Single top production at hadron colliders

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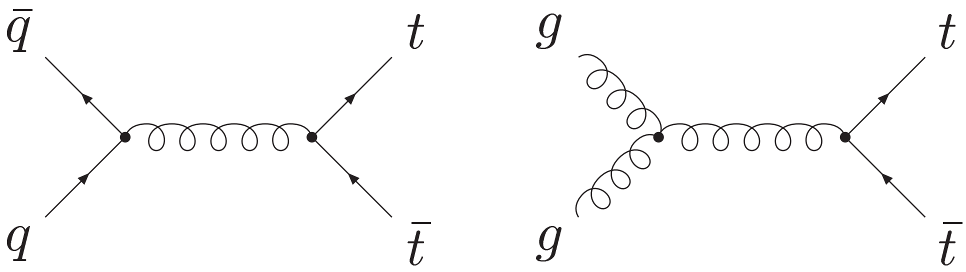
1. **Basic facts about top**
2. **Single top production mechanism**
3. **Short outline of the calculation**
4. **Numerical results**
5. **Outlook**

Basic facts about top

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



- Mass $m_t = 175 \pm 5\ GeV$, width $\Gamma = 1.7\ GeV$.

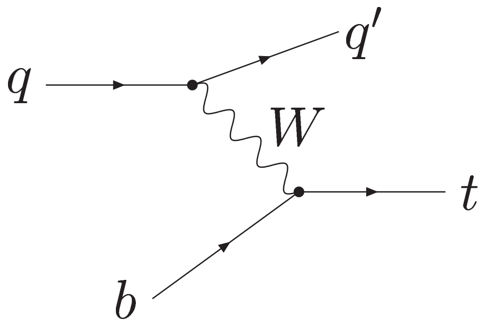
- Top is special: Lifetime shorter than characterisitic hadronization time scale.

- Mass close to the electroweak breaking scale.

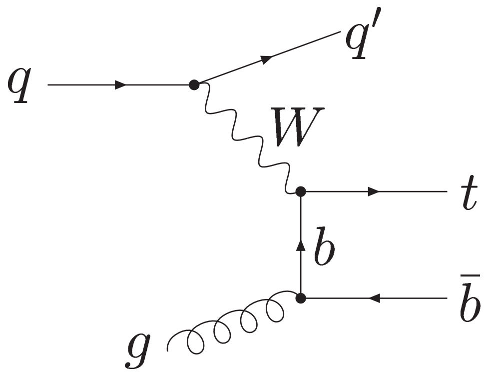
- Can also be produced through an electroweak Wtb-vertex.

Single top production

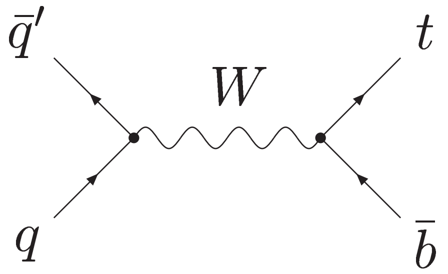
- Top quark can also be produced by weak interaction:



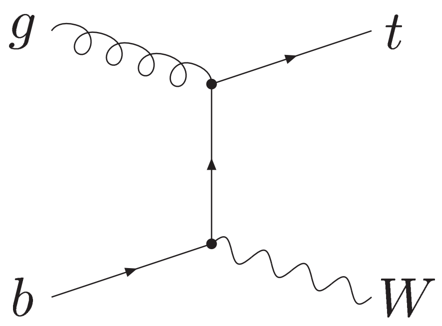
Flavour excitation



W-gluon fusion



s-channel



Associated W-production

Single top production

- 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.
  Opportunity for polarization studies.

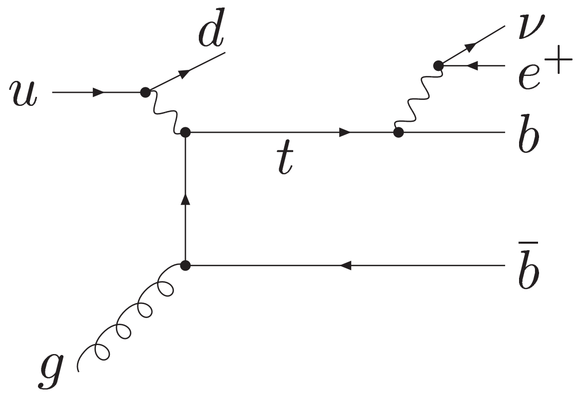
Can it be detected?

- Expected to be seen at Tevatron Run II.

- Feasible at LHC.

A quick glance on the calculation

- Full calculation including the production and the decay of the top quark.



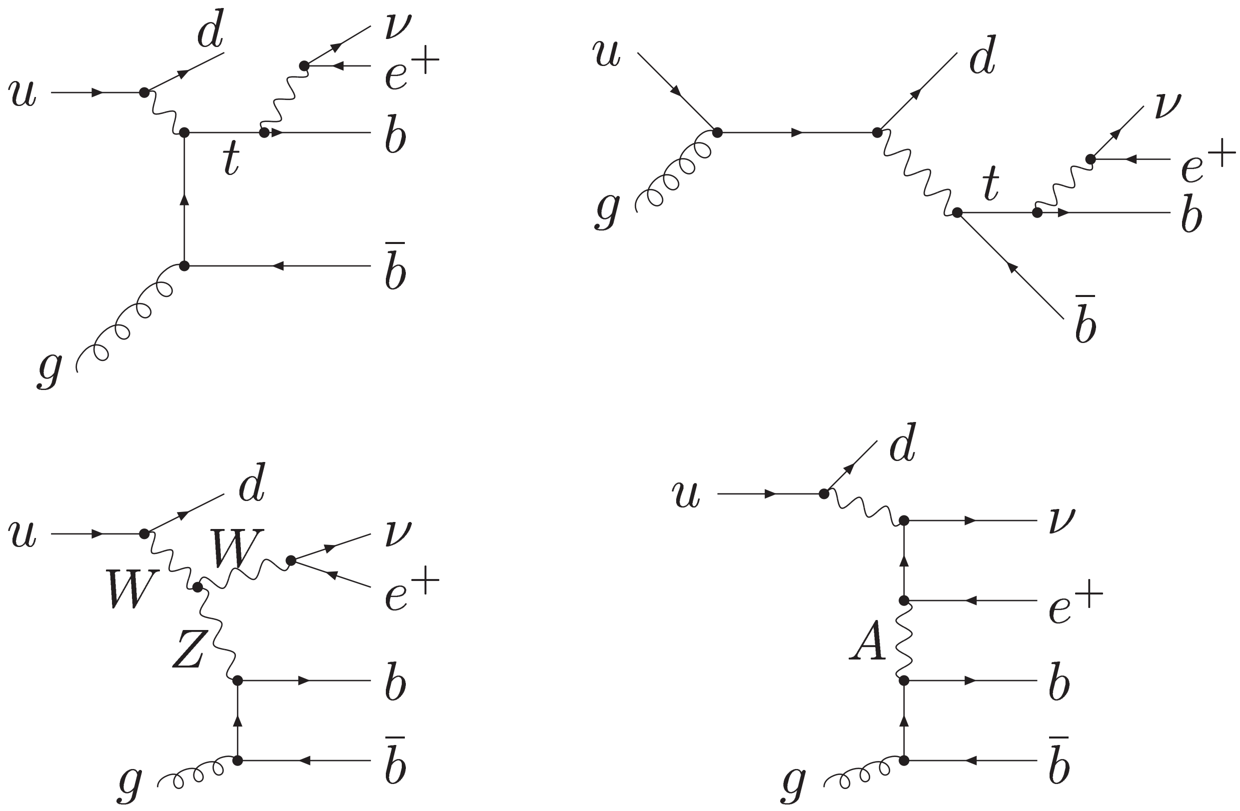
- Verification of the top narrow width approximation.

- Use spinor helicity methods for the calculation.

- Jets defined by hadronic k_T-algorithm.

- Numerical program written in C++.

Some diagrams



- Neglect all fermion masses except the top mass.
- 't Hooft-Feynman R_ξ-gauge with $\xi = 1$.
- Diagrams containing a Higgs or would-be Goldstone do not contribute.
- Still many diagrams (45 for W-gluon fusion).

Colour decomposition

Decompose the amplitude according to the colour structure:

$$A_{Wg} \quad = \quad g T^{a_g}_{i_b j_{\bar{b}}} \delta_{i_d j_u} A^{(1)}_{Wg} + g \delta_{i_b j_{\bar{b}}} T^{a_g}_{i_d j_u} A^{(2)}_{Wg}$$

The partial amplitudes $A^{(1)}_{Wg}$ and $A^{(2)}_{Wg}$ are separately gauge invariant.

Spinor methods

Weyl representation of Dirac matrices:

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{pmatrix}, \quad \sigma^\mu = (1, -\vec{\sigma}), \quad \bar{\sigma}^\mu = (1, \vec{\sigma}).$$

Massless Dirac spinors:

$$u(p) = \begin{pmatrix} p_A \\ p^{\dot{B}} \end{pmatrix} = \begin{pmatrix} |p+\rangle \\ |p-\rangle \end{pmatrix}$$

Explicit expression for Weyl spinors:

$$|p+\rangle = \frac{e^{i\alpha}}{\sqrt{p_+}} \begin{pmatrix} -p_\perp^* \\ p_+ \end{pmatrix}, \quad |p-\rangle = \frac{e^{i\alpha}}{\sqrt{p_-}} \begin{pmatrix} p_\perp^* \\ p_- \end{pmatrix}.$$

with light-cone coordinates $p_+ = p_0 + p_3$, $p_- = p_0 - p_3$ and $p_\perp = p_1 + ip_2$.

Spinor products

Scalar product of two spinors gives a complex number:

$$\langle pq \rangle = \langle p - | q + \rangle = \frac{e^{-i(\alpha_p - \alpha_q)}}{\sqrt{p_- q_+}} (p_- q_+ - p_\perp q_\perp^*)$$

$$\begin{aligned} [qp] &= \langle q + | p - \rangle = \frac{e^{-i(\alpha_q - \alpha_p)}}{\sqrt{p_- q_+}} (p_- q_+ - p_\perp^* q_\perp) \\ &= \langle pq \rangle^* \end{aligned}$$

Spinor methods

- Basic objects: Massless two-component Weyl spinors

$$|p\pm\rangle, \qquad \langle p\pm|$$

- Gluon polarization vectors:

$$\varepsilon_\mu^+(k,q) = \frac{\langle k+|\gamma_\mu|q+\rangle}{\sqrt{2}\langle q-|k+\rangle}, \qquad \varepsilon_\mu^-(k,q) = \frac{\langle k-|\gamma_\mu|q-\rangle}{\sqrt{2}\langle k+|q-\rangle}$$

q is an arbitrary null reference momentum. Dependency on q drops out in gauge invariant quantities.

- Massive spinors:

$$\begin{aligned} u(\pm) &= \frac{1}{\sqrt{2pq}}\left(\not{p}+m\right)|q\mp\rangle \\ \bar{u}(\pm) &= \frac{1}{\sqrt{2pq}}\langle q\mp|\left(\not{p}+m\right) \end{aligned}$$

Spinor methods

Basic identities:

- Fierz identity:

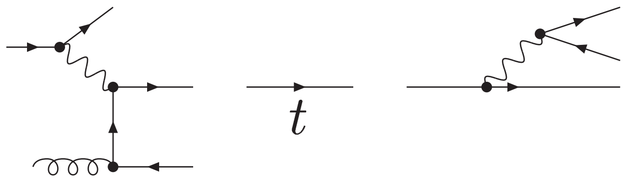
$$\langle A+|\gamma_\mu|B+\rangle\langle C-|\gamma^\mu|D-\rangle \quad = \quad 2\,[AD]\,\langle CB\rangle$$

- Schouten identity:

$$\begin{aligned}\langle AB\rangle\langle CD\rangle &= \langle AD\rangle\langle CB\rangle + \langle AC\rangle\langle BD\rangle \\ [AB]\,[CD] &= [AD]\,[CB] + [AC]\,[BD]\end{aligned}$$

Narrow width approximation

Keep only diagrams with a resonant top propagator:



$$|A|^2 =$$

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

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

Limit of vanishing top width:

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

Factorization of phase space:

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

Jet algorithm

Hadronic $k_\perp$-algorithm (Catani, Dokshitzer, Seymour and Webber):

- Preclustering:
  - Calculate
  $$d_{ij} = R_{ij}^2 \, \mathsf{min}(p_{i\perp}^2, p_{j\perp}^2), \qquad d_i^{(B)} = p_{i\perp}^2$$
  $$R_{ij}^2 = 2\left[\cosh(\eta_i - \eta_j) - \cos(\phi_i - \phi_j)\right]$$
  $$\text{or } R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$
  - If $d_i^{(B)} = \mathsf{min}(d_{ij}, d_i^{(B)})$ and $d_i^{(B)} < d_{cut}$ assign particle i to the beam jet.
  - If $d_{ij} = \mathsf{min}(d_{ij}, d_i^{(B)})$ and $d_{ij} < d_{cut}$ recombine i and j.
  - Repeat until all d_{ij}, $d_i^{(B)} > d_{cut}$.
- Jet clustering:
  - Define $y_{cut} < 1$, $y_{ij} = d_{ij}/d_{cut}$.
  - If y_{ij} is smallest and $y_{ij} < y_{cut}$ recombine i and j.
  - Repeat until all $y_{ij} > y_{cut}$.

Monte Carlo integration

- VEGAS: Integration over unit hypercube with importance sampling.
- Random number generator produces uniformly distributed points in $[0, 1]$.
- Mapping from the unit hypercube into physical four-momenta:
  - Sequential approach: Succesive two-body decays.
  - RAMBO algorithm: Constant weight for massless final state particles.
- Precalculate the spinor products from the four-momenta.

Some numerical results

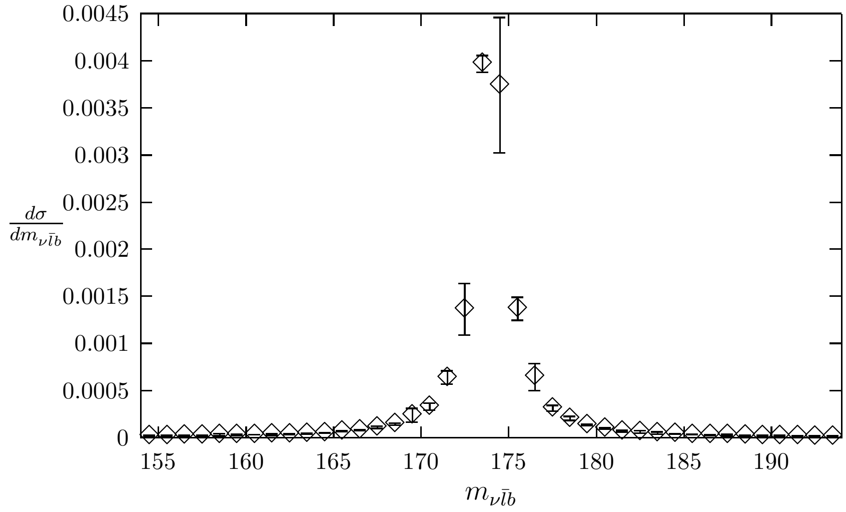
Tevatron	σ_{tot}	± 20 GeV	narrow width
Wg	15.0 ± 0.4 fb	14.3 ± 0.3 fb	14.5 ± 0.1 fb
Wb	87 ± 1 fb	85 ± 2 fb	87 ± 1 fb
$q\bar{q}$	46 ± 1 fb	32.3 ± 0.3 fb	29.0 ± 0.2 fb

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.

Some numerical results



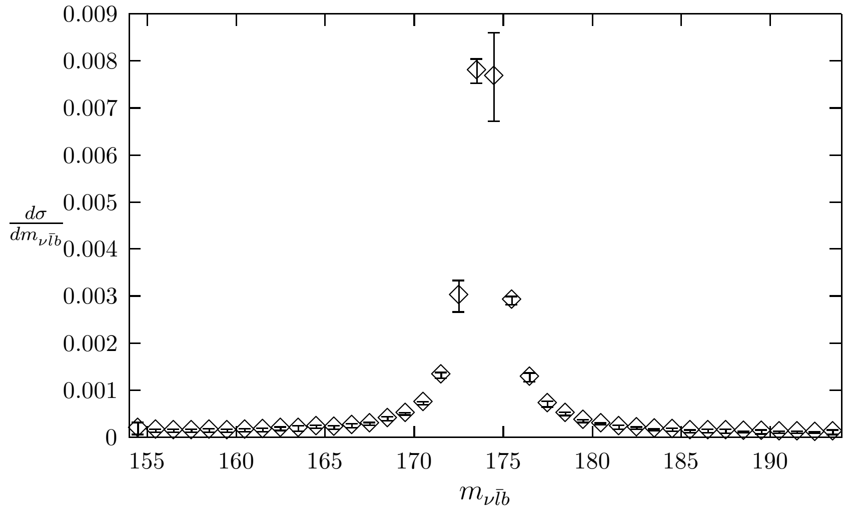


Figure 1: The cross section versus the invariant mass $m_{\nu\bar{l}b}$ for W-gluon fusion (top) and quark-antiquark annihilation (bottom) at the Tevatron.

Pseudo-rapidity distributions

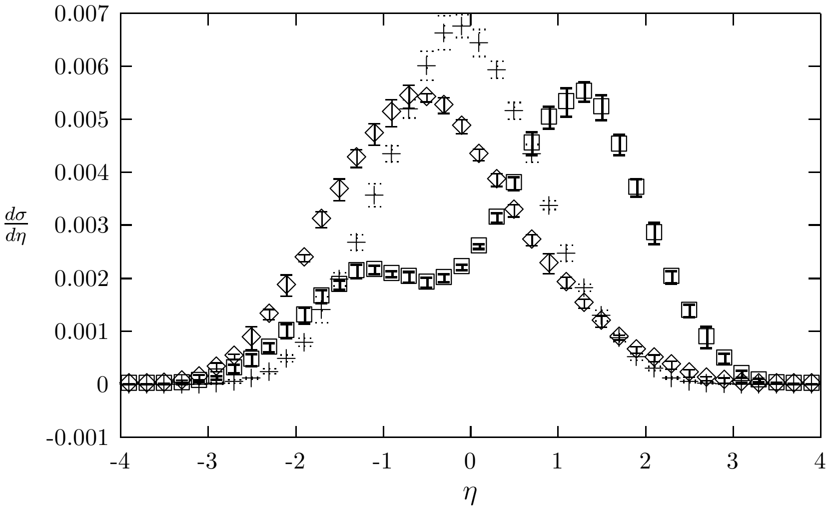


Figure 2: The pseudo-rapidity distribution for W-gluon fusion of the $\bar{b}$-quark (diamonds), the b-quark (crosses) and the light quark q (boxes) in the restframe of the partonic subsystem at the Tevatron.

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

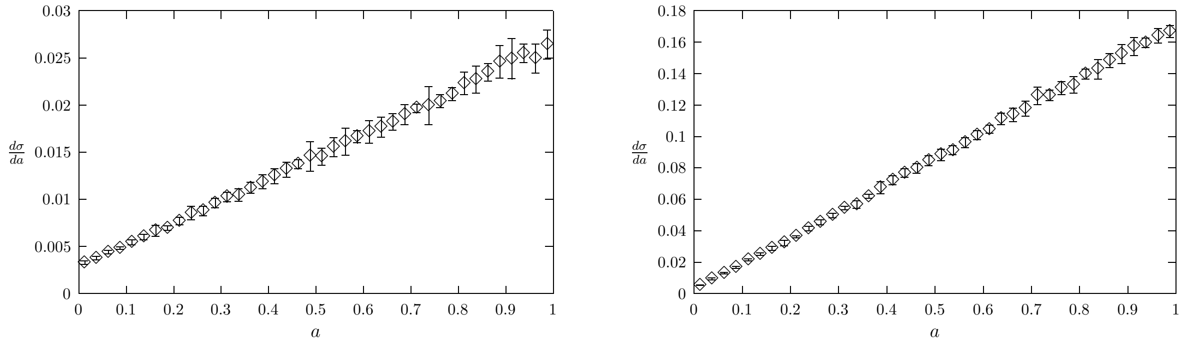


Figure 3: The distribution for the angular correlation a for W-gluon fusion (left) and flavor excitation (right) at the Tevatron.

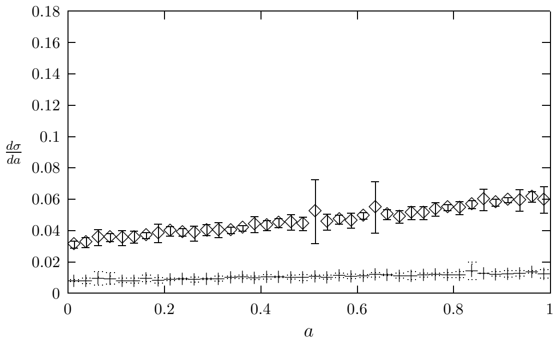


Figure 4: The distribution for the angular correlation a for the "QCD + Weak" background to flavor excitation at the Tevatron.

Conclusions

What has been done:

- Full calculation of singletop production and decay for all channels.
- Numerical program in C++.
- Verification of the top narrow width approximation.
- Angular correlations.

What will been done:

- NLO corrections to W-gluon fusion.
- More reliable prediction on p_T-spectrum.