NLO QCD Corrections to s-channel Single Top Quark Production and Decay at the Tevatron

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Outline

1. Single top production in the SM
   - Single top quark production in the SM
   - Categorizing s-channel single-top processes
   - Methods used in our NLO calculation
2. Acceptance
   - Jet finding algorithm and kinematics cuts
   - Acceptance of inclusive two-jet events
3. Kinematical distributions
   - Kinematical distributions of the final objects
   - Event reconstruction
   - Kinematical and spin correlations
   - Background to SM Higgs searching

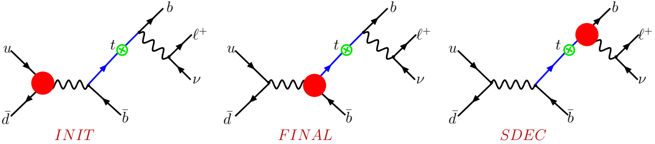
Outline

Single top quark production in the SM

- Single top quarks are produced at hadron colliders through interactions involving a W boson and b quark. Thus, $\sigma \propto |V_{tb}|^2$.
- At tree level there are three modes:
  - s-channel W exchange
    Large rate at Tevatron Run II, small rate at LHC
  - t-channel W exchange
    Dominant rate at Tevatron Run II and LHC
  - Wt associated production
    Very tiny rate at Tevatron Run II, large rate at LHC
- It is very important to understand the acceptances at NLO, including the QCD corrections to both single top quark production and decay.

Categorizing s-channel single top quark processes

- We separate the single-top processes into smaller gauge invariant sets to organize our calculations.



● includes *soft* + *virtual* and *real emission corrections*.

- Keeping track on each individual contribution is useful to compare event generators with exact NLO predictions.

Methods used in our NLO calculation

- To link the top quark production with its decay and also preserve the spin correlation between the final state particles, the narrow width approximation is usually adopted.
- Narrow width approximation (NWA) : fixed top quark mass
    - It does NOT work well in s-channel single-top process because the PDF luminosities drop very fast in the relevant $x \simeq \frac{m_t}{\sqrt{s}} \sim 0.1$ range.
- The "modified" narrow width approximation (MNWA) is adopted in our calculation.
    - Generate Breit-Wigner distribution of the intermediate state top quark mass in phase space.
    - Use the generated top quark mass to calculate the matrix elements.

Inclusive s-channel single-top cross section

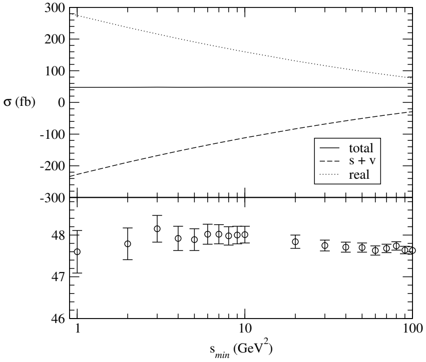
The branching ratio of $t \to bW^+(\to e^+\nu)$ is included.
Use CTEQ6M1 PDF

	MNWA		NWA	
	σ (fb)	Fraction of NLO (%)	σ (fb)	Fraction of NLO (%)
Born Level	31.2	65.0	23.1	64.5
$O(\alpha_s)$ INIT	10.7	22.3	7.3	20.4
$O(\alpha_s)$ FINAL	5.5	11.5	5.0	14.0
$O(\alpha_s)$ SDEC	0.57	1.19	0.42	1.17
$O(\alpha_s)$ sum	16.8	35.0	12.7	35.5
NLO	47.9	100	35.8	100

The INIT contribution dominates in the $O(\alpha_s)$ contributions.

Methods used in our NLO calculation

- Phase space slicing method with one cutoff (s_{min}) is used to regularize both soft and collinear singularities.



Inclusive s-channel single top quark cross section at Tevatron with $\mu_R = \mu_R = m_t$ for $m_t = 178$ GeV. The decay branching ratio $t \rightarrow bW^+(\rightarrow e^+\nu)$ is included.

Our calculation does not depend on the theoretical cutoff s_{min}.

In our calculation, $s_{min} = 5\,\mathrm{GeV}^2$.

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Jet finding algorithm and kinematical cuts

- The cone jet algorithm is used to define the infrared safe observables.
- Smaller $|p_Z(\nu)|$ of two-fold solutions is used to reconstruct the W boson ($\sim 70\%$ efficiency).
- Basic kinematical cuts:

$$
\begin{aligned}
P_T^{\ell} &\geq 15\,\mathrm{GeV} \quad , \quad |\eta_\ell| \leq \eta_\ell^{max}, \\
\not{E}_T &\geq 15\,\mathrm{GeV} \quad , \\
E_T^{j} &\geq 15\,\mathrm{GeV} \quad , \quad |\eta_j| \leq \eta_j^{max}, \\
\Delta R_{\ell j} &\geq R_{cut} \quad , \quad \Delta R_{jj} \geq R_{cut}. \qquad \Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}
\end{aligned}
$$

- To understand the impact of kinematical cuts on the acceptances, two sets of cuts are considered:

loose cuts:

$$\eta_\ell^{max} = 2.5, \quad \eta_j^{max} = 3.0, \quad R_{cut} = 0.5$$

tight cuts:

$$\eta_\ell^{max} = 1.0, \quad \eta_j^{max} = 2.0, \quad R_{cut} = 1.0$$

Acceptances of inclusive two-jet events

$t\bar{b} + t\bar{b}j$	σ [fb]		Acceptances (%)	
	LO	NLO	LO	NLO
(a)	22.7	32.3	73	64
(b)	19.0	21.7	61	46
(c)	14.7	21.4	47	45

(a): loose cuts $\eta_\ell^{max} = 2.5$, $\eta_j^{max} = 3.0$ and $R_{cut} = 0.5$

(b): loose cuts $\eta_\ell^{max} = 2.5$, $\eta_j^{max} = 3.0$ and $R_{cut} = 1.0$

(c): tight cuts $\eta_\ell^{max} = 1.0$, $\eta_j^{max} = 2.0$ and $R_{cut} = 0.5$

- The acceptances are sensitive to the kinematical cuts.
  - A large R_{cut} reduces the acceptance significantly because more events fail the lepton-jet separation cut.
  - With tight cuts, LO and NLO acceptances are almost the same.
  - With loose cuts, LO and NLO acceptances are quite different.
    - $\Longrightarrow$ cannot use k-factor with LO kinematics
    - $\Longrightarrow$ $\Delta\sigma \sim 10\%$, $\Delta\,|V_{tb}| \sim 5\%$
    - $\Longrightarrow$ Important to have full NLO kinematics
- To maximize the acceptance, the loose cuts (a) are used in the following study.

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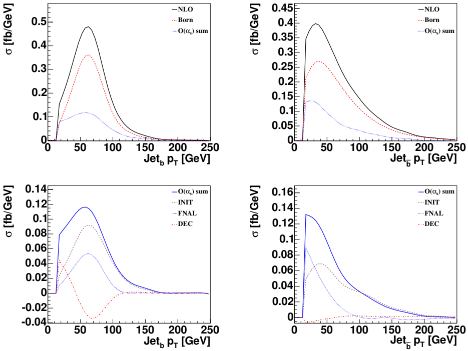
Final object distributions

- Lepton and $\not{E}_T$ distributions are not sensitive to NLO QCD corrrections.
- b and $\bar{b}$ distributions



b $\bar{b}$

NLO corrections broaden the LO distributions and shift the peak position to lower valule.

b and $\bar{b}$ are sensitive to DEC and FINAL contributions, respectively.

INIT contribution dominates over FINAL and DEC.
$\Longrightarrow$ soft gluon resummation
$\Longrightarrow$ improve the prediction on kinematical acceptance

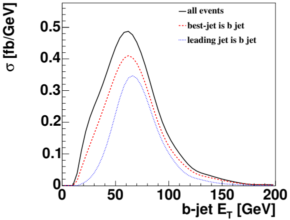
Top quark reconstruction

- The two b-jets in the final state cannot be distinguished experimentally (by detectors).
- Thus, a prescription is needed to identify the correct b in order to reconstruct top quark event.
- Best-jet algorithm (to identify decay products from t)
  - Jet (or 2-jet system) which gives an invariant mass closest to 178 GeV, when combined with W boson.

    Loop over all jets, reconstruct invairant mass of W-jets system
- Leading-jet algorithm
  - highest p_T jet in the event as "b-jet".

b identification efficiency

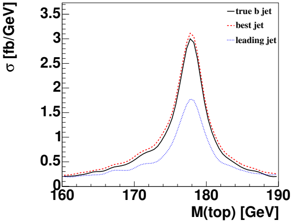
- fraction of picking up correct b



best-jet algorithm: 80%

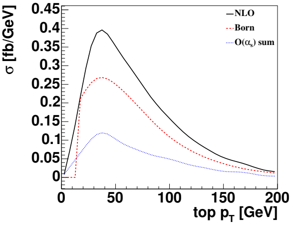
Leading-jet algorithm: 55%

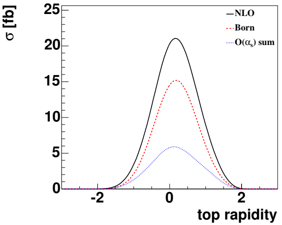
- reconstructed top quark mass



The best-jet algorithm shows higher efficiency than the leading-jet algorithm.

Top quark ($W+$ best-jet) distributions

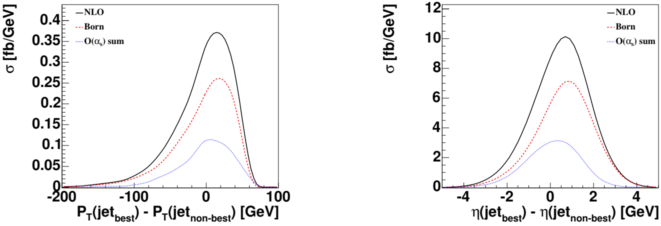




Using the best-jet results in distributions that are very similar to those obtained using the true b (or $b+g$) from the top quark decay.

Kinematical correlation between b and $\bar{b}$

- At Born level, b (best-jet) and $\bar{b}$ (non-best-jet) are highly correlated.



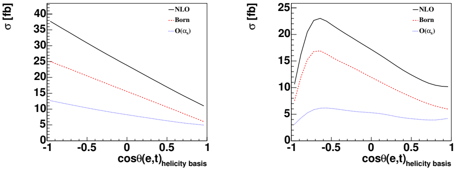
- At NLO
  - Transverse momentum difference is not largely affected.
  - The $O(\alpha_s)$ corrections have a larger effect on the pseudo-rapidity difference.
  - The addtional gluon radiated from FINAL and DEC corrections tends to weaken the correlation between b and $\bar{b}$.

Top quark polarization

- In SM, the top quark produced in single-top event is highly polarized.
- Two bases for polarization:
  - Helicity basis
    Top quark spin is measured along the top quark direction of motion in the c.m. frame of (reconstructed top + non-best-jet).
  - Optimal basis (maximal spin correlation)
    Taking advantage of the fact that top quark is highly polarized along the direction of d-type quark (predominantly, from anti-proton).

Top quark polarization

- Helicity basis

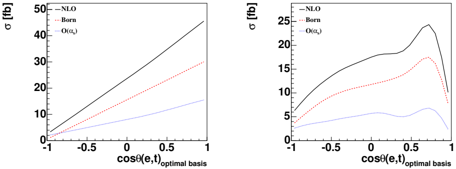


$$\cos\theta_{hel} = \frac{\vec{p}_t \cdot \vec{p}_\ell^{\,\star}}{|\vec{p}_t| \cdot |\vec{p}_\ell^{\,\star}|}$$

$\vec{p}_t$: three-momentum defined in c.m. frame of the two incoming partons

$\vec{p}_\ell^{\,\star}$: charged lepton three-momentum defined in rest frame of top quark.

- Optimal basis



without cuts parton level

with cuts and reconstruction

$$\cos\theta_{opt} = \frac{\vec{p}_{\bar{p}}^{\,\star} \cdot \vec{p}_\ell^{\,\star}}{|\vec{p}_{\bar{p}}^{\,\star}| \cdot |\vec{p}_\ell^{\,\star}|}$$

$\vec{p}_{\bar{p}}^{\,\star}$: anti-proton three-momentum in the rest frame of top quark

$\vec{p}_\ell^{\,\star}$: charged lepton three-momentum in the top quark rest frame.

Top quark polarization

- To quantify the spin correlation, we define the degree of polarization $\mathcal{D}$ and the fraction of polarization $\mathcal{F}$,

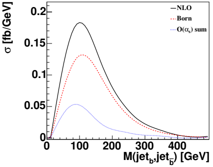
$$\mathcal{D} = \frac{N_{-} - N_{+}}{N_{-} + N_{+}}, \qquad \mathcal{F}\mp = \frac{1 \pm \mathcal{D}}{2}.$$

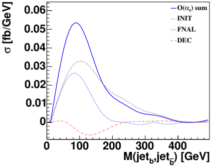
		$\mathcal{D}$		$\mathcal{F}$	
		LO	NLO	LO	NLO
Helicity	Parton level	0.63	0.58	0.82	0.79
	Reconstructed events	0.46	0.37	0.73	0.68
Optimal	Parton level	-0.96	-0.92	0.98	0.96
	Reconstructed events	-0.48	-0.42	0.74	0.71

1. The strong spin correlation at parton level is smeared out after event reconstruction due to the imperfect W-reconstruction.
2. With t-reconstruction, both bases give about the same fraction of polarization.

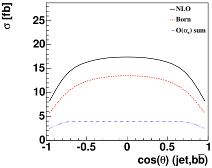
Intrisic background to SM Higgs searching

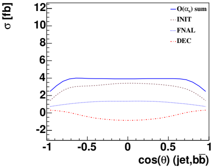
- Invariant mass of (b jet and $\bar{b}$ jet)



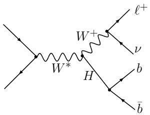


- Angular distribution of $\cos\theta_b$ in $b\bar{b}$





- SM Higgs searching channel



$115 < m_H < 130\,\mathrm{GeV}$

- The DEC contribution flattens out the $O(\alpha_s)$ corrections compared to Born level
  $\Longrightarrow$ closer to Higgs signal distribution
  $\Longrightarrow$ This becomes more important as shape is concerned.

Summary

- In the s-channel single-top process, the initial state contribution dominates the acceptances in all the single particle inclusive distributions.
- With loose kinematical cuts to maxmize the acceptances, the full NLO kinematics needs to be studied. (A constant K-factor with LO kinematics won't work.)
- The best-jet algorithm is better to reconstruct top quark event in the s-channel single-top process.
- Higher order corrections change the kinematical and spin correlations largely. At NLO, the optimal basis give about the same fraction of polarization as the helicity basis.
- NLO QCD corrections to s-channel single-top process is important to SM Higgs boson search via WH production. In particular, DEC contribution has to be included to make more reliable background prediction.

Summary

- Ntuple files of this NLO calculation will be made available for those who are interested.
- A similar study at LHC is in progress.
- The phenomenological study of the exclusive three-jet event will be discussed in Reinhard's talk.