Precision Calculations in the Next-to-Minmal Supersymmetric Standard Model (NMSSM) and Phenomenological Implications

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CATCH22+2

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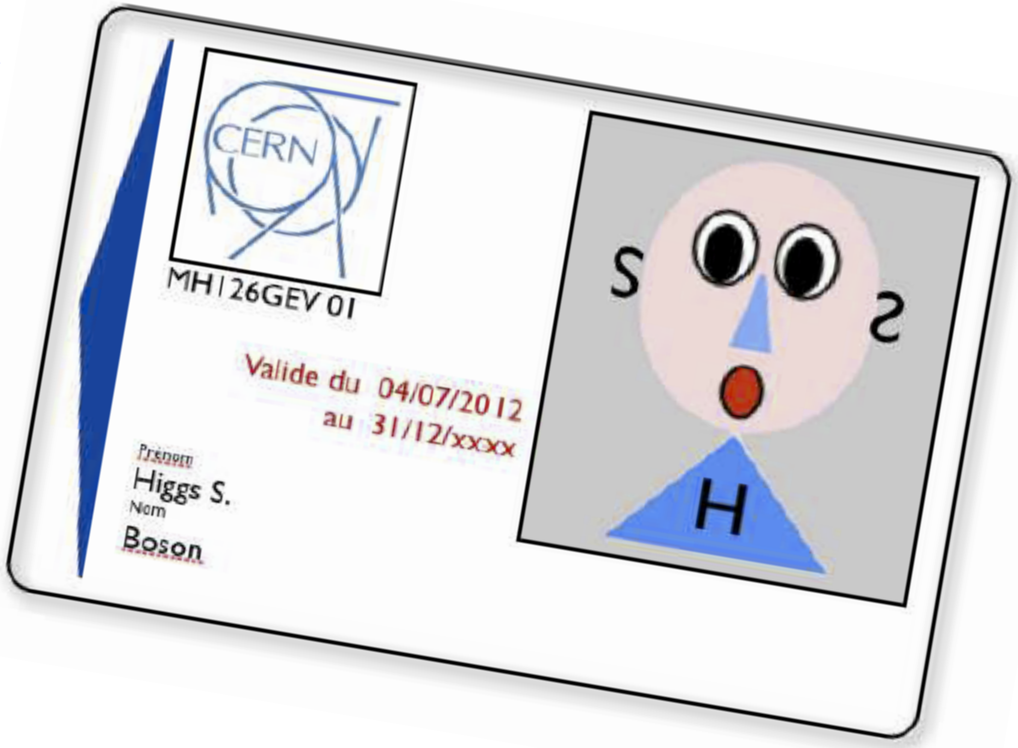
DIAS

Karlsruhe Institute of Technology

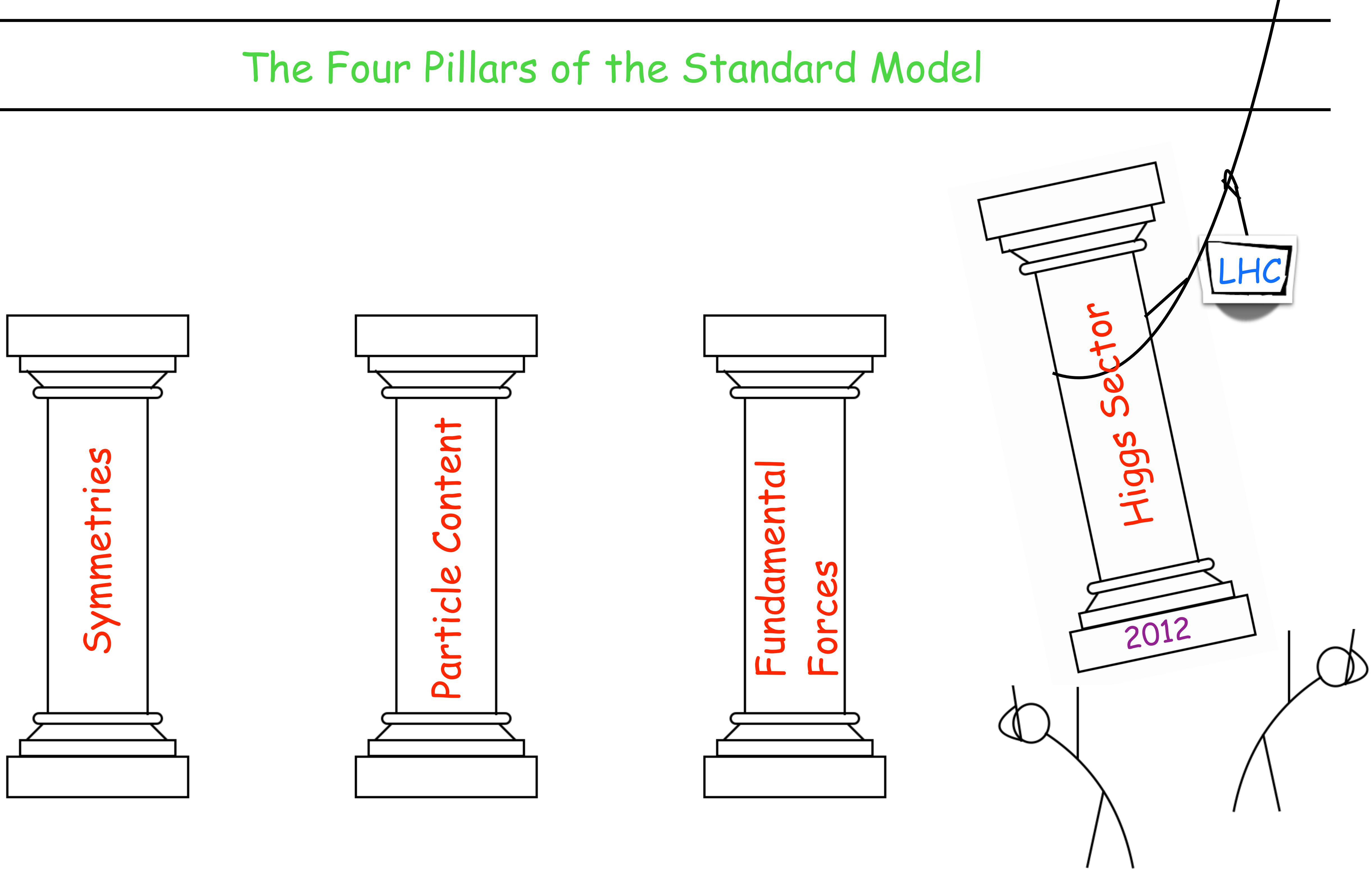
Institute for Theoretical Physics

Outline

- Introduction
- Higgs Mass Predictions in the CP-Violating NMSSM
  - fixed order
  - EFT approach
- $\mathcal{O}(\alpha_t(\alpha_s+\alpha_t))$ corrections to the trilinear Higgs self-coupling in the CP-violating NMSSM
  - impact on Higgs pair production
- Conclusions



The Four Pillars of the Standard Model



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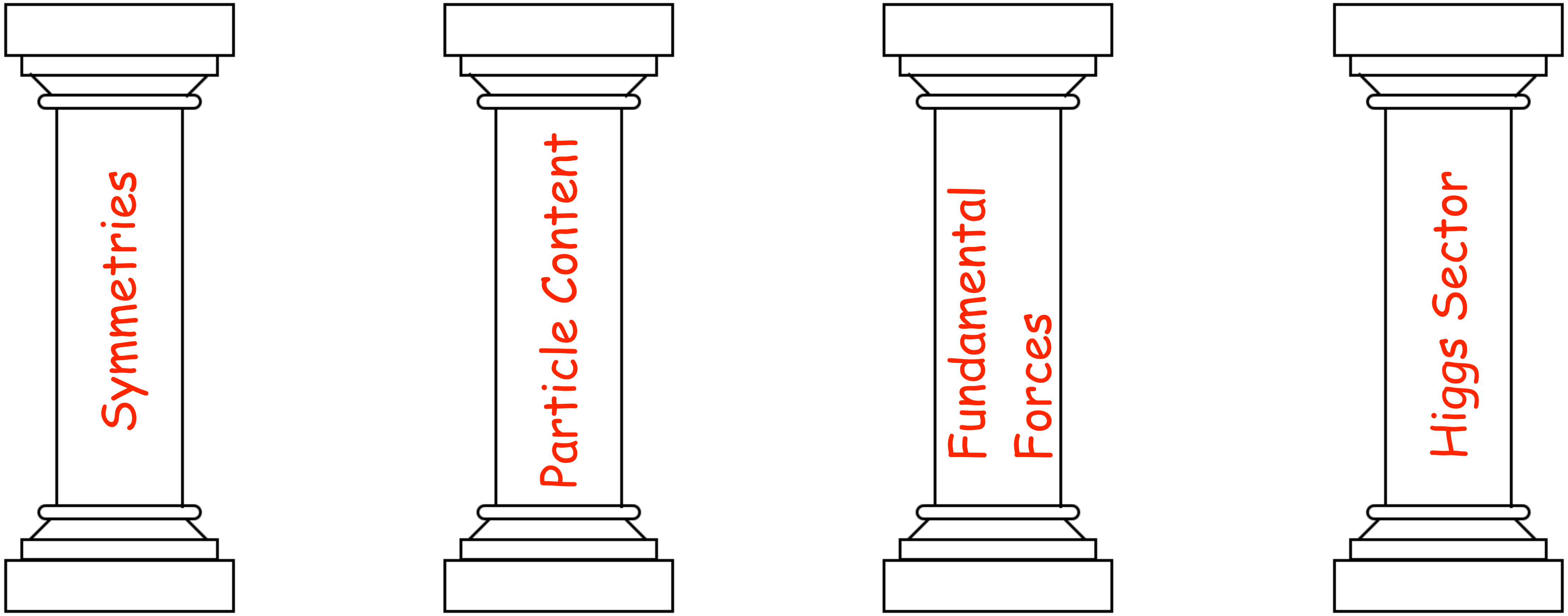
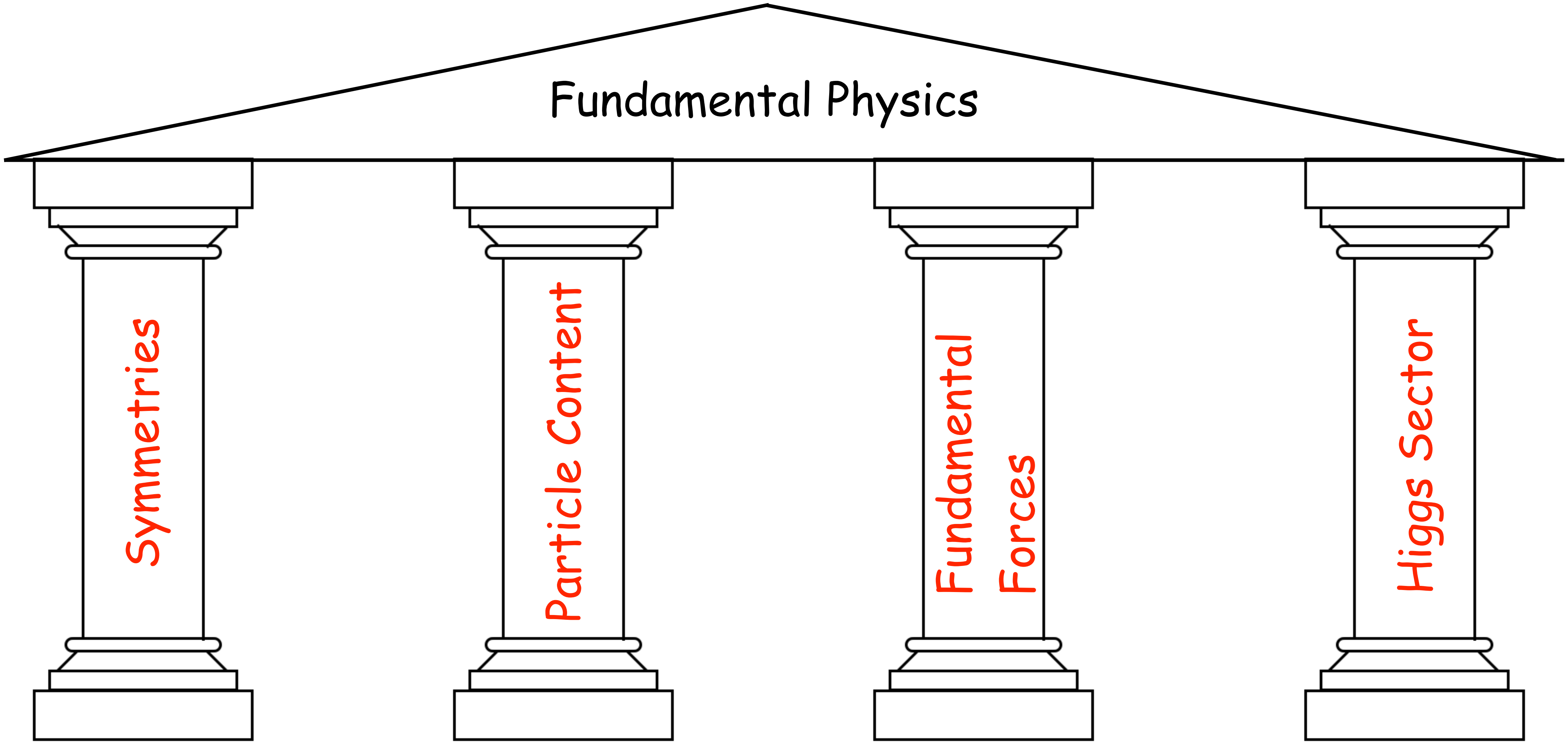
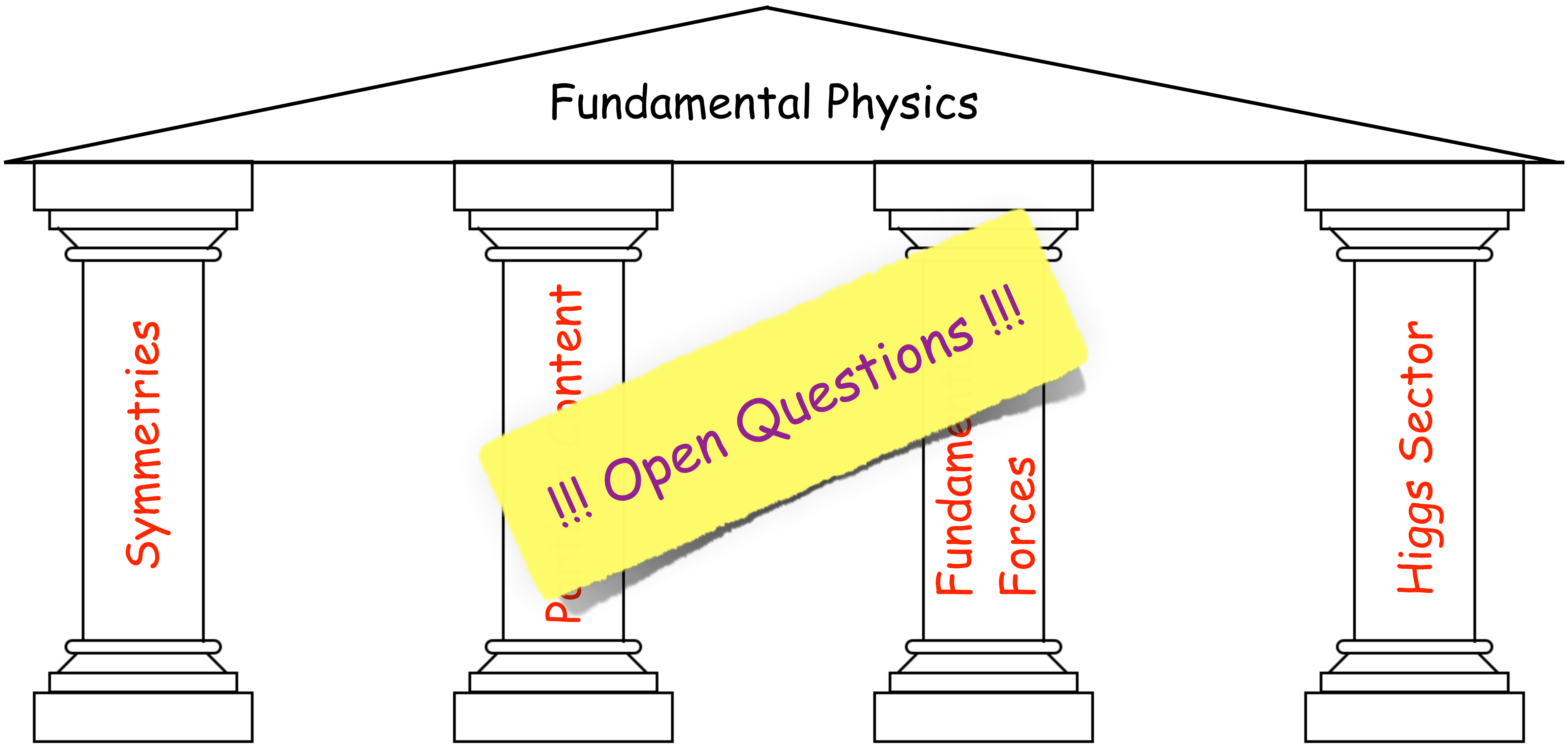
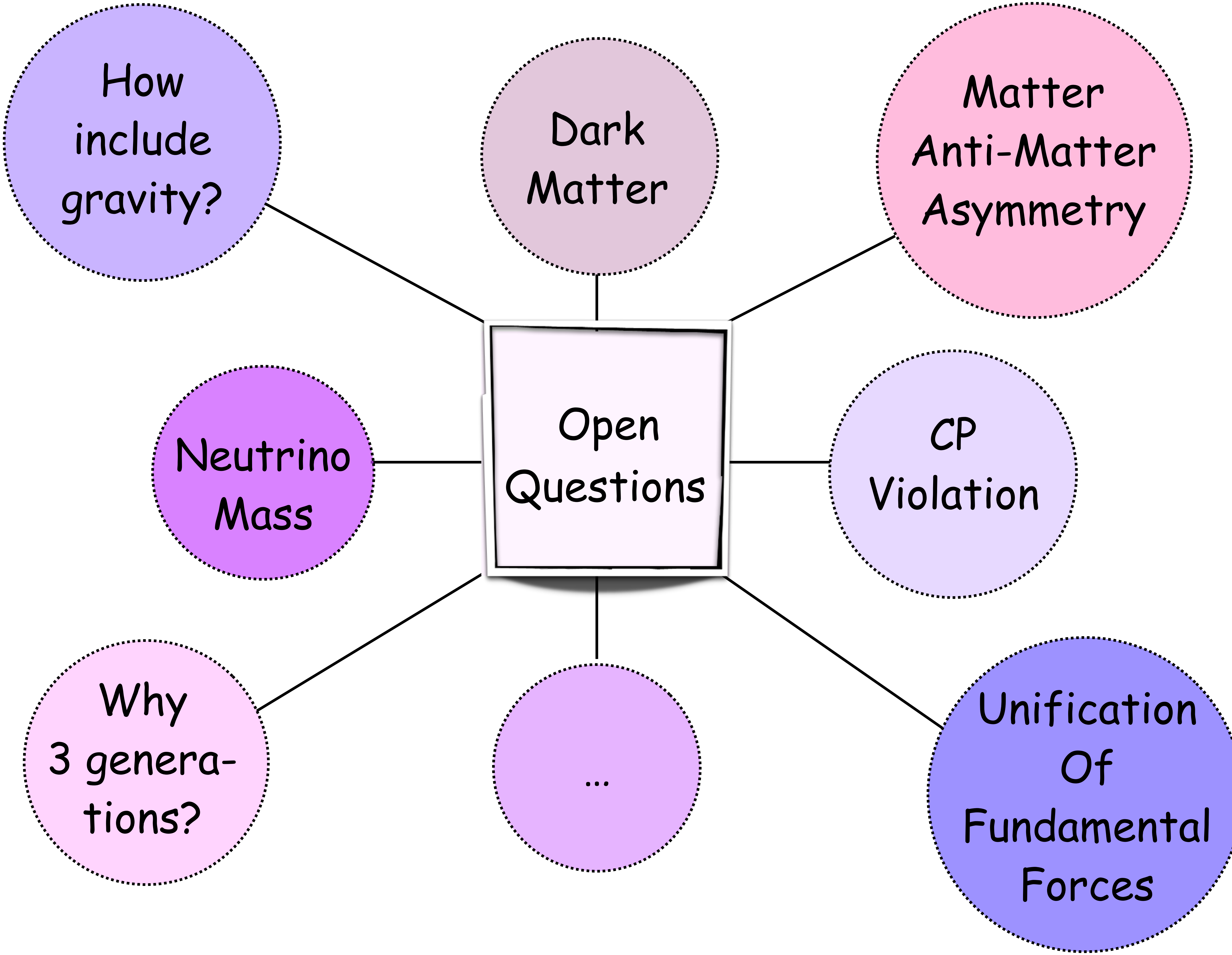


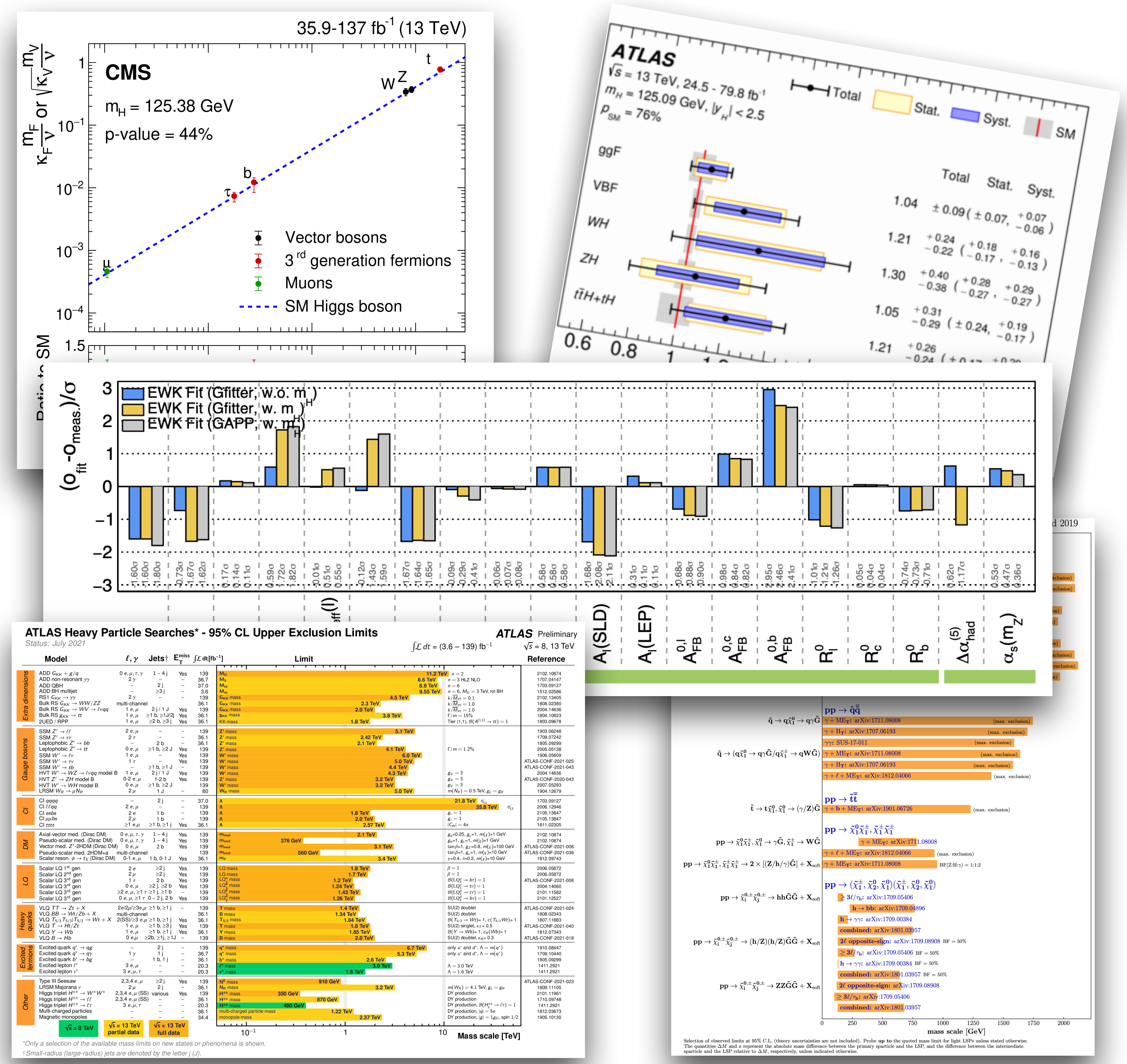
The Standard Model is Structurally Complete




Fundamental Physics
Symmetries
!!! Open Questions !!!
Forces
Higgs Sector


Open Questions
How include gravity?
Dark Matter
Matter Anti-Matter Asymmetry
Neutrino Mass
CP Violation
Why 3 genera-tions?
...
Unification Of Fundamental Forces

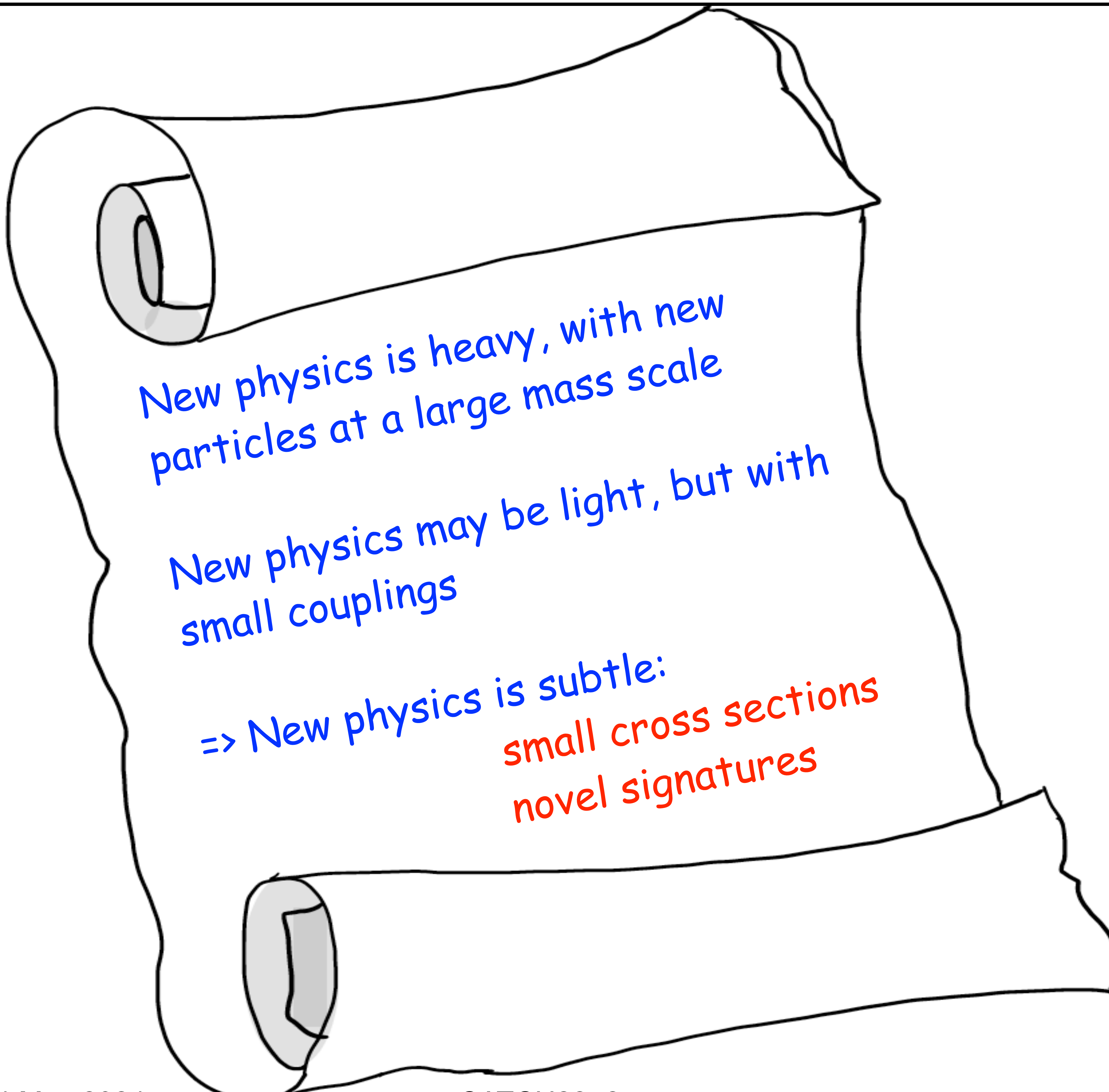
Status



Consistency Test
of the SM
at the quantum level

No direct discovery of
New Physics so far

Where is New Physics?



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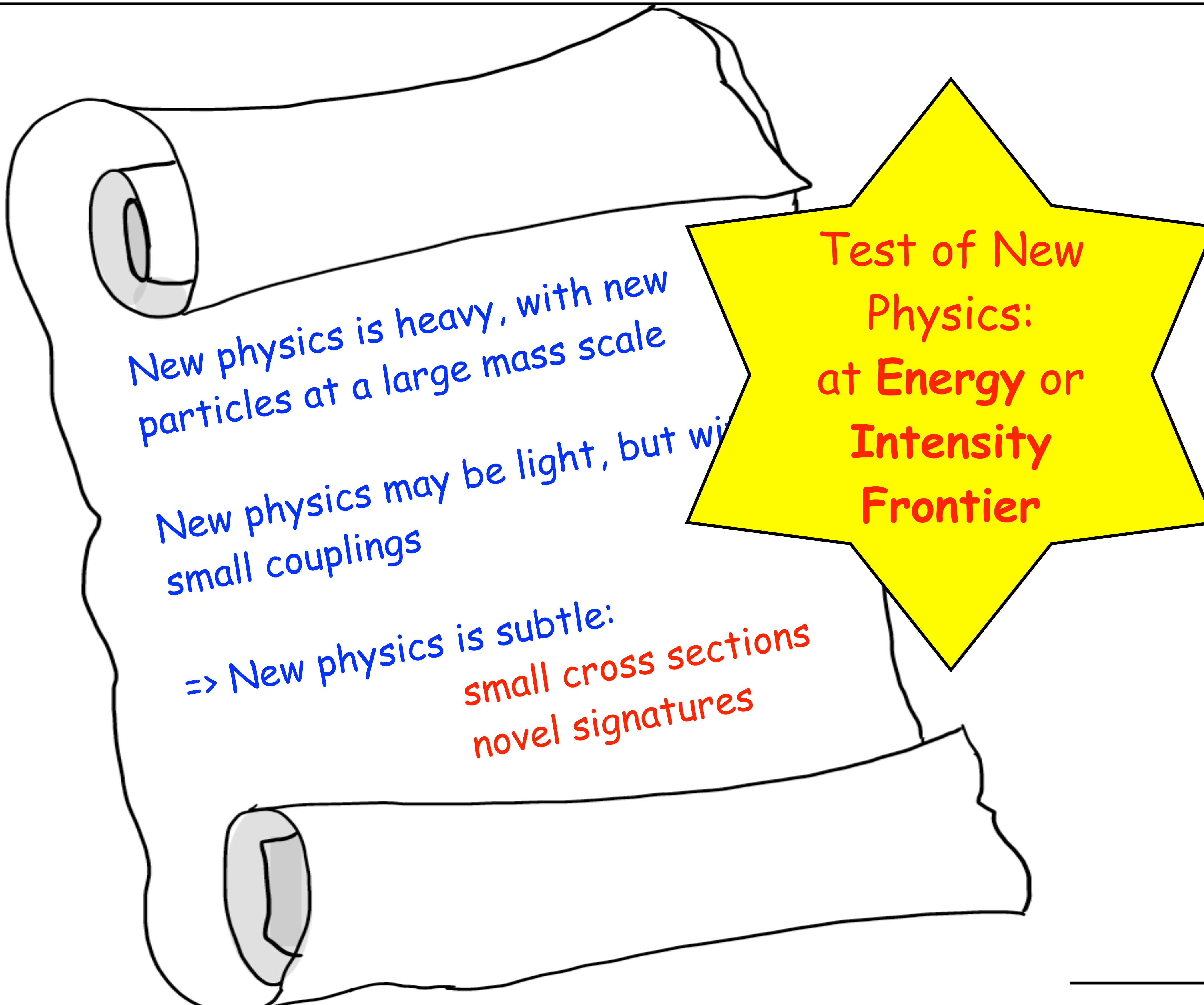

The Role of the Higgs Boson Mass

✦ 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

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indirect constraints on viable BSM parameter space

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 $(\Delta m_H)^2$ are important!

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

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SUSY2215

SUSY: THE NEW HOPE

- QUANTUM MECHANICS AND QFT STILL HOLD
- THE ORBITAL COLLIDER STILL SEES NOTHING

THREE CENTURIES OF TRIUMPH FOR SUSY AND STRINGS!

The seasonal trends

Extremely-weeny constrained SUSY

NSFWMSSM

FF3C10ACBA9-MSSM

MSSM retrograde

Anthropic landscaping and trimming it down

The problem of condensed matter: They still don't get it

Strings - The Perpetual Revolution

Number of free parameters: P or NP complete?

Invited seminar

How to ensure your model remains predictability-free

Forum

Is choice moral?

"Every time you choose a path of action, a multiverse is killed"

Special topic

If the universe is not supersymmetric is it necessarily existing?

The perpetual conference

5 Jan - 5 Mar: Chamonix

15 Mar - 30 June: Hainan Island

1 July - 15 Sep: Wailea, Maui

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Sponsored by:
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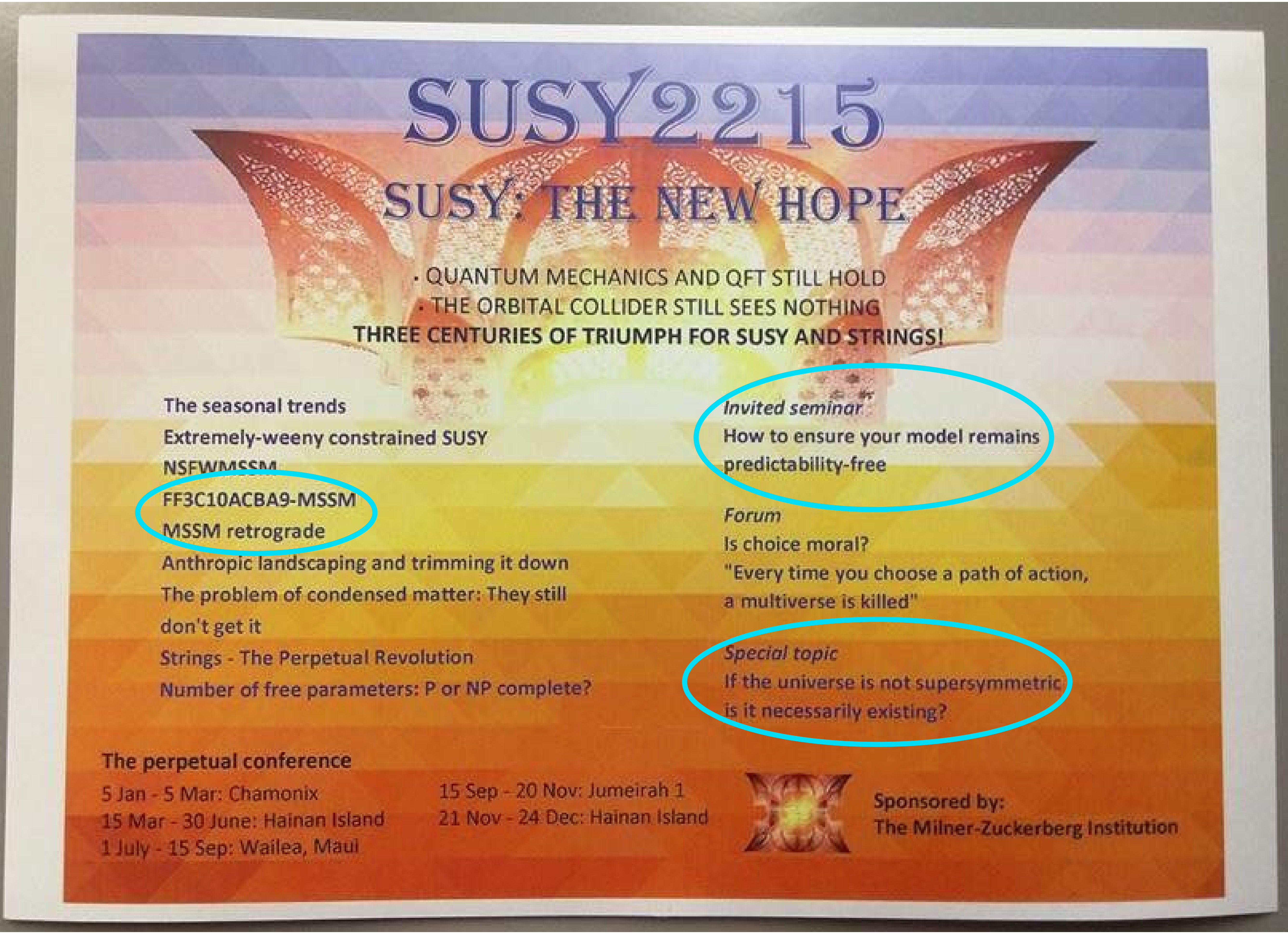
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BSM Example: Supersymmetry

✦ Motivation:

* maximal possible symmetry compatible with Poincaré group (space-time symmetry)
* solves some of the open problems of the SM:
  - candidate for Dark Matter
  - inclusion of gravity
  - unification of fundamental forces

Supersymmetry

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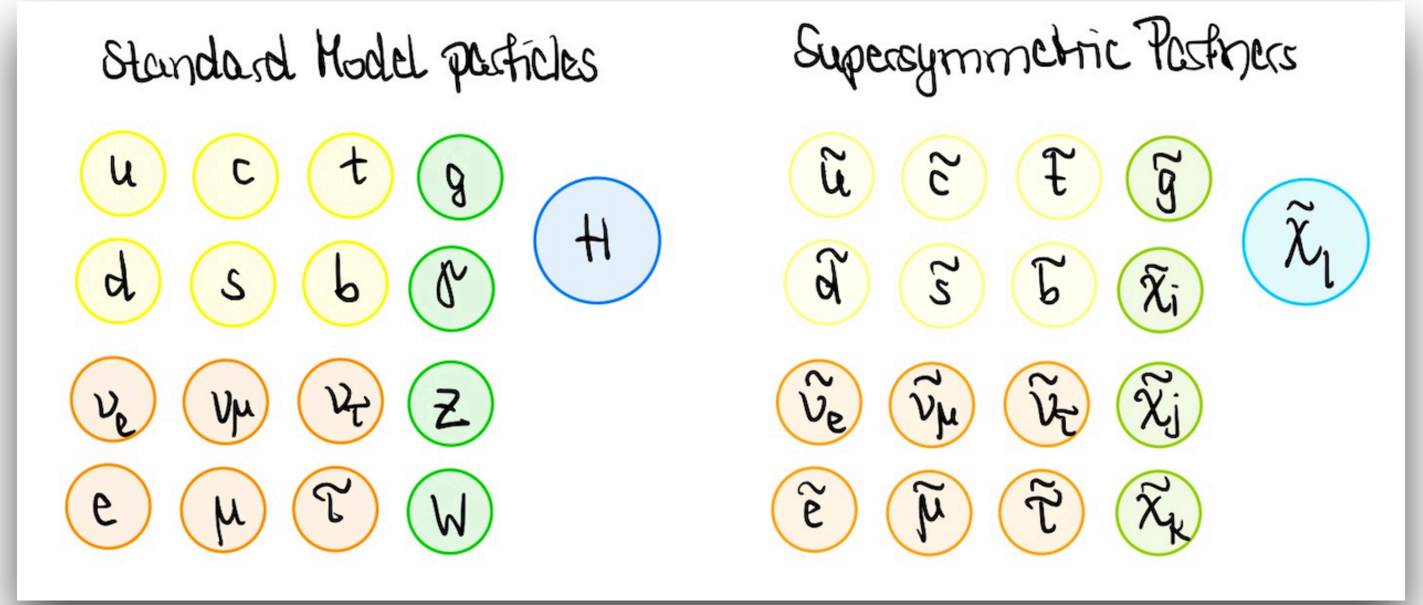
✦ Implications:

* enlarged particle spectrum: each SM particle has supersymmetric partner particle

* enlarged Higgs sector



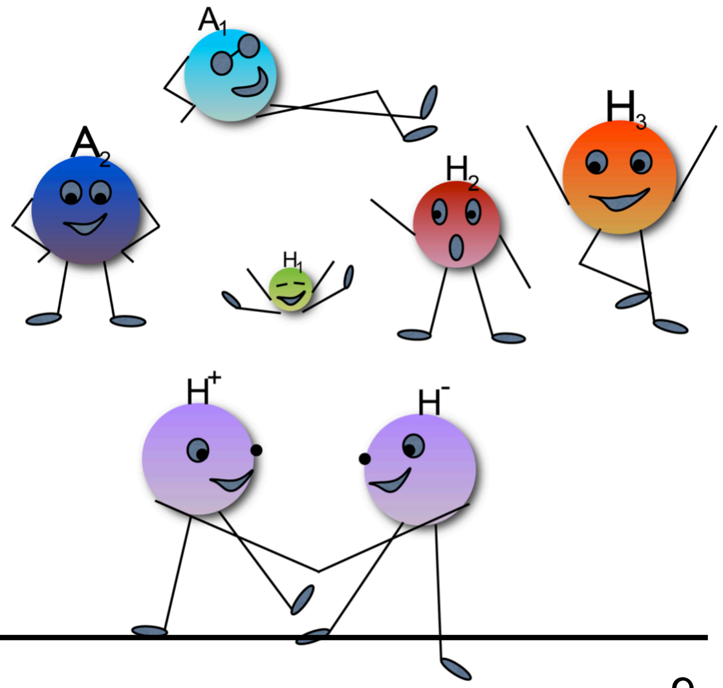
SUSY Higgs Spectrum

- **Supersymmetry:** 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:	$\tilde{\chi}_i^0 \; (i = 1, ..., 5)$



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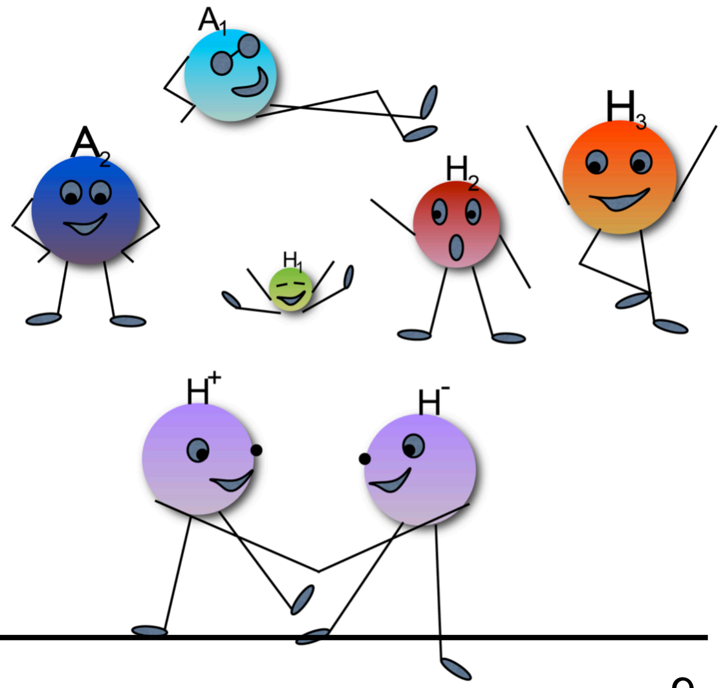

* less important loop corrections needed compared to the MSSM
* solves little hierarchy problem

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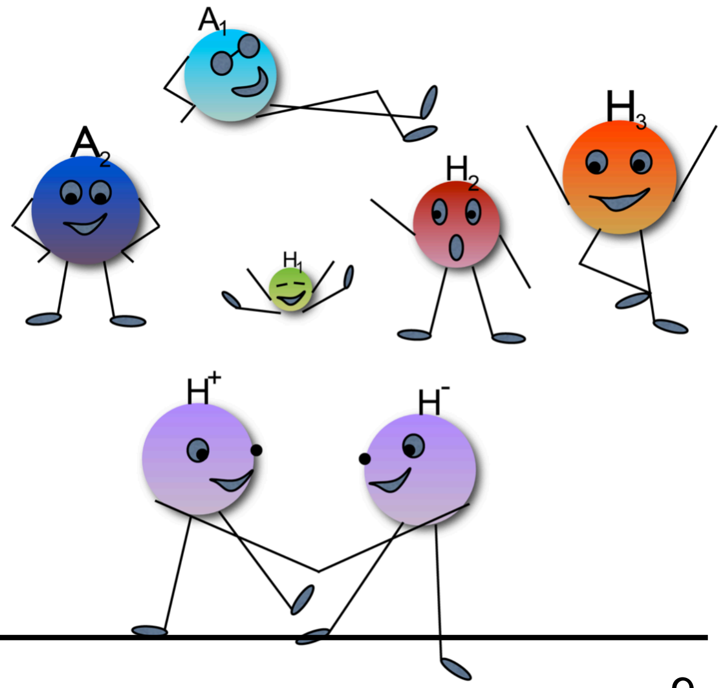

* less important loop corrections needed compared to the MSSM

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

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

Higgs Mass Predictions in the CP-Violating NMSSM

Spectrum Calculations

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

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

❖ Fixed-Order Calculations: exp. exclusion limits push SUSY masses to high scales

~> terms ~ $y_x \ln(M_{Sx}/M_x)$ with y_x Yukawa coupling, M_x (M_{Sx}) mass of (SUSY partner) particle

most important contribution from top/stop sector ~> large hierarchy~> large logs ~> resummation!

needed for reliable results

❖ EFT calculations: full theory matched to to effective low-energy theory at high-scale;
RGE running from high scale to EW scale resums large logs

Spectrum Calculations

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- FO: full (N)MSSM perturb. series truncated at fixed order reliable for not too heavy SUSY masses
- EFT: some very heavy SUSY masses: large logarithms require resummation
- hybrid: 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^{2}LL (included in calculators), N^{3}LL

Hybrid: FeynHiggs, FlexibleEFTHiggs, N^{3}LO+N^{3}LL QCD corrections [Harlander,Klappert,Voigt,´19]

❖ Status NMSSM spectrum calculations:

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

EFT: matching to quartic coupling in NMSSM w/ all BSM particles at TeV scale

e.g. [Gabelmann,MM,Staub,´18,´19][Bagnaschi eal,´22]

Hybrid: FlexibleEFTHiggs, SARAH+SPheno

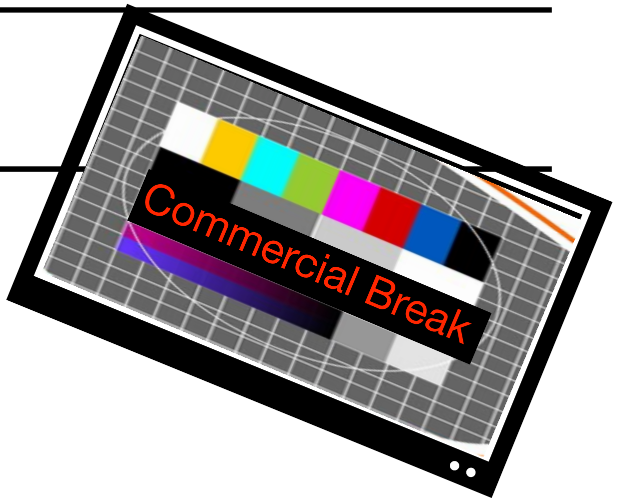
NMSSM Spectrum Calculators

- FlexibleSUSY [Athron,Bach,Harries,Kotlarski,Kwasnitza,Park,Stöckinger,Voigt,Ziebell]: DR, FO & hybrid, through FlexibleEFTHiggs
- NMSSMCALC:[Baglio,Borschensky,Dao,Gabelmann,Gröber,Krause,Le,MM,Rzehak,Spira,Streicher,Walz]: FO, real & complex NMSSM, DR and mixed OS-DR
- NMSSMTools [Ellwanger,Gunion,Hugonie]: FO, DR scheme
- SOFTSUSY [Allanach,Athron,Bednyakov,Tunstall,Voig,RuizdeAustri,Williams]: FO, DR scheme
- SPheno [Porod,Staub]: FO, DR scheme, quartic and pole mass matching

Remarks:

- comparison of codes in DR scheme: [Staub,Athron,Ellwanger,Gröber,MM,Slavich,Voigt,'15] FlexibleSUSY,NMSSMCALC,NMSSMTools, SOFTSUSY,SPheno
- comparison of codes in mixed OS-DR scheme: [Drechsel,Gröber,Heinemeyer,MM,Rzehak,Weiglein,'16] FeynHiggs, NMSSMCALC
- solution of Goldstone boson catastrophe [Braathen,Goodsell,´16], [Braathen,Goodsell,Staub,'17]
- advances in FeynHiggs: [Drechsel,Galeta,Heinemeyer,Hollik,Liebler,Moortgat-Pick,Paßehr,Weiglein] real&complex NMSSM, GNMSSM: 1-loop in, 2-loop&resummation of HO log-effects only in MSSM limit, no public code yet
- OS masses CP-violating NMSSM, consistent description production/decay [Domingo,Drechsel,Paßehr]

The Code NMSSMCALC



Implementation of mass corrections in our code NMSSMCALC
[Baglio,Borschensky,Dao,Gabelmann,Gröber,Krause,MM,Le,Rzehak,Spira,Streicher,Walz]

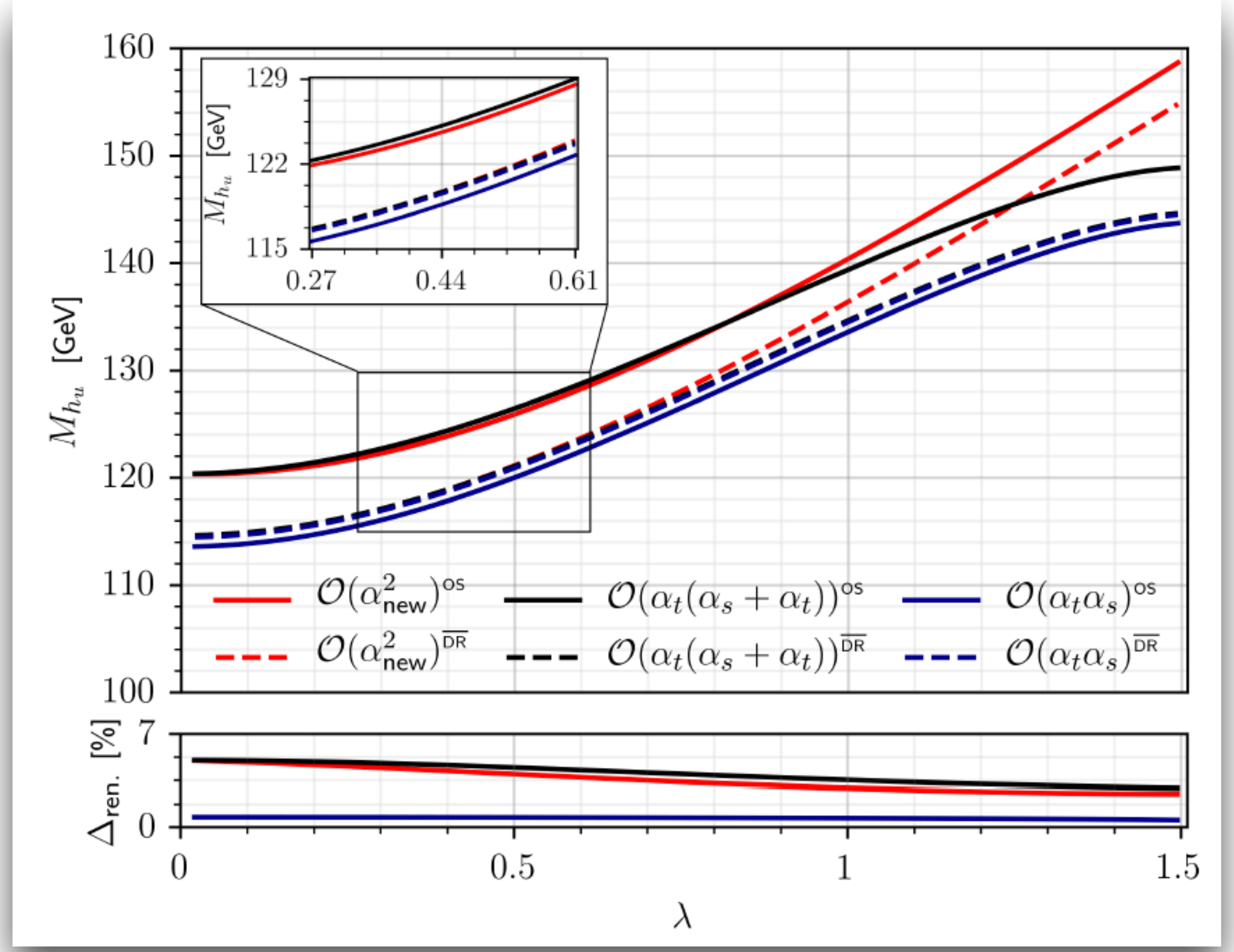
One-loop masses [Ender,Graf,MM,Rzehak,'12], [Graf,Gröber,MM.Rzehak,Walz,'12]
Two-Loop $\mathcal{O}(\alpha_t\alpha_s)$ [MM,Nhung,Rzehak,Walz,'15]
Two-Loop $\mathcal{O}(\alpha_t+\alpha_t\alpha_s)$ [Dao,Gröber,Krause,MM,Rzehak,'19]
Two-Loop $\mathcal{O}((\alpha_t+\alpha_\lambda+\alpha_\kappa)^2 + \alpha_t\alpha_s)$ [Dao,Gabelmann,MM,Rzehak,'21]

The Fortran Code NMSSMCALC:

- Calculator of one- and two-loop Higgs mass corrections and Higgs self-couplings as well as of Higgs decay widths in the CP-conserving and CP-violating NMSSM
- Computation of the muon magnetic and the electric dipole moment
- Computation of the rho parameter and the W mass prediction up to two-loop EW NMSSM

$\mathcal{O}(\alpha_{new}^2) \equiv \mathcal{O}((\alpha_\lambda+\alpha_\kappa+\alpha_t)^2+\alpha_t\alpha_s)$ 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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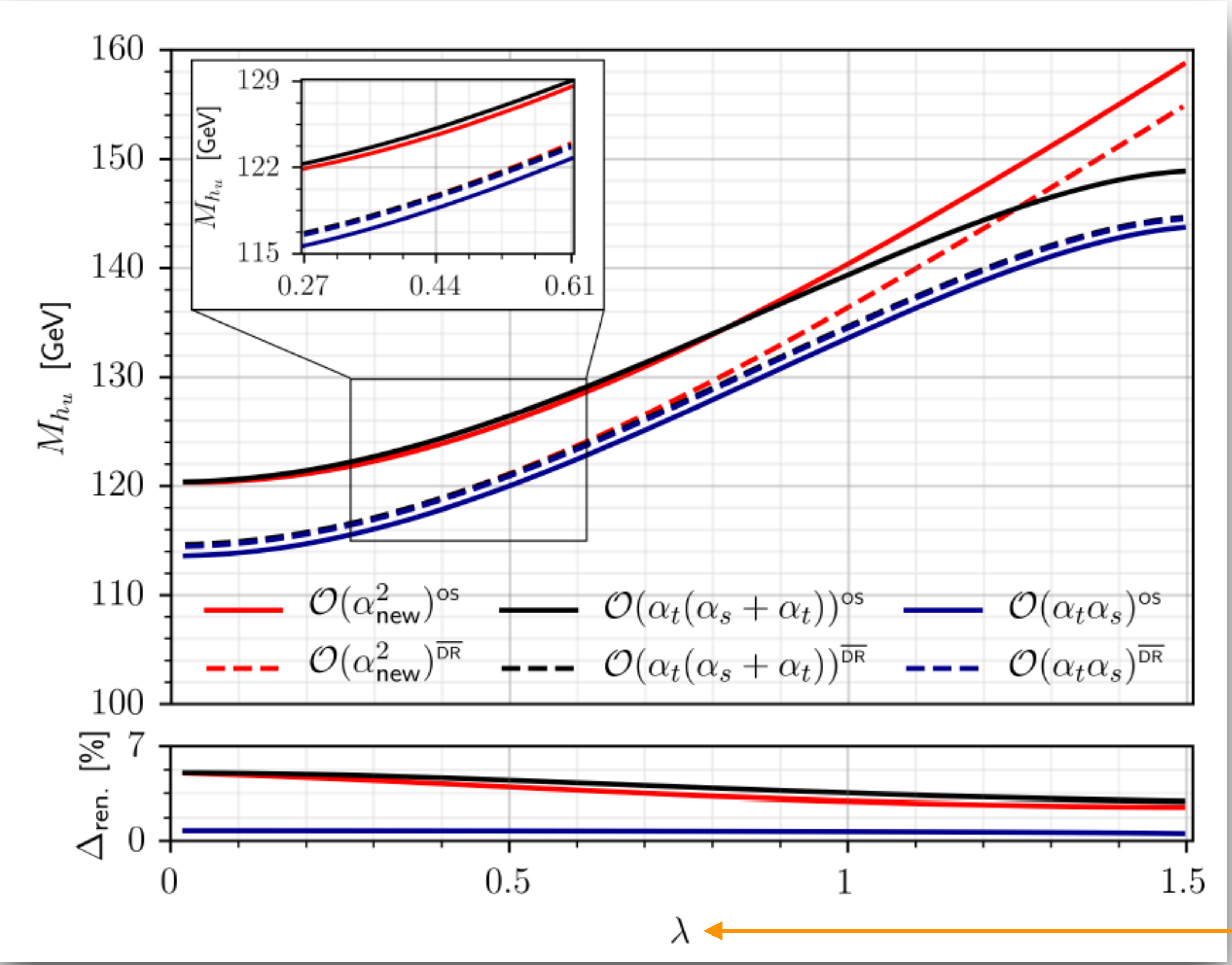

NMSSM specific couplings **λ, κ** related to new singlet field in superpotential

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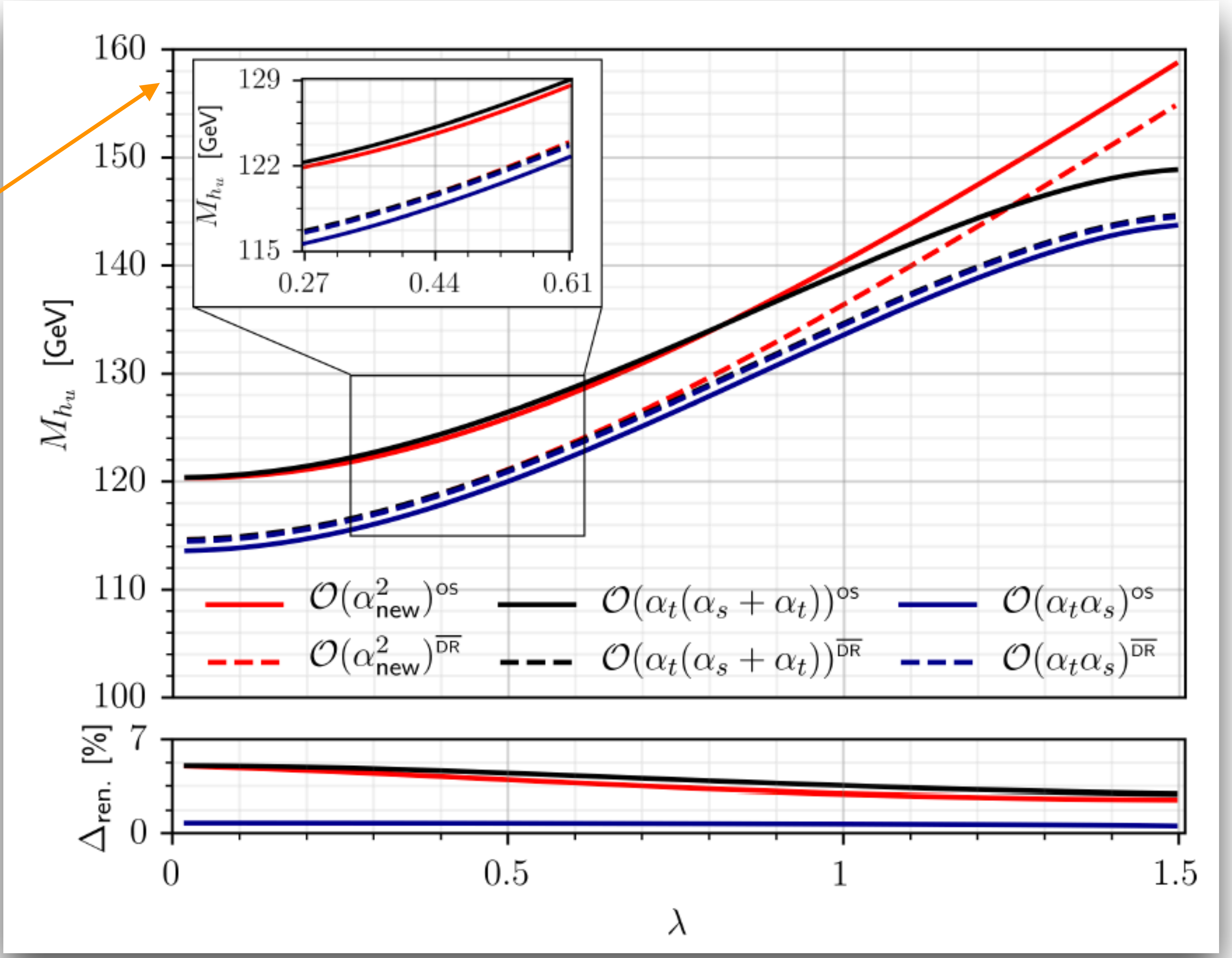
Zoomed: compatible w/ HiggsSignals after including the new correction



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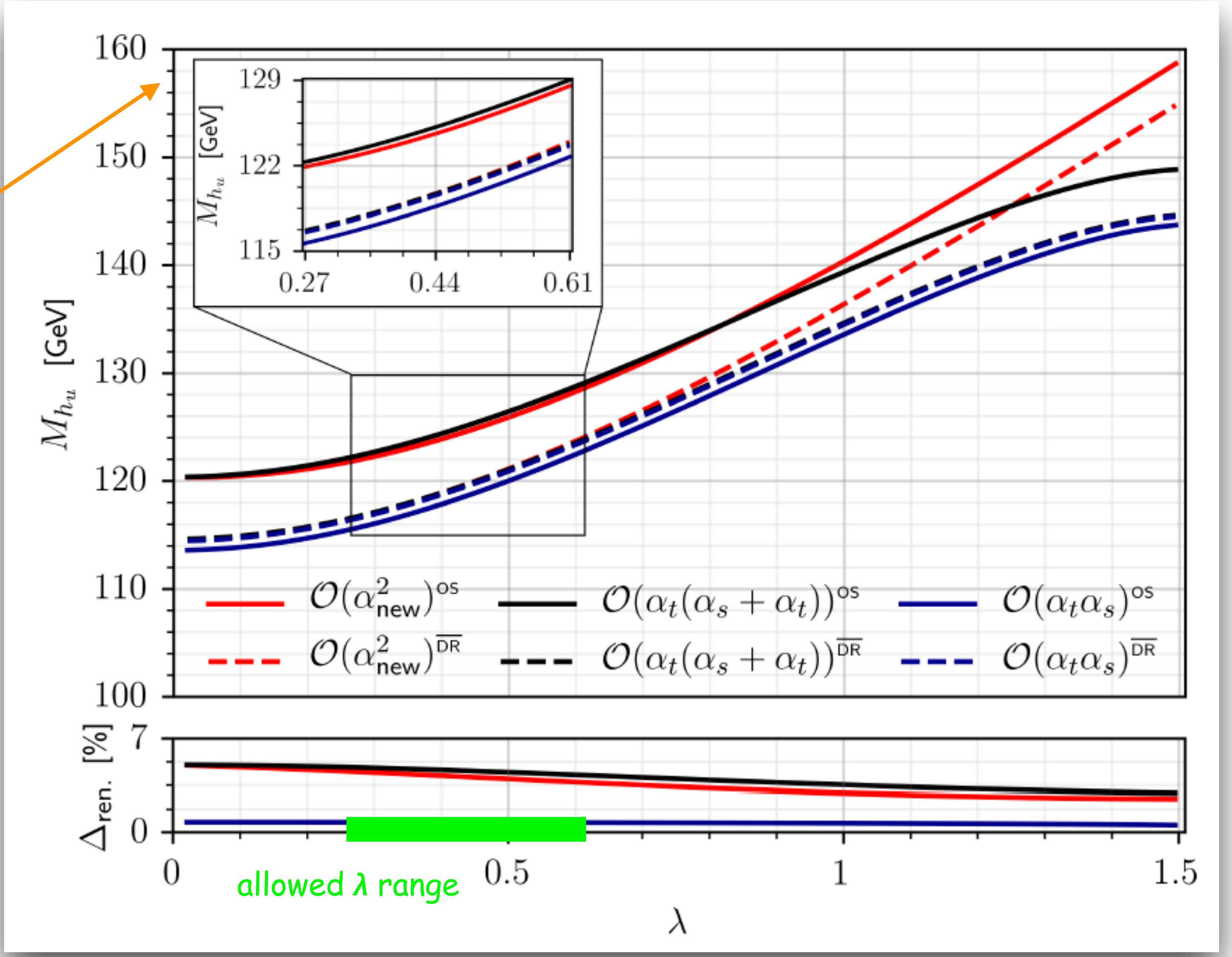

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EFT Approach

Spectrum Calculations - EFT Approach

❖ 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
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❖ EFT calculations, Matching:

- SUSY couplings matched to corresponding couplings in EFT theory such that physics at matching scale μ_R is the same
- In case we have only SM particles plus heavy SUSY particles:
  EFT is the SM => $\lambda_{SM}(\mu_R) = \lambda_{BSM}(\mu_R)$ [receives only BSM contributions]
- We have terms like $y_x \ln(M_{Sx}/M_x)$, respectively $y_x (\ln(M_{Sx}/\mu_R^2) + \ln(\mu_R^2/M_x^2))$, with $\mu_R=M_{Sx}$ =>
  $y_x \ln(\mu_R^2/M_x^2)$ <= resummed via RGEs for y_x

Quartic Coupling Matching

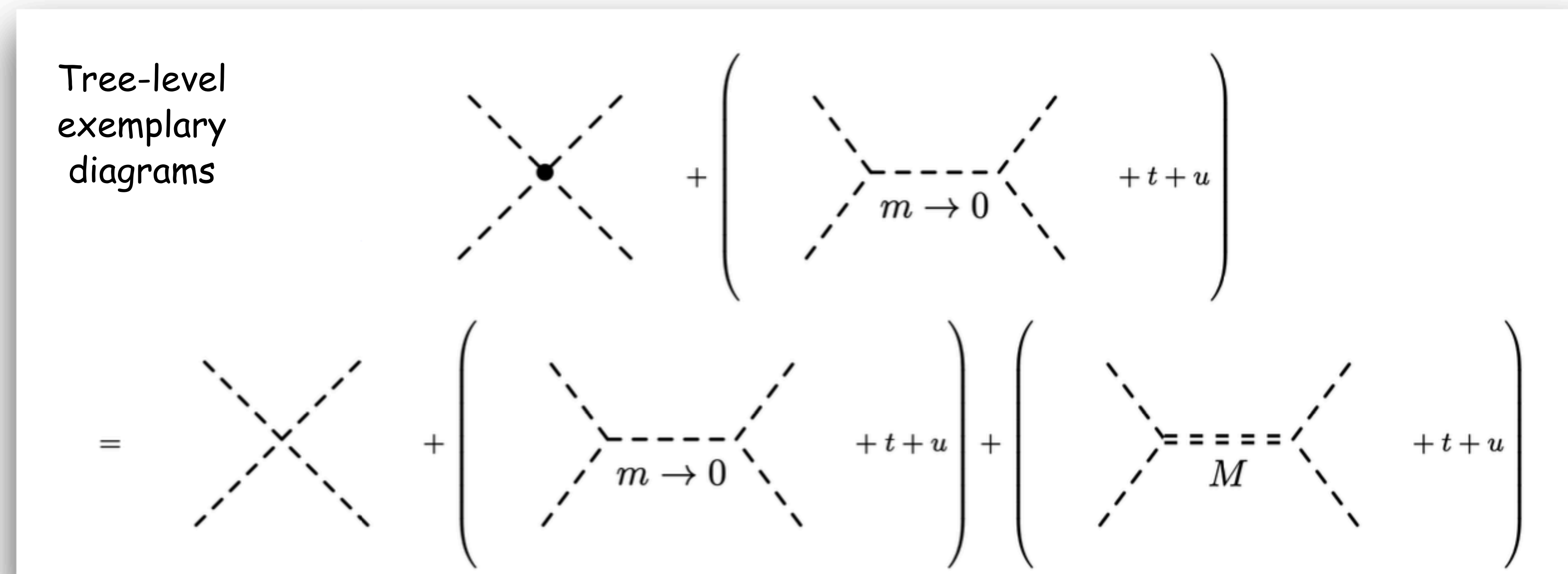
Quartic Coupling Matching (unbroken EW symmetry: $v_u, v_d \to 0$, $\tan\beta = v_u/v_d$=const., $v_S \neq 0$):

[Bagnaschi eal,´22] for real NMSSM
our work: complex NMSSM

$$\lambda_H^{\mathrm{SM},\,\overline{\mathrm{MS}}}(Q_{\mathrm{match}}) = \lambda_H^{\mathrm{NMSSM},\,\overline{\mathrm{MS}}}(Q_{\mathrm{match}})$$

effective quartic coupling after subtracting the SM contributions:

$$\lambda^{\overline{\mathrm{DR}}}_{\mathrm{NMSSM}}(Q_{\mathrm{match}}) = \lambda^{\mathrm{tree}}_{\mathrm{NMSSM}} + \Delta\lambda^{1l}_{\mathrm{NMSSM}} + \Delta\lambda^{2l}_{\mathrm{MSSM}}$$



m (M) light (heavy) mass scale

- - - - - light scalars = = = = = heavy scalars

Pole Mass Matching/„Hybrid" (broken EW symmetry, v«M$_{SUSY}$): e.g. [Athron eal, ´16]

$$M^2_{h,\mathrm{SM}} \stackrel{!}{=} M^2_{h,\mathrm{NMSSM}}$$

$$M^2_{h,X} = m^2_{h,X} - \hat{\Sigma}_{h,X}(M^2_{h,X}) \qquad \text{with} \qquad X = \mathrm{SM}, \mathrm{NMSSM}$$

$m_{h,\mathrm{SM}}$ and $m_{h,\mathrm{NMSSM}}$ denote the running $\overline{\mathrm{MS}}$ and $\overline{\mathrm{DR}}$ masses of the SM(-like) Higgs states

Tree Level: $m^2_{h,\mathrm{SM}} = 2\lambda^{\mathrm{eff.}}_{\mathrm{SM}} v^2_{\mathrm{SM}} \stackrel{!}{=} m^2_{h,\mathrm{NMSSM}}$ $\rightsquigarrow$ $\lambda^{\mathrm{eff.}}_{\mathrm{SM}} = \dfrac{m^2_{h,\mathrm{NMSSM}}}{2v^2_{\mathrm{NMSSM}}}$

One-Loop Level:

$$\lambda^{\mathrm{eff.}}_{\mathrm{SM}} = \frac{1}{2v^2_{\mathrm{SM}}}\left[m^2_{h,\mathrm{NMSSM}} - \hat{\Sigma}_{h,\mathrm{NMSSM}}(m^2_{h,\mathrm{NMSSM}}) + \hat{\Sigma}_{h,\mathrm{SM}}(m^2_{h,\mathrm{SM}})\right]$$

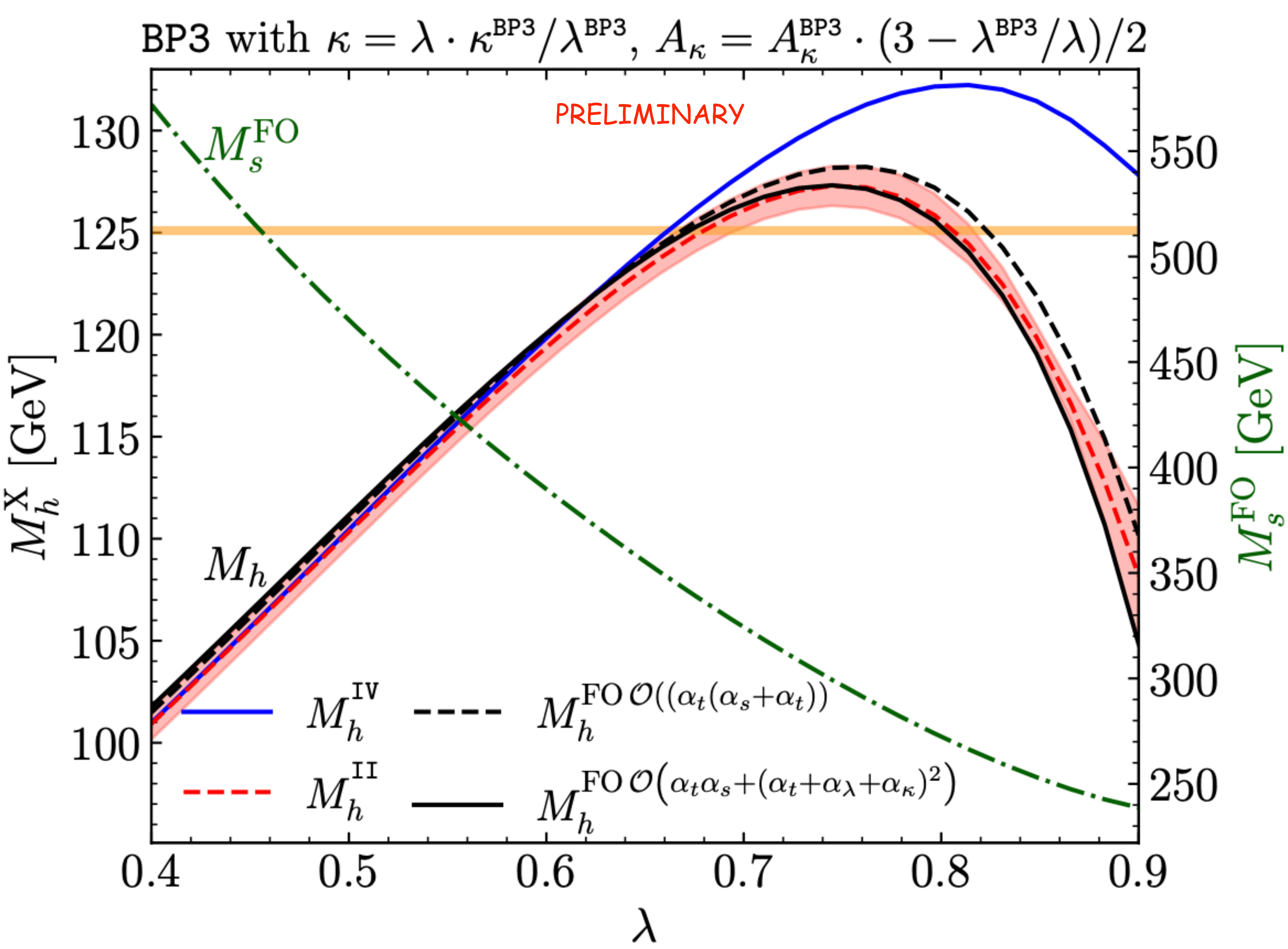
Leading terms in expansion in v/M$_{SUSY}$

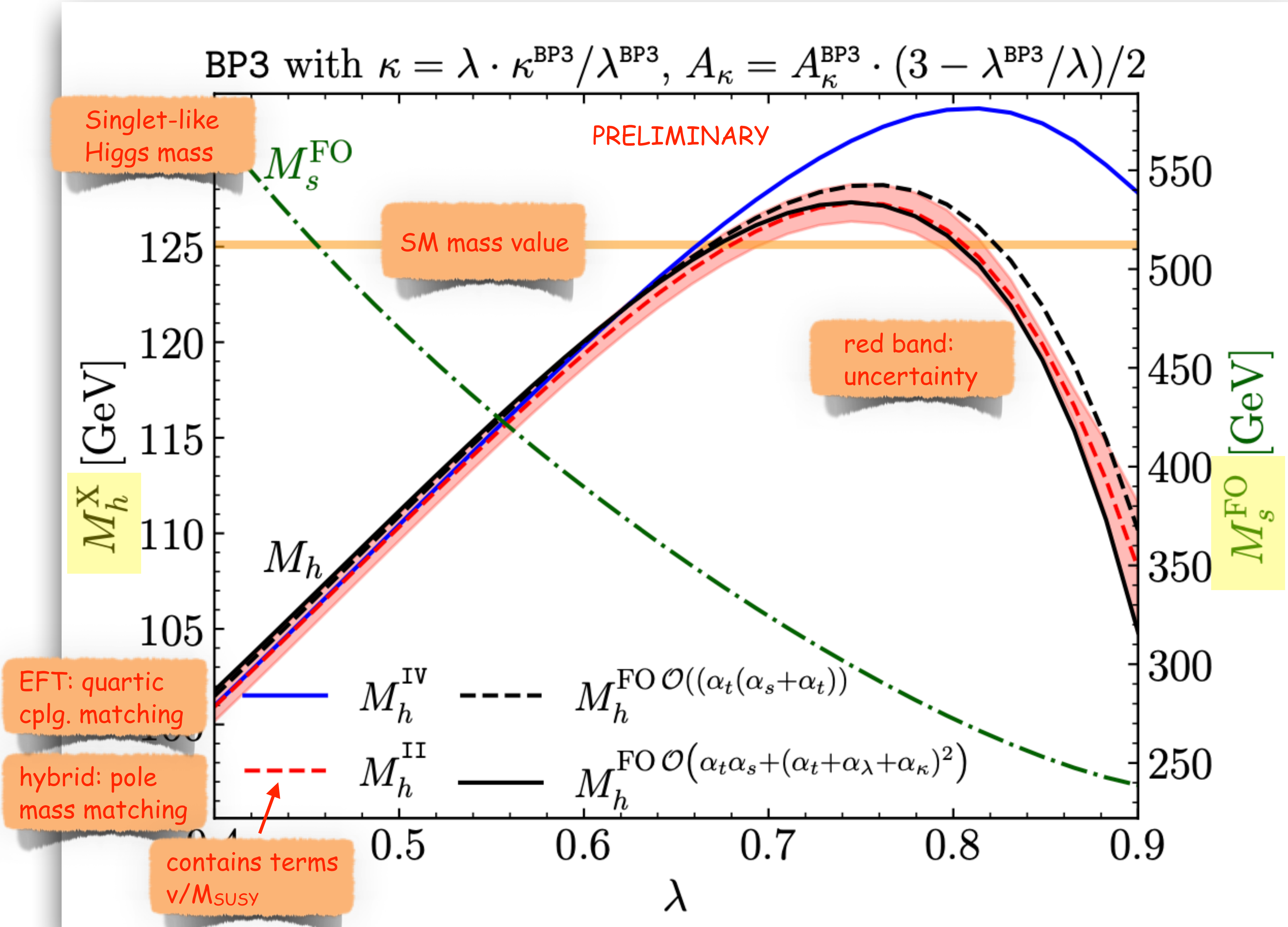
$$\lambda^{\mathrm{eff.}}_{\mathrm{SM}} = \frac{1}{2v^2_{\mathrm{NMSSM}}}\left[m^2_{h,\mathrm{NMSSM}} - \Delta\hat{\Sigma}_h - 2m^2_{h,\mathrm{NMSSM}}\Delta\hat{\Sigma}'_h\right]$$

with $\Delta\hat{\Sigma}^{(\prime)}_h \equiv \Sigma^{(\prime)}_{h,\mathrm{NMSSM}}(0) - \hat{\Sigma}^{(\prime)}_{h,\mathrm{SM}}(0)$

$\hat{\Sigma}_h$ renormalized self-energy

 [Borschensky,Dao,Gabelmann,MM,Rzehak]




BP3 with $\kappa = \lambda \cdot \kappa^{BP3}/\lambda^{BP3}$, $A_\kappa = A_\kappa^{BP3} \cdot (3 - \lambda^{BP3}/\lambda)/2$
PRELIMINARY
Singlet-like Higgs mass
M_s^{FO}
SM mass value
red band: uncertainty
M_h
M_h^X [GeV]
M_s^{FO} [GeV]
λ
M_h^{IV}
M_h^{II}
$M_h^{FO\,\mathcal{O}((\alpha_t(\alpha_s+\alpha_t))}$
$M_h^{FO\,\mathcal{O}(\alpha_t\alpha_s+(\alpha_t+\alpha_\lambda+\alpha_\kappa)^2)}$
EFT: quartic cplg. matching
hybrid: pole mass matching
contains terms v/MSUSY
0.5
0.6
0.7
0.8
0.9
105
110
115
120
125
250
300
350
400
450
500
550

$\mathcal{O}((\alpha_t(\alpha_t+\alpha_s))$ corrections to the trilinear Higgs self-coupling in the CP-violating NMSSM

Trilinear Higgs Self-Couplings

- SM Higgs potential in physical gauge:

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

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

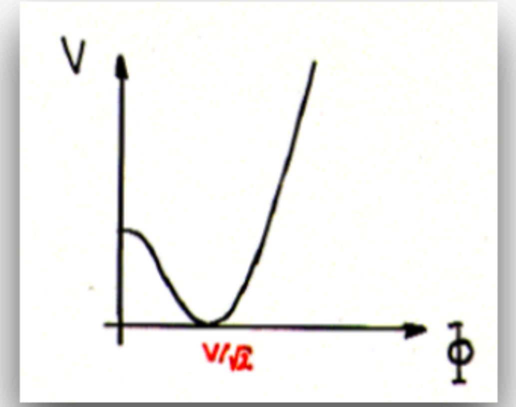
trilinear Higg self-coupling : $\lambda_{HHH} = 3 M_H^2 / M_Z^2$

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

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

- 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

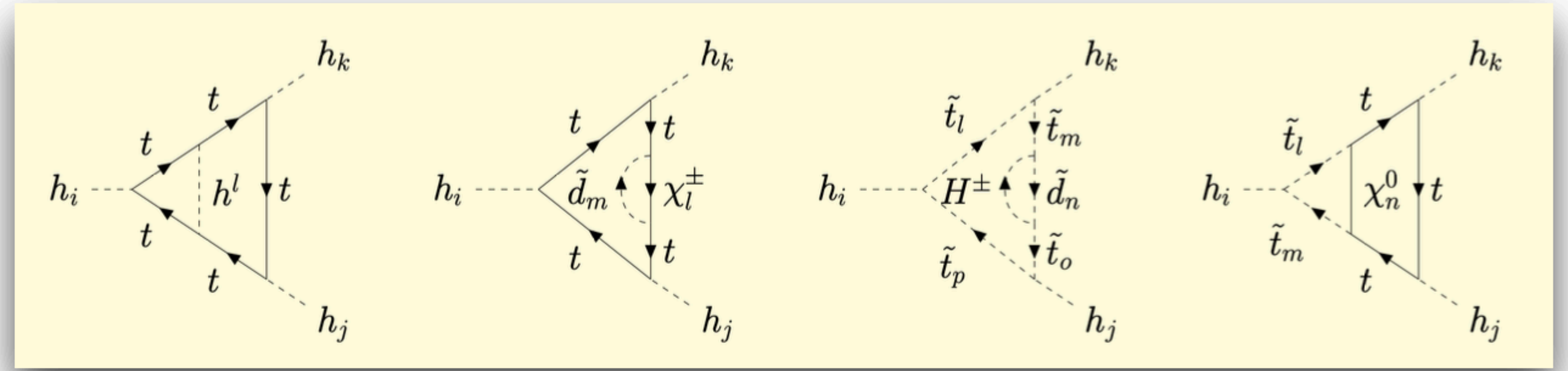
- Importance of the trilinear Higgs self-coupling:
  - determines shape of the Higgs potential
  - Sensitive to beyond-Standard-Model physics
  - Important input for Higgs pair production
  - Important input for Higgs-to-Higgs decays
  - Important input for electroweak phase transitions



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

Trilinear Higgs Self-Couplings at 2L $\mathcal{O}(\alpha_t(\alpha_s+\alpha_t))$

- New corrections at $\mathcal{O}(\alpha_t^2)$: all 2-loop diagrams with top/stops and at most one Higgs/Higgsino field, e.g.



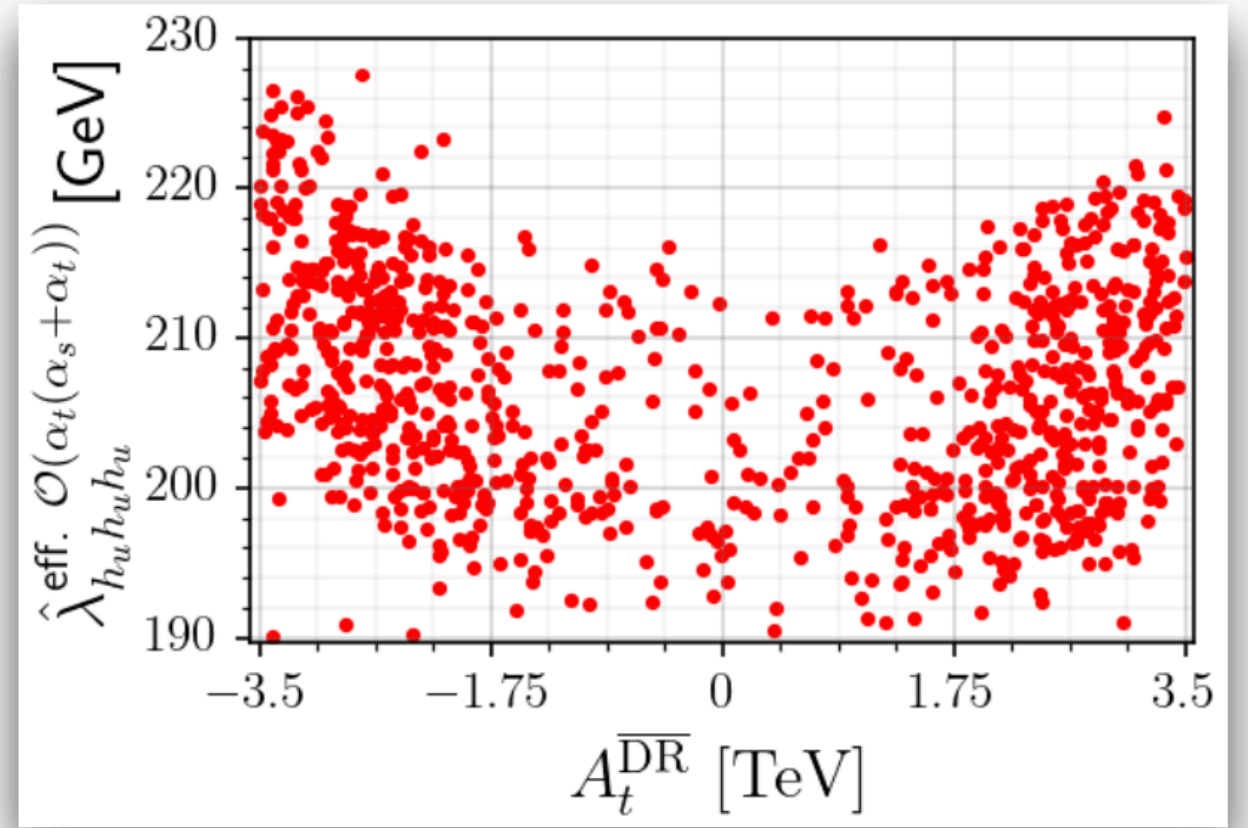
proportional to top mass m_t and soft SUSY-breaking trilinear stop mass parameter A_t

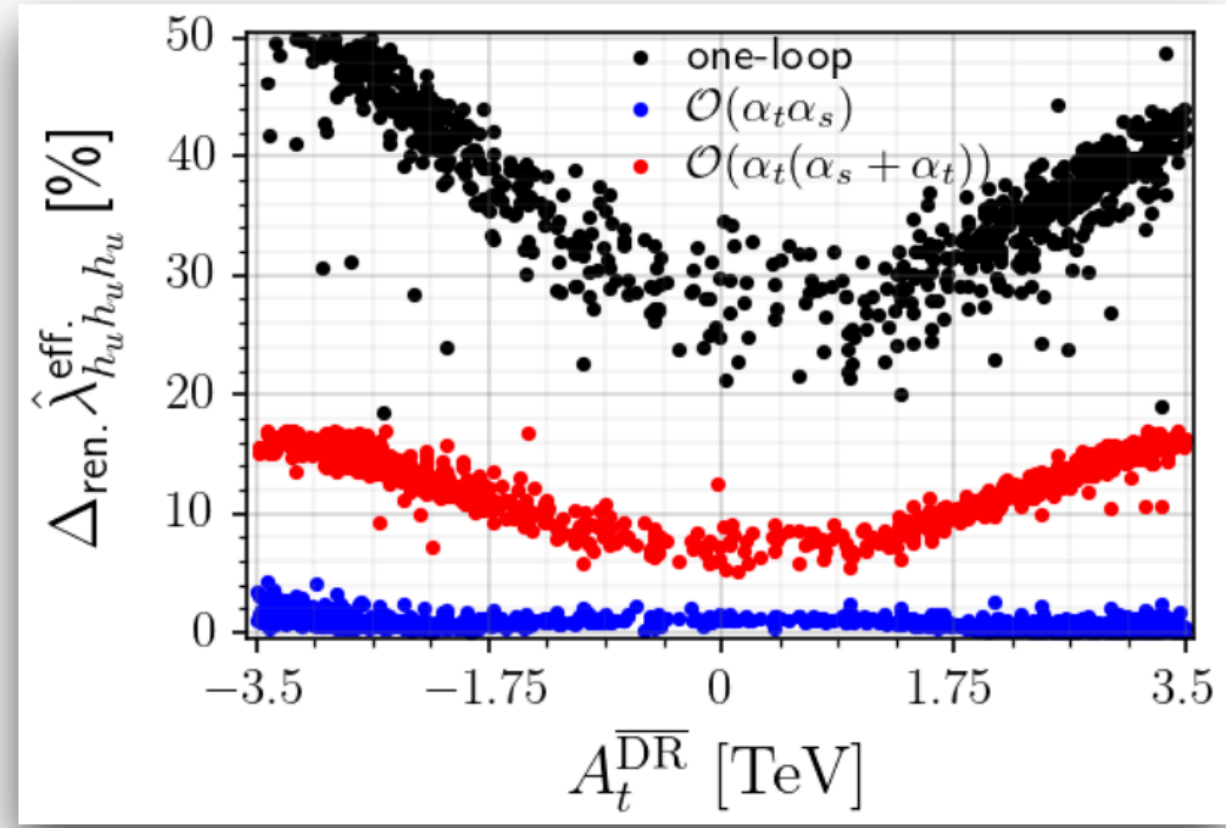
- Approximations:
  - gaugeless limit $g_1,g_2 \to 0$ (keeping $\tan\theta_W = g_2/g_1$ fixed)
  - vanishing external momenta → effective coupling

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

Corrections to h_u-like Higgs (≙SM-like Higgs)

[Borschensky,Dao,Gabelmann,MM,Rzehak,´22]





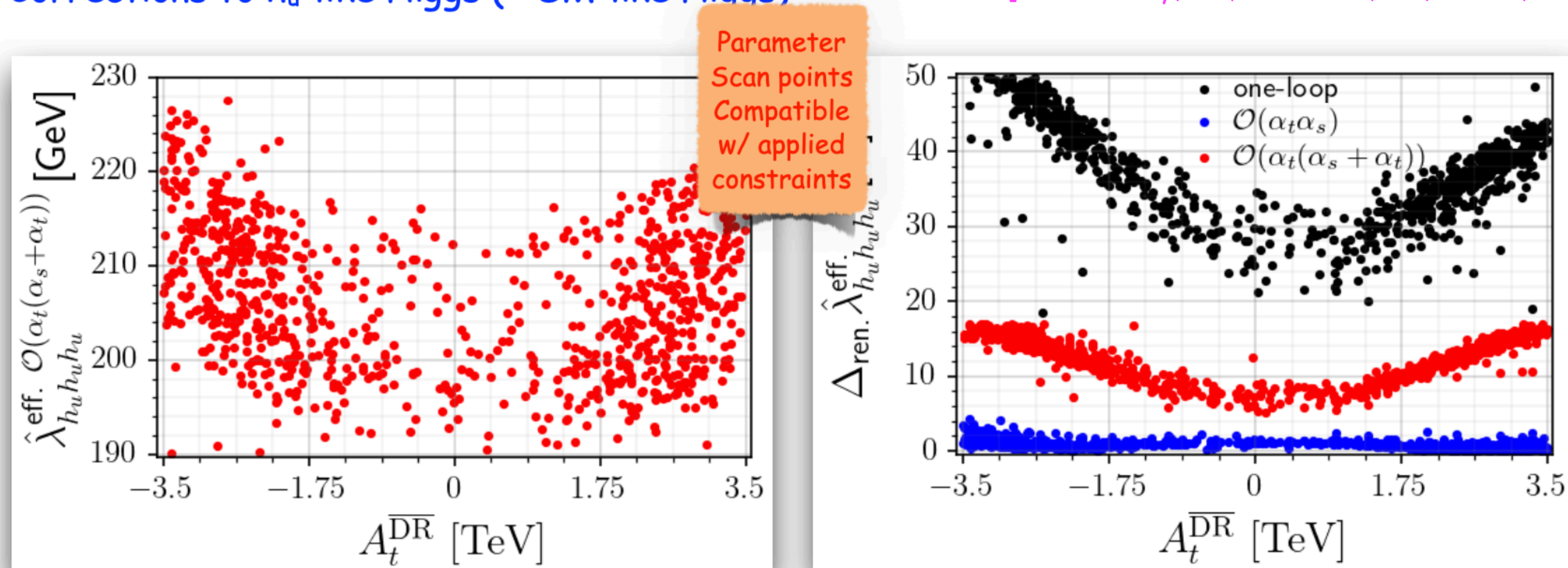
$\hat{\lambda}^{\text{eff}}_{abc}$: renormalized loop-corrected Higgs self-coupling at vanishing external momentum

Estimate of theor. uncertainty via renorm. scheme dependence: $\Delta_{\text{ren}} = \frac{\left|\lambda^{m_t(\overline{\text{DR}})} - \lambda^{m_t(\text{OS})}\right|}{\lambda^{m_t(\overline{\text{DR}})}}$

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

Corrections to h_u-like Higgs ($\triangleq$SM-like Higgs)

[Borschensky,Dao,Gabelmann,MM,Rzehak,´22]



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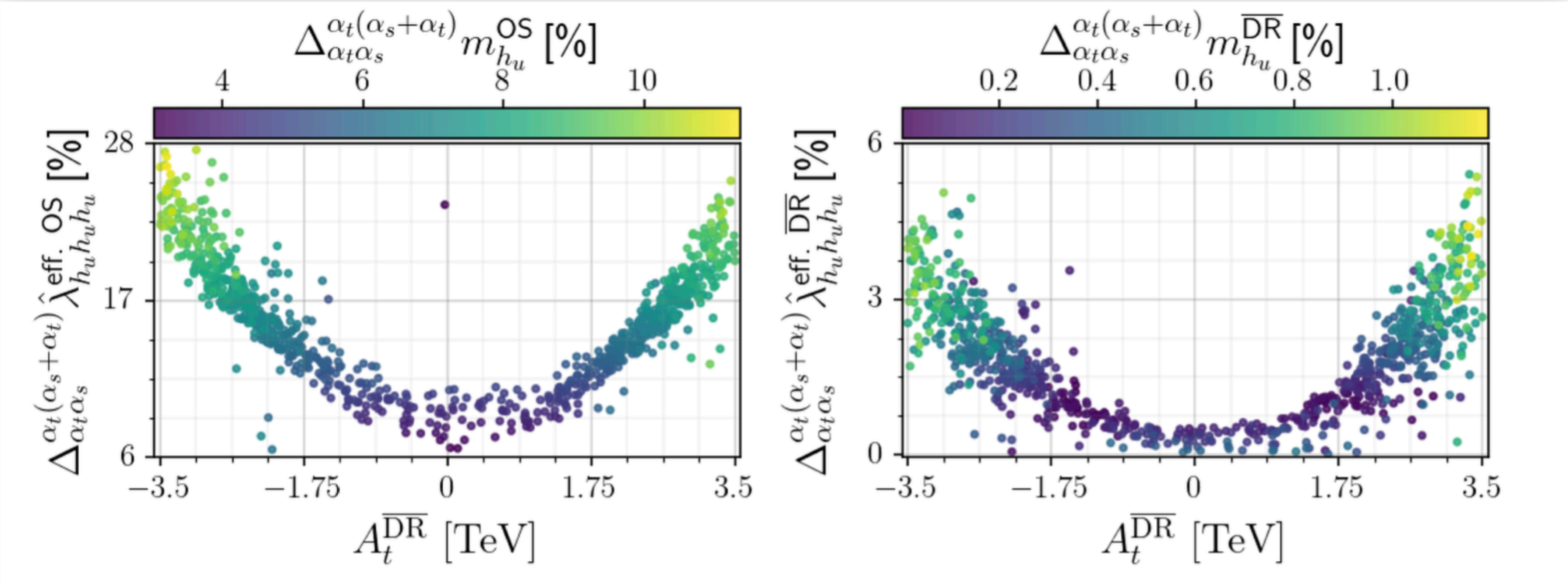
Size of the Corrections at $\mathcal{O}(\alpha_t(\alpha_s+\alpha_t))$

Corrections to h_u-like Higgs ($\triangleq$SM-like Higgs) [Borschensky,Dao,Gabelmann,MM,Rzehak,´22]



$$\Delta^{\alpha_{i+1}}_{\alpha_i} = \frac{|\lambda^{\alpha_{i+1}} - \lambda^{\alpha_i}|}{\lambda^{\alpha_i}}$$

- Correlation with size of mass corrections
- Smaller corrections in the DRbar than in the OS scheme due to partial resummation of of higher-order terms

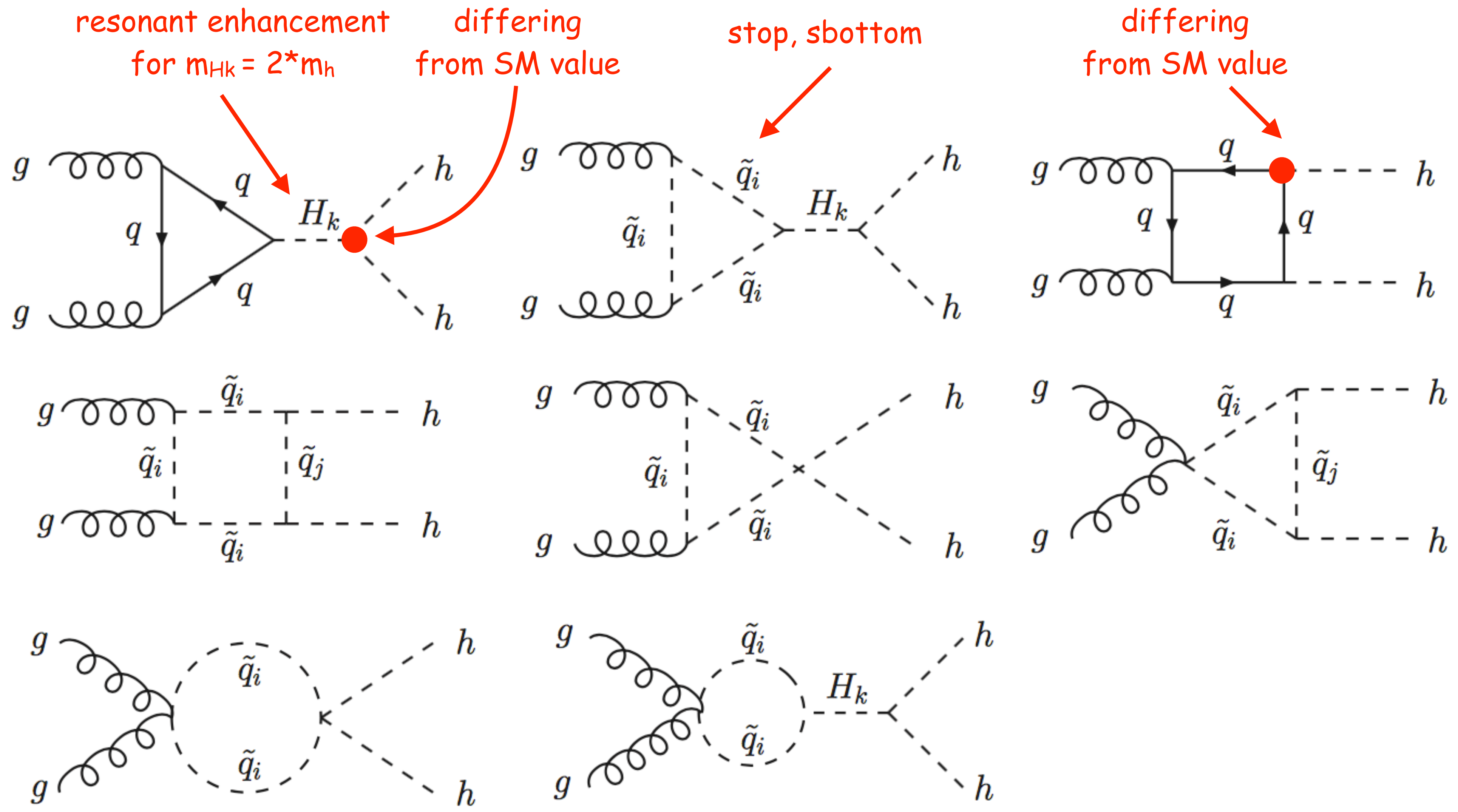
Impact on Higgs Pair Production

New Physics Effects in Higgs Pair Production

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

✦Example NMSSM:

[taken from Dao,MM eal'13]



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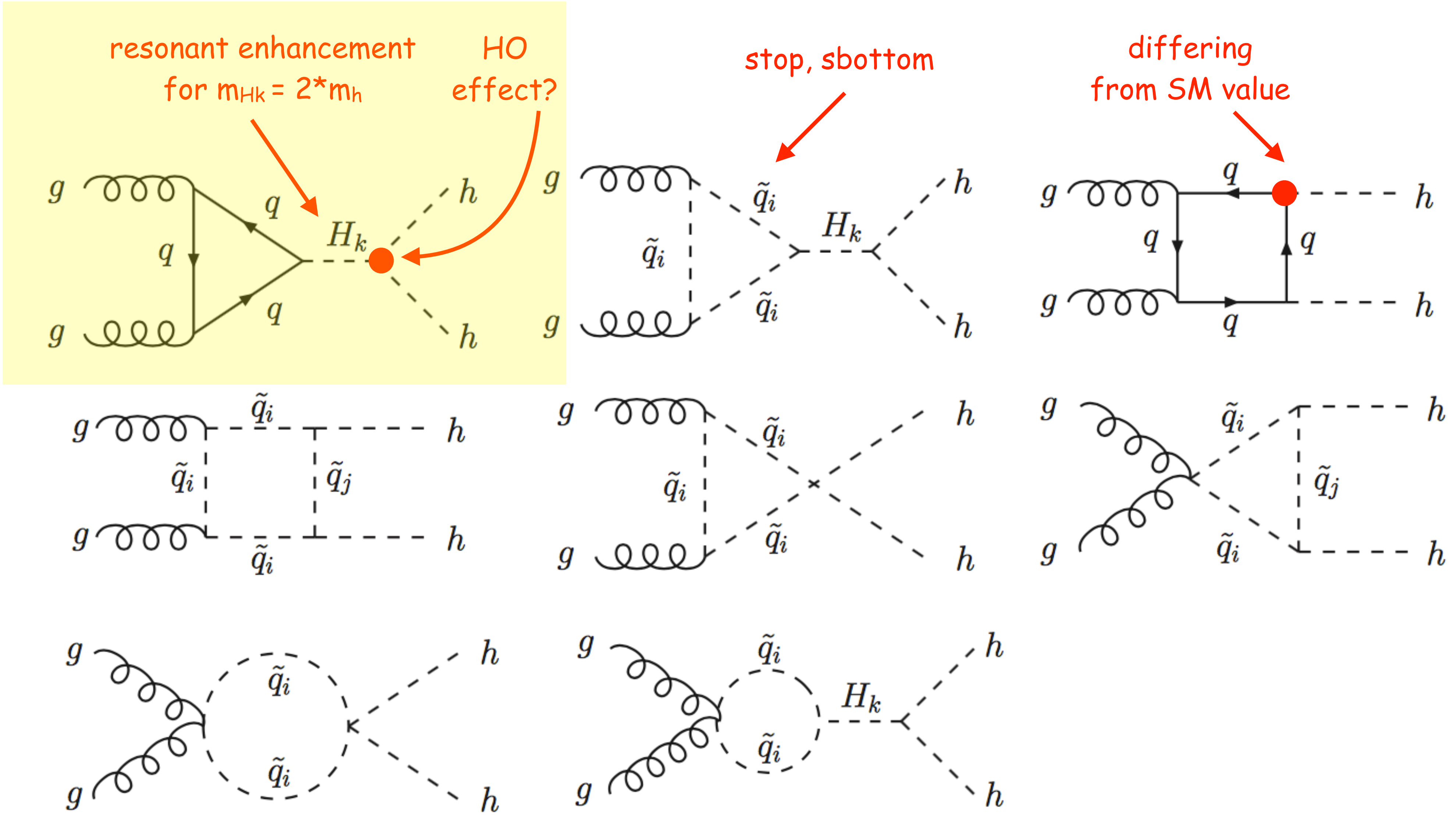

Impact on Higgs Pair Production

Benchmark Point BP10: [Borschensky,Dao,Gabelmann,MM,Rzehak,´22]

Parameter Point BP10**:** All complex phases are set to zero and the remaining input parameters are given by

$$\begin{aligned}
|\lambda| &= 0.65\,,\ |\kappa| = 0.65\,,\ \mathrm{Re}(A_\kappa) = -432\ \mathrm{GeV}\,,\ |\mu_{\mathrm{eff}}| = 225\ \mathrm{GeV}\,,\ \tan\beta = 2.6\,,\\
M_{H^\pm} &= 611\ \mathrm{GeV}\,,\ m_{\tilde{Q}_3} = 1304\ \mathrm{GeV}\,,\ m_{\tilde{t}_R} = 1576\ \mathrm{GeV}\,,\ m_{\tilde{X}\neq\tilde{Q}_3,\tilde{t}_R} = 3\ \mathrm{TeV}\,,\\
A_t &= 46\ \mathrm{GeV}\,,\ A_b = -1790\ \mathrm{GeV}\,,\ A_\tau = -93\ \mathrm{GeV}\,,\ A_c = 267\ \mathrm{GeV}\,,\\
A_s &= -618\ \mathrm{GeV}\,,\ A_\mu = 1851\ \mathrm{GeV}\,,\ A_u = -59\ \mathrm{GeV}\,,\ A_d = -175\ \mathrm{GeV}\,,\\
A_e &= 1600\ \mathrm{GeV}\,,\ |M_1| = 810\ \mathrm{GeV}\,,\ |M_2| = 642\ \mathrm{GeV}\,,\ M_3 = 2\ \mathrm{TeV}\,. \qquad (38)
\end{aligned}$$

	h_1 $[h_u]$	h_2 $[h_s]$	h_3 $[h_d]$	a_1 $[a_s]$	a_2 $[a_d]$
tree-level	97.21	307.80	626.13	556.71	617.22
one-loop	131.46 (114.81)	299.65 (299.28)	625.96 (625.52)	543.58 (543.69)	615.82 (616.01)
two-loop $\mathcal{O}(\alpha_t\alpha_s)$	118.90 (120.36)	299.40 (299.38)	625.78 (625.58)	543.73 (543.60)	615.90 (615.96)
two-loop $\mathcal{O}(\alpha_t(\alpha_s+\alpha_t))$	123.53 (120.14)	299.44 (299.38)	625.89 (625.57)	543.73 (543.60)	615.90 (615.96)
two-loop $\mathcal{O}(\alpha^2_{\lambda\kappa})$	122.36 (119.97)	300.27 (299.90)	625.94 (625.65)	543.34 (543.47)	615.91 (616.01)

Impact on Higgs Pair Production

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di-Higgs cxn dominated by resonant h_2 production w/ $h_2 \to h_u h_u$

Impact on Higgs Pair Production

loop order mass tril.cplg.

[Borschensky,Dao,Gabelmann,MM,Rzehak,´22]

1-loop

'1L1L'	σ^{OS} [fb]	$\sigma^{\overline{DR}}$ [fb]	$\kappa^{OS}_{H_1H_1H_1}$	$\kappa^{\overline{DR}}_{H_1H_1H_1}$	$\kappa^{OS}_{H_2H_1H_1}$	$\kappa^{\overline{DR}}_{H_2H_1H_1}$	$\Delta_{\rm ren}\sigma$
'inp'	63.72	62.14	0.54	0.71	-0.25	-0.30	2.5%
'proc'	76.83	61.48	1.01	1.04	-0.30	-0.31	25%

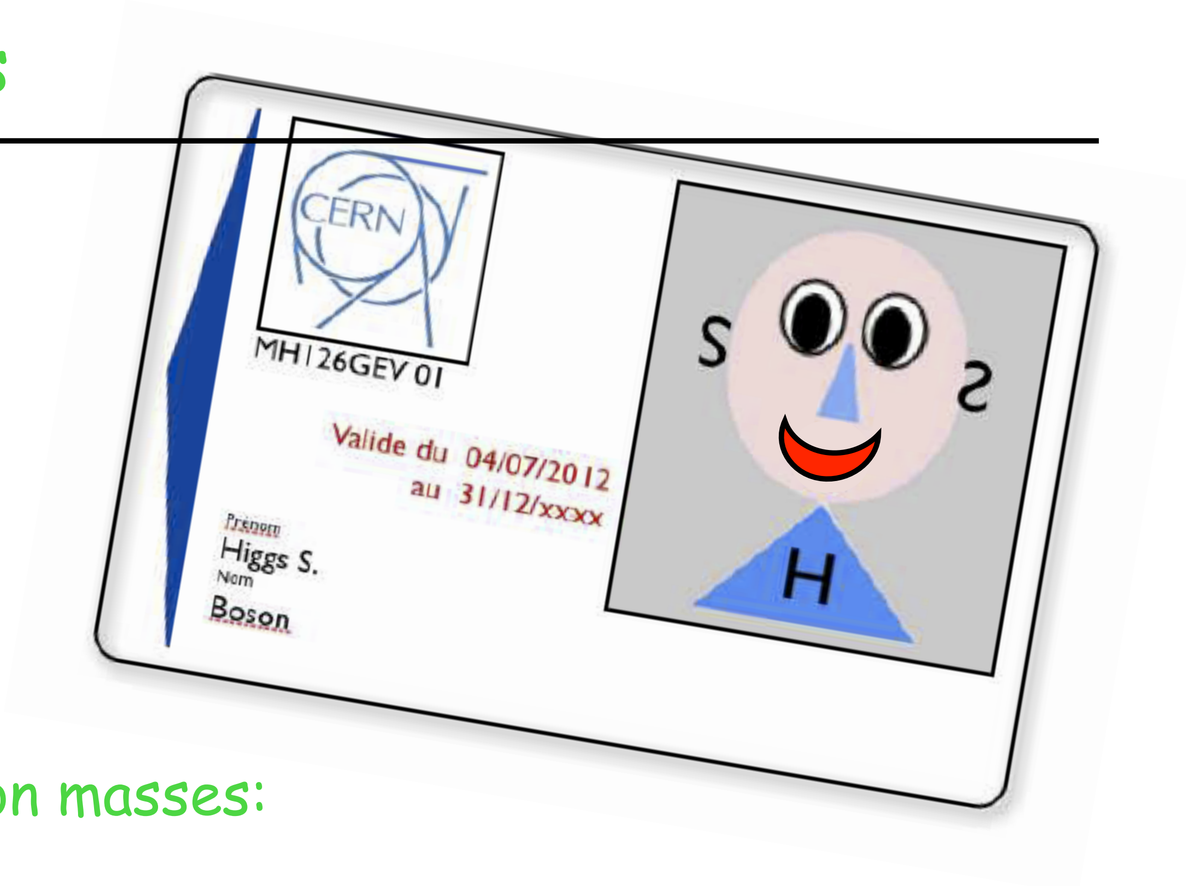
2-loop $O(\alpha_t^2 + \alpha_s\alpha_t)$

'at2at2'	σ^{OS} [fb]	$\sigma^{\overline{DR}}$ [fb]	$\kappa^{OS}_{H_1H_1H_1}$	$\kappa^{\overline{DR}}_{H_1H_1H_1}$	$\kappa^{OS}_{H_2H_1H_1}$	$\kappa^{\overline{DR}}_{H_2H_1H_1}$	$\Delta_{\rm ren}\sigma$
'inp'	68.98	61.25	0.61	0.65	-0.27	-0.28	12.6%
'proc'	71.69	62.57	1.03	1.02	-0.30	-0.31	14.6%

- 'inp': loop-corrected masses and mixing angles (-> Yukawa & trilinear couplings) in tree-level-like formulae: HO corrections to input parameters
- 'proc': additionally including loop-corrected trilinear Higgs self-coupling -> HO corrections to observable included (though **only partially**)

- 'inp': scheme dependence of input parameters uncanceled by scheme dependence of process-dependent corrections (at the same order)
- 'proc': remaining large uncertainty (14.6%): remaining missing EW corrections might be important

Conclusions



- New physics search at intensity frontier
  - Indirect constraints on parameter space
  - Higher order corrections indispensable

- Two-loop mass corrections to NMSSM Higgs boson masses:
  - remaining theoretical uncertainty few percent
  - high-mass exclusion limits: fixed order ~> EFT approach

- Two-loop corrections to trilinear Higgs self-couplings
  - results comply w/ SM value within theoretical uncertainties

- Impact on di-Higgs production
  - remaining relatively large uncertainties require full calculation of EW corrections


Thank you for
your attention!

The NMSSM Higgs Sector

- Tree-level Higgs potential: (neglecting D-term contributions)

$$V_H = (|\lambda S|^2 + m_{H_d}^2) H_d^\dagger H_d + (|\lambda S|^2 + m_{H_u}^2) H_u^\dagger H_u + m_S^2 |S|^2 + \left|\kappa S^2 - \lambda H_d \cdot H_u\right|^2 + \left(\frac{1}{3}\kappa A_\kappa S^3 - \lambda A_\lambda S H_d \cdot H_u + \text{h.c.}\right)$$

- CP violation in the Higgs sector: λ, κ, A_λ, A_κ can be complex

- Higgs fields after electroweak symmetry breaking (EWSB):

$$H_d = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + h_d + i a_d) \\ h_d^- \end{pmatrix}, \quad H_u = e^{i\varphi_u} \begin{pmatrix} h_u^+ \\ \frac{1}{\sqrt{2}}(v_u + h_u + i a_u) \end{pmatrix}, \quad S = \frac{e^{i\varphi_s}}{\sqrt{2}}(v_s + h_s + i a_s)$$

effective μ parameter: $\mu = \frac{\lambda v_s}{\sqrt{2}}$

Masses and Tadpoles

- Input parameters: NMSSM parameters complex phases

$$\{t_{h_d}, t_{h_u}, t_{h_s}, t_{a_d}, t_{a_s}, M^2_{H^\pm}, v, s_{\theta_W}, e, \tan\beta, |\lambda|, v_s, |\kappa|, \mathrm{Re}A_\kappa, \varphi_\lambda, \varphi_\kappa, \varphi_u, \varphi_s\}$$

or

$$\{t_{h_d}, t_{h_u}, t_{h_s}, t_{a_d}, t_{a_s}, v, s_{\theta_W}, e, \tan\beta, |\lambda|, v_s, |\kappa|, \mathrm{Re}A_\lambda, \mathrm{Re}A_\kappa, \varphi_\lambda, \varphi_\kappa, \varphi_u, \varphi_s\}$$

- Tadpoles: (zero at tree level)

$$(\boldsymbol{t})_j = t_{\phi_j} = \frac{\partial V_H}{\partial \phi_j}, \quad j = 1, \ldots, 6$$

- The Higgs potential:

$$V_H \supset \quad \boldsymbol{t\phi} + \frac{1}{2}\boldsymbol{\phi}^T \mathcal{M}_{\phi\phi}\boldsymbol{\phi} + \boldsymbol{h}^{c,\dagger}\mathcal{M}_{h^+h^-}\boldsymbol{h}^c \,,$$
$$\text{with} \quad \boldsymbol{\phi} = (h_d, h_u, h_s, a_d, a_u, a_s)^T, \;\; \boldsymbol{h}^c = (h_d^{-*}, h_u^+)\,,$$

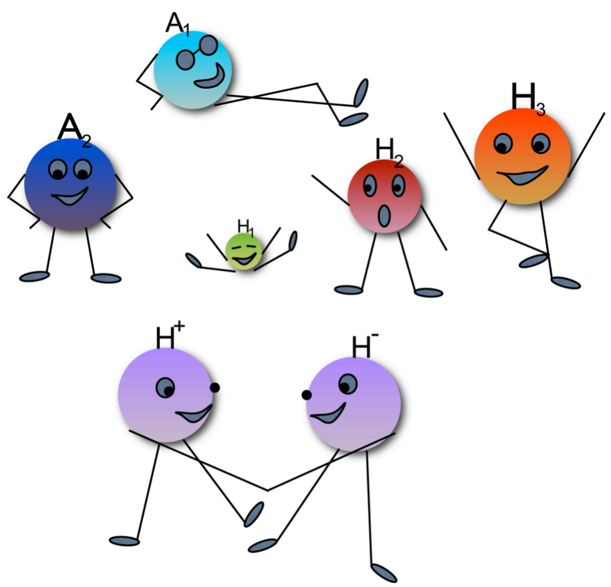
- Mass matrices: neutral $\mathcal{M}_{\phi\phi}$, charged $\mathcal{M}_{h^+h^-}$

The Higgs Spectrum

✦ Tree-level Higgs potential: (neglecting D-term contributions)

CP-conserving (CPC): 3 CP-even Higgs bosons H_i (i=1,2,3),
2 CP-odd Higgs boson A_j (j=1,2),
2 charged H^+,H^-

CP-violating (CPV): 5 CP-mixing Higgs bosons H_k (k=1,…,5),
2 charged Higgs bosons H^+, H^-



✦ Higgs boson mass:

* SM: fundamental parameter, not predicted by the theory

* Supersymmetry: calculable from input parameters;
quantum corrections Δm^2_H are important!

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

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

✦ NMSSM: less important loop corrections needed compared to the MSSM, rich phenomenology
See e.g. [Miller,Nevzorov,Zerwas,'03] [King,MM,Nevzorov,'12,'14] [Carena,Haber,Low,Shah,Wagner,'15] [Ellwanger,Rodriguez-Vazquez,'15] [Baum,Freeze,Shah,Shakya,'17] [Baum,Shah,Freeze,'19] [Biekötter,Grohsjean,Heinemeyer,Schwanenberger,Weiglein,'21]

✦ Why precision predictions for Higgs masses?

Higher-Order NMSSM Higgs Boson Masses

- After EWSB: h_i (i=1,...,5) ordered by mass, no CP eigenstates <- CP-violating NMSSM
- HO Higgs masses: real parts of propagator poles; iteratively obtained from (no Goldstone boson admixture taken included, numerically small)

$$\mathrm{Det}\left(\mathbb{1}_{5\times 5}p^2 - \mathcal{M} \quad + \hat{\Sigma}_{hh}(p^2)\right) = 0$$

[Dao eal,'19]

- Renormalized self-energies:

$$\hat{\Sigma}_{ij} = \hat{\Sigma}^{(1)}_{ij}(p^2) + \hat{\Sigma}^{(2)}_{ij}(p^2)$$ with

$$\hat{\Sigma}^{(1)}(p^2) = \Sigma^{(1)}(p^2) + \frac{1}{2}\left[\delta^{(1)}\mathcal{Z}^\dagger\left(\mathbb{1}p^2 - \mathcal{M}^2\right) + \left(\mathbb{1}p^2 - \mathcal{M}^2\right)\delta^{(1)}\mathcal{Z}\right] + \delta^{(1)}\mathcal{M}^2 .$$

computed at non-zero p^2 in the CP-conserving and CP-violating NMSSM in [Ender eal,'11;Graf eal,'12]

$$\begin{aligned}\hat{\Sigma}^{(2)}(p^2) = \Sigma^{(2)}(p^2) + \frac{1}{2}\Big[&\delta^{(2)}\mathcal{Z}^\dagger\left(\mathbb{1}p^2 - \mathcal{M} \;\right) + \left(\mathbb{1}p^2 - \mathcal{M} \;\right)\delta^{(2)}\mathcal{Z} \\ &+\frac{1}{2}\delta^{(1)}\mathcal{Z}^\dagger\left(\mathbb{1}p^2 - \mathcal{M} \;\right)\delta^{(1)}\mathcal{Z} - \delta^{(1)}\mathcal{Z}^\dagger\delta^{(1)}\mathcal{M} \; - \delta^{(1)}\mathcal{M} \; \delta^{(1)}\mathcal{Z}\Big] \\ &- \delta^{(2)}\mathcal{M}\end{aligned}$$

computed at p^2=0 and in gaugeless limit in the CP-violating NMSSM at $\mathcal{O}(\alpha_t\alpha_s)$ and $\mathcal{O}(\alpha_t^2)$ in [MM eal,'14;Dao eal,'19]

This work: $\mathcal{O}((\alpha_t + \alpha_\lambda + \alpha_\kappa)^2)$

Matching Conditions

Quartic Coupling Matching (unbroken EW symmetry: $v_u, v_d \to 0$, $\tan\beta = v_u/v_d$=const., $v_S \neq 0$):

[Bagnaschi eal,´22] for real NMSSM
our work: complex NMSSM

$$\lambda_H^{\mathrm{SM},\overline{\mathrm{MS}}}(Q_{\mathrm{match}}) = \lambda_H^{\mathrm{NMSSM},\overline{\mathrm{MS}}}(Q_{\mathrm{match}})$$

effective quartic coupling after subtracting the SM contributions:

$$\lambda_{\mathrm{NMSSM}}^{\overline{\mathrm{DR}}}(Q_{\mathrm{match}}) = \lambda_{\mathrm{NMSSM}}^{\mathrm{tree}} + \Delta\lambda_{\mathrm{NMSSM}}^{1l} + \Delta\lambda_{\mathrm{MSSM}}^{2l}$$

$$\begin{aligned}
\lambda_{\mathrm{NMSSM}}^{\mathrm{tree}} = & \underbrace{\frac{1}{4}(g_1^2+g_2^2)\cos^2 2\beta}_{\text{MSSM D-terms}} + \underbrace{\frac{1}{2}|\lambda|\sin^2 2\beta}_{\text{NMSSM F-terms}} \\
& \underbrace{- \frac{1}{24|\kappa|^2 M_S^2(3M_S^2+M_{A_S}^2)}\Bigg(3|\kappa|^2 M_{H^\pm}^2 - 3|\kappa|^2 M_{H^\pm}^2\cos 4\beta + (3M_S^2+M_{A_S}^2)\left(|\kappa||\lambda|\cos\varphi_y \sin 2\beta - 2|\lambda|^2\right)\Bigg)^2}_{\text{s/t/u-channel } S} \\
& \underbrace{- \frac{3}{8M_{A_S}^2}|\lambda|^2(3M_S^2+M_{A_S}^2)\sin^2 2\beta \sin^2\varphi_y}_{\text{s/t/u-channel } A_S}
\end{aligned}$$

Matching Conditions

Quartic Coupling Matching (unbroken EW symmetry: $v_u, v_d \to 0$, $\tan\beta = v_u/v_d = \text{const.}$, $v_S \neq 0$):

[Bagnaschi eal,´22] for real NMSSM
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$$\lambda_H^{\text{SM}, \overline{\text{MS}}}(Q_{\text{match}}) = \lambda_H^{\text{NMSSM}, \overline{\text{MS}}}(Q_{\text{match}})$$

effective quartic coupling after subtracting the SM contributions:

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Remark: shift due to NMSSM calc. done in $\overline{\text{DR}}$ and discarded SM contribution done in $\overline{\text{MS}}$ taken into account

Loop corrected NMSSM masses and couplings from NMSSMCALC

[Baglio,Borschensky,Dao,Gabelmann,Gröber,Krause,Le,MM,Rzehak,Spira, Streicher,Walz]

NMSSMCALC

Calculator of One-Loop and
$O(\alpha_t \alpha_s + (\alpha_t + \alpha_\lambda + \alpha_\kappa)^2)$ Two-Loop
Higgs Mass Corrections
and of Higgs Decay Widths
in the CP-conserving and the CP-violating NMSSM

Computation of the Loop-Corrected Effective Higgs Self-Couplings
and the Loop-Corrected Higgs-to-Higgs Decays
up to $O(\alpha_t \alpha_s + \alpha_t^2)$

Computation of the muon anomalous magnetic moment and the electric dipole moment

New: Computation of the ϱ parameter up to $O(\alpha + \alpha_t \alpha_s + (\alpha_t + \alpha_\lambda + \alpha_\varkappa)^2)$); W-mass prediction in the SM, at 1-loop NMSSM, 2-loop QCD NMSSM, 2-loop EW NMSSM

The program package NMSSMCALC calculates the one-loop and $O(\alpha_t \alpha_s + (\alpha_t + \alpha_\lambda + \alpha_\varkappa)^2)$ corrected Higgs boson masses and the Higgs decay widths and branching ratios within the CP-conserving and the CP-violating NMSSM.
The decay calculator is based on an extension of the program HDECAY 6.10 now.
The effective loop-corrected trilinear Higgs self-couplings and loop-corrected Higgs-to-Higgs decays are provided up to $O(\alpha_t \alpha_s + \alpha_t^2)$.
The program also provides the options to calculate the electron and muon anomalous magnetic moments and, in the CP-violating case, the electric dipole moments.
The program provides the ϱ parameter up to $O(\alpha + \alpha_t \alpha_s + (\alpha_t + \alpha_\lambda + \alpha_\varkappa)^2)$; the W-mass prediction in the SM, at 1-loop NMSSM, 2-loop QCD NMSSM, 2-loop EW NMSSM.

Matching Conditions

Pole Mass Matching/„Hybrid" (broken EW symmetry, v≪M_{SUSY}):

e.g. [Athron eal, ´16]

$$M^2_{h,\mathrm{SM}} \overset{!}{=} M^2_{h,\mathrm{NMSSM}}$$

$$M^2_{h,X} = m^2_{h,X} - \hat{\Sigma}_{h,X}(M^2_{h,X}) \qquad \text{with} \qquad X = \mathrm{SM}, \mathrm{NMSSM}$$

$m_{h,\mathrm{SM}}$ and $m_{h,\mathrm{NMSSM}}$ denote the running $\overline{\mathrm{MS}}$ and $\overline{\mathrm{DR}}$ masses of the SM(-like) Higgs states

Tree Level: $m^2_{h,\mathrm{SM}} = 2\lambda^{\mathrm{eff.}}_{\mathrm{SM}} v^2_{\mathrm{SM}} \overset{!}{=} m^2_{h,\mathrm{NMSSM}} \quad \rightsquigarrow \quad \lambda^{\mathrm{eff.}}_{\mathrm{SM}} = \dfrac{m^2_{h,\mathrm{NMSSM}}}{2v^2_{\mathrm{NMSSM}}}$

use $v^2_{\mathrm{SM}} = v^2_{\mathrm{NMSSM}} + \delta v^2 = v^2_{\mathrm{NMSSM}}\left(1 + \dfrac{\delta v^2}{v^2}\right)$ with $\dfrac{\delta v^2}{v^2} = \left[\hat{\Sigma}'_{h,\mathrm{NMSSM}}(0) - \hat{\Sigma}'_{h,\mathrm{SM}}(0)\right] + \mathcal{O}(v^4/M^4_{\mathrm{SUSY}})$

One-Loop Level: $\lambda^{\mathrm{eff.}}_{\mathrm{SM}} = \dfrac{1}{2v^2_{\mathrm{SM}}}\left[m^2_{h,\mathrm{NMSSM}} - \hat{\Sigma}_{h,\mathrm{NMSSM}}(m^2_{h,\mathrm{NMSSM}}) + \hat{\Sigma}_{h,\mathrm{SM}}(m^2_{h,\mathrm{SM}})\right]$

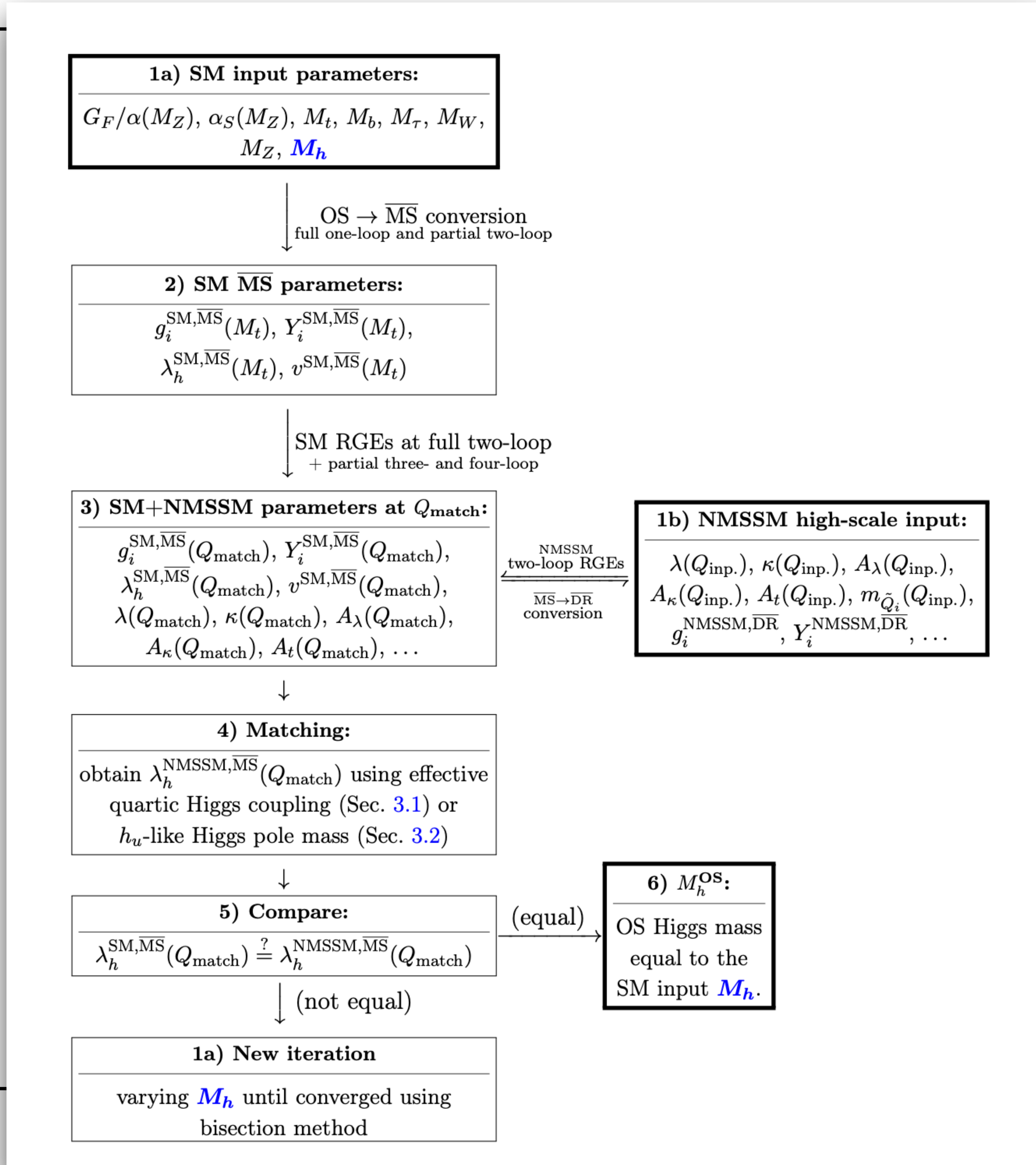
with $\hat{\Sigma}_{h,X}(m^2_{h,X}) = \hat{\Sigma}_{h,X}(0) + m^2_{h,X}\hat{\Sigma}'_{h,X}(0) + \mathcal{O}(m^4_{h,X})$ and $v_{SM} \rightarrow v_{NMSSM}$ so that

Leading terms in expansion in v/M_{SUSY}

$$\lambda^{\mathrm{eff.}}_{\mathrm{SM}} = \frac{1}{2v^2_{\mathrm{NMSSM}}}\left[m^2_{h,\mathrm{NMSSM}} - \Delta\hat{\Sigma}_h - 2m^2_{h,\mathrm{NMSSM}}\Delta\hat{\Sigma}'_h\right]$$

with $\Delta\hat{\Sigma}^{(\prime)}_h \equiv \Sigma^{(\prime)}_{h,\mathrm{NMSSM}}(0) - \hat{\Sigma}^{(\prime)}_{h,\mathrm{SM}}(0)$

Schematic Procedure Implemented in NMSSMCALC



Uncertainty Estimate

Red uncertainty band:

SM uncertainties:

- scheme uncertainty using either G_F or $\alpha_{QED}(m_Z)$ as input (estimates missing 2-loop EW corrections in the relation between Lagrangian MSbar and physical OS parameters)
- scheme and scale uncertainty: M_H^{OS}-$M_H^{MSbar,pole}(\mu_{ren})$ (estimates missing corrections in the relation $\lambda^{SM,MSbar}$ and $M_h^{SM,OS}$)
- Estimate missing corrections in the relation between $m_t^{MSbar}(M_t)$ and M_t^{OS} by in/excluding corrections of $O(\alpha_S^3)$ & higher [mr by Kniehl,Pikelner,Veretin; SMDR by Martin,Robertson]

SUSY uncertainties:

- scale uncertainty by varying Q_{match}: estimates missing 2-loop corrections in the matching condition
- for the quartic coupling matching: difference between the quartic-coupling and pole-mass matching as an estimate of the v/M_{SUSY} terms that are not included in the quartic-coupling matching

Information on Used Benchmark Point

	$\tan\beta$	λ	κ	M_1	M_2	M_3	A_0	A_λ	A_κ	$\mu_{eff.}$	$m_{\tilde{Q}_L}$	$m_{\tilde{t}_R}$
BP1	1.27	0.73	0.62	0.14	1.18	2.3	-0.39	0.06	-1.44	0.49	1.79	1.51

All parameters with mass dimension are given in units of TeV. All soft SUSY breaking trilinear couplings are set equal to A_0, all soft SUSY breaking left-handed doublet and Right-handed singlet masses are set equal to $m_{\tilde{Q}L}$ and $m_{\tilde{t}R}$, respectively.

Di-Higgs Beats Single-Higgs

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

Possible for models w/ singlet-dominated (suppressed couplings to SM particles) and/or h_d-like (suppressed direct production) non-SM-like Higgs boson => **NMSSM benchmark:**

λ	κ	A_λ [GeV]	A_κ [GeV]	$\mu_{\rm eff}$ [GeV]	$\tan\beta$
0.593	0.390	296	5.70	200	2.815
$m_{H^\pm}$ [GeV]	M_1 [GeV]	M_2 [GeV]	M_3 [TeV]	A_t [GeV]	A_b [GeV]
505	989.204	510.544	2	-2064	-1246
$m_{\tilde{Q}_3}$ [GeV]	$m_{\tilde{t}_R}$ [GeV]	$m_{\tilde{b}_R}$ [GeV]	A_τ [GeV]	$m_{\tilde{L}_3}$ [GeV]	$m_{\tilde{\tau}_R}$ [GeV]
1377	1207	3000	-1575.91	3000	3000

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_{A_1} [GeV]	m_{A_2} [GeV]
127.78	253	518	116	508
$\Gamma^{tot}_{H_1}$ [GeV]	$\Gamma^{tot}_{H_2}$ [GeV]	$\Gamma^{tot}_{H_3}$ [GeV]	$\Gamma^{tot}_{A_1}$ [GeV]	$\Gamma^{tot}_{A_2}$ [GeV]
$4.264\ 10^{-3}$	0.466	3.145	9.910^{-7}	4.750
h_{11}	h_{12}	h_{13}	h_{21}	h_{22}
0.325	0.939	-0.112	0.234	0.034
h_{23}	h_{31}	h_{32}	h_{33}	a_{11}
0.971	0.916	-0.321	-0.209	-0.0063
a_{21}	a_{13}	a_{23}		
-0.0022	0.999	0.0067		

singlet-like H_2

Di-Higgs Beats Single-Higgs

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

Possible for models w/ singlet-dominated (suppressed couplings to SM particles) and/or h_d-like (suppressed direct production) non-SM-like Higgs boson => **NMSSM benchmark:**

H_2 is singlet-like: dominant decay channel into A_1 A_1

Single Higgs Production (4b final state)

$$\sigma^{\rm NNLO}(H_2)_{4b} = \sigma^{\rm NNLO}(H_2) \times {\rm BR}(H_2 \to A_1 A_1) \times {\rm BR}(A_1 \to b\bar{b})^2$$
$$= 13.54 \times 0.887 \times 0.704^2 \text{ fb} = 5.95 \text{ fb} \,.$$

Di-Higgs Production (6b final state)

$$\sigma^{\rm NLO}(H_1 H_2) = 111 \text{ fb} \qquad {\rm BR}(H_1 \to b\bar{b}) = 0.539$$

$$\sigma^{\rm NLO}(H_1 H_2) \times {\rm BR}(H_1 \to b\bar{b}) \times {\rm BR}(H_2 \to A_1 A_1) = 53 \text{ fb}$$

$$\sigma^{\rm NLO}(H_1 H_2)_{6b} = 53 \times 0.704^2 \text{ fb} = 26 \text{ fb}$$

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], WW$\gamma\gamma$: [ATLAS,1807.08567]
  bb$\gamma\gamma$: [ATLAS,1807.04873]; bbWW: [ATLAS,1811.04671, bbZZ: [CMS,2006.06391]
  bb$\tau\tau$: [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

Allowed values of the trilinear Higgs self-coupling

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

	R2HDM		C2HDM	
	$y_{t,H_{SM}}^{R2HDM}/y_{t,H}$	$\lambda_{3H_{SM}}^{R2HDM}/\lambda_{3H}$	$y_{t,H_{SM}}^{C2HDM}/y_{t,H}$	$\lambda_{3H_{SM}}^{C2HDM}/\lambda_{3H}$
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	
	$y_{t,H_{SM}}^{N2HDM}/y_{t,H}$	$\lambda_{3H_{SM}}^{N2HDM}/\lambda_{3H}$	$y_{t,H_{SM}}^{NMSSM}/y_{t,H}$	$\lambda_{3H_{SM}}^{NMSSM}/\lambda_{3H}$
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	–	–	–	–

Allowed values of the trilinear Higgs self-coupling

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

	R2HDM		C2HDM	
	$y^{\rm R2HDM}_{t,H_{\rm SM}}/y_{t,H}$	$\lambda^{\rm R2HDM}_{3H_{\rm SM}}/\lambda_{3H}$	$y^{\rm C2HDM}_{t,H_{\rm SM}}/y_{t,H}$	$\lambda^{\rm C2HDM}_{3H_{\rm SM}}/\lambda_{3H}$
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	
	$y^{\rm N2HDM}_{t,H_{\rm SM}}/y_{t,H}$	$\lambda^{\rm N2HDM}_{3H_{\rm SM}}/\lambda_{3H}$	$y^{\rm NMSSM}_{t,H_{\rm SM}}/y_{t,H}$	$\lambda^{\rm NMSSM}_{3H_{\rm SM}}/\lambda_{3H}$
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.
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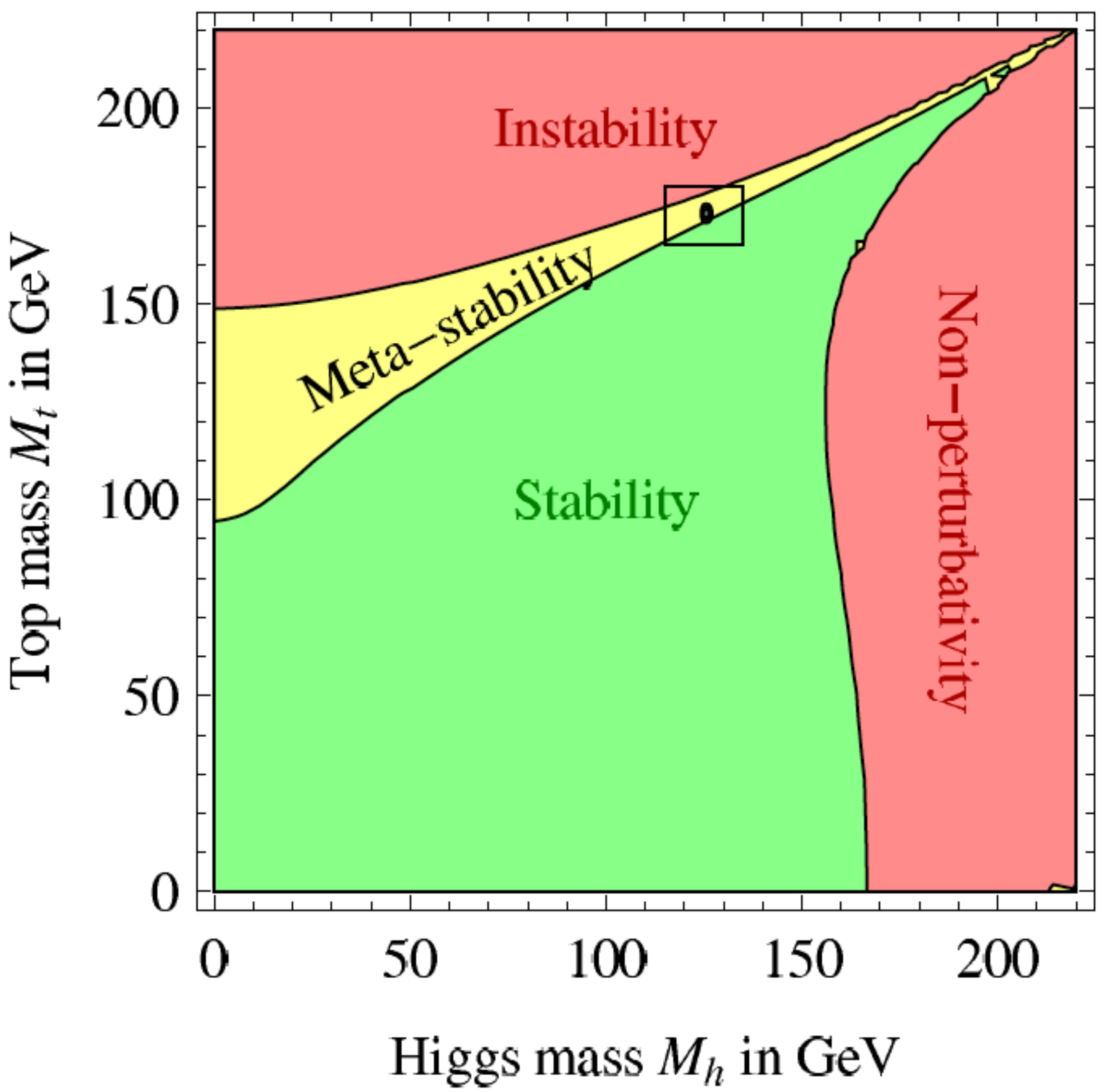
light II	0.942...1.038	-0.608...0.999	0.826...1.003	0.024...0.747
medium II	0.942...1.029	0.613...0.994	0.916...1.000	-0.502...0.666
heavy II	–	–	–	–

some models: λ_{HHH} compatible
w/ zero still possible

Stability of the Electroweak Vacuum

[Degrassi,Di Vita,Elias-Miro,Espinosa,'12]



[Bednyakov,Kniehl,Pikelner,Veretin,'15]