Single top production

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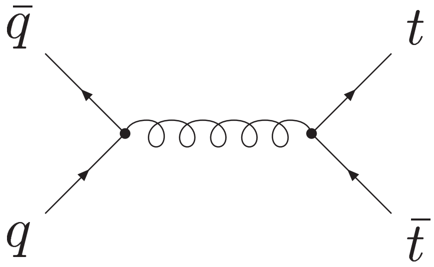
I. **Basic facts about top**

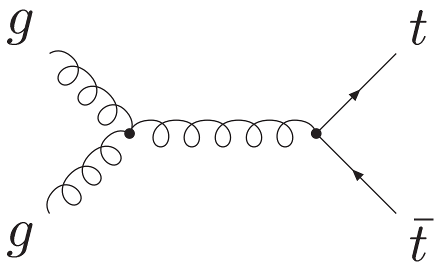
II. **Single top at LHC/Tevatron and LC**

III. **Recent developments in theory**

Basic facts about top

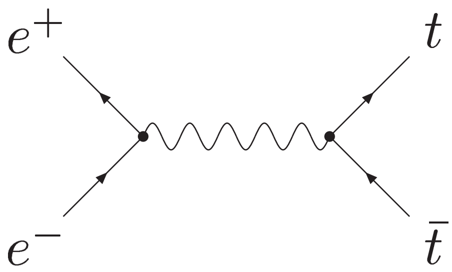
Discovered in 1995 at Tevatron through $t\bar{t}$-pair production:





- Mass $m_t = 175 \pm 5\ GeV$, width $\Gamma = 1.7\ GeV$.
- Top is special: Lifetime shorter than characterisitic hadronization time scale.
- Mass close to the electroweak breaking scale.

Pair production at a linear collider:



with left- and right handed couplings:

$$v_L = \frac{1 - 4/3 \sin^2 \theta_W}{\sin 2\theta_W} \qquad v_R = -\frac{2}{3} \frac{\sin \theta_W}{\cos \theta_W}$$

Single top production

Top quark can also be produced singly by an electroweak Wtb-vertex:

- Process sensitive to Wtb vertex.
  Non-standard couplings can give a hint on physics beyond SM.

- Direct measurement of CKM matrix element V_{tb}.
  Verification of unitarity of CKM matrix.

- The top quark is produced left-handed. Since no hadronization occurs, spin correlations survive in the final decay products.
  Opportunity for polarization studies.

A place for signs of new physics ?

- Non-standard couplings

  R.Peccei and X. Zhang; D.Carlson, E.Malkawi and C.Yuan,

  T.Rizzo; E.Boos, L.Dudko and T.Ohl,

  T.Tait and C.Yuan; D.Espriu and J.Manzano.

- Strong dynamics

  E.Simmons; P.Baringer, P.Jain, D.McKay and L.Smith,

  C.Yue and G.Lu.

- Flavour changing neutral currents

  T.Tai and C.Yuan,

  T.Han, M.Hosch, K.Whisnant, B.Young and X.Zhang.

- CP violation

  D.Atwood, S.Bar-Shalom, G.Eilam and A.Soni,

  E.Christova, S.Fichtinger, S.Kraml and W.Majerotto.

- Supersymmetry

  C.Li, R.Oakes, J.Yang and H.Zhou.

- R-parity violating supersymmetry

  R.Oakes, K.Whisnant, J.Yang, B.Young and X.Zhang,

  P.Chiappetta, A.Deandrea, E.Nagy, S.Negroni, G.Posello and J.Virey.

- Kaluza-Klein modes

  A.Datta, P.O'Donnell, Z.Lin, X.Zhang and T.Huang.

The CKM matrix element V_{tb}

V_{tb} is known indirectly from unitarity

$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 \quad = \quad 1$$

to a very high precision:

$$|V_{tb}| \quad = \quad 0.9990 - 0.9993$$

No way to measure $|V_{tb}|$ directly to this precision !

Sideremark: From top-pair production at the Tevatron:

$$\frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 0.94^{+0.31}_{-0.24}$$

If we do not assume three generations, then only

$$|V_{tb}| >> |V_{ts}|\,, |V_{td}|$$

follows.

Direct measurement of V_{tb}

Direct measurement of $|V_{tb}|$ without any assumptions on the number of generations:

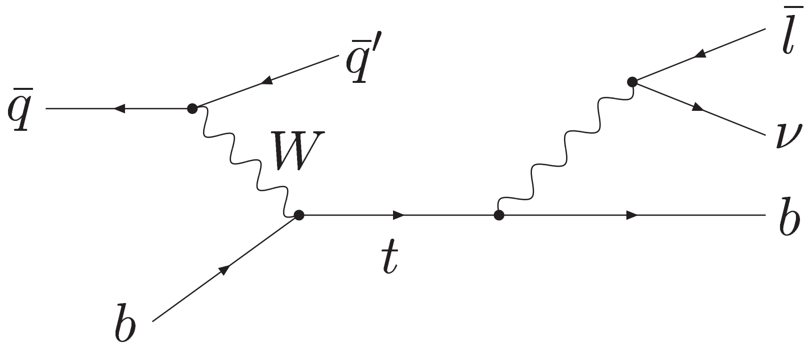
- Single top production: Cross section proportional to $|V_{tb}|^2$.

- Measurement of the top quark width at a linear collider.

The anticipated accuracy of a direct measurement of $|V_{tb}|$ is in the range 1% - 10%.

Spin correlations

At the electroweak Wtb-vertex the top quark is produced left-handed.



Since no hadronization occurs, spin correlations survive in the final decay products.

Of particular importance is the angle between the lepton $\bar{l}$ and the light-quark jet $\bar{q}'$.

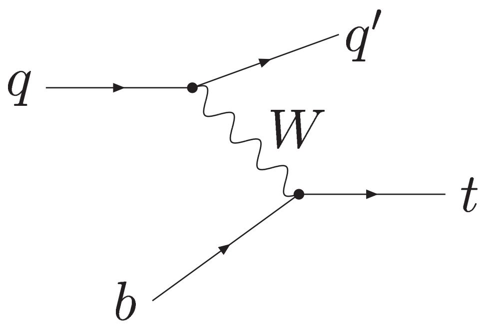
M. Jezabek and J. Kühn;

G. Mahlon and S. Parke;

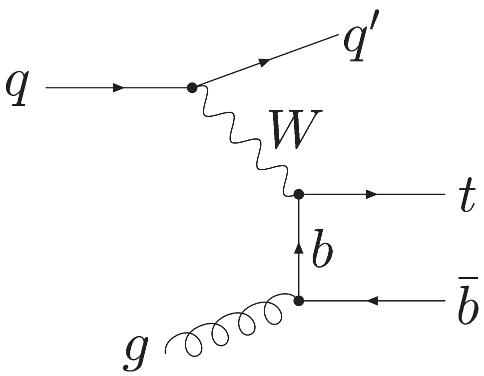
J. van der Heide, E. Laenen, L. Phaf and S.W.

Single top production at hadron colliders

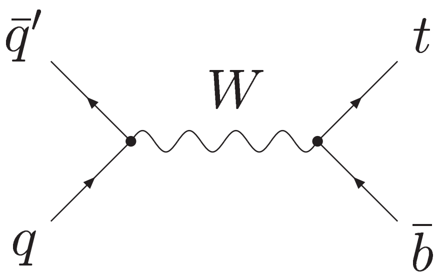
Top quark can also be produced singly by an electroweak Wtb-vertex:



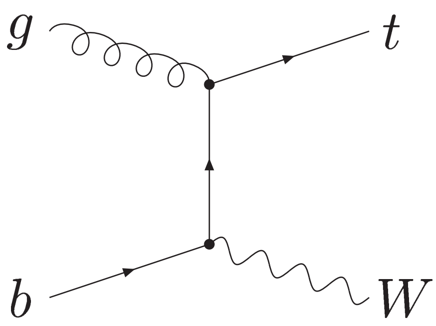
Flavour excitation



W-gluon fusion



s-channel



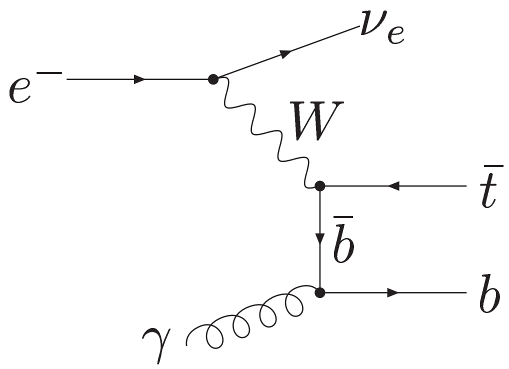
Associated W-production

Single top production at linear colliders

Single top production at linear colliders has been studied for e^+e^-, e^-e^-, $e^-\gamma$ and $\gamma\gamma$ modes.

E. Boos et al.

Most favourable process: $e^-\gamma \to \bar{t}b\nu_e$



W-photon fusion

Also favoured: $e^-e^- \to \bar{t}be^-\nu_e$ due to absence of top pair production.

Cross sections

NLO cross sections for single top production at hadron colliders:

B. Harris, E. Laenen, L. Phaf, Z. Sullivan and S.W.

Process	$\sqrt{s}$	σ_{NLO} (pb)
s-channel	1.96 TeV $p\bar{p}$ (t)	0.447
	14 TeV pp (t)	6.55
	14 TeV pp $(\bar{t})$	4.07
t-channel	1.96 TeV $p\bar{p}$ (t)	0.959
	14 TeV pp (t)	152.6
	14 TeV pp $(\bar{t})$	90.0

LO cross sections for single top production at linear colliders:

E. Boos, M. Dubinin, A. Pukhov, M. Sachwitz and H. Schreiber

Process	$\sqrt{s}$	σ_{LO} (fb)
$e^-\gamma$	0.5 TeV	30.3
	1.0 TeV	67.6
e^-e^-	0.5 TeV	1.7
	1.0 TeV	9.1

Recent developments in theory

Fully differential Monte Carlo programs, which contain the complete spin information, for:

- Full set of tree-level amplitudes for

$$p\bar{p} \to b + \bar{l} + \nu + q$$

  and

$$p\bar{p} \to b + \bar{l} + \nu + \bar{b} + q.$$

- NLO amplitudes for single top production.

$$q + b \to t + q'$$

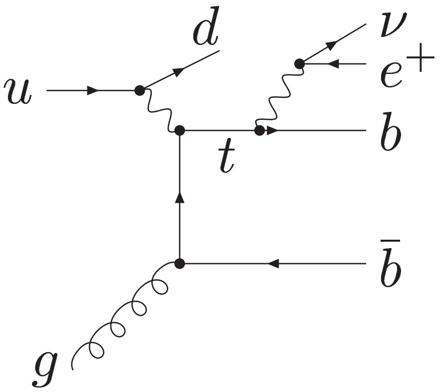
  and

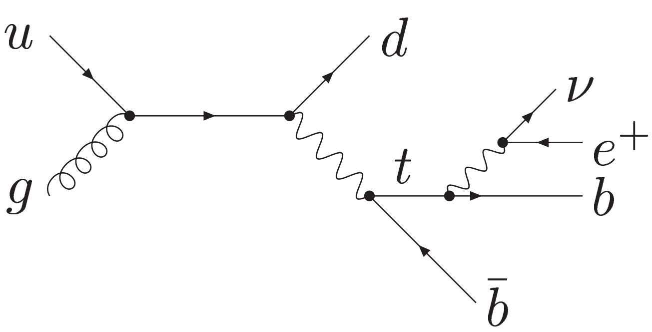
$$q + \bar{q}' \to t + \bar{b}$$

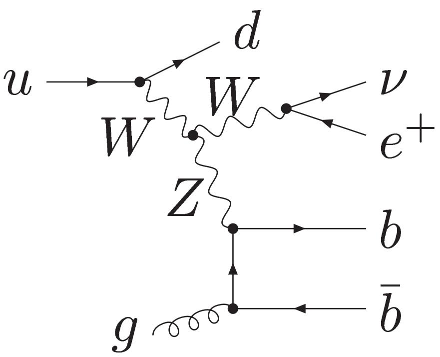
$\rightarrow$ More realistic simulation of experimental acceptance cuts.

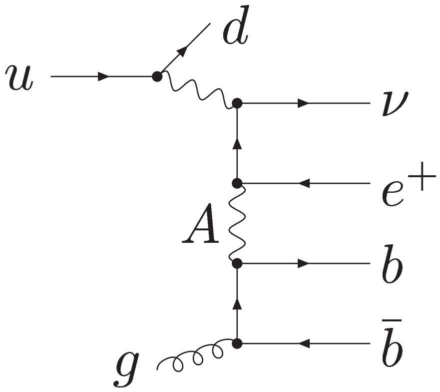
Full set of tree-level diagrams

Full calculation including the production and the decay of the top quark:







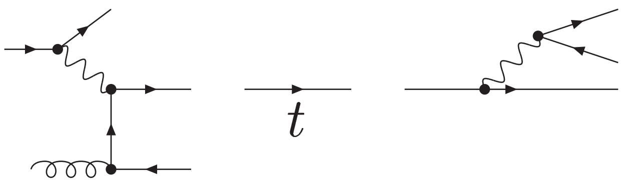


$+$ 41 remaining diagrams.

- Use spinor helicity methods for the calculation.
- Verification of the top narrow width approximation.

Narrow width approximation

Keep only diagrams with a resonant top propagator:



$|A|^2 =$

$$= \left| \sum_\lambda A_{dec}(\ldots, p_{top}^\lambda) \frac{i}{p_{top}^2 - m^2 + im\Gamma} A_{prod}(\ldots, p_{top}^\lambda) \right|^2$$

$$= |A_{dec}(\ldots, p_{\bar{top}})|^2 \frac{1}{(p_{top}^2 - m^2)^2 + m^2\Gamma^2} |A_{prod}(\ldots, p_{\bar{top}})|^2$$

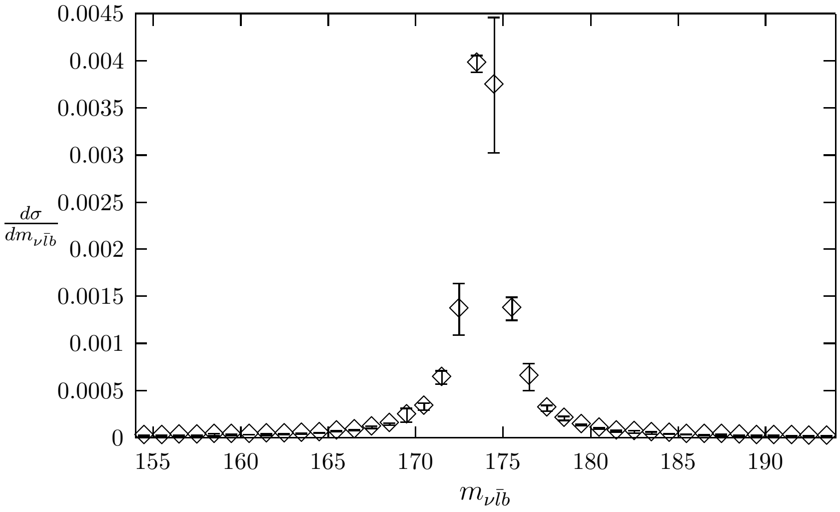
Limit of vanishing top width:

$$\frac{\pi}{m\Gamma} \delta(p_{top}^2 - m^2) |A_{dec}(\ldots, p_{\bar{top}})|^2 |A_{prod}(\ldots, p_{\bar{top}})|^2$$

Factorization of phase space:

$$d\phi_n(Q \to p_1, \ldots, p_n) = \frac{1}{2\pi} d\phi_{n-2}(Q \to p_{top}, p_4, \ldots, p_n)$$
$$\cdot dp_{top}^2 d\phi_3(p_{top} \to p_1, p_2, p_3)$$

Some numerical results



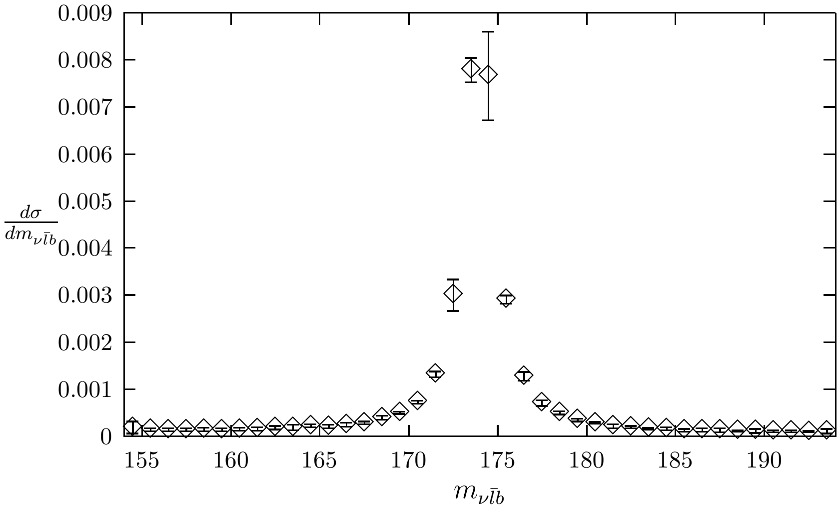


Figure 1: The cross section versus the invariant mass $m_{\nu\bar{l}b}$ for W-gluon fusion (top) and quark-antiquark annihilation (bottom) at the Tevatron.

Check of the narrow width approximation

Tevatron	σ_{tot}	± 20 GeV	narrow width
Wg	15.0 ± 0.4 fb	14.3 ± 0.3 fb	14.5 ± 0.1 fb
Wb	87 ± 1 fb	85 ± 2 fb	87 ± 1 fb
$q\bar{q}$	46 ± 1 fb	32.3 ± 0.3 fb	29.0 ± 0.2 fb

Table 1: Numerical results for Tevatron at 2 TeV.

LHC	σ_{tot}	± 20 GeV	narrow width
Wg	4.6 ± 0.2 pb	4.5 ± 0.4 pb	4.6 ± 0.1 pb
Wb	13.1 ± 0.3 pb	13.0 ± 0.4 pb	13.3 ± 0.1 pb
$q\bar{q}$	685 ± 19 fb	479 ± 16 fb	432 ± 4 fb

Table 2: Numerical results for the LHC at 14 TeV.

Angular correlations

In W-gluon fusion or flavour excitation the top quark is highly polarized along the direction of the $\bar{d}$-quark. In addition the u-quark density is the largest among the quark densities. Look at the quantity

$$a = \frac{1}{2}\left(1 + \cos\theta_{q\bar{l}}\right)$$

where $\theta_{q\bar{l}}$ is the angle between the light quark jet and the charged lepton.

In the rest frame of the top:

$$\frac{d\sigma}{da} = \sigma\left(2Pa + (1 - P)\right),$$

The slope of this distribution is given by

$$2P_{signal}\sigma_{signal} + 2P_{background}\sigma_{background}$$

Angular correlations

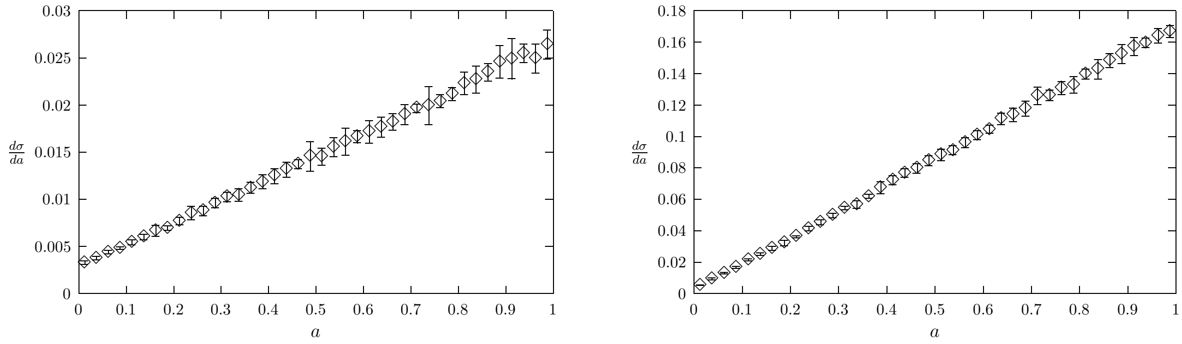


Figure 2: The distribution for the angular correlation a for W-gluon fusion (left) and flavor excitation (right) at the Tevatron.

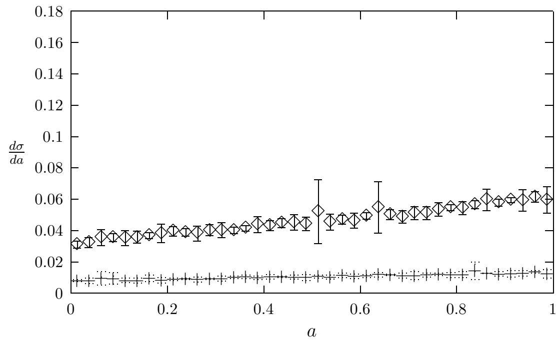


Figure 3: The distribution for the angular correlation a for the "QCD + Weak" background to flavor excitation at the Tevatron.

Next-to-leading order amplitudes

The calculation of the NLO corrections lead to the development of methods to calculate efficiently one-loop amplitudes with massive particles, retaining the complete spin information. These techniques are also useful for other processes.

- Extension of the dipole formalism to massive particles

  L.Phaf and S.W., 01

  S.Catani,S.Dittmaier, M.Seymour and Z. Trocsanyi, 02

- Extension of spinor techniques from massless QCD to processes involving massive particles (and γ_5).

  S.W., 99

- Rules for the conversion of amplitudes calculated in one scheme to another scheme.

  B. Harris, E. Laenen, L. Phaf, Z. Sullivan and S.W., 02

NLO predictions

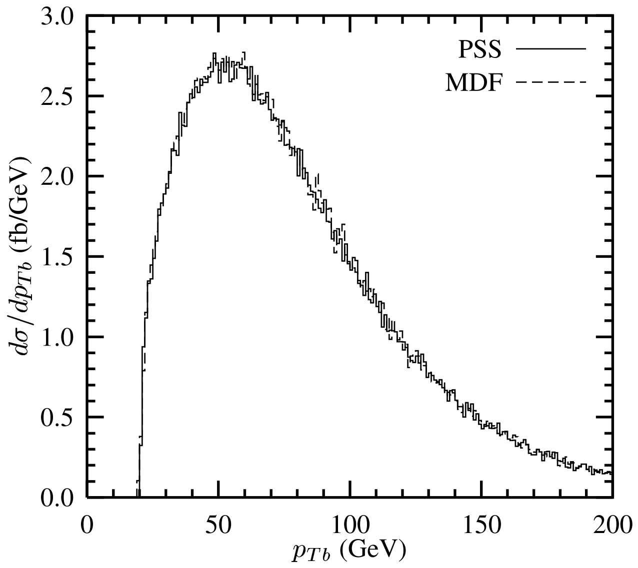


Figure 4: Transverse momentum distribution of the b-jet at NLO in s-channel production of a top quark at the Tevatron.

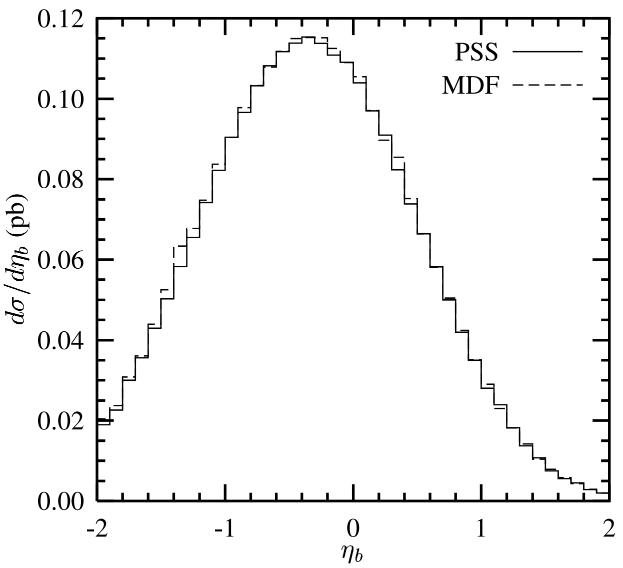


Figure 5: Pseudorapidity distribution of the b-jet at NLO in s-channel production of a top quark at the Tevatron.

Conclusions

- Single top production sensitive to Wtb vertex.
- Direct measurement of CKM matrix element V_{tb}.
- Opportunity to observe the polarization of the top quark.

Fully differential Monte Carlo programs, which contain the complete spin information:

- Full calculation of tree-level amplitudes including the production and the decay.
- NLO amplitudes for single top production.

More to come ...