Workshop on Monte Carlo Generator Physics

for Run II at the Tevatron

FULLY DIFFERENTIAL NLO QCD CORRECTIONS TO SINGLE-TOP-QUARK PRODUCTION

Zack Sullivan

Argonne National Laboratory

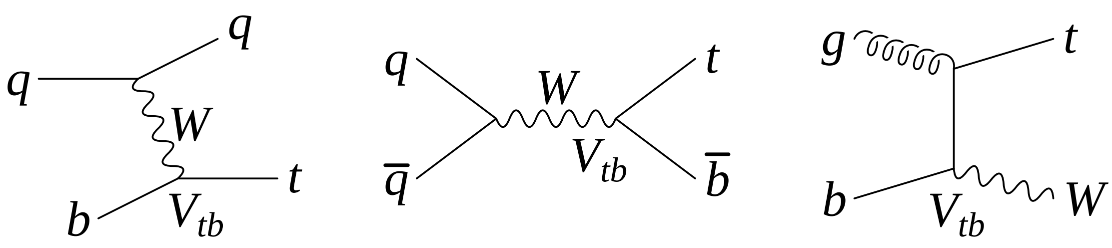
April 20, 2001

with B.W. Harris, E. Laenen, L. Phaf and S. Weinzierl

Contents:

1. Experimental need for fully differential NLO QCD
2. Phase space slicing method
3. s-channel results
4. Summary

Single-Top-Quark Production



Comparing the measured cross section for these processes to the theoretical prediction allows a direct extraction of $|V_{tb}|^2$.

Totally inclusive cross sections

	Tevatron, Run I	Tevatron, Run II	LHC	
$\sigma_t^{\rm NLO} =$	1.45 ± 0.08 pb	2.12 ± 0.10 pb	238 ± 12 pb	[1]
$\sigma_s^{\rm NLO} =$	0.73 ± 0.05 pb	0.88 ± 0.06 pb	10.2 ± 0.7 pb	[2]
$\sigma_{\rm assoc.}^{\rm LL} =$		0.093 ± 0.024 pb	56 ± 8 pb	[3]
$\sigma_{\rm Total} =$	2.2 ± 0.1 pb	3.09 ± 0.11 pb	304 ± 14 pb	

Total single-top-quark production rate $\sim \frac{1}{2}\, t\bar{t}$ rate at Tevatron.

[1] Based on† T. Stelzer, Z.S., S. Willenbrock, PRD 56, 5919 (1997)

[2] M. Smith, S. Willenbrock, PRD 54, 6696 (1996)

[3] T. Tait, PRD 61, 034001 (2000); A. Belyaev, E. Boos, hep-ph/0003260;

Needs NLO calculation

† Updated with CTEQ5M1 PDF's, all old CTEQ and MRS sets had bad b PDF.

CHANGE: $-15\%,\ -13\%,\ -3\%.$

Should we combine all channels to be "inclusive"?

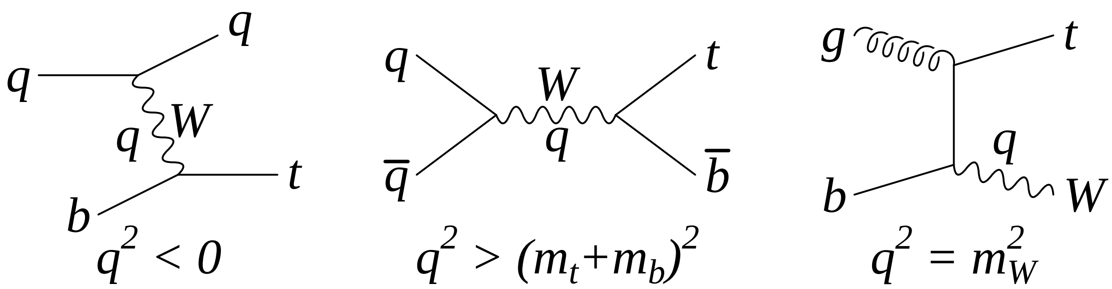
i.e. Look in $W + n$-jets signal, with at least 1 b-tag.

Seems desirable

- Adding all production modes gives largest cross section
- Least possible theoretical uncertainty if allow $W + 3$-jets (once g PDF's are better constrained).

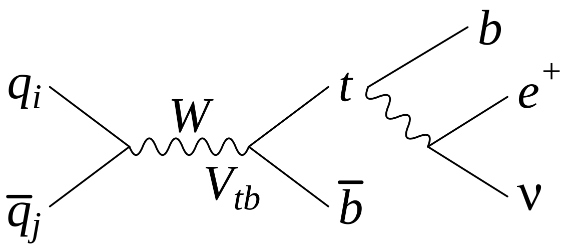
Many difficulties

- Kinematics are generally different for each channel.
- Lose tricks like 'jet veto' to reduce huge $t\bar{t}$ background, especially at LHC.
- Processes probe completely different q^2 of the W boson.



- New physics may affect each production mode separately.

s-channel Production



Signal

2 b-tags, 1 electron/muon, missing energy

$\bar{b} + t \to \bar{b}\, b\, \ell\, \nu$	$\sim 30(20)$ events/fb^{-1}	Run II
	$\sim 200(100)$ events/fb^{-1}	LHC

Backgrounds

Run II	$Wb\bar{b}$	$\sim 100(20)$ events/fb^{-1}
	$t\bar{t}$	$\sim 500(8)$ events/fb^{-1}
	t-channel	$\sim 20(4)$ events/fb^{-1}
LHC	$Wb\bar{b}$	$\sim 540(110)$ events/fb^{-1}
	$t\bar{t}$	$\sim 45000(840)$ events/fb^{-1}
	t-channel	$\sim 2000(215)$ events/fb^{-1}

$S/B \approx 2/3$ at the Tevatron, $S/B \approx 1/12$ at the LHC hard

CDF and DØ have Run I limits of 16 pb and 39 pb respectively.

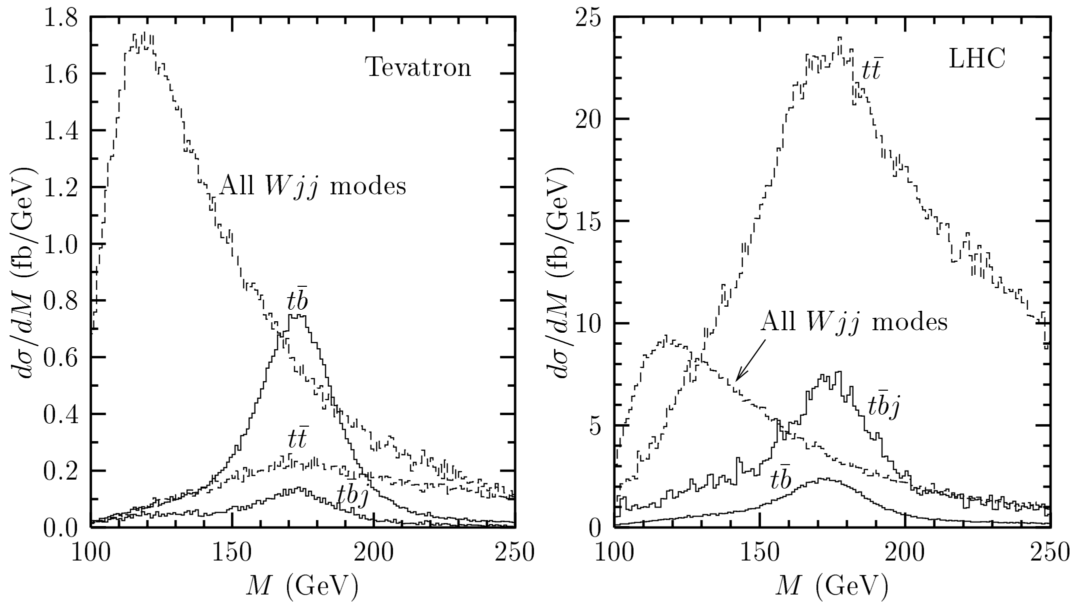
s-channel continued

Advantages

- Parton luminosity ($ud \to W$) is well understood
- Total theoretical error is low $\sim 8\%$
- V_{tb} can be measured to about 12% at Run II, and is statistically dominated (30 fb$^{-1} \to 5\%$ stat.)

Disadvantages

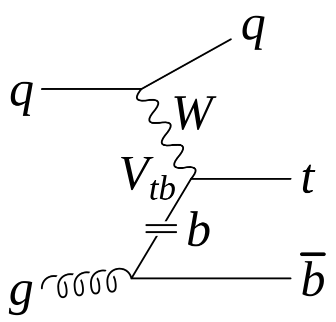
- Small cross section means V_{tb} measurement needs a lot of integrated luminosity to be competitive
- Considerable irreducible background ($t\bar{t}$) at LHC



T. Stelzer, Z. S., S. Willenbrock PRD 58, 094021 (98)

NLO K-factors and LO distributions were used. Is this OK?

t-channel Production



$\sigma(p_{T\bar{b}}<20\mathrm{GeV})=1.07,1.54,160$ pb $\pm 15\%$ at Run I, II, LHC

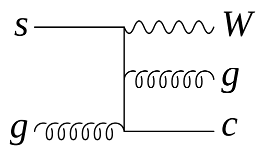
Signal

1 b-tag, 1 forward jet, 1 electron/muon, missing energy

$t + j \to b\ \ell\ \nu\ j$	$\sim 115(70)$ events/fb^{-1}	Run II
	$\sim 12100(5900)$ events/fb^{-1}	LHC

Backgrounds

Biggest contribution is from c/j faking a b-tag



Run II	Wjj	$\sim 750(150)$ events/fb^{-1}
	$t\bar{t}$	$\sim 840(25)$ events/fb^{-1}
	s-channel	$\sim 50(25)$ events/fb^{-1}
LHC	Wjj	$\sim 33000(6900)$ events/fb^{-1}
	$t\bar{t}$	$\sim 100000(2800)$ events/fb^{-1}
	$Wt + s$-chan.	$\sim 8000(1000)$ events/fb^{-1}

$S/B \approx 1/3$ at the Tevatron, $S/B \approx 1/2$ at the LHC

t-channel continued

Advantages

- Large cross section at Tevatron, much larger at LHC.
- Run II can measure this cross section to about 13%, LHC is limited by systematics.
- V_{tb} can be measured to about 11% at Run II, (30 fb^{-1} $\to$ 9%, LHC 9% in first few fb^{-1}).

Disadvantage

Extraction of V_{tb} is limited by theoretical uncertainty in NLO cross section after cuts.

– 15% uncertainty due to inadequate modeling of $p_{T\bar{b}}$.

– 10% uncertainty from q–g luminosity hidden in b PDF.

Solutions?

– Can q–g luminosity be better constrained? w/ Zj/Wj?

– Model $p_{T\bar{b}}$ with fully differential NLO cross section.

Where we are headed.

Polarization of the top quark

$$\frac{1}{\Gamma_{(t\to bl\nu)}}\frac{d\Gamma_{(t\to bl\nu)}}{d\cos\theta} = \frac{1}{2}(1+\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}\cos\theta)$$

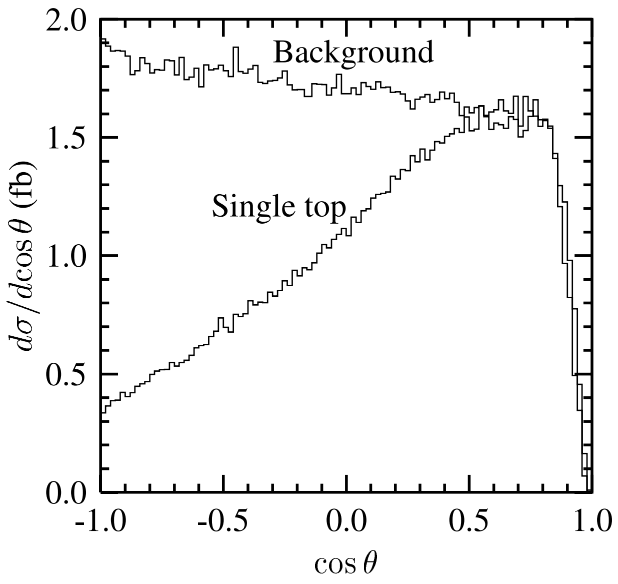
θ is the angle, in the top-quark rest frame, between the direction of the charged lepton and the spin of the top quark.

- At LO $\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = 0.96$ in anti-proton basis for s-channel.
  $\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = 0.91$ in spectator basis for t-channel.

  G. Mahlon, S. Parke, PRD 55, 7249 (97)

  Does this hold at NLO?

- The only analysis uses LO distributions in t-channel:



T. Stelzer, Z. S., S. Willenbrock PRD 58, 094021 (98)

$$A \equiv \frac{\sigma(-1<\cos\theta<-0.1)-\sigma(-0.1<\cos\theta<0.8)}{\sigma(-1<\cos\theta<-0.1)+\sigma(-0.1<\cos\theta<0.8)}$$

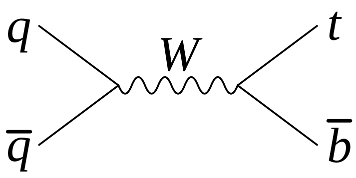
- At LO the asymmetry A is just visible at Run II. At NLO?

Fully Differential NLO QCD Calculations

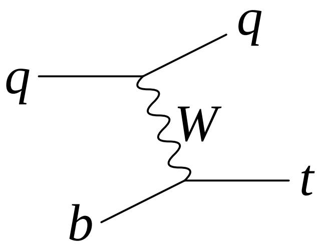
Goals:

1. Generate computer code that produces 4-momenta and spins of all final state particles, and NLO weight.

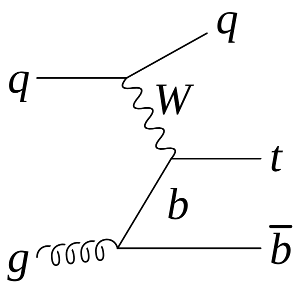
   (a) s-channel (LO: $t + \bar{b}$, NLO: $t + \bar{b} + 1$ jet)

   (b) 2-to-2 t-channel (LO: $t + 1$ jet, NLO: $t + 2$ jets, $t + \bar{b} + j$)

   (c) 2-to-3 t-channel (Wg fusion) (LO: $t + \bar{b} + 1$ jet, NLO: $t + \bar{b} + 2$ jets)

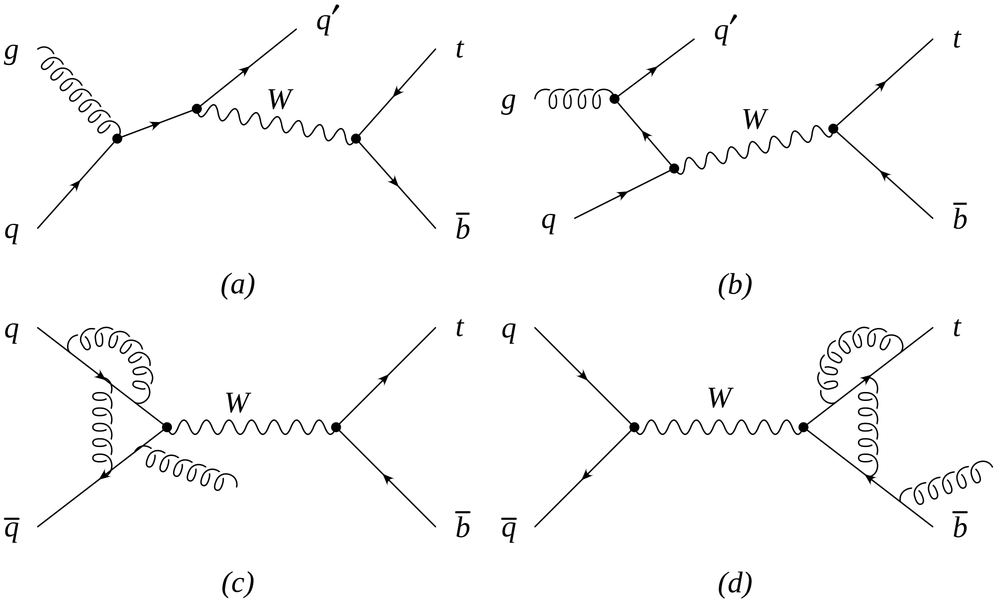
   

2. Add spin-dependent top-quark decays to see polarization.

3. Interface to showering Monte Carlo. Avoid double-counting?

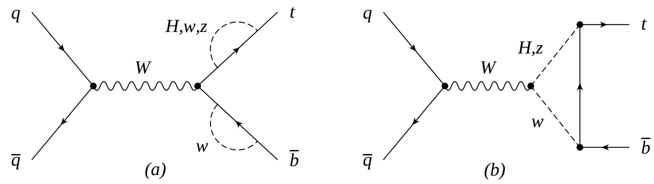
NOTE: Every b or c in the final state may be b-tagged. Hence, we must keep track these.

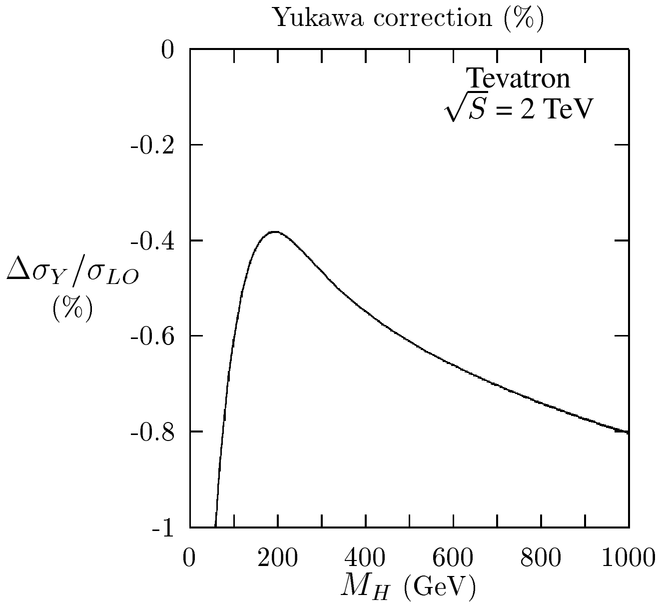
s-channel NLO correction



Corrections to the initial (a–c) and final (d) state are separable at NLO.

Yukawa corrections are small.





M. Smith, S. Willenbrock, PRD 54, 6696 (1996)

Fully Differential NLO Techniques

There are a few modern techniques that allow us to calculate the fully differential QCD corrections. These provide the 4-vectors and corresponding weights of the final-state configuration. The final answers must be independent of the method, so we use more than one as a cross check.

- Phase space slicing method with 2 cutoffs.

  (used in the results described here)

  L.J. Bergmann, Ph.D. Thesis, FSU (89)
  cf. H. Baer, J. Ohnemus, J.F. Owens, PRD 40, 2844 (89)
  B.W. Harris, J.F. Owens, hep-ph/0102128

- Phase space slicing method with 1 cutoff.

  W.T. Giele, E.W.N. Glover, PRD 46, 1980 (92)
  cf. W.T. Giele, E.W.N. Glover, D.A. Kosower, NPB 403, 633 (93)
  E. Laenen, S. Keller, PRD 59, 114004 (99)

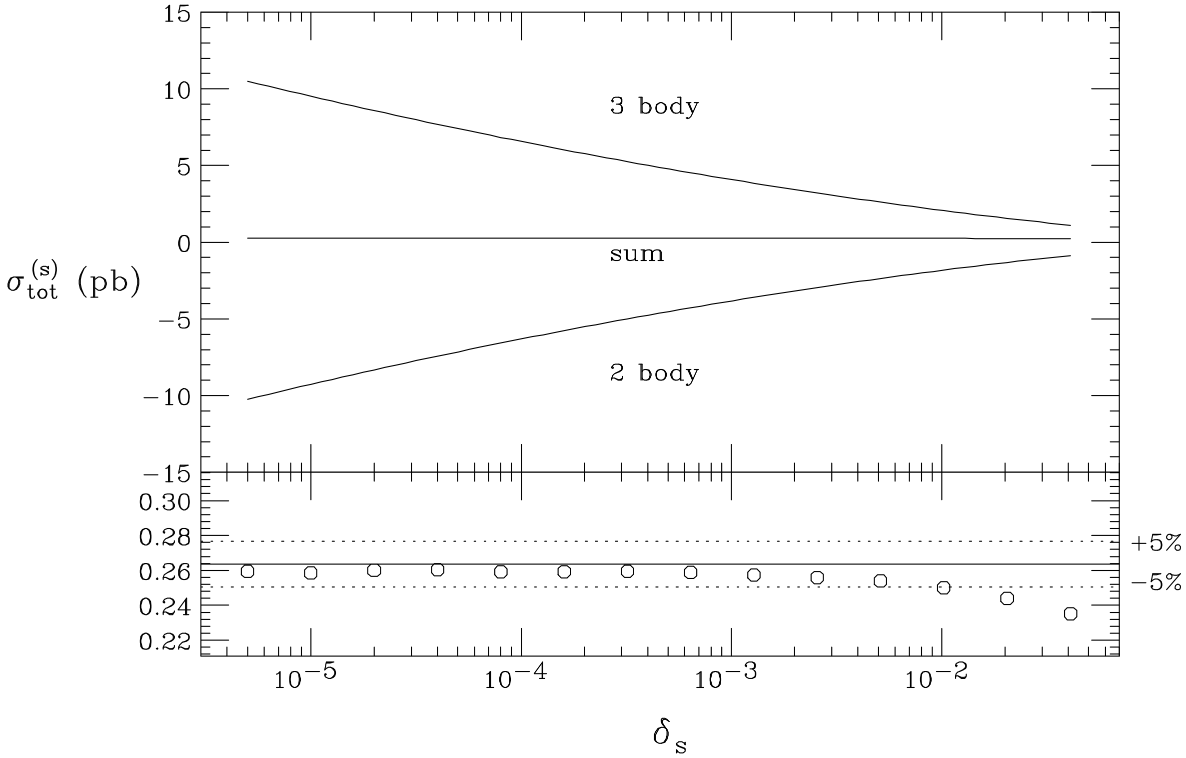
- Massive dipole formalism (a subtraction method) coupled with helicity-spinor calculation.

  cf. L. Phaf, S. Weinzierl hep-ph/0102207

Phase Space Slicing Method (2 cutoffs)

- Phase space is divided into soft, hard-collinear, and hard-non-collinear regions using two parameters: δ_s, δ_c.
  - collinear: any invariant $\hat{s}_{34}, t_{13}, \hat{s}_{35}, \ldots < \delta_c \hat{s}$; soft: $E_g \leq \delta_s \sqrt{\hat{s}}/2$; both are integrated out analytically.
  - Hard-non-collinear region (i.e. 2-to-3, all particles well separated and non-soft) is integrated numerically.
  - After adding virtual and mass factorization terms, all poles cancel.
- Cutoff dependence cancels in any IR-safe observable at histogramming stage. [$\rightarrow$ Fig.]
- Any jet finding algorithm may be implemented (fixed-cone, $k_T, \ldots$). Results here use k_T algorithm with $R = 1$ (roughly equivalent to $R_{\rm cone} = 0.74$). Can study cone-dependence. [see later]
- Experimental cuts may be applied.

Cut-off dependence of s-channel NLO correction



Here $\delta_c = \delta_s/300$, using CTEQ4M PDF's, $\mu = m_t$.

The 2-to-2 and 2-to-3 components of the correction each depend logarithmically on the cutoffs, but the sum is independent of δ_c and δ_s.

Updated Cross Sections

We check that our codes reproduce the previously calculated total cross sections. We then update the cross sections for Tevatron and LHC using CTEQ5M1 PDF's.

Updated totally inclusive cross sections

	Tevatron, Run I	Tevatron, Run II	LHC	
$\sigma_t^{\mathrm{NLO}} =$	1.45 ± 0.08 pb	2.12 ± 0.10 pb	238 ± 12 pb	[1]
$\sigma_s^{\mathrm{NLO}} =$	0.75 ± 0.06 pb	0.91 ± 0.07 pb	11.7 ± 0.9 pb	[2]
$\sigma_{\mathrm{assoc.}}^{\mathrm{LL}} =$		0.093 ± 0.024 pb	56 ± 8 pb	
$\sigma_{\mathrm{Total}} =$	2.2 ± 0.1 pb	3.12 ± 0.12 pb	306 ± 14 pb	

[1] CHANGE: -15%, -13%, -3% from published values. From b PDF.

The scales are $\mu_q^2 = Q^2$ of the W, and $\mu_b^2 = Q^2 + m_t^2$. There is an additional $\pm 10\%$ uncertainty due to q–g luminosity.

[2] CHANGE: $+3\%$, $+3\%$, $+15\%$ from published values.

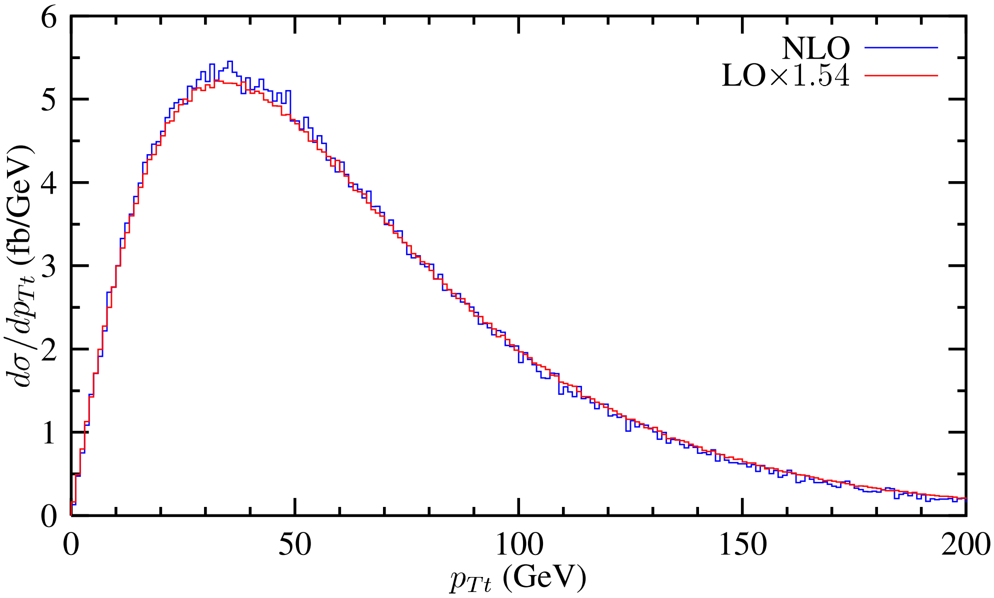
The scale is the invariant mass of the top and bottom quark ($\mu = M_{tb}$). This is equivalent to q^2 in the 2-to-2 processes, but we cannot find q^2 in the 2-to-3 process. Hence, the scale uncertainty is $\pm 5.7\%$ instead of $\pm 4\%$. Top mass uncertainty (175 ± 2 GeV) is $\pm 5\%$. There is an additional $\pm 4\%$ uncertainty from u–$\bar{d}$, $\bar{u}$–d luminosities.

t (no $\bar{t}$) distributions in s-channel at Run II

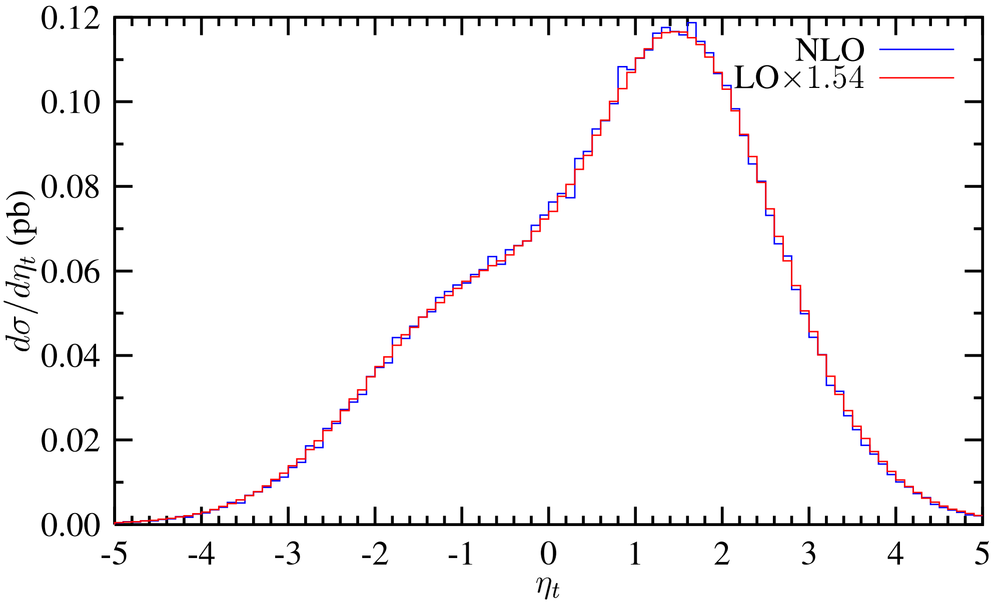
LO: CTEQ5L, 1-loop α_s, $\mu = M_{t\bar{b}}$, $m_t = 175$ GeV, $m_b = 0$.

NLO: CTEQ5M1, 2-loop α_s, k_T with $R = 1.0$.

Shape of top p_{Tt} is unchanged.

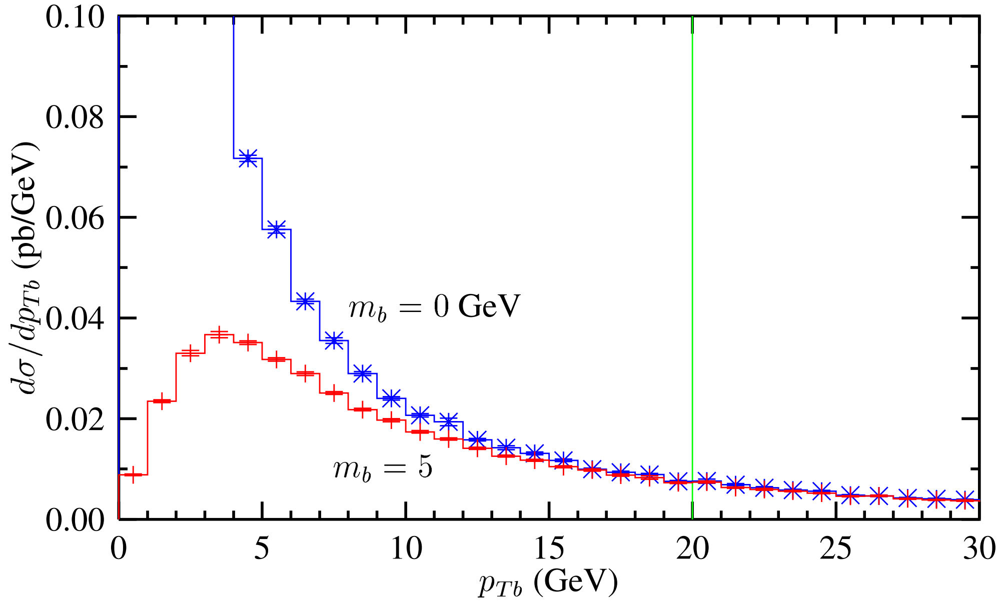


Shape of top pseudo-rapidity η_t is unchanged.



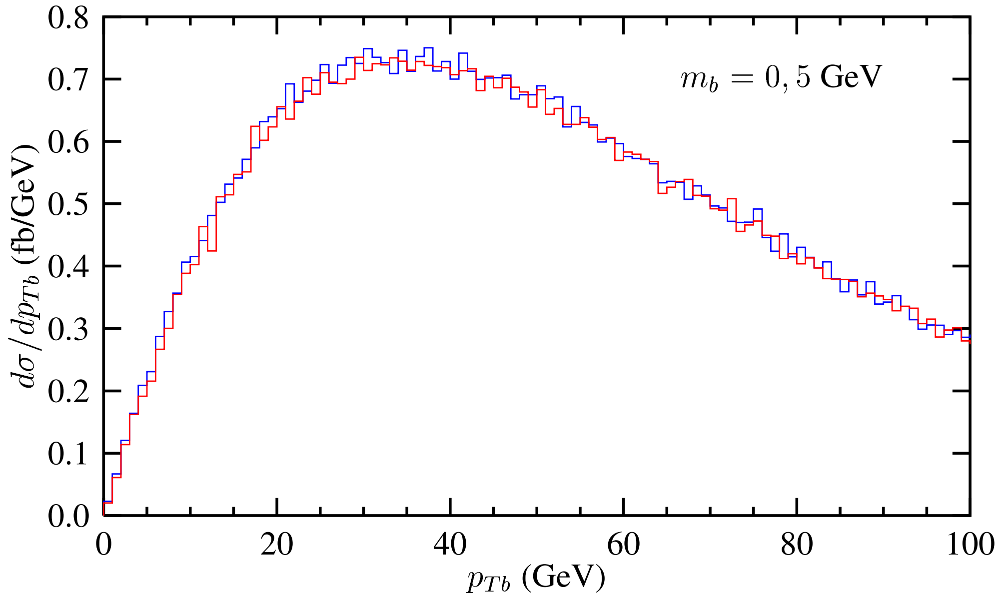
Effect of mass on $\bar{b}$ transverse momentum at LO

t-channel $\left(Wg \to t\bar{b}j \to (bl\nu)\bar{b}j\right)$



There is typically a cut of $p_{Tb} > 15$–20 GeV to tag the b.

s-channel $\left(q\bar{q} \to t\bar{b} \to (bl\nu)\bar{b}\right)$

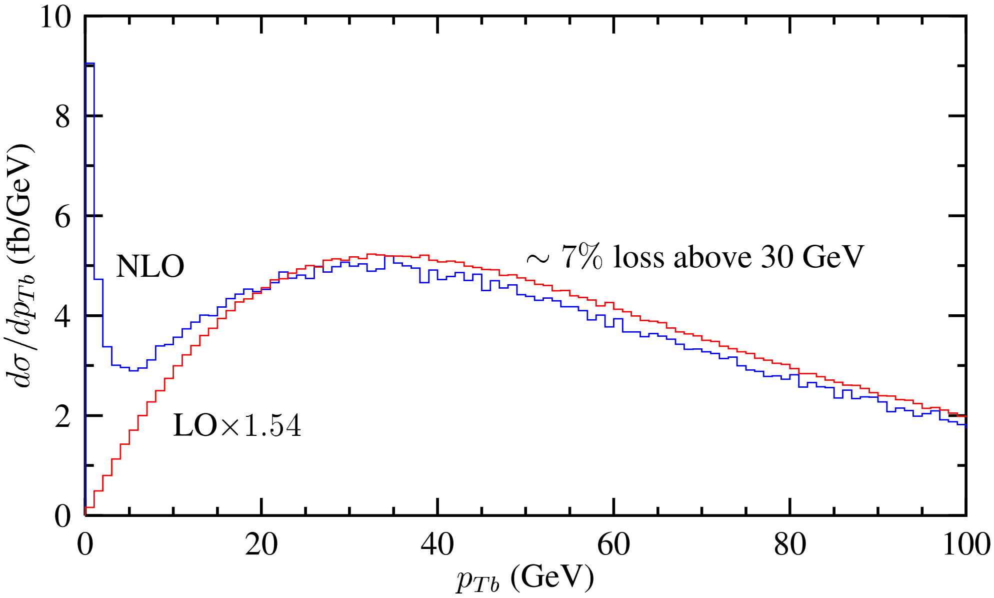


At LO the b is recoiling against the massive top quark.

b jet transverse momentum in s-channel

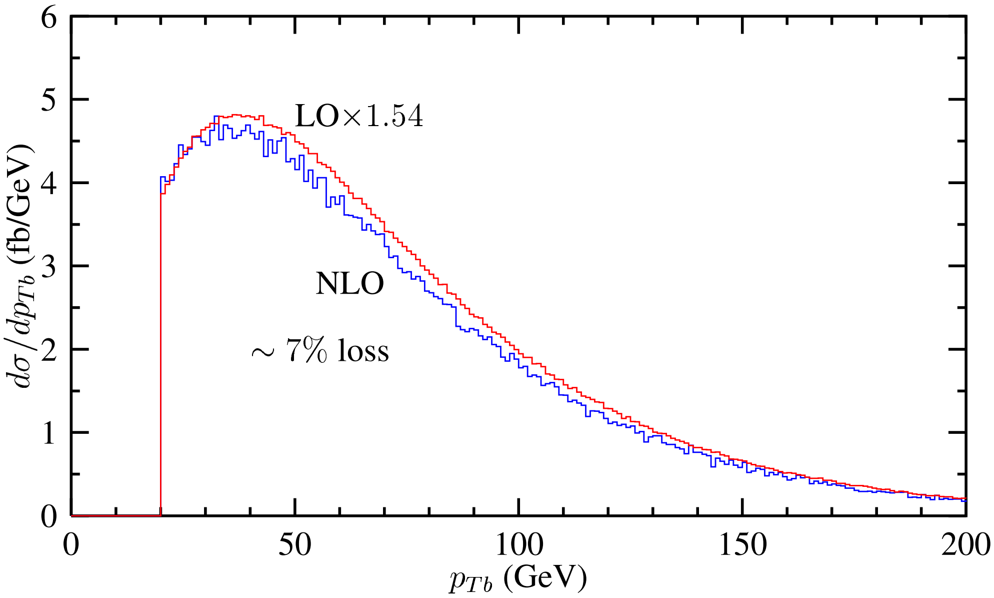
At NLO the total cross section changes by $< 1\%$ for $m_b \neq 0$.

No cuts



A naive K-factor of 1.54 overestimates the cross section above 20 GeV by 7%. The shape is similar at large p_{Tb}.

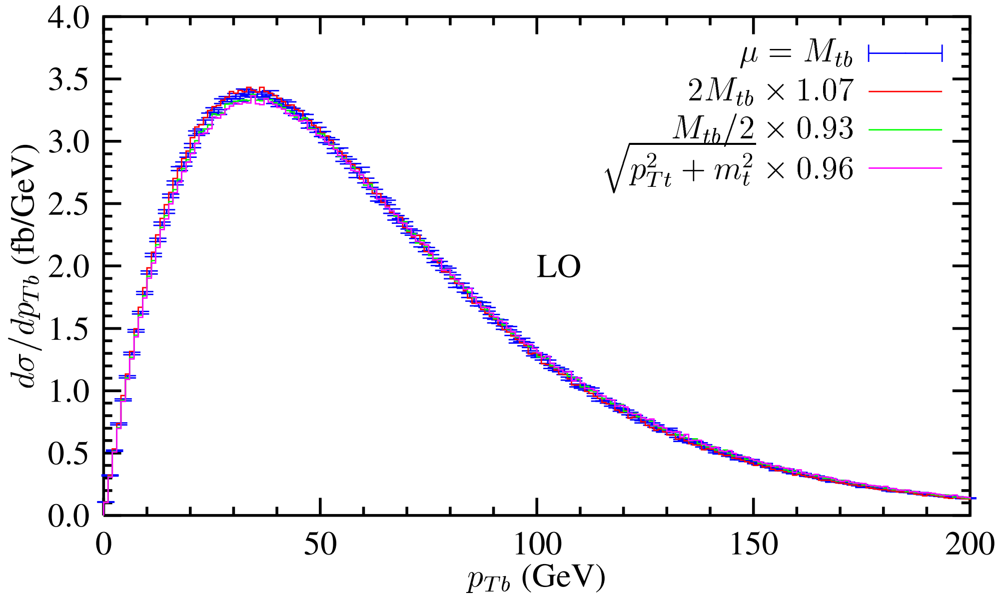
$p_{Tb} > 20$ GeV, $|\eta_b| < 2$



Even with cuts applied, the same overestimation appears.

Scale (μ) dependence on b jet transverse momentum

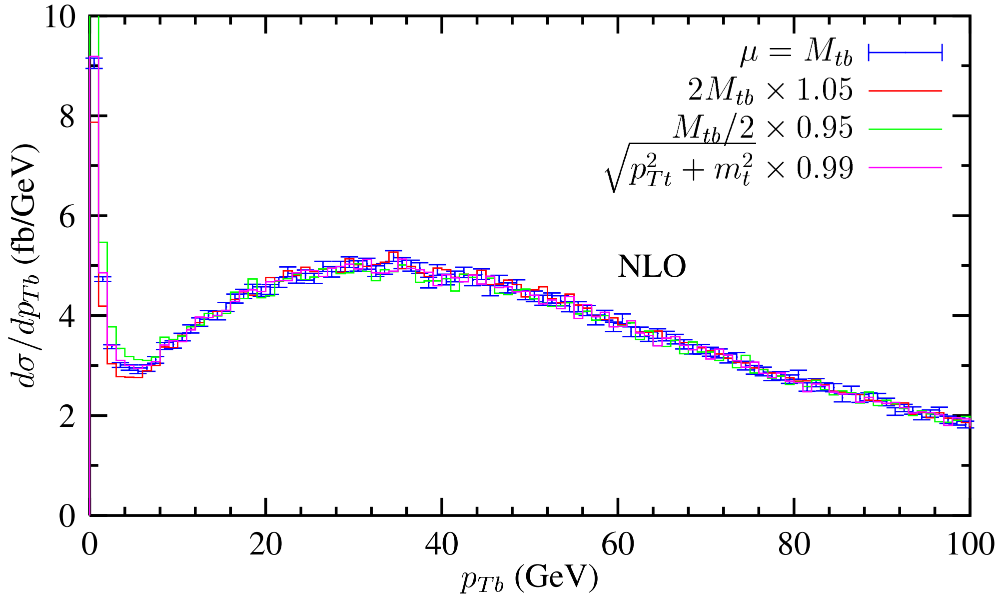
LO



Varying scale by a factor of 2 gives a 7.8% uncertainty at LO.

Shape is not affected. M_{tb} is $t\bar{b}$ invariant mass.

NLO

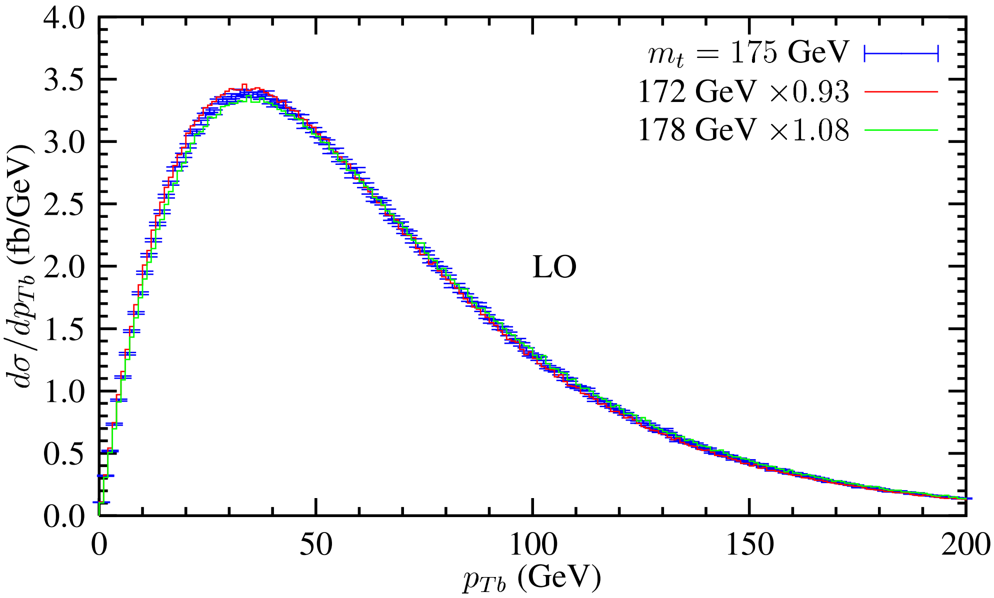


Varying scale by a factor of 2 gives a 5.7% uncertainty at NLO.

Shape is not affected. $\mu = m_t$ is not shown, but it is nearly identical to $\mu = \sqrt{p_{Tt}^2 + m_t^2}$, the transverse mass scale.

m_t dependence on shape of b jet transverse momentum

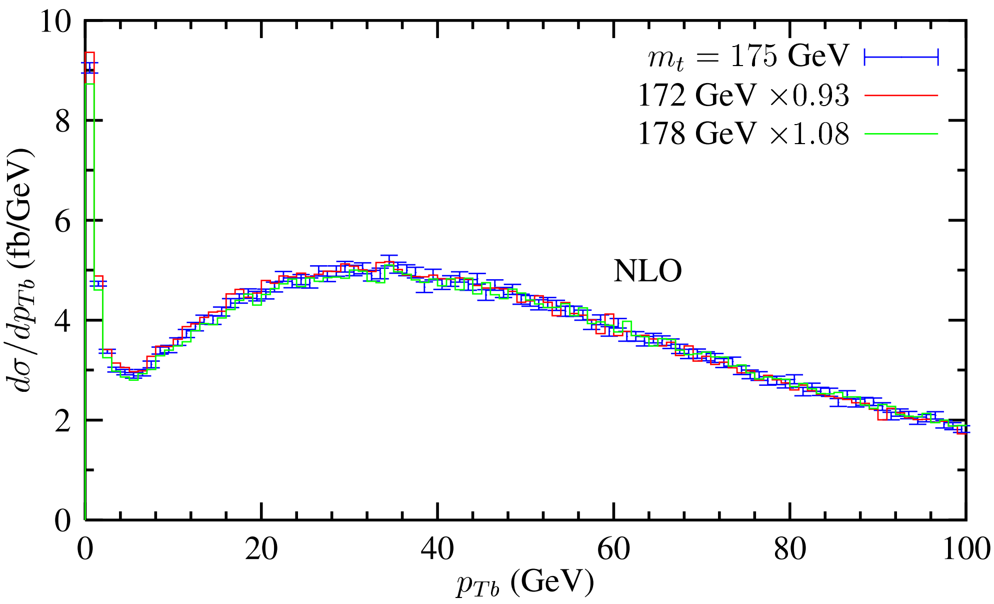
LO



Varying mass 3 GeV gives a 8% uncertainty at LO.

Shape is not affected.

NLO



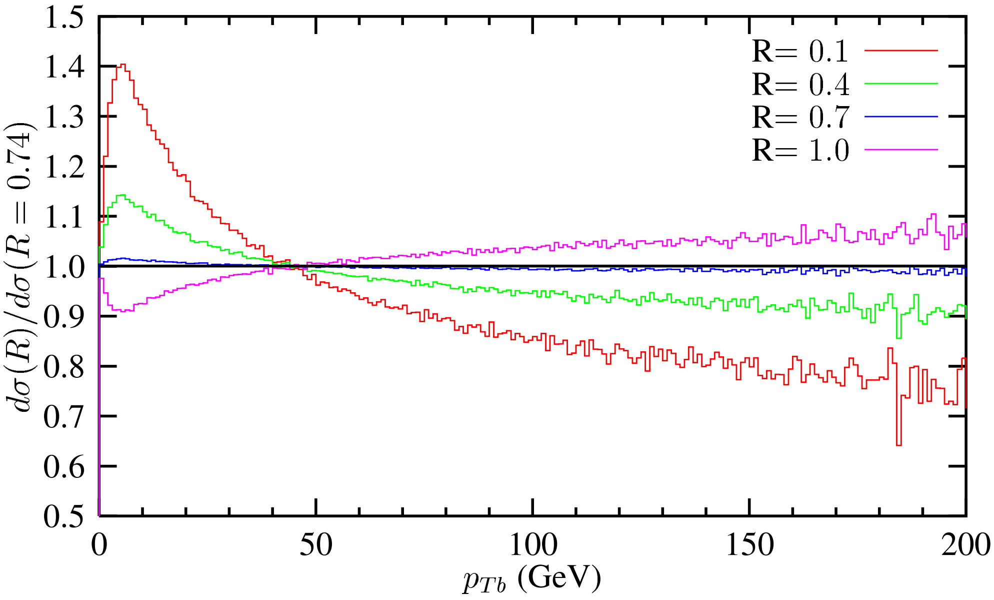
Varying mass 3 GeV gives a 8% uncertainty at NLO.

Shape is not affected. Varying $m_t = 175 \pm 2$ GeV gives a 5% uncertainty at both LO and NLO.

Cone-size dependence on b jet distributions

You can study the effect of the cone size used in the k_T algorithm on the reconstructed p_T and η of the b.

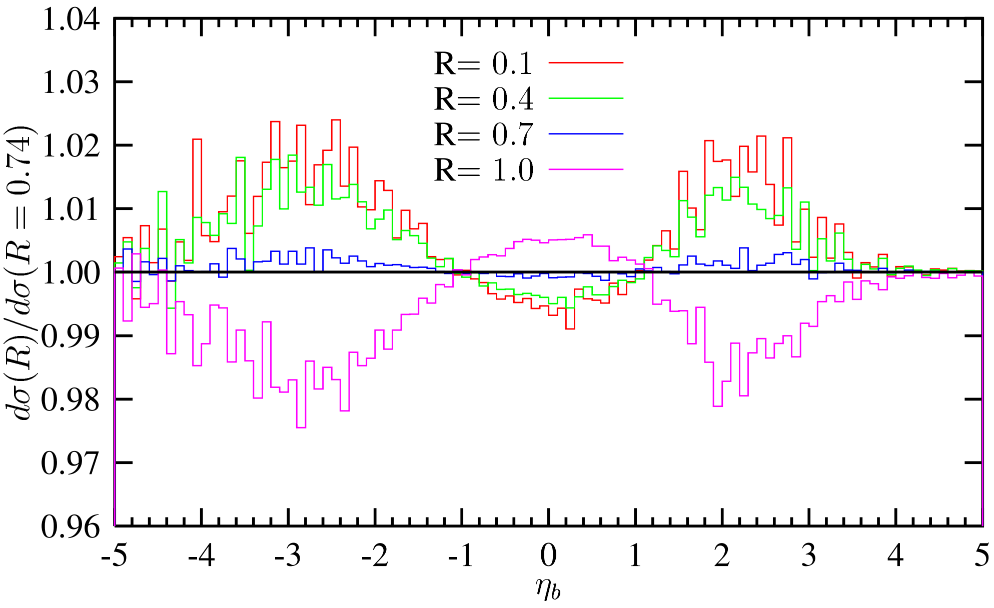
Ratio of $d\sigma(R)/dp_{Tb}$ to $d\sigma(R = 0.74)/dp_{Tb}$



Note: R refers to the "fixed-cone" equivalent, $R_{\mathrm{stnd.}} = 0.7$.

For "reasonable" values of R the variation is $< 10\%$, but should be checked in any given analysis.

Ratio of $d\sigma(R)/d\eta_b$ to $d\sigma(R = 0.74)/d\eta_b$



Summary

- To measure V_{tb} or new physics we want to look for each channel of single-top-quark production.

- NLO QCD corrections to t- and s-channel total rates exist.
  Cross sections updated with CTEQ5M1 PDF's:

	Tevatron, Run I	Tevatron, Run II	LHC
$\sigma_t^{\rm NLO} =$	1.45 ± 0.08 pb	2.12 ± 0.10 pb	238 ± 12 pb
$\sigma_s^{\rm NLO} =$	0.75 ± 0.06 pb	0.91 ± 0.07 pb	11.7 ± 0.9 pb

- Fully differential NLO QCD corrections to (2-to-2) t- and s-channel exist.
  - A modestly reduced K-factor (1.44 after cuts instead of 1.54) $\times$LO Monte Carlo reproduces the NLO s-channel distributions extremely well.
  - Experimental cuts may be varied.
  - Various jet definitions are implemented.
  - Any IR-safe variable can be predicted at NLO.

- Spin-dependent results are being checked.

- Fully differential NLO QCD corrections to t–$\bar{b}$–j under construction.

How do we consistently interface this with HERWIG, PYTHIA, or ISAJET, . . .