FlexibleSUSY

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Precision Higgs mass prediction in minimal and non-minimal SUSY models

Peter Athron (Monash University, CoEPP)

in collaboration with

Jae-hyeon Park, Tom Steudtner, Dominik Stöckinger, Alexander Voigt

FlexibleSUSY = spectrum generator generator

We can do our calculation in any model because
we implement our algorithm in:

FlexibleSUSY

https://flexiblesusy.hepforge.org/

[PA, J.H.Park, D.Stöckinger, A.Voigt CPC 190 (2015) 139-172]

FlexibleSUSY = spectrum generator generator

We can do our calculation in any model because
we implement our algorithm in:

FlexibleSUSY

https://flexiblesusy.hepforge.org/

[PA, J.H.Park, D.Stöckinger, A.Voigt CPC 190 (2015) 139-172]

Model specific details from:

SARAH

[F.Staub arXiv:0806.0538, CPC 182 (2011) 808-833, CPC 181 (2010) 1077-1086]

FlexibleHiggs

The Higgs mass is a very important prediction in SUSY models

Quartic coupling in MSSM is fixed:

$$V_{\phi}^{SM} = \mu^2|\phi|^2 + \lambda|\phi|^4$$

$$V_{H^0}^{MSSM} = m_1^2|H_u^0|^2 + m_2^2|H_d^0|^2 - m_3^2(H_u^0 H_d^0 + h.c.) + \frac{1}{8}(g'^2 + g^2)v^2$$

$$\Rightarrow m_h \leq M_Z$$ Tree level upperbound on lightest Higgs mass

To test if 125 GeV is possible two-loop corrections are essential!

Furthermore Higgs mass and sparticle limits imply large logs need resummed

Many alternatives (NMSSM, E6SSM, MRSSM) raise the Higgs mass.

But then two-loop corrections are also essential to check you actually resolve the problem.

Fixed Order Calculation in full theory

$$M_H^2 + \Sigma(p^2 = m_{h_i}^2) \xrightarrow[\text{for eigenvalues}]{\text{diagonalise}} m_{h_i}^2$$

In practice this is done with:

$$\Sigma(p^2) = \Sigma^{\text{1-loop}}(p^2) + \Sigma^{\text{2-loop}}(0)$$

$\Sigma^{\text{1-loop}}$: complete All models

$\Sigma^{\text{2-loop}}$: $\mathcal{O}(y_t^2 g_s^2, y_b^2 g_s^2)$ MSSM, NMSSM

: $\mathcal{O}(y_t^4, y_t^2 y_b^2, y_b^4, y_\tau^4)$ MSSM

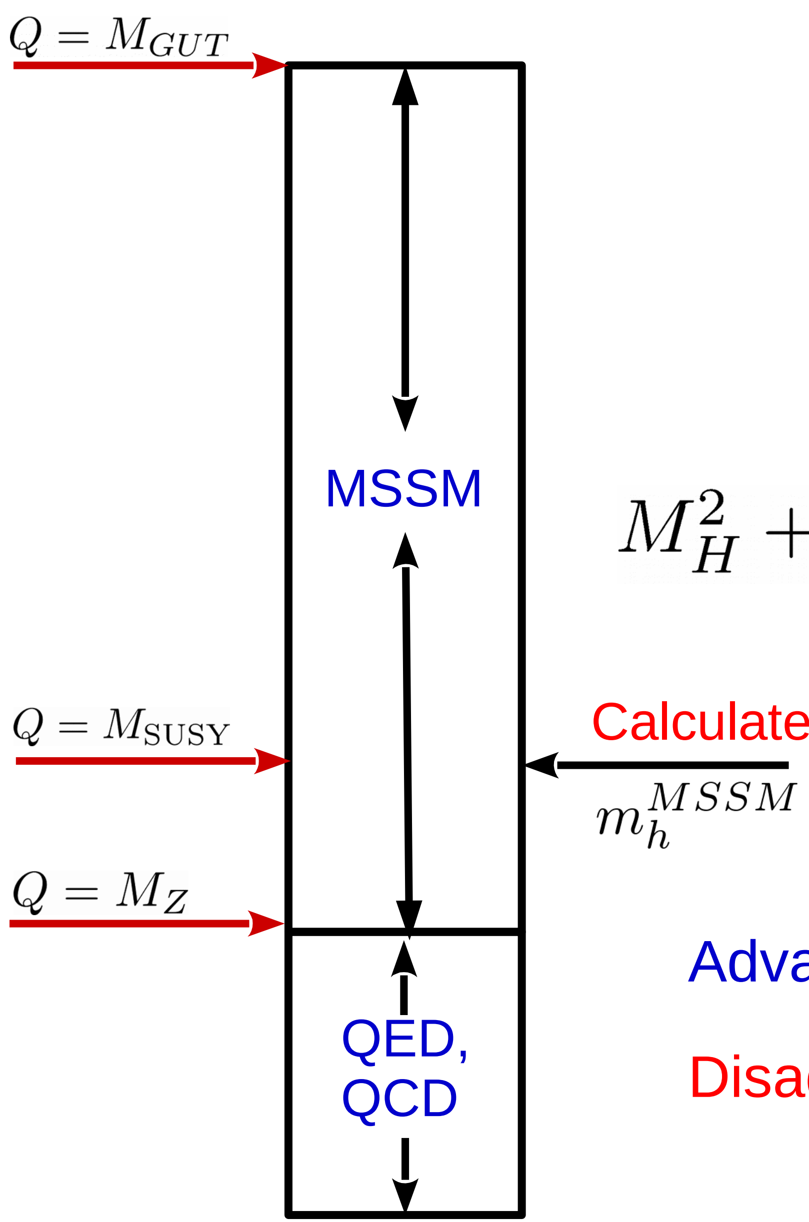
: complete in gaugeless limit All models

(SARAH/SPheno only)

$$\Sigma(p^2) = \Sigma(p^2, Q^2)$$

$Q^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$ - chosen to minimise largest logarithmic corrections

Fixed Order Calculation in full theory



Implemented in a number of public spectrum generators

$$\Sigma(p^2) = \Sigma^{\text{1-loop}}(p^2) + \Sigma^{\text{2-loop}}(0)$$

$$M_H^2 + \Sigma(p^2 = m_{h_i}^2) \xrightarrow[\text{for eigenvalues}]{\text{diagonalise}} m_{h_i}^2$$

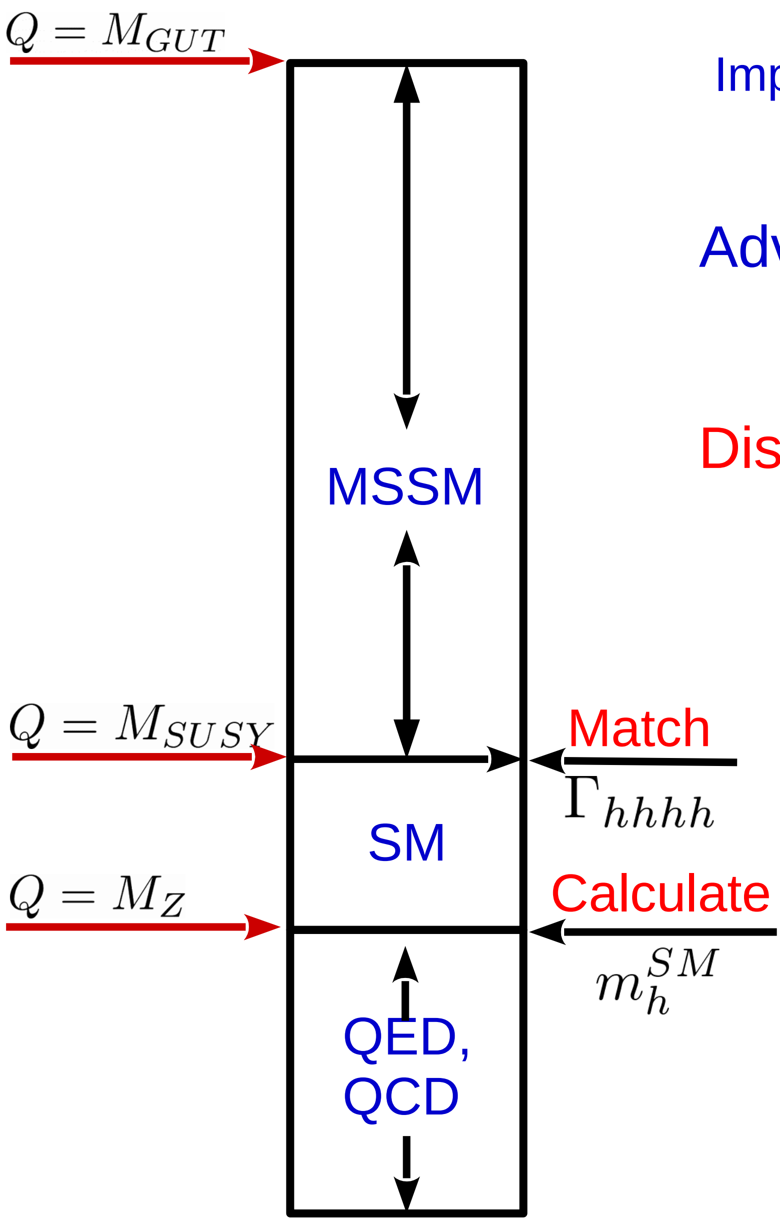
$$Q = M_{\text{SUSY}} = \sqrt{(m_{\tilde{t}_1} m_{\tilde{t}_2})}$$

Advantage: includes terms $\mathcal{O}(p^2/M_{SUSY})$

Disadvantage: no resummed logs

Suffers from large logs when $M_{\text{SUSY}} >> M_Z$

EFT: match 4-point functions



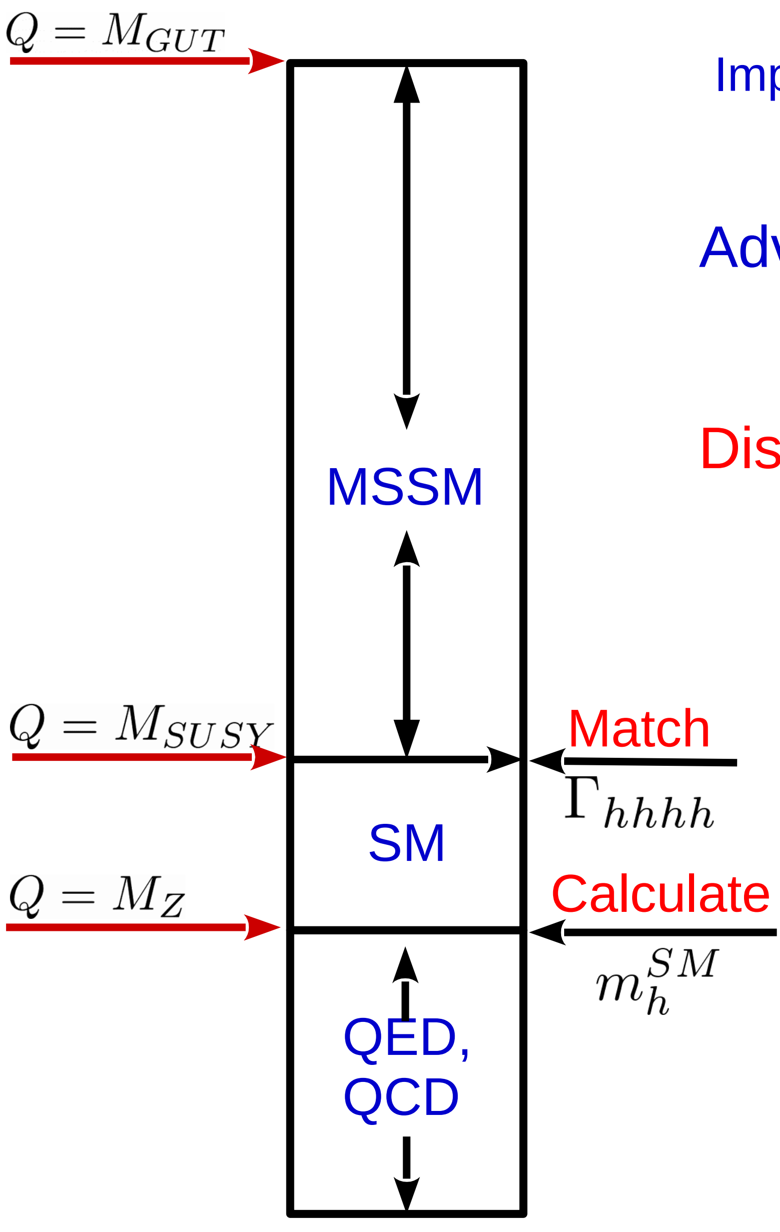
Implemented in SUSYHD and FlexibleSUSY HSSUSY

Advantage: resums large logs
can includes two-loop matching

Disadvantage: Misses p^2/M_{SUSY}^2 terms
Suffers if $M_{SUSY} \approx M_Z$

$$\lambda = \frac{1}{4}\left(g_Y^2 + g_2^2\right)\cos^2 2\beta + \Delta\lambda^{(1)} + \Delta\lambda^{(2)}$$

EFT: match 4-point functions



Implemented in SUSYHD and FlexibleSUSY HSSUSY

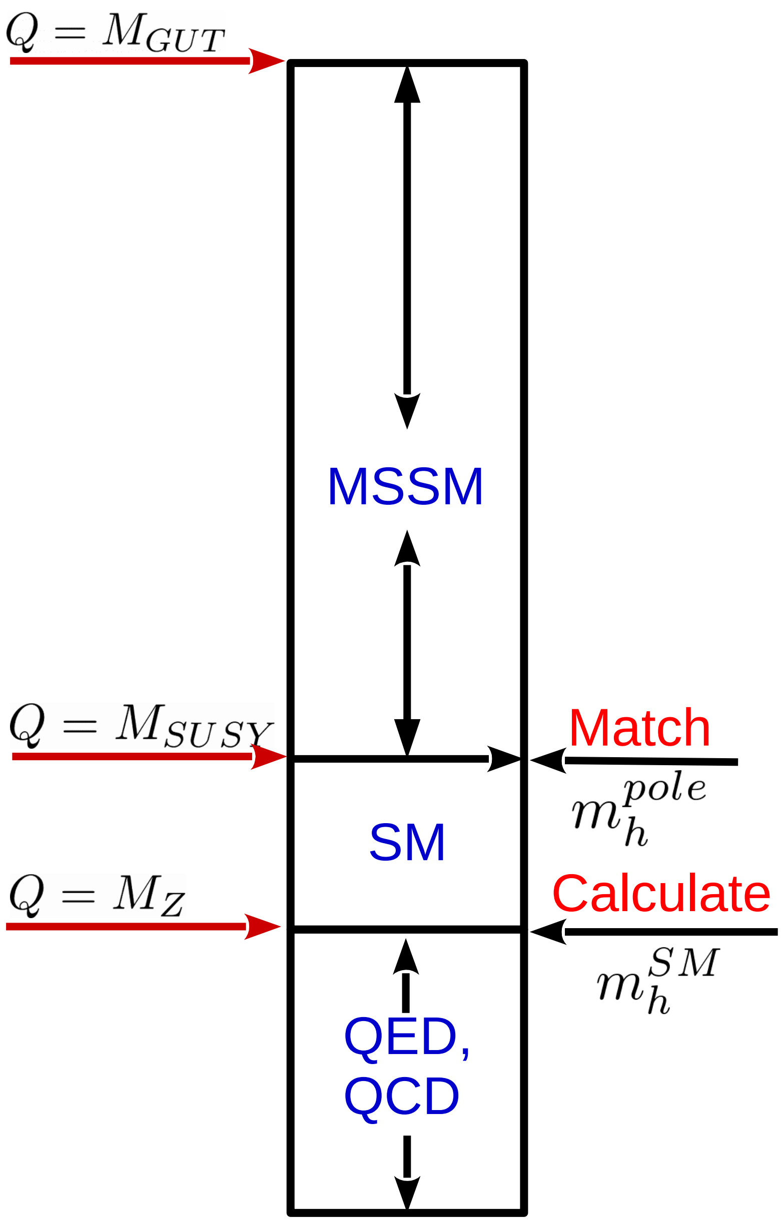
Advantage: resums large logs
can includes two-loop matching

Disadvantage: Misses p^2/M_{SUSY}^2 terms
Suffers if $M_{SUSY} \approx M_Z$

$$\lambda = \frac{1}{4}\left(g_Y^2 + g_2^2\right)\cos^2 2\beta + \Delta\lambda^{(1)} + \Delta\lambda^{(2)}$$

EFT: match pole masses

New FlexibleHiggs approach

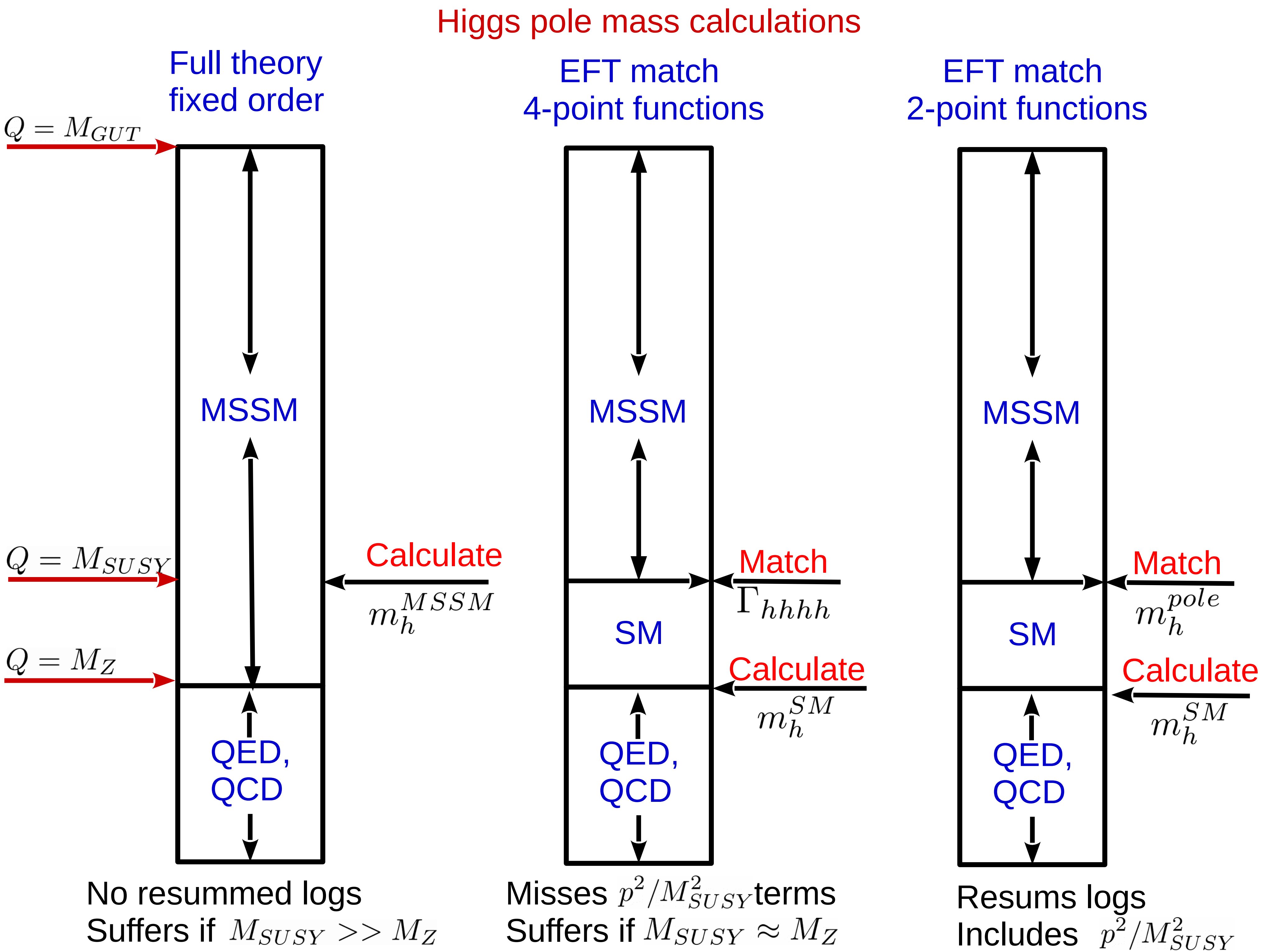


Advantage: Resums logs
Includes p^2/M_{SUSY}^2
Can be used in any model

Disadvantage: two-loop matching not known currently

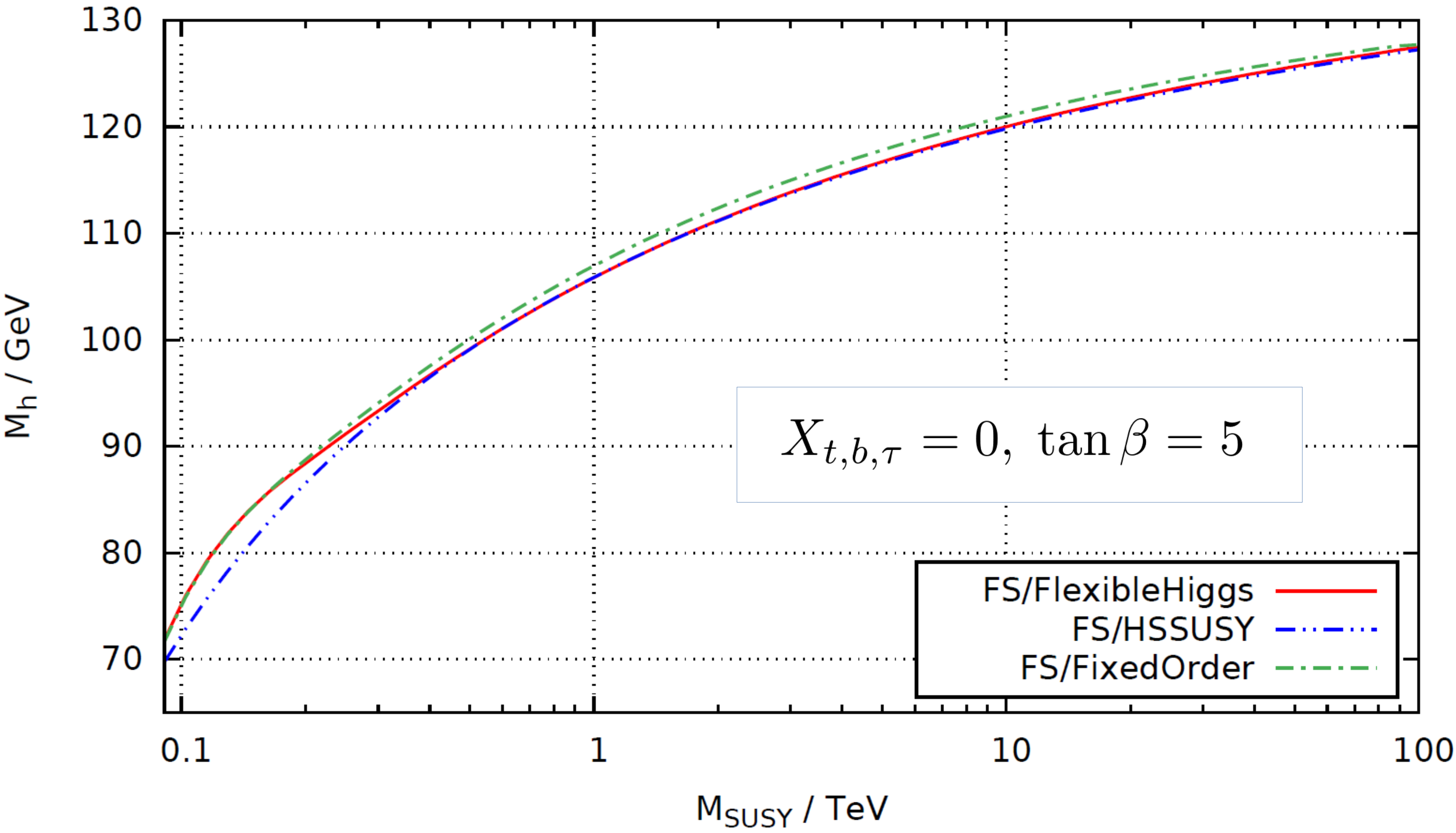
$$(m_h^{\overline{\rm MS},\rm SM})^2 - \Sigma_h^{\rm SM}(M_h^2) = (m_h^{\overline{\rm DR},\rm SUSY})^2 - \Sigma_h^{\rm SUSY}(M_h^2),$$

$$\lambda(M_{\rm SUSY}) = \frac{1}{v^2}\left[(m_h^{\overline{\rm DR},\rm SUSY})^2 - \Sigma_h^{\rm SUSY}(M_h^2) + \Sigma_h^{\rm SM}(M_h^2)\right]$$


Higgs pole mass calculations
Full theory
fixed order
EFT match
4-point functions
EFT match
2-point functions
$Q = M_{GUT}$
MSSM
MSSM
MSSM
$Q = M_{SUSY}$
Calculate
m_h^{MSSM}
Match
Γ_{hhhh}
Match
m_h^{pole}
SM
SM
$Q = M_Z$
Calculate
m_h^{SM}
Calculate
m_h^{SM}
QED,
QCD
QED,
QCD
QED,
QCD
No resummed logs
Suffers if $M_{SUSY} >> M_Z$
Misses p^2/M_{SUSY}^2 terms
Suffers if $M_{SUSY} \approx M_Z$
Resums logs
Includes p^2/M_{SUSY}^2

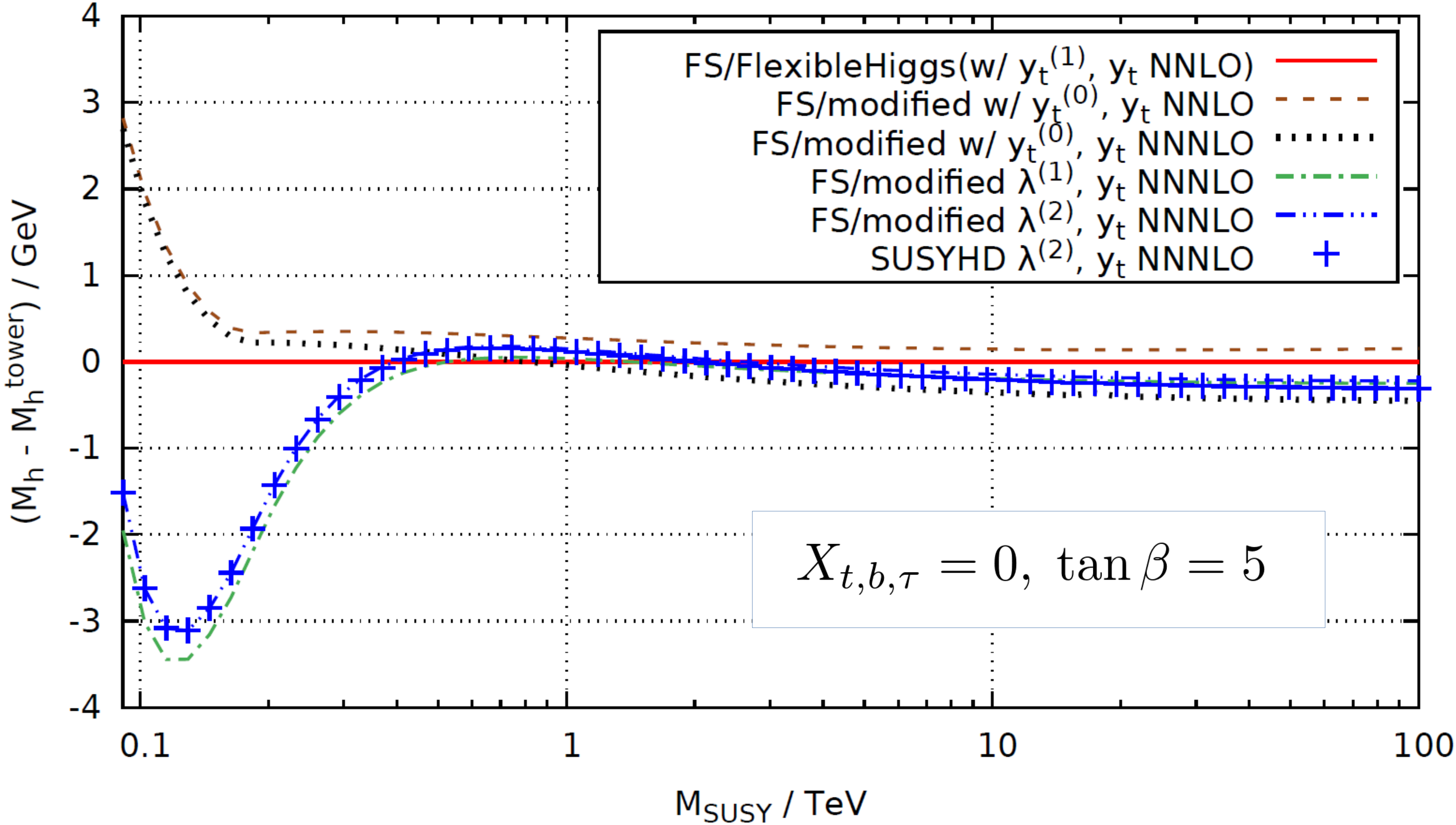
Comparison of FlexibleSUSY EFTs and Fixed order calculations in the MSSM

Note: $\alpha_s \alpha_t$ two-loop matching corrections vanish in these scenarios



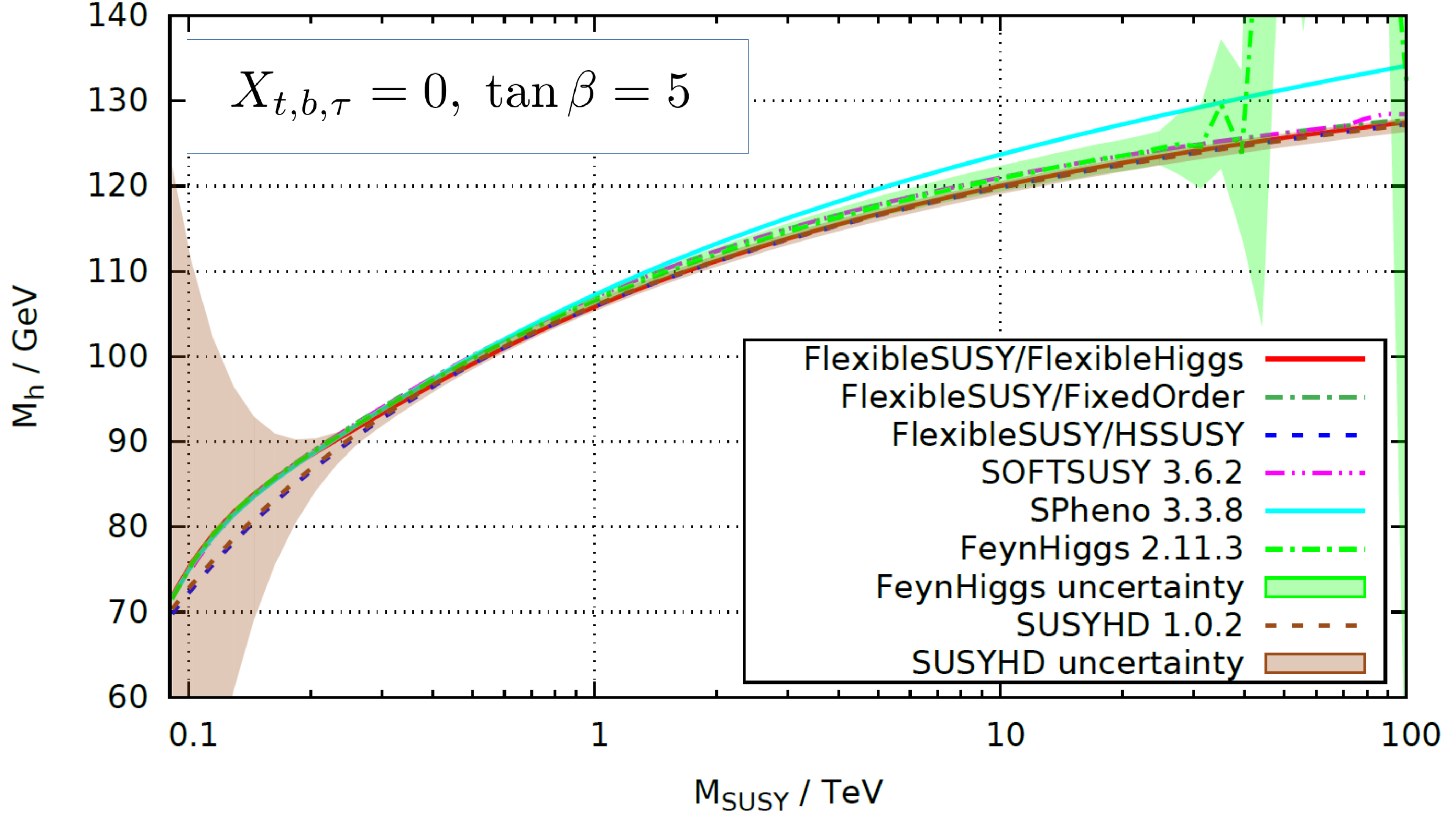
SUSY HD vs FlexibleHiggs (Xt = 0)

Note: $\alpha_s \alpha_t$ two-loop matching corrections vanish in these scenarios



Comparison to public codes (Xt = 0)

Note: $\alpha_s \alpha_t$ two-loop matching corrections vanish in these scenarios

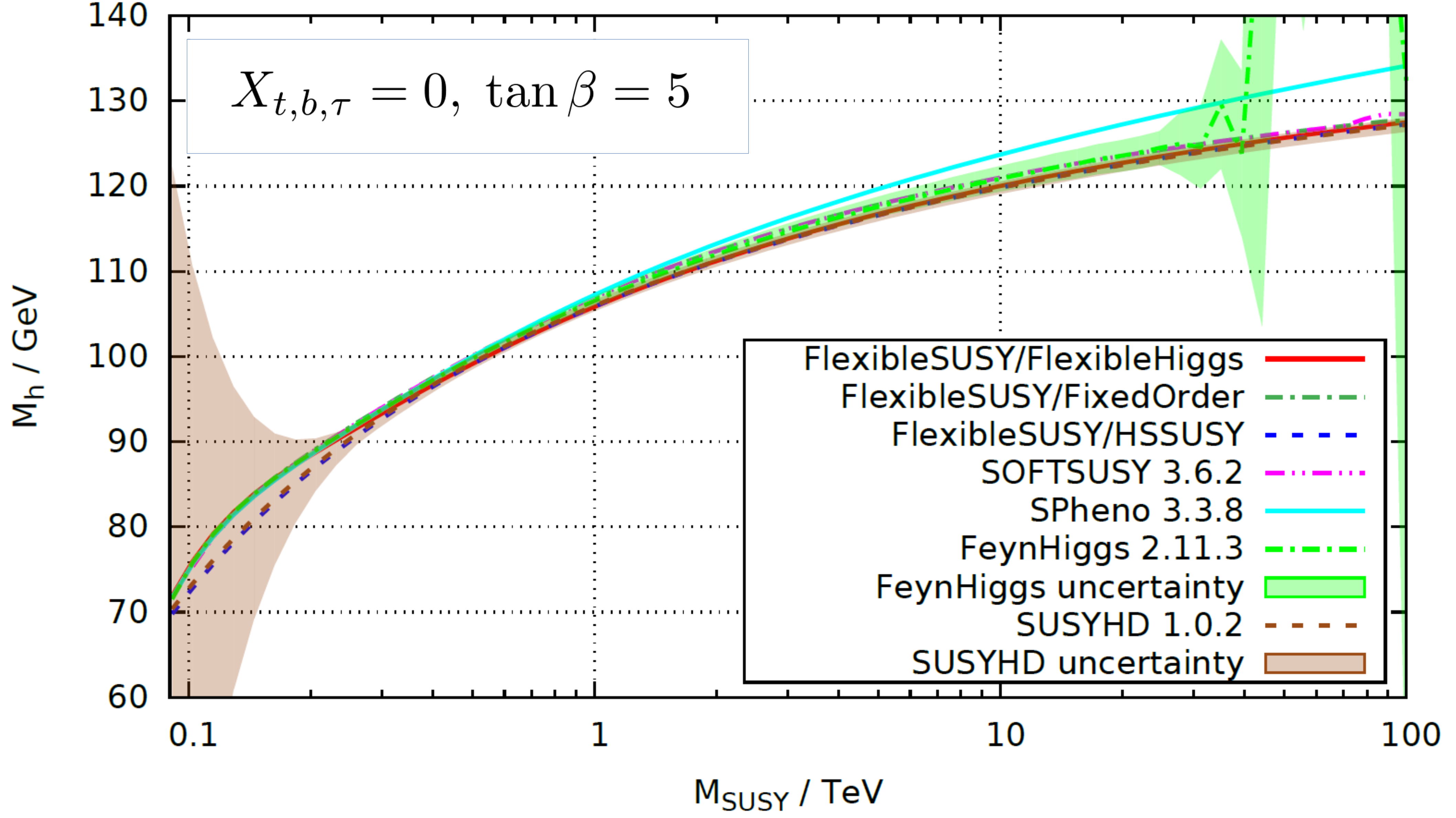


Comparison to public codes

Why is Spheno so different?

Or

Why do FlexibleSUSY and SOFTSUSY agree so well with FlexibleHiggs?



Comparison to public codes

Why is Spheno so different?

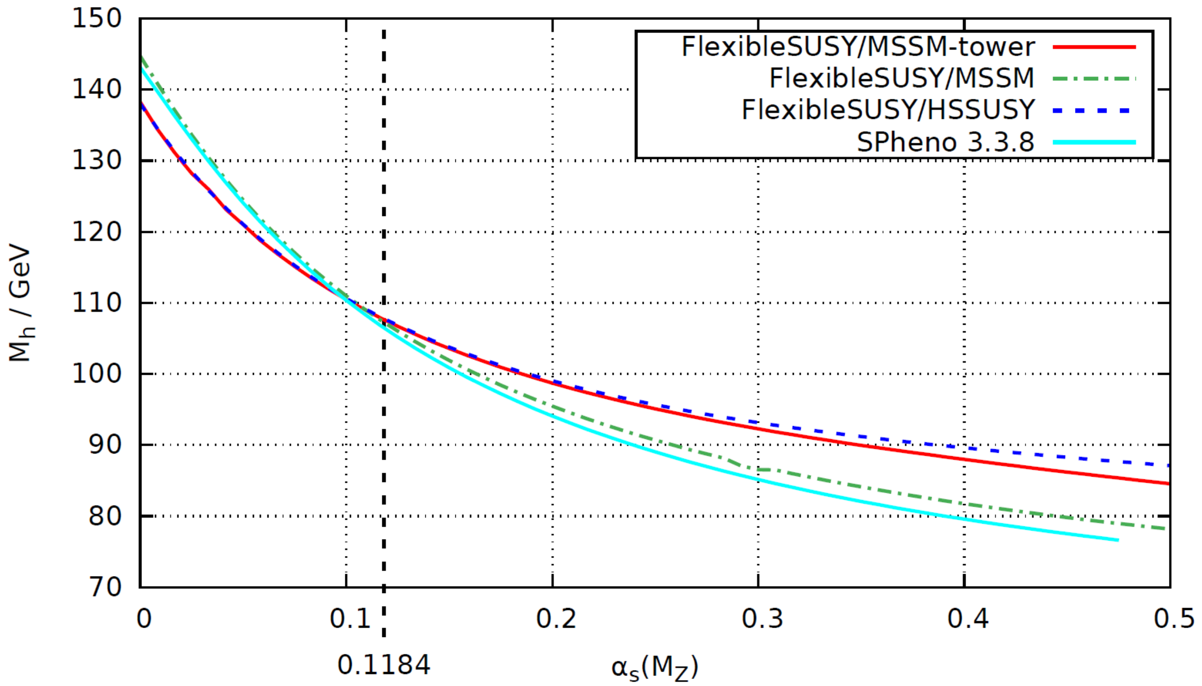
Or

Why do FlexibleSUSY and SOFTSUSY agree so well with FlexibleHiggs?

Cause of difference:
higher order differences from calculation of $m_t^{\overline{\mathrm{DR}}}$

$$\text{FS: } m_t^{\overline{\mathrm{DR}}} = M_t + \left[\widetilde{\Sigma}_t^{(1),S}(M_t)\right] + M_t\left[\widetilde{\Sigma}_t^{(1),L}(M_t) + \widetilde{\Sigma}_t^{(1),R}(M_t)\right] + M_t\left[\widetilde{\Sigma}_t^{(1),\mathrm{qcd}}(m_t^{\overline{\mathrm{DR}}}) + \left(\widetilde{\Sigma}_t^{(1),\mathrm{qcd}}(m_t^{\overline{\mathrm{DR}}})\right)^2 + \widetilde{\Sigma}_t^{(2),\mathrm{qcd}}(m_t^{\overline{\mathrm{DR}}})\right],$$

$$\text{SP: } m_t^{\overline{\mathrm{DR}}} = M_t + \left[\widetilde{\Sigma}_t^{(1),S}(m_t^{\overline{\mathrm{DR}}})\right] + m_t^{\overline{\mathrm{DR}}}\left[\widetilde{\Sigma}_t^{(1),L}(m_t^{\overline{\mathrm{DR}}}) + \widetilde{\Sigma}_t^{(1),R}(m_t^{\overline{\mathrm{DR}}})\right] + m_t^{\overline{\mathrm{DR}}}\left[\widetilde{\Sigma}_t^{(1),\mathrm{qcd}}(m_t^{\overline{\mathrm{DR}}}) + \widetilde{\Sigma}_t^{(2),\mathrm{qcd}}(m_t^{\overline{\mathrm{DR}}})\right].$$



Cause of agreement:
must be an accidental cancellation!

Comparison to public codes

Why is Spheno so different?

Or

Why do FlexibleSUSY and SOFTSUSY agree so well with FlexibleHiggs?

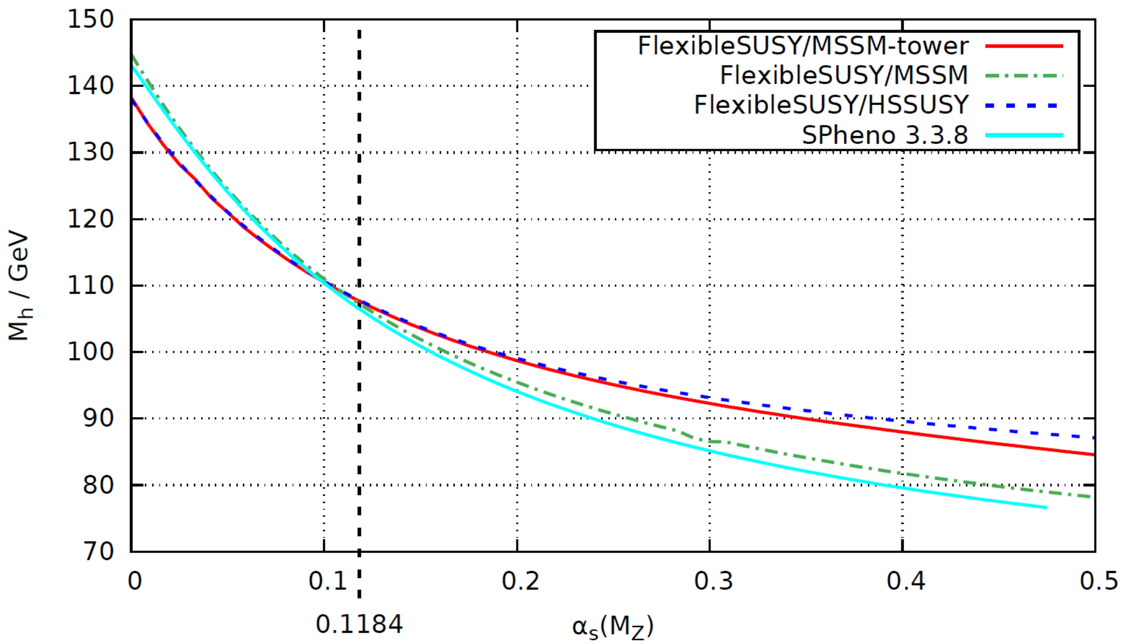
Fixed order expansion:

$$(M_h^2)^{\text{EFT}} = m_h^2 + v^2 y_t^4 \Big[12 t_S \kappa_L + 12 t_S^2 \kappa_L^2 \left(16 g_3^2 - 9 y_t^2\right) + 4 t_S^3 \kappa_L^3 \left(736 g_3^4 - 672 g_3^2 y_t^2 + 90 y_t^4\right) + \dots\Big],$$

$$(M_h^2)^{\text{FlexibleSUSY}} = m_h^2 + v^2 y_t^4 \Big[12 t_S \kappa_L + 12 t_S^2 \kappa_L^2 \left(16 g_3^2 - 9 y_t^2\right) + 4 t_S^3 \kappa_L^3 \left(\frac{736}{3} g_3^4 - 288 g_3^2 y_t^2 + \frac{27}{2} y_t^4\right) + \dots\Big],$$

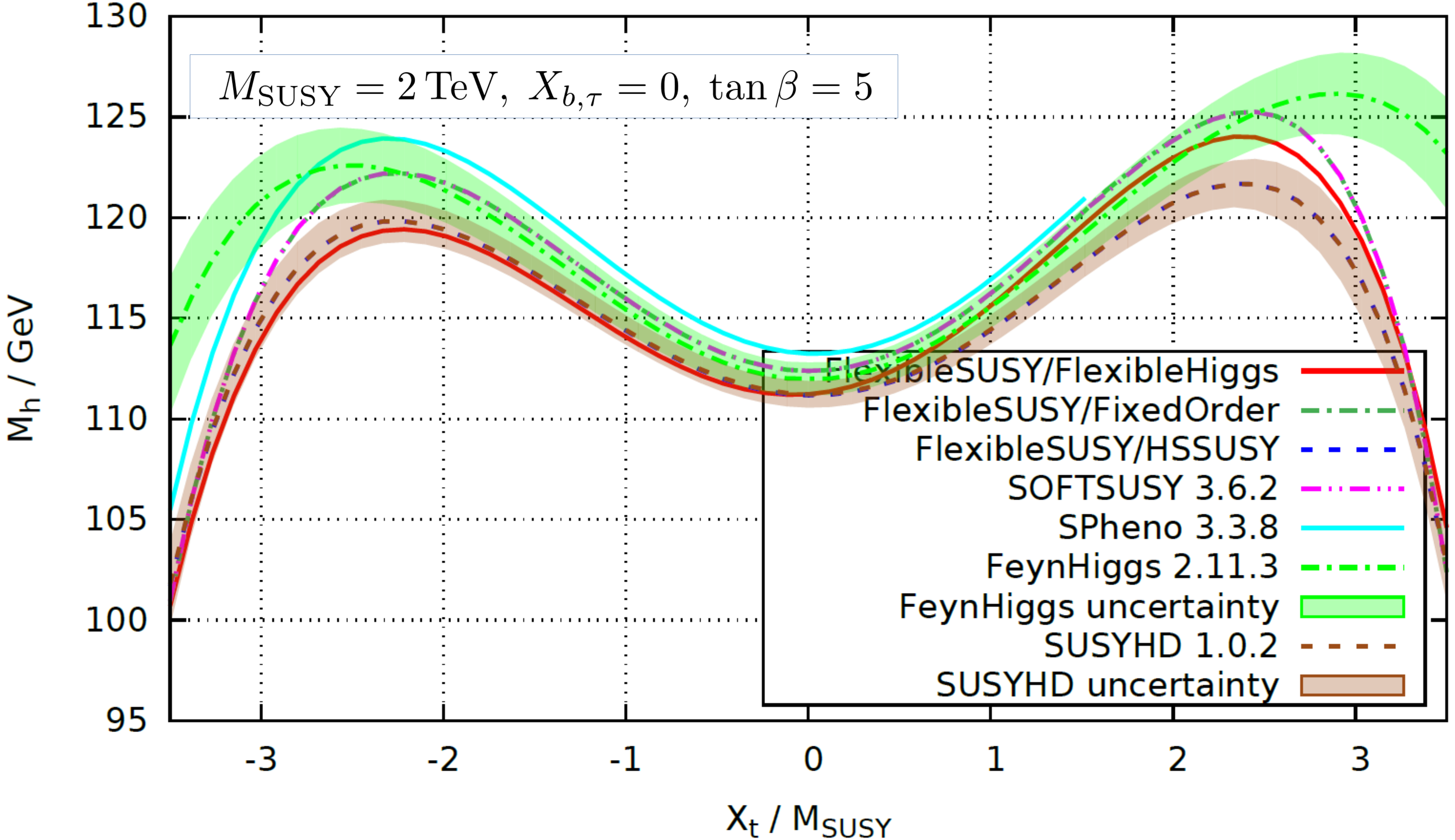
$$(M_h^2)^{\text{SPheno}} = m_h^2 + v^2 y_t^4 \Big[12 t_S \kappa_L + 12 t_S^2 \kappa_L^2 \left(16 g_3^2 - 9 y_t^2\right) + 4 t_S^3 \kappa_L^3 \left(\frac{992}{3} g_3^4 - 192 g_3^2 y_t^2 + \frac{81}{2} y_t^4\right) + \dots\Big].$$

Large coefficients suggest both FlexibleSUSY and Spheno have a larger uncertainty than the difference between the suggests

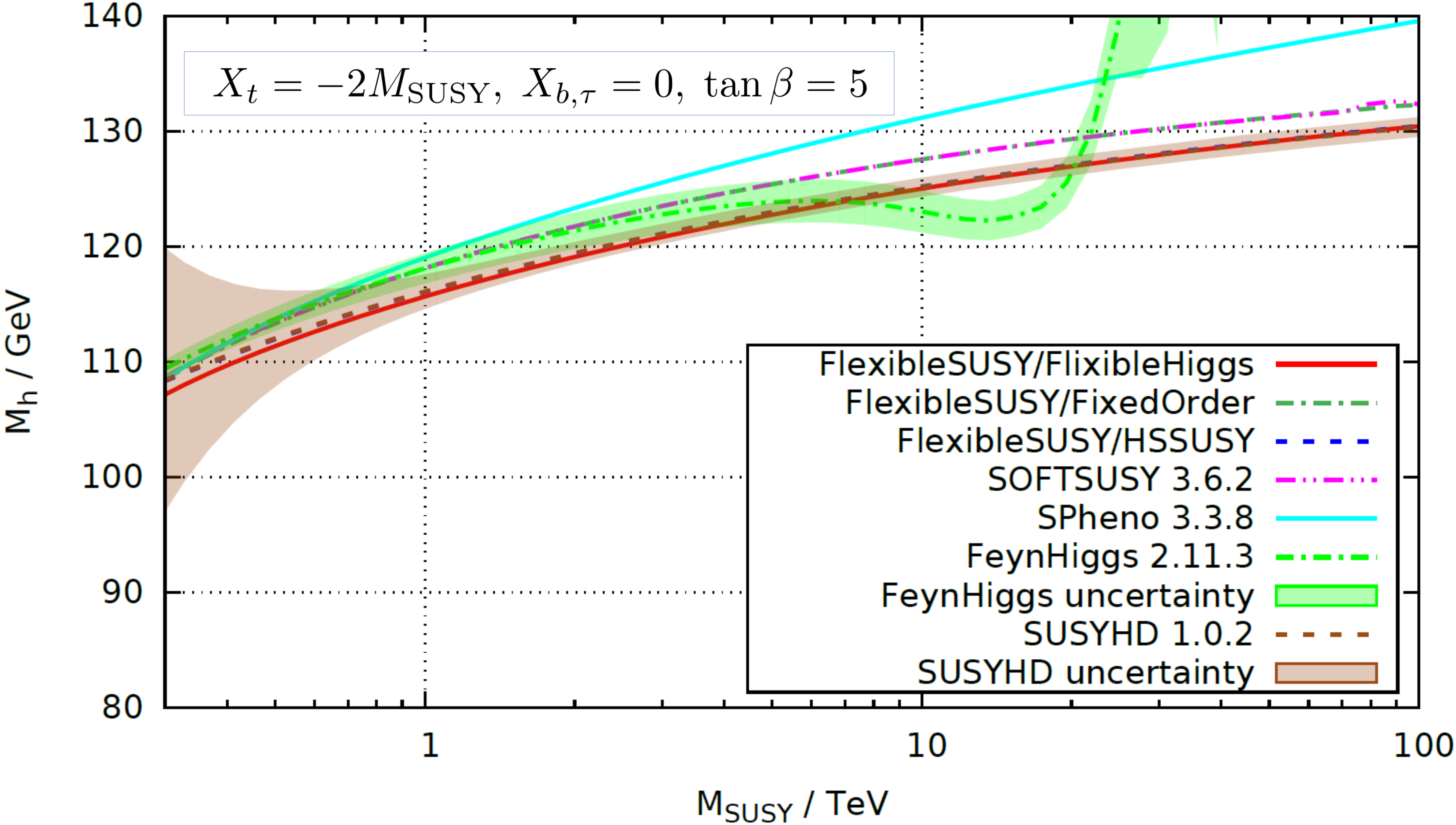


Cause of agreement:
must be an accidental cancellation!

Comparison to public codes (Xt != 0)



Comparison to public codes (Xt != 0)



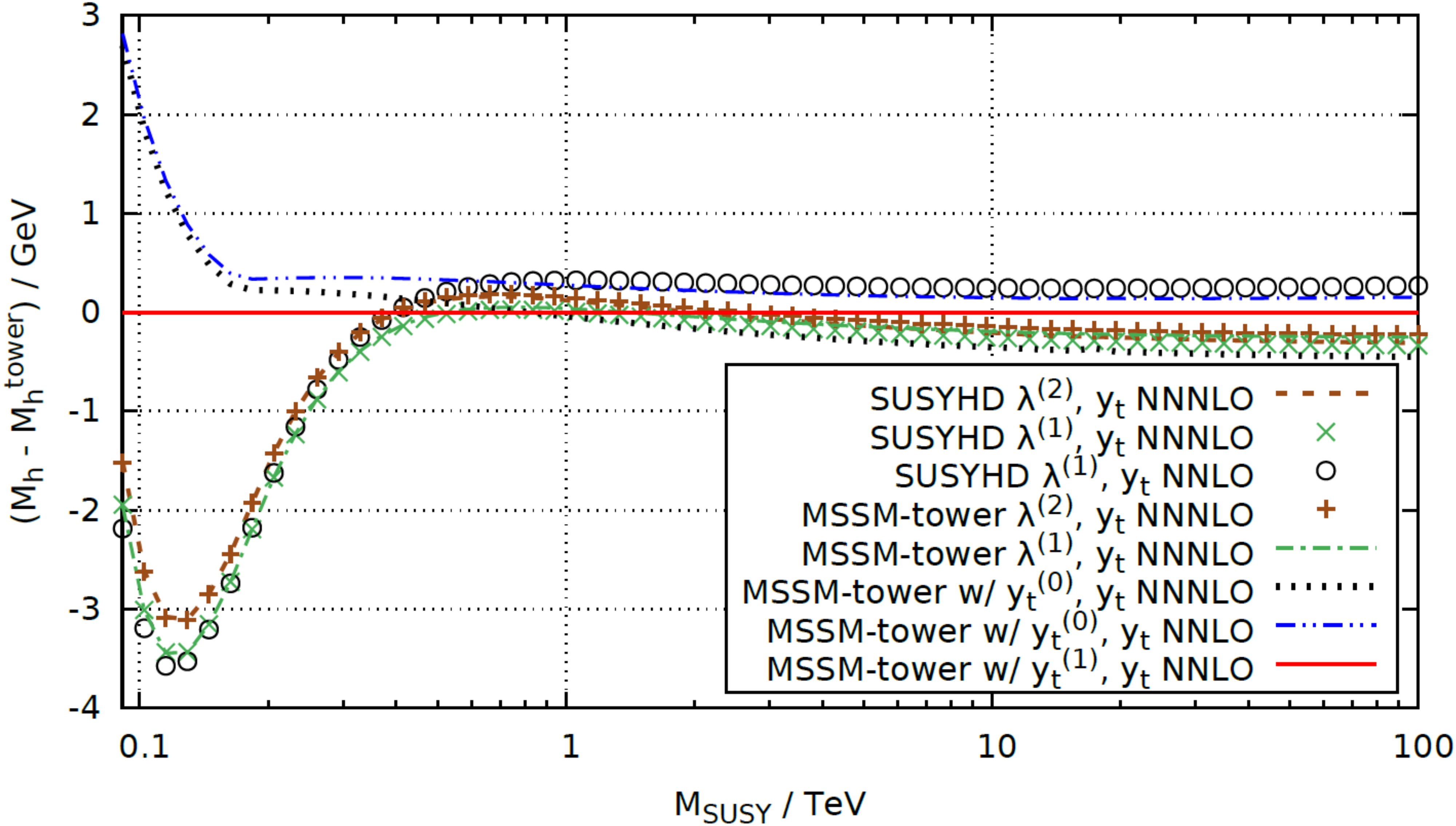
Summary and outlook

- FlexibleHiggs uses a new EFT approach to predict Higgs mass in any SUSY model with resummed two-loop logarithmic corrections.
- The pole-mass matching approach of FlexibleHiggs ensures beautiful agreement with the fixed order calculation when MSUSY = MZ.
- For the MSSM FlexibleHiggs agrees very well with the leading calculations when Xt=0
- When Xt != 0 the two-loop matching corrections can be large are and introduce finite shifts between SUSYHD / HSSUSY and FlexibleHiggs
- We also have done a detailed study of error estimation for FlexibleHiggs, uising methods that are applicable to all models (see forthcoming paper for details)
- FlexibleHiggs has already been applied and studied in the NMSSM, E6SSM and MRSSM (see forthcoming paper for details)
- FlexibleHiggs will be made publicly available as part of FlexibleSUSY in a new release
- Two-loop matching conditions will be provided and studied in a future update

SUSY HD vs MSSM-tower (Xt = 0)
(difference)

Note: $\alpha_s \alpha_t$ two-loop matching corrections vanish in these scenarios

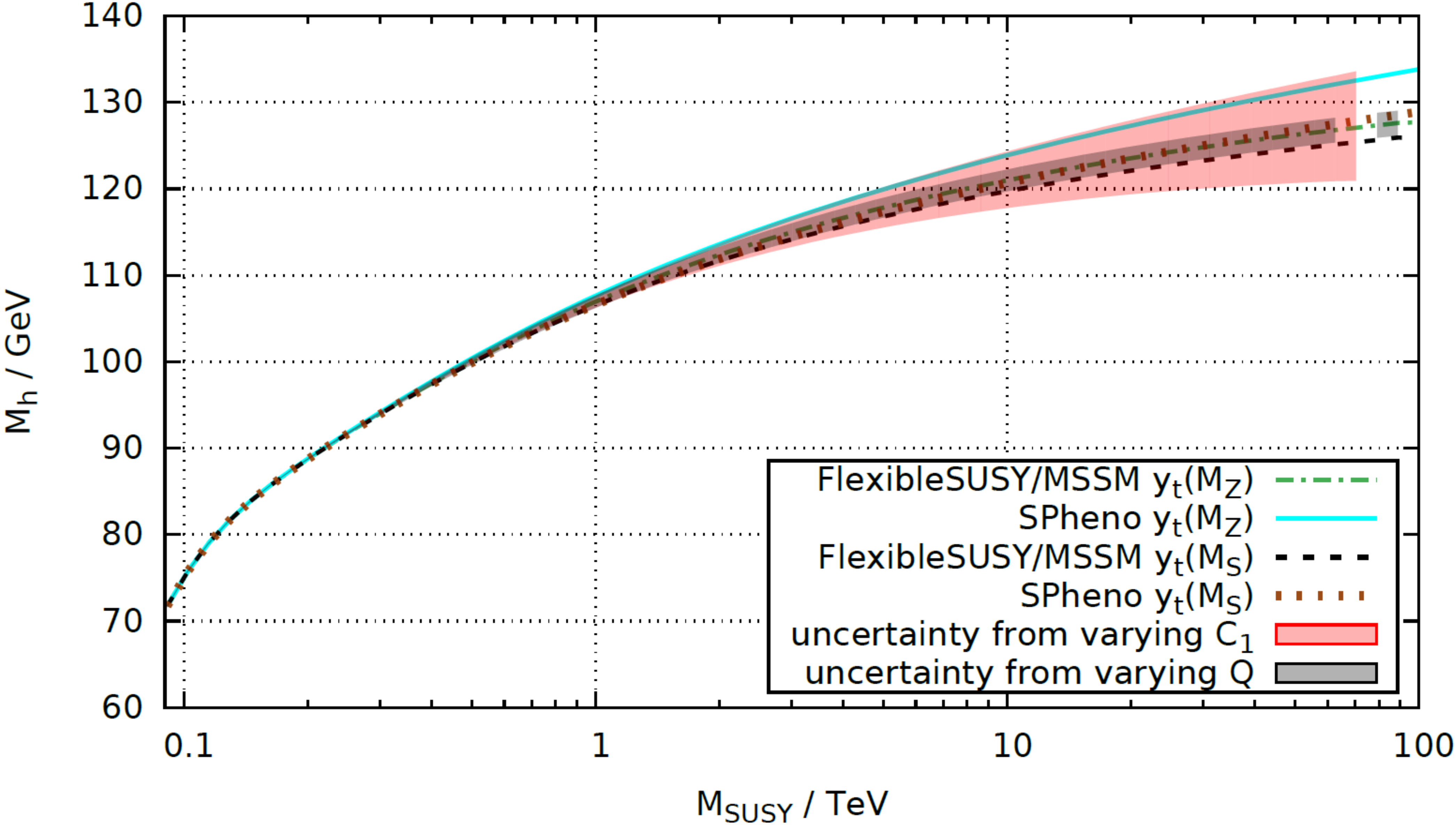
Alternative version of plot with more steps



Fixed order MSSM uncertainty estimation

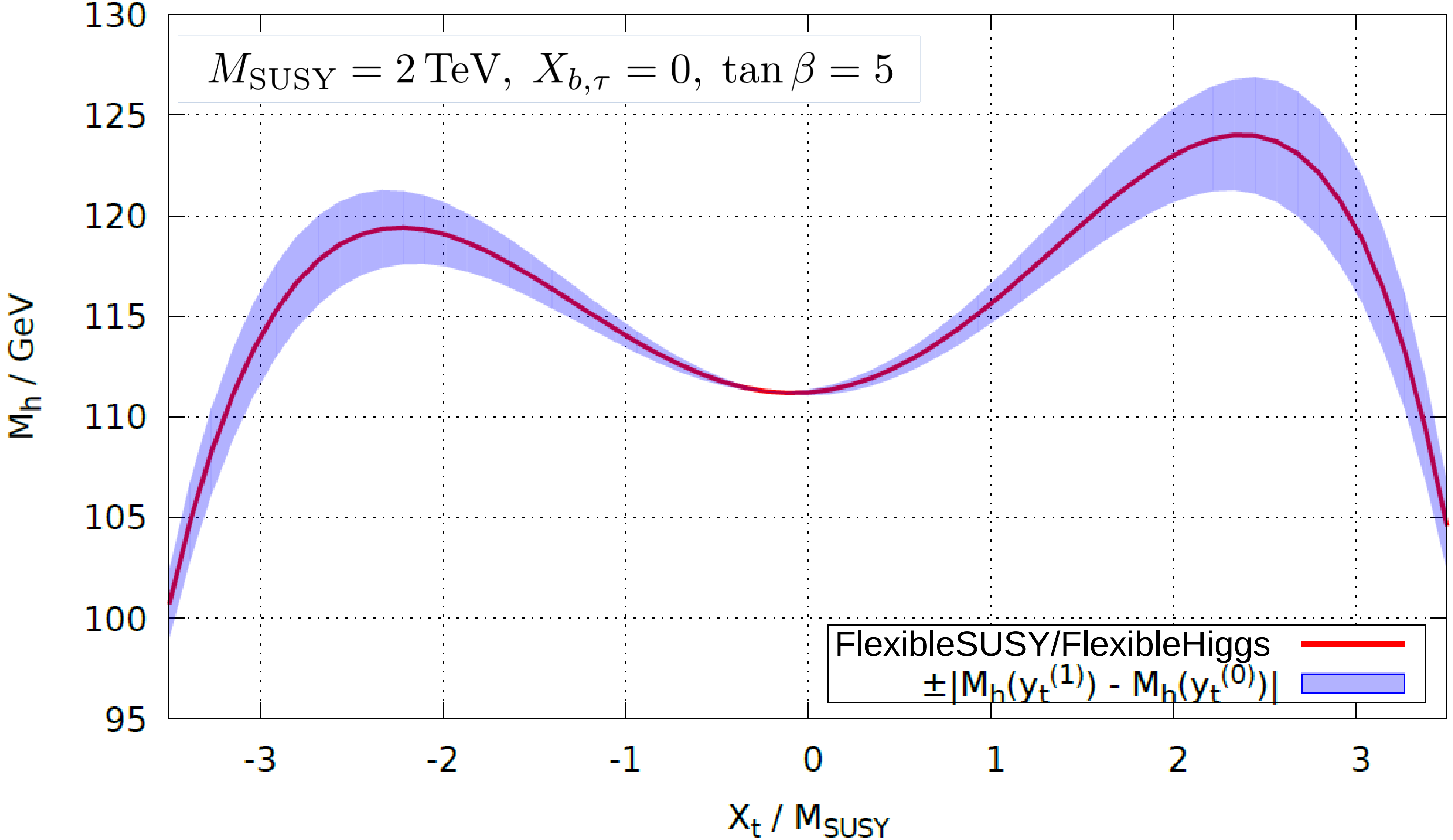
Vary coefficent of g_s^4 $\Delta m_t = \frac{C_1 g_s^4 M_t}{4\pi}^4 \log^2\left(\frac{M_{\text{SUSY}}}{M_Z}\right)$

$C_1 \in \{-184/9, +184/9\}$



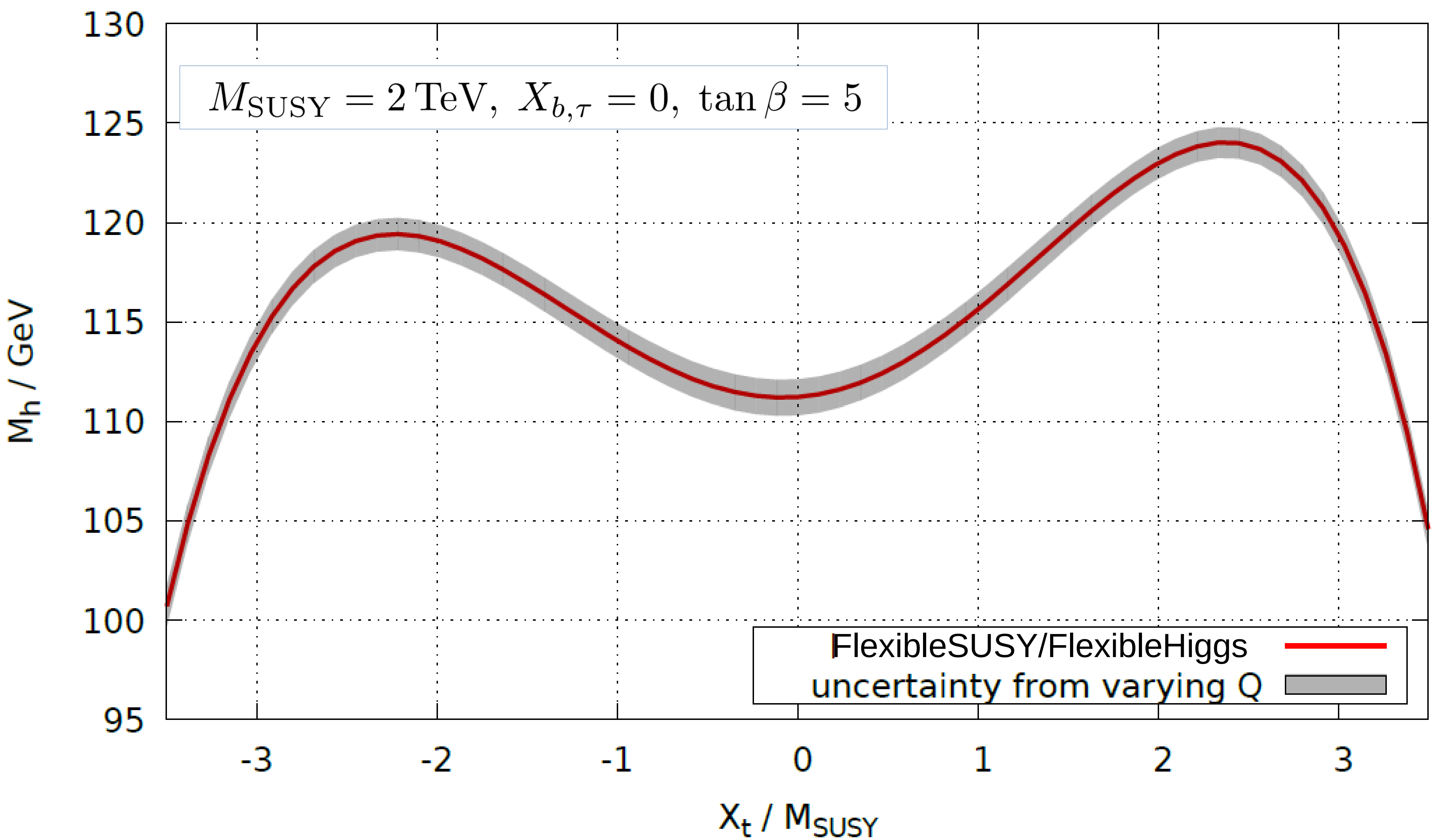
FlexibleHiggs uncertainty estimation

$$y_t^{\text{MSSM},(0)} = \frac{y_t^{\text{SM}}}{s_\beta} \qquad y_t^{\text{MSSM},(1)} = \frac{y_t^{\text{SM}}}{s_\beta} + \frac{\sqrt{2}}{s_\beta v}\left[\Sigma_t^{\text{MSSM}} - \Sigma_t^{\text{SM}}\right]$$



FlexibleHiggs uncertainty estimation

Vary renormalisation scale of SM Higgs mass calculation



Comparison of uncertainties

Note: combining errors linearly is quite conservative, so these are likely an overestimate

Full model approach (2L):

(C_3 and Q uncertainties added linearly)

M_S/TeV	X_t/M_S	ΔM_h/GeV	X_t/M_S	ΔM_h/GeV
1	0	± 1.3	2	± 2.0
2	0	± 2.1	2	± 3.0
10	0	± 4.5	2	± 5.5

EFT-M_h approach (1L):

($y_t^{(i)}$ and Q uncertainties added linearly)

M_S/TeV	X_t/M_S	ΔM_h/GeV	X_t/M_S	ΔM_h/GeV
1	0	± 1.0	2	± 3.1
2	0	± 1.0	2	± 3.1
10	0	± 1.1	2	± 2.8