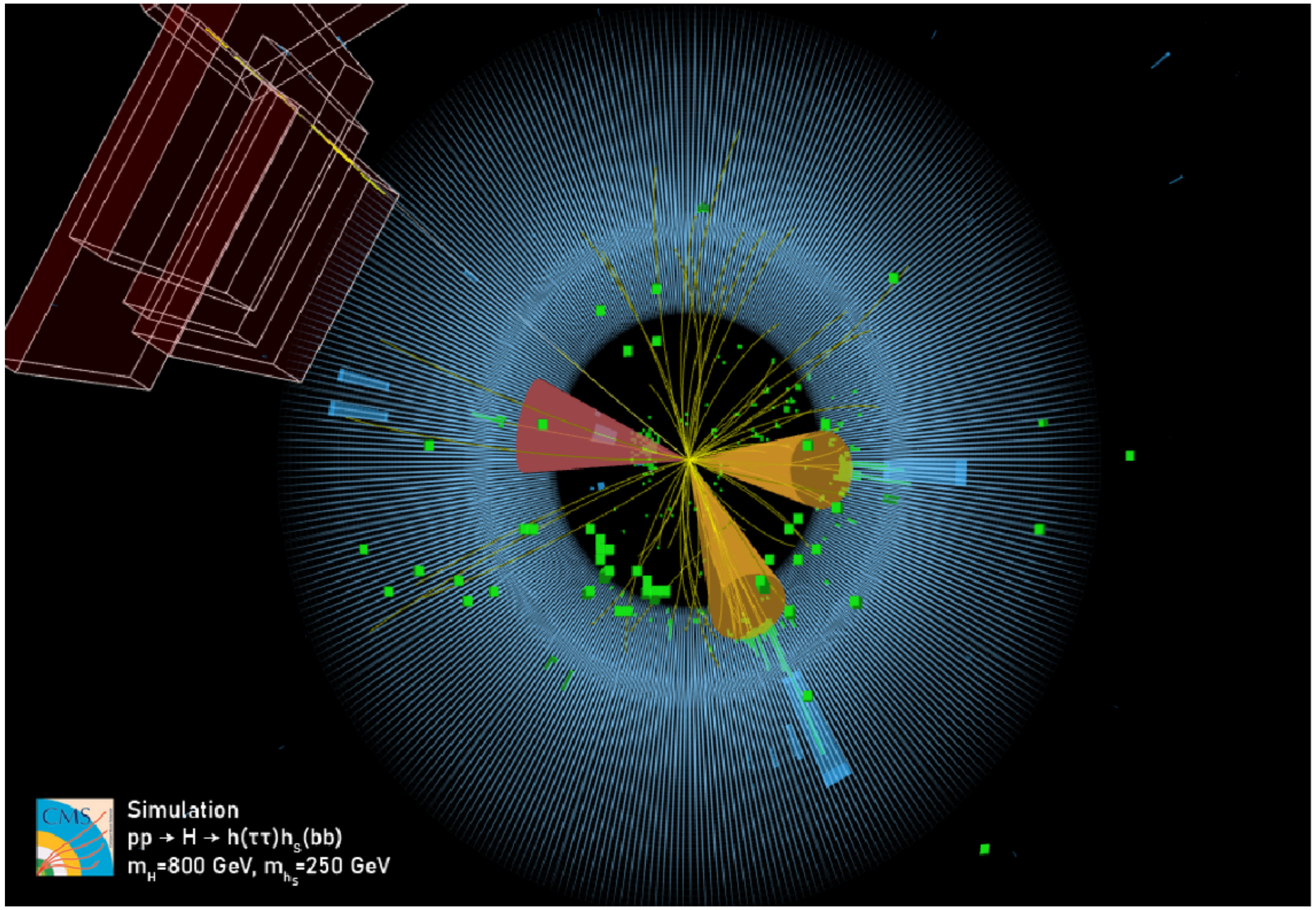
Experimental results for NMSSM
$H \rightarrow H_S\, h_{125} \rightarrow bb\tau\tau$ search



LHC Higgs WG workshop

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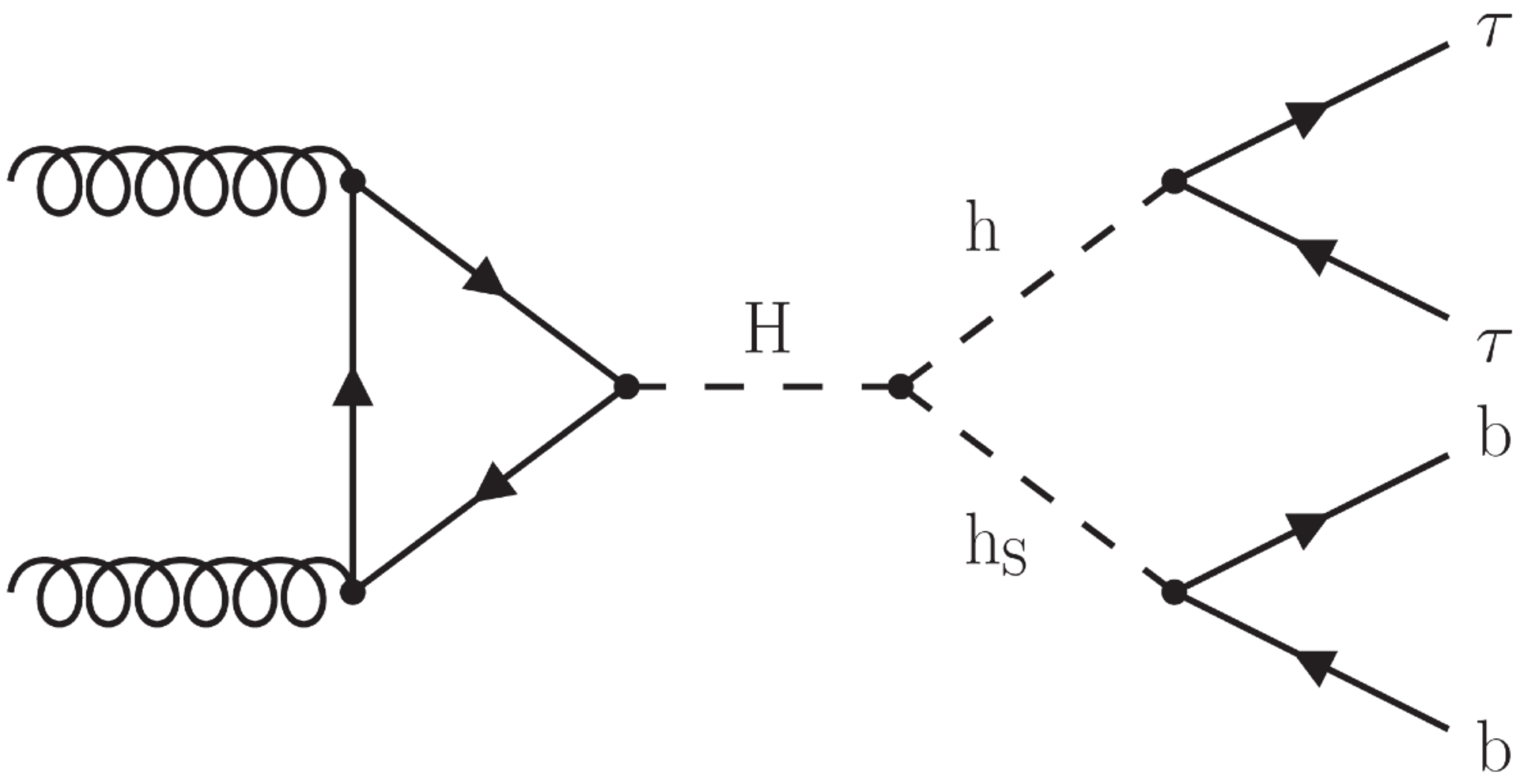
Introduction

- In NMSSM one (pseudo)scalar can have large singlet component which means direct production cross section is suppressed

- But production by decay of heavier H (A) can have sizeable cross section: $H \rightarrow H_S h_{125}$ ($A \rightarrow A_S h_{125}$)

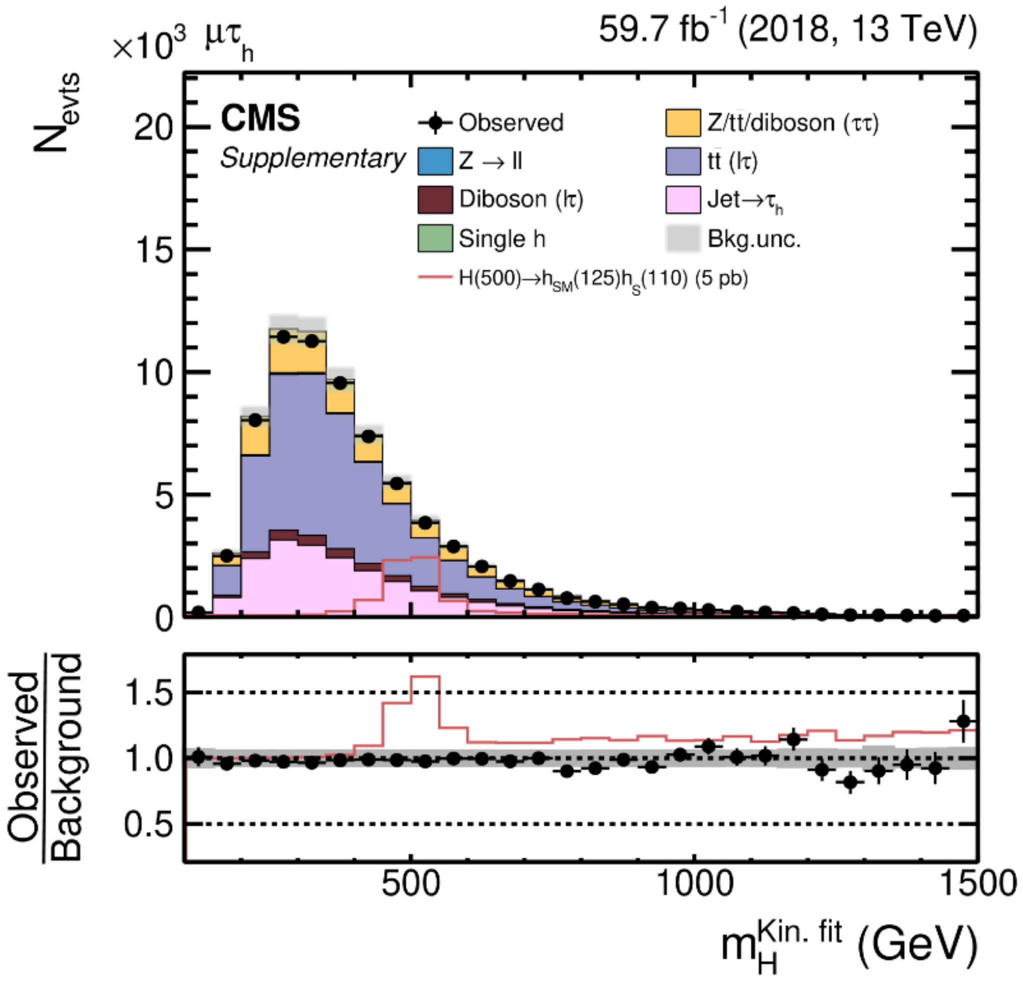
- Several analyses ongoing to search for such decays with various final states

- In these slides we will show an example from CMS in the bb$\tau\tau$ final state: [CMS-HIG-20-014]



Analysis strategy

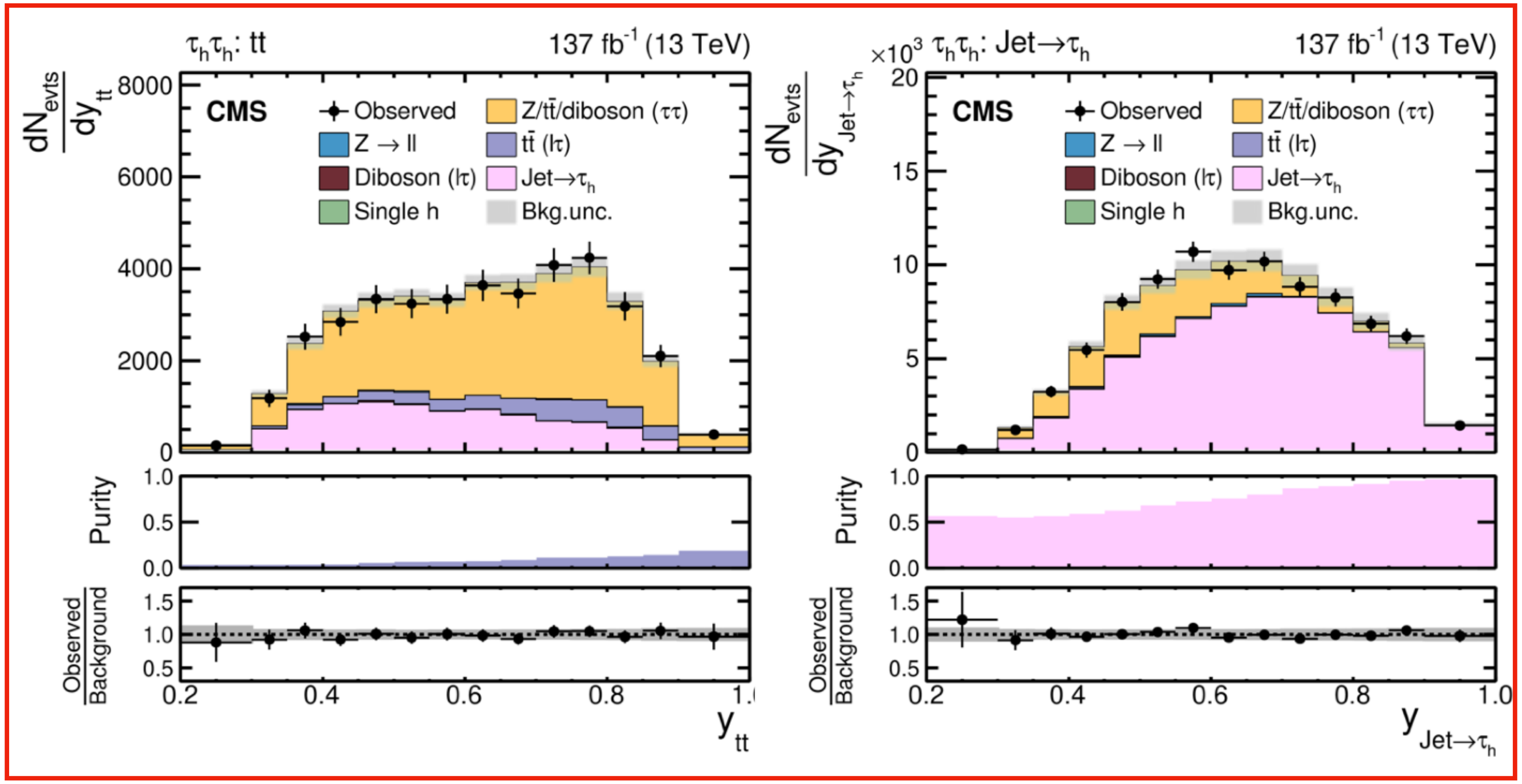
- The analysis uses leptonic (τ_e/τ_μ) and hadronic (τ_h) tau decays
- Events split into three channels: $\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_h\tau_h$
- To separate signal from background a neural network (NN) is used
- Input variables include: masses, τ/jet p_Ts, N_{bjets}, b-jet ID scores
- Trained separately for different mass hypotheses (split by m_H and m_{H_S})
- Backgrounds modelled by data driven methods + simulations



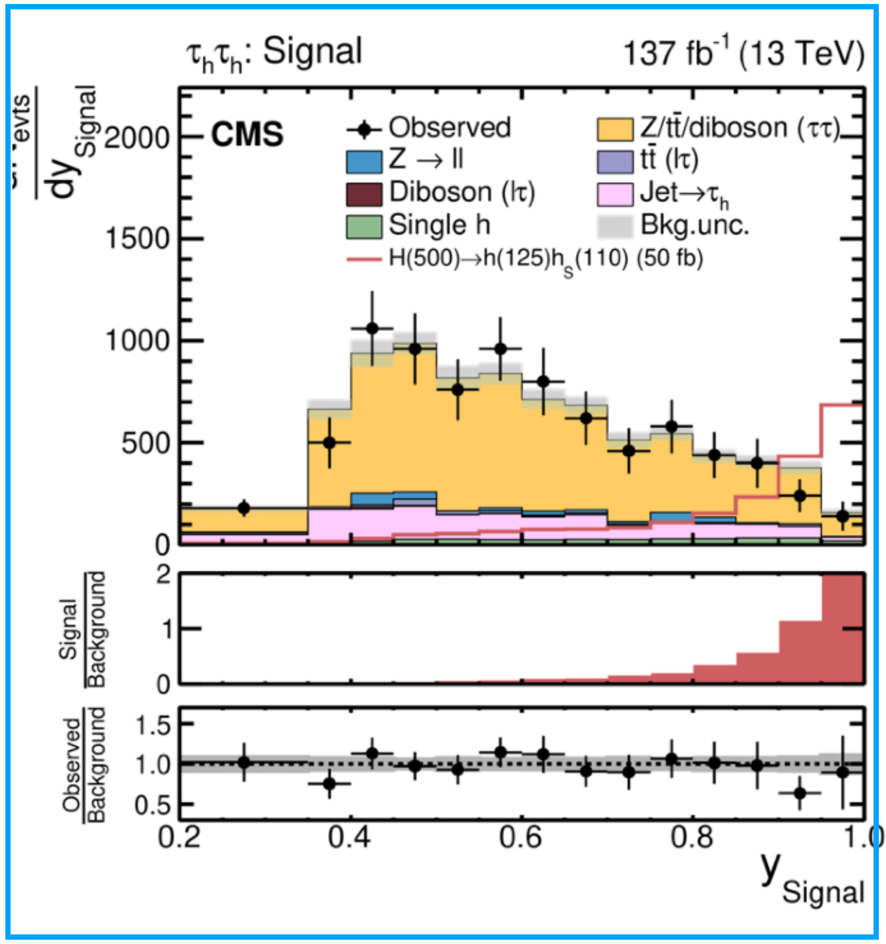
NN Distributions

- Multi-class NN used, 4x background classes + 1 signal class
- Output is 5 scores, yi, that sum to 1
- Allocate events to categories based on largest y_i
- In each category fit maximum y_i as discriminating variable

Background categories



Signal categories

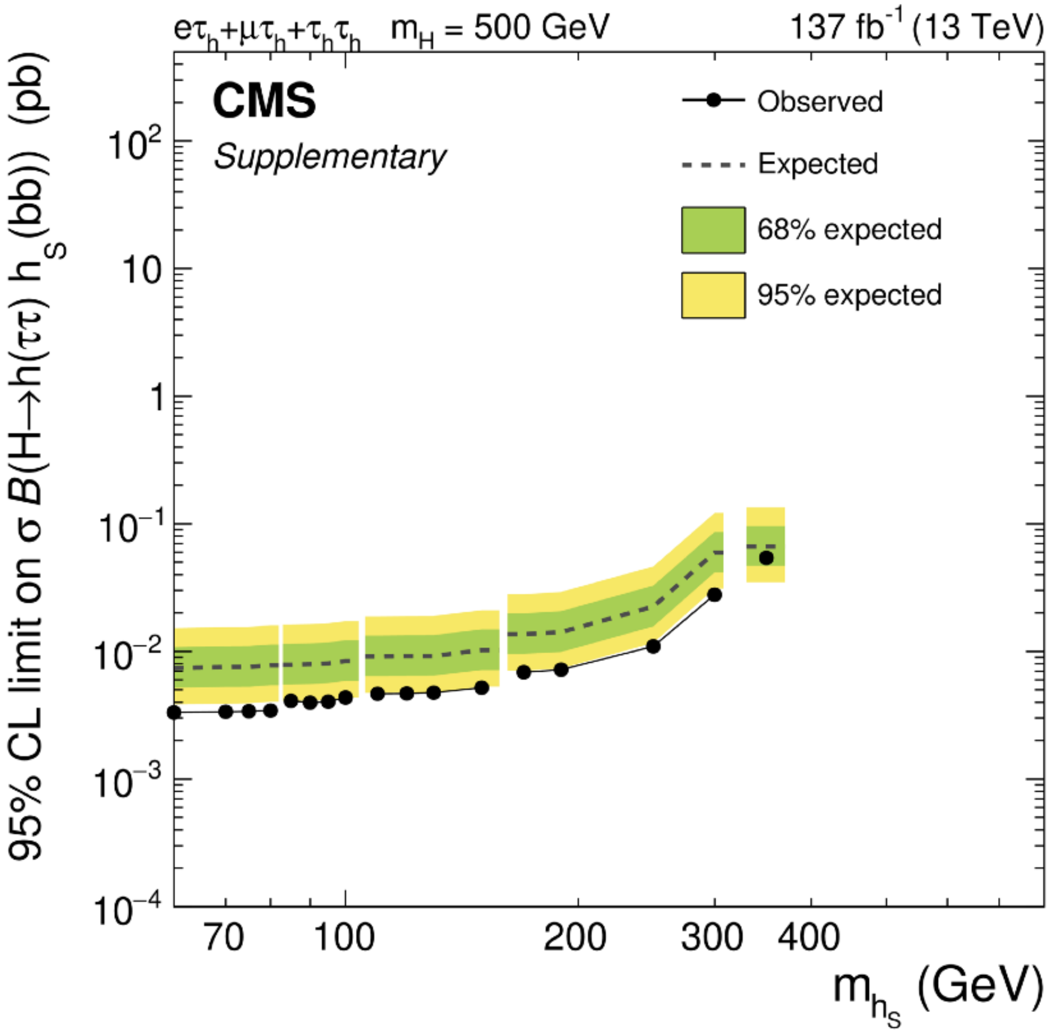


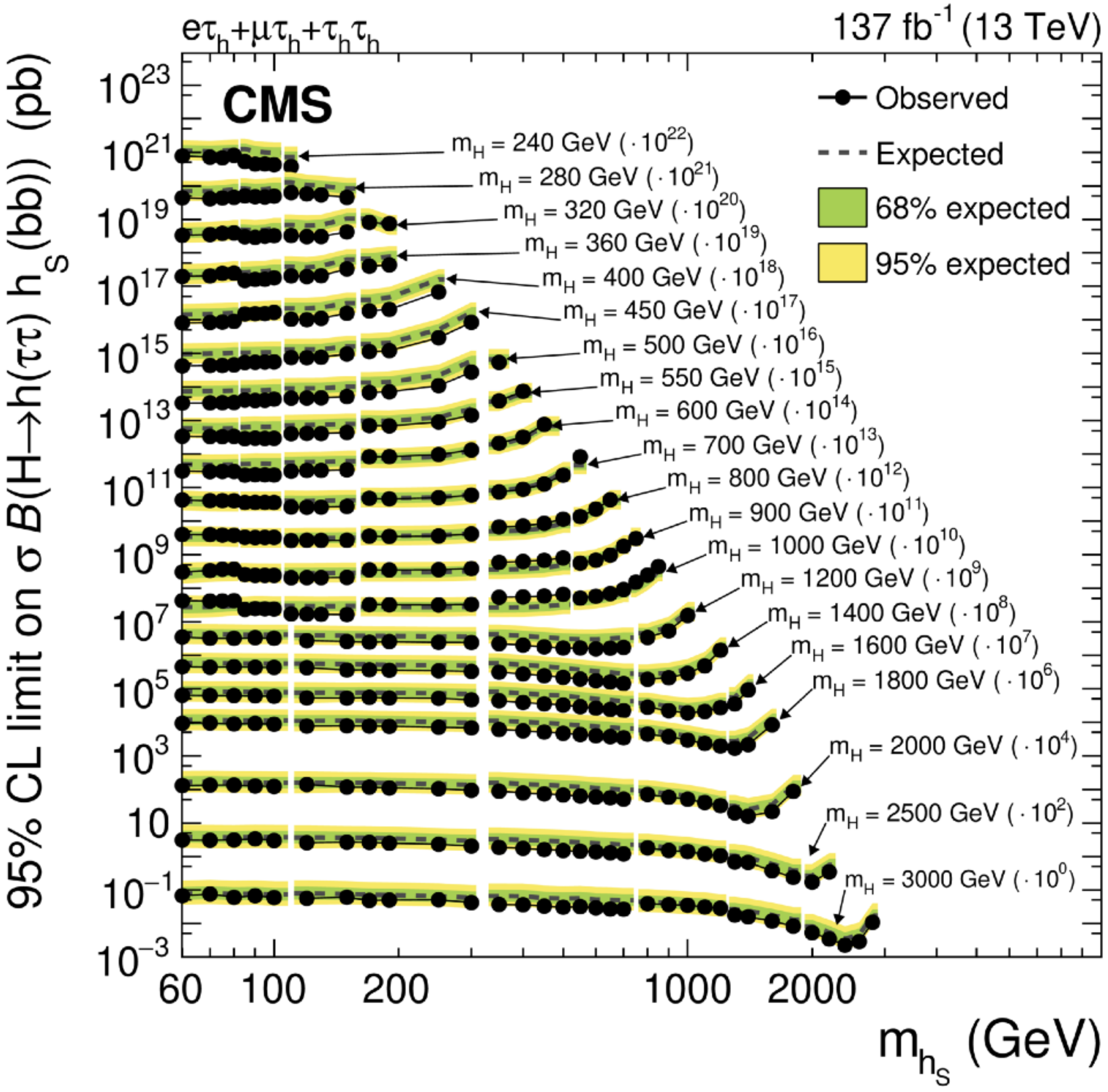
Results

- Analysis searched for m_H between 240—3000 GeV and m_{Hs} between 60–2800 GeV

- No statistically significant excesses observed

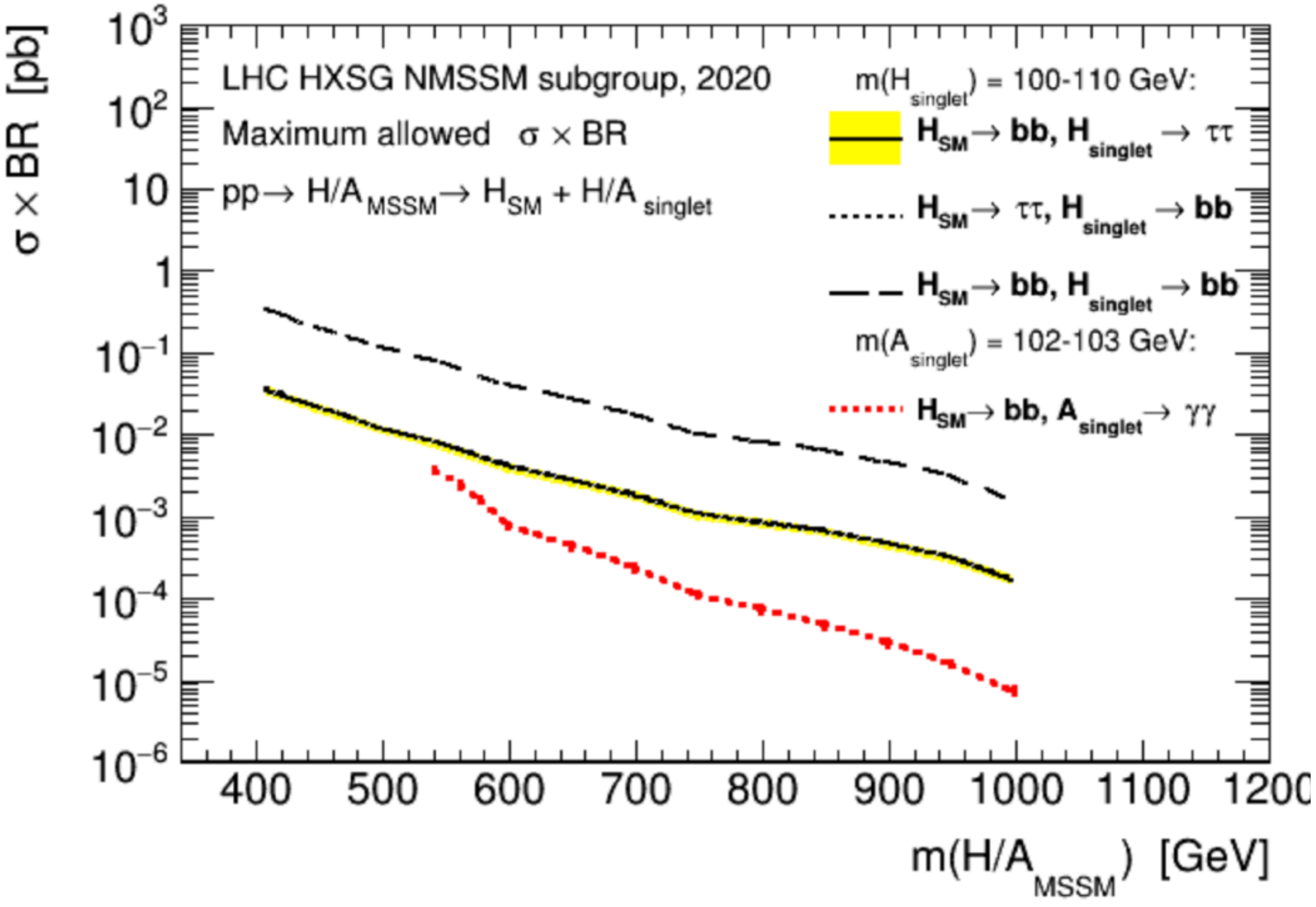
- Upper limits set on $\sigma \times BR$

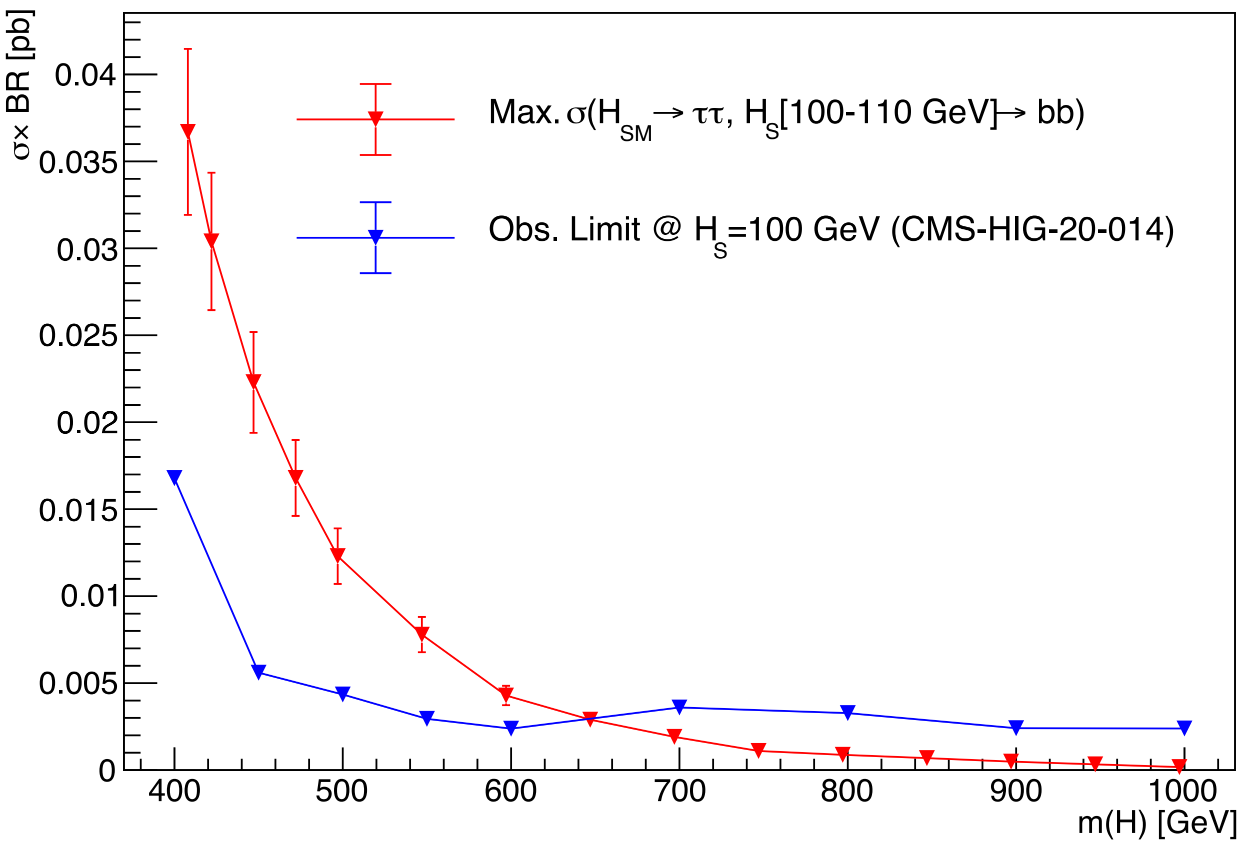




Comparison with NMSSM cross sections

- To assess sensitivity to NMSSM the upper limits are compared to the maximum allowed cross sections (see talk by Ulrich)
- Cross sections original only provided only for ~ constant m_{Hs} (100–110 GeV)
- Analysis is sensitive to NMSSM for m_H ~< 650 GeV





[NMSSMBenchmarksMarch2020]

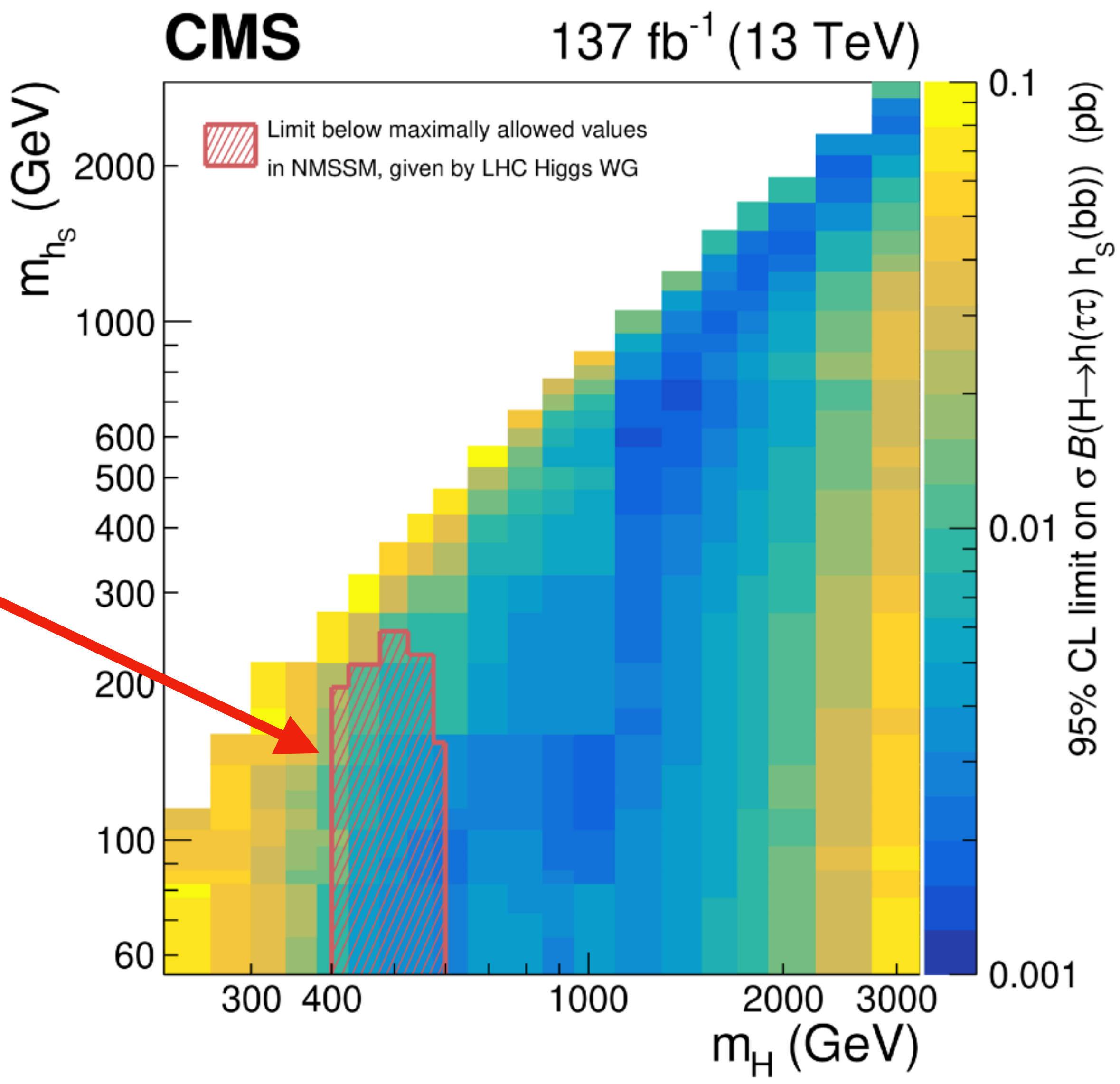
[HepData]

Comparison with NMSSM cross sections

- To enable 2D exclusion region of maximally allowed cross sections NMSSM working group provided additional m_{Hs} points close to exclusion boundaries

- Using linear interpolation 2D exclusion region was determined

More information about how this interpolation was performed is included [here] (linked from the main NMSSM subgroup twiki)



Summary

- Searched for processes well motivated in the NMSSM
- Presented an example experimental result by CMS in the bb$\tau\tau$ final state
- Comparison to maximum allowed cross sections provided by NMSSM working group show that this analysis is sensitive to the NMSSM in some mass regions
- Several complimentary other final states e.g bbbb, bbɣɣ, $\tau\tau$bb ($H_S \rightarrow \tau\tau$ $h_{125} \rightarrow bb$)
  - We strongly encourage the these searched and we look forward to seeing the results in future

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Maximally possible Xsections for $ggF \to H_{heavy} \to (H_{125} \to bb) + (H_{singlet} \to bb)$ in the NMSSM

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December 2, 2021

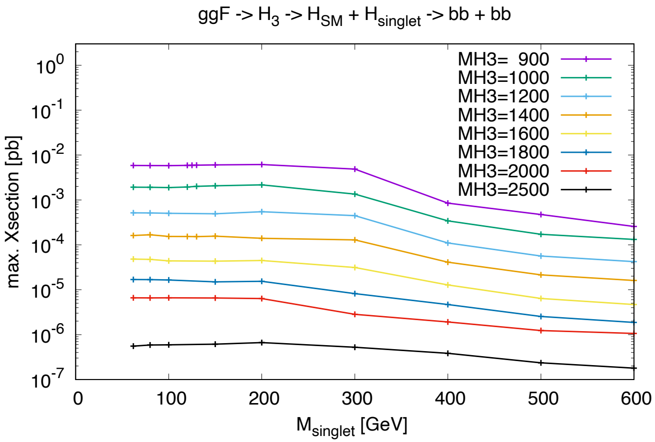
The process $ggF \to H_{heavy} \to (H_{125} \to bb) + (H_{singlet} \to bb)$
is one of the promising channels to look for an extended Higgs sector in the NMSSM

How large can this cross section be, for
various masses of $H_{heavy} \equiv H_3 \simeq H_{MSSM}$ and $H_{singlet}$?

→ Scan the parameter space using NMSSMTools, using a dedicated Monte Carlo routine, consistent with

- SM Higgs Mass + couplings (kappas) within present bounds,
- LHC searches for BSM Higgses,
- B-Physics,
- constraints from dark matter direct detection experiments.

(The NMSSM contains a neutral stable LSP which must not violate these constraints even if its relic density is below the observed one, in which case an additional hidden sector has to be assumed.)



Rough estimate of possible sensitivities:
$\mathcal{O}(10^{-3})$ pb, increase to $\mathcal{O}(10^{-4}) - \mathcal{O}(10^{-5})$ pb for larger masses

→ Discoveries are possible (but not guaranteed!)

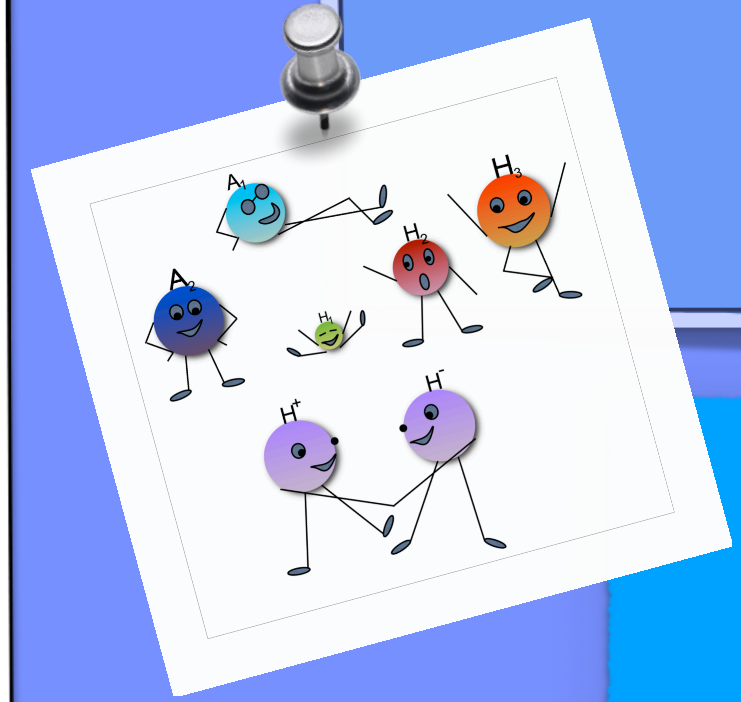
Comments:

- $M_{Hs} > 62$ GeV since otherwise the parameter space is strongly constraint by limits on $H_{125} \to H_s + H_s$ leading to significantly smaller allowed Xsections.
- Otherwise: max. Xsection nearly independent from M_{Hs} (also for $M_{Hs} \sim 125$ GeV; interference effects show up only if $M_{H_{125}} - M_{Hs} \sim \Gamma_{H_{125}} \sim 4$ MeV)
- Decreasing Xsection for $M_{Hs} > 250$ GeV where $Hs \to H_{125} + H_{125}$ becomes possible reducing the $BR(Hs \to bb)$
- Further decrease of the Xsection for $M_{Hs} > 350$ GeV where $Hs \to toptop$ becomes possible reducing the $BR(Hs \to bb)$
- Prospects: Continue towards lighter values of $M_{H_{heavy}} < 900$ GeV, repeat the exercise for other channels

Good Luck!

The 18th Workshop of the LHC Higgs Working Group

NMSSM Mass Calculation Update



M. Margarete Mühlleitner (KIT)
Conveners:
ATLAS: Nikolaos Rompotis
CMS: Daniel Winterbottom
T: Ulrich Ellwanger, MM, Nausheen Shah

Fixed Order Spectrum Calculations

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

- MSSM and NMSSM masses computed from input parameters: predictive power of the MSSM, NMSSM and other extensions -> important experimental test to be passed

Status NMSSM fixed order spectrum calculations:
up to 2-loop in mixed OS-DR scheme and in DR-scheme

- $\mathcal{O}(\alpha_t\alpha_s+\alpha_b\alpha_s)$ CP-conserving, in DRbar scheme, effective potential approach [Degrassi,Slavich,'10]
- Beyond $\mathcal{O}(\alpha_t\alpha_s+\alpha_b\alpha_s)$ CP-conserving, in gaugeless limit, DRbar scheme [Goodsell,Nickel,Staub,'15]
- CP-violating: $\mathcal{O}(\alpha_t\alpha_s)$ [MM,Nhung,Rzehak,Walz,'15] and $\mathcal{O}(\alpha_t^2)$ [Dao,Gröber,Krause,MM,Rzehak,'19] in gaugeless limit, zero-momentum limit, mixed DRbar-OS scheme, Λ=κ=0 at $\mathcal{O}(\alpha_t^2)$ => calculation of $\mathcal{O}((\alpha_t+\alpha_\lambda+\alpha_\kappa)^2)$

Further Recent Precision Developments

Further (recent) developments:

- Complete 1-loop + $\mathcal{O}(\alpha_t(\alpha_s + \alpha_t))$ in NMSSM w/ inverse seesaw mechanism, mixed DRbar-OS scheme [Dao,MM,Phan,'21]
- FlexibleDecay: automated calculator of scalar decay widths in any BSM model [Athron,Büchner,Harries,Kotlarski,Stöckinger,Voigt,'21]
- Curing tachyonic tree-level syndrome in the NMSSM w/ light singlets [Domingo,Paßehr,'21]
- Minimize gauge-fixing parameter and field renormalization dependence in of mass and decay observables at 1-loop order [Domingo,Paßehr,'20]
- 1-loop corrections to 2-body decays of $H^\pm$ in CP-conserving and CP-violating NMSSM [Dao,MM,Patel,Sakurai,'20]

Review:

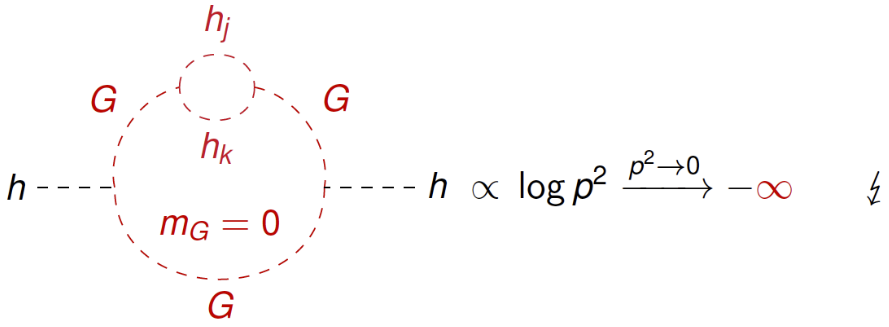
- Higgs mass predictions in the MSSM and beyond [Slavich,Heinemeyer et al.,'20]

Two-Loop $\mathcal{O}((\alpha_t + \alpha_\lambda + \alpha_\kappa)^2)$ Corrections

[Dao,Gabelmann,MM,Rzehak,´21]

Two-Loop $\mathcal{O}((\alpha_t + \alpha_\lambda + \alpha_\kappa)^2)$ corrections in the CP-violating NMSSM:

- mixed DRbar-OS renormalization, choice OS or DRbar in top/stop sector
- vanishing external momentum
- & gaugeless limit -> Goldstone boson catastrophe



Goldstone boson catastrophe:

- MSSM: Higgs self-couplings given by gauge couplings

$$V^{\text{quartic}}_{\text{MSSM}} \propto g_1{}^2(|H_u|^2 - |H_d|^2)^2 + g_2{}^2(H_u\sigma_a H_u + H_d\sigma_a H_d)^2 \xrightarrow{g_1, g_2 \to 0} 0$$

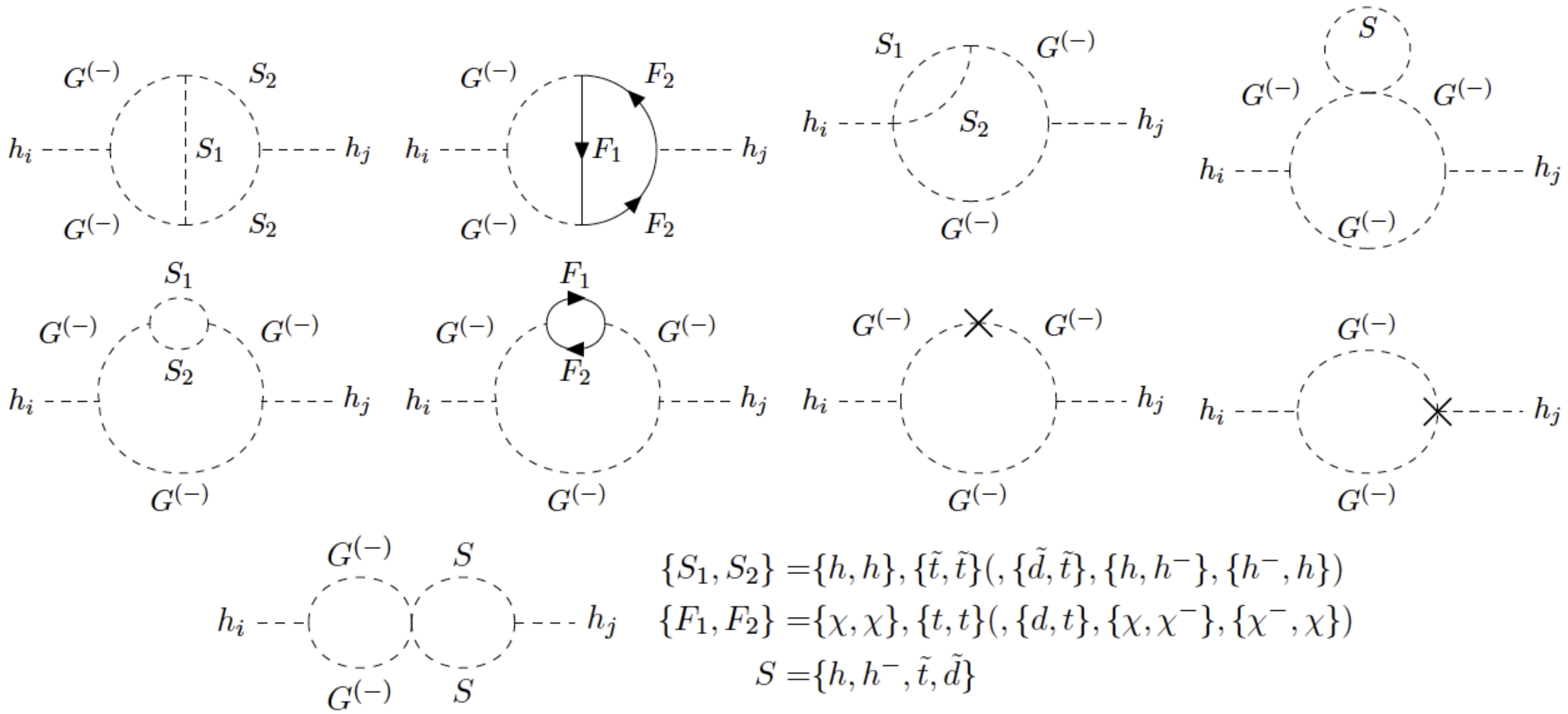
- NMSSM: additional non-zero self-couplings

$$V^{\text{quartic}}_{\text{NMSSM}} \propto V^{\text{quartic}}_{\text{MSSM}} + |\lambda H_u H_d + \kappa S^2|^2 \xrightarrow{g_1, g_2 \to 0} \neq 0$$

=> many new two-loop diagrams with Higgs self-couplings
massless Goldstone bosons => IR divergences

Regularisation of IR Divergences

Infrared-divergent
2-loop self-energies



$$\{S_1,S_2\} = \{h,h\},\{\tilde{t},\tilde{t}\}(,\{\tilde{d},\tilde{t}\},\{h,h^-\},\{h^-,h\})$$
$$\{F_1,F_2\} = \{\chi,\chi\},\{t,t\}(,\{d,t\},\{\chi,\chi^-\},\{\chi^-,\chi\})$$
$$S = \{h,h^-,\tilde{t},\tilde{d}\}$$

Regularisation:

- use mass regulator M^2_R in IR-divergent loop integrals (check dependence on regulator mass)
- assume $p^2 \neq 0$ in $\mathcal{O}((\alpha_t+\alpha_\lambda+\alpha_\kappa)^2)$ diagrams -> multi-scale problem (numerical integration required `TSIL` [Robertson,Martin,'06])
- assume partial $p^2 \neq 0$: only in IR-divergent diagrams, analytic results for small p^2 expansion [Braathen,Goodsell,´16,'17]

Numerical Results

New corrections implemented in `NMSSMCALC` [Baglio,Gabelmann,Gröber,Krause,Rzehak,MM,Nhung,Spira,Streicher,Walz]

Scan in NMSSM parameter space:

$\kappa = \lambda\cdot\xi > 0.7$ omitted

A_i = 3 TeV, i=b,τ,κ

SUSY breaking masses and trilinear couplings: DRbar parameters at

$\mu_0 = M_{\rm SUSY} = \sqrt{m_{\tilde{Q}_3} m_{\tilde{t}_R}}$

parameter	scan range [TeV]
$M_{H^\pm}$	[0.5, 1]
M_1, M_2	[0.4, 1]
M_3	2
$\mu_{\rm eff}$	[0.1, 1]
$m_{\tilde{Q}_3}, m_{\tilde{t}_R}$	[0.4, 3]
$m_{\tilde{X}\neq\tilde{Q}_3,\tilde{t}_R}$	3

parameter	scan range
$\tan\beta$	[1, 10]
λ	[0.01, 0.7]
κ	$\lambda\cdot\xi$
ξ	[0.1,1.5]
A_t	[-3, 3] TeV
$A_{i\neq t}$	[-2, 2] TeV

compatibility with Higgs data, one Higgs, called h, must behave SM-like with $122 \lesssim m_h \lesssim 128$ GeV [HiggsSignals,HiggsBounds]

omit parameter points with mass configurations:

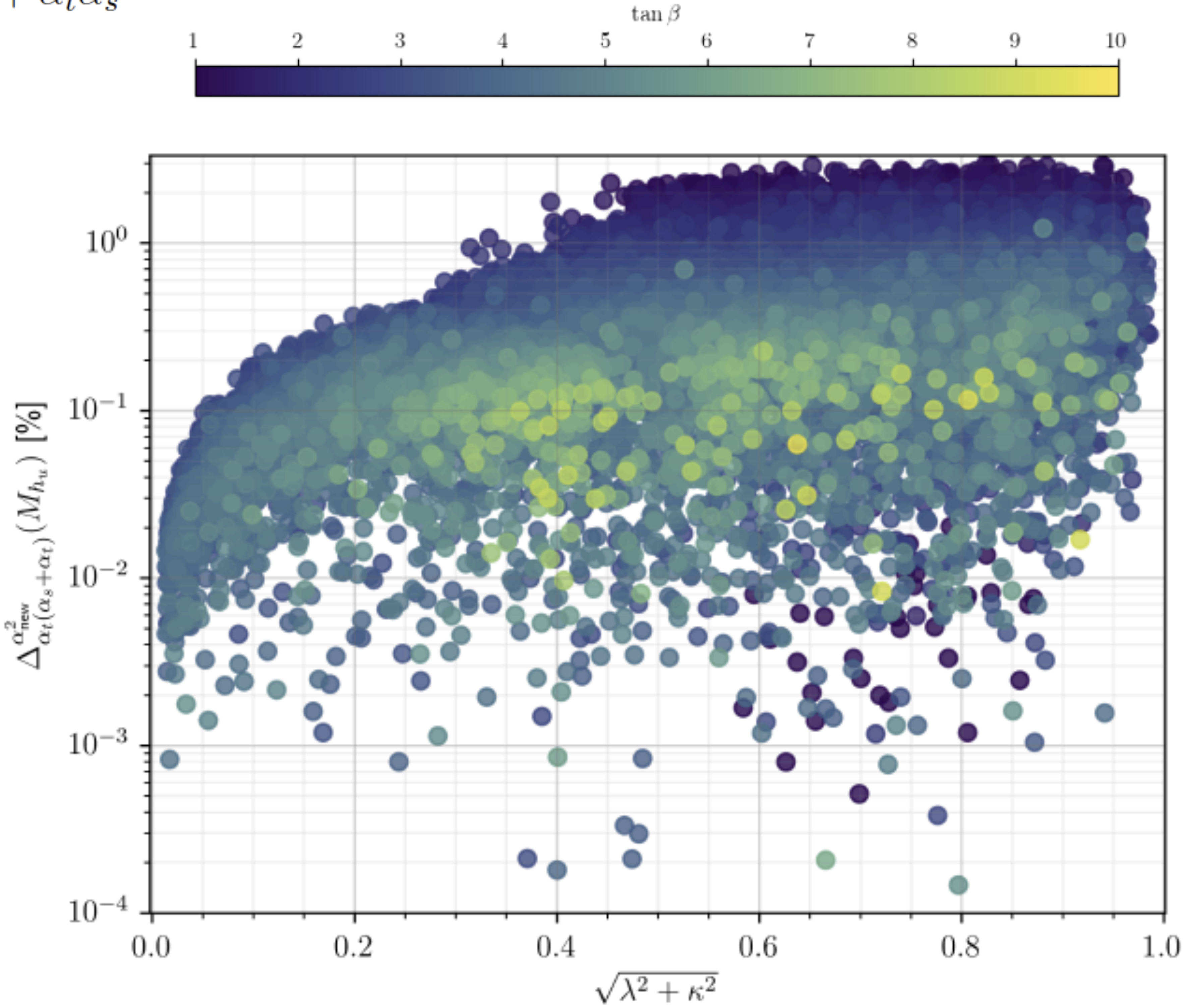
$$
\begin{aligned}
&(i) && m_{\chi_i^{(\pm)}}, m_{h_i} > 1\,\text{TeV}, m_{\tilde{t}_2} > 2\,\text{TeV}, \\
&(ii) && m_{h_i} - m_{h_j} < 0.1\,\text{GeV}, m_{\chi_i^{(\pm)}} - m_{\chi_j^{(\pm)}} < 0.1\,\text{GeV} \\
&(iii) && m_{\chi_1^\pm} < 94\,\text{GeV}, m_{\tilde{t}_1} < 1\,\text{TeV}\ .
\end{aligned}
$$

Impact of New Corrections

$$\alpha^2_{\rm new} \equiv (\alpha_t + \alpha_\lambda + \alpha_\kappa)^2 + \alpha_t\alpha_s$$

$$\Delta^{\alpha^2_{\rm new}}_{\alpha_i^2} = \frac{\left|M_h^{\alpha^2_{\rm new}} - M_h^{\alpha_i^2}\right|}{M_h^{\alpha_i^2}}$$

[Dao,Gabelmann,MM,Rzehak,´21]

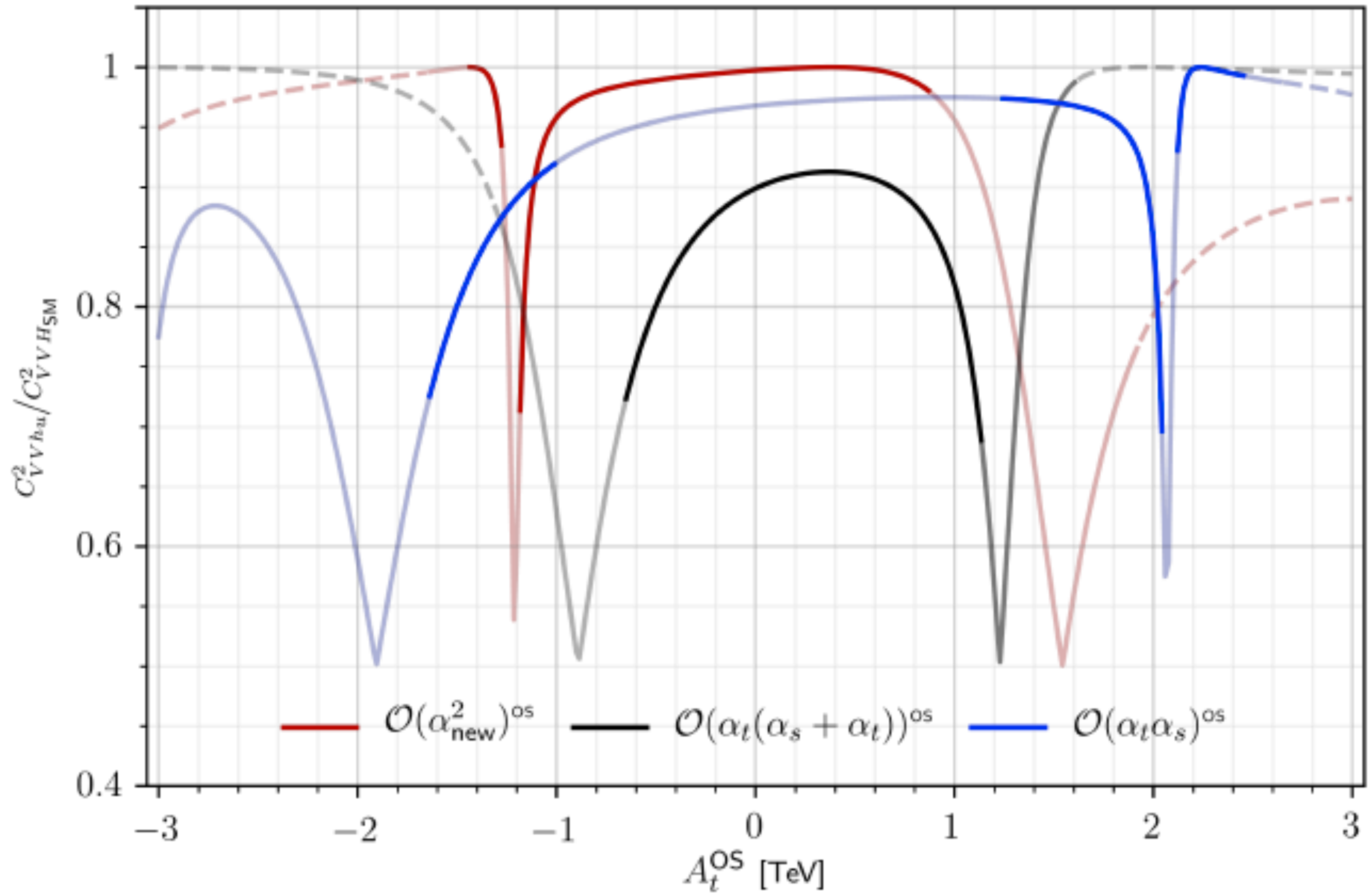


new corrections:
a few percent
relative to
available 2-loop
corrections

Phenomenological Impact

parameter point `P2OS`

[Dao,Gabelmann,MM,Rzehak,´21]



- squared coupling of SM-like Higgs to gauge bosons relative to SM value
- transparent lines: excluded by HiggsSignals or Higgs mass constraints not fulfilled
- full: h_1 is SM-like, dashed: h_2 is SM-like

Conclusions

- computation of $\mathcal{O}((\alpha_t + \alpha_\lambda + \alpha_\kappa)^2)$ corrections to CP-violating NMSSM Higgs masses at zero external momentum, in the gaugeless limit, in mixed OS-DRbar renormalisation scheme, implemented in NMSSMCALC

- 3 regularisation methods for IR divergences:
  regulator mass approach reproduces momentum-dependent results well for squared regulator masses of a permille of the squared renormalisation scale

- for perturbative λ,κ values: new corrections are of a few percent, reduce slightly theoretical uncertainty due to missing higher orders (renormalisation scheme/renormalisation scale variation)

- impact of new corrections on Higgs mixing, hence Higgs couplings to SM particles, is significant => strongly affects compatibility with the Higgs data

- impact of CP-violating phases on the new corrections is small

- next steps/open issues: uncertainty estimate, scheme choice dependence of charged Higgs mass; full external momentum at $O(\alpha_t\alpha_s)$; gauge coupling dependent corrections; 3-loop corrections; …

Thank you for your attention!

Benchmark Points - P1OS

$$\begin{aligned}
|\lambda| &= 0.46\,,\ |\kappa| = 0.43\,,\ \mathrm{Re}(A_\kappa) = -4\text{ GeV}\,,\ |\mu_{\text{eff}}| = 200\text{ GeV}\,,\ \tan\beta = 3.7\,,\\
M_{H^\pm} &= 640\text{ GeV}\,,\ m_{\tilde{Q}_3} = 1\text{ TeV}\,,\ m_{\tilde{t}_R} = 1.8\text{ TeV}\,,\ m_{\tilde{X}\neq\tilde{Q}_3,\tilde{t}_R} = 3\text{ TeV}\,,\\
A_t &= 2\text{ TeV}\,,\ A_{i\neq t,\kappa} = 0\text{ GeV}\,,\ |M_1| = 2|M_2| = 800\text{ GeV}\,,\ M_3 = 2\text{ TeV}\,.
\end{aligned}$$

$$\begin{array}{llllllll}
\text{OS:} & m_{\tilde{t}_1}^{\text{OS}} & = & 1022.64 & \text{GeV}\,, & m_{\tilde{t}_2}^{\text{OS}} & = & 1815.54 \quad \text{GeV}\\
\overline{\text{DR}}: & m_{\tilde{t}_1}^{\overline{\text{DR}}} & = & 991.64 & \text{GeV}\,, & m_{\tilde{t}_2}^{\overline{\text{DR}}} & = & 1815.40 \quad \text{GeV}
\end{array}$$

OS renormalisation in top/stop sector, in brackets: numbers for DRbar renormalisation

	h_1	h_2	h_3	a_1	a_2
tree-level main component	87.64 h_u	365.32 h_s	646.65 h_d	103.09 a_s	639.83 a_d
one-loop	133.97 (115.21)	359.42 (359.35)	646.67 (646.4)	116.51 (116.8)	639.78 (639.8)
two-loop $\mathcal{O}(\alpha_t\alpha_s)$	119.09 (119.98)	359.36 (359.37)	646.5 (646.43)	116.76 (116.69)	639.81 (639.79)
two-loop $\mathcal{O}(\alpha_t(\alpha_s+\alpha_t))$	125.58 (120.15)	359.36 (359.37)	646.6 (646.43)	116.76 (116.69)	639.81 (639.79)
two-loop $\mathcal{O}(\alpha_{\text{new}}^2)$	125.03 (120.18)	359.68 (359.59)	646.62 (646.47)	116.58 (116.63)	639.77 (639.78)

Benchmark Points - P2OS

$$\begin{aligned} |\lambda| &= 0.59\,,\ |\kappa| = 0.23\,,\ \mathrm{Re}(A_\kappa) = -546\ \mathrm{GeV}\,,\ |\mu_{\mathrm{eff}}| = 397\ \mathrm{GeV}\,,\ \tan\beta = 2.05\,, \\ M_{H^\pm} &= 922\ \mathrm{GeV}\,,\ m_{\tilde{Q}_3} = 1.2\ \mathrm{TeV}\,,\ m_{\tilde{t}_R} = 1.37\ \mathrm{TeV}\,,\ m_{\tilde{X}\neq\tilde{Q}_3,\tilde{t}_R} = 3\ \mathrm{TeV}\,, \\ A_t &= -911\ \mathrm{GeV}\,,\ A_{i\neq t,\kappa} = 0\ \mathrm{GeV}\,,\ |M_1| = 656\ \mathrm{GeV}\,,\ |M_2| = 679\ \mathrm{GeV}\,,\ M_3 = 2\ \mathrm{TeV}\,. \end{aligned} \tag{107}$$

$$\begin{array}{lllllllll} \mathrm{OS:} & m_{\tilde{t}_1}^{\mathrm{OS}} & = & 1212.54 & \mathrm{GeV}\,, & m_{\tilde{t}_2}^{\mathrm{OS}} & = & 1402.77 & \mathrm{GeV} \\ \overline{\mathrm{DR}}: & m_{\tilde{t}_1}^{\overline{\mathrm{DR}}} & = & 1190.44 & \mathrm{GeV}\,, & m_{\tilde{t}_2}^{\overline{\mathrm{DR}}} & = & 1392.33 & \mathrm{GeV} \end{array}$$

OS renormalisation in top/stop sector

	h_1	h_2	h_3	a_1	a_2
tree-level	96.86	112.10	926.25	511.34	925.86
main component	h_u	h_s	h_d	a_s	a_d
one-loop	129.01	135.09	926.69	512.55	925.08
main component	h_s	h_u	h_d	a_s	a_d
two-loop $\mathcal{O}(\alpha_t\alpha_s)$	121.36	129.7	926.37	512.62	925.11
main component	h_u	h_s	h_d	a_s	a_d
two-loop $\mathcal{O}(\alpha_t(\alpha_s+\alpha_t))$	126.09	130.04	926.49	512.62	925.11
main component	h_u	h_s	h_d	a_s	a_d
two-loop $\mathcal{O}(\alpha_{\mathrm{new}}^2)$	125.28	129.92	926.63	511.92	925.08
main component	h_u	h_s	h_d	a_s	a_d

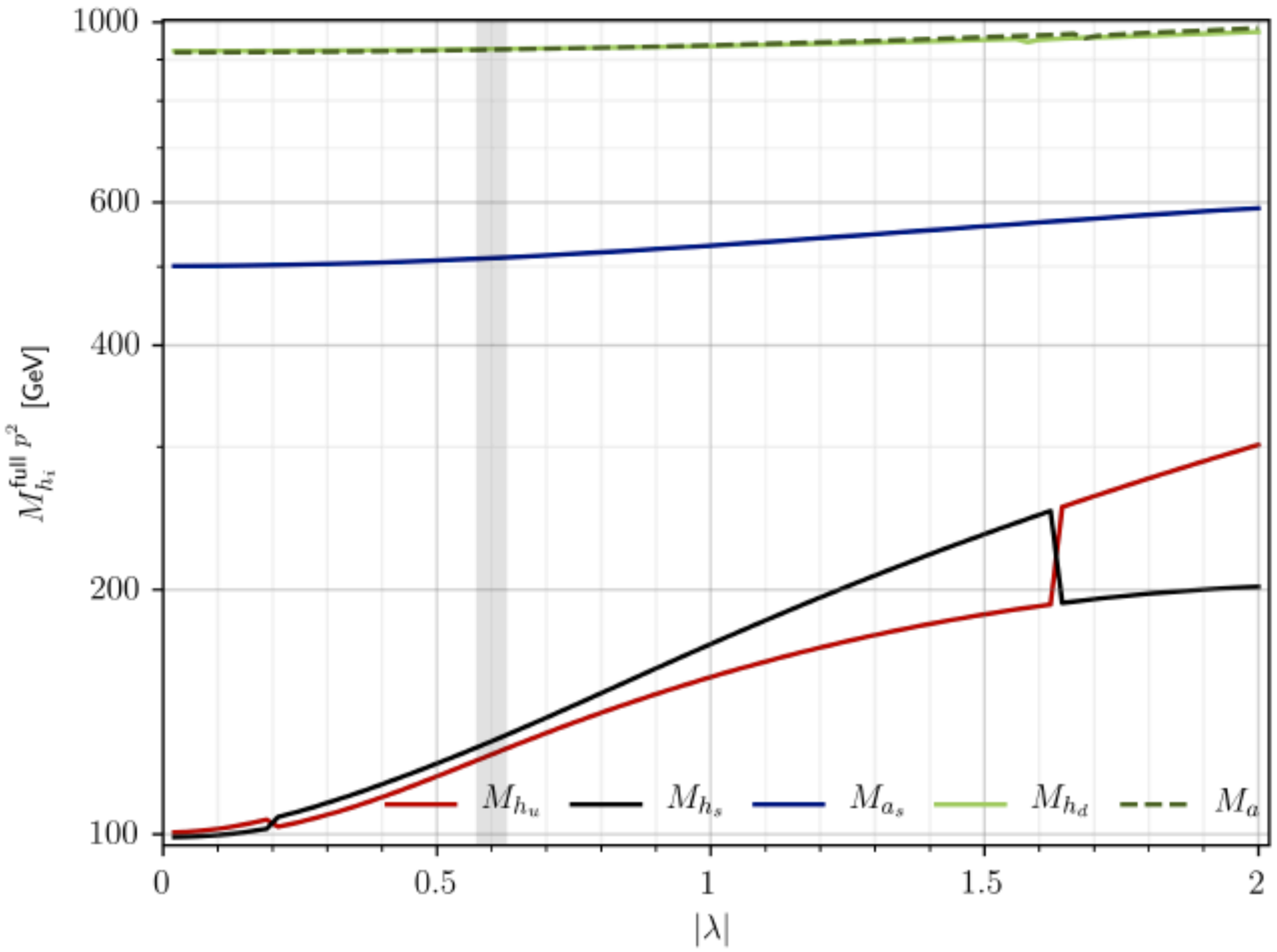
DRbar renormalisation

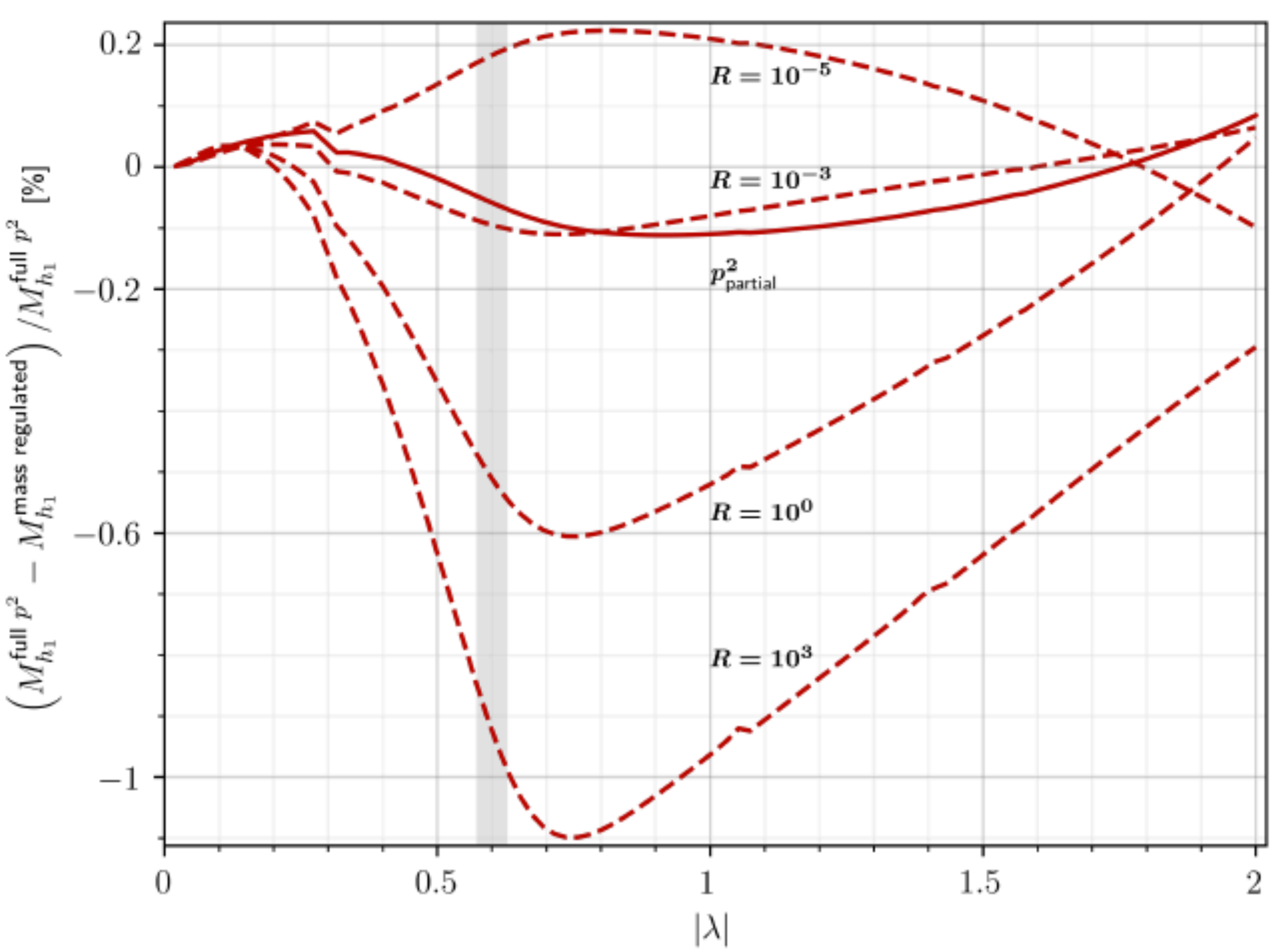
	h_1	h_2	h_3	a_1	a_2
tree-level	96.86	112.10	926.25	511.34	925.86
main component	h_u	h_s	h_d	a_s	a_d
one-loop	116.3	130.1	926.33	512.66	925.18
two-loop $\mathcal{O}(\alpha_t\alpha_s)$	121.65	130.39	926.46	512.61	925.15
two-loop $\mathcal{O}(\alpha_t(\alpha_s+\alpha_t))$	121.54	130.38	926.45	512.61	925.15
two-loop $\mathcal{O}(\alpha_{\mathrm{new}}^2)$	121.69	130.2	926.53	512.12	925.15

Comparison of Regularization Schemes

P20S at $\mathcal{O}(\alpha_{\text{new}}^2)$

[Dao,Gabelmann,MM,Rzehak,´21]





left: $M_{h_1}^{full-p^2}$, i.e. $p^2 \neq 0$ in $\mathcal{O}((\alpha_t + \alpha_\lambda + \alpha_\kappa)^2)$ diagrams

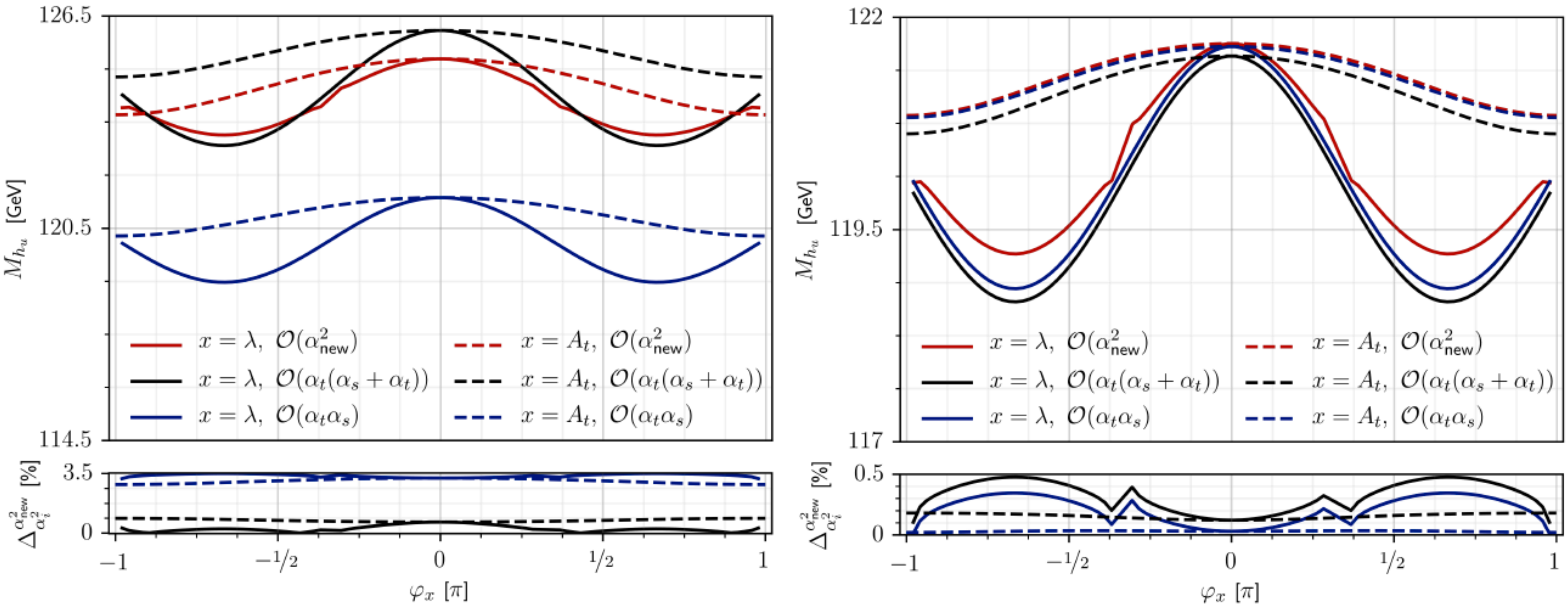
right: comparison of $M_{h_1}^{full-p^2}$ with mass regulator and with partial momentum results

R = M_R^2/μ_R^2

Radiatively Induced Effect of CP Violation

[Dao,Gabelmann,MM,Rzehak,´21]

parameter point `P2OS`



- phases not varied simultaneously
- lambda phase varied such that tree-level CP violation in Higgs sector is zero

$$\Delta^{\alpha^2_{\text{new}}}_{\alpha_i^2} = \frac{\left|M_h^{\alpha^2_{\text{new}}} - M_h^{\alpha_i^2}\right|}{M_h^{\alpha_i^2}}$$

Impact of New Corrections

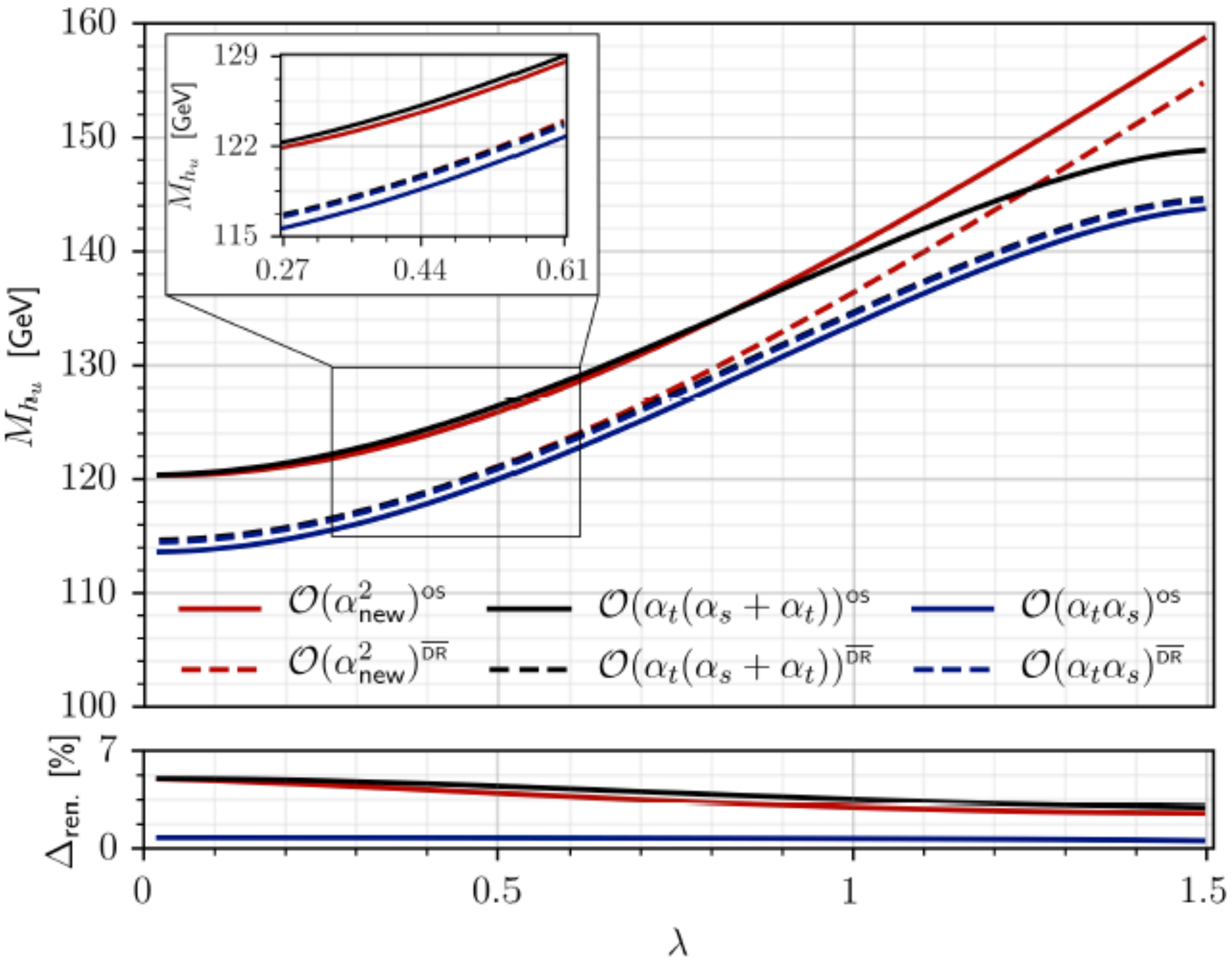
parameter point `P1OS`

[Dao,Gabelmann,MM,Rzehak,´21]

$$\alpha^2_{\text{new}} \equiv (\alpha_t + \alpha_\lambda + \alpha_\kappa)^2 + \alpha_t \alpha_s$$

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

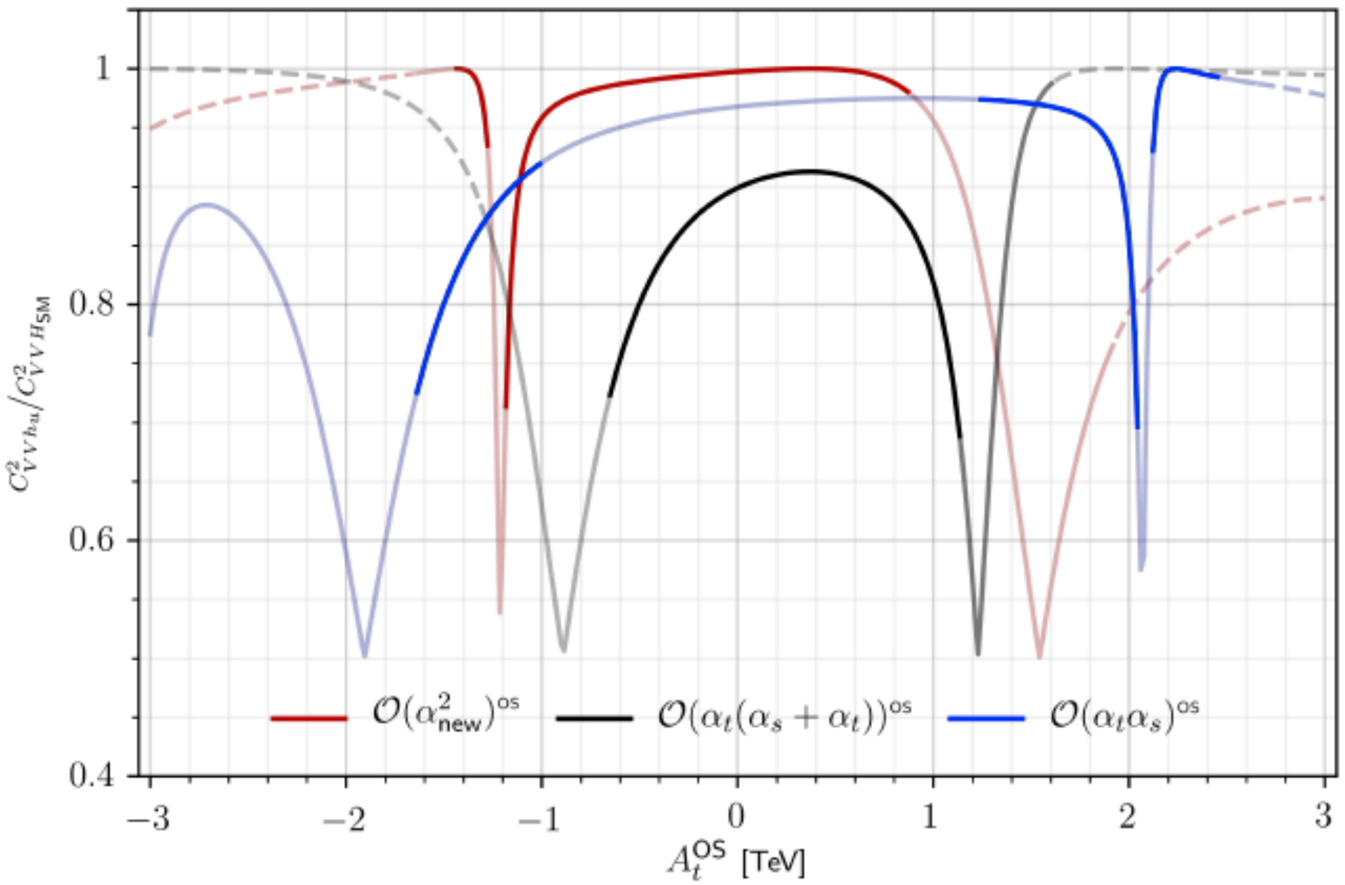
- new corrections a few percent relative to available 2-loop
- renormalisation scheme dependence slightly reduced

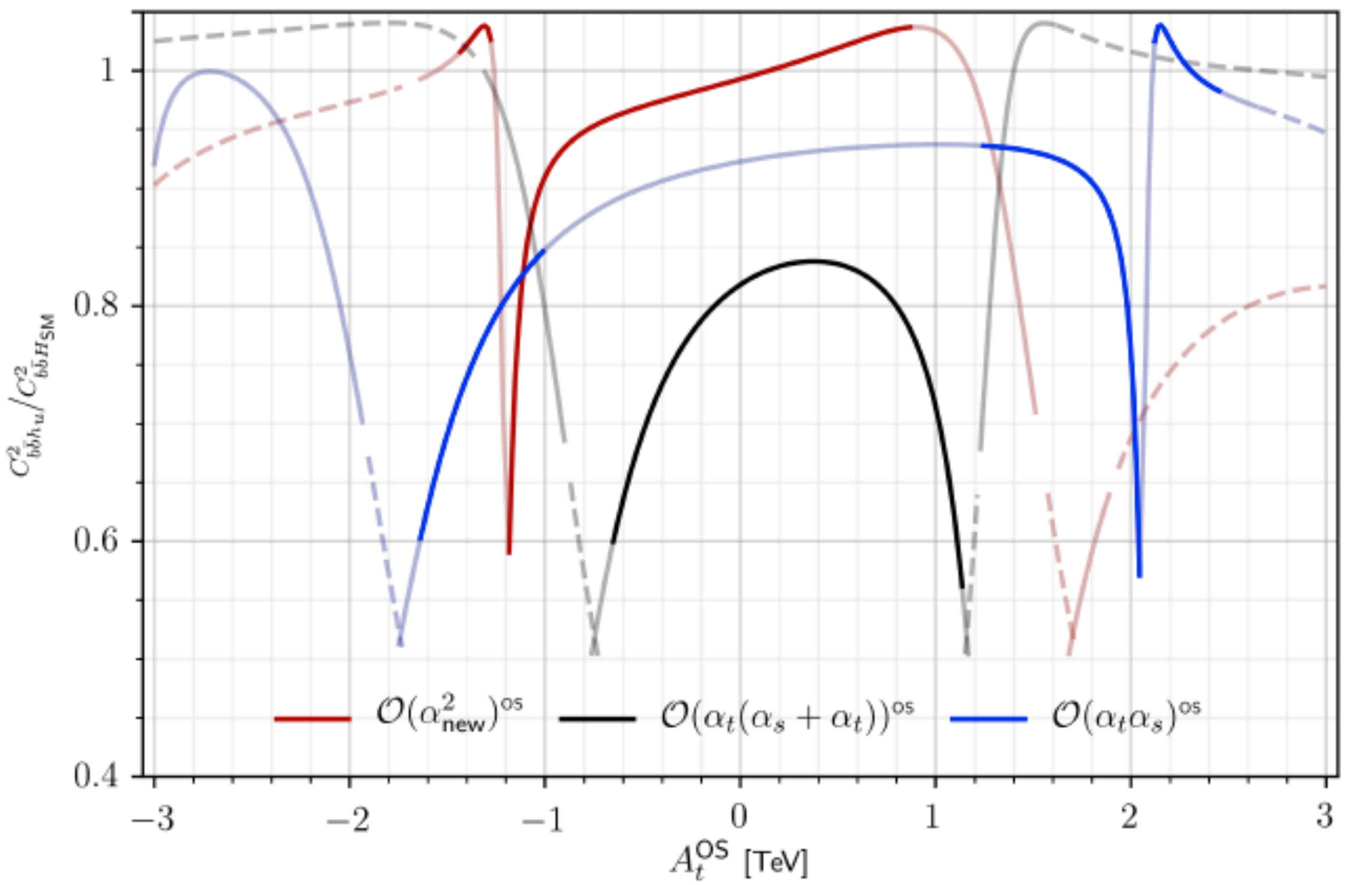


Phenomenological Impact

parameter point `P2OS`

[Dao,Gabelmann,MM,Rzehak,´21]





- squared couplings of SM-like Higgs compared to squared SM coupling for gauge bosons (left) and bottom quarks (right)

- transparent lines: excluded by HiggsSignals or Higgs mass constraints not fulfilled
- full: h_1 is SM-like, dashed: h_2 is SM-like