Angular correlations in t–channel single top production at the LHC

Patrick Motylinski

Uni. Freiburg

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   - Lowering $\sqrt{S}$
   - Varying the jet R–parameter
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Motivations for single top

- Possibly the easiest quark to deal with
- Does not hadronize
- Direct measurement of V_{tb}
- Test the charged current coupling of the top quark
- Determine b quark density
- Single top processes are important backgrounds for several Std. Model physics processes
- Single top processes are important backgrounds for new physics ($W', Z', \ldots$)

Single top @ Tevatron and @ LHC

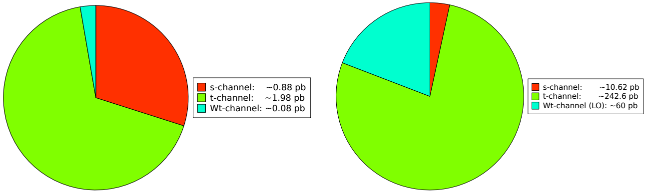


Figure: Single top cross section. Tevatron (left) and LHC (right)

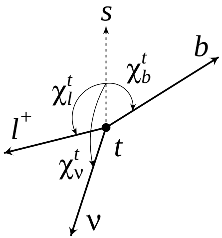
@ Tevatron: *Tevatron Electroweak Working Group (D0 and CDF): arXiv:0908.2171*

- Measured cross section: $\sigma_{s+t} = 2.76^{+0.58}_{-0.47}$ pb
- This has been used to determine V_{tb}: $|V_{tb}| > 0.77$

Top decay and spin correlations

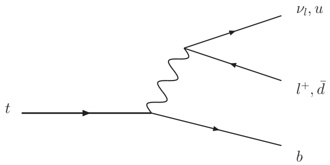
The aim of studying spin correlations in (single) top decay is to determine the handed-ness of the EW coupling of the top. (Std. Model: purely left-handed)

Due to strong correlation with the decay products it will be possible to measure the coupling. (100% correlation between top-spin and lepton direction)



Studying angular correlations gives a handle in distinguishing specific signals from the hybris of different backgrounds

How come there are angular correlations in the first place? Let us start out by having a look at the top quark decay amplitude:

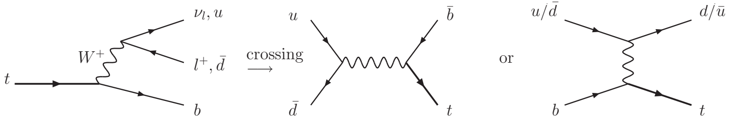


The corresponding decay rate *in the top quark rest frame* is given by:

$$\frac{1}{\Gamma_t}\frac{d\Gamma_t}{d\cos\theta} = \frac{1}{2}(1 + s\cdot\cos\theta) \tag{1}$$

where s is the correlation factor ($s = 1$ for isospin -1/2 particles (i.e. l, d)), and θ is the angle between the charged lepton/d–type quark and the orientation of the top quark spin.

If we apply crossing we get the following situation:



We now see that the top quark in the final-state is (cor)related to the $d - /\bar{d}$–type quarks in the initial-state or final-state. What are the implications of this? Well...
The top quark is also strongly correlated with the direction one of the valence quarks (and hence practically speaking one of the beams) *or* the spectator quark/jet. This is good news!

- We cannot determine the orientation of the top quark spin *directly* but from the previous slides we know that the d–type quark in the initial-state tends to be aligned with the top quark spin axis
- This means that there will be strong correlations between the direction of one of the incoming beams or spectator jet and the direction of flight of the charged lepton from the decaying top
- We now have two seemingly good candidates for spin bases (see Mahlon & Parke)

Spectator basis

- Prior to decay in the t–channel: the final-state consists of a top quark, b-quark (gluon splitting in initial-state) and spectator quark/jet
- For single top production the spectator quark is a d–type (due to large abundance of u–quarks in the initial-state)
- Thus the direction of the spectator jet should be a good choice for spin quantization axis
- For antitop production: spectator jet mainly u–flavored, but jet only slightly deflected from direction of incoming d-type (scattering off W-boson) $\Rightarrow$ still useful as top spin quantization axis

Beam line basis

- Dominant initial-state for single antitop production has a *d*–type quark
- Good choice of spin quantization axis: the beam containing the *d*–type quark
- As mentioned spectator jet only slightly deflected from incoming beam
- Hence, we can use the jet to determine which beam to choose as spin axis
- How? Using the pseudorapidity of the spectator jet:
  - if $\eta_j > 0$ choose right-moving beam
  - else choose left-moving beam
- Turns out to be useful for single *top* production as well
- Can improve it somewhat with $|\eta_j| > \eta_{\rm min}$

How do we quantify the strength of the correlations? We extract the top/antitop spin polarization.

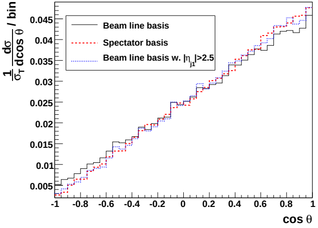
Numerical results

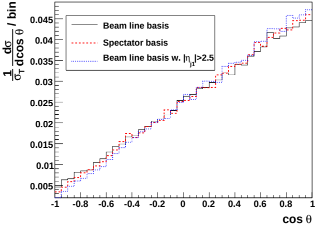
- we used MC@NLO in this study
- CTEQ66 as default PDF set
- $m_t = 173.1$ GeV and $\Gamma_t = 1.4$ GeV
- jet established using k_T–clustering algorithm
- only considered leptonic decays of the top (i.e. e's or μ's)
- work in the top center-of-mass frame
- keep in mind that when we have a general sample of top quarks (can be both spin up and down) the decay rate is properly written as:

$$\frac{1}{\Gamma_t}\frac{d\Gamma_t}{d\cos\theta} = \frac{1}{2}(1 + s \cdot \mathcal{A}_{\uparrow\downarrow} \cdot \cos\theta) \tag{2}$$

where $\mathcal{A}_{\uparrow\downarrow}$ is the spin asymmetry

How do the bases compare?

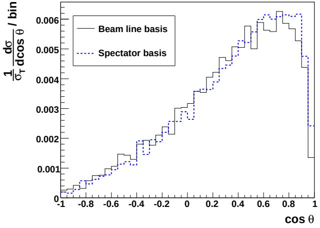


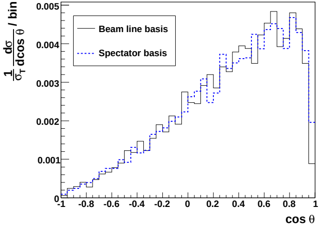


Basis	$\left(\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}\right)_t$	P_t
Spectator	0.923 ± 0.006	$96.16\% \pm 0.30\% \uparrow$
η–bml	0.823 ± 0.006	$91.15\% \pm 0.32\% \uparrow$
η–bml w. η–cut	0.914 ± 0.008	$95.68\% \pm 0.38\% \uparrow$

Basis	$\left(\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}\right)_{\bar{t}}$	$P_{\bar{t}}$
Spectator	-0.882 ± 0.006	$94.10\% \pm 0.32\% \downarrow$
η–bml	-0.837 ± 0.007	$91.87\% \pm 0.33\% \downarrow$
η–bml w. η–cut	-0.936 ± 0.008	$96.82\% \pm 0.41\% \downarrow$

Kinematical cuts





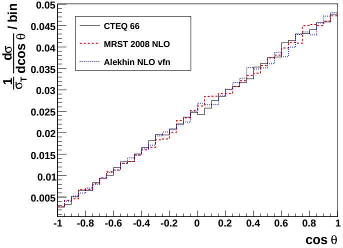
b–cuts:	$\lvert\eta_b\rvert < 2.5,$	$p_{T,b} > 50\mathrm{GeV},$
charged lepton cuts:	$\lvert\eta_l\rvert < 2.5,$	$p_{T,l} > 20\mathrm{GeV},$
spectator jet cuts:	$2.5 < \lvert\eta_{j_1}\rvert < 5,$	$p_{T,j_1} > 50\mathrm{GeV},$
other cuts:		$p_{T,\nu} > 20\mathrm{GeV}.$

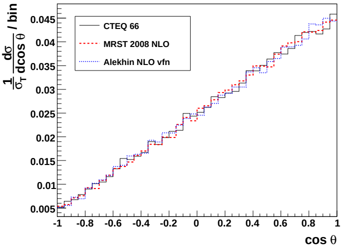
Basis	A_t	$A_{\bar{t}}$
Spectator	-0.608	-0.572
η–bml	-0.583	-0.570

where

$$A_q = \frac{\sigma(0 < \cos\theta_q \leq -0.2) - \sigma(-0.2 < \cos\theta_q \leq 0.6)}{\sigma(0 < \cos\theta_q \leq -0.2) + \sigma(-0.2 < \cos\theta_q \leq 0.6)} \qquad (3)$$

Changing PDFs





PDF set	**Spectator basis**	**Beam line basis w.** $\|\eta_{j_1}\| >$ **2.5**
CTEQ66	$96.16\% \pm 0.30\% \uparrow$	$91.15\% \pm 0.32\% \uparrow$
MSTW2008nlo	$95.28\% \pm 0.38\% \uparrow$	$91.01\% \pm 0.40\% \uparrow$
ALEKHIN vfn	$95.81\% \pm 0.30\% \uparrow$	$91.36\% \pm 0.32\% \uparrow$

PDF uncertainties and varying factorization scale

	Spectator basis	**Beam line basis w. $|\eta_{j_1}| >$2.5**
CTEQ66	$96.16^{+1.70}_{-2.03}$ % ± 0.30% ↑	$95.68^{+2.46}_{-2.19}$% ± 0.38% ↑

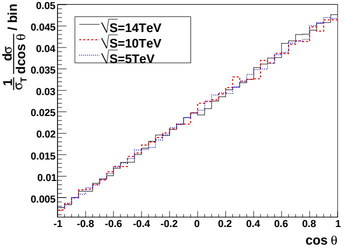
Spectator basis

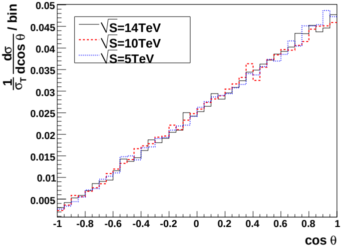
μ_F/m_t	CTEQ66	MSTW2008nlo	AlekhinNLOvfn
0.5	95.34% ± 0.30% ↑	95.75% ± 0.32% ↑	95.84% ± 0.30% ↑
1	96.16% ± 0.30% ↑	95.91% ± 0.31% ↑	95.81% ± 0.30% ↑
2	96.11% ± 0.30% ↑	96.83% ± 0.34% ↑	96.21% ± 0.30% ↑

Beam line basis w. $|\eta_{j_1}| >$2.5

μ_F/m_t	CTEQ66	MSTW2008nlo	AlekhinNLOvfn
0.5	95.33% ± 0.39% ↑	95.39% ± 0.40% ↑	95.42% ± 0.38% ↑
1	95.68% ± 0.38% ↑	95.72% ± 0.39% ↑	95.59% ± 0.38% ↑
2	95.75% ± 0.38% ↑	96.50% ± 0.42% ↑	96.13% ± 0.38% ↑

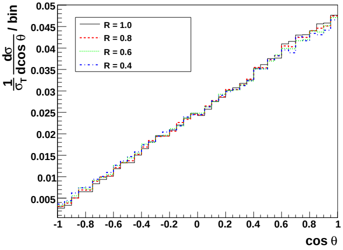
Lowering $\sqrt{S}$

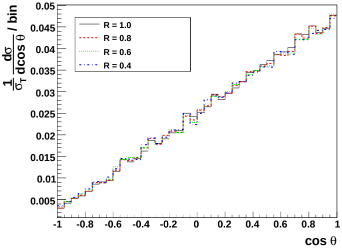




$\sqrt{S}$ (TeV)	**Spectator basis**	**Beam line basis w. $\lvert\eta_{j_1}\rvert >$2.5**
14	$96.16\% \pm 0.30\% \uparrow$	$95.68\% \pm 0.38\% \uparrow$
10	$96.02\% \pm 0.28\% \uparrow$	$95.99\% \pm 0.36\% \uparrow$
5	$95.98\% \pm 0.24\% \uparrow$	$96.48\% \pm 0.36\% \uparrow$

Varying the jet R–parameter

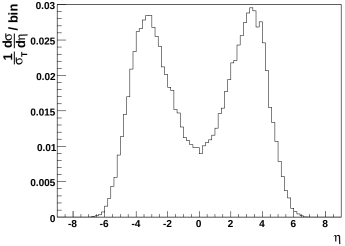


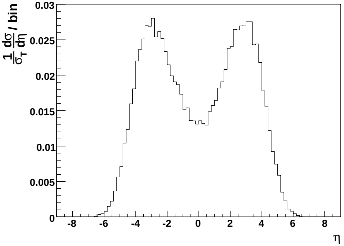


R	**Spectator basis**	**Beam line basis w.** $\|\eta_{j_1}\| >$**2.5**
1.0	96.16% $\pm$ 0.30% $\uparrow$	95.68% $\pm$ 0.38% $\uparrow$
0.8	95.27% $\pm$ 0.28% $\uparrow$	95.31% $\pm$ 0.36% $\uparrow$
0.6	94.51% $\pm$ 0.26% $\uparrow$	94.88% $\pm$ 0.34% $\uparrow$
0.4	93.73% $\pm$ 0.25% $\uparrow$	94.55% $\pm$ 0.33% $\uparrow$

Conclusions

- We have used MC@NLO with all its advantages to study the behavior of angular correlations in t–channel single top production
- We studied the correlations using spin bases introduced by Mahlon & Parke
- We found:
  - that both spectator basis and beam line basis provide samples of highly polarized top quarks
  - that the polarization is robust wrt. choice of PDF set and that PDF uncertainties play a minor role
  - that the correlations are practically speaking stable wrt. varying the factorization scale
  - that the correlations do not change behavior at lower (than 14 TeV) values of $\sqrt{S}$
  - that the effect of changing the R–parameter is minor


$\frac{1}{\sigma_T}\frac{d\sigma}{d\eta}$ / bin
0.03
0.025
0.02
0.015
0.01
0.005
0
-8 -6 -4 -2 0 2 4 6 8
η


$\frac{1}{\sigma_T}\frac{d\sigma}{d\eta}$ / bin
0.03
0.025
0.02
0.015
0.01
0.005
0
-8 -6 -4 -2 0 2 4 6 8
η

Basic principles of inclusion of angular correlations in MC@NLO:

- Use decay chain approximation: Replace resonant diagrams with diagrams with on-shell vec. bosons/top quarks *times* diagrams for decay, i.e. (in case of t-quark)

$$\mathcal{M}_{l\nu b} \to \mathcal{M}_t \times \mathcal{M}_{\rm decay}$$

- introduce angular correlations
- so the idea is that the full (leptonic) matrix element is bounded from above by an overall constant times the undecayed matrix elements, i.e.:

$$\frac{d\sigma_{l\nu b}}{dPS} \leq \frac{4g_W^4 |V_{tb}|^2 (r \cdot k_2)(p \cdot k_1)}{\left(\left(q^2 - m_W^2\right)^2 + \left(m_W \Gamma_W\right)^2\right)\left(\left(p^2 - m_t^2\right)^2 + \left(m_t \Gamma_t\right)\right)} d\sigma_t$$

- a good idea because correlations are not an issue for (in this case) $d\sigma_t$

- Yet angular correlations are hampered by virtual corrections and subtractions terms (FKS) $\rightarrow$ not necessarily positive semi-definite expressions
- Thus the correlation scheme chosen in MC@NLO not accurate to NLO in the whole of phase space but rather correct to NLO for hard (real) emissions and to LO for soft and collinear regions
- should be mentioned that it is possible to *go all the way* but then more computer intensive

How is this done in MC@NLO?

Make angular correlations precise to

- NLO only for real (hard) emissions
- LO for soft/collinear regions

In practice

1. Integrate undecayed matrix element via MC@NLO (creates set of events)
2. Generate hard events using result from step 1
3. For each hard event generate lepton and b quark momenta in the decay space of the top
4. Compute (full) lepton matrix element (using MadGraph) using momenta from 3, and compute undecayed matrix element using momenta from step 2.
5. Do hit-and-miss

- Why not?
- NLO corrections can be large.
- Full NLO treatment: In contrast to present-day *event* generators not only MC-showering is taken into account *but* also possible (hard) NLO emission.
  This gives a more realistic description in that MC@NLO covers more of the possible phase space as opposed to *sole* MC-showering (which is constrained due to angular ordering).
- In the case of single t: It has been estimated that the main source of errors in the measurement of V_{tb} is due to uncertainties in the theoretical prediction of the cross section.
  This measurement is one of the flag-ship measurements of single-t.