Top Quark Pair Production Cross-Section in Tau + Lepton Channel

Probing interactions between members of the third generation

Haryo Sumowidagdo

Fermilab Seminar , July 8, 2008

Outline

- Introduction
  - Historical review of the discovery of top quark and tau lepton
  - Motivation
- Experimental apparatus
- Event selection
  - Lepton+jets event selection
  - Tau reconstruction and identification
  - Tau selection in lepton+jet events
  - B-tagging
- Cross-section extraction and combination
- Impact on search for charged Higgs boson
- Future prospects at the LHC

CONVENTION

LEPTON: *Unless defined otherways, always refers to electron and muon, including electron and muon from tau decays*.

TAU: *Unless defined otherways, always refers to hadronic decay products of tau lepton*.

RESULTS SHOWN *are work in progress and being actively reviewed*.

Now we can proceed …

The Third Generation

The Standard Model *doesn't predict the numbers of generation*.

In early 1970s, with two generations had already been discovered, there seemed to be no need for a third generation.

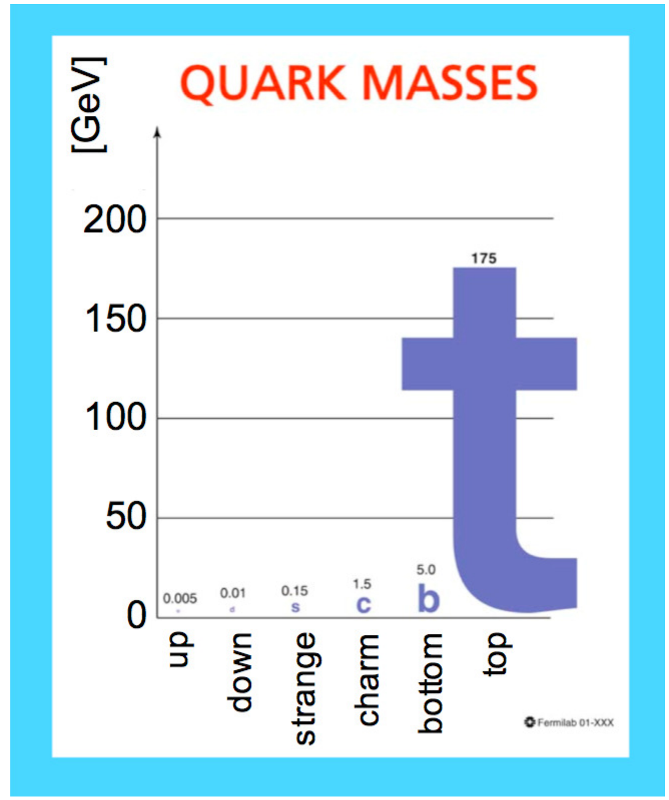
But the discovery of τ lepton triggered the chain of discoveries of third generation particles.

- τ lepton (1975).
- *b* quark (1977).
- top quark (1995).
- τ neutrino (2000).

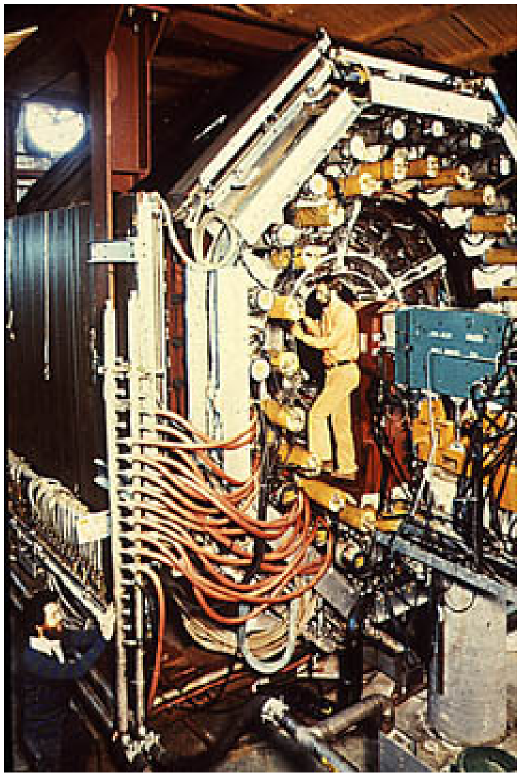
This talk will focus on top quark and tau lepton.

Top Quark Discovery

- Discovered in 1995 at Fermilab Tevatron.
- Large mass make it an ideal probe for physics around EW scale and beyond that.
- Decays before hadronization, ideal tool to study bare quark.
- Scrunitizing top quark properties is an important physics program of Tevatron Run II.



Discovery of The Tau Lepton: 1st paper



Mark I detector (from SLAC Archive)

"We have found 64 events of the form

$$e^+e^- \to e^\pm\mu^\mp + \geq 2 \text{ undetected particles}$$

for which we have no conventional explanation."

Evidence for Anomalous Lepton Production in e^+-e^- Annihilation*

M. L. Perl, G. S. Abrams, A. M. Boyarski, M. Breidenbach, D. D. Briggs, F. Bulos, W. Chinowsky, J. T. Dakin,† G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson, F. B. Heile, B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke,‡ B. A. Lulu, V. Lüth, D. Lyon, C. C. Morehouse, J. M. Paterson, F. M. Pierre,§ T. P. Pun, P. A. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, F. Vannucci,‖ J. S. Whitaker, F. C. Winkelmann, and J. E. Wiss

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 18 August 1975)

We have found events of the form $e^+ + e^- \to e^\pm + \mu^\mp$ + missing energy, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.

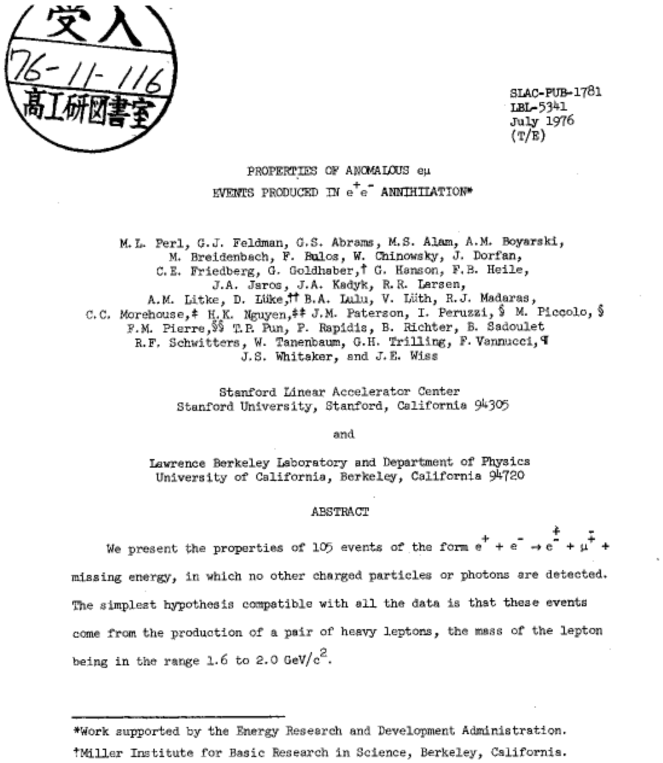
We have found 64 events of the form

$$e^+ + e^- \to e^\pm + \mu^\mp + \geq 2 \text{ undetected particles} \quad (1)$$

for which we have no conventional explanation. The undetected particles are charged particles or photons which escape the 2.6π sr solid angle of the detector, or particles very difficult to detect such as neutrons, K_L^0 mesons, or neutrinos. Most of these events are observed at center-of-mass energies at, or above, 4 GeV. These events were found using the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory (SLAC-

1489

The 2nd paper



SLAC-PUB-1781
LBL-5341
July 1976
(T/E)

PROPERTIES OF ANOMALOUS eμ
EVENTS PRODUCED IN e^+e^- ANNIHILATION*

M.L. Perl, G.J. Feldman, G.S. Abrams, M.S. Alam, A.M. Boyarski,
M. Breidenbach, F. Bulos, W. Chinowsky, J. Dorfan,
C.E. Friedberg, G. Goldhaber,† G. Hanson, F.B. Heile,
J.A. Jaros, J.A. Kadyk, R.R. Larsen,
A.M. Litke, D. Lüke,†† B.A. Lulu, V. Lüth, R.J. Madaras,
C.C. Morehouse,‡ H.K. Nguyen,‡‡ J.M. Paterson, I. Peruzzi,§ M. Piccolo,§
F.M. Pierre,§§ T.P. Pun, P. Rapidis, B. Richter, B. Sadoulet
R.F. Schwitters, W. Tanenbaum, G.H. Trilling, F. Vannucci,¶
J.S. Whitaker, and J.E. Wiss

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Stanford University, Stanford, California 94305

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University of California, Berkeley, California 94720

ABSTRACT

We present the properties of 105 events of the form $e^+ + e^- \rightarrow e^\pm + \mu^\mp +$ missing energy, in which no other charged particles or photons are detected. The simplest hypothesis compatible with all the data is that these events come from the production of a pair of heavy leptons, the mass of the lepton being in the range 1.6 to 2.0 GeV/c^2.

*Work supported by the Energy Research and Development Administration.
†Miller Institute for Basic Research in Science, Berkeley, California.

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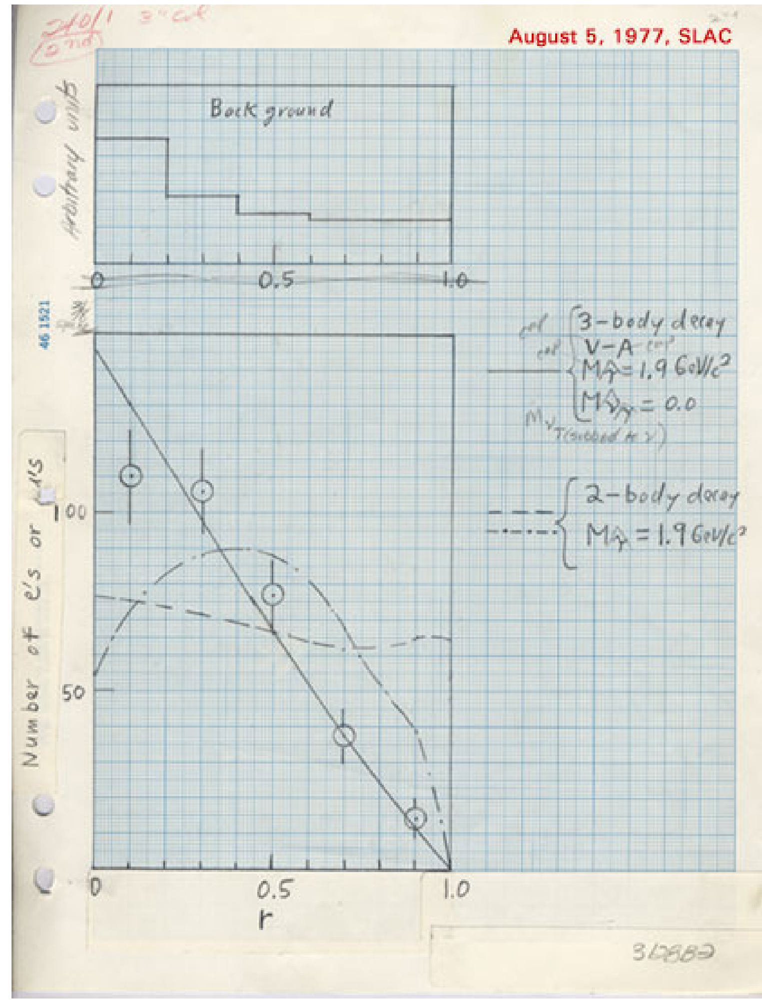

(from Symmetry magazine)

The 3rd paper

SLAC-PUB-1997
LBL-6731
August 1977
(T/E)

PROPERTIES OF THE PROPOSED τ CHARGED LEPTON*

M. L. Perl, G. J. Feldman, G. S. Abrams, M. S. Alam,
A. M. Boyarski, M. Breidenbach, J. Dorfan, W. Chinowsky,
G. Goldhaber, G. Hanson, J. A. Jaros, J. A. Kadyk, D. Lüke**,
V. Lüth, R. J. Madaras, H. K. Nguyen†, J. M. Paterson, I. Peruzzi††,
M. Piccolo††, T. P. Pun, P. A. Rapidis, B. Richter,
W. Tanenbaum, and J. E. Wiss

Stanford Linear Accelerator Center
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and

Lawrence Berkeley Laboratory and Department of Physics
University of California, Berkeley, California 94720

ABSTRACT

The anomalous $e\mu$ and 2-prong μx events produced in e^+e^- annihilation are used to determine the properties of the proposed τ charged lepton. We find the τ mass is $1.90 \pm .10$ GeV/c^2; the mass of the associated neutrino, ν_τ, is less than 0.6 GeV/c^2 with 95% confidence; V-A coupling is favored over V+A coupling for the τ-ν_τ current; and the leptonic branching ratios are $0.186 \pm .010 \pm .028$ from the $e\mu$ events and $0.175 \pm .027 \pm .030$ from the μx events where the first error is statistical and the second is systematic.

(Submitted to Phys. Letters.)

*Work supported by the Energy Research and Development Administration.
**Fellow of Deutsche Forschungsgemeinschaft.
†Permanent address: LPNHE, Université Paris VI, Paris, France.
††Permanent address: Laboratori Nazionali, Frascati, Rome, Italy.

$$m_\tau = 1.90 \pm 0.10 \text{ GeV}/c^2$$

$$m_{\nu_\tau} < 0.6 \text{ GeV}/c^2 \quad (95\% \text{ C.L.})$$

$$\text{BR}(\tau \to \ell \nu_\ell \nu_\tau) = 0.186 \pm 0.010 \pm 0.028 \quad (\text{from } e\mu \text{ events})$$

$$\text{BR}(\tau \to \ell \nu_\ell \nu_\tau) = 0.175 \pm 0.027 \pm 0.030 \quad (\text{from } \mu X \text{ events})$$

Quite close, compared to most recent measurement of tau properties !

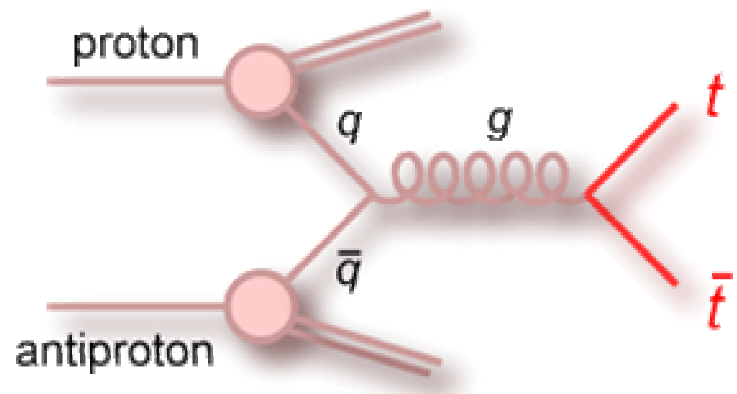
Motivation

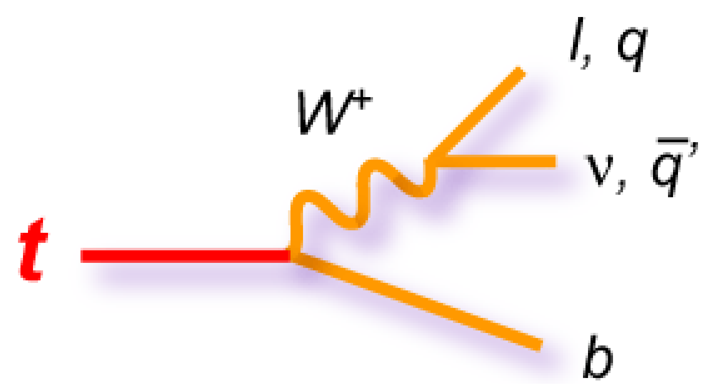
- A pure third generation decay which has not been observed with 3 σ significance.

$$t \to \tau \nu_\tau b$$

- Search for new physics in top quark *decay mechanisms*.
- In many top quark analyses, it is usually assumed that the top quark decays to a *W* boson and a *b* quark.

$$t \to W b$$

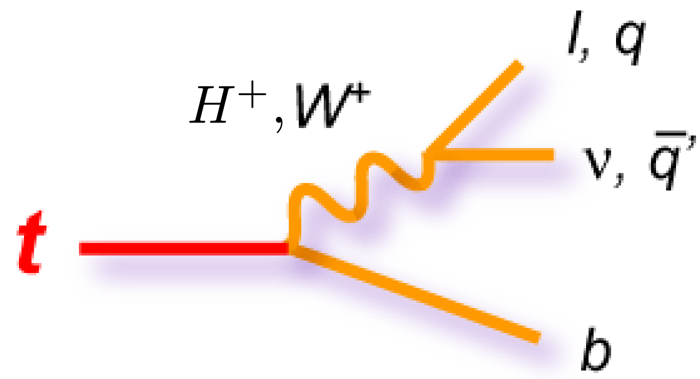


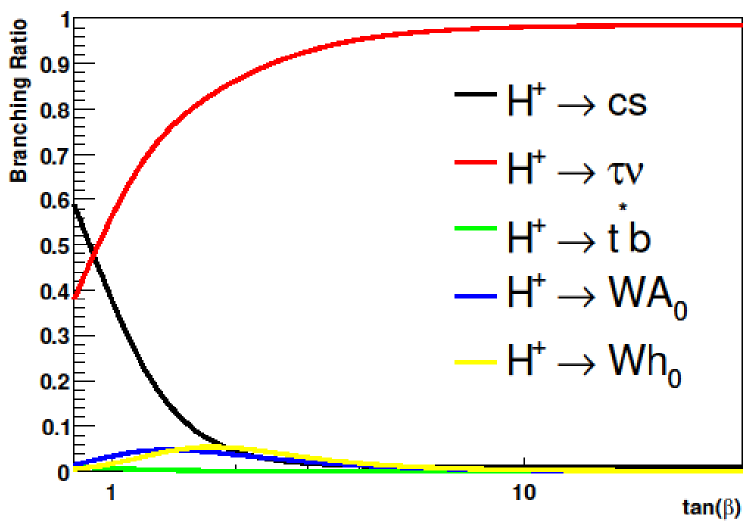


New Physics in Top Quark Decay

Charged Higgs exist in non minimal Higgs model (e.g. 2HDM) or beyond standard model physics (e.g. MSSM). Top quark can decay to charged Higgs, which can decay predominantly into tau final states.

$$t \to H^{\pm} b \to \tau \nu_{\tau} b$$

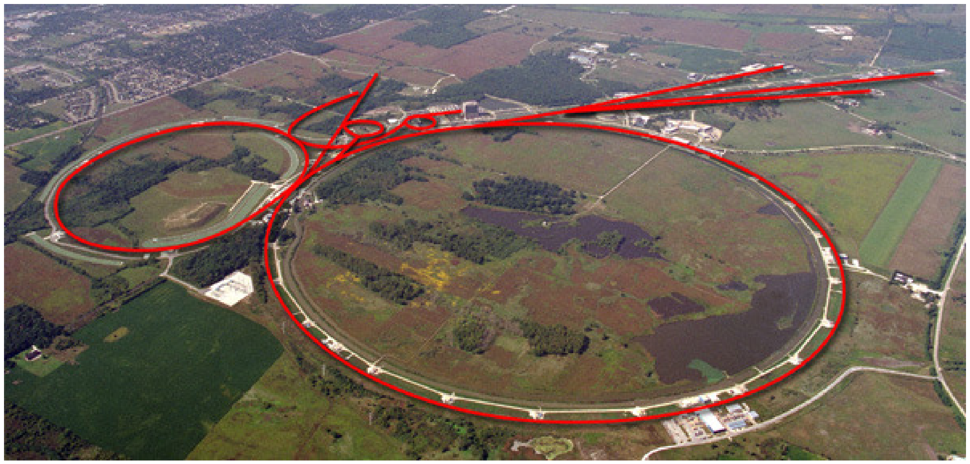




At large tan β, the charged Higgs decay predominantly into taus.

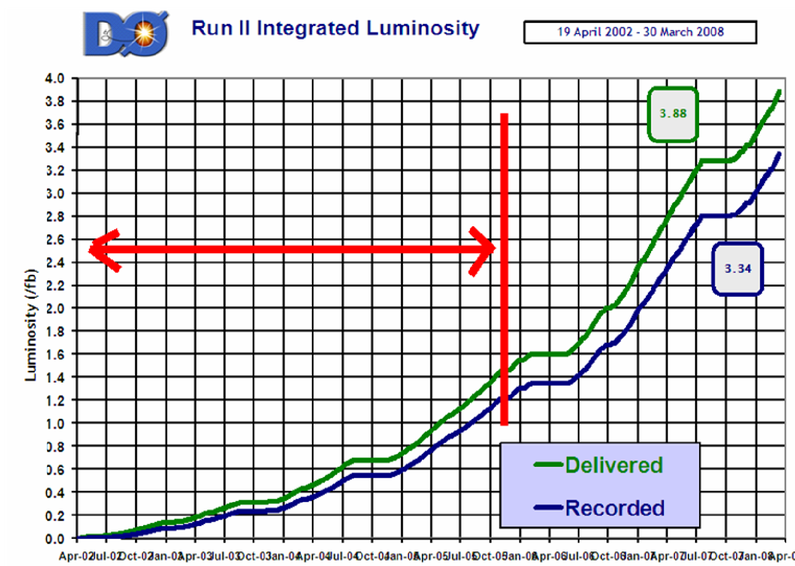
Observation of the pure third generation decay would be a significant boost in the search for charged Higgs.

Tevatron Accelerator

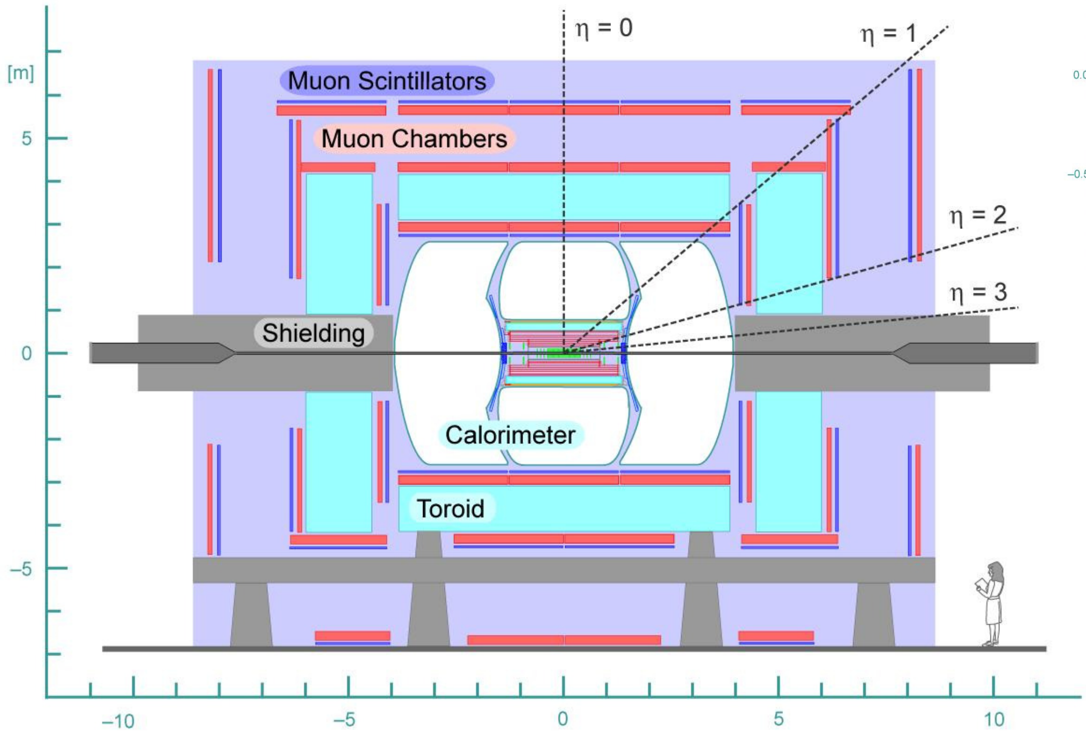


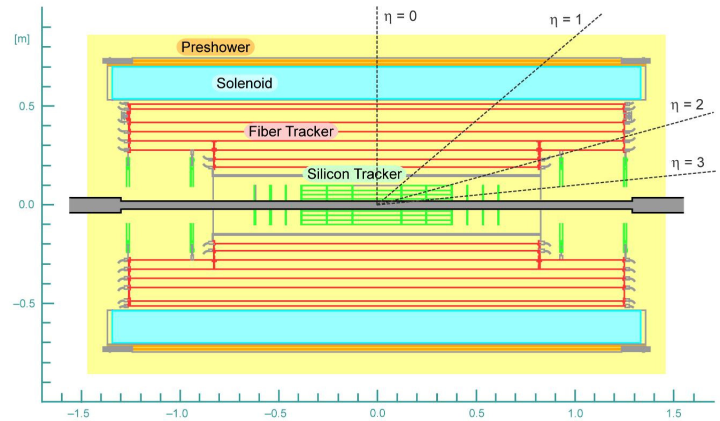
A proton-antiproton collider at c.m. energy of 1.96 TeV. Until LHC begins, the sole place in the world to study top quark.

Analysis uses 1 inverse femtobarn of data recorded from April 2002 to February 2006.



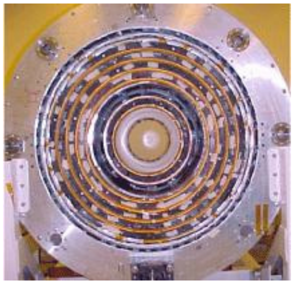
D0 Detector

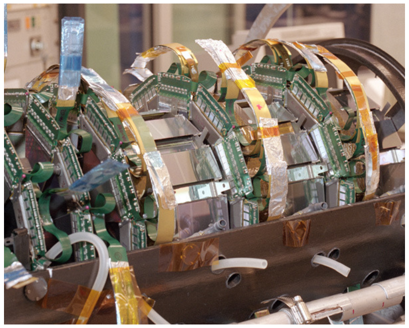




Central tracking: identification of vertices and charged particles' track.

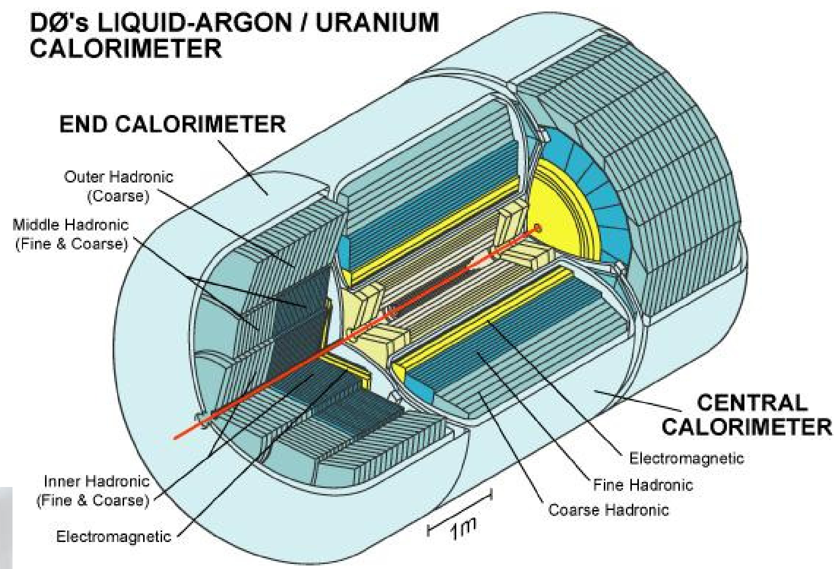
General-purpose detector for high pT physics at hadron collider.

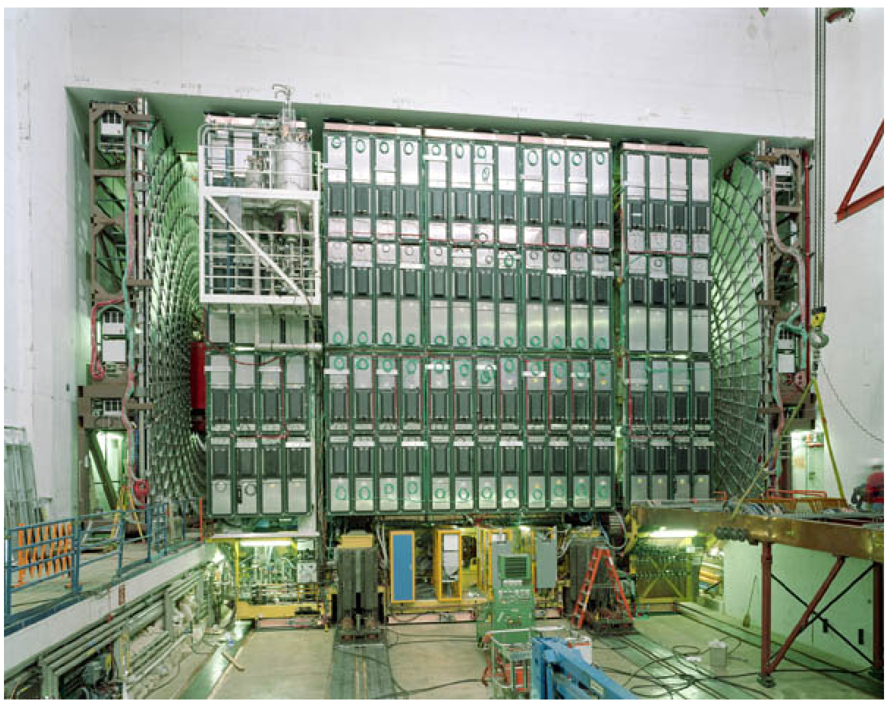




Calorimeter: reconstruction of electrons, jets, and taus.

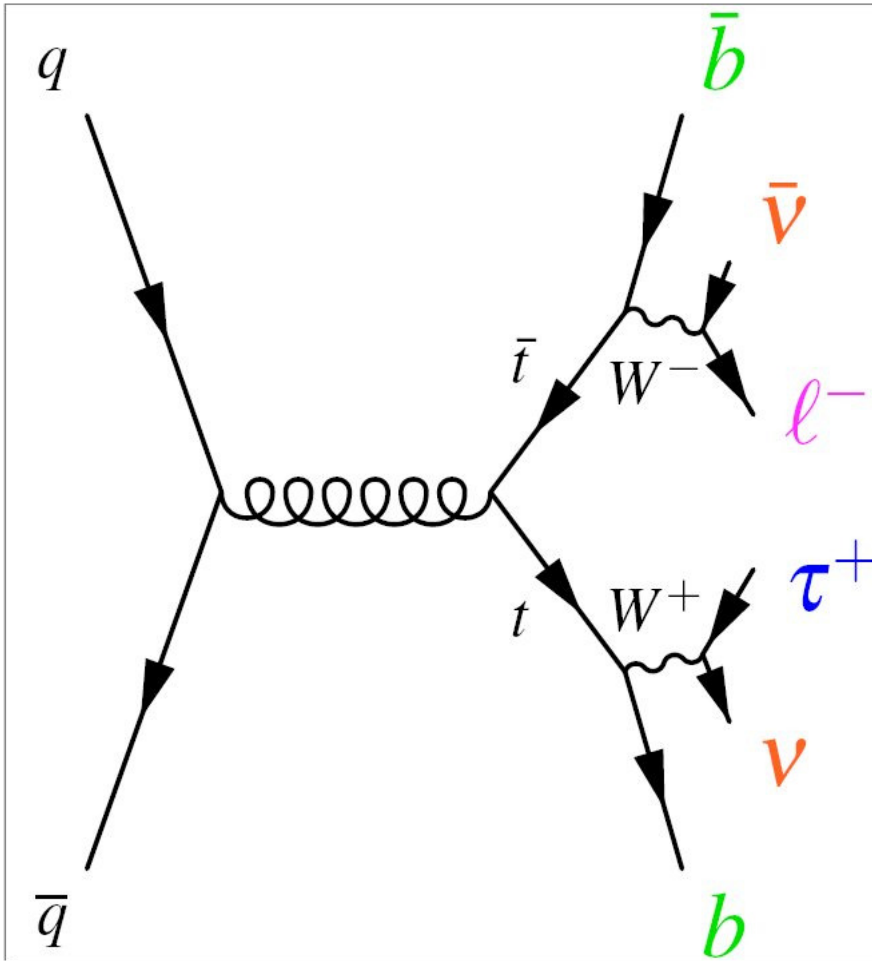
Muon chamber: muon reconstruction.





All sub-detector play important part in identification and reconstruction of objects used in this analysis.

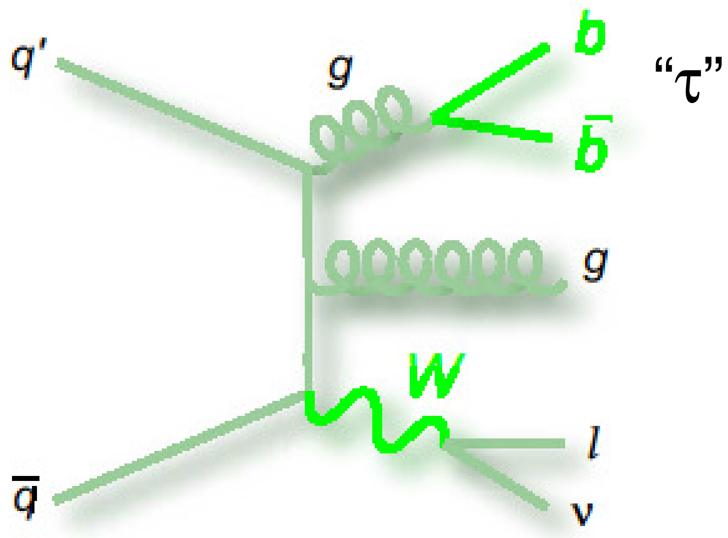
Event Signature



- One high pT electron or muon.
- One tau which decays hadronically, and may be reconstructed as a jet.
- Two high pT b-quark jet.
- Missing momentum from the neutrinos.
- Lepton and tau have opposite charge sign.

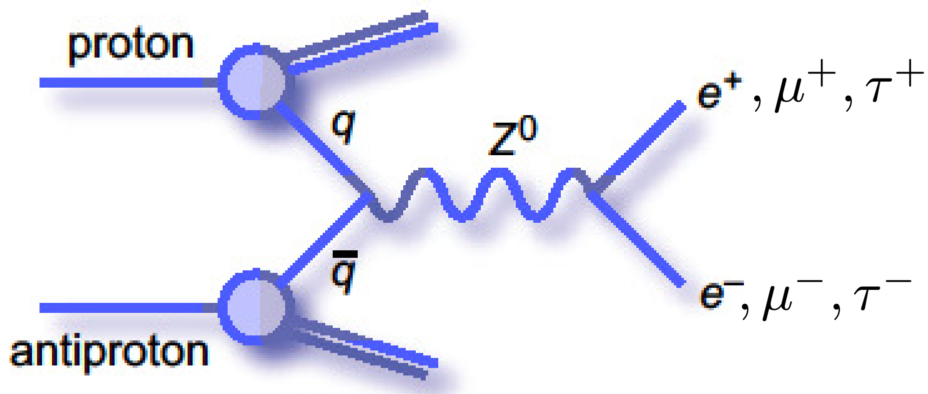
A lepton + three-jet events !

Background Processes (I)



W+jets: jet fakes a tau.

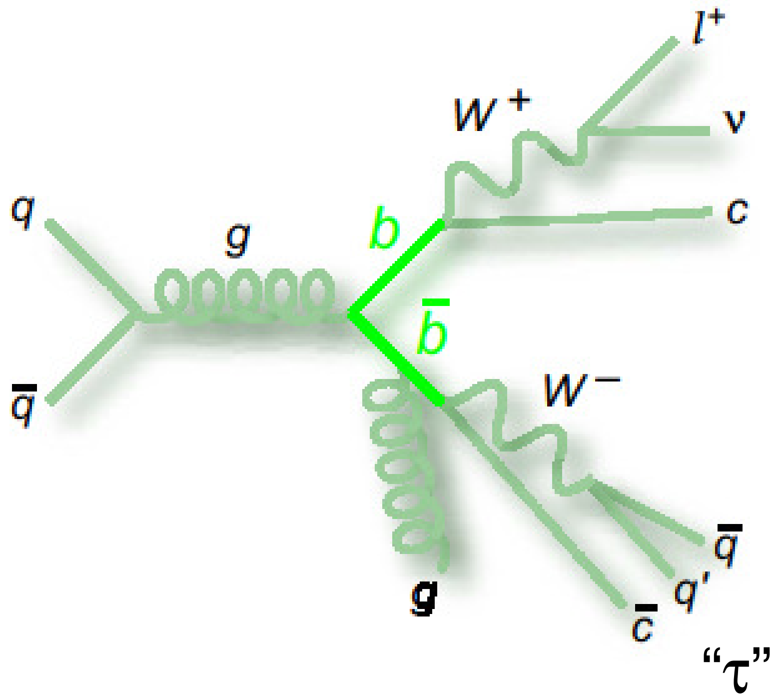
Shape is taken from MC, normalized to data.



Z+jets: one lepton is reconstructed as lepton, while the other lepton (electron,muon,tau) is reconstructed as a tau.

Shape is taken from MC, normalized to theoretical cross-section

Background Processes (II)



Multijet events: jets fake both lepton and taus. Estimated from data.

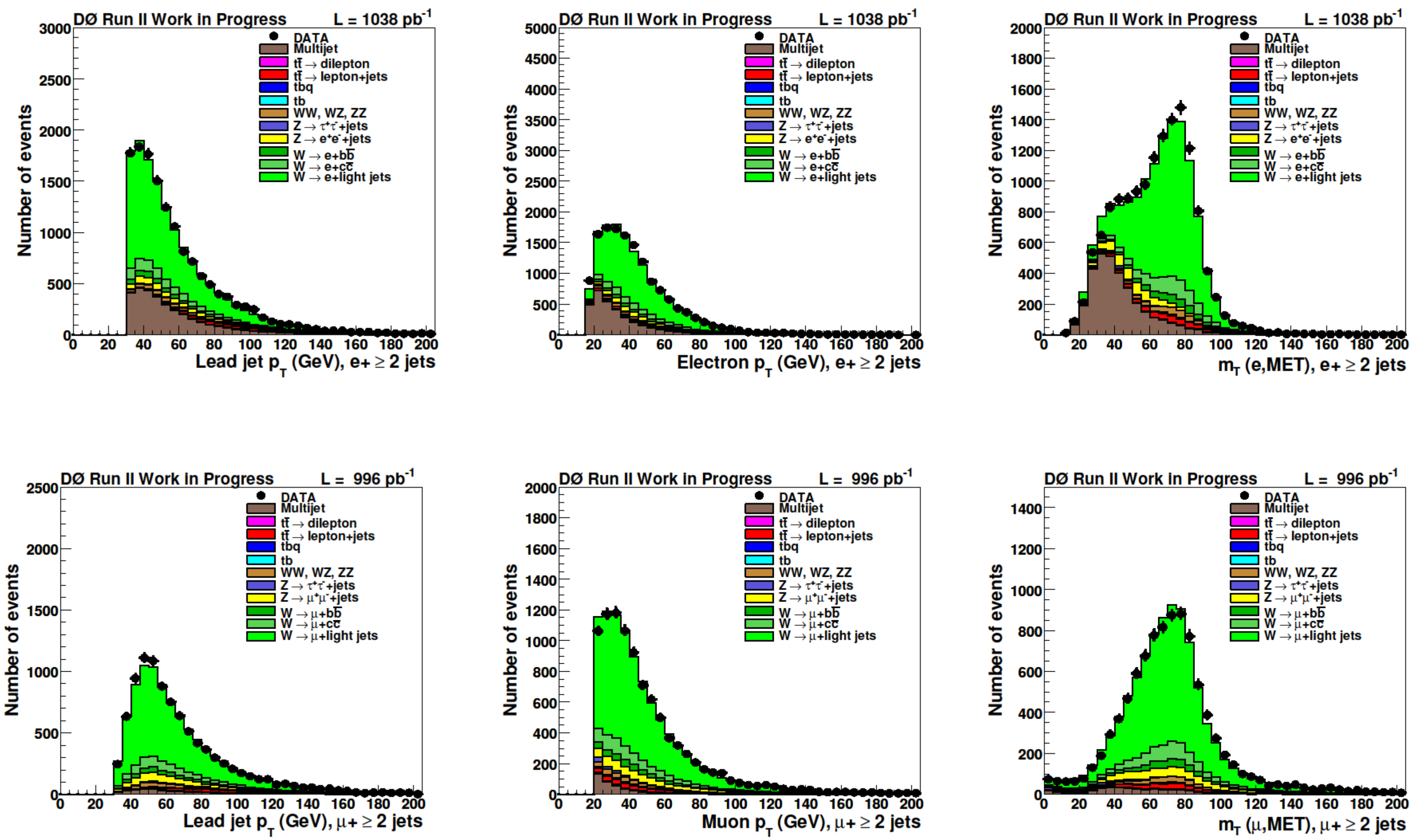
Other small background (single top, diboson) are purely estimated using MC and theoretical cross-section.

Lepton + jets event selection

Strategy: adapt lepton+jets trigger, dataset, and preselection cuts.

- One isolated electron (muon) with pT > 15 (20) GeV.
- Two or more jets with pT > 20 GeV, leading jet has pT > 30 GeV.
- Missing energy > 15 GeV and < 200 GeV.
- Two dimensional cut in the MET-$\Delta\phi$(lepton,MET) plane.
- Normalize W+jets background to data at this selection level.

Data to MC comparison, lepton+jets



Tau reconstruction and identification

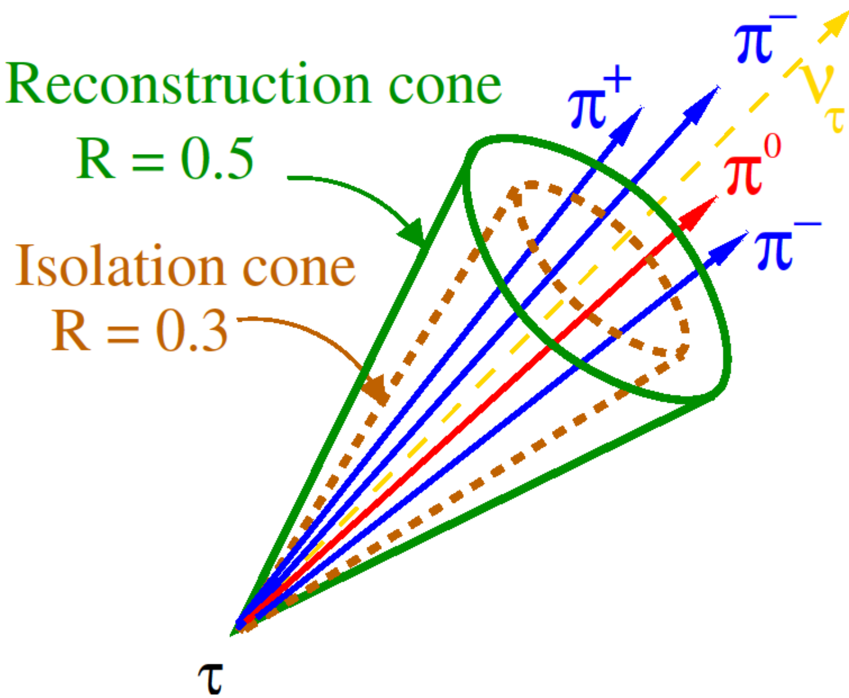
Lifetime ~ 29 ps, ct = 87 μm.

Can decays to electron, muon, and hadron.

$$\tau^- \to \pi^- \nu_\tau \qquad 10\%$$

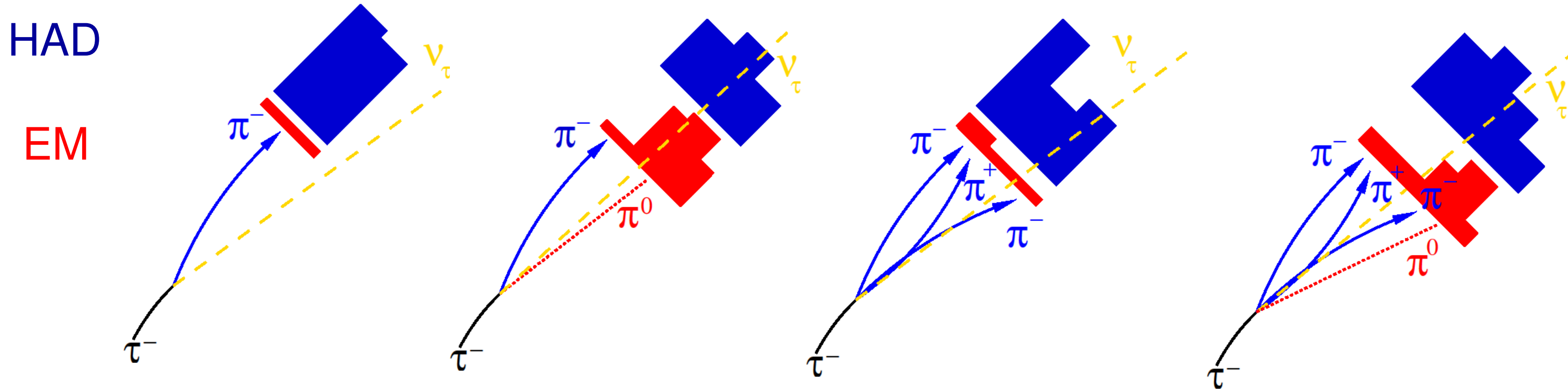
$$\tau^- \to \pi^- N\pi^0 \nu_\tau \qquad 35\%$$

$$\tau^- \to \pi^- \pi^+ \pi^- N\pi^0 \nu_\tau \qquad 15\%$$



Hadronic decay products will appears as a narrow, isolated jets with charged tracks and hadronic energy deposition.

Neutral pions will appear as electromagnetic energy deposition.



Type :one track,
no EM cluster.

BR =10 %

Type 2: one track,
EM cluster.

BR 35 %

Type 3: more than
one tracks.

BR 15 %

- Three neural networks are developed to discriminate each of three tau types against hadronic jets (NNτ)
- A fourth neural network is developed to discriminate type 2 taus agains electrons (NNe)

Tau selection in lepton+jets events

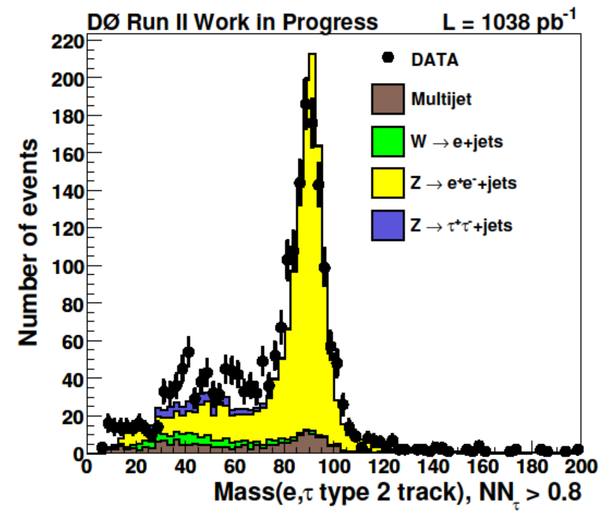
- Cluster of calorimeter energy, ET > 10/5/10 GeV for type 1/2/3.
- Leading track has pT > 7/5/7 GeV for type 1/2/3. For type 3, all tracks have total pT > 10 GeV.
- Separated from the lepton by requiring not sharing the same track, $\Delta R(\text{lepton},\tau) > 0.5$.
- Coming from the same interaction region as the lepton, $\Delta z(\text{lepton},\tau) < 1$ cm.
- $NN\tau > 0.8$.
- Split into two sets: One set with lepton and tau have opposite charge sign (OS), another set with same charge sign (SS).

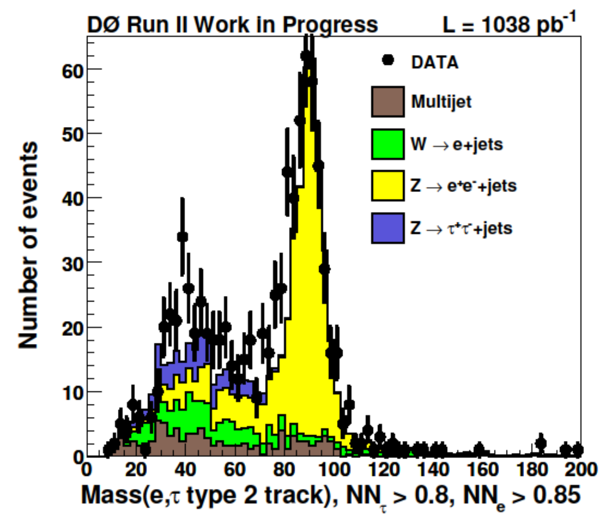
Rejection of electron faking taus

Things which slip through the cracks

- Large contamination from Zee events in the tau+electron channel.
- Add cut on neural network anti-electron.

  NNe > 0.85.
- Reduced but still large.



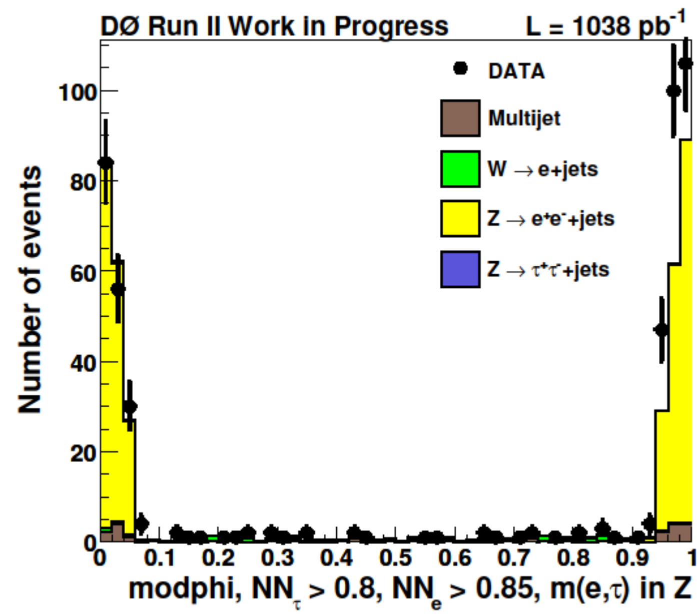


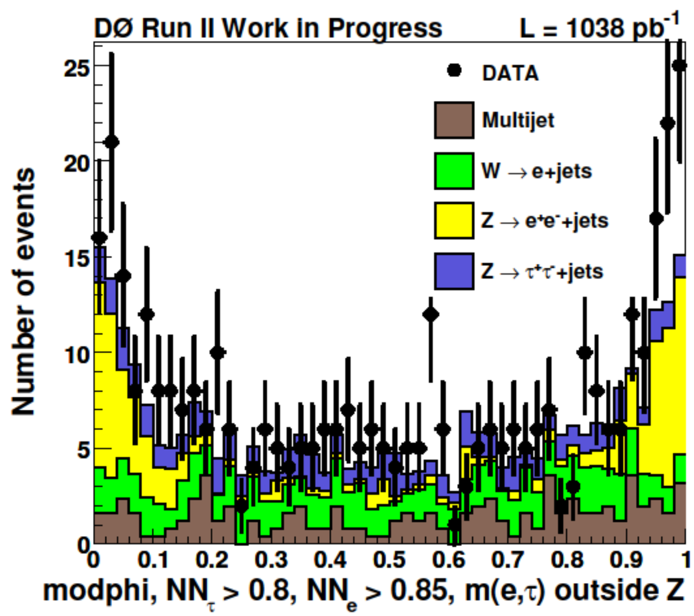
Is there something new can be done to reject electrons ?

Define modphi as the azimuthal position of the tau track at preshower, relative to the boundary between calorimeter module.

$$\texttt{modphi} = \frac{\texttt{fmod}(\phi_{\tau\ \mathrm{track}}, \pi/32)}{\pi/32}$$

modphi is normalized between 0.0 to 1.0 by construction.





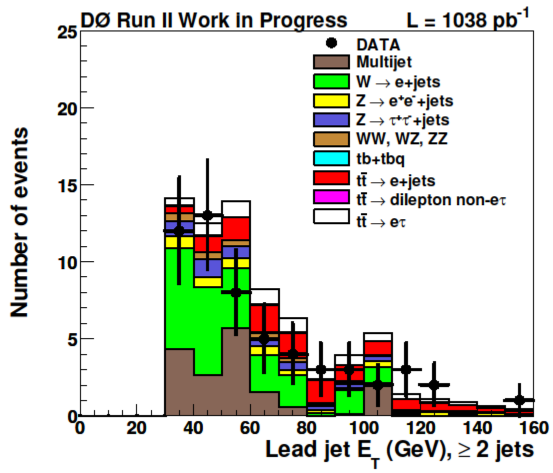
Striking differences between events inside Z mass window, and outside Z mass window.

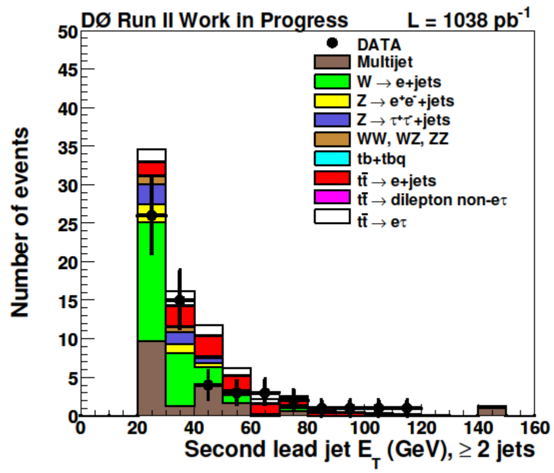
We require

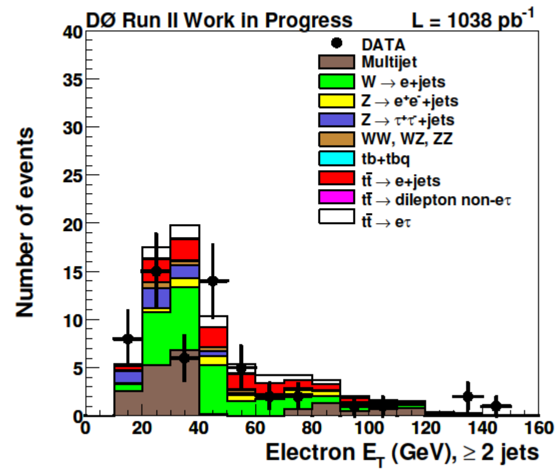
$$0.1 < \texttt{modphi} < 0.9$$

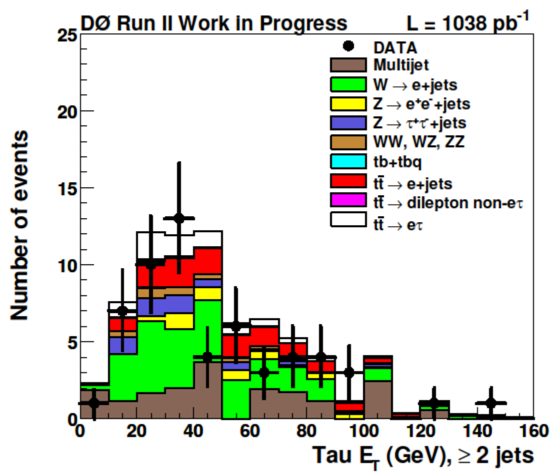
in the tau+electron channel.

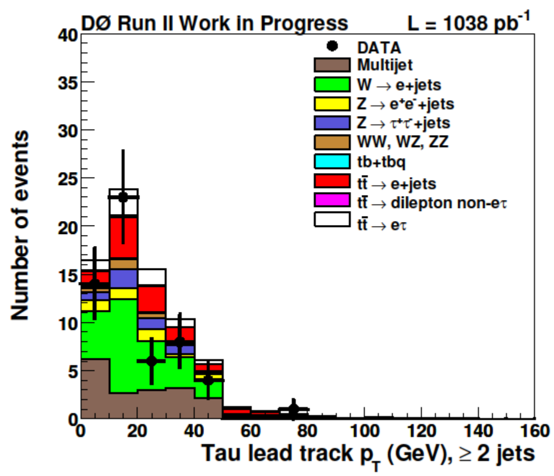
Control Plots: Tau+Electron Channel.

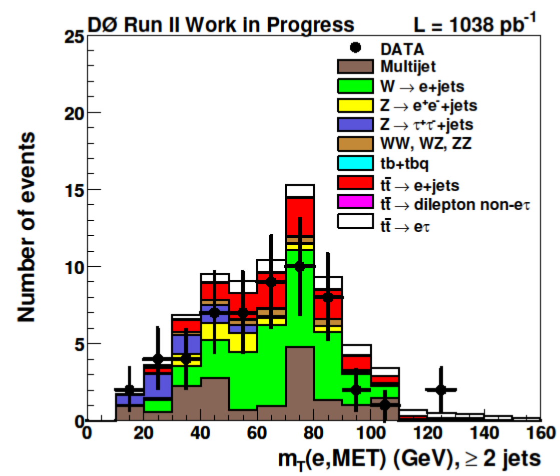




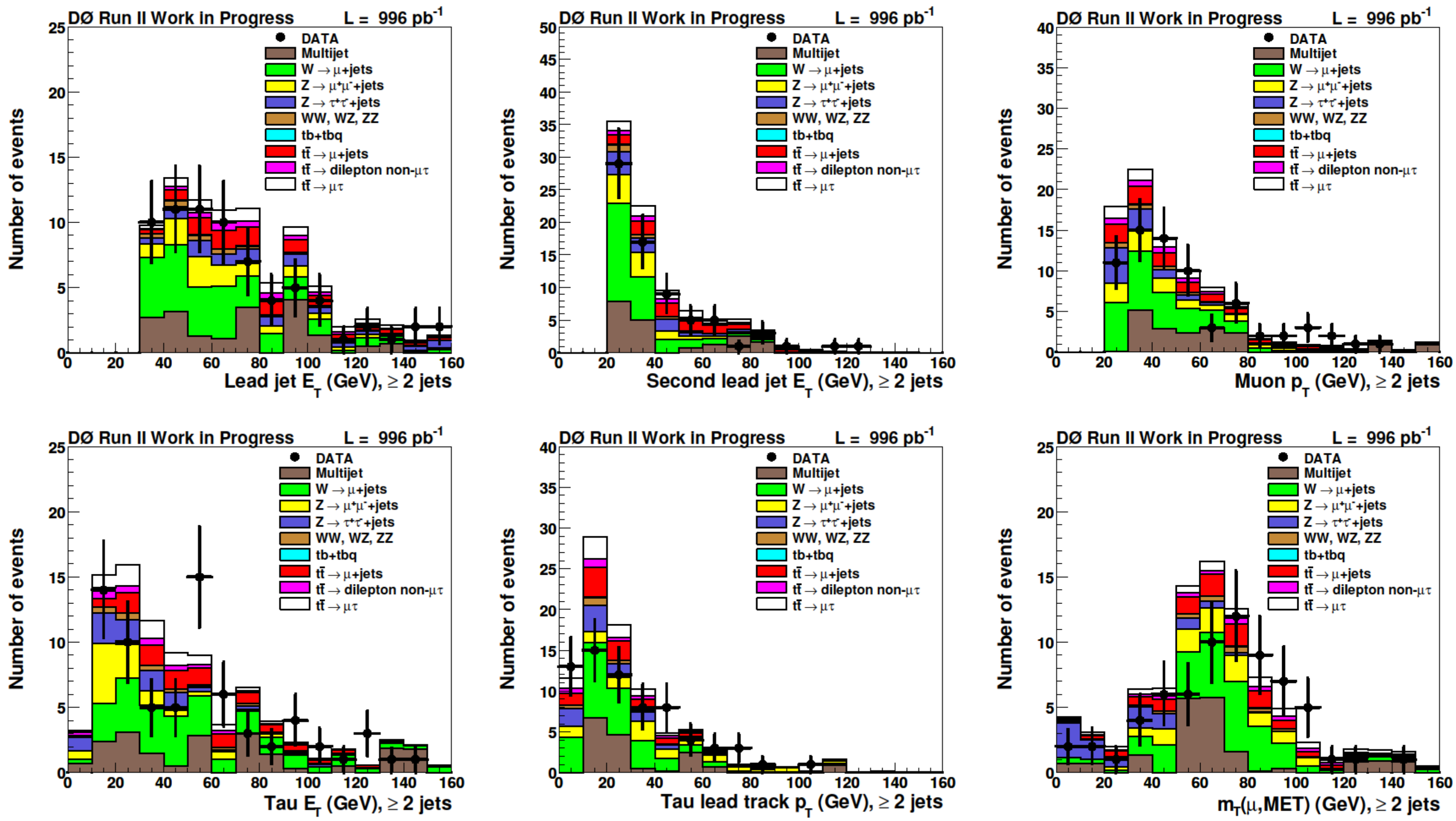






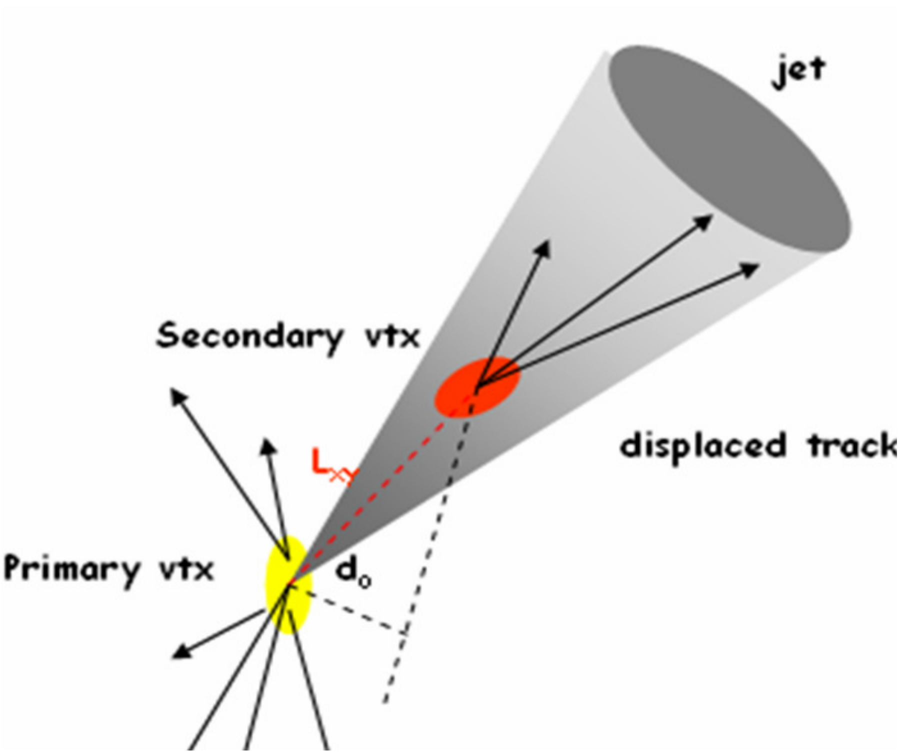


Control Plots: Tau+Muon Channel.

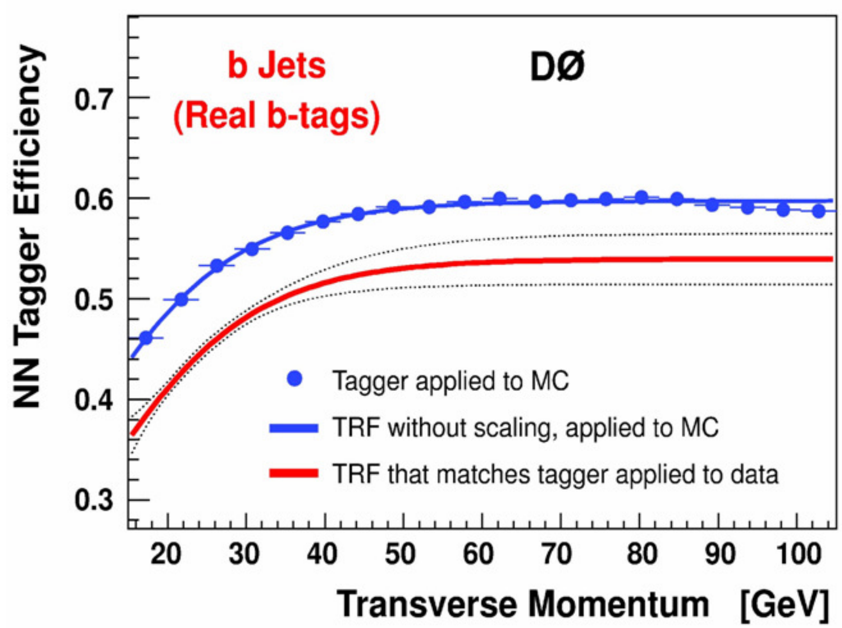


Hints of top events (S:B approx. 1:8), now add b-tagging.

Identification of b-quark jets

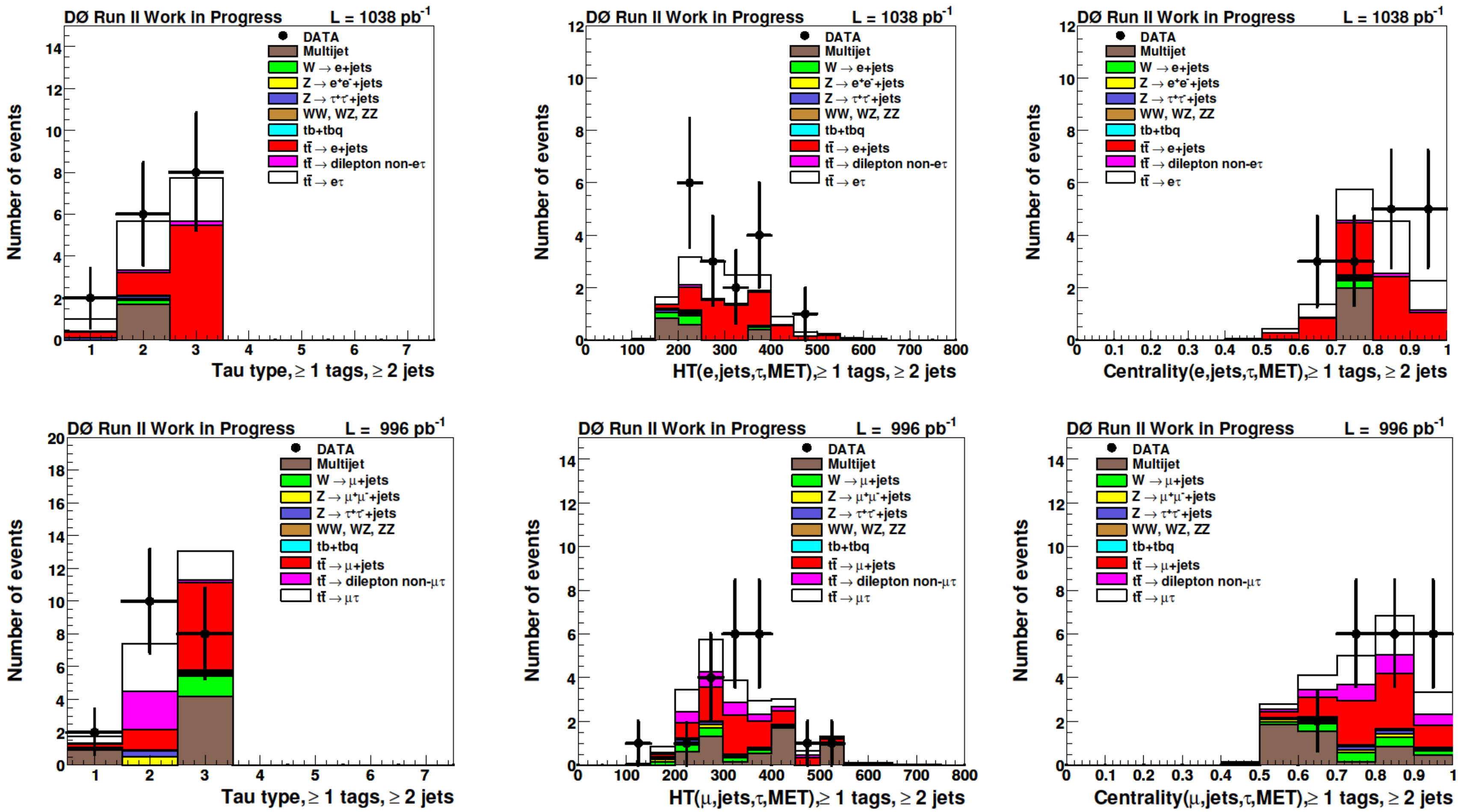


Combine information from displaced tracks and secondary vertices into one neural network output.



Average efficiency to tag b-quark in this analysis is 54 %, with fake rate of 1 %.

After b-tagging



Now, S:B is 2:3. Large contamination from ttbar l+jets.

Elimination of multijet background

Assume that multijet events contribute equally to opposite-charge sign (OS) and same-charge sign (SS) sample. Then:

$$N^{OS}_{\text{expected}} = N^{OS}_{t\bar{t},W,Z,\text{diboson}} + N^{OS}_{\text{Multijet}}$$
$$N^{SS}_{\text{expected}} = N^{SS}_{t\bar{t},W,Z,\text{diboson}} + N^{SS}_{\text{Multijet}}$$

Subtracting, we find:

$$N^{OS}_{\text{expected}} - N^{SS}_{\text{expected}} = N^{OS}_{t\bar{t},W,Z,\text{diboson}} - N^{SS}_{t\bar{t},W,Z,\text{diboson}}$$

Multijet background is “eliminated”.

Some processes only have very small contribution towards the SS sample.

Cross-section extraction

$$
\begin{aligned}
N_{\text{data}}^{OS} &= \sigma_{t\bar{t}}\epsilon_{t\bar{t}}^{OS} \times \mathcal{L} + N_{\text{W-like}}^{OS} + N_{Z}^{OS} + N_{\text{diboson}}^{OS} + N_{\text{Multijet}}^{OS} \\
N_{\text{data}}^{SS} &= \sigma_{t\bar{t}}\epsilon_{t\bar{t}}^{SS} \times \mathcal{L} + N_{\text{W-like}}^{SS} + N_{\text{Multijet}}^{SS}
\end{aligned}
$$

Subtracting the second from the first:

$$
N_{\text{data}}^{OS} - N_{\text{data}}^{SS} = (\epsilon_{t\bar{t}}^{OS} - \epsilon_{t\bar{t}}^{SS}) \times \mathcal{L} + (N_{\text{W-like}}^{OS} - N_{\text{W-like}}^{OS}) + N_{Z}^{OS} + N_{\text{diboson}}^{OS}
$$

Therefore, in the individual channel one can use:

$$
\sigma_{t\bar{t}} = \frac{N_{\text{data}}^{OS} - N_{\text{data}}^{SS} - (N_{\text{W-like}}^{OS} - N_{\text{W-like}}^{SS}) - N_{Z}^{OS} - N_{\text{diboson}}^{OS}}{(\epsilon_{t\bar{t}}^{OS} - \epsilon_{t\bar{t}}^{SS}) \times \mathcal{L}}
$$

Expected and observed yields

	Tau+Electron	Tau+Muon
W	0.573 +/- 0.184	0.790 +/- 0.254
Zee/Zee	0.065 +/- 0.010	0.147 +/- 0.013
Ztautau	0.072 +/- 0.010	0.160 +/- 0.019
Diboson	0.165 +/- 0.019	0.162 +/- 0.017
Single top	0.065 +/- 0.019	0.054 +/- 0.016
ttbar l+jets	5.130 +/- 0.151	4.706 +/- 0.135
ttbar dilepton	5.176 +/- 0.097	7.447 +/- 0.110
SS events	3 +/- 1.732	8 +/- 2.828
Expected	14.836	22.479
OS observed	16	20

Cross-section combination

Combination of the two channels is done by minimizing the likelihood:

$$\mathcal{L} = \Pi_j P(N_j^{obs}, \mathrm{Luminosity}_j, \epsilon_j, N_j^{background})$$

where *j* is the individual channel, and

$$\mathrm{P}(\mathrm{N}_j^{obs}, \mathrm{Luminosity}_j, \epsilon_j, N_j^{background})$$

is the Poisson probability of observing the number of events, given the luminosity, efficiency ε, and number of expected background.

The final, combined cross-section is:

$$\sigma_{t\bar{t}} = 7.7^{+2.2}_{-2.0}(\mathrm{stat})^{+1.6}_{-1.5}(\mathrm{syst.} + \mathrm{lumi.}) \ \ \mathrm{pb.}$$

Measurement of $\sigma(t\bar{t}) \times BR(t\bar{t} \to \ell + \tau + b\bar{b})$

- A simple measure of top quark decay rate to tau lepton.
- Normalize expected amount of ttbar events without real tau in the final states using theoretical cross-section.
- Use acceptance from ttbar with real tau only.

In the combined channel, we measured:

$$\sigma(t\bar{t}) \times BR(t\bar{t} \to \ell + \tau + b\bar{b}) = 0.13^{+0.09}_{-0.08}(\text{stat})^{+0.06}_{-0.06}(\text{syst.+lumi.}) \quad \text{pb.}$$

Standard Model prediction is 0.140 pb (neglecting less than 1 % difference between electron and muon).

Not yet a three-sigma evidence of third generation decay.

Summary of cross-section analysis

- Measurement of both top quark pair production cross-section and the cross-section x branching ratio.
- Very interesting analysis which uses almost all object identification: electron, muon, tau, jets, b-tagging, MET.
- Will be used in a global search for charged Higgs boson.
- Will be published as part of cross-section measurement in dilepton channel.

Global search for charged Higgs

- Combine five different channels (l+jets, electron+muon, dielectron, dimuon, and tau+lepton).

  Similar approach to previous CDF search (PRL 96, 0423003).
- Channels are constructed to be orthogonal.
- This talk will focus on tauonic model only.

Collaborative work of F. Deliot and V. Shary (electron+muon), J.-P. Konrath (dimuon), B. Martin (dielectron), Y. Peters (global fit and l+jets),

S. Sumowidagdo (tau+lepton), plus ~10 other D0 collaborators.

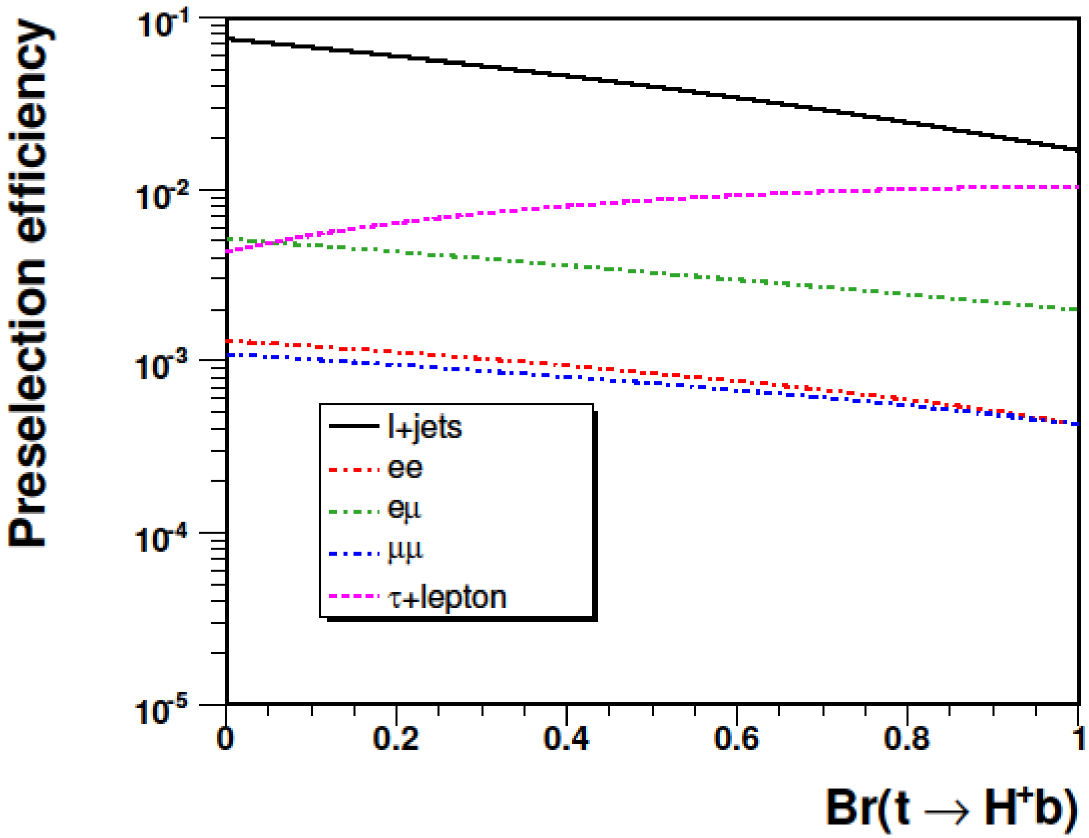
Search strategy

If the top quark can decay to charged Higgs with branching ratio BR, then the total acceptance of ttbar events will be a function of BR

$$\begin{aligned}\epsilon(t\bar{t}) &= BR^2\epsilon(t\bar{t}\to H^+H^-b\bar{b}) + 2BR(1-BR)\epsilon(t\bar{t}\to W^\pm H^\mp b\bar{b}) \\ &\quad +(1-BR)^2\epsilon(t\bar{t}\to W^+W^-b\bar{b})\end{aligned}$$

- **Disappearance channel**: acceptance decreases as a function of increasing BR.
  - For tauonic model, all decay modes of top pair without tau lepton.
- **Appearance channel**: acceptance increases a function of increasing BR.
  - For tauonic model, tau+lepton and tau+jets.
- **Global search**: Compare Standard Model expectation with observation in different decay channels.
  - Use theoretical prediction of top quark pair production cross-section.

Appearance and Disappearance

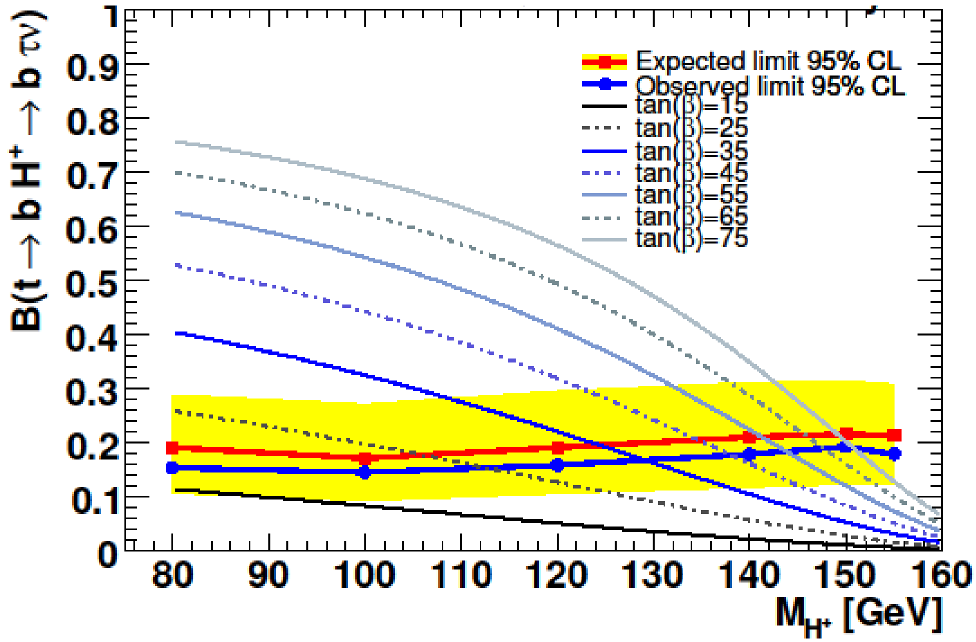


Tau+lepton is the only channel which shows increase in acceptance for increasing BR at low charged Higgs mass.

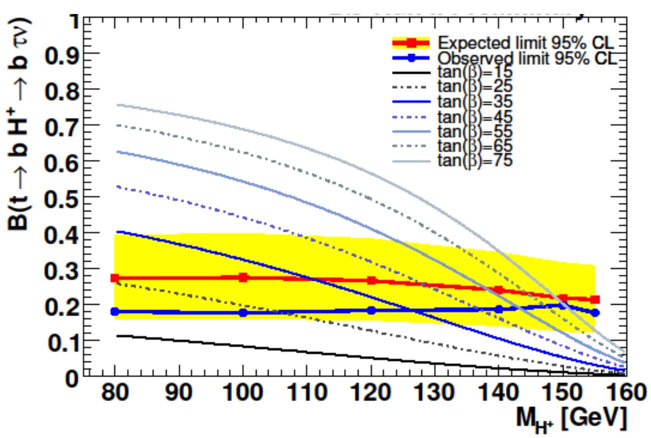
At higher charged Higgs mass, however, tau+lepton also become a disappearance channel.

Impact of tau+lepton cross-section

Right: Results with inclusion of tau+lepton channel. Improvements of order 5-10 %.



Below: Results without inclusion of tau+lepton channel.



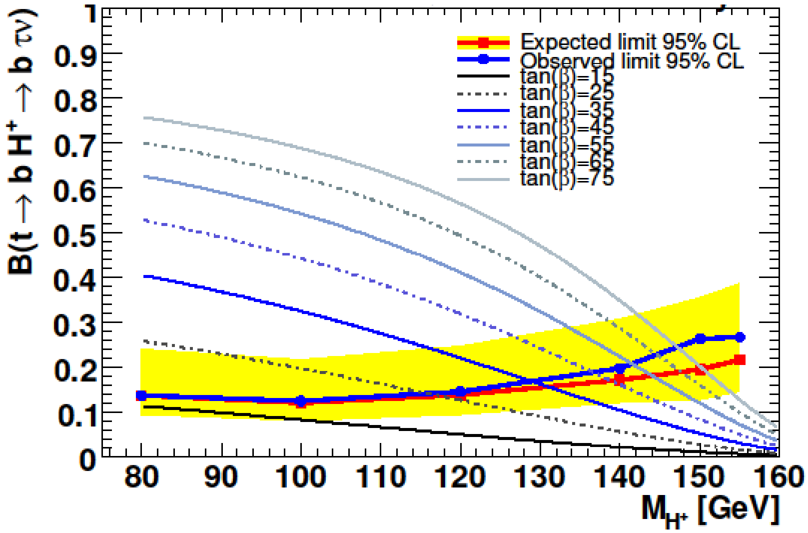
Inclusion of tau+lepton improves the observed limit.

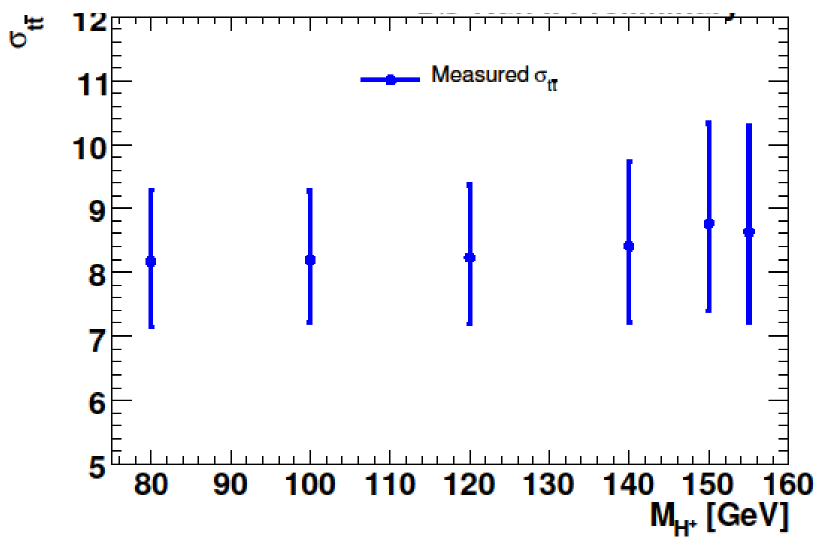
Simultaneous measurement of top quark pair production and limit on BR

- The presence of both disappearance and appearance channels make it possible for a **two-dimensional fit of top quark pair production cross-section and the branching ratio of top quark to charged Higgs.**
- Independent from theoretical calculation of top quark pair production cross-section !

Results of two-dimensional fit.

Observed limit improves by approximately 30 % for low charged Higgs masses.





Fitted cross-section agrees with theoretical predictions and recent measurements.

Very promising despite the limitation of tau+lepton.

Future prospect at the LHC

- With about 80M of ttbar events per year, can expect 100-150K tau+lepton events at LHC if efficiency at LHC is similar to efficiency in this analysis.
- The challenge is to develop tau identification at LHC.
- Tevatron is accumulating data at an astonishing rate, and with 3 or 4 inverse femtobarn can expect to observe pure third generation decay with 3 sigma significance.
- The race is on : which one will observe pure third generation decay first.

Back-up Slides

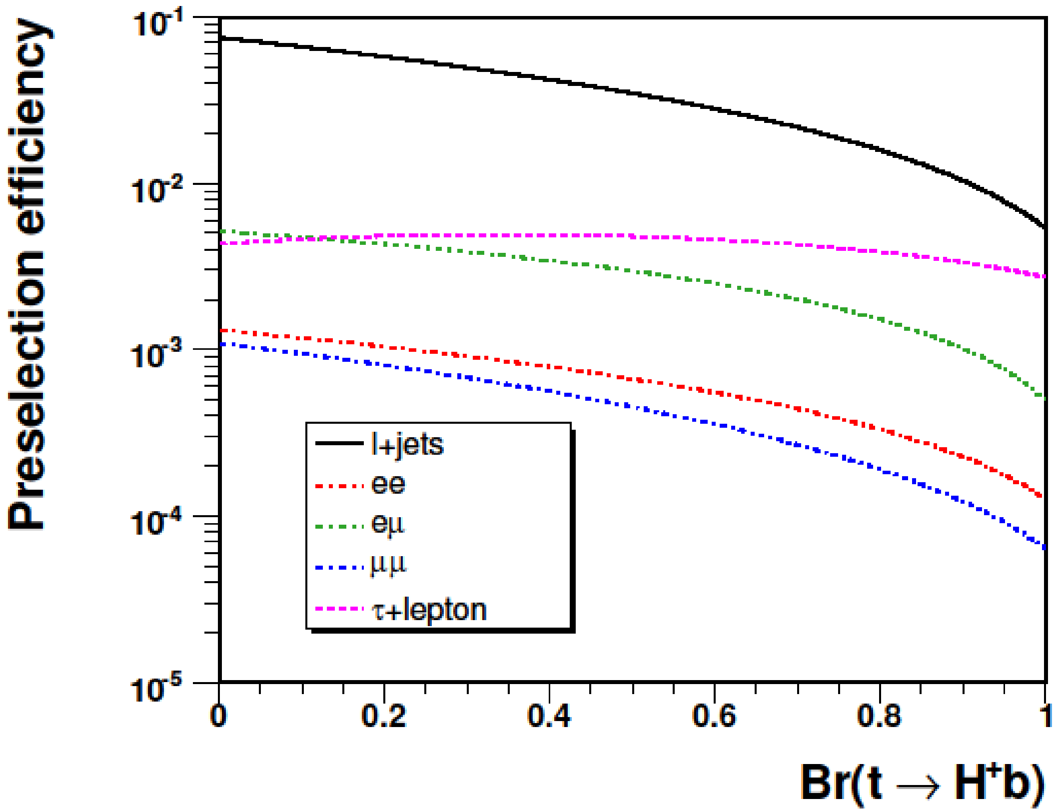
Input to neural network b-tagging algorithm

- Decay length significance of secondary the vertex.
- Weighted combination of the tracks' impact parameter significance.
- Probability that the jet originates from the primary vertex.
- Chi square per d.o.f. of the secondary vertex.
- Number of tracks used to reconstruct the secondary vertex.
- Mass of the secondary vertex.
- Number of secondary vertices found in the jet.

Dominant source of systematic uncertainties in the cross-section

Same-sign events	+1.17	-1.02
B-tagging	+0.34	-0.31
Lepton identification	+0.15	-0.15
Tau identification	+0.45	-0.41
Luminosity	+0.50	-0.44
Signal modeling	+0.75	-0.64
Jet identification	+0.23	-0.19

Disappearance at high charged Higgs mass



At high charged Higgs mass (shown here is 150 GeV), tau+lepton becomes a disappearance channel.