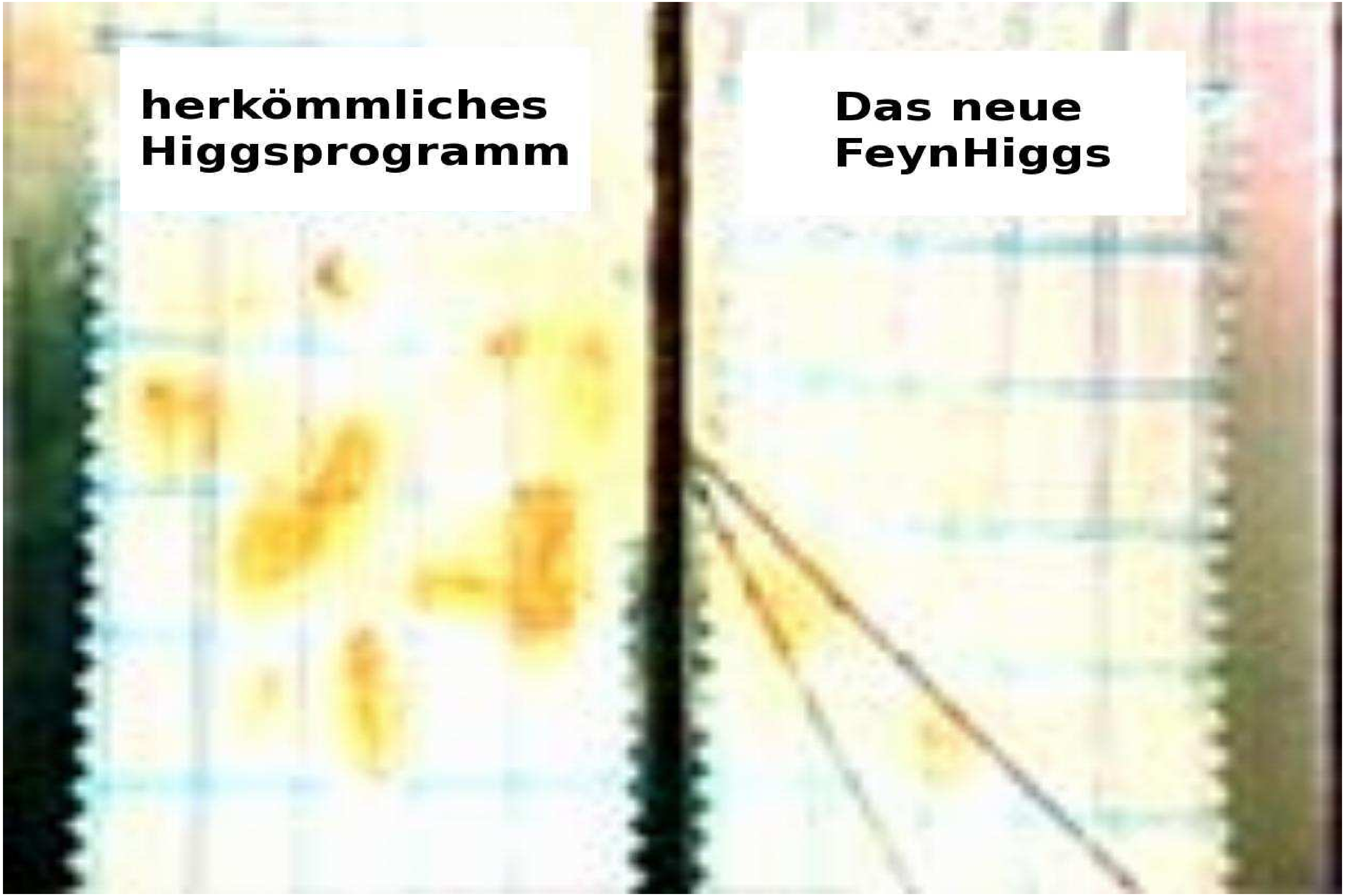

herkömmliches
Higgsprogramm
Das neue
FeynHiggs

FeynHiggs: Status and Prospects

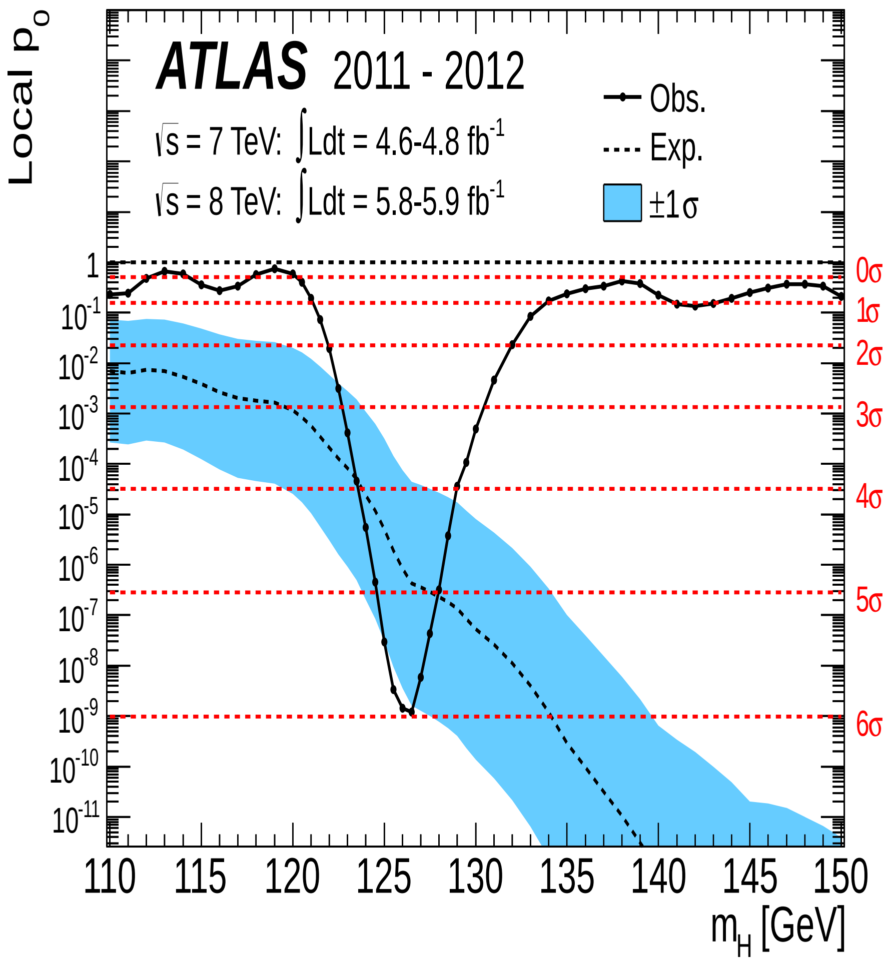
Sven Heinemeyer, IFCA (CSIC, Santander)

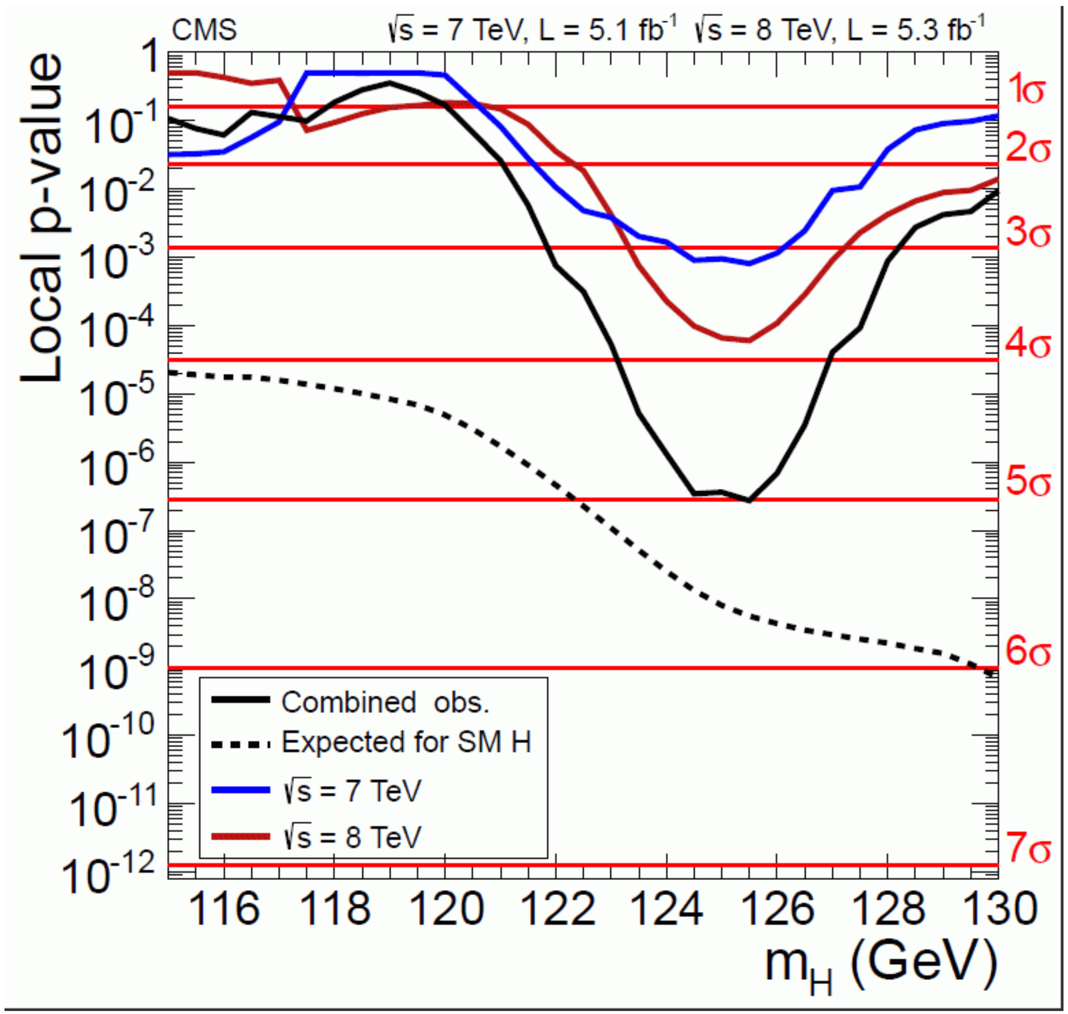
Lake Tahoe, 08/2015

with *T. Hahn, W. Hollik, H. Rzehak and G. Weiglein*

- FeynHiggs status
- Latest additions
- FeynHiggs vs. EFT approach
- FeynHiggs: prospects

1. Motivation



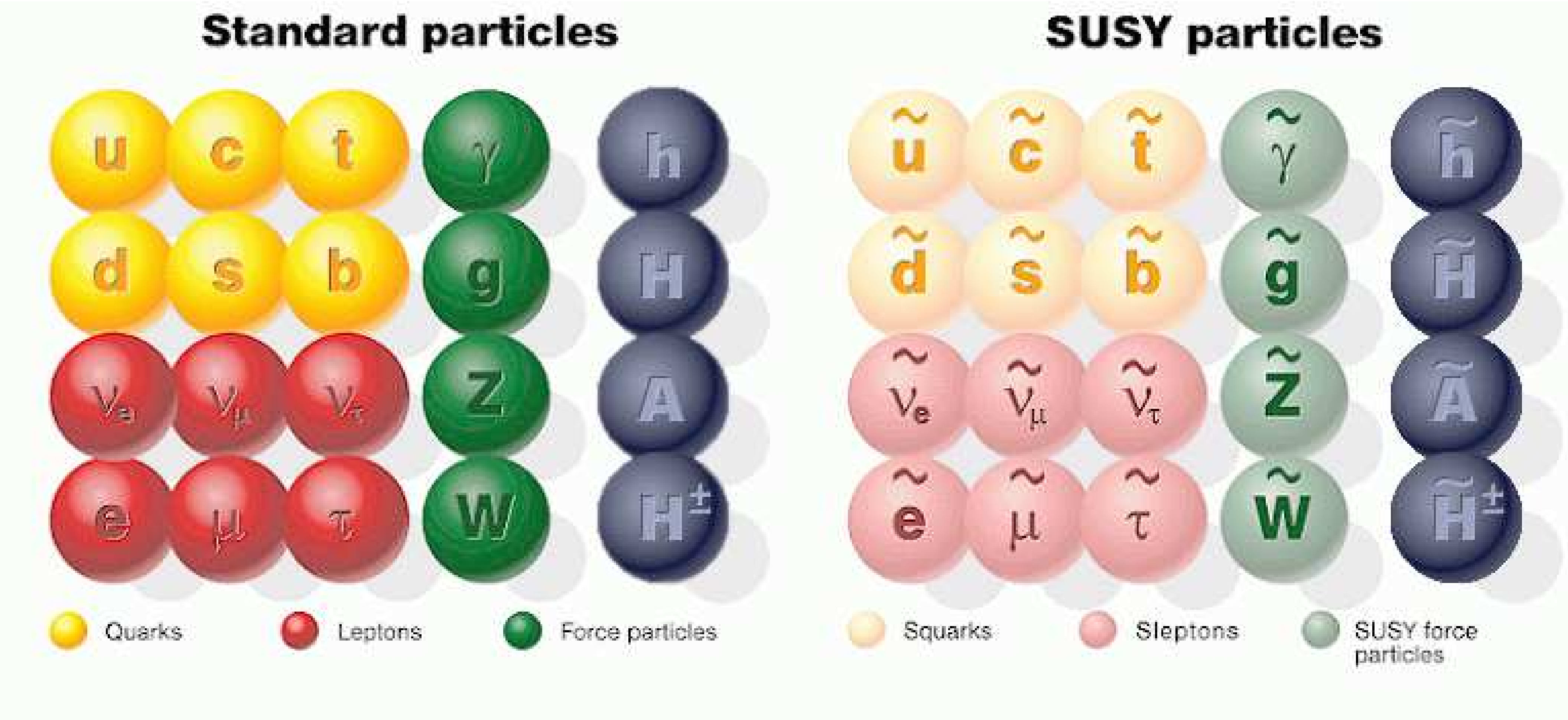


⇒ clear discovery at ∼ 125 GeV!

⇒ can be interpreted as the light(/heavy) $\mathcal{CP}$-even MSSM Higgs

The MSSM:

⇒ Superpartners for Standard Model particles



Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2 (\tan\beta + \cot\beta)$$

Enlarged Higgs sector: Two Higgs doublets with $\mathcal{CP}$ violation

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

2 $\mathcal{CP}$-violating phases: ξ, arg(m_{12}) $\Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}^2$$

Needed for LHC/ILC/. . . physics:

Precise and consistent prediction of

- Higgs boson masses
- Higgs boson mixings
- Higgs boson couplings
- Higgs boson production cross sections
- Higgs boson decay widths/branching ratios
- . . .

$\Rightarrow$ (partially) provided by FeynHiggs

2. FeynHiggs status

Latest version: FeynHiggs 2.11.2 (07/15)

version FeynHiggs 2.11.3 nearly ready . . . :-)

FeynHiggs compiles on all modern platforms

FeynHiggs provides:

- Higgs boson masses
- Higgs boson couplings
- Higgs boson decay widths
- Higgs boson production cross sections (4 π, good approx.)
- evaluation of other observables to test the validity of parameters
- all this for the neutral and charged Higgs bosons
- all this in the MSSM with real or complex parameters

$\Rightarrow$ the Standard Code for masses couplings, some decays in the LHCHXSWG

The core: MSSM Higgs mass calculation

Propagator/Mass matrix at tree-level:

$$\begin{pmatrix} q^2 - m_A^2 & 0 & 0 \\ 0 & q^2 - m_H^2 & 0 \\ 0 & 0 & q^2 - m_h^2 \end{pmatrix}$$

Propagator / mass matrix with higher-order corrections (FD approach):

$$M_{hHA}^2(q^2) = \begin{pmatrix} q^2 - m_A^2 + \hat{\Sigma}_{AA}(q^2) & \hat{\Sigma}_{AH}(q^2) & \hat{\Sigma}_{Ah}(q^2) \\ \hat{\Sigma}_{HA}(q^2) & q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hA}(q^2) & \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ $(i, j = h, H, A)$: renormalized Higgs self-energies

$\hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH} \neq 0$ $\Rightarrow$ $\mathcal{CP}$V, $\mathcal{CP}$-even and $\mathcal{CP}$-odd fields can mix

$\Rightarrow$ complex roots of det$(M_{hHA}^2(q^2))$: $\mathcal{M}_{h_i}^2 (i = 1, 2, 3)$: $\mathcal{M}^2 = M^2 - iM\Gamma$

Corrections included in FeynHiggs 2.10

$$\begin{pmatrix} k^2 - M_h^2 + \hat{\Sigma}_{hh} & \hat{\Sigma}_{hH} & \hat{\Sigma}_{hA} \\ \hat{\Sigma}_{Hh} & k^2 - M_H^2 + \hat{\Sigma}_{HH} & \hat{\Sigma}_{HA} \\ \hat{\Sigma}_{Ah} & \hat{\Sigma}_{AH} & k^2 - M_A^2 + \hat{\Sigma}_{AA} \end{pmatrix}, \quad \hat{\Sigma}_{H^+H^-}$$

- **Full one-loop evaluation (all phases, k^2 dependence).**
  Frank, Heinemeyer, Hollik, Weiglein 2002
- **Leading $\mathcal{O}(\alpha_s\alpha_t)$ two-loop corrections in the cMSSM.**
  Heinemeyer, Hollik, Rzehak, Weiglein 2007
- **Leading $\mathcal{O}(\alpha_t^2)$ + subleading $\mathcal{O}(\alpha_s\alpha_b, \alpha_t\alpha_b, \alpha_b^2)$ two-loop corrections in the rMSSM (phases only partially included).**
  Degrassi, Slavich, Zwirner 2001 – Brignole, Degrassi, Slavich, Zwirner 2001, 02
  Dedes, Degrassi, Slavich 2003
- **RGE-resummed leading logs**
  Hahn, Heinemeyer, Hollik, Rzehak, Weiglein 2013

FeynHiggs Update – p.10

New: k^2 Dependence @ 2L

$$\begin{pmatrix} k^2 - M_h^2 + \hat{\Sigma}_{hh}^{\bullet\bullet\bullet\bullet} & \hat{\Sigma}_{hH}^{\bullet\bullet\bullet\bullet} & \hat{\Sigma}_{hA}^{\bullet\bullet} \\ \hat{\Sigma}_{Hh}^{\bullet\bullet\bullet\bullet} & k^2 - M_H^2 + \hat{\Sigma}_{HH}^{\bullet\bullet\bullet\bullet} & \hat{\Sigma}_{HA}^{\bullet\bullet} \\ \hat{\Sigma}_{Ah}^{\bullet\bullet} & \hat{\Sigma}_{AH}^{\bullet\bullet} & k^2 - M_A^2 + \hat{\Sigma}_{AA}^{\bullet\bullet} \end{pmatrix}, \quad \hat{\Sigma}_{H^+H^-}^{\bullet\bullet}$$

$$\begin{pmatrix} k^2 - M_h^2 + \hat{\Sigma}^{(1)}_{hh}(k^2) + \hat{\Sigma}^{2}_{hh}(k^2) & \hat{\Sigma}^{(1)}_{hH}(k^2) + \hat{\Sigma}^{(2)}_{hH}(k^2) \\ \hat{\Sigma}^{(1)}_{Hh}(k^2) + \hat{\Sigma}^{(2)}_{Hh}(k^2) & k^2 - M_H^2 + \hat{\Sigma}^{(1)}_{HH}(k^2) + \hat{\Sigma}^{(2)}_{HH}(k^2) \end{pmatrix}$$

before FeynHiggs 2.10.1:

$$\begin{pmatrix} k^2 - M_h^2 + \hat{\Sigma}^{(1)}_{hh}(k^2) + \hat{\Sigma}^{2}_{hh}(0) & \hat{\Sigma}^{(1)}_{hH}(k^2) + \hat{\Sigma}^{(2)}_{hH}(0) \\ \hat{\Sigma}^{(1)}_{Hh}(k^2) + \hat{\Sigma}^{(2)}_{Hh}(0) & k^2 - M_H^2 + \hat{\Sigma}^{(1)}_{HH}(k^2) + \hat{\Sigma}^{2}_{HH}(0) \end{pmatrix}$$

FeynHiggs Update – p.11

Included in FeynHiggs 2.11.2 (I):

Evaluation of all Higgs boson masses and mixing angles

- $M_{h_1}, M_{h_2}, M_{h_3}, M_{H^\pm}$, $\alpha_{\rm eff}$, $\mathbf{Z}_{ij}$, $\mathbf{U}_{ij}$, ...

Evaluation of all neutral Higgs boson decay channels

- total decay width $\Gamma_{\rm tot}$
- $\mathrm{BR}(h_i \to f\bar{f})$: decay to SM fermions
- $\mathrm{BR}(h_i \to \gamma\gamma, Z^{(*)}Z^{(*)}, W^{(*)}W^{(*)}, gg)$: decay to SM gauge bosons
- $\mathrm{BR}(h_i \to h_j Z^{(*)}, h_j h_k)$: decay to gauge and Higgs bosons
- $\mathrm{BR}(h_i \to \tilde{f}_i \tilde{f}_j)$: decay to sfermions
- $\mathrm{BR}(h_i \to \tilde{\chi}_i^\pm \tilde{\chi}_j^\mp, \tilde{\chi}_i^0 \tilde{\chi}_j^0)$: decay to charginos, neutralinos

Evaluation for the SM Higgs (same masses as the three MSSM Higgses)

- total decay width $\Gamma_{\rm tot}^{\rm SM}$
- $\mathrm{BR}(h_i^{\rm SM} \to f\bar{f})$: decay to SM fermions
- $\mathrm{BR}(h_i^{\rm SM} \to \gamma\gamma, ZZ^{(*)}, WW^{(*)}, gg)$: decay to SM gauge bosons

Included in FeynHiggs 2.11.2 (II):

Evaluation of all neutral Higgs boson production cross sections at LHC

SM: (more or less) up-to-date, MSSM: additional effective couplings

- $gg \to h_i$: gluon fusion
- $WW \to h_i$, $ZZ \to h_i$: gauge boson fusion
- $W \to Wh_i$, $Z \to Zh_i$: Higgs strahlung
- $b\bar{b} \to b\bar{b}h_i$: bottom Yukawa process
- $b\bar{b} \to b\bar{b}h_i$, $h_i \to b\bar{b}$, one b tagged
- $t\bar{t} \to t\bar{t}h_i$: top Yukawa process
- $\tilde{t}\bar{\tilde{t}} \to \tilde{t}\bar{\tilde{t}}h_i$: stop Yukawa process

Evaluation for the SM Higgs (same masses as the three MSSM Higgses)

- all SM channels as above

Included in FeynHiggs 2.11.2 (III):

Evaluations for the charged Higgs boson (rMSSM/cMSSM)

- total decay width $\Gamma_{\rm tot}$
- BR($H^+ \to f^{(*)}\bar{f}'$): decay to SM fermions
- BR($H^+ \to h_i W^{+(*)}$): decay to gauge and Higgs bosons
- BR($H^+ \to \tilde{f}_i \tilde{f}'_j$): decay to sfermions
- BR($H^+ \to \tilde{\chi}^0_i \tilde{\chi}^+_j$): decay to charginos and neutralinos
- H^+ production cross sections at the LHC
- BR($t \to H^+ \bar{b}$) for $M_{H^\pm} \le m_t$ ($H^\pm$ production)

Evaluation of additional couplings:

- $g(V \to V h_i, h_i h_j)$: coupling of gauge and Higgs bosons
- $g(h_i h_j h_k)$: all Higgs self couplings (including charged Higgs)

Included in FeynHiggs 2.11.2 (IV):

Evaluation of theory error on masses and mixing

$\to$ estimate of uncertainty in $M_{h_i}, \mathbf{U}_{ij}, \mathbf{Z}_{ij}$ from unknown higher-order corr.

Evaluation of masses, mixing and decay in the NMFV/LFV MSSM

NMFV: Non Minimal Flavor Violation LFV: Lepton Flavor Violation

$\Rightarrow$ Connection to Flavor physics

Evaluation of additional constraints (rMSSM/cMSSM)

- ρ-parameter: $\Delta\rho^{\text{SUSY}}$ at $\mathcal{O}(\alpha)$, $\mathcal{O}(\alpha\alpha_s)$, . . . , including FV effects
  $\Rightarrow M_W$, $\sin^2\theta_{\text{eff}}$ via SM formula + $\Delta\rho^{\text{SUSY}}$, including FV effects
- anomalous magnetic moment of the μ: $(g-2)_\mu$
- BR($b \to s\gamma$), including NMFV effects
- BR($B_s \to \mu^+\mu^-$), including NMFV effects
- EDMs of electron, neutron, Hg, . . .

3. Latest additions

- $\mathcal{O}\left(\alpha_t^2\right)$ corrections in cMSSM

- $\mathcal{O}\left(p^2\alpha_t\alpha_s\right)$ corrections in rMSSM
  $\overline{\text{DR}}$ renormalization of m_t in two-loop corrections

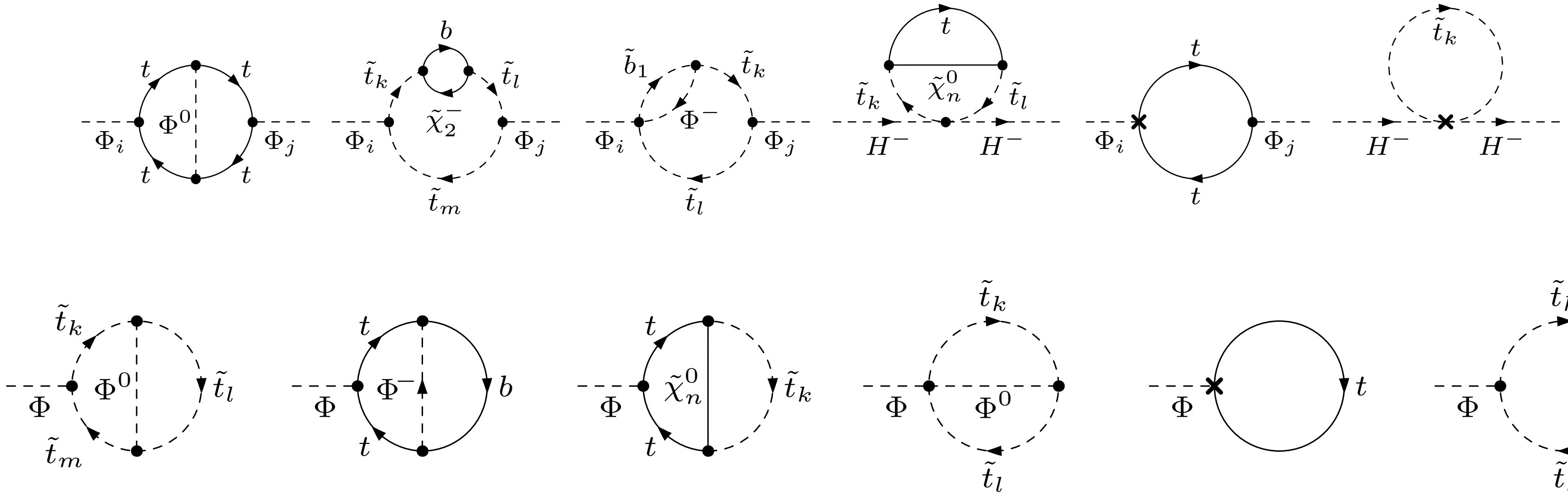
- log-resummation in $t/\tilde{t}$ sector

- ...

3A) $\mathcal{O}\left(\alpha_t^2\right)$ corrections in the cMSSM

Two-loop top-Yukawa-coupling corrections to the Higgs boson masses in the complex MSSM

[W. Hollik, S. Passehr '14]

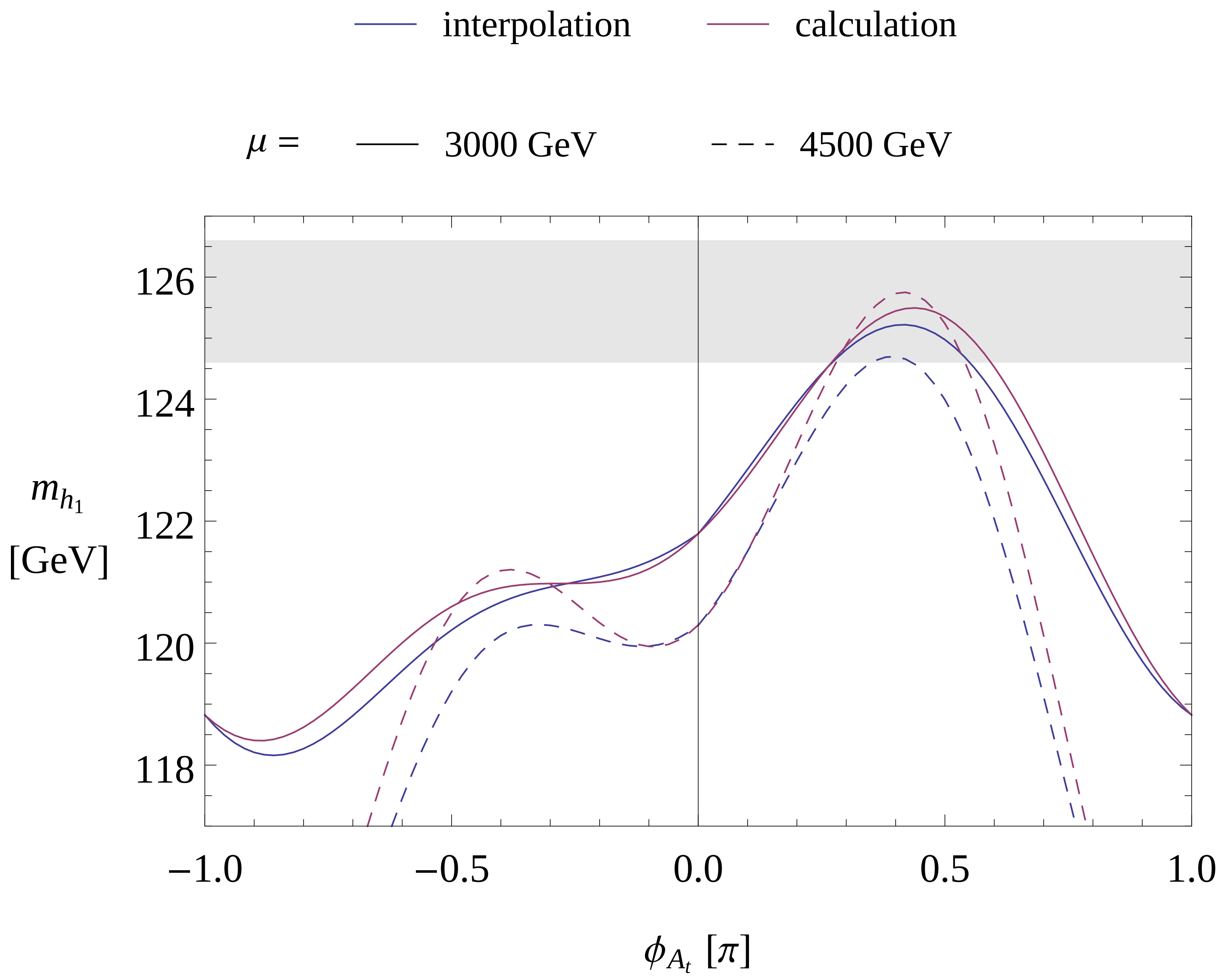


⇒ effects in M_{h_1} of $\mathcal{O}\,(1\text{ GeV})$

⇒ equally $\mathcal{O}\left(\alpha_t^2\right)$ corrections to $M_{H^\pm}$ in rMSSM

Two-loop top-Yukawa-coupling corrections to the Higgs boson masses in the complex MSSM

[*W. Hollik, S. Passehr '14*]



$t_\beta = 5$

$m_{\tilde{q}_3} = m_{\tilde{b}_R} = 1500$ GeV

$m_{\tilde{t}_R} = 1.1 m_{\tilde{q}_3}$

$m_{\tilde{\ell}_3} = m_{\tilde{\tau}_R} = 1000$ GeV

$m_{\tilde{g}} = 0.9 m_{\tilde{q}_3} e^{i\pi/2}$

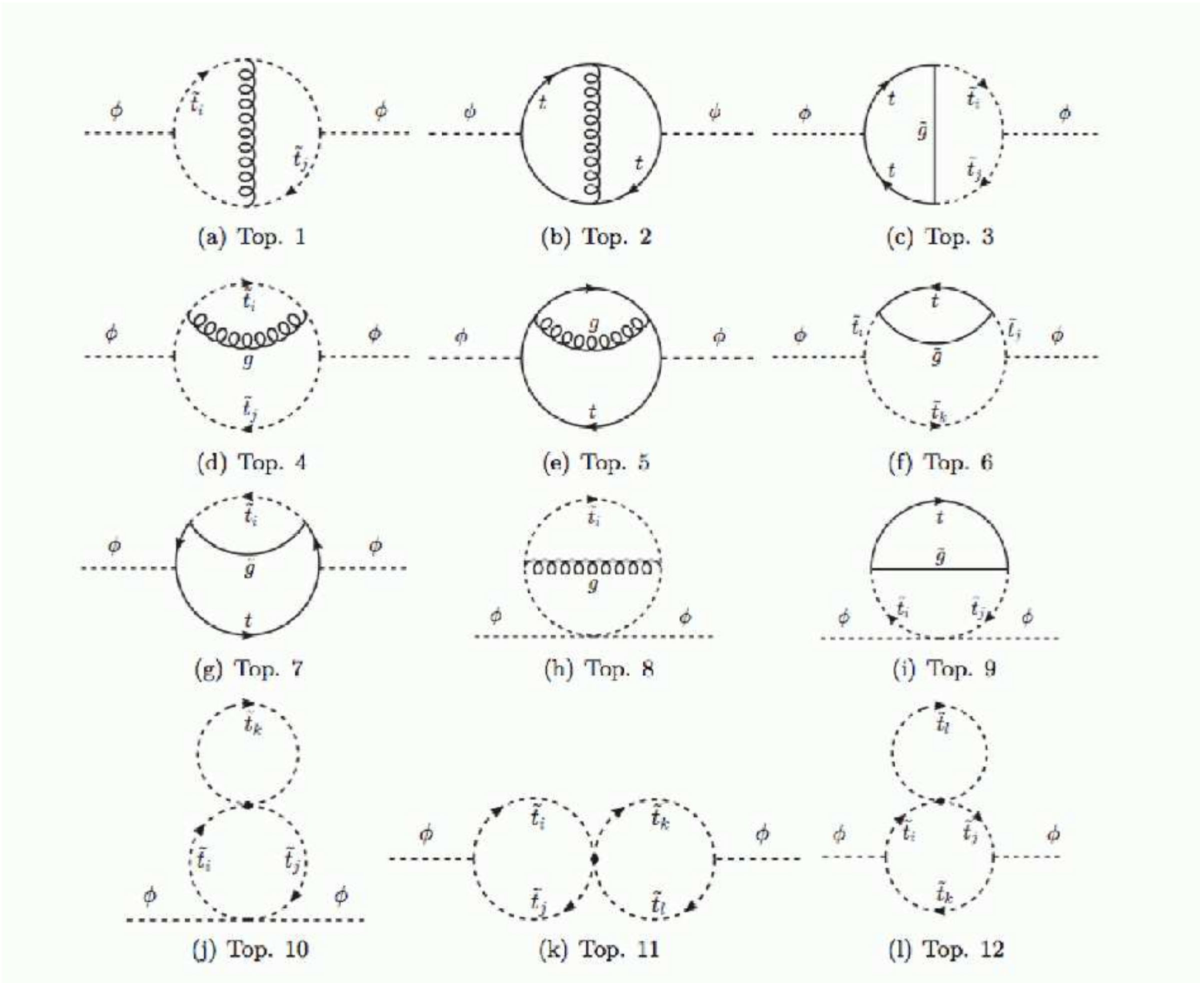
$m_{H^\pm} = 500$ GeV

$|A_t| = |A_b| = |A_\tau| = 2 m_{\tilde{q}_3}$

$\phi_{A_t} = \phi_{A_b} = \phi_{A_\tau}$

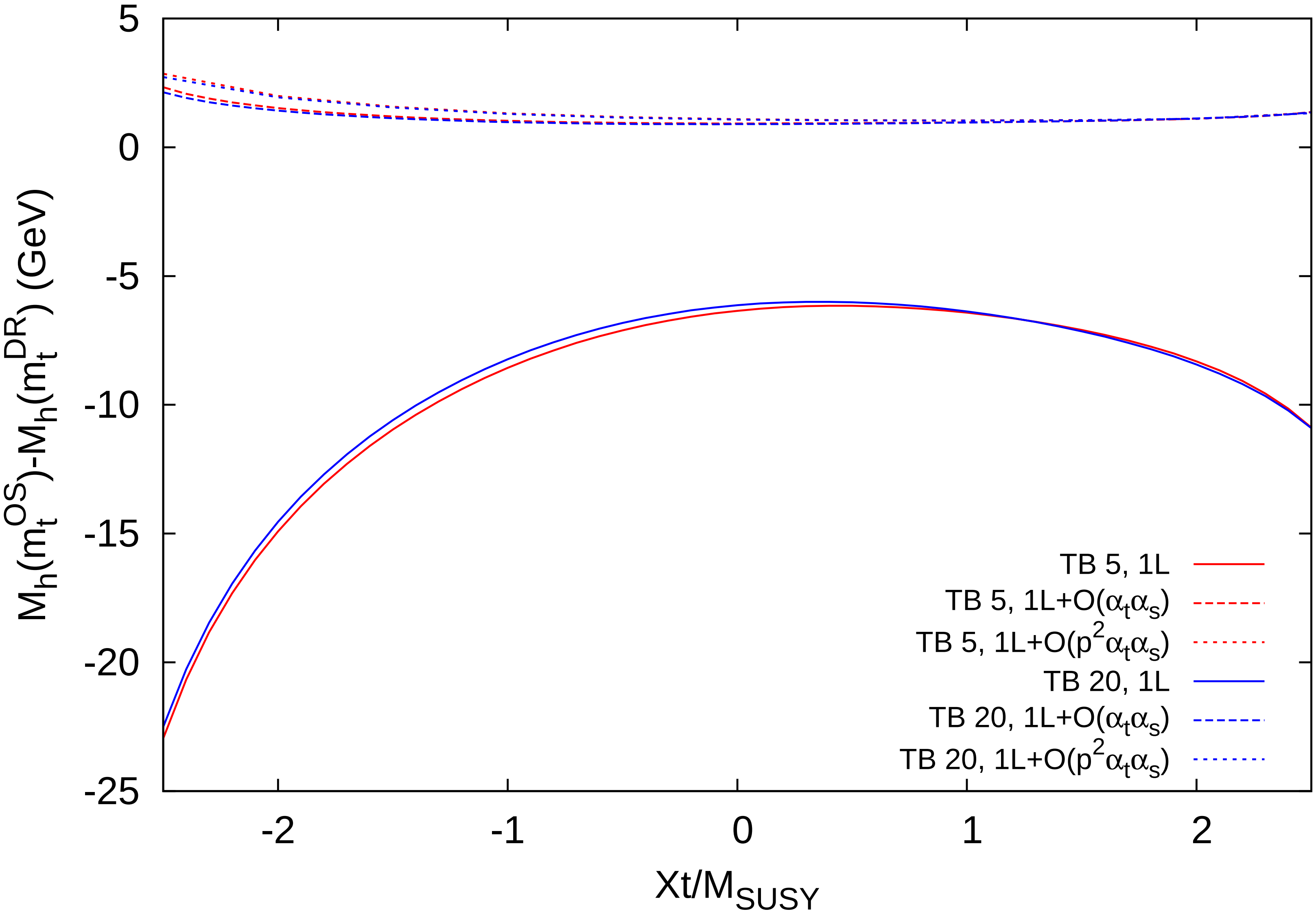
3B) $\mathcal{O}\left(p^2\alpha_t\alpha_s\right)$ corrections in the rMSSM

[S. Borowka, T. Hahn, S.H., G. Heinrich, W. Hollik '14]



$\Rightarrow$ also $\overline{\text{DR}}$ renormalization of m_t in two-loop corrections

X_t dependence in light-stop scenario:



⇒ strong reduction of RS dependence at the two-loop level

⇒ additional possibility of estimate of higher-order uncertainties

3C) Log-resummation in $t/\tilde{t}$ sector via RGE's

[*T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '13*] $\Rightarrow$ see G. Lee's talk

Simple example for log resummation:

SUSY mass scale: $M_{\text{SUSY}} = M_{\text{S}} \sim m_{\tilde{t}}$

Above M_{SUSY}: MSSM
Below M_{SUSY}: SM

Relevant SM parameters:
- quartic coupling λ
- top Yukawa coupling h_t $(\alpha_t = h_t^2/(4\pi))$
- strong coupling constant g_s $(\alpha_s = g_s^2/(4\pi))$

Procedure (as in FeynHiggs):

1. Take: $h_t(m_t), g_s(m_t)$

   SM RGEs for h_t, g_s: $h_t, g_s(m_t) \to h_t, g_s(M_{\text{S}})$

2. Take $\lambda(M_{\text{S}}), h_t(M_{\text{S}}), g_s(M_{\text{S}})$

   SM RGEs for λ, h_t, g_s: $\lambda, h_t, g_s(M_{\text{S}}) \to \lambda, h_t, g_s(m_t)$

3. Evaluate M_h^2

$$M_h^2 \sim 2\lambda(m_t)v^2$$

Combination of FD and RGE result:

$\Rightarrow$ to avoid double counting:
subtract leading and subleading logs at one- and two-loop

Problem:

– FD result with $X_t^{\text{OS}}, M_S^{\text{OS}}, \overline{m}_t$

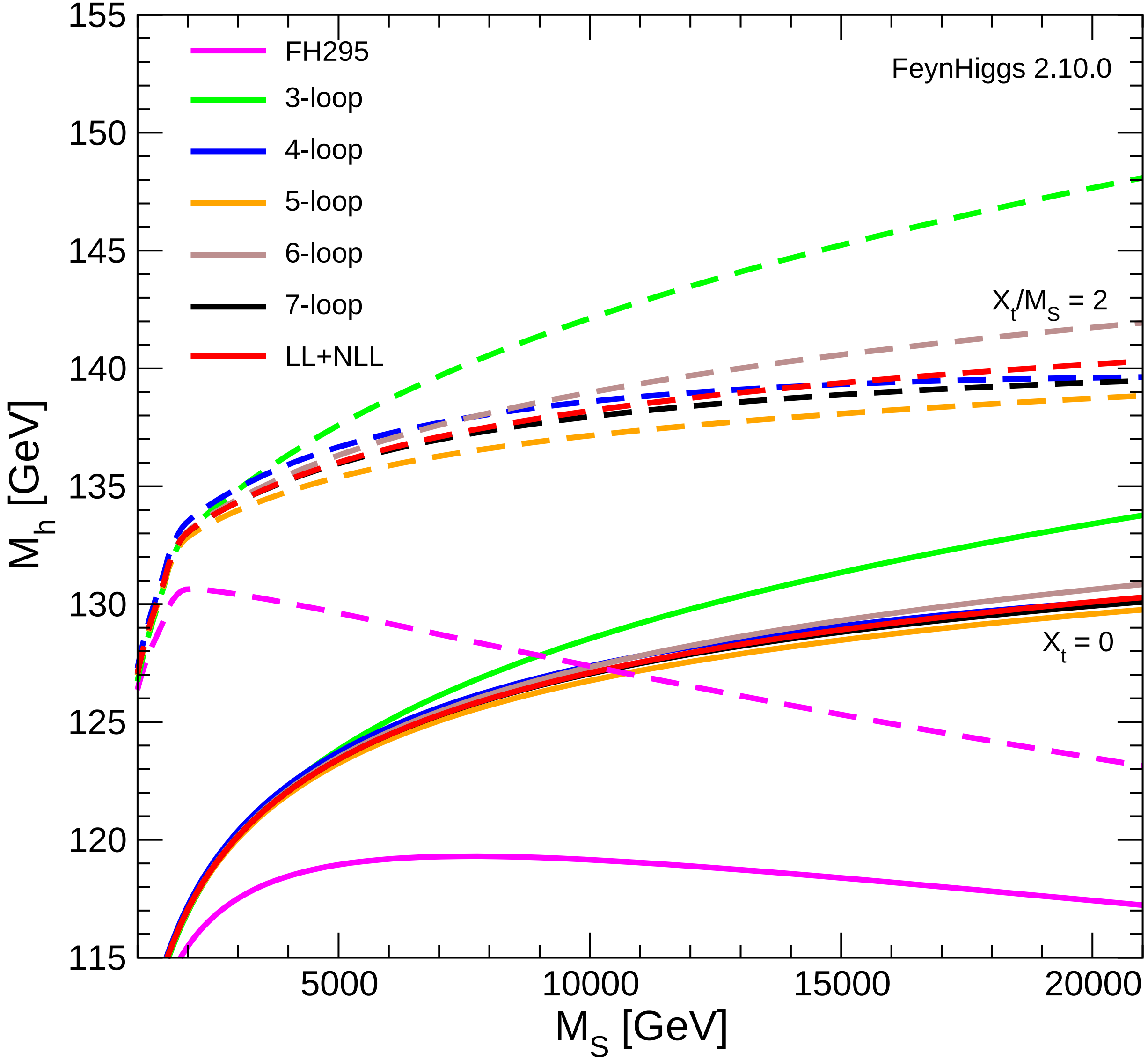
– RGE result with $X_t^{\overline{\text{MS}}}, M_S^{\overline{\text{MS}}}, \overline{m}_t$

$$\overline{m}_t = \frac{m_t^{\text{pole}}}{1 + \frac{4}{3\pi}\alpha_s(m_t^{\text{pole}}) - \frac{1}{2\pi}\alpha_t(m_t^{\text{pole}})}$$

$$X_t^{\overline{\text{MS}}} = X_t^{\text{OS}}\left[1 + 2L\left(\frac{\alpha_s}{\pi} - \frac{3\,\alpha_t}{16\,\pi}\right)\right]$$

$$M_S^{\overline{\text{MS}}} \sim M_S^{\text{OS}} \quad : \text{ no log differences!}$$

$M_h(M_S)$ for various approximations: [*FeynHiggs 2.10.0*]



$\Rightarrow$ 3-loop good for $M_S \lesssim 2$ TeV, 7-loop: $\Delta \sim 1$ GeV for $M_S = 20$ TeV

4. FeynHiggs vs. EFT approach

$\Rightarrow$ Importance of precise M_h^{MSSM} predictions

The Higgs mass accuracy: experiment vs. theory:

Experiment:

ATLAS:	$M_h^{\text{exp}} = 125.36 \pm 0.37 \pm 0.18$ GeV
CMS:	$M_h^{\text{exp}} = 125.03 \pm 0.27 \pm 0.15$ GeV
combined:	$M_h^{\text{exp}} = 125.09 \pm 0.21 \pm 0.11$ GeV

MSSM theory:

LHCHXSWG adopted FeynHiggs for the prediction of MSSM Higgs boson masses and mixings (considered to be the code containing the most complete implementation of higher-order corrections)

FeynHiggs: $\delta M_h^{\text{theo}} \sim 3$ GeV

$\rightarrow$ rough estimate, FeynHiggs contains algorithm to evaluate uncertainty, depending on parameter point

arXiv.org > hep-ph > arXiv:1504.05200

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High Energy Physics - Phenomenology

SusyHD: Higgs mass Determination in Supersymmetry

Javier Pardo Vega, Giovanni Villadoro

(Submitted on 20 Apr 2015)

We present the state-of-the-art of the effective field theory computation of the MSSM Higgs mass, improving the existing ones by including extra threshold corrections. We show that, with this approach, the theoretical uncertainty is within 1 GeV in most of the relevant parameter space. We confirm the smaller value of the Higgs mass found in the EFT computations, which implies a slightly heavier SUSY scale. We study the large tan(\beta) region, finding that sbottom thresholds might relax the upper bound on the scale of SUSY. We present SusyHD, a fast computer code that computes the Higgs mass and its uncertainty for any SUSY scale, from the TeV to the Planck scale, even in Split SUSY, both in the DRbar and in the on-shell schemes. Finally, we apply our results to derive bounds on some well motivated SUSY models, in particular we show how the value of the Higgs mass allows to determine the complete spectrum in minimal gauge mediation.

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Does this mean that now there exists a better prediction for M_h in the MSSM with substantially smaller theory uncertainty?

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Does this mean that now there exists a better prediction for M_h in the MSSM with substantially smaller theory uncertainty?

⇒ We will try to give some answers: full diagrammatic vs. EFT, uncertainty estimates, . . .

FeynHiggs approach (simplified): "from below"

Propagator / mass matrix with higher-order corrections

$$M^2_{hH}(q^2) = \begin{pmatrix} q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ $(i, j = h, H)$: renormalized Higgs self-energies

$\Rightarrow$ complex roots of $\det(M^2_{hH}(q^2))$: $\mathcal{M}^2_{h_i}(i = 1, 2)$: $\mathcal{M}^2 = M^2 - iM\Gamma$

$\Rightarrow$ Feynman-diagrammatic approach

– diagrammatic calculation up to the two-loop level

– all MSSM particles contribute
  main contribution: $t/\tilde{t}$ sector

– all (possibly different) mass scales taken into account explicitely

– self-energies as building blocks for further evaluations

$\Rightarrow$ FeynHiggs provides consistent predictions for Higgs masses, Higgs couplings, Higgs BRs, . . .

FeynHiggs approach (simplified): "from below"

Propagator / mass matrix with higher-order corrections

$$M^2_{hH}(q^2) = \begin{pmatrix} q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ $(i, j = h, H)$: renormalized Higgs self-energies

$\Rightarrow$ complex roots of $\det(M^2_{hH}(q^2))$: $\mathcal{M}^2_{h_i}$ $(i = 1, 2)$: $\mathcal{M}^2 = M^2 - iM\Gamma$

To capture effects of large stop mass scales:

Resummation of leading and next-to-leading Logs from $t/\tilde{t}$ sector:

$$L := \log\left(\frac{m_{\tilde{t}}}{m_t}\right) \qquad \Rightarrow \text{at } n\text{-loop order} :\sim \sum_{k=1}^{n} {\alpha_s}^k {\alpha_t}^{n-k} \times L^n, L^{n-1}$$

Assumes that all SUSY mass scales are high at $m_{\tilde{t}}$

$\Rightarrow$ added consistently to the diagrammatic result

EFT approach (simplified / SusyHD): "from above"

- Assume all SUSY mass scales at one high scale M_S
  Below M_S: only SM ("heavy particles integrated out")
  $\Rightarrow$ mass gap between EW scale and SUSY scale required

- EW scale input: SM parameter: $h_t(m_t), g_s(m_t), \ldots$ at the 2-loop level

- SUSY enters only via threshold corrections at M_S at the 2-loop level

- Between EW scale m_t and SUSY scale M_S :
  SM RGEs at the 3-loop level

$$\lambda(m_t), h_t(m_t), g_s(m_t), \ldots \leftrightarrow \lambda(M_S) h_t(M_S), g_s(M_S), \ldots$$

  $\Rightarrow$ captured: logs of type L^n, L^{n-1}, L^{n-2}

- Evaluate running mass: $M_h^2 \sim 2\lambda(m_t)v^2$ $\Rightarrow$ conversion to pole mass

- Log resummation in $t/\tilde{t}$ sector: SusyHD: 3-loop , FeynHiggs: 2-loop

Ranges of applicability:

1.) SUSY mass scales below ~ 1 TeV require full calculation

2.) Log resum. for $t/\tilde{t}$ (beyond 2L) at M_S

– effects at $M_S = 1$ TeV:

– at $M_S = 2$ TeV:

– at $M_S = 3$ TeV:

Ranges of applicability:

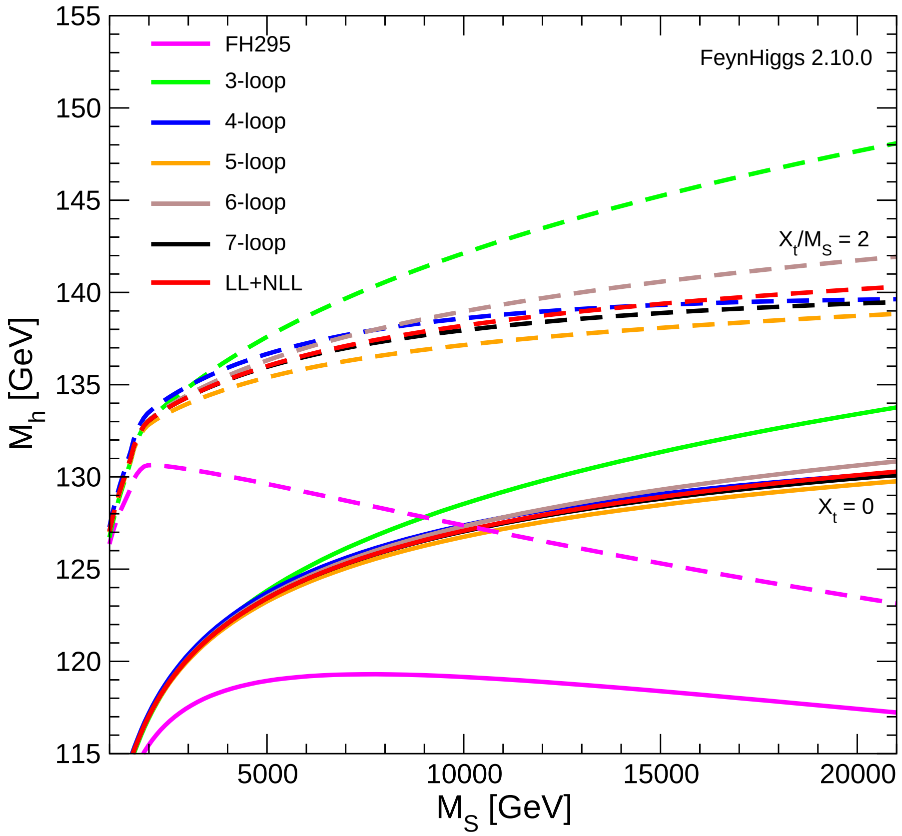
1.) SUSY mass scales below ~ 1 TeV require full calculation

2.) Log resum. for $t/\tilde{t}$ (beyond 2L) at M_S for $\Delta M_h^{\text{diagrammatic}} \sim 40$ GeV

– effects at $M_S = 1$ TeV: tiny

– at $M_S = 2$ TeV: $\Delta M_h^{\text{log-resum}} \sim 2$ GeV

– at $M_S = 3$ TeV: $\Delta M_h^{\text{log-resum}} \gtrsim 3$ GeV



$M_h(M_S)$ for various approximations:

[*FeynHiggs 2.10.0*]

magenta: no log-resum for $t/\tilde{t}$

red: log-resum at 2-loop level

($\rightarrow$ included in FH)

All other logs less relevant!

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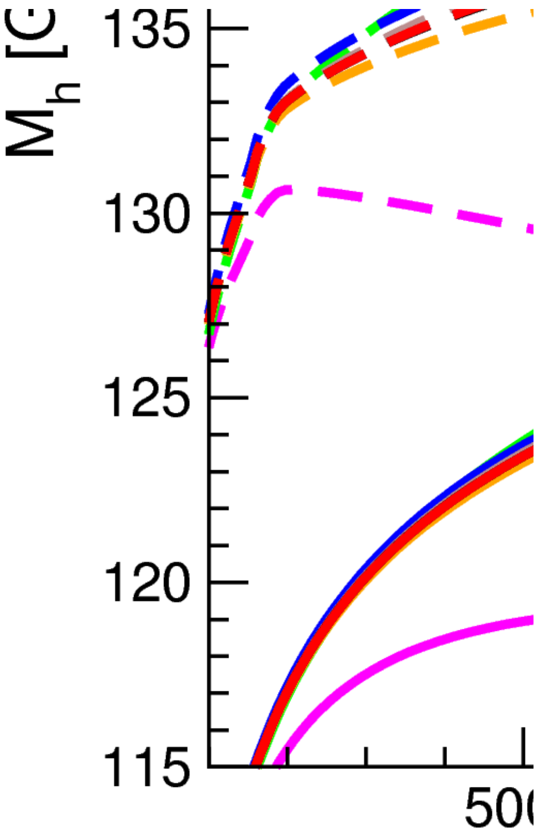

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⇒ FeynHiggs gives most reliable predictions for SUSY mass scales below the level of $2 - 3$ TeV, where log contributions are not too large i.e. at the scales relevant/interesting for LHC physics (e.g. with light EW SUSY particles in the spectrum)

⇒ uncertainty estimate based on diagrammatic calculation reliable

⇒ EFT gives most reliable predictions for all SUSY mass scales in the multi-TeV range

⇒ intermediate region:

both types of calculations can be used for uncertainty estimate

Uncertainty estimates:

FeynHiggs (diagrammatic + log-resum): linear sum of

- missing 3-loop corrections in $t/\tilde{t}$ sector (change of m_t def.)
- missing 2-loop corrections in $b/\tilde{b}$ sector (Δ_b resummation)
- missing 2-loop corrections in EW sector (change of renormalizaion scale)

⇒ reliable estimate up to $2-3$ TeV or higher

SusyHD (EFT): linear sum of

- SM unc.: missing corrections from matching at m_t and RGE evolution
- MSSM unc.: missing corrections from matching at M_S
- EFT unc.: effects not captured by EFT: $\mathcal{O}\left(v^2/M_S^2\right)$ (prefactor 1)

⇒ uncertainty estimate of ~ 1 GeV

⇒ estimate for the multi-TeV range

⇒ unclear to which low scales it can be extrapolated

Uncertainty estimate in SusyHD:

- non-log terms via threshold corrections to $\lambda(M_S)$
  - neglects terms of $\mathcal{O}(m_t/M_{SUSY})$
  - non-log terms can be sizable, $\mathcal{O}(m_t/M_{SUSY})$ can easily be of $\mathcal{O}(\text{GeV})$
  - theoretical unc. in SusyHD for threshold terms via scale variation

  $\Rightarrow$ does not capture non-log terms

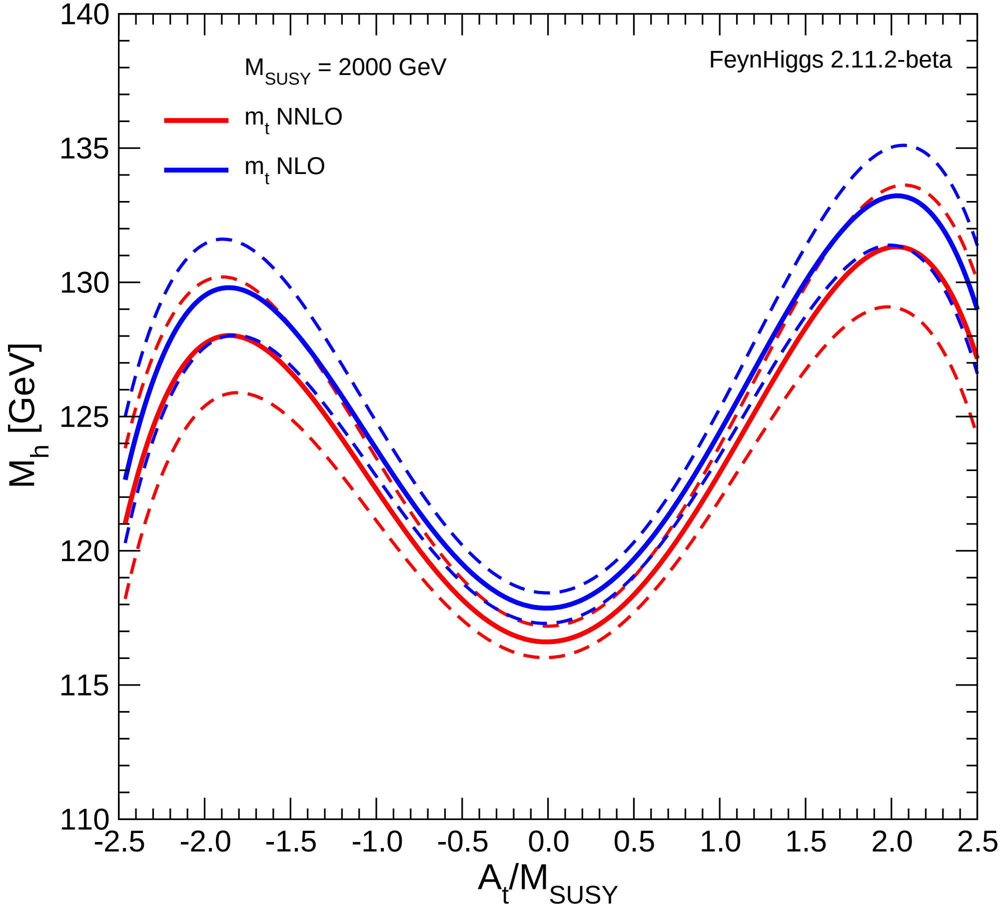
- Effects of $m_t(m_t)^{\text{NLO}} \to m_t(m_t)^{\text{what ever exists}}$ in SusyHD: 4 GeV
  Effects of $m_t(m_t)^{\text{NLO}} \to m_t(m_t)^{\text{NNLO}}$ in [*Draper, Lee, Wagner '13*] : $\lesssim$ 2 GeV (consistent)
  Difference should give indication of theory uncertainties $\gtrsim$ 2 GeV

- Effects of uncertainty of higher-dimensional operators $\mathcal{O}\left(v^2/M_S^2\right)$ (prefactor 1) $\Rightarrow$ very optimistic

- Not clear where (e.g. at $M_S = 2$ TeV) differences between SusyHD and FeynHiggs originate from

SusyHD claim: large effects from top Yukawa coupling $m_t(m_t)$:

SusyHD: 2-loop, FeynHiggs: 1-loop (consistent choice!) $\Rightarrow$ $\Delta \lesssim 9$ GeV
Shift in $m_t(m_t)$ from NLO to NNLO: 1.8 GeV (for $A_t/M_{\text{SUSY}} \sim 2$)



$\Rightarrow$ not the reason for discrepancy, effects captured by FH unc. estimate
$\Rightarrow$ EFT: effect of missing non-log contributions?
Uncertainty estimate too small ...?!

5. FeynHiggs prospects

- Inclusion of further diagrammatic corrections, e.g. $\mathcal{O}(\alpha\alpha_s)$, see [*Degrassi, Slavich, di Vita '14*]

- Inclusion of further log-resummed corrections

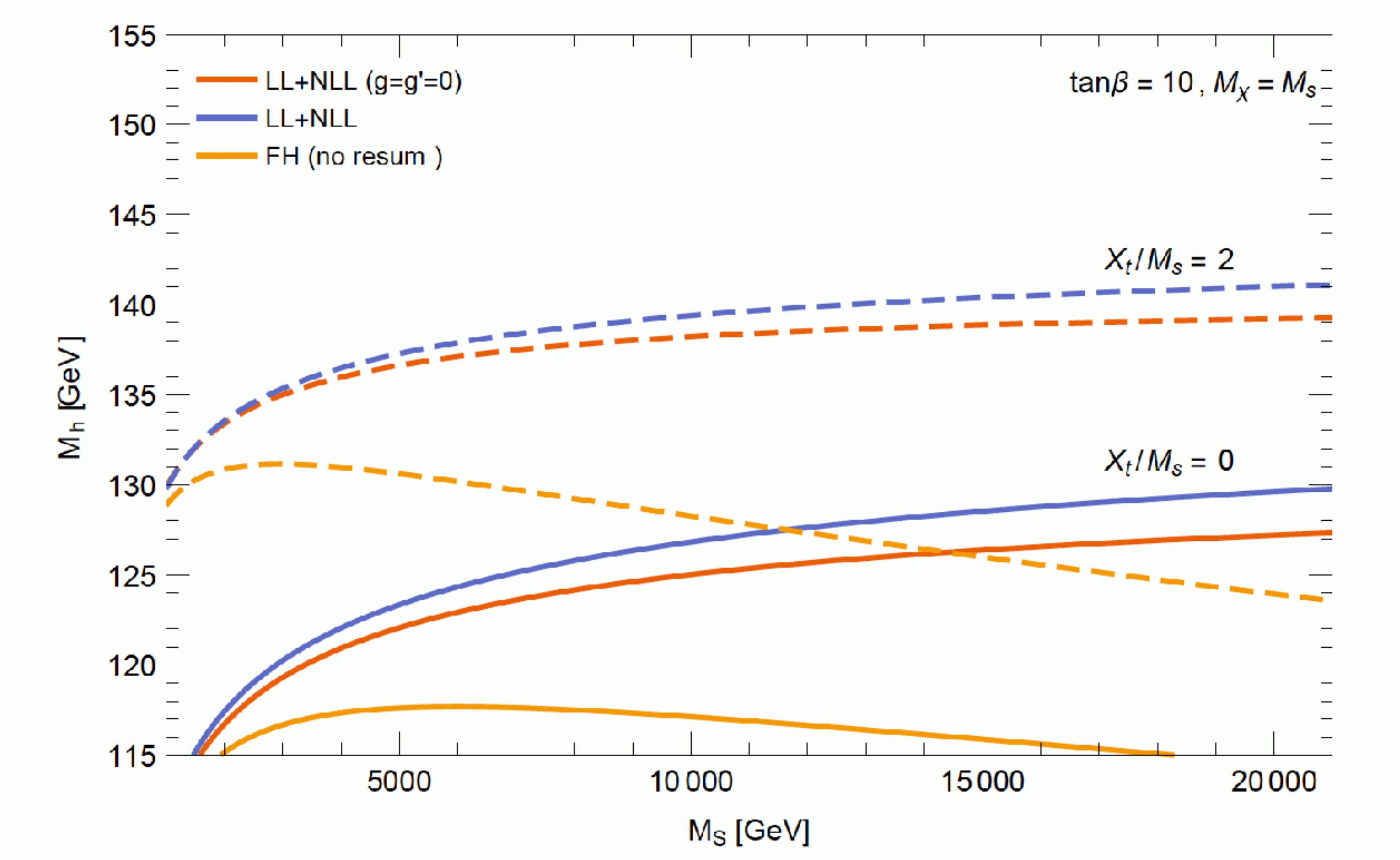
- Extension to the NMSSM
  $\Rightarrow$ with all features as now in the MSSM

- ...

Inclusion of further log-resummed results

[H. Bahl, W. Hollik '15 – PRELIMINARY]

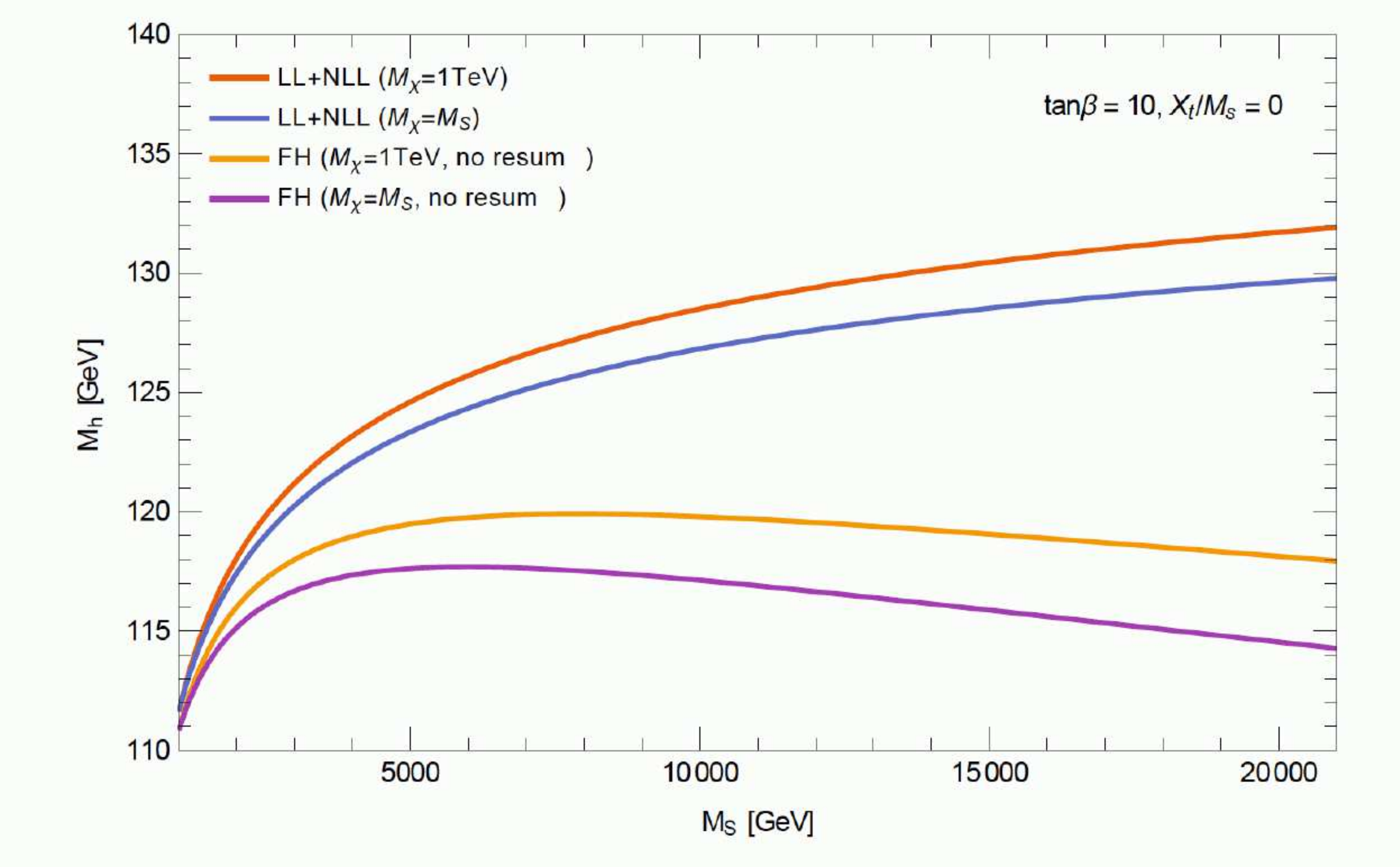
Inclusion of EW effects in RGE's:



Inclusion of further log-resummed results

[H. Bahl, W. Hollik '15 – PRELIMINARY]

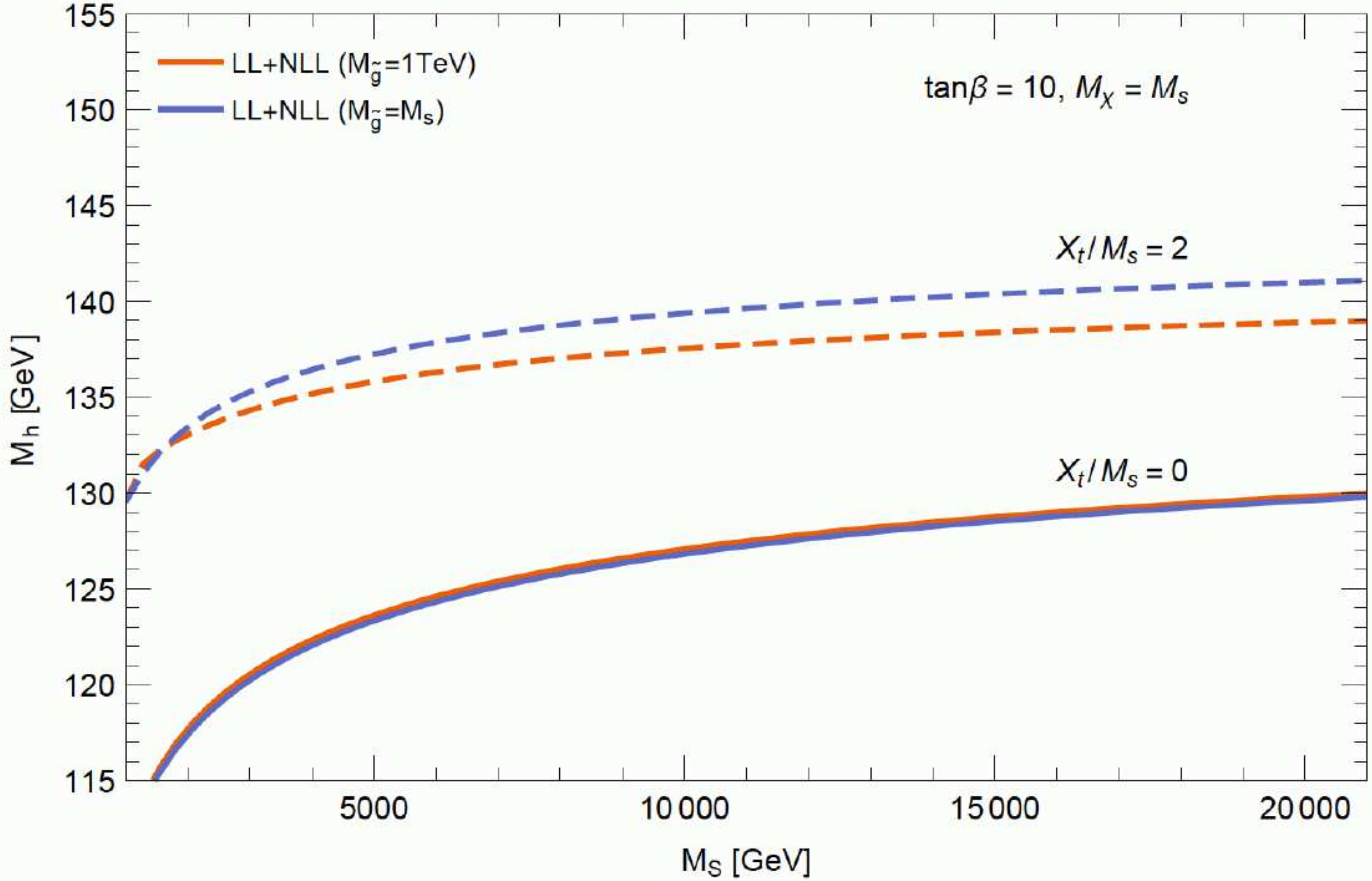
Inclusion of EWino mass scale in RGE's:



Inclusion of further log-resummed results

[H. Bahl, W. Hollik '15 – PRELIMINARY]

Inclusion of gluino mass scale in RGE's:



Extension to the NMSSM

(taken from talk by [*P. Drechsel '15*])

General idea (first step/version):

- full inverse propagator in CP-even sector for mass determination

$$\Delta^{-1}\left(k^2\right) = \mathrm{i}\left[k^2\mathbb{1} - \underbrace{\mathcal{M}_{\phi\phi} + \hat{\Sigma}^{(1L)}_{\phi\phi}\left(k^2\right)}_{\text{NMSSM}} + \underbrace{\hat{\Sigma}^{(2L)}_{\phi\phi}\left(k^2 = 0\right)}_{\text{MSSM/FeynHiggs}}\right]$$

- included corrections from FeynHiggs at 2-loop order:
  - orders $\mathcal{O}\left(\alpha_s\alpha_t, \alpha_s\alpha_b, \alpha_t^2, \alpha_t\alpha_b\right)$
  - resummed large logarithms

⇒ "internal" version exists! :-)

Extension to the NMSSM

(taken from talk by [*P. Drechsel '15*])

Sample Scenario

- genuine NMSSM-scenario with a second lightest CP-even state can be interpreted as the Higgs-boson the signal at 125 GeV and a lighter singlet-like state

$$M_{H^\pm} = 1000 \text{ GeV}, \mu_{\text{eff}} = 125 \text{ GeV},$$
$$A_\kappa = -300 \text{ GeV}, \; A_t = -2000 \text{ GeV},$$
$$\tan\beta = 8, \; \kappa = 0.2$$

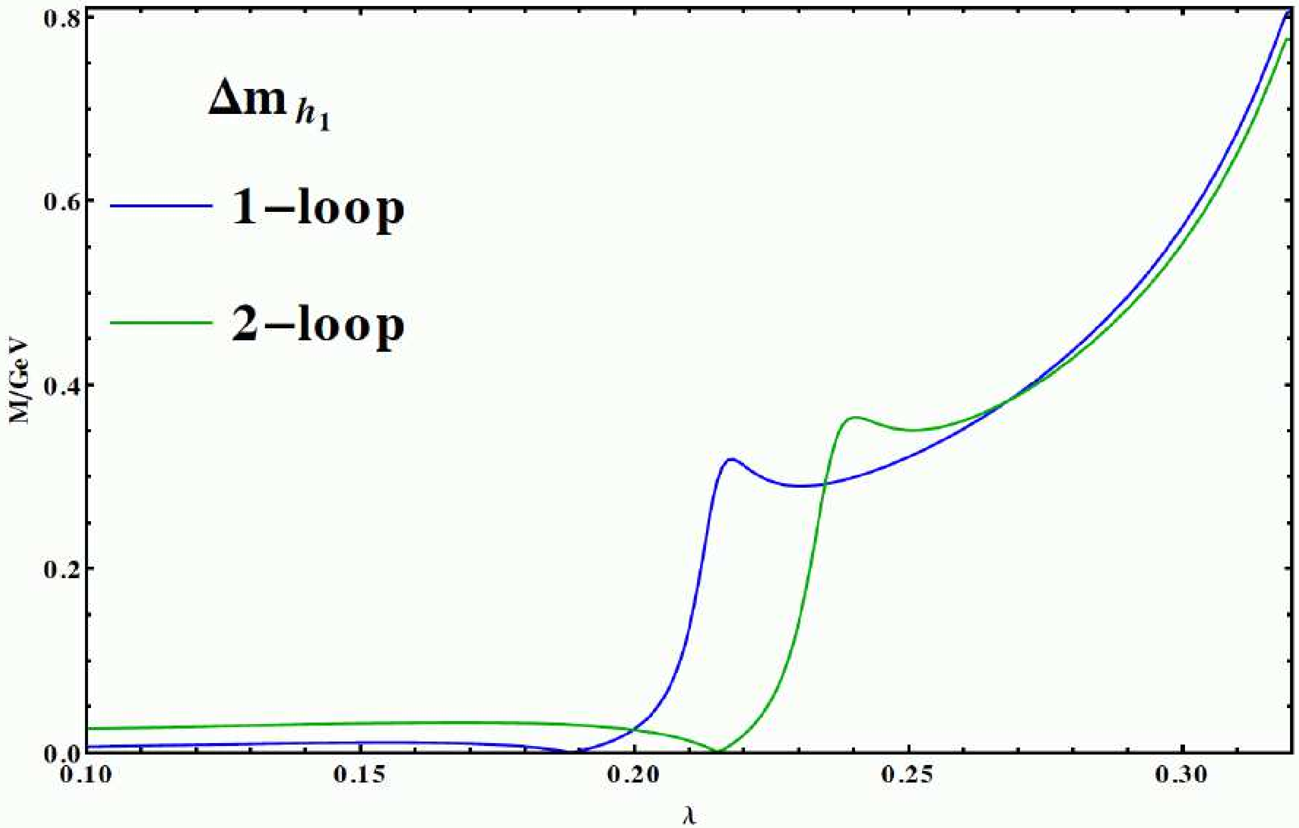
$$m_{\tilde{t}_1} \approx 1400 \text{ GeV}, \; m_{\tilde{t}_2} \approx 1600 \text{ GeV}$$
$$m_{\tilde{b}_i} \approx 1500 \text{ GeV}, \; m_{\tilde{g}} \approx 1500\text{GeV}$$

Extension to the NMSSM

(taken from talk by [P. Drechsel '15])

Backup: Comparison with NMSSMTools I

- difference 1-loop: δZ_e, difference 2-loop: $\mathcal{O}\left(Y_t\lambda, \lambda^2\right)$
- $\Delta m_{h_1} = \left| m_{h_1}^{(\mathrm{FH})} - m_{h_1}^{(\mathrm{NC})} \right|$




Higgs Days at Santander 2015
Theory meets Experiment
14.-18. September
contact: Sven.Heinemeyer@cern.ch
http://www.ifca.es/HDays15
IFCA
Instituto de Física de Cantabria
CSIC
UC
UNIVERSIDAD DE CANTABRIA
MultiDark
Multimessenger Approach for Dark Matter Detection

Back-up

How to run FeynHiggs

1. Go to www.feynhiggs.de

2. Download the latest version

3. type `./configure`, `make`, `make install`
   ⇒ library `libFH.a` is created

4. 4 possible ways to use *FeynHiggs*:

   A) Command-line mode (allows also running on the GRID)

   B) called from a Fortran/C++ code

   C) called within Mathematica

   D) WWW mode

   processing of Les Houches Accord data possible

5. Detailed instructions and help are provided in the man pages

A) Command-line mode

Input File

```
MT          172.7
MB          4.7
MW          80.4
MZ          91.1
MSusy       975
MA0         200
Abs(M_2)    332
Abs(MUE)    980
TB          50
Abs(At)     -300
Abs(Ab)     1500
Abs(M_3)    975
```

Command

`FeynHiggs` *file* [*flags*] →

Screen Output

```
------------------- HIGGS MASSES -------------------
| Mh0     =   116.022817
| MHH     =   199.943497
| MA0     =   200.000000
| MHp     =   216.973920
| SAeff   =  -0.02685112
| UHiggs  =   0.99999346   -0.00361740    0.00000000 \
|             0.00361740    0.99999346    0.00000000 \
|             0.00000000    0.00000000    1.00000000

-------------- ESTIMATED UNCERTAINTIES ------------
| DeltaMh0   =  1.591957
| DeltaMHH   =  0.004428
| DeltaMA0   =  0.000000
| DeltaMHp   =  0.152519
  ...
```

- Loops over parameter values possible (parameter scans).
- Mask off details with `FeynHiggs` *file [flags]* `| grep -v %`
- `table` utility converts to machine-readable format, e.g.
  `FeynHiggs` *file [flags]* `| table TB Mh0 > outfile`

Example for new M_A–$\tan\beta$ planes:

Input File ("normal")

```
MT          172.7
MB          4.7
MW          80.4
MZ          91.1
MSusy       975
MA0         200
Abs(M_2)    332
Abs(MUE)    980
TB          50
Abs(At)     -300
Abs(Ab)     1500
Abs(M_3)    975
```

Input File ("new")

```
MA0         227
TB          23
table ehoww.A2.dat MA0 TB
```

- Loops over parameter values possible (parameter scans).

  ```
  MA0         200 500 10
  TB          5 50 *2
  ```

- Mask off details with `FeynHiggs` *file [flags]* `| grep -v %`
- `table` utility converts to machine-readable format, e.g.
  `FeynHiggs` *file [flags]* `| table TB Mh0 > outfile`

SUSY Les Houches Accord(2) Format

Input File

```
BLOCK MODSEL
    1     1
BLOCK MINPAR
    1    0.10000E+03   # m0
    2    0.25000E+03   # m12
    3    0.10000E+02   # tanb
    4    0.10000E+01   # sgn mu
    5   -0.10000E+03   # A
BLOCK SMINPUTS
    4    0.91187E+02   # MZ
    5    0.42500E+01   # mb(mb)
    6    0.17500E+03   # t
  ...
```

Command

FeynHiggs *file* [*flags*] →

file.fh

```
BLOCK MASS
   25    1.12697840E+02    # Mh0
   35    4.00145460E+02    # MHH
   36    3.99769788E+02    # MA0
   37    4.08050556E+02    # MHp
  ...
BLOCK ALPHA
        -1.10658125E-01    # Alpha
  ...
```

- { Uses / was developed into } the SLHA(2) I/O Library. [*T. Hahn '04, '06*]
- SLHA(2) can also be used in Library Mode with FHSetSLHA.
- *FeynHiggs* tries to read each file in SLHA(2) format first.
  If that fails, fallback to native format.

B) Called from a Fortran/C++ code

Link *FeynHiggs* as a subroutine $\Rightarrow$ link `libFH.a`

`call FHSetFlags(...)` :
$\to$ specification of accuracy etc.

`call FHSetPara(...)` :
$\to$ specify input parameters

`call FHGetPara(...)` :
$\to$ obtain derived parameters

`call FHHiggsCorr(...)` :
$\to$ obtain Higgs boson masses and mixings

`call FHUncertainties(...)` :
$\to$ obtain theory error on Higgs boson masses and mixings from unknown higher-order corrections

`call FHCouplings(...), FHHiggsProds(...), ...` :
$\to$ obtain decay widths, BRs, XSs, etc.

C) Called within Mathematica

- install the math link to *MFeynHiggs* , e.g.:

  `Install[''MFeynHiggs'']`

- `FHSetFlags[...]` :
  → specification of accuracy etc.

  `FHSetPara[...]` :
  → specify input parameters

  `FHGetPara[]` :
  → obtain derived parameters

  `FHHiggsCorr[]` :
  → obtain Higgs boson masses and mixings

  `FHUncertainties[]` :
  → obtain theory error on Higgs boson masses and mixings from unknown higher-order corrections

  `FHCouplings[], FHHiggsProds[], ...` :
  → obtain decay widths, BRs etc.

D) WWW mode

1. The FeynHiggs User Control Center is available at

   www.feynhiggs.de/fhucc

2. Enter you parameters on-line in the web page

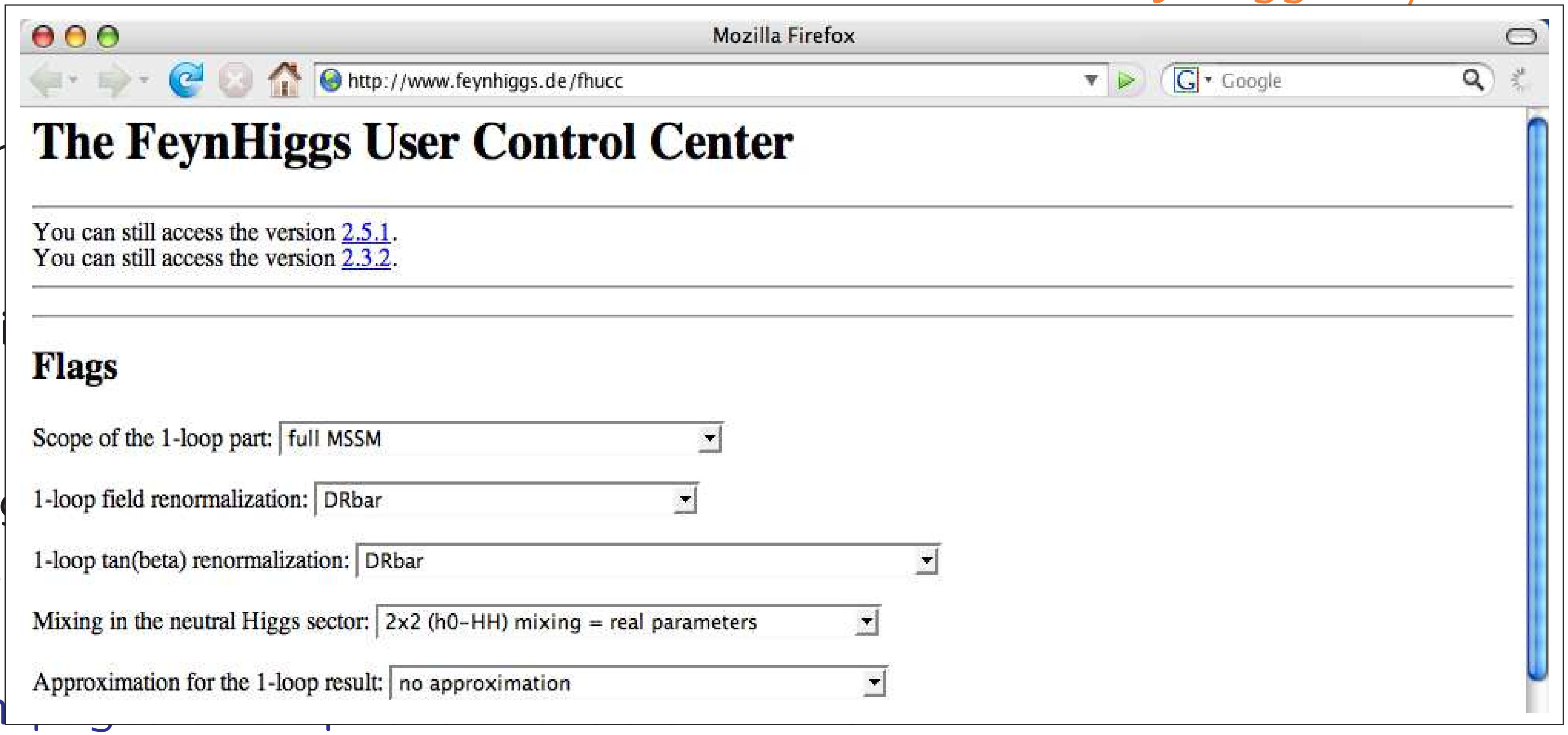
3. Obtain your results with a mouse click

⇒ for single points and checks of your downloaded version of FeynHiggs
⇒ always the latest version

Also man pages and api are available on-line

D) WWW mode

1. The FeynHiggs User Control Center is available at
   www.feynhiggs.de/fhucc



2. Enter

3. Obtai

⇒ for sin

⇒ always

Also man

Resumming Stop-sector Contributions

M_S

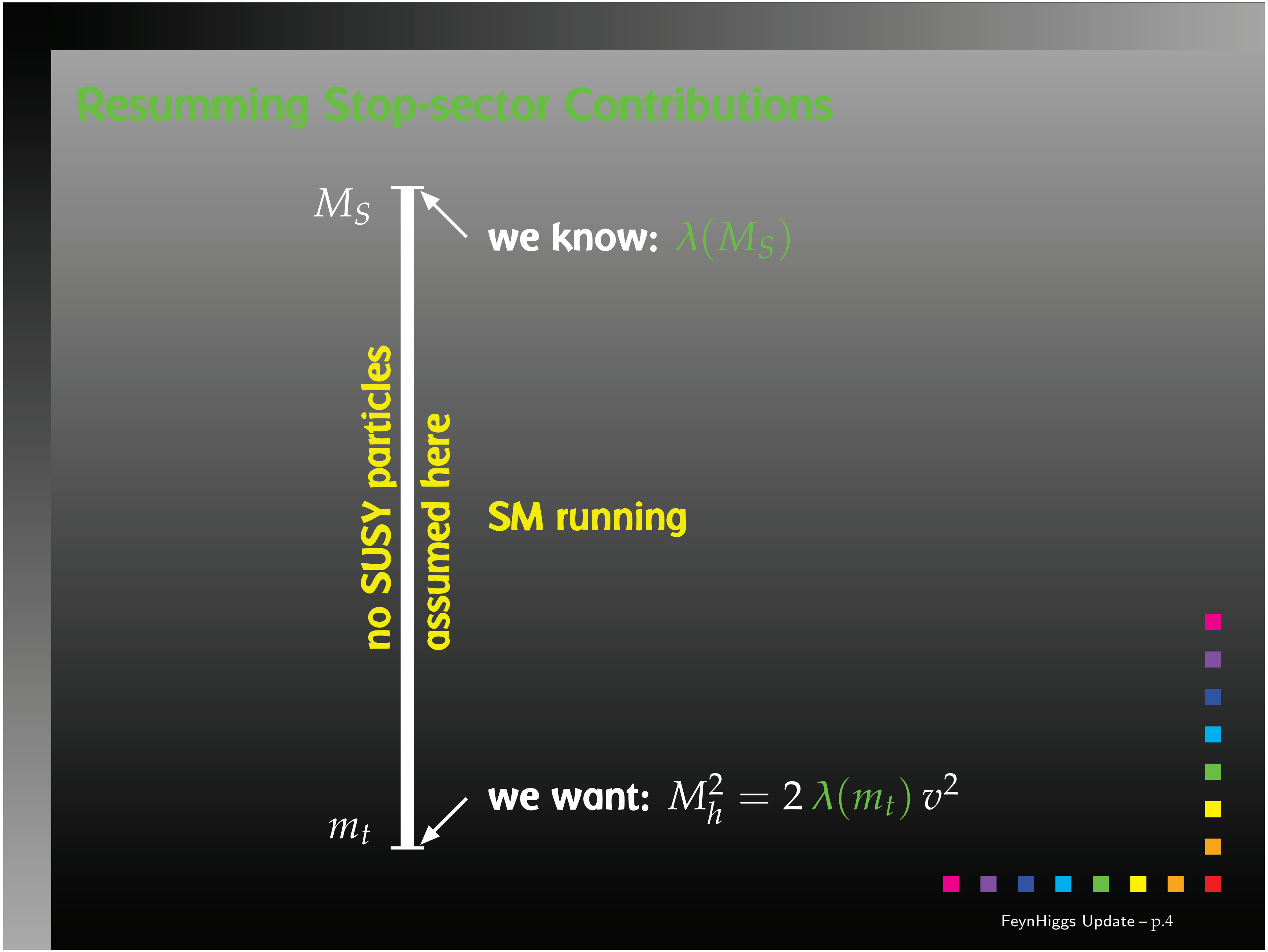
we know: $\lambda(M_S)$

m_t

we want: $M_h^2 = 2\,\lambda(m_t)\,v^2$

FeynHiggs Update – p.3

[HDays14, talk by T. Hahn]



Standard Model RGEs

$$g_s^{2\prime} = \frac{1}{16\pi^2} g_s^4 \left(G_1 + \frac{1}{16\pi^2} G_2\right),$$

$$G_1 = \frac{2}{3} N_f - 11,$$

$$G_2 = \left(\frac{38}{3} N_f - 102\right) g_s^2 - 2h_t^2,$$

$$h_t^{2\prime} = \frac{1}{16\pi^2} h_t^2 \left(H_1 + \frac{1}{16\pi^2} H_2\right),$$

$$H_1 = \frac{9}{2} h_t^2 - 8 g_s^2,$$

$$H_2 = 6h_t^2 (6g_s^2 - 2h_t^2 - \lambda) + \frac{3}{2}\lambda^2 + \left(\frac{40}{9} N_f - \frac{404}{3}\right) g_s^4,$$

$$\lambda' = \frac{1}{16\pi^2} \frac{1}{2} \left(\Lambda_1 + \frac{1}{16\pi^2} \Lambda_2\right),$$

$$\Lambda_1 = 12(\lambda^2 - h_t^4 + \lambda h_t^2),$$

$$\Lambda_2 = h_t^2 (3h_t^2 (20h_t^2 - \lambda) + g_s^2 (80\lambda - 64h_t^2) - 72\lambda^2) - 78\lambda^3.$$

Espinosa, Quiros 1991 – Arason et al. 1992

FeynHiggs Update – p.5

Integrating the RGEs

M_S

start from

g_s^2, h_t^2 from 1L RGE (analytic)

$$\lambda(M_S) = \frac{3}{8\pi^2} h_t^4 \left(\frac{X_t}{M_S}\right)^2 \left(1 - \frac{1}{12}\left(\frac{X_t}{M_S}\right)^2\right)$$

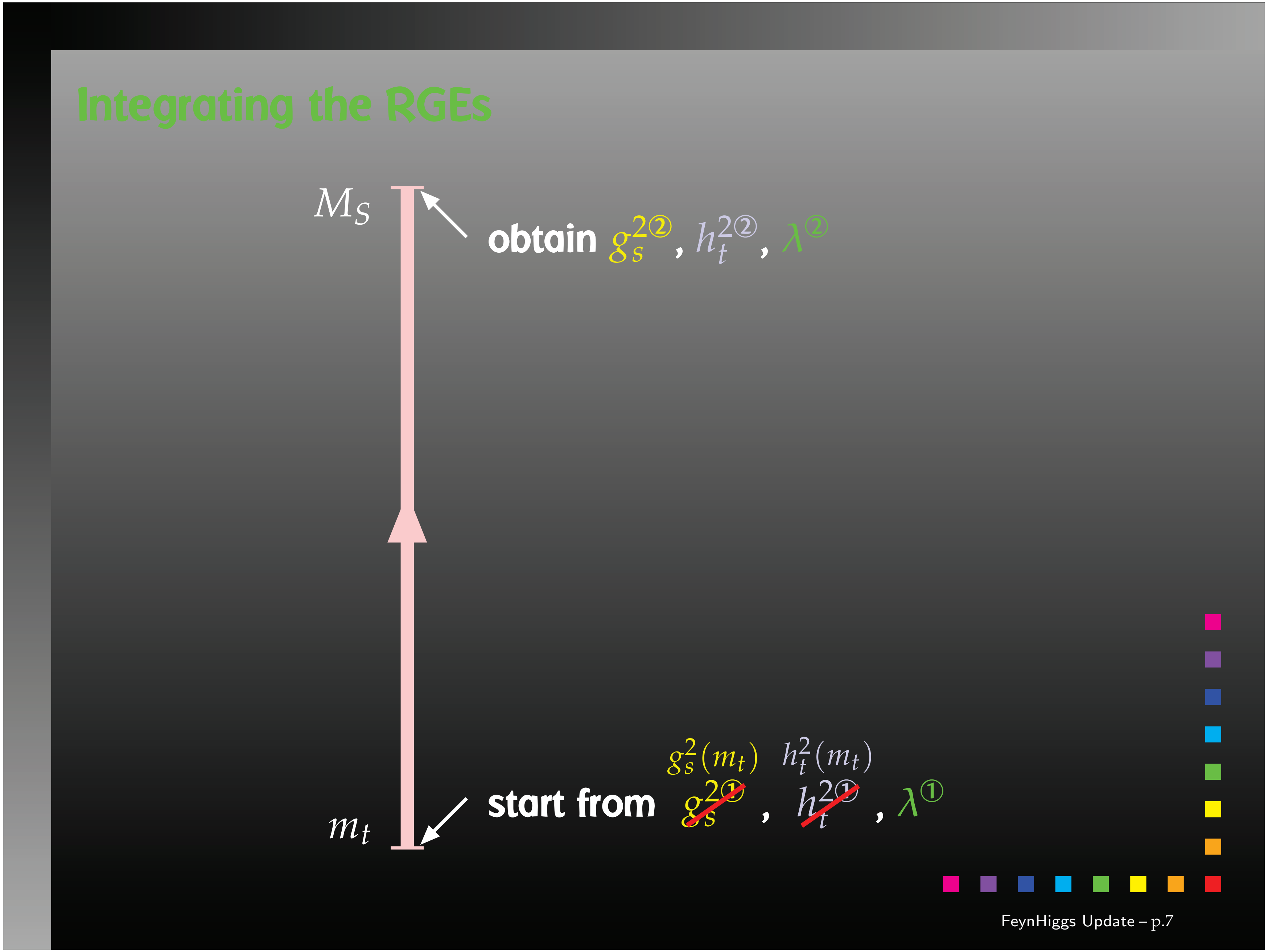
Carena et al. 2000

m_t

obtain $g_s^{2①}$, $h_t^{2①}$, $\lambda^{①}$

FeynHiggs Update – p.6

[HDays14, talk by T. Hahn]



[HDays14, talk by T. Hahn]