Top Physics at the Tevatron

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Content:

- top quark basics
- $t\bar{t}$ production cross section
- top mass
- other analyses
- prospects for Run II

Top quark basics

At present, a reasonable amount of knowledge exists on the top quark:

- Its mass, $m_{\mathrm{t}} \approx 175$ GeV
- Assuming three generations of quarks, its charged-current coupling (PDG '02):

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.9741\text{–}0.9756 & 0.219\text{–}0.226 & 0.0025\text{–}0.0048 \\ 0.219\text{–}0.226 & 0.9732\text{–}0.9748 & 0.038\text{–}0.044 \\ 0.004\text{–}0.014 & 0.037\text{–}0.044 & 0.9990\text{–}0.9993 \end{pmatrix}$$

implying it should decay almost exclusively to Wb

- Based on this, its lifetime. To lowest order (assuming SM couplings):

$$\Gamma_{\mathrm{t}} = \frac{G_{\mathrm{F}}}{8\sqrt{2}\pi} |V_{\mathrm{tb}}|^2 m_{\mathrm{t}}^3 (1 - M_{\mathrm{W}}^2/m_{\mathrm{t}}^2)^2 (1 + 2M_{\mathrm{W}}^2/m_{\mathrm{t}}^2) \approx 1.8 \text{ GeV}$$

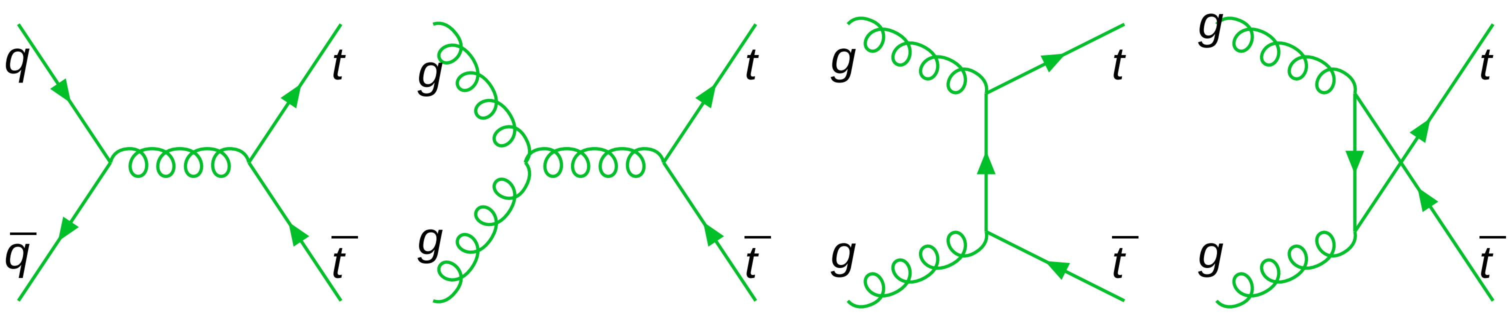
so $\tau_{\mathrm{t}} \sim \mathcal{O}(10^{-24})$s, implying it has no time to fragment and instead decays as a free quark

- Its decay modes: these are simply given by those of the W boson:
  $\mathrm{bq}\overline{\mathrm{q}}$: 2/3, $\mathrm{be}\nu$: 1/9, $\mathrm{b}\mu\nu$: 1/9, $\mathrm{b}\tau\nu$: 1/9 (neglecting $\mathcal{O}(\alpha_{\mathrm{s}})$ corrections)

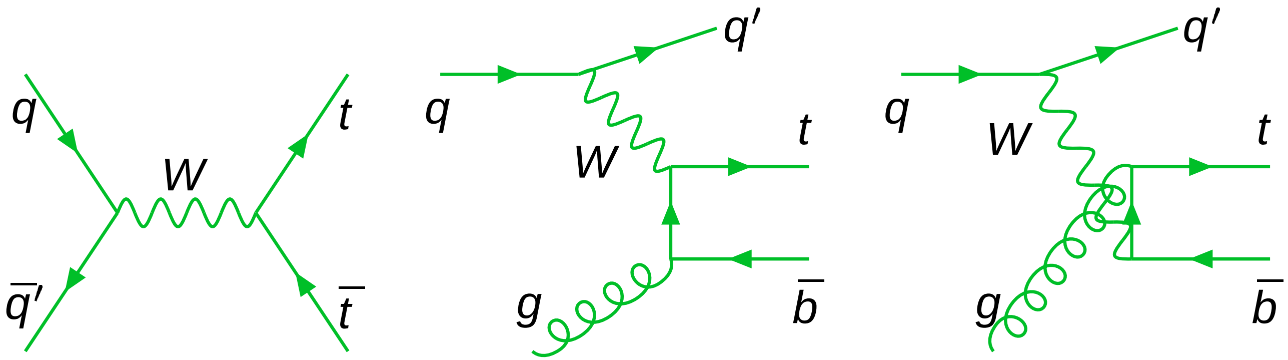
Top quark production at partonic level

Top quarks can be produced either in pairs or singly:

$t\bar{t}$ pair production:



single top production:



I'll be concentrating mostly on $t\bar{t}$ pair production, as its signature is substantially easier to recognise. . .

Folding in the structure functions

Master formula for $\mathrm{t\bar{t}}$ pair production:

$$\sigma(\mathrm{p\bar{p}} \to \mathrm{t\bar{t}}X) = \sum_{a,b} \int dx_a dx_b f_a^{\mathrm{p}}(x_a,\mu^2) f_b^{\mathrm{\bar{p}}}(x_b,\mu^2) \times \hat{\sigma}(ab \to \mathrm{t\bar{t}}; \hat{s}, \mu^2, m_{\mathrm{t}})$$

Relevant range of kinematic variables:

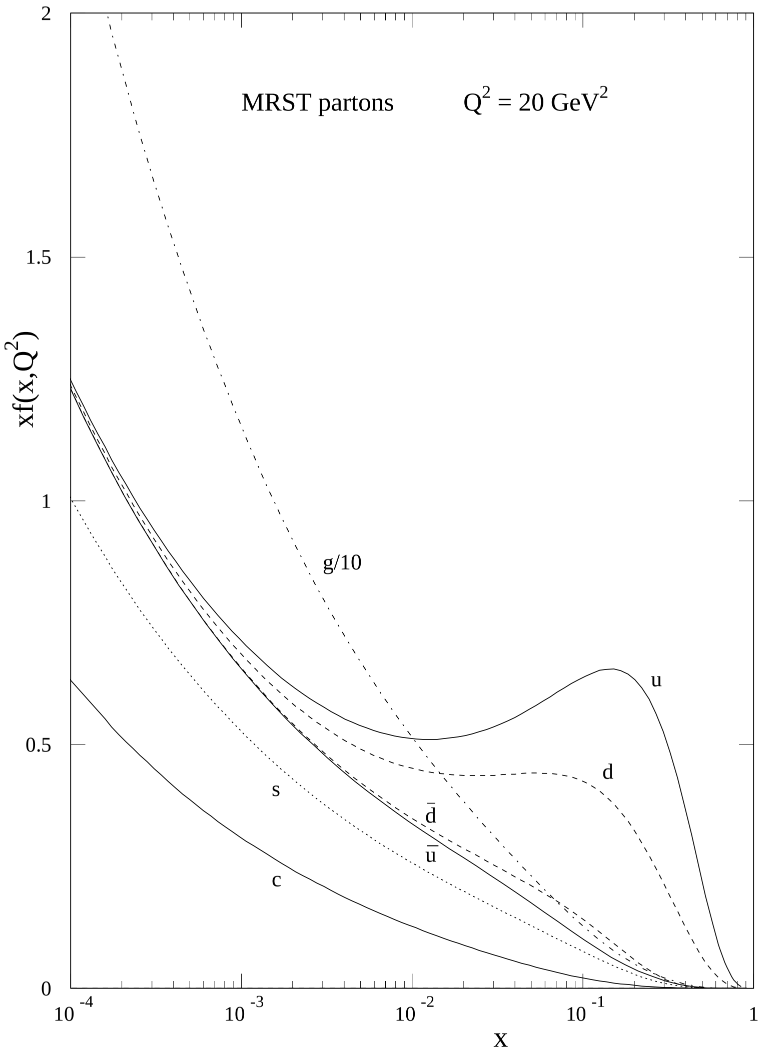
x**:** In this case, $\sqrt{\hat{s}} \geq 2m_{\mathrm{t}}$.

With $\hat{s} = x_a x_b s$, and $\sqrt{s} = 1.8$ TeV:

$$0.04 < x < 1$$

The largest cross section contribution in this *large* x region is from $\mathrm{q\bar{q}}$ annihilation.

Q^2**:** The scale normally taken is $Q^2 = \mu^2 = m_{\mathrm{t}}^2$, *i.e.* well in the perturbative region.



Going beyond leading order

- Needed to achieve best precision
- However, radiation of soft gluons leads to large corrections in order-by-order calculations (NLO ~ 20% (70%) × LO for quark (gluon) initial states)
- Resummation techniques have shown to lead to small corrections beyond NLO, as well as smaller scale uncertainties:

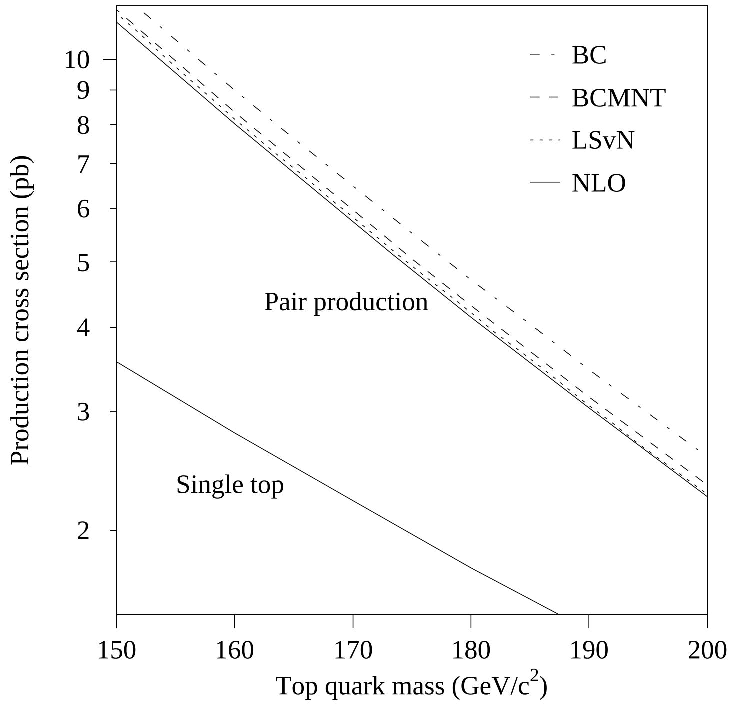
Type	Structure fct.	$\sigma_{t\bar{t}}$ (pb) (175 GeV)
NLO	MRSR2	$4.87^{+0.30}_{-0.56}$
Resummed[*]	MRSD	$4.94^{+0.71}_{-0.45}$
Resummed[†]	CTEQ3	$5.52^{+0.07}_{-0.42}$
Resummed[‡]	MRSR2	$5.06^{+0.13}_{-0.36}$

[*] Laenen, Smith, van Neerven

[†] Berger, Contopanagos

[‡] Bonciani, Catani, Mangano, Nason, Trentadue

Conclusion: good agreement between different calculations ⇒ excellent test of QCD!



The $t\bar{t}$ production cross section measurement

Assume SM top decay characteristics ⇒ final states: all-jets, lepton+jets, leptons (according to decay of W bosons involved):

$q\bar{q}q\bar{q}$: Largest fraction (36/81), but purely hadronic decay mode hard to distinguish from QCD background even with 6 jets

$q\bar{q}\ell\nu$, $\ell = e, \mu$: 24/81 of all decays: a lepton and $\not{E}_T$ in addition to 4 jets

$q\bar{q}\tau\nu$: 12/81 of all decays: more complicated than for e, μ due to the τ decay modes

$\ell\nu\ell\nu$: 4/81 of all decays: two leptons, $\not{E}_T$, two jets

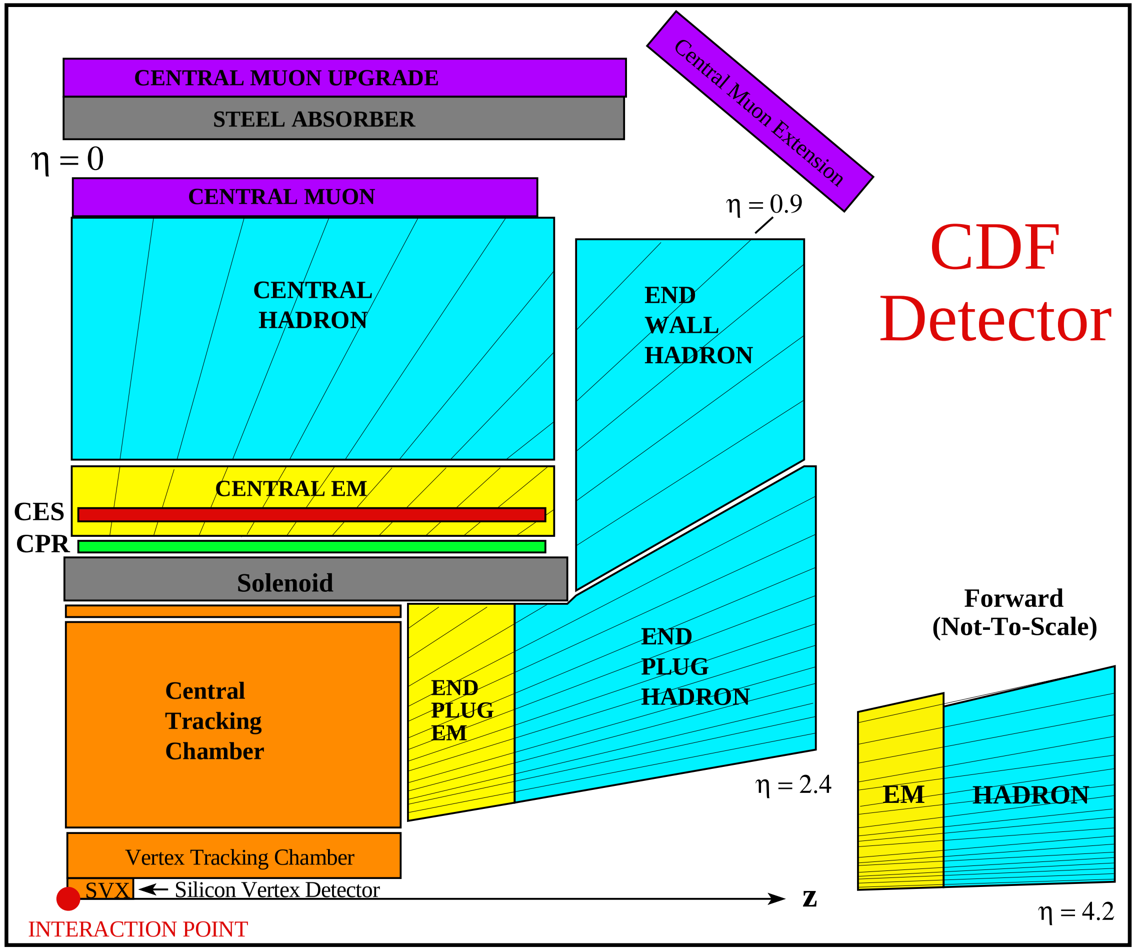
$\ell\nu\tau\nu$, $\tau\nu\tau\nu$: 5/81 of all decays: again more complicated due to τ

All channels (except $\tau\nu\tau\nu$) have been analyzed. I won't discuss channels involving τ's.

Notes:

- In hadron colliders, there is (almost) *always* energy and momentum leaking out along the beam axis: this is not a useful constraint!
  - energy balance in the transverse plane *is* – but this works only to the extent that no transverse energy from the underlying event escapes undetected ⇒ requires good hermeticity
- In all cases, there are two jets originating from b quarks ⇒ b tagging helps!

The detectors



Performance numbers:

- electrons:

  $$\sigma(E)/E = 14\%/\sqrt{E(\text{ GeV})} \oplus 2\%$$

- jets:

  $$\sigma(E)/E = 50\%/\sqrt{E(\text{ GeV})} \oplus 3\%$$

- tracks:

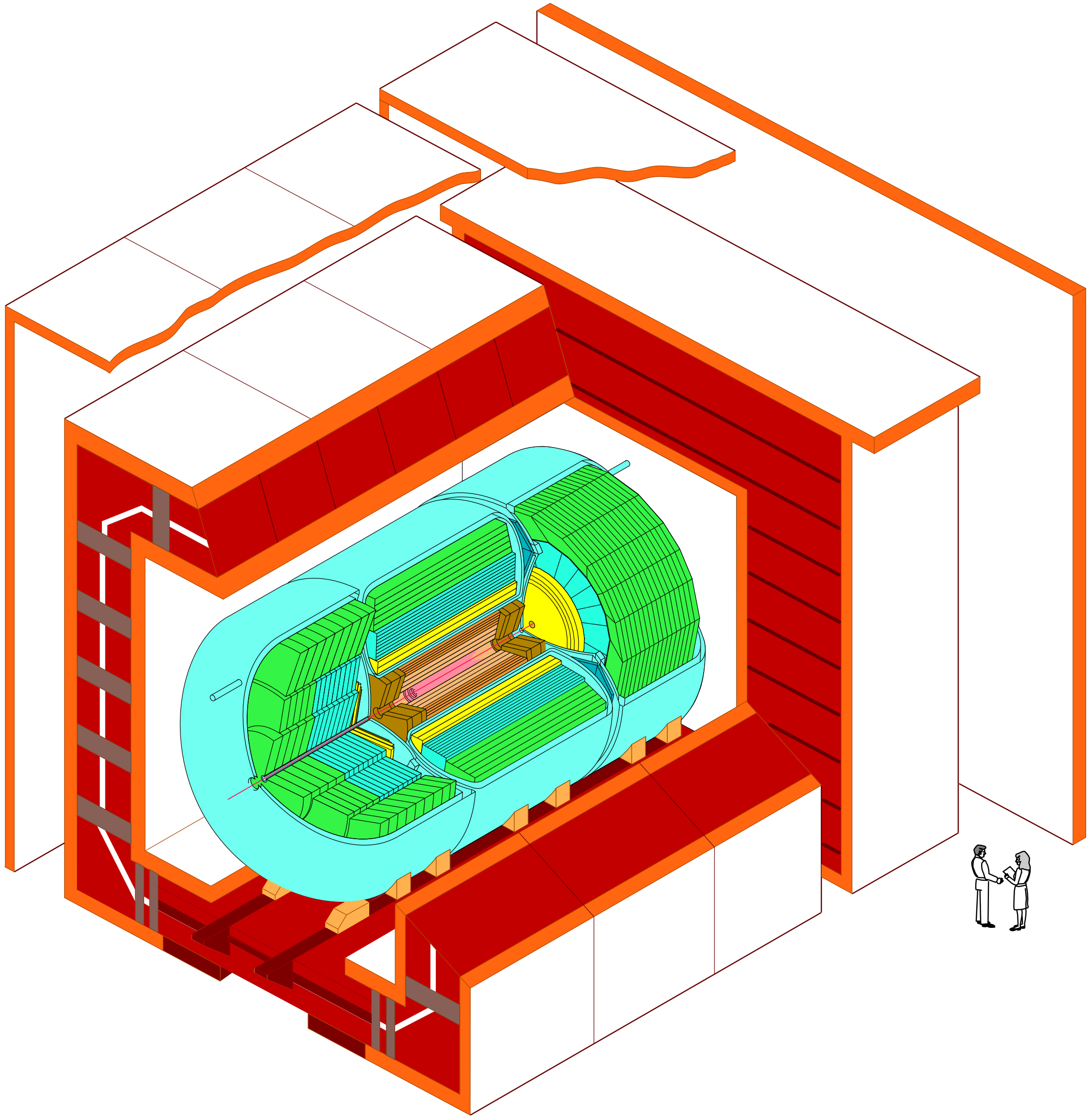
  $$\sigma(p_t)/p_t = 0.0009 p_t \oplus 0.0066$$

  (p_t in GeV)

- missing E_T:

  $$\sigma(\not{E}_T) = 0.7\sqrt{\sum E_T}$$

The detectors



DØ Detector

Performance numbers:

- electrons:

  $\sigma(E)/E = 15\%/\sqrt{E(\text{ GeV})} \oplus 0.4\%$

- jets:

  $\sigma(E)/E = 45\%/\sqrt{E(\text{ GeV})}$

- muons:

  $\sigma(1/p) = 0.18(p-2)/p^2 \oplus 0.003$

  (p in GeV), $|\eta| < 1$

- missing E_T:

  $\sigma(\not{E}_T) = 0.019(\sum E_T) + 1.5$ GeV

Objects

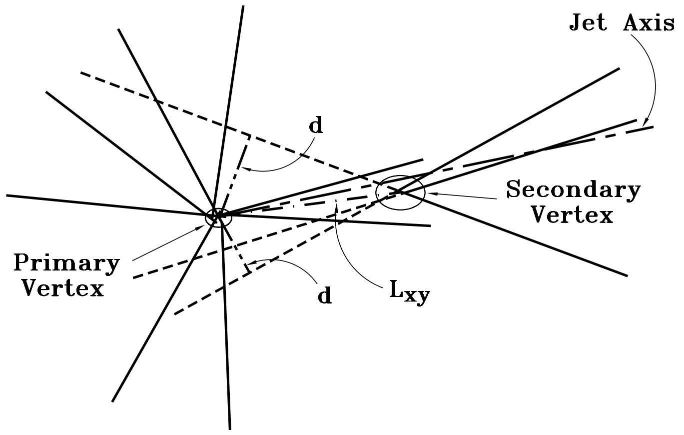
- **Jets** are reconstructed using cone algorithm on basis of calorimeter energy deposits
  1. choose seed clusters
  2. associate all energies within a fixed radius $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ around the seed
  3. compute the energy-weighted $\langle\eta\rangle$, $\langle\phi\rangle$, and, with this as the new seed, iterate until a stable jet axis is found

  Choose $R = 0.5$: compromise between merging jets (large R) and not containing all of the jet's energy in the cone (small R)
- **electrons** are recognised as isolated EM clusters matched with a charged track (with quality criteria on the match, shower shape, isolation)
  - background from QCD jets faking electrons
- **muons** are selected based on track segments reconstructed in the muon chambers, with a matching central track (not a requirement for DØ)
- **neutrinos** are only reconstructed indirectly from the observed $\not{E}_T$ (which should be corrected for any muons)
  - doesn't work well if $> 1\ \nu$ present!

b tagging

The b quark distinguishes itself from its lighter relatives in two important aspects:

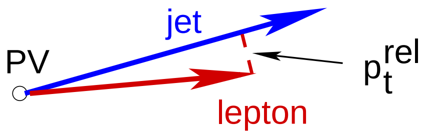
its long lifetime: $\tau_b \approx 1.5$ ps $\Rightarrow c\tau_b \approx 450\mu$m. For sufficiently high p_t quarks this results in



- detectable displaced vertices (sign according to jet hemisphere; cut on decay length significance L_{xy}/σ_{xy})
- or at least tracks with high impact parameters d with respect to the event's primary vertex (construct discriminant from track impact parameter significances w.r.t. PV)

CDF has used these methods (discuss only first).

its hard fragmentation and high mass: in semileptonic decays ($\sim$ 20%) this results in leptons with high p_t and high p_t^{rel} with respect to the jet axis. The lepton kinematics have not been used by either experiment; rather, the mere *presence* of a lepton is used to tag b jets (but large p_t^{rel} $\Rightarrow$ easier e$^{\pm}$ recognition).



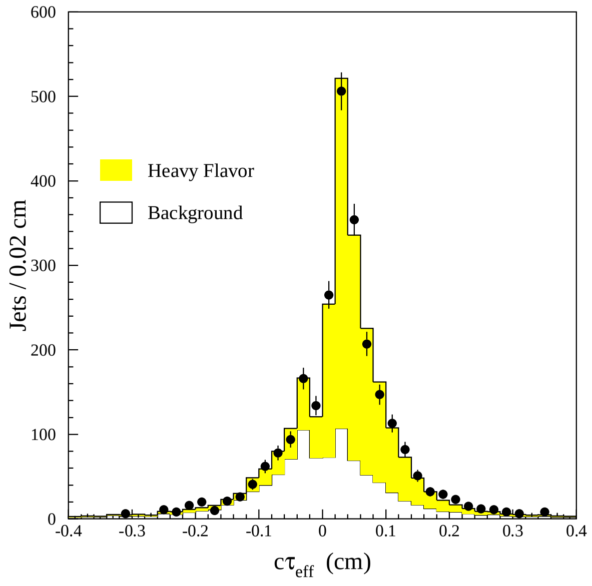
- CDF: μ, e (but low efficiency for e), DØ: μ

b tagging: SVT checks

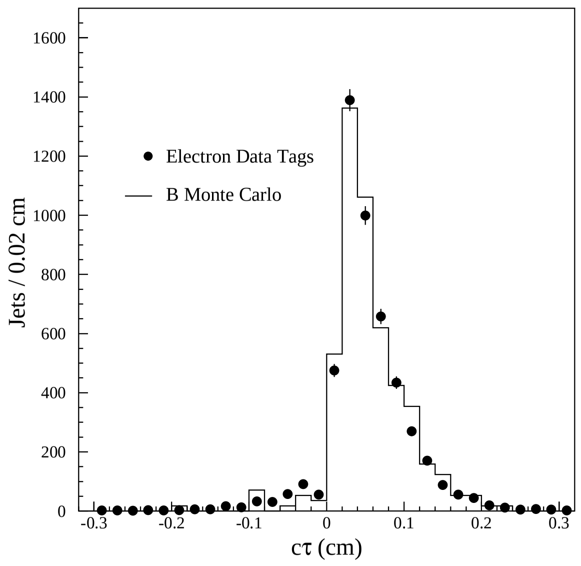
Construct light, b, c MC $c\tau_{\text{eff}}$ templates:

- known track resolution functions, eff.
- apply vertexing

Fit to templates to extract fractions:



- Template fit results cross-checked with rates expected from exclusive B meson decays
- Templates cross-checked with e+jets data containing secondary vertices:



$c\tau_{\text{eff}} = L_{xy}m/p_tF$: p_t, m are momentum, mass of the tracks associated to SV

F is derived from MC

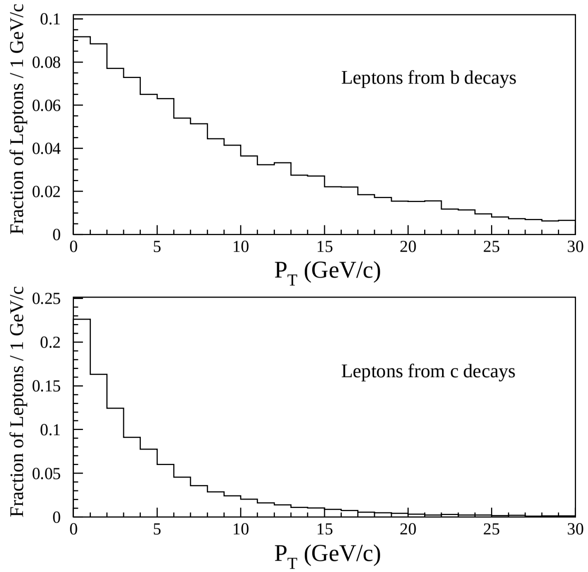
Correct efficiency for semileptonic → generic B decays using MC

(~factor 0.7 ⇒ $39 \pm 3\%$ on average: time dependent due to SVX chip radiation damage)

b tagging: lepton tags

Leptons from semileptonic decays are soft!

(and typically buried in jets. . .)



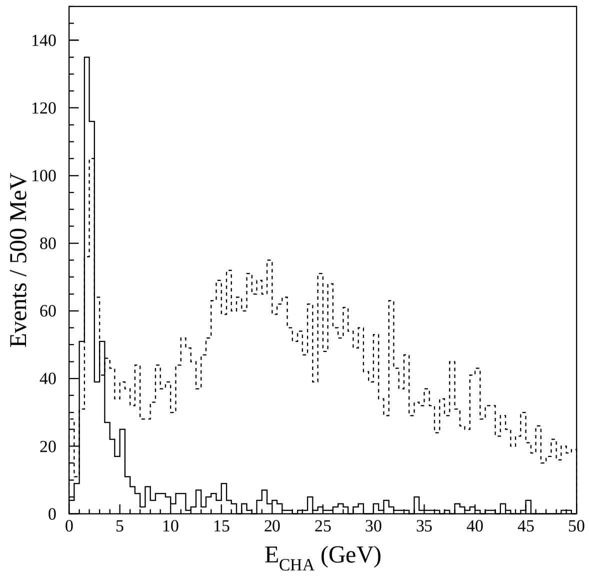
Electrons: tight ID cuts to reject hadrons

- track match, E/p with narrow cone, dE/dx, PS
- efficiency ~53% (~23%) for $b \to eX$ ($c \to eX$) decays from MC
- check with recoil jets in e+jets data

In principle, only irreducible muon background is from decays in flight. . .

In practice, CDF (“thin” calorimeter, nice: $p_t^{\mu} > 2$ GeV) suffers from punch-through: need add’l (HCAL) isolation criteria

DØ: require $p_t^{\mu} > 4$ GeV

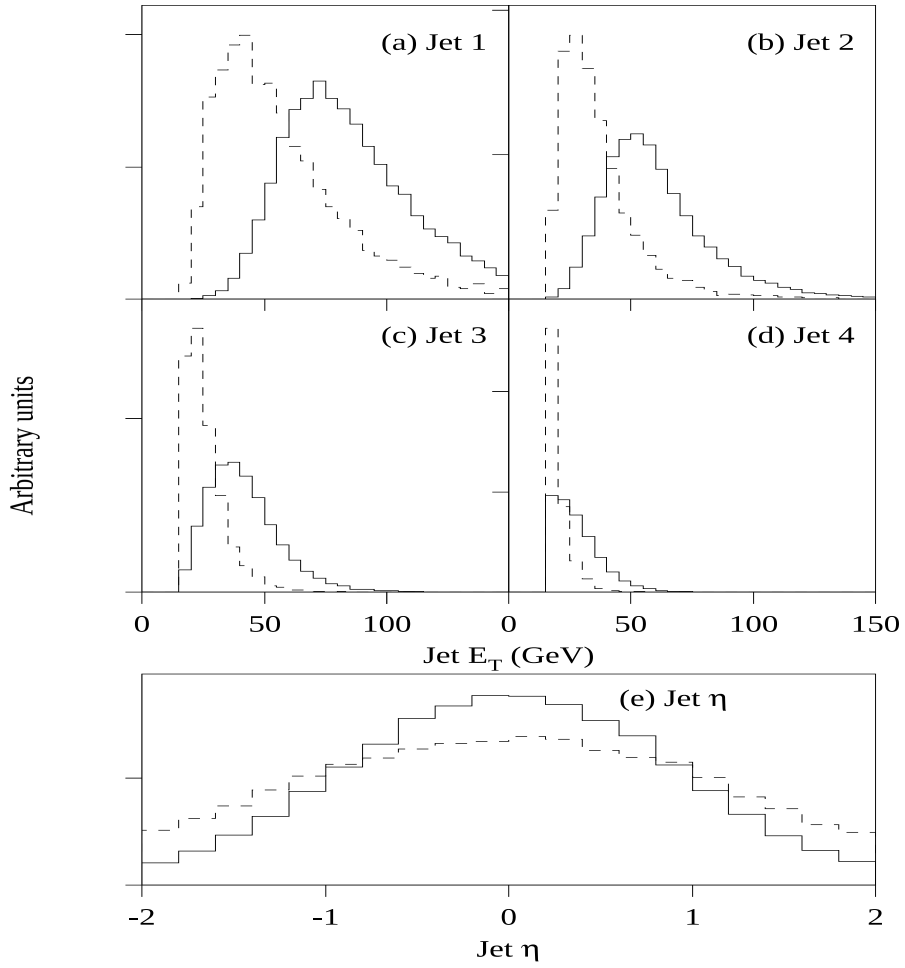


Reconstruction efficiency obtained from Z $\to \mu^+\mu^-$, J/$\psi \to \mu^+\mu^-$ decays: ~95% (CDF), ~ 60–85% (DØ).

- low DØ eff. mainly due to geometric acceptance!

lepton+jets: characteristics

Some characteristics of $t\bar{t}$ events compared to W+jets background:



W+jets expected to be the only "irreducible" background,
σ(W+jets) ~ $\mathcal{O}$(pb),
and the following are not even used:

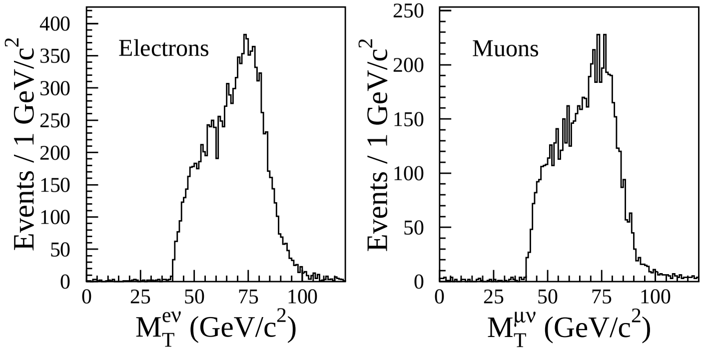
- $\not\!\!E_T$
- b tagging

⇒ an easy analysis?

lepton+jets: CDF

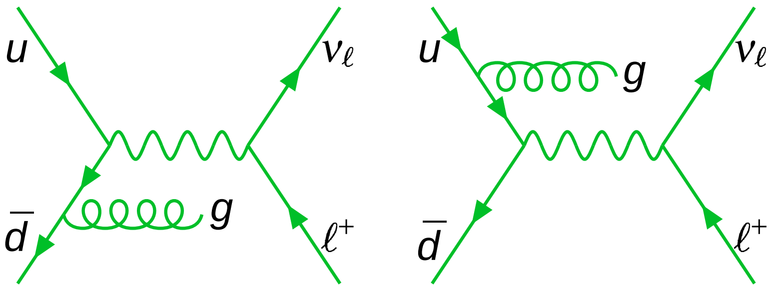
Basic selection criteria:

- one isolated, high-p_t lepton ($p_t > 18$ GeV)
- significant $\not{E}_T$ ($\not{E}_T > 20$ GeV)
- ≥ 3 jets (to account for merging, inefficiencies)



Seeing the W (from the $M_T^{\ell\nu} = \sqrt{2|\vec{p}_t^{\,\ell}||\vec{p}_t^{\,\nu}| - \vec{p}_t^{\,\ell} \cdot \vec{p}_t^{\,\nu}}$ distribution) is easy. . .

Principal background: from W+jets processes. For W+1 parton production:

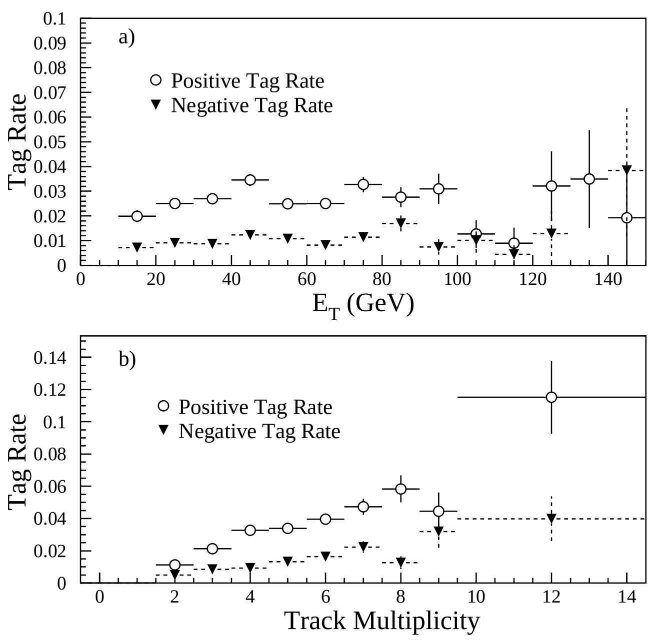


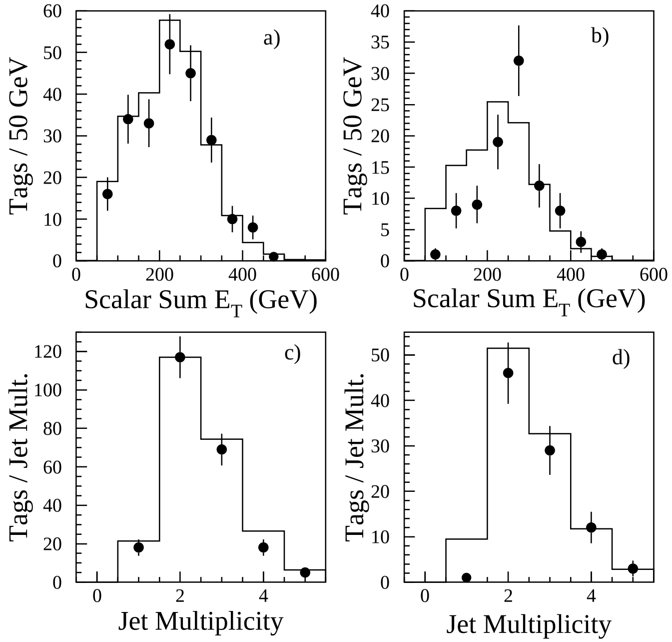
For W+3 (4) parton production there are 110 (~1300) tree level diagrams to be computed! Handled by the VECBOS MC program, which doesn’t account for higher order corrections (also HERWIG can be used for estimates)

lepton+jets: CDF

The main effort is in determining the background... For SVT tags:

1. Obtain *tag rates* from generic jet samples (50 GeV jet trigger)
2. Cross-check these tag rates in independent samples (*e.g.* 100 GeV jet trigger)



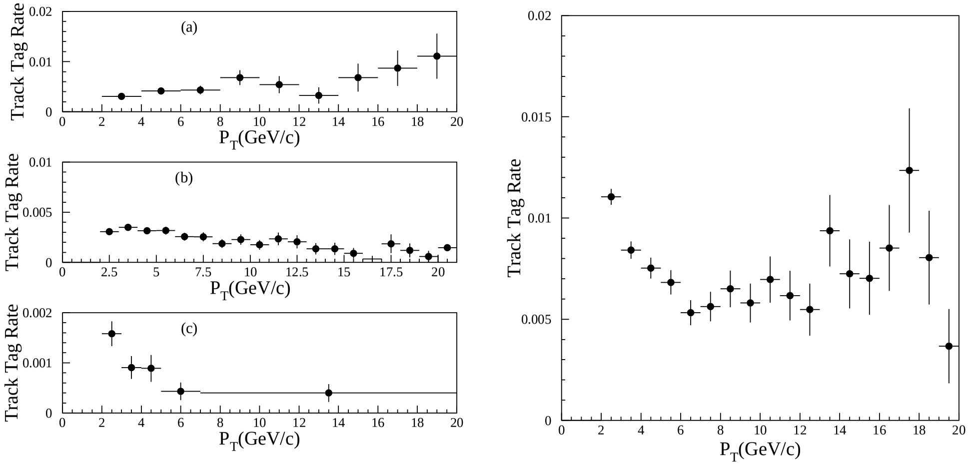


3. Extrapolate these to tag rates in W+jets samples: use MC to estimate heavy flavour content as function of number of jets in W+jets (and in generic jets). Nontrivial!. *e.g.* gluon splitting scaled up by 1.4 (from multijet sample)
   Result: mis-tags contribute largest fraction (~ 2/3), rest from $Wb\bar{b}$, $Wc\bar{c}$
4. Remaining backgrounds (from $Z \rightarrow \tau^+\tau^-$, W^+W^-, WZ) small, estimated from MC

lepton+jets: CDF

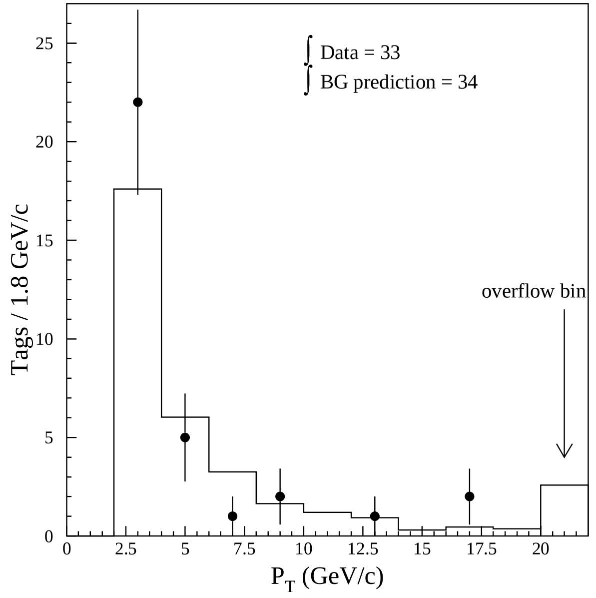
Similar approach for SLT:

1. Obtain tag rates for e, μ from multijet triggers (as a function of isolation in case of e$^{\pm}$)
2. Assume the same tag rates for W+jets events (slight overestimation of background as less gluon splitting expected in W+jets than in multijet samples), and cross-check with W+1 jet sample



Additional useful cross-check (both SVT, SLT): Z($\rightarrow \ell^+\ell^-$)+jets sample

- $\sigma \times$ BR ~ factor 10 below W($\rightarrow \ell\nu$)+jets
- but find good agreement between expected, observed number of tagged events



lepton+jets: CDF

Results:

	SVT	SLT
$\varepsilon_{\rm tag}$ (%)	39±3	18±2
$\varepsilon_{\rm geom}$ (%)	10.4±1.0	
$\varepsilon_{\rm trig}$ (%)	90±7	
$\varepsilon_{\rm total}$ (%)	3.7±0.5	1.7±0.3
observed events	34	40
background	9.2±1.5	22.6±2.8
$\sigma_{t\bar{t}}$ (pb)	5.1±1.5	$9.2^{+4.3}_{-3.6}$

lepton+jets: DØ

Basic selection criteria similar to CDF's:

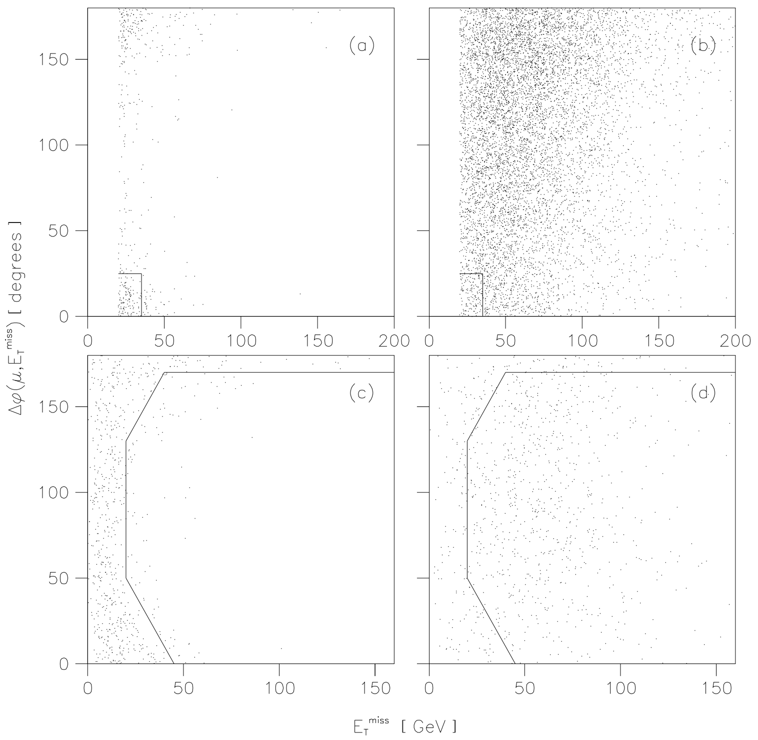
- one isolated, high-p_t lepton ($p_t > 20$ GeV)
- significant $\not{E}_T$ ($\not{E}_T > 20$ GeV)
- ≥ 3 jets

μ tagged events:

1. Additional $(\not{E}_T, \Delta\phi(\not{E}_T, \mu))$ cuts needed due to inferior μ momentum resolution

left: QCD multijet, right: $t\bar{t}$

top: e+jets, bottom: μ+jets



lepton+jets: DØ

2. use data to estimate light jet tag rates: apply $e^{\pm}$, isolated μ mis-tag rate to samples satisfying all but these ID criteria.

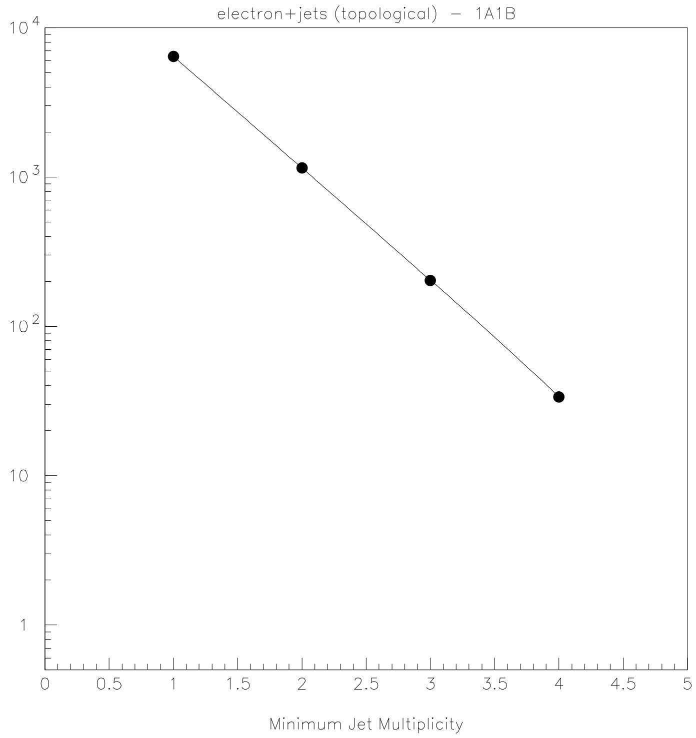
   From loose $\rightarrow$ tight e ID:

$$\begin{aligned} N_{\text{loose}} &= N_{\text{e}} + N_{\text{fake}}, \\ N_{\text{tight}} &= \varepsilon_{\text{t}}^{\text{e}} N_{\text{e}} + \varepsilon_{\text{t}}^{f} N_{\text{fake}} \end{aligned}$$

   with $\varepsilon_{\text{t}}^{\text{e}}$ derived from $Z \rightarrow e^+e^-$, $\varepsilon_{\text{t}}^{f}$ from "loose" e+jets without $\not{E}_T$

   $\Rightarrow$ solve for N_{fake}

3. estimate W+3 jets background (dominant contribution) from W+1 jet, W+2 jets



lepton+jets: DØ

Only μ SLT tag available $\Rightarrow$ find other ways to improve background rejection:
Tour de force #1: topological selection

1. ≥ 4 jets ($E_T^{\text{jet}} > 15$ GeV)
2. Further selection on event topology:
   - $H_T \equiv \sum_{\text{jets}} E_T > 180$ GeV
   - Aplanarity: $\mathcal{A}(\text{jets+W}) > 0.065$

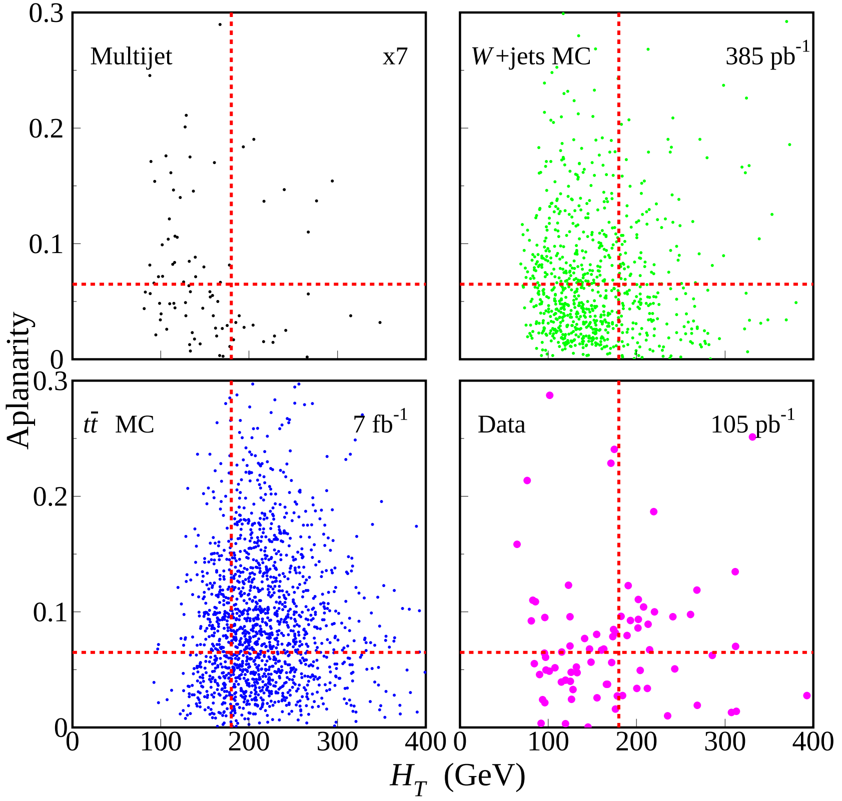
     diagonalise momentum tensor

$$Q_{ij} = \left(\sum_k p_i^k p_j^k \right) / \left(\sum_k |\vec{p}_k|^2 \right)$$

     to obtain $Q_1 < Q_2 < Q_3$, $Q_1 + Q_2 + Q_3 = 1$

     $\Rightarrow 0 < A \equiv \frac{3}{2} Q_1 < 0.5$

     (simililarly: $0 < S \equiv \frac{3}{2}(Q_1 + Q_2) < 1$)
   - $E_T^L \equiv \not{E}_T + |\vec{p}_t^{\,\ell}| > 60$ GeV



At this point, the background is dominated by QCD multijets and W+jets events

In the following, will concentrate on μ+jet events

lepton+jets: DØ

1. Estimate QCD multijet background from a control sample of $\mu + n$ jets, $n \geq 0$:
   - assume isolated $\mu \Rightarrow$ accompanying jet not reconstructed, estimate from $\not{E}_T < 20$ GeV sample:

$$P(\text{isolated } \mu) = \frac{\#\text{isolated } \mu,\ n \text{ jets}}{\#\text{non-isolated } \mu,\ n{+}1 \text{ jets}}$$

   - apply this probability to $\not{E}_T > 20$ GeV sample

   This procedure gives the QCD prediction for 1, 2, 3, 4 jets

2. After subtracting QCD, the remainder is W+jets: extrapolate from W+1 jet, W+2 jets to W+4 jets
   - Would be nice to use also W+3 jets for extrapolation – but this is expected to contain $t\bar{t}$!

3. Apply QCD, W+jets efficiencies for topological cuts
   - Determining the probability to find a μ needs statistics $\Rightarrow$ topological cuts not applied

Results:

	ℓ+jets (topological)	ℓ+jets (μ tag)
$\varepsilon\cdot$ BR (%)	2.28±0.46	0.96±0.15
background	8.7±1.7	2.4±0.5
observed	19	11
$\sigma_{t\bar{t}}$	4.1±2.1	8.3±3.5

di-leptons

The signature for leptonic decays of both W bosons is significantly more pronounced:

- 2 leptons, 2 b jets, significant $\not{E}_T$

Main backgrounds:

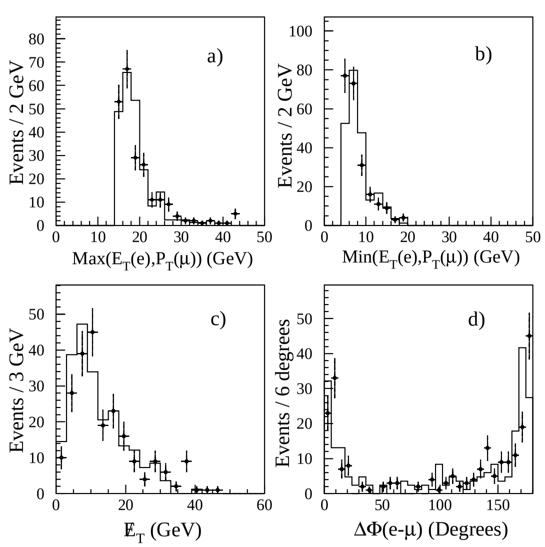
- $W^+W^- \to \ell^+\ell^- 2\nu$
  (reject using topology: H_T)
- For ee and $\mu\mu$ channels: $Z/\gamma^* \to \ell^+\ell^-$
  (reject using invariant mass cut)
- W+jets (with mis-identified $e^\pm$)
- Drell-Yan $\tau^+\tau^- \to \ell^+\ell^- 6\nu$

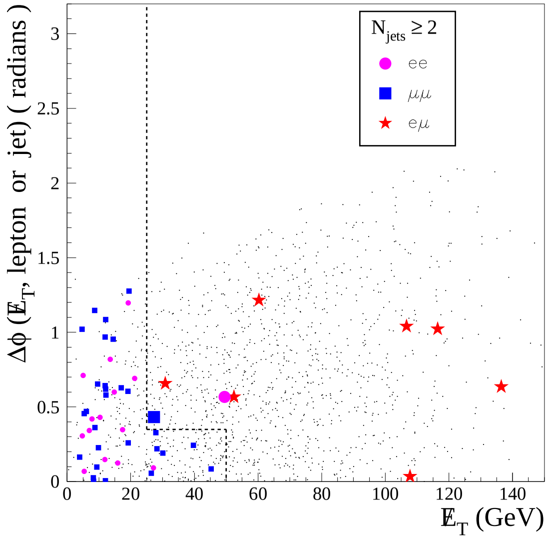
b tagging not necessary!

Results:

CDF: $\sigma_{t\bar{t}} = 8.2^{+4.4}_{-3.4}$ pb

DØ: $\sigma_{t\bar{t}} = 6.4 \pm 3.3$ pb





all-hadronic mode

No (isolated) leptons or $\not{E}_T$ in this mode. . . only 2 b jets and 4 light quark jets

Conditio sine qua non:

- ≥ 5 jets (for CDF; 6 for DØ)
- one b tag

Two possible approaches have been followed by CDF:

1. two (SVX) tags
2. topological cuts
   - $H_T/\sqrt{\hat{s}} > 0.75$
   - $\mathcal{A} > -0.0025 H_{T3} + 0.54$

   where $H_{T3} = H_T - E_T^{j1} - E_T^{j2}$

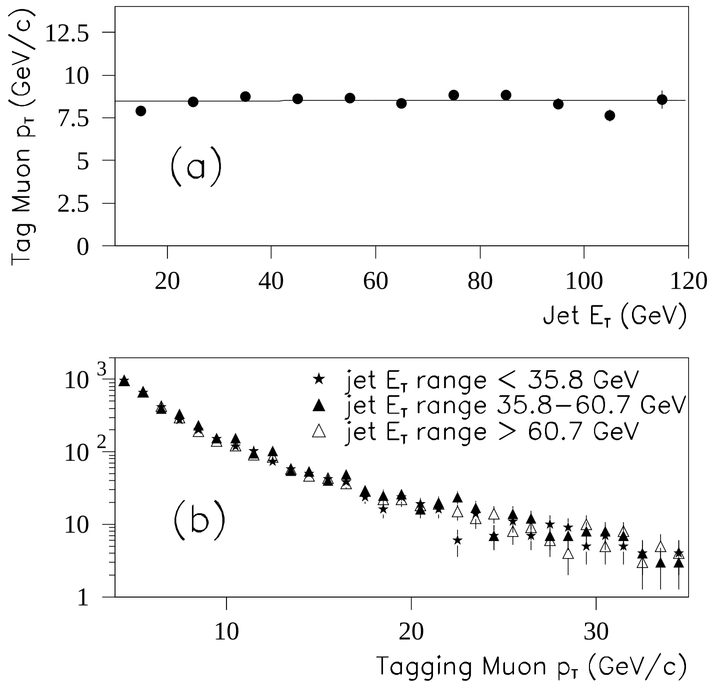
Results:

	2 b tags	topological
$\varepsilon \cdot$ BR (%)	3.2±0.8	9.9±1.6
background	123±13	165±11
observed	157	222
$\sigma_{t\bar{t}}$ (pb)	$11.5 \pm 5.0^{+5.9}_{-5.0}$	$9.6 \pm 2.9^{+3.3}_{-2.1}$

all-hadronic mode: DØ

Focus on the DØ topological analysis:
tour de force # 2
(μ tagging not performant enough to require two tags)
After jet selection: 600k data events
(expect ~ 200 $t\bar{t}$) ⇒ hopeless?

1. Use NN, with as input:
    - topological variables:
      H_T, $\sqrt{\hat{s}}$, H_{T3}, $\mathcal{A}$, S, $H_T/(\sum_{\text{jets}} E)$, E_T^{j1}/H_T, $\sqrt{E_T^{j5}E_T^{j6}}$, $\langle\eta^2\rangle$
    - measure of jet widths ($t\bar{t}$: mainly quarks, QCD: mainly gluons)
    - measure of compatibility w/ W & (equal) top mass constraints
    - p_t^μ of tagging μ



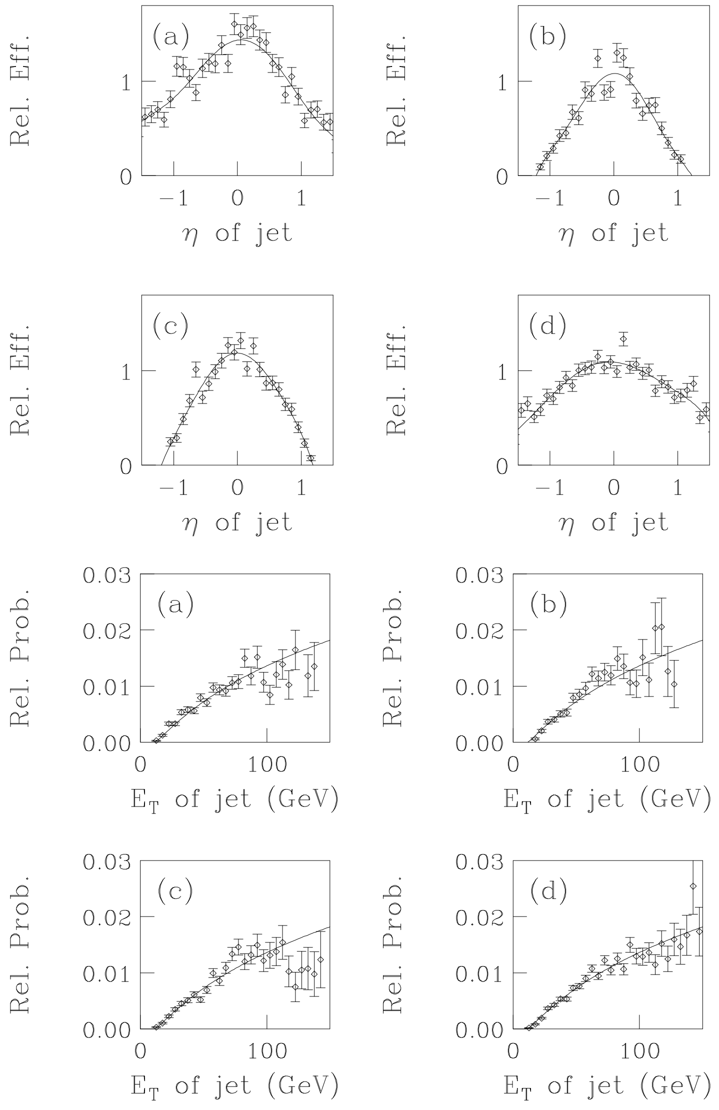
2. Train NN with $t\bar{t}$ signal MC and *untagged data as background*
    - don't rely on QCD MC
    - but NN needs μ tags! Solution: "add" muons with measured p_t spectrum to untagged events

all-hadronic mode: DØ

3. Require a tagging μ associated to a jet ($\Delta R < 0.5$)
4. Require $p_t^\mu > 4$ GeV to suppress decays in flight.
5. Construct a tag probability (derived from a multijet sample) for a QCD jet to give rise to a tag
   - as a function of jet E_T, η, time*, ($\sqrt{\hat{s}}$)

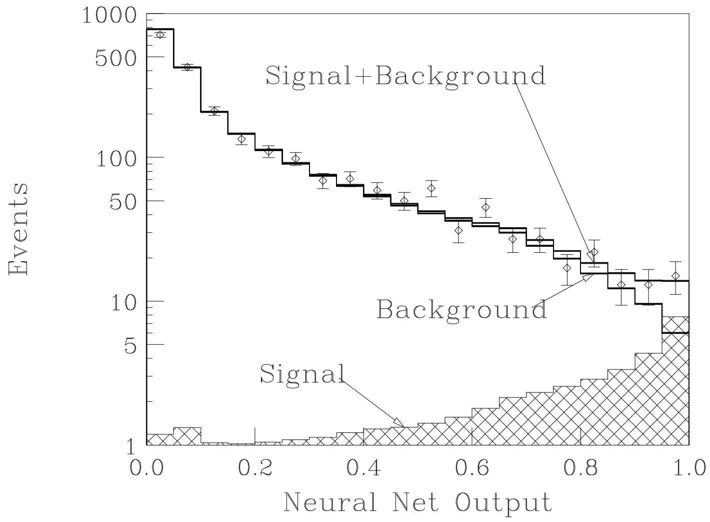
   and computing each event's tag probability as the sum over its jet tag probabilities

*due to muon chamber radiation damage

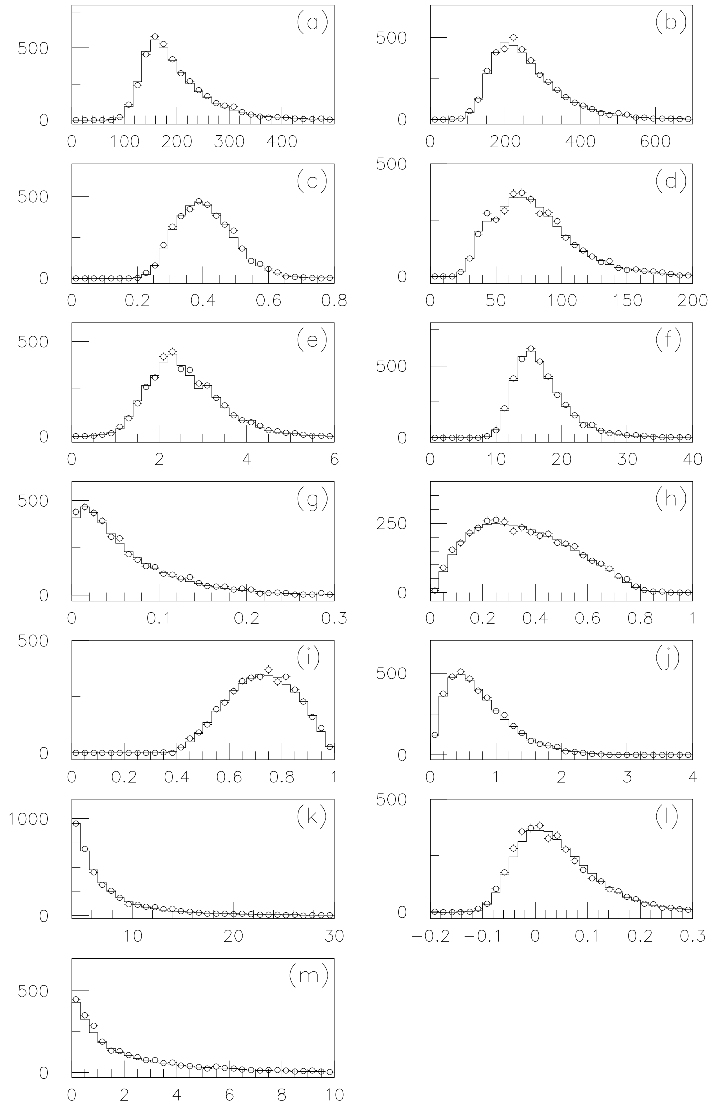


all-hadronic mode: DØ

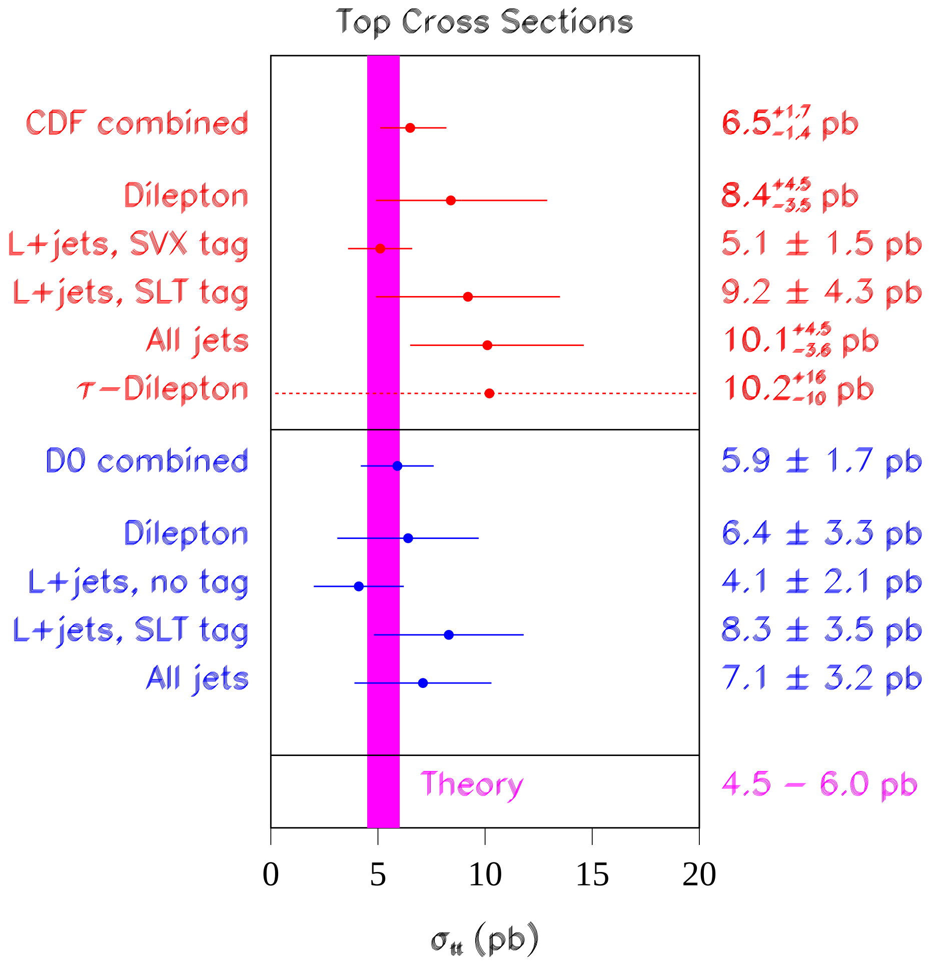
6. Cross-check NN input variables for tagged sample with those obtained from tag probabilities applied to untagged sample
7. Fit NN output to sum of signal & background shapes



Result: $\sigma_{t\bar{t}} = 7.1 \pm 2.8 \pm 1.5$ pb



Top cross section: results

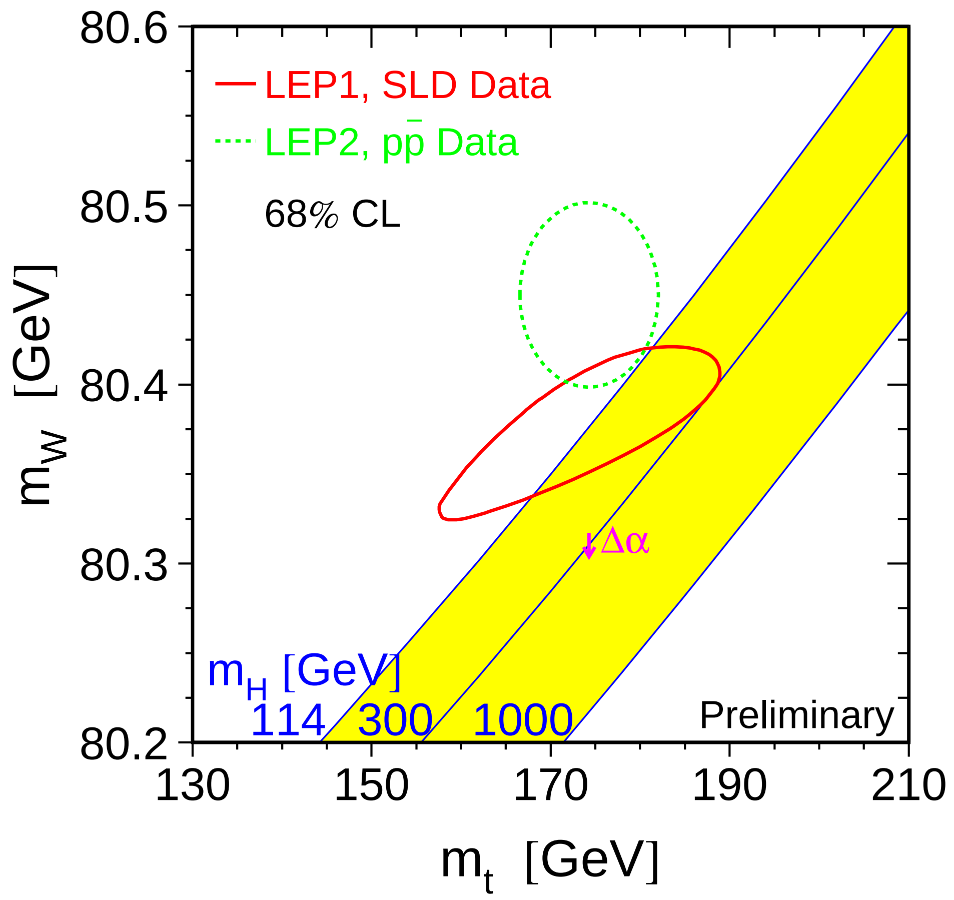


Note that I haven't talked at all about systematic uncertainties.

- In general, the largest uncertainty comes from the efficiency, which depends on the assumed top mass. . .
- The next largest contribution (especially for the all-hadronic channel) is from the uncertainty on the jet energy scale

⇒ see next topic

Top mass



In the grander scheme of things, among the most important tasks of the top quark mass are:

- constrain global EW fits
- (in the SM context) predict M_H

The Tevatron is the only place where m_t can be measured directly!

m_t analyses have been carried out for all three (lepton+jets, dilepton, all-hadronic) channels

Many analysis details (selection criteria, tag rates, . . .) are the same as for the cross section analyses

⇒ will not cover these

Top mass:lepton+jets

Analysis strategy (follow DØ):

1. Require ≥ 4 jets, and use leading 4
2. Correct jet energies to “parton” level (see next slides)
3. Apply a 2C Lagrange multiplier kinematic fit to $t\bar{t} \to \ell\nu bq\bar{q}\bar{b}$:
   - one unknown: p_z^ν
   - three mass constraints:
     - $m_{\ell\nu} = m_{q\bar{q}} = M_W$
     - $m_{\ell\nu b} = m_{q\bar{q}\bar{b}}$
4. There are 12 ways to assign the jets (6 if one is tagged): try all, and use the combination with the smallest

   $$\chi^2 = (\vec{x}_{\text{pred}} - \vec{x}_{\text{meas}})^T \mathbf{V}^{-1} (\vec{x}_{\text{pred}} - \vec{x}_{\text{meas}})$$

   where $\vec{x}$ represents the (jet,ℓ,ν) kinematics, and **V** the corresponding error matrix

   $\Rightarrow$ fitted mass m_{fit} for each event
5. Compute signal likelihood $\mathcal{D}$ for each event (see later)
6. Do all of the previous for signal, background “templates” as well
7. Fit 2D $(\mathcal{D}, m_{\text{fit}})$ distribution to templates for various assumed m_t

   $\Rightarrow$ likelihood as function of m_t
8. Extract m_t from likelihood curve

Intermezzo: Jet energy scale

The measured jet energies have to be corrected before they can be interpreted as parton energies:

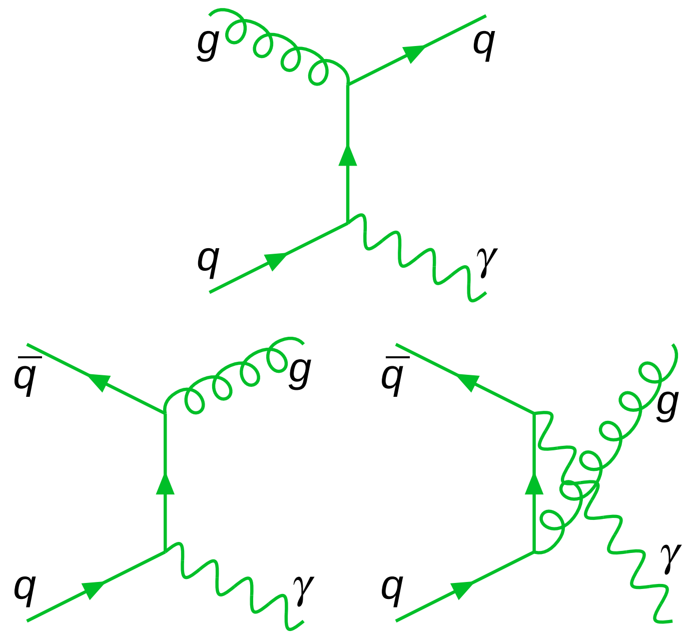
$$E_{\mathrm{corr}} = \frac{E_{\mathrm{meas}} - O}{R(1-S)}$$

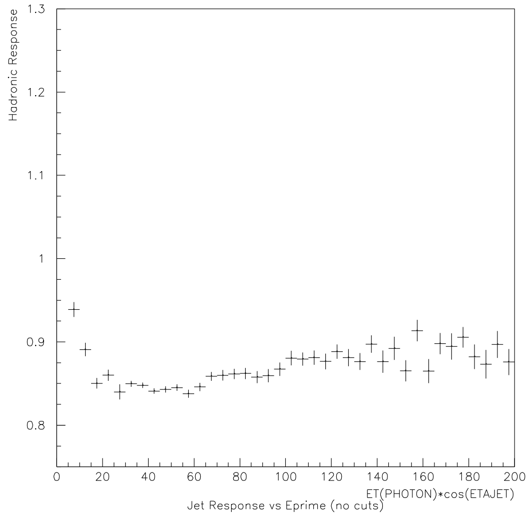
where:

O: offset due to multiple interactions, underlying event, ^{238}U radioactivity
determined from comparing data at different luminosities; zero-bias triggers

R: calorimeter response
determined (as function of E^{jet}) from γ+jet events, using EM scale as reference (use known M_Z)

S: correction for radiation effects
determined from MC, separate for light quark jets, tagged b jets, untagged b jets (depends on jet assignment)



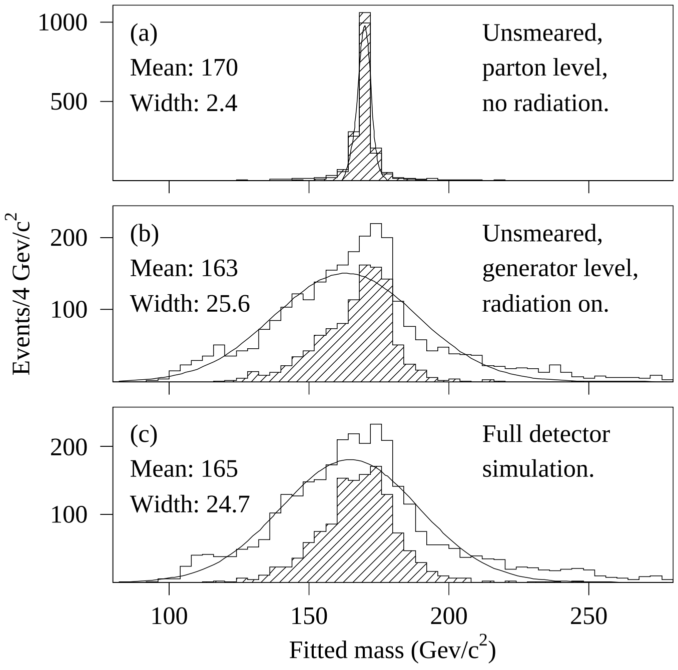


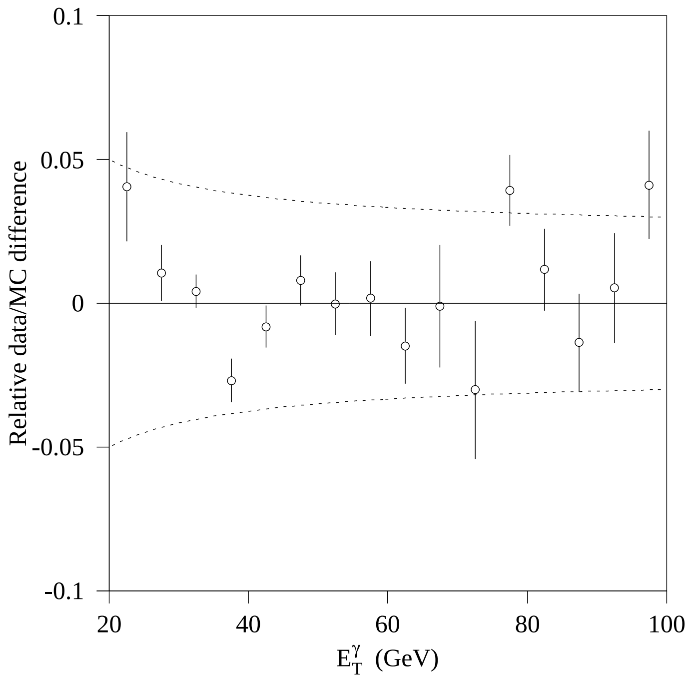
Intermezzo: Jet energy scale

Notes:

- jet energy resolution is dominated by radiation rather than by detector effects!
- jet energy scale uncertainty: $\sigma_E = 0.025E + 0.5$ GeV

CDF uses E/p to measure energy scale, then cross-checks using γ+jet events





Top mass:lepton+jets

At this point, the background is from W+jets and QCD multijets (as for the cross-section analysis).

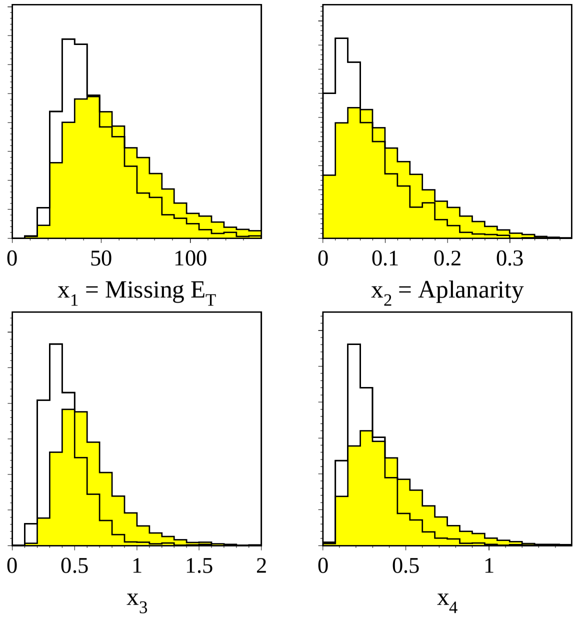
Plot signal and background distributions s_i, b_i of variables x_i only weakly correlated to m_t (and among each other):

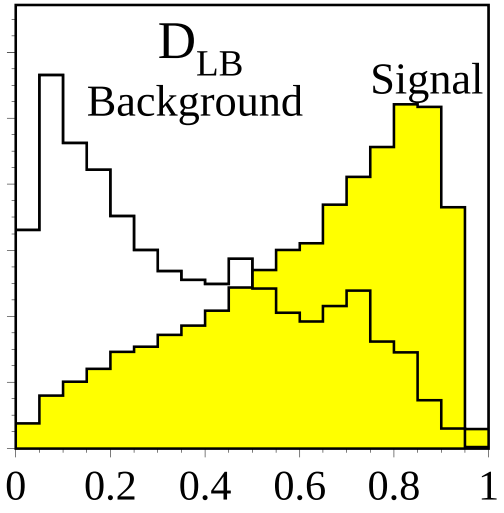
- $\not{E}_T$, $\mathcal{A}$, $\frac{H_{T2} \equiv H_T - E_T^{j1}}{|p_z^\ell| + |p_z^\nu| + \sum_j |p_z^j|}$, $\frac{\Delta R_{jj}^{\min} E_T^{\min}}{E_T^L}$

From these distributions, construct a likelihood for an event to be $t\bar{t}$ as opposed to background:

$$
\begin{aligned}
\mathcal{L}_i &= s_i(x_i)/b_i(x_i), \\
\mathcal{L} &= \prod_{i=1}^{4} \mathcal{L}_i, \\
\mathcal{D} &= \mathcal{L}/(1+\mathcal{L})
\end{aligned}
$$

For untagged events, cut on $\mathcal{D}$

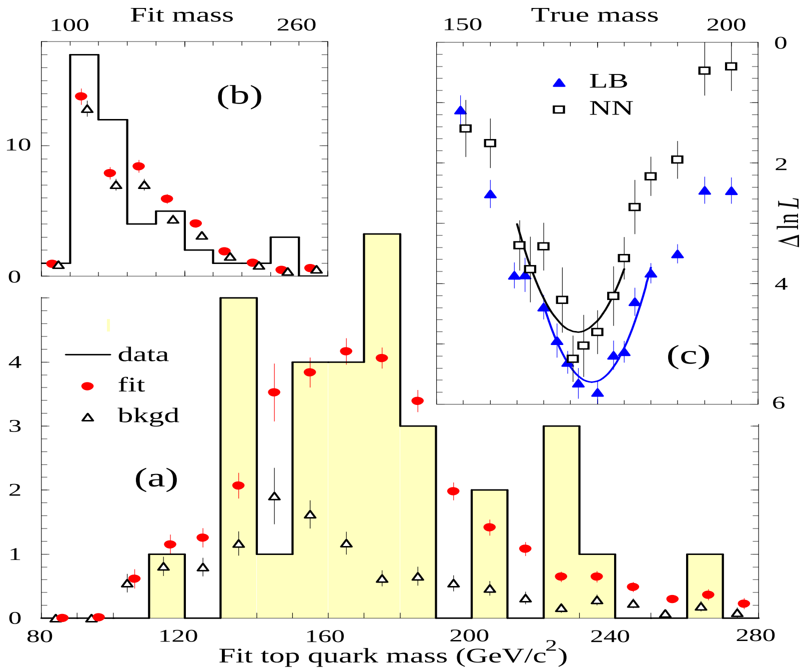




Top mass:lepton+jets

Fit results:

$$m_t = 173.3 \pm 5.6 \text{ GeV}$$



Systematic uncertainties:

Source	$\sigma(m_t)$ (GeV)
Jet energy scale	4.0
$t\bar{t}$ Modeling	1.9
Background modeling	2.5
Noise / multiple interactions	1.3
MC statistics	0.9
Fit method	1.3
Total	5.5

CDF have obtained similar results:

$$m_t = 175.9 \pm 4.8(\text{stat.}) \pm 4.9(\text{syst.}) \text{ GeV}$$

where the systematic uncertainty is again dominated by the jet energy scale uncertainty (4.4 GeV)

Top mass:dilepton channel

Tour de force #3 (and an exercise in advanced statistics)

1. Two ν in final state rather than one ⇒ underconstrained (“-1C”) system
2. *Assume* m_t
   - just enough constraints to “solve” system
   - but not enough to estimate goodness of constraint??
3. . . . But the event should also be consistent with *dynamics*!
   - Mass-dependent top decay spectra from SM couplings

$$P(E_0^\ell|m_t) \sim \frac{d\sigma}{dE_0^\ell} \sim \frac{4m_t E_0^\ell(m_t^2 - m_b^2 - 2m_t E_0^\ell)}{(m_t^2 - m_b^2)^2 + M_W^2(m_t^2 + m_b^2) - 2M_W^4}$$

where E_0^ℓ is the lepton energy in the top rest frame

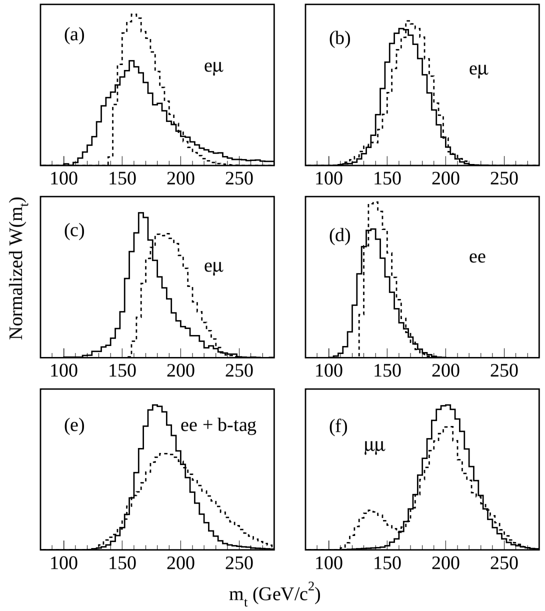
- Parton x values fixed by choice of m_t should be consistent with known parton distribution functions

⇒ weight each event, for each assumed m_t, with

$$w(m_t) = N(m_t)P(E_0^{\ell^+}|m_t)P(E_0^{\ell^-}|m_t)f(x_a)f(x_b)$$

where the normalisation $N(m_t)$ ensures $\langle w(m_t)\rangle = 1$

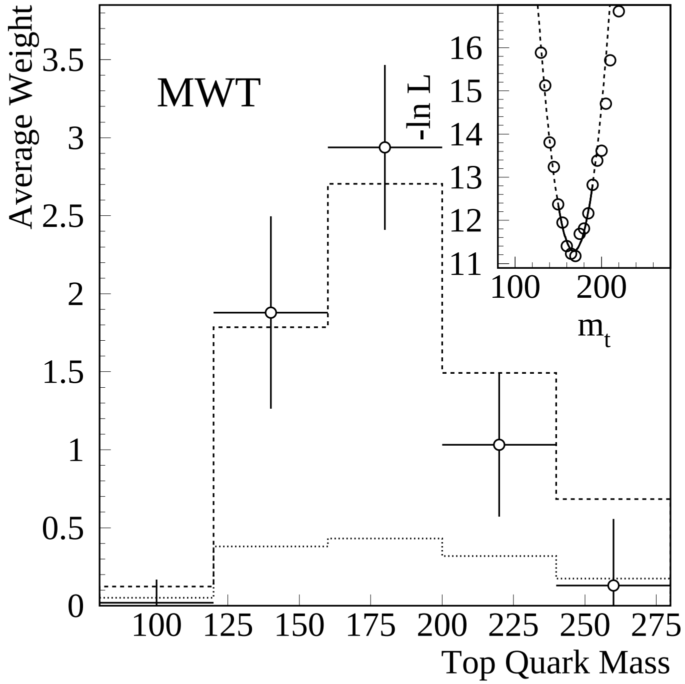
For all (6!) events:



Top mass:dilepton channel

4. Resolutions have to be accounted for:
   - each event's kinematics is smeared many times, and the result is averaged

     (the small event sample helps here. . .)
5. Also average over pairings of jets with leptons
6. Obtain corresponding distributions f_s, f_b for signal, background; normalise data, signal, background to 1
7. Fit signal, background, true m_t to binned $w(m_t)$ distributions



$$\mathcal{L} = \frac{1}{\sqrt{2\pi}\sigma_b} e^{-(n_b-\bar{n}_b)^2/2\sigma_b^2} \frac{(n_s+n_b)^N e^{-(n_s+n_b)}}{N!}$$

$$\times \prod_{i=1}^{N} \frac{n_s f_s(\{w\}_i|m_t) + n_b f_b(\{w\}_i)}{n_s+n_b}$$

$m_t = 168.4 \pm 12.3(\text{stat.}) \pm 3.6(\text{syst.})$ GeV

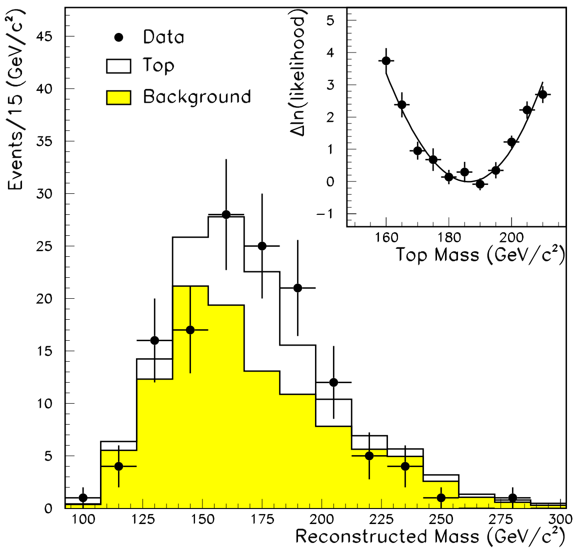
Systematics *again* dominated by jet energy scale (2.4 GeV). Similarly for CDF:

$m_t = 167.4 \pm 10.3(\text{stat.}) \pm 4.8(\text{syst.})$ GeV

Top mass:all-hadronic channel and results

CDF have also performed a mass measurement in the all-hadronic channel (not accessible to DØ because of overwhelming background):

- Analysis as for cross section, but require 6 jets; relax H_T cut, require only 1 b tag
- Apply 3C kinematic fit, assigning tagged jets to be b jets ⇒
  30 combinations (6 in case of 2 b tags), choose combination yielding lowest χ^2

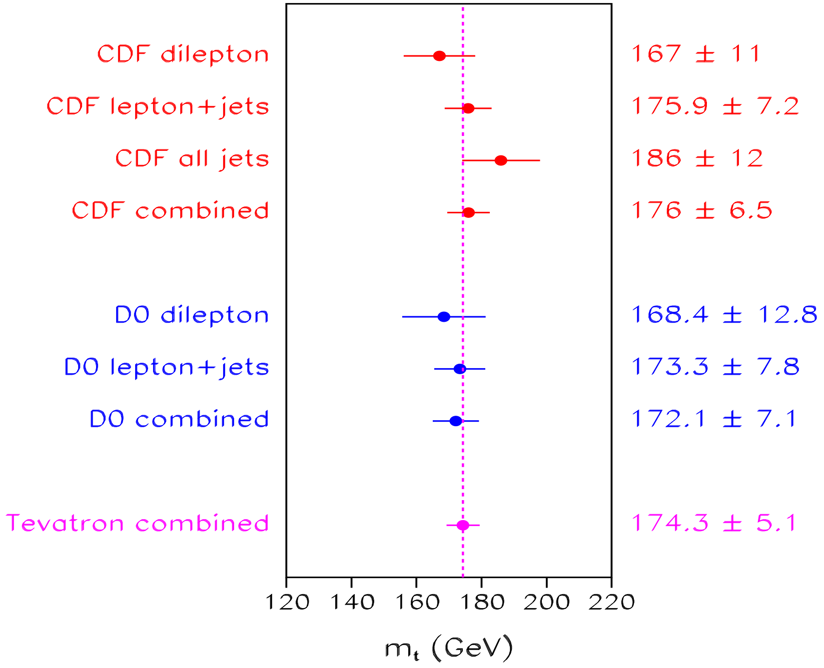


Again, the largest systematic uncertainty in the result

$$m_t = 186 \pm 10(\text{stat.}) \pm 8(\text{syst.})\ \text{GeV}$$

is due to the jet energy scale uncertainty. . .

Combination:



Single top production

As said in the beginning, $|V_{tb}| \approx 1$. *This is true only in the case of three generations.* For more generations the CKM matrix elements are significantly less constrained:

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.9721\text{–}0.9747 & 0.215\text{–}0.224 & 0.002\text{–}0.005 & \ldots \\ 0.209\text{–}0.227 & 0.966\text{–}0.976 & 0.038\text{–}0.044 & \ldots \\ 0\text{–}0.09 & 0\text{–}0.12 & 0.08\text{–}0.9993 & \ldots \\ \ldots & \ldots & \ldots & \ldots \end{pmatrix}$$

This cannot be tested with $t\bar{t}$ production, as

- the extra generations are presumably large $\Rightarrow$ no additional top quark decay modes
- the top decay width cannot be measured ($\ll$ experimental resolution)

However, it would show up as a decreased single top production cross section $\sim |V_{tb}|^2$

The cross section would also be sensitive to other extensions of the “known” electroweak interactions

- extra gauge bosons coupling specifically to the 3rd family, extra scalars, . . .
- many of these lead to an *increased* cross section

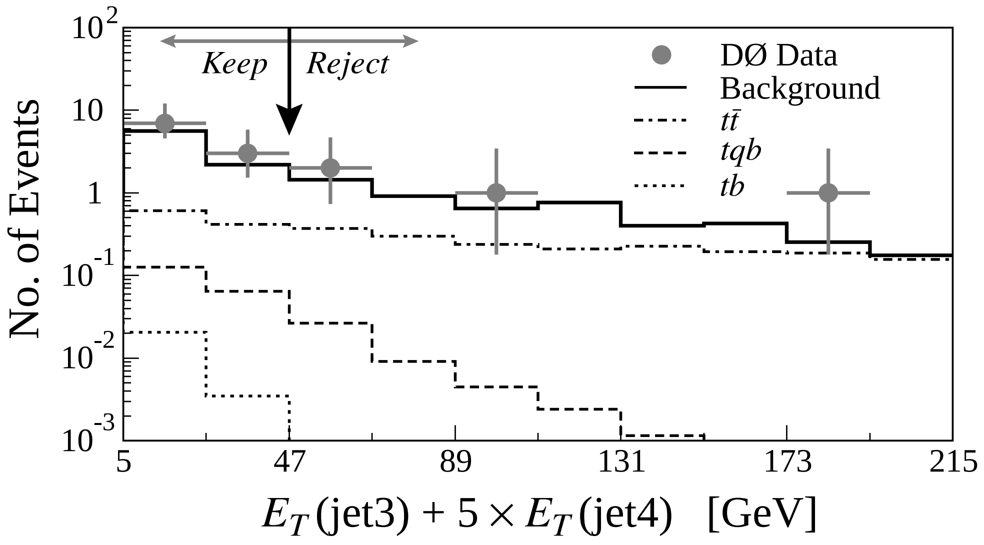
Single top production

The SM single top production cross section is of the same order as that for $t\bar{t}$. At NLO:

$$\begin{aligned}\sigma(q'\bar{q} \to tb) &= 0.73 \pm 0.10 \text{ pb}\\ \sigma(q'g \to tqb) &= 1.70 \pm 0.24 \text{ pb}\end{aligned}$$

However, the background situation is much worse: two (one) jets less for the *s*-channel (*t*-channel) process, and lower $\hat{s}$, so QCD and W+jets are expected to be overwhelming

DØ has been brave enough to try nevertheless. . .

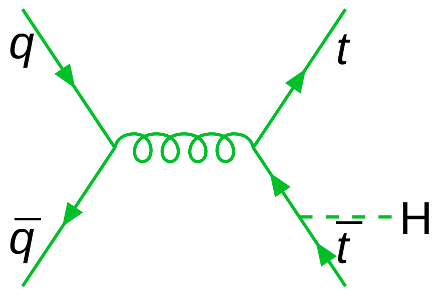


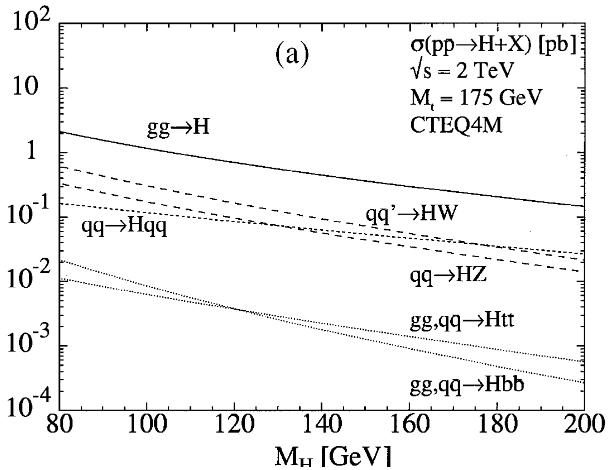
Result:

$$\begin{aligned}\sigma(q'g \to tqb) &< 58 \text{ pb},\\ \sigma(q'\bar{q} \to tb) &< 39 \text{ pb}\end{aligned}$$

An opportunity for Higgs searches

Consider the following process:



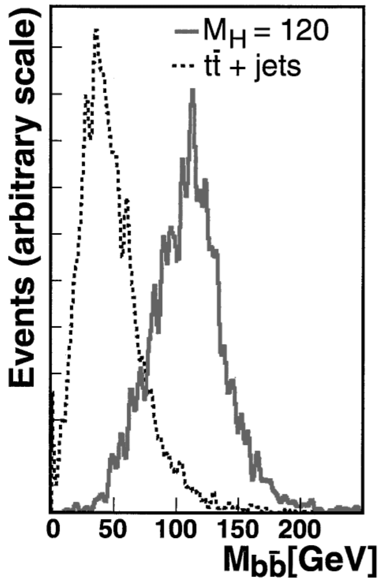


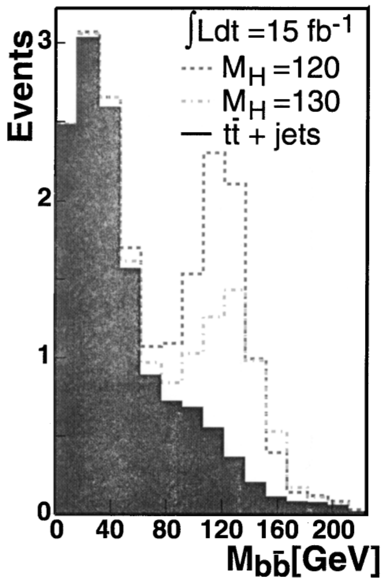
(and with H branching off t)

- adds another heavy boson to already heavy $t\bar{t}$ system
- but coupling $g_{\mathrm{ttH}} = m_t/v \Rightarrow$ non-negligible cross section

This final state has a low cross section (requiring full Run II luminosity), but is practically background free (backgrounds from $t\bar{t}jj$, $t\bar{t}W$, $t\bar{t}Z$)

- $W^+W^-b\bar{b}b\bar{b}$ for $M_H < 140$ GeV
- $W^+W^-W^+W^-b\bar{b}$ for $M_H > 140$ GeV





Prospects for Run II

- Top quark analysis in Run I at the Tevatron has been challenging, but very rewarding
  - analysis of Run I data is in fact *still* going on: so far we've been smart only where it was really necessary!
    - ∗ a new DØ m_t analysis (with substantially reduced uncertainties) has been presented at conferences
- In Run II ($\mathcal{O}$(10 fb^{-1})), expect improvements in several areas:
  - statistics: factor 100 from luminosity, factor 1.4 from increase of $\sqrt{s}$: $1.8 \to 1.96$ TeV
  - b tagging: both experiments have improved their tracking and vertexing
  - systematics (especially for m_t): jet energy scale uncertainty is to a large extent *statistics* dominated
  - systematics: effects of *e.g.* gluon radiation are becoming better understood $\Rightarrow$ more reliable MC predictions?

These improvements won't come overnight – but Run II data are being analyzed *now*!