EFT Calculations and FeynHiggs

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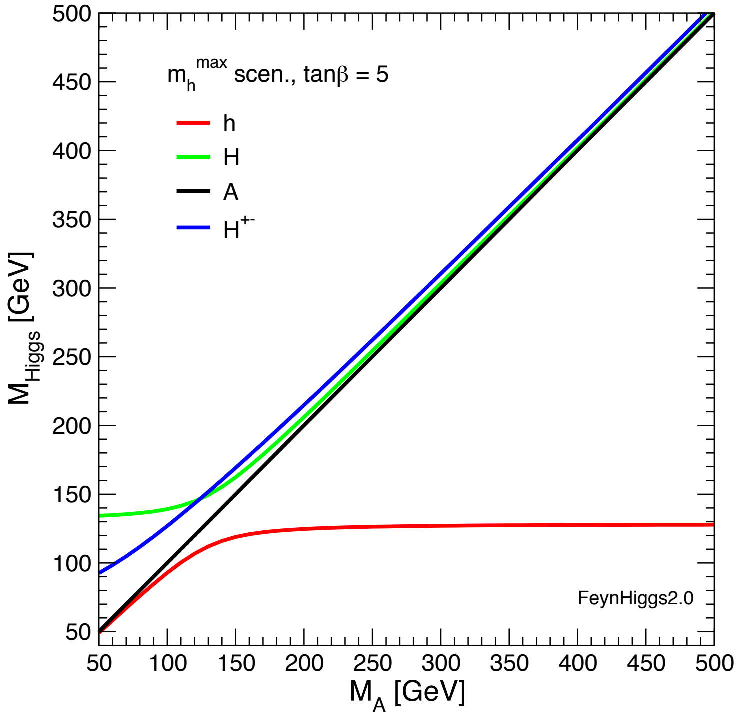
Outline

- Introduction
- Present status of FeynHiggs
- Further improvements
  - electroweak contributions
  - chargino/neutralino threshold
  - gluino threshold
- Scheme conversion and $\tan\beta$
- Conclusions

based on

Henning Bahl: Master Thesis, MPI/TUM July 2015

Higgs bosons in the MSSM: $h^0,\ H^0,\ A^0,\ H^\pm$



- *light Higgs boson* h^0

  $m_h \leq m_Z|\cos(2\beta)| + \Delta m_{h^0}$

- *for heavy* $A^0,\ H^0,\ H^\pm$*:*

  h^0 *like Standard Model Higgs boson*

- Feynman-diagrammatic approach

  full mass spectrum from dressed propagators

- EFT approach (RGEs for SM Higgs below SUSY mass scale)

  mass of light h^0

- EFT calculations

  P. Draper, G. Lee, C. Wagner, arxiv:1312.5743

  E. Bagnaschi, G. Giudice, P. Slavich, A. Strumia, arxiv:1407.4081

  G. Lee, C. Wagner, arxiv:1508.00576

- Feynman-diagrammatic calculations (fixed order)

  basis of FeynHiggs

  involves large logarithms $\log \frac{M_S^2}{m_t^2}$

- Combining diagrammatic and EFT calculations in FeynHiggs

  T. Hahn, S. Heinemeyer, WH, H. Rzehak, G. Weiglein, arxiv:1312.4937

  resummation of large logarithms from α_t and α_s
  on top of fixed-order 1- and 2-loop terms

LL and NLL resummation for large logarithms

one-loop: $\Delta M_h^2 \sim m_t^2 \, \alpha_t \left[L + L^0 \right], \quad L = \log \frac{M_S^2}{m_t^2}$

two-loop: $\Delta M_h^2 \sim m_t^2 \left\{ \alpha_t \alpha_s \left[L^2 + L + L^0 \right] + \alpha_t^2 \left[L^2 + L + L^0 \right] \right\}$

L^0 *from explicit Feynman-diagrammatic calculation*

three-loop: $\Delta M_h^2 \sim m_t^2 \left\{ \alpha_t \alpha_s^2 \left[L^3 + L^2 \right] + \alpha_t^2 \alpha_s \left[L^3 + L^2 \right] + \alpha_t^3 \left[L^3 + L^2 \right] \right\}$

etc ....

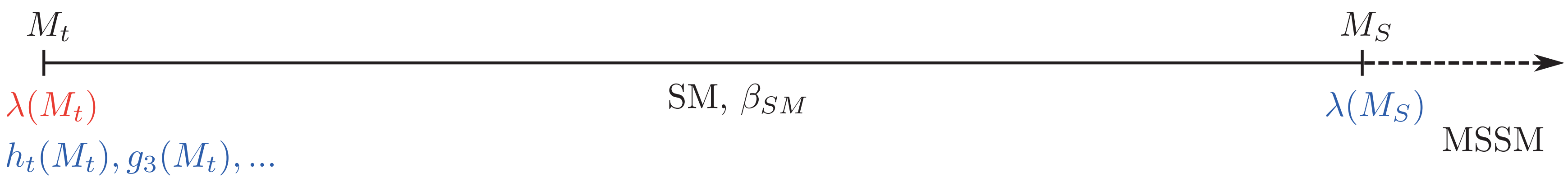
$\Rightarrow$ **combination with Feynman-diagrammatic result in** FEYNHIGGS

EFT calculations – basic strategy

$$\boxed{M_h^2 = 2\,\lambda(m_t)\,v^2}$$

M_S mass scale of SUSY-particles, above $\to$ MSSM, below $\to$ SM

- λ fixed in MSSM: $\lambda(M_S) = \frac{1}{4}(g^2 + g'^2)c^2_{2\beta}$ at tree-level



$\Rightarrow$ use SM-RGEs to run λ down:

$$\lambda(M_S) \stackrel{\beta_{\rm SM}}{\to} \lambda(m_t)$$

Notation: $t = \ln Q^2$, $k = 1/(16\pi^2)$, $h_t = m_t/v$

$$\frac{d\lambda}{dt} = 6k\left(\lambda^2 + \lambda h_t^2 - h_t^4\right)$$

Solve iteratively:

$$\lambda(m_t) \approx \lambda(M_S) + \int_{M_S}^{m_t} \frac{d\lambda}{dt} dt \approx$$

$$\approx \lambda(M_S) - 6k\left(\lambda^2(M_s) + \lambda(M_s)h_t^2(m_t) - h_t^4(m_t)\right) \ln\left(\frac{M_S^2}{m_t^2}\right) \approx$$

$$\approx \lambda_{tree} + 6kh_t^4(m_t) \ln\left(\frac{M_S^2}{m_t^2}\right)$$

Solve **numerically**:

$\Rightarrow$ **Resummation of large logarithms to all orders**

(sub)leading logarithms

Use 1-loop RGEs $\rightarrow$ Resummation of leading logarithms ($k^n L^n$)
Use 2-loop RGEs $\rightarrow$ Also subleading logarithms ($k^n L^{n-1}$)

Additional complication:

Threshold corrections

$\lambda(M_S) = \frac{1}{4}(g^2 + g'^2)c_{2\beta}^2 + \Delta\lambda_{thres}$

- originate from integrating out heavy sparticles
- n-loop threshold corrections result in sub^n-leading logarithms
- $\Delta\lambda_{thres} = 6kh_t^4\left(\hat{X}_t^2 - \frac{1}{12}\hat{X}_t^4\right)$
  $(X_t = A_t - \mu/t_\beta, \hat{X}_t = X_t/M_s)$

combination with fixed-order calculation

Double counting has to be avoided:

$\Rightarrow$ Subtract logarithms from the diagrammatic result

RGEs derived in $\overline{\text{MS}}$, diagrammatic calculation in OS:

$\Rightarrow$ Conversion $\overline{\text{MS}} \leftrightarrow$ OS is mandatory: $A^{\text{OS}} = A^{\overline{\text{MS}}} + \delta A^{\text{OS}}_{\text{fin.}}$

$$\Downarrow$$

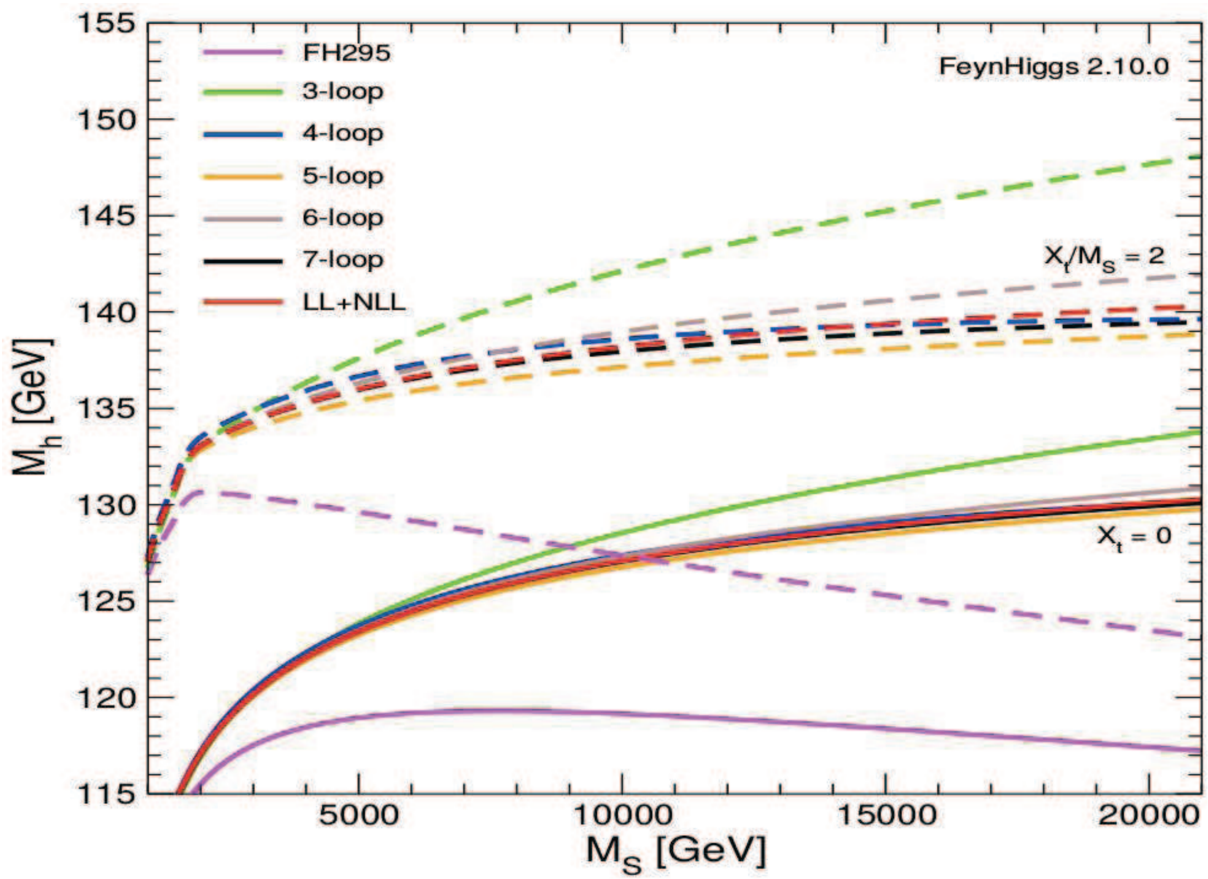
$$M_h^2 = (M_h)^{\text{FD}} + \Delta M_h^2$$

$$\Delta M_h^2 = (\Delta M_h^2)^{\text{RGE}}(X_t^{\overline{\text{MS}}}) - (\Delta M_h^2)^{\text{FD,Logs}}(X_t^{OS})$$

FeynHiggs 2.10

Resummation of leading/subleading logarithms $\propto \alpha_t, \alpha_s$

- weak gauge couplings are neglected ($g = g' = 0$)



Hahn et al.: arXiv:1312.4937

Extension I

Use of full 2-loop SM-RGEs, including g, g'

- avoid double-counting of electroweak logarithms at 1-loop
- new threshold corrections (e.g. Draper et al.: arXiv:1312.5743)

$$\lambda(M_S) = \lambda_{tree} + \Delta\lambda_{\text{stop}} + \Delta\lambda_{\text{heavy Higgs}} + \Delta\lambda_{\text{chargino/neutralino}}$$

- additional terms in $\overline{\text{MS}} \leftrightarrow$ OS conversion

$$X_t^{\overline{\text{MS}}} = X_t^{\text{OS}} \left[1 + \left(\underbrace{\frac{\alpha_s}{\pi}}_{g,\tilde{g}} \underbrace{- \frac{3\alpha_t}{16\pi}\left(1 - \hat{X}_t^2\right)}_{\text{Higgs}} \underbrace{- \frac{\alpha}{96\pi}(1 - 26c_w^2)}_{\text{Z,W}^{\pm}} \right) \ln\left(\frac{M_S^2}{m_t^2}\right) \right]$$

$$\lambda(M_S) =$$

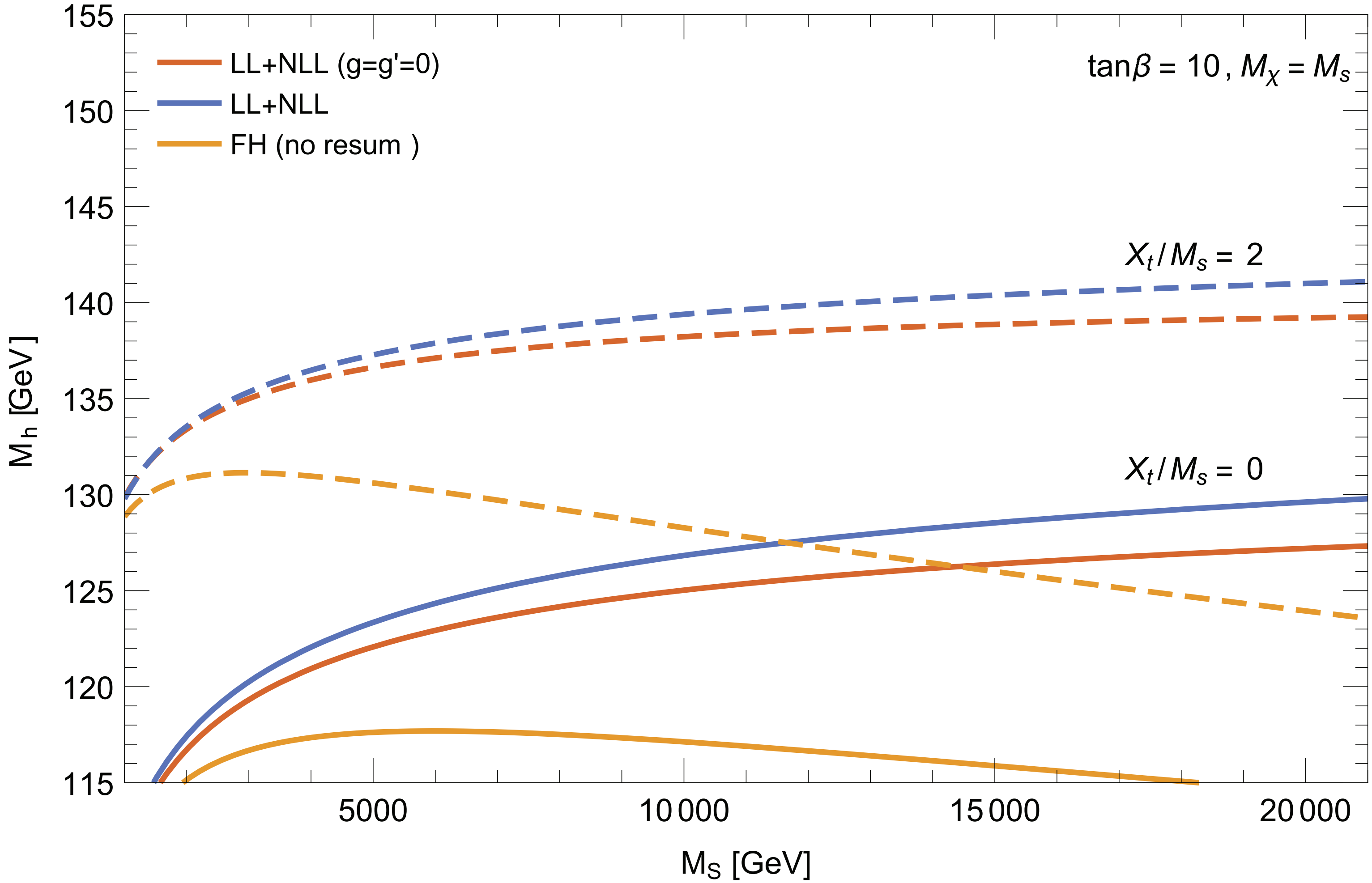
$$= \underbrace{\frac{1}{4}\cos^2(2\beta)\left(g^2 + g'^2\right)}_{\text{tree level}}$$

$$\underbrace{-k\left[\left(\frac{3}{4} - \frac{1}{6}c_{2\beta}^2\right)g^4 + \frac{1}{2}g^2 g'^2 + \frac{1}{4}g'^4\right]}_{\text{tree-level term }\overline{\text{DR}} \to \overline{\text{MS}}}$$

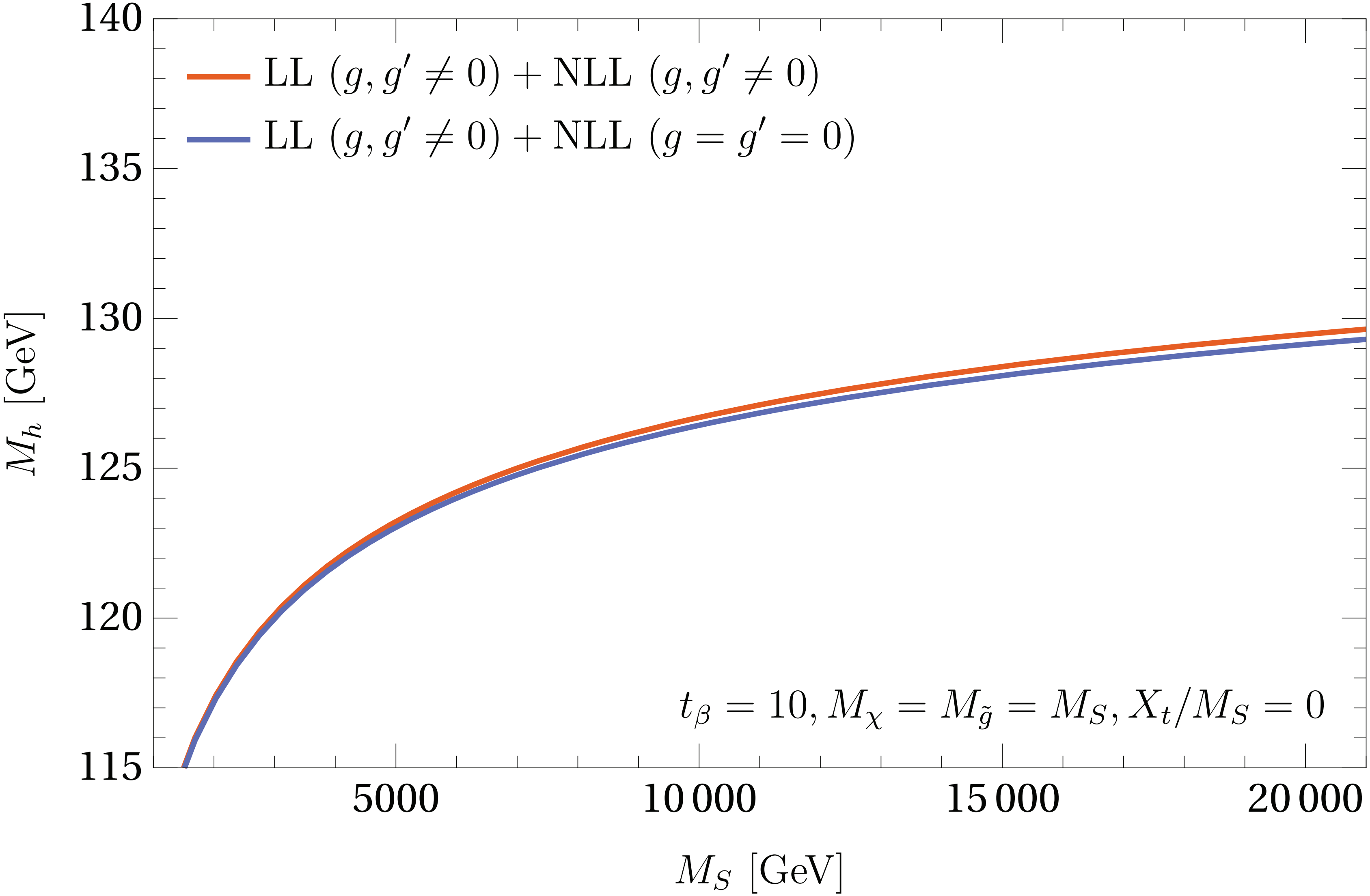
$$\underbrace{+6h_t^2 k\left\{\left[h_t^2 + \frac{1}{8}\left(g^2 + g'^2\right)c_{2\beta}\right]\left(\frac{X_t^2}{M_S^2}\right) - \frac{1}{12}h_t^2\left(\frac{X_t^4}{M_S^4}\right)\right\} - \frac{1}{4}kh_t^2\left(g^2 + g'^2\right)c_{2\beta}^2\left(\frac{X_t^2}{M_S^2}\right)}_{\text{stop-threshold corr.}}$$

$$\underbrace{-\frac{3}{16}k(g'^2 + g^2)^2 s_{4\beta}^2}_{\text{heavy Higgs threshold corr.}}$$

$$\underbrace{+\frac{1}{24}k(c_\beta + s_\beta)^2\left\{-51g^4 - 24g^2g'^2 - 13g'^4 + (3g^2 + g'^2)\left[(g^2 + g'^2)c_{4\beta} + 2(g^2 - g'^2)s_{2\beta}\right]\right\}}_{\text{chargino/neutralino threshold corr.}}.$$



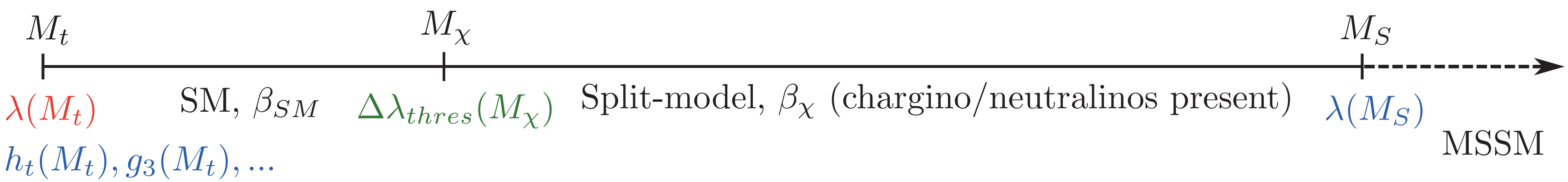
LL+NLL (g=g'=0)
LL+NLL
FH (no resum)
tanβ = 10 , $M_\chi = M_s$
$X_t / M_s = 2$
$X_t / M_s = 0$
155
150
145
140
135
130
125
120
115
M_h [GeV]
5000
10 000
15 000
20 000
M_S [GeV]



LL $(g, g' \neq 0)$ + NLL $(g, g' \neq 0)$
LL $(g, g' \neq 0)$ + NLL $(g = g' = 0)$
$t_\beta = 10, M_\chi = M_{\tilde{g}} = M_S, X_t/M_S = 0$
M_h [GeV]
M_S [GeV]
140
135
130
125
120
115
5000
10 000
15 000
20 000

Extension II

Additional threshold $M_\chi \equiv M_1 = M_2 = \mu$ ($m_t \ll M_\chi < M_S$), above which charginos/neutralinos contribute to RGE running



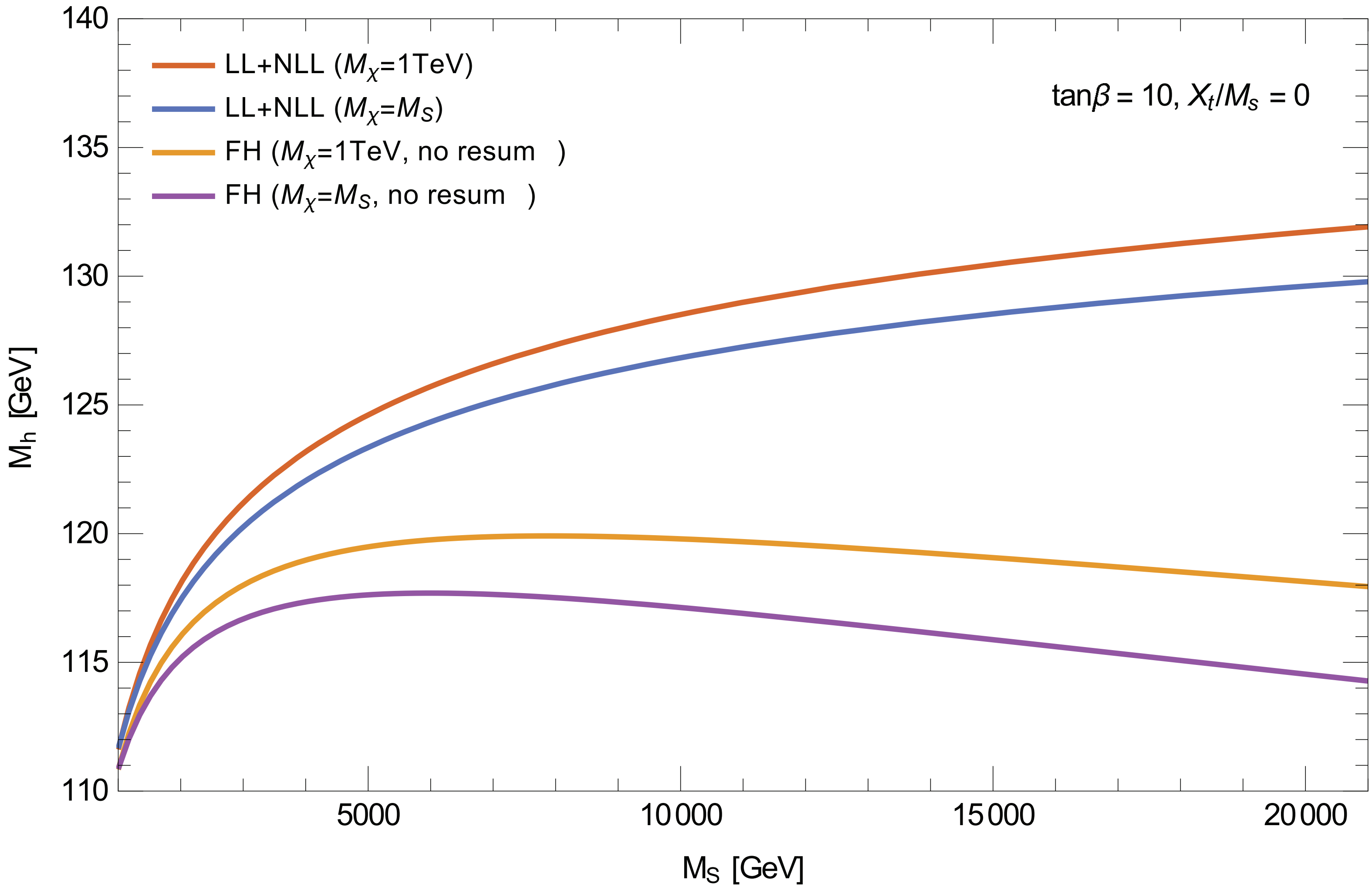
- gaugino-gaugino-Higgs couplings $\tilde{g}_{1u,1d,2u,2d}$ fixed at $Q = M_S$

  (e.g. Giudice et al. arXiv:1108.6077)

- threshold corrections at $Q = M_\chi$

  $\lambda_{\mathrm{SM}}(M_\chi) = \lambda_\chi(M_\chi) + \Delta\lambda_{\mathrm{chargino/neutralino}}$

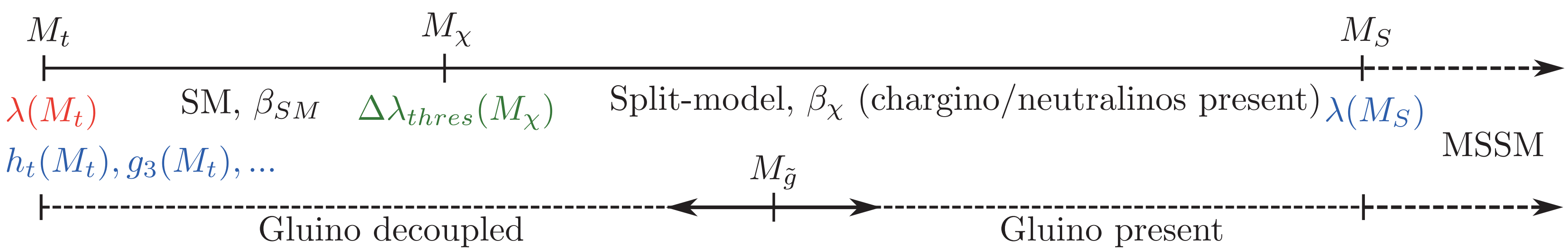
  $h_{t,\mathrm{SM}}(M_\chi) = h_{t,\chi}(M_\chi) + \Delta h_{t,\mathrm{chargino/neutralino}}$



LL+NLL (M_χ=1TeV)
LL+NLL (M_χ=M_S)
FH (M_χ=1TeV, no resum)
FH (M_χ=M_S, no resum)
tanβ = 10, X_t/M_s = 0
140
135
130
125
120
115
110
M_h [GeV]
5000
10 000
15 000
20 000
M_S [GeV]

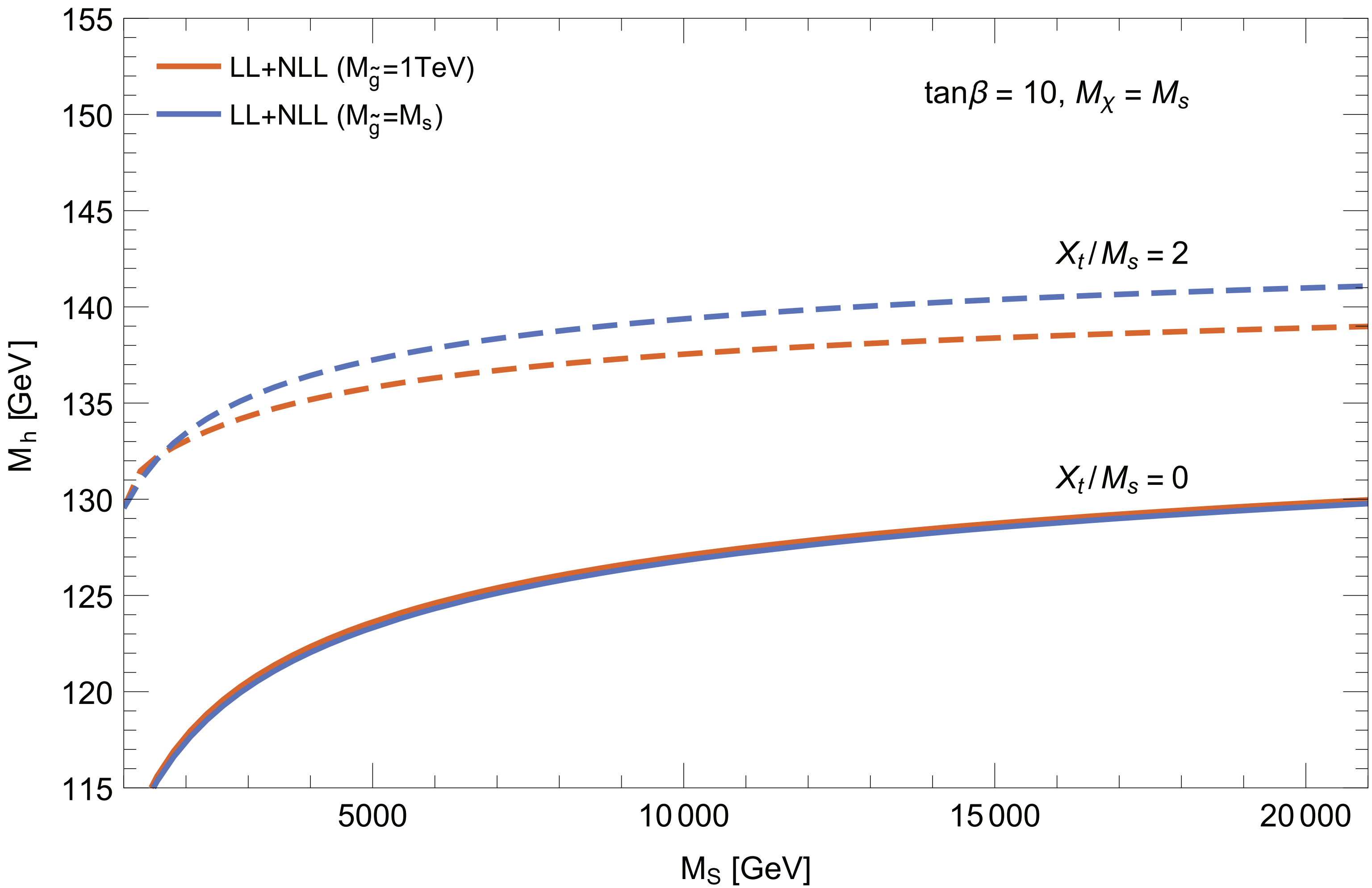
Extension III

Additional threshold $M_{\tilde{g}}$ ($m_t \ll M_{\tilde{g}} < M_S$), above which gluinos contribute to RGE running



- no additional threshold corrections at one-loop (gluino enters at two-loop level)
- only modifications of RGEs above $Q = M_{\tilde{g}}$ necessary, e.g.

$$\frac{dg_3}{dt} = \begin{cases} -\frac{7}{2} k g_3^3 & \text{for } Q < M_{\tilde{g}} \\ -\frac{5}{2} k g_3^3 & \text{for } Q > M_{\tilde{g}} \end{cases}$$



LL+NLL ($M_{\tilde{g}}$=1TeV)
LL+NLL ($M_{\tilde{g}}$=M_s)
tanβ = 10, M_χ = M_s
$X_t/M_s = 2$
$X_t/M_s = 0$
M_h [GeV]
M_S [GeV]
155
150
145
140
135
130
125
120
115
5000
10 000
15 000
20 000

Scheme conversion

$\overline{\text{MS}} \leftrightarrow$ OS conversion: $X_t, M_S, M_\chi, M_{\tilde{g}}, m_t, M_W, M_Z$

- only logarithmic terms relevant
- definition of counterterms:
  - $M_s \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \to \delta M_S^2 = \frac{1}{2}\left(\frac{m_{\tilde{t}_2}}{m_{\tilde{t}_1}}\delta M_{\tilde{t}_1}^2 + \frac{m_{\tilde{t}_1}}{m_{\tilde{t}_2}}\delta M_{\tilde{t}_2}^2\right)$
  - $M_\chi \equiv M_{\tilde{\chi}_2^0} \to$ use mass counterterm of $\tilde{\chi}_2^0$
  - $M_{\tilde{g}} \to$ use mass counterterm of $\tilde{g}$
- $m_t \to$ use running mass in Feynman diagrammatic result
- M_W, M_Z $(g, g') \to$ no logarithms (effective theory is SM)

How to handle t_β?

- $\underbrace{\overline{\text{DR}}}_{\text{FeynHiggs}} \leftrightarrow \underbrace{\overline{\text{MS}}}_{\text{RGEs}}$ conversion
- running of t_β:
  - FeynHiggs takes $t_\beta(\mu = m_t)$ as input, $t_\beta(M_s)$ needed
  - definition of t_β in effective model below M_s?
- so far ($\tilde{h}_t = h_t / s_\beta$):

$$\frac{1}{\tan^2\beta}\frac{d\tan^2\beta}{dt} = -3k\tilde{h}_t^2 + k^2\left[9\tilde{h}_t^4 - \left(\frac{4}{3}g'^2 + 16g_3^2\right)\tilde{h}_t^2\right]$$

$\rightarrow$ *Haber, Hempfling, hep-ph/9307201*

2-loop: Sperling, Stöckinger, Voigt, arxiv:1305.1548, 1310.7629

How to handle t_β?

- $\underbrace{\overline{\text{DR}}}_{\text{FeynHiggs}} \leftrightarrow \underbrace{\overline{\text{MS}}}_{\text{RGEs}}$ conversion
- running of t_β:
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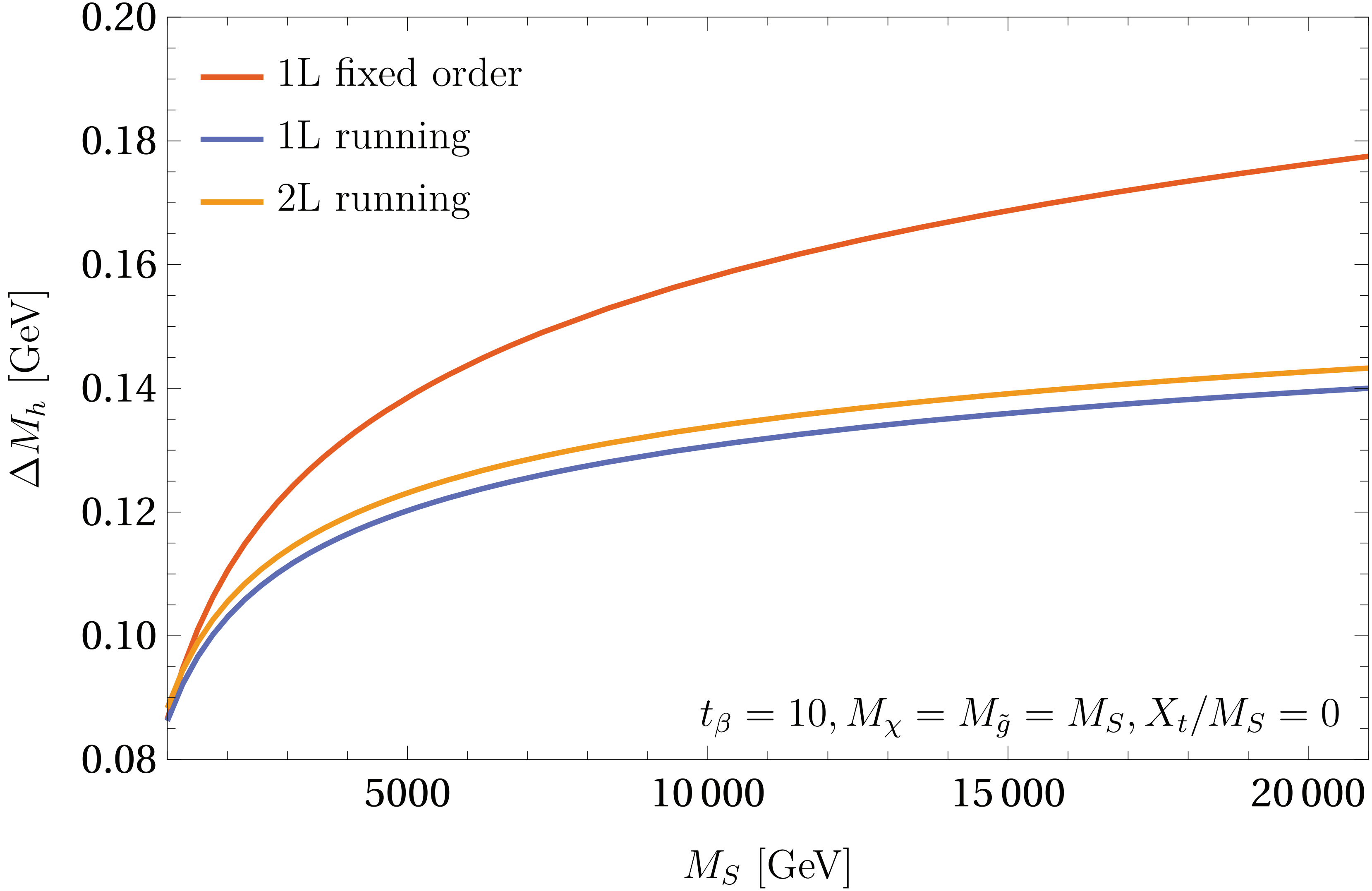
$$\frac{1}{\tan^2\beta}\frac{d\tan^2\beta}{dt} = -3k\tilde{h}_t^2 + k^2\left[9\tilde{h}_t^4 - \left(\frac{4}{3}g'^2 + 16g_3^2\right)\tilde{h}_t^2\right]$$

reproduces correct log terms in fixed-order FeynHiggs



1L fixed order
1L running
2L running
$t_\beta = 10, M_\chi = M_{\tilde{g}} = M_S, X_t/M_S = 0$
0.20
0.18
0.16
0.14
0.12
0.10
0.08
5000
10 000
15 000
20 000
ΔM_h [GeV]
M_S [GeV]

Summary

- Large SUSY-scale $\rightarrow$ large logarithms $\Rightarrow$ resummation necessary
- FeynHiggs 2.10: resummation of logarithms $\propto \alpha_t, \alpha_s$
- Extension I: resummation of logarithms $\propto \alpha_{em}$ up to ~ 3 GeV
- Extension II: intermediate chargino/neutralino threshold up to ~ 2 GeV
- Extension III: intermediate gluino threshold up to ~ 0.3 GeV ($\hat{X}_t = 0$), ~ 2 GeV ($\hat{X}_t = 2$)