Karlsruher Institut für Technologie

Squark-Pair-Production in the POWHEG-BOX

Institutsseminar 2011/12

Christian Hangst | February 2^{nd}, 2012

Outline

Motivation

- QCD-NLO-prediction for pair-production of SQCD particles ($\tilde{q}\tilde{q}$,$\tilde{q}\bar{\tilde{q}}$,$\tilde{q}\tilde{g}$,$\tilde{g}\tilde{g}$) at hadron-collider: PROSPINO [Beenakker et.al. 1997]
  - NLO-calculations only for mass-degenerate $\tilde{q}$-spectrum
  - no possibility to consider influence of specific channel, all summed up
  - returns only K-factor (and in principle p_T-,y-distribution of $\tilde{q}$)
- so far no (public) code for different masses and arbitrary NLO-distributions
- (re)calculate the (S)QCD-corrections to these processes ($\longrightarrow$ Eva) and write parton-level-MC
- realistic simulation requires production at parton-level + decay + shower + ...
- first step: production at NLO, decay at LO; ultimate goal: combine with production at LO, decay at NLO
- to match the NLO-calculation with parton-shower: consistent matching-scheme to avoid double-counting in soft/collinear region of phase-space: MC@NLO or POWHEG

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The POWHEG-method - a short recap

- basic idea
  - generate the hardest emission first
  - then shower with a p_T-veto $\Rightarrow$ subsequent radiation is guaranteed to be softer
  - works directly for p_T-ordered shower
  - for angular-ordered shower: introduce so called truncated shower [Nason 2004]
- "master-formula": [Frixione, Nason, Oleari 2007]

$$d\sigma_{PWG} = \overline{\mathcal{B}}(\Phi_n)\, d\Phi_n \left[\Delta_{PWG}(\Phi_n, p_T^{min}) + \Delta_{PWG}(\Phi_n, k_T) \frac{\mathcal{R}(\Phi_n, \Phi_{rad})}{\mathcal{B}(\Phi_n)} \theta(k_T - p_T^{min}) d\Phi_{rad} \right]$$

with the POWHEG-Sudakov

$$\Delta_{PWG}(\Phi_n, p_T) = exp\left[- \int d\Phi'_{rad} \frac{\mathcal{R}(\Phi_n, \Phi_{rad})}{\mathcal{B}(\Phi_n)} \theta(k_T(\Phi_n, \Phi'_{rad}) - p_T) \right]$$

and the $\overline{\mathcal{B}}$-function

$$\overline{\mathcal{B}}(\Phi_n) = \left[\mathcal{B}(\Phi_n) + \mathcal{V}(\Phi_n) + \int \left[\mathcal{R}(\Phi_n, \Phi_{rad}) - \mathcal{C}(\Phi_n, \Phi_{rad}) \right] d\Phi_{rad} \right] d\Phi_n$$

The POWHEG-BOX and SUSY

- POWHEG-BOX [Alioli, Nason, Oleari, Re 2010]: provides process-independent ingredients for a POWHEG-implementation of arbitrary processes
- so far: only SM-processes implemented
- is it possible to use this framework for SUSY-processes? Differences/necessary changes?
- consider the different steps which concern the hard part of the process, modify them appropriately
- in the end: only minor changes necessary

Finding the divergent regions

- **FKS-subtraction:** basic idea: split the real part in different parts in a way that at most one soft and or coll singularity is contained in each part of the sum:

$$\mathcal{R} = \sum_i \mathcal{R}_i + \sum_{ij} \mathcal{R}_{ij}$$

[Frixione, Kunszt, Signer 1995]

$$\mathcal{R}_i = \mathcal{S}_i \mathcal{R} \qquad \mathcal{R}_{ij} = \mathcal{S}_{ij} \mathcal{R}\,, \qquad \sum_i \mathcal{S}_i + \sum_{ij} \mathcal{S}_{ij} = 1$$

- combinatoric problem of finding ALL "regions"; implemented algorithm:
  1. loop over pairs of massless pairs of partons
  2. check if these 2 partons can come from splitting of the same parton
  3. if this is possible: construct underlying Born-flavour-structure by replacing this pair by a parton of appropriate flavour and check if this structure corresponds to a Born-structure
  4. try to minimize the number of regions (e.g. *gg*-case: only 1 *g* combination taken)

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Subtraction of soft/collinear divergences

- soft approximation for the radiaton of a parton k (eikonal factor):

$$\mathcal{R} = 4\pi\alpha_s\mu_r^{2\epsilon}\left[\sum_{i\neq j}\mathcal{B}_{ij}\frac{k_i\cdot k_j}{(k_i\cdot k)(k_j\cdot k)} - \mathcal{B}\sum_i \frac{k_i^2}{(k_i\cdot k)^2}\,C_i\right] + \mathcal{R}^f,$$

  with the so-called colour-correlated Born amplitudes

$$\mathcal{B}_{ij} = -N\sum_{\substack{\text{spins}\\\text{colours}}}\mathcal{M}_{\{c_k\}}\left(\mathcal{M}^\dagger_{\{c_k\}}\right)_{\substack{c_i\to c_i'\\c_j\to c_j'}} T^a_{c_i,c_i'}\,T^a_{c_j,c_j'}\,; \qquad \sum_{i,i\neq j}\mathcal{B}_{ij} = C_{f_j}\mathcal{B}$$

  with the Born-matrixelements $\mathcal{M}$ and the colour-operators T

- this is independent from the spin of the emitter:

  Scalar:

$$\propto g_s t^a_{ji}\frac{((p+q)+p)^\mu\epsilon(q)^*_{\mu,a}}{2p\cdot q}\mathcal{M}^j_{un} \xrightarrow{q_0\to 0} g_s t^a_{ji}\frac{p\cdot\epsilon(q)^*_a}{p\cdot q}\mathcal{M}^j_{un}$$

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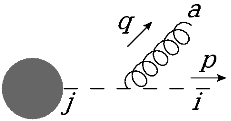

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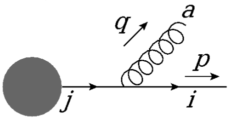

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soft limit: $q_0 \to 0$, Dirac-equation $\bar{u}(p)\not{p} = \bar{u}(p)m$ and $\{\gamma_\mu, \gamma_\nu\} = 2g_{\mu\nu}$

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$\to$ structure is always $g_s\epsilon(q)^*_\mu\, j^\mu_{\text{soft}}(p)\,\mathcal{M}^j_{un}$
summing over all external 'partons' $\Rightarrow q_\mu \sum_i j^\mu_{\text{soft}}(p_i) = 0$ (color-singlet!)
$\Rightarrow \sum \epsilon(q)^*_\mu \epsilon(q)_\nu = -g_{\mu\nu}$, which gives directly the soft approximation

- collinear divergences occur only in radiaton from IS-partons
- 'advantage' of FKS-method: no changes necessary (in CS: different dipoles for scalar particles!)
- only minor changes (ranges of do-loops $\to$ PDG-codes)

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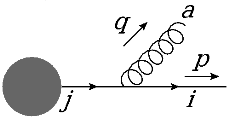

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The virtual part

- subtraction of complete eikonal-factor (and collinear limits) contains finite parts $\rightarrow$ integrate analytically in d dimensions over 1-particle radiation phase-space (compare CS: *I*-terms)
- general formula:

$$\mathcal{V} = \frac{\alpha_s}{2\pi}\left(\mathcal{Q}\,\mathcal{B} + \sum_{i \neq j} \mathcal{I}_{ij}\,\mathcal{B}_{ij} - \mathcal{B}\sum_{i} \mathcal{I}_i + \mathcal{V}_{\text{fin}}\right)$$

- Q is determined by the collinear limits of $\mathcal{R}$, $\mathcal{I}_{ij}$ and $\mathcal{I}_i$ arise from soft radiation ($\rightarrow$ eikonal integrals)
- different forms for $\mathcal{I}$-terms for $m_i, m_j = 0$ or $\neq 0$, but see above: independent of emitter-spin! (results in [Alioli, Nason, Oleari, Re 2010])
- $\mathcal{I}_i \propto C_i$, but $\tilde{q}$ and $\tilde{g}$ are in the same $SU(3)_C$ representation as q,g
- again only minor changes: extend sums and include SQCD-Casimirs

Running of α_s

- SQCD: additional contributions to β-function (for $n_F = 5$ light flavours):

$$\beta_0 = \beta_{\text{light}} + \beta_{\text{heavy}} = \overbrace{(11 - 2/3 \cdot n_F)}^{\beta_{0,\text{SM}}} + [\overbrace{-2}^{\tilde{g}} - \overbrace{2/3}^{t} - \overbrace{1/3 \cdot (1 + n_F)}^{\tilde{q}}]$$

- decouple heavy particles (t,$\tilde{q}$,$\tilde{g}$) from running of α_s ($\rightarrow$ Evas talk)
- modified $\overline{\text{MS}}$-scheme:

$$\Delta - \ln\left(\frac{Q^2}{\mu^2}\right) - \sum_i c_i \ln\left(\frac{m_i^2}{Q^2}\right)$$

- running of α_s:

$$\frac{\partial g_s^2(Q^2)}{\partial \log(Q^2)} = -\alpha_s^2(Q^2)[\beta_{0,SM} + 2 + 2/3 + 1/3(1 + n_F)]$$

- this corresponds to the 1-loop decoupling-coefficient $\rightarrow$ use 2-loop-result for running α_s for 5 active flavour (already implemented in the POWHEG-BOX)

$$\alpha_s^{(5)} = \left(\zeta_g^{\text{SUSY}}\right)^2 \alpha_s^{(\text{SUSY})} = \left(1 + \frac{\alpha_s^{(\text{SUSY})}}{\pi}\left[-\frac{1}{6}\ln_t + \ldots\right]\right)\alpha_s^{(\text{SUSY})}$$

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Implementation of $\tilde{q}\tilde{q}$-production

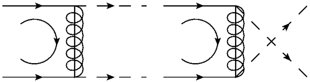
The necessary ingredients for the POWHEG-BOX

1. Flavour structures of Born & Real processes
2. Parameters (couplings,masses,...)
3. Born phase space
4. Born squared amplitude $\mathcal{B}$, colour-correlated Born $\mathcal{B}_{ij}$, spin-correlated Born $\mathcal{B}_{\mu\nu}$
5. Virtual UV-renormalized, IR-finite part $2Re(\mathcal{M}_B \mathcal{M}_R^*)$
6. Real matrix elements squared
7. Born/Real colour-flows in $N_c \to \infty$ limit

Flavour-structure, parameters, Born, phase-space

- **Flavour-structure:**
  - **Born:** $q_i q_j \longrightarrow \tilde{q}_i \tilde{q}_j$
    all in all 4 possiblities: same/different flavour, same/different chirality implement the specific cases
    $$uu \longrightarrow \tilde{u}_L \tilde{u}_{L/R} \text{ and } ud \longrightarrow \tilde{u}_L \tilde{d}_{L/R}$$
  - **Real:** $q_i q_j \longrightarrow \tilde{q}_i \tilde{q}_j g$ and $q_{i/j} g \longrightarrow \tilde{q}_i \tilde{q}_j \bar{q}_{j/i}$
  - adapt the other cases by switching particles (e.g. $gq_{i/j}$, t/u-channel,...)
- **Parameters:** read in from SLHA-file
- **Born-phasespace:**
  - 2-particle-phasespace for massive particles $\longrightarrow$ 'standard '
  - checked vs $t\bar{t}$-example in the POWHEG-BOX

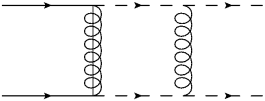
- **Born-amplitudes:** at most 2 graphs



- **Colour-correlated Born:**
  - use colour-conservation $\sum_{j\neq i}\mathcal{B}_{ij} = C_i\mathcal{B}$, the fact that $C_q = C_{\tilde{q}}$ and the symmetry $\mathcal{B}_{ij} = \mathcal{B}_{ji}$
  - in the end (here) only 2 independent entries

results compared to Eva's implementation, MadGraph

- **Virtual part:**
  - calculated by Eva using FEYNARTS/FORMCALC; numerical evaluation of loop-integrals via LOOPTOOLS
  - again only 4 cases ($uu \to \tilde{u}_L \tilde{u}_{L/R}$, $ud \to \tilde{u}_L \tilde{d}_{L/R}$) calculated
  - change masses in the loops for the general case:



  - check UV-finiteness

$$B_0(0,0,0) = \Delta_{UV} - \Delta_{IR} = 0$$

  - check IR-structure of the virtual part (for massless and massive particles $\mathcal{I}_{l/m}$):

$$\begin{aligned}
\mathcal{V} \;=\; & \frac{\alpha_s}{2\pi}\frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)}\left(\frac{\mu^2}{Q^2}\right)^\epsilon \Bigg[\Bigg(-\frac{1}{\epsilon^2}\sum_{k\in\mathcal{I}_l} C_k - \frac{1}{\epsilon}\sum_{k\in\mathcal{I}_l}\gamma_k - \frac{1}{\epsilon}\sum_{k\in\mathcal{I}_m} C_k\Bigg)\mathcal{B} \\
+ \; & \frac{2}{\epsilon}\sum_{k,l\in\mathcal{I}_l,k>l}\log\frac{2k_k\cdot k_l}{Q^2}\mathcal{B}_{kl} + \frac{2}{\epsilon}\sum_{k\in\mathcal{I}_l,l\in\mathcal{I}_m}\left(\log\frac{2k_k\cdot k_l}{Q^2} - \frac{1}{2}\log\frac{m_l^2}{Q^2}\right)\mathcal{B}_{kl} \\
+ \; & \frac{1}{\epsilon}\sum_{k,l\in\mathcal{I}_m,k>l}\frac{1}{\beta_{kl}}\log\frac{1+\beta_{kl}}{1-\beta_{kl}}\mathcal{B}_{kl} + \mathcal{V}_{fin}\Bigg] \; ; \quad \beta_{kl} = \sqrt{1-\frac{k_k^2 k_l^2}{(k_k\cdot k_l)^2}}
\end{aligned}$$

- Looptools: $\frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)}$ already factorised (contrary to the manual...)
- after 'splitting' the $B_0\big(0,0,0\big)$-divergencies: IR-part correct

- **Real part:**
  - generated the necessary contributions with MADGRAPH
  - modified code appropiately (change masses of occuring $\tilde{q}$-propagators, switch particles to match MADGRAPH-numbering,...)
  - set (almost) all widths to 0 $\longrightarrow$ cancellation of IR-divergencies (alternative: complex-mass-scheme, but here not necessary)

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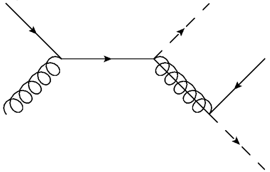
On-shell-intermediate states - I

- one additional problem in case $m_{\tilde{q}} < m_{\tilde{g}}$: in the $q_i g \to \tilde{q}_i \tilde{q}_j \bar{q}_j$-channels an intermediate $\tilde{g}$ can go on-shell
- regularized by resummation of higher-order-contributions to $\tilde{g}$-propagator $\rightsquigarrow$ Breit-Wigner-form:



$$\frac{1}{p_{\tilde{g}}^2 - m_{\tilde{g}}^2} \to \frac{1}{p_{\tilde{g}}^2 - m_{\tilde{g}}^2 + i m_{\tilde{g}} \Gamma_{\tilde{g}}}$$

- in principle no problem with cancellation of IR-singularities
- BUT: in a complete calculation of all production-channels of $\tilde{q}/\tilde{g}$: this occurs again as $qg \to \tilde{q}\tilde{g} \to \tilde{q}\tilde{q}\bar{q} \Rightarrow$ Double-counting!
- similar problem in tW/tH-production ('interference' with $t\bar{t} \to tW^-\bar{b}$)

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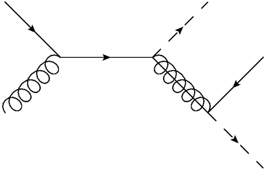

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On-shell-intermediate states - II

- apply a cut $|m_{\tilde{q}\bar{q}} - m_{\tilde{g}}| > \Lambda \rightarrow$ gives only very crude approximation; has to be chosen very 'loose' $\rightarrow$ distort result
- method applied in PROSPINO:
  1. parametrize phase-space such that $s_4 = p_{\tilde{g}}^2 - m_{\tilde{g}}^2$ is integration-variable $\rightarrow$ pole for $s_4 = 0$, the total cross-section reads then $\hat{\sigma} = \int ds_4 \frac{F(s_4)}{s_4^2} = \int ds_4 \frac{F(s_4) - F(0) + F(0)}{s_4^2}$
  2. replace the propagator $s_4^2 \rightarrow s_4^2 + (m_{\tilde{g}}\Gamma_{\tilde{g}})^2$ and use the narrow-width-approximation $m_{\tilde{g}}\Gamma_{\tilde{g}}/[s_4^2 + (m_{\tilde{g}}\Gamma_{\tilde{g}})^2] \rightarrow \pi\delta(s_4)$
  3. the contribution $F(s_4 = 0)$ is in this limit $\hat{\sigma}_{\tilde{q}\tilde{g}} \frac{m_{\tilde{g}}\Gamma_{\tilde{g}}}{\pi} \times BR(\tilde{g} \rightarrow \tilde{q}\bar{q})$, which is exactly the part that has to be subtracted
  4. the remaining term $\Delta\hat{\sigma} = \int ds_4 \frac{F(s_4) - F(0)}{s_4^2 + (m_{\tilde{g}}\Gamma_{\tilde{g}})^2}$ is integrable as a principal-value-integral ($s_4/[s_4^2 + (m_{\tilde{g}}\Gamma_{\tilde{g}})^2] \rightarrow \mathcal{P}(1/s_4)$ for $\Gamma_{\tilde{g}} \rightarrow 0$)
- problem: has to be adapted for every distribution under consideration; moreover: real phase-space in POWHEG-BOX automatized $\rightarrow$ need a subtraction of these on-shell-contributions for every phase-space-point

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  1. parametrize phase-space such that $s_4 = p_{\tilde{g}}^2 - m_{\tilde{g}}^2$ is integration-variable $\rightarrow$ pole for $s_4 = 0$, the total cross-section reads then $\hat{\sigma} = \int ds_4 \frac{F(s_4)}{s_4^2} = \int ds_4 \frac{F(s_4) - F(0) + F(0)}{s_4^2}$
  2. replace the propagator $s_4^2 \rightarrow s_4^2 + (m_{\tilde{g}}\Gamma_{\tilde{g}})^2$ and use the narrow-width-approximation $m_{\tilde{g}}\Gamma_{\tilde{g}}/[s_4^2 + (m_{\tilde{g}}\Gamma_{\tilde{g}})^2] \rightarrow \pi\delta(s_4)$
  3. the contribution $F(s_4 = 0)$ is in this limit $\hat{\sigma}_{\tilde{q}\tilde{g}} \frac{m_{\tilde{g}}\Gamma_{\tilde{g}}}{\pi} \times BR(\tilde{g} \rightarrow \tilde{q}\bar{q})$, which is exactly the part that has to be subtracted
  4. the remaining term $\Delta\hat{\sigma} = \int ds_4 \frac{F(s_4) - F(0)}{s_4^2 + (m_{\tilde{g}}\Gamma_{\tilde{g}})^2}$ is integrable as a principal-value-integral ($s_4/[s_4^2 + (m_{\tilde{g}}\Gamma_{\tilde{g}})^2] \rightarrow \mathcal{P}(1/s_4)$ for $\Gamma_{\tilde{g}} \rightarrow 0$)
- problem: has to be adapted for every distribution under consideration; moreover: real phase-space in POWHEG-BOX automatized $\rightarrow$ need a subtraction of these on-shell-contributions for every phase-space-point

On-shell-intermediate states - II

- apply a cut $|m_{\tilde{q}\bar{q}} - m_{\tilde{g}}| > \Lambda \rightarrow$ gives only very crude approximation; has to be chosen very 'loose' $\rightarrow$ distort result
- method applied in PROSPINO:
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- problem: has to be adapted for every distribution under consideration; moreover: real phase-space in POWHEG-BOX automatized $\rightarrow$ need a subtraction of these on-shell-contributions for every phase-space-point

On-shell-intermediate states - III

- in tW-implementation in MC@NLO two methods discussed: [Frixione et al 2008]
  - **Diagram Removal:** simply remove all diagrams at the amplitude-level which contain on-shell-intermediate states (remove 'too much': interference-terms)
  - **Diagram Subtraction:** construct a subtraction term which subtracts the pole locally
- requirements for this subtraction-term:
  1. match EXACTLY the contribution of the resonant terms when $(p_{\tilde{q}} + p_{\bar{q}})^2 = m_{\tilde{g}}^2$
  2. fall off quickly away from the resonant region in phase-space $\rightarrow$ Breit-Wigner
- write $\mathcal{R} = |\mathcal{M}_{reg}|^2 + 2Re(\mathcal{M}_{reg}\mathcal{M}^*_{res}) + |\mathcal{M}_{res}|^2$ with the full matrix-elements (spin-correlations!)
- subtraction: $\tilde{\mathcal{R}}(\Phi_3) = \mathcal{R}(\Phi_3) - BW(m_{\tilde{q}\bar{q}})|\mathcal{M}_{res}(\Phi'_3)|^2$ with $BW(q) = \frac{(m_{\tilde{g}}\Gamma_{cut})^2}{(q^2 - m_{\tilde{g}}^2)^2 + (m_{\tilde{g}}\Gamma_{cut})^2}$ and Φ'_3 is a point in the 3-particle-phase-space obtained by reshuffling the Φ_3-kinematics to guarantee $(p_{\tilde{q}} + p_{\bar{q}})^2 = m_{\tilde{g}}^2$
- Γ_{cut} interpreted as (small) regulator-width
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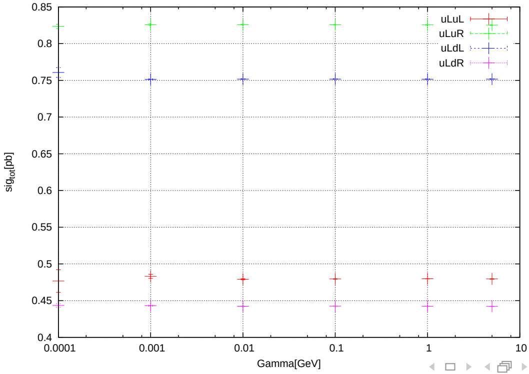
(In-)Dependence on regulator-width

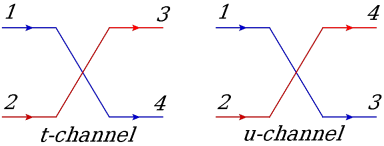
consider e.g. SPS1a-point with the following masses:

$$m_{\tilde{d}_L} = 568.4\text{GeV}\,,\; m_{\tilde{d}_R} = 545.2\text{GeV}\,,\; m_{\tilde{u}_L} = 561.1\text{GeV}\,,\; m_{\tilde{u}_R} = 549.3\text{GeV}$$

$$m_{\tilde{g}} = 607.7\text{GeV}$$



- **Colour-flows:**
  - **Born:**
    - 1/2 possible flows for different/same flavour:



    - for same flavour: choose flow according to its contribution to $|\mathcal{M}|^2$, in case of same chirality: neglect interference-term which is $\propto 1/N_c \rightarrow$ large-N_c-limit
  - **Real:**
    - all in all 4 different colour-flows
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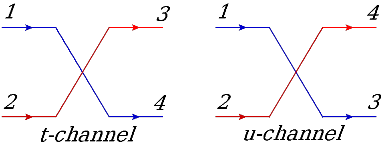

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Conclusion

- in principle implementation of $\tilde{q}\tilde{q}$ finished
- still todo:
  - comparison with PROSPINO for total cross-section
  - comparison with Eva's NLO-MC (with CS-dipoles) for distributions
  - look at influence of Γ_{cut} on distributions for specific scenarios
  - implement $\tilde{q}\bar{\tilde{q}}$,...
  - do some physics