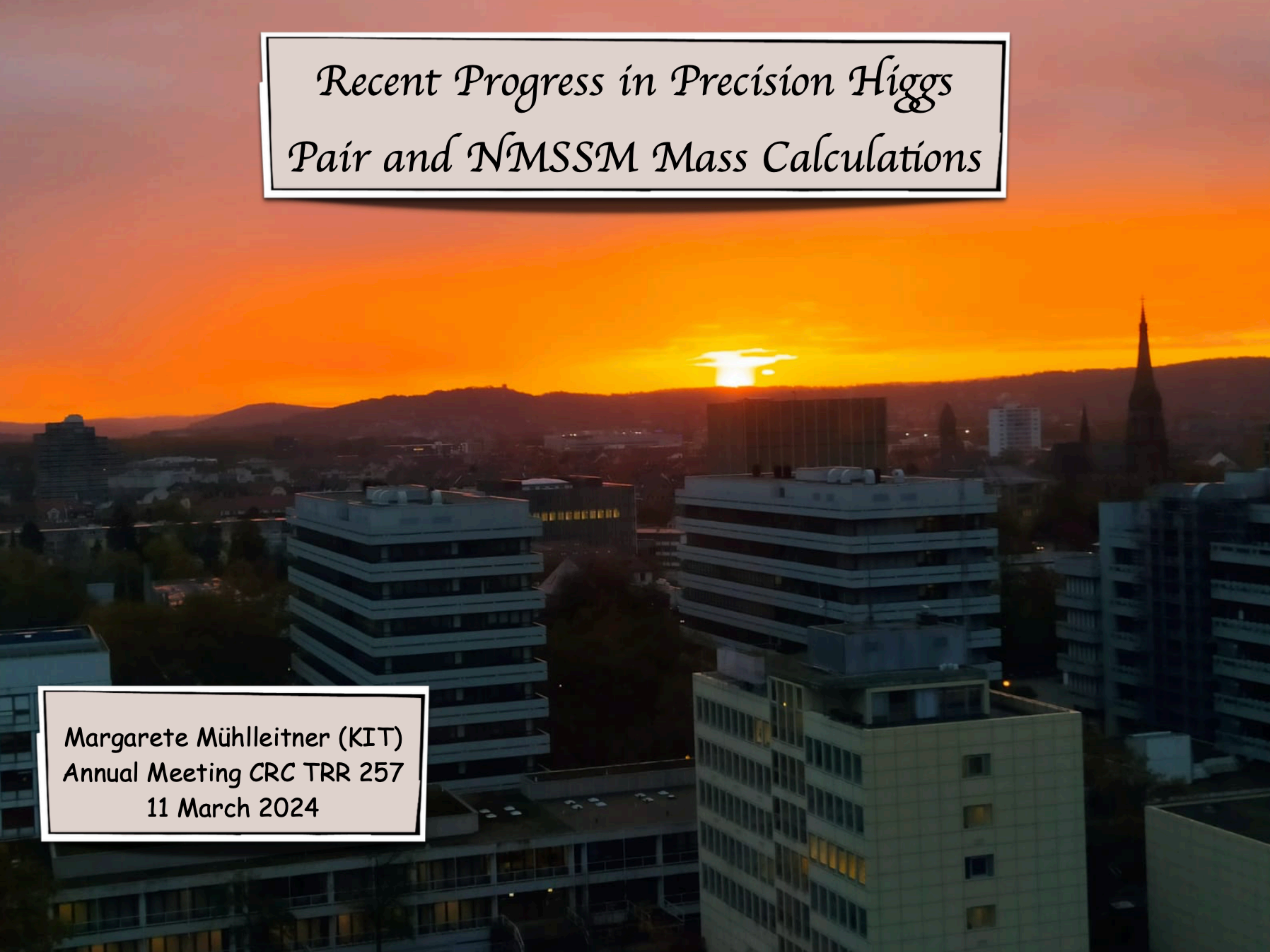
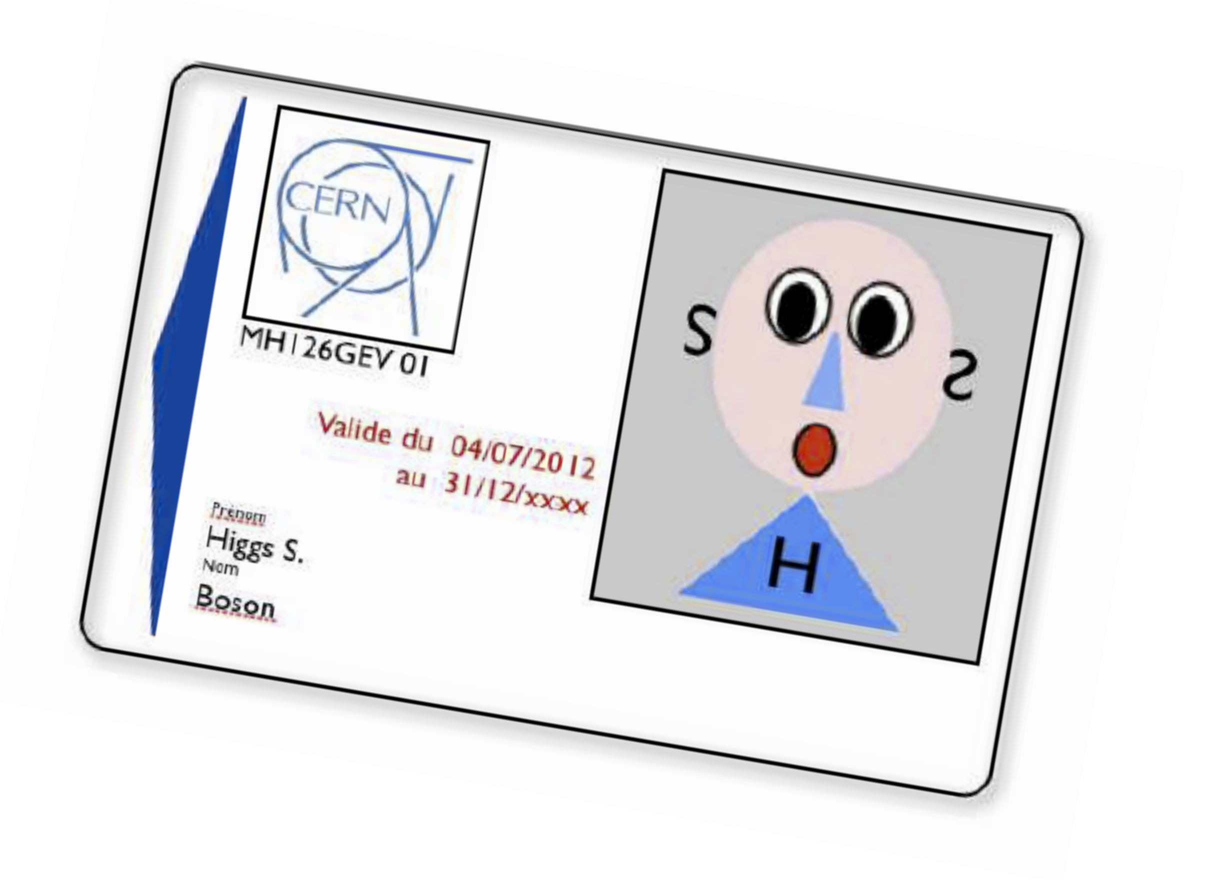
Recent Progress in Precision Higgs Pair and NMSSM Mass Calculations



Margarete Mühlleitner (KIT)
Annual Meeting CRC TRR 257
11 March 2024

Outline

- Higgs Mass Predictions in the CP-Violating High-Scale NMSSM
- $\mathcal{O}(\alpha_t^2)$ corrections to the trilinear Higgs self-coupling in the CP-violating NMSSM
- NLO QCD Corrections w/ full top-mass dependence to 2HDM hH and AA production
- Top-Yukawa induced EW corrections to SM HH



Involved ITP members in A3a and A3b projects:

Thomas Biekötter, Lisa Biermann, Christoph Borschensky, Sauro Carlotti, Pedro Gabriel, Stefan Liebler, Dat Nguyen

Higgs Mass Predictions in the CP-Violating High-Scale NMSSM

Higgs Mass in Supersymmetry

Higgs boson mass:

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

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

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

NMSSM:

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

[Kim, Nilles, '84]

Comparison of calculated mass value (at high precision) w/ experimental data:

* indirect constraint on (N)MSSM parameter space

SUSY Higgs Masses

- **Supersymmetry:** requires at least 2 complex Higgs doublets

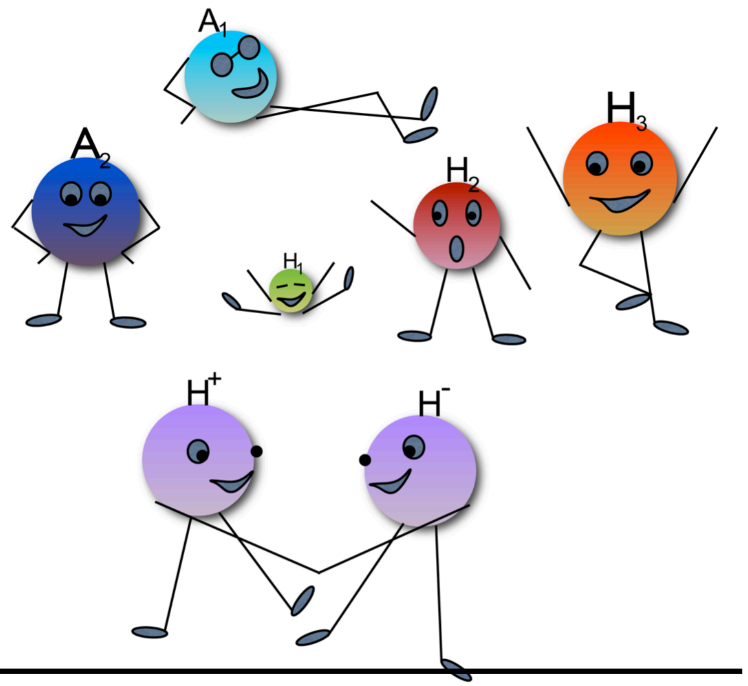
- **Minimal Supersymmetric extension (MSSM):** 2 complex Higgs doublets

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



Spectrum Calculations

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

- Fixed-order calculation and large mass scales:

  FO contains terms $\sim y_x \ln(M_{Sx}^2/M_x^2)$ with y_x Yukawa coupling, M_x (M_{Sx}) mass of (SUSY) particle most important contribution from top/stop sector ⤳ large hierarchy ⤳ large logs! ⤳ resummation needed for reliable results

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

Spectrum Calculations

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

- **fixed-order (FO):** full (N)MSSM perturb. series truncated at fixed order reliable for not too heavy SUSY masses
- **effective field theory (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

<u>Remarks:</u>

- 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]

Matching Conditions

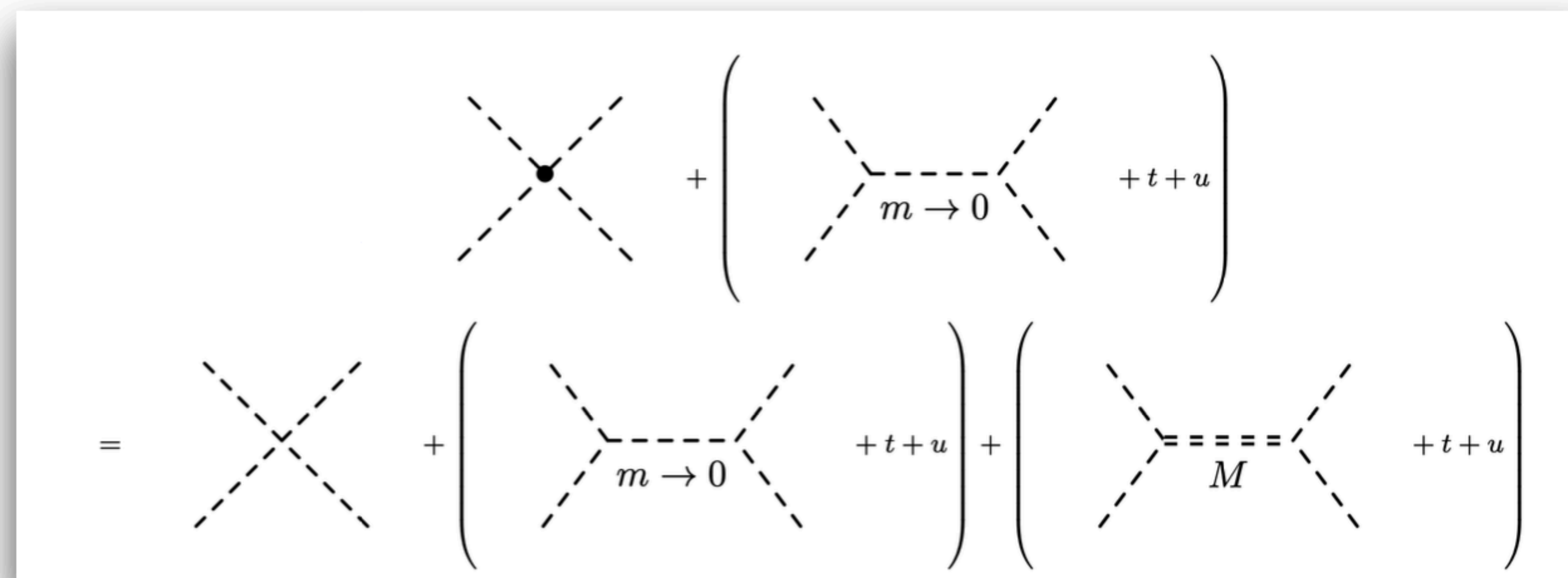
Quartic Coupling Matching (unbroken EW symmetry: $v_u, v_d \to 0$, $\tan\beta = v_u/v_d = \text{const.}$, $v_S \neq 0$):

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

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

effective quartic coupling after subtracting the SM contributions:

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



m (M) light (heavy) mass scale

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

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

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

effective quartic coupling after subtracting the SM contributions:

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

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

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
our work: complex NMSSM

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

effective quartic coupling after subtracting the SM contributions:

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

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]

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

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

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

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

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:

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

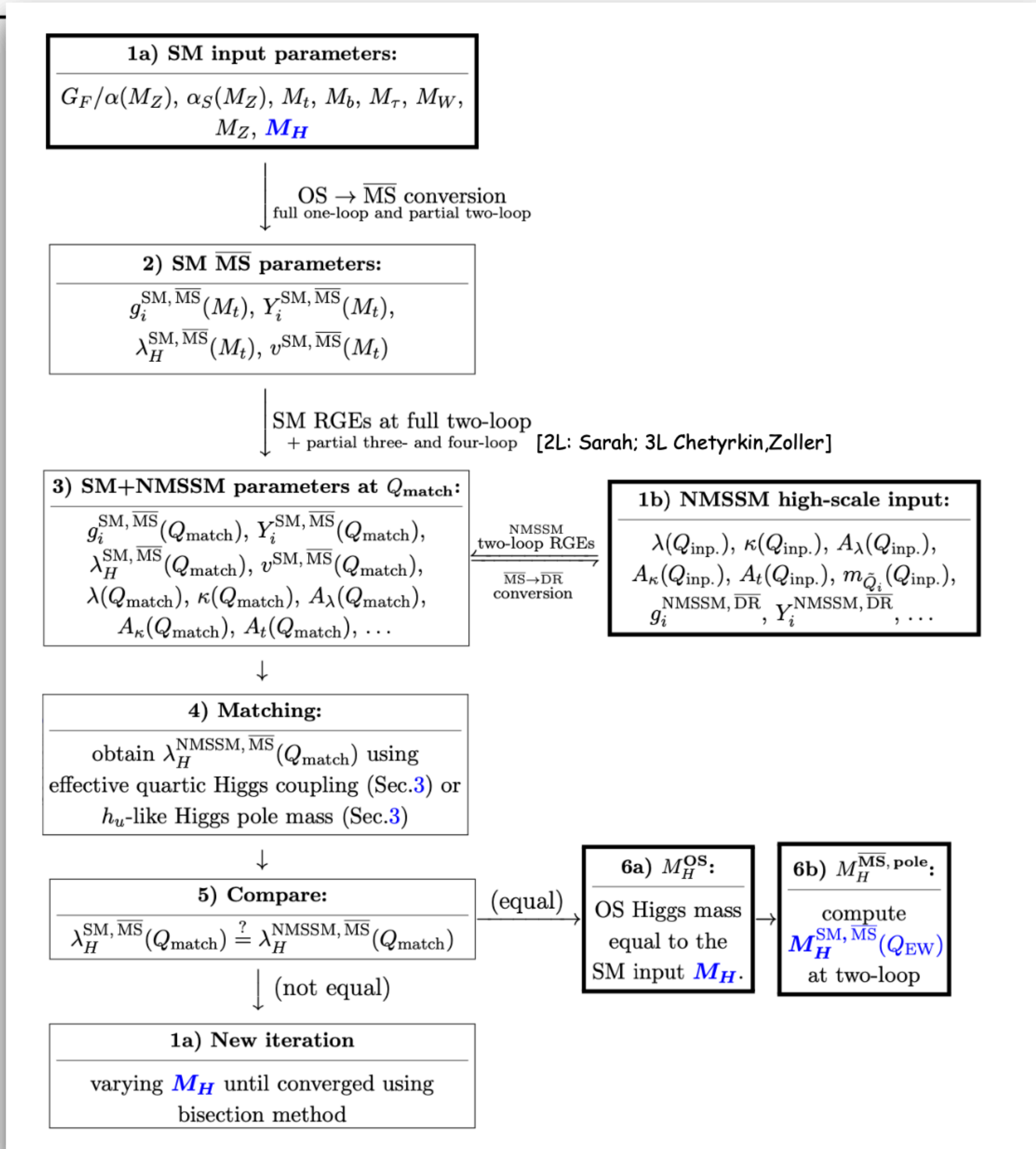
with $\hat{\Sigma}_{h,X}(m^2_{h,X}) = \hat{\Sigma}_{h,X}(0) + m^2_{h,X}\hat{\Sigma}'_{h,X}(0) + \mathcal{O}(m^4_{h,X})$ **and v$_{SM}$→v$_{NMSSM}$ so that**

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

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

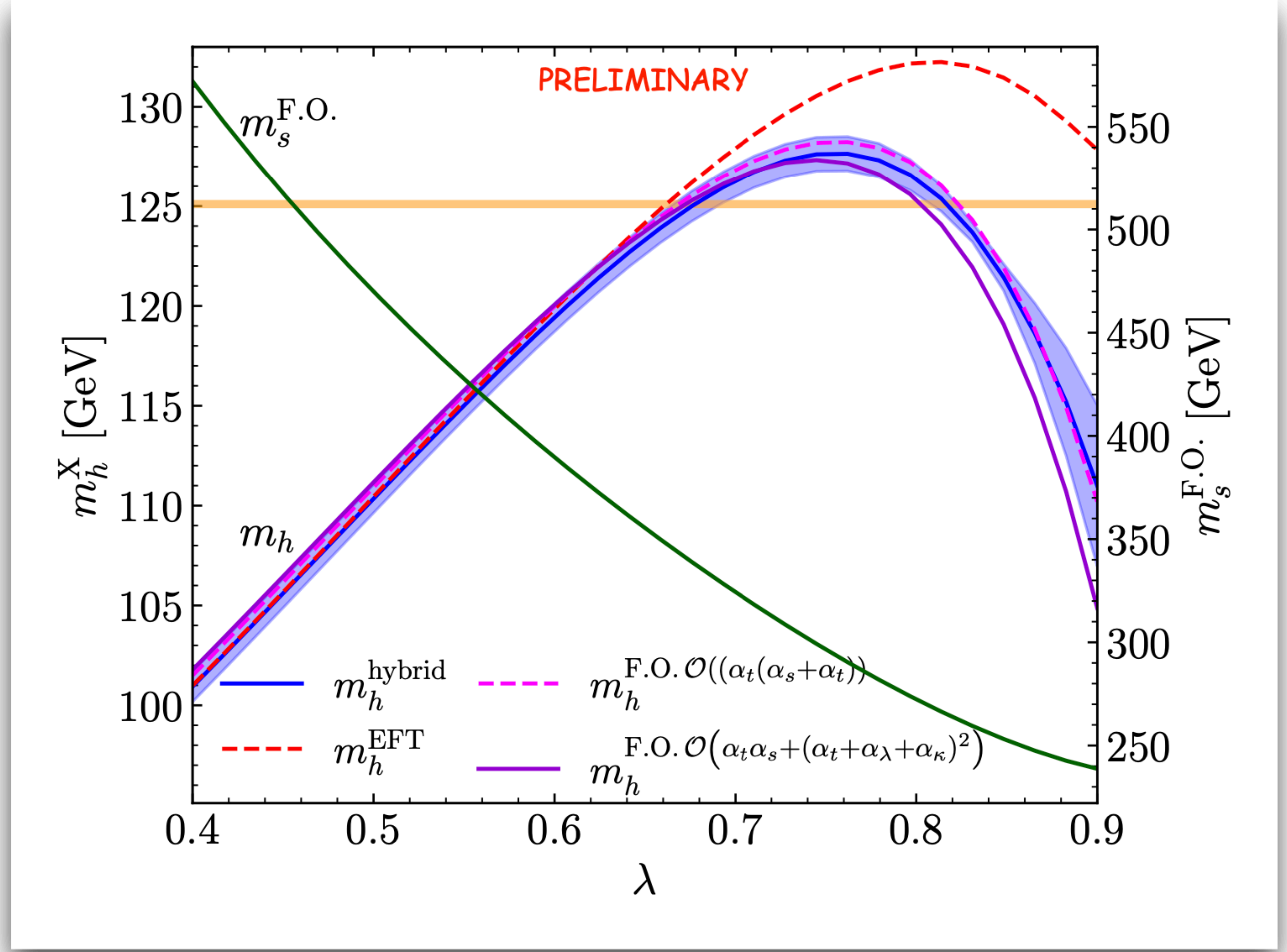
with $\Delta\hat{\Sigma}^{(\prime)}_h \equiv \Sigma^{(\prime)}_{h,\mathrm{NMSSM}}(0) - \hat{\Sigma}^{(\prime)}_{h,\mathrm{SM}}(0)$

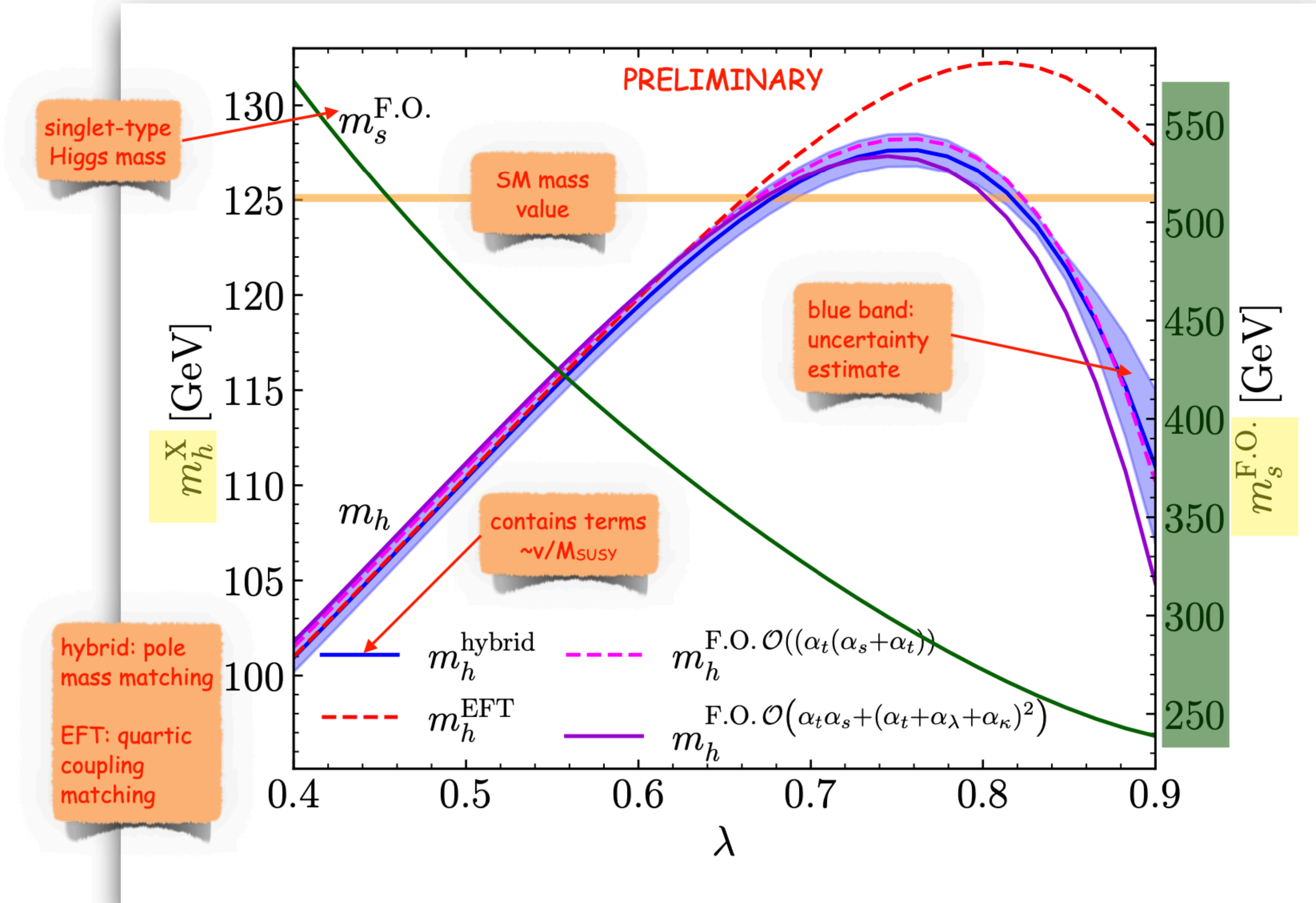
Schematic Procedure implemented in NMSSMCALC



Results

[Borschensky,Dao,Gabelmann,MM,Rzehak]




PRELIMINARY
singlet-type Higgs mass
SM mass value
blue band: uncertainty estimate
contains terms ~v/MSUSY
hybrid: pole mass matching
EFT: quartic coupling matching
$m_s^{\mathrm{F.O.}}$
m_h
m_h^{hybrid}
m_h^{EFT}
$m_h^{\mathrm{F.O.}\,\mathcal{O}((\alpha_t(\alpha_s+\alpha_t))}$
$m_h^{\mathrm{F.O.}\,\mathcal{O}(\alpha_t\alpha_s+(\alpha_t+\alpha_\lambda+\alpha_\kappa)^2)}$
m_h^{X} [GeV]
$m_s^{\mathrm{F.O.}}$ [GeV]
λ
0.4
0.5
0.6
0.7
0.8
0.9
100
105
110
115
120
125
130
250
300
350
400
450
500
550

Blue 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.

$\mathcal{O}(\alpha_t^2)$ corrections to the trilinear Higgs self-coupling in the CP-violating NMSSM

Trilinear Higgs Self-Couplings

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

- SM Higgs potential in physical gauge:

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

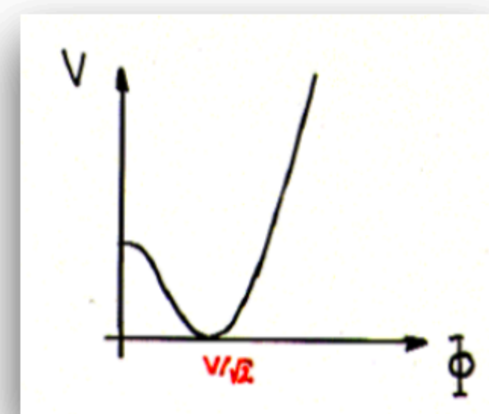
trilinear Higg self-coupling : $\lambda_{HHH} = 3M_H^2/M_Z^2$

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

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

- 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

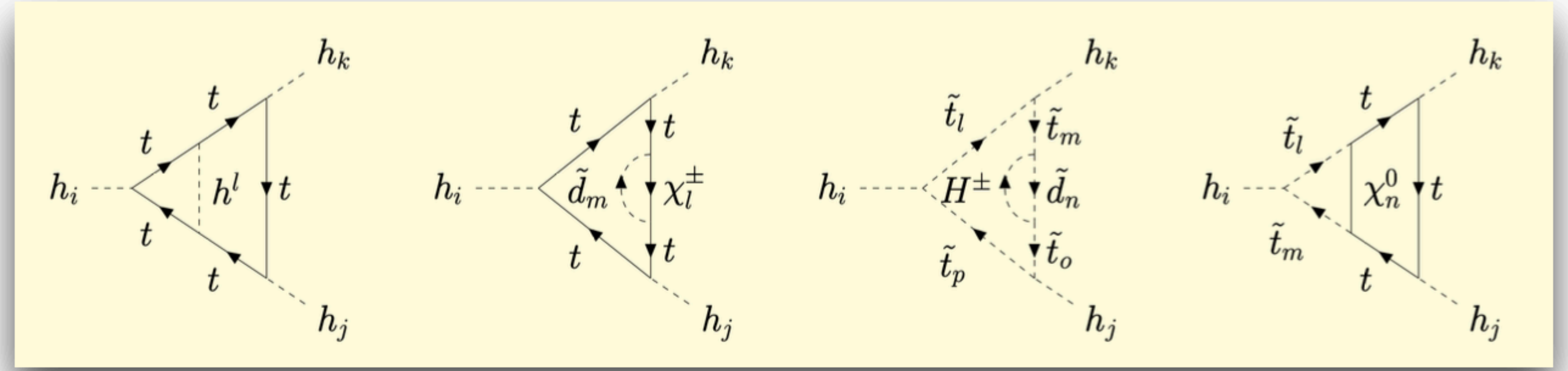
- Importance of the trilinear Higgs self-coupling:
  - determines shape of the Higgs potential
  - sensitive to beyond-Standard Model physics
  - important input for Higgs pair production
  - important input for Higgs-to-Higgs decays
  - important input for electroweak phase transitions



- 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 $\mathcal{O}(\alpha_t^2)$ [Borschensky,Dao,Gabelmann,MM,Rzehak,'22]

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

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



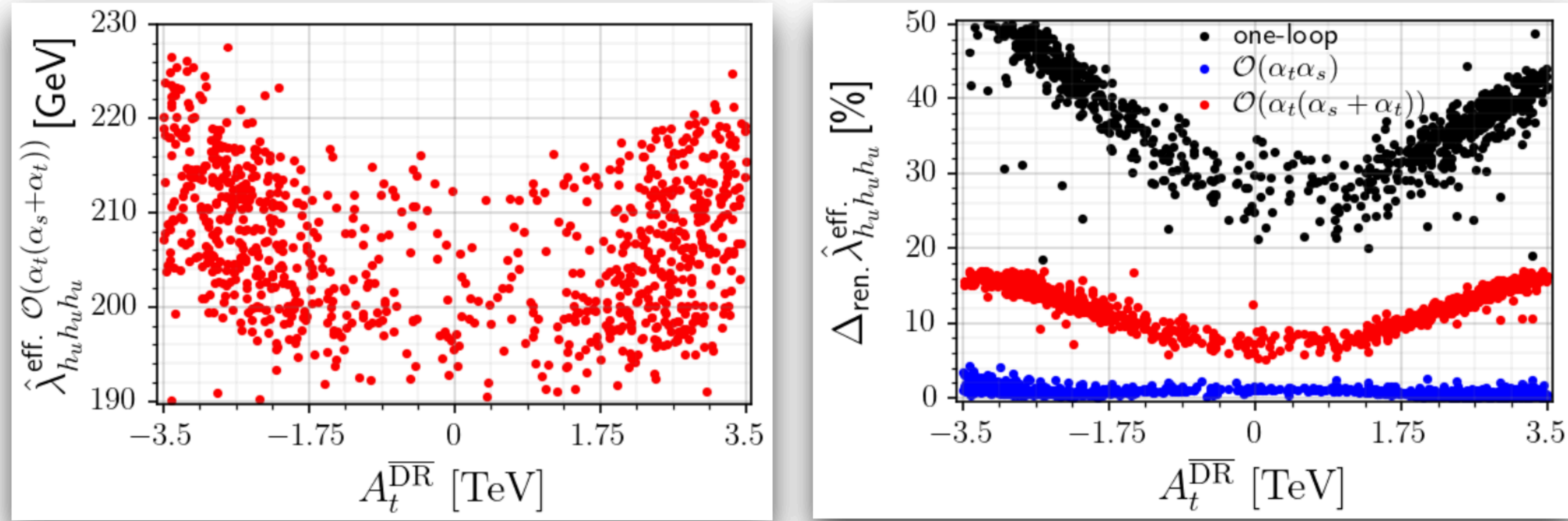
proportional to top mass m_t and soft SUSY-breaking trilinear stop mass parameter A_t

- 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 ($\triangleq$SM-like Higgs)

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



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

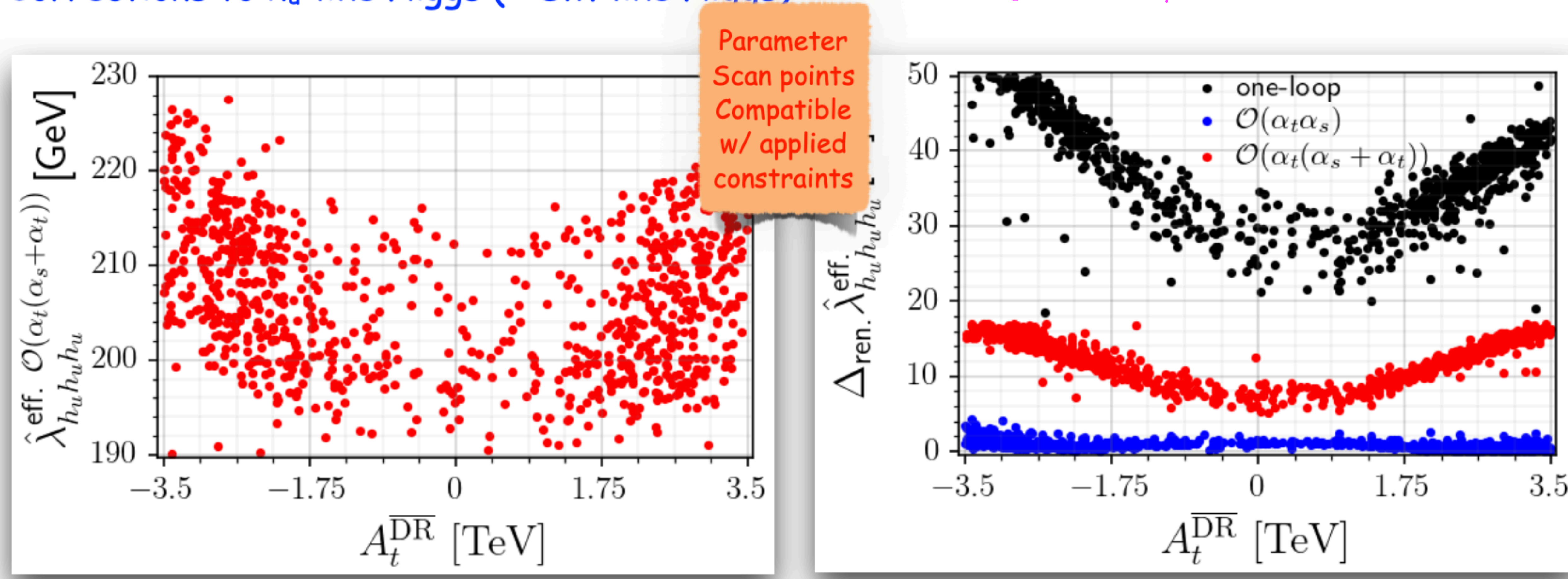
Estimate of theor. uncertainty via renorm. scheme dependence: $\Delta_{\text{ren}} = \frac{\left|\lambda^{m_t(\overline{\text{DR}})} - \lambda^{m_t(\text{OS})}\right|}{\lambda^{m_t(\overline{\text{DR}})}}$

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

Loop Corrected Trilinear Higgs Self-Couplings 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]



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

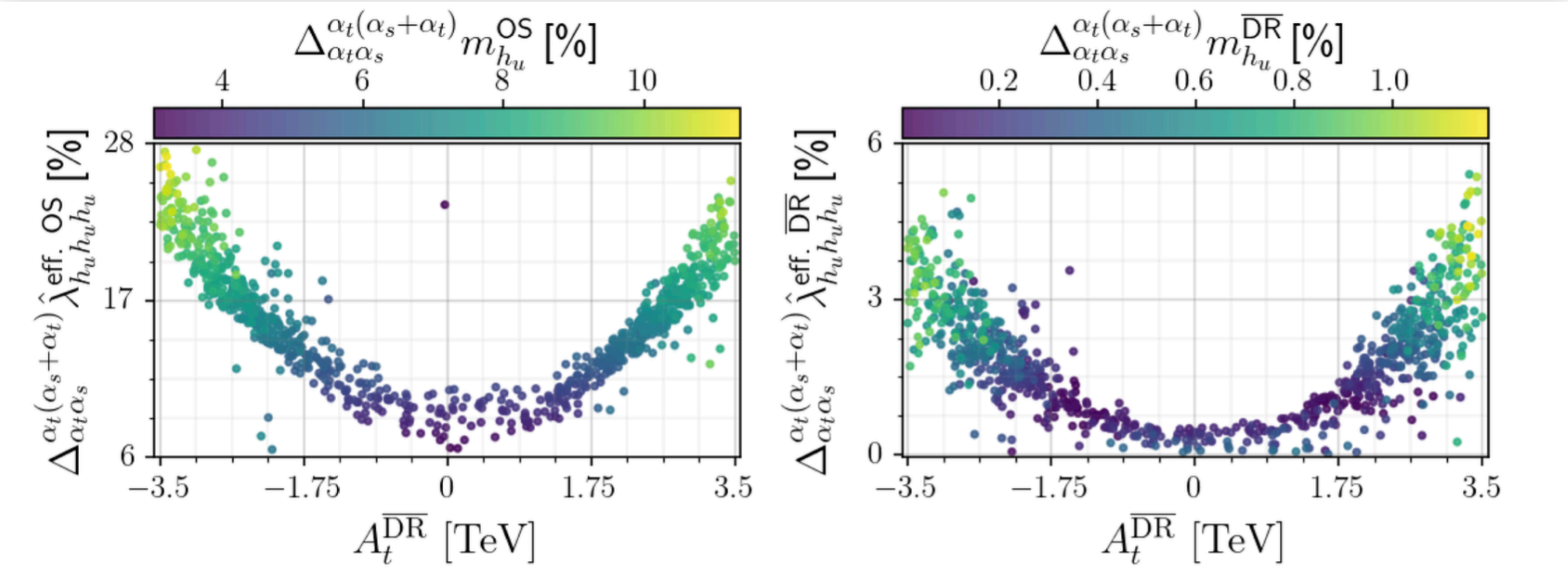
Estimate of theor. uncertainty via renorm. scheme dependence: $\Delta_{\text{ren}} = \frac{\left|\lambda^{m_t(\overline{\text{DR}})} - \lambda^{m_t(\text{OS})}\right|}{\lambda^{m_t(\overline{\text{DR}})}}$

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

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

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

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

	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 $\mathcal{O}(\alpha_{\lambda\kappa}^2)$	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

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

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

	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)
-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)
-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)

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]

'1L1L'	$\sigma^{\rm OS}$ [fb]	$\sigma^{\overline{\rm DR}}$ [fb]	$\kappa^{\rm OS}_{H_1H_1H_1}$	$\kappa^{\overline{\rm DR}}_{H_1H_1H_1}$	$\kappa^{\rm OS}_{H_2H_1H_1}$	$\kappa^{\overline{\rm DR}}_{H_2H_1H_1}$	$\Delta_{\rm ren}\sigma$
'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%

'at2at2'	$\sigma^{\rm OS}$ [fb]	$\sigma^{\overline{\rm DR}}$ [fb]	$\kappa^{\rm OS}_{H_1H_1H_1}$	$\kappa^{\overline{\rm DR}}_{H_1H_1H_1}$	$\kappa^{\rm OS}_{H_2H_1H_1}$	$\kappa^{\overline{\rm DR}}_{H_2H_1H_1}$	$\Delta_{\rm ren}\sigma$
'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 formula: 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 loop order)
- ´proc´: remaining large uncertainty (14.6%): remaining missing EW corrections might be important

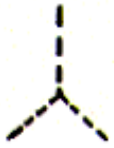
NLO QCD Corrections to 2HDM hH and AA production

Ultimate Test of the Higgs Mechanism

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

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

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



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

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

(a) trilinear coupling : via Higgs pair production

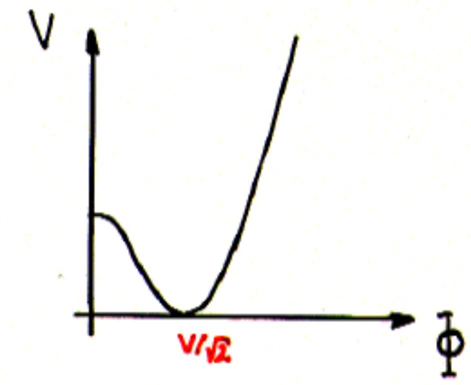
(b) quadrilinear coupling : via triple Higgs production

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

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

v = 246 GeV

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



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

Dominant process
at the LHC: gg -> HH

Higher-Order Corrections to Higgs Pair Production in Gluon Fusion

- 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]
- NLO QCD w/ full top mass dependence: ~15% mass effects on top of LO,20-30% for distributions [Borowka,Greiner,Heinrich,Jones,Kerner,Schlenk,Schubert,Zirke], [Baglio,Campanario, Glaus,MM,Ronca,Spira,Streicher]
  Combined uncertainties [Baglio,Campanario,Glaus,MM,Ronca,Spira]
- NNLO QCD corrections: ~ 20% [HTL] [de Florian,Mazzitelli; Grigo,Melnikov,Steinhauser]
- Light fermion three-loop corrections [Davies,Schönwald,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]

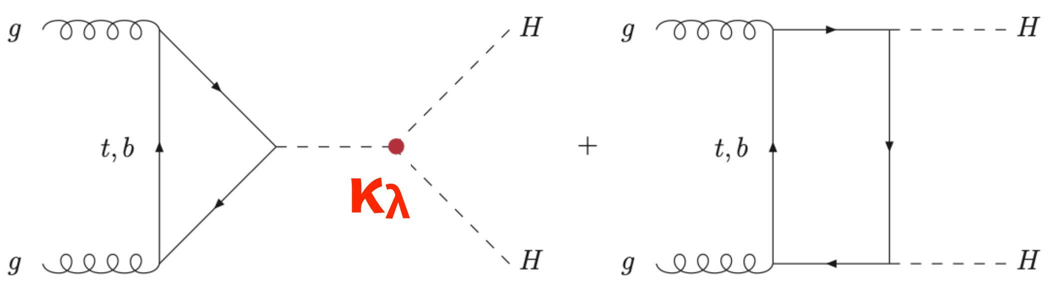
Higher-Order Corrections to Higgs Pair Production in Gluon Fusion

- 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]

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



Higher-Order Corrections in the CP-Conserving 2HDM

[Lee,'73], [Branco eal,'11]

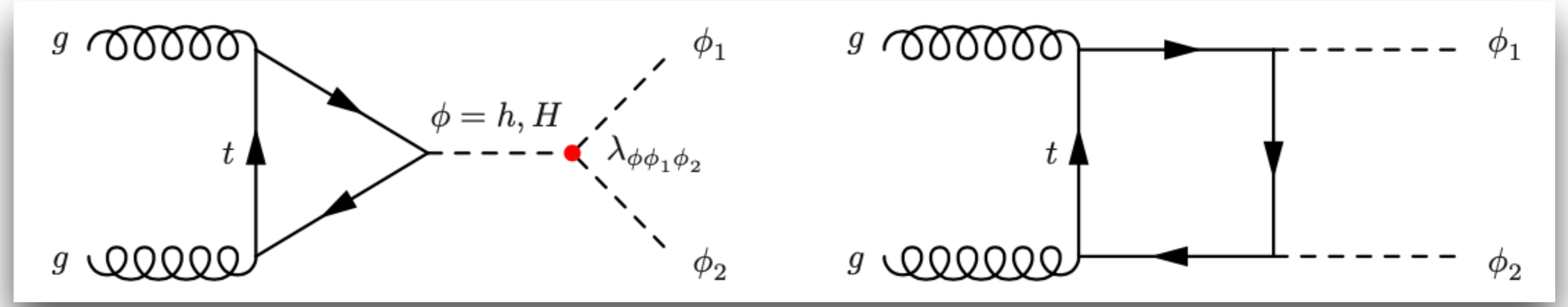
- 2HDM Higgs potential w/ softly broken $\mathbb{Z}_2$ symmetry:

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

- Higgs spectrum after EWSB: 2 CP-even h,H with $m_h < m_H$,
  1 CP-odd A,
  charged Higgs pair $H^\pm$

Gluon Fusion into $\phi_1\phi_2$ with $\phi_1\phi_2$=hH, AA

- Contributing diagrams at leading order:



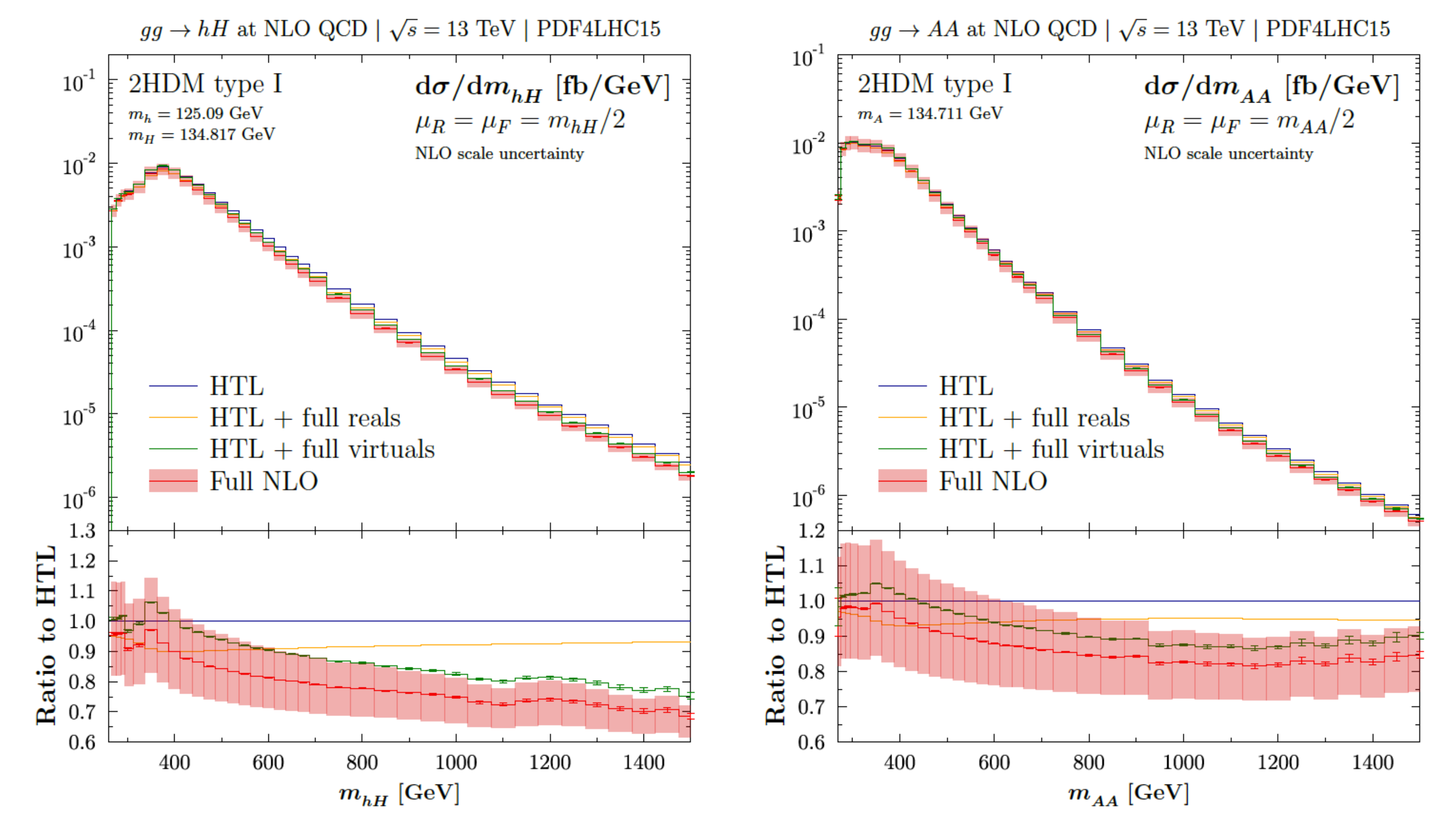
- 2HDM type 1 benchmark point (compatible w/ theor. & exp. constraints):

[taken from Abouabid et al.,'22]

$$
\begin{aligned}
m_h &= 125.09\ \text{GeV}, & m_H &= 134.817\ \text{GeV}, \\
m_A &= 134.711\ \text{GeV}, & m_{H^\pm} &= 161.5\ \text{GeV}, \\
m_{12}^2 &= 4305\ \text{GeV}^2, & \alpha &= -0.102, \\
\tan\beta &= 3.759, & v &= 246.22\ \text{GeV}\,.
\end{aligned}
$$

NLO Top Mass Effects in Invariant Mass Distributions

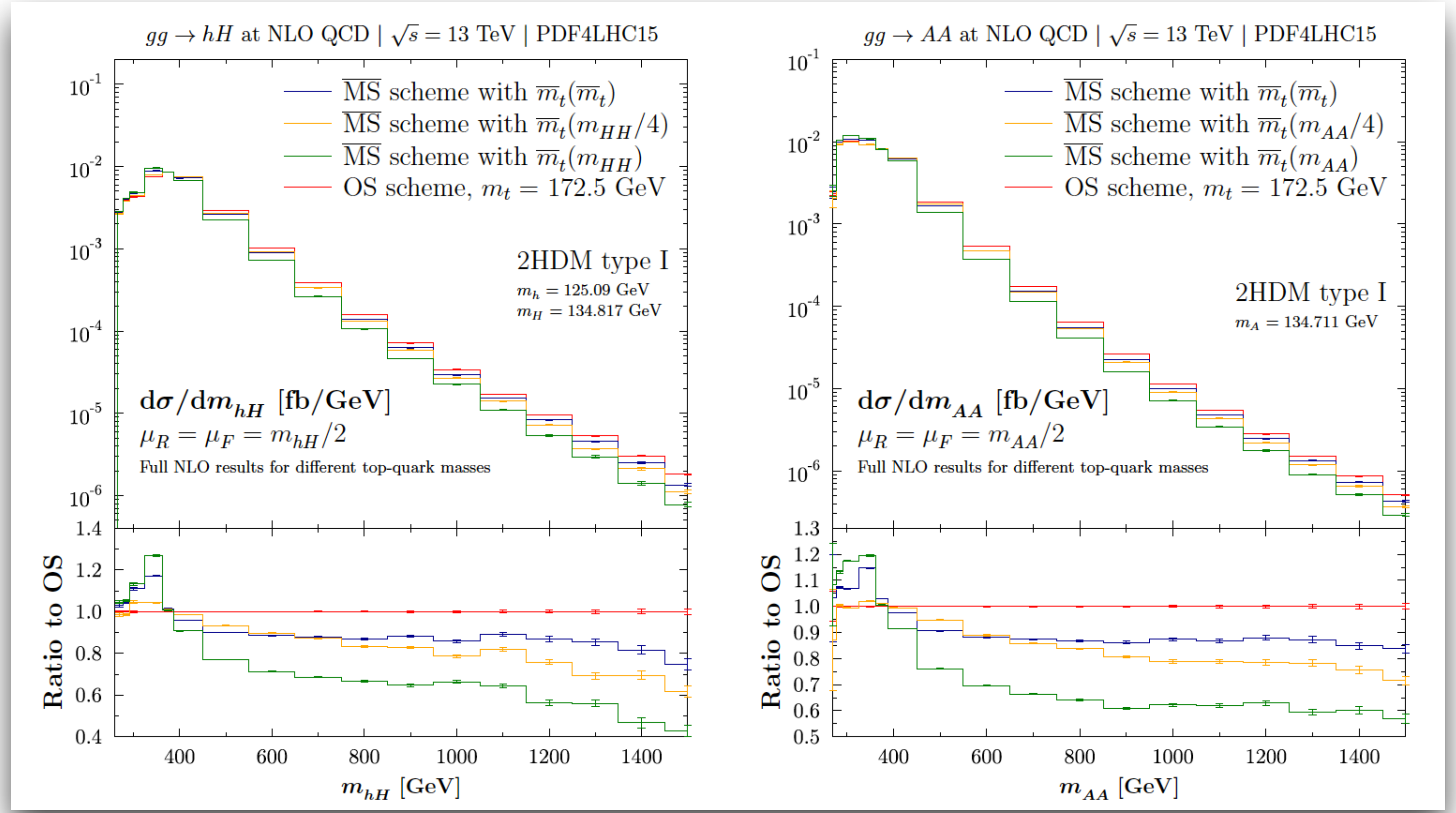
[Baglio,Campanario,Glaus,MM,Ronca,Spira,'23]



- Mass effects in distributions: -30% (-15%) at Q~1.5 TeV for hH (AA)
- increases w/ c.m. energy (results provided for 14, 27, 100 TeV)
- Mass effects on total cxn: -12% (-5%) at 13 TeV (increases w/ c.m. energy)

Top Quark Scale and Scheme Uncertainties

[Baglio,Campanario,Glaus,MM,Ronca,Spira,'23]



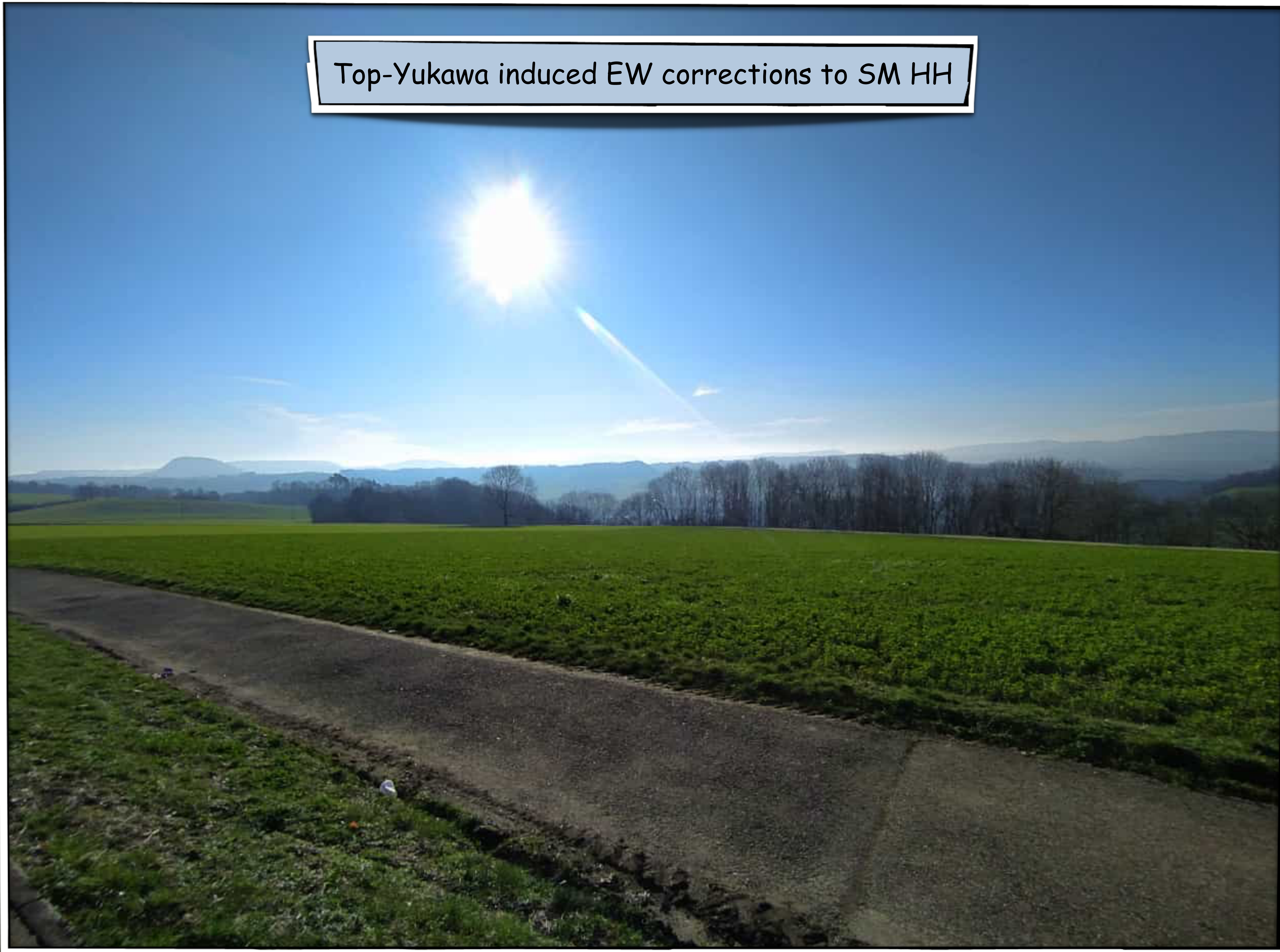
Top Quark Scale and Scheme Uncertainties in Total Cross Section

[Baglio,Campanario,Glaus,MM,Ronca,Spira,'23]

$$
\begin{aligned}
13\text{ TeV}: &\quad \sigma_{gg\to hH} = 1.592(1)^{+6\%}_{-11\%}\text{ fb},\\
14\text{ TeV}: &\quad \sigma_{gg\to hH} = 1.876(1)^{+6\%}_{-11\%}\text{ fb},\\
27\text{ TeV}: &\quad \sigma_{gg\to hH} = 7.036(4)^{+5\%}_{-12\%}\text{ fb},\\
100\text{ TeV}: &\quad \sigma_{gg\to hH} = 60.49(4)^{+4\%}_{-14\%}\text{ fb},
\end{aligned}
$$

$$
\begin{aligned}
13\text{ TeV}: &\quad \sigma_{gg\to AA} = 1.643(1)^{+9\%}_{-7\%}\text{ fb},\\
14\text{ TeV}: &\quad \sigma_{gg\to AA} = 1.927(1)^{+9\%}_{-8\%}\text{ fb},\\
27\text{ TeV}: &\quad \sigma_{gg\to AA} = 7.012(4)^{+8\%}_{-8\%}\text{ fb},\\
100\text{ TeV}: &\quad \sigma_{gg\to AA} = 58.12(3)^{+7\%}_{-9\%}\text{ fb}.
\end{aligned}
$$

Top-Yukawa induced EW corrections to SM HH



Electroweak Corrections to SM Higgs Pair Production

See also:

- Next-to-leading order electroweak correction to gg->HH and gg->gH in the large mt-limit
  [Davies,Schönwald,Steinhauser,Zhang,´23]

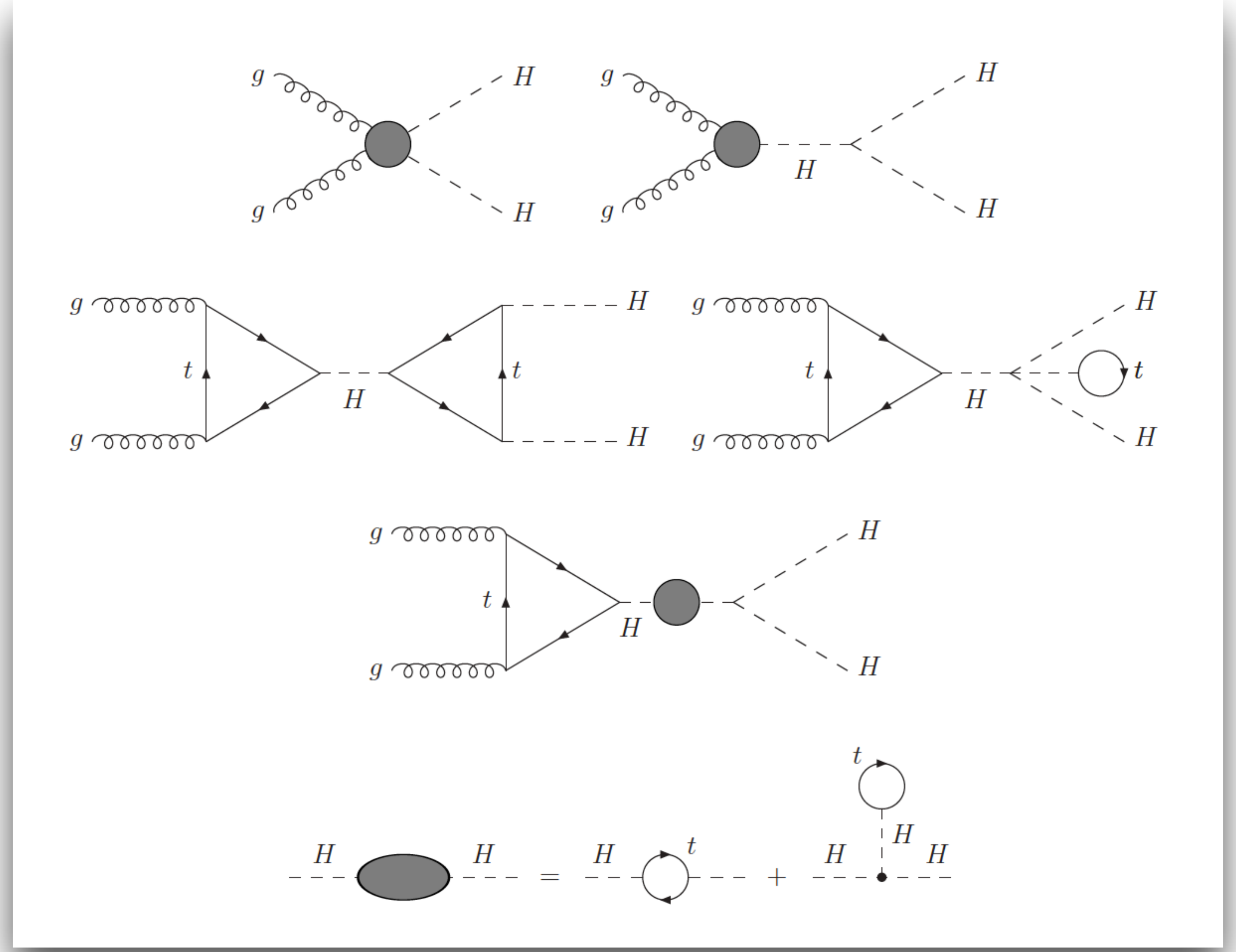
- Higgs boson contribution to the leading two-loop Yukawa corrections to gg->HH
  [Davies,Mishima,Schönwald,Steinhauser,Zhang,´22]

- Complete NLO EW corrections [Bi, Huang, Huang, Ma, Yu,´23]

- NLO Yukawa and self-coupling corrections to gg->HH (DPG Spring Conference,´24)
  [Heinrich,Jones,Kerner,Stone,Vestner]

Top-Yukawa-Induced Corrections to Higgs Pair Production

- Part of the electroweak corrections to Higgs pair production
- Full top-mass dependence in the triple Higgs vertex and self-energy corrections
  HTL in radiative corrections to the effective ggH and ggHH vertices (b-loops neglected)

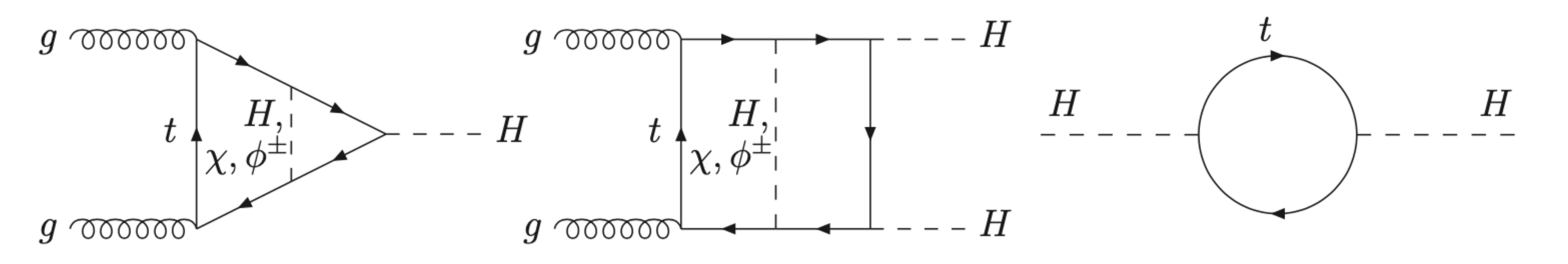


Effective Lagrangians

- Effective ggH and ggHH vertices (top-Yukawa induced EW corrections in HTL):

$$\mathcal{L}_{eff} = \frac{\alpha_s}{12\pi} G^{a\mu\nu} G^a_{\mu\nu} \left\{ (1+\delta_1)\frac{H}{v} + (1+\eta_1)\frac{H^2}{2v^2} + \mathcal{O}(H^3) \right\}$$

$$\delta_1 = \frac{x_t}{2} + \mathcal{O}(x_t^2) \qquad \eta_1 = 4x_t + \mathcal{O}(x_t^2) \qquad x_t = \frac{m_t^2}{(4\pi)^2 v^2}$$



- Effective Higgs self-couplings: from effective Higgs potential

$$\lambda^{eff}_{HHH} = 3\frac{M_H^2}{v} - \frac{3m_t^4}{\pi^2 v^3} \approx 0.91 \times 3\frac{M_H^2}{v}$$

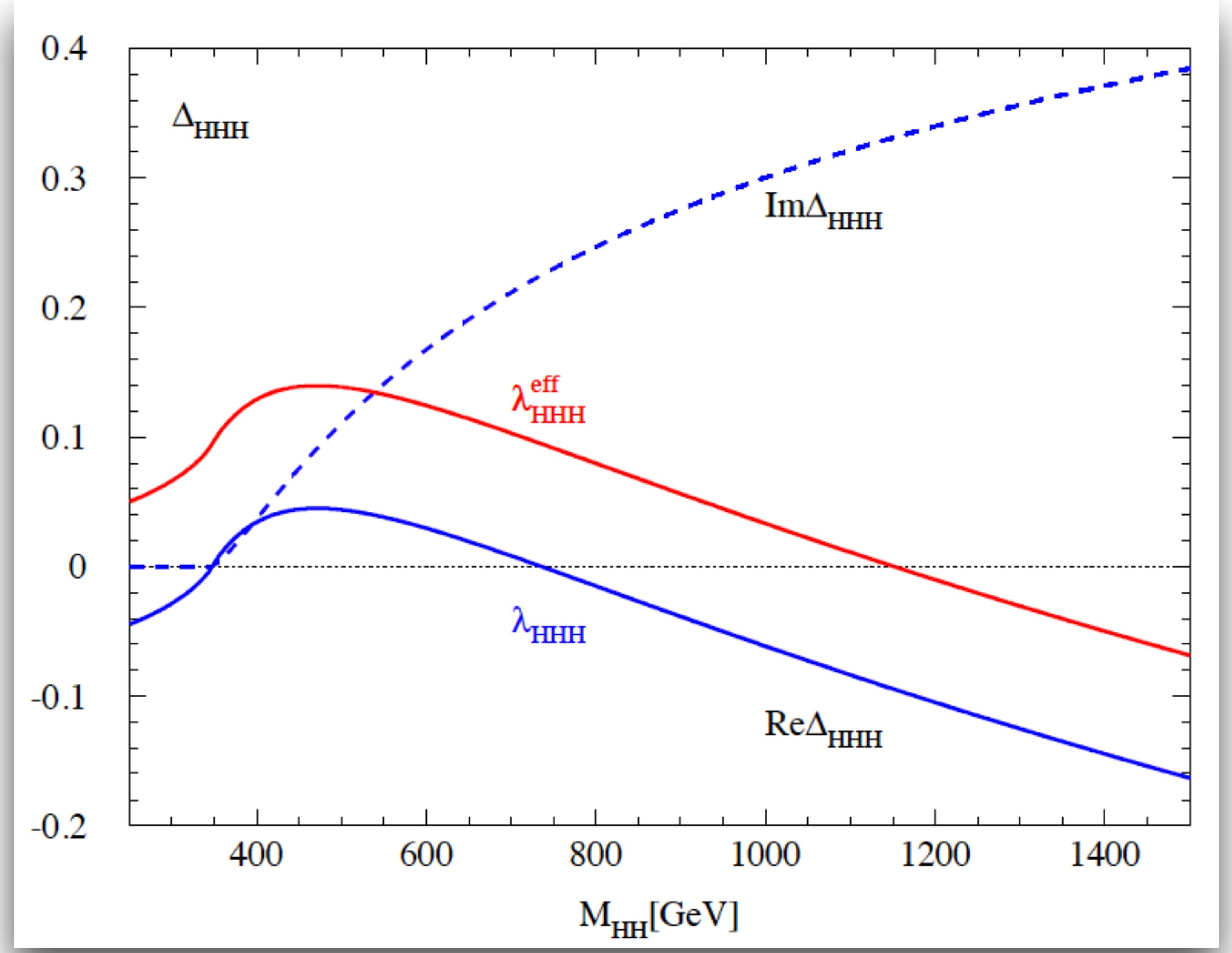
$$\Delta\lambda_{HHH} = -\frac{3m_t^4}{\pi^2 v^3}$$

$$\lambda^{eff}_{HHHH} = 3\frac{M_H^2}{v^2} + \Delta\lambda_{HHHH}$$

$$\Delta\lambda_{HHHH} = -\frac{12m_t^4}{\pi^2 v^4}$$

Relative Top-Yukawa-Induced EW Correction Factor Δ_{HHH}

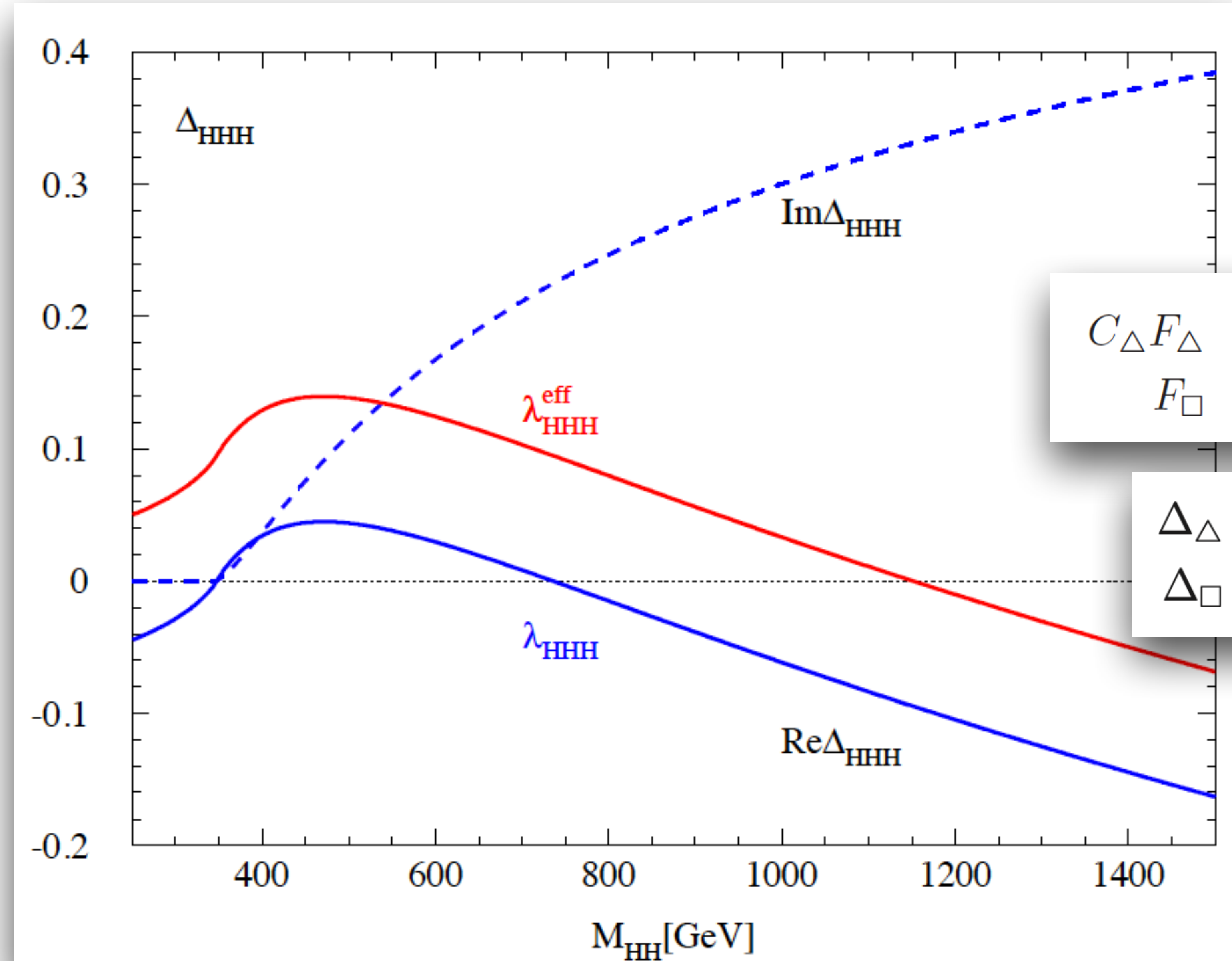
[MM,Schlenk,Spira,'22]



Effective trilinear coupling does not capture the bulk of the EW corrections

Relative Top-Yukawa-Induced EW Correction Factor Δ_{HHH}

[MM,Schlenk,Spira,'22]



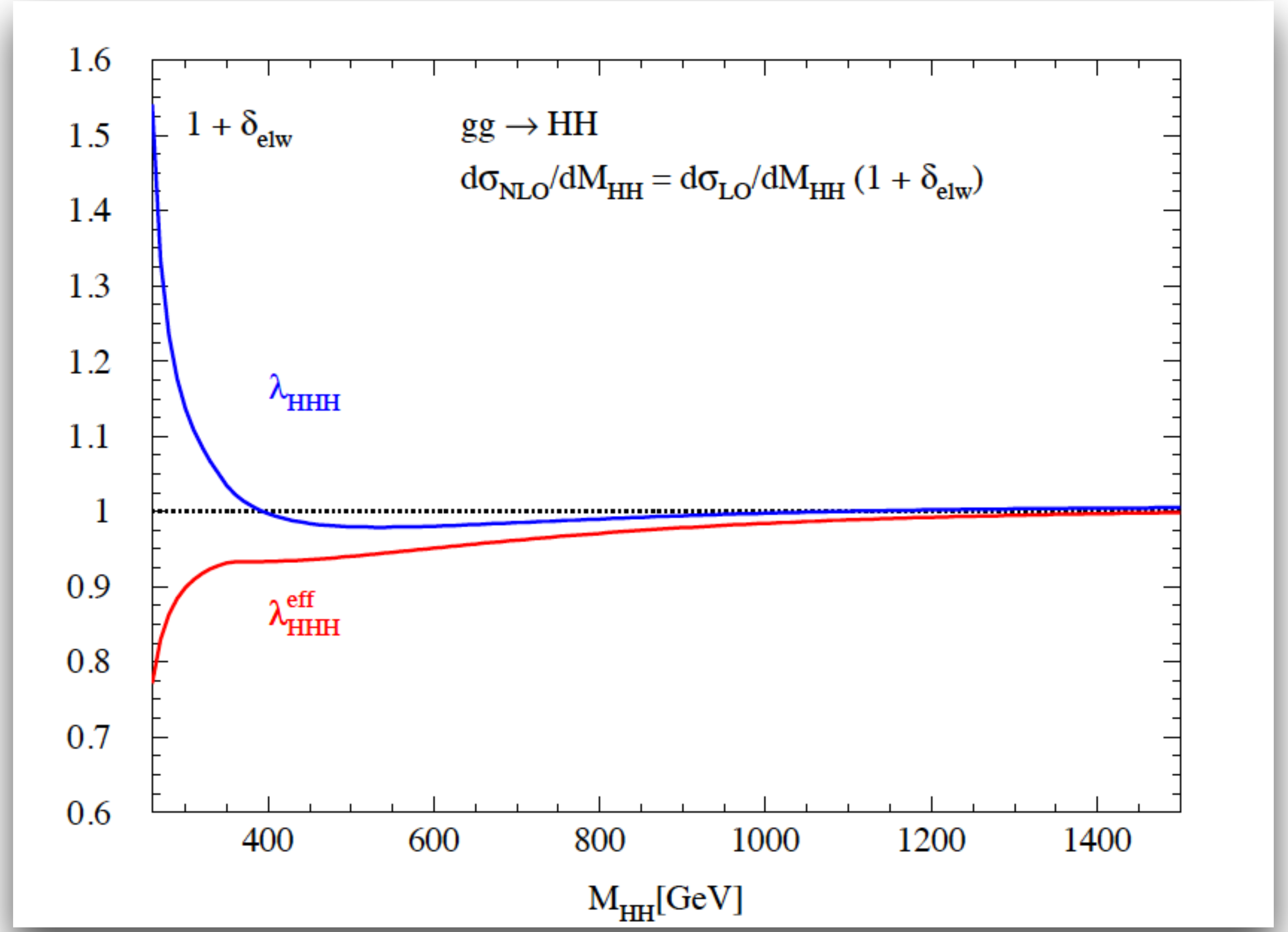
$$
\begin{aligned}
C_\triangle F_\triangle &\to C_\triangle F_\triangle (1+\Delta_\triangle) \\
F_\Box &\to F_\Box (1+\Delta_\Box)\,,
\end{aligned}
$$

$$
\begin{aligned}
\Delta_\triangle &= \delta_1 + \Delta_{HHH} \\
\Delta_\Box &= \eta_1\,,
\end{aligned}
$$

Effective trilinear coupling does not capture the bulk of the EW corrections

Relative Top-Yukawa-Induced EW Correction to differential HH prod

[MM,Schlenk,Spira,'22]



- Large enhancement near threshold because of vanishing LO matrix element
- Suppression is lifted by mismatch of EW corrections to triangle and box diagrams

Effect of Top-Yukawa-Induced EW Corrections on Total Cxn

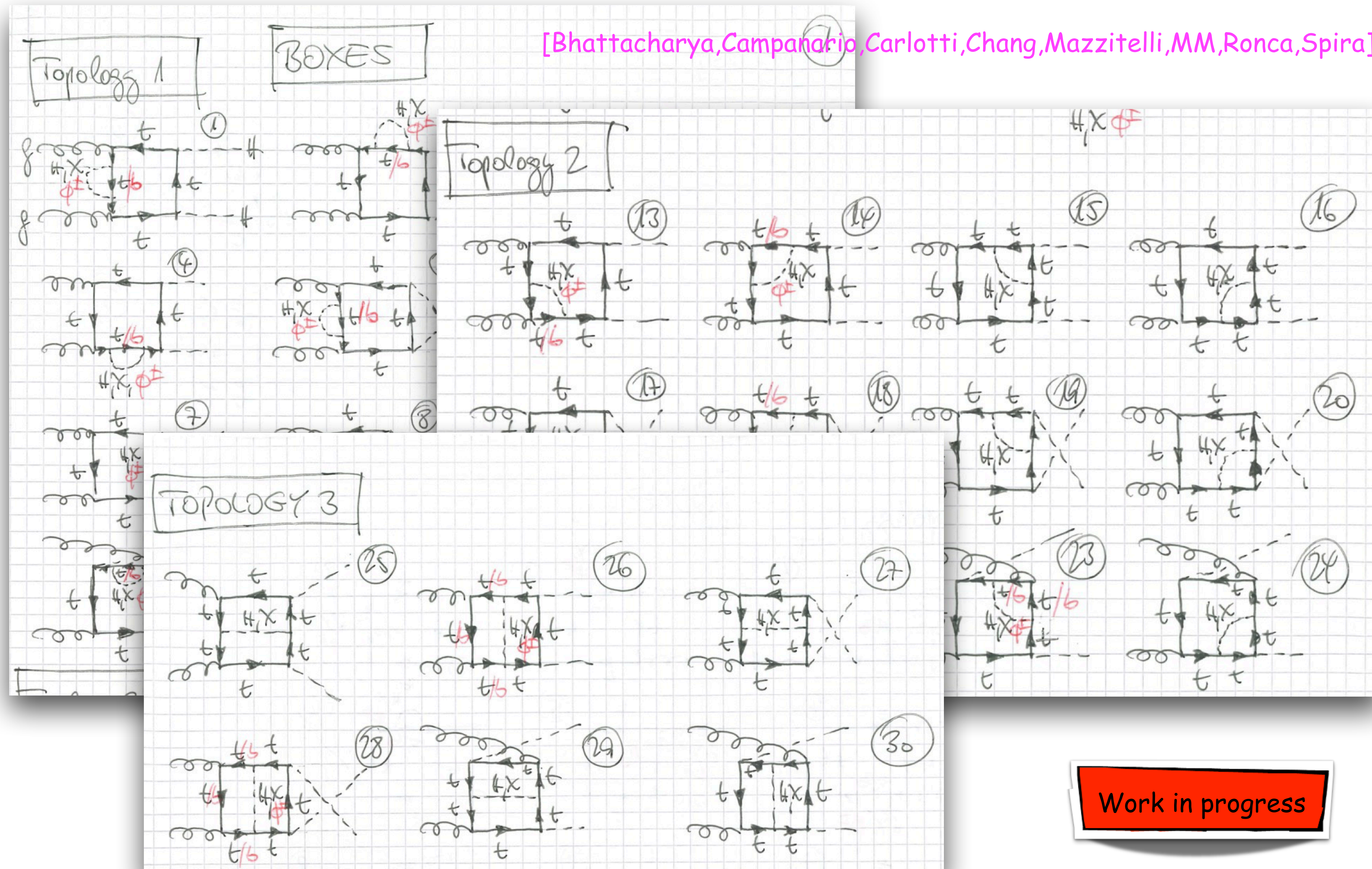
✦ Effect of top-Yukawa-induced EW correction on total integrated hadronic cross section:

$$\begin{aligned} \sigma &= K_{elw} \times \sigma_{LO} \\ K_{elw} &\approx 1.002 \qquad (\lambda_{HHH}) \\ K_{elw}^{eff} &\approx 0.938 \qquad (\lambda_{HHH}^{eff}) \end{aligned}$$

- Corrections induce an effect of about 0.2%
- Bulk of corrections cannot be absorbed in the effective trilinear Higgs coupling (leads to an artificial increase of the relative EW corrections)
- ~> Inclusion of complete EW corrections is mandatory

Top-Yukawa-Induced EW Corrections (w/ m_{top}&m_{bottom} dependence, gaugeless limit)

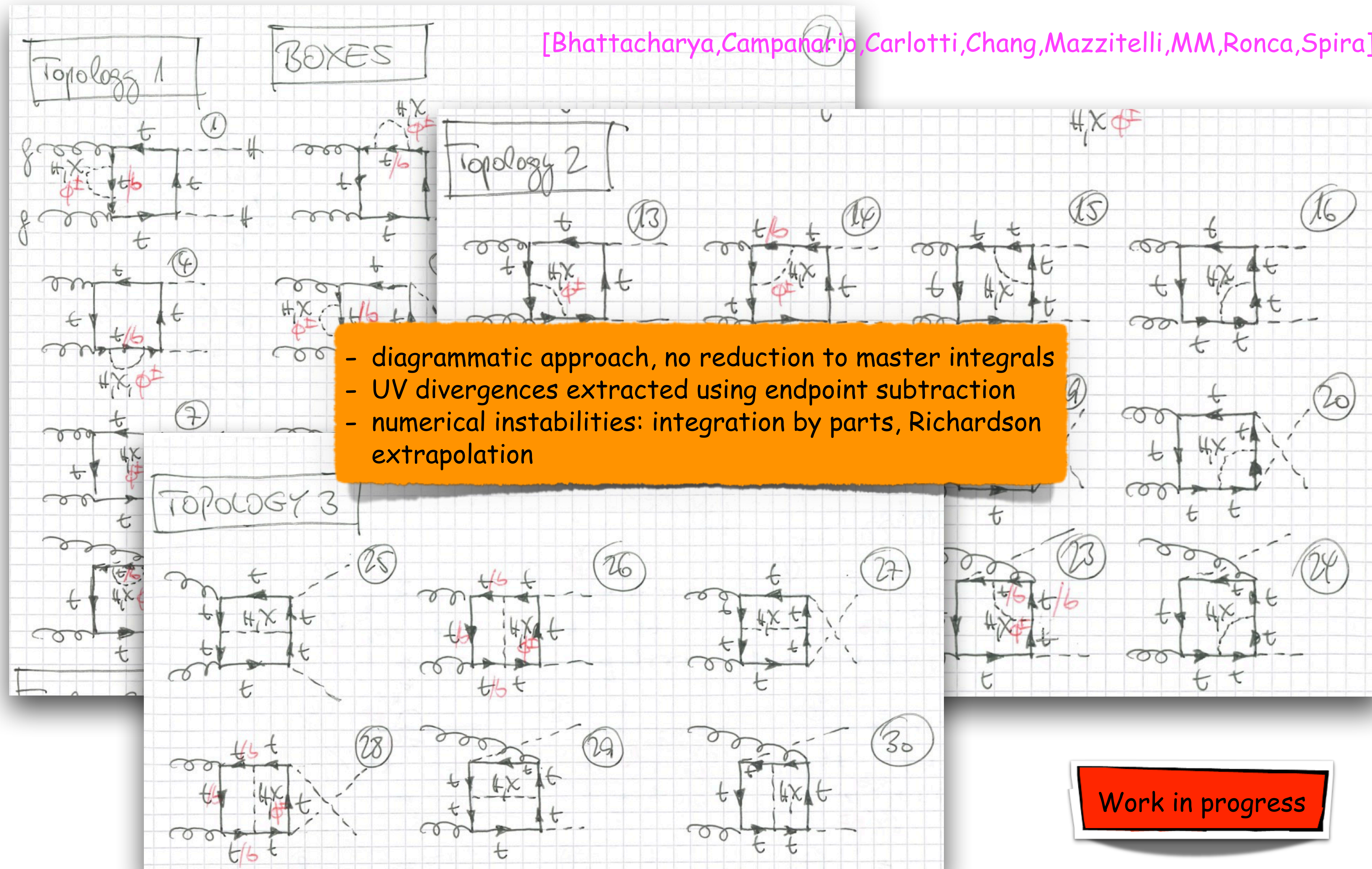
[Bhattacharya,Campanario,Carlotti,Chang,Mazzitelli,MM,Ronca,Spira]



Work in progress

Top-Yukawa-Induced EW Corrections (w/ m_{top}&m_{bottom} dependence, gaugeless limit)

[Bhattacharya,Campanario,Carlotti,Chang,Mazzitelli,MM,Ronca,Spira]



- diagrammatic approach, no reduction to master integrals
- UV divergences extracted using endpoint subtraction
- numerical instabilities: integration by parts, Richardson extrapolation

Work in progress

Further Work within A3a and A3b

- A global view of the EDM landscape [Degenkolb,Elmer,Modak,MM,Plehn,´24]
- Impact of new experimental data on the C2HDM: the strong interdependence between LHC Higgs data and the electron EDM [Biekötter,Fontes,MM,Romao,Santos,Silva,´24]
- Dark colored scalars impact on single and di-Higgs production at the LHC [Gabriel,MM,Neacsu,Santos,´23]
- Intermediate charge-breaking phases and symmetry non-restoration in the 2HDM [Aoki,Biermann,Borschensky,Ivanov,MM,Shibuya,´23]
- The $\mathcal{O}(\alpha_t+\alpha_\lambda+\alpha_\kappa)^2$ correction to the ϱ parameter and its effect on the W boson mass [Dao,Gabelmann,MM,´23]
- Charged Higgs-boson decays into quarks [Chang,Kirk,MM,Spira,´23]
- Leptonic anomalous magnetic and electric dipole moments in the CP-violating NMSSM with and without inverse seesaw mechanism [Dao,Le,MM,´22]
- Pseudoscalar Higgs production at NLO SUSY QCD [Bagnaschi,Fritz,Liebler,MM,Nguyen,Spira,´22]
- Electroweak phase transition in a dark sector with CP violation [Biermann,MM,Müller,´22]


Thank you for your attention!

Considered Constraints in the NMSSM

- SM-like Higgs mass $m_h \in [122,129]$ GeV
  at $\mathcal{O}((\alpha_t+\alpha_\lambda+\alpha_\kappa)^2+\alpha_t\alpha_s)$ in the default mixed $\overline{\mathrm{DR}}$-OS scheme
  with OS renormalisation in the top/stop and charged Higgs boson sectors

- Compatibility w/ Higgs data and BSM Higgs searches

- λ, κ required to be below 0.7 (ensure roughly perturbativity below the GUT scale)

- Neglected points with

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

LO Cross Section

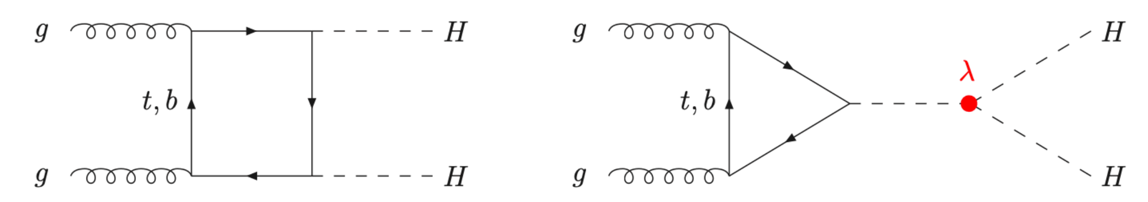
✦ The LO cross section: 2 form factors

$$\mathcal{M}(g^a g^b \to HH) = -i\frac{G_F \alpha_s(\mu_R) Q^2}{2\sqrt{2}\pi} \mathcal{A}^{\mu\nu} \epsilon_{1\mu}\epsilon_{2\nu}\delta_{ab}$$

$$\text{with} \quad \mathcal{A}^{\mu\nu} = F_1 T_1^{\mu\nu} + F_2 T_2^{\mu\nu}\,,$$

$$F_1 = C_\triangle F_\triangle + F_\Box\,, \qquad F_2 = G_\Box$$

$$C_\triangle = \frac{\lambda_{H^3} v}{Q^2 - M_H^2 + i M_H \Gamma_H}$$



Heavy top limit:

$$F_\triangle \to \frac{2}{3}, \qquad F_\Box \to -\frac{2}{3}, \qquad G_\Box \to 0$$

Hadronic cross section

$$\sigma_{LO} = \int_{\tau_0}^{1} d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \hat{\sigma}_{LO}(Q^2 = \tau s)$$

Partonic cross section

$$\hat{\sigma}_{LO} = \frac{G_F^2 \alpha_s^2(\mu_R)}{512(2\pi)^3} \int_{\hat{t}_-}^{\hat{t}_+} d\hat{t} \left[|F_1|^2 + |F_2|^2 \right]$$

$$\hat{t}_\pm = -\frac{1}{2}\left[Q^2 - 2M_H^2 \mp Q^2 \sqrt{1 - 4\frac{M_H^2}{Q^2}} \right]$$

Gluon luminosity

$$\frac{d\mathcal{L}^{gg}}{d\tau} = \int_\tau^1 \frac{dx}{x} g(x, \mu_F) g\left(\frac{\tau}{x}, \mu_F\right)$$

NLO Cross Section

- The NLO cross section:

$$\sigma_{\text{NLO}}(pp \to HH + X) = \sigma_{\text{LO}} + \Delta\sigma_{\text{virt}} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}}$$

C and d_{ij} depend on Q^2

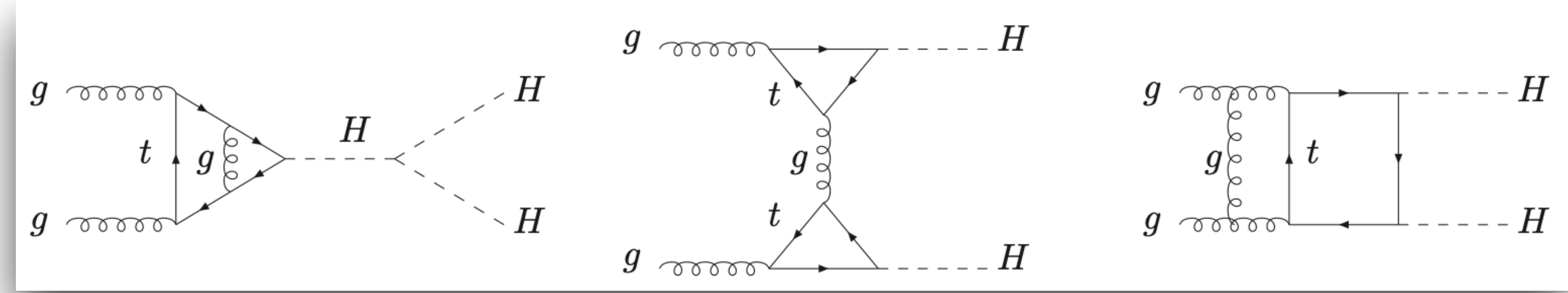
$$\begin{aligned}
\sigma_{\text{LO}} &= \int_{\tau_0}^{1} d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \hat{\sigma}_{\text{LO}}(Q^2 = \tau s) \\
\Delta\sigma_{\text{virt}} &= \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^{1} d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \hat{\sigma}_{\text{LO}}(Q^2 = \tau s)\, C \\
\Delta\sigma_{gg} &= \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^{1} d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \hat{\sigma}_{\text{LO}}(Q^2 = z\tau s) \left\{ -zP_{gg}(z) \log\frac{\mu_F^2}{\tau s} \right. \\
&\quad \left. + d_{gg}(z) + 6[1 + z^4 + (1-z)^4] \left(\frac{\log(1-z)}{1-z}\right)_+ \right\} \\
\Delta\sigma_{gq} &= \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^{1} d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}^{gq}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \hat{\sigma}_{\text{LO}}(Q^2 = z\tau s) \left\{ -\frac{z}{2} P_{gq}(z) \log\frac{\mu_F^2}{\tau s(1-z)^2} + d_{gq}(z) \right\} \\
\Delta\sigma_{q\bar{q}} &= \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^{1} d\tau \sum_{q} \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \hat{\sigma}_{\text{LO}}(Q^2 = z\tau s)\, d_{q\bar{q}}(z)
\end{aligned}$$

- HTL:

$$C \to \pi^2 + \frac{11}{2} + C_{\triangle\triangle}, \quad d_{gg} \to -\frac{11}{2}(1-z)^3, \quad d_{gq} \to \frac{2}{3}z^2 - (1-z)^2, \quad d_{q\bar{q}} \to \frac{32}{27}(1-z)^3$$

Virtual Corrections

✦ Contributing diagrams: 47 generic box diagrams, 8 triangle diagrams ($\leftarrow$ single Higgs), 1 PR ($\leftarrow$ H$\rightarrow$Zγ)



✦ Full diagram w/o tensor reduction $\rightarrow$ 6-dim. Feynman integral (for 2 form factors)

✦ UV singularities: $\rightarrow$ endpoint subtractions

$$\int_0^1 dx \, \frac{f(x)}{(1-x)^{1-\epsilon}} = \int_0^1 dx \, \frac{f(1)}{(1-x)^{1-\epsilon}} + \int_0^1 dx \, \frac{f(x)-f(1)}{(1-x)^{1-\epsilon}} = \frac{f(1)}{\epsilon} + \int_0^1 dx \, \frac{f(x)-f(1)}{1-x} + \mathcal{O}(\epsilon)$$

✦ IR singularities: IR subtraction (based on structure of integr. and rel. to HTL)

✦ Thresholds: $Q^2 \geq 0, 4m_t^2$ $\rightarrow$ IBP $\rightarrow$ reduction of power of denominator

$$[m_t^2 \rightarrow m_t^2(1-ih)]$$

$$\int_0^1 dx \, \frac{f(x)}{(a+bx)^3} = \frac{f(0)}{2a^2 b} - \frac{f(1)}{2b(a+b)^2} + \int_0^1 dx \frac{f'(x)}{2b(a+bx)^2}$$

Further Calculational Details

- Renormalization: α_S: MSbar, 5 flavors, m_t: on-shell
- Phase space integration → 7-dim. integrals for $d\sigma/dQ^2$
- Subtraction of HTL → IR-finite mass effects [adding back HTL results ← HPAIR]
- Extrapolation to NWA (h→0): Richardson extrapolation

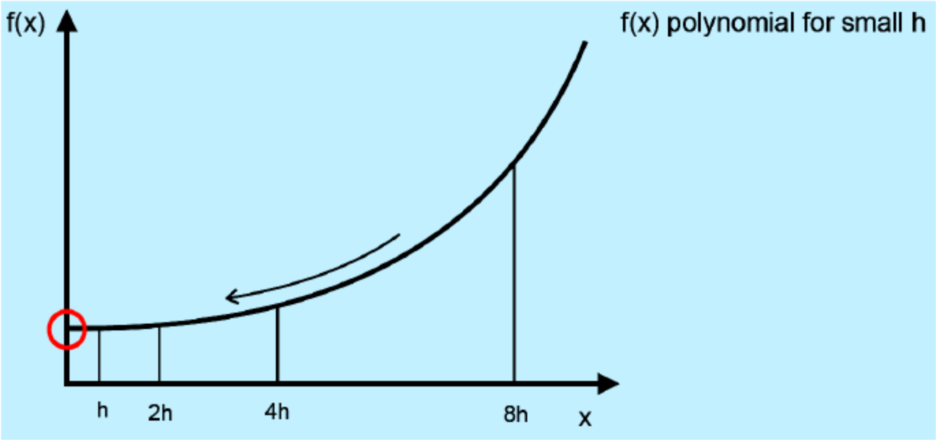
$$M_2 = 2f(h) - f(2h) = f(0) + \mathcal{O}(h^2)$$

$$M_4 = \{8f(h) - 6f(2h) + f(4h)\}/3 = f(0) + \mathcal{O}(h^3)$$

$$M_8 = \{64f(h) - 56f(2h) + 14f(4h) - f(8h)\}/21 = f(0) + \mathcal{O}(h^4)$$

etc.

$[h \geq 0.025]$



Real Corrections

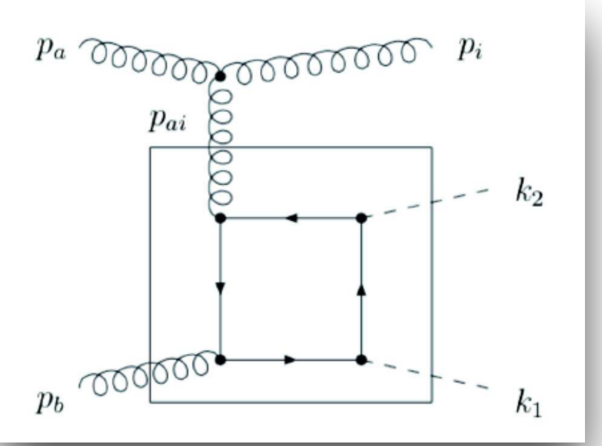
- Full matrix element: generated with FeynArts and FormCalc
- Matrix elements in HTL involving full LO sub-matrix elements subtracted
  → IR-, COLL-finite [adding back HTL results ← HPAIR]

$$\sum \overline{|\mathcal{M}_{gg}|^2} = \sum \overline{\left|\tilde{\mathcal{M}}_{LO}\right|^2} \frac{24\pi^2}{Q^4}\frac{\alpha_s}{\pi}\left\{\frac{s^4+t^4+u^4+Q^8}{stu} - 4\frac{\epsilon}{1-\epsilon}Q^2\right\}$$

$$\sum \overline{|\mathcal{M}_{gq}|^2} = \sum \overline{\left|\tilde{\mathcal{M}}_{LO}\right|^2} \frac{32\pi^2}{3Q^4}\frac{\alpha_s}{\pi}\left\{\frac{s^2+u^2}{-t} + \epsilon\frac{(s+u)^2}{t}\right\}$$

$$\sum \overline{|\mathcal{M}_{q\bar{q}}|^2} = \sum \overline{\left|\tilde{\mathcal{M}}_{LO}\right|^2} \frac{256\pi^2}{9Q^4}\frac{\alpha_s}{\pi}(1-\epsilon)\left\{\frac{t^2+u^2}{s} - \epsilon\frac{(t+u)^2}{s}\right\}$$

- PDFs: MSbar, 5 flavors



Results

	PDF4LHC15	MMHT2014
σ_{LO}	19.80 fb	23.75 fb
σ_{NLO}^{HTL}	38.66 fb	39.34 fb
σ_{NLO}	32.78(7) fb	33.33(7) fb

Conversion from Pole to MSbar Mass

$$F_i = F_{i,LO} + \Delta F_i = F_{i,LO} + \Delta F_{1,HTL} + \Delta F_{1,mass}$$

Pole mass: $F_{1,LO} = 4 m_t^2 / \hat{s}$

Conversion pole mass → $\overline{MS}$ mass at μ_t: $m_t \to \bar{m}_t(\mu_t)\left[1 + \frac{\alpha_s}{\pi}\left(\frac{4}{3} + \log\frac{\mu_t^2}{m_t^2}\right)\right]$

$$F_{1,LO} + \Delta F_{1,HTL}$$

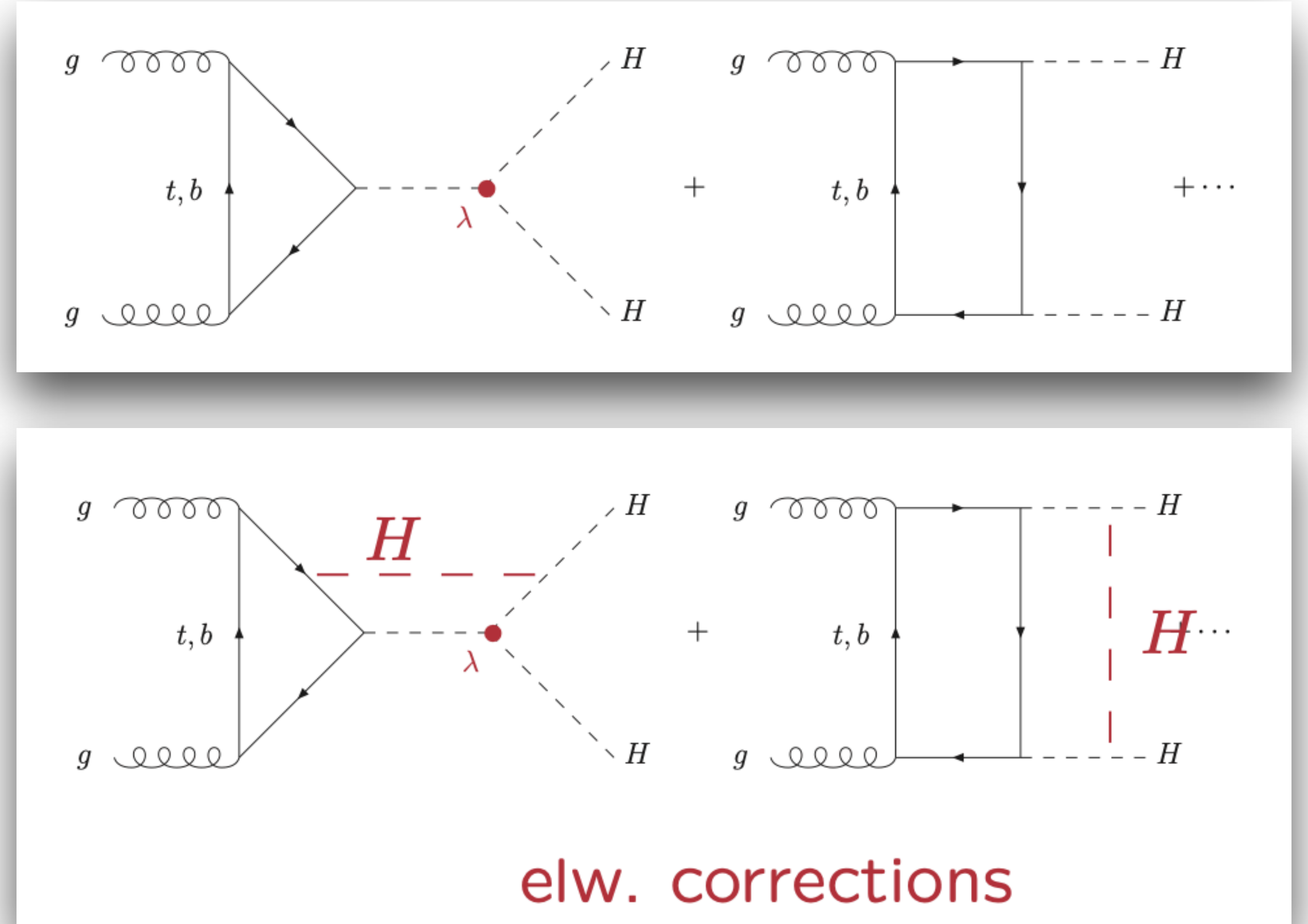
$$\to \frac{4\bar{m}_t^2(\mu_t)}{\hat{s}}\left[1 + 2\cdot\frac{\alpha_s}{\pi}\cdot\frac{4}{3} + 2\frac{\alpha_s}{\pi}\log\frac{\mu_t^2}{m_t^2}\right]$$

$$+ \frac{4\bar{m}_t^2(\mu_t)}{\hat{s}}\cdot 2\cdot\frac{\alpha_s}{\pi}\log\frac{m_t^2}{\hat{s}}$$

$$= \frac{4\bar{m}_t^2(\mu_t)}{\hat{s}}\left[1 + 2\frac{\alpha_s}{\pi}\left[\log\frac{\mu_t^2}{\hat{s}} + \frac{4}{3}\right]\right]$$

Scales for y_t

- Different scales for y_t in triangle (Q) and box (M_H) diagrams?
  → has to hold to all orders



⇒ Same scale in all diagrams

LO Uncertainties

- Scale and scheme uncertainties at LO

$$\frac{d\sigma(gg \to HH)}{dQ}|_{Q=300\ \text{GeV}} = 0.01656^{+62\%}_{-2.4\%}\ \text{fb/GeV}$$

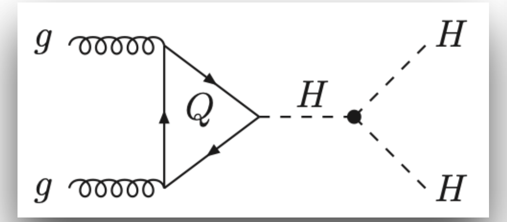
$$\frac{d\sigma(gg \to HH)}{dQ}|_{Q=400\ \text{GeV}} = 0.09391^{+0\%}_{-20\%}\ \text{fb/GeV}$$

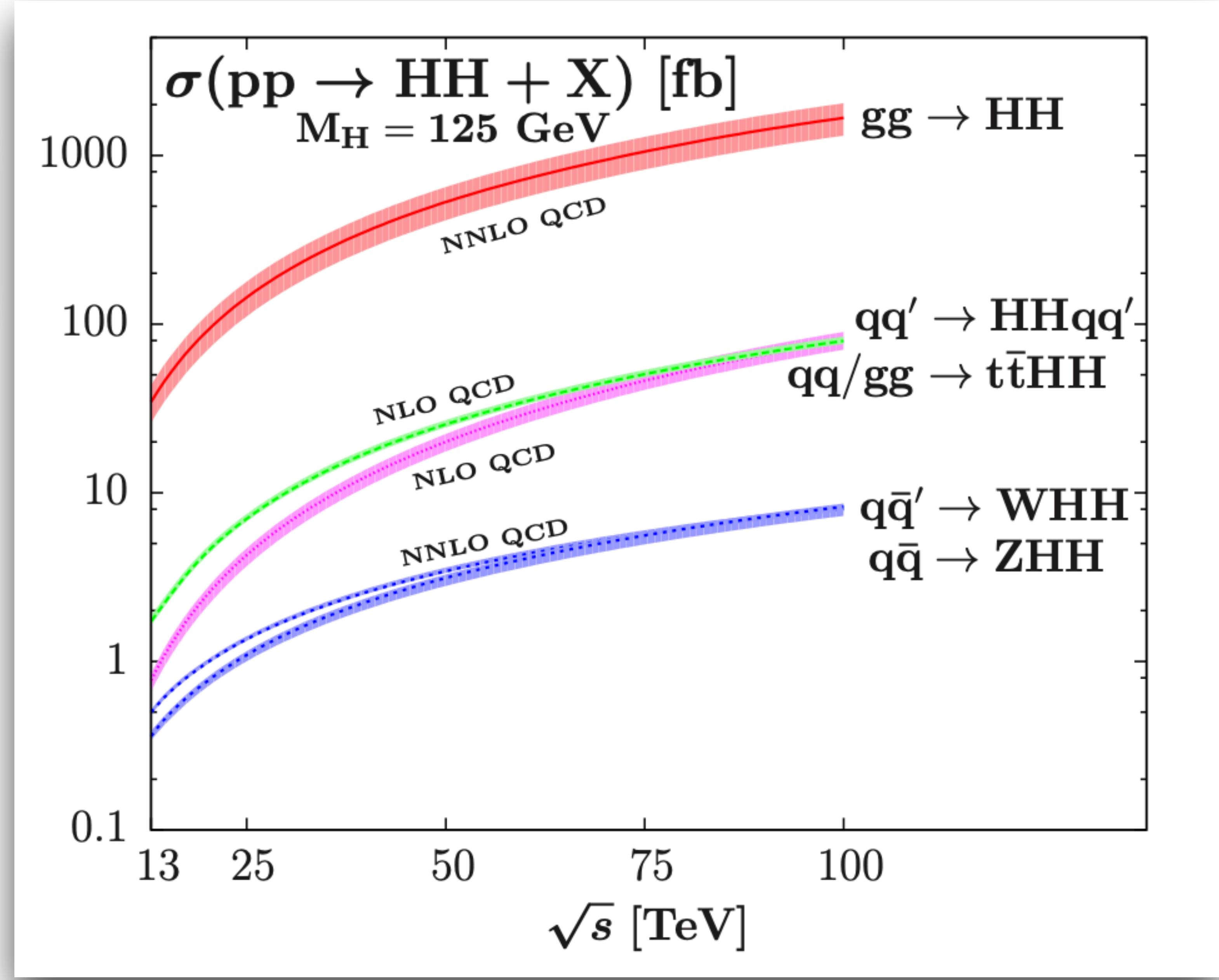
$$\frac{d\sigma(gg \to HH)}{dQ}|_{Q=600\ \text{GeV}} = 0.02132^{+0\%}_{-48\%}\ \text{fb/GeV}$$

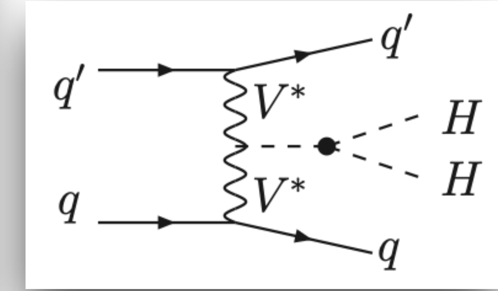
$$\frac{d\sigma(gg \to HH)}{dQ}|_{Q=1200\ \text{GeV}} = 0.0003223^{+0\%}_{-56\%}\ \text{fb/GeV}$$

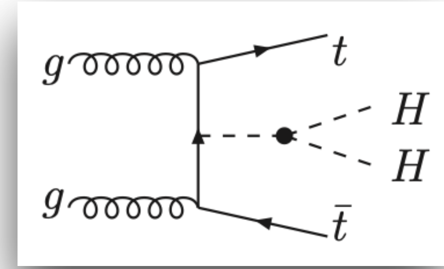
Double Higgs Production Processes

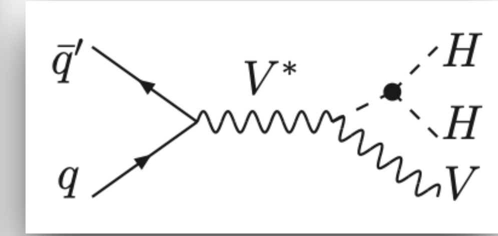
[Baglio,Djouadi,Quévillon,'15]





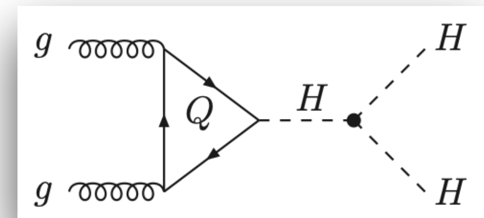


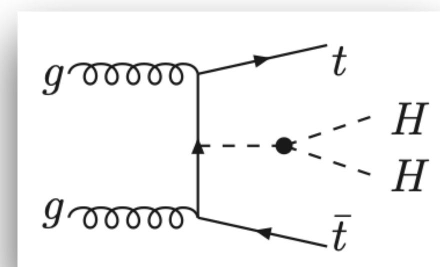


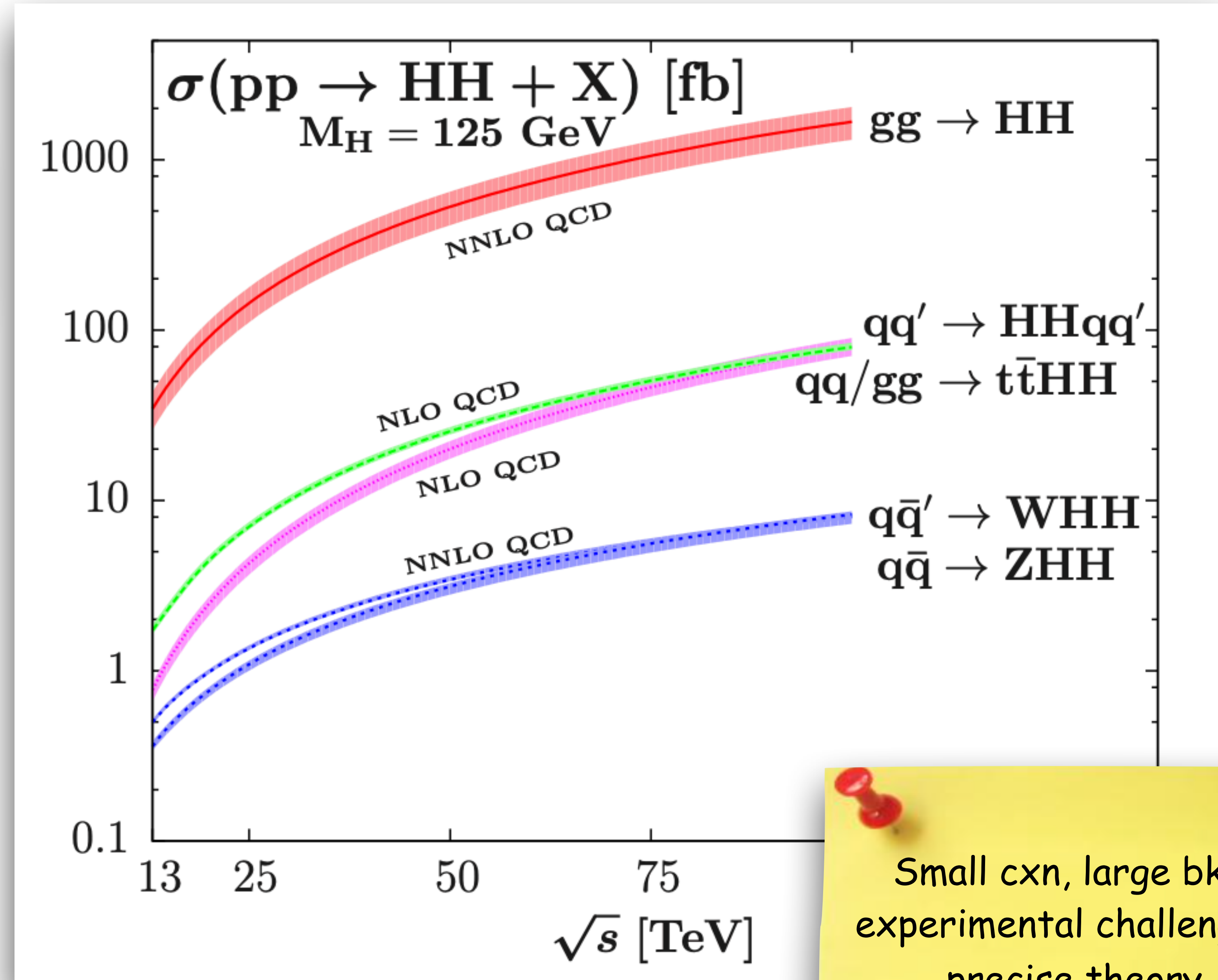


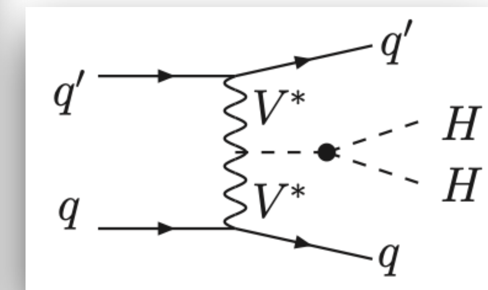
Double Higgs Production Processes

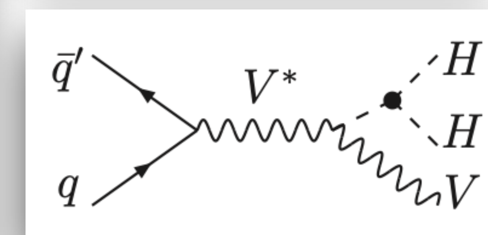
[Baglio,Djouadi,Quévillon,'15]











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