NLO MATCHING CONDITIONS IN EXTENDED HIGGS SECTORS

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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

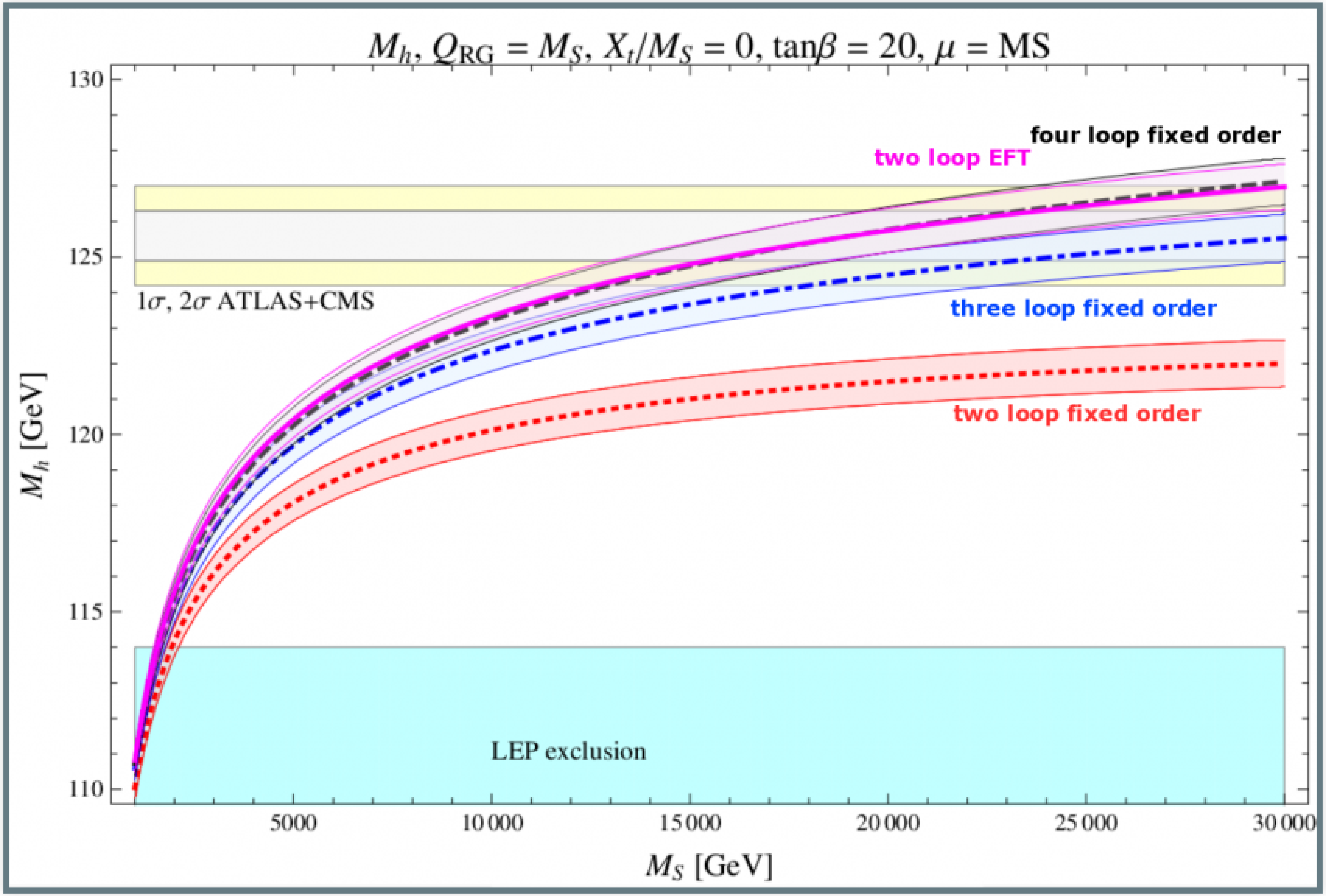
BSM HIGGS MASS PREDICTIONS

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

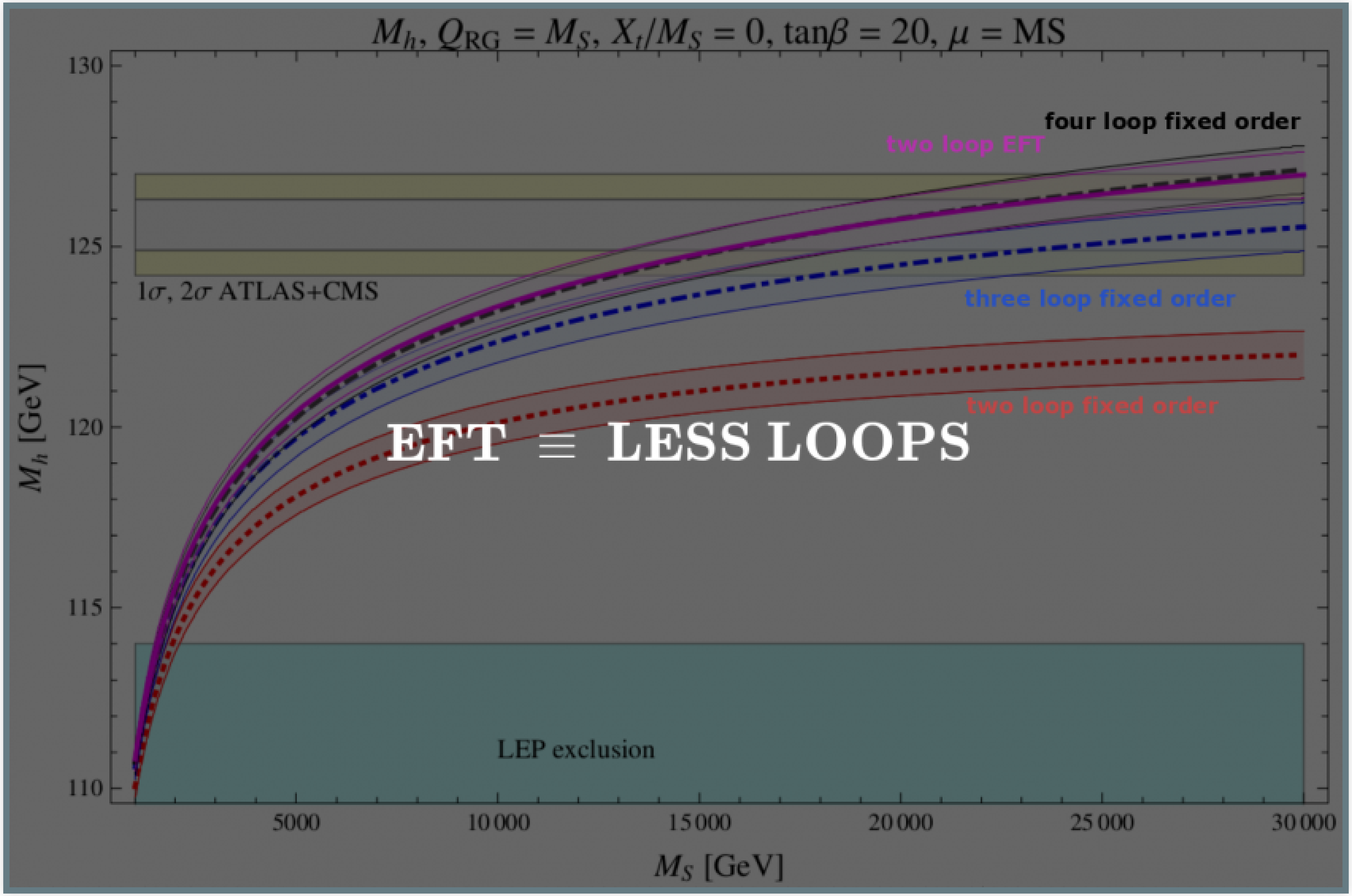
MSSM: EFT VS. FIXED ORDER

[Draper, Wagner, Lee]



MSSM: EFT VS. FIXED ORDER

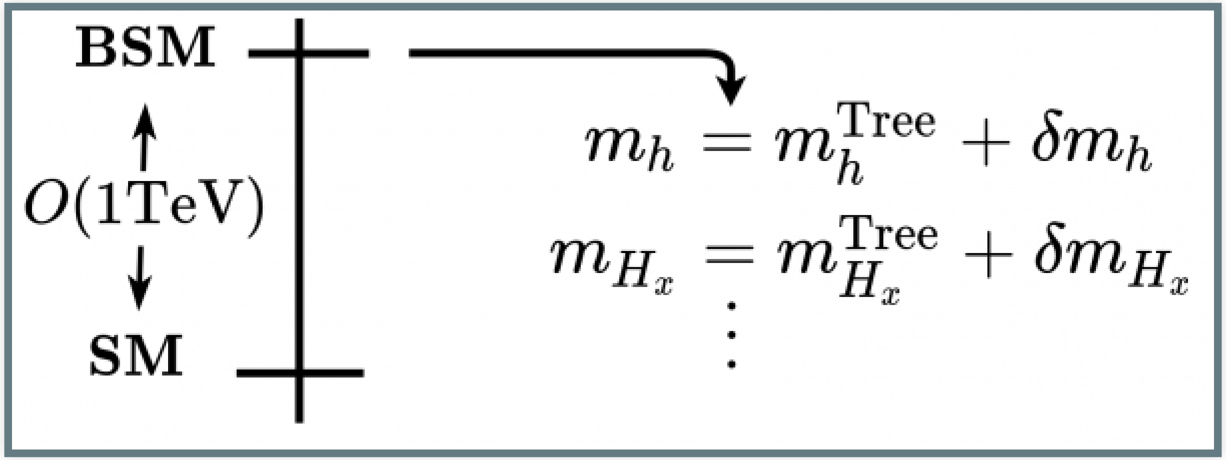
[Draper, Wagner, Lee]



IMPLEMENTATION IN SARAH

STATE OF THE ART I

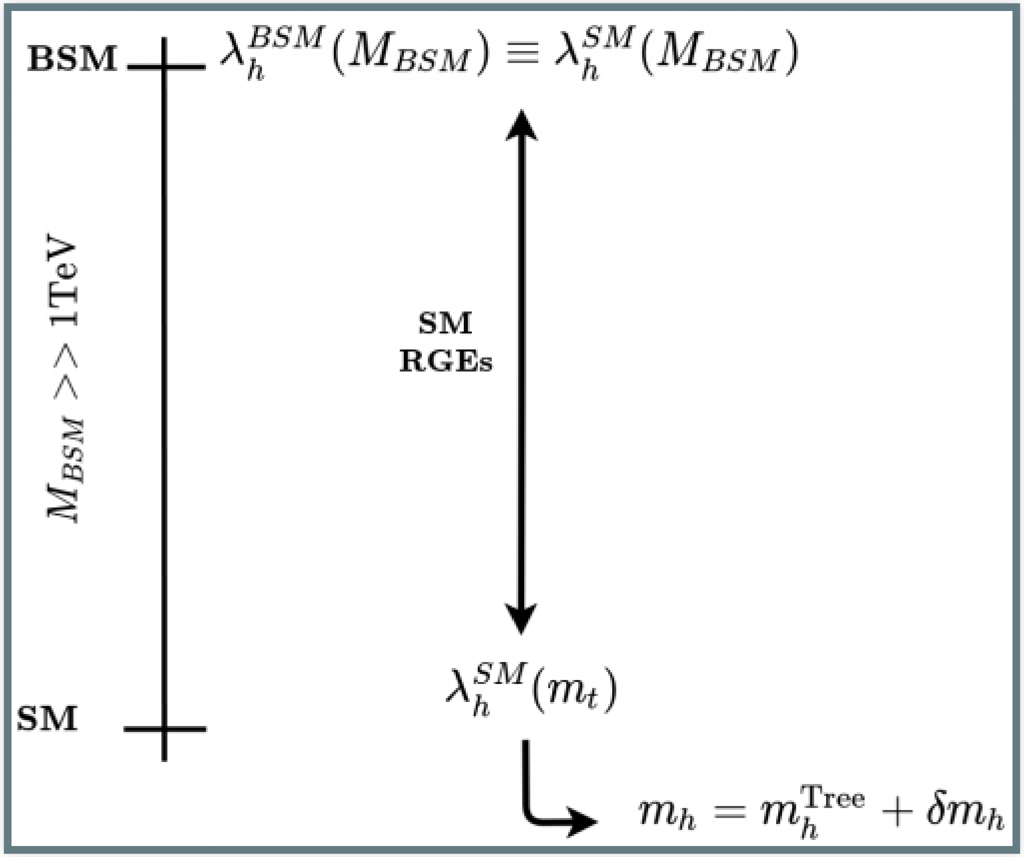
Fixed order calculation



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

STATE OF THE ART II

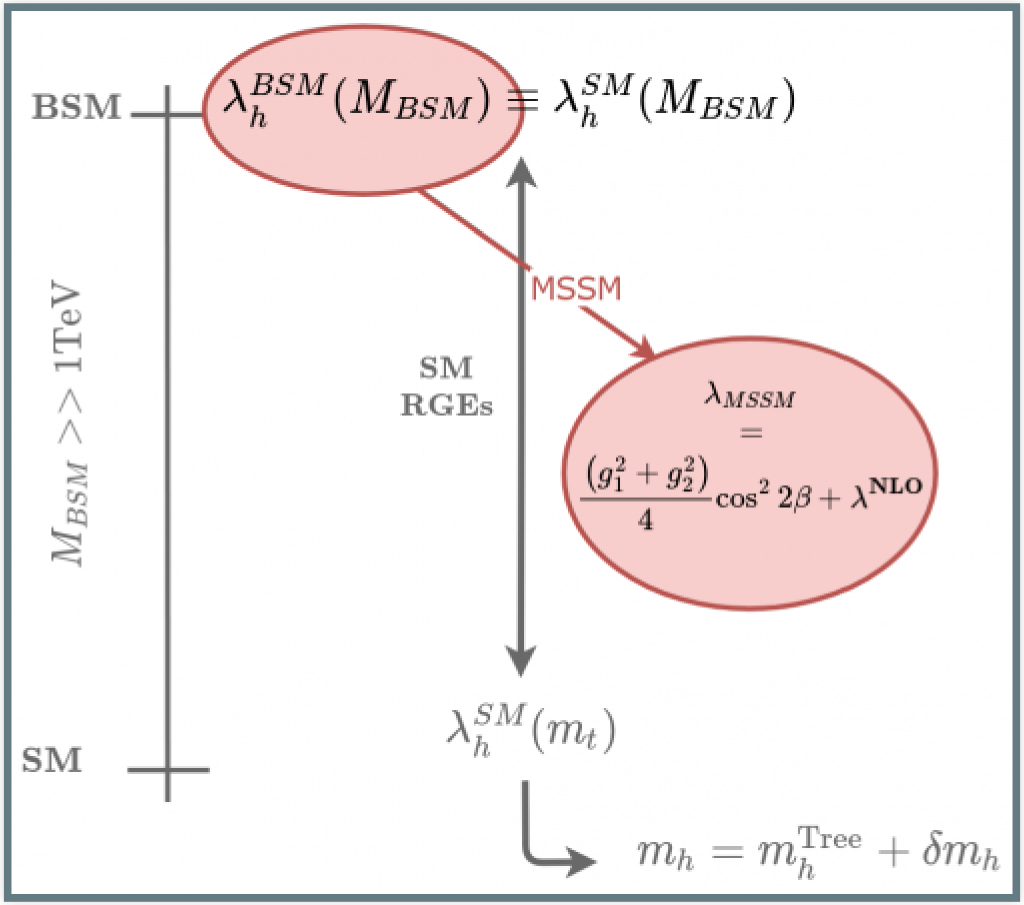
EFT Higgs mass calculation



- only if one light scalar is present

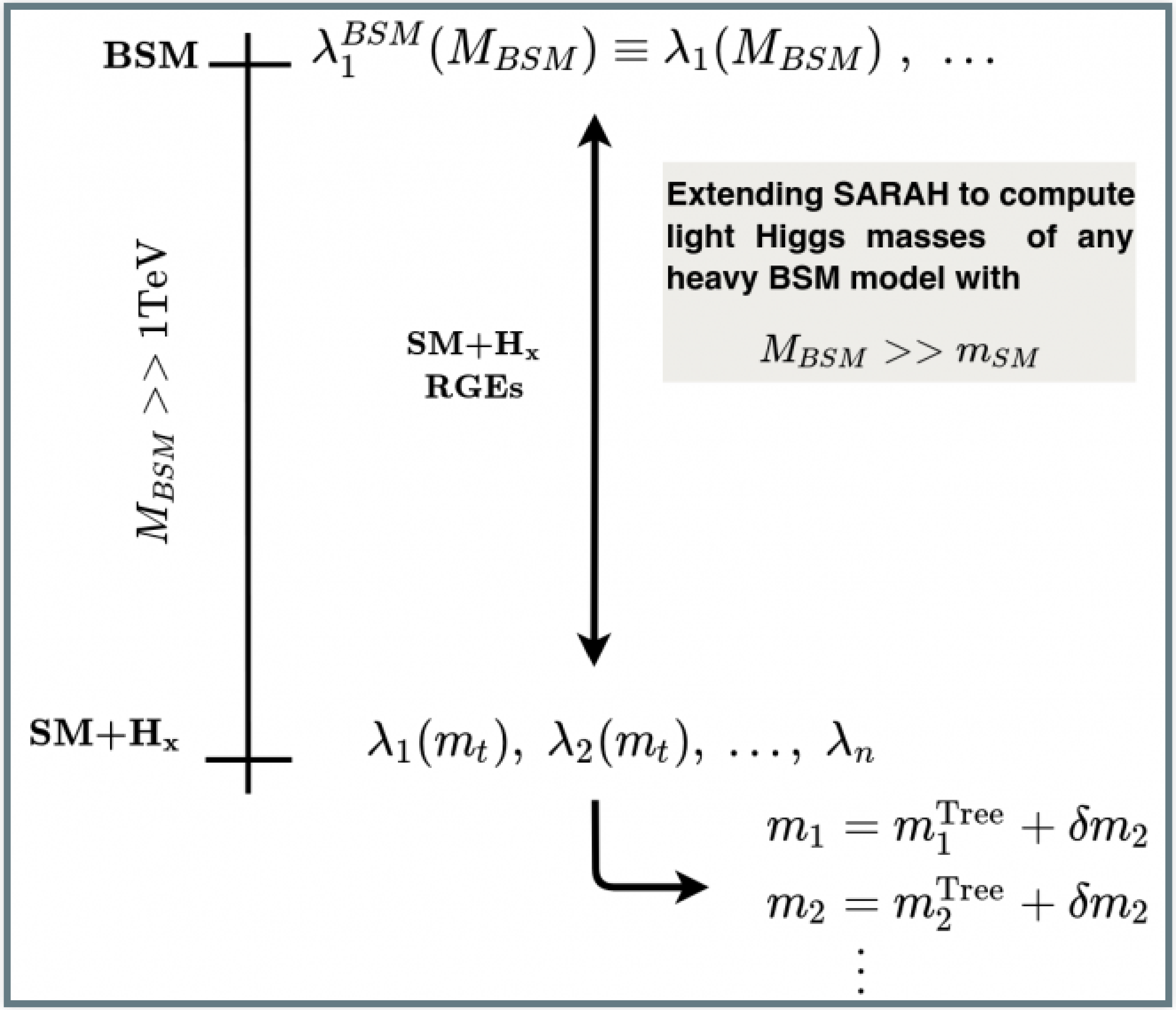
STATE OF THE ART II

EFT Higgs mass calculation



- only if one light scalar is present

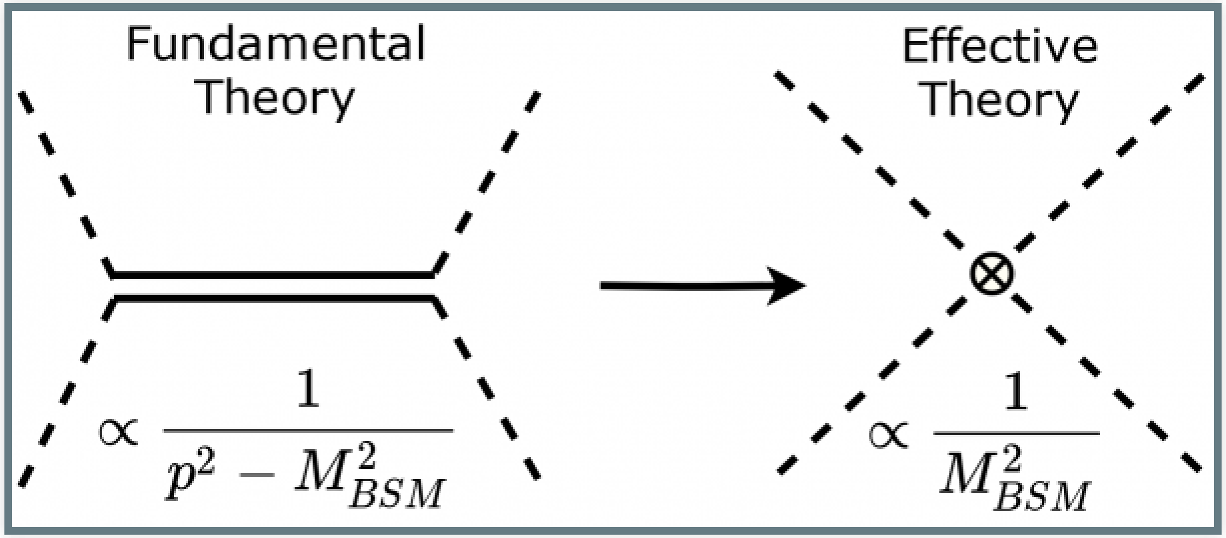
NEW IMPLEMENTATION



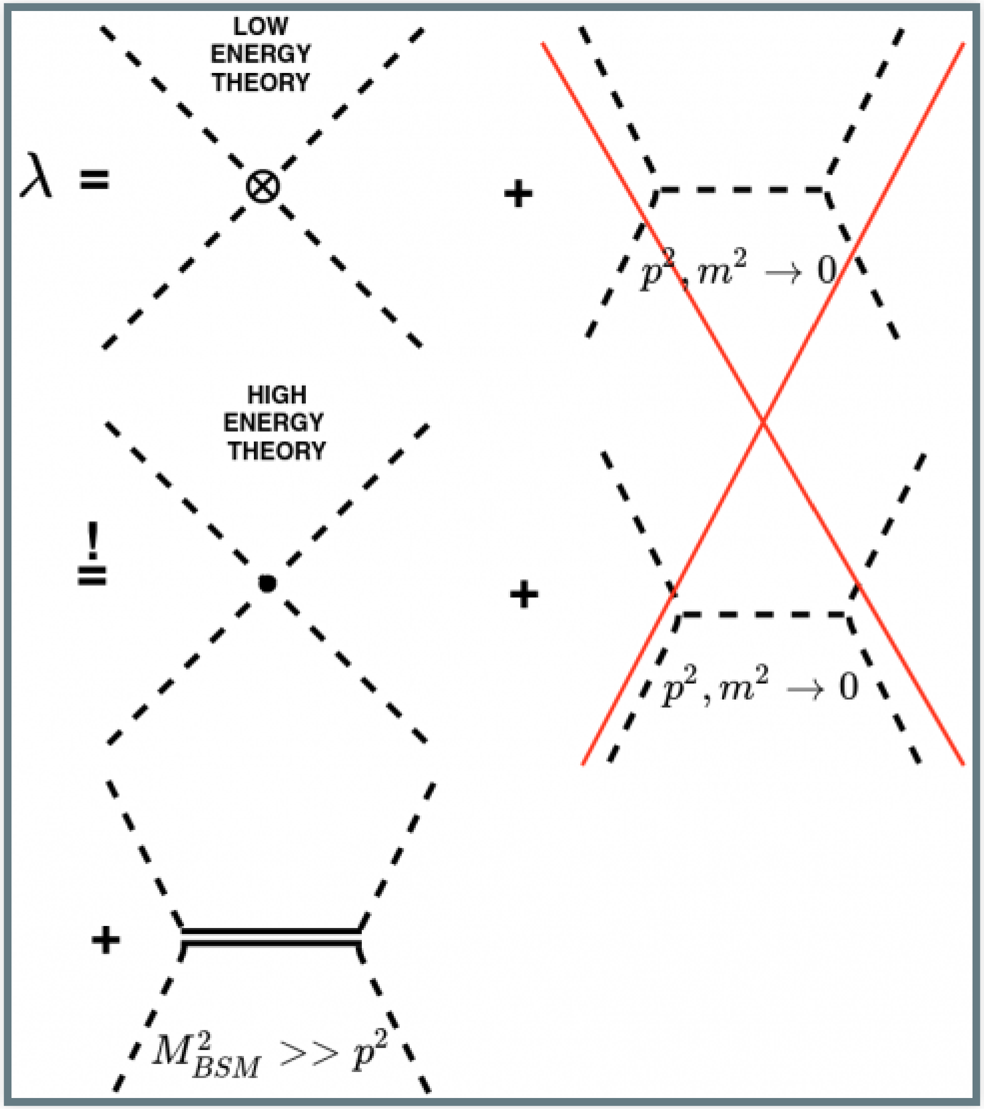
MATCHING CONDITIONS

EFT IN A NUTSHELL

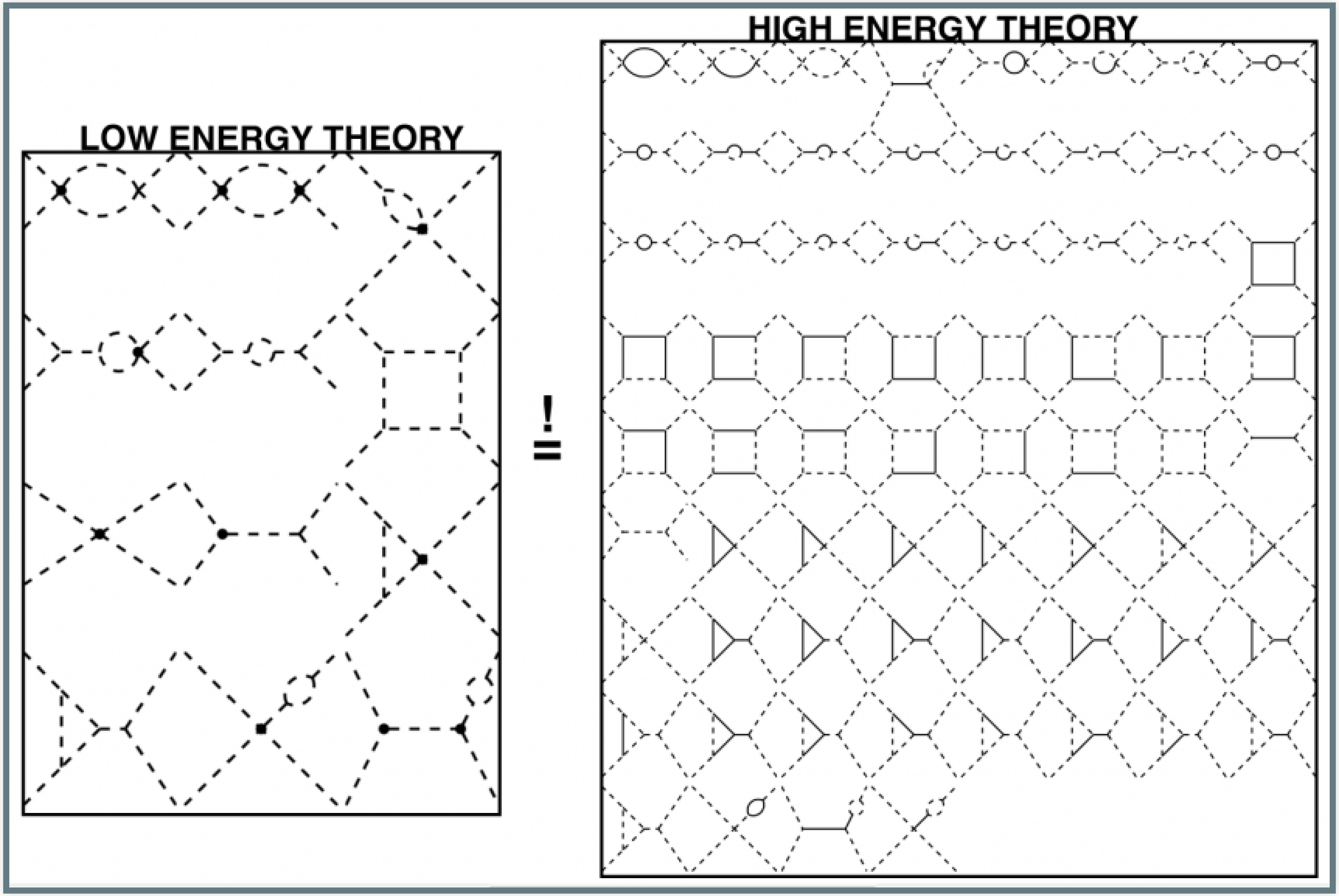
- **Top-Down:** integrating out heavy degrees of freedom
- Feynman diagrammatic approach
- Expand amplitudes in $\frac{p^2}{M_{BSM}^2}$



TREE-LEVEL MATCHING



ONE-LOOP MATCHING



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

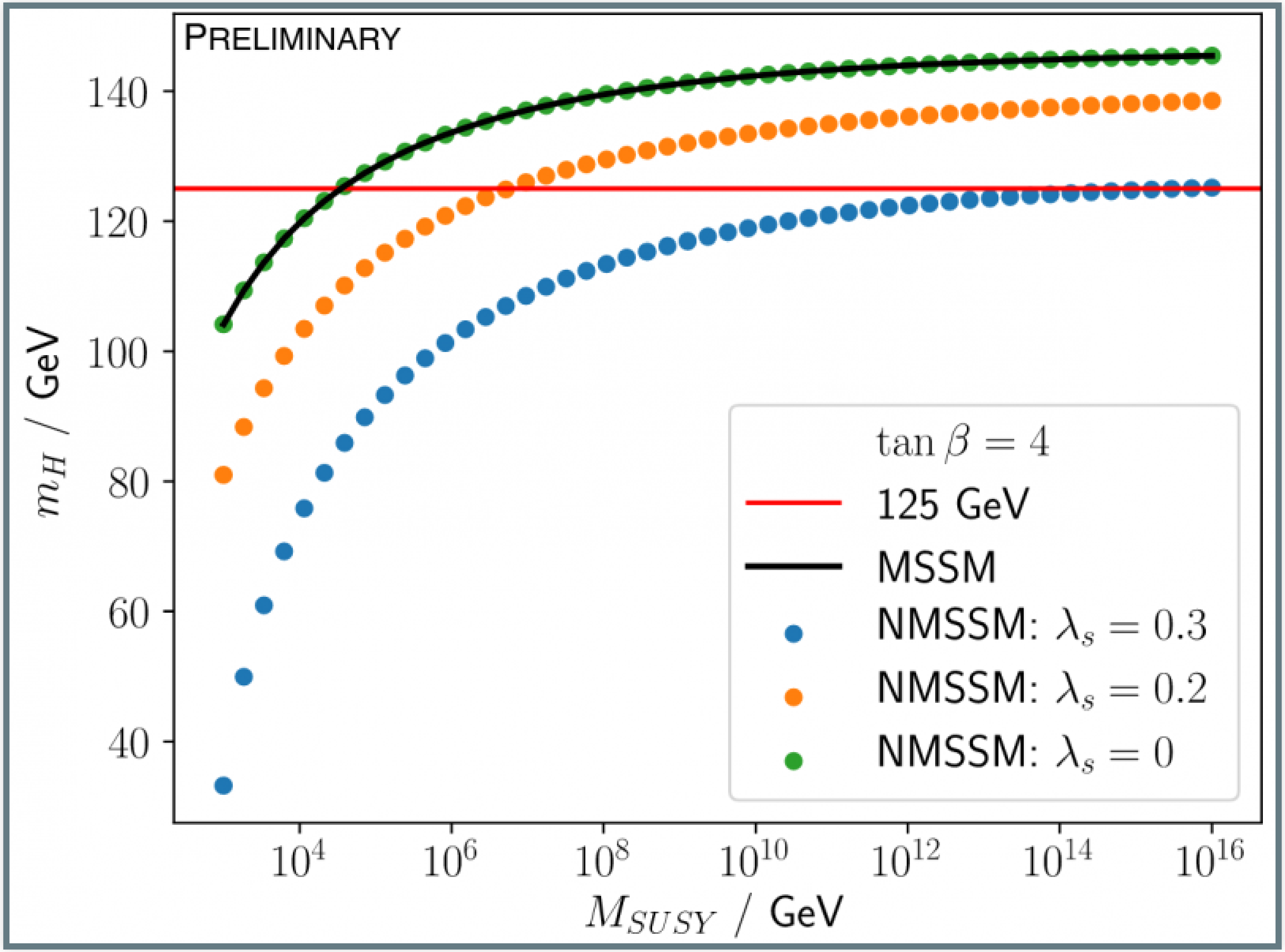
APPLICATION: NMSSM

$$W_{NMSSM} \propto \lambda_s S H_u H_d \xrightarrow{SSB} v_s \lambda_s H_u H_d$$

- 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@ $\tan\beta = 4$



CONCLUSIONS & OUTLOOK

- Precise Higgs mass predictions for large mass gaps:
  - running and matching of **multiple** quartics
  - able to study extended Higgs sectors

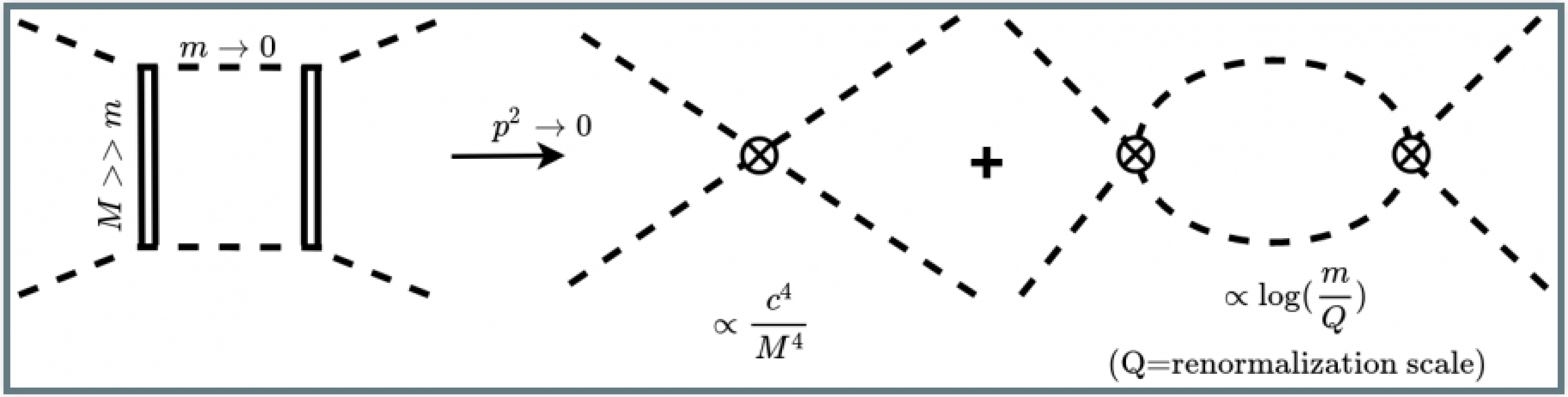
- Take advantage of the new implementation:
  - MSSM $\longrightarrow$ 2HDM
    - already in literature [Wagner et. al],[Nierste et. al]
    - reproduced within minutes of runtime
  - NMSSM $\longrightarrow$ SSM
  - NMSSM $\longrightarrow$ N2HDM
  - ...

THANK YOU FOR YOUR ATTENTION

BACKUP

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



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

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

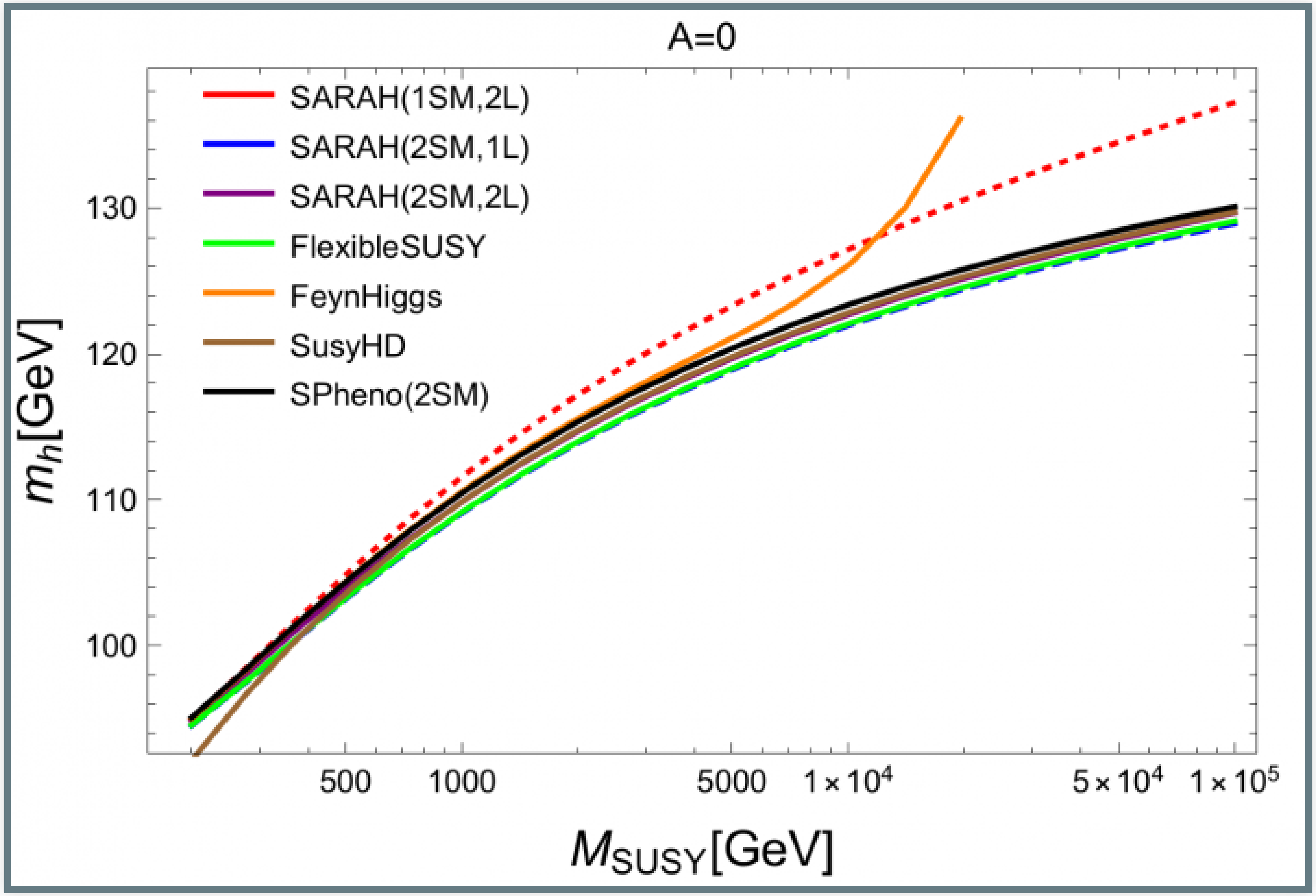
POLE MASS MATCHING

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]



LOOPS OR OPERATORS?

Depending on the nature of the UV completion we have important

- contributions from “NLO” higher dimensional operators in the power counting
- NLO corrections to effective operators
- new effective couplings appearing at higher orders

Which contributions are of leading order?

LOOPS OR OPERATORS?

Answer in the: **matching** condition

$$\lambda_{SM}(\Lambda) \equiv \lambda_{BSM}(\Lambda)$$

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Assume that both, the SM(+EFT) and the UV completion give the
same prediction for an given process at the matching scale.
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$$\frac{c_6}{\Lambda^2}\Phi^6_{SM} \xrightarrow[bottom-up]{SSB} \frac{c' v^2}{\Lambda^2} h^4_{SM} \xleftarrow[top-down]{v<\Lambda} \Delta\lambda_{\mathbf{BSM}}$$

LOOPS OR OPERATORS?

Decoupling

- For $v << \Lambda$ dimension six operators become less important.
- no sizeable mixing through SM VEV $\propto O\left(\frac{v^2}{\Lambda^2}\right)$

$$\lambda_{\mathbf{BSM,NLO}} \propto \frac{1}{16\pi^2}\log(\frac{\Lambda}{Q})$$

$\rightarrow$ Loop contributions to dimension 4 operators are of leading order