$\boxed{\text{Seeking Truth in Proton-Antiproton Collisions}}$

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Part I

- Top Quark Physics
- Recent Results from CDF
- Prospects with CDF II

Part II

- TRIUMF's role in Canadian Subatomic Physics
- The Science Agenda for TRIUMF
  - The Next Five Years
  - ···and the Next Ten
- Some Concluding Remarks

TRIUMF, 24 May 2000

$\boxed{\text{The Standard Model}}$

The ingredients of the SM are

- 12 fermions
  - 6 quarks (u, d, s, c, b, t)
  - 6 leptons (e^-, ν_e, μ, ν_μ, τ, ν_τ)
- 3 electroweak bosons (W^+, W^-, Z°, γ)
- 8 gluons to describe the strong force
- ?? to describe gravity

Enormously successful paradigm since $\sim$ 1975

- Predicted rich phenomenology
- Accurate! (eg. $\delta_{M_z}/M_z \sim 8 \times 10^{-5}$)

$\boxed{\text{Why a Top Quark?}}$

In 1977, Lederman et al. reported a new resonance

- Mass of 9.54 ± 0.04 GeV/c^2
- Decayed to $\mu^+\mu^-$ pairs

$\Rightarrow$ A fifth quark

  - Production rate $\Rightarrow Q = -1/3$

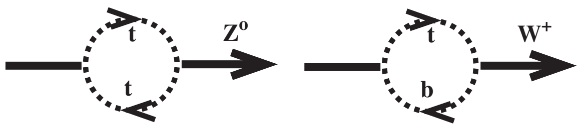
Studies established that it should have a partner

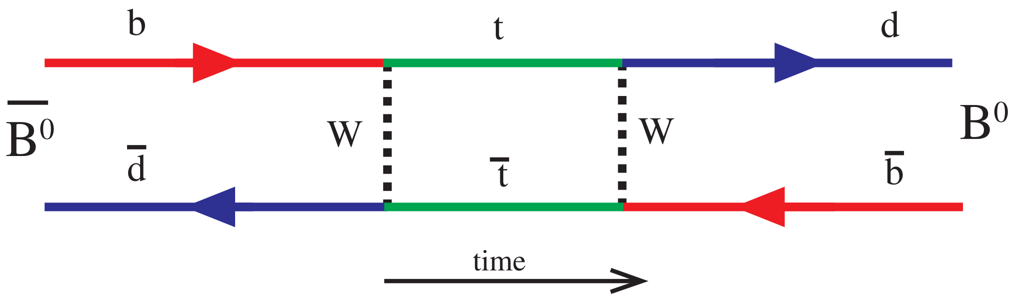
- Certain types of decays didn't occur
  - decays like $b \to \mu^+\mu^- d$ not observed
- $e^+e^- \to b\bar{b}$ scattering suggested an $SU(2)$ state

The Top Quark Mass in the Standard Model

The SM "needs" a massive top quark

- Loop effects in SM driven by M_{top}
  - W/Z boson mass ratio
  - $b-\bar{b}$ mixing





However, no real information on M_{top}

- In 1983, knew it had to be large ($\gtrsim$ 20 GeV/c^2)

- Searches limited by collider centre-of-mass energies

SM Top Quark Phenomenology

Top quarks decay via the weak force

- Predict $\sim 100\%$ $t \rightarrow W^+ b$
- For heavy top ($M_{top} \gtrsim 100 - 120$ GeV/c^2), decays before it hadronises

Can be viewed as "pure" β decay

$$\begin{aligned}\Gamma_{\mathrm{top}} &= \frac{G_F M_t^3}{8\sqrt{2}\pi}\left(1 - \frac{M_W^2}{M_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{M_t^2}\right) \\ &\sim 175\ \mathrm{MeV}\left(\frac{M_t}{M_W}\right)^3 \sim 2\ \mathrm{GeV}\end{aligned}$$

- Toponium doesn't have time to form
- T mesons $\sim$ degenerate (if there was time...)

Decay dominated by "longitudinal W^+"

- Means the W^+ prefers helicity 0
- Result of large top and W^+ mass

$\boxed{\text{The Hunt for the Top Quark}}$

SM didn't tell us the top quark mass

- Search for evidence in e^+e^- and $p\bar{p}$
  - Rate decreases sharply with M_{top}
  - By 1989, had set limit of $M_{top} > 77$ GeV/c^2

By 1992, had new measurements of M_Z and M_W

- SM predicted top quark with $M_{top} \gtrsim 140$ GeV/c^2
- Only place to look was in high-energy $p\bar{p}$ collisions
- Two experiments
  - Collider Detector at Fermilab (CDF)
  - DØ

Discovery of Top

Hints of top production appeared as early as 1993

- CDF published a 61 page PRD in Sep 1994
- Gave "cagey" label to the reports
  - "Evidence for top quark production..."
- DØ's analysis not as definitive

With a factor of two more data, result was unequivocal

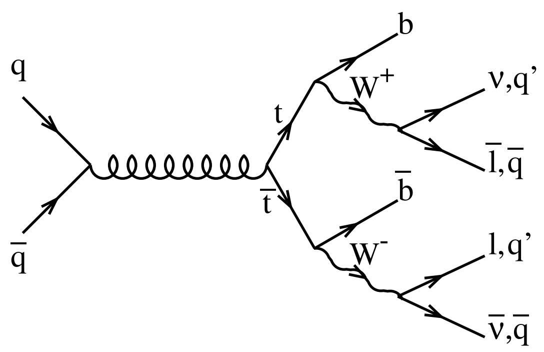
- April 1995, both collaborations announced discovery
- Confirmed SM predictions – $M_{top} \sim 170 - 190$ GeV/c^2
- Gave us a "free quark" system to study

  ⇒ New frontier in particle physics

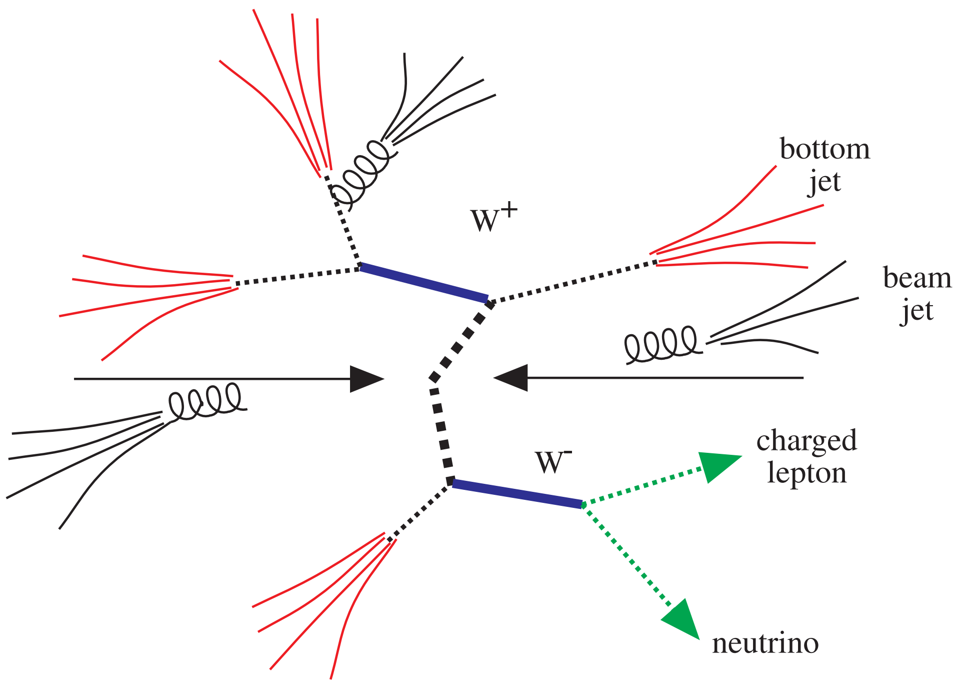
Reconstructing Top

Since top is pair-produced and β decays

- Expect to see 6 final state particles



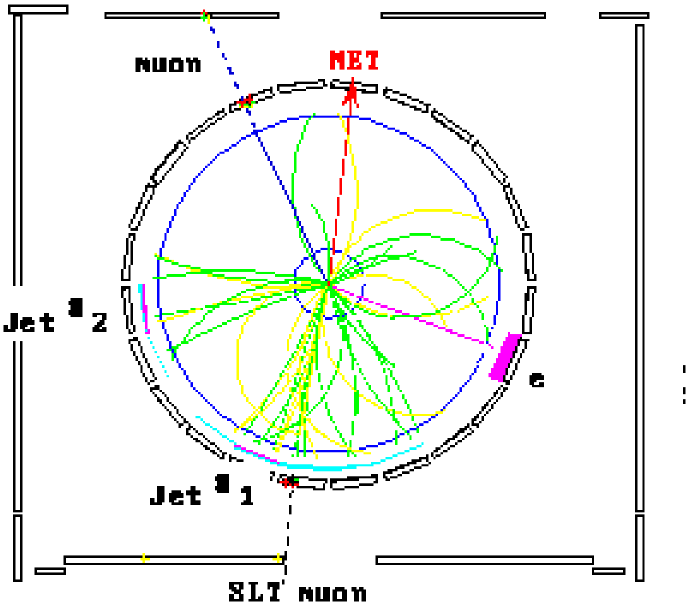
Life is normally not that easy – in reality:



Identifying Top Decays in $p\bar{p}$ Collisions

In order to identify top candidates

- Search for $W \to l\nu_l$ candidate
  - Electron or muon with $P_T > 20$ GeV/c
  - Missing transverse energy $\not{E}_T > 20$ GeV
- Search for at least one b jet
  - Most effective tool is to find a secondary vertex
- Some evidence of other W in event
  - Either two more jets or another lepton



The Status of Top Today

CDF and DØ collected ~ 110 pb^{-1} of data in 92-96

- Lepton + Jets mode (for mass analysis)
  - lepton $P_T > 20$ GeV/c and $\not{E}_T > 20$ GeV
  - ≥ 3 jets, $E_T > 15$ GeV and $|\eta| < 2$
  - Require 1 b-tagged jet OR a 4th jet with $E_T > 15$
  - $\Rightarrow$ 76 candidates (expect 31 ± 7 bkg)

- Dileptons
  - 2 leptons with $P_T > 20$ GeV/c
  - Remove Drell-Yan and Z° background
  - $\Rightarrow$ 9 candidates (2.4 ± 0.5 events bkg)

- All hadronic decays
  - between 5 and 8 jets ($E_T > 15$ GeV and $|\eta| < 2.0$)
  - $\sum E_T > 300$ GeV + additional kinematic cuts
  - $\Rightarrow$ Observe 187 b-tagged jets (142 ± 11 expected bkg)

What are the Interesting Top Properties?

- Top Quark Mass
  - SM constrains it to M_W/M_Z
  - Important consistency check of theory

- Top Quark Production Cross Section
  - Predicted by QCD with less uncertainties than σ_b
  - Look for single top production

- Top Quark Decay Rates
  - Measured $t \to W^+b/t \to W^+q$
  - Look for $t \to H^+b$

- Top Quark Decay Kinematics
  - SM expects decay to be polarized
  - Have made first measurement of polarization

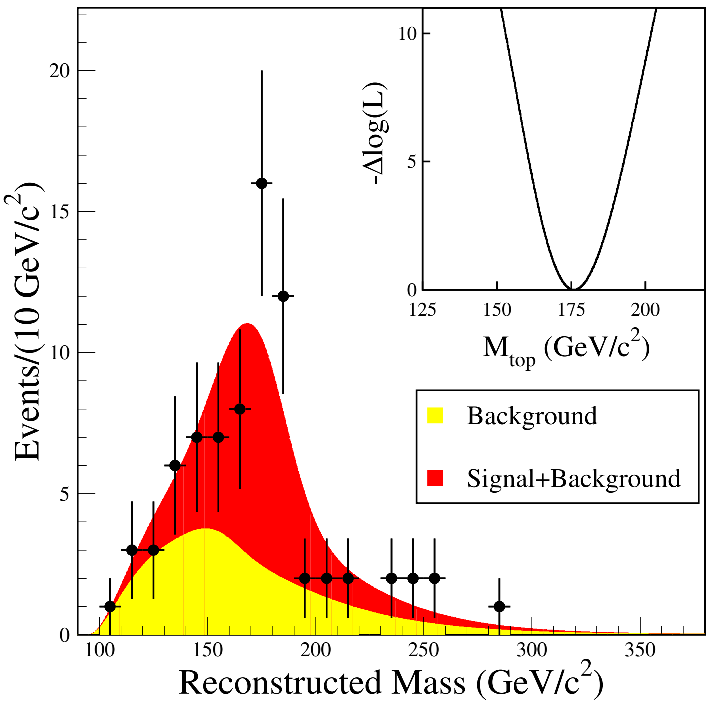
- Single Top Production

Top Quark Mass

Measurements now limited by statistical uncertainties

- Overall systematic uncertainty is ~ 5 GeV/c^2
  - Dominated by uncertainties in soft gluon contributions and energy scale

- Run I statistics limit systematic uncertainty

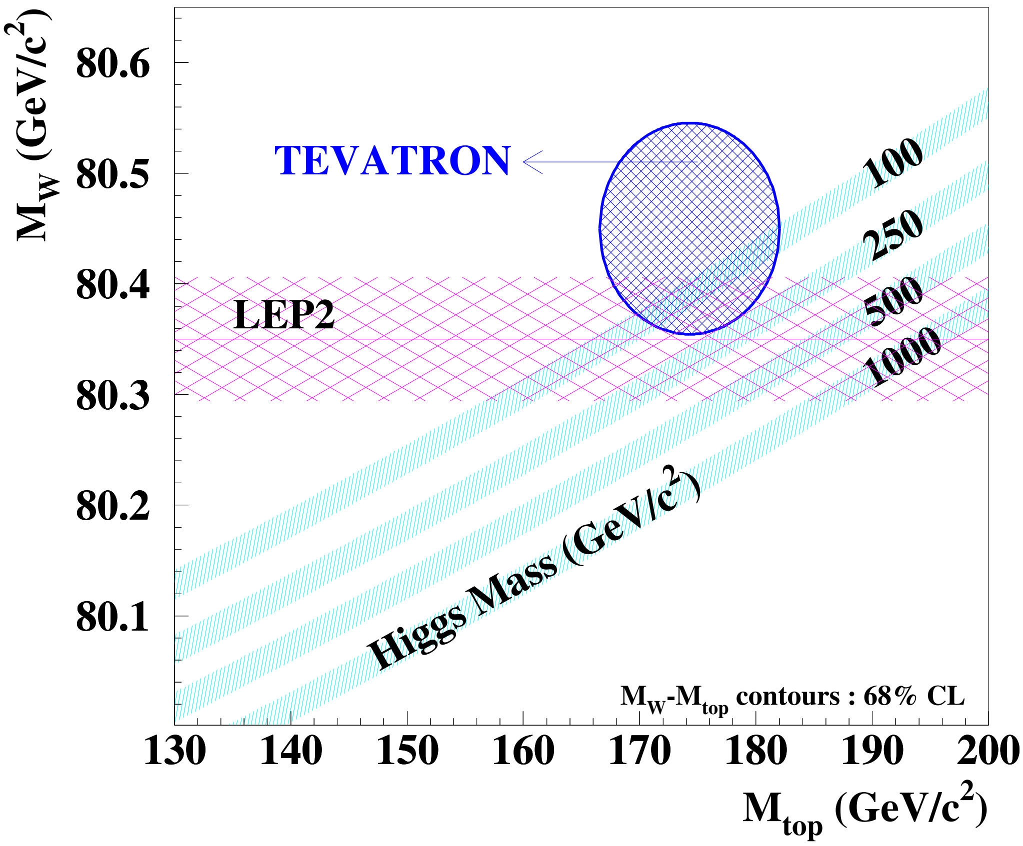


The final Run I values are

$$
\begin{aligned}
M_{top} &= 176.0 \pm 6.5 \text{ GeV c}^2 \text{ (CDF)} \\
M_{top} &= 172.1 \pm 7.1 \text{ GeV c}^2 \text{ (DØ)} \\
M_{top} &= 174.3 \pm 5.1 \text{ GeV c}^2 \text{ (RunI)}
\end{aligned}
$$

Latest W boson mass results

$$M_W = 80.433 \pm 0.079 \text{ GeV c}^2 \quad \text{CDF}$$
$$M_W = 80.474 \pm 0.093 \text{ GeV c}^2 \quad \text{D0}$$
$$M_W = 80.350 \pm 0.056 \text{ GeV c}^2 \quad \text{LEP2}$$

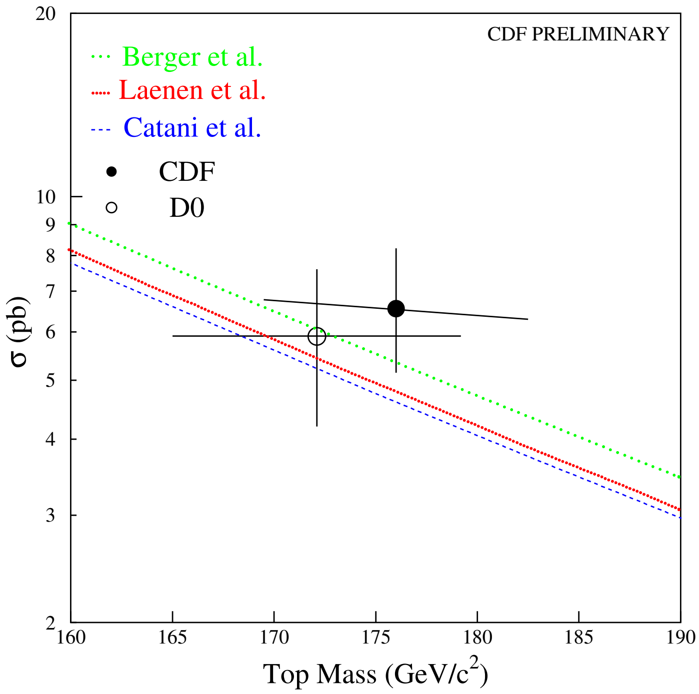


Top Quark Production Cross Section

The cross section obtained by a fit to

- Lepton + jets, dileptons and all hadronic event rates
- Depends on M_{top} because of acceptance
- Recent improvement is more accurate b-tagging efficiency

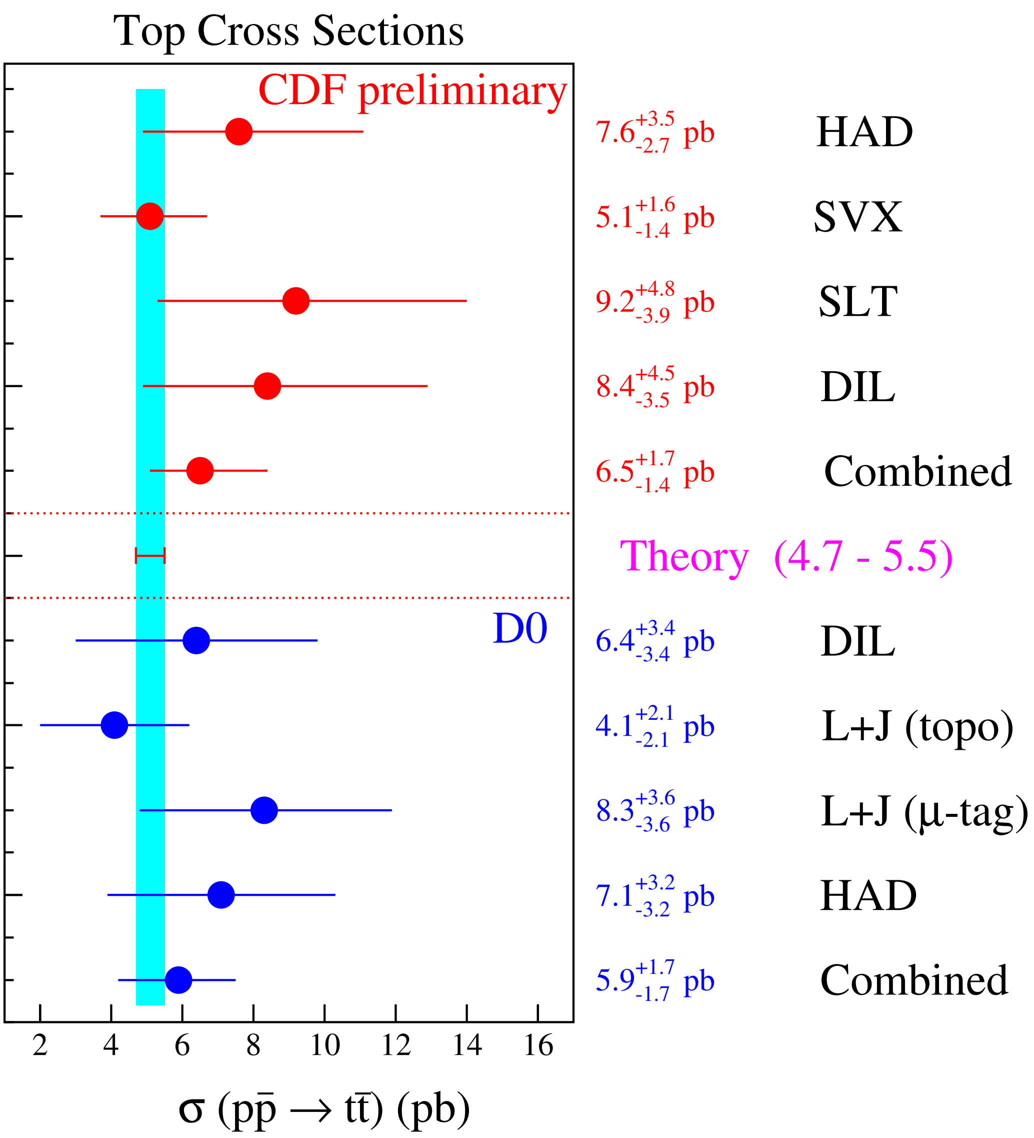
$$\sigma_{t\bar{t}} \;=\; 6.5^{+1.7}_{-1.4} \text{ pb}$$



- Theory predictions range from 4.7 to 5.5 pb

Comparison with DØ

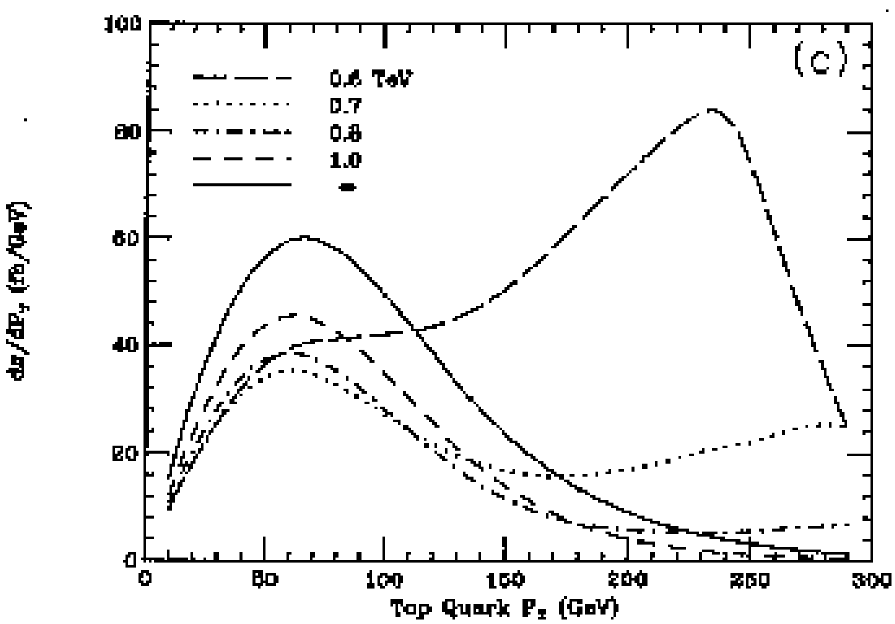
Measurements by DØ also quite consistent



Top Quark Transverse Momentum

SM predicts top quarks produced "back-to-back"

- Broad P_T distribution – $< P_T > \sim M_{top}/2$
- Non-SM predictions can be quite different
  - Can test models (such as Top colour or ADD)



Limited statistics and experimental resolution present challenge

- Produce a set of confidence limits on $\frac{d\sigma_t}{dP_T}$
- Limited to large bins ($\Delta P_T = 75$ GeV/c)

Event Selection

Use the "standard" lepton + jets event selection:

- Single isolated $e(\mu)$ having $P_T > 20$ GeV/c and $|\eta| < 1.0$
- $\not{E}_T > 20$ GeV
- ≥ 4 jets, 3 with $E_T > 15$ GeV and $|\eta| < 2.0$
  - fourth with $E_T > 8$ GeV, $|\eta| < 2.4$
- To increase signal significance, require that

$$N_{\text{jet15}} \geq 4 \text{ the or } N_{tag} \geq 1$$

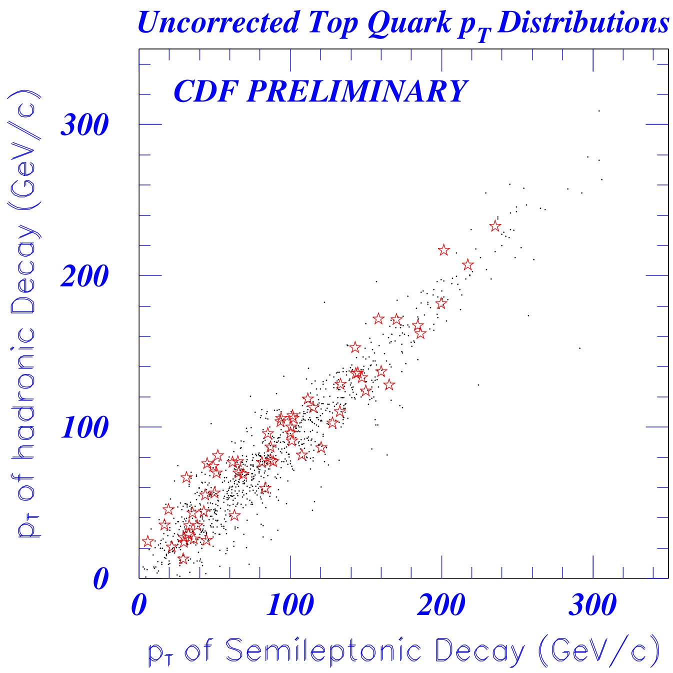
Kinematically fit event, constraining $M_{top} = 175$ GeV/c^2

- Require $\chi^2 < 10$

$\Rightarrow$ Left with 61 events

Measurement of P_T

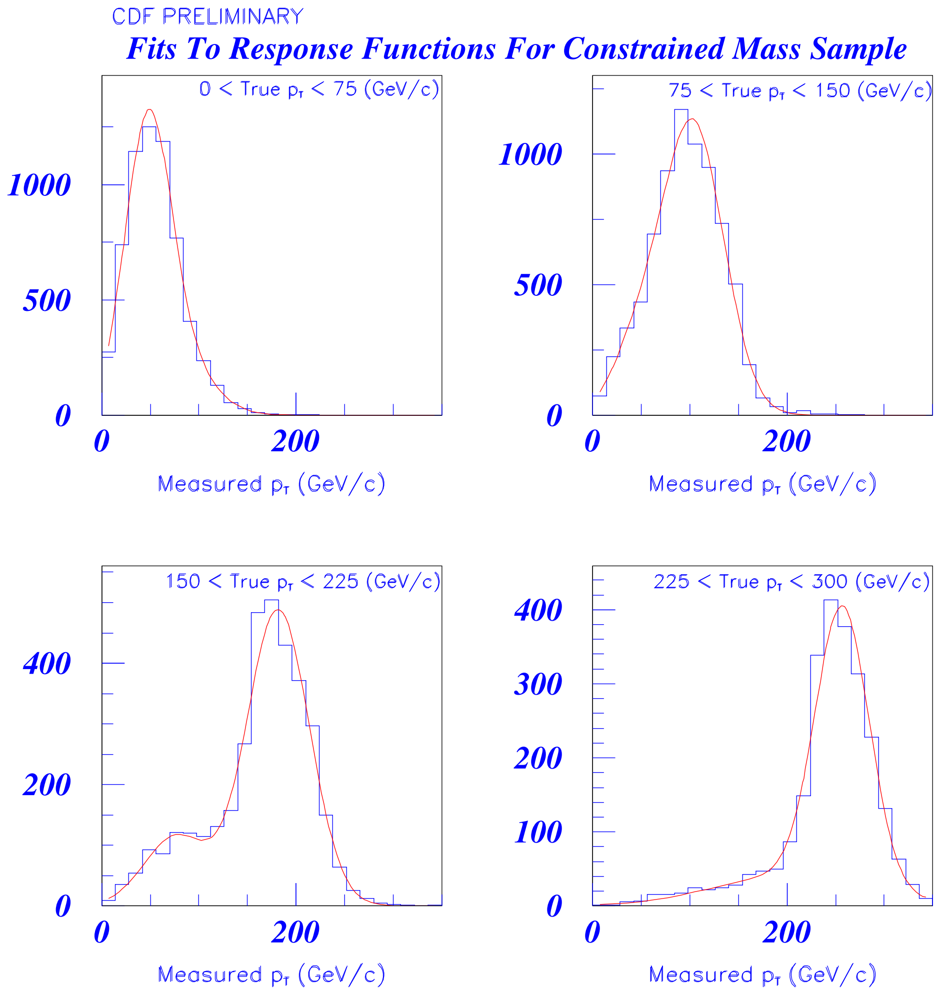
Measurements on lepton-side and jet-side are strongly correlated!



- Make measurement using only jet-side top quarks

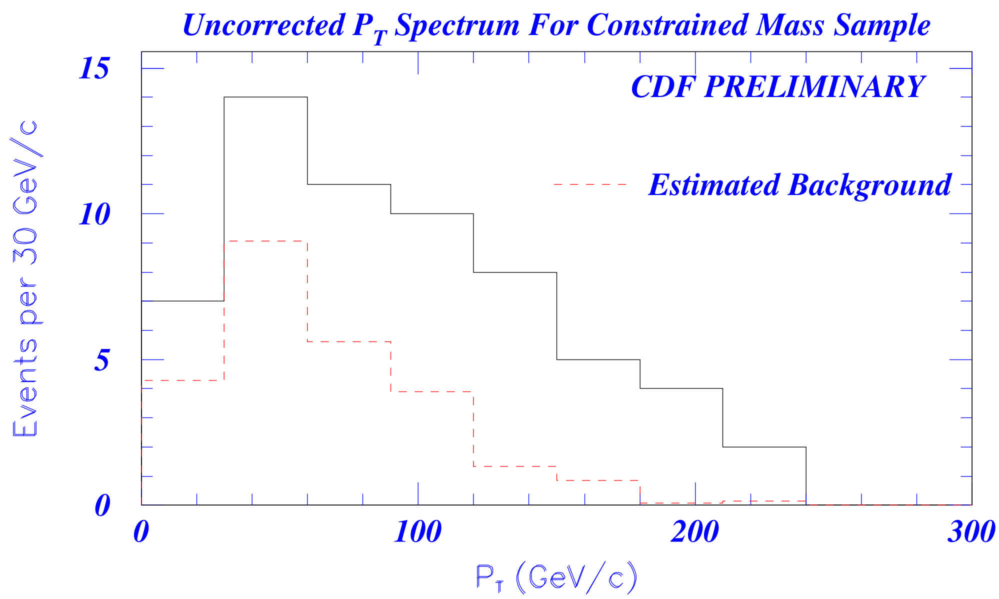
P_T Response Functions

Measured P_T smearing using MC/detector simulation



- Use standard HERWIG MC calculations
- Most smearing arises from incorrect jet assignments

Uncorrected P_T Distribution



- 61 events pass selection criteria
- Background distribution normalized to estimated rate
  - We estimate $N_{bgd} = 31.9 \pm 4.6$ events

Resulting Fitted P_T Distribution

Perform unbinned likelihood fit

- Include four response functions and bkg shapes
- Fit tagged and untagged events with different templates
- Use "bootstrap" technique to minimize assumptions about shape of P_T spectrum within each true bin
- Define

$$R_i \equiv \frac{\text{fraction in } i\text{th bin}}{\sigma_{t\bar{t}}}$$

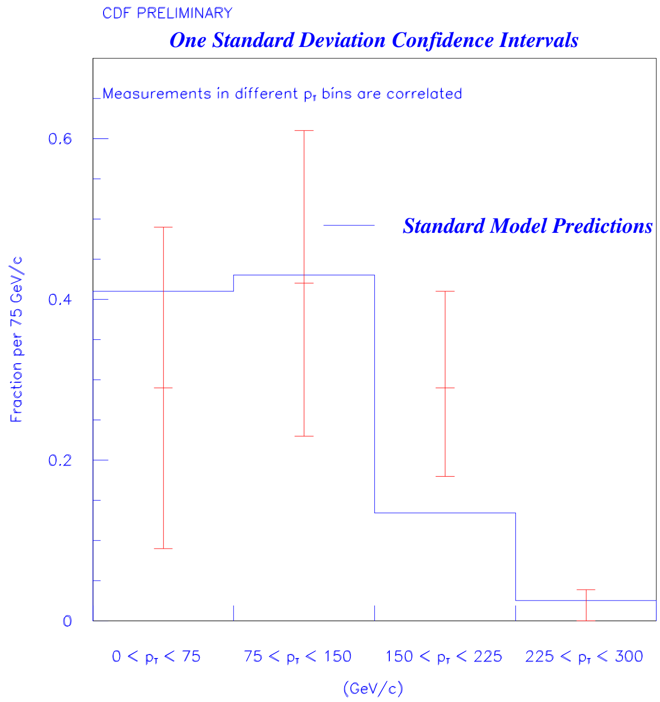
Apply P_T-dependent acceptance correction

- Acceptance increases with P_T

$$\begin{aligned} R_1 &= 0.21^{+0.22}_{-0.21} \\ R_2 &= 0.45^{+0.23}_{-0.23} \\ R_3 &= 0.34^{+0.14}_{-0.12} \\ R_4 &= 0.000^{+0.031}_{-0.000} \end{aligned}$$

Top Quark Differential Cross Section

$$R_1 + R_2 = 0.66^{+0.17}_{-0.17}(\text{stat})^{+0.06}_{-0.06}(\text{syst})$$
$$R_4 < 0.16 \text{ at } 95\% \text{ C.L.}$$



P_T Bin	Measured Fraction of Top Quarks
$0 < P_T < 75$ GeV/c	$R_1 = 0.21^{+0.22}_{-0.21}(\text{stat})^{+0.10}_{-0.08}(\text{syst})$
$75 < P_T < 150$ GeV/c	$R_2 = 0.45^{+0.23}_{-0.23}(\text{stat})^{+0.04}_{-0.07}(\text{syst})$
$150 < P_T < 225$ GeV/c	$R_3 = 0.34^{+0.14}_{-0.12}(\text{stat})^{+0.07}_{-0.05}(\text{syst})$
$225 < P_T < 300$ GeV/c	$R_4 = 0.000^{+0.031}_{-0.000}(\text{stat})^{+0.019}_{-0.000}(\text{syst})$

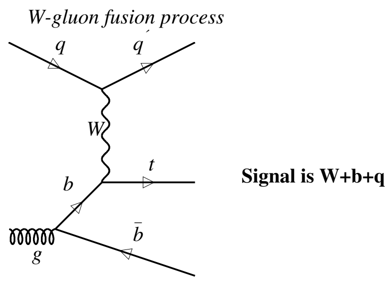
Single Top Production

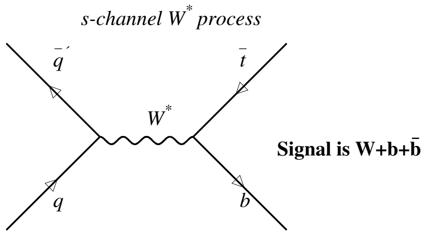
Single top production is a much lower rate process

- Sensitive to Γ_t
- Also could have contributions from non-SM sources

There are two primary SM production processes

1. t-channel $W-g$ fusion $\Rightarrow W^+bq$ final state
2. s-channel W^* process $\Rightarrow W^+b\bar{b}$ final state





- Predicted cross sections are 1.7 ± 0.3 and 0.7 ± 0.1 pb

Search Technique

Kinematics of production processes different

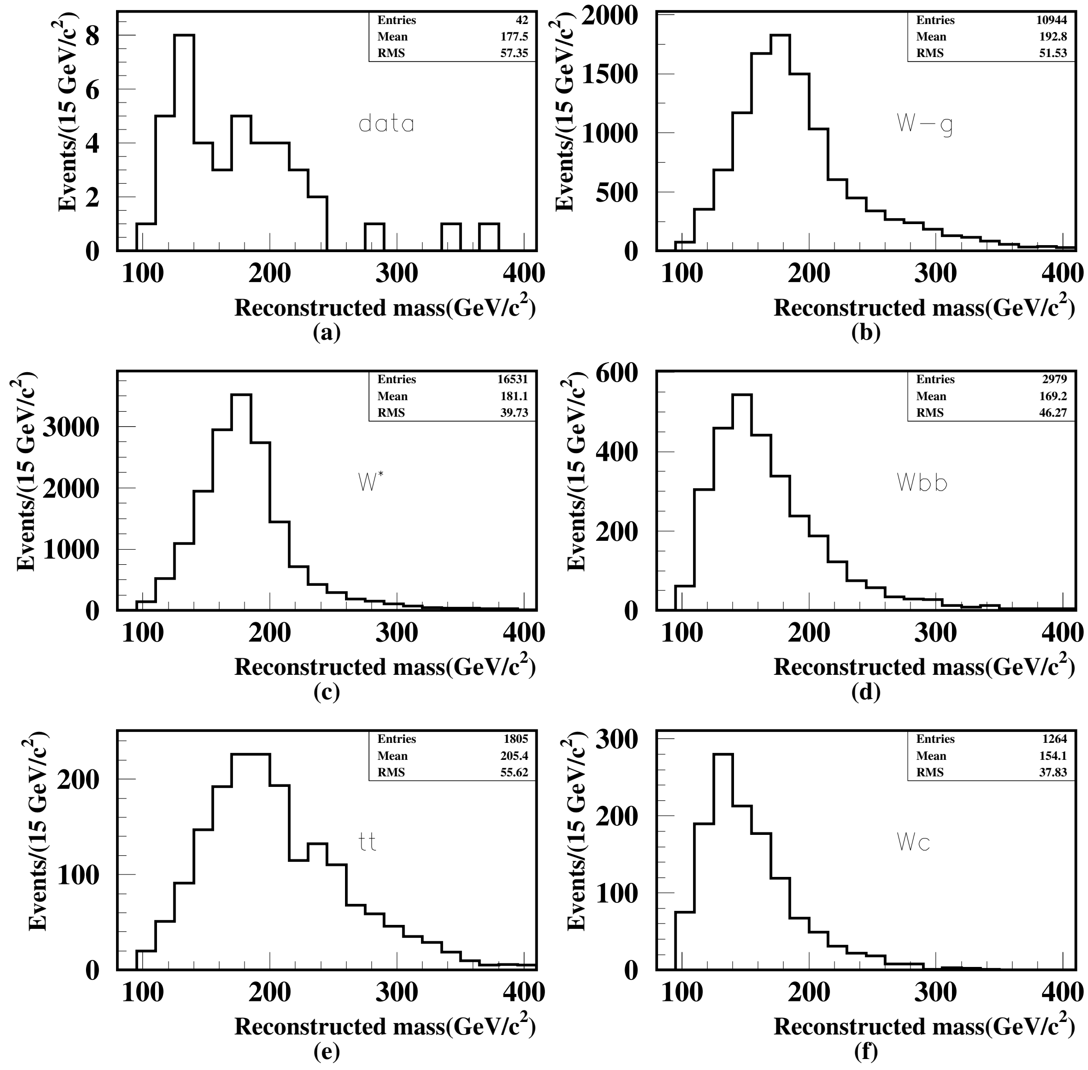
- Use the same selection for both processes
  - 1, 2 or 3 jets with $E_T > 15$ Gev and $|\eta| < 2.0$
  - At least one b-tagged jet
  - Require $140 \leq M_{top} \leq 210$ GeV/c^2
- Fit H_T distribution with signal and background terms

$$H_T \equiv \sum_{\text{partons}} E_T$$

	W^*	W-gluon
σ_{theory} (pb)	0.73 ± 0.10	1.7 ± 0.3
Integrated luminosity (pb^{-1})	106 ± 4	106 ± 4
$W + n$ jet acceptance (%)	4.5 ± 0.7	6.7 ± 1.0
SVX b-tag efficiency (%)	37.5 ± 3.1	24.8 ± 2.0
Number of expected events	1.3 ± 0.3	3.0 ± 0.6

Top Mass Reconstruction

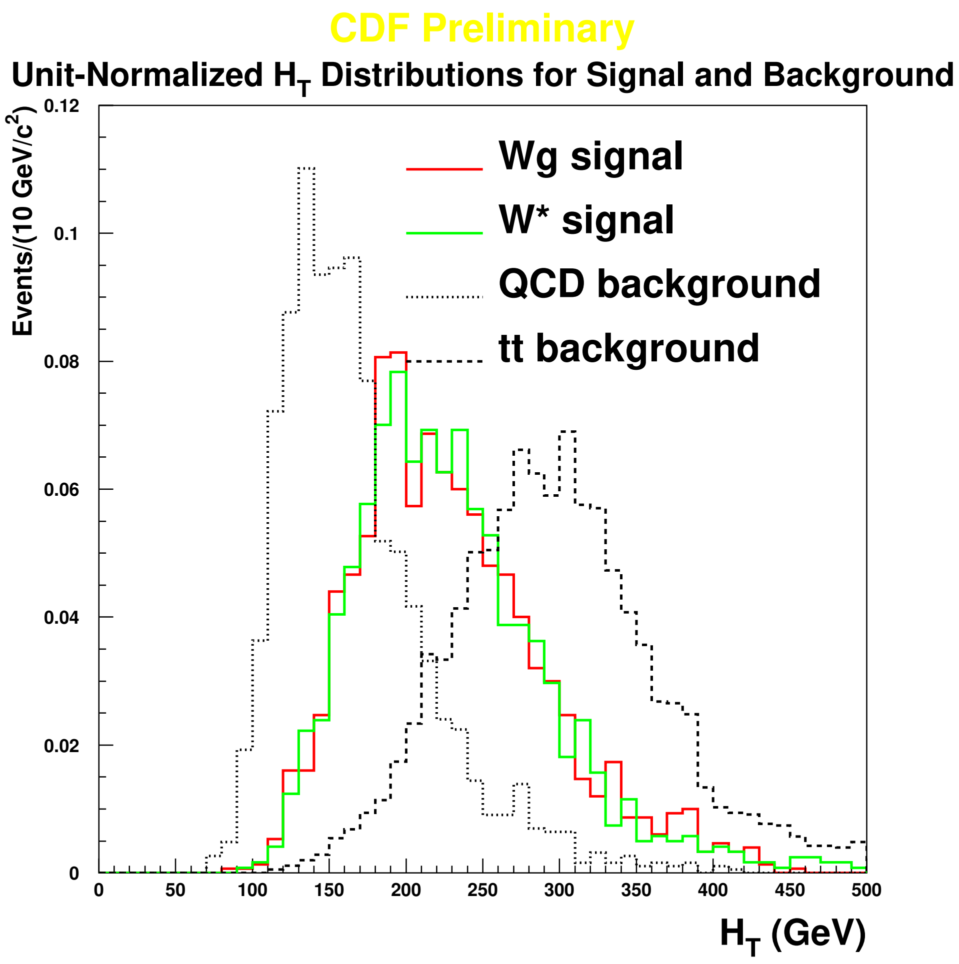
CDF preliminary



H_T Reconstruction

The variable H_T is an effective discriminator

- QCD Background
- $t\bar{t}$ background
- Single top signal



Results of Search

Observed 65 events in this sample

- Largest single background are mistags
  - $t\bar{t}$ itself is a problem now

Process	Event Yield
Mistags	25.9 ± 7.5
$Wb\bar{b} + Wc\bar{c}$	28.7 ± 7.5
Wc	17.2 ± 6.2
Non-W	12.1 ± 4.1
Miscellaneous	5.1 ± 0.9
After M_t cut	54 ± 11
$t\bar{t}$	8.4 ± 2.7
W-gluon	3.0 ± 0.6
W^*	1.3 ± 0.3
Total expected	67 ± 11
Observed	65

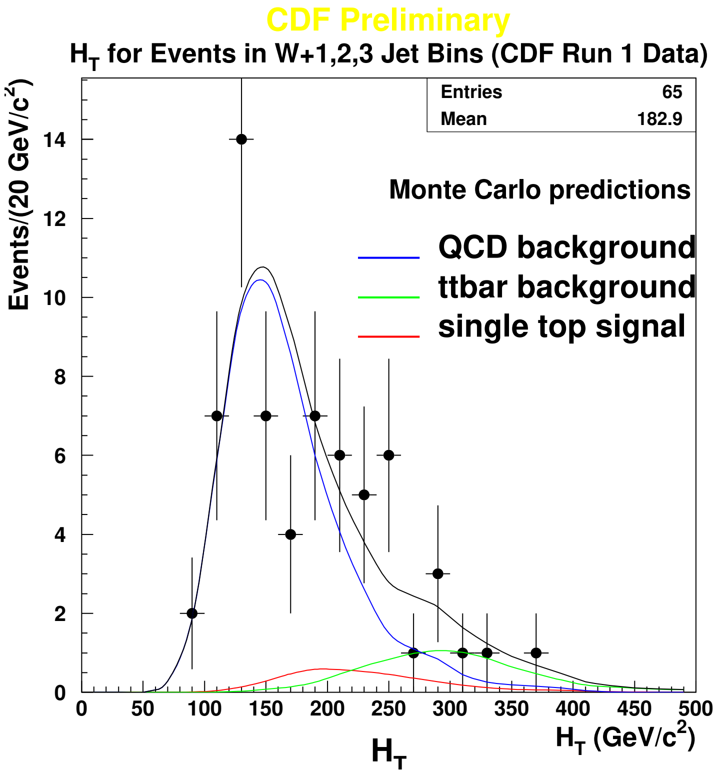
Not yet sensitive to SM single top rate

- Can set limits on total single top rate

Single Top Production Cross Section Limits

Use H_T distribution to fit signal and background shapes

- Set upper limit using a Bayesian technique
- Fit gives $\sigma_t < 13.5$ pb at 95% CL



Still well away from SM rate

- Can conclude that there is no huge anomaly
- It is a feasable measurement for Run II
  - Can get $S/N = 2.9$ on $W + 2, 3$ jet sample

Run II Forecasts

Run II will start this summer at $\sqrt{s} = 2.0$ TeV

- CDF will begin with engineering run (no SVX II)
- Both detectors will be completed by end of 2000
- Physics running will commence in 2001

Will be worth the wait

- Begin with ~ 3 fb^{-1}/year per detector
- Finish up with ~ 5 fb^{-1}/year
- Literal "Top Factory" with
  - 300 dilepton events
  - 3000 tagged lepton+jet events
  - 1500 events in "mass sample"

Top Physics Goals in Run II

Mass analysis uncertainties scale with statistics

- Can expect $\delta M_t \sim$ 3.0~GeV/c^2
- With $\delta M_W \sim$ 40 MeV/c^2

$$\frac{\delta M_{Higgs}}{M_{Higgs}} \sim 40\%$$

- Powerful “pointer” for LHC searches

Measure angular correlations and decay kinematics

- Polarization of W^+ will be measurable
- Spin correlations (expect 90%) also detectable

Single top production

- Measure σ_t with 10% uncertainty
- Measure V_{tb} with 12% uncertainty

Summary

Debut of top using Run I data coming to close

- Have seen that it looks much like a SM fermion
- But top mass scale is enigmatic

All this sets the stage for Run II

- Run for 2-4 years, with goal of ~ 6 fb^{-1}

  $\Rightarrow$ Increase top quark sample $\times 50$

By the time next generation collider turns on,

- Top will be pretty well-studied
- Will be able to reconstruct millions at the LHC!
  - It will become the "high-statistics" probe of the next energy scale

TRIUMF and Subatomic Physics in Canada

NSERC Reallocation Exercise in 1998

- identified
  1. Sudbury Neutrino Observatory
  2. ISAC
  3. ATLAS

  as the highest priorities for next five years

- It also gave importance to
  1. Strong Base Programme at TRIUMF
  2. Support for “off-shore” particle physics
  3. Detector R&D

These priorities have been reiterated by

- Peer-review granting decisions (GSC-19)

- TRIUMF Five-Year Plan

- Federal Funding Decision for TRIUMF

So, is the future clear?

Review of TRIUMF's Role

Base programme a vital component of Canadian SAP

- Has had to be reduced in scope
- Quality of science has been main criteria
  - CHAOS - π-nucleon interactions
  - E614 - precision weak interaction studies
- Should continue as a significant effort

Infrastructure role extremely important

- Support for other high priority projects
  - BaBar drift chamber
  - SNO engineering and electronics
  - ATLAS Hadronic End Cap
  - GEANT 4
- Opportunity for TRIUMF to be a true National Facility

ISAC and ISAC-II

ISAC is now poised to become the leading RIB facility

- Unaccelerated beam programme
  - Early TRINAT results with ^{38m}K
  - GPS has impressive preliminary lifetime measurements
  - Polarized ^{8}Li beam and β-NMR
- Lab correctly prioritized low-energy programme

Focus now on getting accelerated beam

- DRAGON and TUDA vital to ISAC's success
- Although much work remains to be done, progress has been excellent
  - Community is expecting great things!

Superbly managed project – great science

ISAC-II

Lab's next five-year focus has to be ISAC-II

- Put's focus back on nuclear structure physics
  - heavy ion fusion reactions
  - exotic nuclei with resonance reactions
  - nuclei far from stability
  - higher-mass nuclear astrophysics studies

Ambitious given need to complete & exploit ISAC-I

- Have to adopt new accelerator technology
- Continue to service an increasingly diverse facility
- Will almost certainly require some "hard" decisions regarding priorities

Scientific reward is worth the effort

Near-Term Challenges for TRIUMF

1. Maintain productive and "balanced" nuclear science programme
   - Exploit unaccelerated RIB and ISAC-I
   - Develop ISAC-II
   - Keep a focussed base programme
   - Support the CMP effort and Tech Transfer
2. Invest in scientific staff in key areas
   - Radioactive Beam Programme
   - "Off-site" research programme, e.g. SNO, ATLAS
   - Theory
3. Support Canadian subatomic physics
   - Infrastructure support essential
   - Scientific leadership in all areas

Beyond the Horizon for TRIUMF

Next few years are fairly clearly mapped out

- Exploit ISAC-I and develop ISAC-II
- Maintain role in existing projects (SNO, ATLAS)
- Strengthen laboratory's scientific staff

TRIUMF's future beyond ISAC-II must be defined

- Some ideas discussed in five-year plan
- Some R&D effort must be focussed on possible opportunities
- Fully integrated with long-range community planning

Concluding Remarks

TRIUMF should continue to play a lead role in Canadian SAP

- ISAC-I/II should remain science priority
- Fully engage in its "national" role
  - Provision of infrastructure
  - Contribute to the science

Personnel a key resource and challenge

- Maintain cadre of excellent accelerator and detector experts
- Strengthen role as scientific leader

Director plays a key role

- Managerial support to "people on the ground"
- Develop and maintain lab's long-range goals
- Champion lab's role in Canadian science and Ottawa