Helmholtz International School - Workshop
"Calculations for Modern and Future Colliders"

Status of QCD NLO corrections for t-channel single top production in SANC

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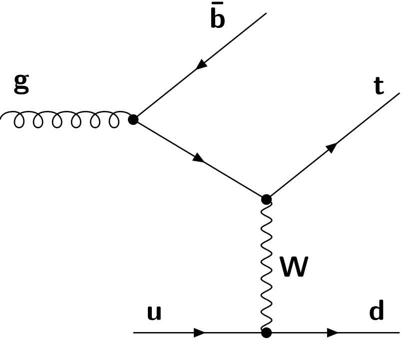
Outline

- Introduction
- Overview of Theoretical Calculations
- t channel Single Top Production in SANC
- Results and plans

Experimental Situation - Tevatron

Single *top* quark production was first observed in 2007 by CDF and D0 collaborations at the Fermilab Tevatron. (Abazov et al. 2008)



Their NLO result for the t channel process $p\bar{p} \to tq\bar{b} + X$ (and $p\bar{p} \to \bar{t}\bar{q}b + X$), elementary process on this diagram;

$$1.98 \pm 0.30 pb \text{ for } m_{top} = 175\,GeV$$
$$\text{c.m.s. energy } \sqrt{s} = 1.96\,TeV$$

at next-to-leading order (NLO) in perturbation theory

Experimental Situation - LHC

CERN Large Hadron Collider (LHC) - a factory for production of **single top and anti top quarks**, $\sqrt{s} = 14\,TeV$. (W. Bernreuther, 2008)

t-channel parton processes	cross sections
$ub \to dt$	74 %
$\bar{d}b \to \bar{u}t$	12 %
$\bar{s}b \to \bar{c}t$	8 %
$cb \to st$	6 %

t-channel parton processes	cross sections
$d\bar{b} \to u\bar{t}$	56 %
$\bar{u}\bar{b} \to \bar{d}\bar{t}$	20 %
$s\bar{b} \to c\bar{t}$	13 %
$\bar{c}\bar{b} \to \bar{s}\bar{t}$	11 %

The t production cross sections are larger then $\bar{t}$ production one because the LHC is a pp collider and the proton contains more valence u quarks then d quarks. Total cross section for the process $pp \to t\,(or\ \bar{t}) + X$ is a convolution of the all cross sections for the partonic subprocesses and the parton distribution functions (PDF)

Analytical Calculations

The NLO QCD the t channel cross section was calculated:

- in 1995 by G.Bordes and B.van Eijk, *Nucl.Phys.* **B 435** *23*
- in 1997 by T. Stelzer, Z. Sullivan and S. Willenbrock, *Phys.Rev.* **D 56** *5919*, [arXiv:hep-ph/9705398]
  Authors calculate all one - loop QCD corrections to the process $bq \to tq'$ in the minimal subtraction ($\overline{MS}$) scheme using a structure - function approach. They sum virtual gluon and emitted gluon corrections to the heavy - quark and to the light - quark vertices and corrections from so called W - gluon fusion processes $gq \to t\bar{b}q'$ and $gb \to t\bar{q}q'$, subtract collinear singularities ($\ln \frac{m_t}{m_b}$). They show that the correct scale in the light - quark distribution function is $\mu^2 = Q^2$ (momentum transferred by W boson, squared) and the appropriate scale in the b quark distribution function is $\mu^2 \approx Q^2 + m_t^2$.

Numerical Calculations

- in 2004 by J.Campbell, R.K. Ellis, F. Tramontano, *Phys.Rev.* **D 70** *094012*, [arXiv:hep-ph/0408158]
  Authors report the method of inclusion of single top processes into the general NLO Monte Carlo program MCFM, summing over all contributing partons in the initial state. They also include the leptonic decay of the top quark.
- in 2005 by Q.H. Cao, R. Schwienhorst, J.A. Benitez, R. Brock, C.P. Yuan, *Phys.Rev.* **D 72** *094027*, [arXiv:hep-ph/0504230]
  Numerical results for inclusive cross section obtained using a narrow width approximation ($t \to bW^+(\to e^+\nu)$ is included). But still the CTEQ6M PDFs are used. $m_t = 178 GeV$ The collinear divergences are absorbed into the PDFs. Examination of scale dependence ($mu = m_t, \mu = M_W$) is shown.

MC@NLO

- in 2006 by S. Frixoine, E. Laenen, P. Motylinski and B. Webber, *JHEP* **0603** *092*, [arXiv:hep-ph/0512250]
  Authors match NLO QCD results for single top production on realistic hadron level with parton shower Monte Carlo simulation, according to the prescription of the MC@NLO formalism. They talk of fully-exclusive computations having in mind that the cancellation of the infrared singularities is formally achieved analytically in an observable-independent manner, and the four-momenta of all of the final-state partons are available for defining the observables. In order to implement a process in MC@NLO, its NLO cross section must be computed according to the subtraction formalism (FKS) of this program.

Updated Calculations

- in 2007 by N. Kidonakis, *Phys.Rev.* **D 75** *071501*, [arXiv:hep-ph/0701080]
  Author presents updated numerical NLO results for t channel single top production at the LHC obtained by the MRST2004 PDFs. He emphasizes on the fact that the NLO soft-gluon corrections are not a good approximation to the full NLO QCD corrections in the t channel. They are large and negative while the exact NLO corrections are small. Results for LHC:
  $\sigma_{top}^{t-channel} = 150 \pm 6pb, \;\; m_t = 171.4 \pm 2.1 GeV$
  $\sigma_{antitop}^{t-channel} = 92 \pm 4pb.$

Updated Calculations

- in 2009 by J.Campbell, R.Frederix, F.Maltoni, F.Tramontano, *Phys.Rev.Lett.* **102** *182003*, [arXiv:0903.0005(hep-ph)]
  Results for LHC:
  $\sigma_{top} = 152pb(LO); = 165^{+5}_{-4}pb(NLO)$,
  $\sigma_{antitop} = 91pb(LO); = 99^{+3}_{-2}pb(NLO)$, $m_t = 172GeV$
  Authors used (MRST2004lo) and MRST2004FF4nlo PDFs for the (LO) and NLO predictions. NLO distributions in pseudo rapidity η and transverse momentum p_T are shown $(gq \to t\bar{b}q')$.

t-channel Single Top Production in SANC

The scheme of analytical calculations for the process $qb \to tq'$ in SANC:

- Programs for calculation of self energy and the counter terms of quark, needed to cancel the ultraviolet divergences; programs for calculation of the one - loop heavy - and light - quark vertices.
- Program for calculation of Form Factors and the amplitude of the one - loop virtual corrections free from ultraviolet divergences.
- Program for calculation of real soft - and hard - gluon contributions, process $qb \to tq' + g$.
  't Hooft - Veltman trick is used for calculation of soft-gluon integrals.
- Program for calculation of so called W - gluon fusions, attendant processes $gq \to t\bar{b}q'$ and $gb \to t\bar{q}q'$.

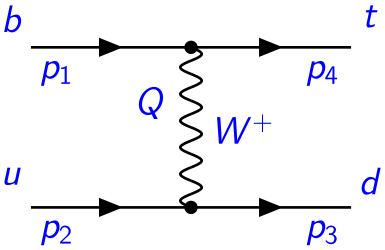
The sum of Soft and Virtual gluon contributions do not contain infrared divergences. Parameter ω, the gluon energy cut, separate the soft and hard contributions. The sum of both contributions do not contain it.

LO diagram for t-channel process $ub \to dt$ and c.t.

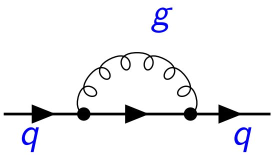
We work in quark parton approach. Therefore we at first consider the elementary quark - parton processes, corresponding to Feynman diagrams, shown bellow.

Leading order diagram

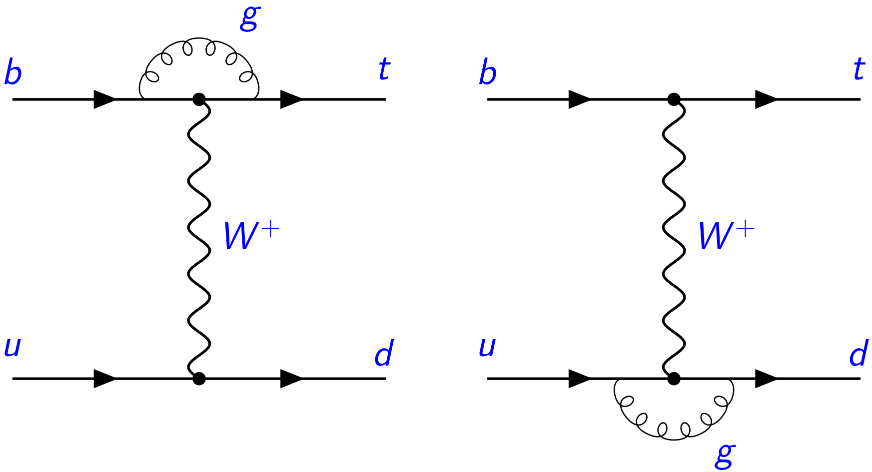
$$p_1 + p_2 = p_3 + p_4$$
$$Q = p_2 - p_3$$



Preparing of counter terms

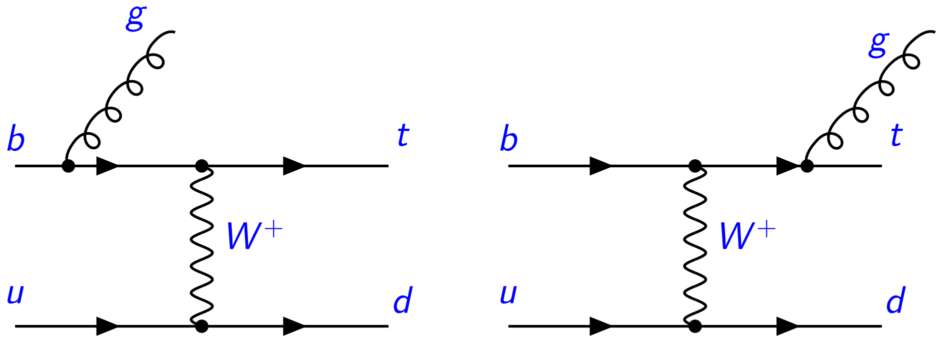


Diagrams for t-channel virtual gluon corrections



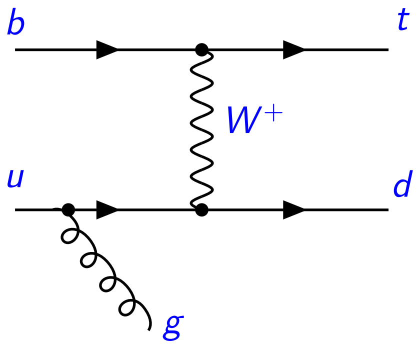
Diagrams for t-channel real gluon corrections

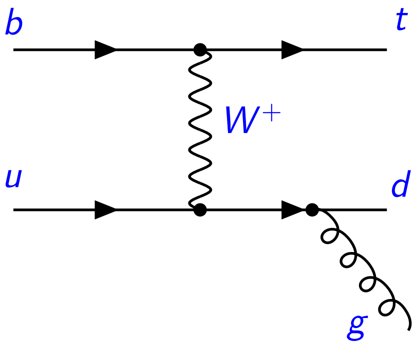
Gluon emitted from heavy - quark vertex



Diagrams for t-channel real gluon corrections

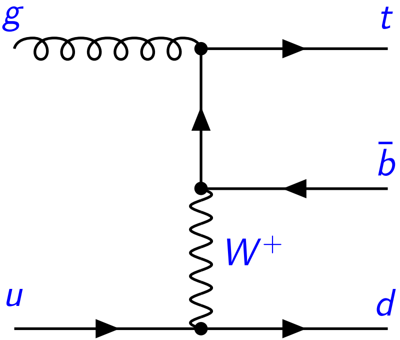
Gluon emitted from light - quark vertex

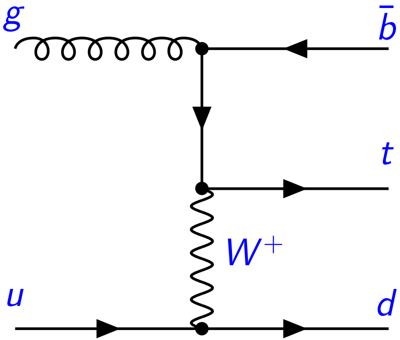




Diagrams for t-channel W - gluon fusion corrections

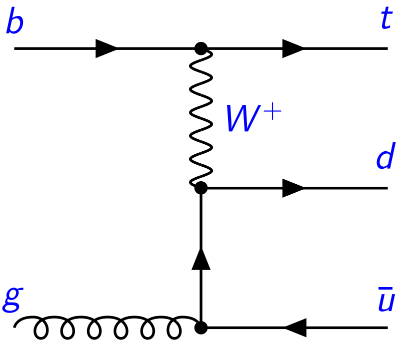
gluon interacts with heavy - quark vertex

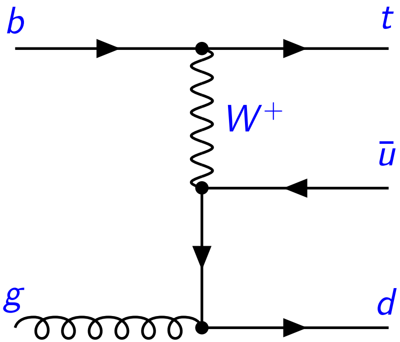




Diagrams for t-channel W - gluon fusion corrections

gluon interacts with light - quark vertex





Numerical results on quark - parton level

We can see that the sum of soft and virtual gluon corrections is large and negative. Hard gluon contribution is large but not enough large to make whole one - loop result positive. At least, we observe the independence of one - loop result on ω (the parameter of separation of the soft and hard gluon contribution).

cross section $\sqrt{s} = 500 GeV$	$b + u \to t + d$		
	$\omega = 0.25 GeV$	$\omega = 0.025 GeV$	$\omega = 0.0025 GeV$
$\sigma^{\mathrm{VirtSoft}}$	-412.9988(4)	-567.5580(6)	-722.1172(8)
σ^{Hard}	360.11(5)	514.59(6)	669.16(8)
$\sigma^{1-\mathrm{loop}}$	-6.17(5)	-6.25(6)	-6.24(8)
δ, %	-113.2(1)	-113.4(1)	-113.4(2)

Numerical results on quark - parton level

Here we give our results in setup of SANC: $m_t = 174.2 GeV$, $m_b = 4.7 GeV$, $G_F = 1.16637.!0^{-5} GeV^{-2}$, $M_W = 80.403 GeV$.

cross section	$b + u \to t + d$		
	$\sqrt{s} = 200 GeV$	$\sqrt{s} = 500 GeV$	$\sqrt{s} = 1000 GeV$
σ^{Born}	7.349969(2)	43.40041(5)	48.98066(6)
$\sigma^{1-\mathrm{loop}}$	-10.61(5)	-9.69(7)	-33.76(11)
$\delta, \%$	-244.31(7)	-122.319872	-168.93(23)

cross section	$b + \bar{d} \to t + \bar{u}$		
	$\sqrt{s} = 200 GeV$	$\sqrt{s} = 500 GeV$	$\sqrt{s} = 1000 GeV$
σ^{Born}	4.491457(3)	37.96466(4)	46.67435(6)
$\sigma^{1-\mathrm{loop}}$	-6.812(4)	-14.34(7)	-36.43(11)
$\delta, \%$	-251.66(8)	-137.78(18)	-178.06(24)

Plans

We continue our work on the process of t - channel single top production including in SANC the calculation of QCD and EW one - loop corrections not only on quark-parton level but also on hadron level. We have solved the problems about the choice of PDFs, choice of a model of subtraction of collinear divergences, how to include parton showers, et setera.