NLO MATCHING CONDITIONS IN EXTENDED HIGGS SECTORS

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From the **SUSY** scale to the EW scale

OUTLINE

1. Motivation of Effective Field Theories (EFTs) in Context of Higgs Mass Calculations
2. Implementation in SARAH
3. Introduction to Matching Conditions
4. Application: High Scale NMSSM
5. Conclusions & Outlook

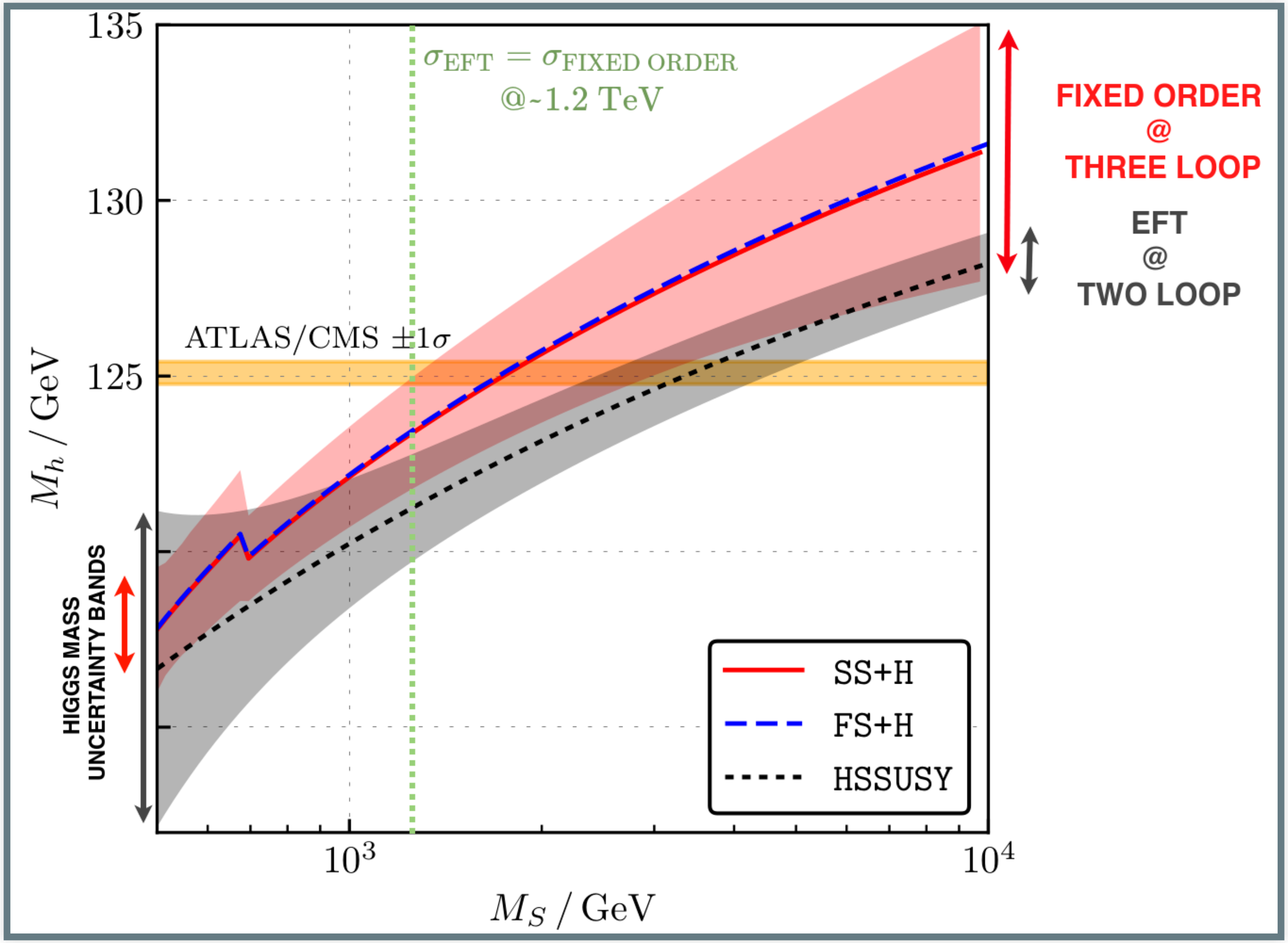
BSM HIGGS MASS PREDICTIONS

Experimental data pushes new physics scale M_{BSM} towards the multi-TeV scale.

- Relaxing the requirement of naturalness
- BSM models still contrained to correctly predict the measured Higgs mass value
- Problem: **large mass gaps** spoil fixed order calculations through **large logarithms**
- Solution: resummation with effective field theory (**EFT**) techniques

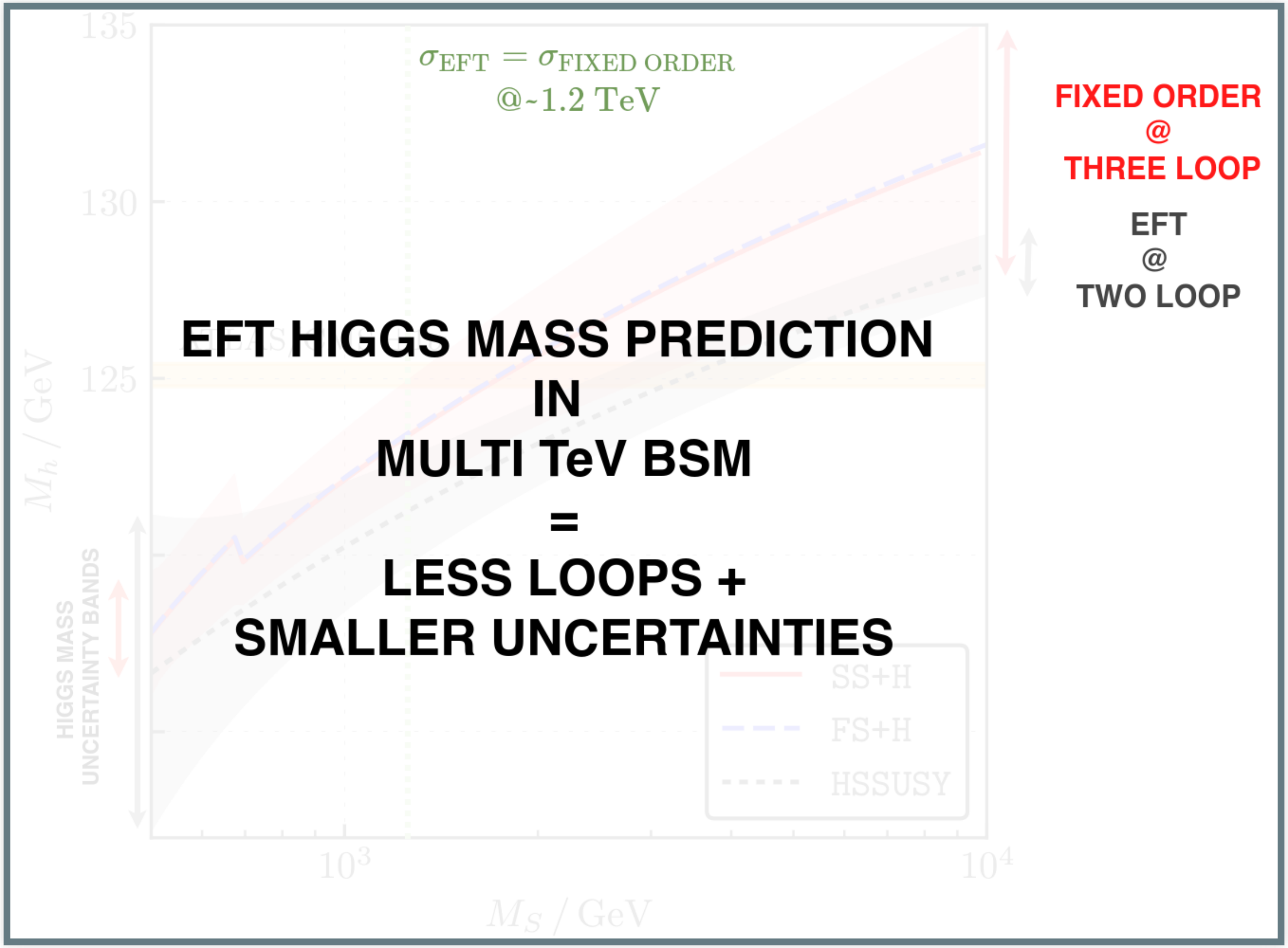
MOTIVATION: EFT VS. FIXED ORDER IN THE MSSM

[Allanach, Voigt]



MOTIVATION: EFT VS. FIXED ORDER IN THE MSSM

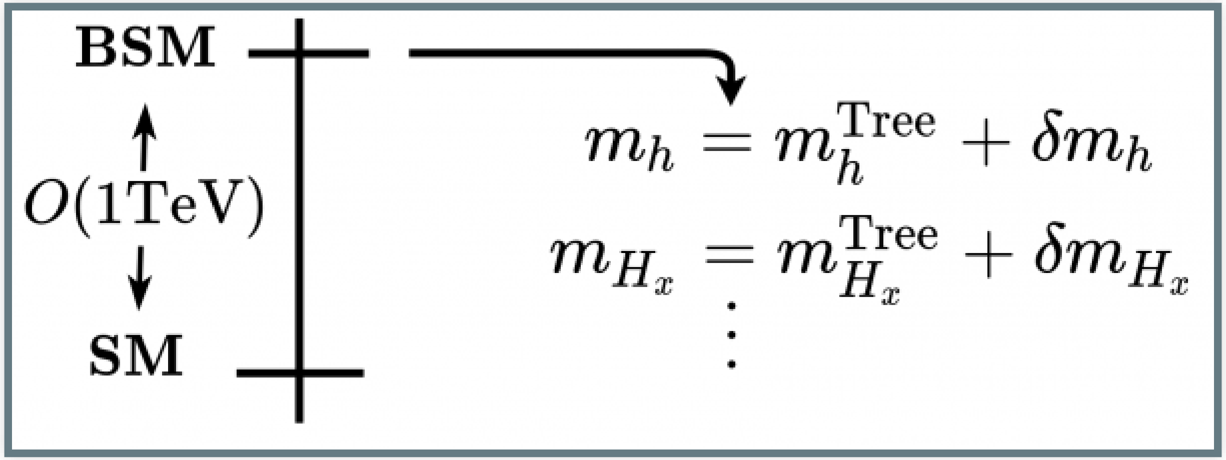
[Allanach, Voigt]



IMPLEMENTATION IN SARAH

STATE OF THE ART I

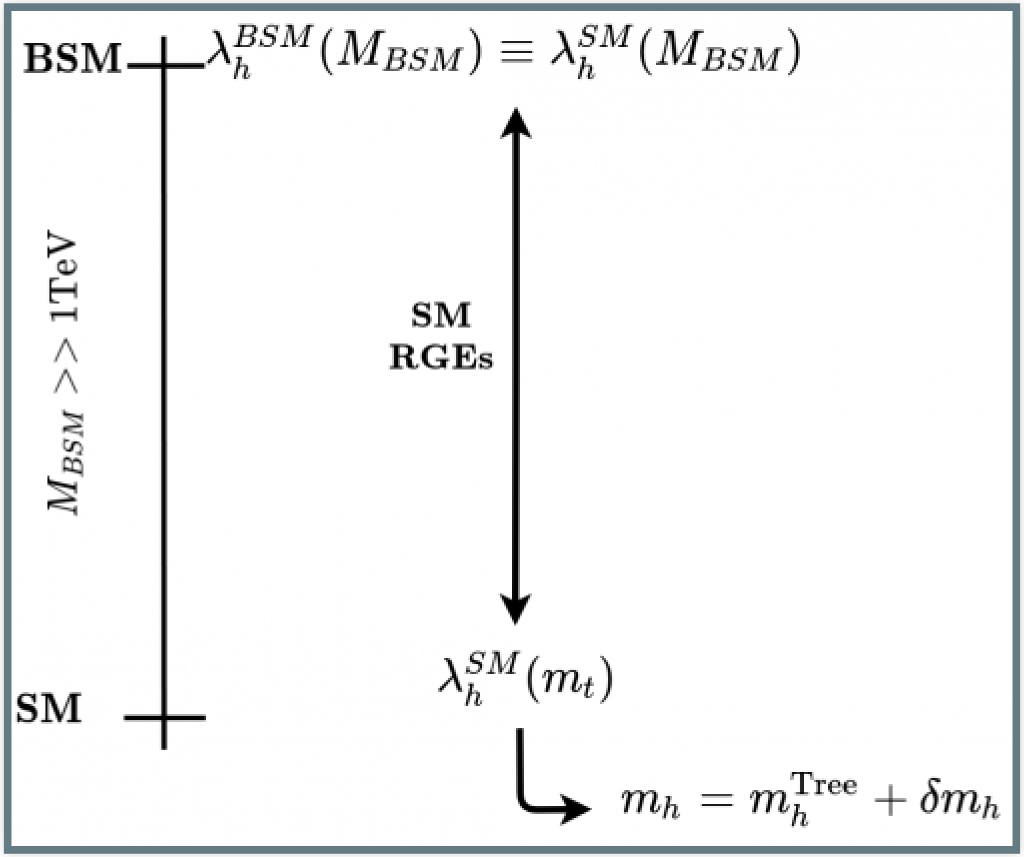
Fixed order calculation



- one loop self energies for all particles
- two loop self energies for scalars

STATE OF THE ART II

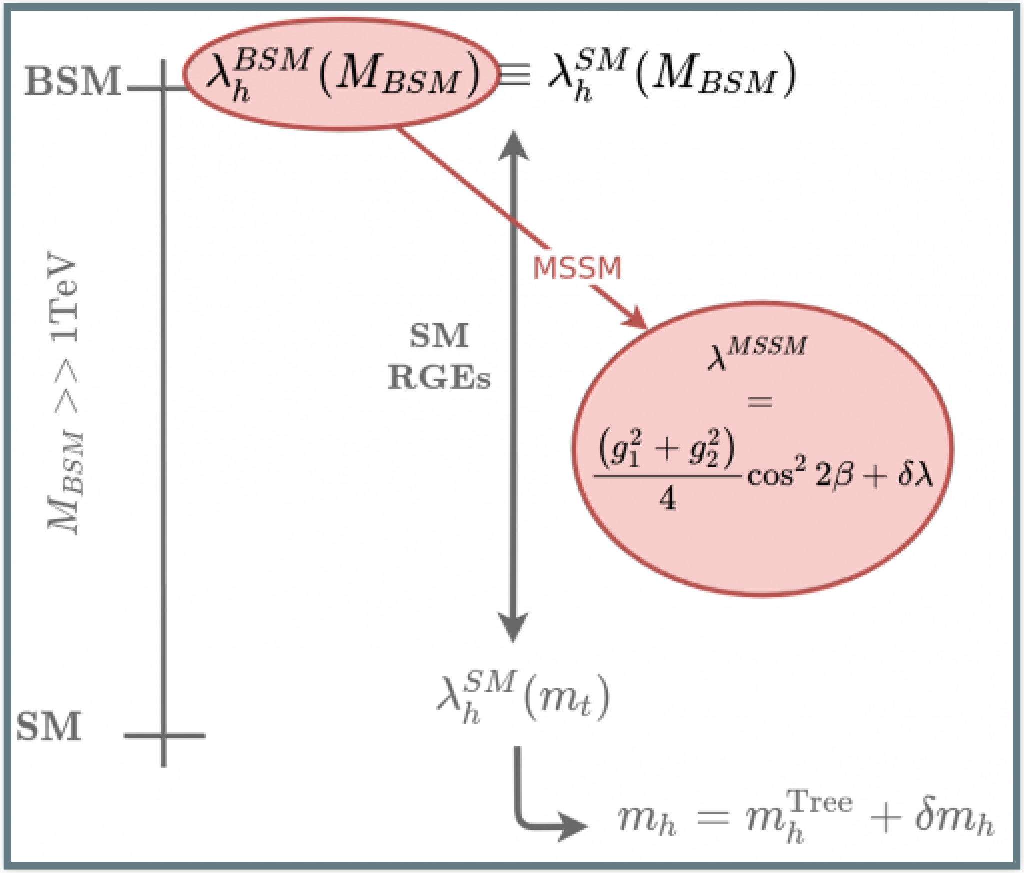
EFT Higgs mass calculation



- only if one light scalar is present

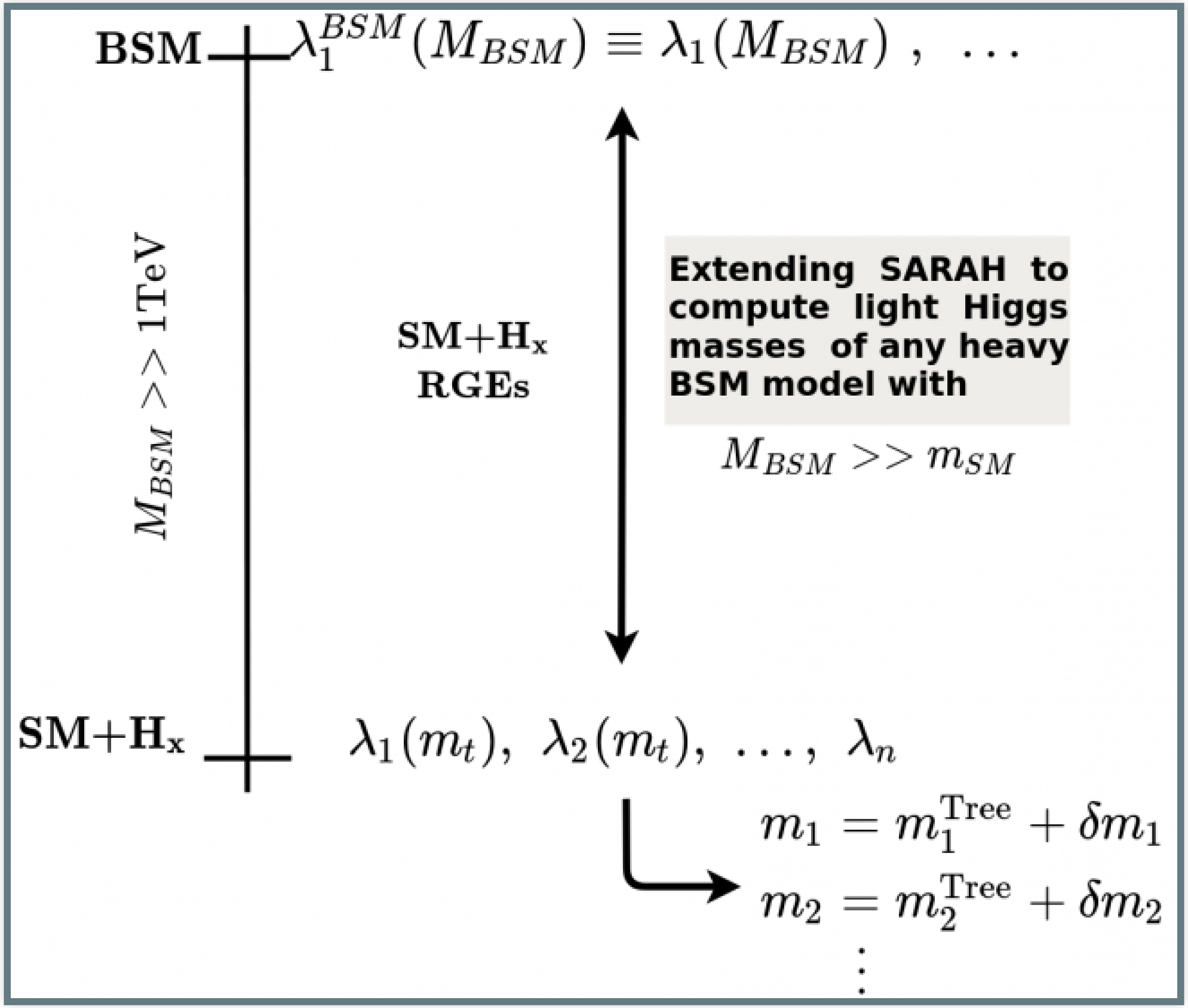
STATE OF THE ART II

EFT Higgs mass calculation



- only if one light scalar is present

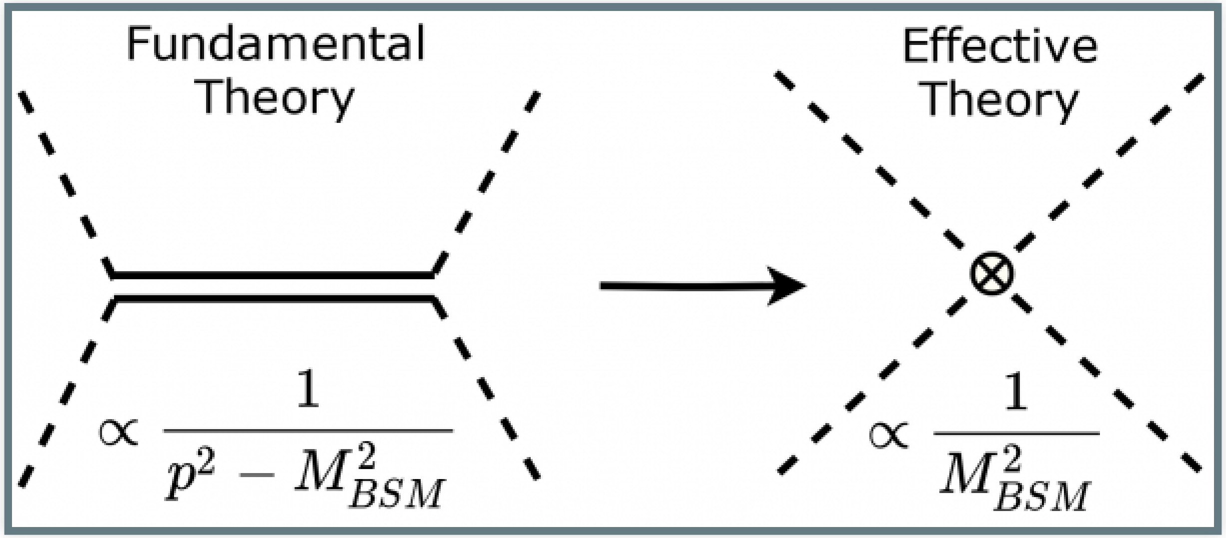
NEW IMPLEMENTATION



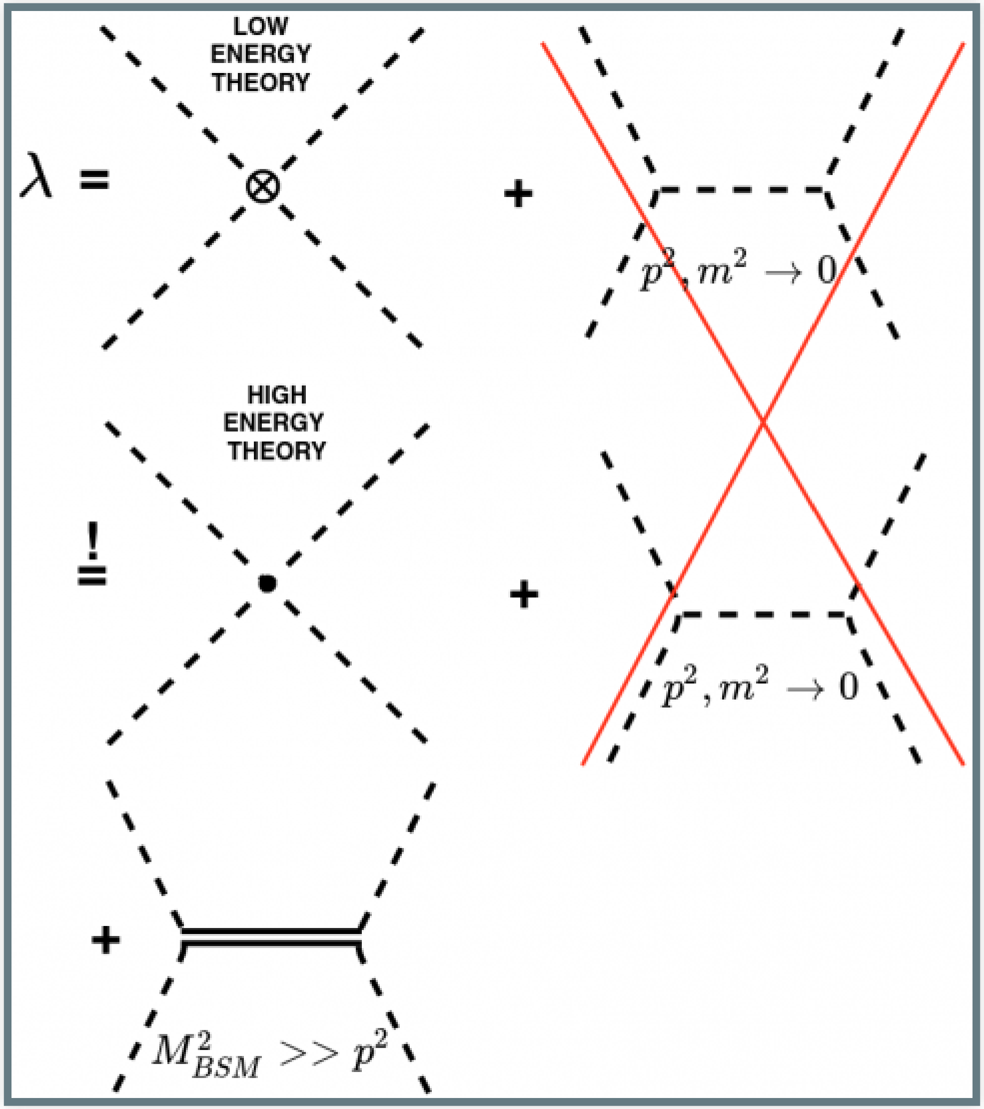
MATCHING CONDITIONS

TOP-DOWN

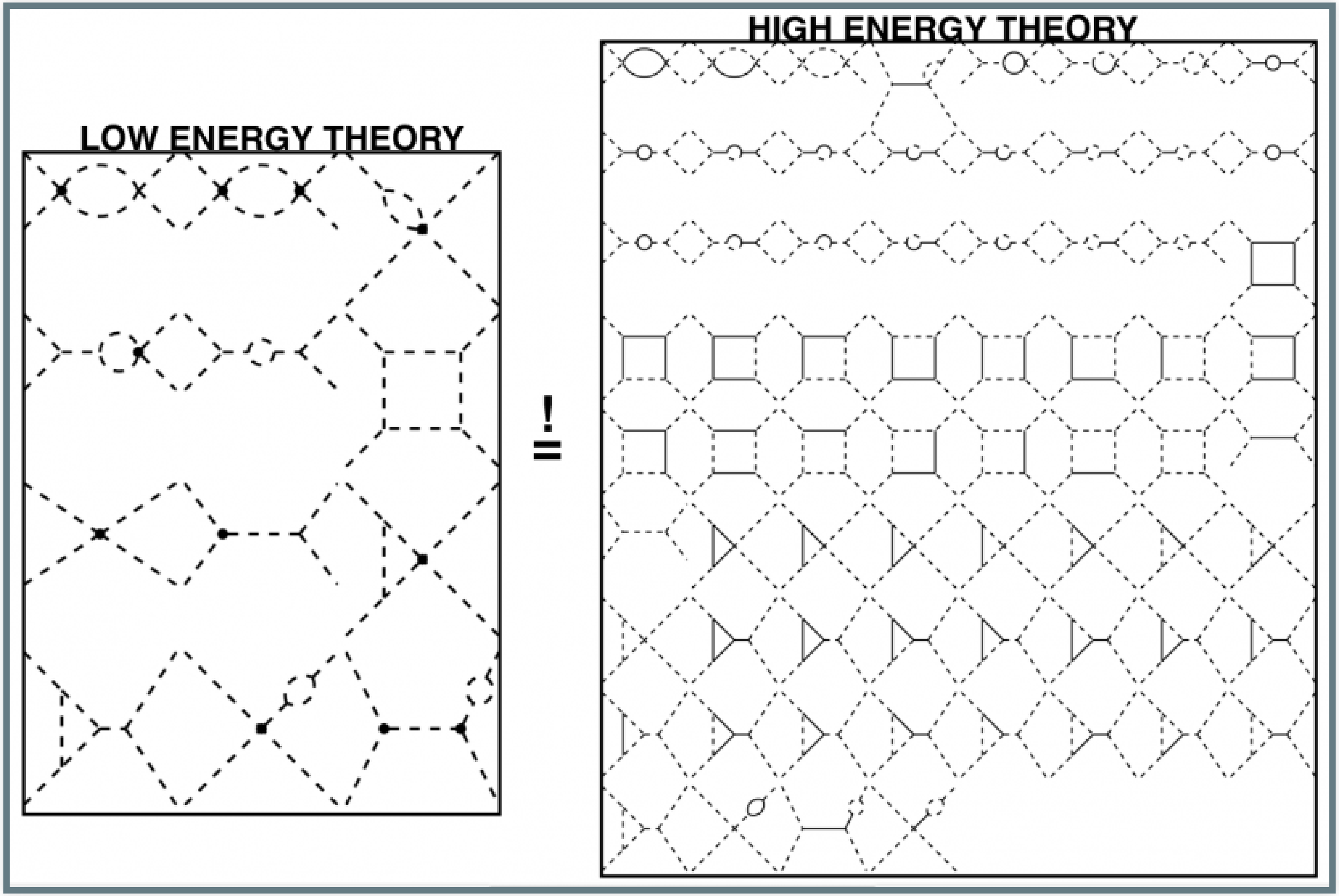
- integrating out heavy degrees of freedom
- Feynman diagrammatic approach
- Expand amplitudes in $\frac{p^2}{M_{BSM}^2}$



TREE-LEVEL MATCHING

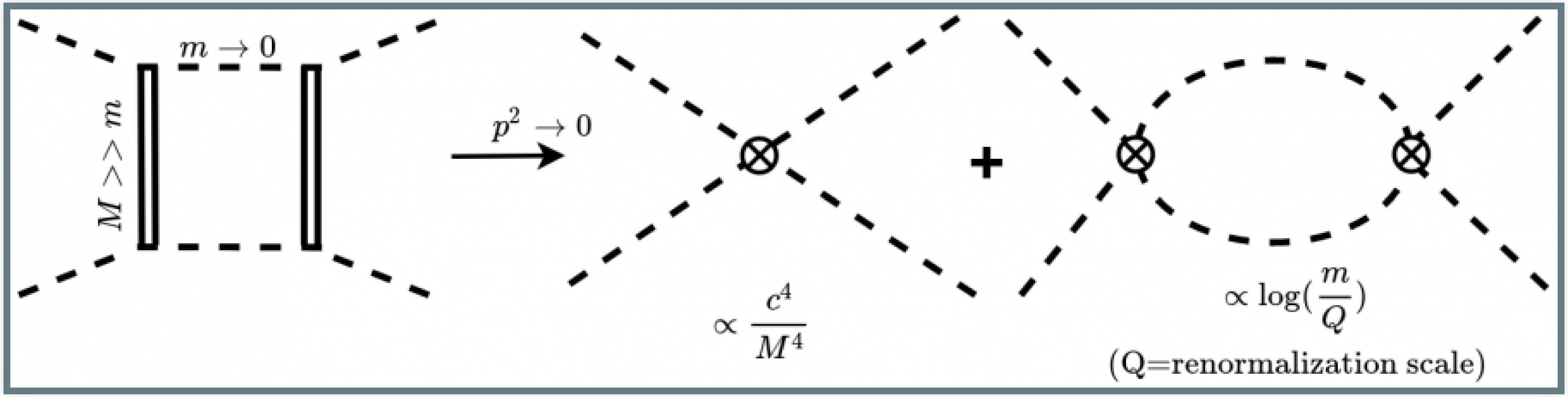


ONE-LOOP MATCHING

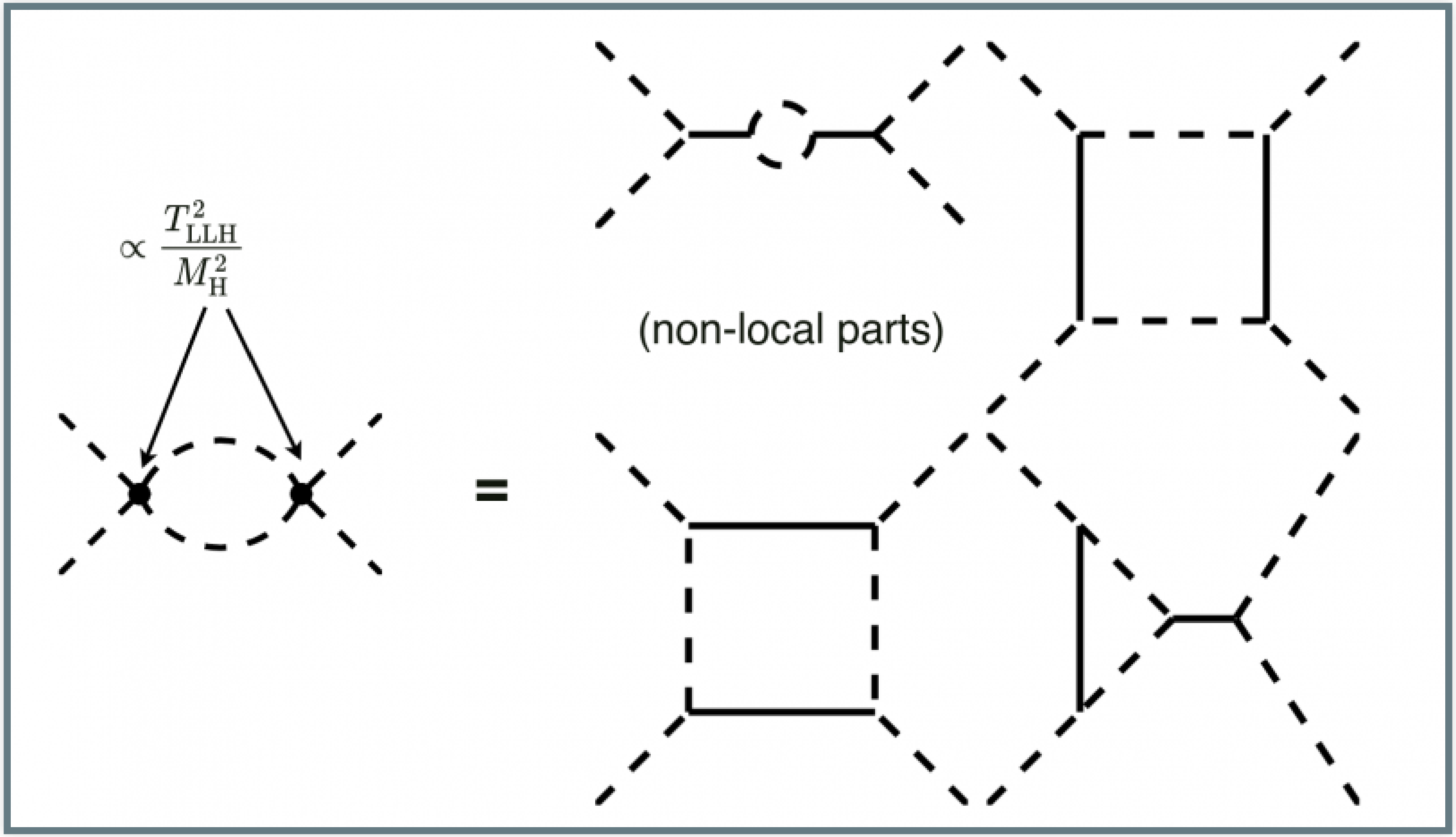


MIXED LOOPS

- Mixed loop = contains heavy and light fields
- Non local -possibly divergent- loop contributions may enter the matching condition
- IR divergences caused by light fields must cancel in the matching condition



CANCELLATION IN SUBSETS



APPLICATIONS

PREVIOUS WORKS

Many studies already exist in literature

Ref	Date	High Scale	Low Scale
[Wells]	2003	MSSM	SM(+EWinos)
[Giudice et al.]	2004	MSSM	SM(+EWinos)
[Haber et al.]	2009	MSSM	2HDM
[Giudice et al.]	2011	MSSM	SM(+EWinos)
[Bagnaschi et al.]	2014	MSSM	SM(+EWinos)
[Lee et al.]	2015	MSSM	2HDM(+EWinos)
[Bagnaschi et al.]	2017	MSSM	SM
[Zarate]	2017	NMSSM	SM

CODES

Also a long list of computer codes exist:

Tool	High Scale	Low Scale (Higgs Sector)
SusyHD [Vega, Villadoro]	MSSM	SM
FeynHiggs [Heinemeyer et al.]	(N)MSSM	2HDM
FlexibleSUSY [Athron et al.]	generic	2HDM
SARAH/SPheno [Staub, Porod]	generic	SM (+ X)

They all have either SM or 2HDM Higgs sectors in the low energy theory

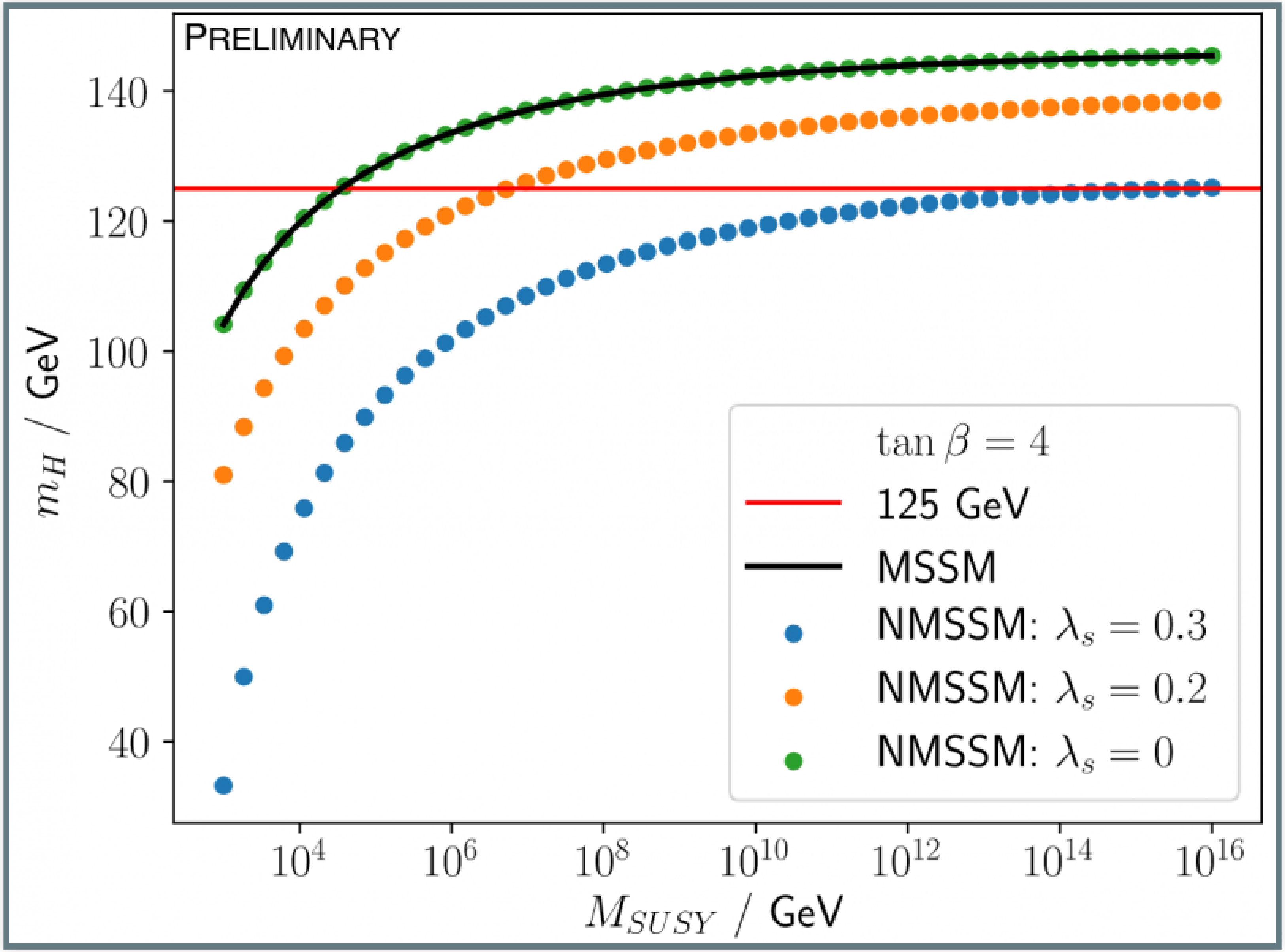
APPLICATION: NMSSM

$$W_{NMSSM} \supset \lambda_s S H_u H_d \xrightarrow{SSB} \underbrace{v_s \lambda_s}_{=\mu_{\text{eff}}^{\text{MSSM}}} H_u H_d$$

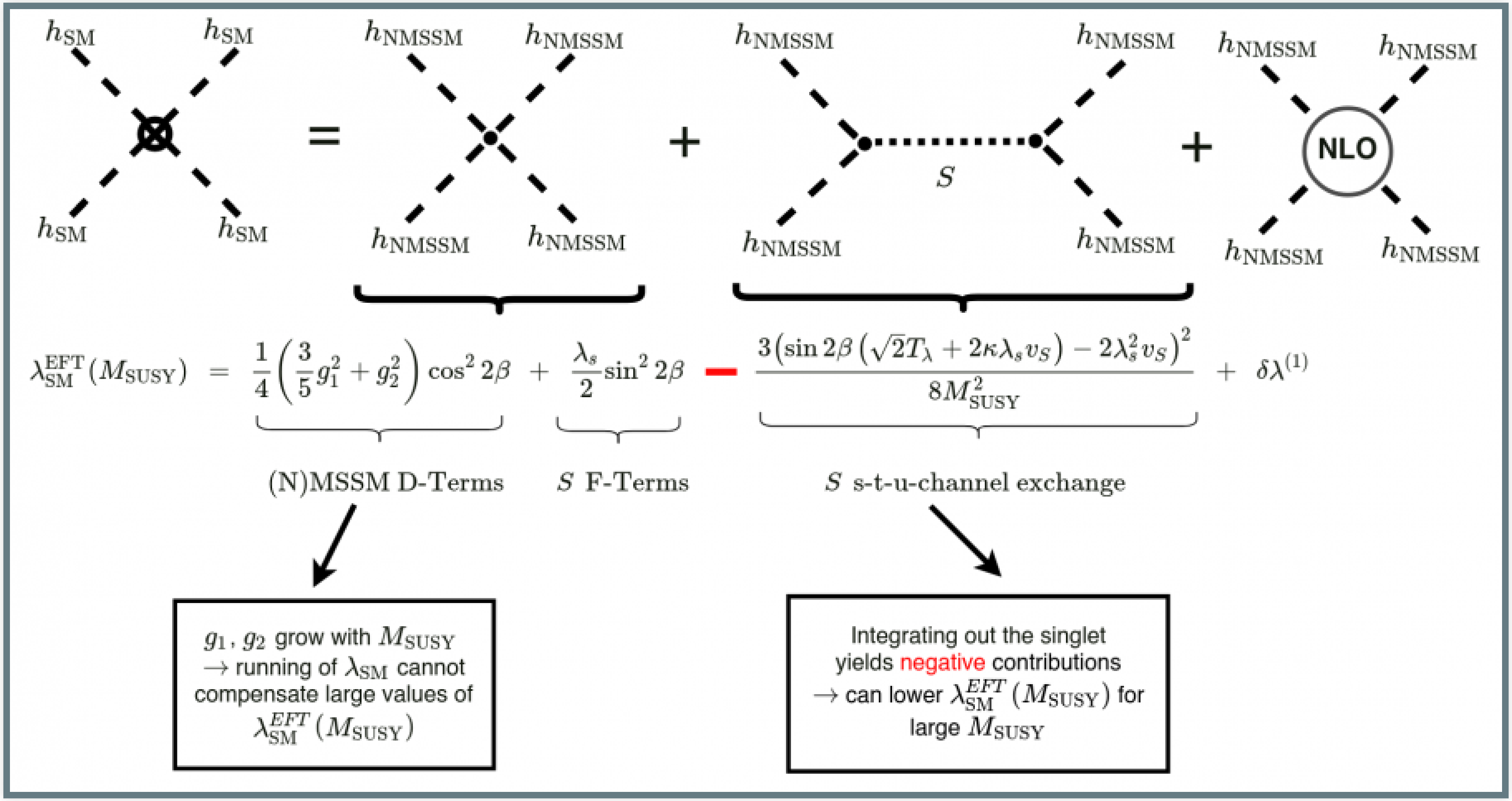
- Tree-Level matching already in literature [Zarate]
- First cross-check: **decouple the singlet**
- heavy singlet mass
- heavy singlet VEV $v_s \propto \frac{M_{SUSY}}{\lambda_s}$
- $\lambda_s \to 0$ while keeping $v_s \lambda_s$ constant

$\to$ should recover the MSSM!

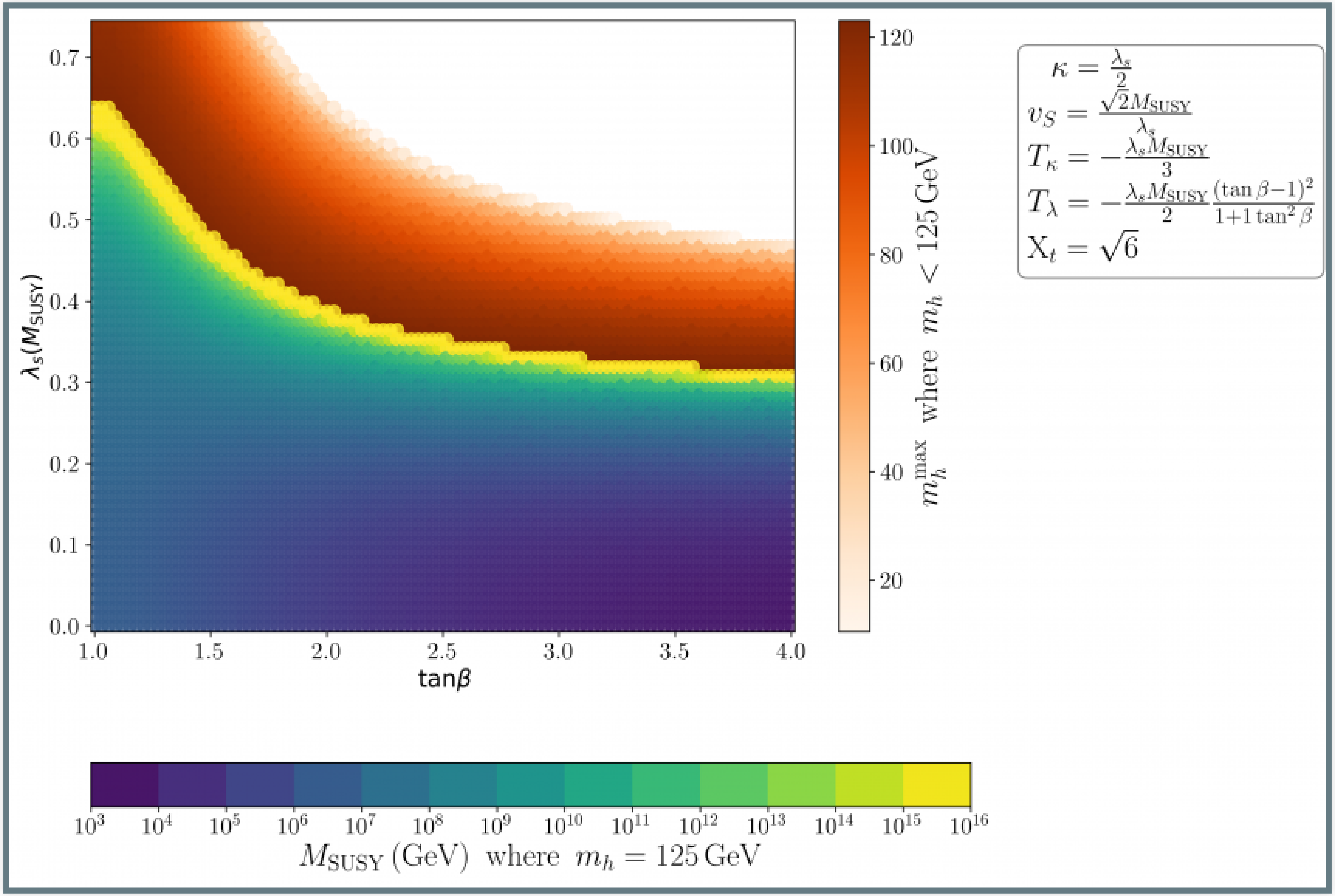
NMSSM@ $\tan\beta = 4$



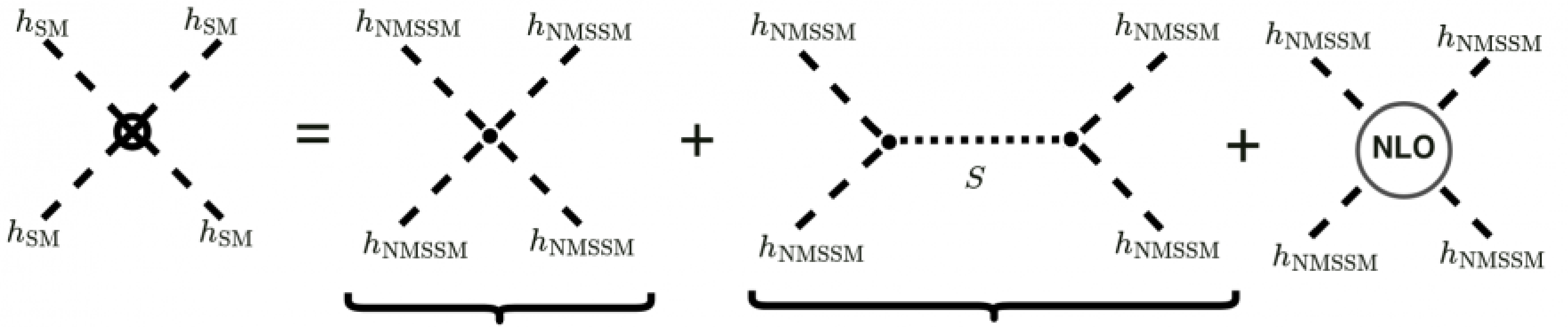
NMSSM VS MSSM



CONTOURSCAN WITH DEGENERATED MASSES



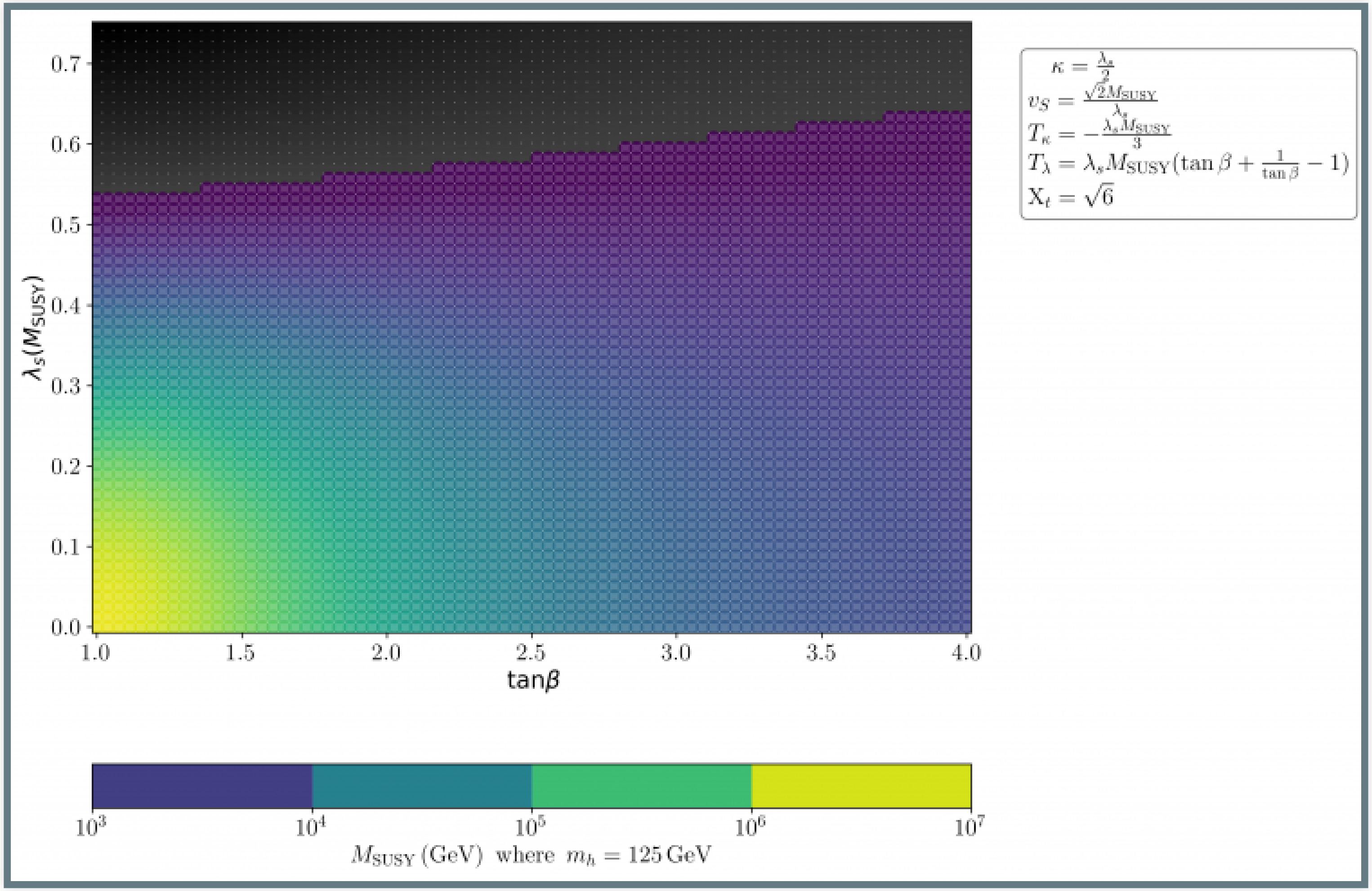
DECOUPLING WITH MINIMAL SINGLET CONTRIBUTION



$$\lambda_{\mathrm{SM}}^{\mathrm{EFT}}(M_{\mathrm{SUSY}}) = \frac{1}{4}\left(\frac{3}{5}g_1^2 + g_2^2\right)\cos^2 2\beta + \frac{\lambda_s}{2}\sin^2 2\beta - \frac{3\left(\sin 2\beta\left(\sqrt{2}\mathbf{T}_\lambda + 2\kappa\lambda_s v_S\right) - 2\lambda_s^2 v_S\right)^2}{8M_{\mathrm{SUSY}}^2} + \delta\lambda^{(1)}$$

- choose T_λ such that the singlet diagram vanishes.

DECOUPLING WITH MINIMAL SINGLET CONTRIBUTION

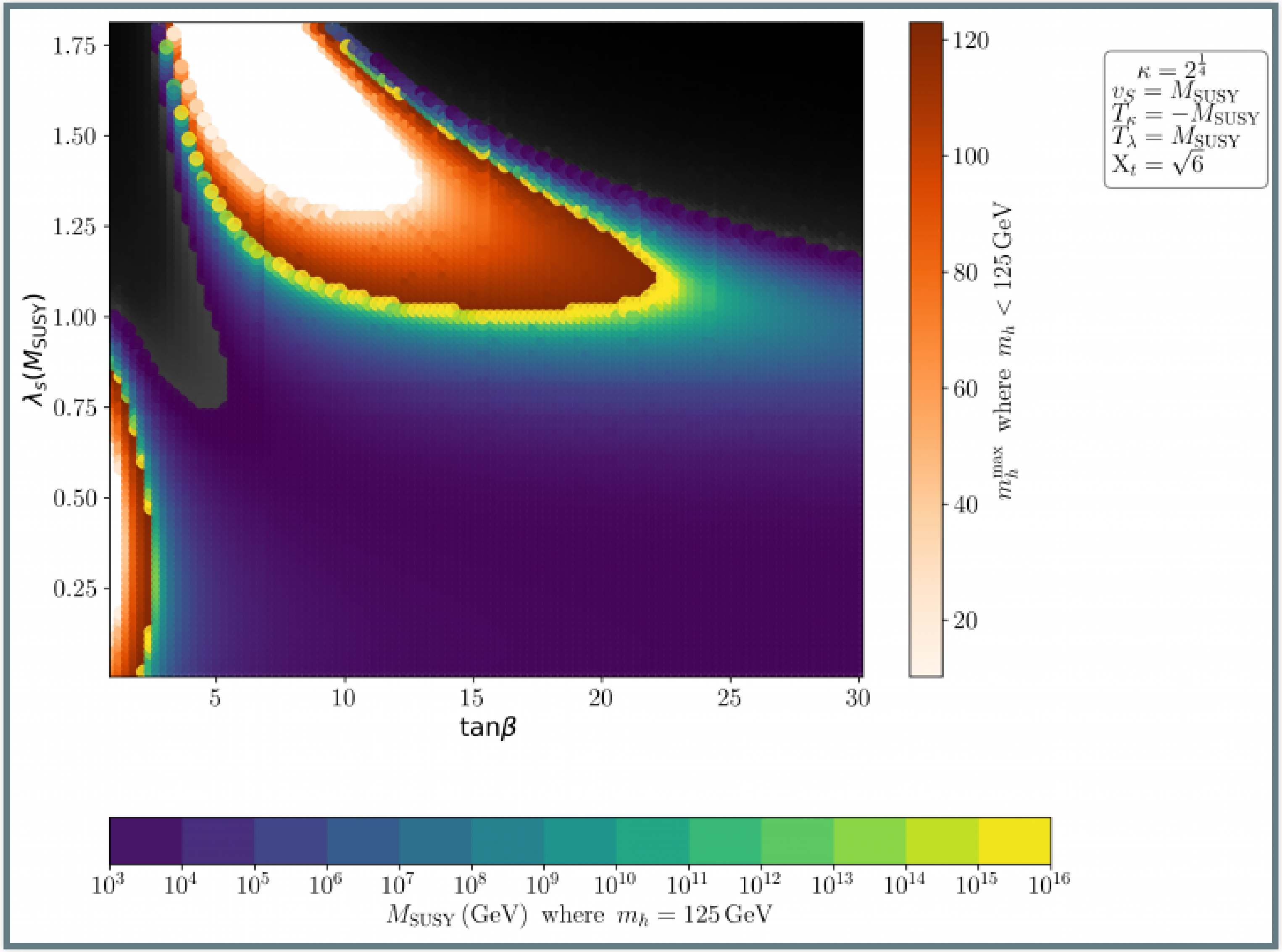


(black points have m_h always above 125 GeV)

NON-DECOUPLING PARAMETRISATION

- parametrise v_S **not** with $v_S \to \frac{\mu}{\lambda_S}$
  - set $v_S = M_{\text{SUSY}}$
  - $\lambda_s \to 0$ does **not** give the MSSM
  - universal trilinear soft couplings $\propto M_{SUSY}$
- heavy Higgs mass: $M_{h_2}^2 \propto \lambda_s M_{\text{SUSY}}^2$
  - $\rightarrow$ EFT only valid for not too small λ_s

NON-DECOUPLING PARAMETRISATION



CONCLUSIONS & OUTLOOK

- Precise Higgs mass predictions for large mass gaps:
  - (N)MSSM $\to$ SM matchings
  - running and matching of **multiple** quartics
  - able to study extended Higgs sectors

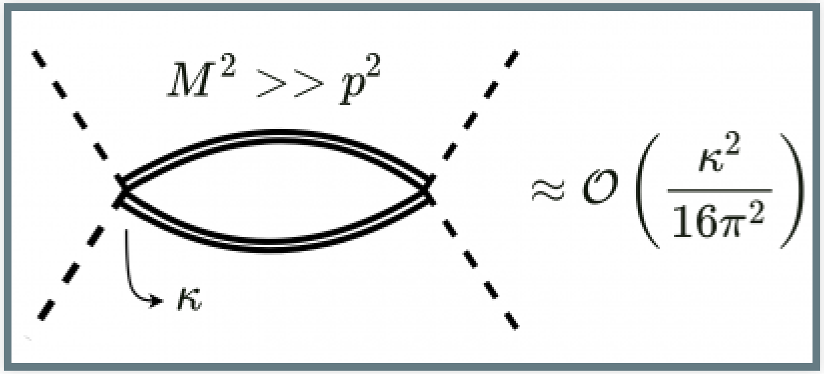
- Take advantage of the new implementation:
  - MSSM $\longrightarrow$ 2HDM
    - already in literature [Wagner et. al],[Nierste et. al]
    - reproduced within minutes of runtime
  - NMSSM $\longrightarrow$ SSM + EWinos
  - …

THANK YOU FOR YOUR ATTENTION

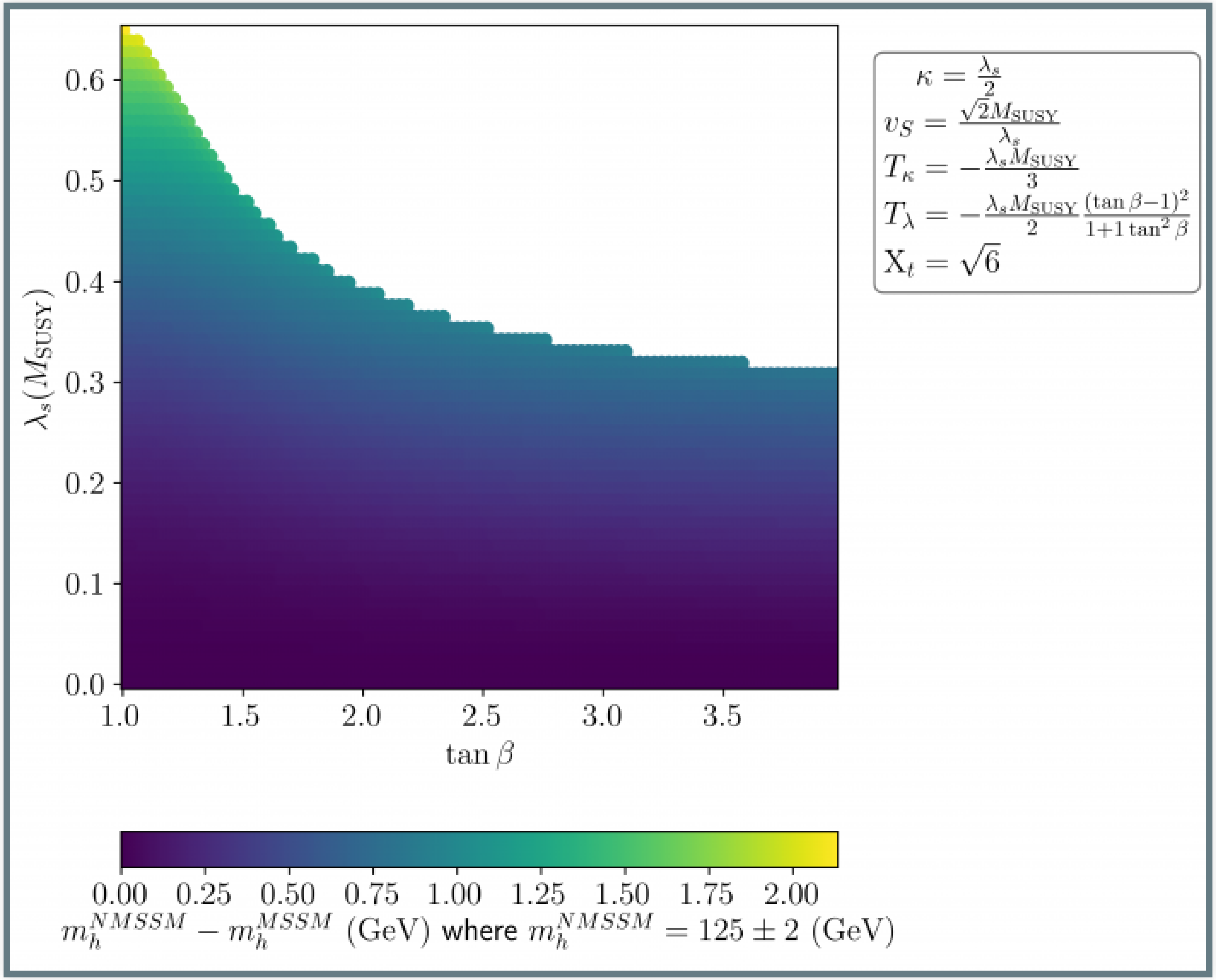
BACKUP

NMSSM NLO ESTIMATE

- already done in literature [Zarate]
  - take singlet tree-level thresholds
  - take MSSM NLO thresholds
    - replace $\mu \to v_S \lambda_S$
  - misses the NLO singlet contributions



SINGLET NLO CONTRIBUTIONS



POLE MASS MATCHING

- match pole masses of SM an BSM theories

$$ {m_H^{BSM}}^2(M_{BSM}) = {m_H^{SM}}^2(M_{BSM}) $$

- use relation for the SM pole mass

$$ {m_H^{SM}}^2(M_{BSM}) = v^2(M_{BSM})\lambda_{SM}(M_{BSM}) $$

- extract effective quartic coupling at the matching scale

$$ \lambda_{SM} = \frac{1}{v^2}({m_H^{BSM}}^2 - \Pi_{SM}) $$

POLE MASS MATCHING

In case of more then one light Higgs
(e.g. effective 2HDM):

- non-trivial releations between multiple quartics, VEVs and mass parameters
- system often overconstrained (more quartics than mass parameters)

MSSM HIGGS MASS PREDICTIONS

[Porod, Staub, '17]