the top
top ten list

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The top quark is the heaviest known quark, and perhaps the last quark that we will find.

Its properties, from samples of a few hundred studied at the Fermilab Tevatron, conform well to the Standard Model. Still, it is tempting to imagine that the top quark is not a Standard Model object, but rather something more mysterious.

At the LHC, we should find out.

What are the top ten top quark measurements that we must perform at the LHC ?

Outline of this lecture:

Review of the properties of the top quark
in the Standard Model

Three pictures for how the top quark fits into
the fundamental interactions

The top quark top ten list

The important property of the top quark that controls most of its phenomenology is the fact that

$$m_t - m_b > m_W$$

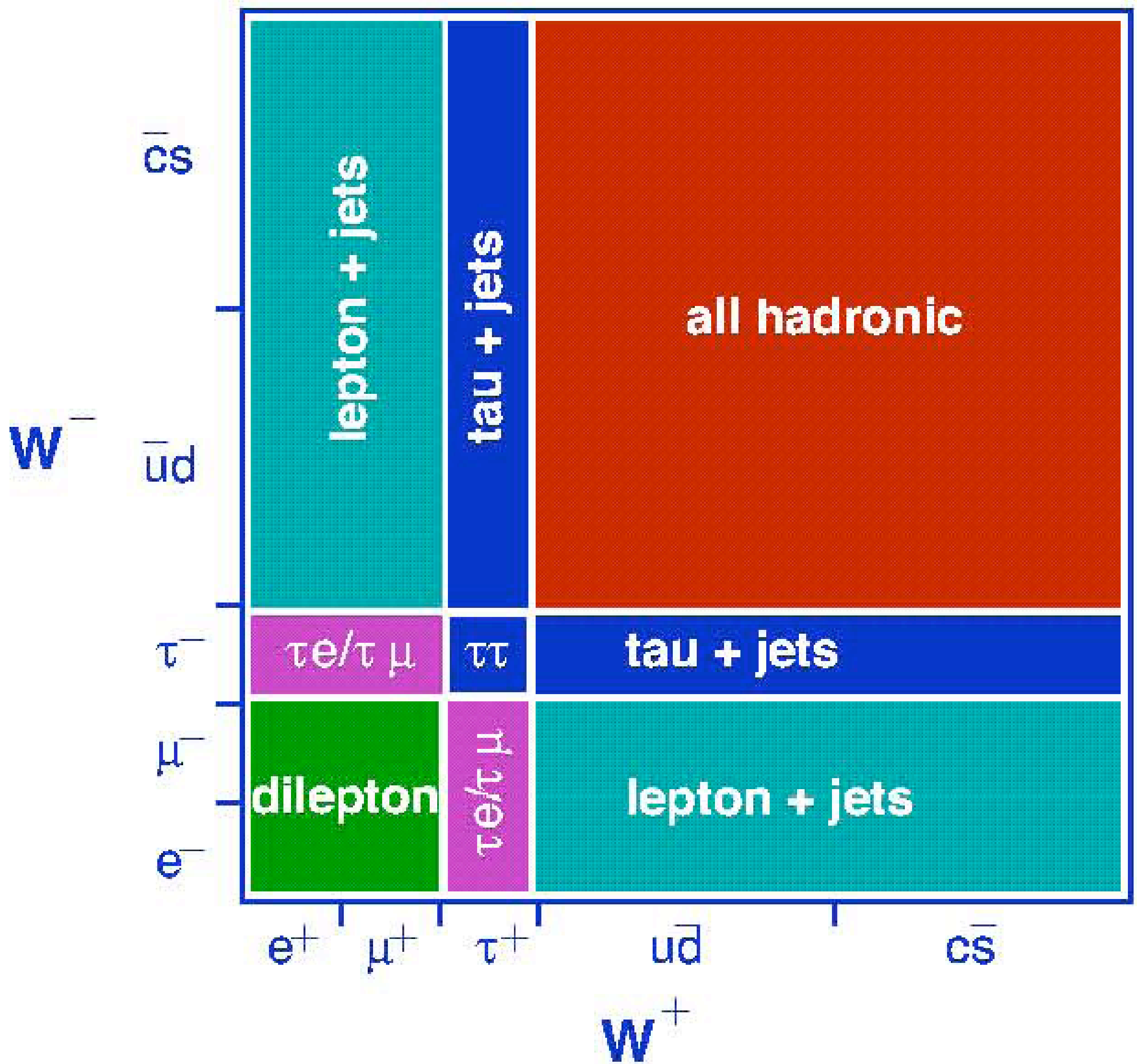
Together with $|V_{td}|, |V_{ts}| \ll |V_{tb}|$ this implies that the dominant decay mode will be the two-body, on-shell decay

$$t \rightarrow bW^+$$

The branching ratios of the W are well-established:

34% to $e^+\nu$, $\mu^+\nu$, $\tau^+\nu$ 66% to $u\overline{d}$, $c\overline{s}$

and so the decay pattern of the top quark is already highly constrained.



W⁻
$\bar{c}s$
$\bar{u}d$
τ^-
μ^-
e^-
lepton + jets
tau + jets
all hadronic
τe/τ μ
ττ
tau + jets
dilepton
τe/τ μ
lepton + jets
e^+
μ^+
τ^+
$u\bar{d}$
$c\bar{s}$
W⁺

This already signals characteristic types of events that have been searched for and found at the Tevatron.

e + 4 jet event

40758_44414

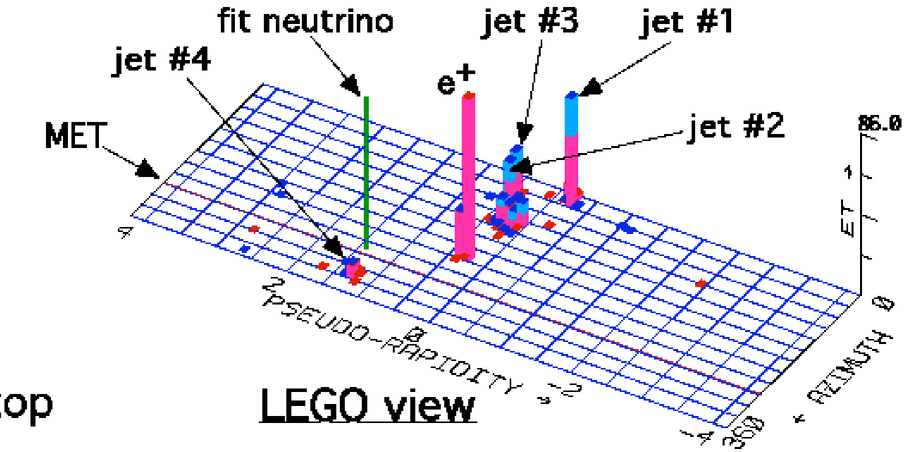
24-September, 1992

TWO jets tagged by SVX

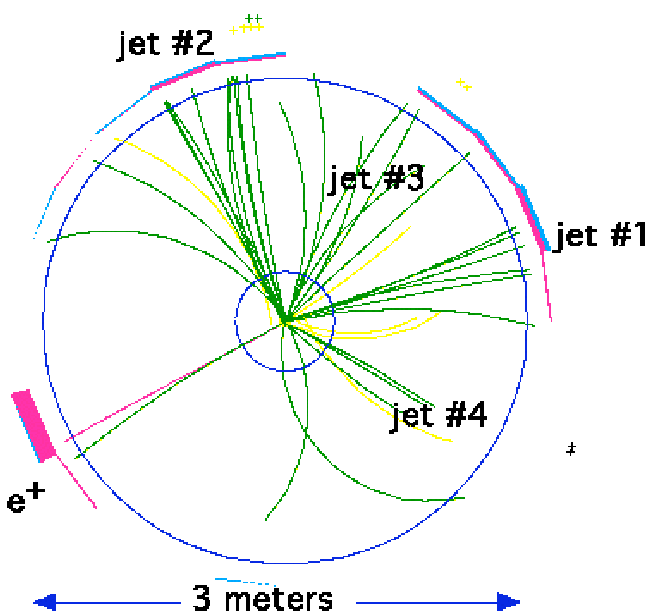
fit top mass is 170 +- 10 GeV

e^+, Missing E_t, jet #4 from top

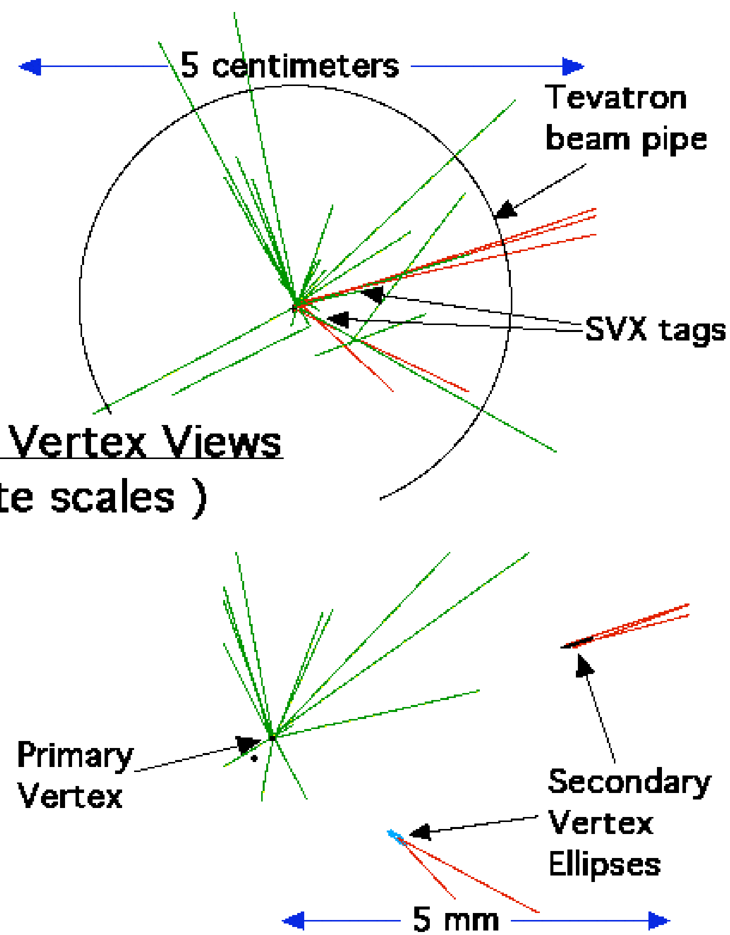
jets 1,2,3 from top (2&3 from W)



LEGO view



Tracking View

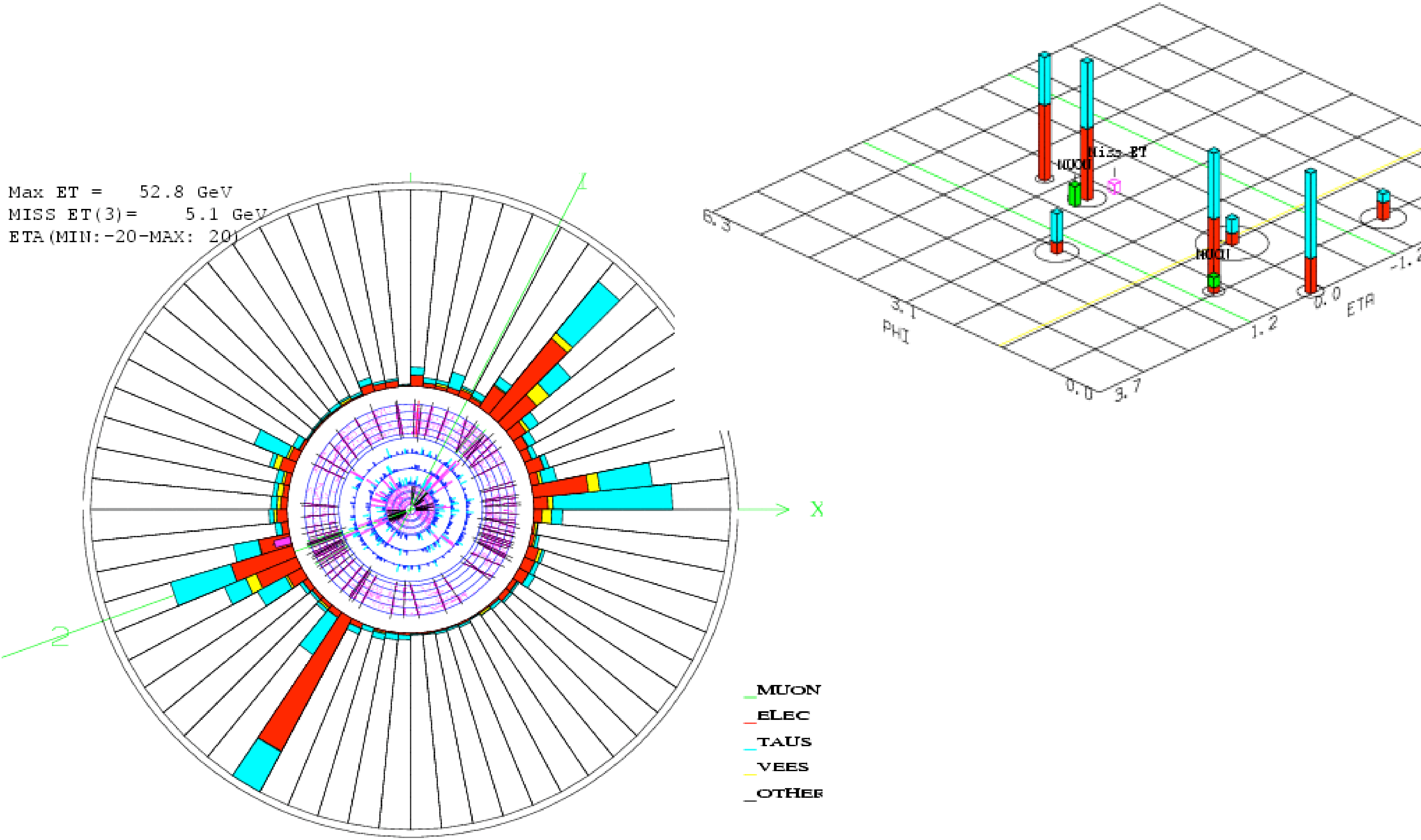


Two Vertex Views

(note scales)

CDF

DO 6-jet top quark event



I should say only that these events are probably top.

Standard Model processes, such as

$$pp \longrightarrow W + (g \longrightarrow b\bar{b}) + ISR$$

have significant cross sections at hadron colliders and can fill in events with almost any non-Standard signature.

If even Dalitz could get it wrong, we had better be careful !

Physics Letters B 287 (1992) 225–230

Analysis of top–antitop production and dilepton decay events and the top quark mass

R.H. Dalitz [a] and Gary R. Goldstein [b]

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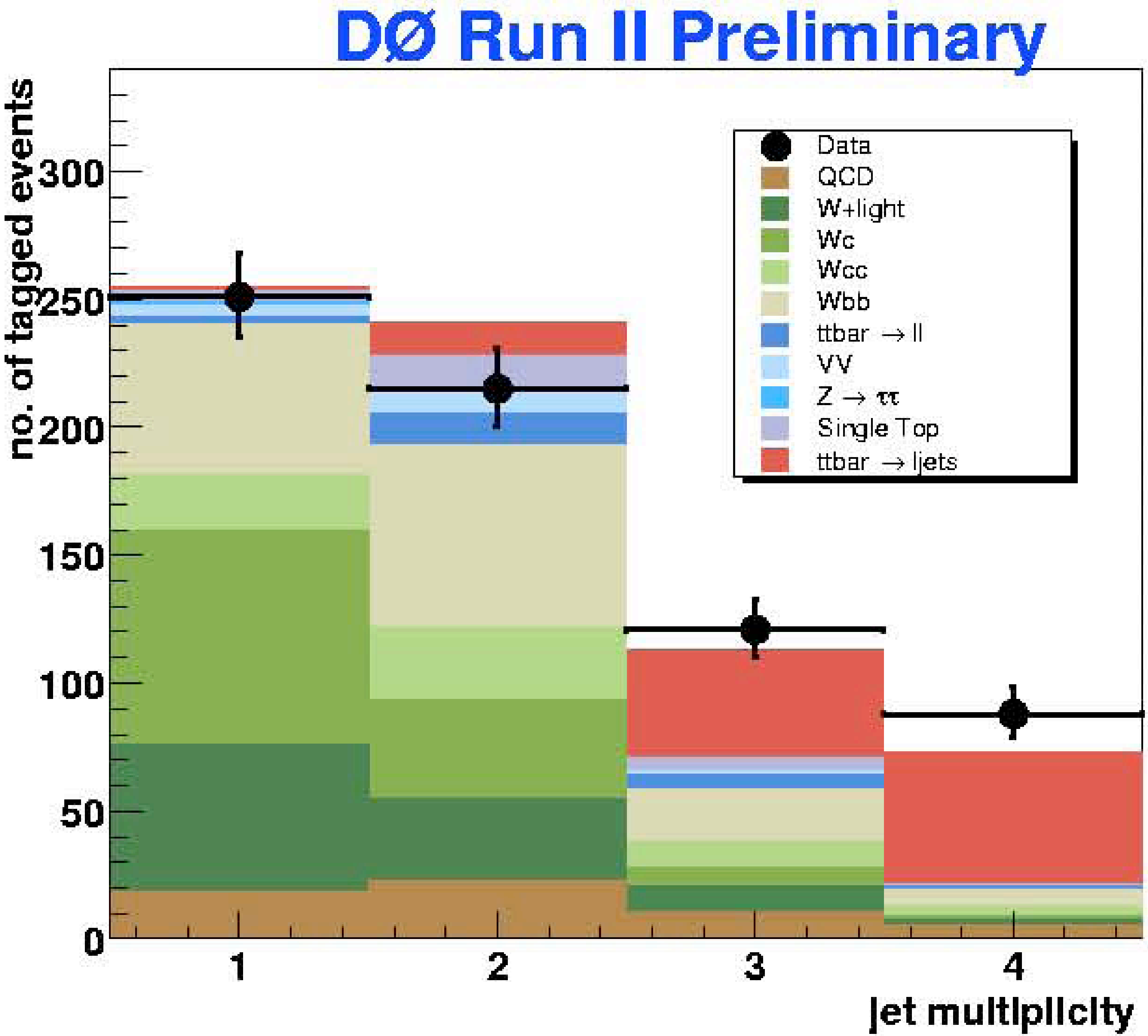
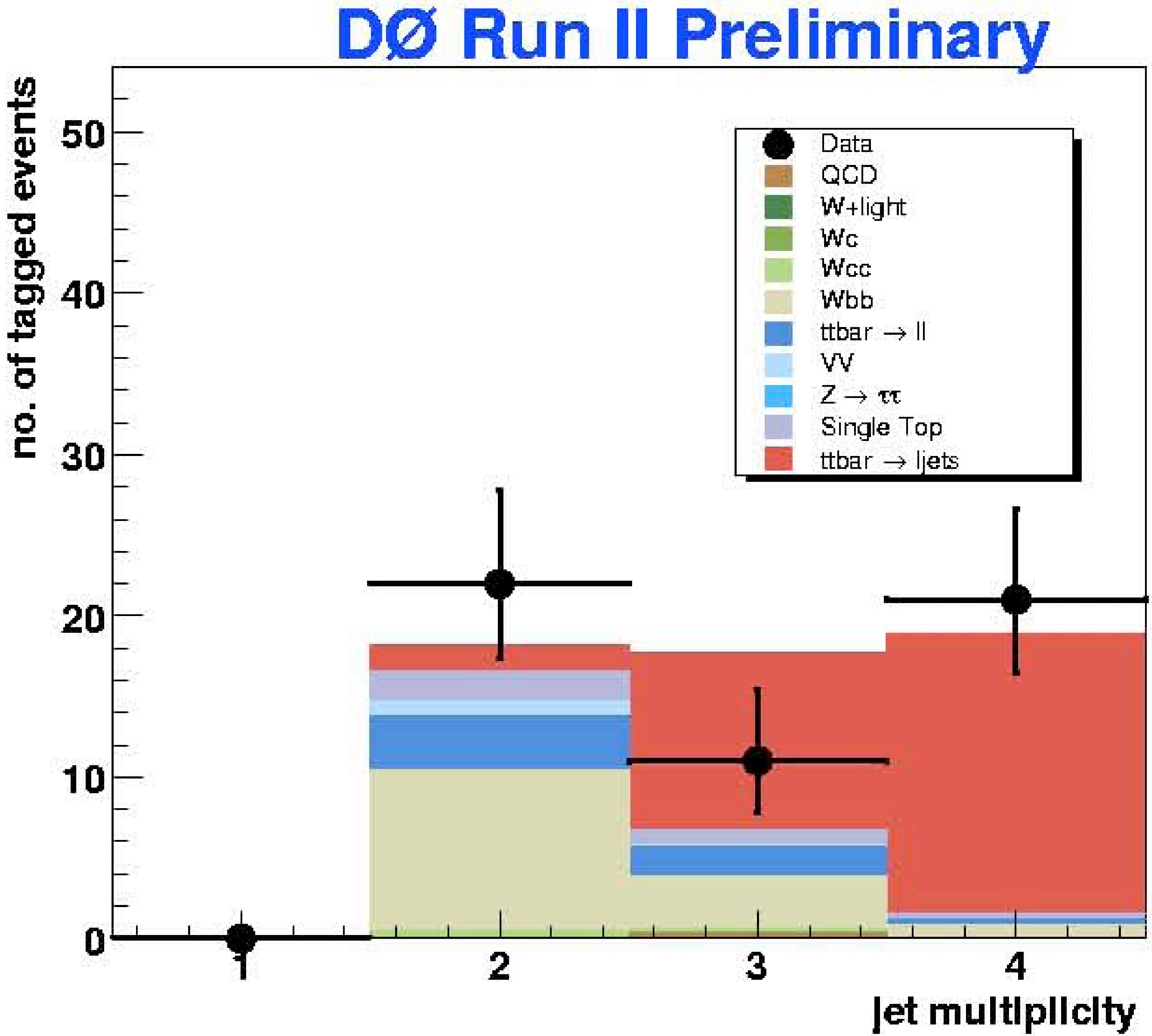
[b] *Physics Department, Tufts University, Medford, MA 02155, USA*

Received 22 May 1992

If this event really represents top–antitop production and decay, then the top quark mass would be 131^{+22}_{-11} GeV.

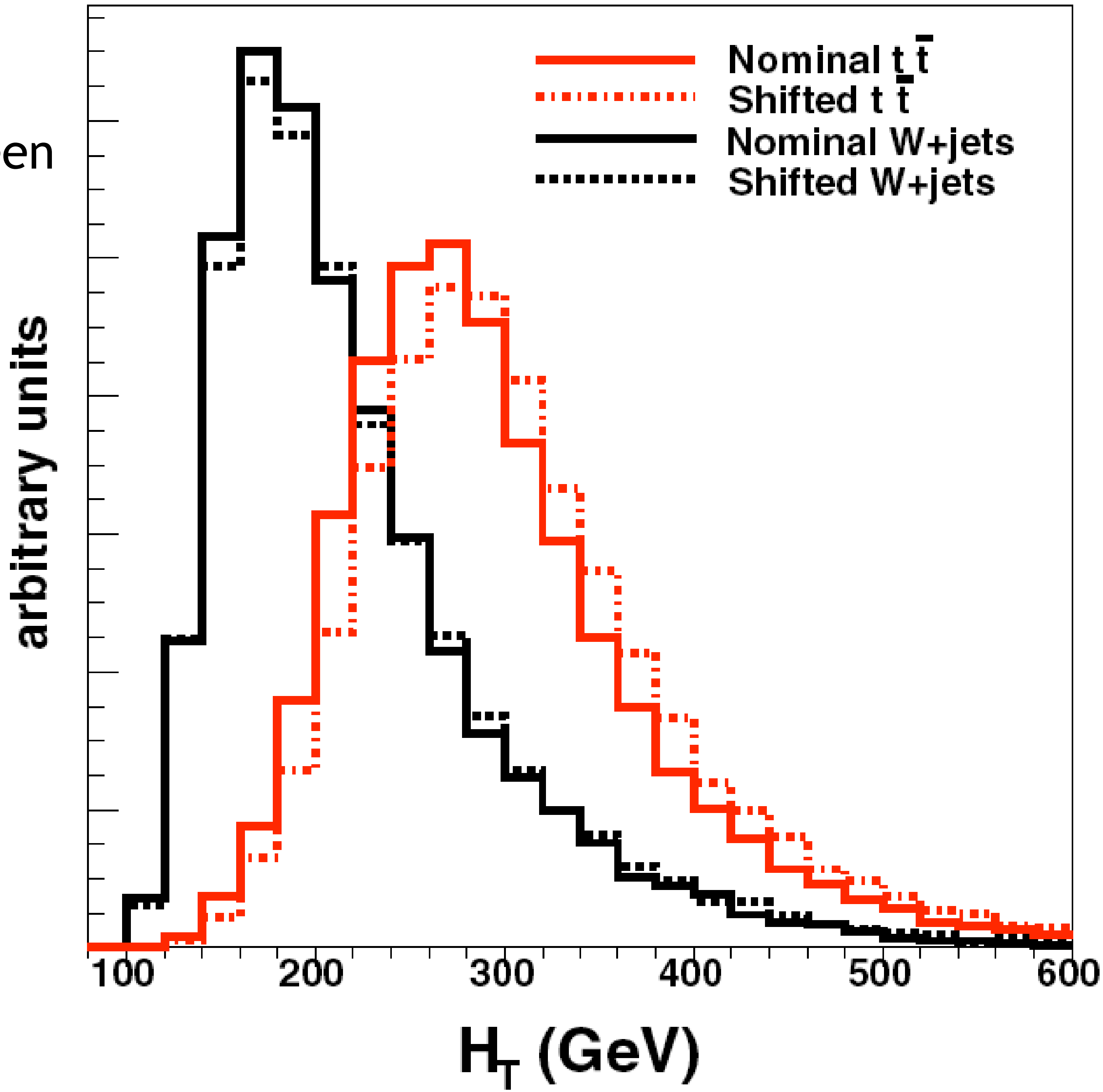
Nevertheless, careful analyses attentive to these backgrounds can convince us that we are seeing the top quark.


DØ Run II Preliminary
no. of tagged events
0
50
100
150
200
250
300
1
2
3
4
jet multiplicity
Data
QCD
W+light
Wc
Wcc
Wbb
ttbar → ll
VV
Z → ττ
Single Top
ttbar → ljets

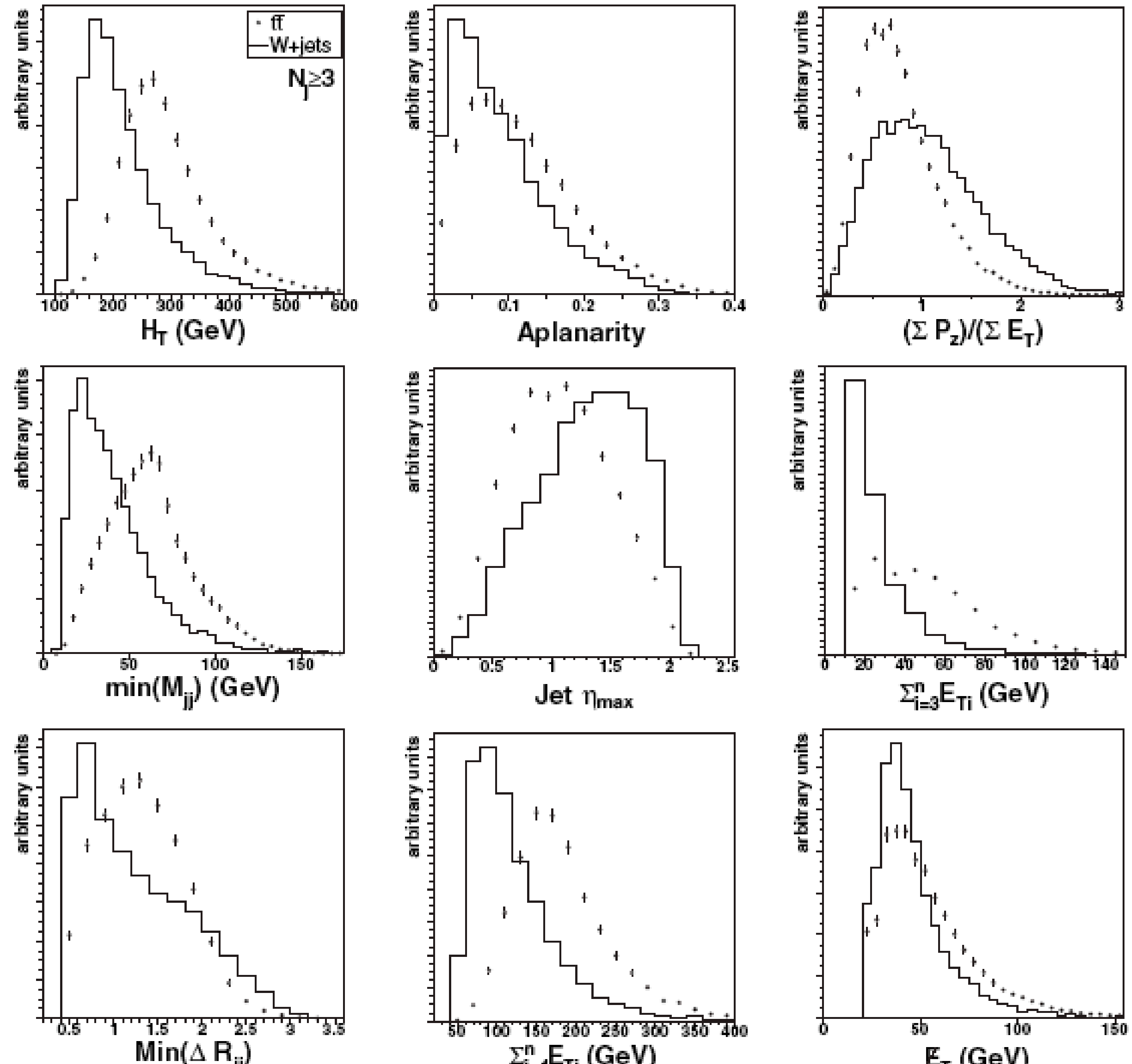

DØ Run II Preliminary
no. of tagged events
0
10
20
30
40
50
1
2
3
4
jet multiplicity
Data
QCD
W+light
Wc
Wcc
Wbb
ttbar → ll
VV
Z → ττ
Single Top
ttbar → ljets

CDF

Comparison of HT distributions between ttbar and W + jets events



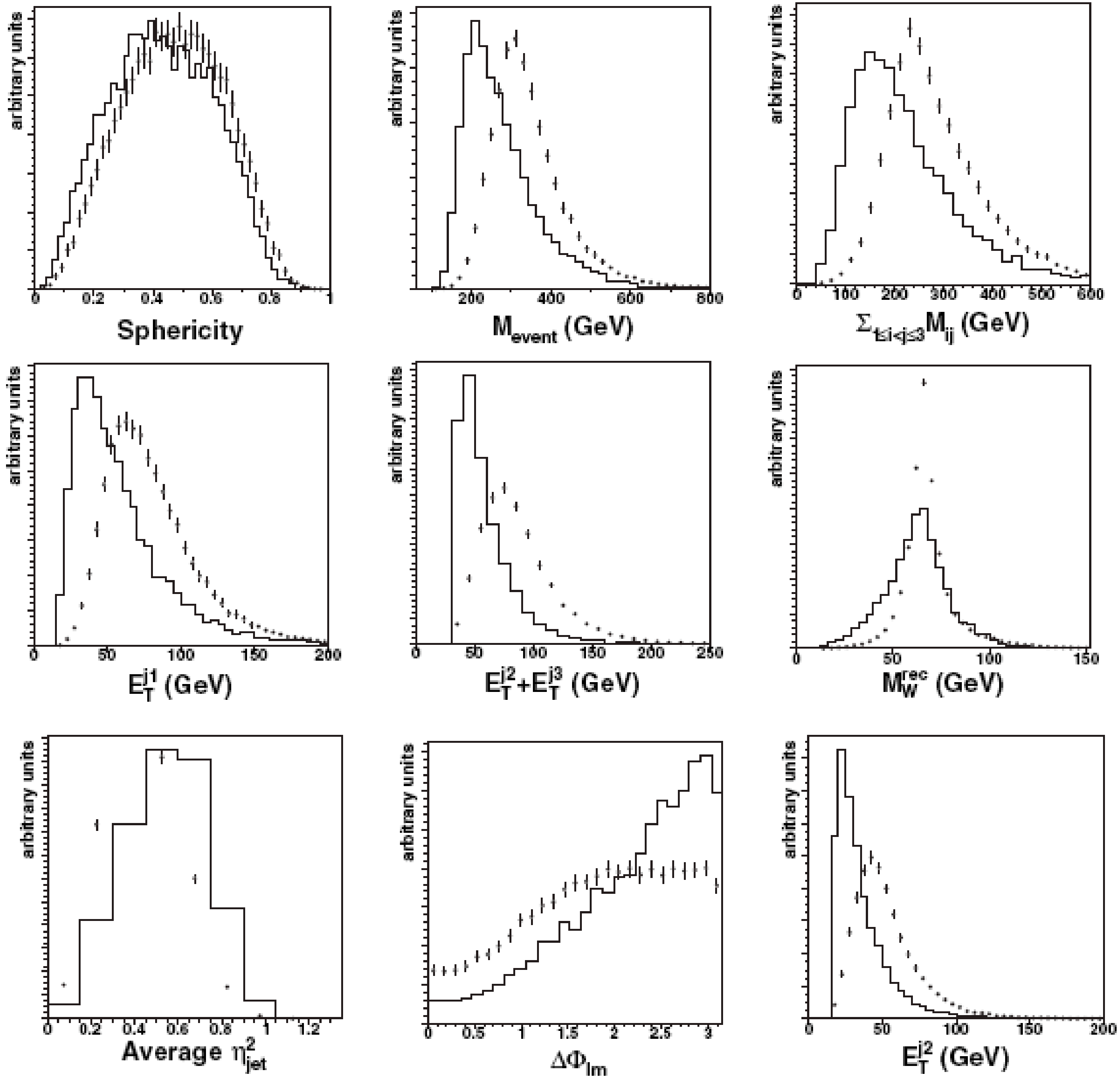
ttbar/W+jets shape comparisons for 9 kinematic observables.



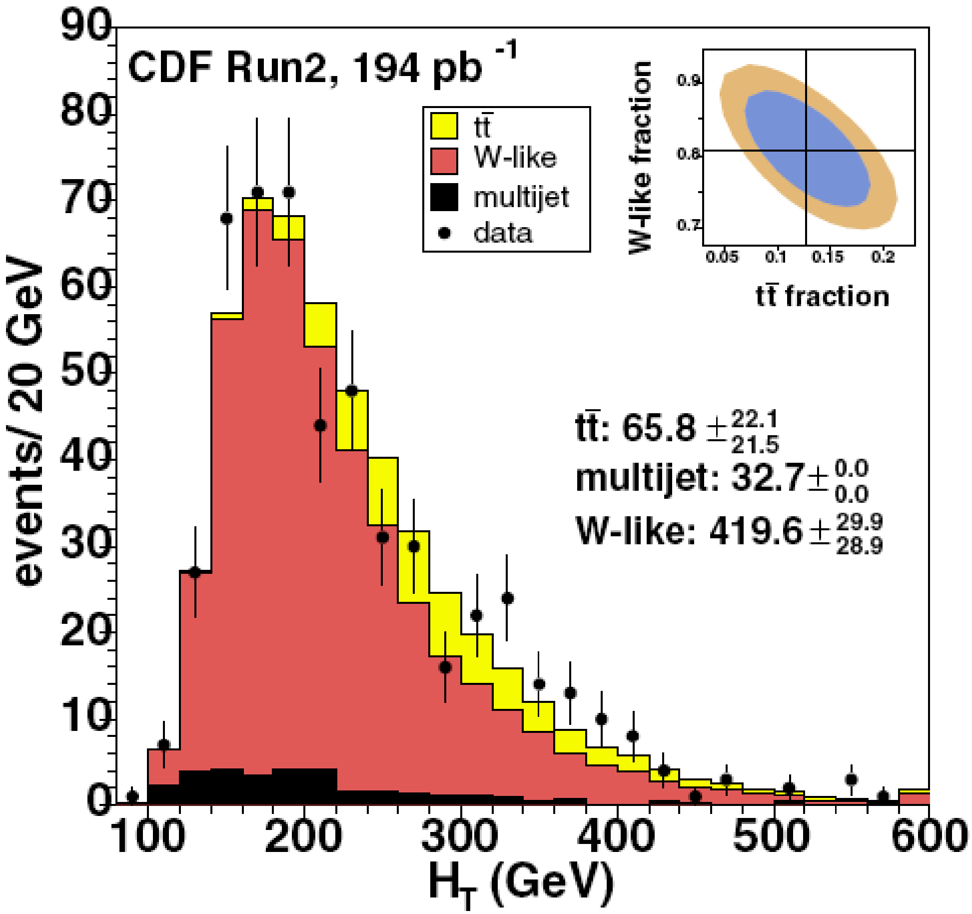
CDF

ttbar/W+jets shape comparisons for 9 more kinematic observables.

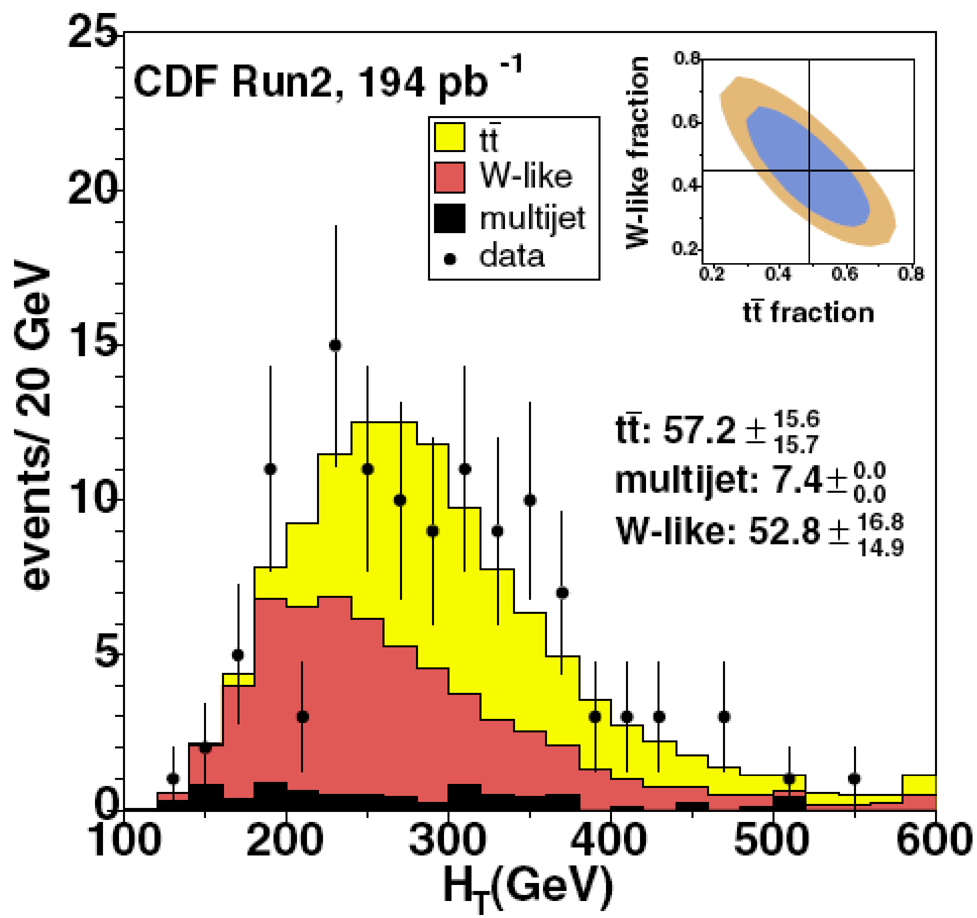
CDF



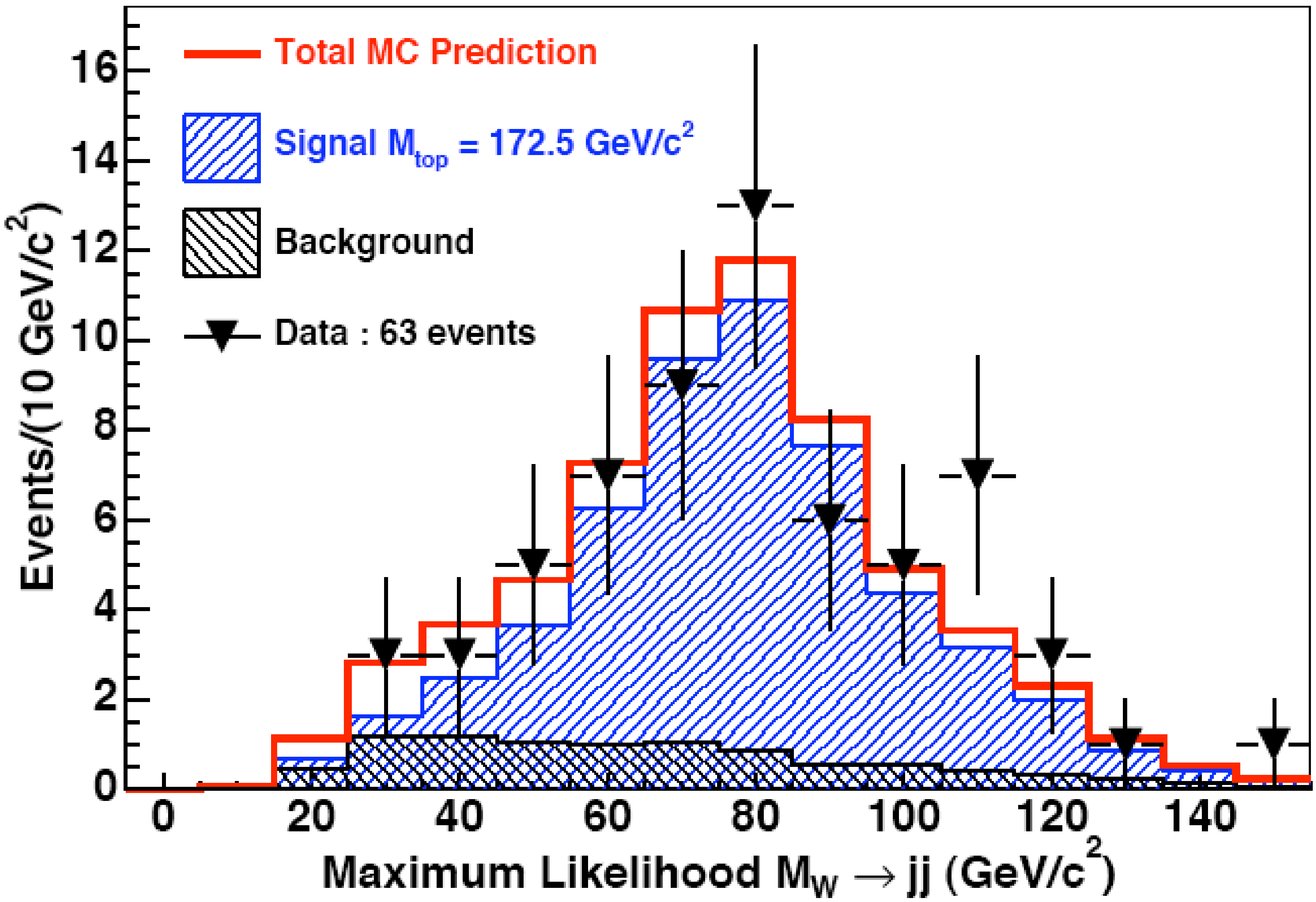
W+3 jets



W + 4 jets



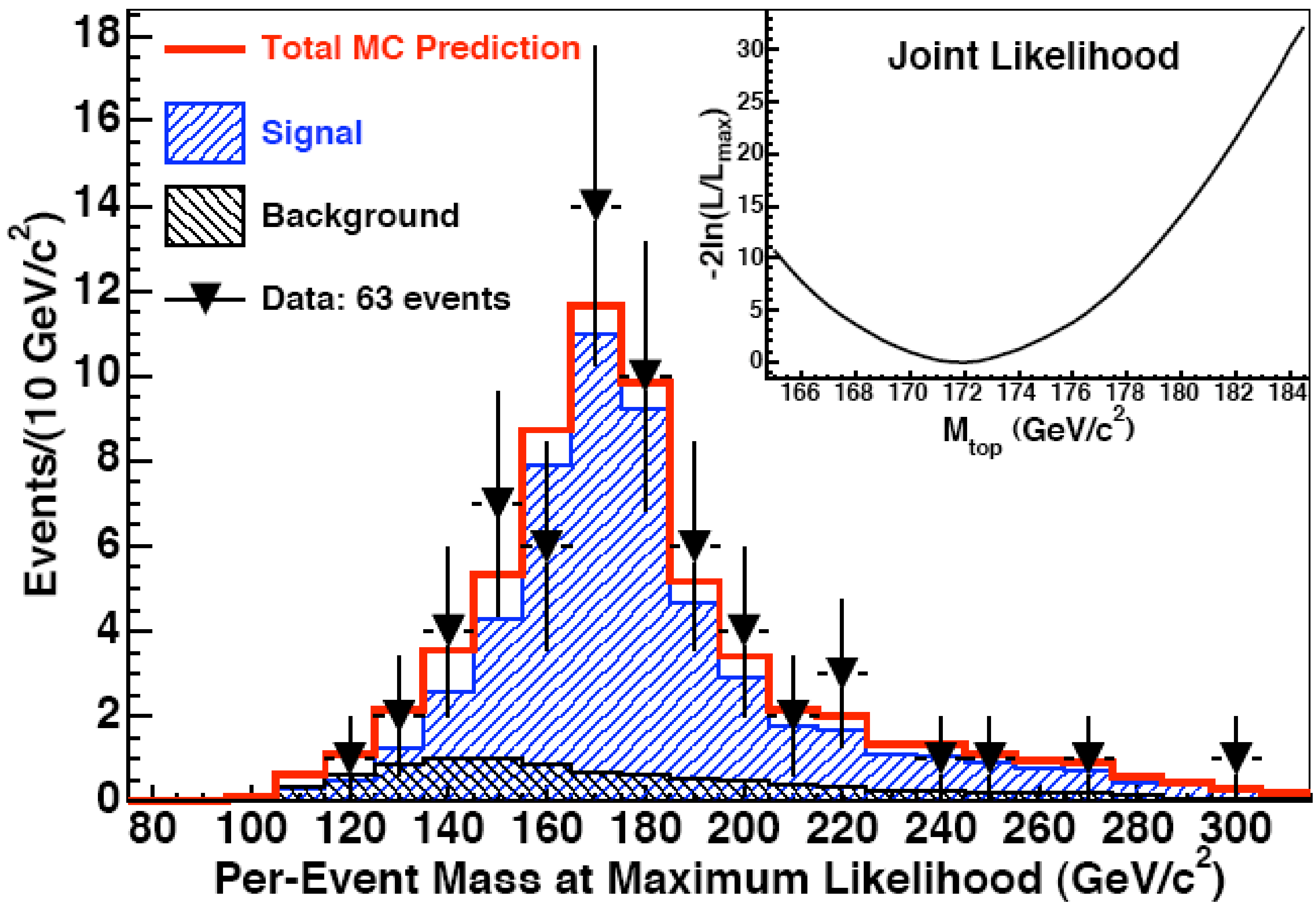
$$H_T = \not{E}_T + E_{T\ell} + \sum_i E_{Ti}$$


Total MC Prediction
Signal M_{top} = 172.5 GeV/c^2
Background
Data : 63 events
Events/(10 GeV/c^2)
Maximum Likelihood $M_W \to jj$ (GeV/c^2)
0
2
4
6
8
10
12
14
16
0
20
40
60
80
100
120
140

CDF

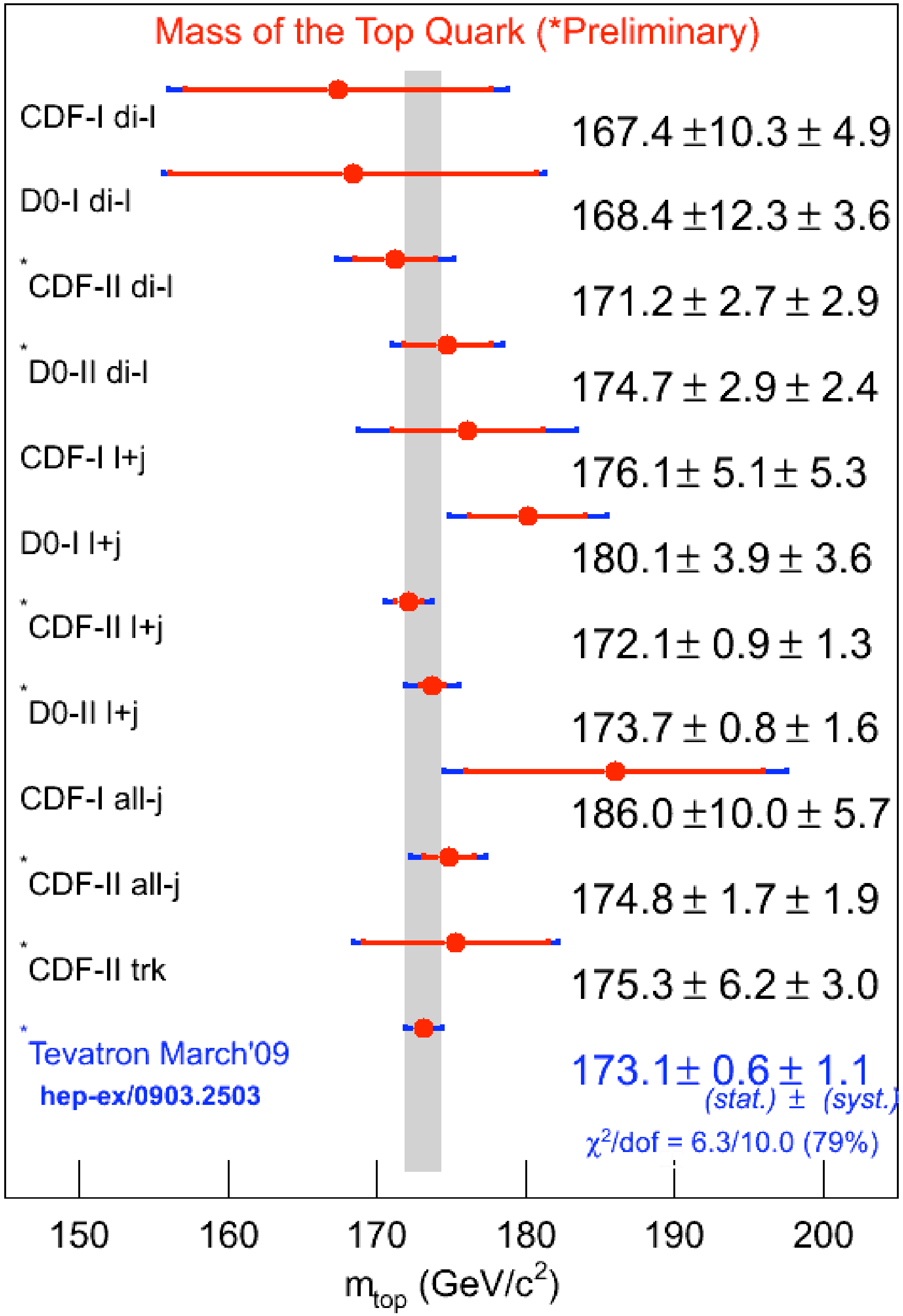
Extraction of the top quark mass from these events gives this mass with an error of 1.3 GeV (0.7%).

This is by far our most precise knowledge of any quark mass.



Total MC Prediction
Signal
Background
Data: 63 events
Events/(10 GeV/c²)
Per-Event Mass at Maximum Likelihood (GeV/c²)
Joint Likelihood
-2ln(L/Lmax)
Mtop (GeV/c²)

CDF



Mass of the Top Quark (*Preliminary)
CDF-I di-l
167.4 ±10.3 ± 4.9
D0-I di-l
168.4 ±12.3 ± 3.6
*CDF-II di-l
171.2 ± 2.7 ± 2.9
*D0-II di-l
174.7 ± 2.9 ± 2.4
CDF-I l+j
176.1 ± 5.1 ± 5.3
D0-I l+j
180.1 ± 3.9 ± 3.6
*CDF-II l+j
172.1 ± 0.9 ± 1.3
*D0-II l+j
173.7 ± 0.8 ± 1.6
CDF-I all-j
186.0 ±10.0 ± 5.7
*CDF-II all-j
174.8 ± 1.7 ± 1.9
*CDF-II trk
175.3 ± 6.2 ± 3.0
*Tevatron March'09
hep-ex/0903.2503
173.1 ± 0.6 ± 1.1
(stat.) ± (syst.)
χ^2/dof = 6.3/10.0 (79%)
150
160
170
180
190
200
m_{top} (GeV/c^2)

The dominant error is on the top quark mass is systematic: What exactly do we mean by the top quark mass in a QCD event ?

In the analyses, the top quark mass is defined to be the on-shell mass of the quark as modeled in the event simulation.

A more fundamental definition might be

$$m_{t\overline{MS}}(m_t)$$

which is directly connected to the top-Higgs coupling. This differs from the kinematic mass by about 10 GeV.

An observable quantity directly related to the short-distance mass of the top is the position of the 1S resonance. In principle, this position could be measured at the ILC, giving a measurement of the short-distance m_t to better than 100 MeV.

It is worth studying the decay distributions of the top quark in more detail.

The width of the top quark is predicted to be 1.3 GeV. Thus,

the top quark decays before it forms a hadron

The spin with which the top quark was created is preserved through to its decay.

In the decay $t \to b\ell^+\nu \; (t \to b\bar{s}c)$, the lepton (s quark) is a maximally effective spin analyzer,

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{1}{2}(1+\cos\theta_\ell)$$

where θ_ℓ is the angle between the lepton and the top spin.

There is one more important feature in the $t \to bW^+$ decay:

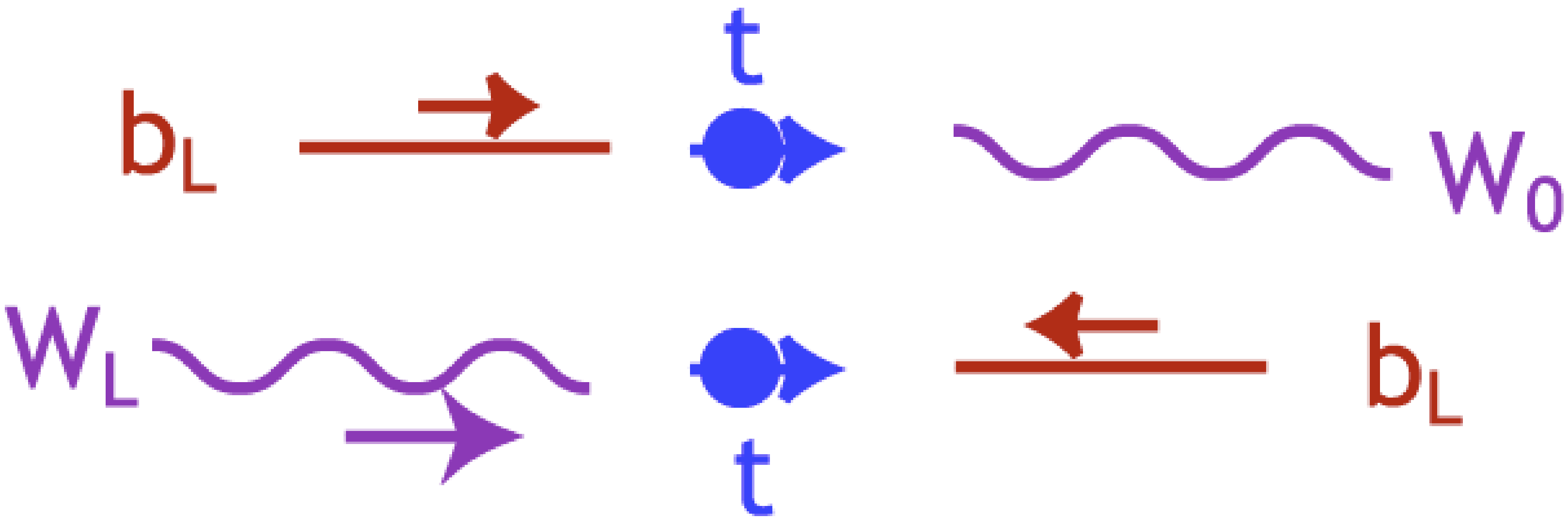
A W boson boosted along the 3 direction has the polarization vectors:

$$
\begin{aligned}
R: &\quad \frac{1}{\sqrt{2}}(0,1,i,0) &\to&\quad \frac{1}{\sqrt{2}}(0,1,i,0) \\
L: &\quad \frac{1}{\sqrt{2}}(0,1,-i,0) &\to&\quad \frac{1}{\sqrt{2}}(0,1,-i,0) \\
0: &\quad (0,0,0,1) &\to&\quad (\frac{p_W}{m_W},0,0,\frac{E_W}{m_W})
\end{aligned}
$$

The probability of emitting a longitudinally polarized W is enhanced by the factor

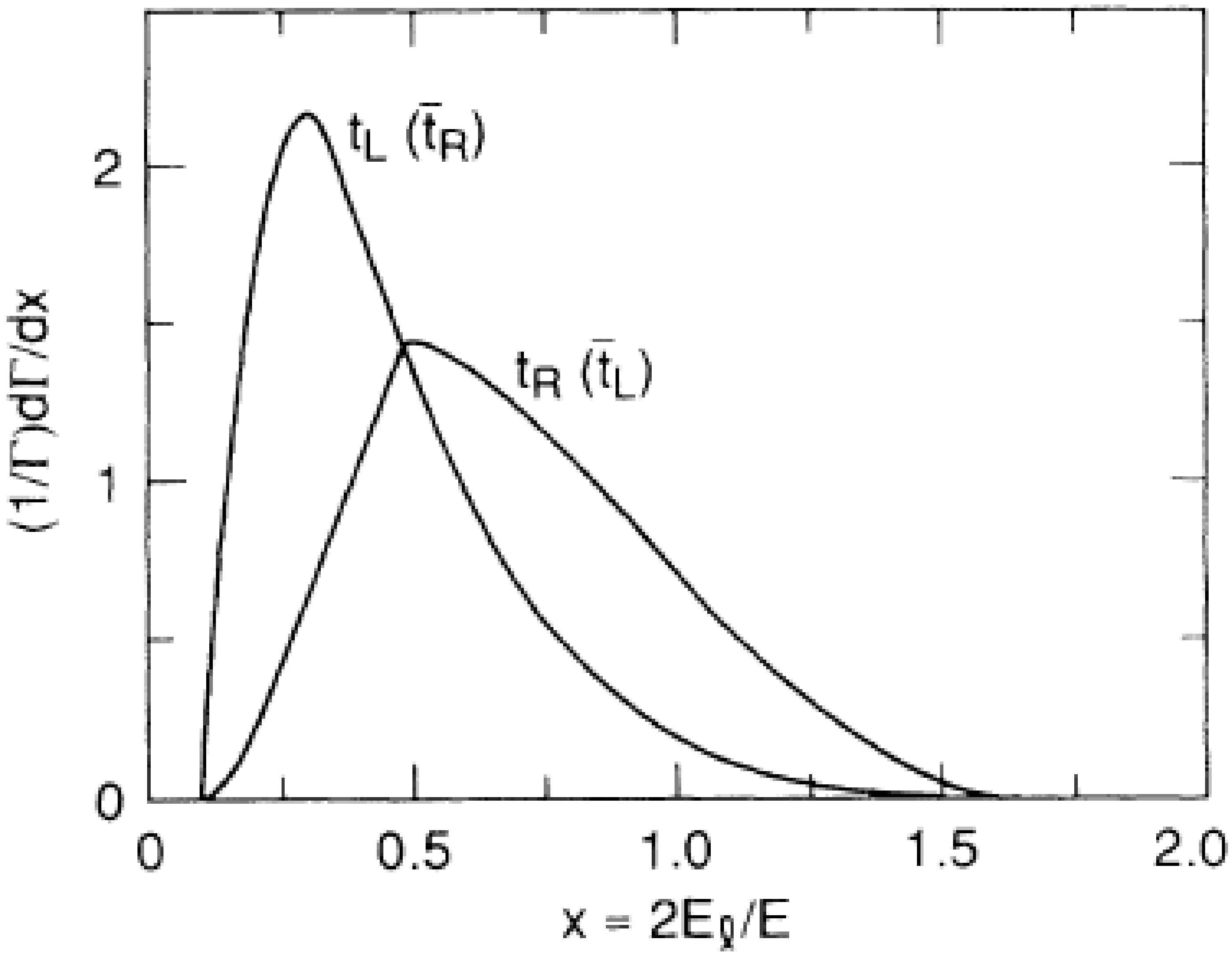
$$\frac{m_t^2}{2m_W^2}$$

Then -- if a left-handed current couples t and b -- there are two modes of t decay:



with decays to W_R forbidden by angular momentum conservation.

The probabilities are 70% / 30% .



t_L ($\bar{t}_R$)
t_R ($\bar{t}_L$)
(1/Γ)dΓ/dx
2
1
0
0
0.5
1.0
1.5
2.0
x = 2E$_\ell$/E

The dominance of decays to W_0 raises an important issue.

A massless W boson has no W_0 state. It has only transverse polarizations.

The W_0 arises through the Higgs mechanism, when the W field eats the Goldstone boson of broken SU(2).

The strong coupling of the top quark to this state -- which is a property of any Standard or non-Standard top quark coupling to vector currents -- signals the relatively strong coupling of the top quark to the Higgs sector.

Now we come to the crucial question about the nature of the top quark:

Is it an 'ordinary' quark, or is it a 'heavy' quark ?

In the Standard Model, the top quark obtains its mass from its Yukawa coupling to the Higgs boson. The strength of this coupling is

$$\frac{\lambda_t^2}{4\pi} = \frac{1}{13}$$

that is, stronger than SU(2) but weaker than asymptotically free QCD.

Can we consider this a weak coupling, making the top quark an ordinary quark ?

There are three logical possibilities,

1. The top quark is weakly coupled
   to a weakly coupled Higgs sector.

2. The top quark is weakly coupled
   to a strongly coupled Higgs sector.

3. The top quark is strongly coupled
   to a strongly coupled Higgs sector.

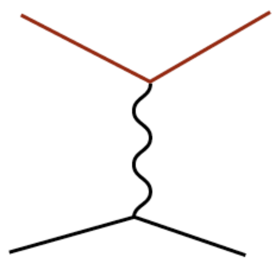
Top quark compositeness, but also Randall-Sundrum warped extra dimensions, give examples of the third possibility.

Now we have the issues on the table.

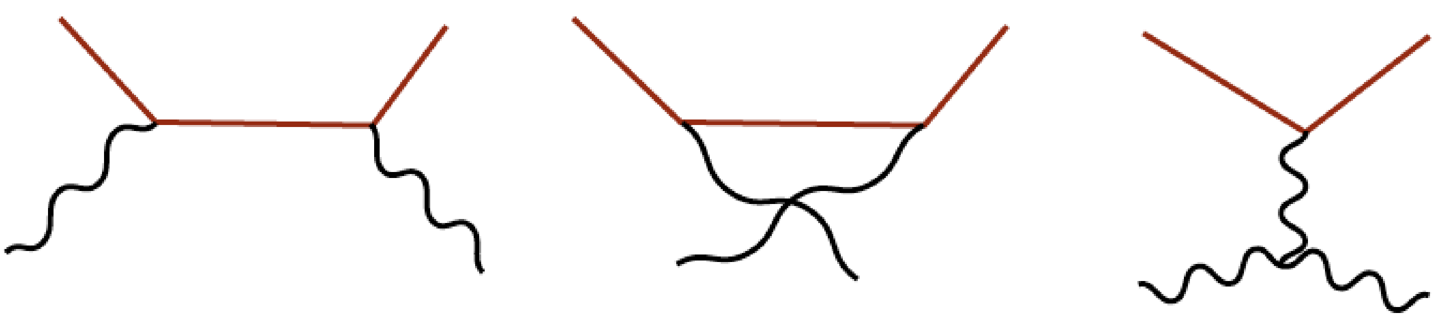
Let's discuss the top quark experiments at the LHC.

10. measurement of $\sigma(t\bar{t})$

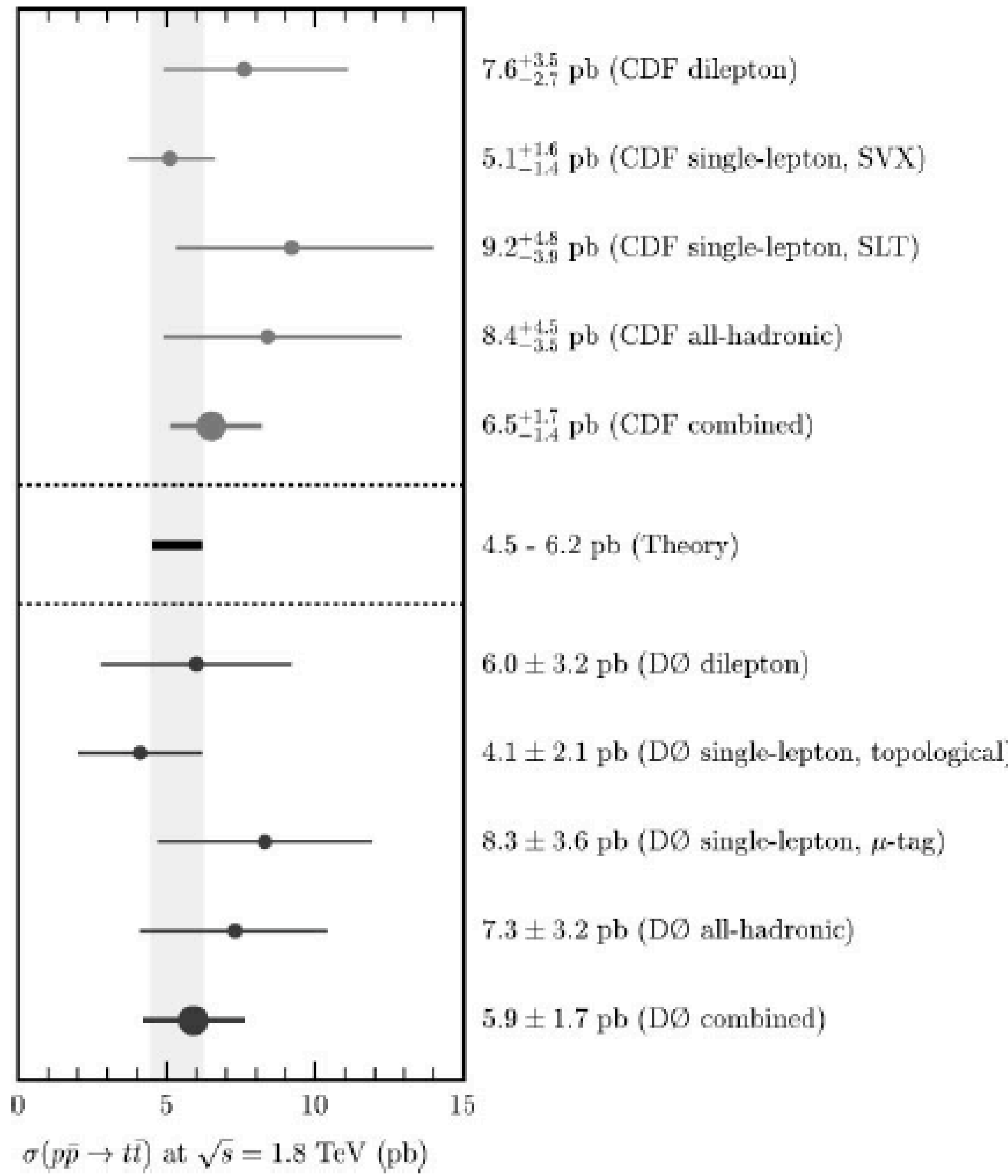
At the Tevatron, the cross section for top quark pair production is about 8 pb. At the LHC (at 14 TeV), it is expected to be about 950 pb. This reflects, first, the higher energy, but, more importantly, the crossover from quark-antiquark



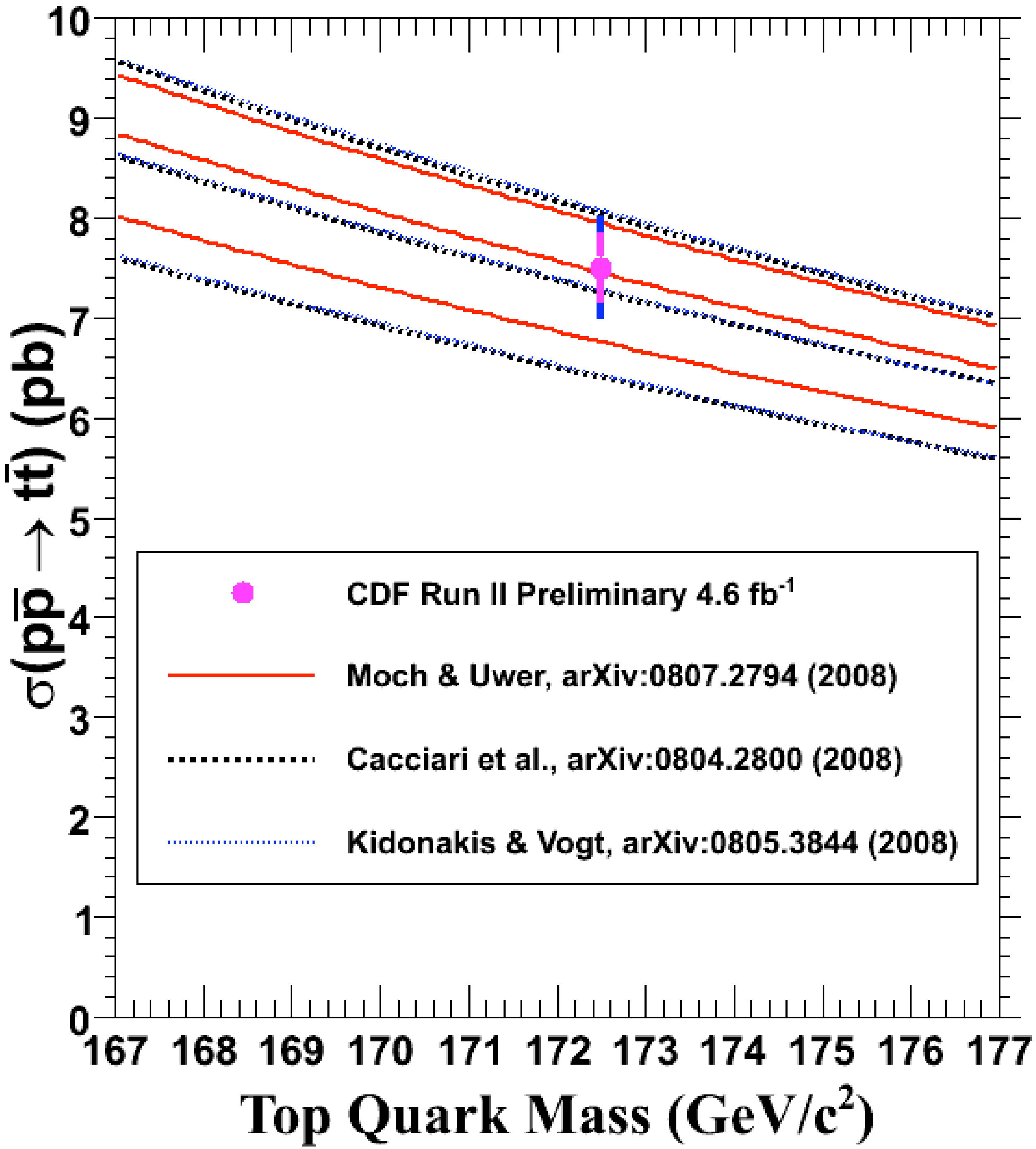
to gluon-gluon production



CDF and DO measurements of the ttbar production cross section



Chakraborty, Konigsberg, Rainwater review



10
9
8
7
6
5
4
3
2
1
0
167
168
169
170
171
172
173
174
175
176
177
Top Quark Mass (GeV/c^2)
$\sigma(p\bar{p} \rightarrow t\bar{t})$ (pb)
CDF Run II Preliminary 4.6 fb^{-1}
Moch & Uwer, arXiv:0807.2794 (2008)
Cacciari et al., arXiv:0804.2800 (2008)
Kidonakis & Vogt, arXiv:0805.3844 (2008)

Cacciari et al. (2008) top quark cross section:
LHC NLO + NLL

CTEQ 6.5	$908 \,{}^{+82}_{-85}\,{}^{+30}_{-29}$ pb
MRST 2006 NNLO	$961 \,{}^{+89}_{-91}\,{}^{+11}_{-12}$ pb

(Moch and Uwer, Kidonakis and Vogt show similar results)

The first error is the scale uncertainty, the second is propagated from the pdf errors.

The discrepancy from different pdf sets has now been settled in favor of CTEQ. The 2009 MSTW pdf set has a corrected gluon distribution (propagated from a correction to the treatment of heavy quarks) that is fairly close the the CTEQ one.

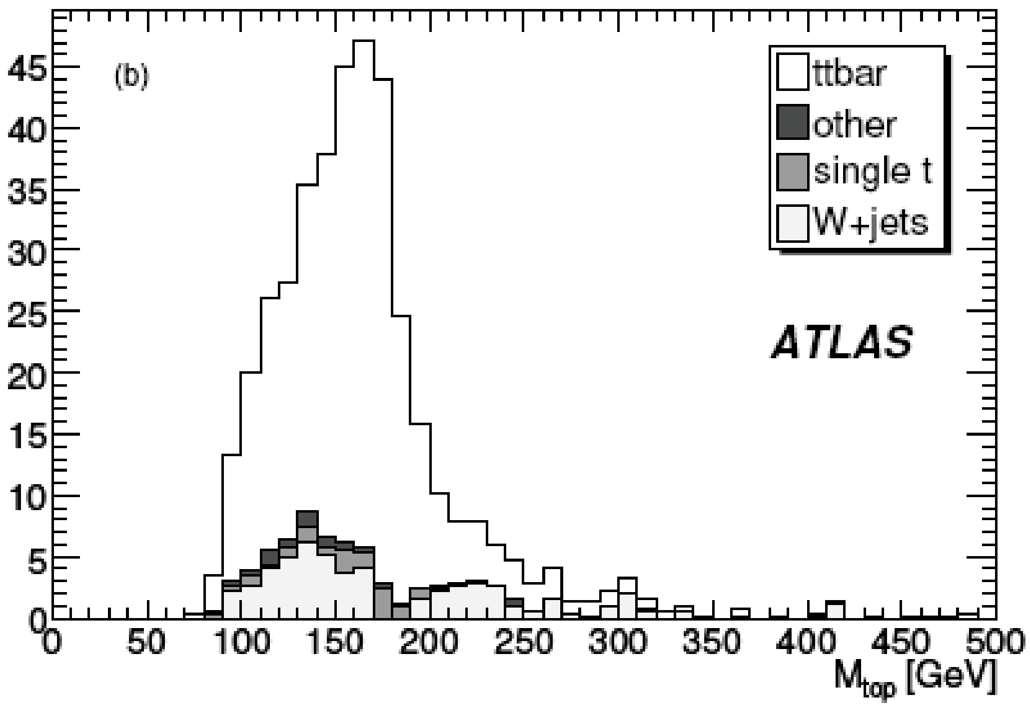
With a full NNLO calculation, the pdfs will be the dominant source of error.

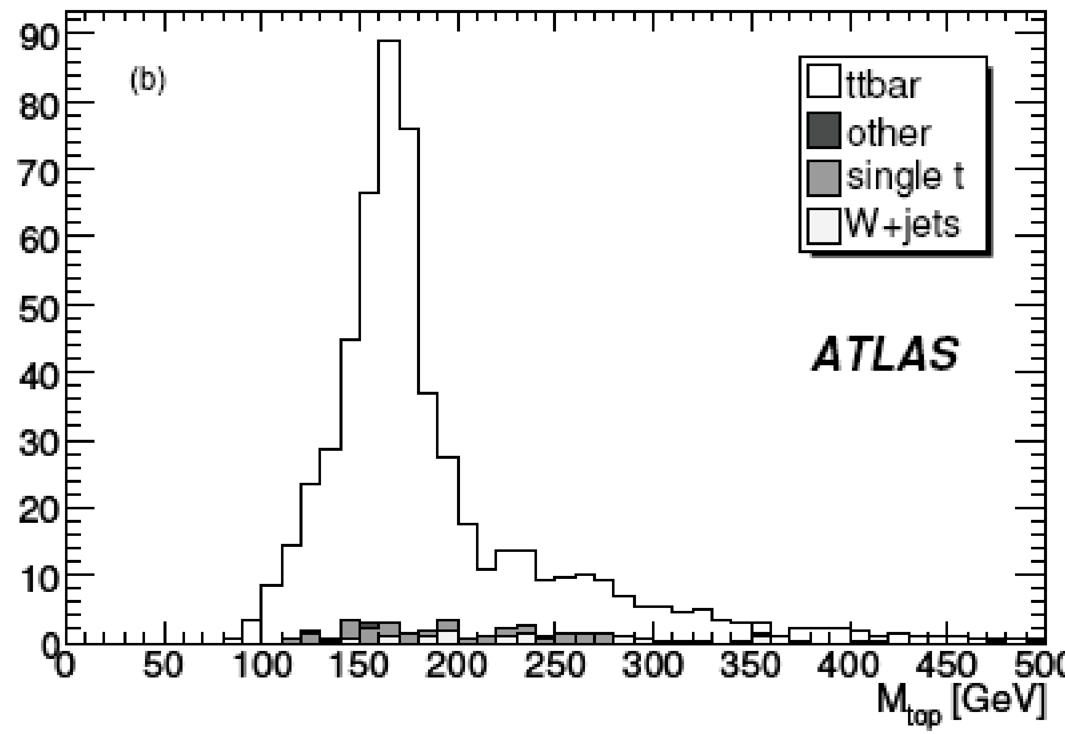
The large size of this cross section at the LHC make top quark production a more obvious process that can be found without b-tagging.

It also means that $t\bar{t} + n \text{ jet}$ backgrounds have tens of pb cross sections, constituting a very significant background to new particle searches.

Oddly, the 20/1 dominance of $gg \to t\bar{t}$ over $q\bar{q} \to t\bar{t}$ means that, even at this pp collider, top pair are produced in a CP-even, zero quantum number state.

ATLAS e + 3 jet analysis
without/with b tagging





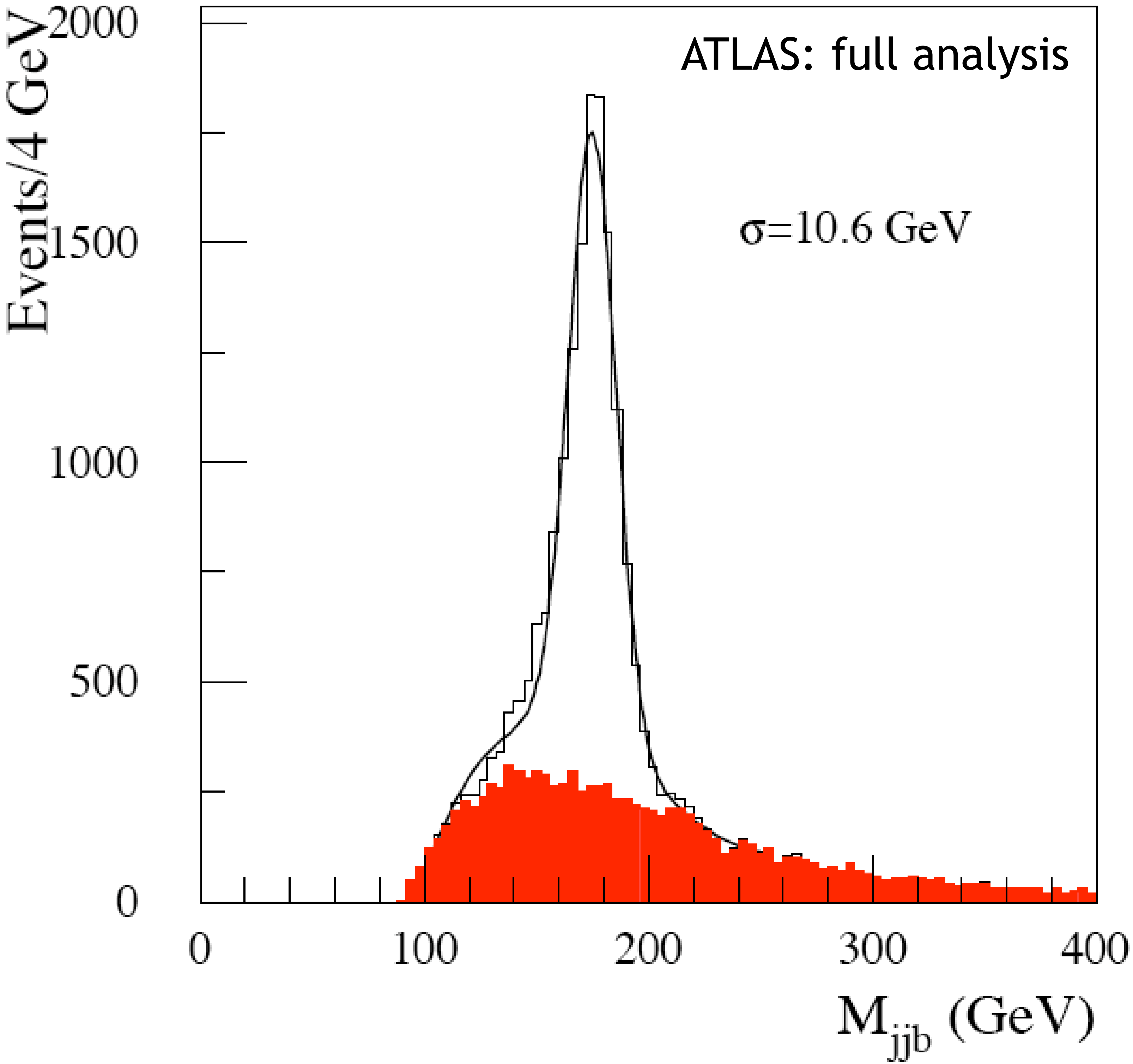
100 pb-1 at 14 TeV

9. measurement of m_t

The large cross section will allow us to collec very pure samples of top quark pairs. Measurement of jet masses in these events, with calibration to the W mass, should allow the error on m_t to be pushed below 1 GeV.

Pushing the error below 500 MeV, besides requiring heroic work on calorimetry, will require a better theoretical understanding of how the kinematic top mass used is related to a more fundamental definition of the top mass.

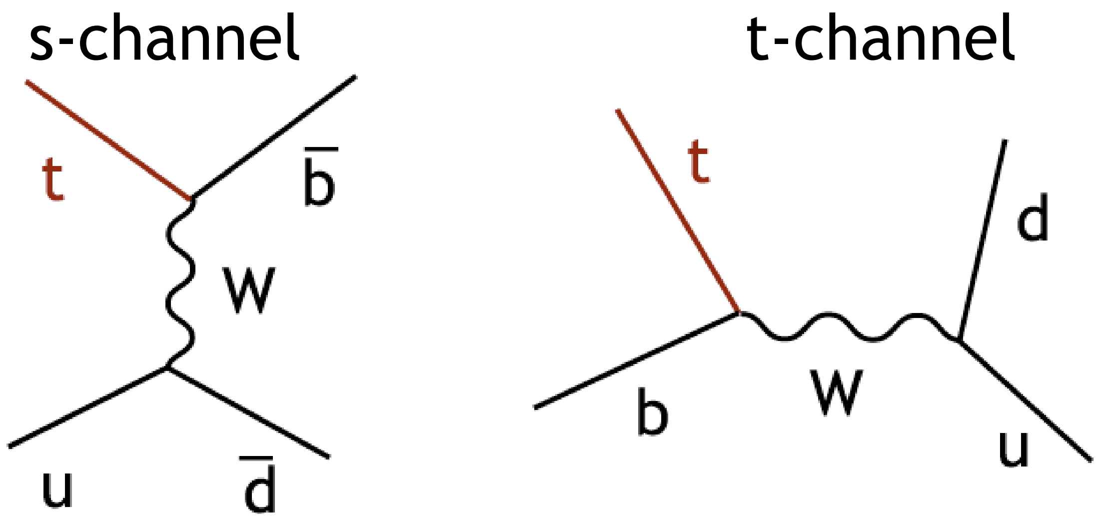
Hoang and Stewart



ATLAS: full analysis
σ=10.6 GeV
Events/4 GeV
2000
1500
1000
500
0
0
100
200
300
400
M_jjb (GeV)

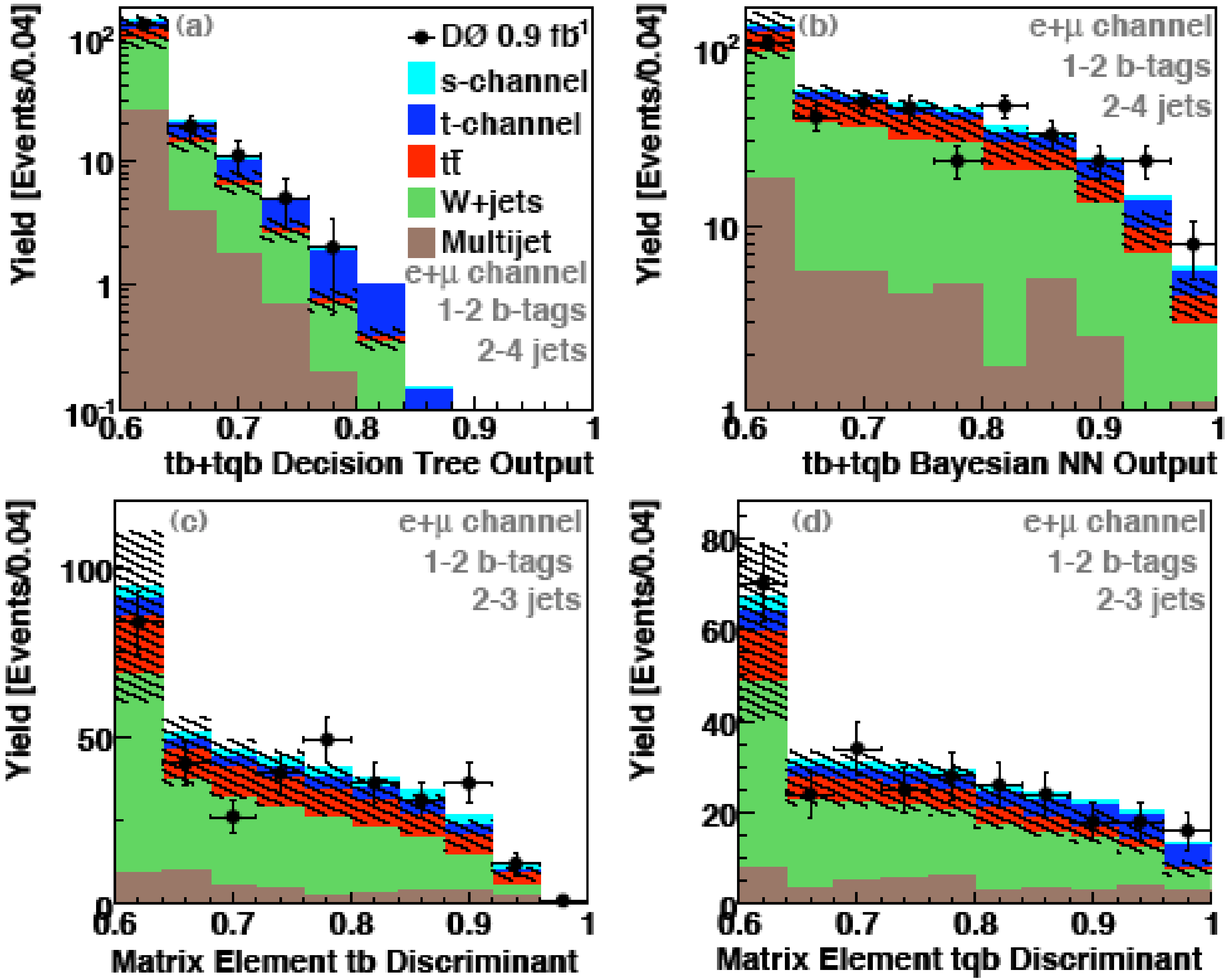
8. measurement of the single top cross section

Single top production goes through the two processes

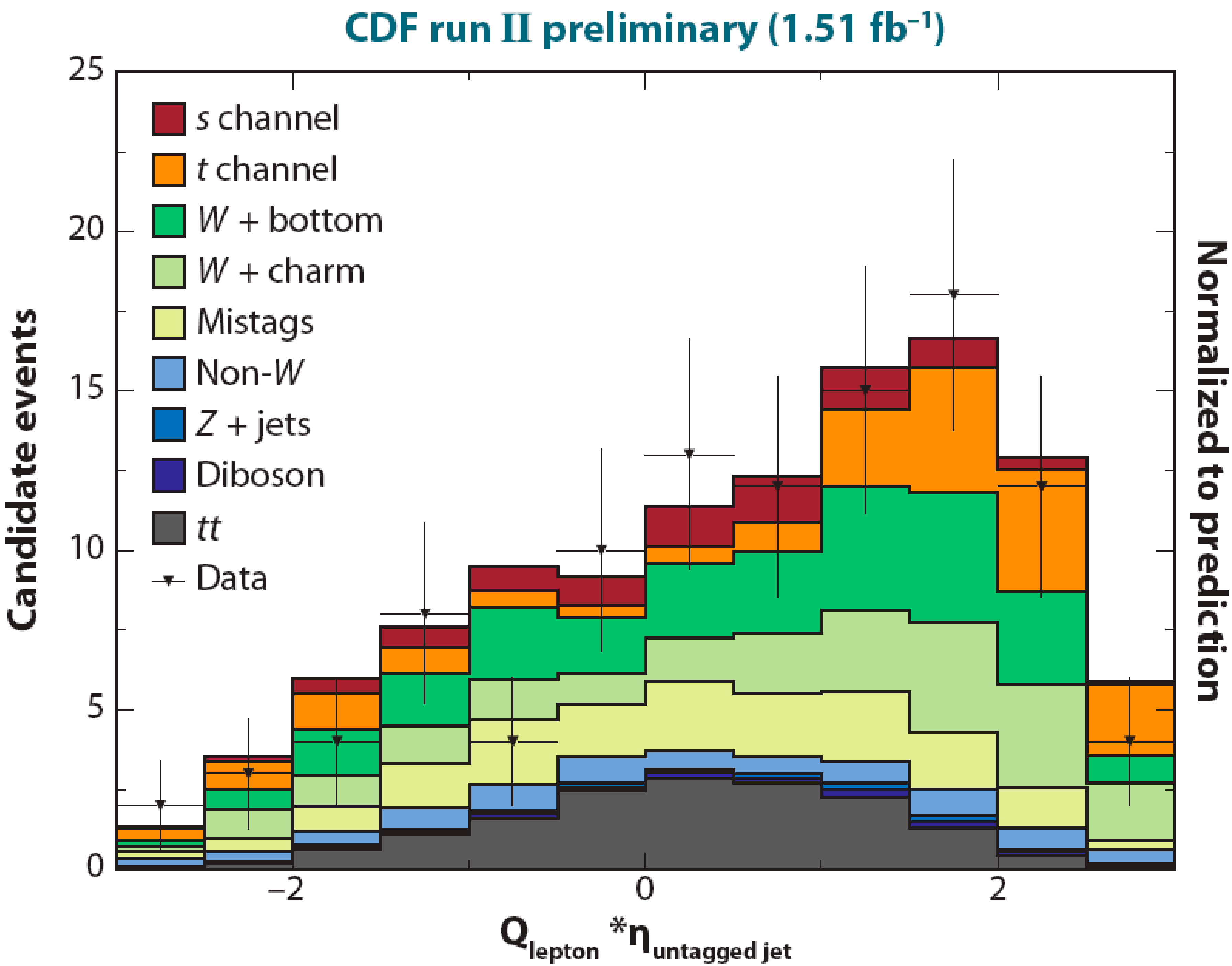


even at the Tevatron, the t-channel process is dominant. The cross sections are proportional to $|V_{tb}|^2$ and allow a measurement of this quantity.

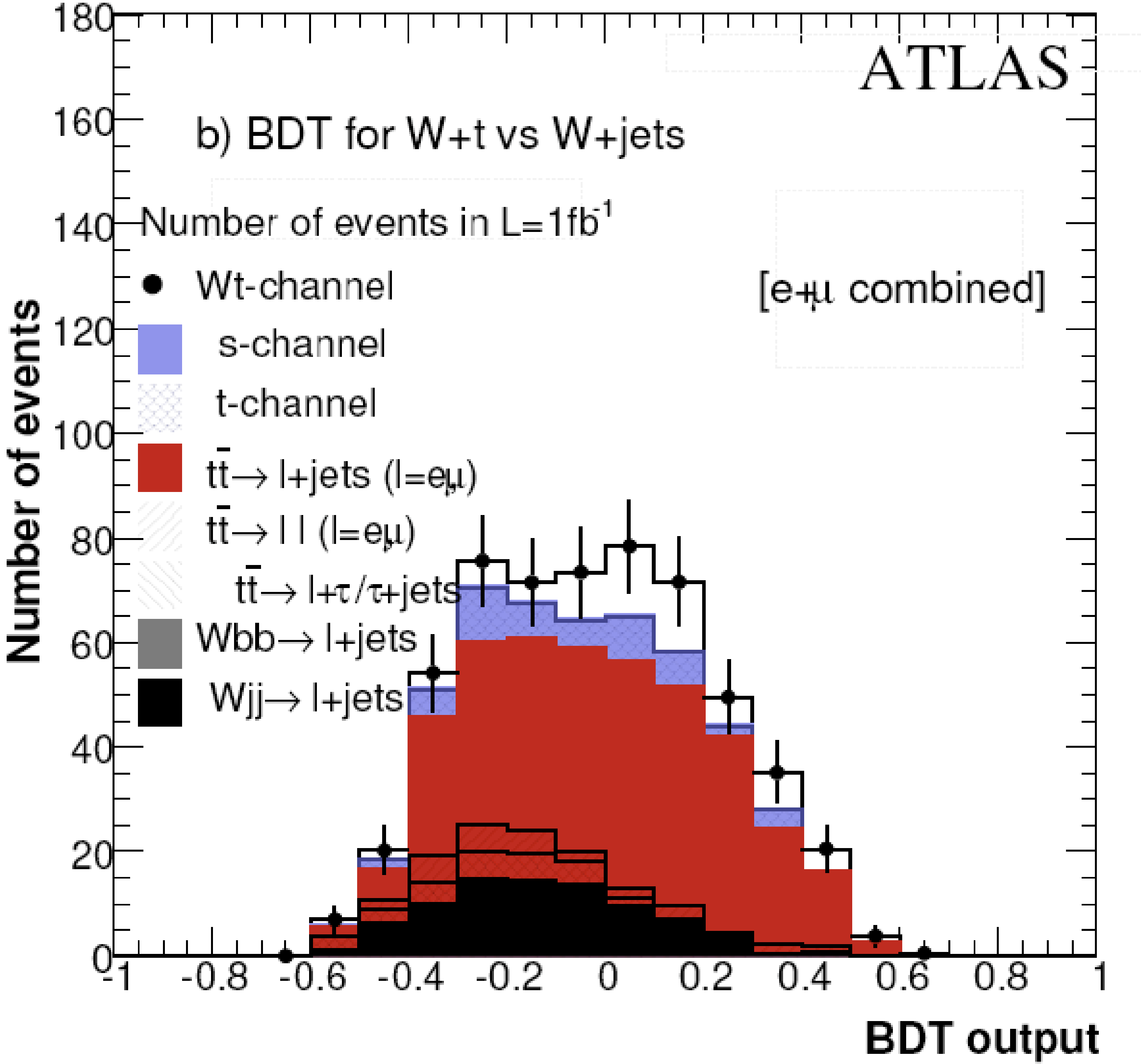
At the Tevatron, the isolation of this cross section, which is smaller than $p\overline{p} \to W + \text{jets}$ and $p\overline{p} \to t\overline{t}$ and is sandwiched between them, required a heroic effort in event discrimination.


(a)
DØ 0.9 fb^{-1}
s-chanel
t-channel
$t\bar{t}$
W+jets
Multijet
e+μ channel
1-2 b-tags
2-4 jets
Yield [Events/0.04]
tb+tqb Decision Tree Output
(b)
e+μ channel
1-2 b-tags
2-4 jets
tb+tqb Bayesian NN Output
(c)
e+μ channel
1-2 b-tags
2-3 jets
Matrix Element tb Discriminant
(d)
e+μ channel
1-2 b-tags
2-3 jets
Matrix Element tqb Discriminant

D0



CDF run II preliminary (1.51 fb⁻¹)
s channel
t channel
W + bottom
W + charm
Mistags
Non-W
Z + jets
Diboson
tt
Data
Candidate events
Normalized to prediction
Q_lepton *η_untagged jet
25
20
15
10
5
0
−2
0
2

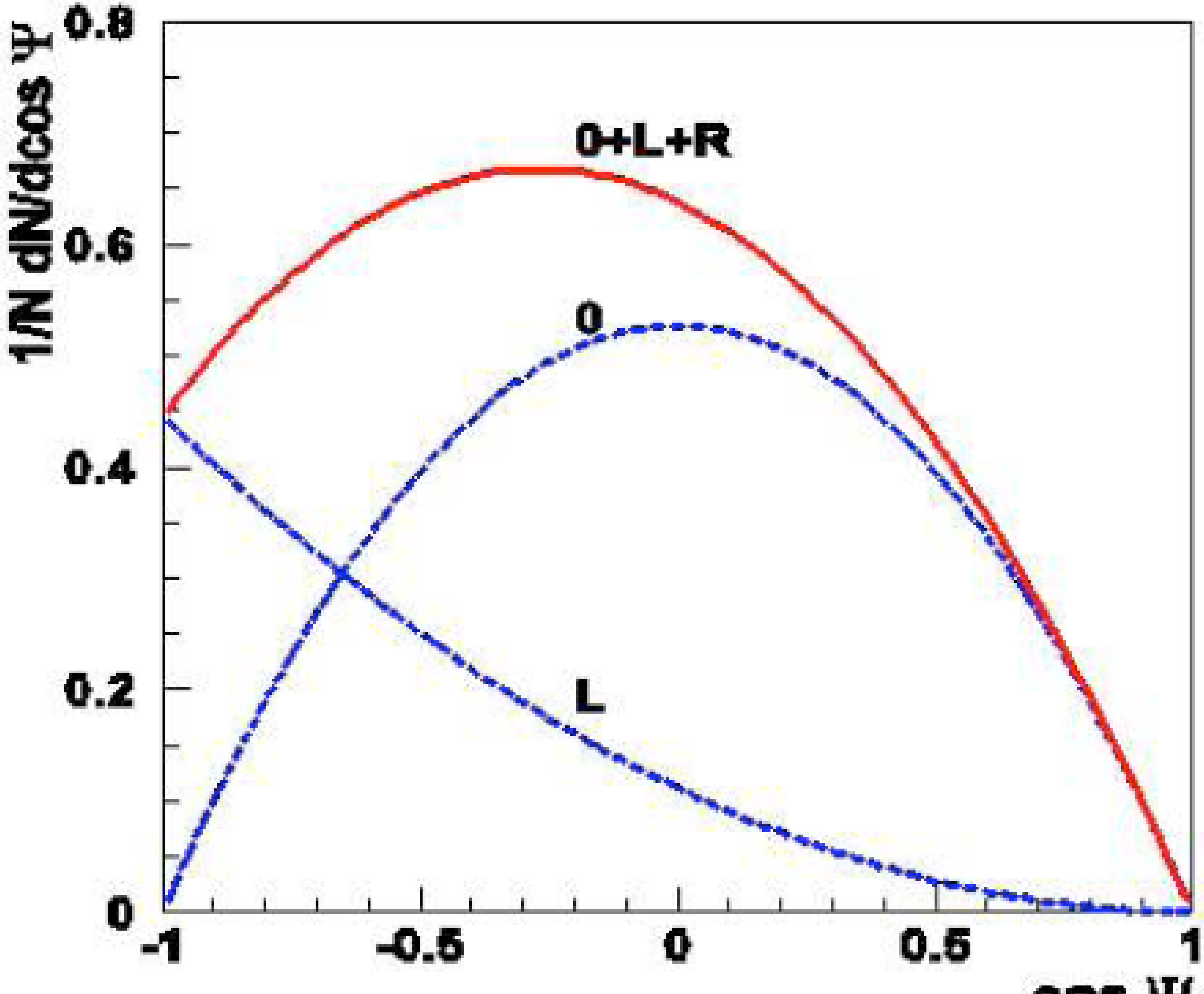

ATLAS
b) BDT for W+t vs W+jets
Number of events in L=1fb-1
Wt-channel
s-channel
t-channel
tt̄→ l+jets (l=eμ)
tt̄→ l l (l=eμ)
tt̄→ l+τ/τ+jets
Wbb→ l+jets
Wjj→ l+jets
[e+μ combined]
Number of events
BDT output
0
20
40
60
80
100
120
140
160
180
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

7. measurement of the W helicity in top decays

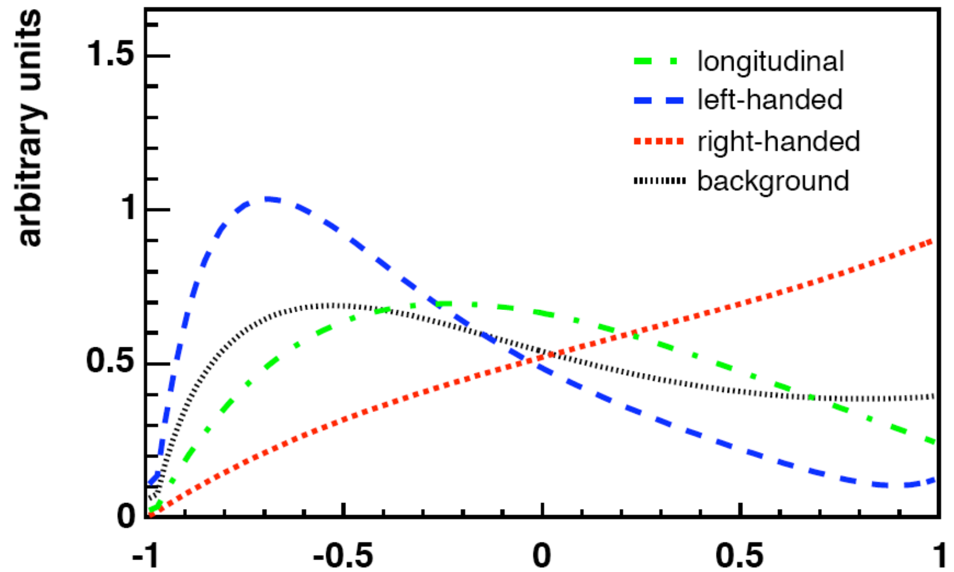
I have already discussed the physics of the W helicity in Standard Model top decays.

Enhancement of the coupling to longitudinal W bosons might be a sign of top quark compositeness or new physics in the Higgs sector.

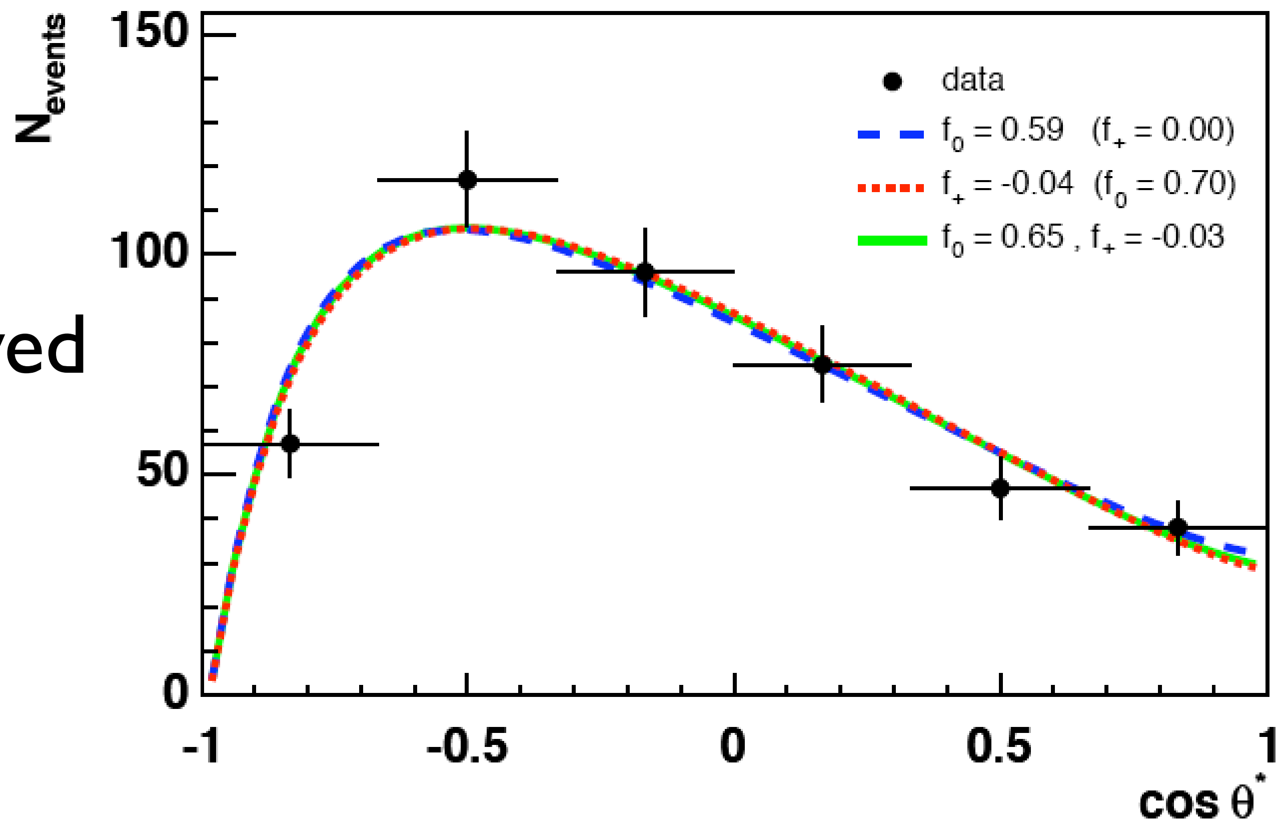
It is also important to search for possible right-handed couplings of top, which would require new heavy quarks.


1/N dN/dcos Ψ
0.8
0.6
0.4
0.2
0
0+L+R
0
L
-1
-0.5
0
0.5
1
cos Ψ

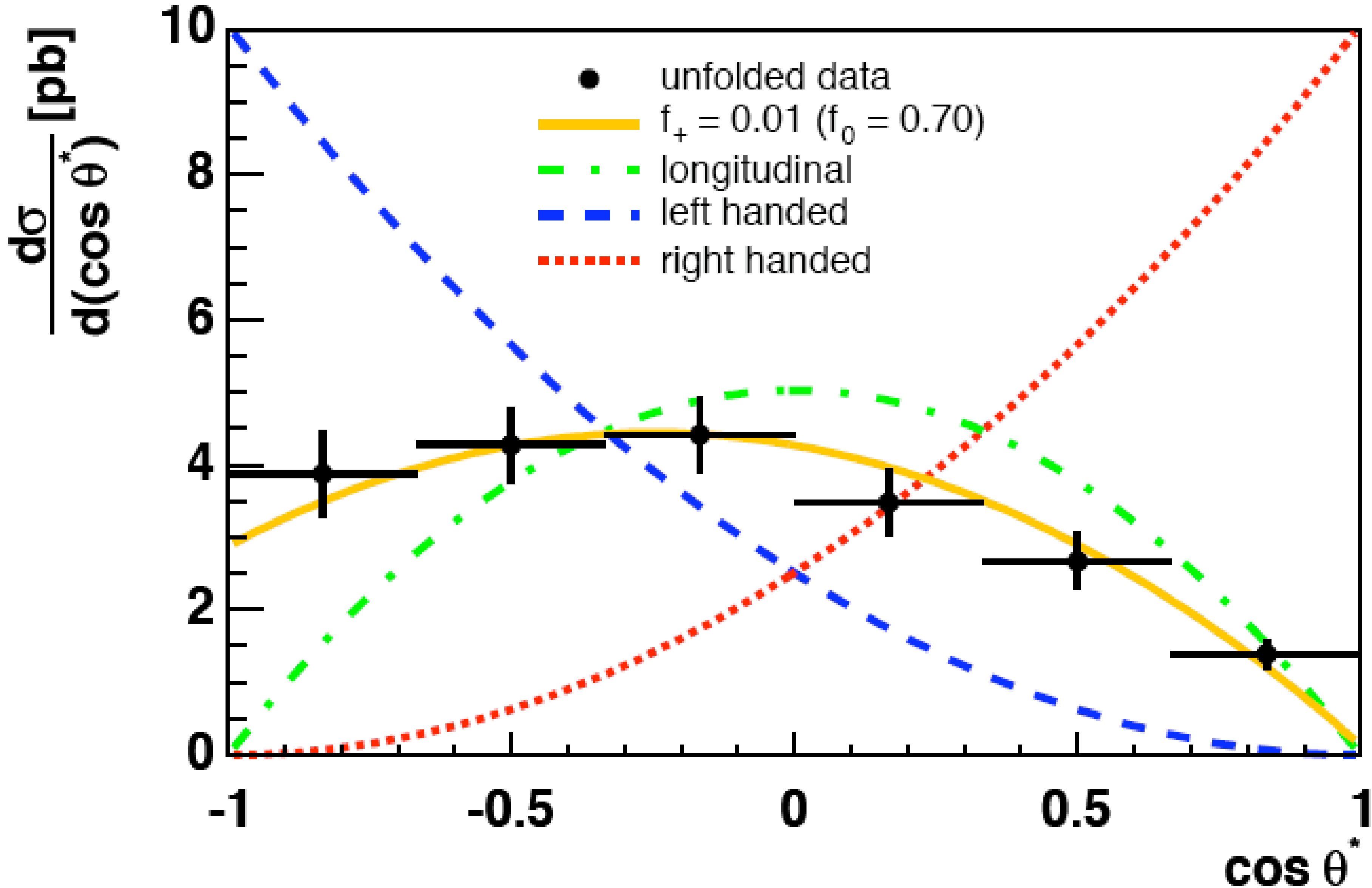
templates



observed

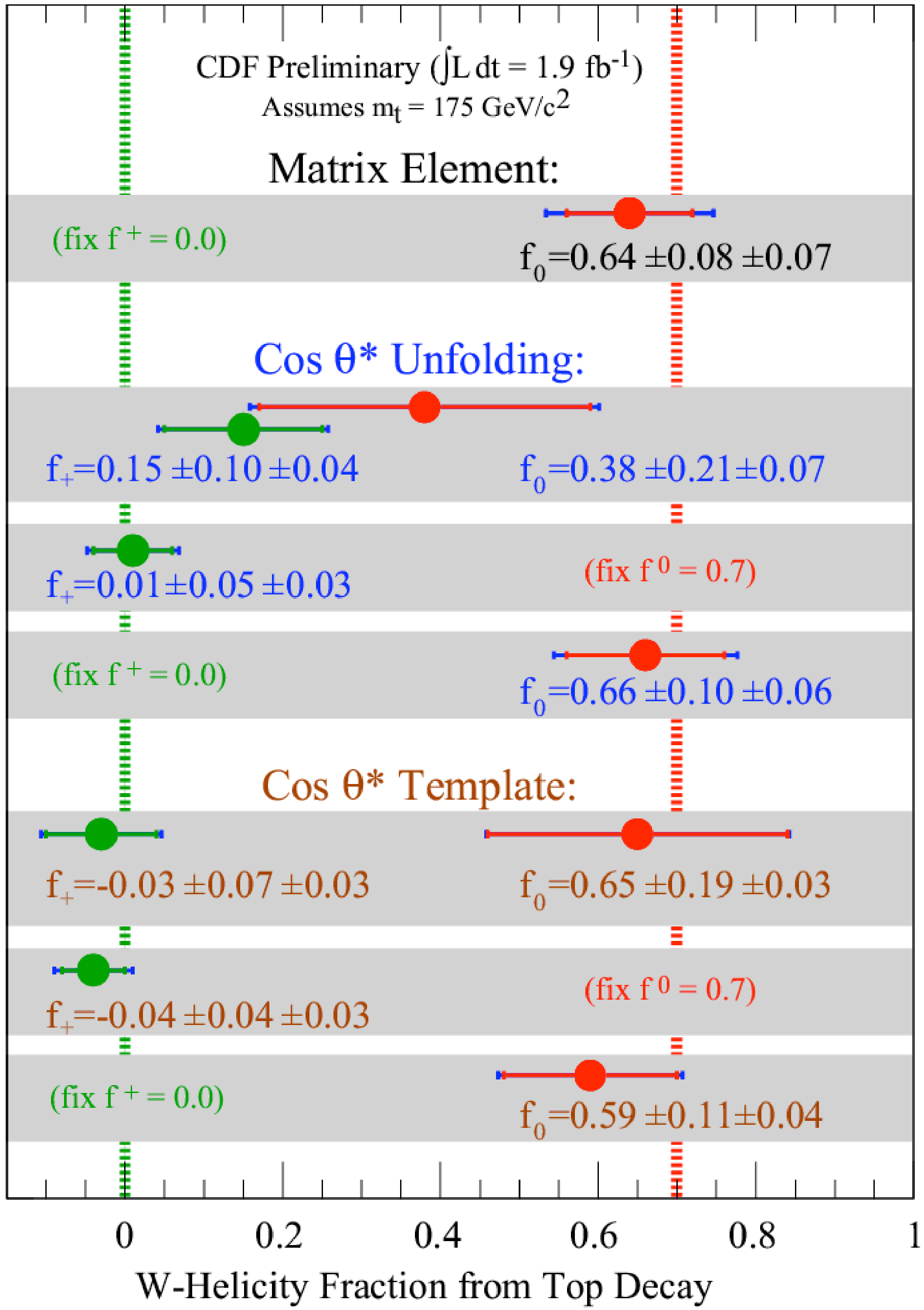


CDF

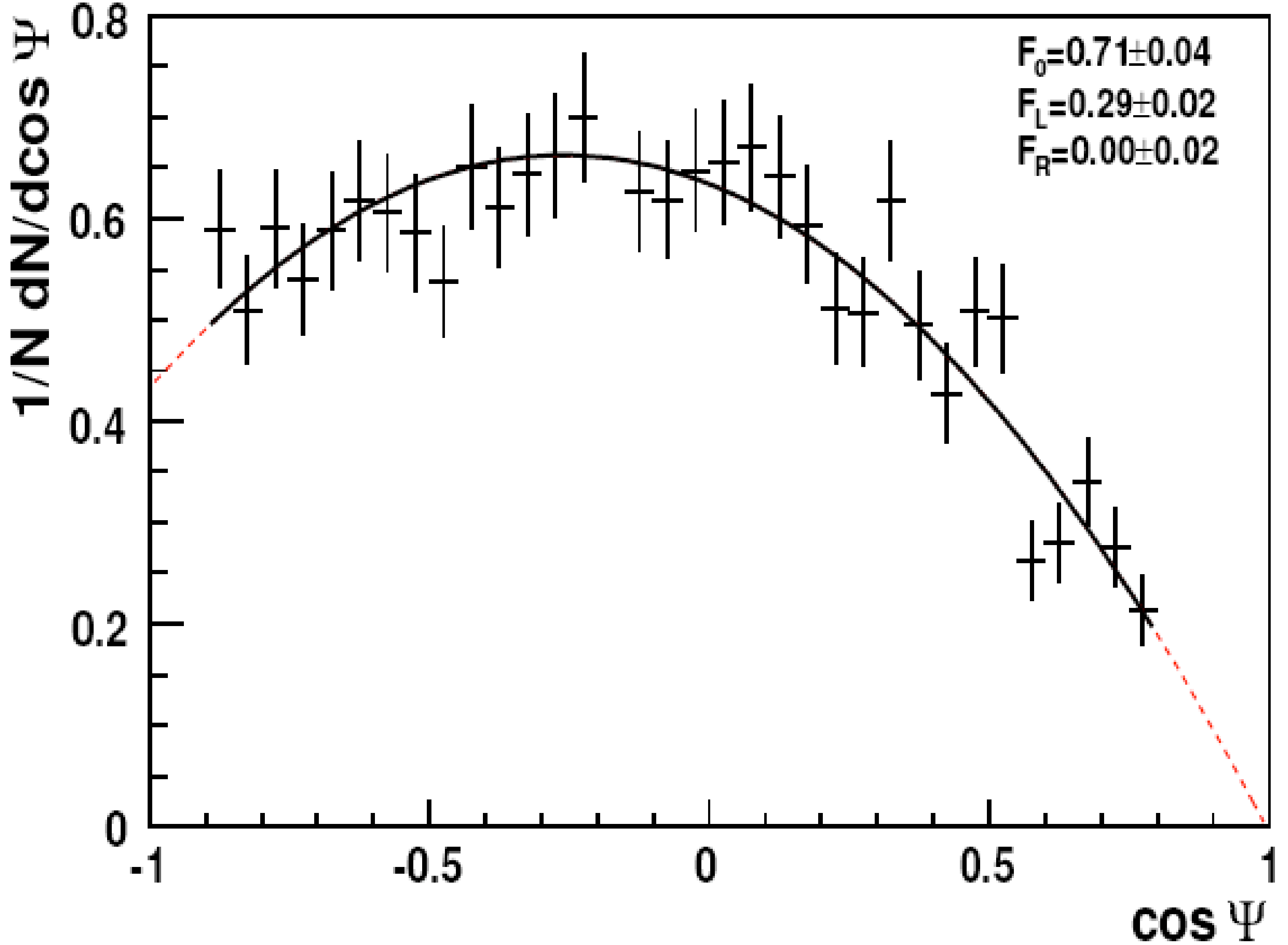


unfolded data
f+ = 0.01 (f0 = 0.70)
longitudinal
left handed
right handed
dσ / d(cos θ*) [pb]
cos θ*
0
2
4
6
8
10
-1
-0.5
0
0.5
1

CDF



CDF Preliminary (∫L dt = 1.9 fb-1)
Assumes mt = 175 GeV/c2
Matrix Element:
(fix f + = 0.0)
f0=0.64 ±0.08 ±0.07
Cos θ* Unfolding:
f+=0.15 ±0.10 ±0.04
f0=0.38 ±0.21±0.07
f+=0.01±0.05 ±0.03
(fix f 0 = 0.7)
(fix f + = 0.0)
f0=0.66 ±0.10 ±0.06
Cos θ* Template:
f+=-0.03 ±0.07 ±0.03
f0=0.65 ±0.19 ±0.03
f+=-0.04 ±0.04 ±0.03
(fix f 0 = 0.7)
(fix f + = 0.0)
f0=0.59 ±0.11±0.04
0
0.2
0.4
0.6
0.8
1
W-Helicity Fraction from Top Decay



ATLAS expectation

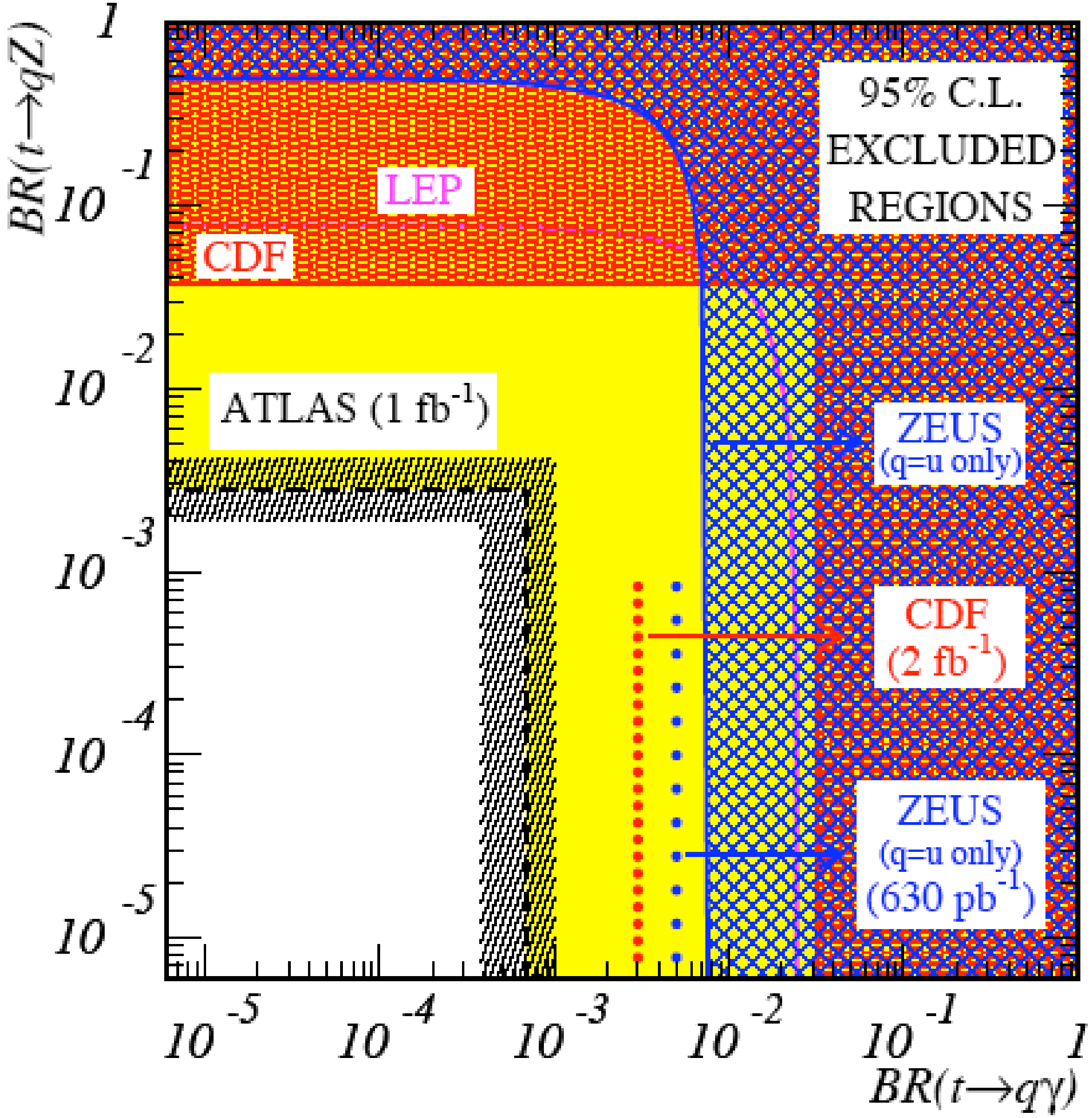
6. search for $t \to c\gamma$, $t \to cZ$

In the Standard Model, the expectation for branching ratios of these flavor-changing neutral current decay is

$$BR < 10^{-12}$$

However, these decays might be induced by new sources of flavor violation, from supersymmetry or other heavy sectors. The Tevatron constraints are relatively weak.

Studies for the LHC claim a sensitivity at the 10^{-3} level. With charm tagging, can't one do better ?



95% C.L.
EXCLUDED
REGIONS
LEP
CDF
ATLAS (1 fb^{-1})
ZEUS
(q=u only)
CDF
(2 fb^{-1})
ZEUS
(q=u only)
(630 pb^{-1})
$BR(t\to qZ)$
$BR(t\to q\gamma)$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

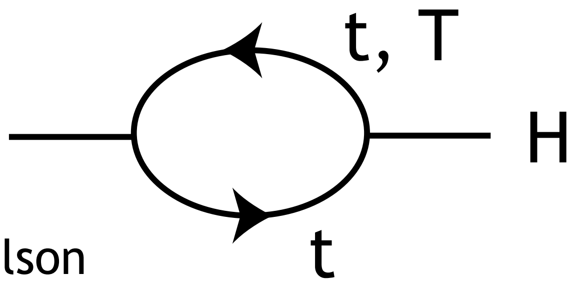
5. search for supersymmetry through $\widetilde{t}\ ,\widetilde{b} \rightarrow t + \not{E}_T$

In models of supersymmetry or extra dimensions, the top quark has partners in the new physics sector. In these models, the top quark is a weakly-coupled, Standard Model particle. However, the new particles with the quantum numbers of the top play a crucial role in the theory.

Even the weakly coupled top is more strongly coupled to the Higgs sector than any other Standard Model particle. The top partners share this coupling. Thus, diagrams with top partners can dominate the radiative corrections to the Higgs potential.

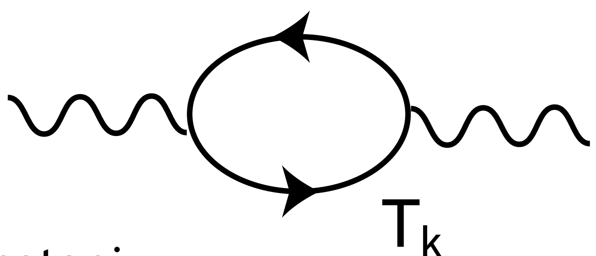
In many cases, these particles have specific effects that generate a negative Higgs mass-squared.

In Little Higgs models, the loop corrections due to the top quark and its partner cancel with a negative residue.



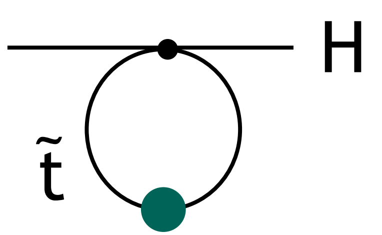
Katz-Nelson

In extra-dimensional models, the Kaluza-Klein excitations of the top quark give a symmetry-breaking potential for A^5



Hosotani

In supersymmetry, the renormalization of masses by the top quark-Higgs coupling gives a negative correction.



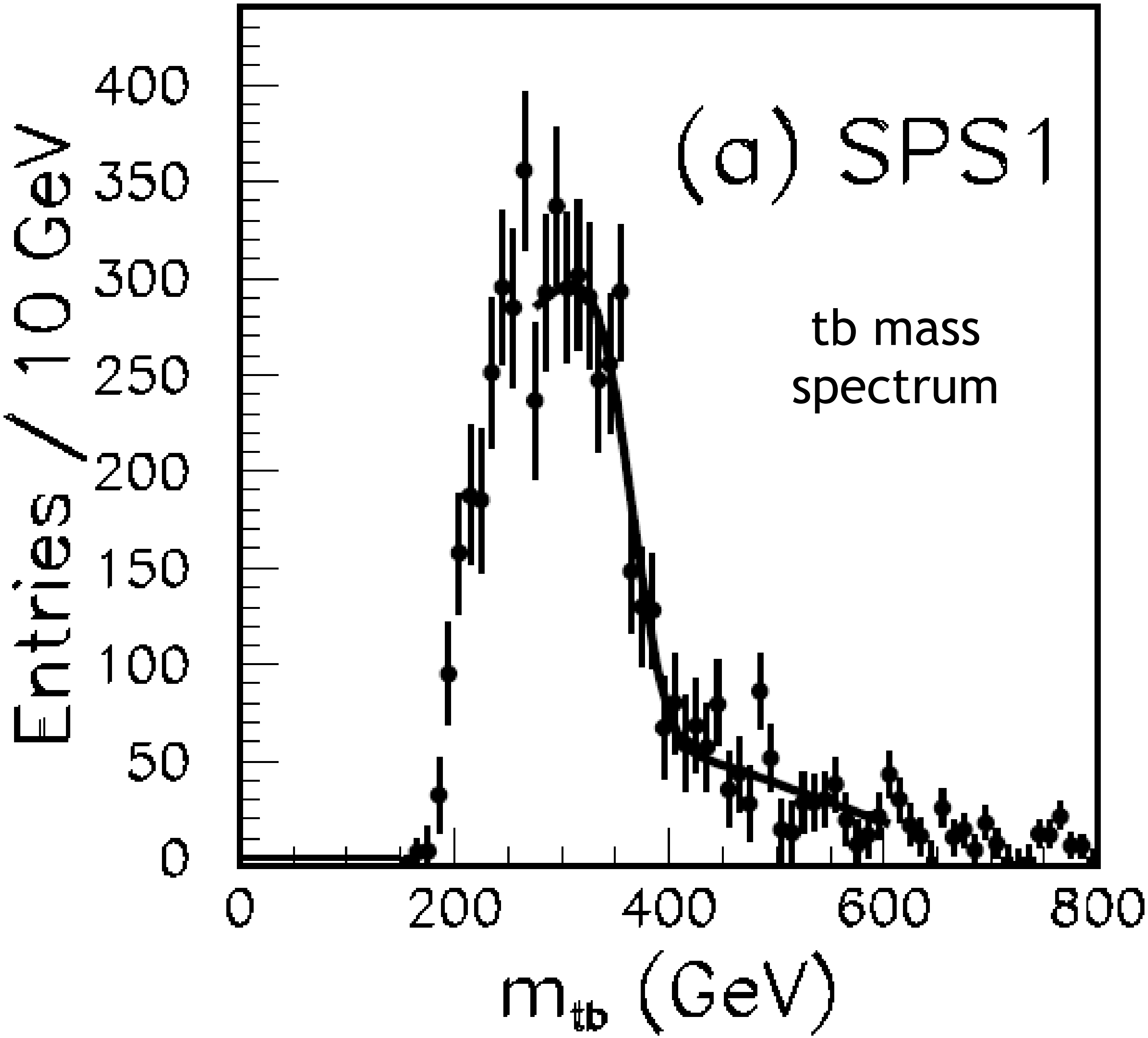
Ibanez-Ross-Alvarez-Gaume-Polchinski-Wise

The top partners decay to top if this is kinematically allowed.

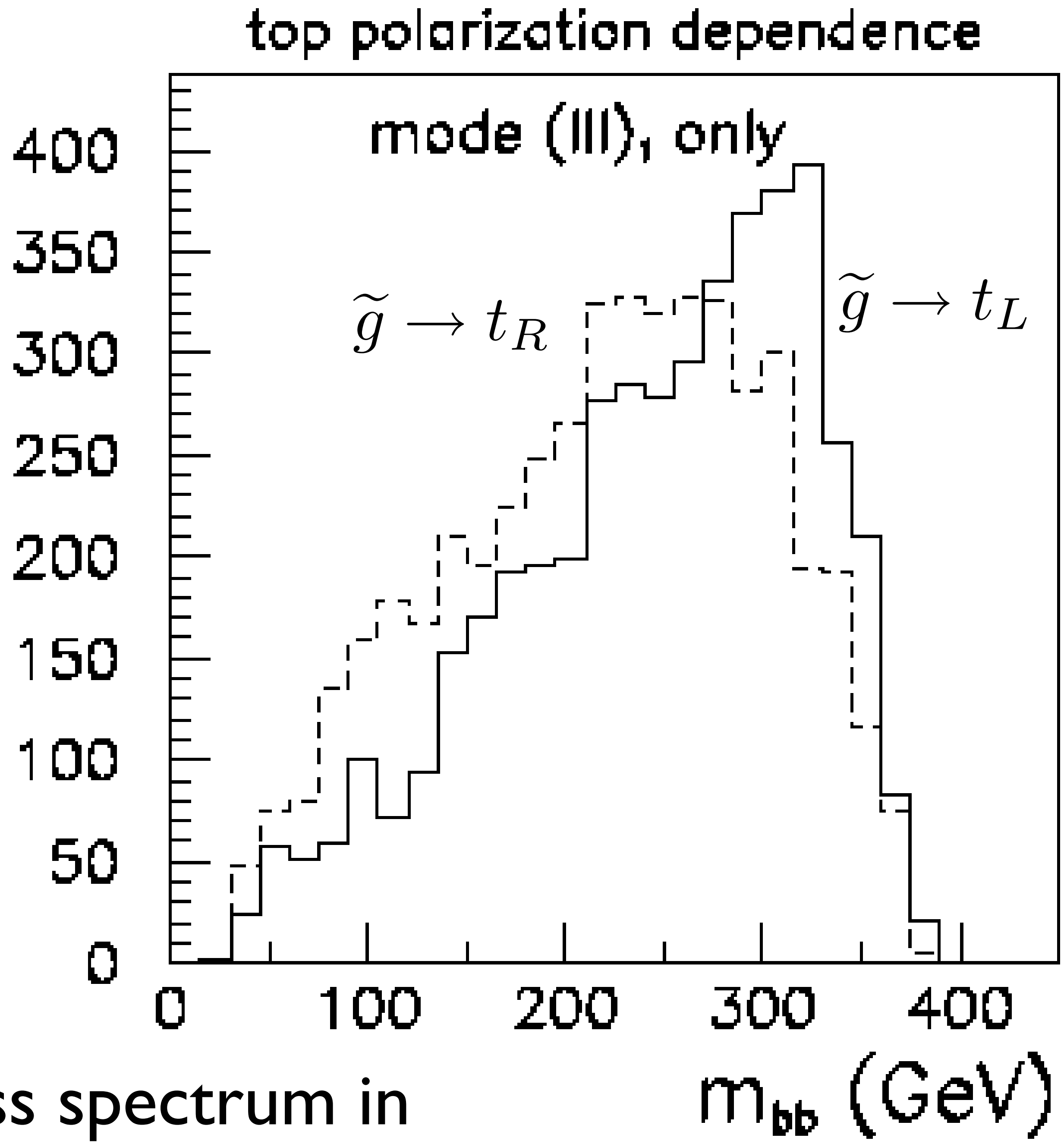
A typical production and decay pattern is

$$pp \to \widetilde{g}\widetilde{g} \ , \ \widetilde{g} \to \widetilde{t}\bar{t} \to b\chi^+\bar{t}$$

If there are on-shell tops in the final state, we can use our knowledge of the polarization dynamics of top quark decay to analyze the couplings of the top partners.



Hisano, Kawagoe, Nojiri



bb mass spectrum in
$\widetilde{g} \to t\bar{b}\chi^- \to b\bar{b} + X$

Hisano, Kawagoe, Nojiri

4. search for $T \to t + Z, h \ , \ T \to bW$

Consider next models of top compositeness and strong interactions. From precision electroweak measurements -- in particular, to agreement of $\Gamma(Z^0 \to b\bar{b})$ with the Standard Model prediction to 0.5% accuracy -- we suspect that the multiplets

$$(t_L, b_L) \ , \ b_R$$

are elementary. We still need to cancel the SU(3)xU(1) anomalies of this multiplet. The simplest way is to have t_R strongly interacting with another vector-like U(1) singlet quark T. Naturally t and T mix.

This structure is found, for example, in the simplest little Higgs models.

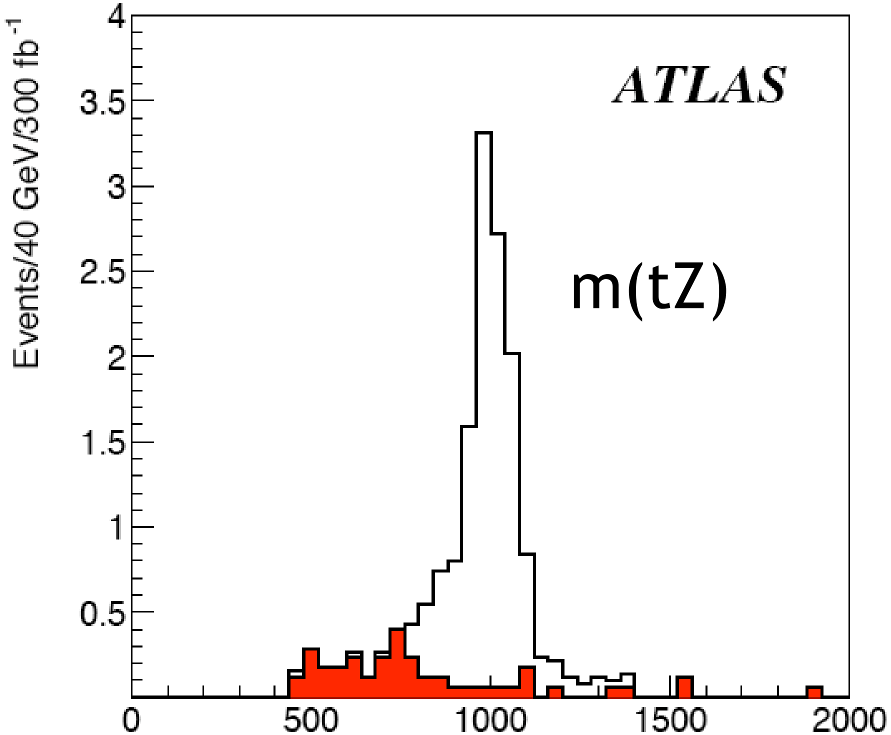
Then the coupling of $(t_R, T_R) \cdot \bar{t}_L$ through the Higgs or electroweak symmetry breaking induces the couplings

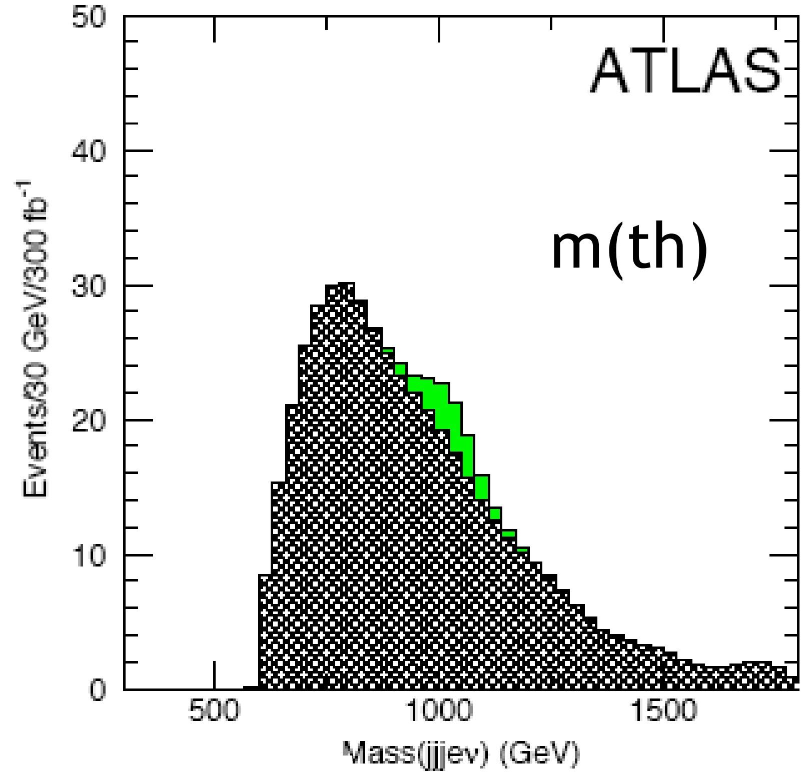
$$T \to t_L h^0 \;,\; T \to t_L \pi^0 \;,\; T \to b_L \pi^+$$

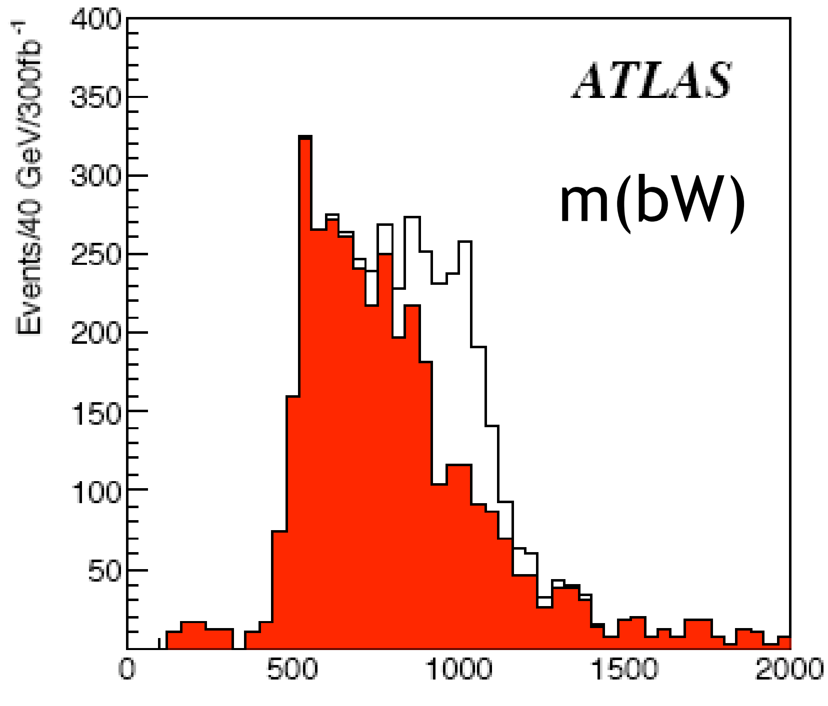
After the Goldstone bosons are eaten in the Higgs mechanism, these decays become

$$T \to t h^0 \;,\; T \to t Z^0 \;,\; T \to b W^+$$

with braching ratios 25%, 25%, 50% up to phase space.







Azuelos et al.

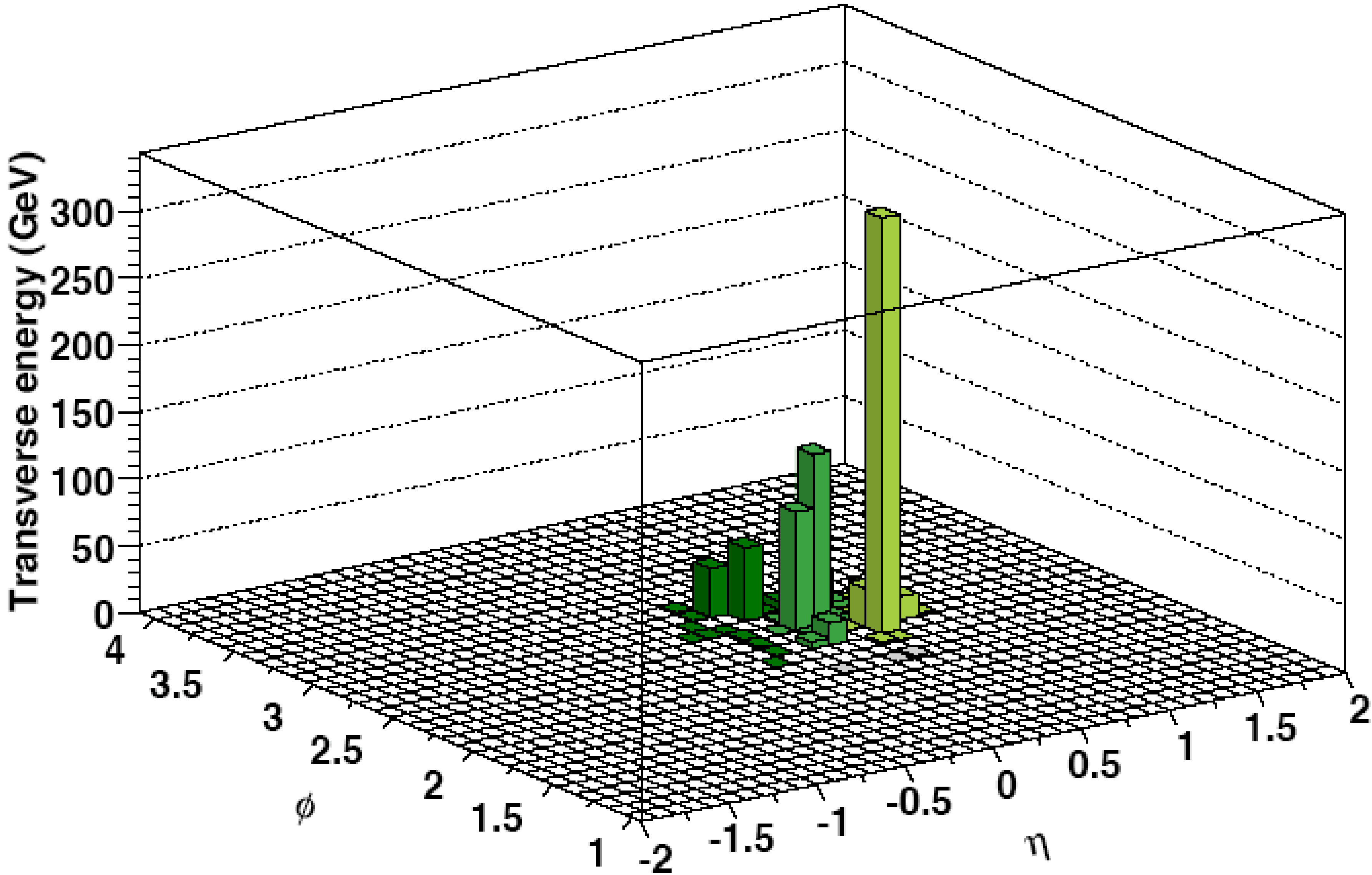
3. study of boosted top jet tagging

In view of these and other ways that top quarks enter new physics, it would be wonderful if we could select a top as a kind of exotic jet.

This looks very difficult to do near threshold, but it might be possible when the tops are highly boosted in the transverse direction (as they often are in new physics decays).

A hadronically decaying top then makes a jet with three subjets.

The problem is to tell this jet from a gluon splitting to three partons.



ET = 800 GeV top jet and subjets

Kaplan, Reherman, Schwartz, Tweedie

A basic idea: pruning:

Think about the jet as built up from subjets (e.g. using the Cambridge/Aachen jet algorithm).

As each subjet is added, compute the z of the softer jet

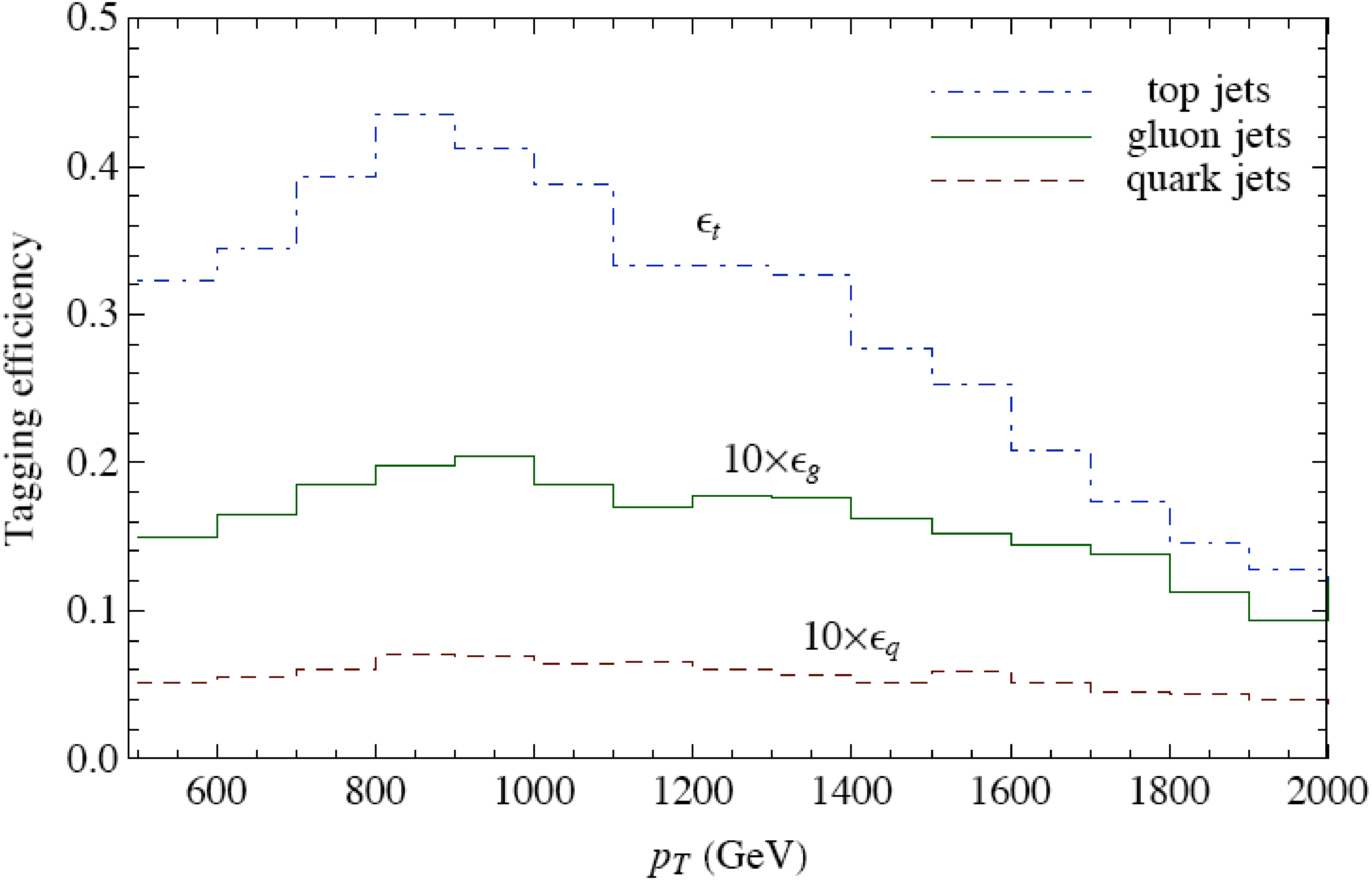
$$z = E_{T2}/(E_{T1} + E_{T2})$$

If z is small, the new subjet is probably a QCD radiation; discard it.

This degrades QCD jets, but leaves jets whose substructure is due to heavy particle decays.

Brooijmans, Kaplan et al., Ellis, Vermilion, Walsh, Butterworth, Davison, Rubin, Salam

have proposed specific realizations of this idea.



Kaplan, Reherman, Schwartz, Tweedie

2. search for $t\bar{t}$ resonances

Many models of new strong interaction physics in the Higgs sector contain resonances that decay to $t\bar{t}$

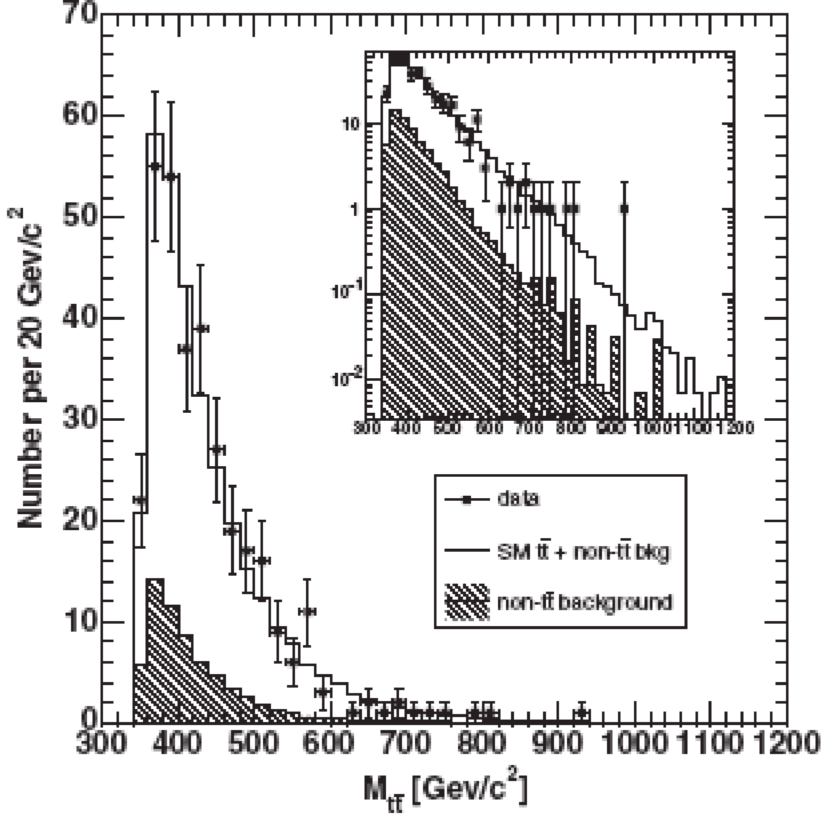
Two prominent examples are:

Topcolor gluons: SU(3) x SU(3) gauge symmetry, broken to SU(3) QCD at 1 TeV, such that (t, b) couple strongly to one of the factors.

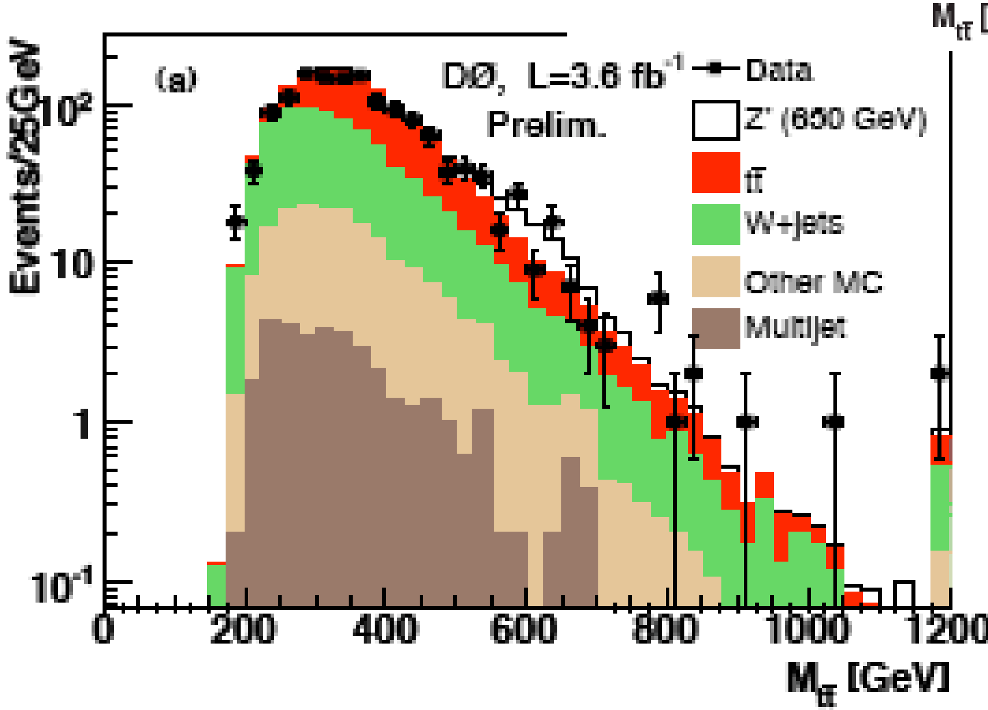
Hill

KK gluons: In Randall-Sundrum warped compactifications, the first Kaluza-Klein excitations will decay most strongly to the fermions that are most peaked toward the TeV brane. The strongest coupling will be to t_R .

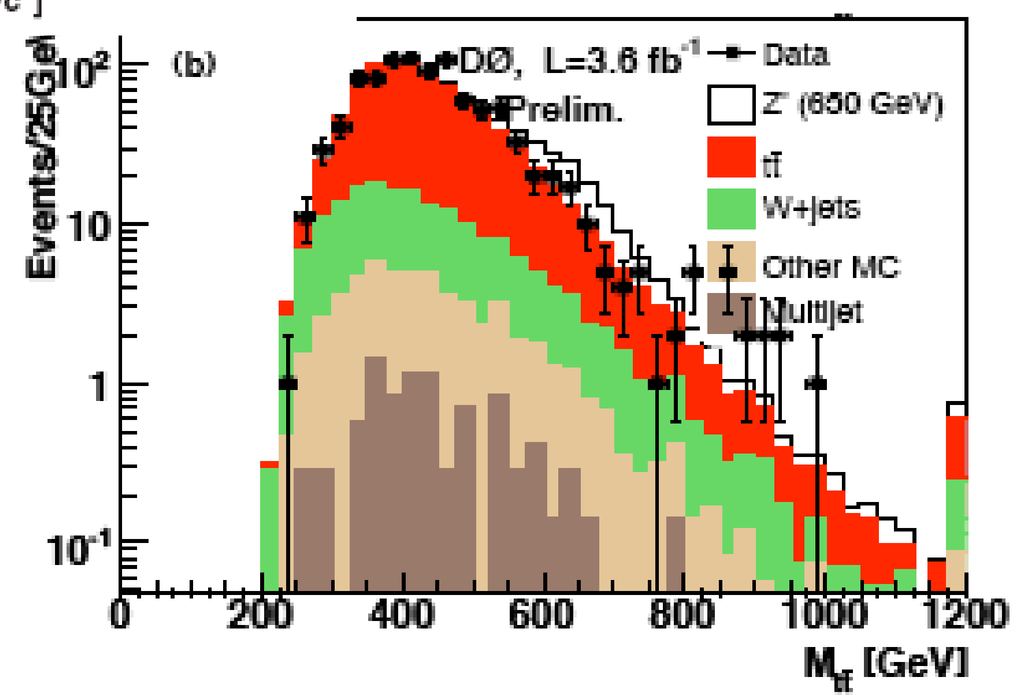
Agashe



CDF 1 fb-1

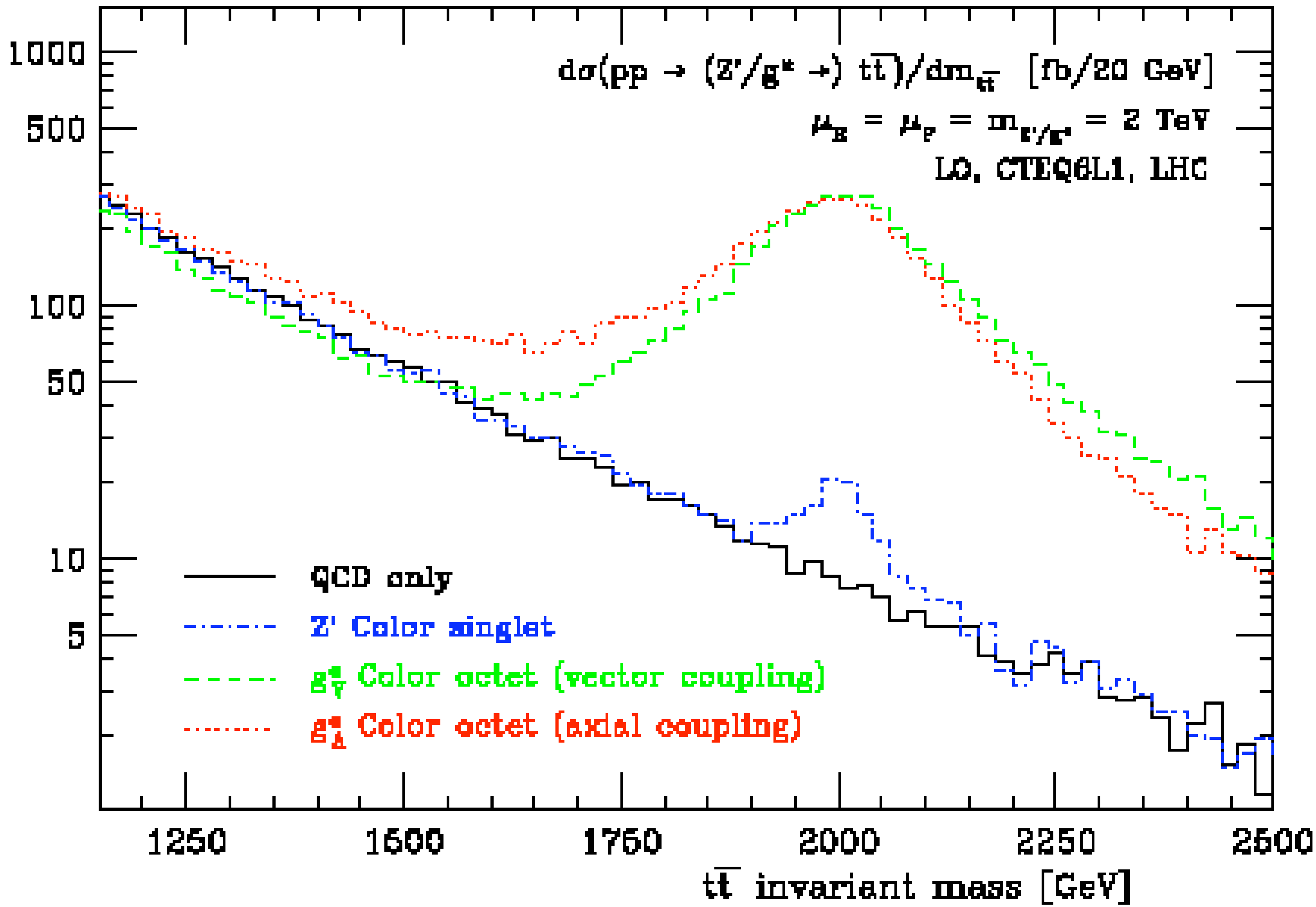


DO W + 3 jet



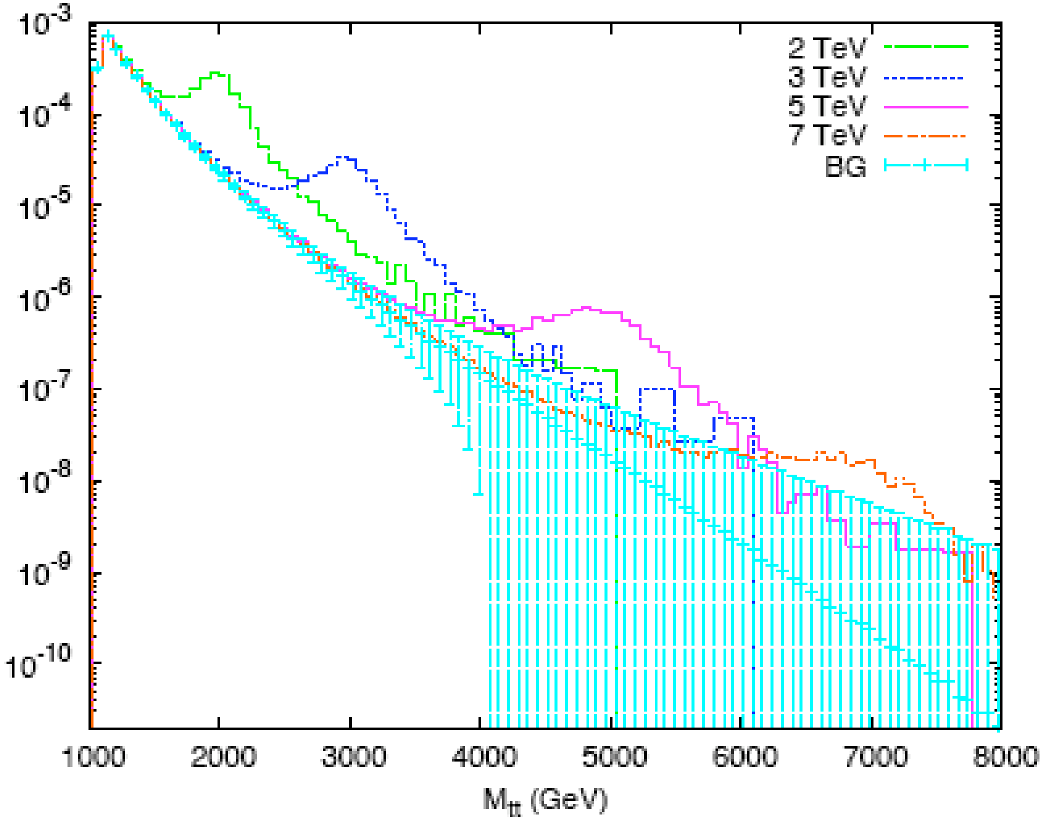
W+ 4 or more jets

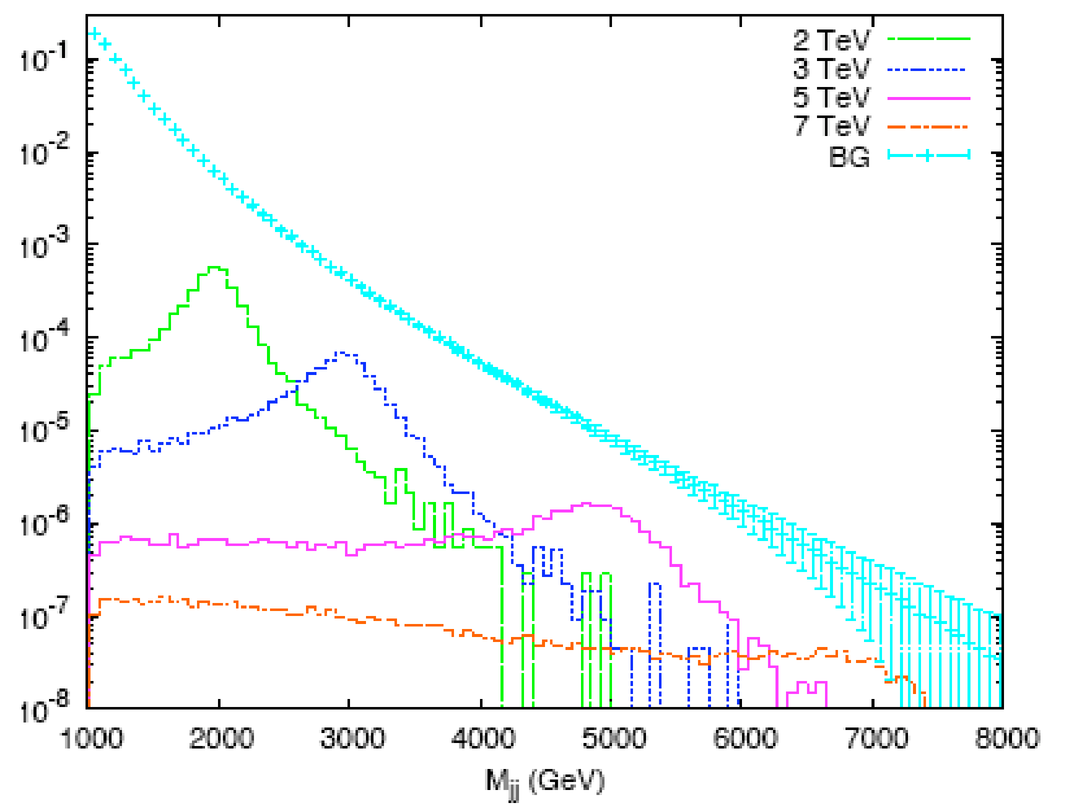
topcolor gluons



Maltoni, Frederix

KK gluons





Lillie, Randall, Wang

An effective top-tagging method would be very important for $t\bar{t}$ resonance searches.

If the estimates of Kaplan et al. for their method are correct, we should be able to discover a $t\bar{t}$ resonance up to 1.5 TeV already in the fall 2010 run of LHC.

1. search for CP violation in top production and decay

We still need a source of CP violation not in the CKM model to explain the excess of baryons over antibaryons in the universe.

It would be very attractive for this source to be visible experimentally at the TeV. Perhaps it comes from the Higgs or other new physics sector and is visible in top decays.

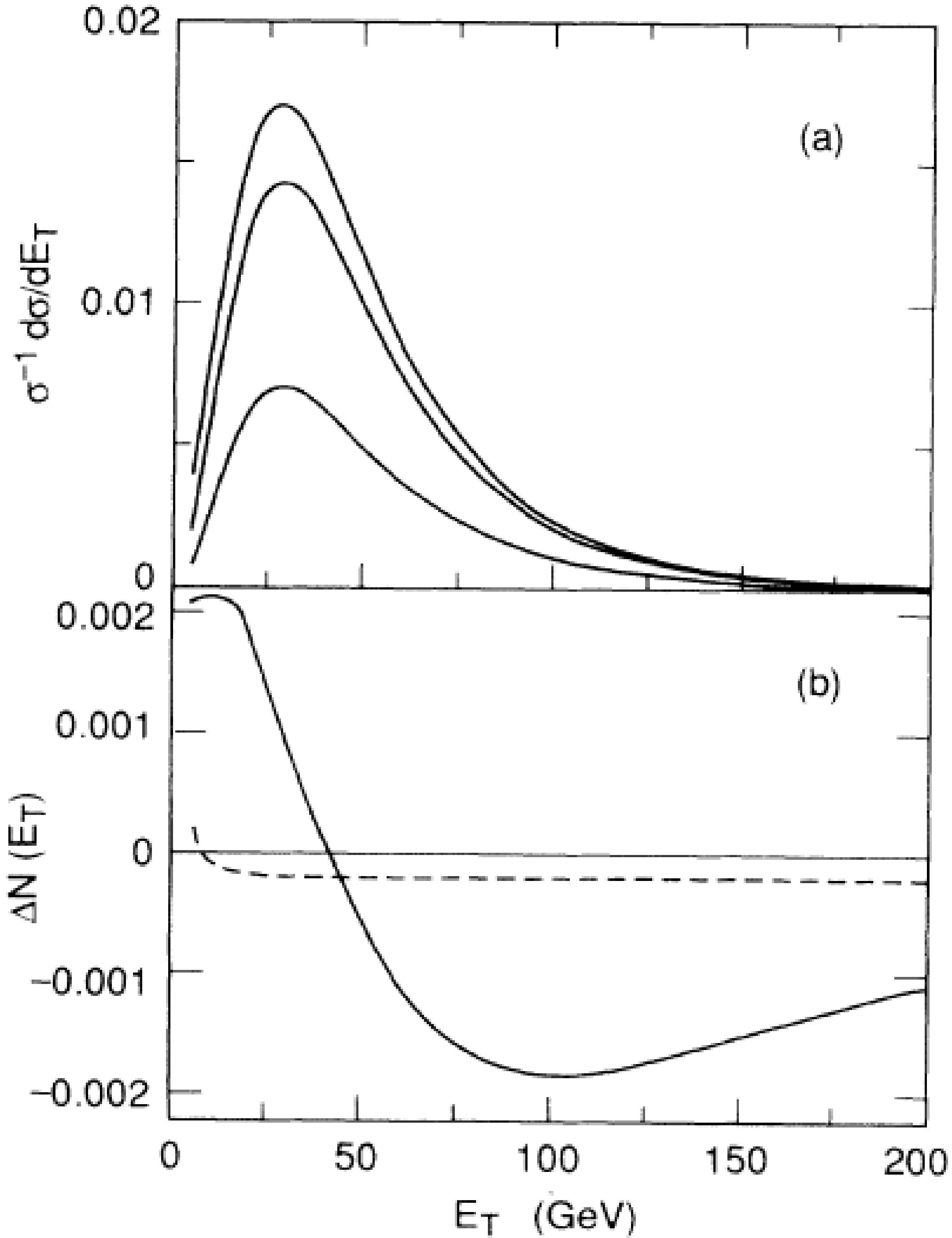
A robust observable is the difference

$$\frac{d\Gamma_t}{dE(e^+)} - \frac{d\Gamma_{\bar{t}}}{dE(e^-)}$$

in top quark pair production events, signalling a difference

$$\sigma(pp \to t_R \bar{t}_R) - \sigma(pp \to t_L \bar{t}_L)$$

Recall that, even though LHC is a pp collider, these events come dominantly from a CP-even initial state.



0.02
0.01
0
(a)
$\sigma^{-1}\, d\sigma/dE_T$
0.002
0.001
0
−0.001
−0.002
(b)
$\Delta N\ (E_T)$
0
50
100
150
200
E_T (GeV)

MEP-Schmidt

Even if the top quark is a Standard Model object, it offers many new handles for understanding physics at TeV energies.

And, perhaps, the top quark has more importance that simply a probe into TeV physics.   It might be a integral part of new physics, even the key part.

Hopefully, in the next year, we will begin to find out.

summary: top 10 top quark measurements at the LHC

10. measurement of $\sigma(t\bar{t})$
9. measurement of m_t
8. measurement of the single top cross section
7. measurement of the W helicity in top decay
6. search for $t \to c\gamma$, $t \to cZ$
5. search for supersymmetry through $\widetilde{t}$, $\widetilde{b} \to t + \not{E}_T$
4. search for $T \to t + Z, h$, $T \to bW$
3. study of boosted top jet tagging
2. search for $t\bar{t}$ resonances
1. search for CP violation in top production and decay

Extra:

‘Top Ten Reasons not to run the LHC’

a la David Letterman

Top Ten Reasons not to run the LHC

10. Quarks and gluons are so last century.

9. To make room for the data,
   I'll have to throw away my ABBA CD's.

8. "When you're a Jet, you're a Jet all the way ... "

7. Exclusion of supersymmetry will put 2,000 theorists
   out of work.

6. The entire population of Switzerland will have squeaky voices.

Top Ten Reasons not to run the LHC

5. Attack of the killer b's !

4. My pet top quark Alphonse won't feel special anymore.

3. No # 3; writer's Root analysis crashed in ATHENA.

2. Black holes in your underwear -- too itchy !

1. Those physicists will just want another 10 billion dollar toy...