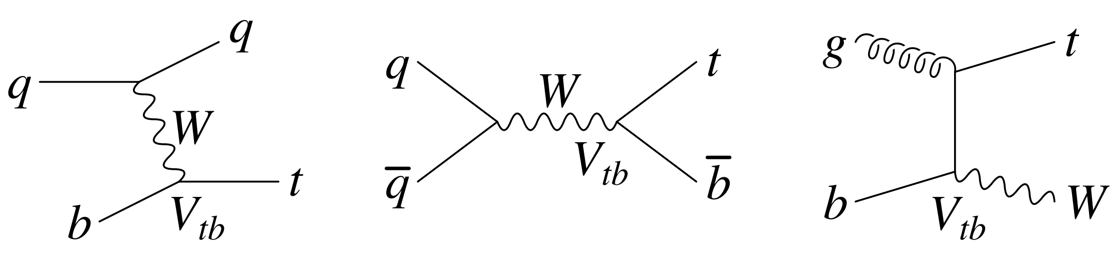
What does single-top-quark production teach us about LHC physics?



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May 15, 2007

Thanks

For their elucidating insights:

Brian Harris, Eric Laenen, Pavel Nadolsky, Lucas Phaf, Tim Stelzer, Tim Tait, Stefan Weinzierl, Scott Willenbrock

CDF single-top group
DØ single-top group

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Southern Methodist University
Argonne National Laboratory
Fermi National Accelerator Laboratory
University of Chicago
University of Illinois

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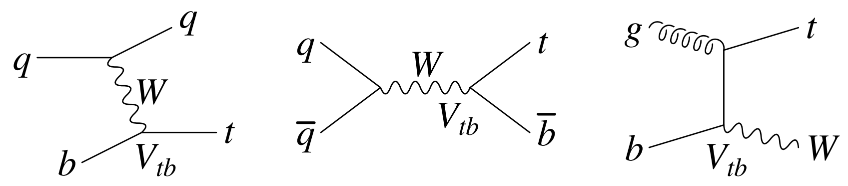
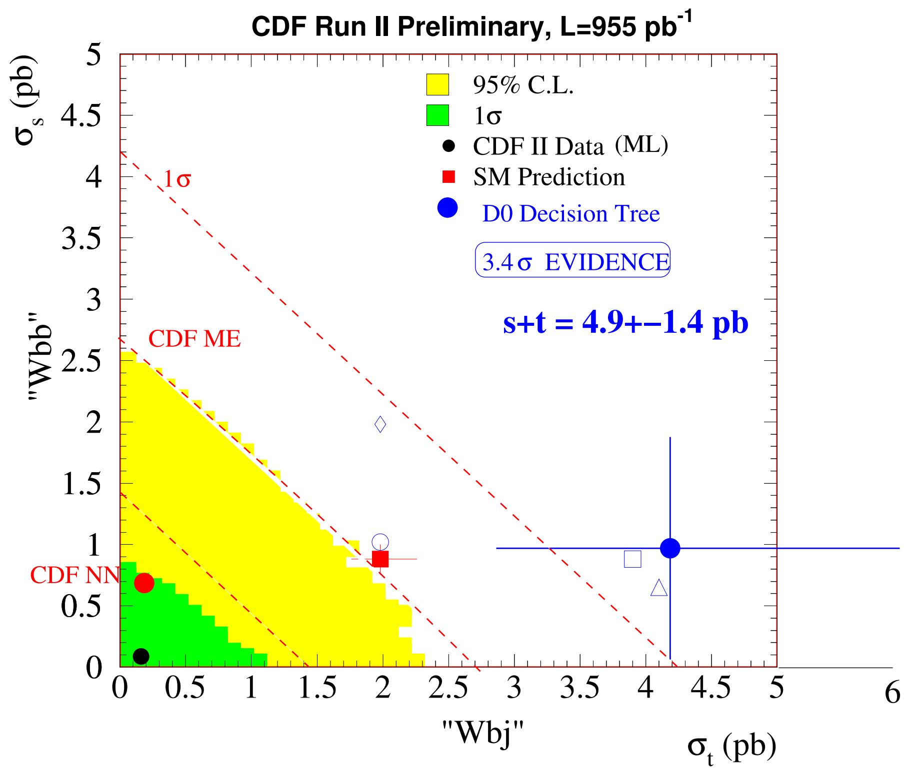
Evidence for single-top-quark production

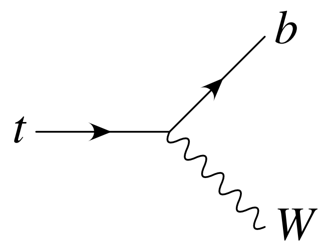


t-channel s-channel Wt-associated

This flagship measurement of the Fermilab Tevatron has been sighted.



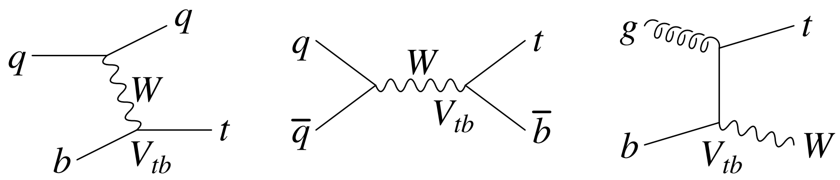
Production modes distinguished by the number of tagged b jets.



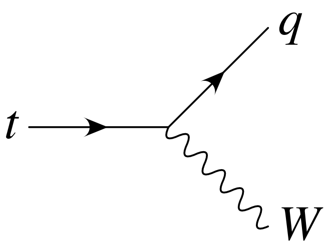
DATA DRIVEN THEORY

CDF Notes 8585, 8588; DØ, hep-ex/0612052

Why we look at single-top-quark production



Weak interaction structure



$$-i\frac{g}{\sqrt{2}}V_{tq}\gamma^{\mu}\frac{1}{2}(1-\gamma_5)$$

Goal: Determine the structure of the W-t-q vertex.

- Measure CKM couplings
  "direct measurement of V_{tb}"
- Measure Lorentz structure
  "spin correlations"

Why measure CKM elements V_{tq}?

Assuming 3 generations and unitarity, V_{tq} are well determined.

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9739-0.9751 & 0.221\ \ -0.227 & 0.0029-0.0045 \\ 0.221\ \ -0.227 & 0.9730-0.9744 & 0.039\ \ -0.044 \\ 0.0048-0.014 & 0.037\ \ -0.043 & 0.9990-0.9992 \end{pmatrix}$$

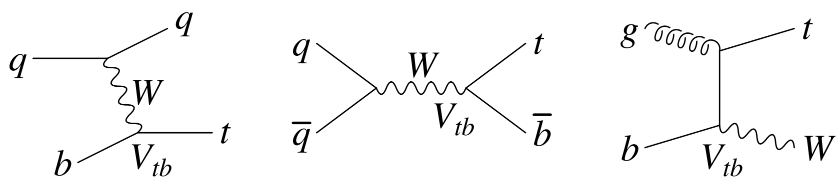
PDG, PLB 592, 1 (2004)

Relaxing the assumption of 3 generations, V_{tb} is barely constrained.

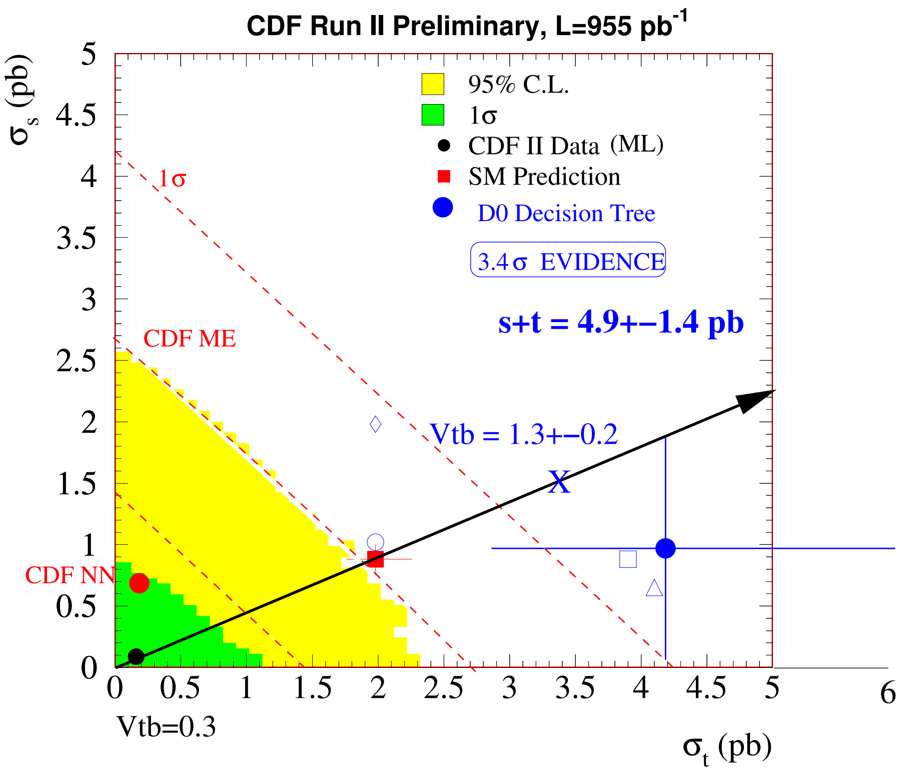
$$\Rightarrow \begin{pmatrix} 0.9730-0.9746 & 0.2174-0.2241 & 0.0030-0.0044 \ldots \\ 0.213\ \ -0.226 & 0.968\ \ -0.975 & 0.039\ \ -0.044\ \ \ldots \\ 0\ \ \ \ \ \ -0.08 & 0\ \ \ \ \ \ -0.11 & 0.07\ \ \ -0.9993 \ldots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

Single-top-quark production cross section proportional to $|V_{tb}|^2$.

Measure $\mathrm{BR}(t \to Wb)$in $t\bar{t}$, extract $|V_{tb}|$ from σ_t with an error $\sim\delta\sigma_t/2$.



First measurement(s) of V_{tb}



ΔV_{tb} falls along the black line.

DØ

- Extracted: $V_{tb} = 1.3 \pm 0.2\ (s+t)$
- s only: $V_{tb} \approx 1.0$;
  t only: $V_{tb} \approx 1.5$

CDF

- $s+t$ (ME): $V_{tb} \approx 1.0$
- s or t (ML): $V_{tb} \approx 0.3$
- s only (NN): $V_{tb} \approx 0.9$;
  t only (NN): $V_{tb} \approx 0.3$

The additional 1fb^{-1} of data on tape will clarify this.

Observing Lorentz structure in single-top

$$\mathcal{L} = -\frac{g}{\sqrt{2}} \sum_{q=dsb} \bar{t}\gamma^{\mu}\frac{1}{2}(1-\gamma_5)V_{tq}qW^{+}_{\mu}$$

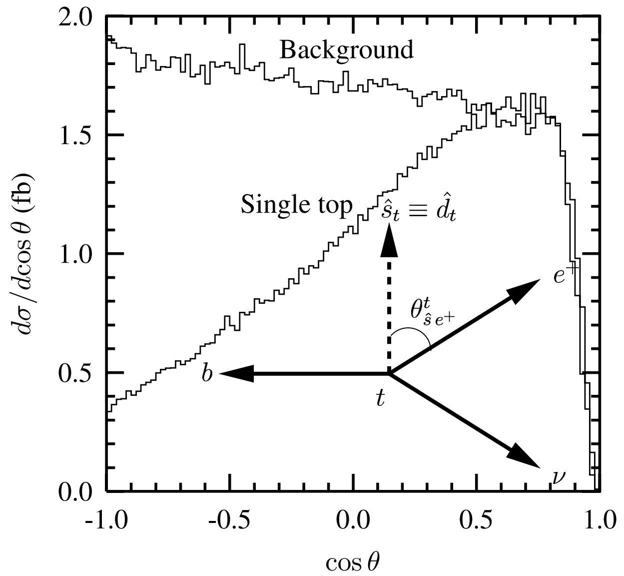
- The $V-A$ structure of the Lagrangian produces a 100% correlation between the direction of the d quark and the spin s_t of the top quark.
  M. Jeżabek, NPBPS 37B, 197 (1994)

- The large width of the top quark (~ 1.5 GeV) allows it to decay before it depolarizes ($\sim \lambda^2_{QCD}/m_t = 1$ MeV), or hadronizes ($\sim \lambda_{QCD} = 300$ MeV).
  A. Falk, M. Peskin, PRD 49, 3320 (1994)

- $$\frac{1}{\Gamma_{(t\to bl\nu)}}\frac{d\Gamma_{(t\to bl\nu)}}{d\cos\theta} = \frac{1}{2}\left(1+\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}\cos\theta\right)$$
  θ is the angle, in the top-quark rest frame, between the direction of the charged lepton and the spin of the top quark.

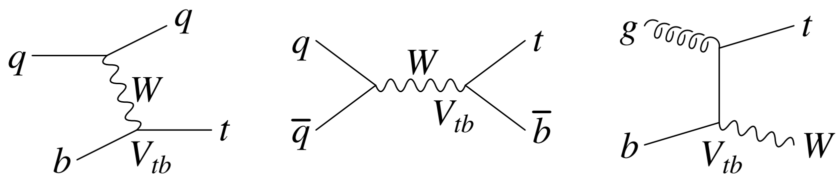
  Does this hold at NLO? after cuts?

  We'll come back to this...

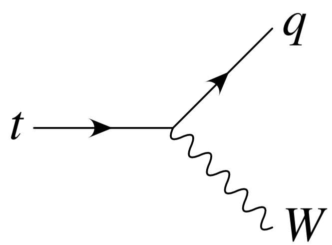


T. Stelzer, Z.S., S. Willenbrock PRD 58, 094021 (98)

Why we look at single-top-quark production



Weak interaction structure



$$-i\frac{g}{\sqrt{2}}V_{tq}\gamma^{\mu}\frac{1}{2}(1-\gamma_5)$$

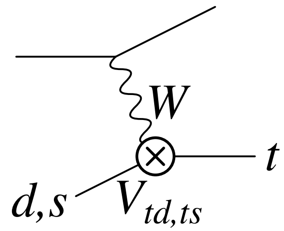
Goal: Determine the structure of the W-t-q vertex.

- Measure CKM couplings "direct measurement of V_{tb}"
- Measure Lorentz structure "spin correlations"

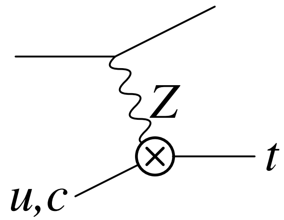
Direct or indirect new physics

New t-q couplings mostly affect t-channel measurement (Wbj).

- Larger V_{ts} or V_{td} give PDF enhancement to σ_t.



- FCNC production modes from, e.g. Z-t-c, increase σ_t.

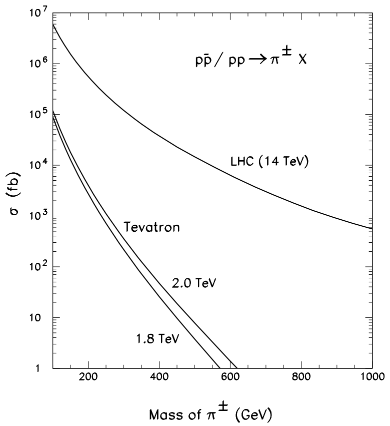


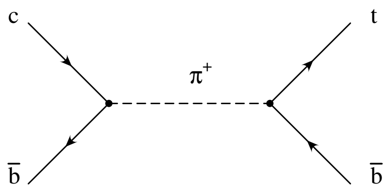
s-channel looks like t-channel, since distinguished by number of b-tags.

New physics in s-channel vs. t-channel

$t + b$ resonant production affects s-channel (Wbb)

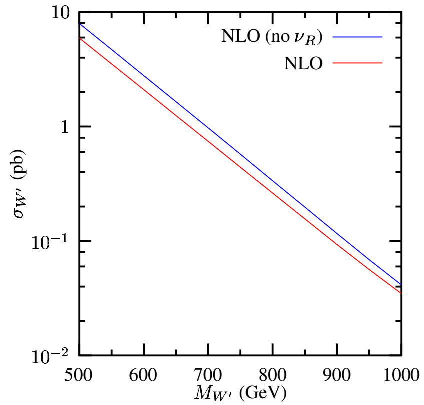
Charged scalars (spin-0)

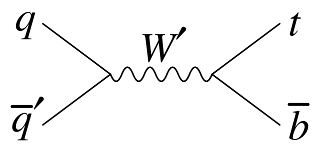




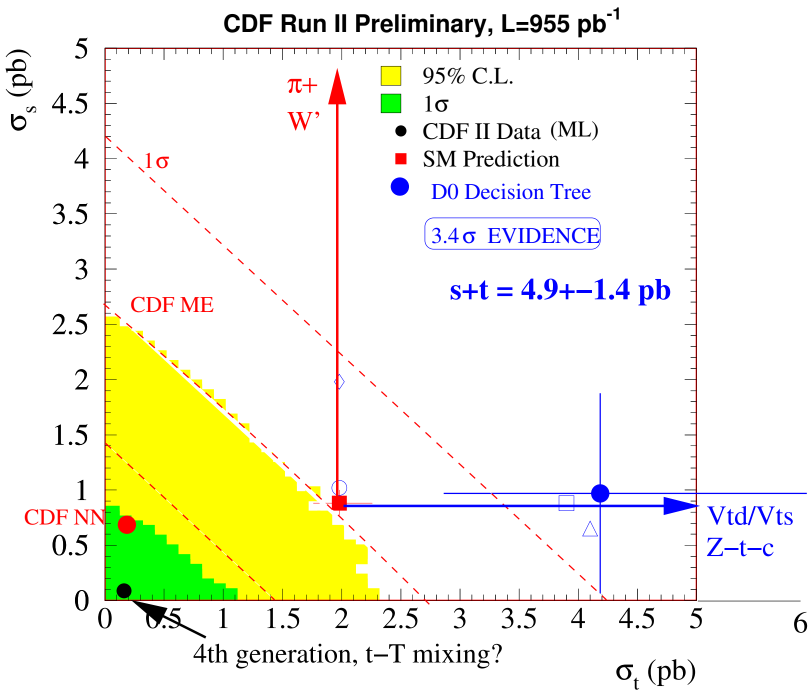
T. Tait, C.P. Yuan PRD 63, 014018 (2001)

W' bosons (spin-1)



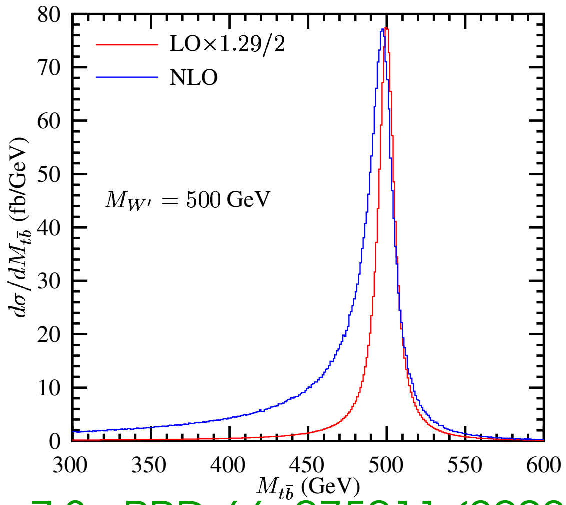


Z.S., PRD 66, 075011 (2002)



Measuring both production cross sections provides strong constraints on many new physics scenarios.

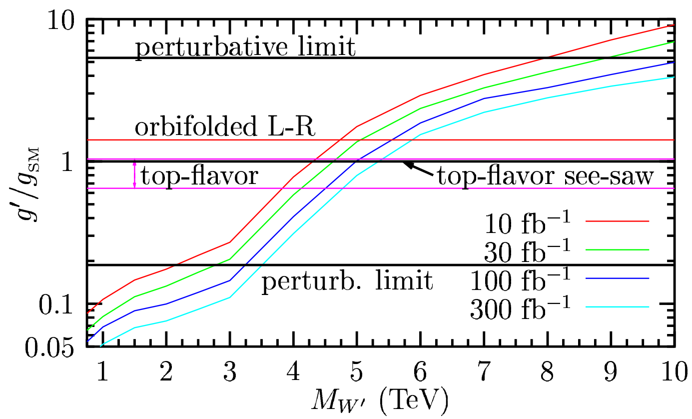
Model-independent W' searches

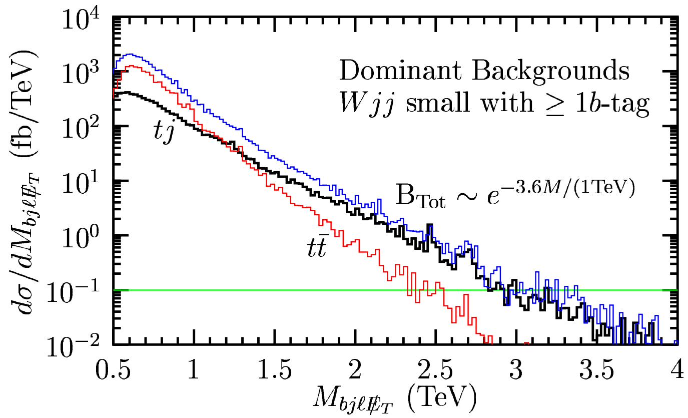


Z.S., PRD 66, 075011 (2002)

- Run I: CDF set bound $M_{W'} > 536(566)$ GeV. PRL 90, 081802 (03)
- Run II:
  $M_{W'} > 630(670)$ GeV. DØ, PLB 641, 423 (06)
  $M_{W'} > 760(790)$ GeV. CDF, Note 8747
- Run II reach ~ 900 GeV (w/ 2 fb^{-1}).
- Use spin correlations to tell if W' has left- or right-handed interactions.

Model-independent W' at LHC





Z.S., hep-ph/0306266

LHC can test SM-like W' bosons up to 5.5 TeV!

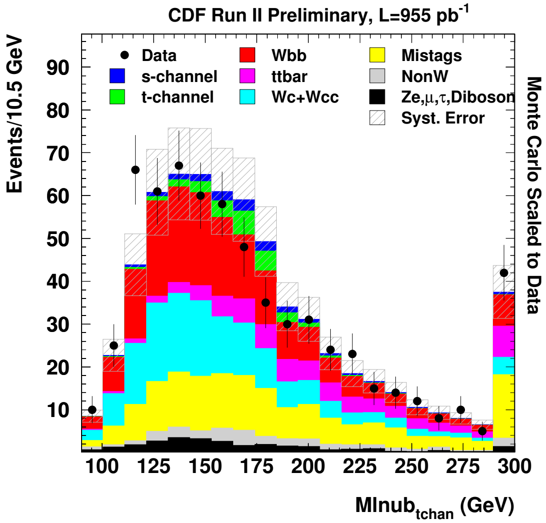
Understanding Perturbative QCD

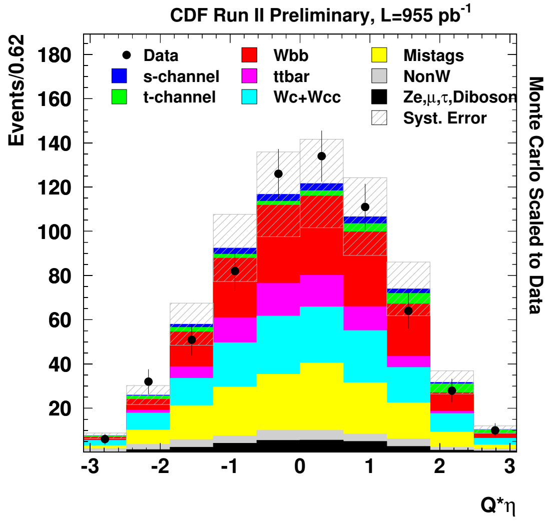
The real reasons to study single-top-quark production

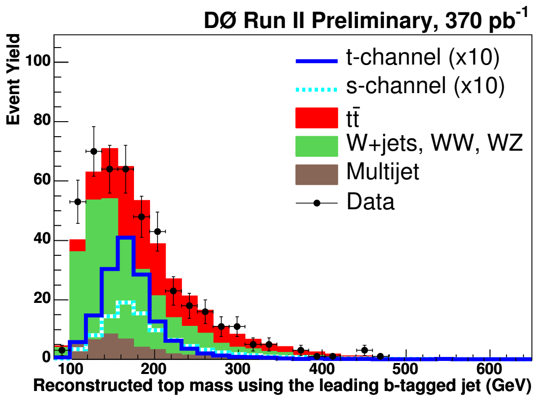
- A generalized Drell-Yan and DIS leads to deeper understanding.
- First required use of b PDF.
  - First real test of heavy-quark PDFs.
  - Progenitor of the PDF uncertainty formulae you currently use.
- Intrinsically multi-scale
- Progenitor of techniques to calculate exclusive final states of massive systems.
  - Massive dipole formalism (MDF), tightening up of PSSM2
- Clearest case where NLO jet matching is required.
- and MUCH, MUCH more.

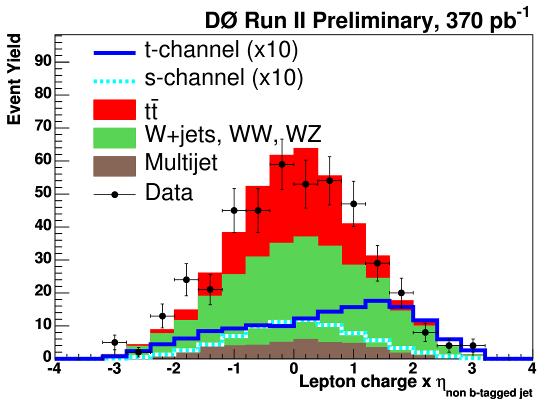
Angular correlations:
the current frontier

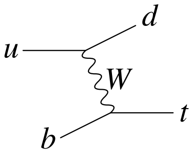
CDF and DØ have signals, and yet. . .

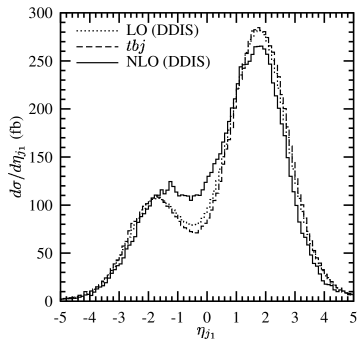






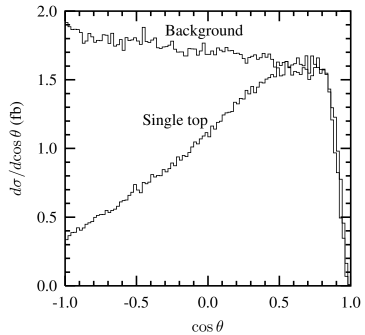






Single-top is dominated by a large $W + 2$ jet background.

Can 100% spin correlations from $V - A$ interactions help?



Why the Mahlon-Parke spin-basis works

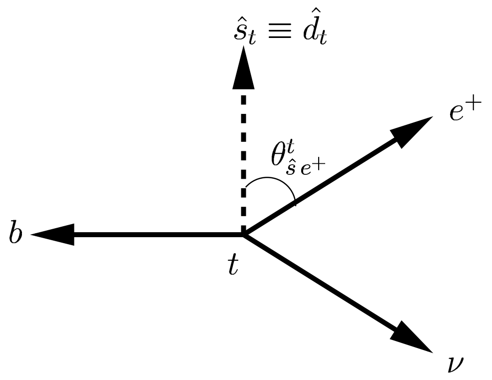
Both s- and t-channel single-top are matrix elements go like:

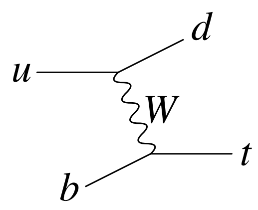
$$[p_d \cdot (p_t - m_t s_t)][p_e \cdot (p_t - m_t s_t)]$$

In top rest frame, $p_t = m_t(1,0,0,0)$, and $s_t = (0, \hat{s})$.

Choose top spin projection $\hat{s} = \hat{d}$. $\Rightarrow \sigma \propto (1 + \cos\theta^t_{e^+ d})$

- s-channel 98% of $\bar{d}$ from $\bar{p}$
  $\Rightarrow \sigma \propto (1 + \cos\theta^t_{e^+ \bar{p}})$
- t-channel d in highest-E_t non-b-tagged jet j_1
  $3/4$ of the time. $\Rightarrow \sigma \propto (1 + \cos\theta^t_{e^+ j_1})$
  For rest, $\Rightarrow \sigma \propto (1 + \cos\theta^t_{d\,j_1} \cos\theta^t_{e^+ j_1})$
  dilution $\cos\theta^t_{d\,j_1} = 1 - Q^2/(E^t_d E^t_{j_1}) \sim 0.86$

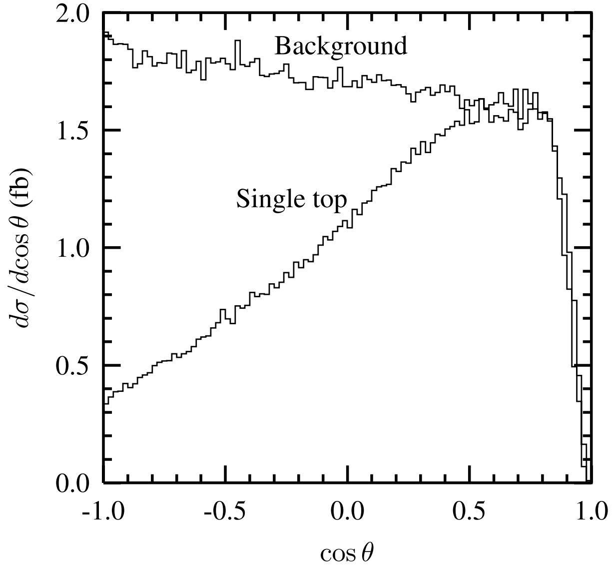




We are saved by kinematically-induced correlations.
i.e., t-channel pole pushes jet forward.

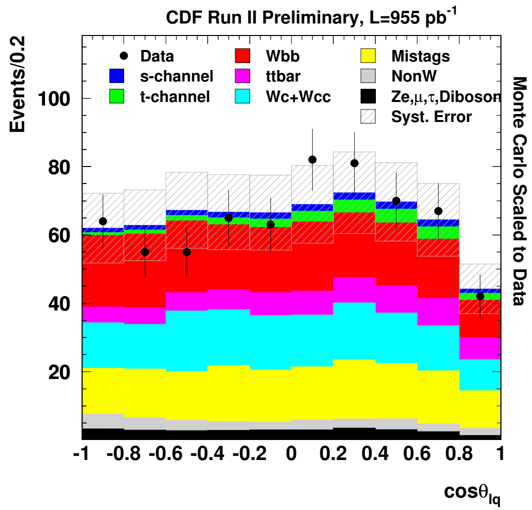
Angular correlations in single-top-quark and Wjj production at NLO

Z.S., PRD 72, 094034 (2005) (hep-ph/0510224)



Original comparison of t-channel single-top and Wjj background done at LO.

Used in neural-nets by CDF and DØ.



1. Do spin-induced angular correlations survive higher-order radiation?
2. Is the background really insensitive to the angular distributions that typify the signal? If so, does this survive complex cuts on the data?
3. The angular distributions are properly defined in the top quark rest frame. How much of these correlations is an artifact of that frame?
4. Does this lead to better discriminates between S, B? e.g., ways to avoid b-tagging? Are there other useful particle correlations?

LO vs. NLO at the Tevatron

t-channel

- Insensitive to top reconstruction (similar in LAB frame) — top is non-relativistic, so little boost.
- Additional ISR b-jets confuse which jet has the d.

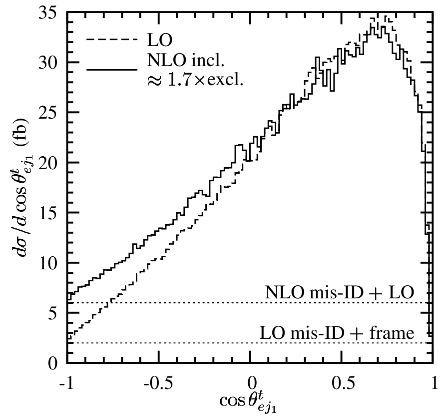
s-channel

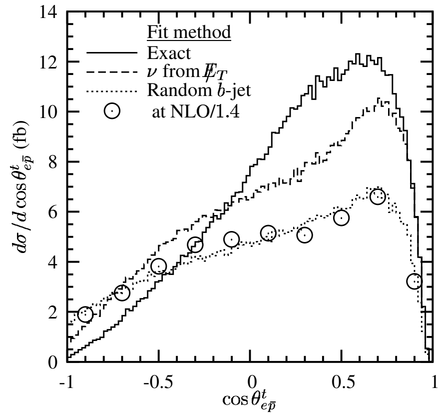
- NLO $=$ LO $\times$ K-factor
- Issue: Dominated by top reconstruction.
  - W fit to $e + \not{E}_T$.
  - I naively assigned a random b jet to top decay.

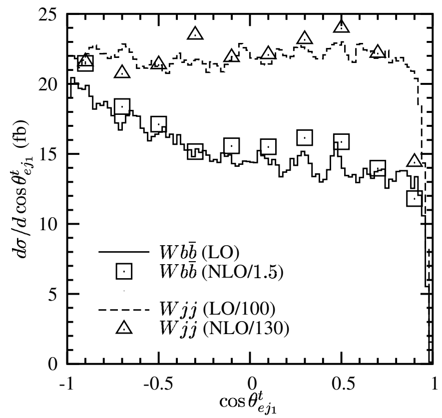
Wjj $(+Wb\bar{b}, Wc\bar{c})$

- NLO $=$ LO $\times$ K-factor

Spin-dependent ME fed into PYTHIA/HERWIG get all correlations (not all shown), as long as NLO-matched ME are used for t-channel.

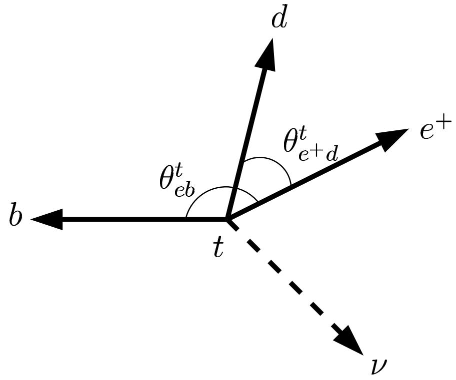






Can you avoid b-tagging?
No, but it raises a subtlety…

In the top rest frame, the b recoils against the W (and the e), while j_1 wants to be close to e.

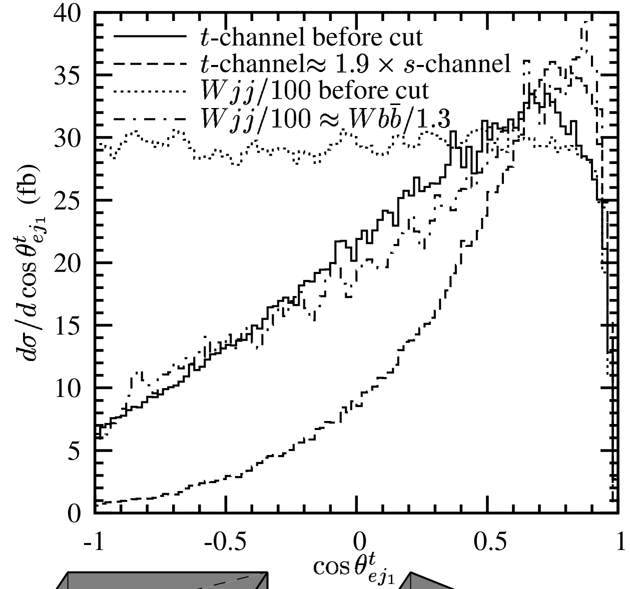


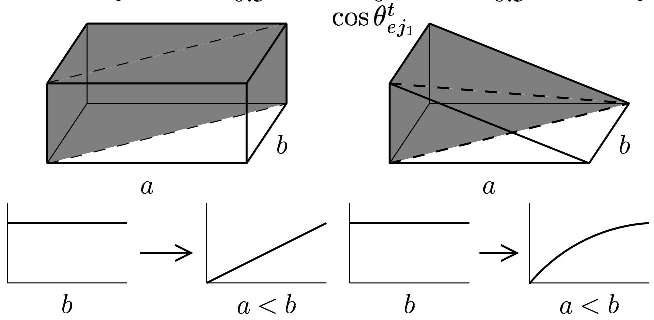
Proposal: Define "b" to be the jet with the largest angle w.r.t. e^+ in the top rest frame.

Correct $b > 80\%$ for s-/t-chan.

Equiv. cut: $\cos\theta^t_{e\text{“}b\text{''}} < \cos\theta^t_{ej_1}$

Wjj looks like signal!



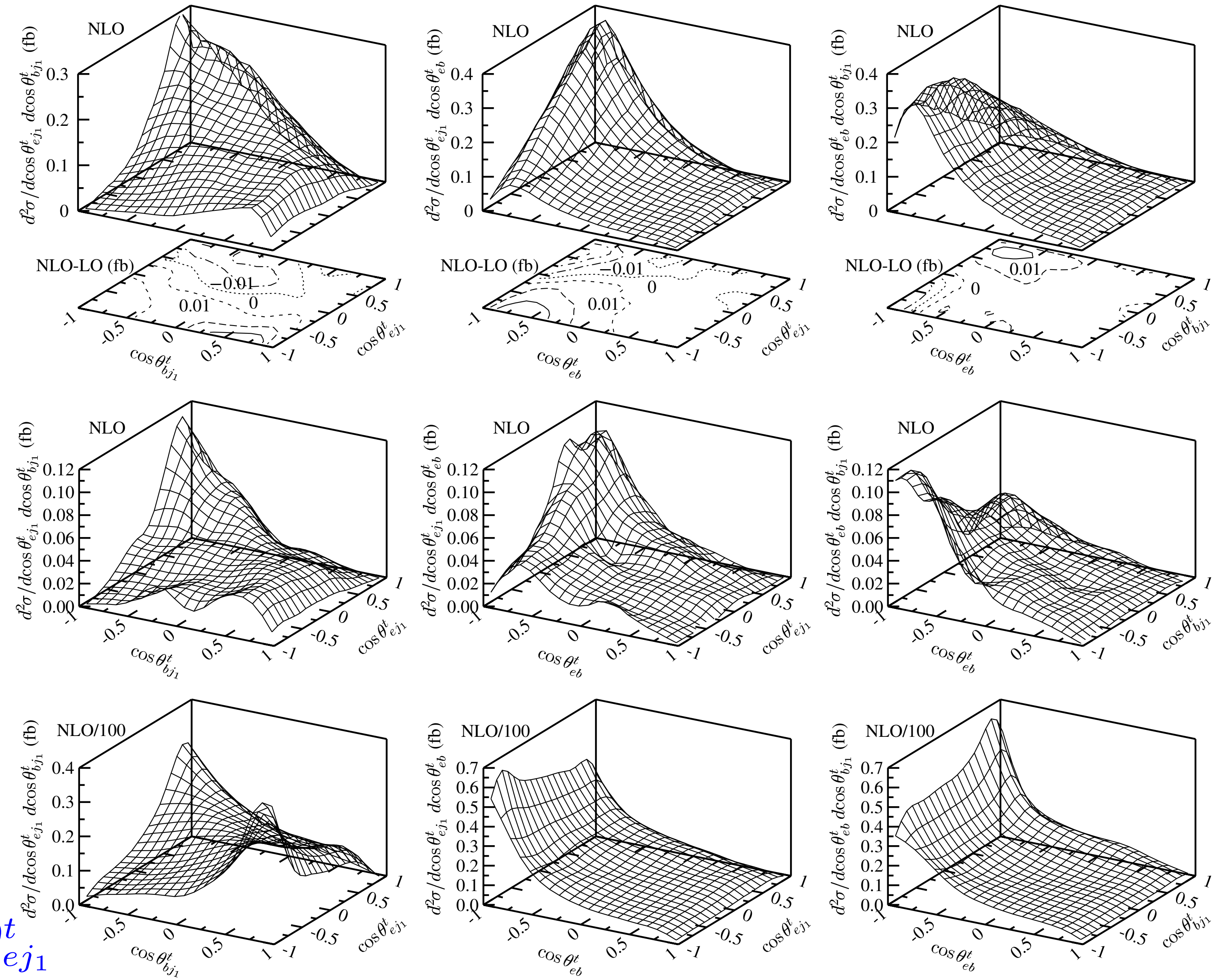


Angular cuts generically induce correlations.
This is why we need reliable predictions.

Warning: Two experimental biases select the largest angle jet (this cut):

1. b-tagging $\propto E_{Tb}$, picks jet recoiling vs. W.
2. Top-mass cut, also picks jet recoiling vs. W.

NLO $\cos\theta^t_{ej_1}$ vs. $\cos\theta^t_{eb}$ vs. $\cos\theta^t_{bj_1}$ — correlations



t-channel

NLO−LO$< 3\%$

s-channel

NLO−$K\times$LO negligible, also true in

all Wjj

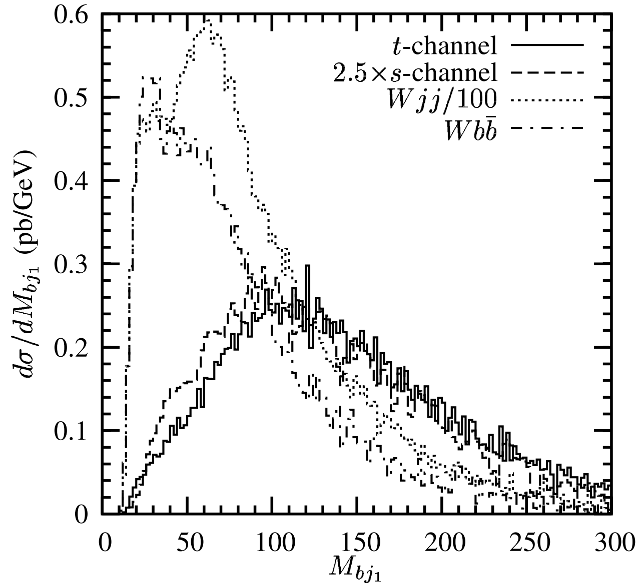
$\cos\theta^t_{ej_1}$ looked flat, but sum of 2 peaks + tails.

$\Rightarrow \cos\theta^t_{bj_1} < \cos\theta^t_{ej_1}$

The power of reliable angular cuts

I propose these acceptance cuts as a starting point:

1. $\cos\theta^t_{eb} < \cos\theta^t_{ej_1}$.
2. $\cos\theta^t_{bj_1} < \cos\theta^t_{ej_1}$.
3. $\cos\theta^t_{bj_1} < 0.6$–$0.8$.
4. $\cos\theta^t_{ej_1} > 0$–0.4 or $\cos\theta^t_{eb} > -0.8$.
5. $M_{bj_1} > 80$–120 GeV



Result: $S/\sqrt{B} \approx 1.25 \times S_0/\sqrt{B_0}$,
$S/B \approx 3 \times S_0/B_0$

Overall $S \sim 0.4 \times S_0$, but $B \sim B_0/7$!

— These correlations are not completely utilized in the Tevatron analyses.

— Strong angular cuts are typical in difficult analyses: SUSY, $H \to WW, \ldots$
We MUST check angular correlations for the LHC analyses
for ALL processes.

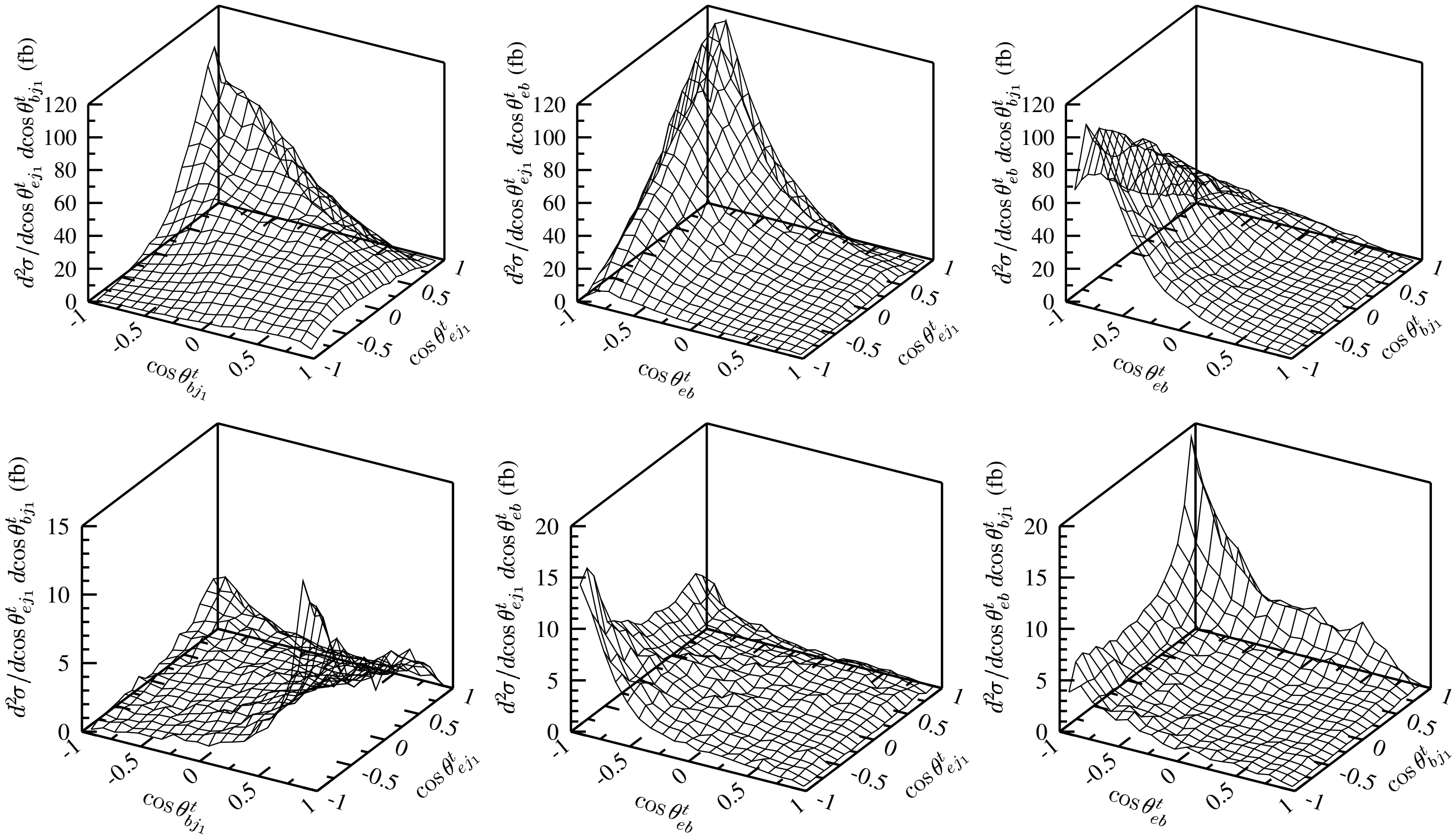
$\cos\theta^t_{ej_1}$ vs. $\cos\theta^t_{eb}$ vs. $\cos\theta^t_{bj_1}$ at LHC

t-channel

Similar to Tevatron

$Wb\bar{b}$

Small and opposite single-top!!!



The main background at LHC is from $t\bar{t}$, but there are large handles here.

NOTE: $\bar{t}$ production is just like s-channel, i.e., if you boost the system to average $\eta = 0$, $\cos\theta^{\bar{t}}_{ep}$ is the relevant angle, where p is on the same side as the electron.

Single-top-quark theory status

NLO cross sections

	Tevatron$(t+\bar{t})$	LHC (t)	LHC $(\bar{t})$
t-channel	1.98 ± 0.2 pb	155.9 ± 7.2 pb	90.7 ± 4.2 pb
s-channel	0.88 ± 0.1 pb	6.6 ± 0.6 pb	4.1 ± 0.4 pb
$Wt(p_{T\bar{b}} < 50$ GeV)	~ 0.07 pb	~ 33 pb	~ 33 pb

Z.S., PRD 70, 114012 (2004); J. Campbell, F. Tramontano, NPB 726, 109 (2005)

Spin-dependent NLO exclusive cross sections

MCFM 5.1

Matrix-element calculation of t-,s-channel, Wt

Gives distributions

MC@NLO 3.3

Showering MC (w/ HERWIG) of t-,s-channel

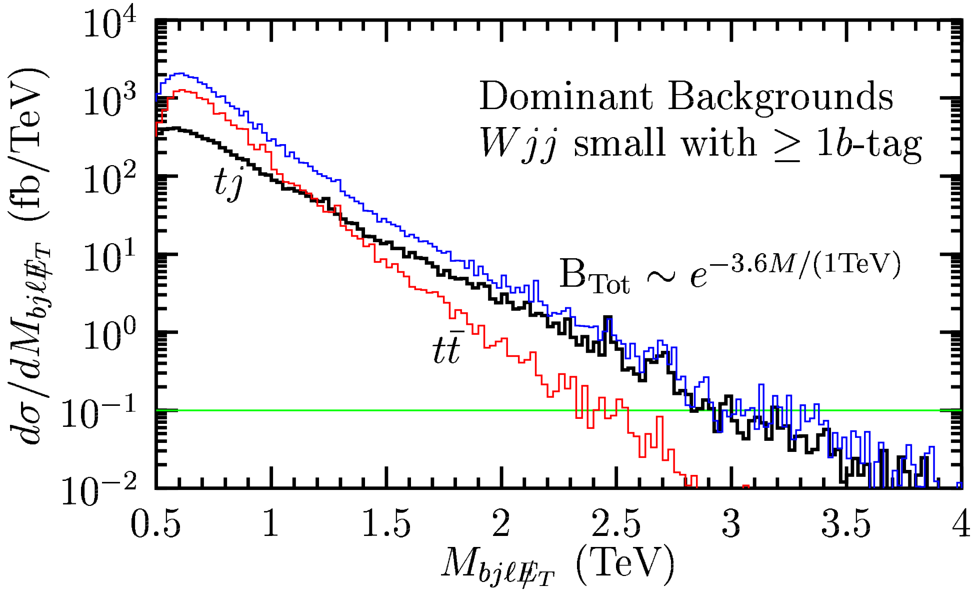
Gives events

Need to verify angular correlations

BOTH tools should be used to confirm quality of predictions.

Single-top-quark theory is in good shape.

Dominant backgrounds to W' production



Searching for peaks in the Wbj final state is proven to be the best way to look for W' production above 1 TeV.

cf. Full simulation in Z.S., hep-ph/0306266

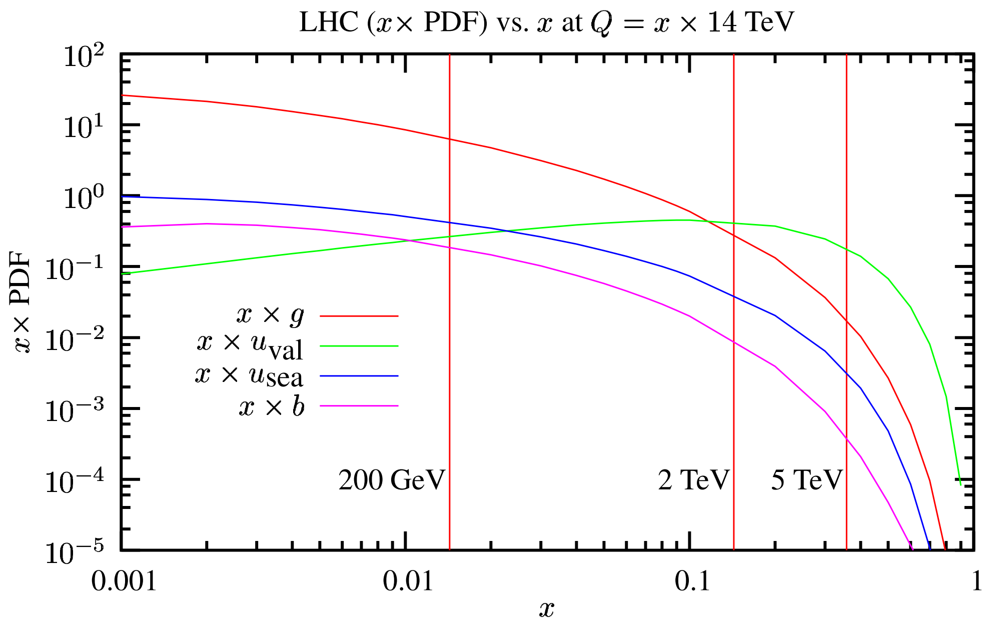
This is dominated by single-top-quark production at large invariant mass.

If the b tag is relaxed, $Wjj > tj$, with the same shape.

Both this figure, and the possibility of a 6 TeV W' signal, provide a clue to what really differentiates physics at the LHC vs. physics at the Tevatron. . .

And challenges one of the most common misstatements. . .

PDFs control relevant physics at LHC



3 important pivot points:

200 GeV $u_{\text{val}} \approx u_{\text{sea}}$ — valence is important here.

2 TeV $u_{\text{val}} > g$ — above a TeV, valence quarks dominate.

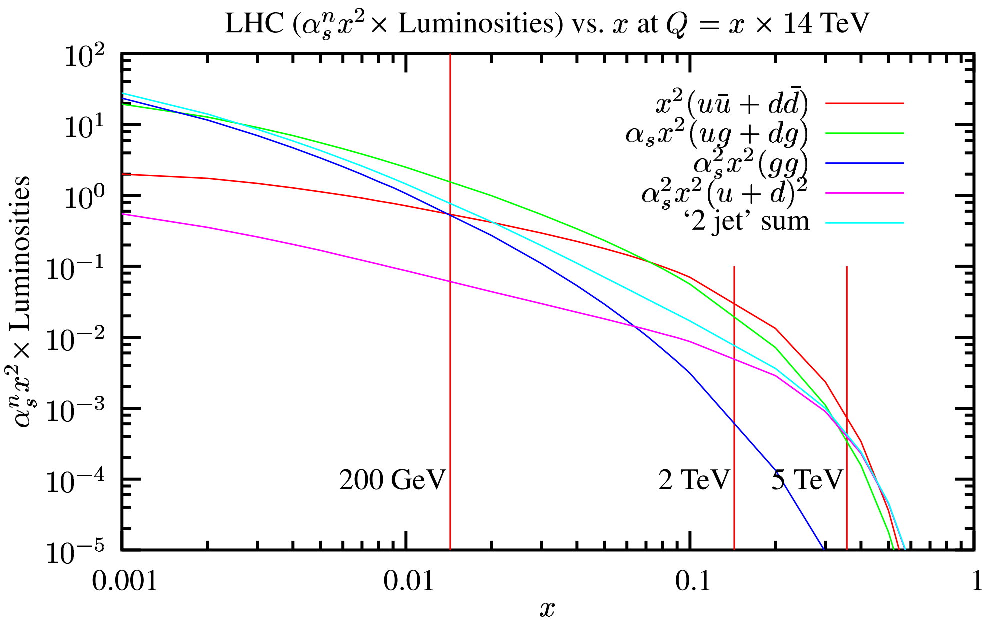
5 TeV PDFs "running out" — nothing heavier gets produced on-shell.

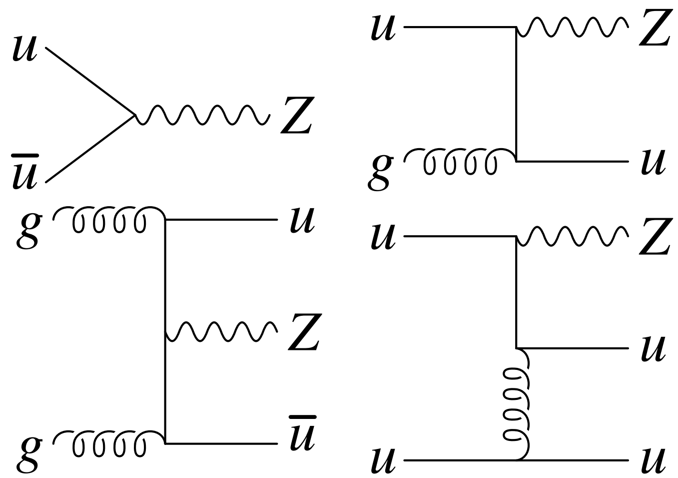
This explains large average rapidity for $q\bar{q}$, qg events
— q_{val} pulled to large x, g and q_{sea} want small x.

The LHC is not a glue factory for physics you care about.
— Color-neutral particles couple to quarks, not gluons.
— New colored particles tend to be heavy (1+ TeV), and see valence.

This figure is almost identical to the Tevatron (at 7 times the energy).
What differs is that LHC is a pp collider. This changes everything.

Example luminosity (with power counting) at LHC





val.–val.

From a luminosity (with power-counting) point of view,

$Z \approx Z + 1$ jet $\approx Z + 2$ jets! (Same in $W + X$, $Wb\bar{b} + X$, $Zb\bar{b} + X$, etc.)

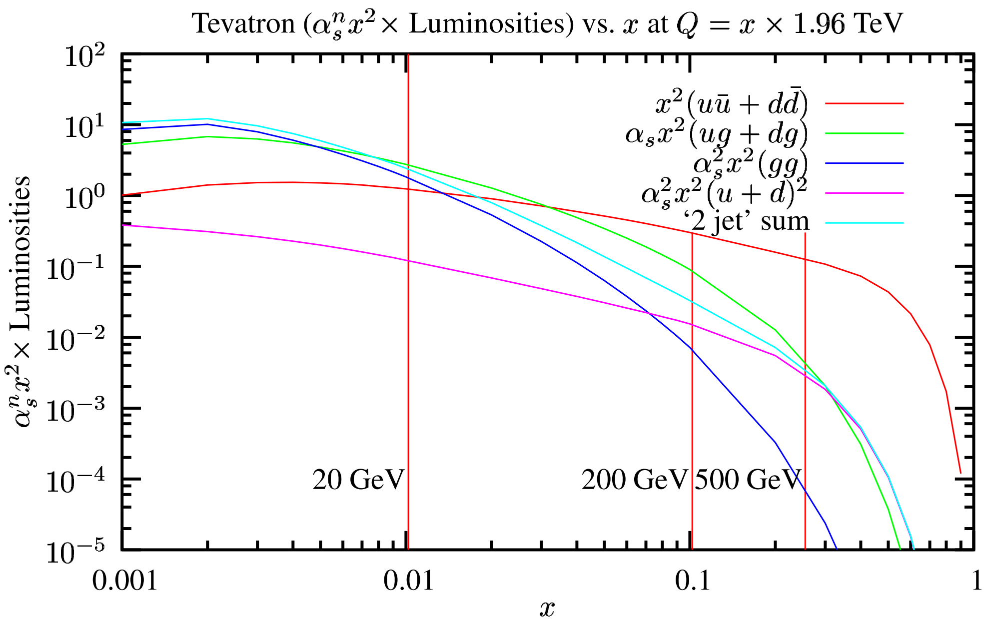
Color factors and topology are important:

$\Rightarrow$ This is VERY sensitive to cuts.

Naive jet counting is ill-defined or poorly-defined

In Wjj and t-channel single-top, $u_{\rm val}u_{\rm val}$ is important at a few TeV.

Tevatron is $p\bar{p}$ at lower energy — a totally different luminosity balance



This is what we are used to.

Above Z threshold:

$Z > Z + 1\text{j} > Z + 2\text{j}$.

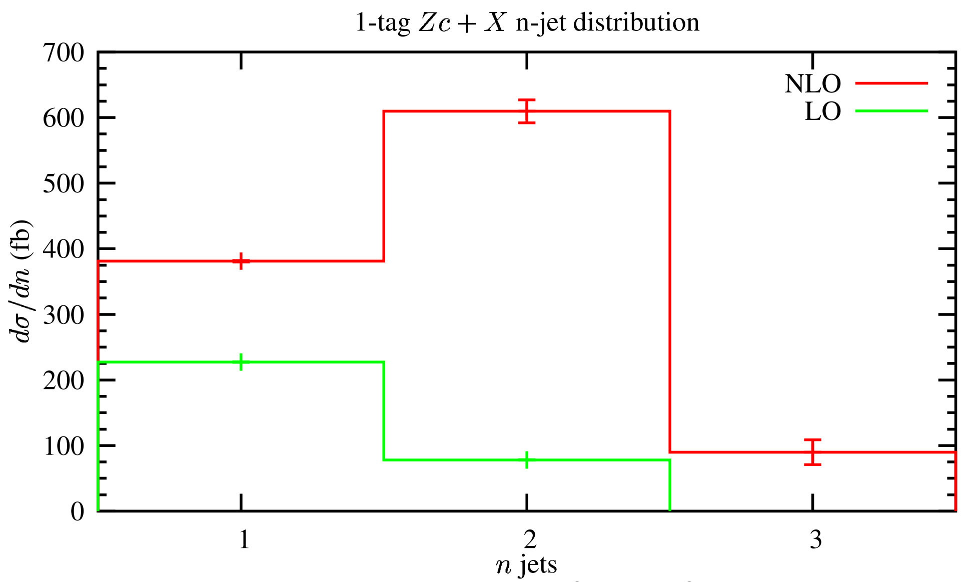
A nice ordering of jets.

WATCH OUT

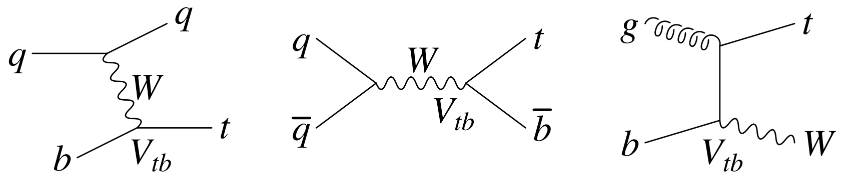
Jet counting fails in some cases at the Tevatron too!

$Zcj > Zc, Wcj > Wc$, etc.

This is a teaser...



Single-top-quark production is the new Drell-Yan and DIS



$\sigma_{\rm tot} = 4.9 \pm 1.4$ pb (DØ)

2.7 ± 1.5 pb (CDF)

1. We study single-top-quark production to
   - measure $V_{tb} = 1.3 \pm 0.2$ (DØ)
   - measure $V - A$ interaction and top-quark polarization
   - search for entire classes of new physics (FCNC, charged currents)
   - most importantly, to understand perturbative QCD
2. We must critically examine correlated angular distributions
   - These are useful for single-top itself, and vital in backgrounds
3. LHC is a valence-quark factory (and quark-gluon, and gluon-gluon)
   - We must find a way to either calculate exclusive final states that are stable against experimental cuts or
   - look for alternate quantities for which we can calculate.

It will be vital to the success of the LHC to develop close interactions between theory and experiment of the type single-top-quark production has enjoyed.

Extra slides

PDFs at Tevatron ∼ scaled down LHC