Sparticle Decays and Intelligent Scans in the NMSSM

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DESY.

Emmy Noether-Programm
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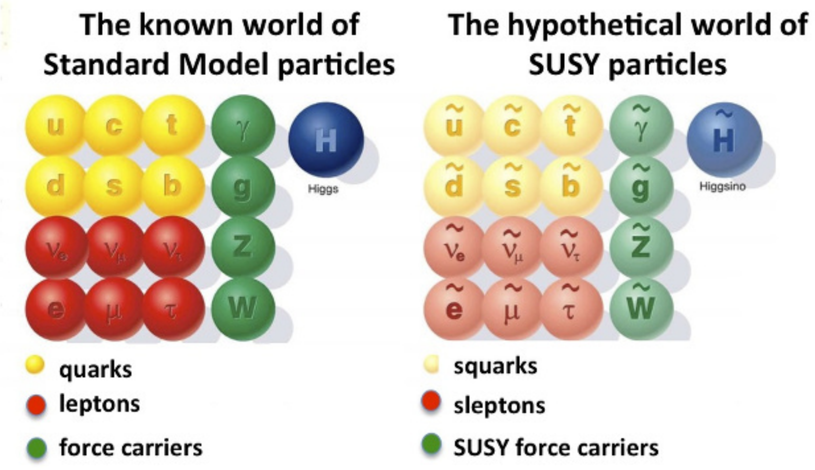
Introduction

Goals of the Project

- Calculate the supersymmetric particle decays in the (complex) next-to-minimal supersymmetric extension of the Standard Model (NMSSM)
- Update the code `SDECAY` [M. Mühlleitner, Djouadi, and Mambrini 2005] from the MSSM to the NMSSM
- Link the code to `NMSSMCALC` [Baglio et al. 2014] to calculate Higgs masses
- Caveat in SUSY models: scalar masses are derived quantities, no "easy" scan of viable benchmark points with desired masses
  $\Rightarrow$ set up program chain to perform "intelligent" scans, including current experimental limits

Illustration by Sandbox Studio, Chicago

Introduction



Reviews for SUSY

- MSSM: [Dawson 1997; Martin 1998; DJOUADI 2008]
- NMSSM: [Maniatis 2010; Ellwanger, Hugonie, and Teixeira 2010]

Introduction to the NMSSM

NMSSM Lagrangian

- NMSSM Superpotential $\mathcal{W}_{\text{NMSSM}}$ and soft breaking Lagrangian $\mathcal{L}^{\text{soft}}_{\text{NMSSM}}$:

$$
\begin{aligned}
\mathcal{W}_{\text{NMSSM}} =& \mathbf{Y}_u \hat{u}(\hat{Q}^{\mathsf{T}}\epsilon\hat{H}_u) - \mathbf{Y}_e \hat{e}(\hat{L}^{\mathsf{T}}\epsilon\hat{H}_d) - \mathbf{Y}_d \hat{d}(\hat{Q}^{\mathsf{T}}\epsilon\hat{H}_d) + \lambda\hat{S}(\hat{H}_u^{\mathsf{T}}\epsilon\hat{H}_d) + \frac{1}{3}\kappa\hat{S}^3 , \\
\mathcal{L}^{\text{soft}}_{\text{NMSSM}} =& - m^2_{H_d} H_d^\dagger H_d - m^2_{H_u} H_u^\dagger H_u - \mathbf{m}^2_{\tilde{Q}} \tilde{Q}^\dagger \tilde{Q} - \mathbf{m}^2_{\tilde{L}} \tilde{L}^\dagger \tilde{L} \\
& - \mathbf{m}^2_{\tilde{u}_{\text{R}}} \tilde{u}^*_{\text{R}} \tilde{u}_{\text{R}} - \mathbf{m}^2_{\tilde{d}_{\text{R}}} \tilde{d}^*_{\text{R}} \tilde{d}_{\text{R}} - \mathbf{m}^2_{\tilde{l}_{\text{R}}} \tilde{l}^*_{\text{R}} \tilde{l}_{\text{R}} \\
& - \Big(-\mathbf{T}_l H_d^{\mathsf{T}} \epsilon \tilde{L} \tilde{l}^*_{\text{R}} - \mathbf{T}_d H_d^{\mathsf{T}} \epsilon \tilde{Q} \tilde{d}^*_{\text{R}} + \mathbf{T}_u H_u^{\mathsf{T}} \epsilon \tilde{Q} \tilde{u}^*_{\text{R}} \\
& + \frac{M_1}{2}\tilde{B}\tilde{B} + \frac{M_2}{2}\tilde{W}_i\tilde{W}_i + \frac{M_3}{2}\tilde{G}\tilde{G} + \text{h.c.} \Big) \\
& - m_S^2 |S|^2 + \Big(T_\lambda S H_d^{\mathsf{T}} \epsilon H_u - \frac{1}{3} T_\kappa S^3 + \text{h.c.} \Big) ,
\end{aligned}
$$

- All parameters in brackets can be complex

Superfield		scalar	fermion	generations	$(U(1)_{\text{Y}}, SU(2)_{\text{L}}, SU(3)_{\text{C}})$
quark-squark	$\hat{Q}$	$\tilde{Q} = (\tilde{u}_{\text{L}}, \tilde{d}_{\text{L}})^{\text{T}}$	$Q = (u_{\text{L}}, d_{\text{L}})^{\text{T}}$	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3})$
	$\hat{u}$	$\tilde{u}^{*}_{\text{R}}$	$u^{\dagger}_{\text{R}}$	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}})$
	$\hat{d}$	$\tilde{d}^{*}_{\text{R}}$	$d^{\dagger}_{\text{R}}$	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}})$
lepton-slepton	$\hat{L}$	$\tilde{L} = (\tilde{v}, \tilde{l}_{\text{L}})^{\text{T}}$	$L = (v, l_{\text{L}})^{\text{T}}$	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
	$\hat{l}$	$\tilde{l}^{*}_{\text{R}}$	$l^{\dagger}_{\text{R}}$	3	$(1, \mathbf{1}, \mathbf{1})$
Higgs-Higgsino	$\hat{H}_u$	$H_u = (H_u^+, H_u^0)^{\text{T}}$	$\tilde{H}_u = (\tilde{H}_u^+, \tilde{H}_u^0)^{\text{T}}$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1})$
	$\hat{H}_d$	$H_d = (H_d^0, H_d^-)^{\text{T}}$	$\tilde{H}_d = (\tilde{H}_d^0, \tilde{H}_d^-)^{\text{T}}$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
	$\hat{S}$	S	$\tilde{S}$	1	$(0, \mathbf{1}, \mathbf{1})$
		Vector boson	fermion		
B-Bino	$\hat{B}$	B	$\tilde{B}$	1	$(0, \mathbf{1}, \mathbf{1})$
W-Wino	$\hat{W}$	W	$\tilde{W}$	1	$(0, \mathbf{3}, \mathbf{1})$
gluon-gluino	$\hat{G}$	g	$\tilde{g}$	1	$(0, \mathbf{1}, \mathbf{8})$

Introduction to the NMSSM

Summary

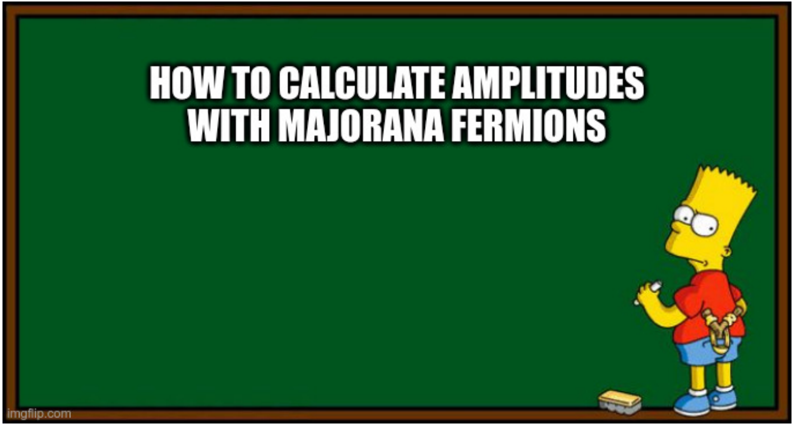
- NMSSM: MSSM with an additional singlet superfield $\Rightarrow$ solves the μ problem, more parameters
- NMSSM provides an interesting extended scalar sector, a DM candidate and overall rich phenomenology

Illustration by Sandbox Studio, Chicago

Sparticle Decays in the NMSSM

Decay Channels

- Two-body decays (+ QCD corrections)
- Three-body decays
- Radiative loop decays



[A. Denner et al. 1992; Ansgar Denner et al. 1992]

Two-Body Decays

Notation

- Φ: neutral Higgs scalars
- f, f': are generic fermions; q, q' generic quarks (suppressed generation indices)
- Tilde indicates the corresponding superpartners
- $\tilde{\chi}_i^0$: neutralinos ($i = 1, ..., 5$, $j = 1, ..., 4$)
- $\tilde{\chi}_k^\pm$ charginos ($k = 1, 2$)

Two-Body Decay Channels

- Slepton ($\tilde{l}$) decays: $\tilde{l} \to \tilde{\chi}_i^0 l,\, \tilde{\chi}_k^- \nu,\, H^- \tilde{\nu},\, W^- \tilde{\nu},\, \Phi \tilde{l},\, Z \tilde{l}$
- Sneutrino ($\tilde{\nu}$) decays: $\tilde{\nu} \to \tilde{\chi}_i^0 \nu,\, \tilde{\chi}_k^+ l,\, H^+ \tilde{l},\, W^+ \tilde{l}$
- Neutralino ($\tilde{\chi}^0$) decays: $\tilde{\chi}_i^0 \to W^\pm \tilde{\chi}_k^\mp,\, H^\pm \tilde{\chi}_k^\mp,\, Z \tilde{\chi}_j^0,\, \Phi \tilde{\chi}_j^0,\, \tilde{f} \bar{f},\, \tilde{f}^* f$
- Chargino ($\tilde{\chi}^+$) decays: $\tilde{\chi}_k^+ \to W^+ \tilde{\chi}_i^0,\, H^+ \tilde{\chi}_i^0,\, Z \tilde{\chi}_1^+,\, \Phi \tilde{\chi}_1^+,\, \tilde{f} f'$
- Gluino ($\tilde{g}$) decays: $\tilde{g} \to \tilde{q}^* q,\, \tilde{q} \bar{q}$
- Squark ($\tilde{q}$) decays: $\tilde{q} \to \tilde{\chi}_i^0 \tilde{q}',\, \tilde{\chi}_k^\pm \tilde{q}',\, \tilde{g} \tilde{q}',\, H^\pm \tilde{q}',\, W^\pm \tilde{q}',\, \Phi \tilde{q}',\, Z \tilde{q}'$

Three-Body Decays

Three-Body Decay Channels

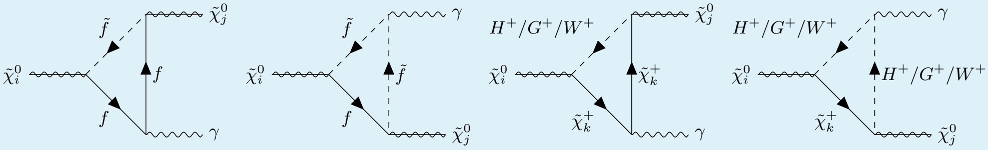
> If two-body decays are kinematically forbidden, three-body decays become important.

- Neutralino ($\tilde{\chi}^0$) decays: $\tilde{\chi}_i^0 \to f\bar{f}\tilde{\chi}_j^0,\ f\bar{f}'\tilde{\chi}_k^\pm,\ q\bar{q}\tilde{g}$
- Chargino ($\tilde{\chi}^+$) decays: $\tilde{\chi}_k^+ \to f\bar{f}\tilde{\chi}_1^+,\ f\bar{f}'\tilde{\chi}_i^0,\ q\bar{q}'\tilde{g}$
- Gluino ($\tilde{g}$) decays: $\tilde{g} \to q\bar{q}\tilde{\chi}_i^0,\ q\bar{q}'\tilde{\chi}_k^\pm,\ q'\tilde{q}H^\pm/W^\pm$
- Squark ($\tilde{q}$) decays: $\tilde{q} \to q'\tilde{\chi}_i^0W^\pm/H^\pm,\ q'\tilde{g}W^\pm/H^\pm,\ q'\bar{f}'\tilde{f},\ \tilde{q}'f'\bar{f}$

Radiative Loop Decays [Haber and Wyler 1989]

Radiative Neutralino Decay

- $\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 \gamma$ kinematically always allowed $(i, j = 1, ..., 5, i > j)$



Notation

- Electrically charged fermions f, and superpartners $\tilde{f}$
- Charginos $\tilde{\chi}_k^+$ $(k = 1, 2)$, charged Higgs boson $H^\pm$, charged Goldstone boson $G^\pm$
- Diagrams with inverted arrows also have to be considered.

NLO QCD Corrections to Two-Body Decays

Literature

- NLO QCD corrections in the MSSM: [S. Kraml et al. 1996; Beenakker, Höpker, and Zerwas 1996; Djouadi, Hollik, and Jünger 1997; Beenakker, Höpker, Plehn, et al. 1997; Bartl, Eberl, Hidaka, Kon, et al. 1997; Bartl, Eberl, Hidaka, S. Kraml, et al. 1998; Arhrib et al. 1998]
- Compared results also with [Hollik, Lindert, and Pagani 2013; R. Gröber et al. 2015; Gavin et al. 2015]

QCD Corrections to Two-Body Decays

- QCD corrections to Neutralino/Chargino/Gluino decays into squark-quark pairs and all squark decays
- Dimensional regularization breaks supersymmetry $\rightarrow$ SUSY restoring counterterms
- Numerical checks for UV and IR finiteness, small gluon and quark mass as IR and colinear regulators
- Implementation of loop integrals taken from `QCDloop` [Ellis and Zanderighi 2008]

Field Renormalization

Field and Mass Renormalization

$$\tilde{q}_0 = \left(1 + \frac{1}{2}\delta Z^{\tilde{q}}\right)\tilde{q}\,, \qquad m^2_{\tilde{q},0} = m^2_{\tilde{q}} + \delta m^2_{\tilde{q}}\,,$$

$$q_{\mathsf{L/R},0} = \left(1 + \frac{1}{2}\delta Z^{q_{\mathsf{L/R}}}\right) q_{\mathsf{L/R}}\,, \qquad m_{q,0} = m_q + \delta m_q\,,$$

$$\tilde{g}_{\mathsf{L/R},0} = (1 + \frac{1}{2}\delta Z^{\tilde{g}_{\mathsf{L/R}}})\tilde{g}_{\mathsf{L/R}}\,, \qquad m_{\tilde{g},0} = m_{\tilde{g}} + \delta m_{\tilde{g}}\,,$$

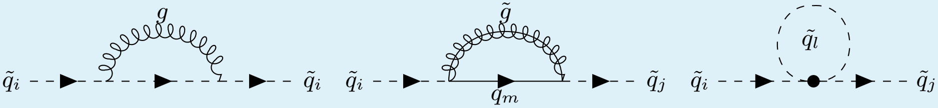
$$\Sigma^q_{ij}(p^2) = \not{p}\Sigma^{q,\mathsf{L}}_{ij}(p^2)P_{\mathsf{L}} + \not{p}\Sigma^{q,\mathsf{R}}_{ij}(p^2)P_{\mathsf{R}} + \Sigma^{q,\mathsf{Ls}}_{ij}(p^2)P_{\mathsf{L}} + \Sigma^{q,\mathsf{Rs}}_{ij}(p^2)P_{\mathsf{R}}\,,$$

$$U^{0,q_{\mathsf{L/R}}} = (\mathbb{1} + \delta u^{q_{\mathsf{L/R}}})U^{q_{\mathsf{L/R}}}\,, \quad W^{0,\tilde{q}} = (\mathbb{1} + \delta w^{\tilde{q}})W^{\tilde{q}}\,,$$

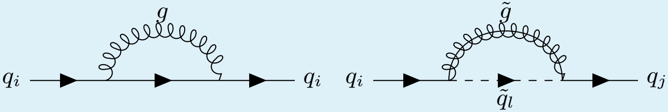
Notation

- q ($\tilde{q}$): quark (squark fields, $\tilde{g}$: gluino field
- δZ: wave function renormalization constant
- $P_{\mathsf{L/R}} = (\mathbb{1} \mp \gamma_5)/2$
- $U^{q_{\mathsf{L/R}}}$ ($W^{\tilde{q}}$): quark (squark) rotation matrix
- Σ^q_{ij}: quark self-energy

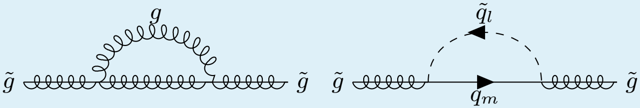
Squark Self-Energy



Quark Self-Energy



Gluino Self-Energy



Field Renormalization

Wave Function Renormalization Constants

$$\delta Z^{\tilde{q}}_{st} = \begin{cases} -\widetilde{\mathrm{Re}} \frac{\partial \Sigma^{\tilde{q}}_{ss}(p^2)}{\partial p^2}\Big|_{p^2=m^2_{\tilde{q}_s}} & s=t \\ \frac{2}{m^2_{\tilde{q}_s}-m^2_{\tilde{q}_t}} \widetilde{\mathrm{Re}}\Sigma^{\tilde{q}}_{st}(p^2=m^2_{\tilde{q}_t}) & s \neq t \ . \end{cases} ,$$

$$\delta Z^{q\mathrm{L}}_{ij} = \frac{2}{m^2_{q_i}-m^2_{q_j}} \Big(m_{q_i} \widetilde{\mathrm{Re}}\Sigma^{q,\mathrm{Ls}}_{ij}(m^2_{q_j}) + m_{q_j} \widetilde{\mathrm{Re}}\Sigma^{q,\mathrm{Rs}}_{ij}(m^2_{q_j}) + m^2_{q_j} \widetilde{\mathrm{Re}}\Sigma^{q,\mathrm{L}}_{ij}(m^2_{q_j}) + m_{q_i} m_{q_j} \widetilde{\mathrm{Re}}\Sigma^{q,\mathrm{R}}_{ij}(m^2_{q_j}) \Big) \ (i \neq j) ,$$

$$\delta Z^{q\mathrm{R}}_{ij} = \frac{2}{m^2_{q_i}-m^2_{q_j}} \Big(m_{q_j} \widetilde{\mathrm{Re}}\Sigma^{q,\mathrm{Ls}}_{ij}(m^2_{q_j}) + m_{q_i} \widetilde{\mathrm{Re}}\Sigma^{q,\mathrm{Rs}}_{ij}(m^2_{q_j}) + m_{q_i} m_{q_j} \widetilde{\mathrm{Re}}\Sigma^{q,\mathrm{L}}_{ij}(m^2_{q_j}) + m^2_{q_j} \widetilde{\mathrm{Re}}\Sigma^{q,\mathrm{R}}_{ij}(m^2_{q_j}) \Big) \ (i \neq j) ,$$

Field Renormalization

Counterterms for Mixing Matrices

$$\delta u^{q_{\mathrm{L/R}}} = \frac{1}{4}\left(\delta Z^{q_{\mathrm{L/R}}} - \delta Z^{q_{\mathrm{L/R}}\dagger}\right)$$
$$\delta w^{\tilde{q}} = \frac{1}{4}\left(\delta Z^{\tilde{q}} - \delta Z^{\tilde{q}\dagger}\right)$$

- Problem arises if squark masses are degenerate, or if quarks are massless.
- Overall Vertex CT remains finite (do limit carefully)

Renormalization of the Strong Coupling Constant

Counterterm for Strong Coupling Constant

$$g_s^0 = g_s + \delta g_s \,,$$
$$\delta g_s^{\overline{\text{MS}}} = -\frac{\alpha_s}{8\pi}\beta_0 \Delta_{\text{UV}} g_s \,,$$

- 5-flavour scheme for the running of the coupling.
- Decouple the top quark and all heavy SUSY particles:

$$\delta g_s^{\overline{\text{MS}},5} = \delta g_s^{\overline{\text{MS}}} - \frac{\alpha_s}{8\pi}\left[2\log\frac{m_{\tilde{g}}^2}{\mu_R^2} + \frac{1}{6}\sum_{i=1}^{12}\log\frac{m_{\tilde{q}_i}^2}{\mu_R^2} + \frac{2}{3}\log\frac{m_t^2}{\mu_R^2}\right] g_s$$

Notation

- $\overline{\text{MS}}$: minimal subtraction scheme
- μ_R^2: renormalization scale
- $\beta_0 = 3$
- $\Delta_{\text{UV}} = \epsilon^{-1} - \gamma_{\text{E}} + \log 4\pi$

Dimensional Regularization and SUSY [Martin and Vaughn 1993]

SUSY Restoring Counterterms

- Dimensional regularization (DReg) breaks SUSY in contrast do dimensional reduction (DRed)
- Additional counterterms to restore SUSY:

$$\hat{g}_s^{\text{DReg}} = \hat{g}_s^{\text{DRed}} \left(1 + \frac{g_s^2}{32\pi^2}\frac{5}{3}\right) , \qquad \hat{g}_2^{\text{DReg}} = \hat{g}_2^{\text{DRed}} \left(1 - \frac{g_s^2}{32\pi^2}\frac{4}{3}\right) ,$$

$$g_s^{\text{DReg}} = g_s^{\text{DRed}} \left(1 - \frac{3g_s^2}{96\pi^2}\right) , \qquad \hat{Y}_q^{\text{DReg}} = \hat{Y}_q^{\text{DRed}} \left(1 - \frac{g_s^2}{32\pi^2}\frac{4}{3}\right) ,$$

$$m_q^{\text{DReg}} = m_q^{\text{DRed}} \left(1 + \frac{g_s^2}{16\pi^2}\frac{4}{3}\right) , \qquad Z_q^{\text{L/R,DReg}} = Z_q^{\text{L/R,DRed}} \left(1 + \frac{g_s^2}{16\pi^2}\frac{4}{3}\right) ,$$

$$m_{\tilde{g}}^{\text{DReg}} = m_{\tilde{g}}^{\text{DRed}} \left(1 + \frac{g_s^2}{16\pi^2}3\right) , \qquad Z_{\tilde{g}}^{\text{L/R,DReg}} = Z_{\tilde{g}}^{\text{L/R,DRed}} \left(1 + \frac{g_s^2}{16\pi^2}3\right) ,$$

Conversion of $\overline{\text{DR}}$ to OS Parameters [Bartl, Eberl, Hidaka, Kon, et al. 1997; Heinemeyer et al. 2007; Margarete Mühlleitner et al. 2015]

Squark Mass Matrix

$$\mathcal{M}_{\tilde{u}} = \begin{pmatrix} m_{\tilde{Q}}^2 + m_u^2 + \frac{-g_1^2+3g_2^2}{24} v^2 \cos(2\beta) & m_u \left(A_u^* e^{-i\varphi_u} - \mu_{\text{eff}} \cot\beta\right) \\ m_u \left(A_u e^{i\varphi_u} - \mu_{\text{eff}}^* \cot\beta\right) & m_{\tilde{u}_R}^2 + m_u^2 + \frac{g_1^2}{6} v^2 \cos(2\beta) \end{pmatrix},$$

$$\mathcal{M}_{\tilde{d}} = \begin{pmatrix} m_{\tilde{Q}}^2 + m_d^2 + \frac{-g_1^2-3g_2^2}{24} v^2 \cos(2\beta) & m_d \left(A_d^* - \mu_{\text{eff}} e^{i\varphi_u} \tan\beta\right) \\ m_d \left(A_d - \mu_{\text{eff}}^* e^{-i\varphi_u} \tan\beta\right) & m_{\tilde{d}_R}^2 + m_d^2 - \frac{g_1^2}{12} v^2 \cos(2\beta) \end{pmatrix},$$

$$\tilde{q}^m = W^{\tilde{q}} \tilde{q}\,,$$

$$\begin{pmatrix} m_{\tilde{q}_1^2} & 0 \\ 0 & m_{\tilde{q}_2^2} \end{pmatrix} = W^{\tilde{q}} \mathcal{M}_{\tilde{q}} W^{\tilde{q}\dagger}\,.$$

Conversion of $\overline{\text{DR}}$ to OS Parameters [Bartl, Eberl, Hidaka, Kon, et al. 1997; Heinemeyer et al. 2007; Margarete Mühlleitner et al. 2015]

Squark Mass Matrix Counterterms

$$W^{\tilde{q}\dagger}(\mathbb{1} + \delta w^{\tilde{q}\dagger}) \begin{pmatrix} m^2_{\tilde{q}_1} + \delta m^2_{\tilde{q}_1} & 0 \\ 0 & m^2_{\tilde{q}_2} + \delta m^2_{\tilde{q}_2} \end{pmatrix} (\mathbb{1} + \delta w^{\tilde{q}}) W^{\tilde{q}} = W^{\tilde{q}\dagger} \begin{pmatrix} m^2_{\tilde{q}_1} + \delta m^2_{\tilde{q}_1} & \delta Y_{\tilde{q}} \\ \delta Y^*_{\tilde{q}} & m^2_{\tilde{q}_2} + \delta m^2_{\tilde{q}_2} \end{pmatrix} W^{\tilde{q}} \,,$$

with $\delta Y_{\tilde{q}}$ defined as

$$\delta Y_{\tilde{q}} \equiv \delta w^{\tilde{q}}_{12} (m^2_{\tilde{q}_1} - m^2_{\tilde{q}_2}) \,.$$

Conversion of $\overline{\text{DR}}$ to OS Parameters [Bartl, Eberl, Hidaka, Kon, et al. 1997; Heinemeyer et al. 2007; Margarete Mühlleitner et al. 2015]

Squark Mass Matrix Counterterms

$$W^{\tilde{u}\dagger}\begin{pmatrix}\delta m^2_{\tilde{u}_1} & \delta Y_{\tilde{u}} \\ \delta Y^*_{\tilde{u}} & \delta m^2_{\tilde{u}_2}\end{pmatrix} W^{\tilde{u}} = \begin{pmatrix} \delta m^2_{\tilde{U}} + \delta m^2_u & \delta m_u \left(A^*_u e^{-i\varphi_u} - \mu_{\text{eff}} \cot\beta\right) + \delta A^*_u m_u e^{-i\varphi_u} \\ \delta m_u \left(A_u e^{i\varphi_u} - \mu^*_{\text{eff}} \cot\beta\right) + \delta A_u m_u e^{i\varphi_u} & \delta m^2_{\tilde{u}_R} + \delta m^2_u \end{pmatrix},$$

$$W^{\tilde{d}\dagger}\begin{pmatrix}\delta m^2_{\tilde{d}_1} & \delta Y_{\tilde{d}} \\ \delta Y^*_{\tilde{d}} & \delta m^2_{\tilde{d}_2}\end{pmatrix} W^{\tilde{d}} = \begin{pmatrix} \delta m^2_{\tilde{D}} + \delta m^2_d & \delta m_d \left(A^*_d - \mu_{\text{eff}} e^{i\varphi_u} \tan\beta\right) + \delta A^*_d m_d \\ \delta m_d \left(A_d - \mu^*_{\text{eff}} e^{-i\varphi_u} \tan\beta\right) + \delta A_d m_d & \delta m^2_{\tilde{d}_R} + \delta m^2_d \end{pmatrix},$$

Remark

- Considere up-type squarks $\tilde{u}$ and down-type squarks $\tilde{d}$ separately
- Introduce two counterterms $\delta m^2_{\tilde{U}}$, $\delta m^2_{\tilde{D}}$ for $m^2_{\tilde{Q}}$

Conversion of $\overline{\text{DR}}$ to OS Parameters [Bartl, Eberl, Hidaka, Kon, et al. 1997; Heinemeyer et al. 2007; Margarete Mühlleitner et al. 2015]

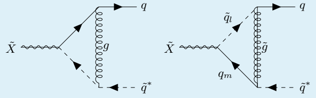
Translation of Counterterms

$$\delta A_u = \frac{e^{-i\varphi_u}}{m_u}\Big(W^{\tilde u}_{11}W^{\tilde u *}_{12}\delta m^2_{\tilde u_1} + W^{\tilde u *}_{22}W^{\tilde u}_{21}\delta m^2_{\tilde u_2} + W^{\tilde u *}_{12}W^{\tilde u}_{21}\delta Y_u + W^{\tilde u *}_{22}W^{\tilde u}_{11}\delta Y^*_u$$
$$-\delta m_u\left(A_u e^{i\varphi_u} - \mu^*_{\text{eff}}\cot\beta\right)\Big)\ ,$$
$$\delta A_d = \frac{1}{m_d}\Big(W^{\tilde d}_{11}W^{\tilde d *}_{12}\delta m^2_{\tilde d_1} + W^{\tilde d *}_{22}W^{\tilde d}_{21}\delta m^2_{\tilde d_2} + W^{\tilde d *}_{12}W^{\tilde d}_{21}\delta Y_d + W^{\tilde d *}_{22}W^{\tilde d}_{11}\delta Y^*_d$$
$$-\delta m_d\left(A_d - \mu^*_{\text{eff}}e^{-i\varphi_u}\tan\beta\right)\Big)\ ,$$
$$\delta m^2_{\tilde Q} = |W^{\tilde q}_{11}|^2\delta m^2_{\tilde q_1} + |W^{\tilde q}_{21}|^2\delta m^2_{\tilde q_2} + W^{\tilde q *}_{11}W^{\tilde q}_{21}\delta Y_{\tilde q} + W^{\tilde q *}_{21}W^{\tilde q}_{11}\delta Y^*_{\tilde q} - 2m_q\delta m_q\ ,$$
$$\delta m^2_{q\text{R}} = |W^{\tilde q}_{12}|^2\delta m^2_{\tilde q_1} + |W^{\tilde q}_{22}|^2\delta m^2_{\tilde q_2} + W^{\tilde q *}_{12}W^{\tilde q}_{22}\delta Y_{\tilde q} + W^{\tilde q *}_{22}W^{\tilde q}_{12}\delta Y^*_{\tilde q} - 2m_q\delta m_q\ ,$$

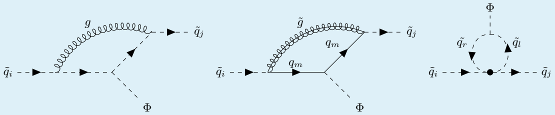
$$A^{\text{OS}}_q = A^{\overline{\text{DR}}}_q - \delta A^{\text{fin}}_q\ ,$$
$$m^{2,\text{OS}}_{\tilde U} = m^{2,\overline{\text{DR}}}_{\tilde Q} - \delta m^{2,\text{fin}}_{\tilde U}\ , \qquad m^{2,\text{OS}}_{\tilde D} = m^{2,\overline{\text{DR}}}_{\tilde Q} - \delta m^{2,\text{fin}}_{\tilde D}\ ,$$
$$m^{2,\text{OS}}_{\tilde q\text{R}} = m^{2,\overline{\text{DR}}}_{\tilde q\text{R}} - \delta m^{2,\text{fin}}_{\tilde q\text{R}}\ , \qquad m^{\text{OS}}_{\tilde g} = |M^{\overline{\text{DR}}}_3| - \delta m^{\text{fin}}_{\tilde g}\ .$$

NLO Vertex Corrections

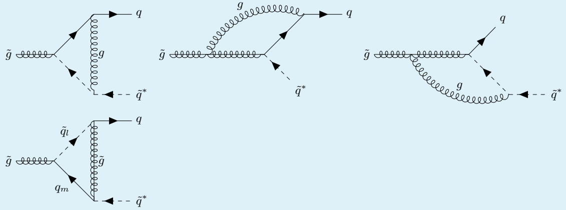
Neutralino/Chargino Decays



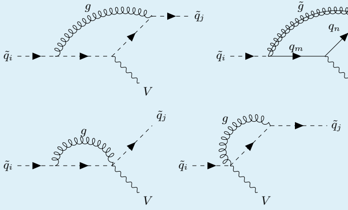
Squark Decays to Scalars



Gluino Decays



Squark Decays to Vector Bosons

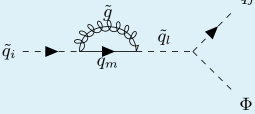


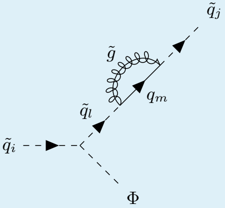
Absorptive Corrections

Remarks

- OS scheme: Only the real parts of the loop integrals are absorbed ($\widetilde{\mathrm{Re}}$)
- Imaginary parts may appear, play a role if couplings are complex
- Only squark self energies have to be considered (gluino does not mix, quarks are always lighter than squarks)

Feynman Diagrams





Code Implementation

Implementation

- Analytic results implemented into a new code and linked to `NMSSMCALC`
- $\overline{\text{DR}}$/OS parameter conversion is implemented iteratively
- 3-body decays are calculated if necessary
- Results are appended to output in SLHA format

Phenomenological Analysis

Setup

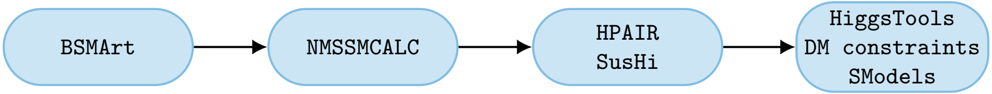
- Use code `BSMArt` to link `NMSSMCALC` + decay code to `HiggsTools`, `SModels` and other tools
- Do intelligent parameter scan (i.e. active learning, MCMC, ...) to scan the vast parameter regions
- Do phenomenological analysis

NMSSMCALC [Ender et al. 2012; Graf et al. 2012; Nhung et al. 2013; Baglio et al. 2014; Mühlleitner et al. 2015; King et al. 2015; Mühlleitner et al. 2015; Dao, Gröber, et al. 2019; Dao et al. 2021; Borschensky et al. 2023; Dao et al. 2022, 2023]

Program Summary

- Calculation of Higgs boson masses including loop corrections (up to $\mathcal{O}(\alpha_t\alpha_s + (\alpha_t + \alpha_\lambda + \alpha_\kappa)^2)$) and Higgs decay widths and branching ratios
- Calculation of trilinear Higgs couplings including loop corrections (up to $\mathcal{O}(\alpha_t\alpha_s + \alpha_t^2)$)
- Additional precision predictions (W boson mass, muon anomalous magnetic moment, electric dipole moments)

Program Chain



Setup

- BSMArt [Goodsell and Joury 2024]: handling of scan procedure, generation of input parameters. Several options (MCMC, active learning,..) $\Rightarrow$ **dedicated search for benchmark points with interesting mass scenarios**
- Calculation of electroweakino production with additional code
- Calculation of di-Higgs production with adapted version of HPAIR for the NMSSM [Nhung et al. 2013] and single-Higgs production with SusHi [Harlander, Liebler, and Mantler 2013, 2017]
- HiggsTools [Bahl et al. 2023]: limits from Higgs searches and measurements
- SModels [Sabine Kraml et al. 2014; Ambrogi et al. 2017, 2020; Alguero et al. 2022; Altakach et al. 2023]: limits from SUSY searches
- Dark matter (DM) constraints (relic density, direct detection) $\Rightarrow$ work in progress

Example Benchmark Points

Benchmark Point 1

- $m_{h_{1,2,3}} = 127,\, 305,\, 664$ GeV, $m_{A_{1,2}} = 660,\, 1309$ GeV (2L)
- $\sigma(gg \to h_1 h_1) = 100$ fb (NLO HTL, SM: 32 fb)
- $\lambda_{h_1 h_1 h_1} = 0.65(\text{LO})\,, 0.91(1\text{L})\,, 0.98(2\text{L})$ (normalized to $3m_{h_1}^2/v$)
- $\Gamma_{\tilde{t}_1}^{\text{NLO}} = 26$ GeV ($m_{\tilde{t}_1} = 1575$ GeV, QCD corrections: -44 %)

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- $\Gamma_{\tilde{t}_1}^{\text{NLO}} = 26$ GeV ($m_{\tilde{t}_1} = 1575$ GeV, QCD corrections: -44 %)

Benchmark Point 2

- $m_{h_{1,2,3}} = 124.7, 294, 625$ GeV, $m_{A_{1,2}} = 538, 615$ GeV (2L)
- $\sigma(gg \to h_1 h_1) = 158$ fb (NLO HTL)
- $\lambda_{h_1 h_1 h_1} = 0.6$(LO) $, 0.93(1\text{L}), 1.02(2\text{L})$ (normalized to $3m_{h_1}^2/v$)

Conclusion

Summary

- Implementation of supersymmetric particle decays
- Setup of program chain to perform parameter scans, including current experimental limits
- First sample scans, discussion of benchmark points

Outlook

- Implementation of dark matter constraints and other tools (`Prospino` [Beenakker, Hopker, Spira, Plehn], vacuum stability, ...)
- Setup and execution of intelligent scans with `BSMArt`

Literature I

- Mühlleitner, M., A. Djouadi, and Y. Mambrini (May 2005). "SDECAY: a Fortran code for the decays of the supersymmetric particles in the MSSM". In: Computer Physics Communications 168.1, pp. 46–70. ISSN: 0010-4655. DOI: 10.1016/j.cpc.2005.01.012.
- Baglio, J. et al. (Dec. 2014). "NMSSMCALC: A program package for the calculation of loop-corrected Higgs boson masses and decay widths in the (complex) NMSSM". In: Computer Physics Communications 185.12, pp. 3372–3391. ISSN: 0010-4655. DOI: 10.1016/j.cpc.2014.08.005.
- Dawson, S. (1997). The MSSM and Why it Works. arXiv: hep-ph/9712464 [hep-ph].
- Martin, Stephen P. (1998). "A Supersymmetry primer". In: Adv. Ser. Direct. High Energy Phys. 18. Ed. by Gordon L. Kane, pp. 1–98. DOI: 10.1142/9789812839657_0001. arXiv: hep-ph/9709356.
- DJOUADI, A (Apr. 2008). "The anatomy of electroweak symmetry breaking Tome II: The Higgs bosons in the Minimal Supersymmetric Model". In: Physics Reports 459.1–6, pp. 1–241. ISSN: 0370-1573. DOI: 10.1016/j.physrep.2007.10.005.

Literature II

- Maniatis, M. (2010). "The Next-to-Minimal Supersymmetric extension of the Standard Model reviewed". In: International Journal of Modern Physics A 25.18n19, pp. 3505–3602. DOI: 10.1142/S0217751X10049827. arXiv: 0906.0777 [hep-ph].
- Ellwanger, Ulrich, Cyril Hugonie, and Ana M. Teixeira (Nov. 2010). "The Next-to-Minimal Supersymmetric Standard Model". In: Physics Reports 496.1–2, pp. 1–77. ISSN: 0370-1573. DOI: 10.1016/j.physrep.2010.07.001.
- Denner, A. et al. (1992). "Compact Feynman rules for Majorana fermions". In: Physics Letters B 291.3, pp. 278–280. ISSN: 0370-2693. DOI: https://doi.org/10.1016/0370-2693(92)91045-B.
- Denner, Ansgar et al. (1992). "Feynman rules for fermion number violating interactions". In: Nucl. Phys. B 387, pp. 467–481. DOI: 10.1016/0550-3213(92)90169-C.
- Haber, Howard E. and Daniel Wyler (1989). "RADIATIVE NEUTRALINO DECAY". In: Nucl. Phys. B 323, pp. 267–310. DOI: 10.1016/0550-3213(89)90143-0.
- Kraml, S. et al. (Oct. 1996). "SUSY-QCD corrections to scalar quark decays into charginos and neutralinos". In: Physics Letters B 386.1–4, pp. 175–182. ISSN: 0370-2693. DOI: 10.1016/0370-2693(96)00944-6.

Literature III

- Beenakker, W., R. Höpker, and P.M. Zerwas (June 1996). “SUSY-QCD decays of squarks and gluinos”. In: Physics Letters B 378.1–4, pp. 159–166. ISSN: 0370-2693. DOI: 10.1016/0370-2693(96)00379-6.
- Djouadi, A., W. Hollik, and C. Jünger (June 1997). “QCD corrections to scalar quark decays”. In: Physical Review D 55.11, pp. 6975–6985. ISSN: 1089-4918. DOI: 10.1103/physrevd.55.6975.
- Beenakker, W., R. Höpker, T. Plehn, et al. (June 1997). “Stop decays in SUSY-QCD”. In: Zeitschrift für Physik C Particles and Fields 75.2, pp. 349–356. ISSN: 1431-5858. DOI: 10.1007/s002880050478.
- Bartl, A., H. Eberl, K. Hidaka, T. Kon, et al. (June 1997). “QCD corrections to Higgs boson decays into squarks in the minimal supersymmetric standard model”. In: Physics Letters B 402.3–4, pp. 303–313. ISSN: 0370-2693. DOI: 10.1016/s0370-2693(97)00457-7.
- Bartl, A., H. Eberl, K. Hidaka, S. Kraml, et al. (Feb. 1998). “SUSY-QCD corrections to stop and sbottom decays into W± and Z0 bosons”. In: Physics Letters B 419.1–4, pp. 243–252. ISSN: 0370-2693. DOI: 10.1016/s0370-2693(97)01475-5.

Literature IV

- Arhrib, A. et al. (May 1998). "Supersymmetric Higgs boson decays into scalar quarks: QCD corrections". In: Physical Review D 57.9, pp. 5860–5870. ISSN: 1089-4918. DOI: 10.1103/physrevd.57.5860.
- Hollik, W., J. M. Lindert, and D. Pagani (Mar. 2013). "NLO corrections to squark-squark production and decay at the LHC". In: Journal of High Energy Physics 2013.3. ISSN: 1029-8479. DOI: 10.1007/jhep03(2013)139.
- Gröber, R. et al. (Sept. 2015). "Light stop decays: implications for LHC searches". In: The European Physical Journal C 75.9. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-015-3626-z.
- Gavin, R. et al. (Jan. 2015). "Squark production and decay matched with parton showers at NLO". In: The European Physical Journal C 75.1. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-014-3243-2.
- Ellis, R. Keith and Giulia Zanderighi (Feb. 2008). "Scalar one-loop integrals for QCD". In: Journal of High Energy Physics 2008.02, pp. 002–002. ISSN: 1029-8479. DOI: 10.1088/1126-6708/2008/02/002.

Literature V

- Martin, Stephen P. and Michael T. Vaughn (1993). "Regularization dependence of running couplings in softly broken supersymmetry". In: Physics Letters B 318.2, pp. 331–337. ISSN: 0370-2693. DOI: https://doi.org/10.1016/0370-2693(93)90136-6.
- Heinemeyer, S. et al. (Sept. 2007). "The Higgs sector of the complex MSSM at two-loop order: QCD contributions". In: Physics Letters B 652.5–6, pp. 300–309. ISSN: 0370-2693. DOI: 10.1016/j.physletb.2007.07.030.
- Mühlleitner, Margarete et al. (2015). "Two-loop contributions of the order $\mathcal{O}\left(\alpha_t \alpha_s\right)$ to the masses of the Higgs bosons in the CP-violating NMSSM". In: JHEP 05, p. 128. DOI: 10.1007/JHEP05(2015)128. arXiv: 1412.0918 [hep-ph].
- Ender, K. et al. (Apr. 2012). "Analysis of the NMSSM Higgs boson masses at one-loop level". In: Physical Review D 85.7. ISSN: 1550-2368. DOI: 10.1103/physrevd.85.075024.
- Graf, T. et al. (Oct. 2012). "Higgs boson masses in the complex NMSSM at one-loop level". In: Journal of High Energy Physics 2012.10. ISSN: 1029-8479. DOI: 10.1007/jhep10(2012)122.
- Nhung, Dao Thi et al. (2013). "Higher Order Corrections to the Trilinear Higgs Self-Couplings in the Real NMSSM". In: JHEP 11, p. 181. DOI: 10.1007/JHEP11(2013)181. arXiv: 1306.3926 [hep-ph].

Literature VI

- King, S.F. et al. (Dec. 2015). "Exploring the CP-violating NMSSM: EDM constraints and phenomenology". In: Nuclear Physics B 901, pp. 526–555. ISSN: 0550-3213. DOI: 10.1016/j.nuclphysb.2015.11.003.
- Mühlleitner, M., Dao Thi Nhung, and Hanna Ziesche (2015). "The order $\mathcal{O}(\alpha_t \alpha_s)$ corrections to the trilinear Higgs self-couplings in the complex NMSSM". In: JHEP 12, p. 034. DOI: 10.1007/JHEP12(2015)034. arXiv: 1506.03321 [hep-ph].
- Dao, Thi Nhung, Ramona Gröber, et al. (Aug. 2019). "Two-loop $\mathcal{O}(\alpha_t^2)$ corrections to the neutral Higgs boson masses in the CP-violating NMSSM". In: Journal of High Energy Physics 2019.8. ISSN: 1029-8479. DOI: 10.1007/jhep08(2019)114.
- Dao, Thi Nhung, Martin Gabelmann, Margarete Mühlleitner, and Heidi Rzehak (2021). "Two-loop $\mathcal{O}((\alpha_t + \alpha_\lambda + \alpha_\kappa)^2)$ corrections to the Higgs boson masses in the CP-violating NMSSM". In: JHEP 09, p. 193. DOI: 10.1007/JHEP09(2021)193. arXiv: 2106.06990 [hep-ph].
- Borschensky, Christoph et al. (2023). "The trilinear Higgs self-couplings at $\mathcal{O}(\alpha_t^2)$ in the CP-violating NMSSM". In: Eur. Phys. J. C 83.2, p. 118. DOI: 10.1140/epjc/s10052-023-11215-5. arXiv: 2210.02104 [hep-ph].

Literature VII

Dao, Thi Nhung, Duc Ninh Le, and Margarete Mühlleitner (2022). "Leptonic anomalous magnetic and electric dipole moments in the CP-violating NMSSM with and without inverse seesaw mechanism". In: Eur. Phys. J. C 82.10, p. 954. DOI: 10.1140/epjc/s10052-022-10928-3. arXiv: 2207.12618 [hep-ph].

Dao, Thi Nhung, Martin Gabelmann, and Margarete Mühlleitner (2023). "The $\mathcal{O}(\alpha_t + \alpha_\lambda + \alpha_\kappa)^2$ correction to the ρ parameter and its effect on the W boson mass calculation in the complex NMSSM". In: Eur. Phys. J. C 83.11, p. 1079. DOI: 10.1140/epjc/s10052-023-12236-w. arXiv: 2308.04059 [hep-ph].

Goodsell, Mark D. and Ari Joury (2024). "BSMArt: Simple and fast parameter space scans". In: Comput. Phys. Commun. 297, p. 109057. DOI: 10.1016/j.cpc.2023.109057. arXiv: 2301.01154 [hep-ph].

Harlander, Robert V., Stefan Liebler, and Hendrik Mantler (2013). "SusHi: A program for the calculation of Higgs production in gluon fusion and bottom-quark annihilation in the Standard Model and the MSSM". In: Comput. Phys. Commun. 184, pp. 1605–1617. DOI: 10.1016/j.cpc.2013.02.006. arXiv: 1212.3249 [hep-ph].

Literature VIII

- Harlander, Robert V., Stefan Liebler, and Hendrik Mantler (2017). "SusHi Bento: Beyond NNLO and the heavy-top limit". In: Comput. Phys. Commun. 212, pp. 239–257. DOI: 10.1016/j.cpc.2016.10.015. arXiv: 1605.03190 [hep-ph].
- Bahl, Henning et al. (Oct. 2023). "HiggsTools: BSM scalar phenomenology with new versions of HiggsBounds and HiggsSignals". In: Computer Physics Communications 291, p. 108803. ISSN: 0010-4655. DOI: 10.1016/j.cpc.2023.108803.
- Kraml, Sabine et al. (2014). "SModelS: a tool for interpreting simplified-model results from the LHC and its application to supersymmetry". In: Eur.Phys.J. C74, p. 2868. DOI: 10.1140/epjc/s10052-014-2868-5. arXiv: 1312.4175 [hep-ph].
- Ambrogi, Federico et al. (2017). "SModelS v1.1 user manual". In: arXiv: 1701.06586 [hep-ph].
- Ambrogi, Federico et al. (2020). "SModelS v1.2: long-lived particles, combination of signal regions, and other novelties". In: Comput. Phys. Commun. 251, p. 106848. DOI: 10.1016/j.cpc.2019.07.013. arXiv: 1811.10624 [hep-ph].
- Alguero, Gaël et al. (2022). "Constraining new physics with SModelS version 2". In: JHEP 08, p. 068. DOI: 10.1007/JHEP08(2022)068. arXiv: 2112.00769 [hep-ph].

Literature IX

Altakach, Mohammad Mahdi et al. (2023). “SModelS v2.3: Enabling global likelihood analyses”. In: SciPost Phys. 15.5, p. 185. DOI: 10.21468/SciPostPhys.15.5.185. arXiv: 2306.17676 [hep-ph].