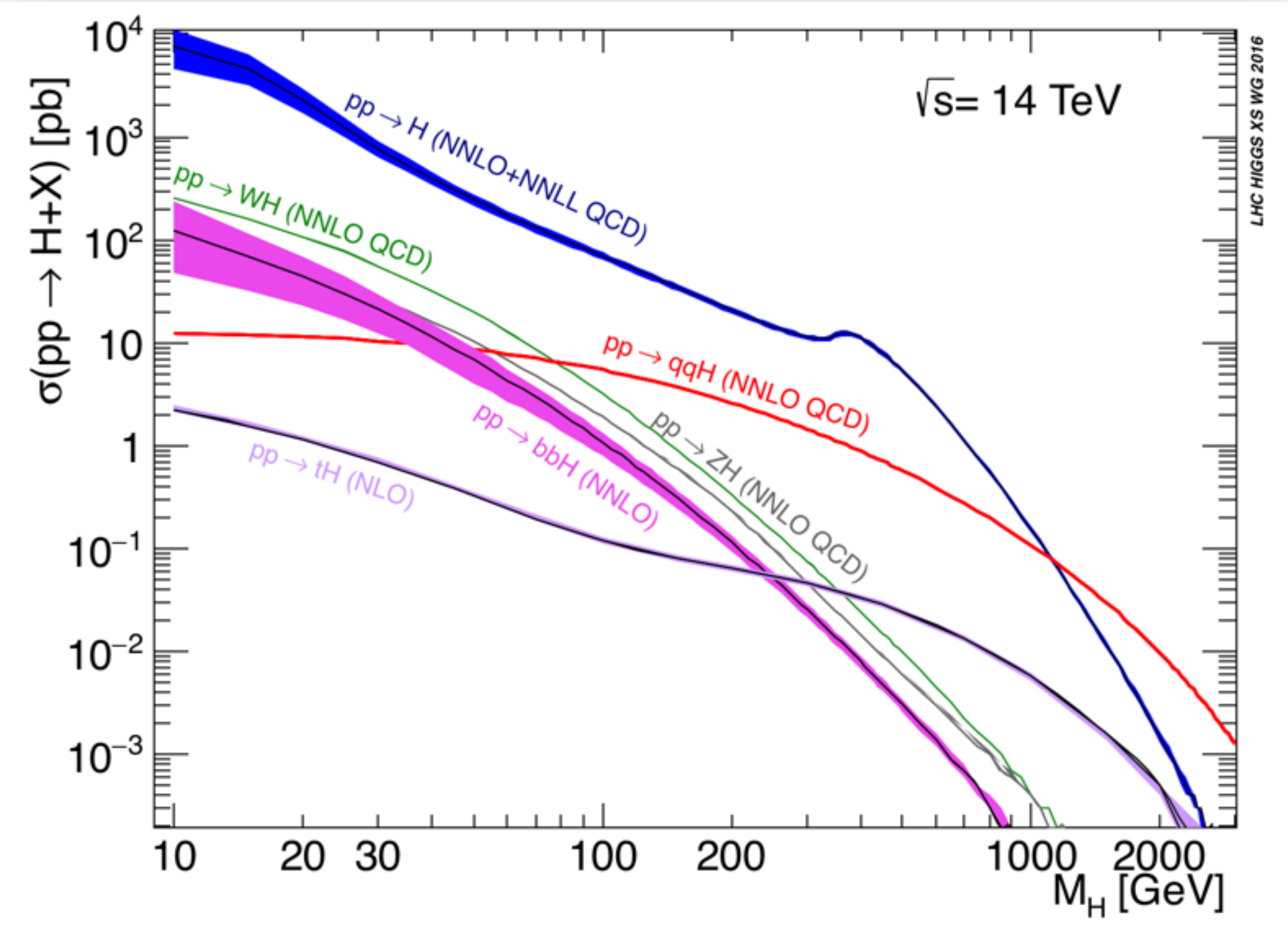
$$\kappa_\lambda = 3: \quad \sigma_{tot} = 18.67^{+12\%}_{-22\%}\ \text{fb}$$

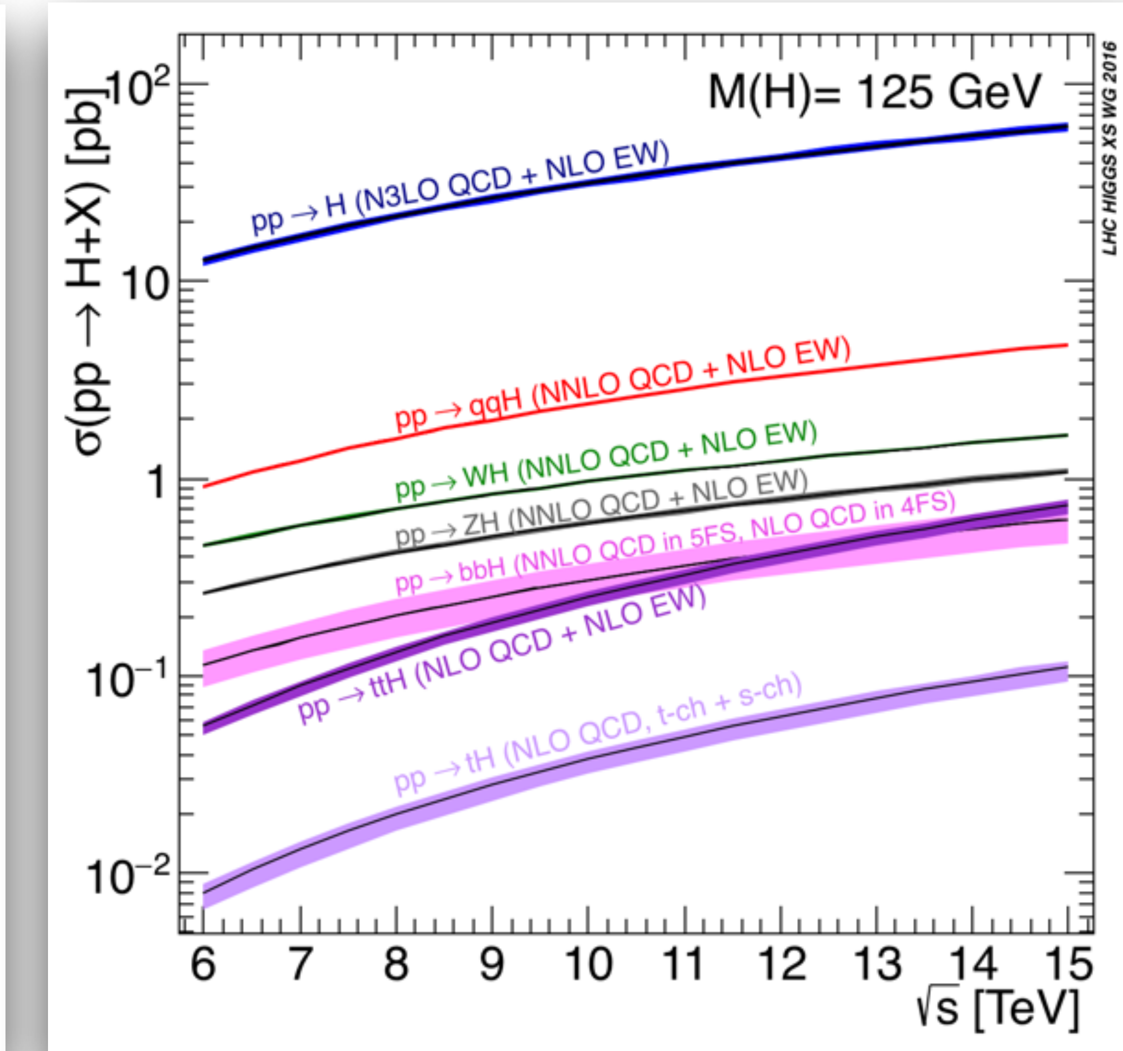
$$\kappa_\lambda = 5: \quad \sigma_{tot} = 94.82^{+18\%}_{-13\%}\ \text{fb}$$

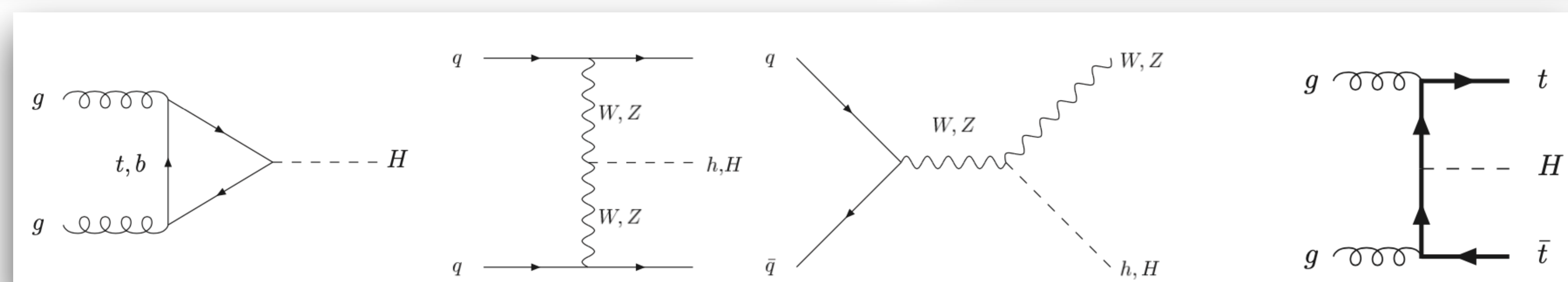
$$\kappa_\lambda = 10: \quad \sigma_{tot} = 672.2^{+16\%}_{-13\%}\ \text{fb}$$

Standard Model Higgs Production

[Higgs Working Group, YR4]



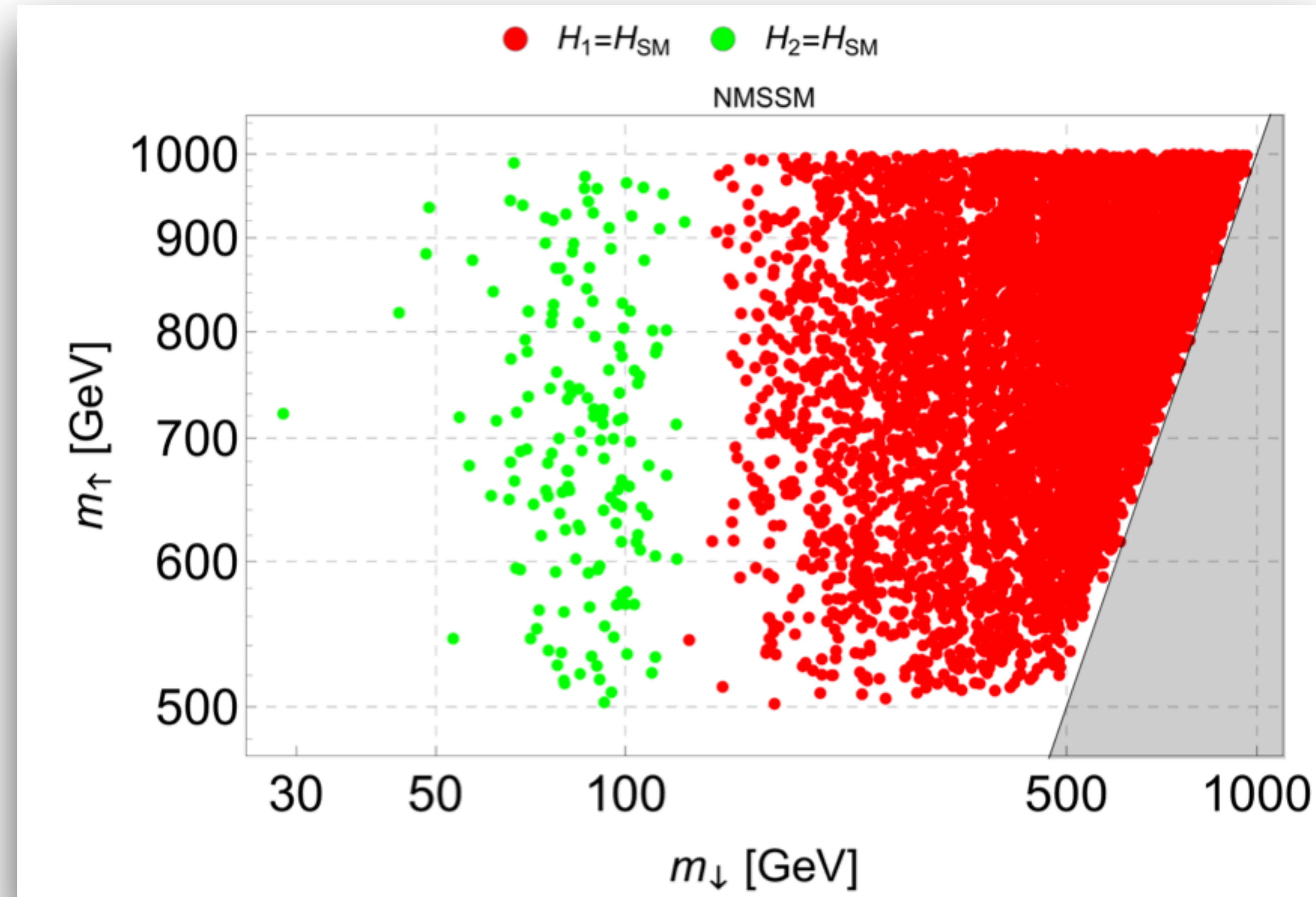




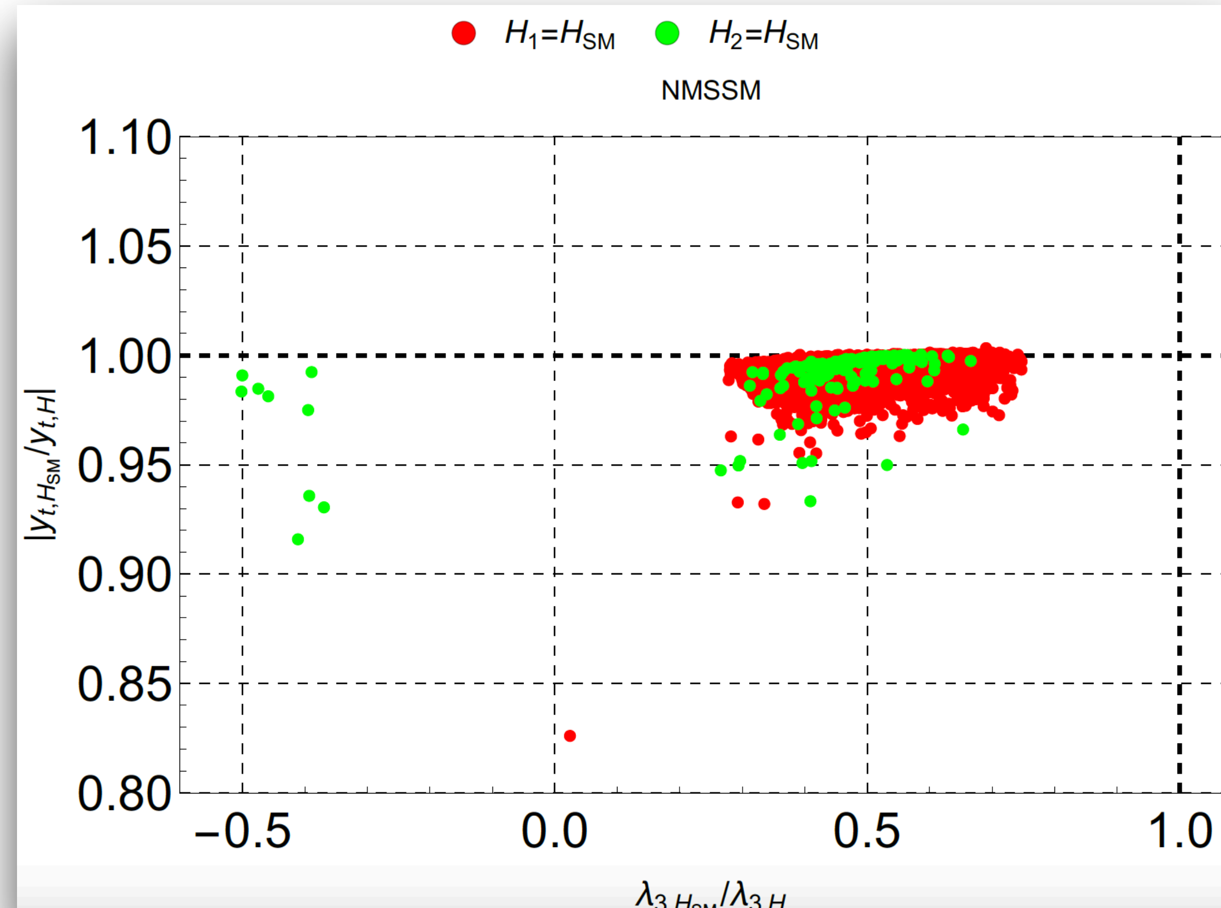
Scan Result: Mass and Couplings Distributions

[Abouabid,Arhrib,Azevedo,El Falaki,Ferreira,MM,Santos,'21]

Masses



Couplings



Non-SM-like heavier versus non-SM-like lighter

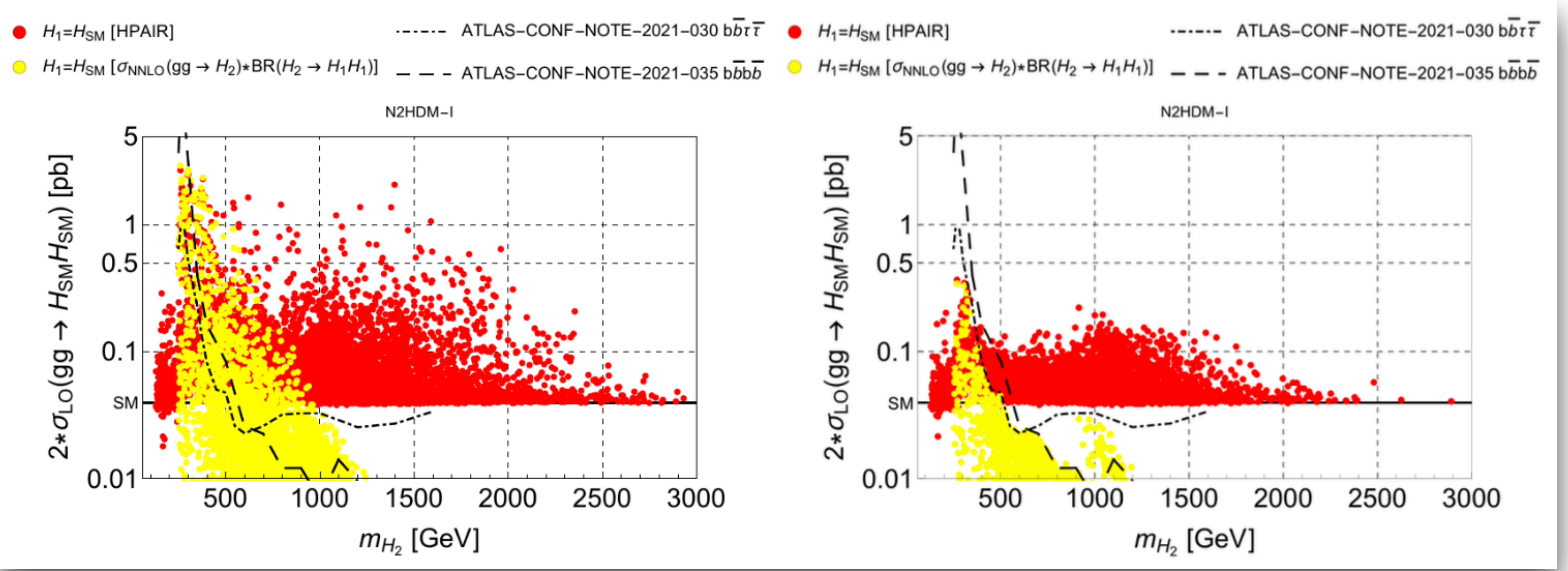
Yukawa y_{top} versus λ_{3HSM}

Red: H_1=H_{SM}, Green: H_2=H_{SM}

Impact of Constraints - Example N2HDM Type I H_{SM} H_{SM} Production

[Abouabid,Arhrib,Azevedo,El Falaki,Ferreira,MM,Santos,'21]

Yellow - Resonant Prod: $\sigma_{NNLO}(H2)*BR(H2\to H_{SM}H_{SM})$ Red - Continuum Prod: $2*\sigma_{LO}(H_{SM}\, H_{SM})$



- Factor 2 roughly accounts for NLO QCD corrections (benchmark points w/ HPAIR at NLO QCD in heavy-top-limit)
- Resonant searches start constraining BSM models

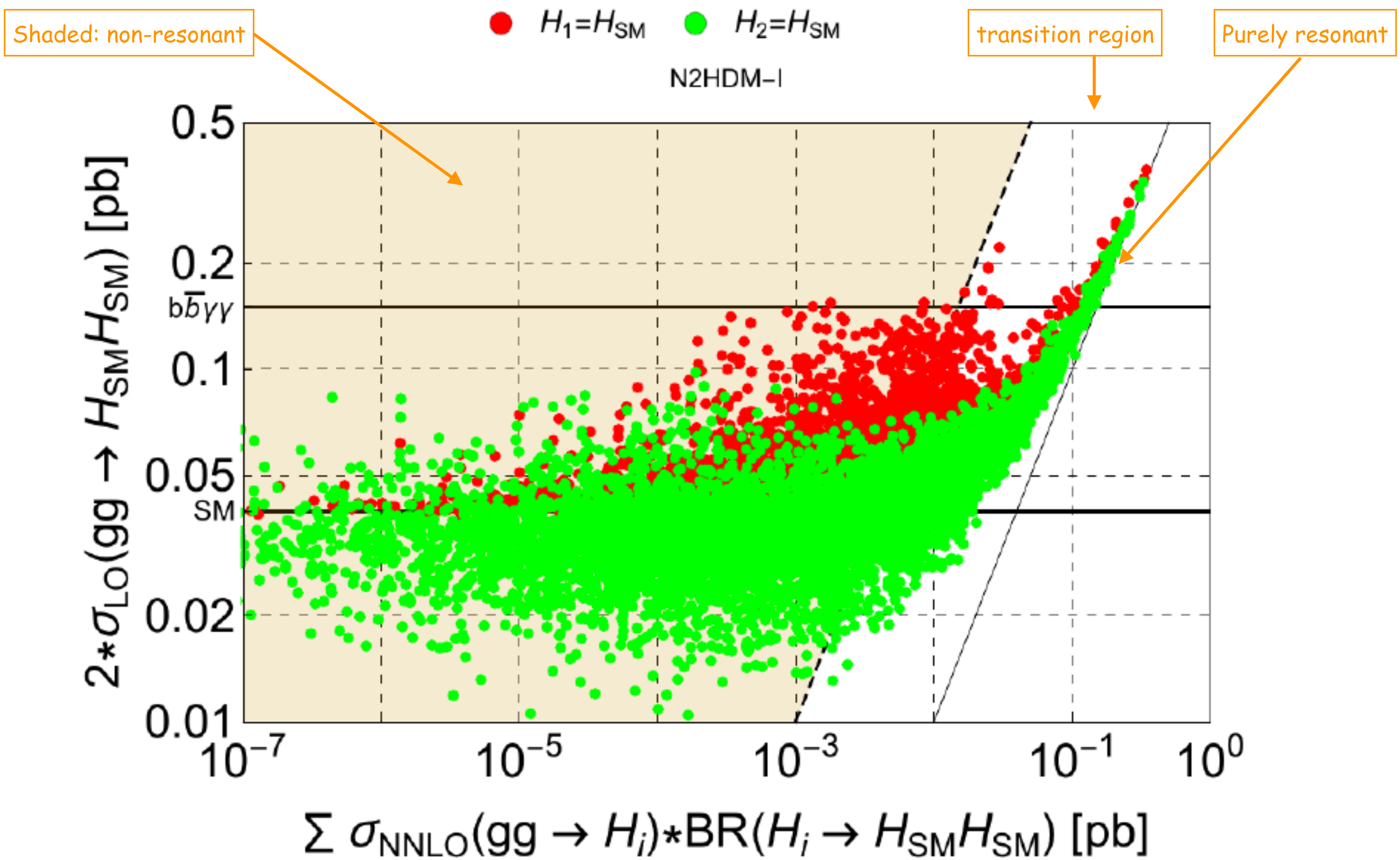
Impact of Non-resonant Searches

- Our definition:

take into account all relevant theoretical and experimental constraints
+ limits from di-Higgs searches

$\sigma_{res}^{HH} < 0.1 * \sigma_{full}$ -> non-resonant production

Impact of Non-resonant Searches - Example N2HDM



Allowed values of the trilinear Higgs self-coupling

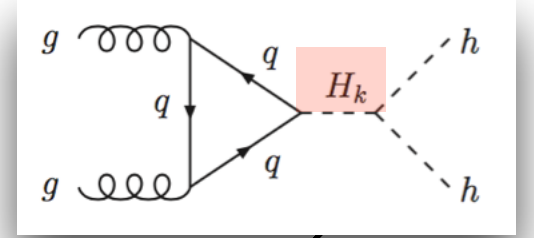
	R2HDM		C2HDM	
	$y_{t,H_{\rm SM}}^{\rm R2HDM}/y_{t,H}$	$\lambda_{3H_{\rm SM}}^{\rm R2HDM}/\lambda_{3H}$	$y_{t,H_{\rm SM}}^{\rm C2HDM}/y_{t,H}$	$\lambda_{3H_{\rm SM}}^{\rm C2HDM}/\lambda_{3H}$
light I	0.893...1.069	-0.096...1.076	0.898...1.035	-0.035...1.227
medium I	n.a.	n.a.	0.889...1.028	0.251...1.172
heavy I	0.946...1.054	0.481...1.026	0.893...1.019	0.671...1.229
light II	0.951...1.040	0.692...0.999	0.956...1.040	0.096...0.999
medium II	n.a.	n.a.	–	–
heavy II	–	–	–	–

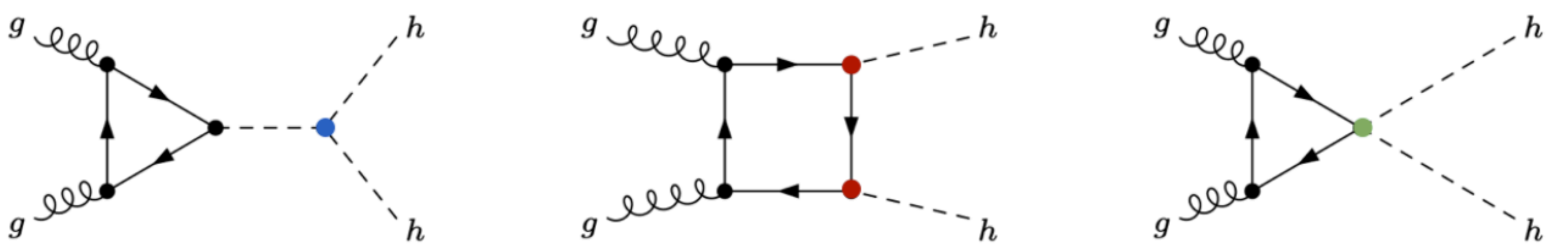
	N2HDM		NMSSM	
	$y_{t,H_{\rm SM}}^{\rm N2HDM}/y_{t,H}$	$\lambda_{3H_{\rm SM}}^{\rm N2HDM}/\lambda_{3H}$	$y_{t,H_{\rm SM}}^{\rm NMSSM}/y_{t,H}$	$\lambda_{3H_{\rm SM}}^{\rm NMSSM}/\lambda_{3H}$
light I	0.895...1.079	-1.160...1.004	n.a.	n.a.
medium I	0.874...1.049	-1.247...1.168	n.a.	n.a.
heavy I	0.893...1.030	0.770...1.112	n.a.	n.a.
light II	0.942...1.038	-0.608...0.999	0.826...1.003	0.024...0.747
medium II	0.942...1.029	0.613...0.994	0.916...1.000	-0.502...0.666
heavy II	–	–	–	–

Comparison with EFT

- **Effective Lagrangian:** $$\Delta\mathcal{L}_{\text{non-lin}} \supset -m_t t\bar{t}\left(c_t \frac{h}{v} + c_{tt}\frac{h^2}{2v^2}\right) - c_3 \frac{1}{6}\left(\frac{3M_h^2}{v}\right) h^3$$

c_3: trilinear coupling modification; c_t: top-Yukawa coupling modification;
c_{tt}: effective two-Higgs-two-fermion coupling
no c_g, c_{gg}: no new heavy colored BSM particles assumed





- **Matching relations of our specific BSM models:**

Higgs-top Yukawa coupling	:	$g_t^{H_{\text{SM}}}(\alpha_i,\beta)$	$\rightarrow$	c_t
trilinear Higgs coupling	:	$\dfrac{g_3^{H_{\text{SM}}H_{\text{SM}}H_{\text{SM}}}(p_i)}{3M_{H_{\text{SM}}}^2/v}$	$\rightarrow$	c_3
two-Higgs-two-top quark coupling	:	$\sum_{k=1}^{k_{\max}}\left(\dfrac{-v}{m_{H_k}^2}\right) g_3^{H_k H_{\text{SM}} H_{\text{SM}}}(p_i)\, g_t^{H_k}(\alpha_i,\beta)$	$\rightarrow$	c_{tt}

2HDM versus EFT

- R2HDM T2 sample parameter point:

m_{H_1} [GeV]	m_{H_2} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	α	$\tan\beta$	m_{12}^2 [GeV^2]
125.09	1131	1082	1067	-0.924	0.820	552749

- corresponding EFT values:

$$g_t^{H_2} = -1.126$$

$$c_3 = 0.782\,, \; c_t = 0.951\,, \; c_{tt} = -0.122$$

- goodness of approximation?:

m_{H_2} [GeV]	Γ_{H_2} [GeV]	c_{tt}	$g_3^{H_2H_1H_1}$ [GeV]	$\sigma_{\text{R2HDM}}^{\text{w/ res}}$ [fb]	$\sigma_{\text{SMEFT}}^{c_{tt}\neq 0}$ [fb]	ratio
1131	78.80	-0.1222	-504.52	30.5	26.1	86%
1200	89.74	-0.1031	-479.29	27.7	24.8	90%
1500	470.2	$-4.853\ 10^{-2}$	-352.42	21.8	21.4	98%

- Remark:

$$\sigma_{\text{R2HDM}}^{\text{w/o res}} = 18.6 \text{ fb} \quad \text{and} \quad \sigma_{\text{SMEFT}}^{c_{tt}=0} = 18.6 \text{ fb}$$

N2HDM versus EFT

✦ N2HDM T1 sample parameter point:

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$
125.09	269	582	390	380	4.190
α_1	α_2	α_3	v_s [GeV]	$\text{Re}(m_{12}^2)$ [GeV^2]	
1.432	-0.109	0.535	1250	28112	

$$g_t^{H_2} = 0.179 \quad \text{and} \quad g_t^{H_3} = 2.337 \times 10^{-2}$$

✦ corresponding EFT values:

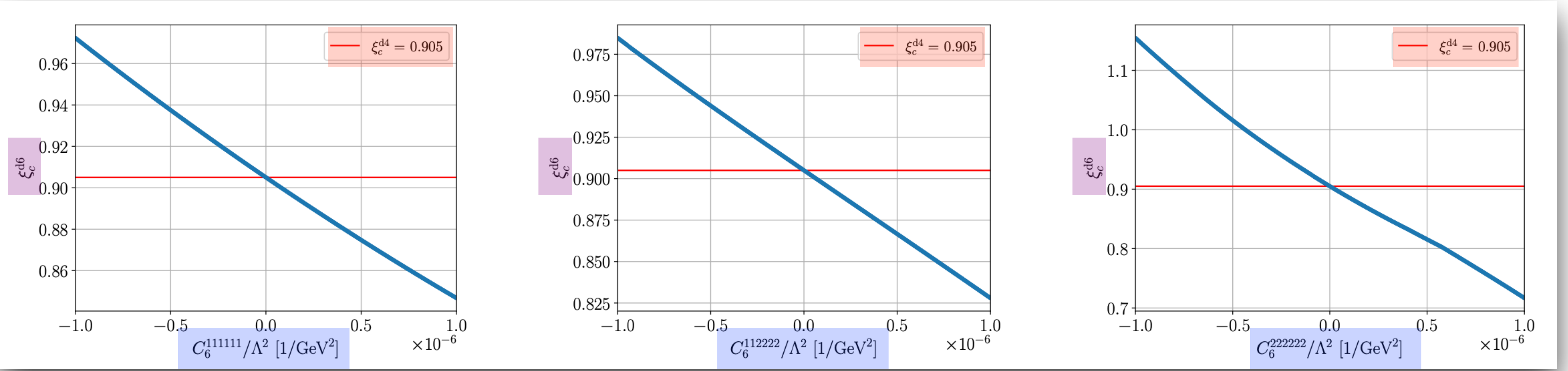
$$c_3 = 0.877\,,\ c_t = 1.012\,,\ c_{tt} = 4.127 \times 10^{-2}$$

✦ goodness of approximation?: (m_{H_3} kept fixed)

m_{H_2}	Γ_{H_2}	$c_{tt}^{H_2}$	c_{tt}	$g_3^{H_2H_1H_1}$	$\sigma_{\text{N2HDM}}^{\text{w/ res}}$ [fb]	$\sigma_{\text{SMEFT}}^{c_{tt}\neq 0}$ [fb]	ratio
269	0.075	4.410×10^{-2}	4.127×10^{-2}	-72.42	183.70	20.56	11%
300	0.083	3.170×10^{-2}	2.877×10^{-2}	-64.80	162.80	21.28	13%
400	0.177	9.544×10^{-3}	6.721×10^{-3}	-34.68	43.33	22.60	52%
420	0.229	6.895×10^{-3}	4.063×10^{-3}	-27.62	31.70	22.76	72%
440	0.284	4.600×10^{-3}	1.767×10^{-3}	-20.22	26.26	22.90	87%
450	0.315	3.564×10^{-3}	7.323×10^{-4}	-16.39	24.84	22.96	92%
500	2.567	-7.132×10^{-4}	-3.545×10^{-3}	4.05	23.56	23.22	99%

Effect of Dim-6 Operators

[Anisha,Biermann,Englert,MM,'22]



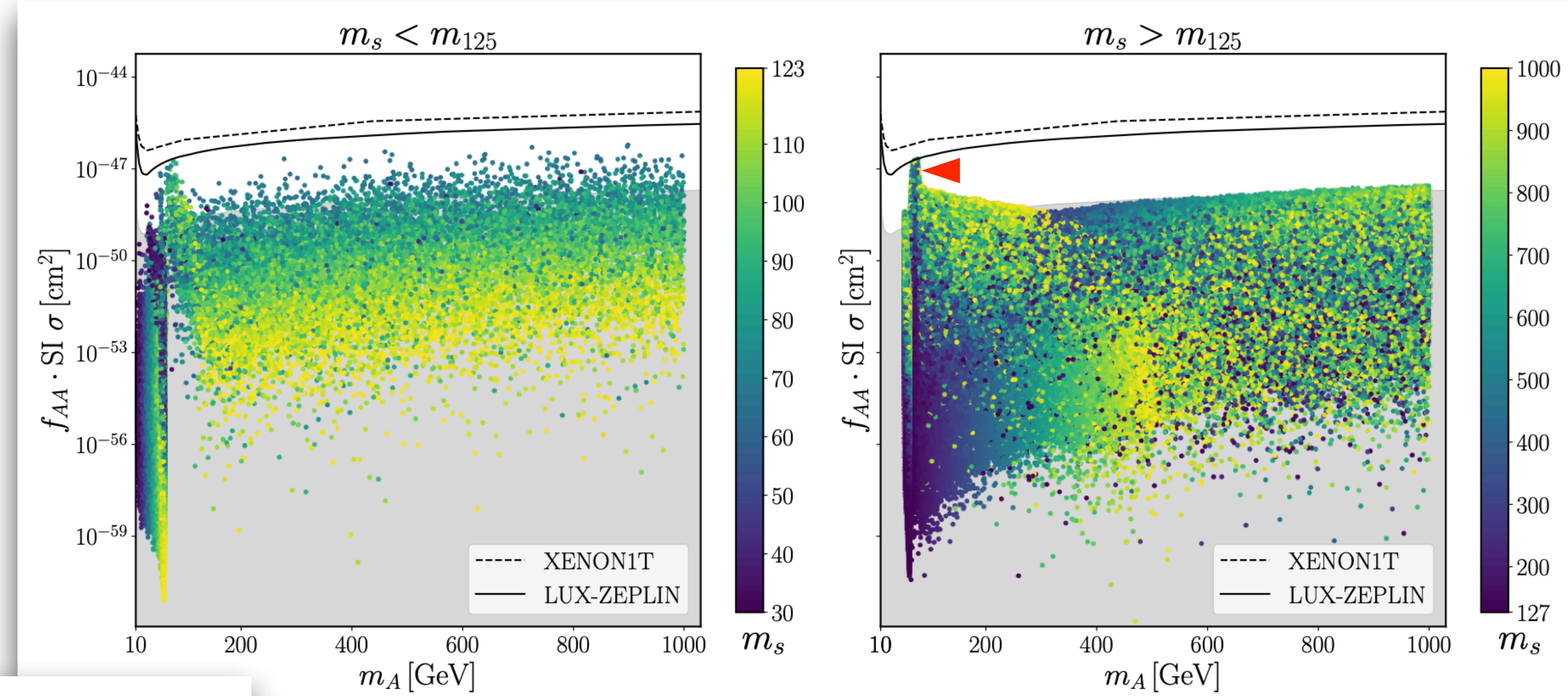
impact of individual Wilson coefficients on ξ_c^{d6} for $\xi_c^{d4} \cong 0.9$:

- linear response ~ C^i_6 -> perturbativity ok
- SFOEWPT achievable in agreement with experimental constraints

interference effects in heavy Higgs production in tt final state are width dependent -> sensitive to EFT modifications: overall effect is small after taking the Higgs data constraints into account => hh production important tool for fingerprinting SFOEWPT

Dark Matter Direct Detection

[Egle,MM,Santos,Viana,'23]



$$f_{AA} = \frac{(\Omega h^2)_A}{(\Omega h^2)^{\text{obs}}_{\text{DM}}}$$

◀ : LZ sensitive to 66 GeV $\lesssim m_A \lesssim$ 78 GeV region (not testable through H(125 GeV) → AA decay)