Andreas Crivellin

Effective Field Theory, Higgs-quark couplings and Dark Matter Direct Detection in the MSSM

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Outline:

- Introduction: Effective Filed Theories
  - Matching
  - Running / Mixing
- Effective Higgs vertices in the MSSM
  - Resummation of chirally enhanced corrections
  - 2-loop SQCD calculation
- Loop effects in Dark Matter direct detection
- Dark Matter scattering in the natural MSSM
  - Higgs contributions
  - Squark contributions
- Conclusions

Introduction: Effective field theory approach

Why EFT methods:

- Properly connect physics at different scales via
  - Matching of the high energy theory
  - Running, Mixing and threshold correction
  - Calculation of the low-energy observables

⇒ Separation of UV and IR physics important for QCD processes (modular approach)

- Beyond the Standard Model the EFT can be used to correlate different experiments
- Can be easily extended to account for DM, right-handed neutrinos, …

EFT for Low Energy Processes (Flavour, DM direct detection, etc.)

- Matching at the high scale Λ (electroweak or new physics scale) on the effective operators

➡ Determination of the Wilson coefficients

⬇

- Calculation of the anomalous dimension

➡ Renormalization group evolution to the low scale

⬇

- Calculation of the matrix elements

➡ Determination of the observables

Full Theory and Effective Theory

- Full theory: Contains all fields of the UV complete theory as dynamical degrees of freedom.
- Effective theory: Only contains the light particles as dynamical fields.
- Matching scale: Scale of some (heavy) particles at which the full and the effective theory are compared.
- Threshold correction: Difference between the coefficient of an operator in the effective and in the full theory.

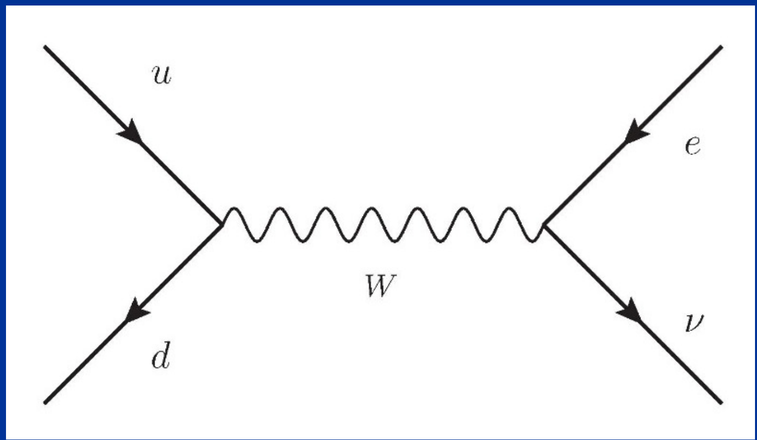
Evolution of Wilson coefficients

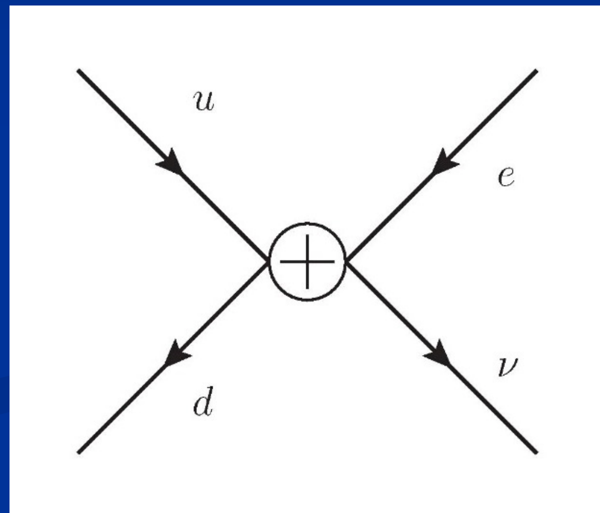
- Running: Scale dependence of a Wilson coefficient in the effective theory (most times induced by QCD effects).
- Mixing: Scale dependence in the case of a matrix valued evolution for the Wilson coefficients
- Anomalous dimension: Divergent part of the loop diagrams generating running and mixing
- Renormalization Group Evolution: Solution to the differential equation for the running/mixing

⇒ Resummation of large logs e.g. $\alpha_s^n \log^n \left(\frac{\mu_{high}}{\mu_{\log}} \right)$

Matching Example: Fermi Theory

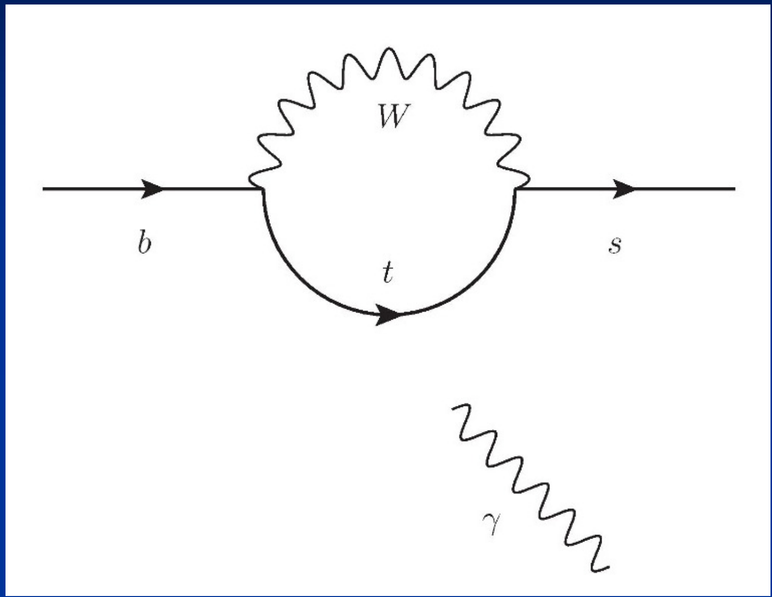
Full Theory ⟷ EFT

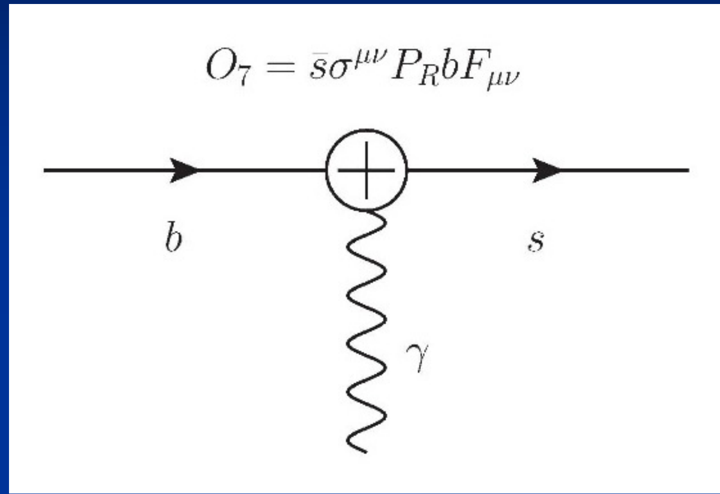


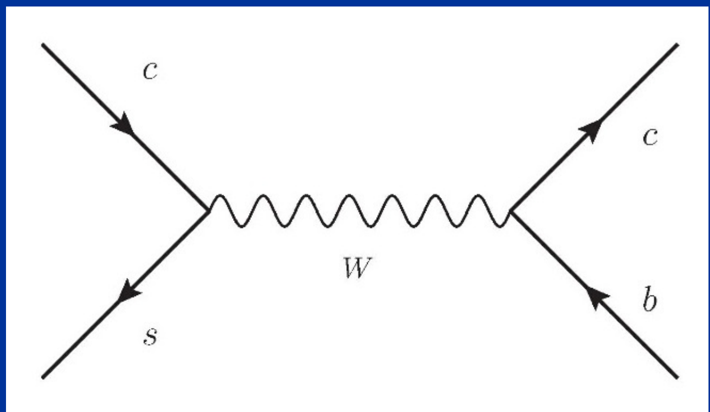


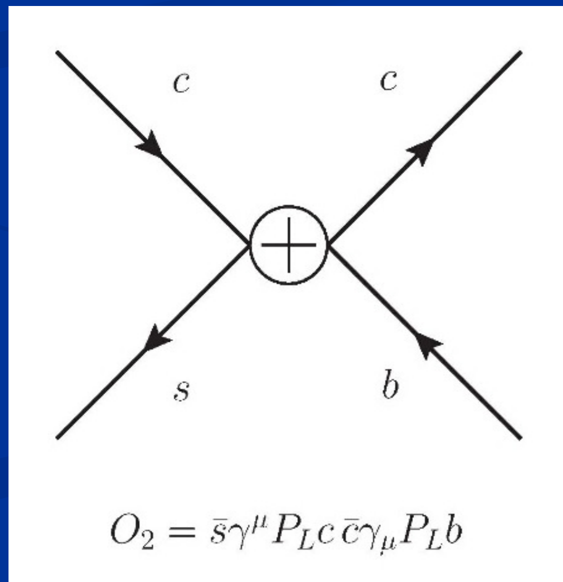
$$\frac{g_{\mu\nu} + \frac{p^{\mu} p^{\nu}}{m_W^2}}{p^2 - m_W^2} \quad \Longleftrightarrow \quad \frac{-g_{\mu\nu}}{m_W^2} + O\left(\frac{1}{m_W^4}\right)$$

Example: b→sγ matching



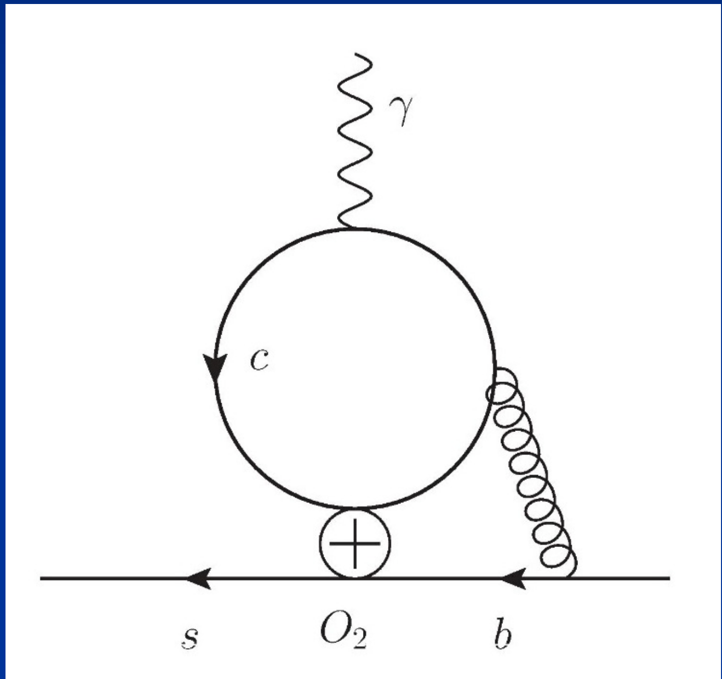


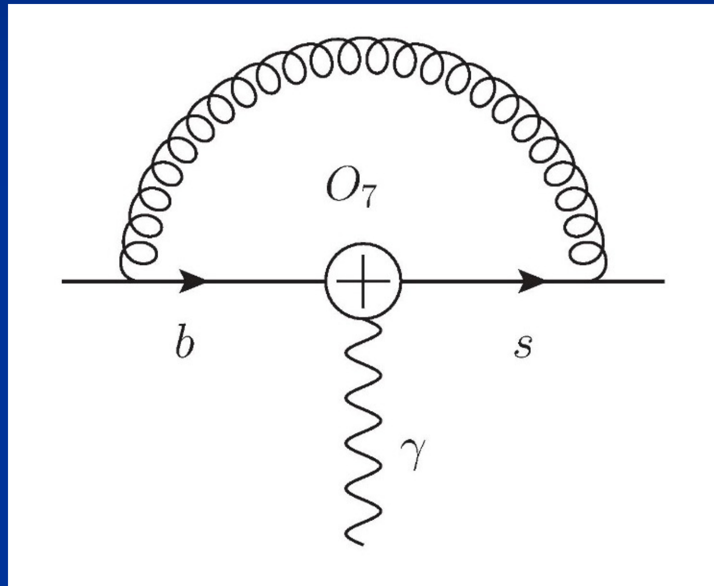




⇒ Wilson Coefficients $C_2, C_7, \ldots$

Example:
b→sγ running and mixing





mixing $O_2 \to O_7$

running O_7

➡ Evolution to the low scale

Higher dimensional operators beyond the SM

- NP at the scale $\Lambda > v$ must be invariant under the SM gauge group
- The heavy degrees of freedom can be integrated out T. Appelquist, J. Carazzone

⇒ The resulting effective operators must be Lorentz invariant, respect the SM gauge group and are suppressed by powers of $1/\Lambda$.

B. Grzadkowski et al., arXiv:1008.4884
W. Buchmüller, D. Wyler, Nucl.Phys. B268 (1986) 621-653

Operator classification

$$L_{SM} = L_{SM}^{(4)} + 1/\Lambda \sum_k C_k^{(5)} Q_k^{(5)} + 1/\Lambda^2 \sum_k C_k^{(6)} Q_k^{(6)} + O\left(1/\Lambda^3\right)$$

- Dim 5: 1 operator, the Weinberg operator

$$Q_{\nu\nu} = \varepsilon_{jk}\varepsilon_{mn}\varphi^j\varphi^m \left(\ell_p^k\right)^T C l_r^n = \left(\varphi^\dagger l_p\right)^T C\left(\varphi^\dagger \ell_r\right)$$

- Dim 6: 59 operators
  - 30 four-fermion operators $Q_{le} = \left(\bar{\ell}_p \gamma_\mu \ell_r\right)\left(\bar{e}_s \gamma^\mu e_t\right)$
  - 4 pure field-strength tensor operators $Q_G = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
  - 3 SM-scalar-doublet operators $Q_\varphi = (\varphi\varphi^\dagger)^3$
  - 8 Higgs-field-strength operators $Q_{\varphi G} = \varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$
  - 3 Higgs-fermion operators $Q_{\varphi e} = \varphi^\dagger \varphi \bar{\ell}_i \varphi e_j$
  - 8 “magnetic” operators $Q_{eB} = \bar{\ell}_i \sigma_{\mu\nu} e_j \varphi B^{\mu\nu}$
  - 8 Higgs-fermion-derivative $Q_{\varphi\ell}^{(1)} = \varphi^\dagger D_\mu \varphi \bar{\ell}_i \gamma^\mu \ell_j$

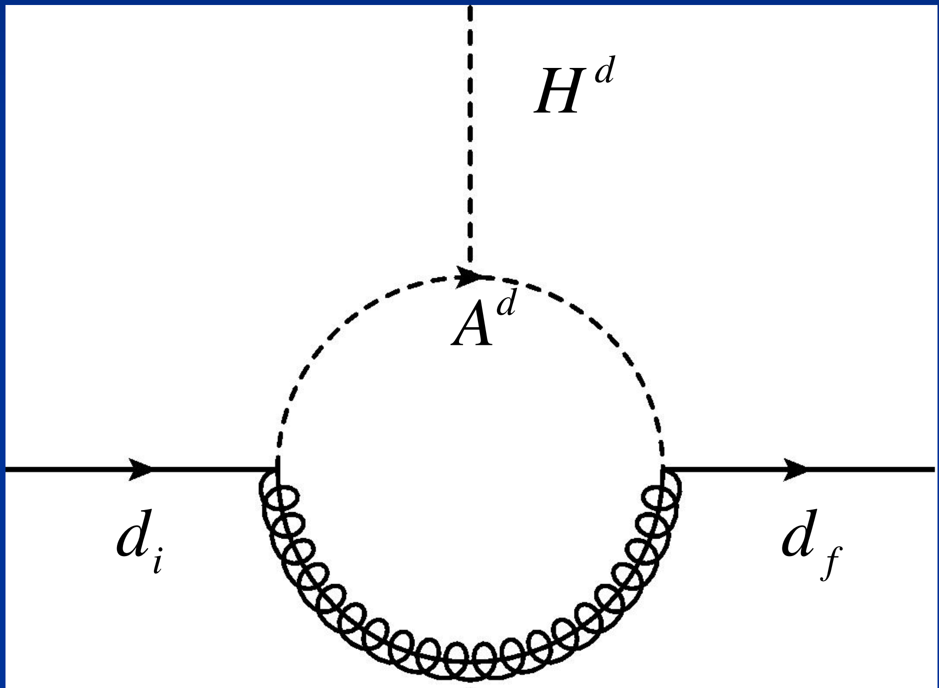
General procedure

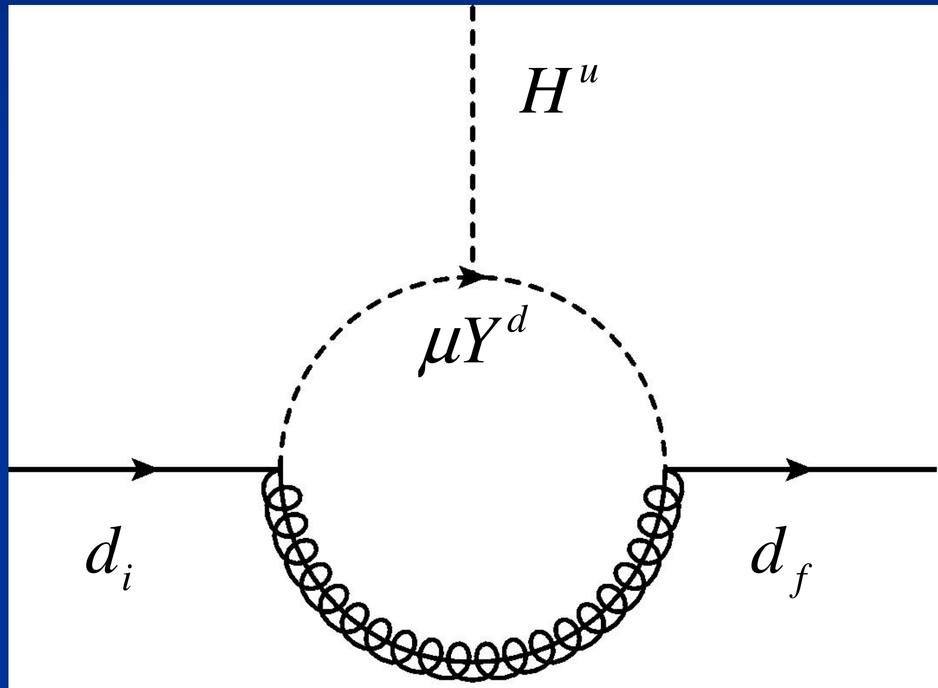
- Perform EW symmetry breaking
- Derive the Feynman rules
- Calculate the Feynman diagrams
- Perform the matching (integrate out W,Z, t and h)
- RGE evolution to the low scale
- Calculation of decay width, cross sections, etc.

(Effective) Higgs-quark vertices in the MSSM

Loop corrections to Higgs quark couplings

- Before electroweak symmetry breaking
- After electroweak symmetry breaking





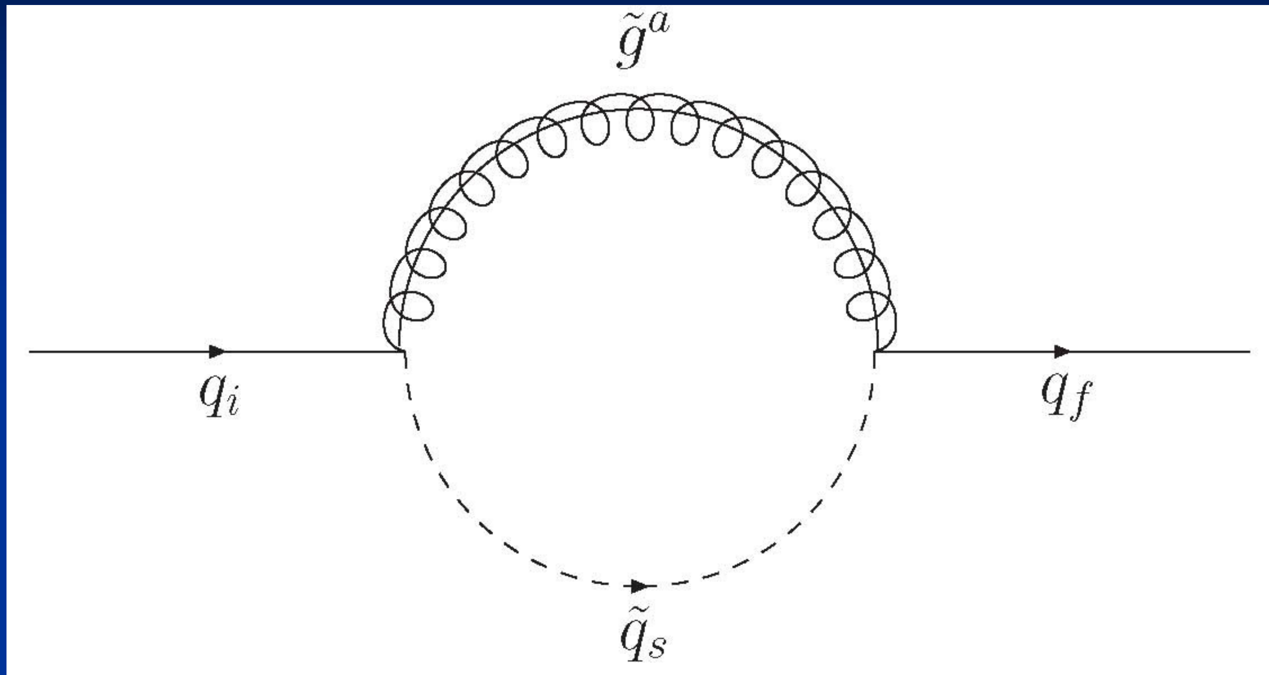
$$\Sigma^{d\,LR}_{fi\,A} = v_d \Gamma^{H^d}_{d_f d_i} \qquad \Gamma^{H^d}_{d_f d_i}$$

$$\Sigma^{d\,LR}_{fi\,Y} = v_u \Gamma^{H^u}_{d_f d_i} \qquad \Gamma^{H^u}_{d_f d_i}$$

➡ One-to-one correspondence between Higgs-quark couplings and chirality changing self-energies. (In the decoupling limit)

SQCD self-energy:

$$-i\Sigma(0)^{q\,LR}_{fi} =$$



$$\Sigma^{q\,LR}_{fi} = \alpha_s \frac{2}{3\pi} m_{\tilde{g}} W_{fs} W^*_{i+3,s} B_0\left(m_{\tilde{g}}^{\;2}, m^2_{\tilde{q}_s}\right)$$

Finite and proportional to at least one power of $\Delta^{q\,LR}_{fi}$

$$\Sigma^{q\,LR}_{fi} = \alpha_s \frac{2}{3\pi} m_{\tilde{g}} W^q_{fs} W^{q*}_{js} \Delta^{q\,LR}_{jl} W^q_{l+3.t} W^{q*}_{i+3,t} C_0\left(m_{\tilde{g}}^{\;2}, m^2_{\tilde{q}_s}, m^2_{\tilde{q}_t}\right)$$

decoupling limit

Decomposition of the self-energy

Decompose the self-energy

$$\Sigma_{ii}^{d\,LR} = \Sigma_{ii\,A}^{d\,LR} + \Sigma_{ii\,Y}^{d\,LR}$$

into a holomorphic part proportional to an A-term

$$\Sigma_{fi\,A}^{d\,LR} = -v_d \alpha_s \frac{2}{3\pi} m_{\tilde{g}} W_{fs}^{d} W_{js}^{d*} A_{jl}^{q} W_{lt}^{d} W_{it}^{d*} C_0\left(m_{\tilde{g}}^{2}, m_{\tilde{q}_s}^{2}, m_{\tilde{q}_t}^{2}\right)$$

non-holomorphic part proportional to a Yukawa

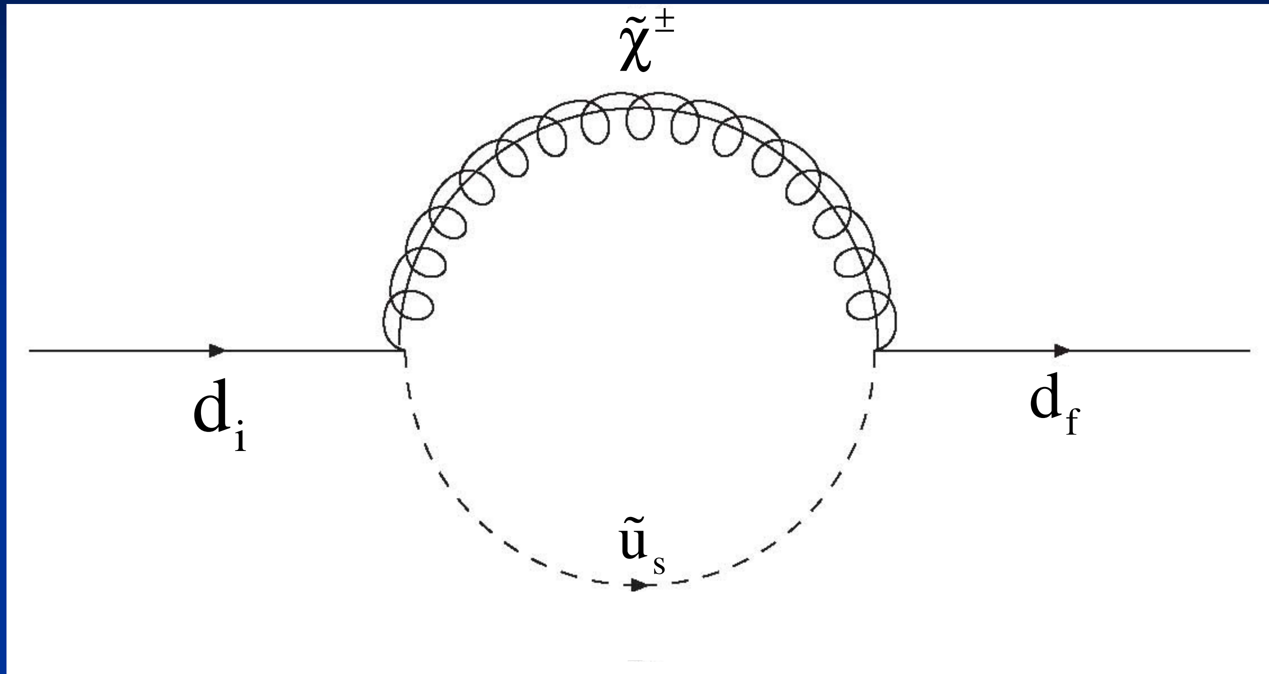
$$\Sigma_{fi\,Y}^{d\,LR} = -v_u \mu \alpha_s \frac{2}{3\pi} m_{\tilde{g}} W_{fs}^{d} W_{js}^{d*} Y^{d_j} W_{jt}^{d} W_{it}^{d*} C_0\left(m_{\tilde{g}}^{2}, m_{\tilde{q}_s}^{2}, m_{\tilde{q}_t}^{2}\right)$$

Define dimensionless quantity $\varepsilon_i^{d} = \Sigma_{ii\,Y}^{d\,LR} \big/ v_u Y^{d_i}$

which is independent of a Yukawa coupling

Chargino self-energy:

$$-i\Sigma(0)^{d\,LR}_{fi\,\tilde{\chi}^{\pm}} =$$



$$\Sigma^{\tilde{\chi}^{\pm}\,LR}_{d_f d_3} = \frac{-1}{16\pi^2}\mu Y^{d_3}\left[V^{CKM(0)*}_{3f} Y^{u_3*} \Delta^{u\,RL}_{33} \sum_{s,t=1}^{6} V^{u\,RR}_{s\,33} V^{d\,LL}_{t\,33} C_0\left(|\mu|^2, m^2_{\tilde{u}_s}, m^2_{\tilde{u}_t}\right)\right.$$

$$\left. -\sqrt{2} g_2 \sin(\beta) M_W M_2 \sum_{s=1}^{6} V^{d\,LL}_{s\,f\,3} C_0\left(m^2_{\tilde{q}_s}, |\mu|^2, |M_2|^2\right)\right]$$

Renormalization I

- All corrections are finite; counter-term not necessary.
- Minimal renormalization scheme is simplest.

Mass renormalization

$$m_{d_i} = v_d Y^{d_i (0)} + \Sigma_{ii}^{d\,LR}$$
$$= v_d Y^{d_i (0)} + \Sigma_{ii\,A}^{q\,LR} + v_d \tan(\beta) Y^{d_i (0)} \varepsilon_{d_i}$$

$$\Rightarrow \quad Y^{d_i (0)} = \frac{m_{d_i} - \Sigma_{ii\,A}^{q\,LR}}{v_d \left(1 + \tan(\beta) \varepsilon_i^d\right)}$$

- tan(β) is automatically resummed to all orders

Renormalization II

- Flavour-changing corrections

important two-loop corrections

A.C. Jennifer Girrbach 2010

$$U^{q\,L} = \begin{pmatrix} 1 - \frac{\left|\Sigma_{12}^{q\,LR}\right|^2}{2m_{q_2}^2} & \frac{1}{m_{q_2}}\Sigma_{12}^{q\,LR} & \frac{1}{m_{q_3}}\Sigma_{13}^{q\,LR} \\ \frac{-1}{m_{q_2}}\Sigma_{21}^{q\,RL} & 1 - \frac{\left|\Sigma_{12}^{q\,LR}\right|^2}{2m_{q_2}^2} & \frac{1}{m_{q_3}}\Sigma_{23}^{q\,LR} \\ \frac{-1}{m_{q_3}}\Sigma_{31}^{q\,RL} + \frac{\Sigma_{32}^{q\,RL}\Sigma_{21}^{q\,RL}}{m_{q_2}m_{q_3}} & \frac{-1}{m_{q_3}}\Sigma_{32}^{q\,RL} & 1 \end{pmatrix}$$

Renormalization III

- Renormalization of the CKM matrix:

$$V^{(0)} = U^{u\,L} V \; U^{d\,L\dagger}$$

- Decomposition of the rotation matrices

$$U^{q\,L} = U^{q\,L}_{\not{CKM}} U^{q\,L}_{CKM}$$

- Corrections independent of the CKM matrix

$$\tilde{V} = U^{u\,L\dagger}_{\not{CKM}} V^{(0)} U^{d\,L}_{\not{CKM}}$$

- CKM dependent corrections

$$U^{u\,L\dagger}_{CKM} \tilde{V} U^{d\,L}_{CKM}$$

$$\Rightarrow \quad V^{(0)}_{13,23} = \frac{\tilde{V}_{13,23}}{1+\varepsilon_{FC}}$$

Effective gaugino and higgsino vertices

- No enhanced genuine vertex corrections.

- Calculate $\varepsilon_{d_i}, \varepsilon^{d}_{FC}, \Sigma^{q\,LR}_{ii\,\cancel{Y_i}}, \Sigma^{q\,LR}_{ii\,\cancel{CKM}}$
- Determine the bare Yukawas and bare CKM matrix
- Insert the bare quantities for the vertices.
- Apply rotations $U^{q\,L,R}_{fi}$ to the external quark fields.
- Similar procedure for leptons (up-quarks)

Chiral enhancement

$$\Sigma_{fi}^{d\,LR} \approx \frac{1}{50}\frac{\Delta_{fi}^{q\,LR}}{M_{SUSY}} = \frac{-v_d}{50}\left(\tan(\beta)\,Y_i^{d(0)}\delta_{ij} + \frac{A_{ij}^d}{M_{SUSY}}\right)$$

- For the bottom quark only the term proportional to tan(β) is important.

  ➡ tan(β) enhancement

  Blazek, Raby, Pokorski, hep-ph/9504364

$$\Sigma_{33\,Y}^{d\,LR} = \frac{-1}{100} v_d \tan(\beta)\,Y^{b(0)} \sim m_b$$

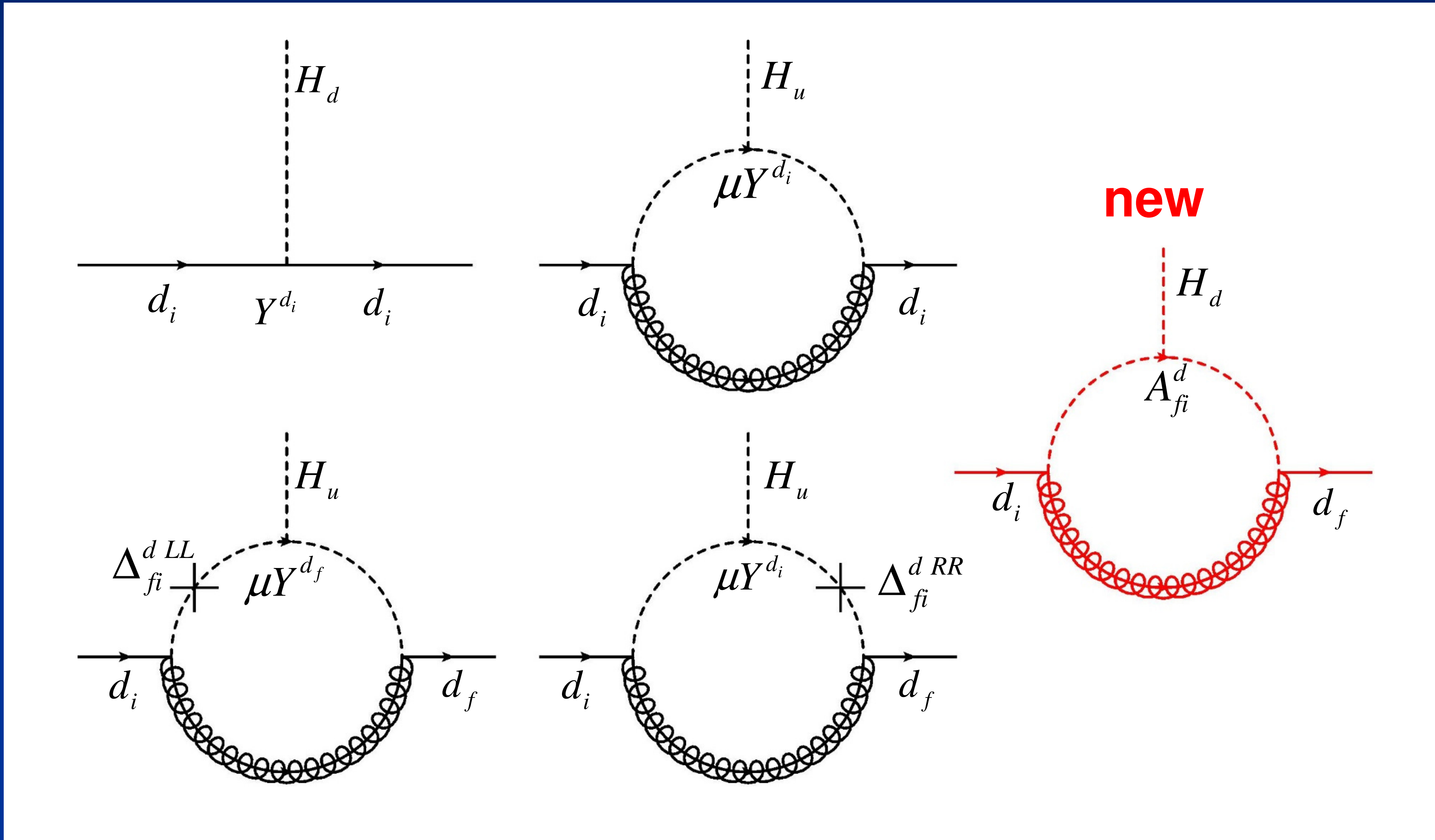
$$O\left(\frac{\tan(\beta)}{100}\right)$$

- For the light quarks also the part proportional to the A-term is relevant.

$$\Sigma_{22\,A}^{d\,LR} = O(1), \quad A_{22}^d \approx M_{SUSY}$$

$$\Sigma_{11\,A}^{d\,LR} = O(1), \quad A_{11}^d \approx \frac{1}{50} M_{SUSY}$$

Higgs vertices in the EFT I



Higgs vertices in the EFT II

$$\mathcal{L}_{Y}^{eff} = \bar{Q}^{a}_{f\,L}\left(\left(Y^{d}_{i}\delta_{fi} + E^{d}_{fi}\right)\varepsilon_{ba}H^{b}_{d} + E'^{d}_{fi}H^{a*}_{u}\right)d_{i\,R}$$

- Non-holomorphic corrections $E'^{d}_{fi} = \Sigma^{d\,LR}_{fi\,Y} / v_u$
- Holomorphic corrections $E^{d}_{fi} = \Sigma^{d\,LR}_{fi\,A} / v_d$
- The quark mass matrix $m^{d}_{fi} = v_d\left(Y^{d_i}\delta_{fi} + E^{d}_{fi}\right) + v_u E'^{d}_{fi}$ is no longer diagonal in the same basis as the Yukawa coupling

⇒ Flavor-changing neutral Higgs couplings

Effective Yukawa couplings

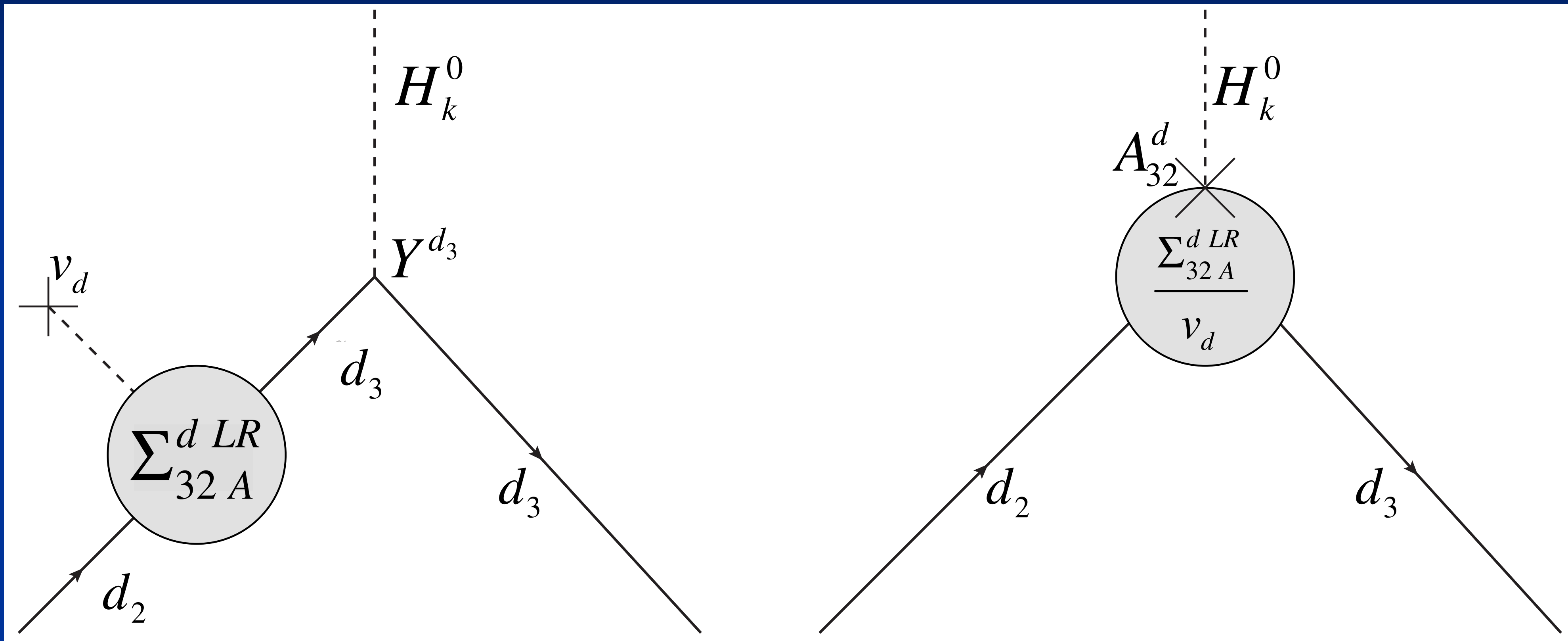
- Final result: $Y_{ij}^{d\,\mathrm{eff}} = \frac{1}{v_d}\left(m_{d_i}\delta_{ij} - \tilde{\Sigma}_{ij\,Y}^{d\,LR}\right)$ with

$$\tilde{\Sigma}_{jk\,Y}^{d\,LR} = U_{jf}^{d\,L*}\Sigma_{jk\,Y}^{d\,LR}U_{ki}^{d\,R}$$

$$\approx \Sigma_{fi\,Y}^{d\,LR} - \begin{pmatrix} 0 & \frac{\Sigma_{22\,Y}^{d\,LR}}{m_{d_2}}\Sigma_{12}^{d\,LR} & \frac{\Sigma_{33\,Y}^{d\,LR}}{m_{d_3}}\Sigma_{13}^{d\,LR} \\ \frac{\Sigma_{22\,Y}^{d\,LR}}{m_{d_2}}\Sigma_{21}^{d\,LR} & 0 & \frac{\Sigma_{33\,Y}^{d\,LR}}{m_{q_3}}\Sigma_{23}^{d\,LR} \\ \frac{\Sigma_{33\,Y}^{d\,LR}}{m_{d_3}}\Sigma_{31}^{d\,LR} & \frac{\Sigma_{33\,Y}^{d\,LR}}{m_{q_3}}\Sigma_{32}^{d\,LR} & 0 \end{pmatrix}$$

Diagrammatic explanation in the full theory:

Higgs vertices in the full theory



- Cancellation incomplete since $v_d Y^{d_3} \neq m_{d_3}$
  Part proportional to $\Sigma_{33\,Y}^{d\,LR}$ is left over.

➡ A-terms generate flavor-changing Higgs couplings

NLO Calculation

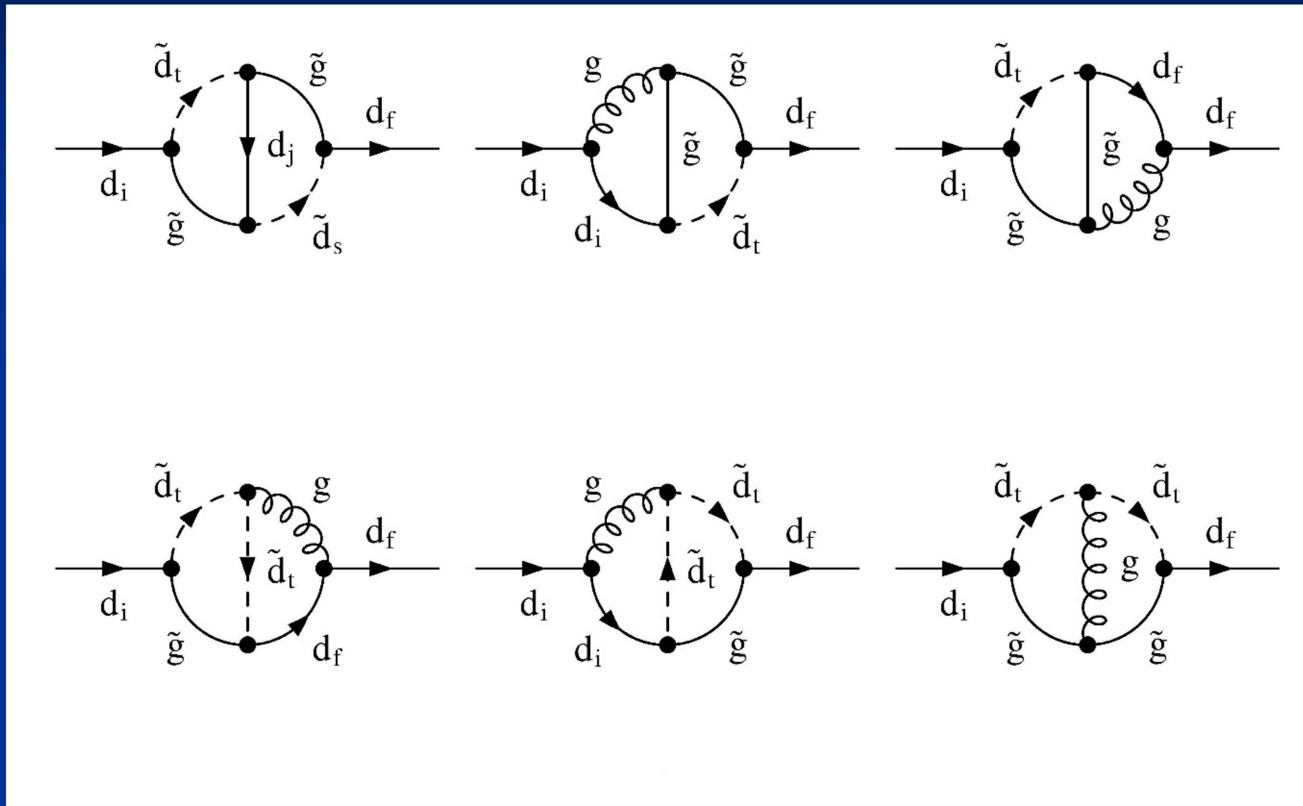
NLO calculation of the quark self-energies

NLO calculation is important for:

- Computation of effective Higgs-quark vertices.
- Determination of the Yukawa couplings of the MSSM superpotential (needed for the study of Yukawa unification in GUTs).
- NLO calculation of FCNC processes in the MSSM at large tan(β).

Reduction of the matching scale dependence

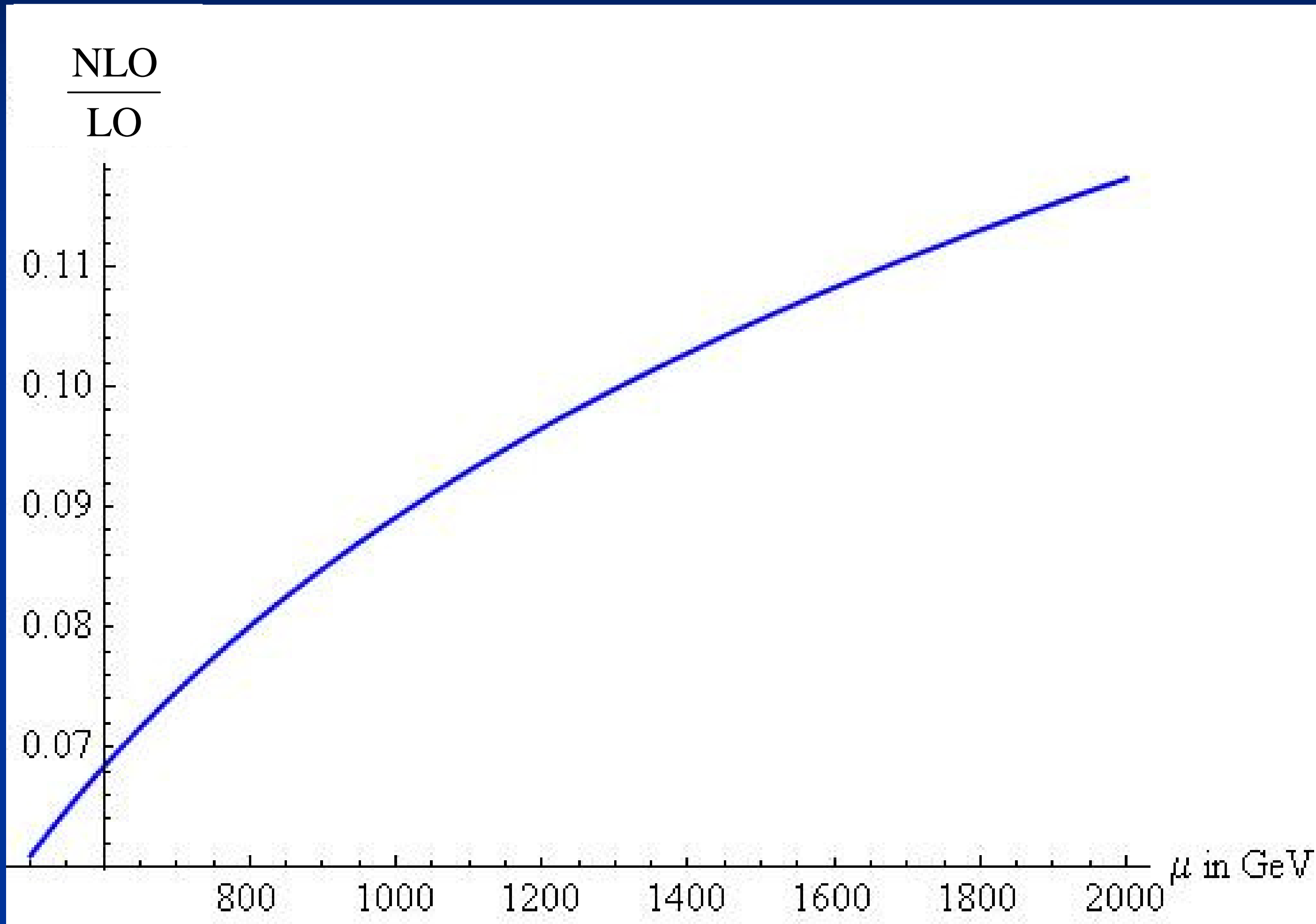
NLO calculation



Examples of 2-loop diagrams

- NLO calculation includes analytic results and tan(β) resummation in the generic MSSM. Δ_b at order α_s^2

NLO results



Relative importance of the 2-loop corrections approximately 9%

Extension to the NMSSM

A.C., Youichi Yamada, arXiv:1508.02855

NMSSM

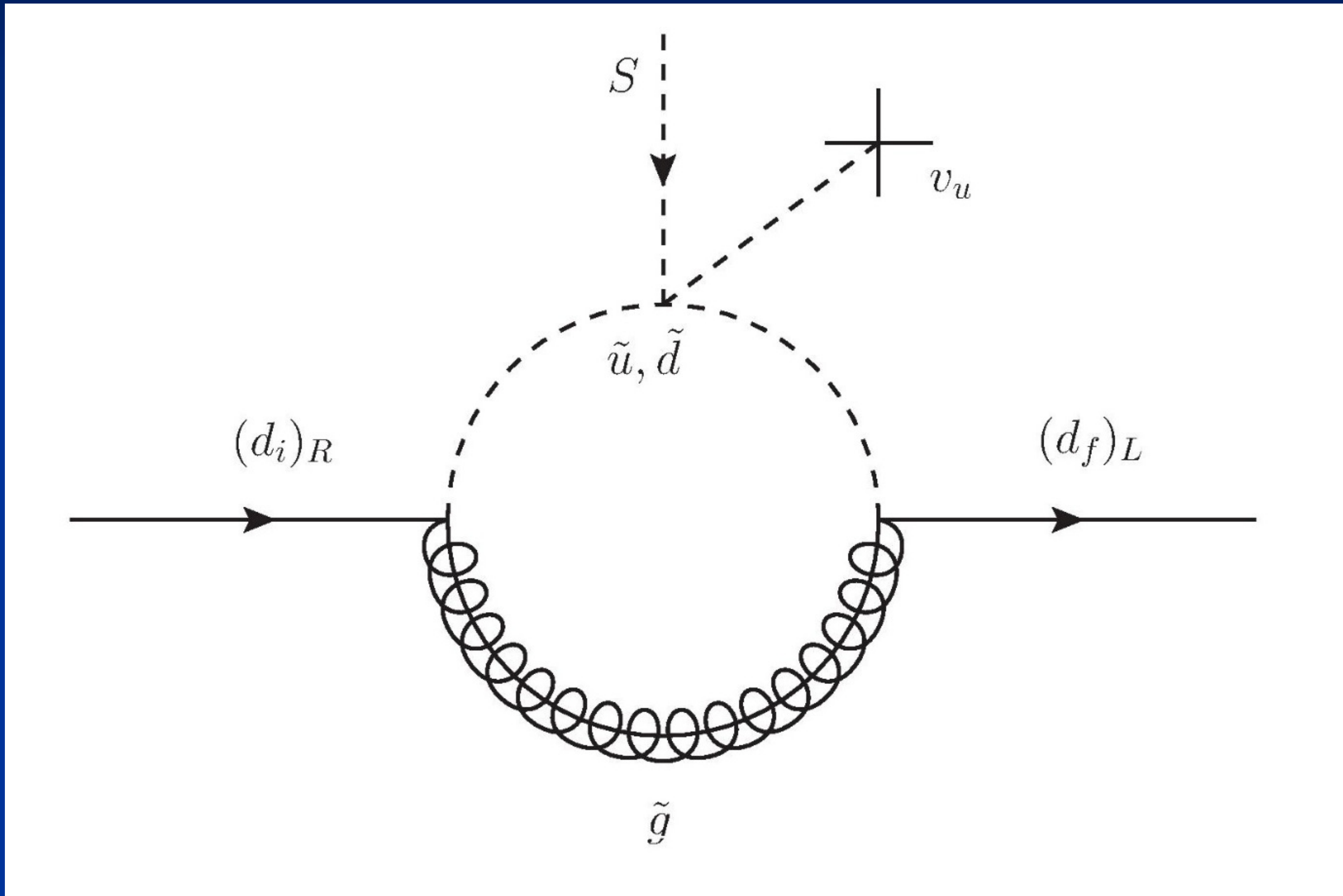
- Additional gauge singlet Superfield S
- The mu term of the MSSM superpotnential is generated by the vacuum expectation value of the scalar component of this singlet

$$\mu = \lambda v_S$$

⇒ Extended Higgs sector

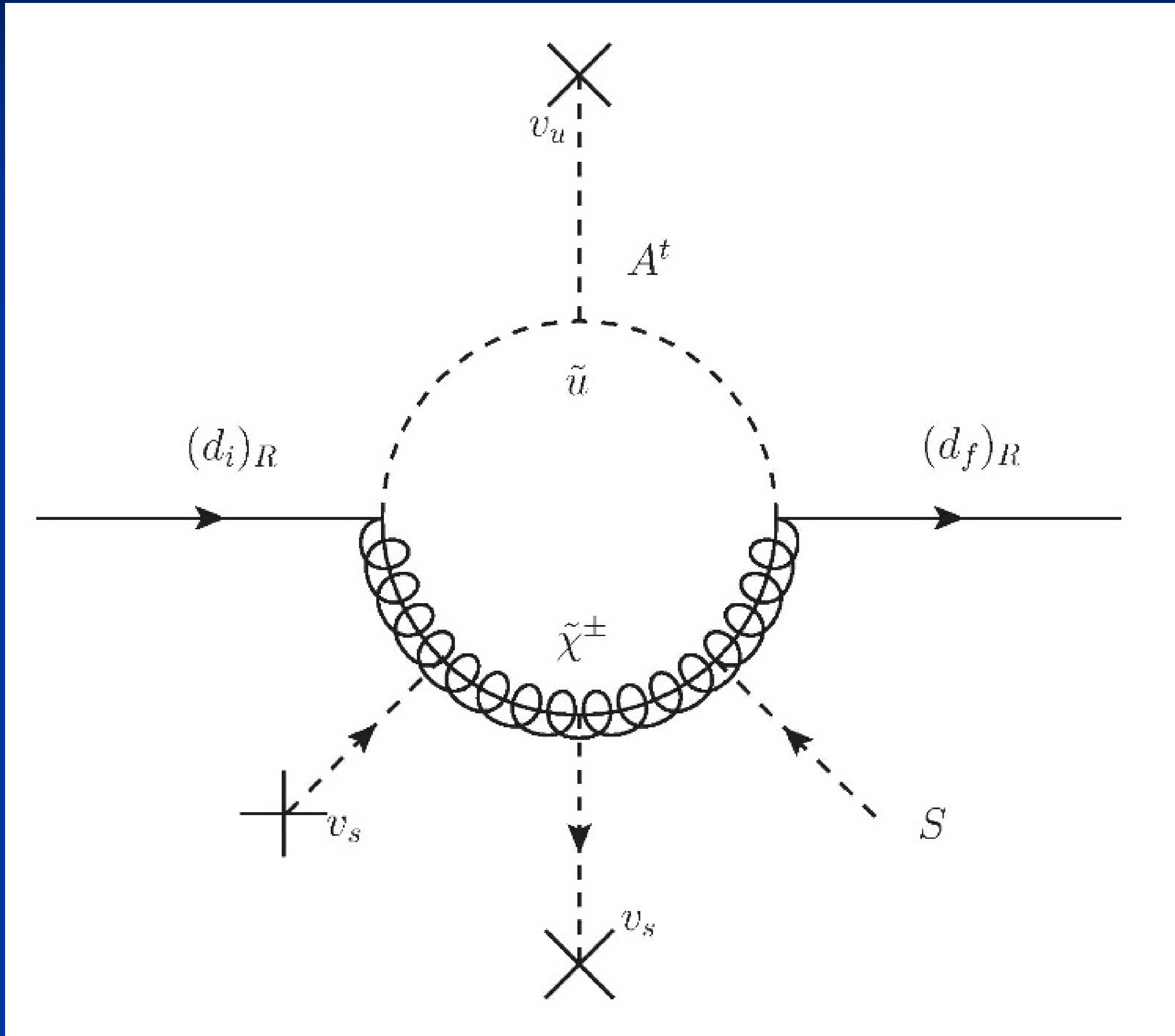
- Higgs mass can be generated with less fine tuning
- The mostly singlet does not couple to SM fermions at tree-level and can be very light

Gluino contribution



$$\Gamma^S_{dd} = \frac{\lambda}{\mu_{eff}} \Sigma^{LR}_{dd}$$

Chargino contribution



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Solution with Dyson series

$$\frac{\not{k}+\mu_{eff}}{k^2+\left|\mu_{eff}^2\right|}=\frac{1}{\not{k}}+\frac{1}{\not{k}}\mu_{eff}\frac{1}{\not{k}}+\frac{1}{\not{k}}\mu_{eff}\frac{1}{\not{k}}\mu_{eff}\frac{1}{\not{k}}+\ldots$$

- Odd power of μ

$$\frac{1}{\not{k}}+\frac{1}{\not{k}}\mu_{eff}\frac{1}{\not{k}}+\frac{1}{\not{k}}\mu_{eff}\frac{1}{\not{k}}\mu_{eff}^{*}\frac{1}{\not{k}}\mu_{eff}\frac{1}{\not{k}}+\ldots=\frac{\mu_{eff}}{k^2+\left|\mu_{eff}^2\right|}$$

- One μ_{eff} replaced by λS

$$\frac{1}{\not{k}}+\frac{1}{\not{k}}\lambda S\frac{1}{\not{k}}+2\frac{1}{\not{k}}\lambda S\frac{1}{\not{k}}\mu_{eff}^{*}\frac{1}{\not{k}}\mu_{eff}\frac{1}{\not{k}}+\ldots$$

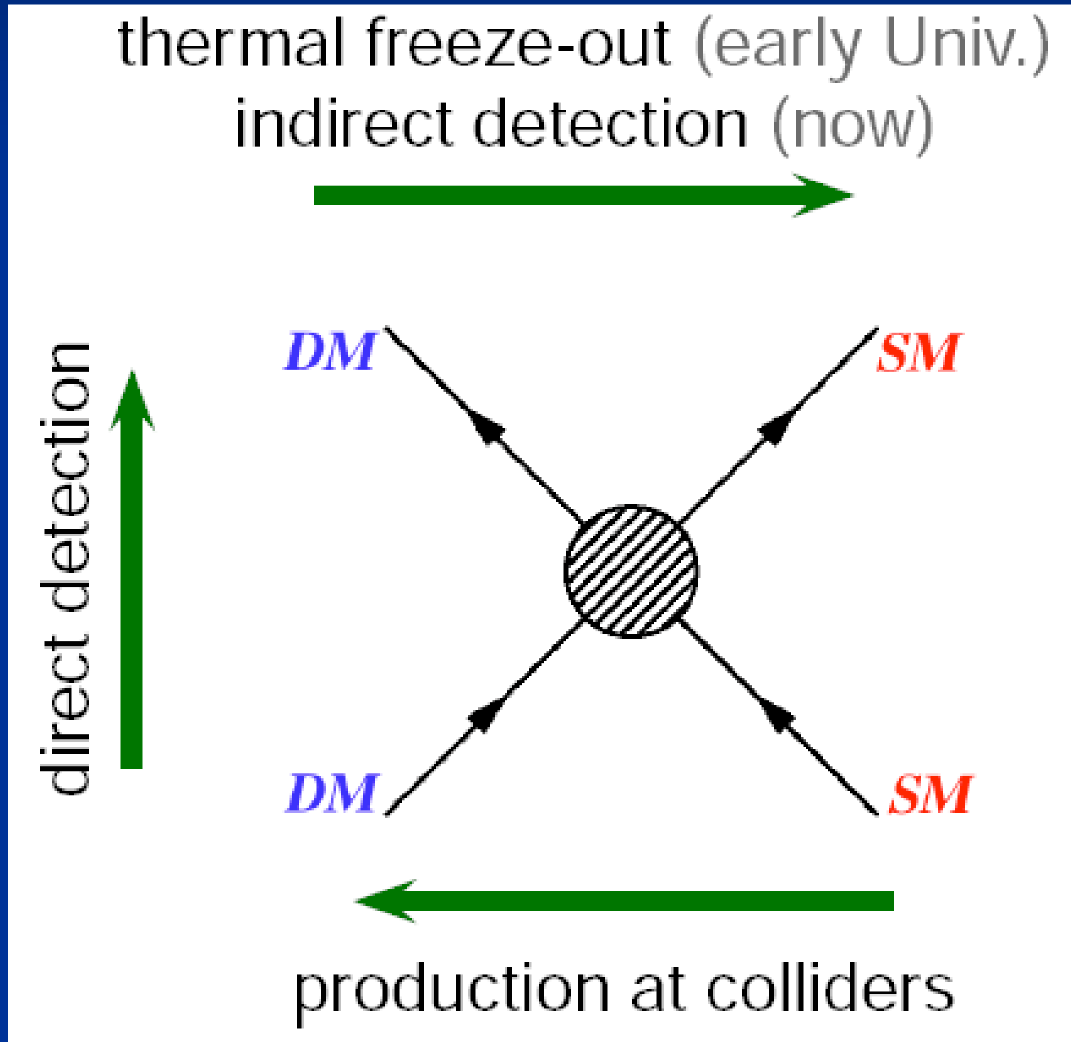
$$=\lambda S\left(\frac{1}{k^2+\left|\mu_{eff}^2\right|}+\frac{\left|\mu_{eff}^2\right|}{\left(k^2+\left|\mu_{eff}^2\right|\right)^2}\right)$$

Effective field theory approach to Dark Matter

A.C., F. d'Eramo, M. Procura, arXiv:1402.1173
A.C., M. Hoferichter, M. Procura arXiv:1312.4951
A.C., U. Haisch, arXiv:1408:5046

Direct/inderect Detection and LHC searches

- Same couplings and particles, but at different energy scales
- LHC and direct detection mainly sensitive to quark couplings



Spin independent scattering cross section

- Up to Dim 7 (at the direct detection scale)

$$\sigma_N^{\mathrm{SI}} \approx \frac{m_N^2}{\pi\Lambda^4}\left|\sum_{q=u,d} C_{qq}^{VV} f_{V_q}^N + \frac{m_N}{\Lambda}\left(\sum_{q=u,d,s} C_{qq}^{SS} f_q^N - 12\pi C_{gg}^S f_Q^N\right)\right|^2$$

$$L_{eff} = \sum_X C_X O_X$$

$$O_{gg}^S = \frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$$

$$O_{qq}^{SS} = \frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$$

$$O_{qq}^{VV} = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

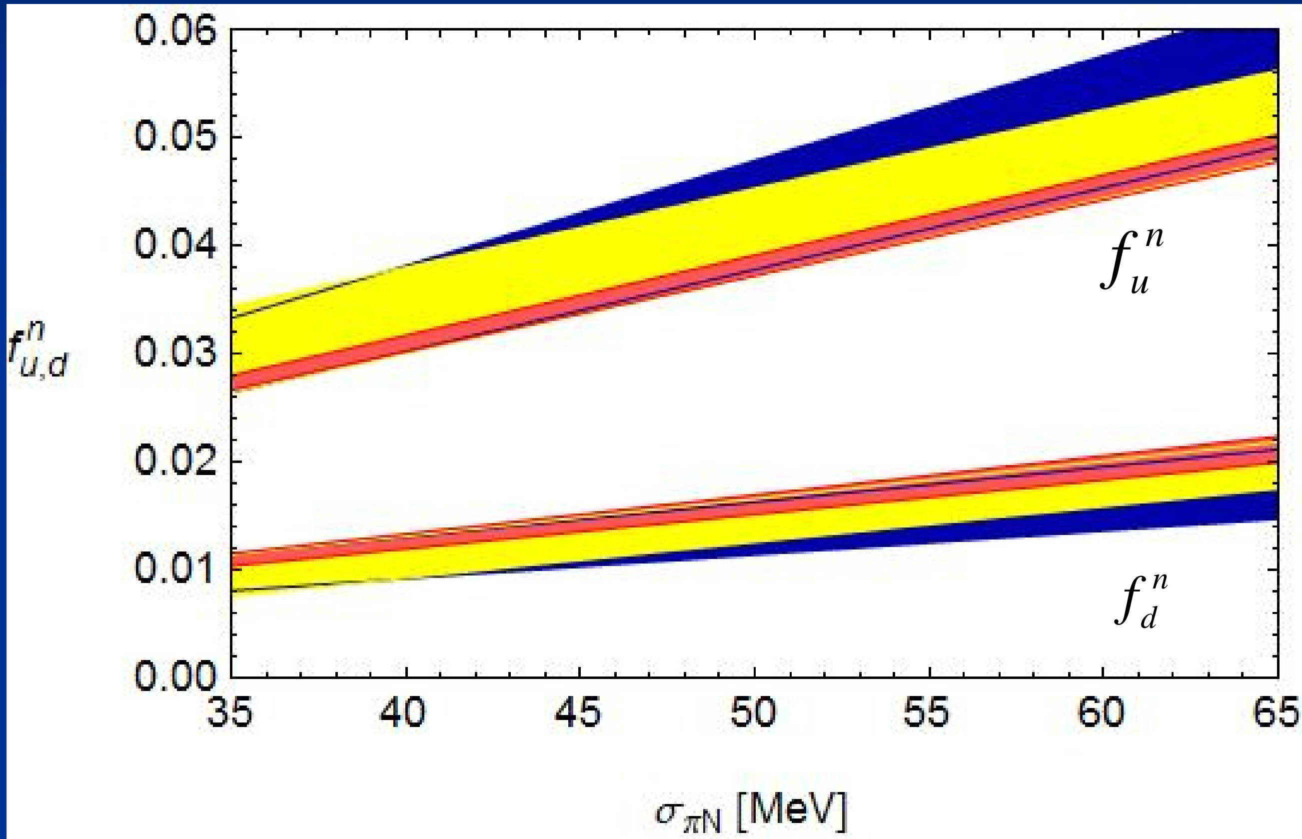
f^N : nucleon couplings

m_N : nucleon mass

The Wilson coefficients C_X must be connected to UV physics

Scalar quark content of the nucleon

- Tradiational approach: SU(3) chiral pertubation
- Better: SU(2) chiral pertubation theory and f_s from lattice



our result

SU(3)

SU(3) with f_s

EFT for Dark Matter

- We assume that DM is:
  - A SM singlet (other choices are also possible)
  - A Dirac fermion (biggest number of operators)
- Interactions of DM with the SM arise through messengers at a high scale Λ
- Construct operators which are invariant under the SM gauge group
- This scale Λ must be connected to the direct detection scale via running, mixing and threshold effects.

Operators dim-5

$$O_M^T = \frac{1}{\Lambda}\bar{\chi}\sigma^{\mu\nu}\chi B_{\mu\nu}, \quad O_{HH}^S = \frac{1}{\Lambda}\bar{\chi}\chi H^\dagger H, \quad O_{HH}^P = \frac{1}{\Lambda}\bar{\chi}\gamma^5\chi H^\dagger H$$

- O_M^T : Tree-level contribution to direct detection
- O_{HH}^P : Affects only spin dependent direct detection
- O_{HH}^S : Enters only via matching corrections

Matching:

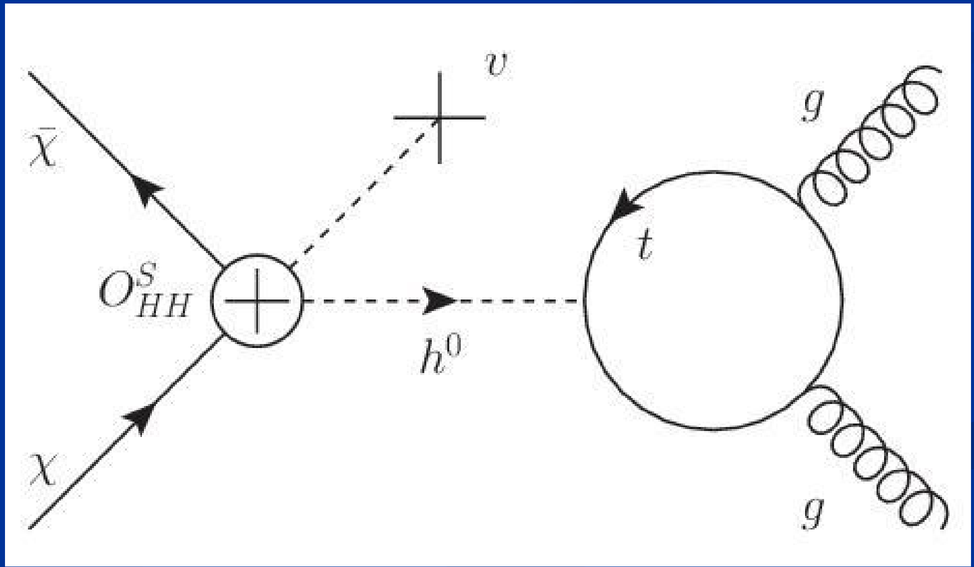
$$C_{gg}^S = \frac{1}{12\pi}\frac{\Lambda^2}{m_{h^0}^2}C_{HH}^S$$

$$C_{qq}^{SS} = -\frac{\Lambda^2}{m_{h^0}^2}C_{HH}^S$$

- Mixing turns out to be small

$$C_{qq}^{SS}(\mu_0) = \left[\frac{1}{12\pi}\left(U_{m_b,m_t}^{(5)} + 2\,U_{\mu_0,m_b}^{(4)}\right) - 1\right]\frac{\Lambda^2}{m_{h^0}^2}C_{HH}^S$$

$$U_{\mu,\Lambda}^{(n_f)} = \frac{-3C_F}{\pi\beta_0}\ln\frac{\alpha_s(\Lambda)}{\alpha_s(\mu)}.$$

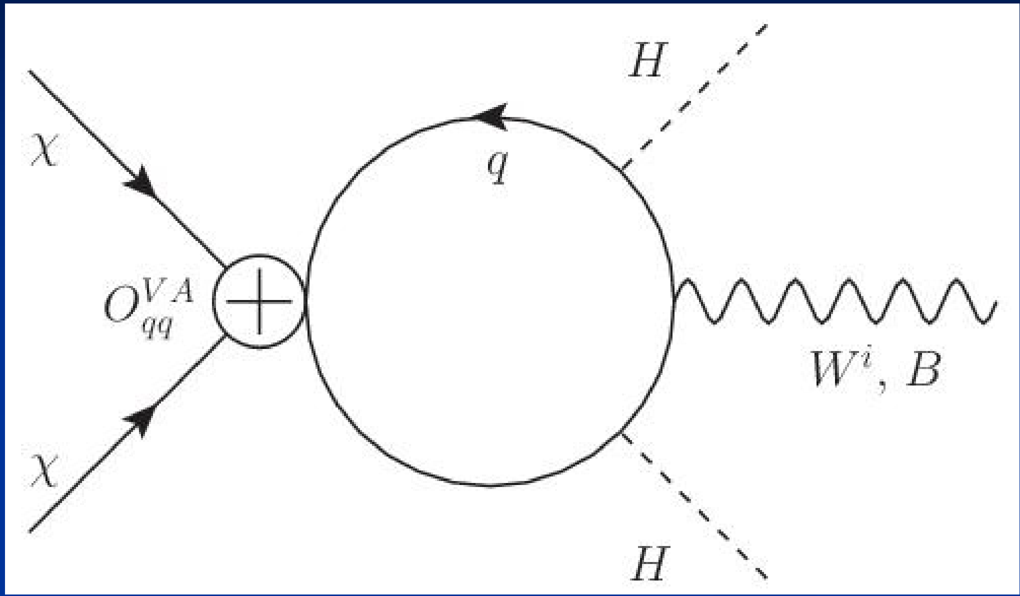


Operators dim-6

$$O_{qq}^{VV} = \frac{1}{\Lambda^2} \bar{\chi}\gamma^\mu \chi \, \bar{q}\gamma_\mu q$$

$$O_{qq}^{VA} = \frac{1}{\Lambda^2} \bar{\chi}\gamma^\mu \chi \, \bar{q}\gamma_\mu \gamma^5 q$$

$$O_{\phi\phi D}^{V} = \frac{i}{\Lambda^2} \bar{\chi}\gamma^\mu \chi \phi^\dagger \overleftrightarrow{D}_\mu \phi$$



- No QCD effects
- EW-mixing of O_{qq}^{VA} into O_{HHD}^{V}

$$C_{\phi\phi D}^{V}(\mu) = C_{\phi\phi D}^{V}(\Lambda) - \frac{\alpha_t N_c}{\pi} C_{tt}^{VA}(\Lambda) \ln\frac{\mu}{\Lambda} - (t \to b)$$

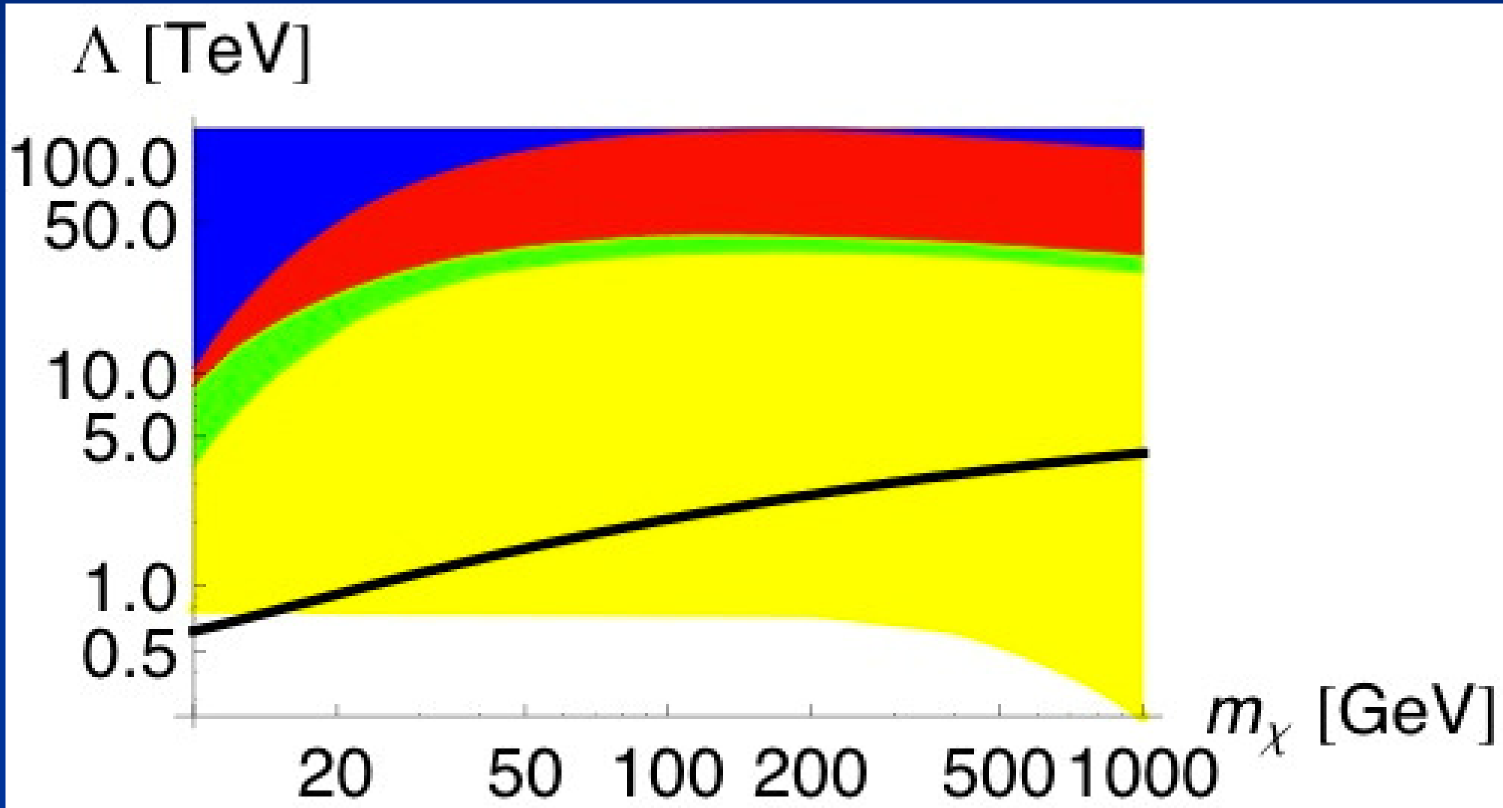
- Matching contributions

$$C_{uu}^{VV} \to C_{uu}^{VV} + \frac{1}{2} C_{HHD}^{V}, \; C_{dd}^{VV} \to C_{dd}^{VV} - \frac{1}{2} C_{HHD}^{V}$$

Bounds on previously unconstrained operators

Experimental constraints

$$C_{qq}^{VA} = 1$$



XENON1T

superCDMS

LUX

LHC

relic density

Operators dim-7

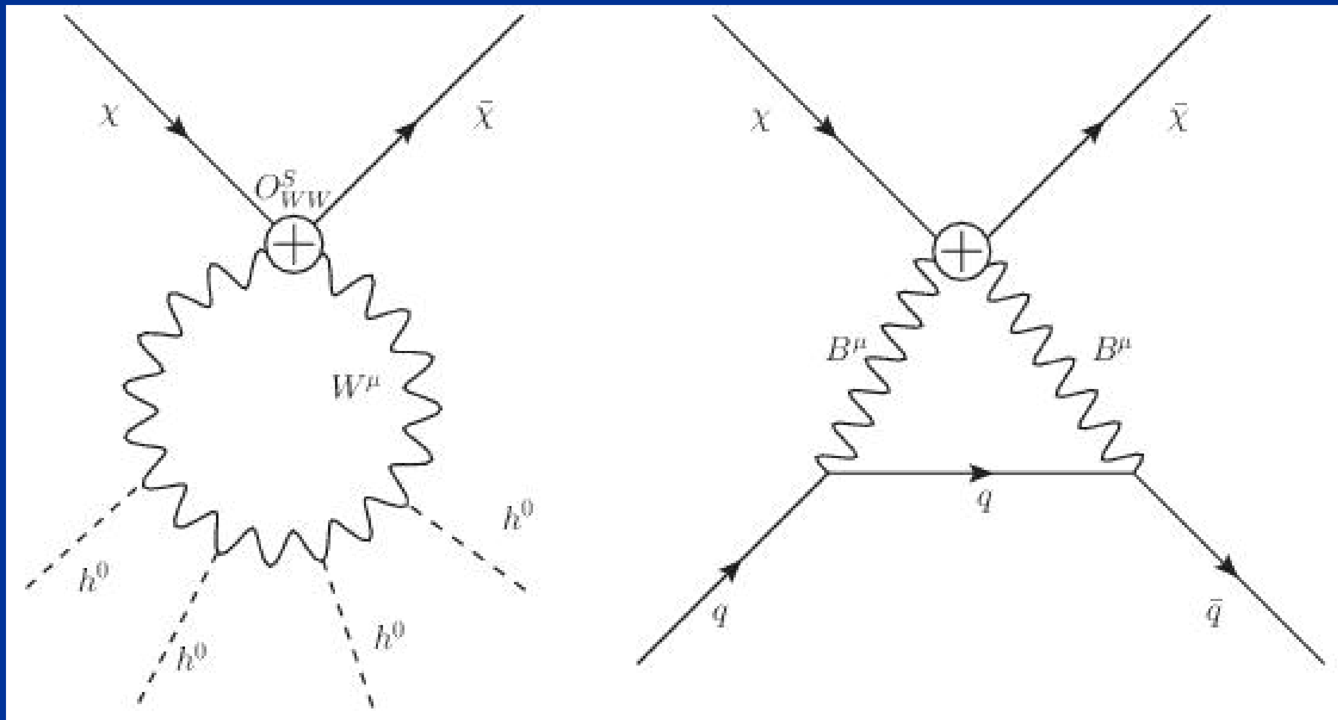
- Field strength tensors especially interesting

$$O_B = \frac{1}{\Lambda^2}\bar{\chi}\chi B^{\mu\nu}B_{\mu\nu}\ , \quad O_W = \frac{1}{\Lambda^2}\bar{\chi}\chi W^{\mu\nu}W_{\mu\nu}$$

- Mixing into

$$O_\phi^S = \frac{1}{\Lambda^3}\bar{\chi}\chi\phi\phi^\dagger\phi\phi^\dagger$$

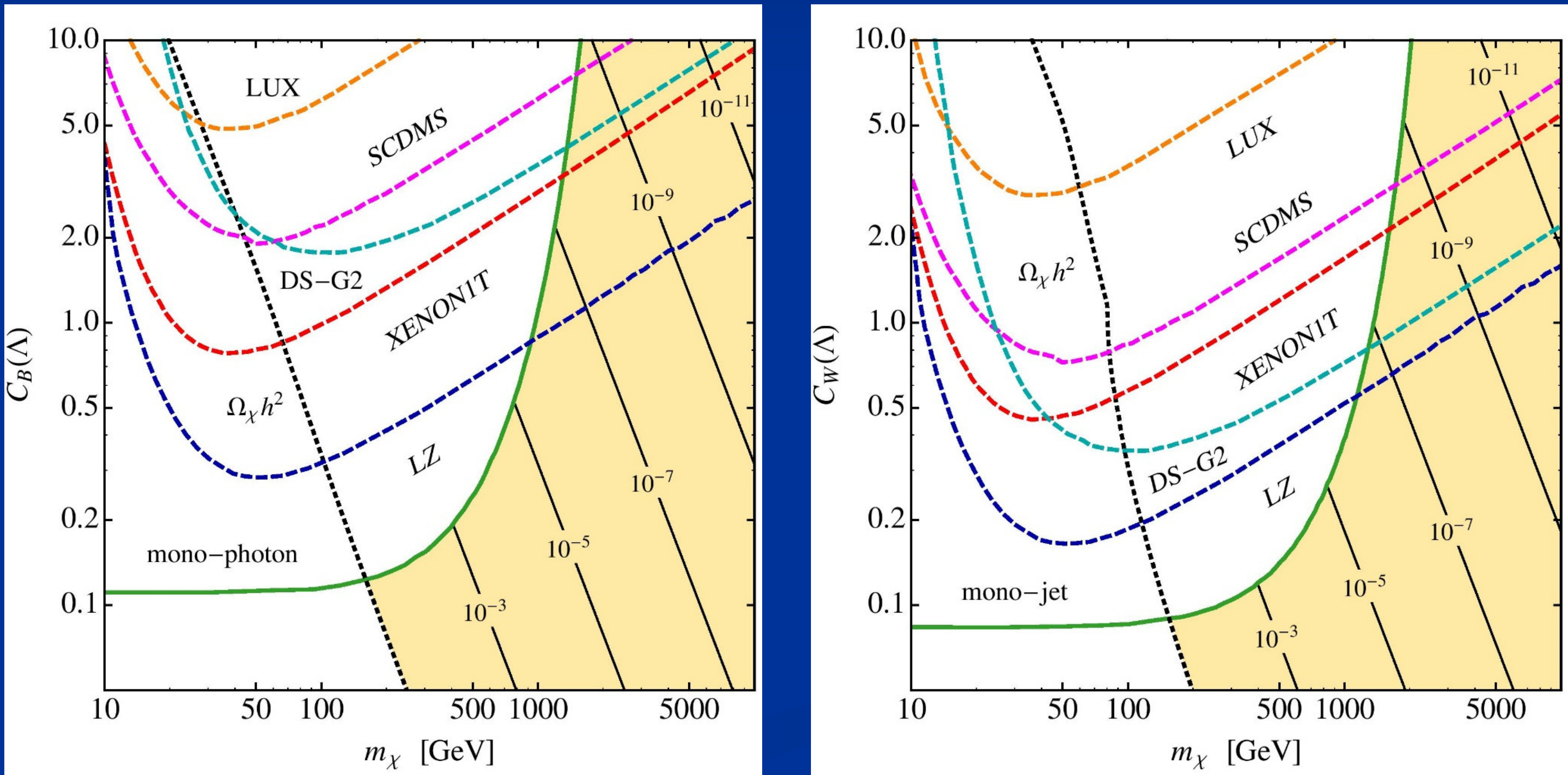
$$O_{qq}^\phi = \frac{Y^q}{\Lambda^3}\bar{\chi}\chi\bar{q}\phi q$$



Contributions to direct detection after EW symmetry breaking and integrating out the Higgs.

Constraints on C_{WW}

- Interesting interplay between direct detection and LHC searches

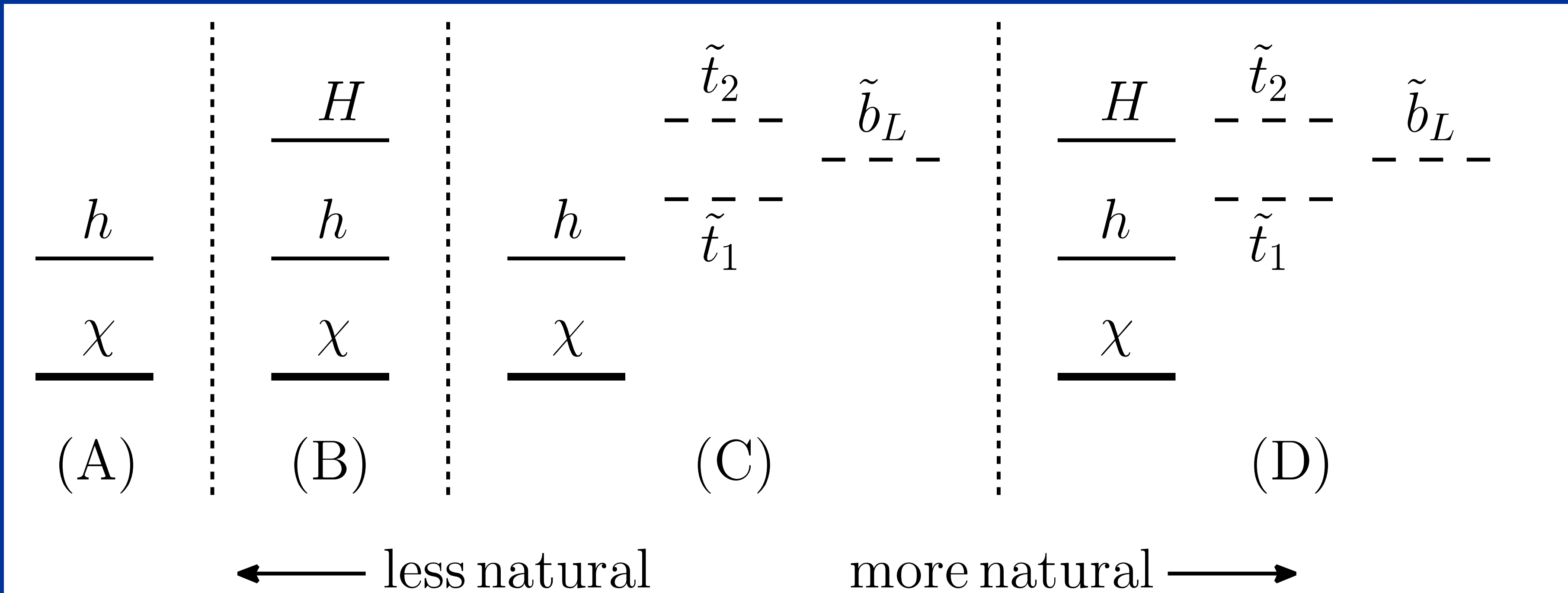


Dark Matter Direct Detection and LHC searches in the MSSM

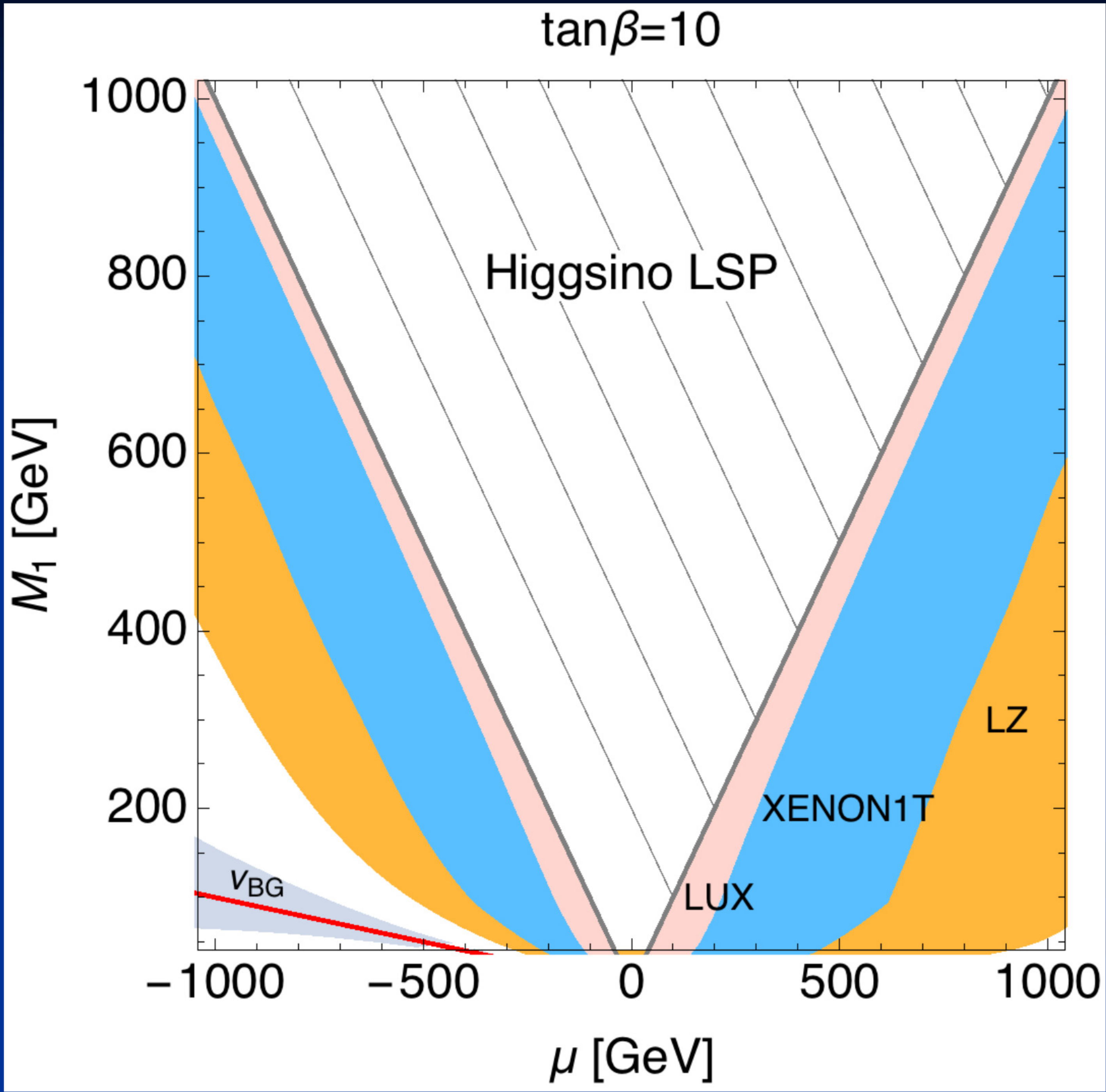
A.C., M. Hoferichter, M. Procura and L. C. Tunstall,
Light stops, blind spots, and isospin violation in the MSSM,
arXiv:1503.03478 [hep-ph].

Naturalness and MSSM spectra

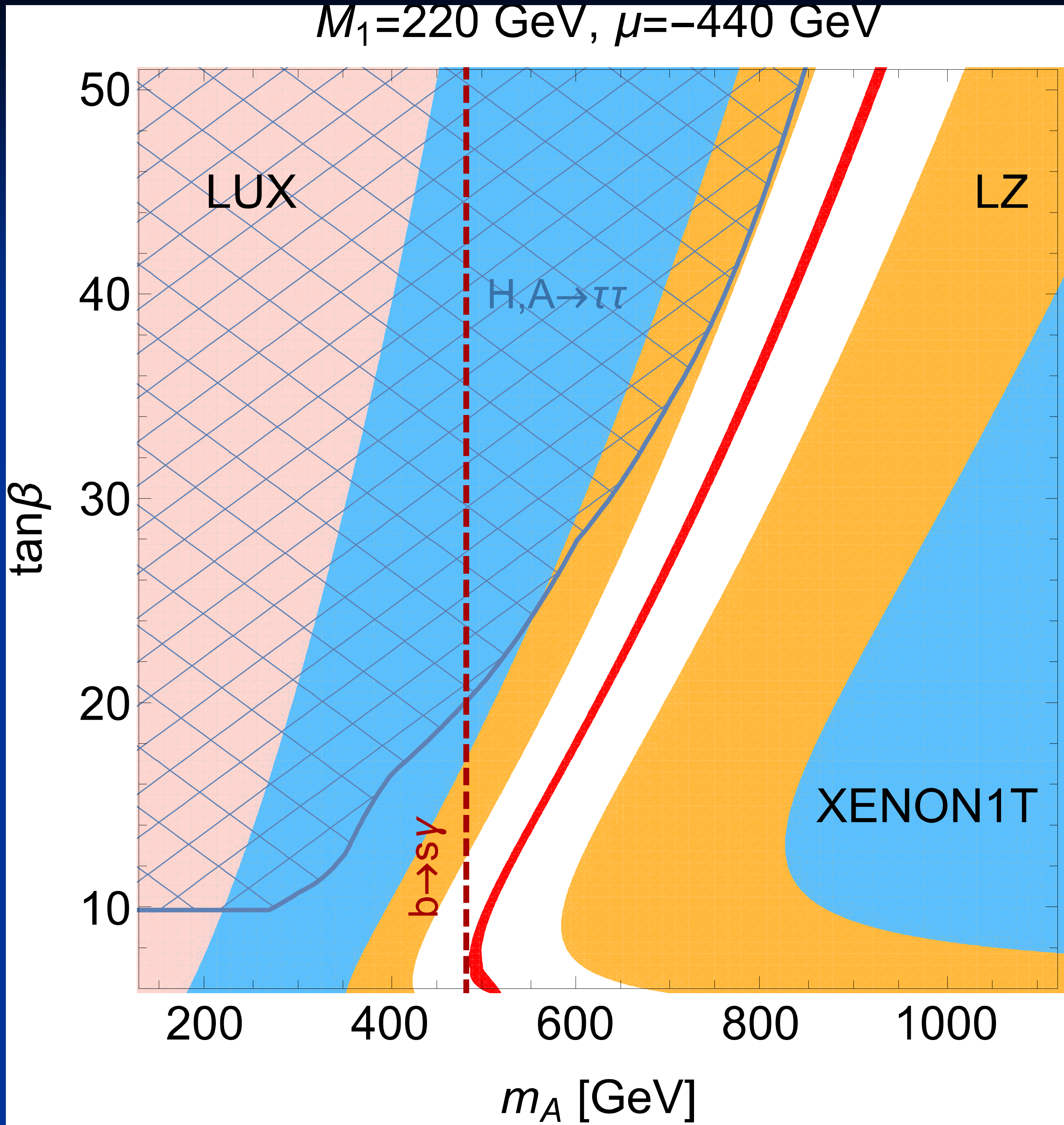
- Standard model like Higgs discovered
- Lepton sector unimportant for direct detection
- 2nd Higgs light?
- Light stops (and sbottoms)?



SM Higgs only



SM and heavy Higgs



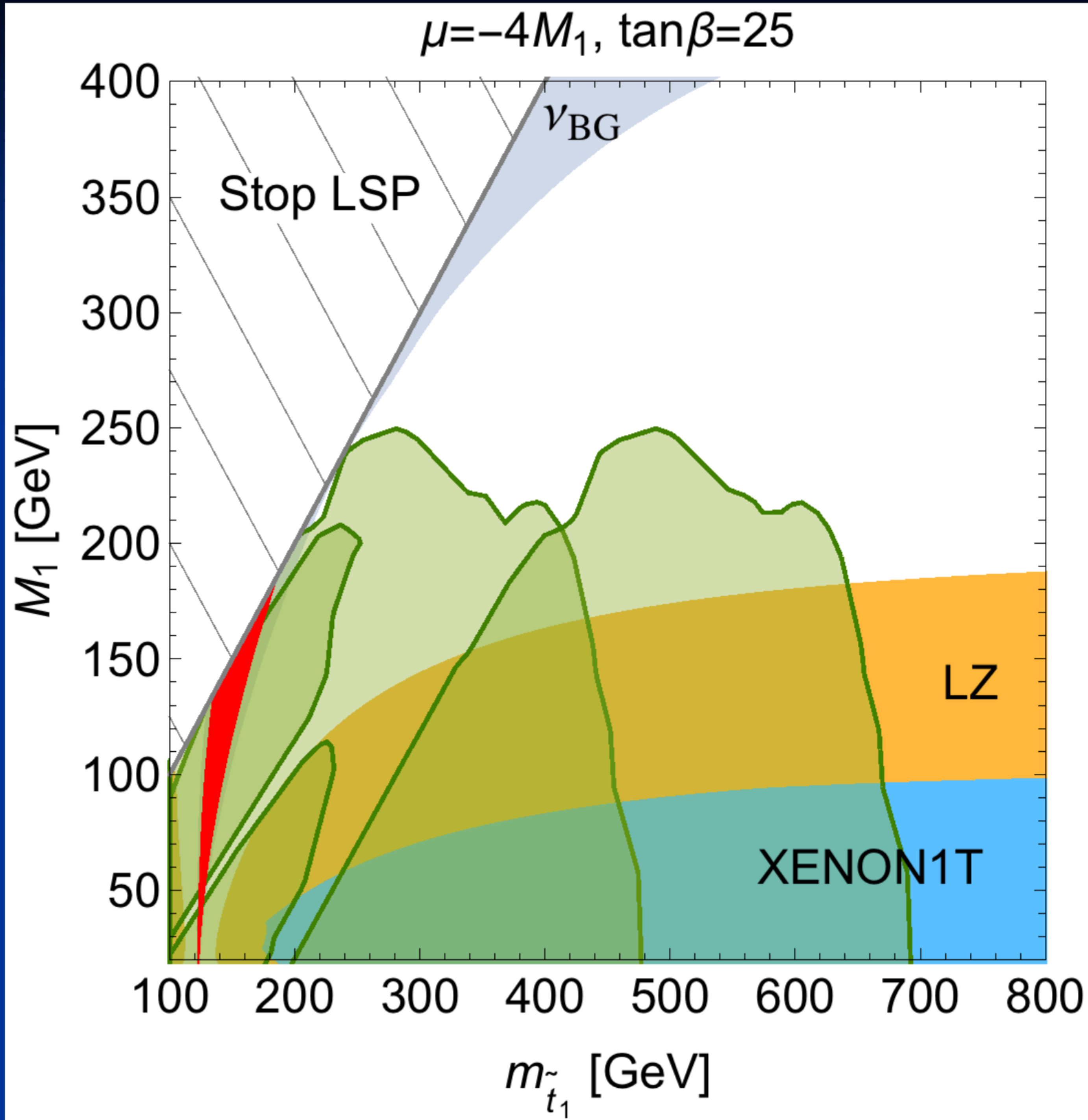
- Blind spot:

Different contributions cancel

Cheung et al.

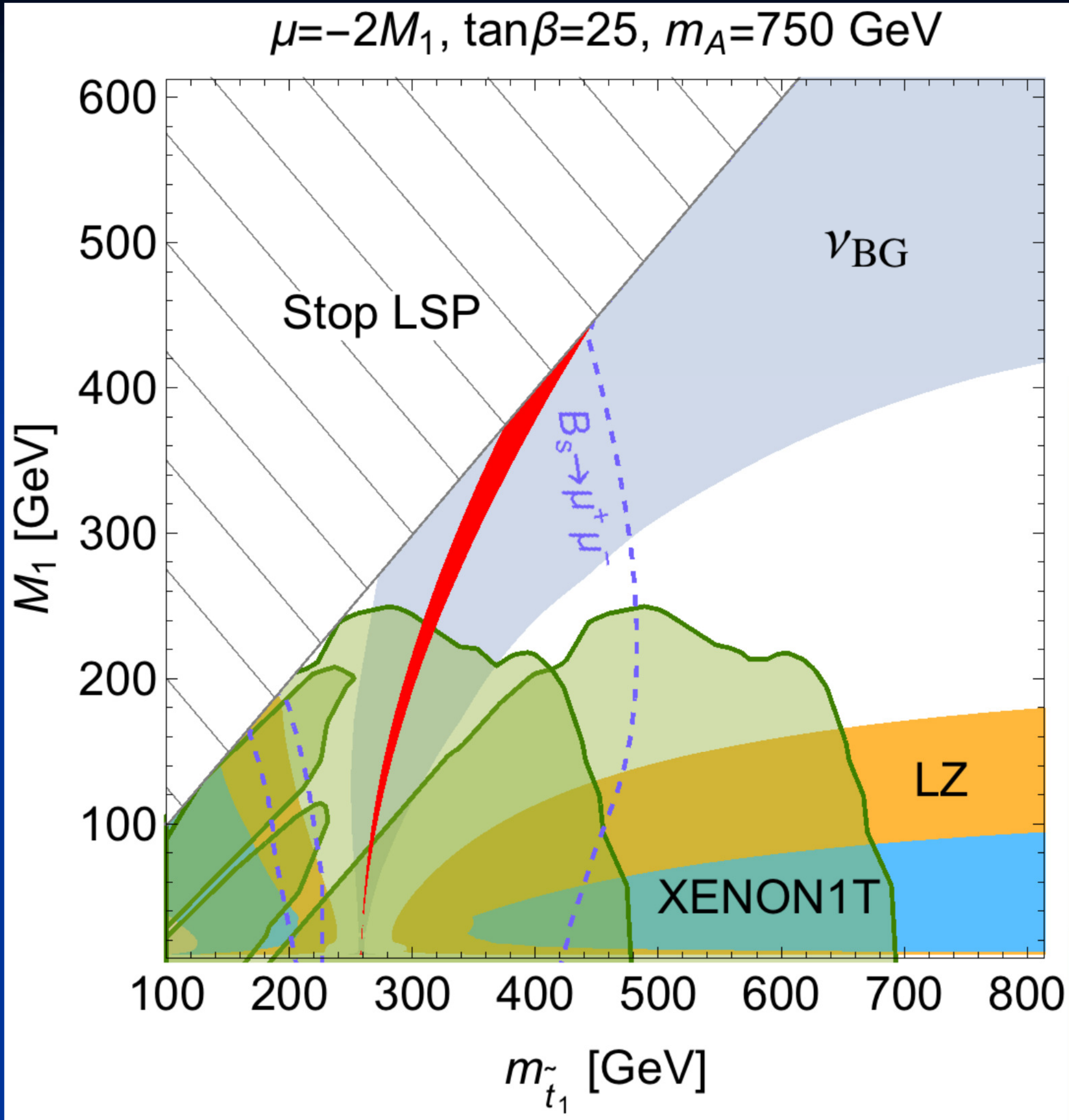
Huang & Wagner

Light Stop



$\mu=-4M_1$, $\tan\beta=25$
400
350
300
250
200
150
100
50
M_1 [GeV]
ν_{BG}
Stop LSP
LZ
XENON1T
100
200
300
400
500
600
700
800
$m_{\tilde{t}_1}$ [GeV]

Stop and heavy Higgs



Conclusions

- Effective Field Theories simplify the calculations and allow for a consistent treatment of QCD effects.
- EFTs can be used to explore systematically physics beyond the SM
- Effective Higgs-quark vertices in the (N)MSSM can be determined by a matching on a 2HDM (+singlet), allowing for a resummation of tan(beta) enhanced effects.
- Interesting loop effects in DM direct detection: new constraints on operators
- The natural MSSM posses blind spots and is a prime example for the interplay between different searches