Higgs Theory or Cracking the Code of the Universe with the Higgs boson

M. Mühlleitner (KIT)

30th Anniversary of the

Recontres du Vietnam

Windows on the Universe

ICISE, Quy Nhon, 6-12 Aug 2023

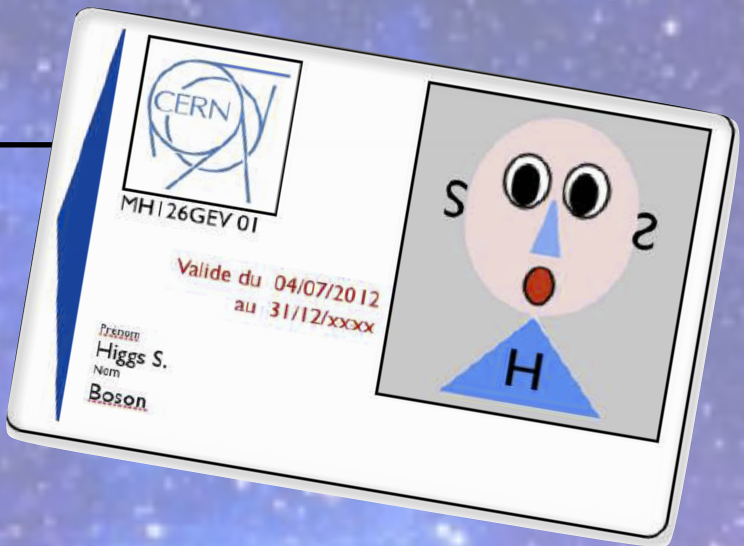
KIT
Karlsruhe Institute of Technology

Collaborative Research Center TRR 257

P H

Particle Physics Phenomenology after the Higgs Discovery

Outline



- Introduction
- Potential Parameters
  - Higgs Masses
  - Higgs Self-Couplings
- More on Precision: BSM Decays
- Higgs Pair Production
  - Precision
  - Phenomenology
- HH and Baryogenesis
- Conclusions

Outline

Disclaimer 1: Not covered Higgs production cross sections, Dark Matter

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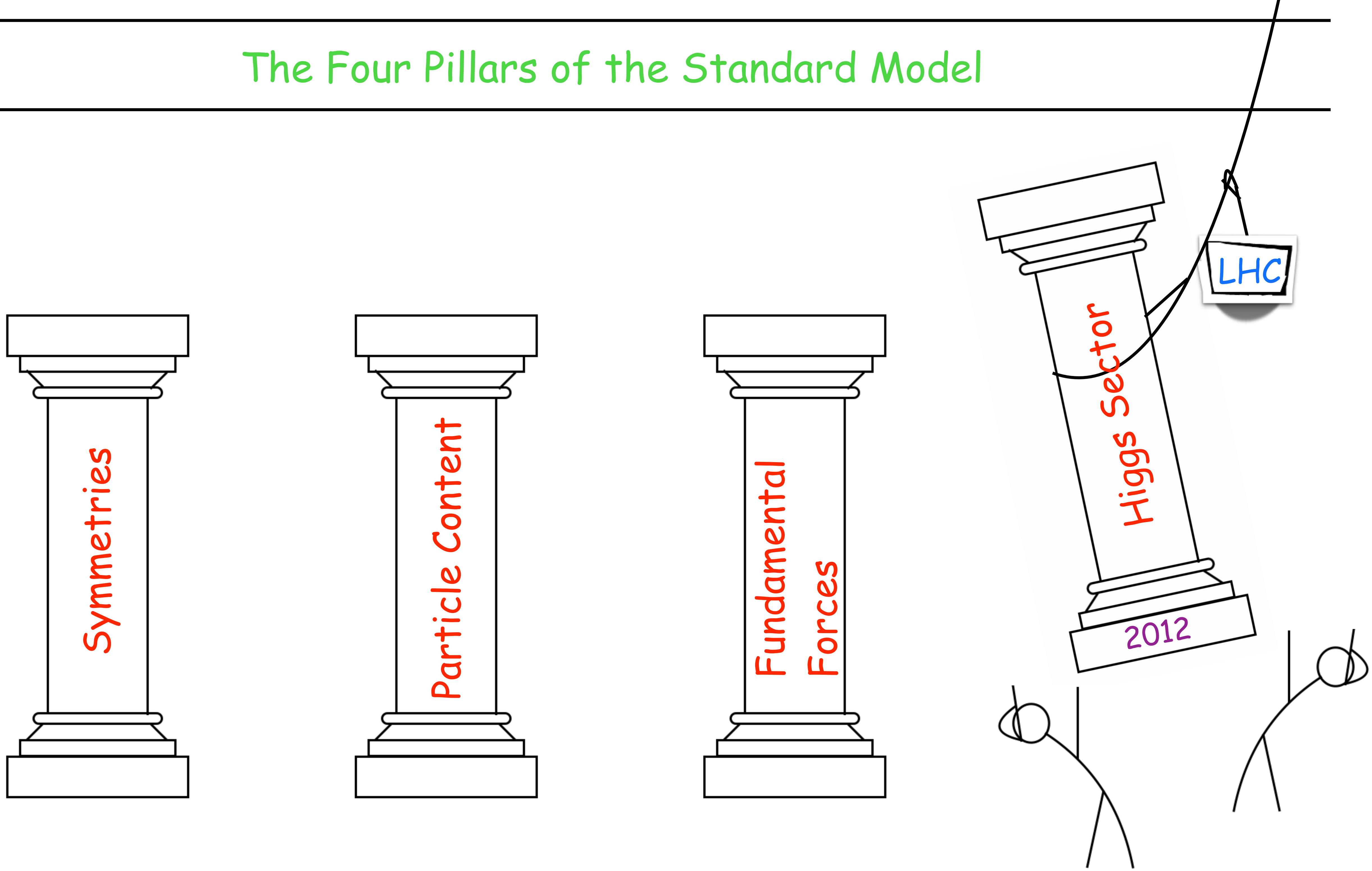
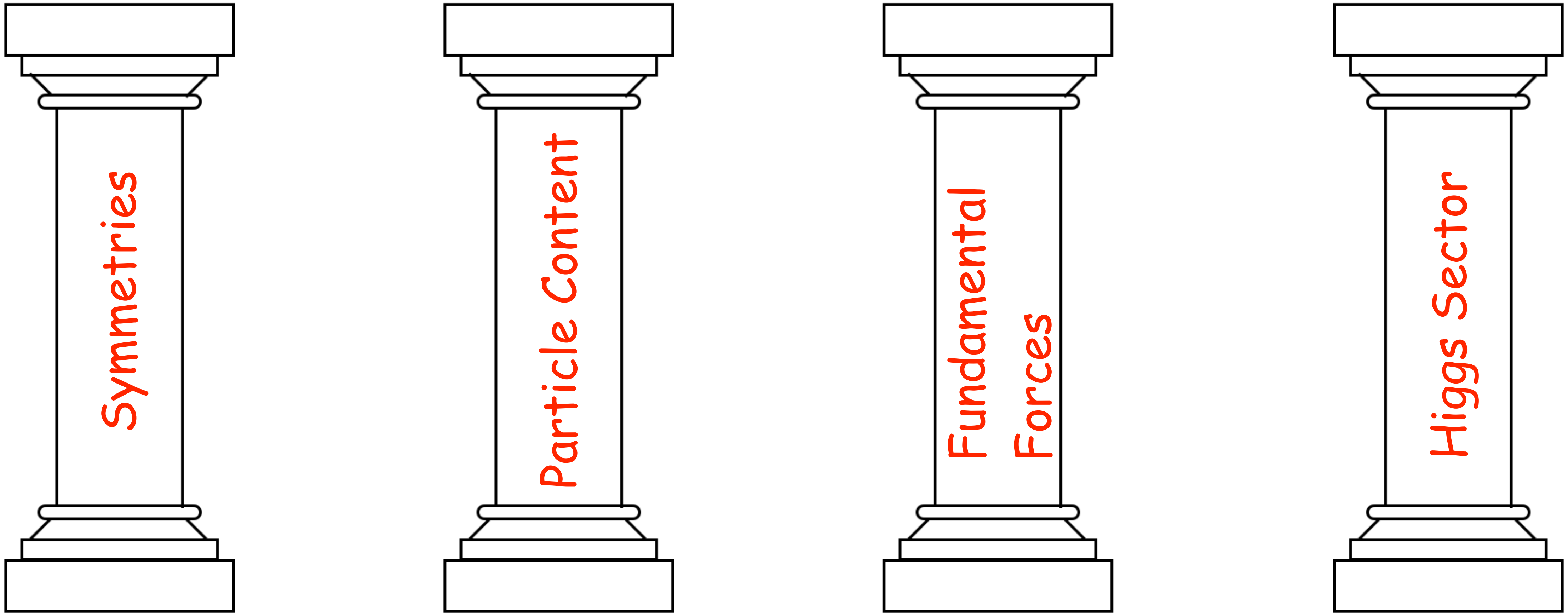
Disclaimer 2: Focus on Beyond-Standard-Model Theories & Phenomenology

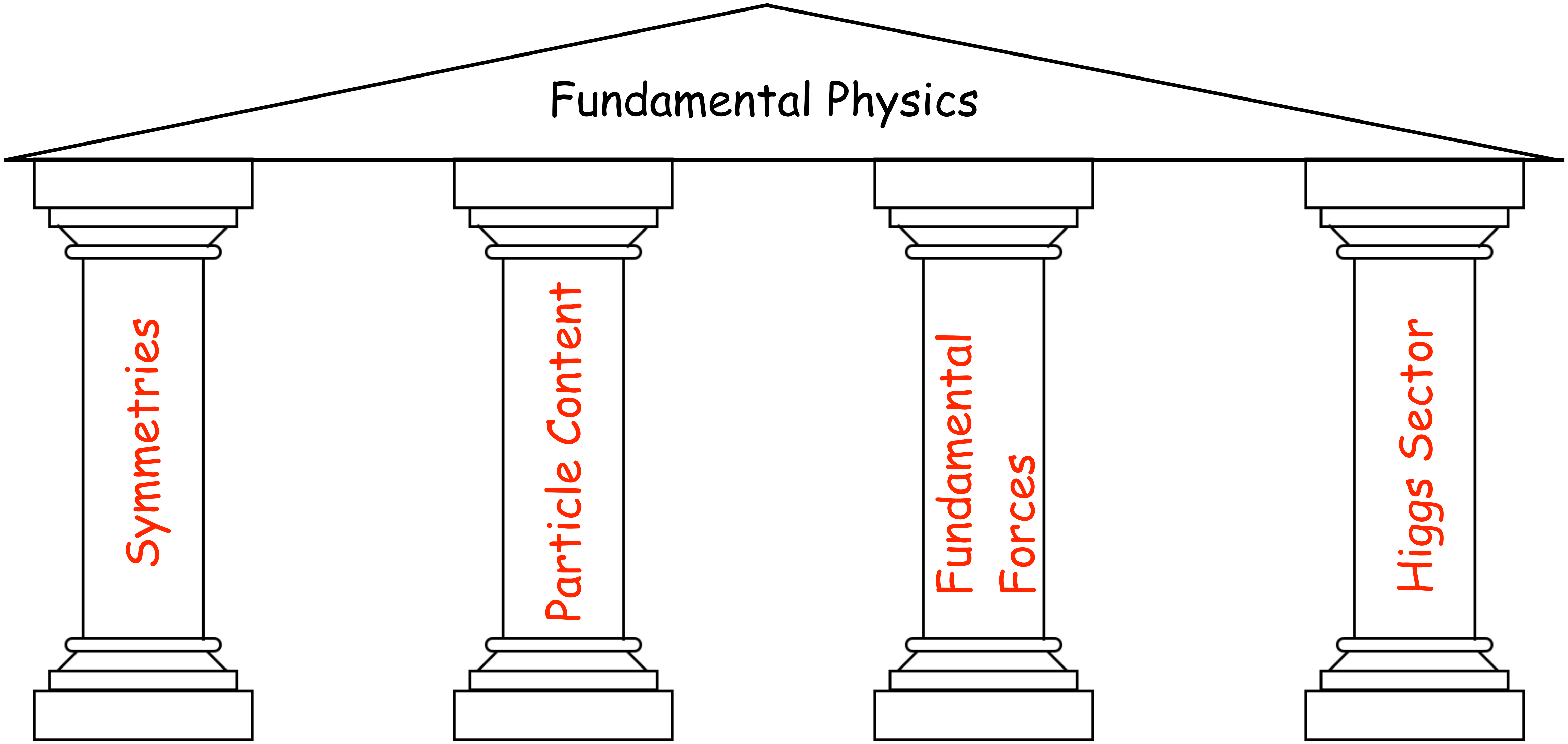
The Four Pillars of the Standard Model



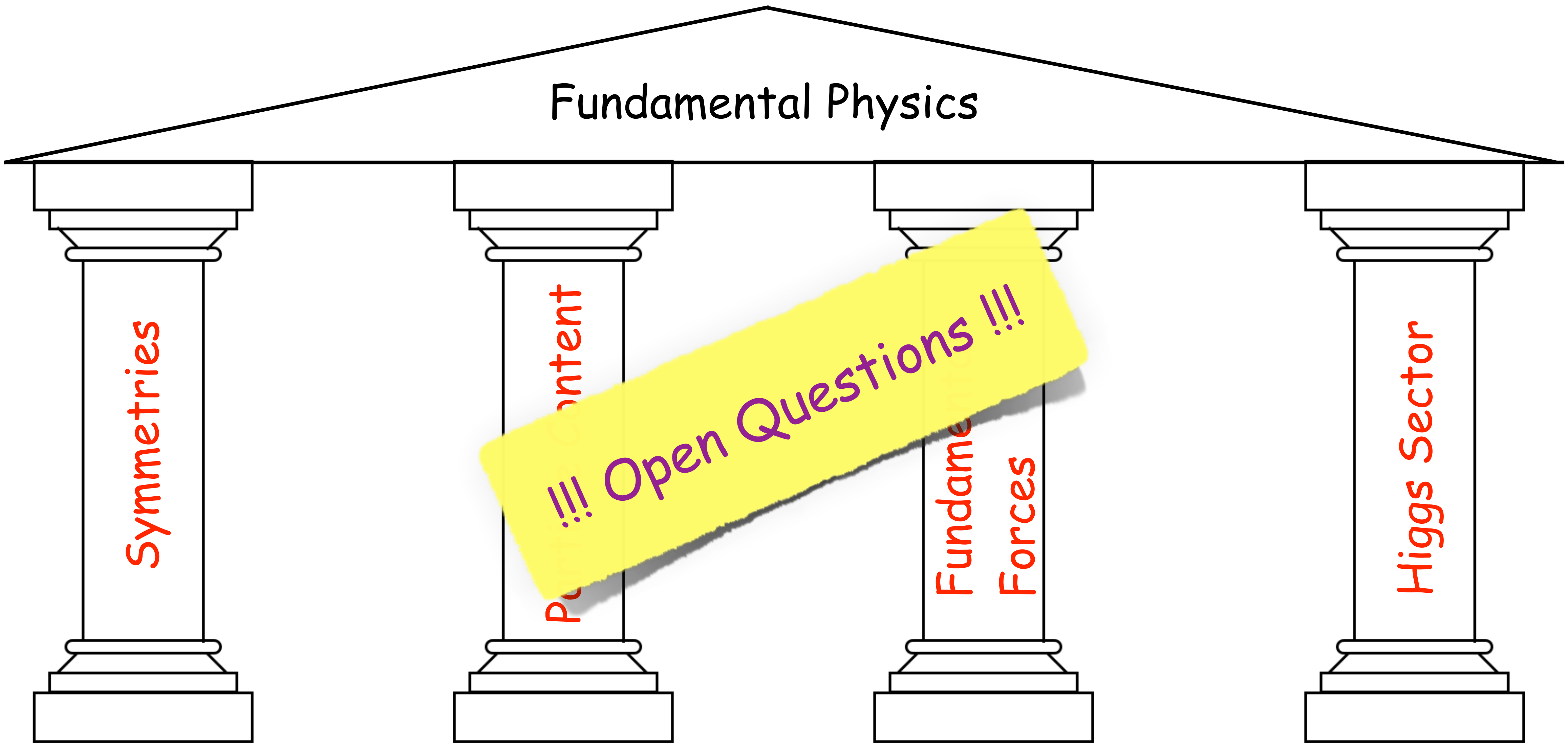
The Four Pillars of the Standard Model

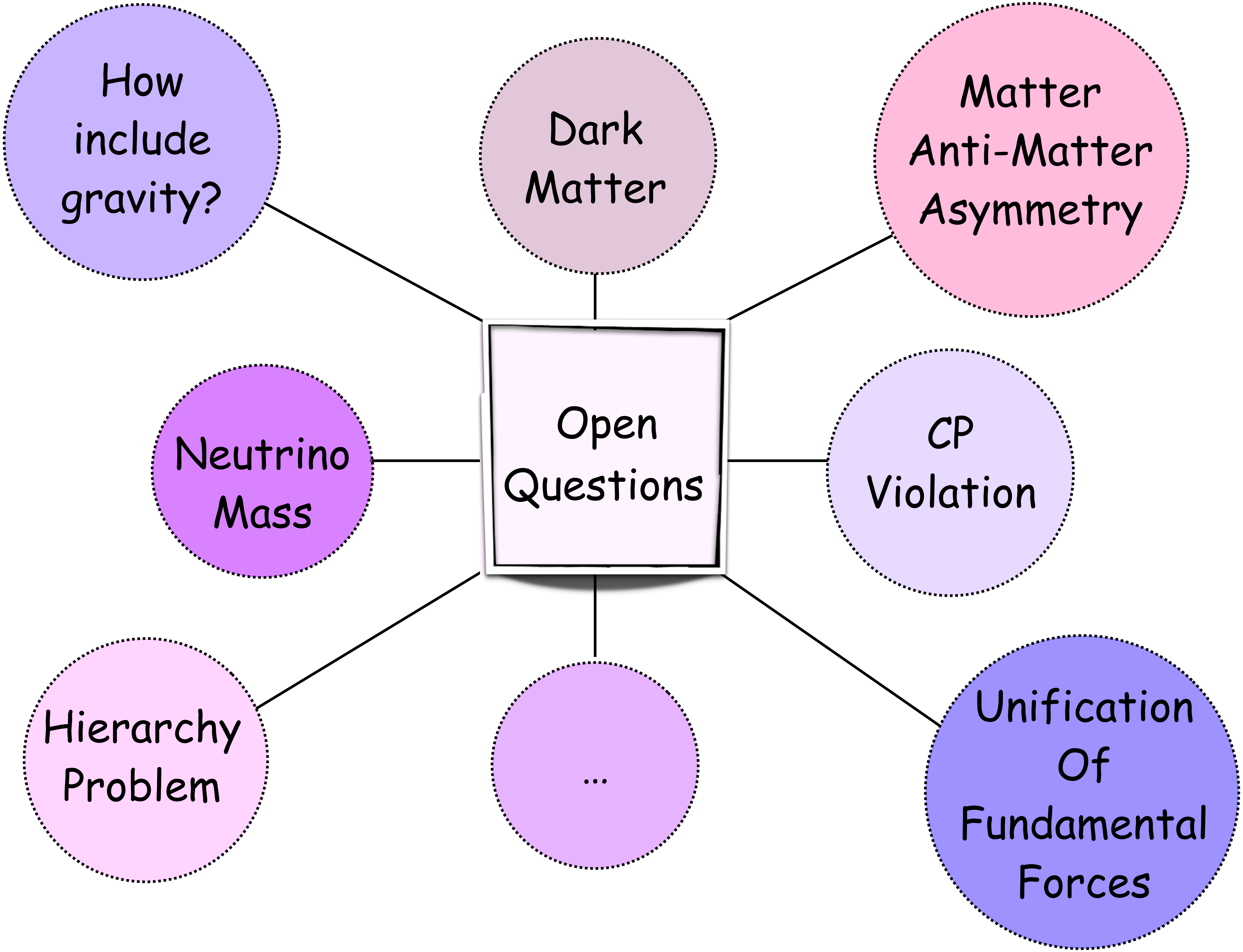


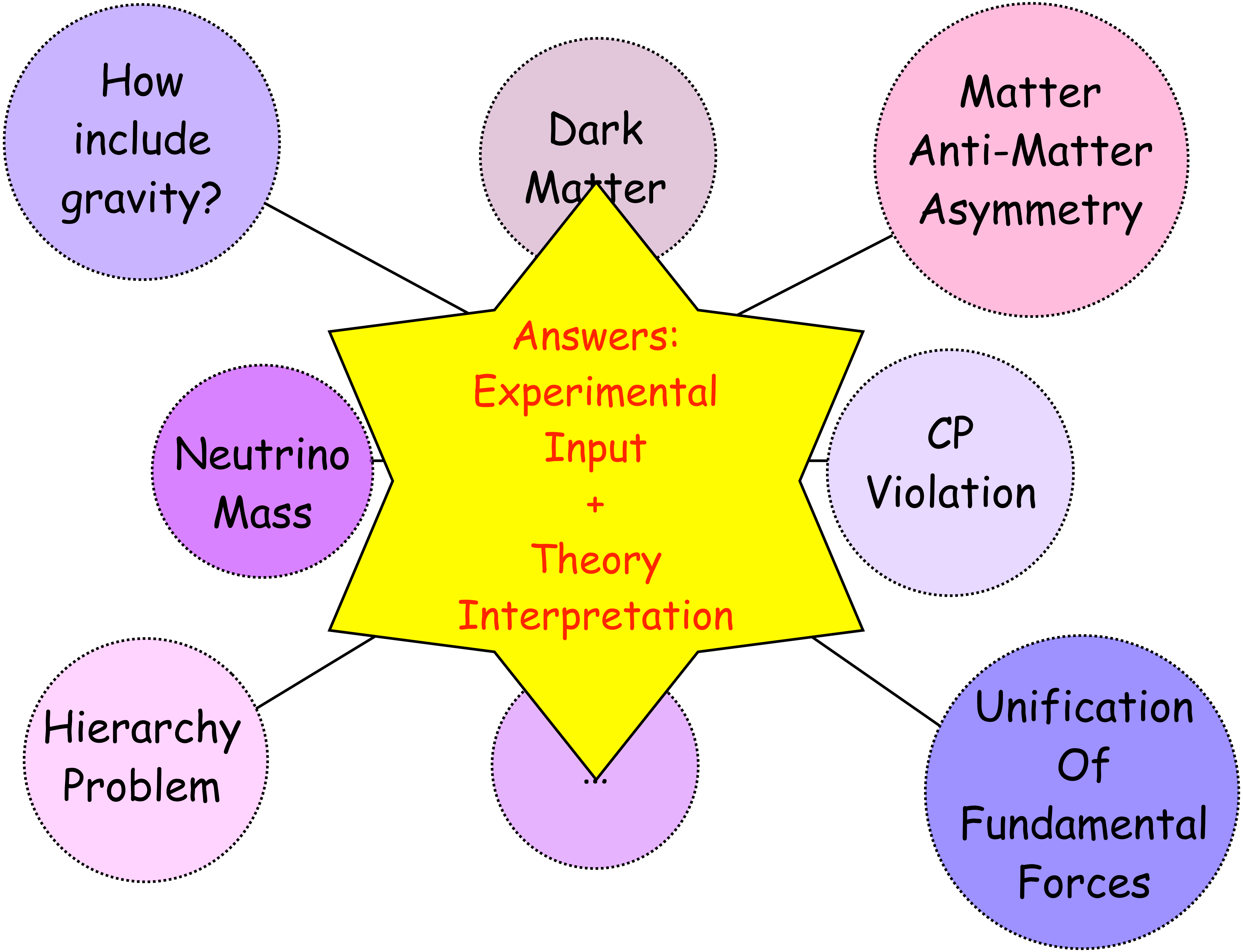
The Standard Model is Structurally Complete



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
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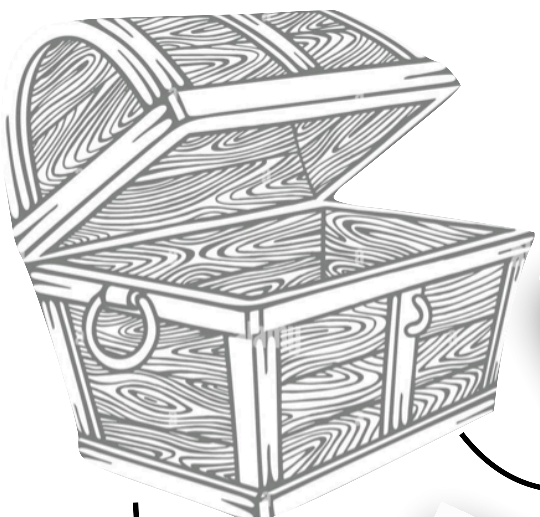
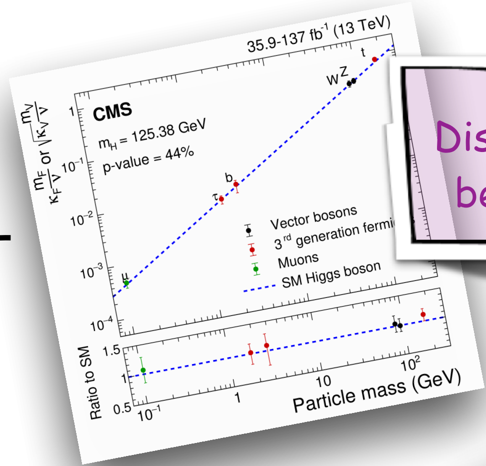
Neutrino Mass
Answers: Experimental Input + Theory Interpretation
CP Violation
Hierarchy Problem
...
Unification Of Fundamental Forces

Status

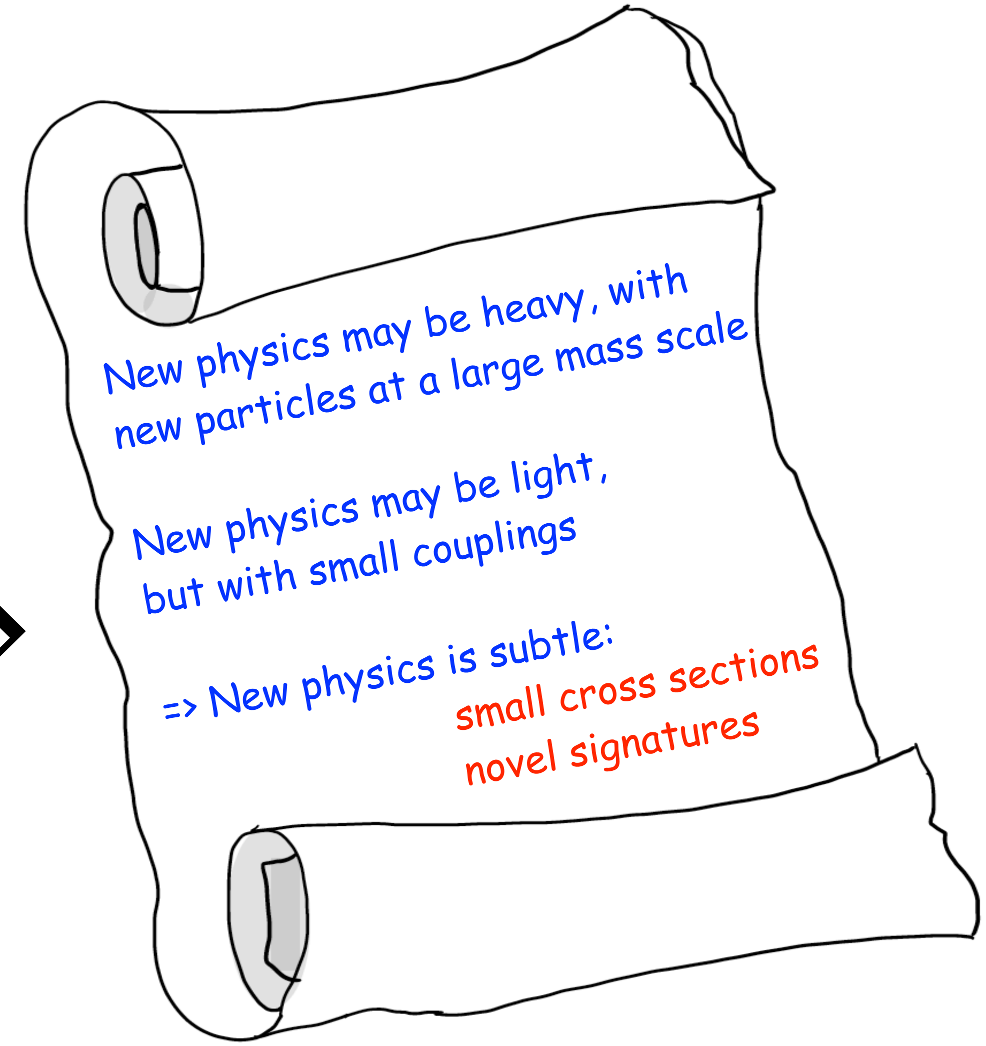




Discovered Higgs Boson behaves very SM-like

Consistency Test of the SM at the quantum level

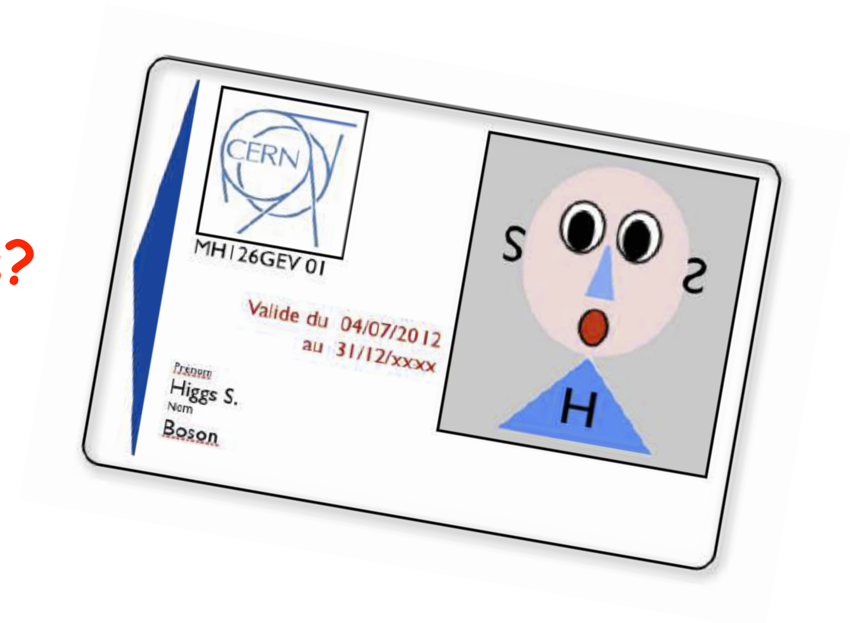
No direct discovery of New Physics so far



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)

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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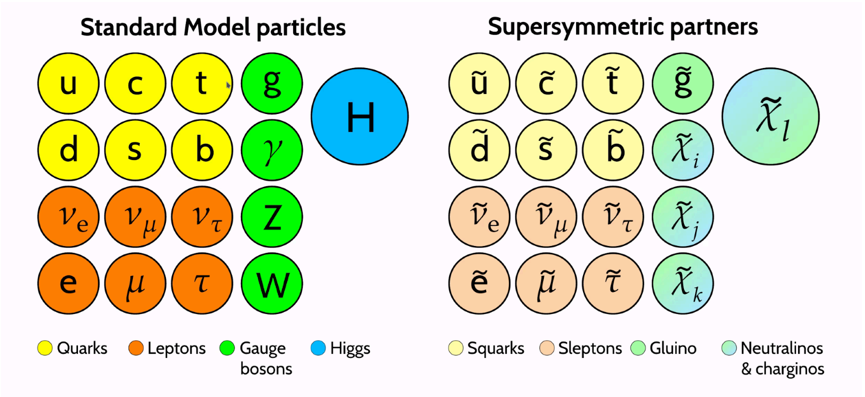
Supersymmetry

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

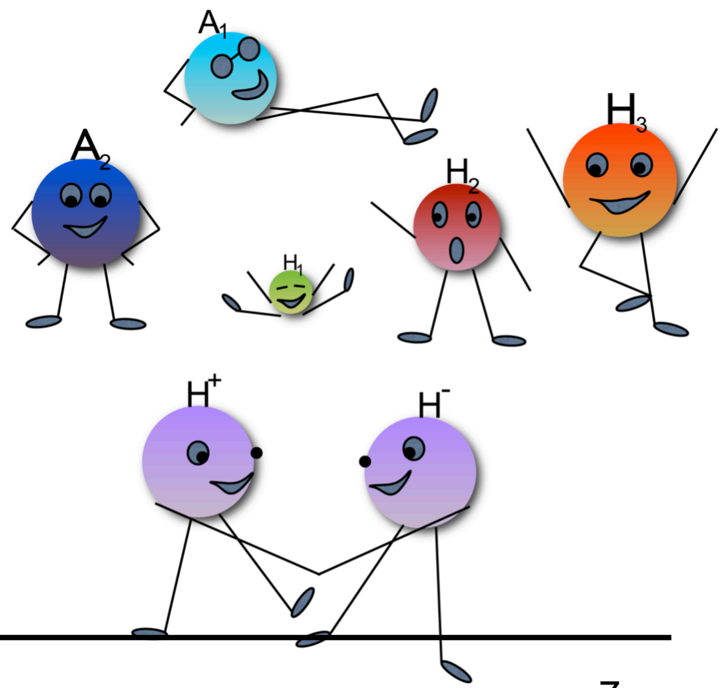
✦ Next-to-MSSM (NMSSM): 2 complex Higgs doublets plus complex singlet field

- enlarged Higgs and neutralino sector

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

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

- solves mu problem, interesting phenomenology



Higgs boson mass:

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

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

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

NMSSM:

* less important loop corrections needed compared to the MSSM

Status Spectrum Calculations

❖ Methods for Higgs mass calculations: fixed-order (FO) - effective field theory (EFT) - hybrid

- full (N)MSSM perturb. series truncated at fixed order reliable for not too heavy SUSY masses
- some very heavy SUSY masses: large logarithms require resummation
- combines virtues of fixed order and EFT calculation

❖ Status MSSM spectrum calculations:

FO: up to 2-loop in on-shell (OS) and DR scheme, partial 3-loop in DR scheme

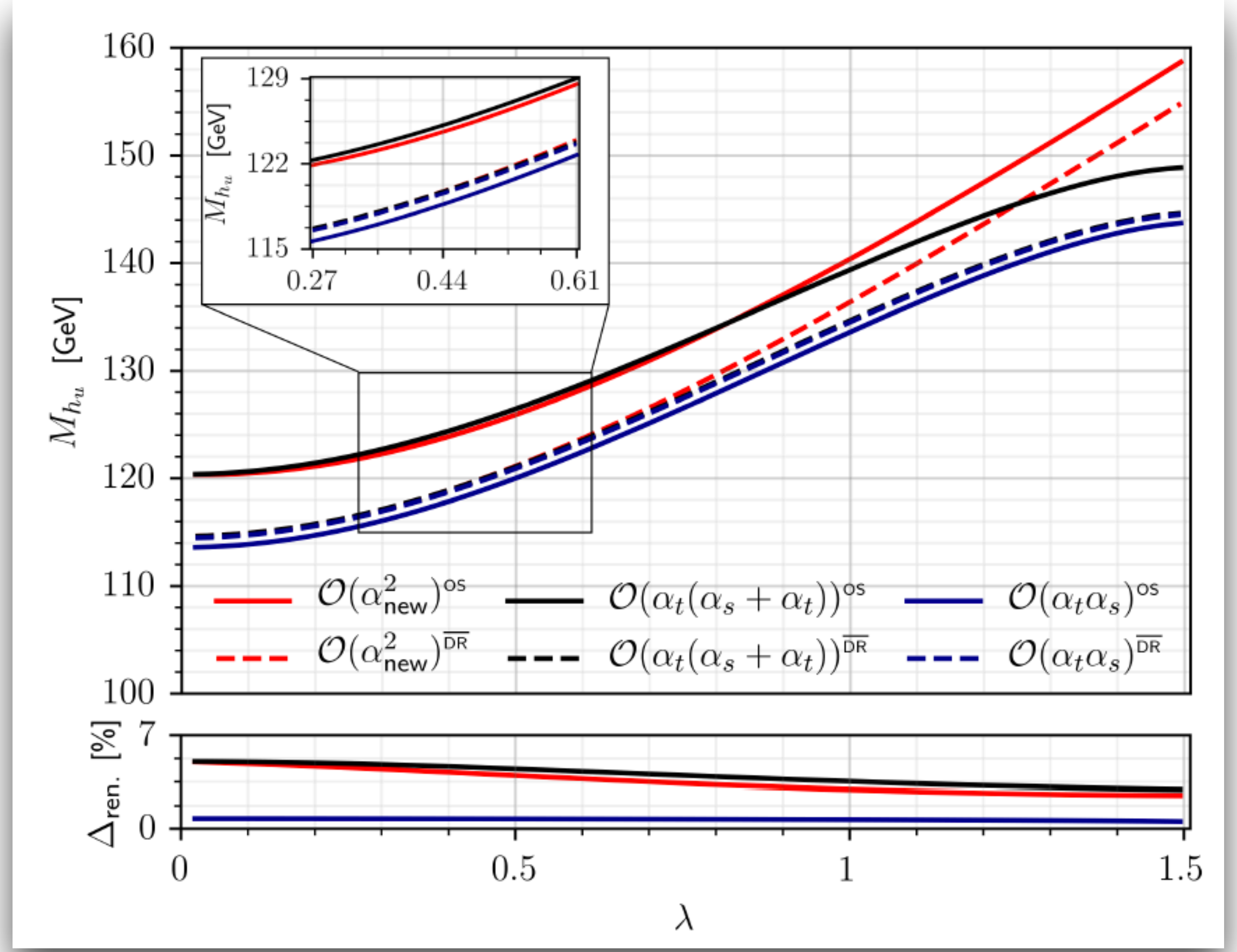
EFT: up to N^3LL

❖ Status NMSSM spectrum calculations:

up to 2-loop in mixed OS-DR scheme and in DR-scheme

$\mathcal{O}(\alpha_{new}{}^2) \equiv \mathcal{O}((\alpha_\lambda + \alpha_\kappa + \alpha_t)^2)$ 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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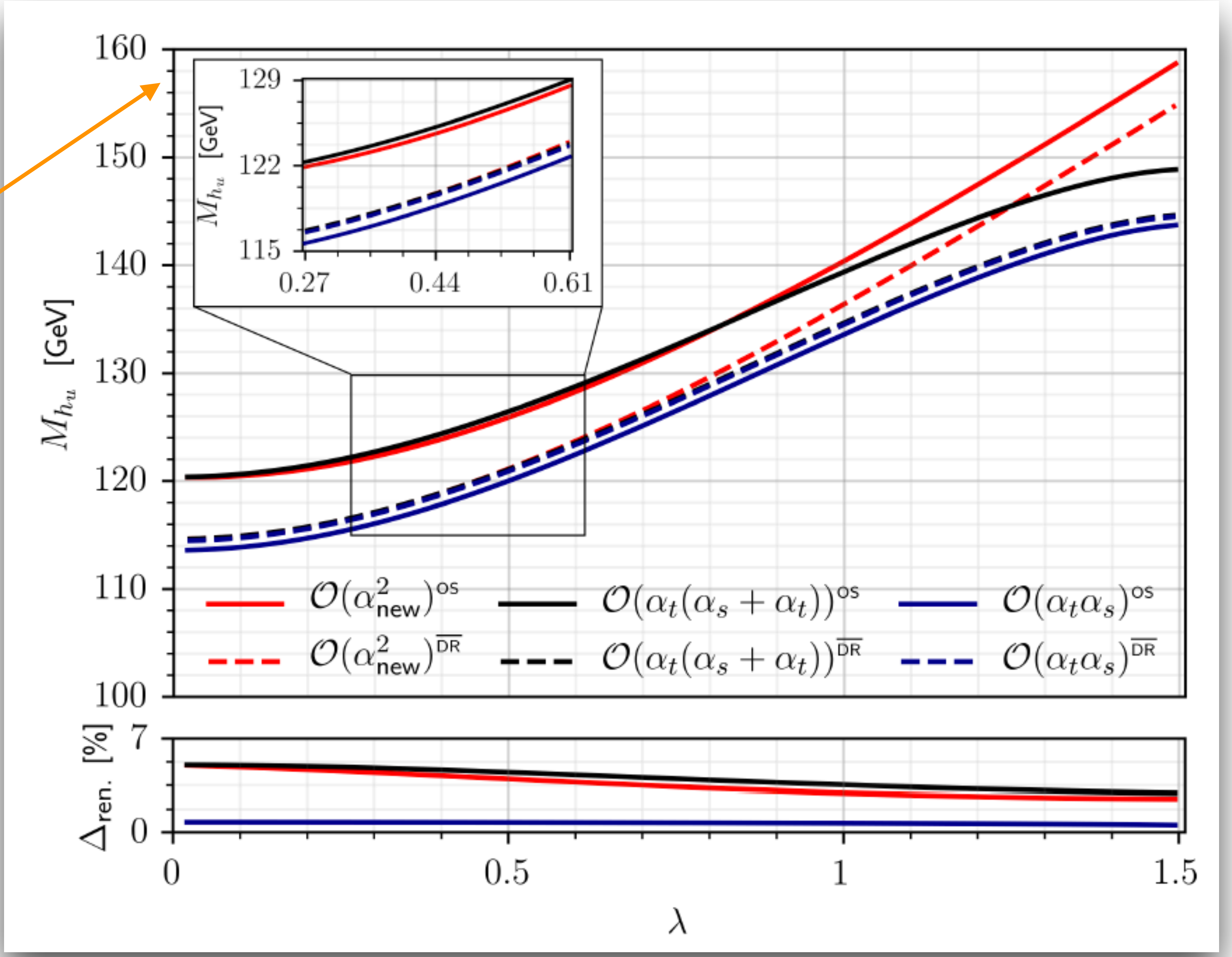
Corrections to h_u-like Higgs ($\triangleq$SM-like Higgs)

[Dao,Gabelmann,MM,Rzehak,'21]

Zoomed: compatible w/ HiggsSignals after including the new correction



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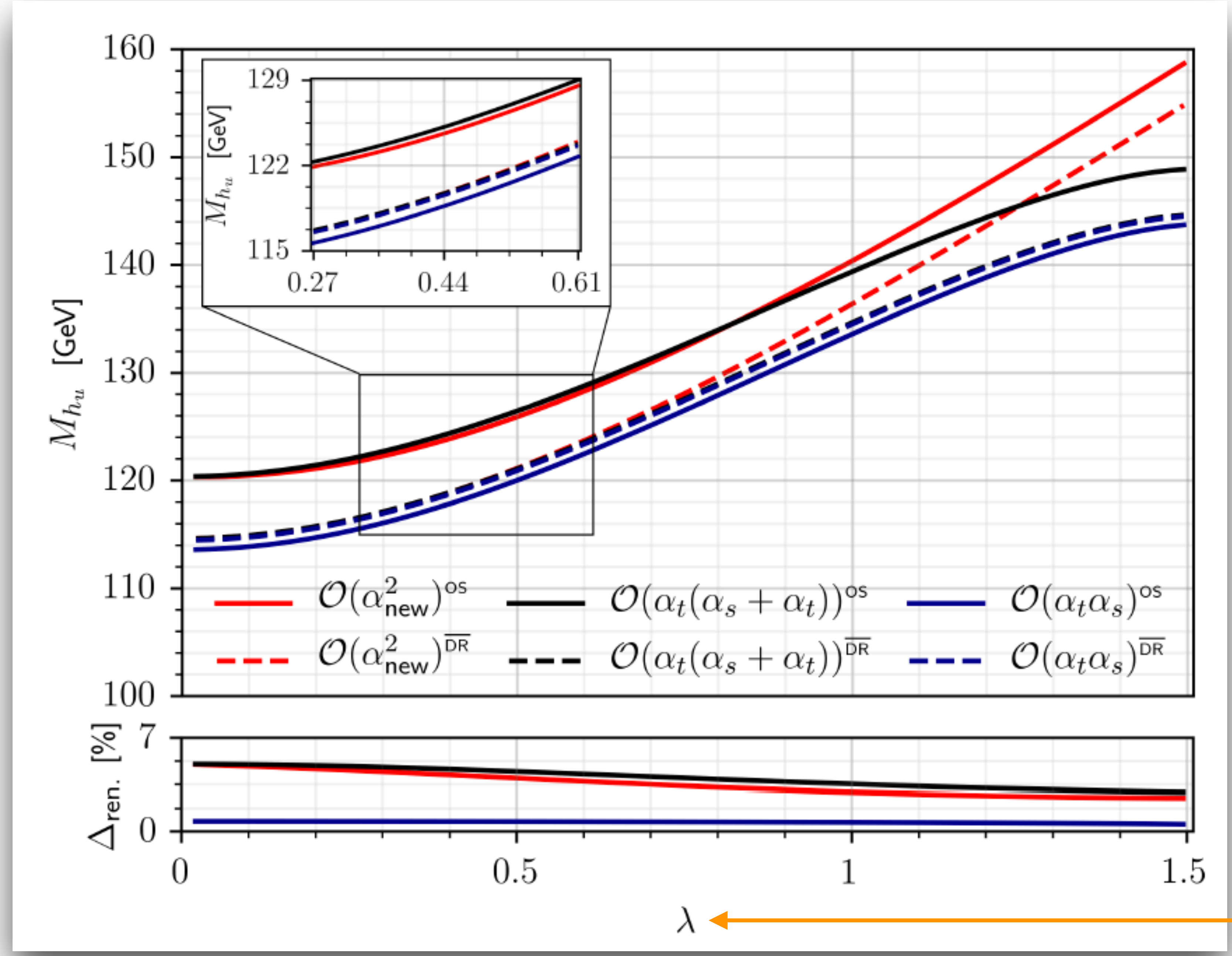


NMSSM specific couplings λ, κ related to new singlet field in superpotential

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

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

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

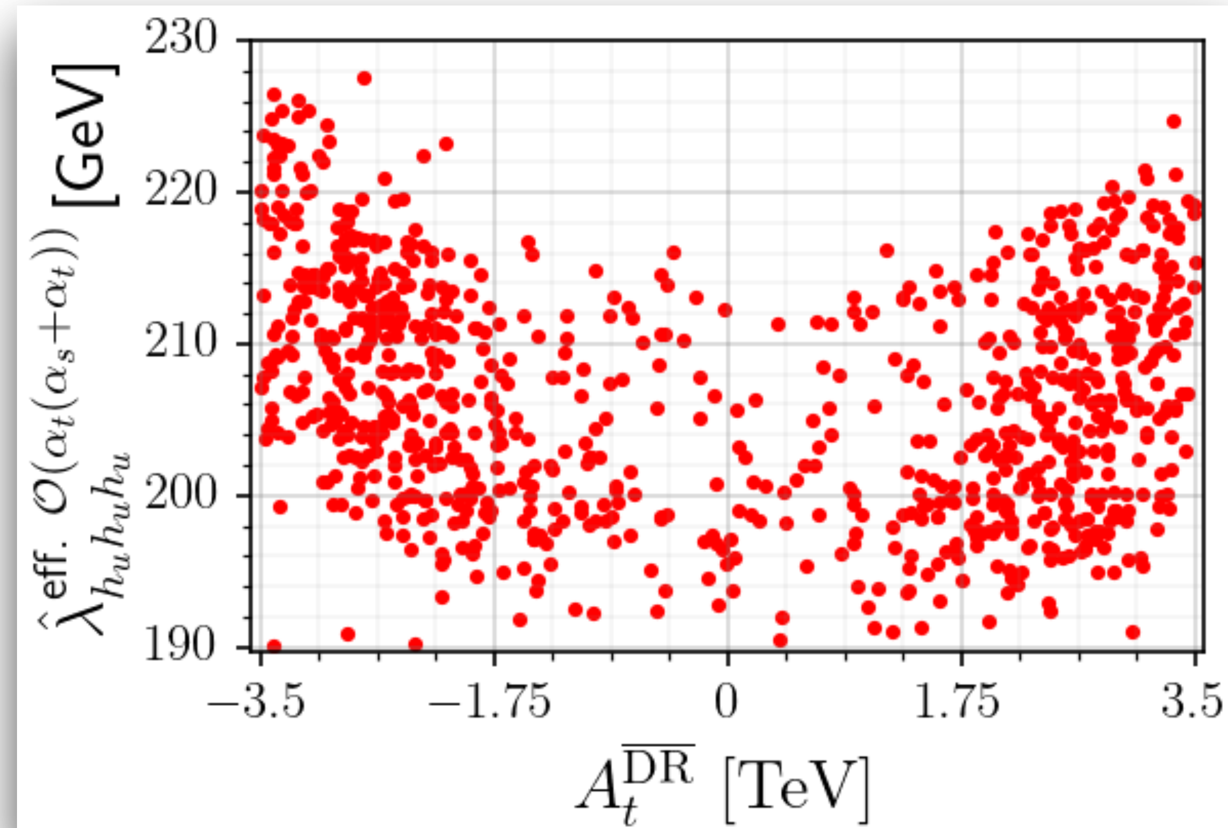
- Masses $M_{ij}=(\partial^2 V_H/\phi_i\, \phi_j)|_{\phi=0}$ and Higgs self-couplings $\lambda_{ijk}=(\partial^3 V_H/\phi_i\, \phi_j\, \phi_k)|_{\phi=0}$
  related through Higgs potential V_H => catch up in precision w/ masses

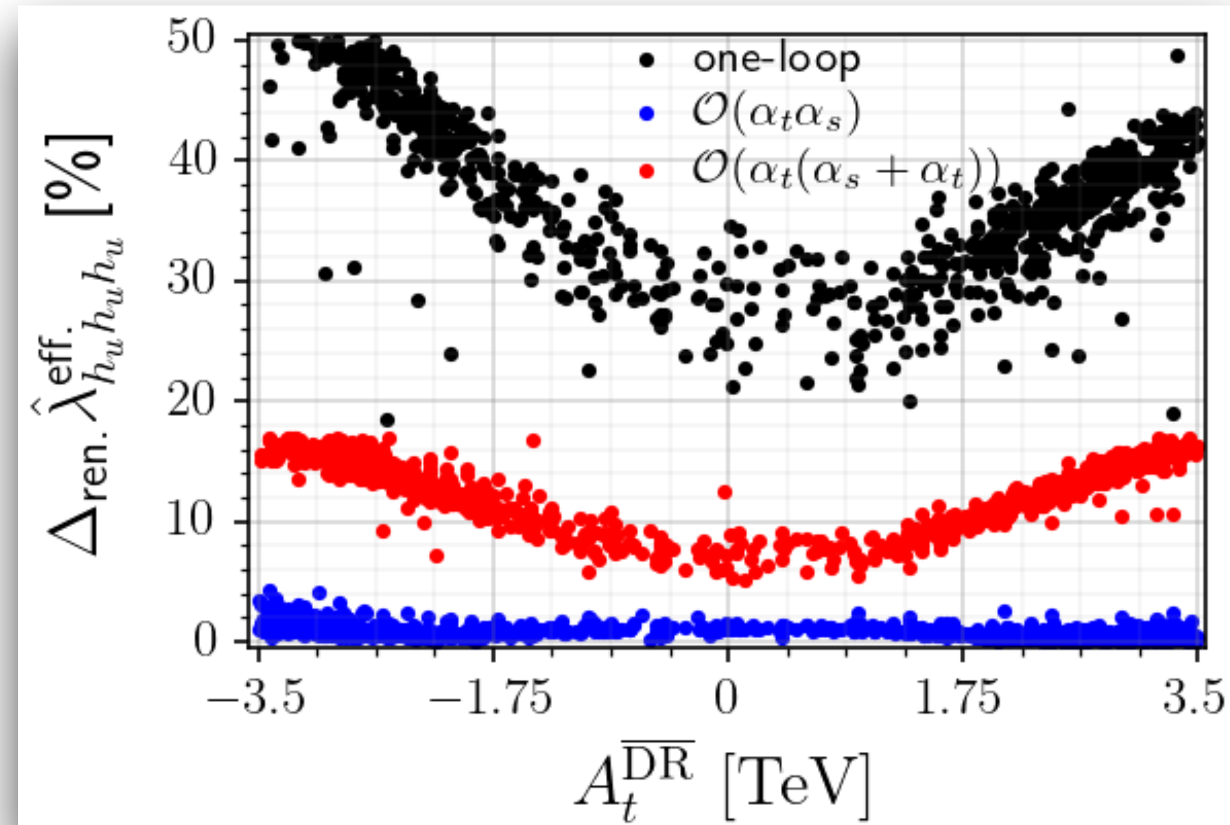
- Very sensitive to physics beyond the SM (BSM)
  important input for di-Higgs production
  important input for Higgs-to-Higgs decays
  important input for electroweak phase transitions

- 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 $\mathcal{O}(\alpha_t(\alpha_s+\alpha_t))$

Corrections to h_u-like Higgs ($\hat{=}$ SM-like Higgs) [Borschensky,Dao,Gabelmann,MM,Rzehak,'22]





$\hat{\lambda}^{\text{eff}}_{abc}$: renormalized loop-corrected Higgs self-coupling at vanishing external momentum

Theoretical uncertainty via renormalization scheme variation: $\Delta_{\text{ren}} = \frac{\left|\lambda^{m_t(\overline{\text{DR}})} - \lambda^{m_t(\text{OS})}\right|}{\lambda^{m_t(\overline{\text{DR}})}}$

Results comply w/ SM value $\lambda^{\text{SM}}_{HHH} = \frac{3M_H^2}{v} = 191 \text{ GeV}$ within theoretical uncertainty

More on Precision: BSM 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

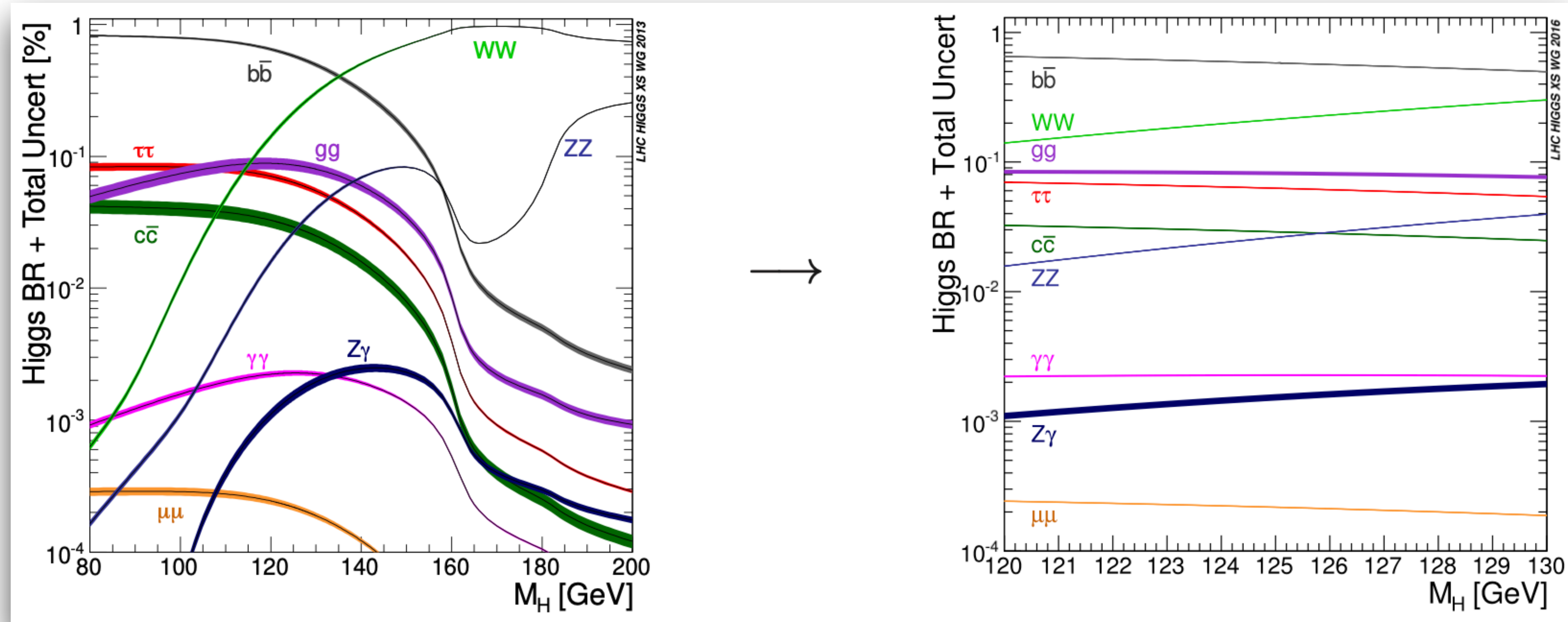
Impact of EW corrections on SM Higgs branching ratios $\Delta\mathrm{BR} = \frac{\mathrm{BR}^{\mathrm{QCD\&EW}} - \mathrm{BR}^{\mathrm{QCD}}}{\mathrm{BR}^{\mathrm{QCD}}}$ [HDECAY]

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 $\Delta\text{BR} = \frac{\text{BR}^{\text{QCD\&EW}} - \text{BR}^{\text{QCD}}}{\text{BR}^{\text{QCD}}}$ [HDECAY]

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

[Krause,MM,'19]

Type	$\Delta\text{BR}^{S_1}_{hb\bar{b}}$	$\Delta\text{BR}^{S_2}_{hb\bar{b}}$	$\Delta\text{BR}^{S_3}_{hb\bar{b}}$	$\Delta\text{BR}^{\text{OS2}}_{hb\bar{b}}$	$\Delta\text{BR}^{\overline{\text{MS}}}_{hb\bar{b}}$
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	$\Delta\text{BR}^{S_1}_{h\gamma\gamma/hZZ}$	$\Delta\text{BR}^{S_2}_{h\gamma\gamma/hZZ}$	$\Delta\text{BR}^{S_3}_{h\gamma\gamma/hZZ}$	$\Delta\text{BR}^{\text{OS2}}_{h\gamma\gamma/hZZ}$	$\Delta\text{BR}^{\overline{\text{MS}}}_{h\gamma\gamma/hZZ}$
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	$\Delta\text{BR}^{S_1}_{h\tau^+\tau^-}$	$\Delta\text{BR}^{S_2}_{h\tau^+\tau^-}$	$\Delta\text{BR}^{S_3}_{h\tau^+\tau^-}$	$\Delta\text{BR}^{\text{OS2}}_{h\tau^+\tau^-}$	$\Delta\text{BR}^{\overline{\text{MS}}}_{h\tau^+\tau^-}$
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 $\Delta\mathrm{BR} = \frac{\mathrm{BR}^{\mathrm{QCD\&EW}} - \mathrm{BR}^{\mathrm{QCD}}}{\mathrm{BR}^{\mathrm{QCD}}}$ [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%

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

[Krause,MM,'19]

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

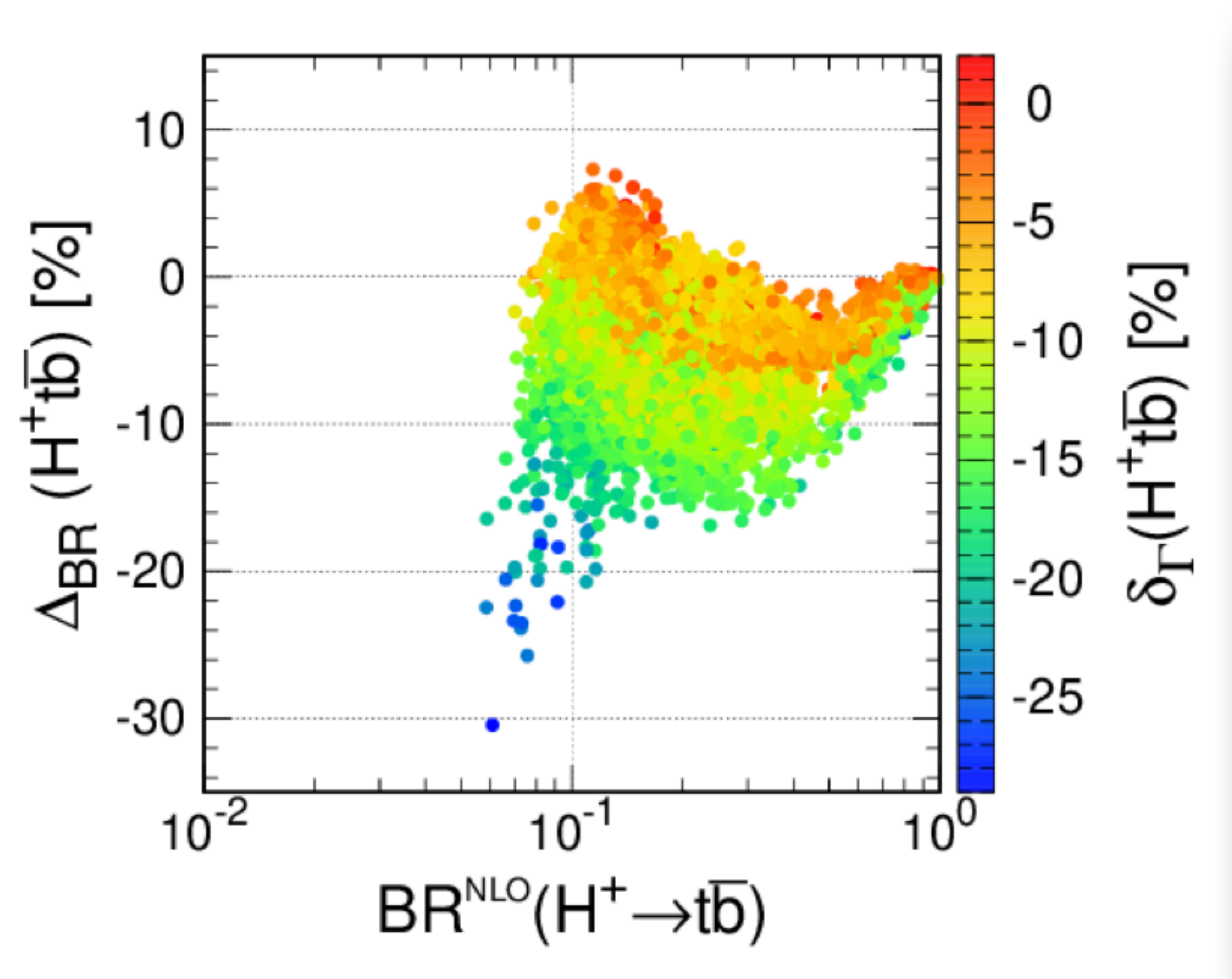
Type	$\Delta\mathrm{BR}^{S_1}_{HZA}$	$\Delta\mathrm{BR}^{S_2}_{HZA}$	$\Delta\mathrm{BR}^{S_3}_{HZA}$	$\Delta\mathrm{BR}^{S_4}_{HZA}$	$\Delta\mathrm{BR}^{\overline{\mathrm{MS}}}_{HZA}$
I	≲ 5.0 % (51 %)	≲ 5.0 % (51 %)	≲ 10.0 % (46 %)	≲ 10.0 % (53 %)	≲ 80.0 % (26 %)
	≲ 15.0 % (80 %)	≲ 15.0 % (80 %)	≲ 30.0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

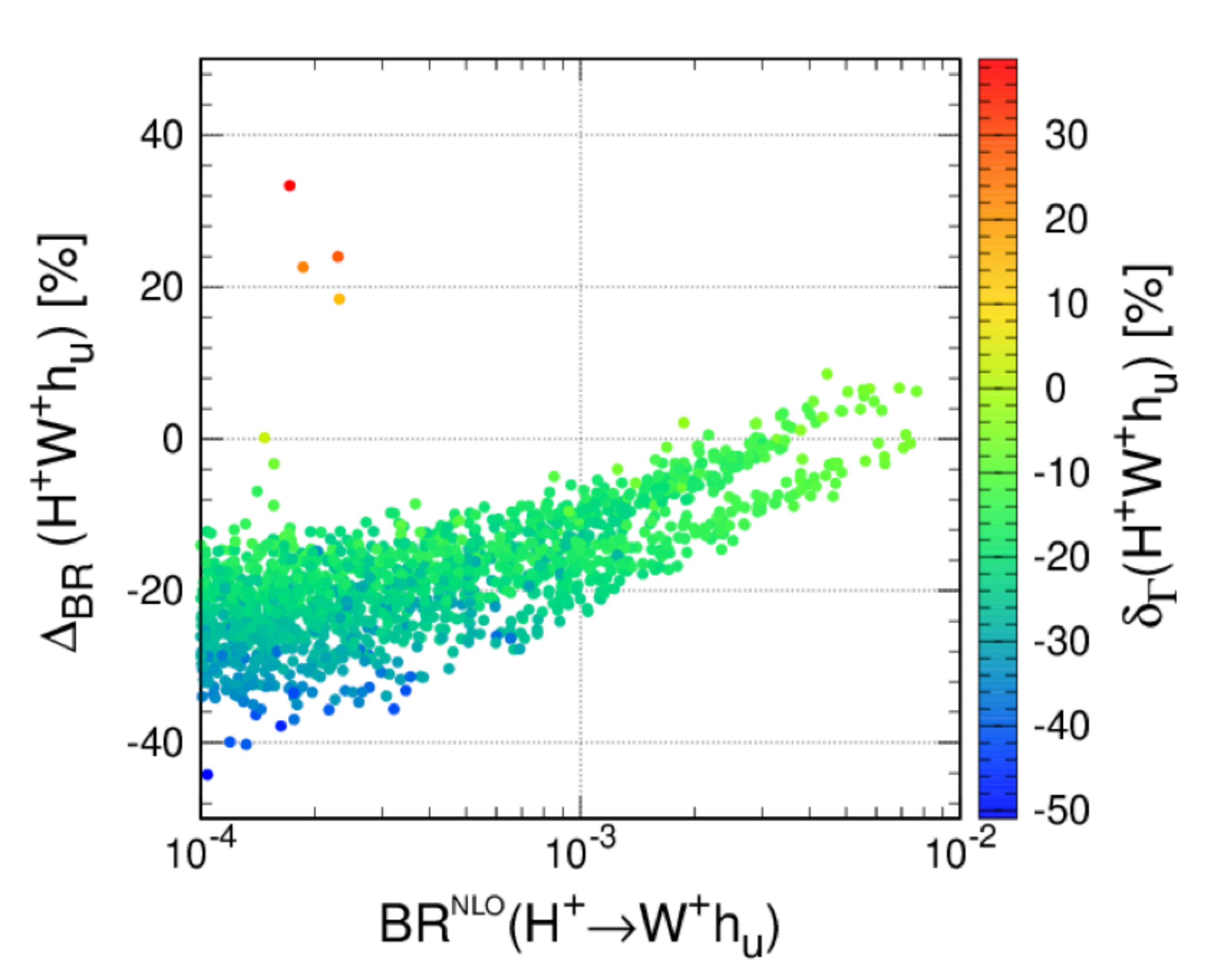
Type	$\Delta\mathrm{BR}^{S_1}_{HW^\pm H^\mp}$	$\Delta\mathrm{BR}^{S_2}_{HW^\pm H^\mp}$	$\Delta\mathrm{BR}^{S_3}_{HW^\pm H^\mp}$	$\Delta\mathrm{BR}^{S_4}_{HW^\pm H^\mp}$	$\Delta\mathrm{BR}^{\overline{\mathrm{MS}}}_{HW^\pm H^\mp}$
I	≲ 5.0 % (56 %)	≲ 5.0 % (55 %)	≲ 10.0 % (49 %)	≲ 10.0 % (57 %)	≲ 70.0 %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



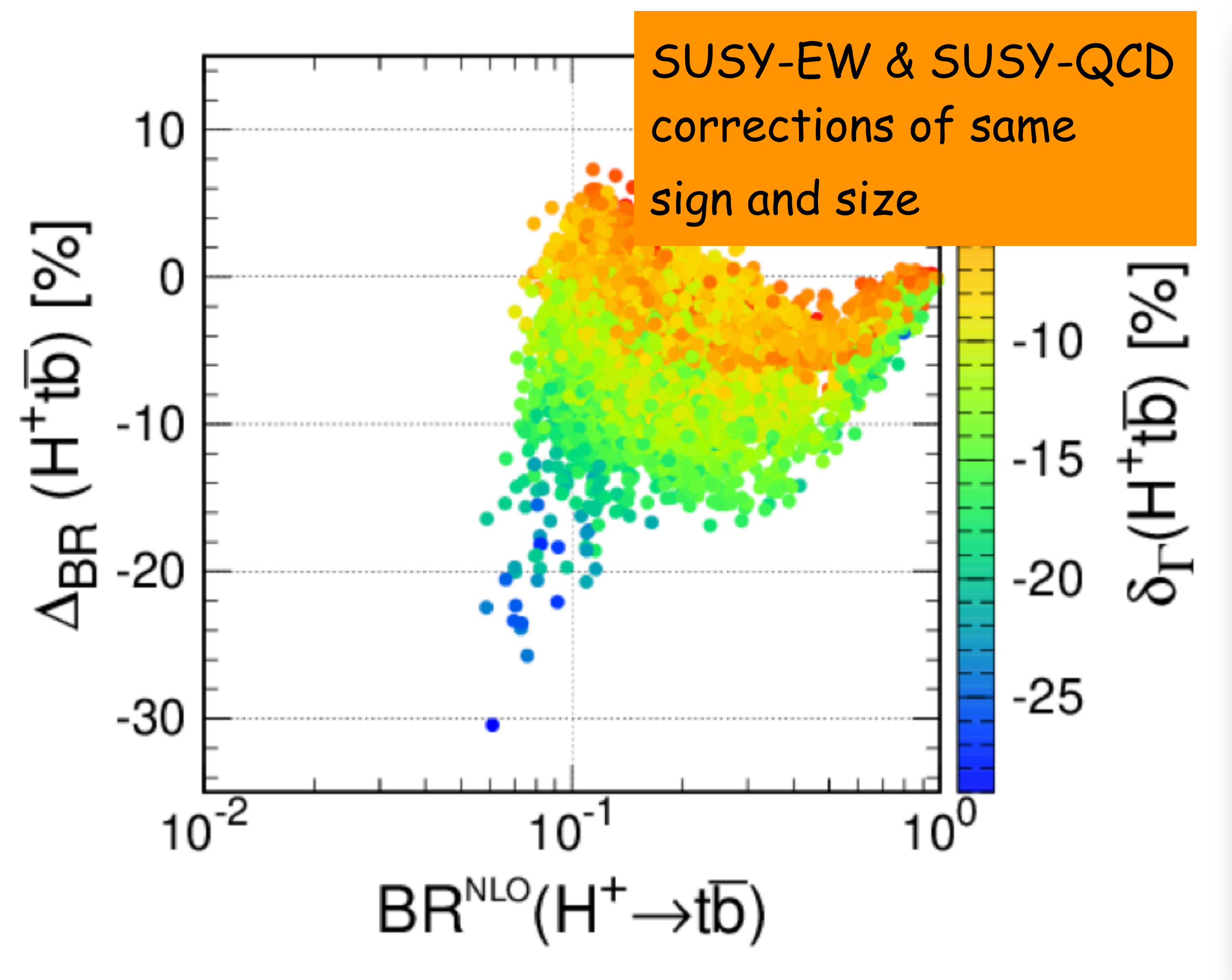


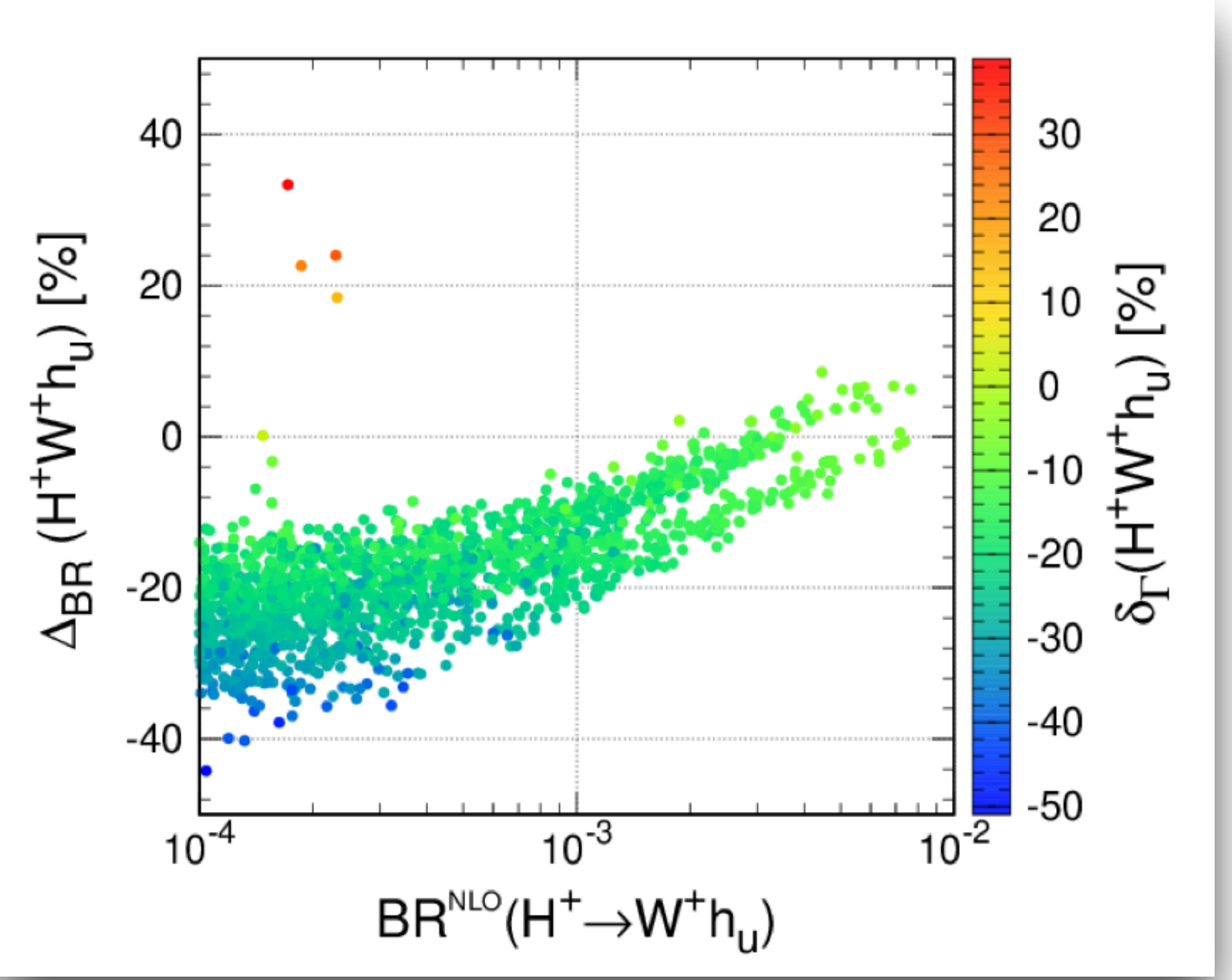
- Corrections to charged Higgs decays:
  Δ_{BR}: NLO impact on branching ratio, δ_Γ: NLO impact on partial width
- Implemented in NMSSMCALCEW [Dao,Baglio,MM,Patel,Sakurai]

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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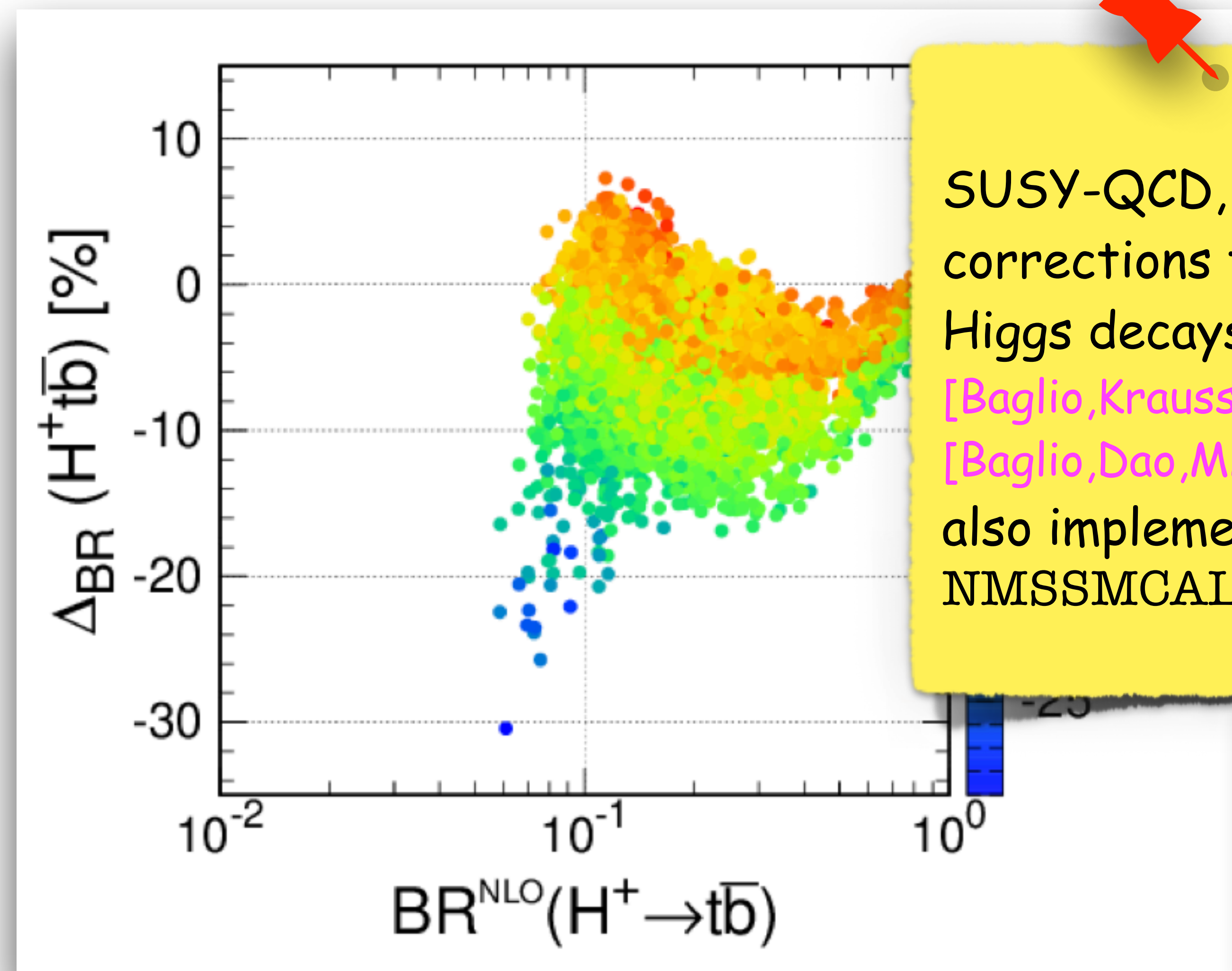
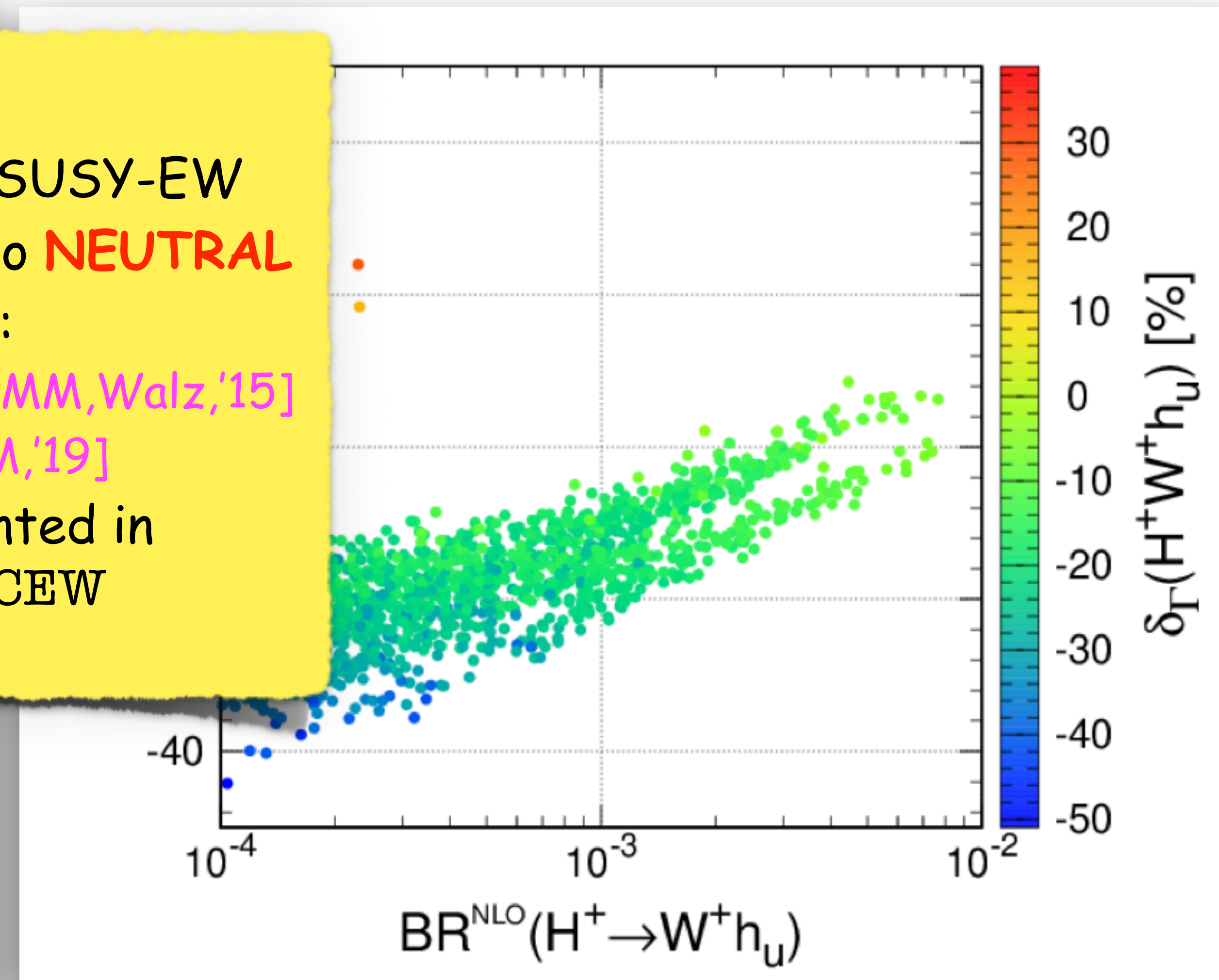




SUSY-QCD, SUSY-EW corrections to **NEUTRAL** Higgs decays:
[Baglio,Krauss,MM,Walz,'15]
[Baglio,Dao,MM,'19]
also implemented in NMSSMCALCEW

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

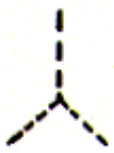

HH Production
Precision
Thời Trang Trẻ Em
ANH DUNG
QUẦN · ÁO · GIẦY DÉP · ĐỒ DÙNG SƠ SINH
15 Lưu Văn Lang Q.1
Tel : 8 298 704
HOTEL
Shop 14

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 : $\lambda_{HHH} = 3M_H^2/M_Z^2$



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

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

(a) trilinear coupling : via Higgs pair production

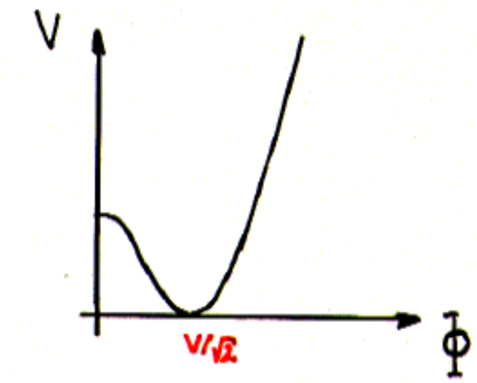
(b) quadrilinear coupling : via triple Higgs production

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

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

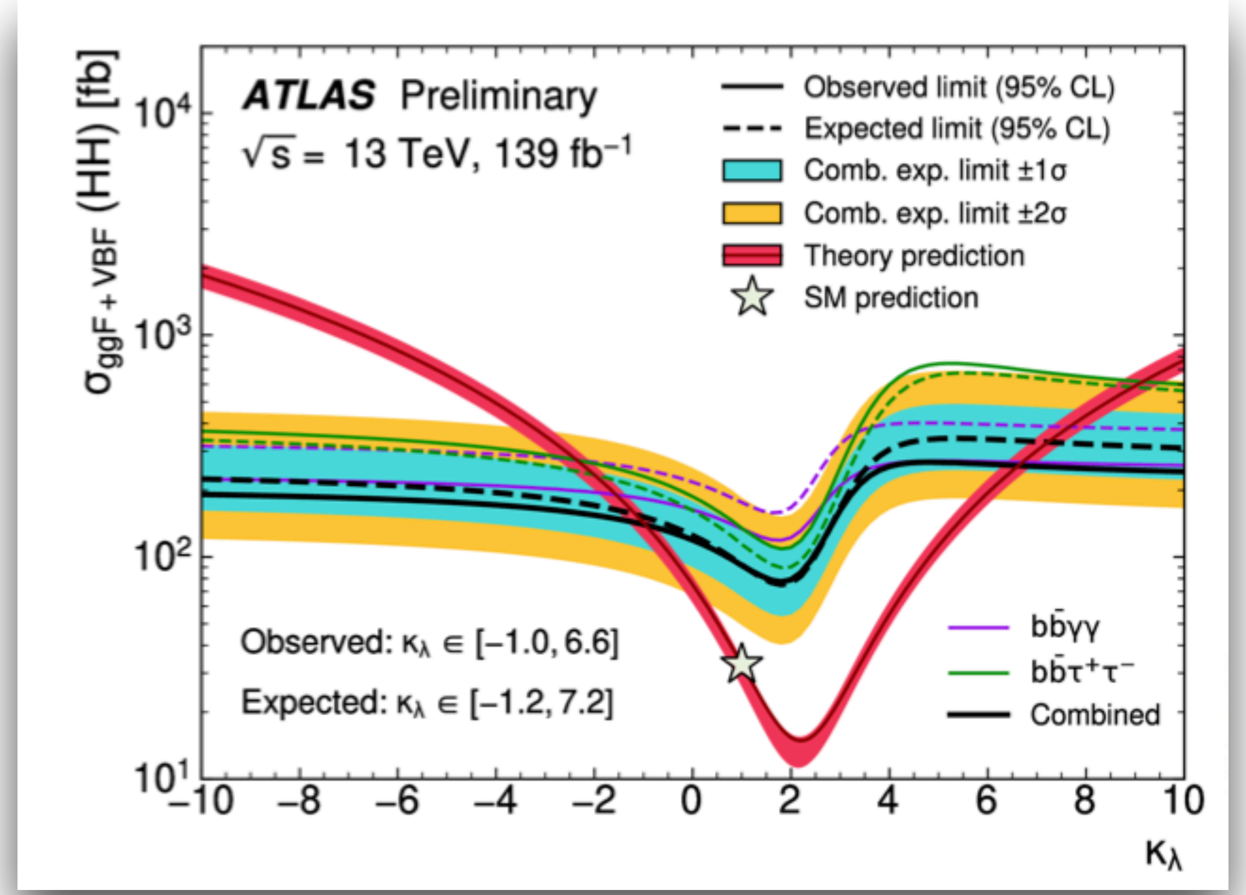
v = 246 GeV

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



Slides from LCWS, Fermilab, 10/2000
[Djouadi,Kilian,MM,Zerwas,03/99,04/99]

Experimental Results - Limits on Trilinear Higgs Self-Coupling

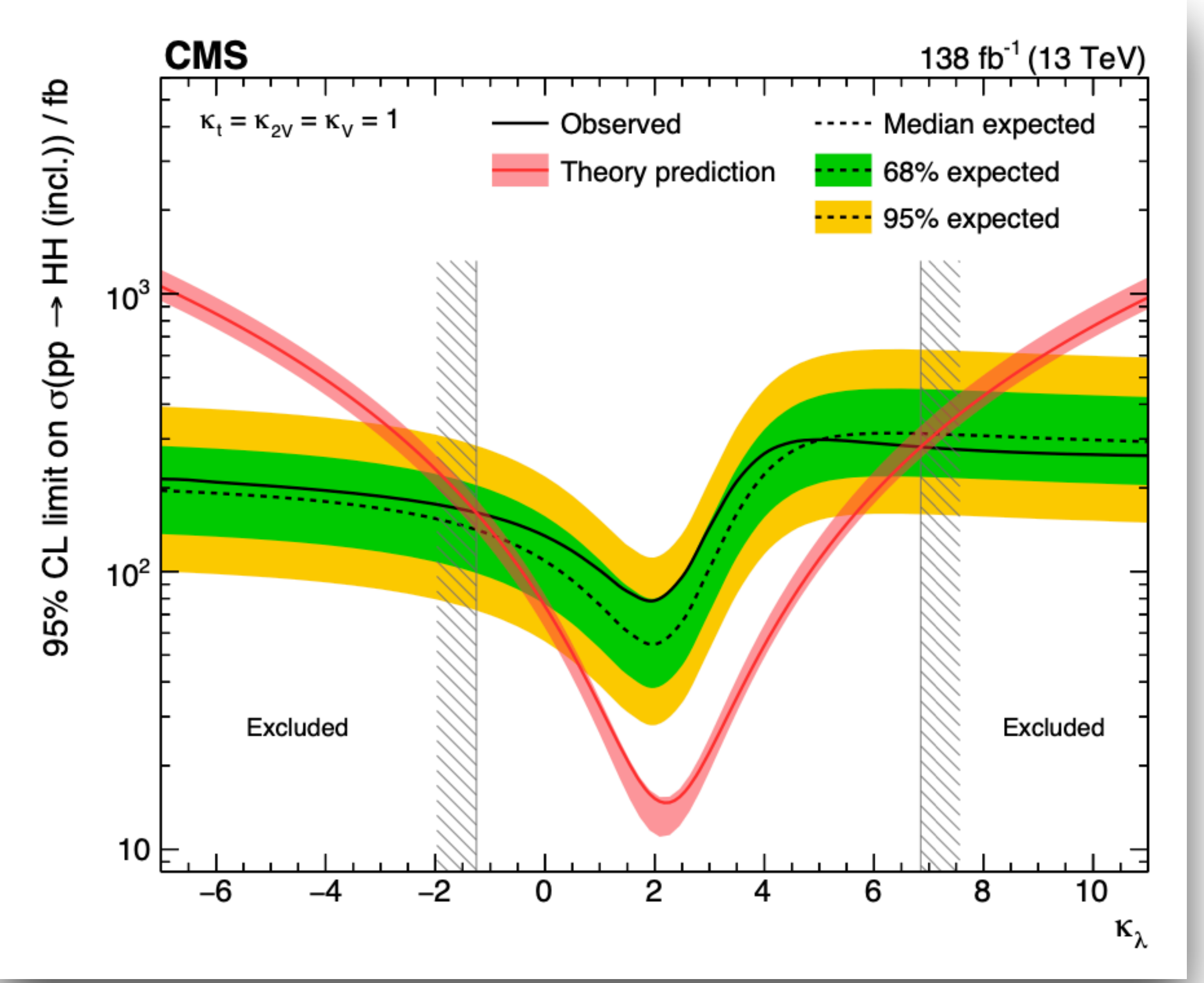


[Rui Zhang, ATLAS, HH Workshop´22]

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

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

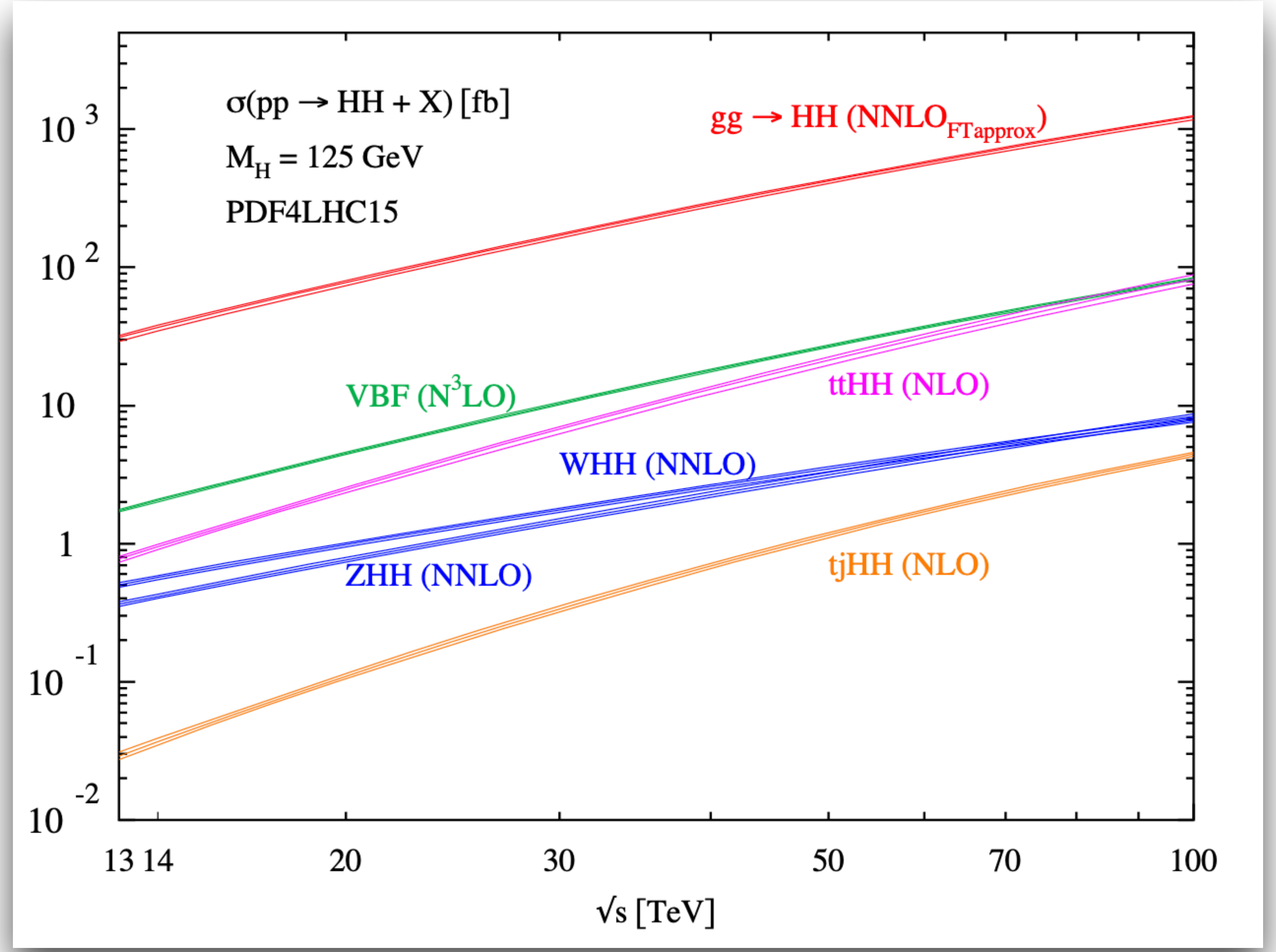
[CMS,2207.00043]



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

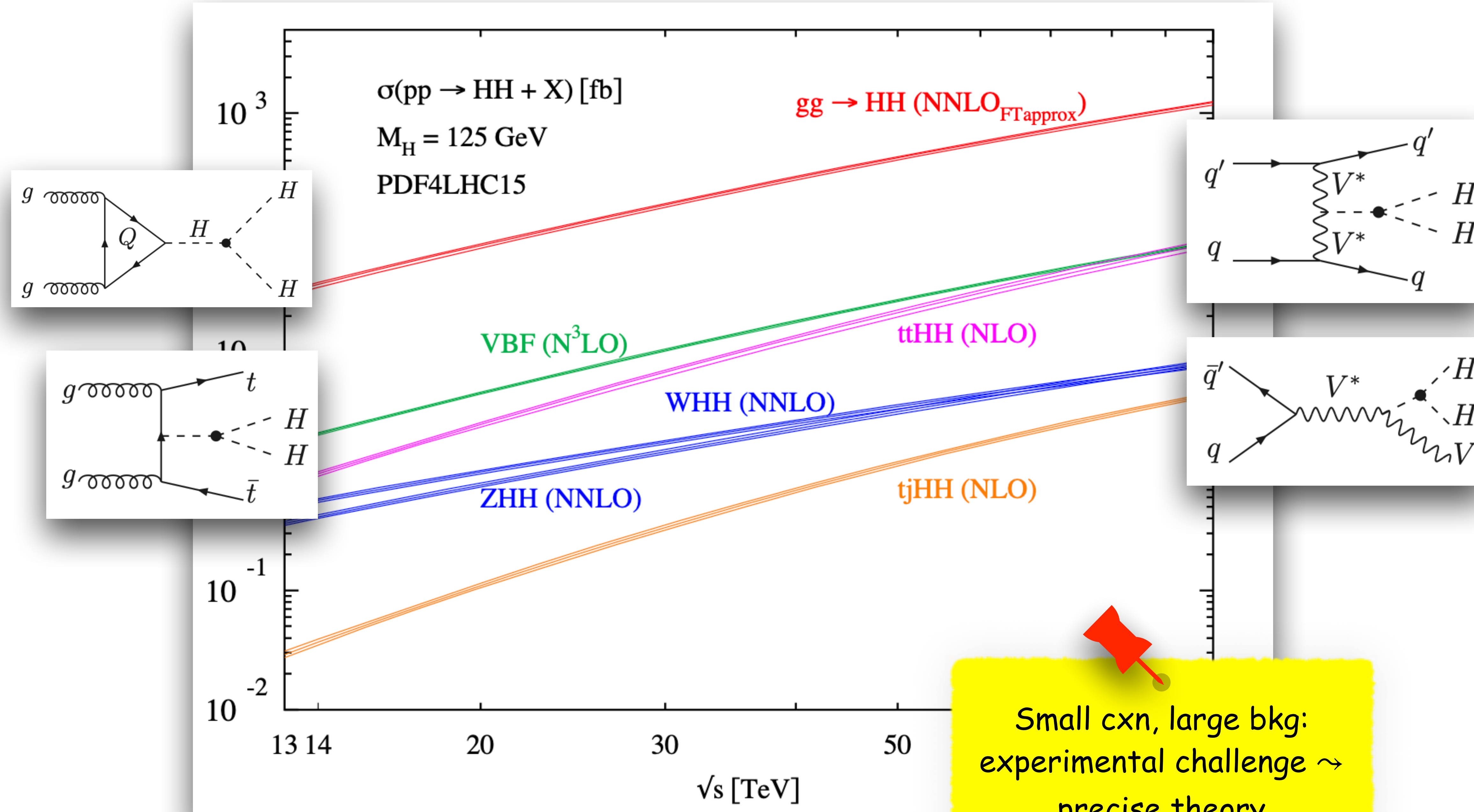
Double Higgs Production Processes

[HH, White paper]



Double Higgs Production Processes

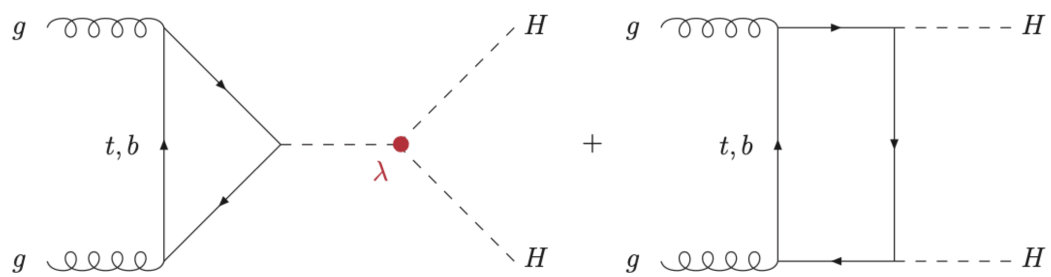
[HH, White paper]



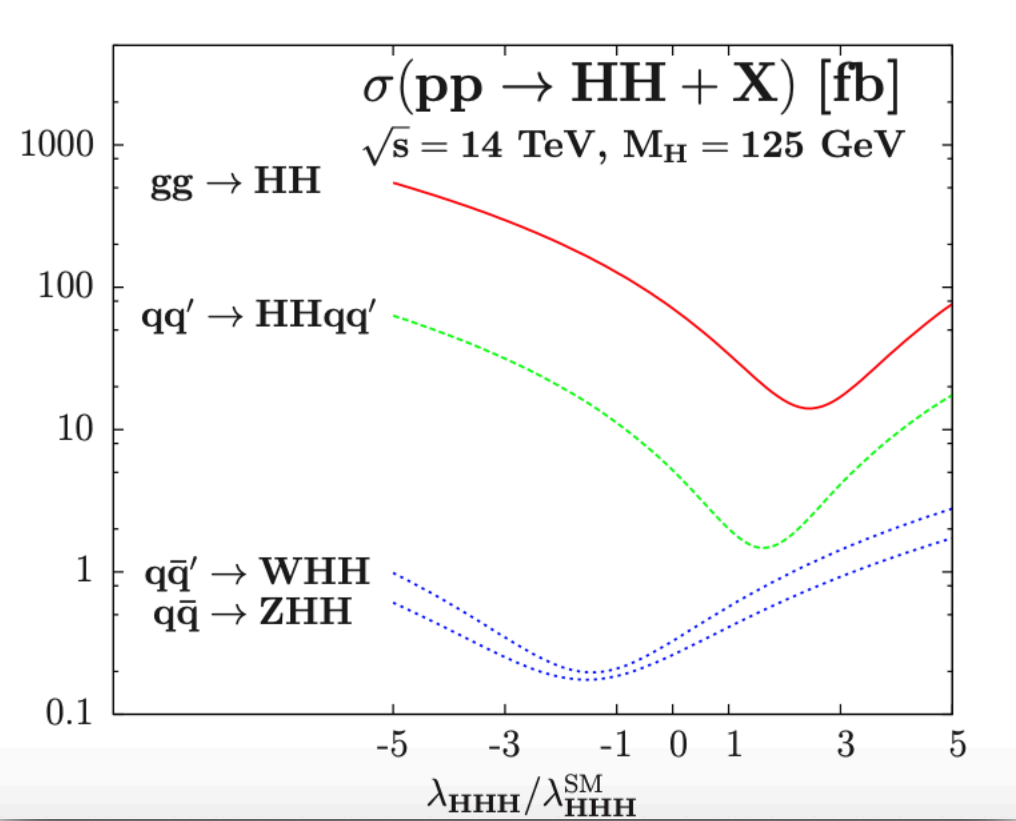
Small cxn, large bkg:
experimental challenge ⇝
precise theory
predictions required

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 c_{tt}/c_{bb} [e.g. boosted Higgs pairs]



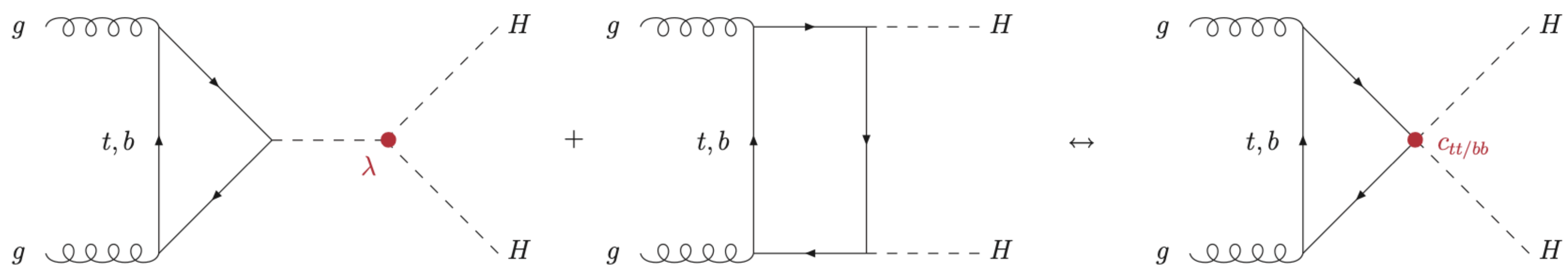
[Baglio,Djouadi,Gröber,MM,Quévillon,Spira]

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

decreasing with M_{HH}

Higgs Pair Production through Gluon Fusion

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



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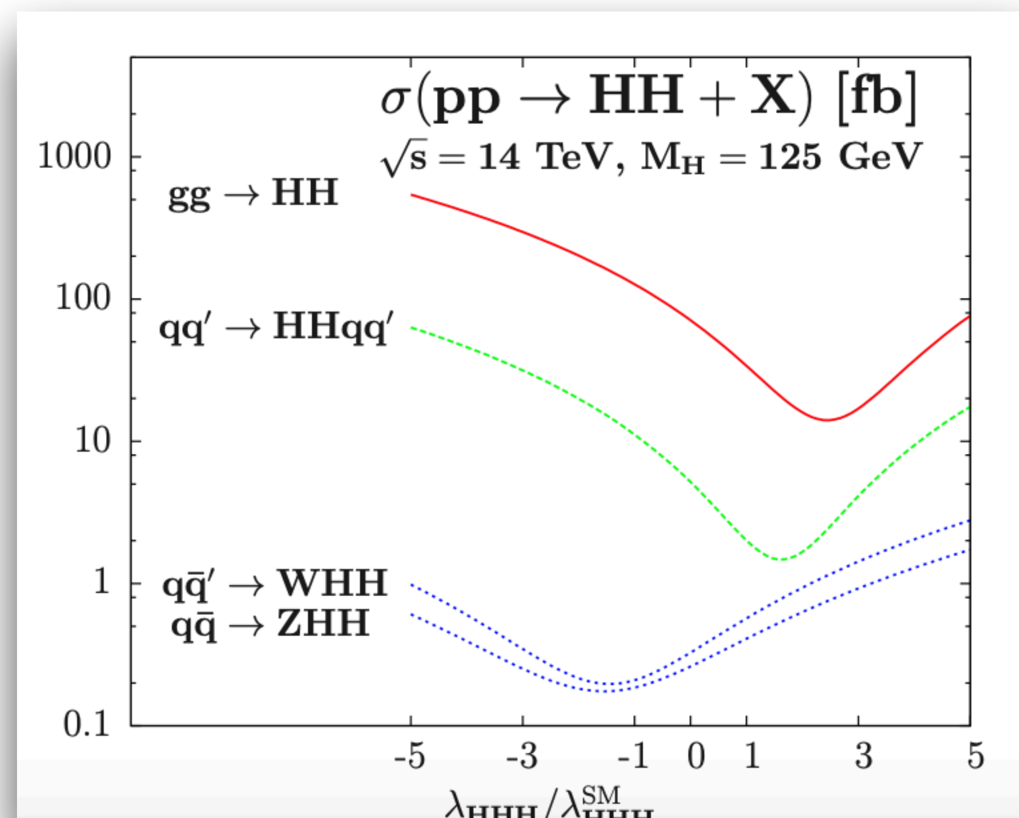


[Baglio,Djouadi,Gröber,MM,Quévillon,Spira]

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

decreasing with M_{HH}

Higher-Order QCD Corrections to Higgs Pair Production

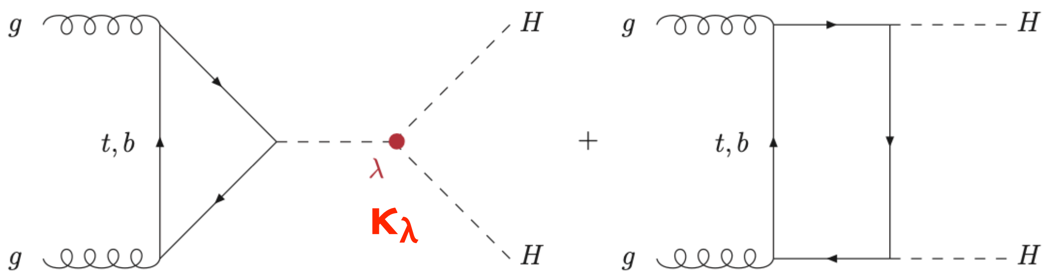
- 2-loop QCD corrections: $\lesssim$ 70% [HTL, $\mu = M_{HH}/2$] [Dawson,Dittmaier,Spira]
- 2-loop QCD corrections: $\sigma = \sigma_0 + \sigma_1/m_t^2 + \ldots + \sigma_4/m_t^8$
  [refinement: full LO at differential level] [Grigo,Hoff,Melnikov,Steinhauser]
- Mass effects @ NLO in real corrections: ~ - 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]

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:

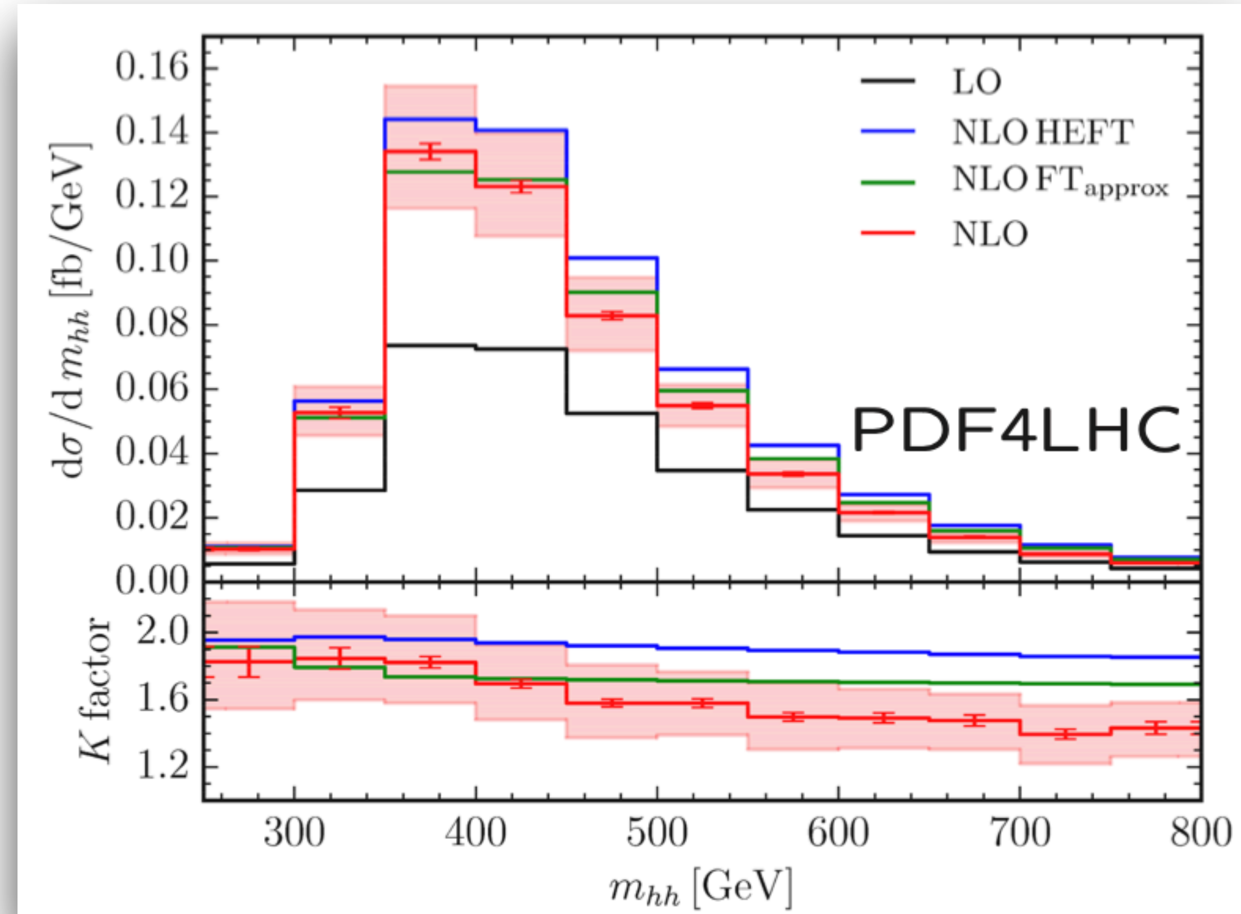
✦ top-Yukawa induced corrections: 0.2%, not absorbable in effective trilinear coupling [MM,Schlenk,Spira,'22]

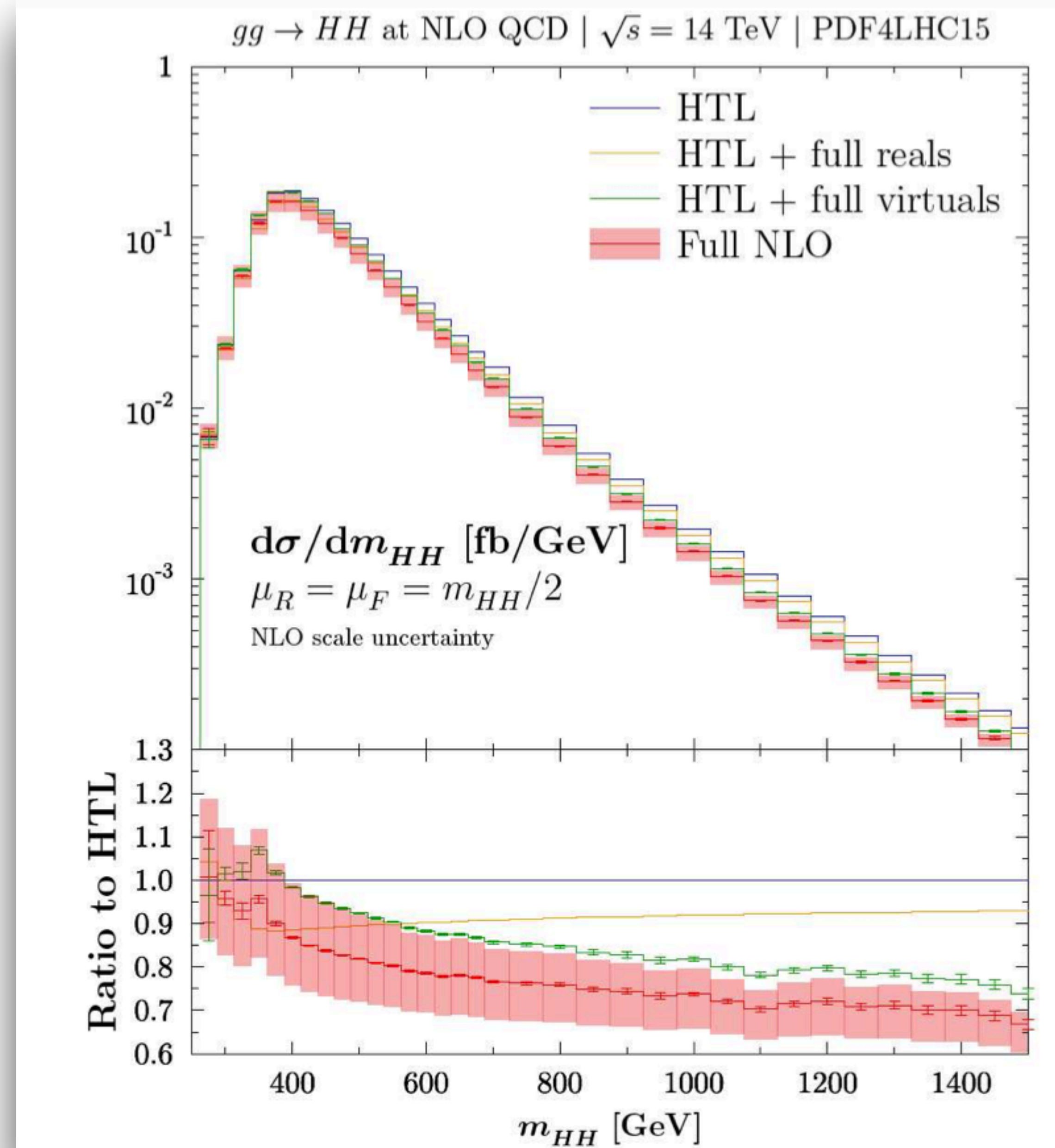
✦ top Yukawa corrections in the high-energy limit [Davies,Mishima,Schönwald, Steinhauser,Zhang,'22]

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:

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

- m_t scale/scheme uncertainties at NLO:

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

- 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

Uncertainties for Different Higgs Self-Coupling Values

- Final combined uncertainties at $\mathrm{NNLO}_{\mathrm{FTapprox}}$:

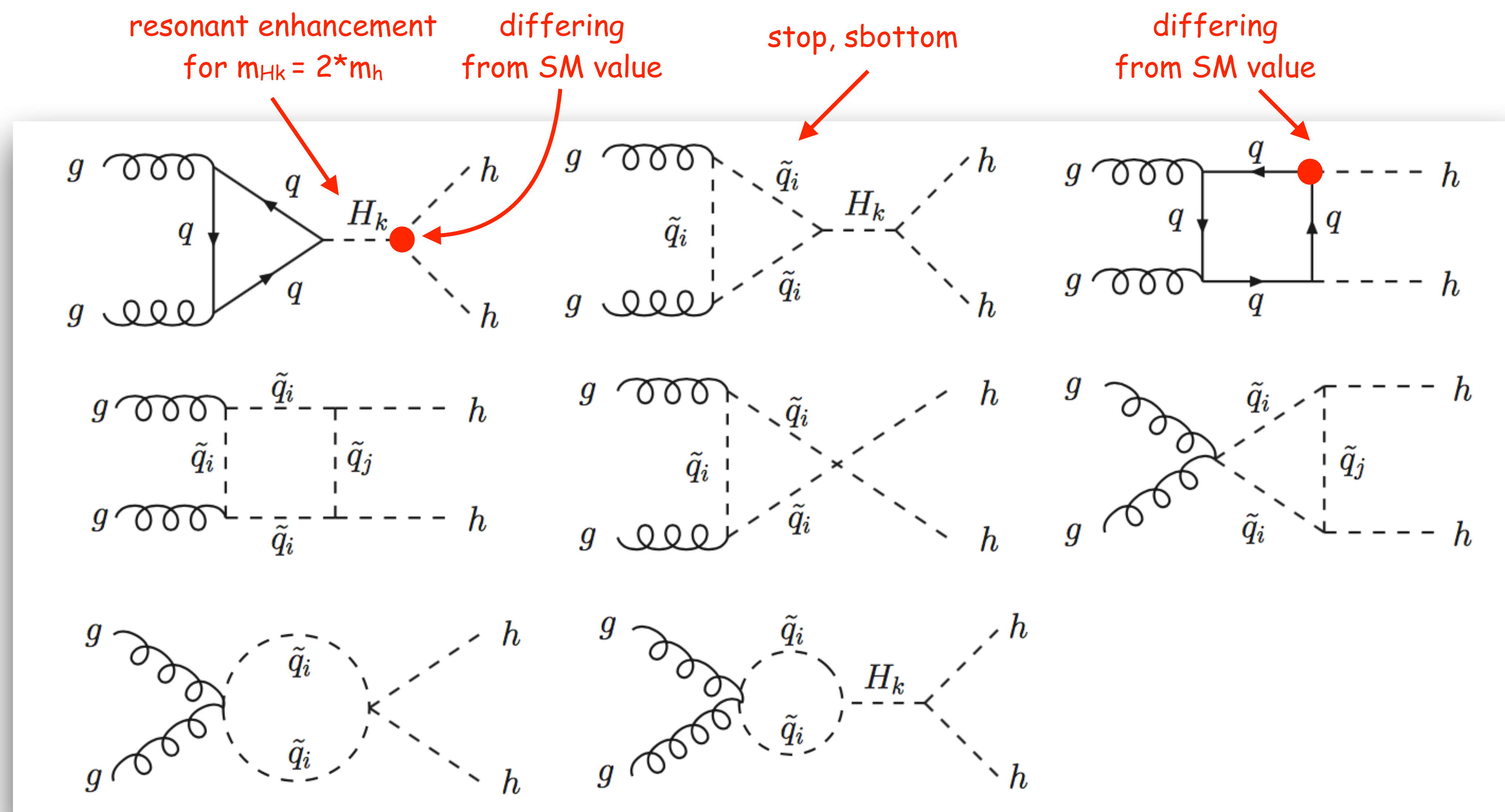
$$
\begin{aligned}
\kappa_\lambda = -10: &\quad \sigma_{tot} = 1680^{+13\%}_{-14\%}\ \text{fb} \\
\kappa_\lambda = -5: &\quad \sigma_{tot} = 598.9^{+13\%}_{-15\%}\ \text{fb} \\
\kappa_\lambda = -1: &\quad \sigma_{tot} = 131.9^{+11\%}_{-16\%}\ \text{fb} \\
\kappa_\lambda = 0: &\quad \sigma_{tot} = 70.38^{+8\%}_{-18\%}\ \text{fb} \\
\kappa_\lambda = 1: &\quad \sigma_{tot} = 31.05^{+6\%}_{-23\%}\ \text{fb} \\
\kappa_\lambda = 2: &\quad \sigma_{tot} = 13.81^{+3\%}_{-28\%}\ \text{fb} \\
\kappa_\lambda = 2.4: &\quad \sigma_{tot} = 13.10^{+6\%}_{-27\%}\ \text{fb} \\
\kappa_\lambda = 3: &\quad \sigma_{tot} = 18.67^{+12\%}_{-22\%}\ \text{fb} \\
\kappa_\lambda = 5: &\quad \sigma_{tot} = 94.82^{+18\%}_{-13\%}\ \text{fb} \\
\kappa_\lambda = 10: &\quad \sigma_{tot} = 672.2^{+16\%}_{-13\%}\ \text{fb}
\end{aligned}
$$


HH Production
Phenomenology

New Physics Effects in Higgs Pair Production

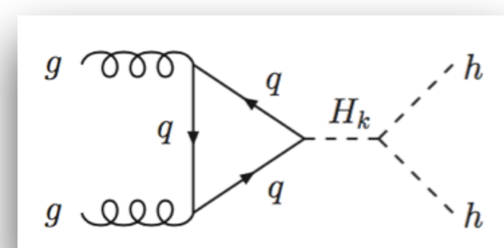
✦Cross section: - different trilinear couplings - different Yukawa couplings - novel particles in the loops - resonant enhancement - novel couplings

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



2HDM	C2HDM	N2HDM	NMSSM
2 Higgs doublets	CP-violating	Singlet extension	Supersymmetry
h,H,A,H^+,H^-	$H1,H2,H3,H^+,H^-$	$H1,H2,H3,H^+,H^-$	$H1,H2,H3,A,H^+,H^-$
SFOEWPT, DM, plus charged Higgs	plus CP violation baryogenesis	rich pheno, DM	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]

- Computation of Higgs pair production cxn:

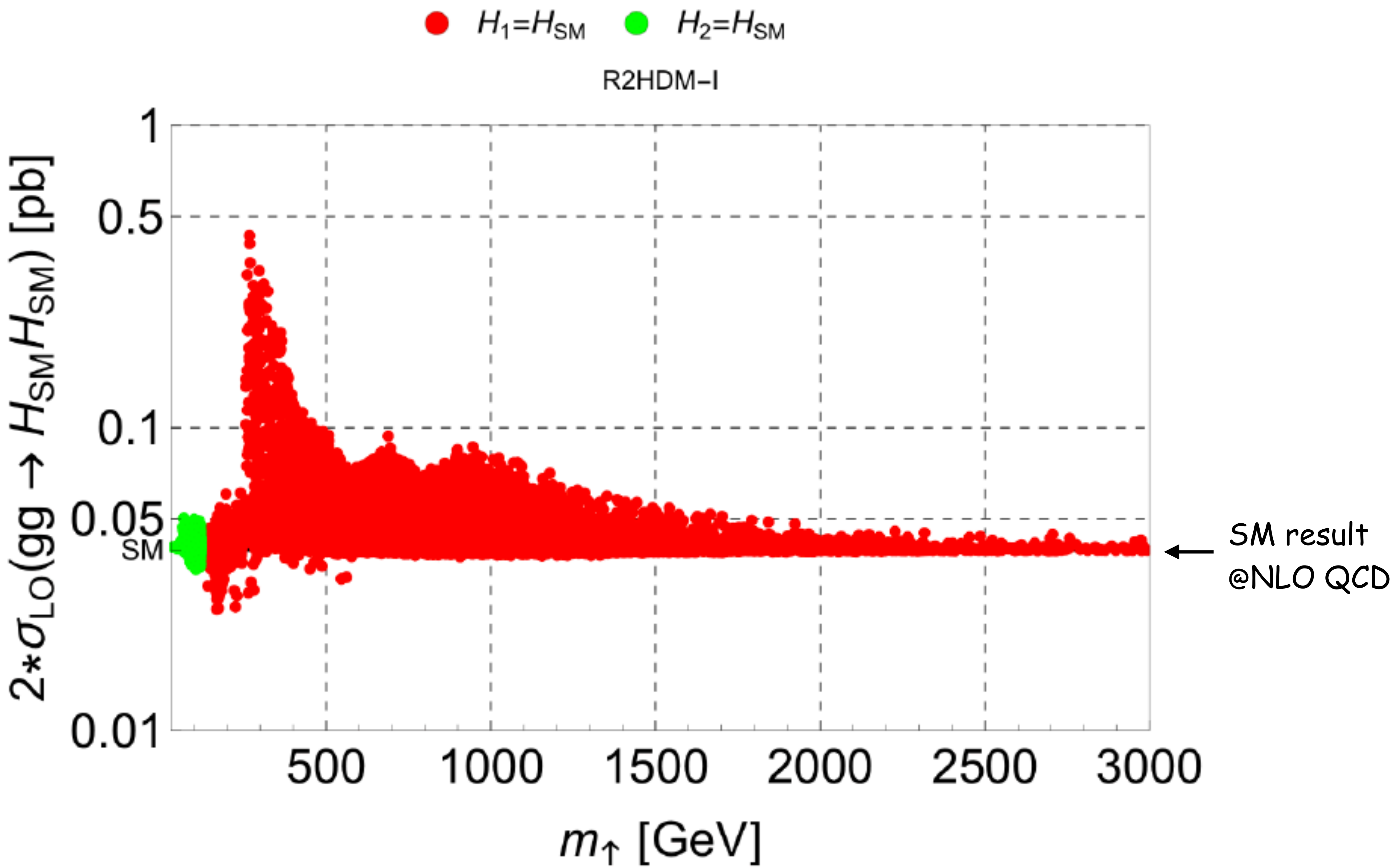
HPAIR [Spira] for C2HDM [Gröber,MM,Spira,'17], NMSSM [Dao,MM,Streicher,Walz,'13],
2HDM [MM], N2HDM [MM]: Born-improved HTL cxn; K-factors 1.4-2.1

- 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]



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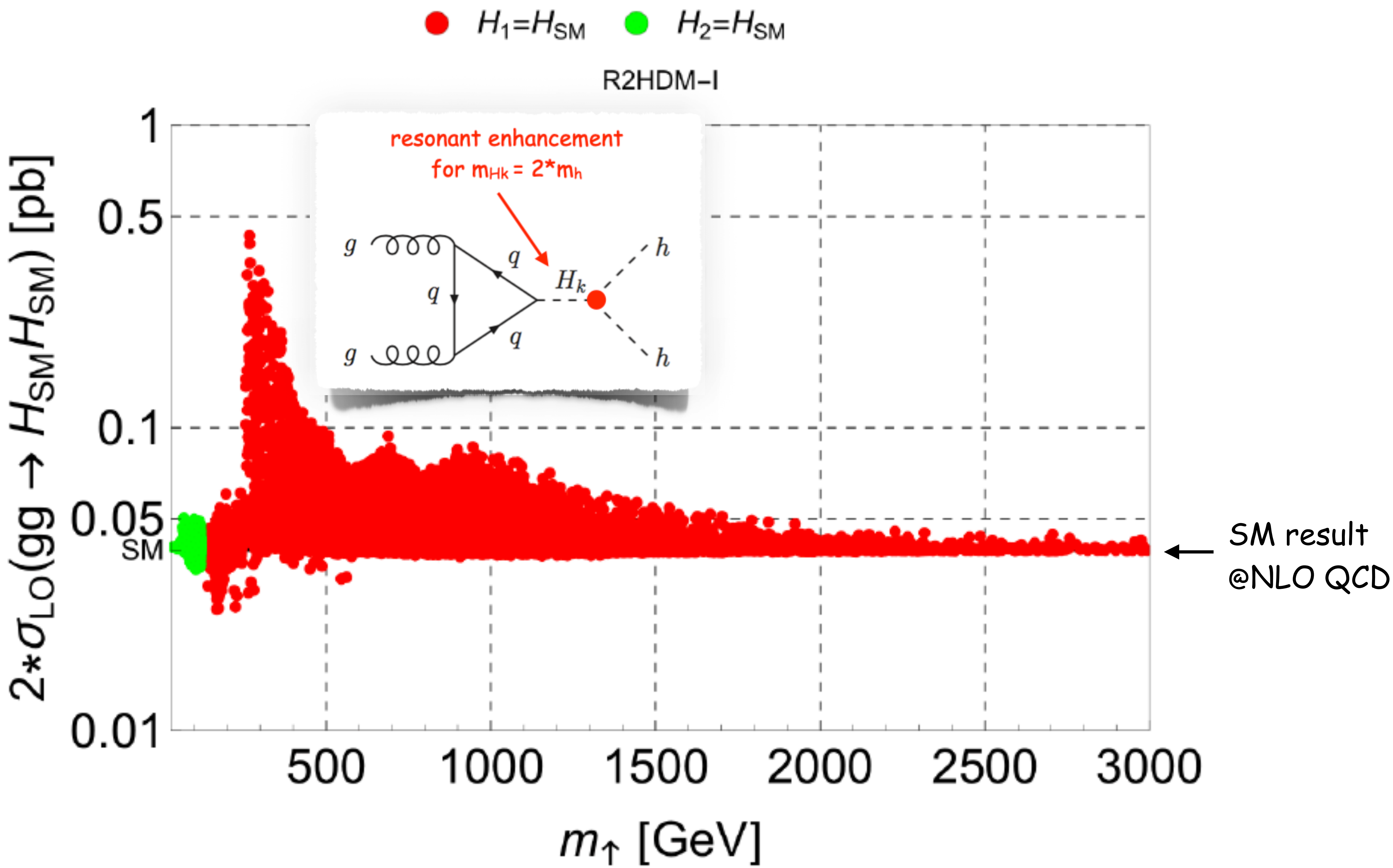
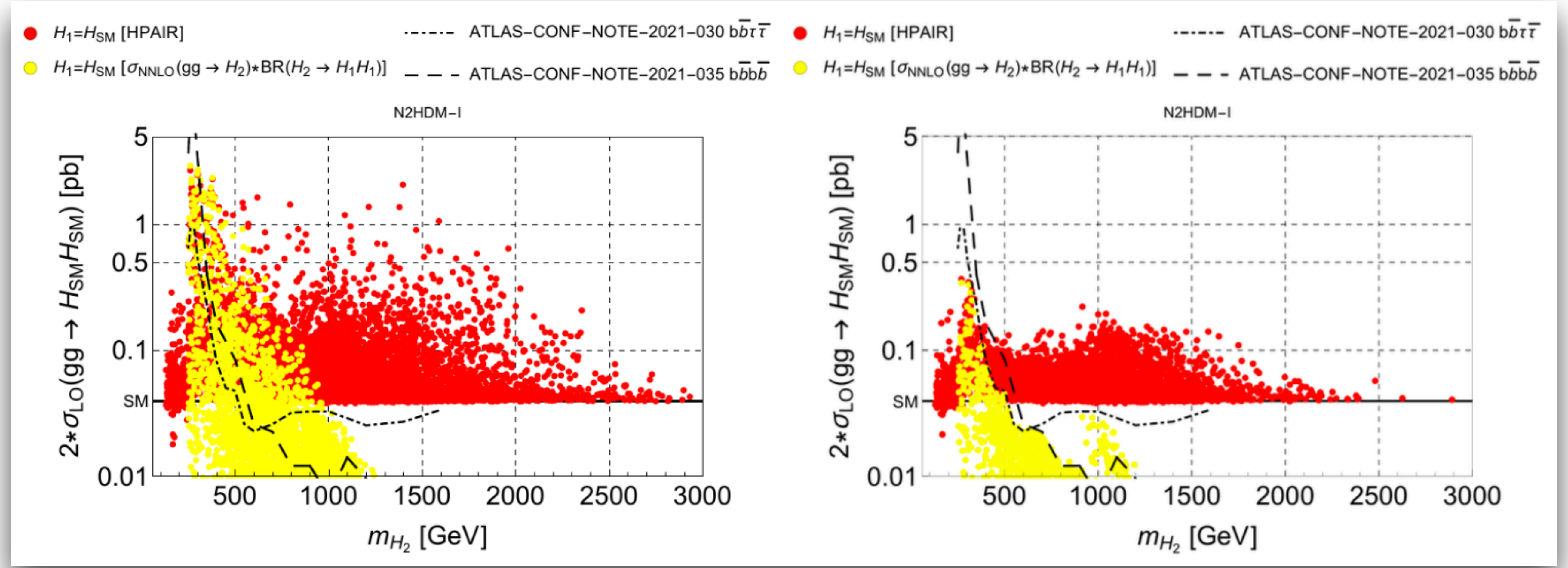


Impact of Constraints - Example N2HDM Type I H_{SM} H_{SM} Production

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

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



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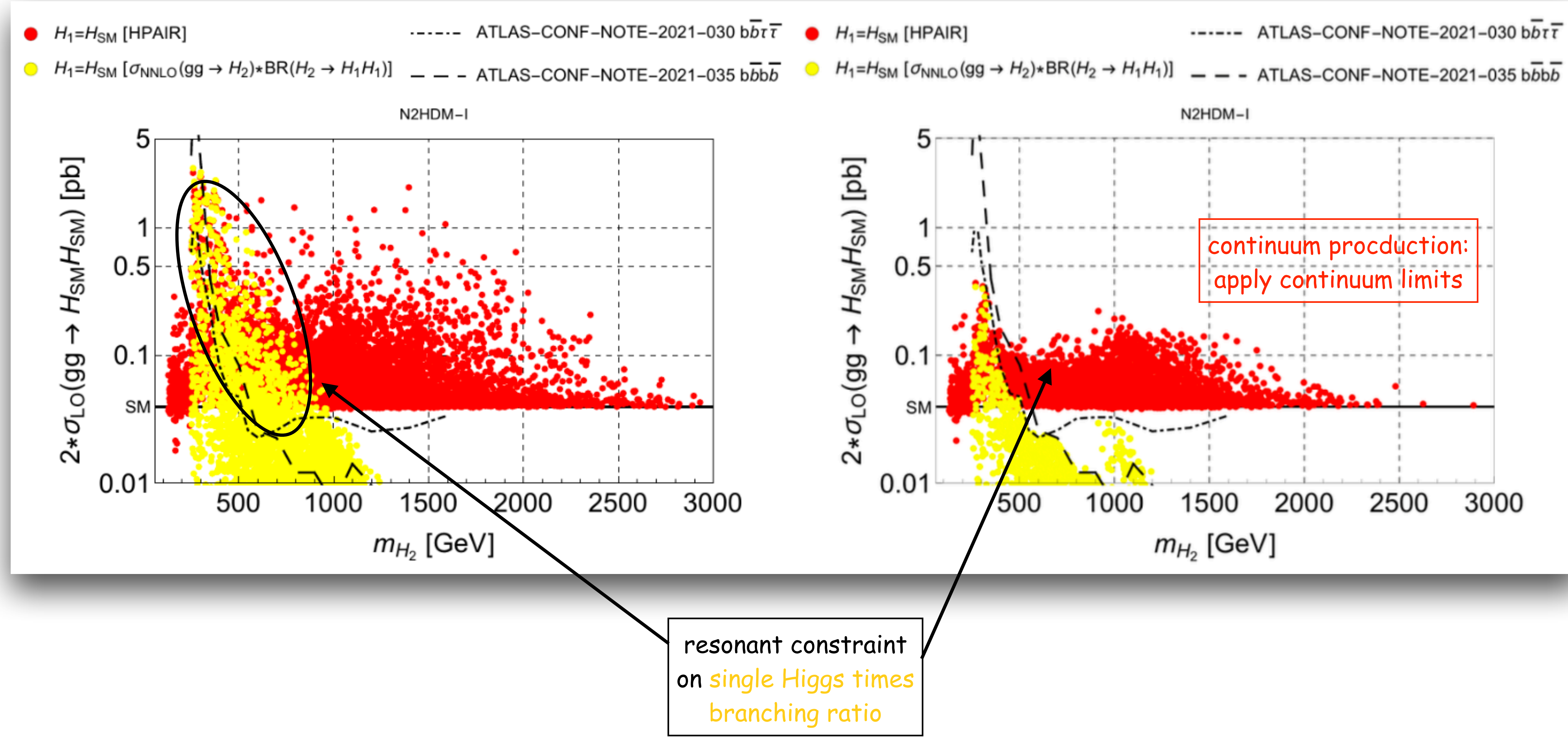
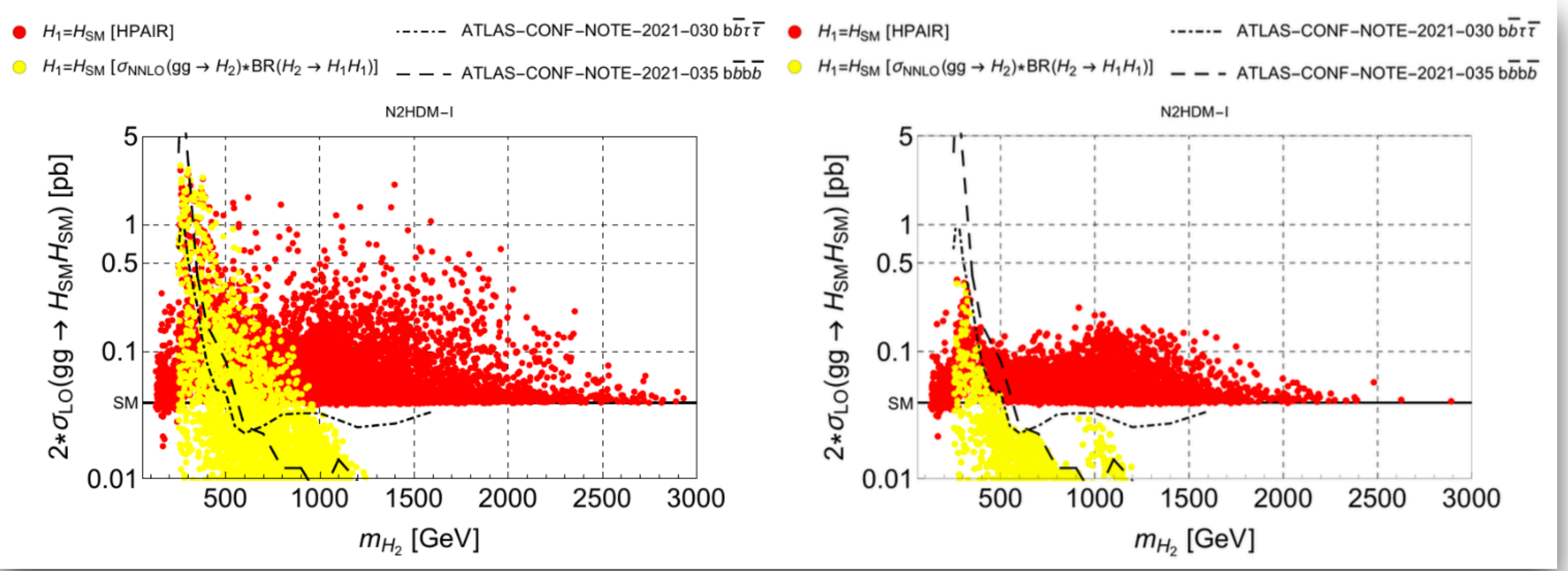


Impact of Constraints - Example N2HDM Type I $H_{SM} H_{SM}$ Production

[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

Single Higgs versus Di-Higgs Cascade Decays

- Singlet extended N2HDM, NMSSM: non-SM 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: $$\sigma^{\text{NLO}}_{H_1 H_2} \times \text{BR}(H_2 \to H_1 H_1) \times \text{BR}(H_1 \to b\bar{b})^3 = 509 \cdot 0.37 \cdot 0.60^3 \text{ fb} = 40 \text{ fb}$$

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

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

HH & Baryogenesis

- **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

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

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

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

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

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.

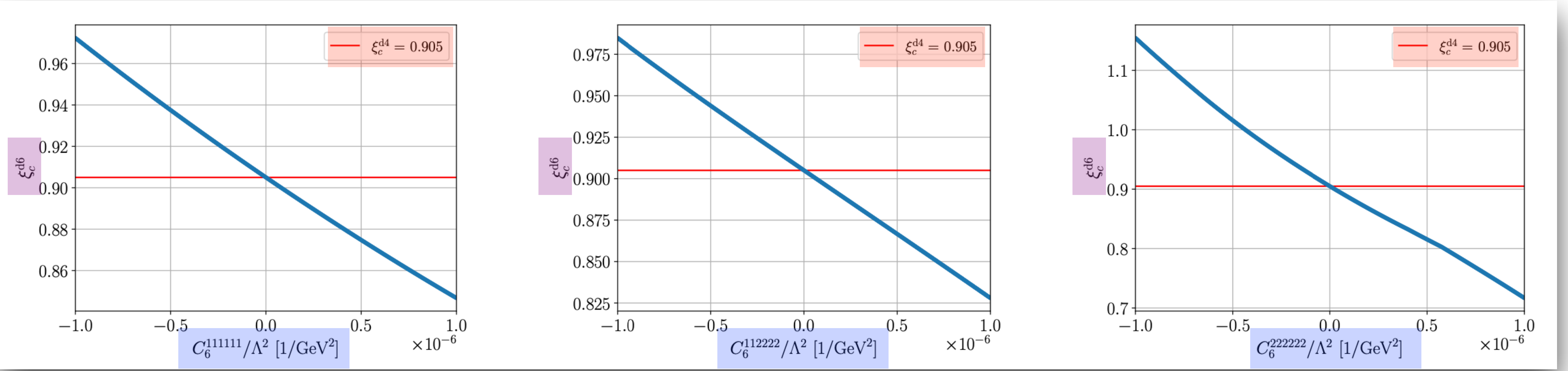
- absorb dim-6 contributions (to scalar masses) in shifts $\lambda_i \to \lambda_i + \delta\lambda_i$, $m_{12}^2 \to m_{12}^2 + \delta m_{12}^2$

$\Rightarrow$ 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

Effect of Dim-6 Operators

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



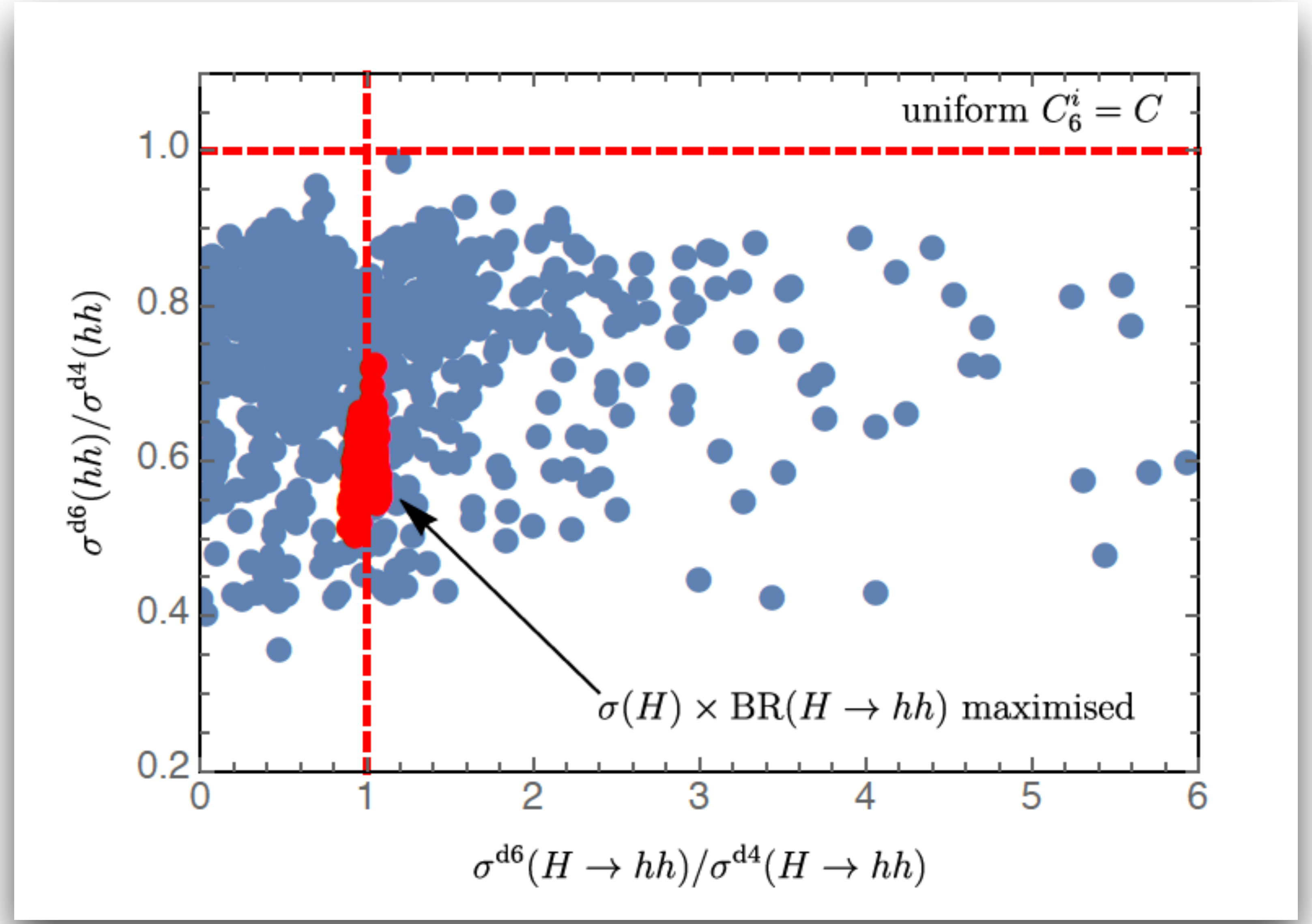
impact of individual Wilson coefficients on ξ_c^{d6} for $\xi_c^{d4} \cong 0.9$:

- 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

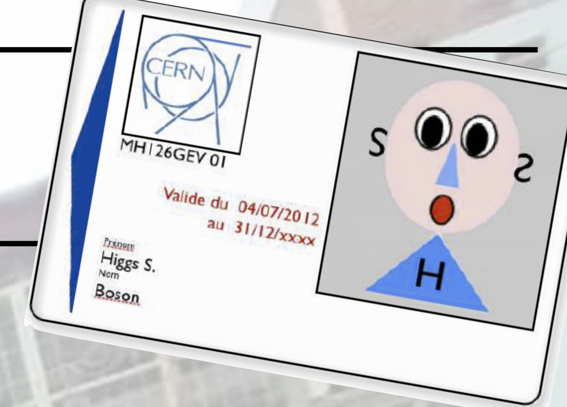
Correlation of ξ_c^{d4}, continuum and resonant hh production

[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%

Conclusions



✦ **Flaws of SM** call for new physics; no direct signs of new physics => Higgs boson

✦ **Combine results** of all available observables, precision important

✦ **Both QCD&EW corrections** are important; corrections can be more important in BSM models

✦ **Precision in HH**
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
resonant searches start testing BSM models in HH
interesting effects in singlet models: di-Higgs can beat single Higgs

✦ **Electroweak baryogenesis** requires strong first order EWPT
extension of 2HDM by scalar dim-6 operators can lead to SFOEWPT
can be probed through combination of resonant-non-resonant di-Higgs production

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

Thank you for your attention!