Flavour up the physics!

Renormalisation rocks!

SUSY-QCD corrections to squark production at LHC in the MSSM with general quark-flavour mixing

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a project in progress
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Introduction

- The LHC has restarted its collisions with a center-of-mass energy of 13 TeV on its way to discover new physics
- The observed Higgs boson has confirmed the SM as a very well working low energy theory
- Nevertheless we have many reasons to believe that it needs a generalisation. The measured Higgs mass does not give us a hint about it - it neither favours nor disfavours SUSY
- Although there is no sign of new particles yet, the MSSM is still favoured as a discoverable theory beyond the SM and will be searched with high priority at CMS and ATLAS
- The MSSM has been studied a lot (as much as it could be due to its many free parameters). Nevertheless it has yet unstudied potential related to more general treatment of its squark sector parameters
- Despite the stringent constraints from B and K physics, such parameters can lead to quark-flavour violation (QFV) and can change the phenomenological observables significantly
- We study the impact of QFV on the squark production at hadron colliders, taking into account the next-to-leading order SUSY-QCD corrections in the MSSM with general quark flavour-mixing

General quark-flavour mixing in the MSSM

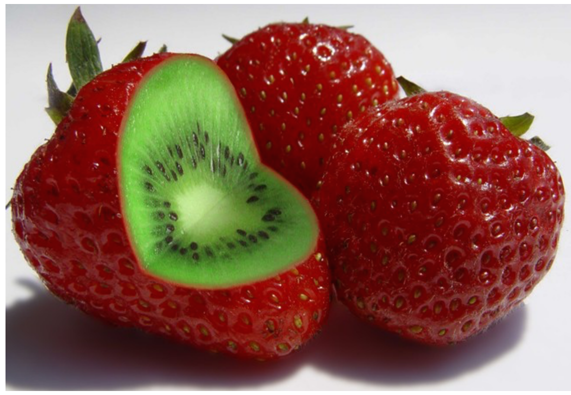
- In the SM all QFV terms are proportional to the CKM matrix

- In the general MSSM there are two concepts:

  * Minimal quark flavour violation - no new sources of QFV, in the super-CKM basis the squarks undergo the same rotations like the quarks, all flavour-violating entries are related to the CKM matrix (e.g. $\tilde{\chi}_l^{\pm}\tilde{q}_i\tilde{q}_j \sim V_{q_i q'_j}$)

  * Non-minimal quark flavour violation - new sources of QFV, independent on the CKM, considered as free parameters in the theory

- In the following we assume non-minimal quark flavour violation



General quark-flavour mixing in the MSSM

- The flavour-violating terms are contained in the mass matrices of the squarks at the electroweak scale

$$\mathcal{M}^2_{\tilde{q}} = \begin{pmatrix} \mathcal{M}^2_{\tilde{q},LL} & \mathcal{M}^2_{\tilde{q},LR} \\ \mathcal{M}^2_{\tilde{q},RL} & \mathcal{M}^2_{\tilde{q},RR} \end{pmatrix}, \quad q = u, d$$

- The 3x3 soft SUSY-breaking matrices can introduce QFV (off-diagonal) terms, e.g. in the up-squark sector

$$(\mathcal{M}^2_{\tilde{u},LL})_{\alpha\beta} = (M^2_Q)_{\alpha\beta} + \left[\left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right)\cos 2\beta m_Z^2 + (\hat{m}_u^2)_\alpha\right]\delta_{\alpha\beta},$$

$$(\mathcal{M}^2_{\tilde{u},RR})_{\alpha\beta} = (M^2_U)_{\alpha\beta} + \left[\left(\frac{2}{3}\sin^2\theta_W\right)\cos 2\beta m_Z^2 + (\hat{m}_u^2)_\alpha\right]\delta_{\alpha\beta},$$

$$(\mathcal{M}^2_{\tilde{u},RL})_{\alpha\beta} = \frac{v_2}{\sqrt{2}}(T_U)_{\alpha\beta} - (\hat{m}_u)_\alpha \mu^* \cot\beta\delta_{\alpha\beta}$$

- The mass eigenstates are obtained after diagonalization with a 6x6 rotation matrix

$$\begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \\ \tilde{u}_3 \\ \tilde{u}_4 \\ \tilde{u}_5 \\ \tilde{u}_6 \end{pmatrix} = R^{\tilde{u}} \begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix} \qquad \begin{pmatrix} \tilde{d}_1 \\ \tilde{d}_2 \\ \tilde{d}_3 \\ \tilde{d}_4 \\ \tilde{d}_5 \\ \tilde{d}_6 \end{pmatrix} = R^{\tilde{d}} \begin{pmatrix} \tilde{d}_L \\ \tilde{s}_L \\ \tilde{b}_L \\ \tilde{d}_R \\ \tilde{s}_R \\ \tilde{b}_R \end{pmatrix}$$

$$R^{\tilde{u}} \mathcal{M}^2_{\tilde{u}} U^{\tilde{u}\dagger} = diag(m^2_{\tilde{u}_1}, ..., m^2_{\tilde{u}_6})$$

$$R^{\tilde{d}} \mathcal{M}^2_{\tilde{d}} U^{\tilde{d}\dagger} = diag(m^2_{\tilde{d}_1}, ..., m^2_{\tilde{d}_6})$$

General quark-flavour mixing in the MSSM

- Dimensionless QFV parameters are introduced in the up-type sector ($\alpha \neq \beta$)

$$\begin{aligned}
\delta^{LL}_{\alpha\beta} &\equiv M^2_{Q\alpha\beta}/\sqrt{M^2_{Q\alpha\alpha}M^2_{Q\beta\beta}} \, , \\
\delta^{uRR}_{\alpha\beta} &\equiv M^2_{U\alpha\beta}/\sqrt{M^2_{U\alpha\alpha}M^2_{U\beta\beta}} \, , \\
\delta^{uRL}_{\alpha\beta} &\equiv (v_2/\sqrt{2})T_{U\alpha\beta}/\sqrt{M^2_{U\alpha\alpha}M^2_{Q\beta\beta}}
\end{aligned}$$

- And in the down-type sector

$$\begin{aligned}
\delta^{dRR}_{\alpha\beta} &\equiv M^2_{D\alpha\beta}/\sqrt{M^2_{D\alpha\alpha}M^2_{D\beta\beta}} \\
\delta^{dRL}_{\alpha\beta} &\equiv (v_1/\sqrt{2})T_{D\alpha\beta}/\sqrt{M^2_{D\alpha\alpha}M^2_{Q\beta\beta}}
\end{aligned}$$

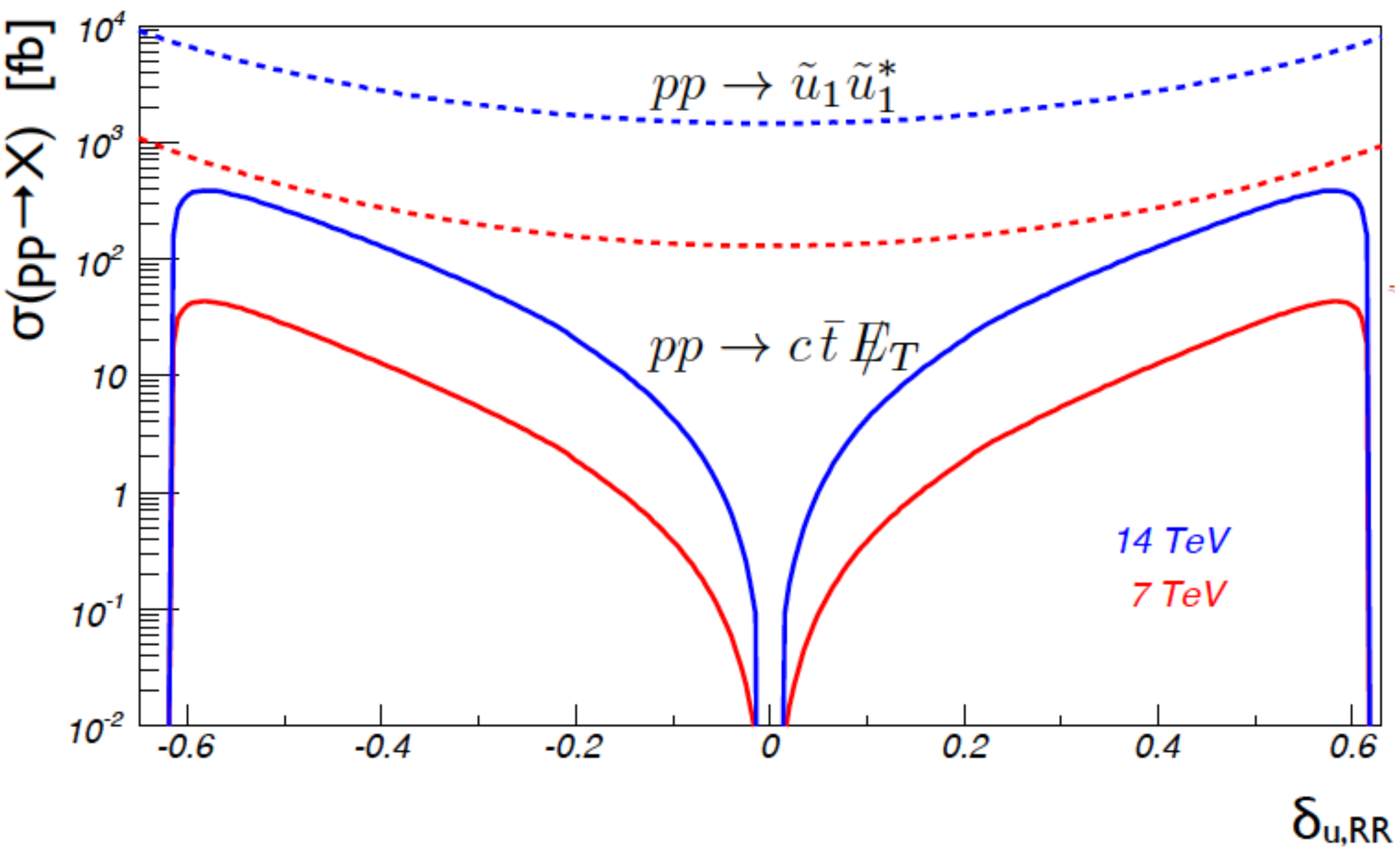
$pp \to \tilde{q}_i \bar{\tilde{q}}_j$

the process

- The tree-level squark production cross section at LHC was previously studied in the context of QFV subsequent squark decays
  [A. Bartl, H. Eberl, B. Herrmann, K. Hidaka, W. Majerotto, W. Porod ,Phys.Lett.B698:380-388,2011]

- It was shown that the quark flavour-mixing can influence squark masses, their flavour-decomposition and the production cross section, as well as to open new decay channels, non existing in the SM, nor in the QFC MSSM, characteristic signatures

- The study also showed that the dependence on the QFV parameters can be recognisable already at tree-level - a good motivation to study the leading 1-loop contributions



$pp \to \tilde{q}_i \bar{\tilde{q}}_j$

the process

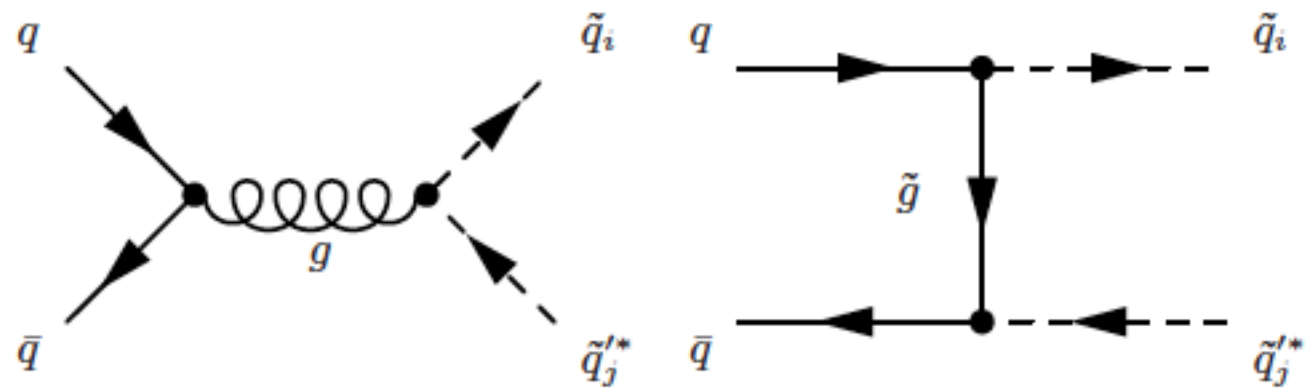
- #1 We study: squark-antisquark pair production in proton collisions
- #2 Next step: squark pair production, straight forward once #1 is completed
- The matrix elements squared are generated with FeynArts/FormCalc (axial gauge)
- The couterterms are missing there, own calculation
- Everything is implemented in an own Fortran code

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ the process - tree-level

At parton level proceeds from:

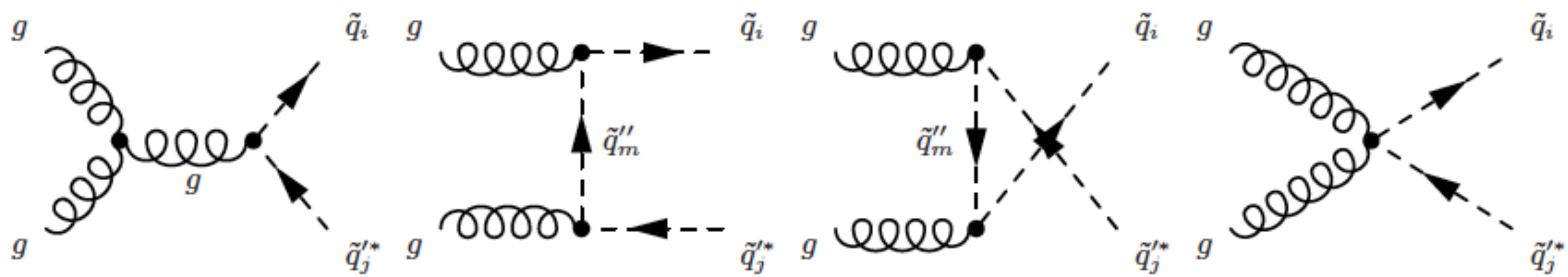
- quark-antiquark initial state

$$q(p_a)\ \bar{q}'(p_b) \to \tilde{q}_i(p_1)\ \tilde{q}_j'^*(p_2)$$



- gluon-gluon initial state

$$g(p_a)\ g(p_b) \to \tilde{q}_i(p_1)\ \tilde{q}_j'^*(p_2)$$



$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ the process - tree-level

- from quark-antiquark initial state: matrix elements squared of the s- and t-channel, and interference term

$$
\begin{aligned}
|M^B_{q,s}|^2 &= (n_c^2-1)\frac{2g_s^4}{s^2}(ut - m^2_{\tilde{q}_i} m^2_{\tilde{q}_j})\delta_{qq'}\delta_{\tilde{q}_i\tilde{q}'_j} \ , \\
|M^B_{q,t}|^2 &= (n_c^2-1)\frac{g_s^4}{t_{\tilde{g}}^2}\Big[\Big(|R_{i1}R'_{j1}|^2 + |R_{i2}R'_{j2}|^2\Big)\Big(ut - m^2_{\tilde{q}_i} m^2_{\tilde{q}_j}\Big) \\
&\quad + m^2_{\tilde{g}} s\Big(|R_{i2}R'_{j1}|^2 + |R_{i1}R'_{j2}|^2\Big)\Big]\delta_{q\tilde{q}}\delta_{q'\tilde{q}'} \ ,
\end{aligned}
$$

$$
\begin{aligned}
2\mathrm{Re}\{M^B_{q,s} M^{B\,*}_{q,t}\} &= -\frac{n_c^2-1}{n_c}\frac{2g_s^4}{s t_{\tilde{g}}}\Big(ut - m^2_{\tilde{q}_i} m^2_{\tilde{q}_j}\Big) \times \\
&\quad \mathrm{Re}\{R_{i1}R'^{*}_{j1} + R_{i2}R'^{*}_{j2}\}\delta_{qq'}\delta_{\tilde{q}_i\tilde{q}'_j}
\end{aligned}
$$

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ the process - tree-level

- from gluon-gluon initial state: matrix elements squared of the s-, t- and u-channel, 4-point interaction, as well as the interference terms

$$|M^B_{g,s}|^2 = (n_c^2-1)n_c \frac{g_s^4}{s^2}\left[8m^4_{\tilde{q}_i} - t^2 - u^2 - 6tu + r\varepsilon(t-u)^2\right]\delta_{\tilde{q}_i\tilde{q}'_j} \,,$$

$$|M^B_{g,t}|^2 = \frac{(n_c^2-1)^2}{n_c}\frac{g_s^4}{t^2_{\tilde{q}_i}}(t+m^2_{\tilde{q}_i})^2\delta_{\tilde{q}_i\tilde{q}'_j} \,,$$

$$|M^B_{g,u}|^2 = \frac{(n_c^2-1)^2}{n_c}\frac{g_s^4}{u^2_{\tilde{q}_i}}(u+m^2_{\tilde{q}_i})^2\delta_{\tilde{q}_i\tilde{q}'_j} \,,$$

$$|M^B_{g,4}|^2 = (2+r\varepsilon)\frac{(n_c^2-1)(n_c^2-2)}{n_c}g_s^4\delta_{\tilde{q}_i\tilde{q}'_j} \,,$$

$$2\mathrm{Re}\{M^B_{g,s}M^{B\,*}_{g,t}\} = -(n_c^2-1)n_c\frac{g_s^4}{4st_{\tilde{q}_i}}\left[4(t^2+m^4_{\tilde{q}_i}) + s^2 - 8m^2_{\tilde{q}_i}(s+t)\right]\delta_{\tilde{q}_i\tilde{q}'_j} \,,$$

$$2\mathrm{Re}\{M^B_{g,s}M^{B\,*}_{g,u}\} = -(n_c^2-1)n_c\frac{g_s^4}{4su_{\tilde{q}_i}}\left[4(u^2+m^4_{\tilde{q}_i}) + s^2 - 8m^2_{\tilde{q}_i}(s+u)\right]\delta_{\tilde{q}_i\tilde{q}'_j} \,,$$

$$2\mathrm{Re}\{M^B_{g,s}M^{B\,*}_{g,4}\} = 0 \,,$$

$$2\mathrm{Re}\{M^B_{g,t}M^{B\,*}_{g,u}\} = \frac{n_c^2-1}{n_c}\frac{-g_s^4}{2t_{\tilde{q}_i}u_{\tilde{q}_i}}s^2\delta_{\tilde{q}_i\tilde{q}'_j} \,,$$

$$2\mathrm{Re}\{M^B_{g,t}M^{B\,*}_{g,4}\} = \frac{(n_c^2-1)(n_c^2-2)}{n_c}\frac{g_s^4}{4t_{\tilde{q}_i}}\left[s - 4(t+m^2_{\tilde{q}_i})\right]\delta_{\tilde{q}_i\tilde{q}'_j} \,,$$

$$2\mathrm{Re}\{M^B_{g,u}M^{B\,*}_{g,4}\} = \frac{(n_c^2-1)(n_c^2-2)}{n_c}\frac{g_s^4}{4u_{\tilde{q}_i}}\left[s - 4(u+m^2_{\tilde{q}_i})\right]\delta_{\tilde{q}_i\tilde{q}'_j} \,,$$

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ the process - tree-level

- Here

$$r = 0: \quad \overline{\mathrm{DR}} \text{ scheme}$$
$$r = 1: \quad \overline{\mathrm{MS}} \text{ scheme}$$

$$\Delta = \frac{1}{\bar{\varepsilon}} = \frac{1}{\varepsilon} + \ln 4\pi - \gamma$$
$$\mathrm{D} = n = 4 - 2\varepsilon$$

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ the process - tree-level

- Summing up and taking $\varepsilon \to 0$ we get the 4-dimensional result in agreement with the limiting cases

W. Beenakker, R. Hopker, M. Spira, and P. M. Zerwas, "Squark and gluino production at hadron colliders," *Nucl. Phys.* **B492** (1997) 51–103, arXiv:hep-ph/9610490.

T. Gehrmann, D. Maitre, and D. Wyler, "Spin asymmetries in squark and gluino production at polarized hadron colliders," *Nucl. Phys.* **B703** (2004) 147–176, arXiv:hep-ph/0406222.

G. Bozzi, B. Fuks, and M. Klasen, "Non-diagonal and mixed squark production at hadron colliders," *Phys. Rev.* **D72** (2005) 035016, arXiv:hep-ph/0507073.

G. Bozzi, B. Fuks, B. Herrmann, and M. Klasen, "Squark and gaugino hadroproduction and decays in non- minimal flavour violating supersymmetry," *Nucl. Phys.* **B787** (2007) 1–54, arXiv:0704.1826 [hep-ph].

- Next we have to integrate the spin and colour averaged squared matrix elements over the phase space to get the partonic cross section

$$\hat{\sigma}(s) = \frac{1}{2s}\int_{-1}^{1} \overline{\sum} |M|^2 d\cos\theta$$

- And then we have to integrate the partonic cross section over the PDFs to get the hadronic cross section

$$\sigma(ij \to \tilde{q}_k \tilde{q}_l) = \int_0^1 f_i(x_1) f_j(x_2) \hat{\sigma}(ij \to \tilde{q}_k \tilde{q}_l; s = x_1 x_2 S) dx_1 dx_2$$

$$\{i,j\} = \{q,\bar{q}\},\{g,g\}$$

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ the process -1-loop

- 1-loop calculations introduce UV and IR divergences: require renormalisation, most involving part of the project

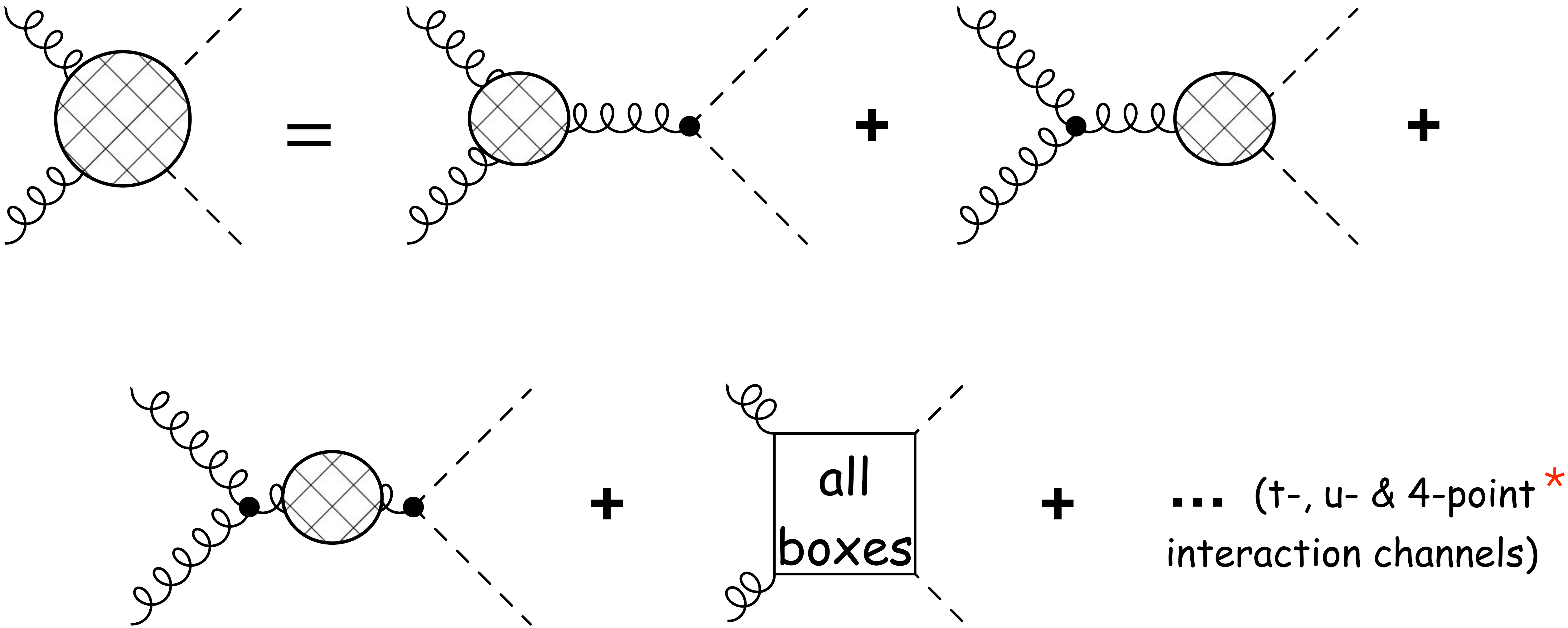
- Present status:

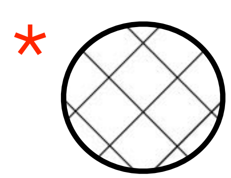
  UV problem - solved! Our code is already UV convergent!

  IR problem - main part solved! Still some work to do

- Now details

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ 1-loop UV renormalisation

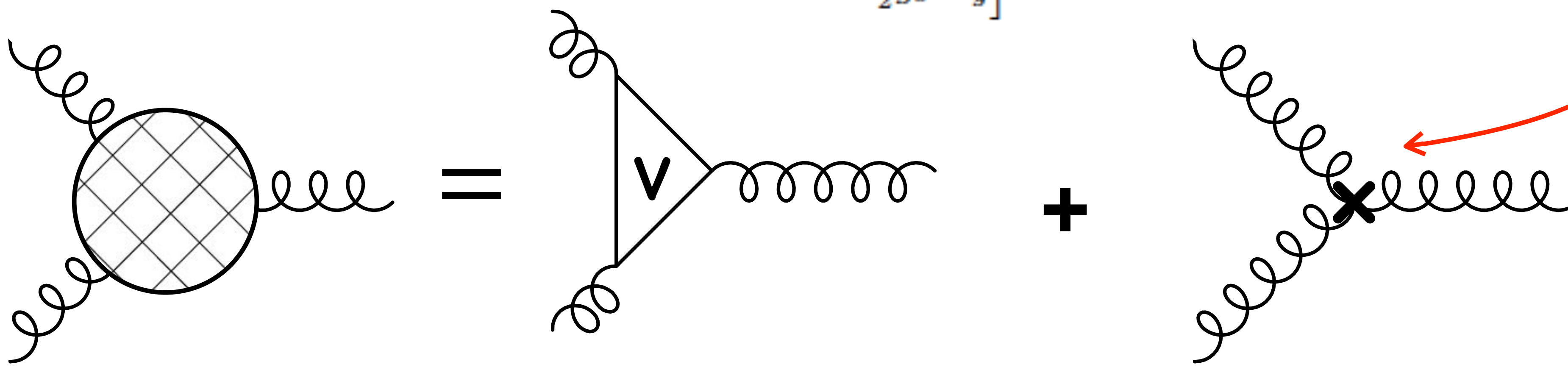




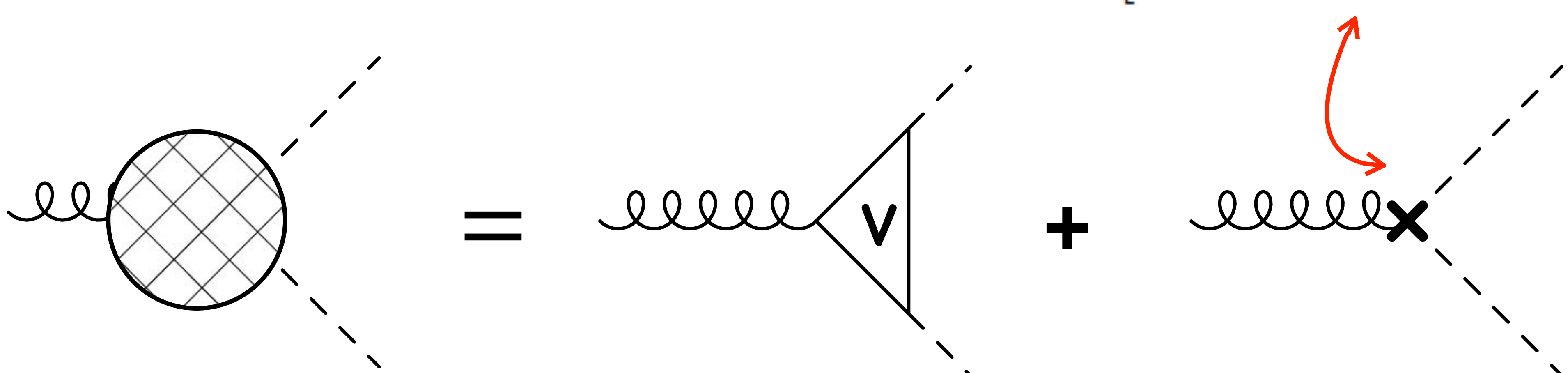
= renormalised

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ 1-loop UV renormalisation

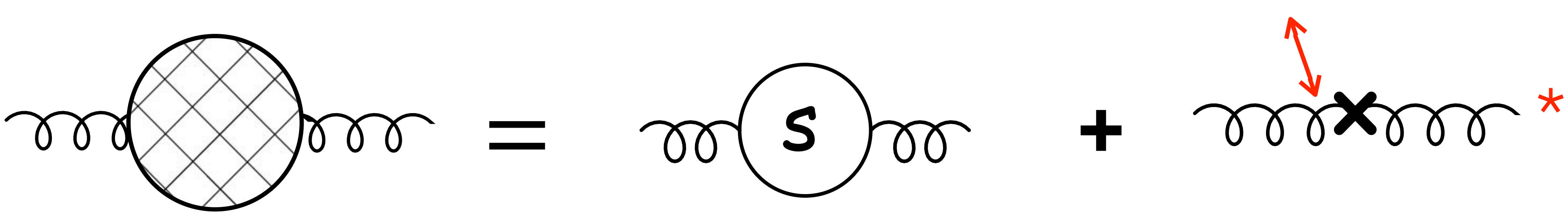
$f_{abc}\left[(p_1-p_2)^\rho\eta^{\mu\nu}+(p_3-p_1)^\nu\eta^{\rho\mu}+(p_2-p_3)^\mu\eta^{\nu\rho}\right]\left[\delta g_s+\frac{3}{2}g_s\delta Z_g\right]$



$i(p_3^\mu-p_2^\mu)\left[\delta g_s\delta_{ij}+\frac{1}{2}g_s\left((\delta Z_{\tilde{q}}+\delta Z^\dagger_{\tilde{q}})_{ij}+\delta Z_g\delta_{ij}\right)\right]T^a_{mn}$



$-i\delta_{ab}\,\delta Z_g\,(p^2\eta^{\mu\nu}-p^\mu p^\nu)$



* v = vertices, s = self energies, x = counter terms

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ 1-loop UV renormalisation

- Field renormalisation: bare fields as functions of the renormalised ones

$$g_b^\mu = \sqrt{Z_g} g^\mu \simeq (1 + \frac{1}{2}\delta Z_g) g^\mu \ ,$$

$$q_{b,f}^L = \left(\sqrt{Z_q^L}\right)_{ff'} q_{f'}^L \simeq \left[\delta_{ff'} + \frac{1}{2}\left(\delta Z_q^L\right)_{ff'}\right] q_{f'}^L \ ,$$

$$q_{b,f}^R = \left(\sqrt{Z_q^R}\right)_{ff'} q_{f'}^R \simeq \left[\delta_{ff'} + \frac{1}{2}\left(\delta Z_q^R\right)_{ff'}\right] q_{f'}^R \ ,$$

$$\tilde{g}_b^L = \sqrt{Z_{\tilde{g}}^L}\ \tilde{g}^L \simeq \left[1 + \frac{1}{2}\delta Z_{\tilde{g}}^L\right] \tilde{g}^L \ ,$$

$$\tilde{g}_b^R = \sqrt{Z_{\tilde{g}}^R}\ \tilde{g}^R \simeq \left[1 + \frac{1}{2}\delta Z_{\tilde{g}}^R\right] \tilde{g}^R \ ,$$

$$\tilde{q}_{b,i} = \left(\sqrt{Z_{\tilde{q}}}\right)_{ij} \tilde{q}_j \simeq \left[\delta_{ij} + \frac{1}{2}\left(\delta Z_{\tilde{q}}\right)_{ij}\right] \tilde{q}_j \ ,$$

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ 1-loop UV renormalisation

- Parameter renormalisation: shifts quark, squark and gluino masses

$$\left(m_{q,b}\right)_{ff'} = \left(m_{q,b}\right)_f \delta_{ff'} \simeq \left(m_q + \delta m_q\right)_{ff'} = m_q \delta_{ff'} + \left(\delta m_q\right)_{ff'} ,$$
$$\left(m^2_{\tilde{q},b}\right)_{ii'} = m^2_{\tilde{q}_i,b}\delta_{ii'} \simeq \left(m^2_{\tilde{q}} + \delta m^2_{\tilde{q}}\right)_{ii'} = m^2_{\tilde{q}_i}\delta_{ii'} + \left(\delta m^2_{\tilde{q}}\right)_{ii'} ,$$
$$m_{\tilde{g},b} \simeq m_{\tilde{g}} + \delta m_{\tilde{g}} ,$$

- requires redefinition of the squark mixing matrices

$$(R^{\tilde{q}})_{ij} \simeq (R^{\tilde{q}})_{ij} + (\delta R^{\tilde{q}})_{ij} ,$$

- and shifts the strong coupling constant

$$g_{s,b} \simeq g_s + \delta g_s$$

- All the renormalisation constants and parameter shifts are calculated, everything works good, the process is UV convergent!

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$

1-loop IR problem

$$\sigma^{\text{ren}} = \sigma^{\text{tree}} + \sigma^{\text{virt}}(\Delta_{IR}, \Delta^2_{IR}) + \sigma^{\text{real}}(\Delta_{IR}, \Delta^2_{IR}, \Delta E_g)$$

✓ ✓ ✗

- For the real radiation part we use phase space slicing technique

$$\sigma^{\text{real}} = \sigma^{3,\text{hard}}(\Delta_{IR}, \Delta E_g) + \sigma^{\text{soft}}(\Delta_{IR}, \Delta^2_{IR}, \Delta E_g) + \sigma^{\text{coll}}(\Delta_{IR}, \Delta E_g)$$

✓ ✗ ✗

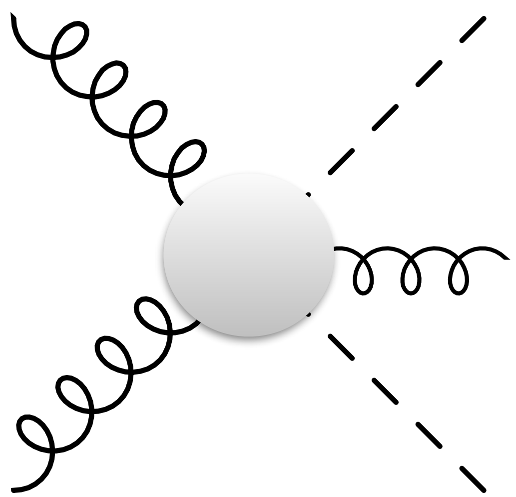
- we have 2 cuts in the game: $\Delta E_g, \Delta cos\theta$

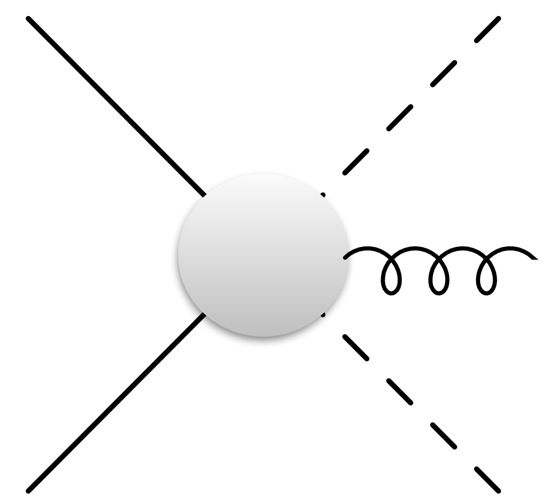
- but effectively only 1: ΔE_g

B. W. Harris and J. F. Owens, Phys. Rev. D **65** (2002) 094032 [arXiv:hep-ph/0102128]

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ 1-loop IR problem - hard radiation

- Real radiation contributions for each squark sector up/down





* s-channel: 7 graphs
* t-channel: 7 graphs
* u-channel: 7 graphs
* 4-point interaction: 4 graphs

* s-channel: 6 graphs
* t-channel: 5 graphs

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ 1-loop IR problem - soft radiation

- The 2 $\to$ 3 contributions to the partonic cross section

$$\sigma = \sigma_H + \sigma_S = \frac{1}{2\Phi} \int \overline{\sum} |M_3|^2 d\Gamma_3$$

$$\sigma_H = \frac{1}{2\Phi} \int_H \overline{\sum} |M_3|^2 d\Gamma_3$$

$$\sigma_S = \frac{1}{2\Phi} \int_S \overline{\sum} |M_3|^2 d\Gamma_3$$

- The soft region is defined in terms of gluon energy in the rest frame of the incoming partons

$$0 \leq E_5 \leq \delta_s \sqrt{s_{12}}/2 = \Delta E_g$$

  - We parametrise the divergences using dimensional regularisation
    [B. W. Harris, J. F. Owens, PhysRevD.65.094032]

  - The result in n (=D) dimensions

$$d\sigma_S = \left[\frac{\alpha_s}{2\pi} \frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)} \left(\frac{4\pi\mu_r^2}{s_{12}} \right)^{\epsilon} \right] \sum_{f,f'=1}^{4} d\sigma^0_{ff'} \int \frac{-p_f \cdot p_{f'}}{p_f \cdot p_5 \; p_{f'} \cdot p_5} dS$$

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ 1-loop IR problem - soft radiation

- where $$d\sigma^0_{ff'} = \frac{1}{2\Phi} \overline{\sum} M^0_{ff'} d\Gamma_2$$

are the colour linked Born amplitudes in n (=D) dimensions

- and $$\int \frac{-p_f \cdot p_{f'}}{p_f \cdot p_5 \; p_{f'} \cdot p_5} dS$$

are the eikonal integrals in n (=D) dimensions

Status:

- The colour linked Born amplitudes in for quark-antiquark initial state are calculated and checked
- We have derived all eikonal integrals using the integrals of t'Hooft Veltman and making the transformation $\ln \lambda^2 \to -\Delta + \ln \mu^2$

[t'Hooft, Veltman, Nucl. Phys B153 (1979) 365]

- Still unfinished - the colour linked Born amplitudes in n (=D) dimensions for gluon-gluon initial state and the cross-check of the eikonal integrals

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ 1-loop IR problem - collinear divergences

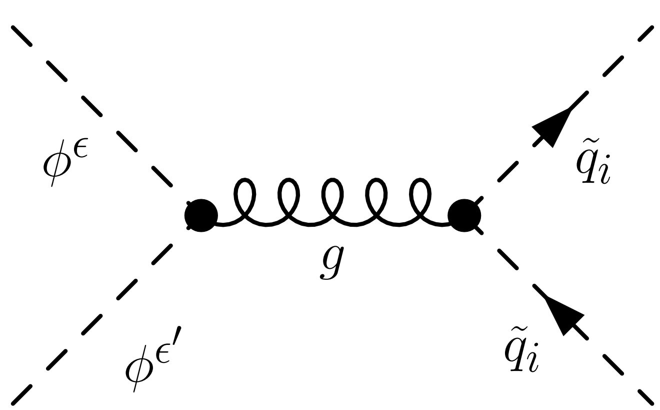
- When a gluon is radiated off in the same direction - parameterised with the angle between the initial and the radiated gluons

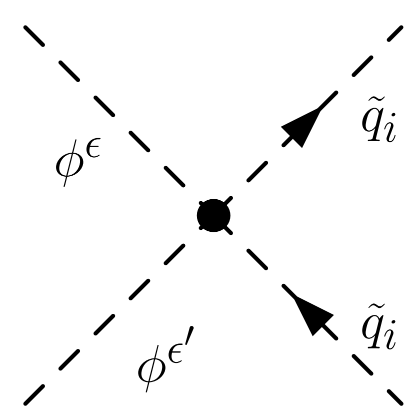
- The problem requires mass factorisation - in principle can be done in DREG and in DRED schemes

- We work in DRED - 4-dimensional gluon, does not break SUSY, but additional epsilon scalars contributions have to be calculated

$$|\mathcal{M}_{GG}|^2 = |\mathcal{M}_{gg}|^2 + |\mathcal{M}_{\phi\phi}|^2$$

- These are two graphs





$pp \to \tilde{q}_i\bar{\tilde{q}}_j$ 1-loop IR problem - collinear divergences

- Their contribution gives

$$|\mathcal{M}_{\phi\phi}|^2 = \varepsilon\,(n_c^2-1)g_s^4\left(\frac{(t-u)^2}{s^2}+\frac{n_c^2-2}{n_c}\right)$$

- In DRED for the subtracted hard scattering cross section at NLO, we get

$$\begin{aligned}\int d\hat{\sigma}^{\rm DRED}_{GG\to\tilde{q}\tilde{q}^*G} \quad &= \quad \int d\sigma^{\rm DRED}_{GG\to\tilde{q}\tilde{q}^*G} + \frac{\alpha_s}{2\pi}\frac{1}{\varepsilon}\Bigg(\\ &\int_0^{1-\delta} dx_1\Big(P_{g\to gg}(x_1)d\sigma_{gg\to\tilde{q}\tilde{q}^*}(x_1p_1,p_2)+P_{\phi\to\phi g}(x_1)d\sigma_{\phi\phi\to\tilde{q}\tilde{q}^*}(x_1p_1,p_2)\Big) \\ &+\int_0^{1-\delta} dx_2\Big(P_{g\to gg}(x_2)d\sigma_{gg\to\tilde{q}\tilde{q}^*}(p_1,x_2p_2)+P_{\phi\to\phi g}(x_2)d\sigma_{\phi\phi\to\tilde{q}\tilde{q}^*}(p_1,x_2p_2)\Big)\end{aligned}$$

- Here the x=1 regions are missing

- As a cross-check we will do the whole IR renormalisation also in the dipole function formalism

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ hadronic cross section

- When having everything done at parton level, we need to integrate over the PDFs to get the hadronic cross section
- In our approach with only one cut ΔE_g this procedure reduces to the one in the tree-level case

Flavour up the physics!

Conclusions

Renormalisation rocks!

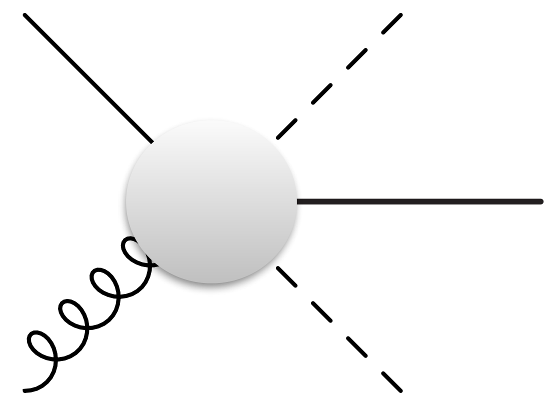
- We study squark production at LHC including next-to-leading order SUSY-QCD corrections within the MSSM with non-minimal flavour violation. The project is still on-going, at present:
- We already have a UV convergent result

- The process is still not completely free from IR divergences though
- For a complete result missing: color linked Born amplitudes for gluon-gluon and the cross-check of the eikonal integrals in D dimensions for the mass factorisation procedure
- We are soon to be ready with this job and make many beautiful plots for our paper, so stay tuned!!!


Thank you!

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ 1-loop IR problem, collinear divergences- extra

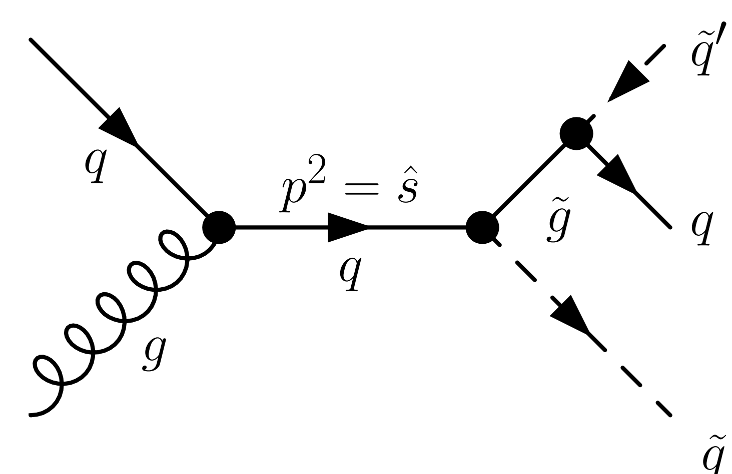
- For massless quarks we have an additional contribution from the kind



- Here we can only have collinear divergences

$$\sigma^{\text{real}} = \sigma^{3,\text{hard}}(\Delta_{IR}) + \sigma^{\text{coll}}(\Delta_{IR})$$

- There exists a resonant graph with gluino



- We have removed this contribution by requiring the following kinematic conditions to be true

$$\sqrt{\hat{s}} > m_{\tilde{g}} + m_{\tilde{q}}$$
$$m_{\tilde{g}} > m_{\tilde{q}'}$$

$pp \to \tilde{q}_i\bar{\tilde{q}}_j$ 1-loop IR problem, collinear divergences- extra

- We can write the phase space integrals as

[see 0102128 and therein Z. Kunszt and D. E. Soper, PRD 46 (1992) 192]

$$I = \lim_{\epsilon \to 0^+} \left\{ \int_0^1 \frac{dx}{x} x^\epsilon F(x) - \frac{1}{\epsilon} F(0) \right\}$$

where F(x) is related to the 2 → 3 matrix element

- Phase space slicing method - the integration is divided in two parts $0 < x < \delta$ and $\delta < x < 1$ for $\delta << 1$

- Maclaurin expansion of F(x)

$$\begin{aligned} I &= \lim_{\epsilon \to 0^+} \left\{ \int_0^\delta \frac{dx}{x} x^\epsilon F(x) + \int_\delta^1 \frac{dx}{x} x^\epsilon F(x) - \frac{1}{\epsilon} F(0) \right\} \\ &= \int_\delta^1 \frac{dx}{x} F(x) + F(0) \ln \delta + \mathcal{O}(\delta) \end{aligned}$$

$pp \to \tilde{q}_i \bar{\tilde{q}}_j$ 1-loop IR problem, collinear divergences- extra

- It is then simple to get the coefficient of the divergence:

$$I = F(0)\ln\delta_i + I(\delta_i) \quad \text{with} \quad I(\delta_i) = \int_0^\delta \frac{dx}{x} x^\epsilon F(x)$$

- For two small values we get the same integral

$$F(0) = \frac{I(\delta_2) - I(\delta_1)}{\ln\delta_1 - \ln\delta_2}$$

- We use this procedure to get rid of the second (cos theta) cut and to use one-cutoff technique in the mass factorisation