New Ideas on Single Top

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Outline

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- t at Tevatron: What Went Wrong?

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- t at Tevatron: What Can Be Done?

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- t at Tevatron: What Can Be Done?

  Shapes: asymmetries and correlations

  W-plus-jets: coherent studies needed

- t at LHC: Good News! Bowen

Single Top Production

- Electroweak process: calculable.
- Carefully examined in 1990s after m_t measured.
- Large (3 pb) cross-section ($\sigma_{t\bar{t}} \sim 6.7$ pb.)
- Lepton, missing energy, heavy flavor in final state.
- Precision (?) test of standard model (measure V_{tb}).
- Sensitive to new physics:

... *change in $V - A$ vertex*

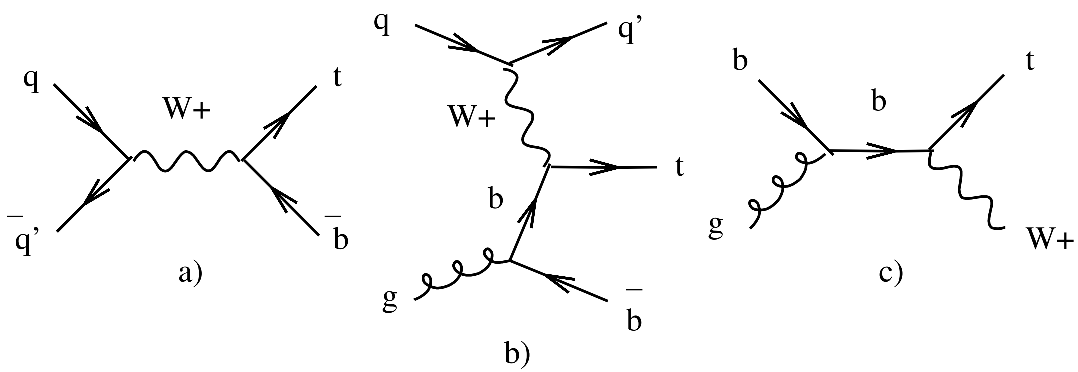
... *direct effects on single t* — Tait & Yuan

... *effects on W-plus-jets*

... *3rd generation leptoquarks*

... *Higgsinos, t', $\tilde{t}$, ...*

Single Top Production



Tevatron: tb 1 pb, tbq 2 pb, tW 0.1 pb $\Rightarrow$ 1500 events already

LHC: tb 10 pb, tbq 250 pb, tW 60 pb $\Rightarrow$ 3,000,000 events/yr (low lum.)

After $t \to Wb \to \ell\nu b$, observables are:
lepton, missing p_T, 1 or 2 b jets, other jets.

(Recall: in tbq, second b jet often not seen or tagged.)

The Backgrounds

Top-antitop production: "$t\bar{t}$"

$p\bar{p} \to t\bar{t} \to W^+b\ W^-\bar{b} \to \ell\nu b\ jj\bar{b}$

W plus jets: "Wj^n"

$p\bar{p} \to Wjj, Wjjj, Wjjjj, \ldots$, etc., $W \to \ell\nu$

QCD:

$p\bar{p} \to$ jets, with energy mismeasurement *and*

hadron which fakes a lepton *or*

μ from heavy flavor decay

Earlier Calculations:

Ellis & Parke 92; Carlson & Yuan 93; Heinson, Belyaev & Boos 96; Tait & Yuan 97

. . .

Stelzer, Sullivan and Willenbrock 1998

SSW is the classic reference for the pre-Run II era.

. . .

Sullivan 04 ; Campbell, Ellis & Tramontano 04; Cao, Schwienhorst, Yuan 04

Method of SSW

- Require one "b"-tagged jet (single tag for tbq)
- Compute $t\bar{t}$ – straightforward
- Impose jet veto (two and only two jets) to remove $t\bar{t}$.

  Dangerous! ok here though.

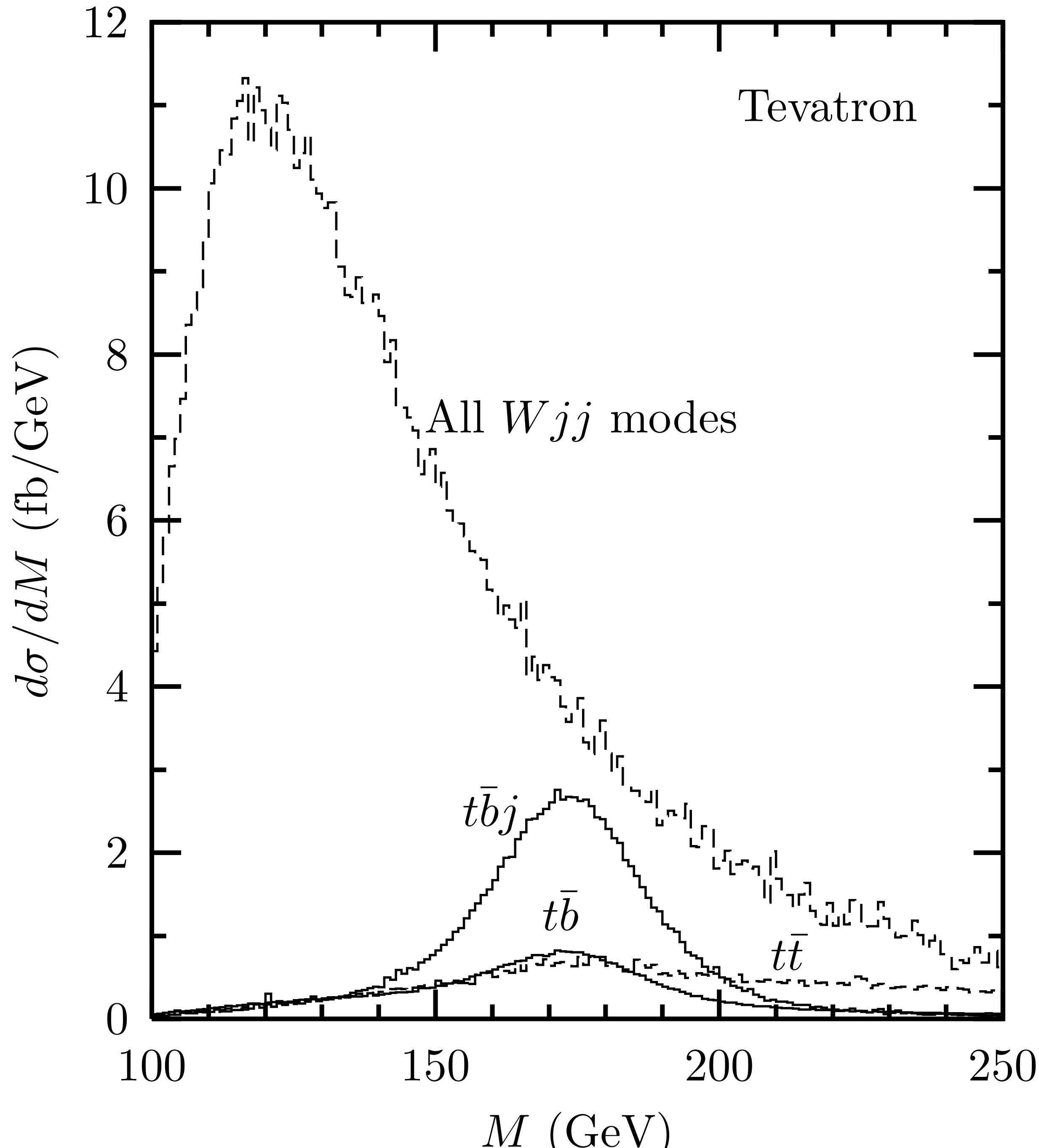
- Compute Wj^n – actually Wjj only [jet veto!]:

  b-tag $\Rightarrow$ $Wb\bar{b}$: straightforward

  ...but must also include

  $Wc\bar{c}$, Wqc, Wgc, $Wq\bar{q}$, Wqq, Wqg, Wgg

- Estimate QCD? No... expect small enough
- Reconstruct "m_t" from $\ell + \not{p}_T = W$, $W + b = t$
- Plot m_t, do "sideband subtraction"; remove Wj^n using *data*.
- Count events.



Tevatron
All Wjj modes
$t\bar{b}j$
$t\bar{b}$
$t\bar{t}$
$d\sigma/dM$ (fb/GeV)
M (GeV)
0
2
4
6
8
10
12
100
150
200
250

SSW concluded: for 1 fb^{-1}, 100 signal events, 150 background.

Counting experiment looks perfectly feasible, with 1 fb^{-1} of luminosity: end of 2004.

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Counting experiment looks perfectly feasible, with 1 fb^{-1} of luminosity: end of 2004.

Unfortunately, this is not true.

Most of it is just bad luck:

- $\sqrt{s} = 1.96$ TeV, not 2.00 (hurts signal)
- $m_t \sim 178$-180 GeV, not 175 (hurts signal)
- gluon pdf went down (hurts signal)
- Next-to-leading order correction increases overall Wjj rate by 1.5

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- Next-to-leading order correction increases overall Wjj rate by 1.5
- b-tagging is not so good:

  b tagged 40-45 %

  c tagged 15-20 %

  g, q tagged 1 %

This significantly increases Wj^n relative to signal.

- Resolution in "m_t" is lower than assumed (decreases separation of signal from Wj^n.)

Another subtle, important problem: Miscommunication!

Experimentalists: “Light quark jets are tagged about one percent of the time.”

Theorists: “g, q tagged $\sim 1\%$”

But these aren’t the same, of course...

Experimentalists mean: “Jets with no heavy-flavor hadrons are tagged about one percent of the time.”

Gluon in tree graph can split, at next order, to $c\bar{c}$ or $b\bar{b}$ pair.

Rare, but almost exactly compensated by increased tagging!

TRIPLES the effective tagging rate for gluons! (large error bar)

Bottom Line: A counting experiment will not work.

Signal to background **1:4**; both low statistics and systematic errors on predicting W plus jets are prohibative.

We need a different approach.

Use energy/angular shapes, correlations?

General Remarks on Tevatron

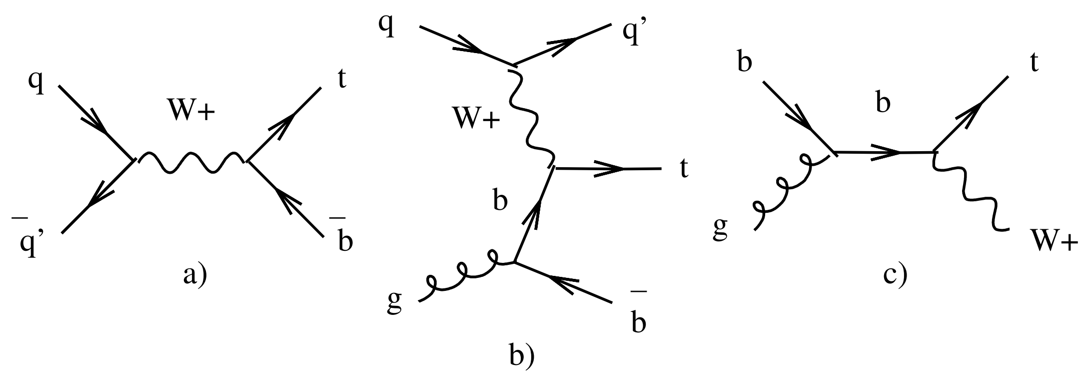
The $p\bar{p}$ initial state of the Tevatron is flipped by C and P:

$$p \rightarrow \leftarrow \bar{p} \quad \Longleftrightarrow \quad \bar{p} \rightarrow \leftarrow p$$

Therefore, in principle, any observable may show a parity (and charge) asymmetry.

$$A_{FB} = \frac{\sigma_{W_+}^{\eta>0} - \sigma_{W_+}^{\eta<0}}{\sigma_{W_+}^{\eta>0} + \sigma_{W_+}^{\eta<0}} \sim 25\%$$

The t-channel process tbq is very distinctive:



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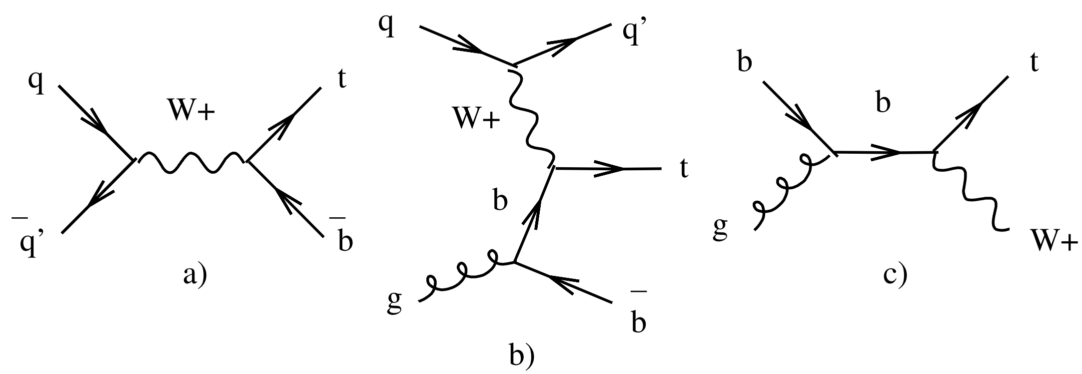

To make a t (not a $\bar{t}$) need

- u from p and g from $\bar{p}$
- g from p and $\bar{d}$ from $\bar{p}$

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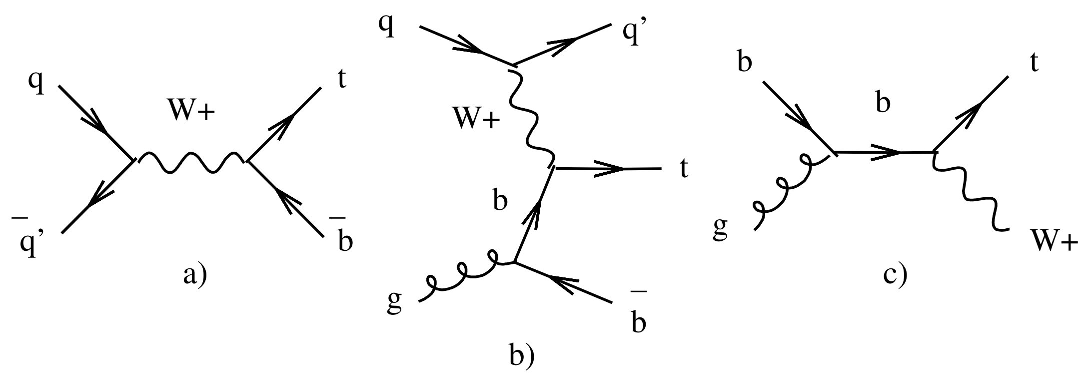

To make a t (not a $\bar{t}$) need

- u from p and g from $\bar{p}$
- g from p and $\bar{d}$ from $\bar{p}$

$\Rightarrow$ **Asymmetry:** the q in $t\bar{b}q$ tends to travel in the p direction

$\eta_j > 0$ for t, $\eta_j < 0$ for $\bar{t}$

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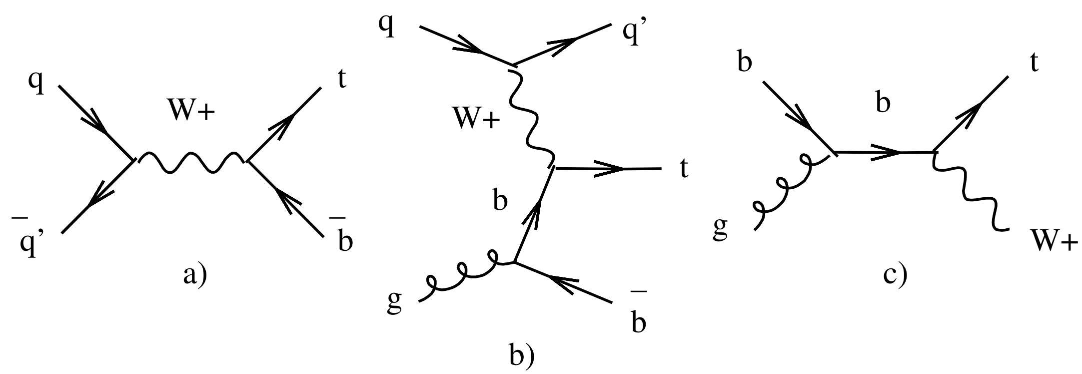


- the top spin orientation
- the lepton momentum direction
- the q momentum direction

all tend to align.

Correlation: Typically, if $\eta_j > 0$, $\eta_\ell > 0$

Top versus Anti-top

Combine t and $\bar{t}$ data by weighting η_j, η_ℓ by lepton charge Q.

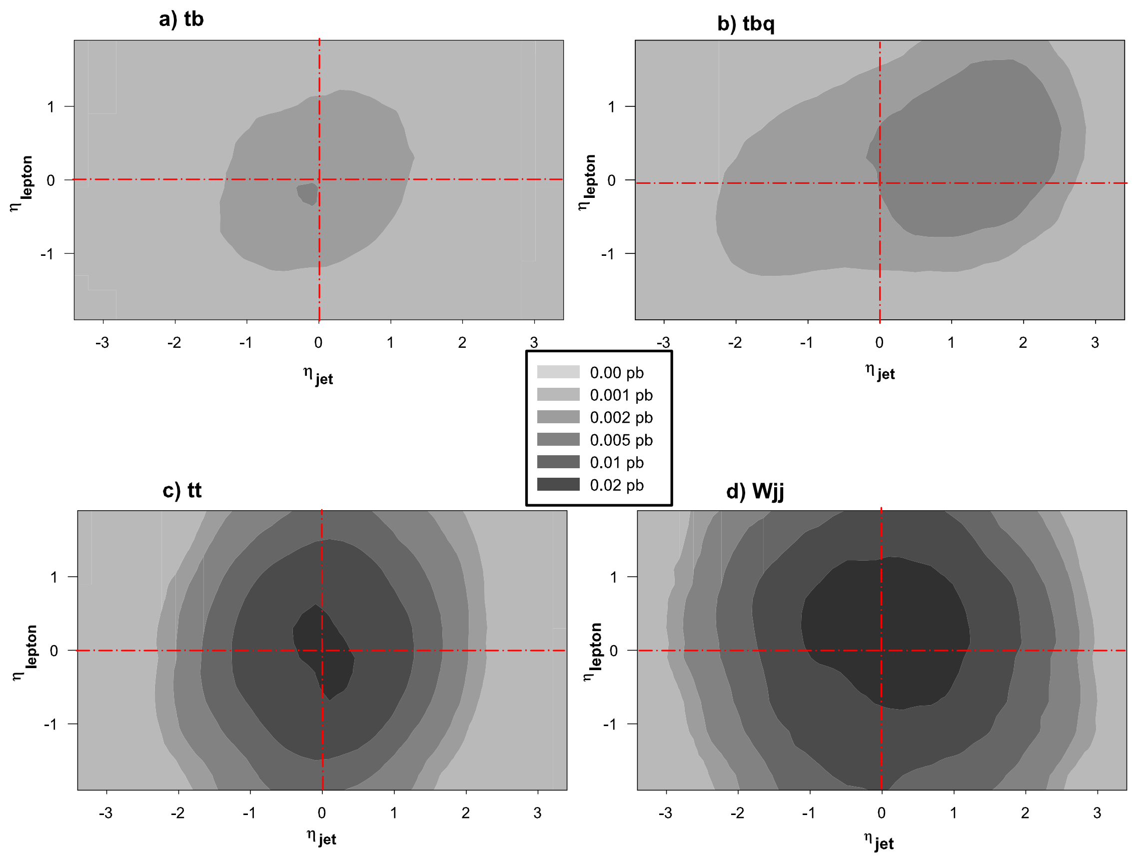
Thus $Q\eta_j > 0$, $Q\eta_\ell > 0$ for single t, $\bar{t}$.

Plot distributions in the (η_j, η_ℓ) plane.

Look for the asymmetries, correlations in the signal and the backgrounds.

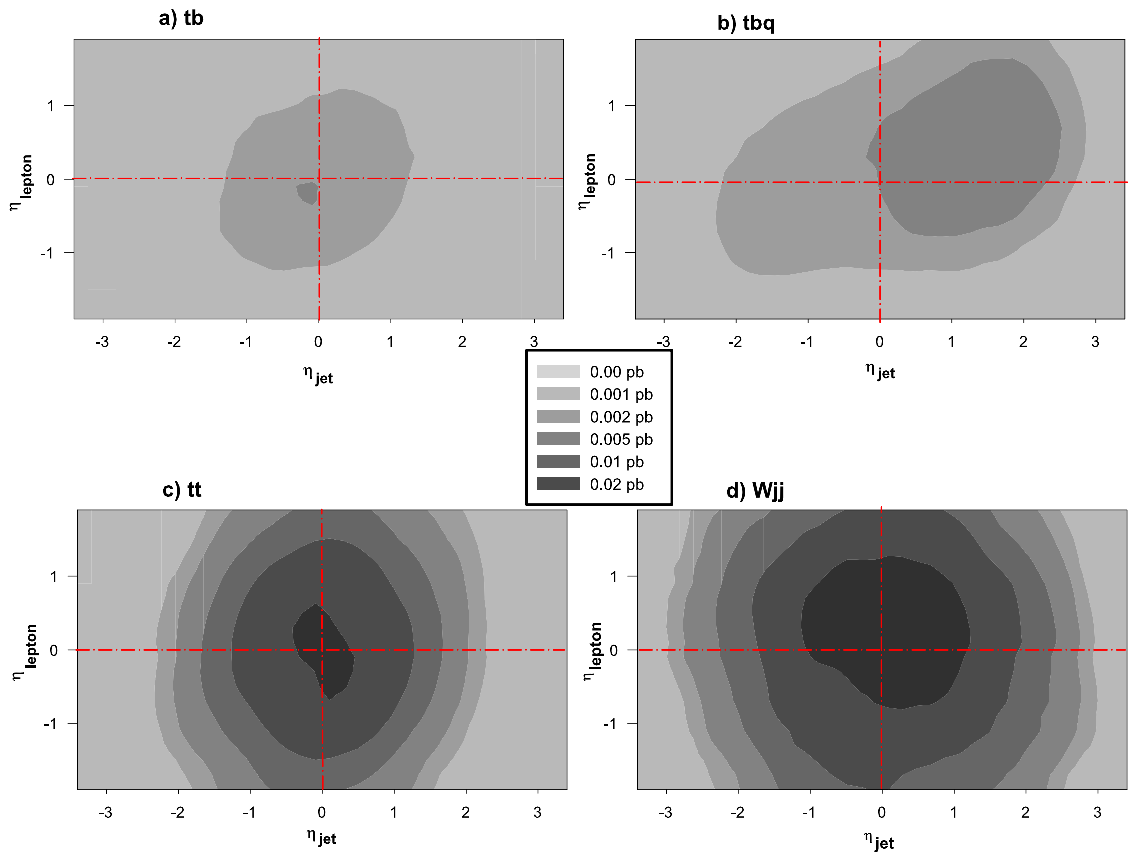
$Q\eta_\ell$ *vs.* $Q\eta_j$ for tb, tbq, $t\bar{t}$, Wj^n

(CDF has used $Q\eta_j$.)

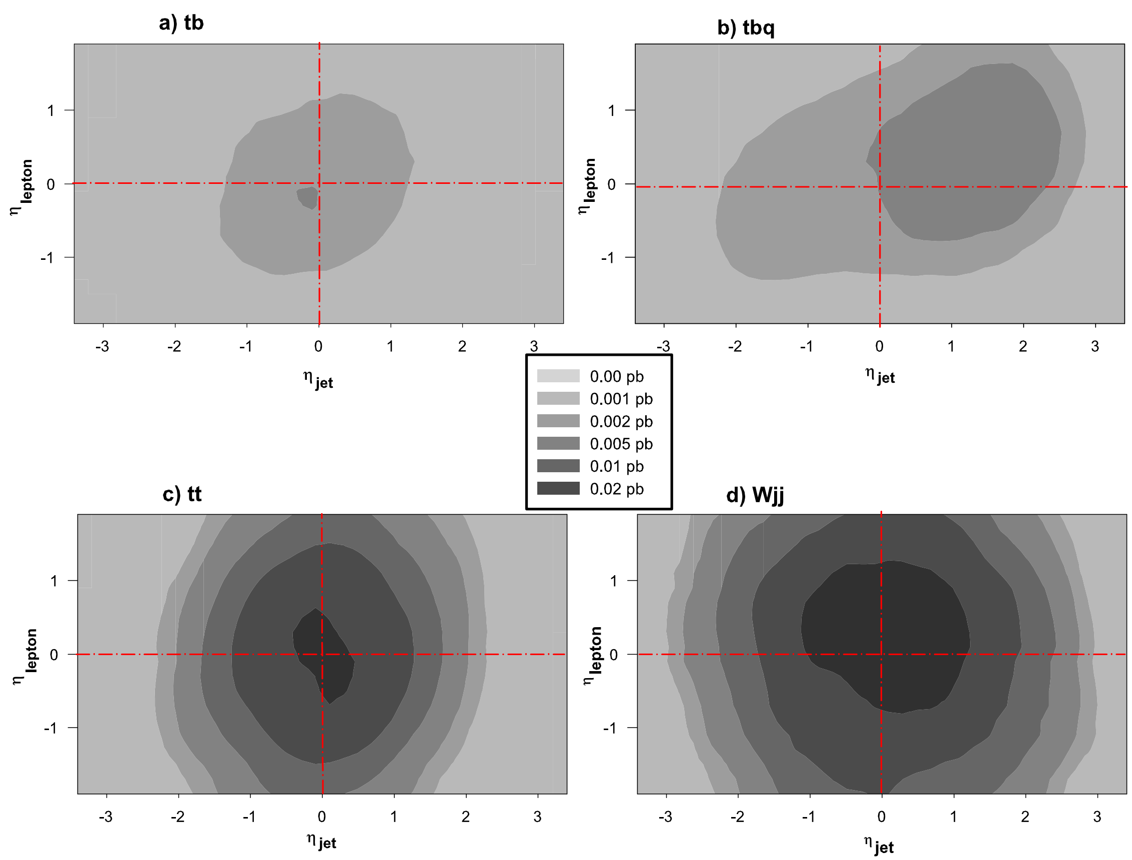


MadEvent ⇒ Pythia ⇒ PGS

Note $Q\eta_j > 0$, $Q\eta_\ell > 0$ for single t, $\bar{t}$.



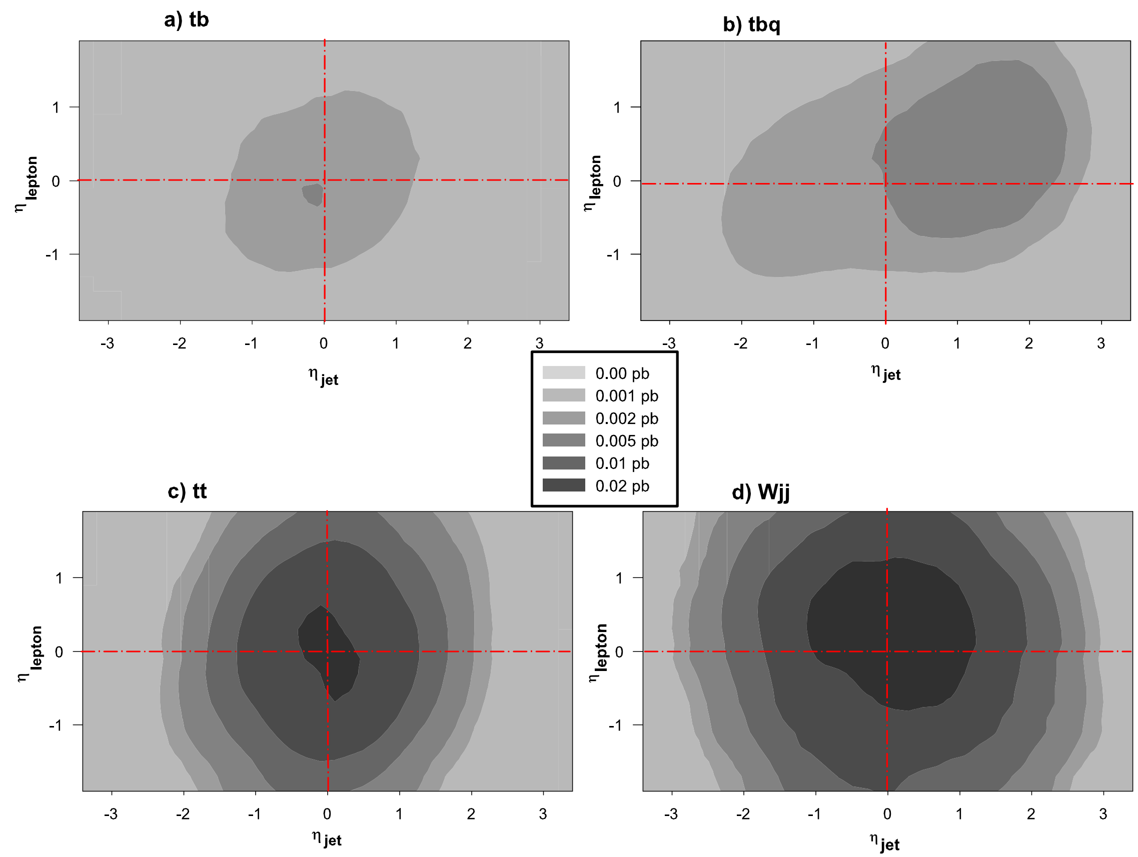
At tree level, $t\bar{t}$ does not have any asymmetry...



though at next order it does (few percent)

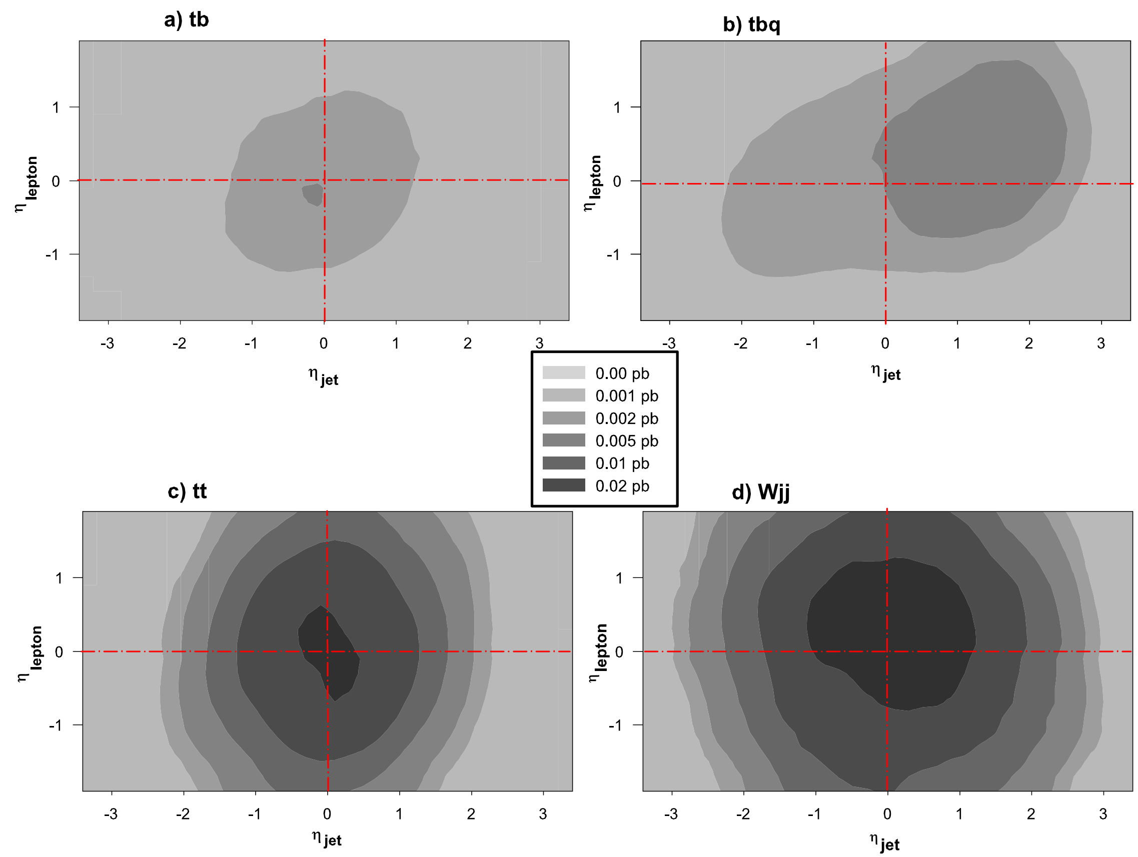
Kuhn; Bowen, S.Ellis, Rainwater

QCD effects similarly symmetric, uncorrelated!



W plus jets has an asymmetry/correlation but not so large

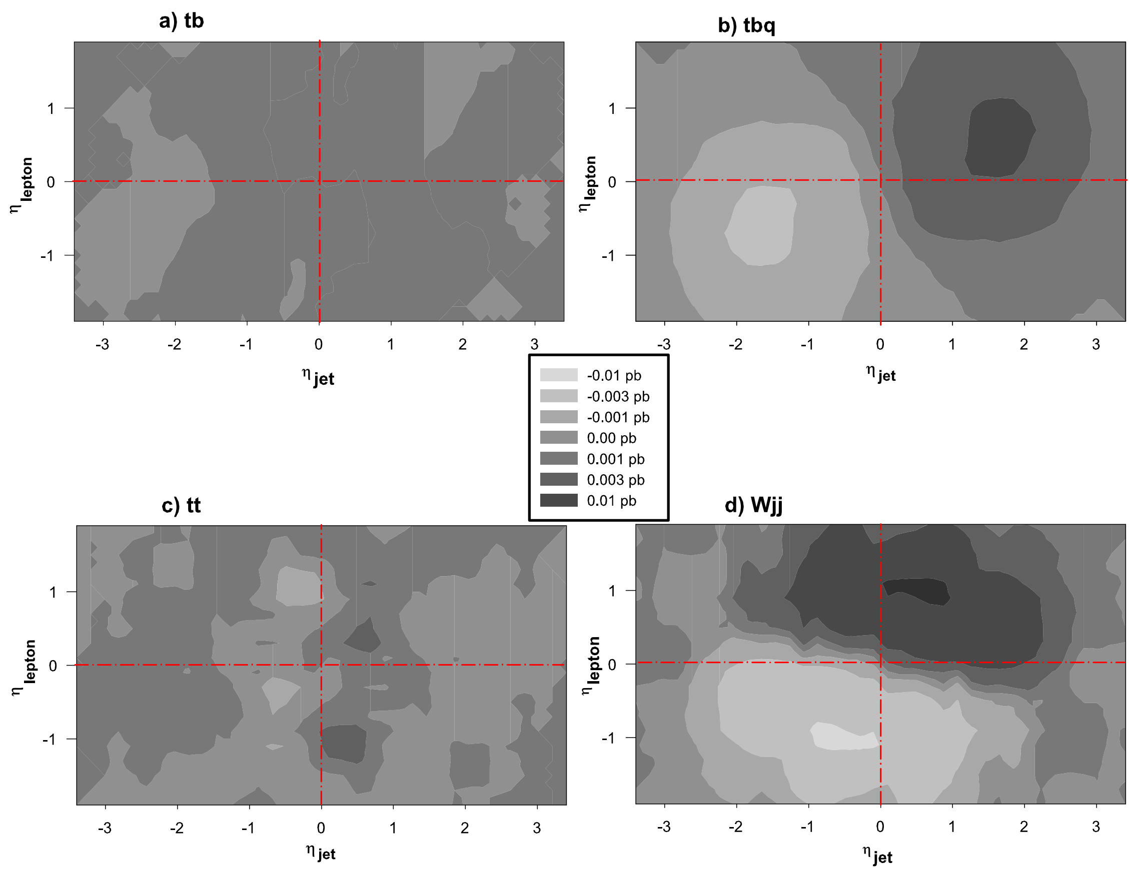
So – construct observables that measure the asymmetry and correlations...



In principle, such observables should have much smaller backgrounds.

This works!

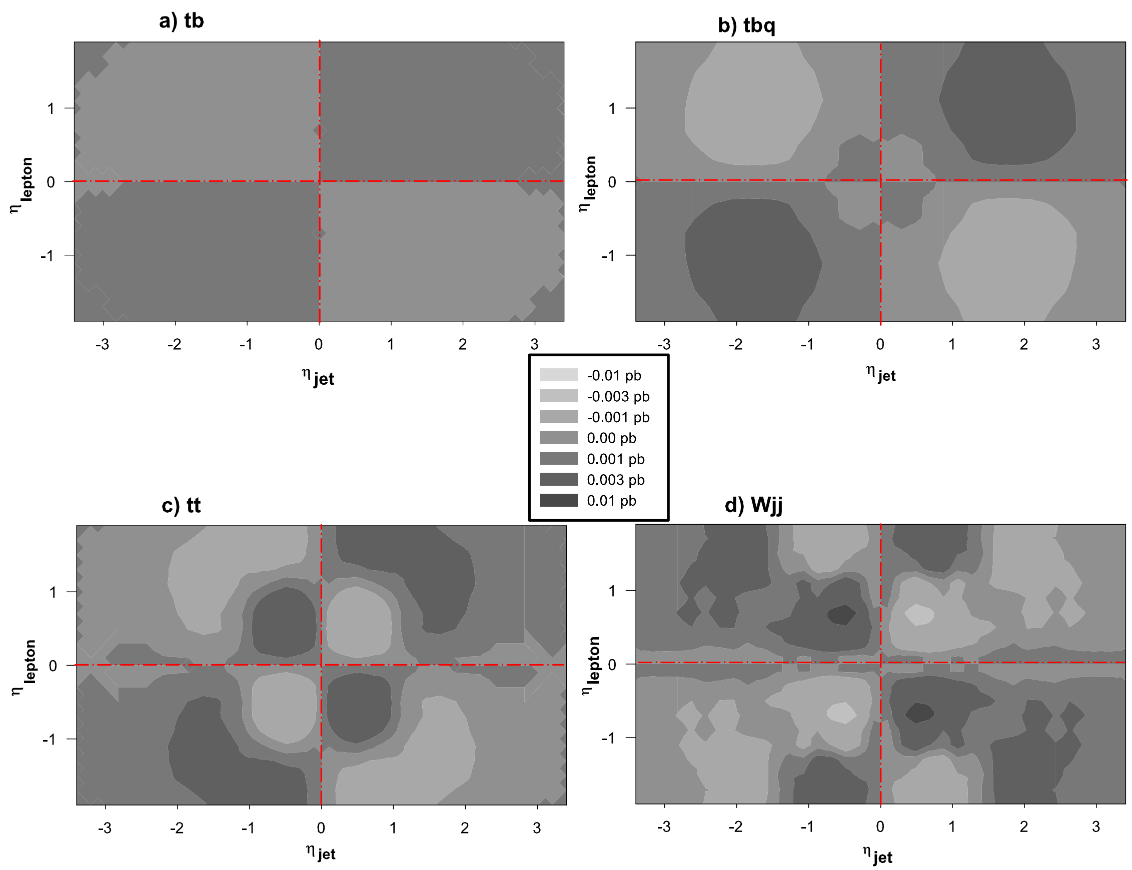
Parity-Asymmetric Observable



S/B ∼ 1:1. Note region with no signal; test background.

This works!

Lepton-Jet Correlation Observable



S/B $\sim$ 1:1.

This works! ... sort of...

Can improve S/B ratio to about 1:1.

Jet Veto not needed.

But statistics still bad. Need at least 4 fb^{-1} even for 2:1 $S/\sqrt{B+S}$.

And systematics not very good: must subtract Wj^n and NLO $t\bar{t}$ asymmetry — smaller, but still not well-known.

Can't we remove Wj^n using the data, as SSW suggested?

What happened to the SSW sideband subtraction?

Any useful cut which reduces Wj^n to a reasonable level *shapes the background*, makes background non-monotonic: not suitable for sideband analysis.

So we have to predict Wj^n, at least in part, using theory.

This is very, very hard. Don't trust your Monte Carlo (especially with a >2-jet veto!). In particular, don't try to train a neural net on it, at least not yet. Let's see why...

We'll explore this in the single-tag sample:

Wjj at tree level [Madgraph]

$\Downarrow$

Parton showering and hadronization [Pythia]

$\Downarrow$

Jet identification and heavy-flavor tagging [PGS]

$b:\ 50\%,\ c:\ 15\%,\ \text{mistag}:\ 1\%$ maximum

What are the properties of the sample with *one b-tagged jet*?

The single-tag sample: how made *vs.* how tagged

Tree-level process *vs.* flavor-content of tagged jet

Wjj Channel	b-jet	c-jet	non b/c-jet	Total
Wqq	2%	1%	6%	9%
Wqg	11%	8%	14%	33%
Wgg	7%	5%	5%	17%
Wcq	0%	14%	1%	15%
Wcg	1%	10%	0%	11%
$Wc\bar{c}$	0%	5%	0%	5%
$Wb\bar{b}$	10%	0%	0%	10%
Total	31%	43%	26%	100%

So, the single "b"-tag Wj^n sample is made from a large variety of different processes...

...each with its own shape ...each with its own normalization ...each with its own uncertainties from pdfs, gluon splitting, tagging rates.

But a reliable prediction of the shape is necessary.

- No Monte Carlo can give you the shape yet, even if you know the next-to-leading-order matrix elements. We find the uncertainties are far too large at present.
- To improve the prediction, many steps necessary; no single calculation, measurement, or detector improvement will make a huge difference.
- The problems with Wj^n stem from many places, and to solve them will require a blue-ribbon panel of expert theorists and experimentalists of different stripes working together.

Ideally, we will improve our understanding of Wj^n over the coming two years.

- Test understanding using comprehensive study of Wj^n, Zj^n with $0, 1, 2$ b-tags
- Null experiment in signal-free region tests Wj^n.
- Use data to measure c/b ratio in gluon splitting?!?

But we will never predict it with precision, so we must **also** reduce it; how?

- Increase b tagging, decrease c contamination
- Reduce energy resolution on m_t reconstruction
- Discard events with wrong-sign $B^\pm$ meson in tagged jet?!?
- Identify/discard events where tagged jet shows signs of gluon splitting? (two heavy-flavor mesons, or double-jet shape?!?)

On to LHC

SSW: Standard Lore at LHC, also

- Again, jet veto to remove $t\bar{t}$.
- Again, m_t reconstruction to remove W plus jets.
- Can see tbq in single tag sample but not in double tag sample.
- Other cuts... will skip...

Apply the same trick?

LHC initial state is P-symmetric, C-asymmetric.

Even total cross-sections have charge asymmetries:

$$A_C \equiv \frac{\sigma_{W^+} - \sigma_{W^-}}{\sigma_{W^+} + \sigma_{W^-}} \approx 0.14$$

Can charge asymmetries make signal easier to observe?

All of the following results on LHC single top production are entirely the work of Matt Bowen, fourth-year graduate student at the University of Washington.

Bowen's Observations

- Relative to Tevatron, many more gluons. Boosts $t\bar{t}$ sharply, tbq somewhat, W+jets not so much.

- $\sigma_{t\bar{b}q} = 160$ pb, $\sigma_{\bar{t}bq} = 90$ pb: so $A_C > 25\%$. Harris et al. '02

- But $t\bar{t}$ (biggest background) has $A_C = 0$!!

(Caution — actually nonzero at NLO, but $|A_C| < 0.00025$.)

- With a single b tagged jet, W+jets has only a 7% asymmetry.

Contributions with $A_C < 0$ from *e.g.* $dg \to W^- cg$;

- If two b tagged jets, $Wb\bar{b}$ is main background (under good theoretical control and has rather small rate.)

- Asymmetry so large that no complicated cuts, jet veto, top quark reconstruction, or even careful simulation is necessary. MadGraph/Madevent Maltoni, Stelzer is sufficient; Pythia, PGS not needed here.

Item	p_T	$\|\eta\|$
$\ell^{\pm}$	≥ 20 GeV	≤ 2.5
MET (ν)	≥ 20 GeV	-
b-tagged jets	≥ 30 GeV	≤ 2.5
other jets	≥ 30 GeV	≤ 4.5

Table 1: Detector cuts used to select events.

$N_{\pm} = \#$ events w/ $\ell^{\pm}$; $N_{total} = N_{+} + N_{-}$; $\Delta = N_{+} - N_{-}$;

Channel	N_{total}	Δ	$\sqrt{N_{total}}$
tb	4,550	990	67
tbq	116,000	30,900	340
$Wb\bar{b}$	21,900	4,820	150
Wjj	236,000	18,000	490
$t\bar{t}$	958,000	-479	980
Total	1.34M	54,200	1,200

Table 2: Numbers of events with 1 b-tag for 10 fb^{-1}.
$t\bar{t}$ is assumed to have a -0.05% charge asymmetry.

$$A_C = 3.2\% \pm 0.1\% \text{ (stat) } \pm 0.4? \text{ (syst from } Wj^n\text{)}$$

$N_{\pm} = \#$ events w/ $\ell^{\pm}$; $N_{total} = N_{+} + N_{-}$; $\Delta = N_{+} - N_{-}$;

Channel	N_{total}	Δ	$\sqrt{N_{total}}$
tb	1,790	330	42
tbq	15,100	4,030	120
$Wb\bar{b}$	8,800	1,800	94
Wjj	1,550	30	40
$t\bar{t}$	336,000	-167	580
Total	363,000	6,020	600

Table 3: Numbers of events with 2 b-tags for 10 fb^{-1}. $t\bar{t}$ is assumed to have a -0.05% charge asymmetry.

$$A_C = 1.8\% \pm 0.2\% \text{ (stat) } \pm 0.1? \text{ (syst from } Wb\bar{b})$$

Bowen's Conclusion for LHC

• Single top is easily measured, and precisely so, in both the single-tag and double-tag samples.

• Double-tag sample actually may have lower systematic errors.

• Method is extremely robust: no attempt made to separate signal from background other than A_C. Lower efficiencies, unexpectedly tough experimental environment no problem; more integrated luminosity and/or more targeted cuts.

• • • Caution: C-asymmetry method is crucially sensitive to systematic uncertainties in charge-asymmetric effects. Systematic uncertainty in unequal efficiencies for ℓ^+ versus ℓ^- of order 0.5% will impact $t\bar{t}$ at a level large enough to ruin the measurement. *Real-Time Calibration Needed.*

Summary

- Single top is harder at Tevatron than thought; parity asymmetries and lepton-jet correlations almost save the day, but this is going to be very tough.
- W plus jets is the problem, not $t\bar{t}$.
- Be very cautious requiring two *and only two* jets; theoretical error on normalizing Wj^n with a jet veto probably exceeds the signal.
- Be very cautious with neural nets that train on Monte Carlos for Wj^n; uncertainties in the shape of Wj^n with one tag currently are of order half the signal.
- Be cautious about splitting 1-tag and 2-tag sample? (when a gluon splits, how often do you get 1 tag, how often 2?)

Summary

- Single top is harder at Tevatron than thought; parity asymmetries and lepton-jet correlations almost save the day, but this is going to be very tough.
- W plus jets is the problem, not $t\bar{t}$.
- Need community-wide effort to reduce its size and to constrain its shape and normalization. Only a coherent effort to bring Wj^n under control can make single top (and other physics!) accessible at the Tevatron.
- BOWEN: Single top is much easier at LHC than previously thought, using charge asymmetries. A precision measurement in both single-tag and double-tag will be possible, assuming not swamped by new physics.

Extra Slides:

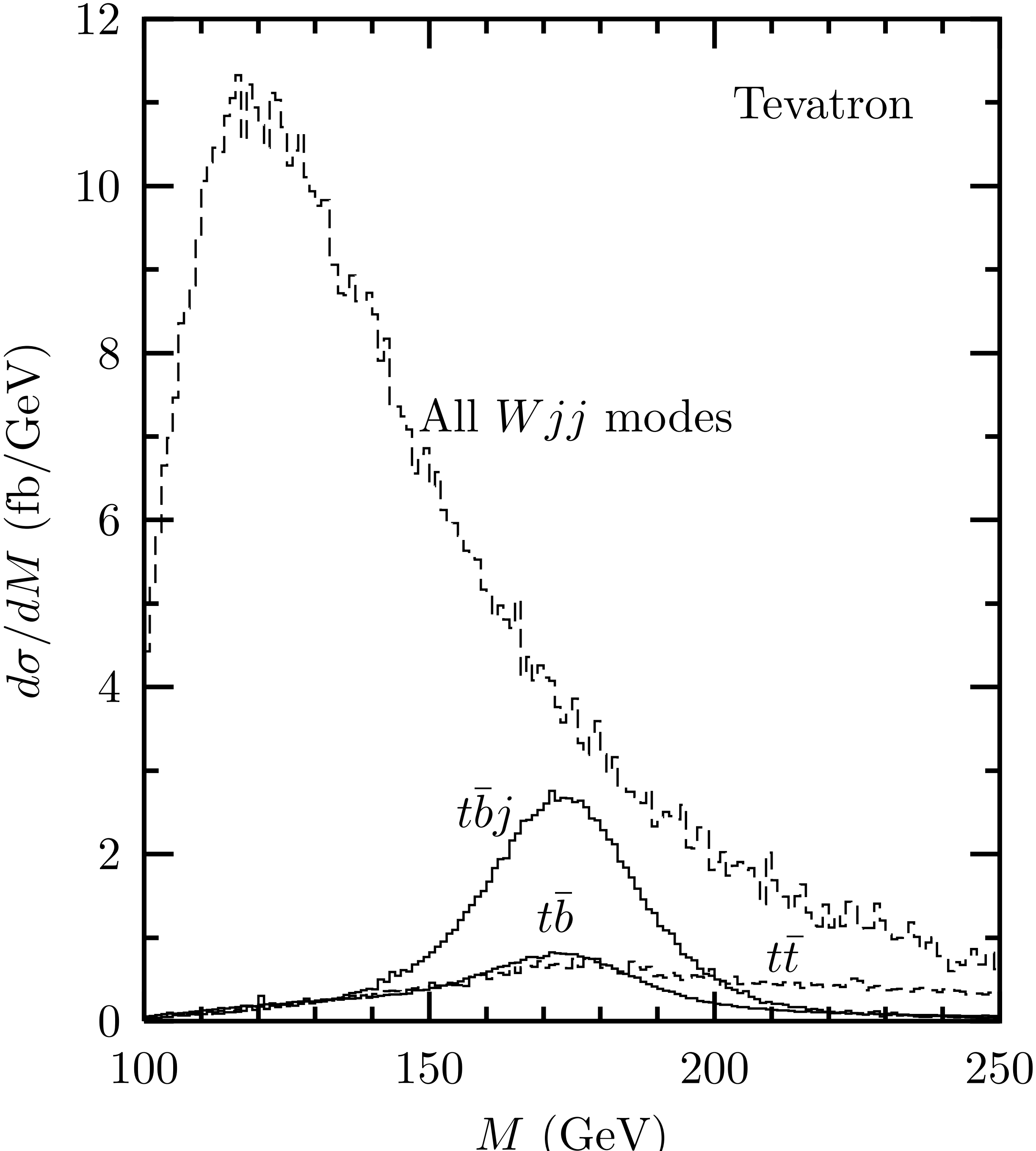
Danger of $>$ 2-Jet Veto

- 2-or-More jet calculation is completed to NLO.
  - LO is order $\alpha^2(\mu)$
  - NLO is order $\alpha^3(\mu)$ AND
  - is stable against varying μ.
- 3-or-More jet calculation is completed to LO,
  - order $\alpha^3(\mu)$.
  - NOT stable against varying μ.

- 2-only = (2-or-More) minus (3-or-More)
- but we count using some dividing line at small scale μ_{cut}.
- Relative uncertainties are of order (3-or-More)/(2-only), of order $\alpha_s(\mu_{cut})$ — not small!

Error *larger* than for NLO 2-or-More.

let's compare...



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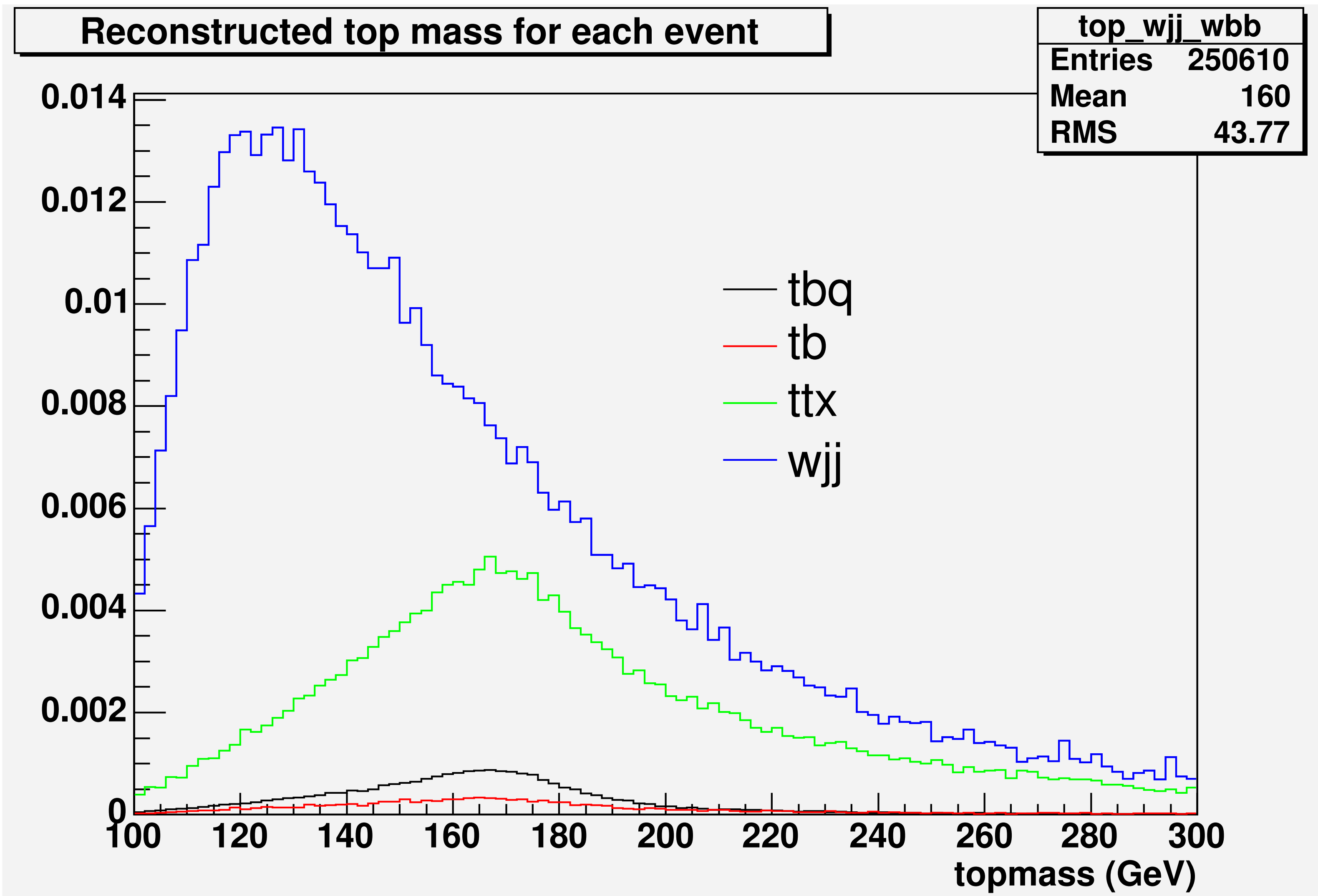


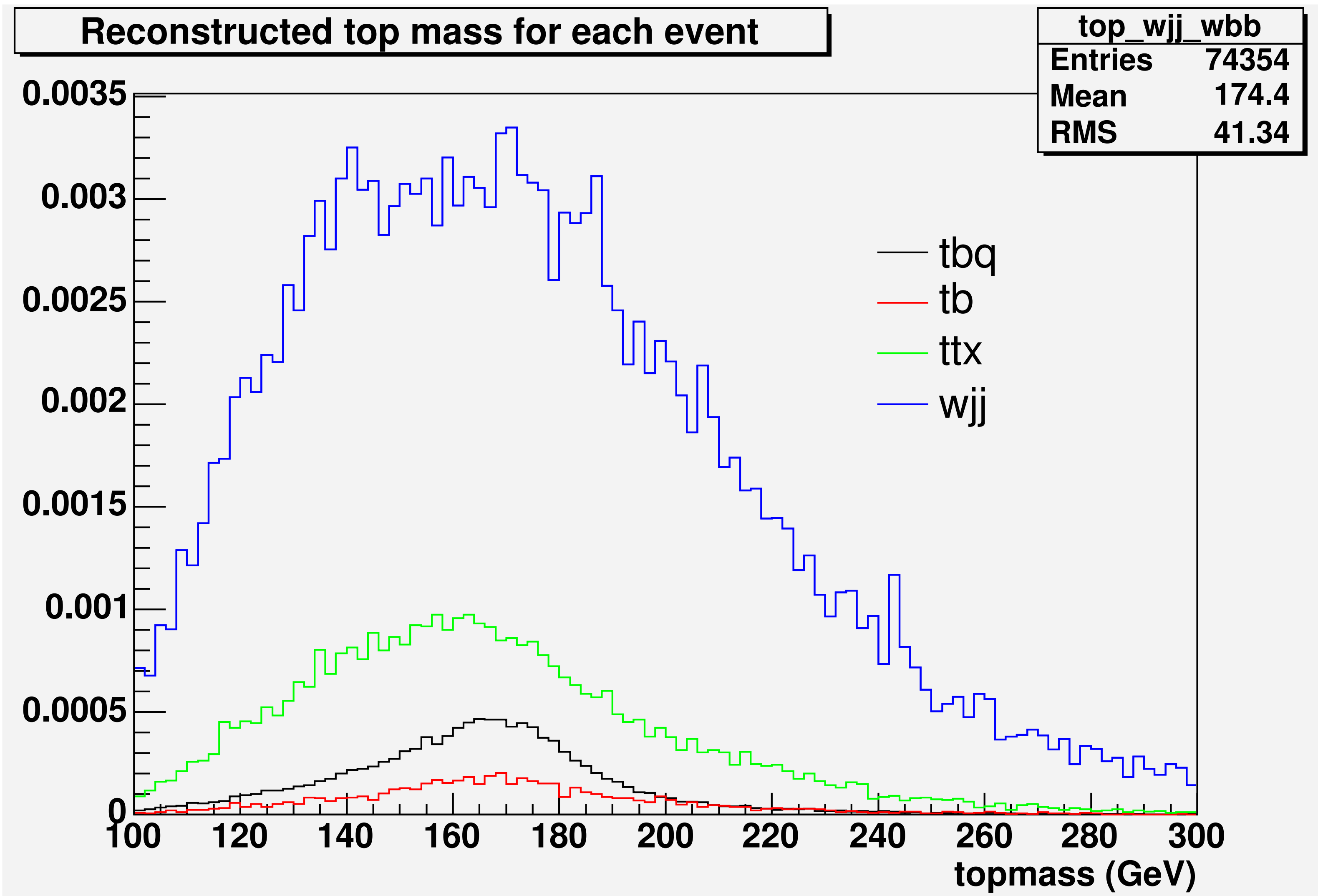
Reconstructed top mass for each event
top_wjj_wbb
Entries 250610
Mean 160
RMS 43.77
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
tbq
tb
ttx
wjj
100
120
140
160
180
200
220
240
260
280
300
topmass (GeV)

So, the actual signal to background situation looks vastly less promising than in SSW.

Can we cut harder?

Certainly we can try to introduce cuts that use the fact that Wj^n does have other differences, from the signal, but…

let's look at the plot of "m_t"


Reconstructed top mass for each event
top_wjj_wbb
Entries 74354
Mean 174.4
RMS 41.34
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
100
120
140
160
180
200
220
240
260
280
300
topmass (GeV)
tbq
tb
ttx
wjj