Search for charged Higgs bosons in decays of pair-produced top quarks at DØ

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For the DØ Collaboration

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Outline

- Motivation
- Introduction
- Production of a charged Higgs lighter than the top quark
- Decay of a charged Higgs lighter than the top quark
- The parameter space
- The DØ detector
- Run 1 analyses
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  - The appearance search
- Run 2 status, plans, and expectations
  - Measurement of $\sigma(t\bar{t})$ from the $\tau+$ jets final state with SM assumptions.
- Summary and outlook

Motivation

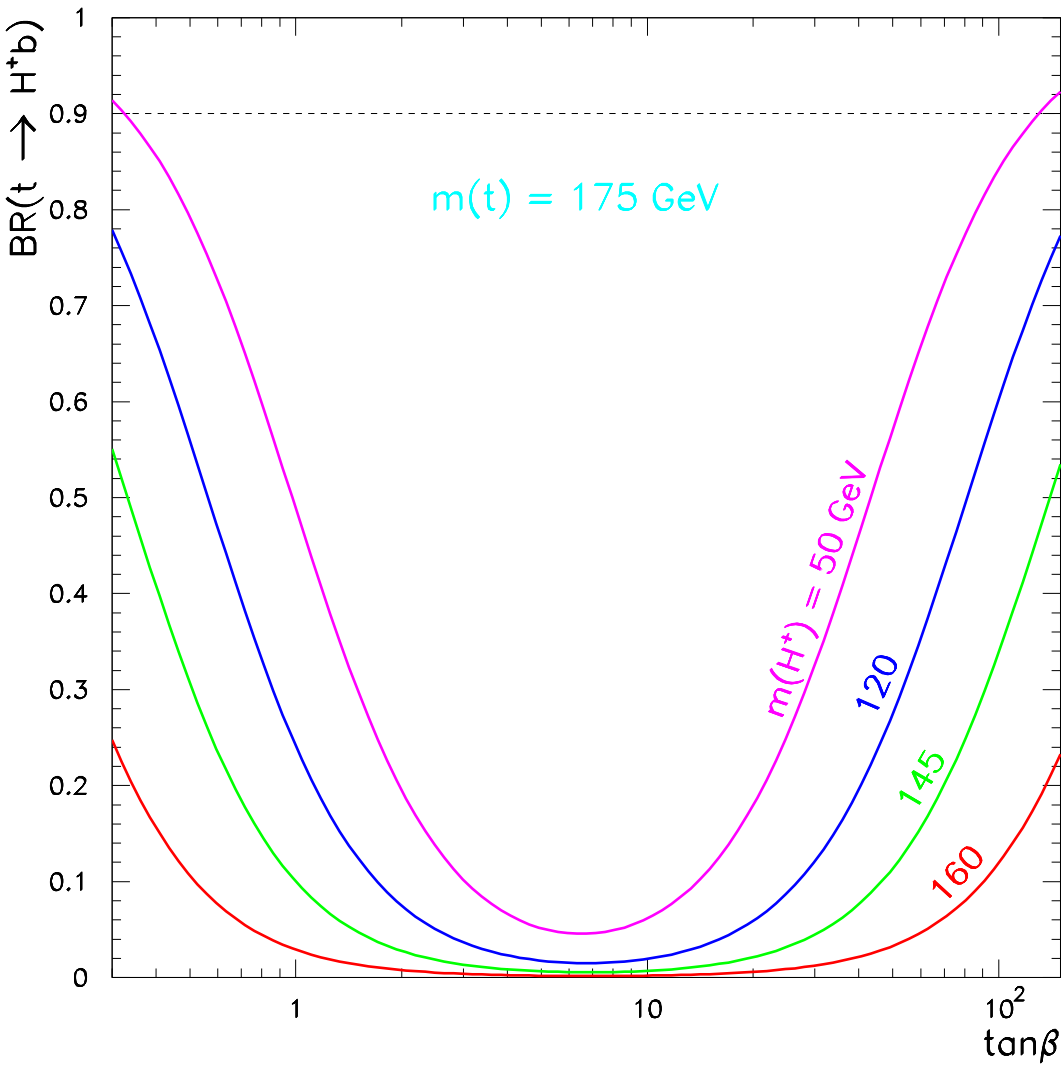
- Charged Higgs bosons appear in the simplest extension of the SM Higgs sector, an integral feature of some popular models beyond the SM (including SUSY).
- Observation of a non-SM Higgs may well be the first indication of physics beyond the SM.
- An extended Higgs sector offers an elegant means of closing the gap between the minimum level of CP violation needed to explain the apparent matter-antimatter asymmetry in the Universe and the maximum allowed by the SM with 3 generations of fermions.
- Tevatron experiments have a good chance of finding a charged Higgs if it is lighter than the top quark.

Production of a light H^+

If $M_{H^+} < m_t - m_b$, then $\Gamma(t \to H^+ b)$ can be large depending on $[M_{H^+}, \tan\beta]$. At the LO,

$$\Gamma(t \to H^+ b) \propto m_b^2 \tan^2\beta + m_t^2 \cot^2\beta \qquad (1)$$

BR($t \to H^+ b$) vs $\tan\beta$ for different values of M_{H^+}:



Expect search capabilities to follow these contours.

Decay of a light H^+

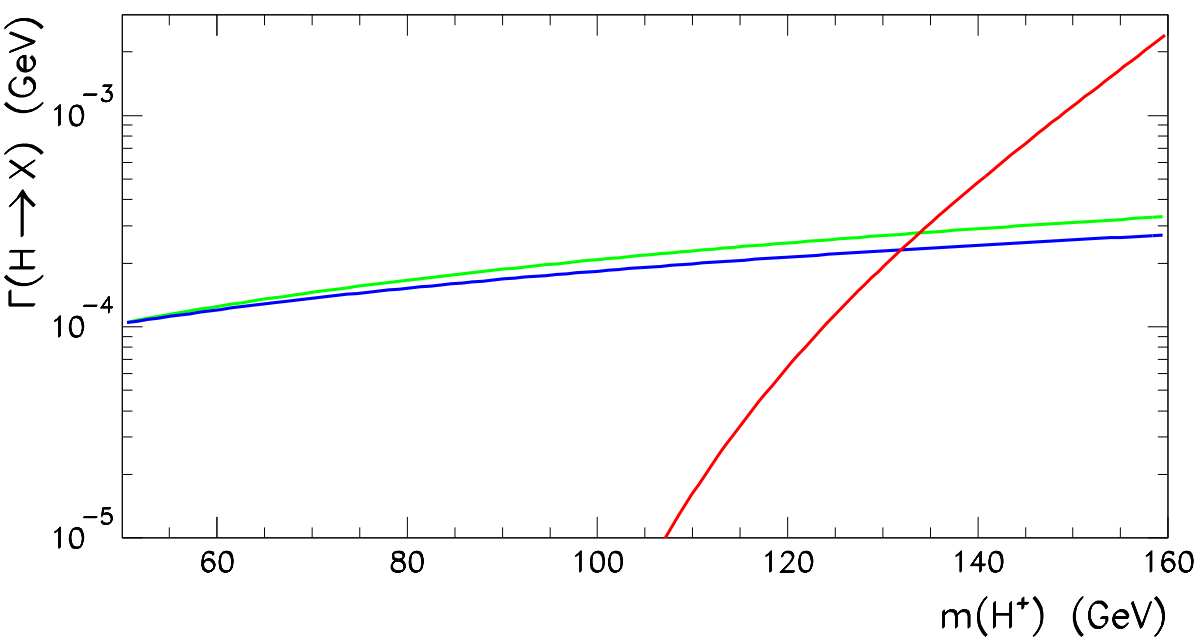
If we assume that $m_{S^0} > M_{H^+} - M_{W^+}$, where $S^0 = h^0$ or A^0, then H^+ can only decay to $f_U \bar{f}_D$.

($H^+ \to VW^+$, where $V = \gamma$ or Z, are absent at tree level.)

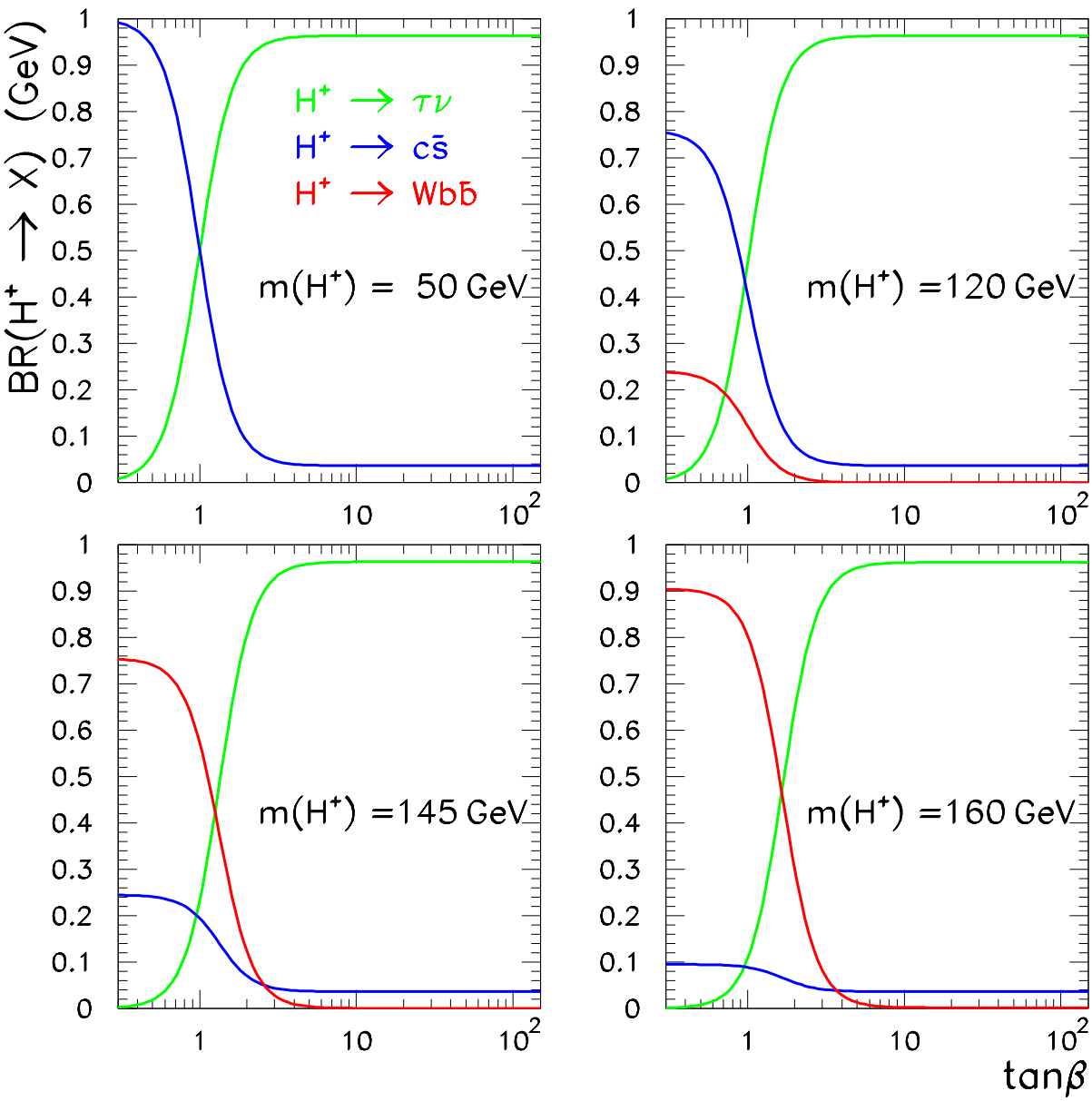
3 decay modes for H^+:

- $H^+ \to c\bar{s}$ ($\sim H^+ \to c\bar{b}$ at large $\tan\beta$)
- $H^+ \to t^*\bar{b} \to W^+ b\bar{b}$
- $H^+ \to \bar{\tau}\nu_\tau$

Partial widths vs. M_{H^+} (for $\tan\beta = 1$):



$\mathrm{BR}(H^+ \to X)$ vs $\tan\beta$



$\mathrm{BR}(H^+ \to c\bar{b})$ (not shown) is comparable to $\mathrm{BR}(H^+ \to c\bar{b})$ at large $\tan\beta$. Thus, $\mathrm{BR}(H^+ \to \tau^+\nu_\tau) \approx 0.93$ for $\tan\beta > 5$.

The parameter space

$$h_t = \frac{m_t}{v \sin\beta}, \qquad h_b = \frac{m_b}{v \cos\beta}. \tag{2}$$

We require $H^+ - t - b$ Yukawa coupling to be small enough for LO calculations to be valid:

$$\alpha_h \equiv \frac{h_f^2}{4\pi} < 1, \tag{3}$$

which translates approximately to

$$0.3 < \tan\beta < 150, \tag{4}$$

Total widths of t and H^+ must be limited:

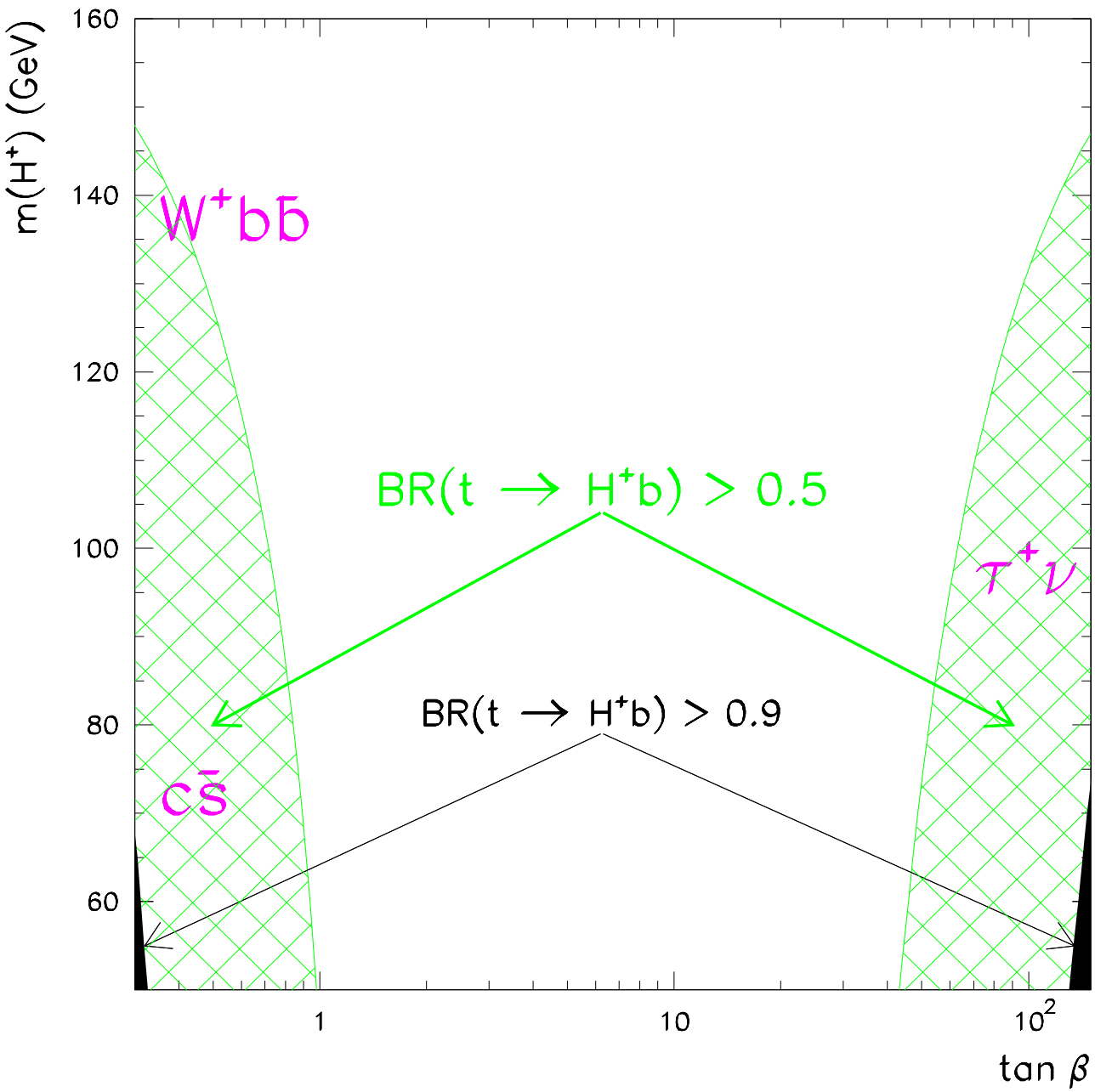
$$\begin{aligned} \Gamma(t) &< 10 \times \Gamma(t \to W^+ b) \approx 15\,\text{GeV} \\ \Rightarrow\ & \text{BR}(t \to H^+ b) < 0.9, \end{aligned} \tag{5}$$

and

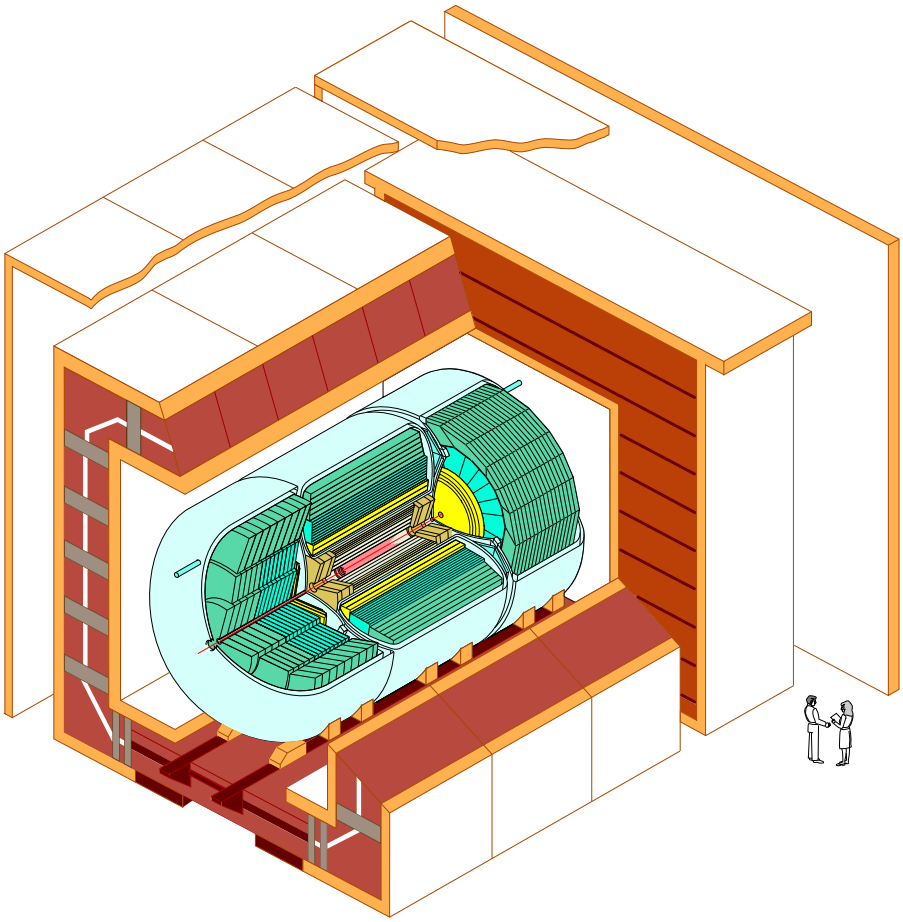
$$\Gamma(H^+) < 7.5\,\text{GeV} \Rightarrow M_{H^+} < 160\,\text{GeV}. \tag{6}$$

Results prior to DØ Run 1 (95% C.L.)

- LEP: $M_{H^+} > 60$ GeV (direct search),
- CDF: BR$(t \to H^+b) < 0.5$ (approx., improving),
- CLEO: $M_{H^+} >\sim 230$ GeV (?).



The DØ detector



DØ Detector

The Disappearance Search (Run 1)

$t\bar{t}$ decay modes

Four possible decays for each top quark:

1. $t \to W^+b$ (no constraint on W decays);
2. $t \to H^+b$, $H^+ \to c\bar{s}$;
3. $t \to H^+b$, $H^+ \to W^+b\bar{b}$;
4. $t \to H^+b$, $H^+ \to \bar{\tau}\nu_\tau$.

For any given selection criteria,

$$A(M_{H^+}, \tan\beta) = \sum_{i,j=1}^{4} \epsilon_{i,j}(M_{H^+}) \cdot \rho_i(M_{H^+}, \tan\beta) \cdot \rho_j(M_{H^+}, \tan\beta) \quad (7)$$

- All ρ_i depend on [M_{H^+},$\tan\beta$].
- All $\epsilon_{i,j}$, except the one for SM, depend on M_{H^+}.

$\Rightarrow$Use of selection criteria optimized for SM decay of $t\bar{t}$ obviates the need to re-tune cuts depending on [M_{H^+},$\tan\beta$].

Standard lepton+jets event selection

Single lepton+jets event selection criteria, accounting for 30 of 39 events on which the standard measurement of $\sigma(t\bar{t})$ is based (not including the all jets channel), are chosen for this analysis.

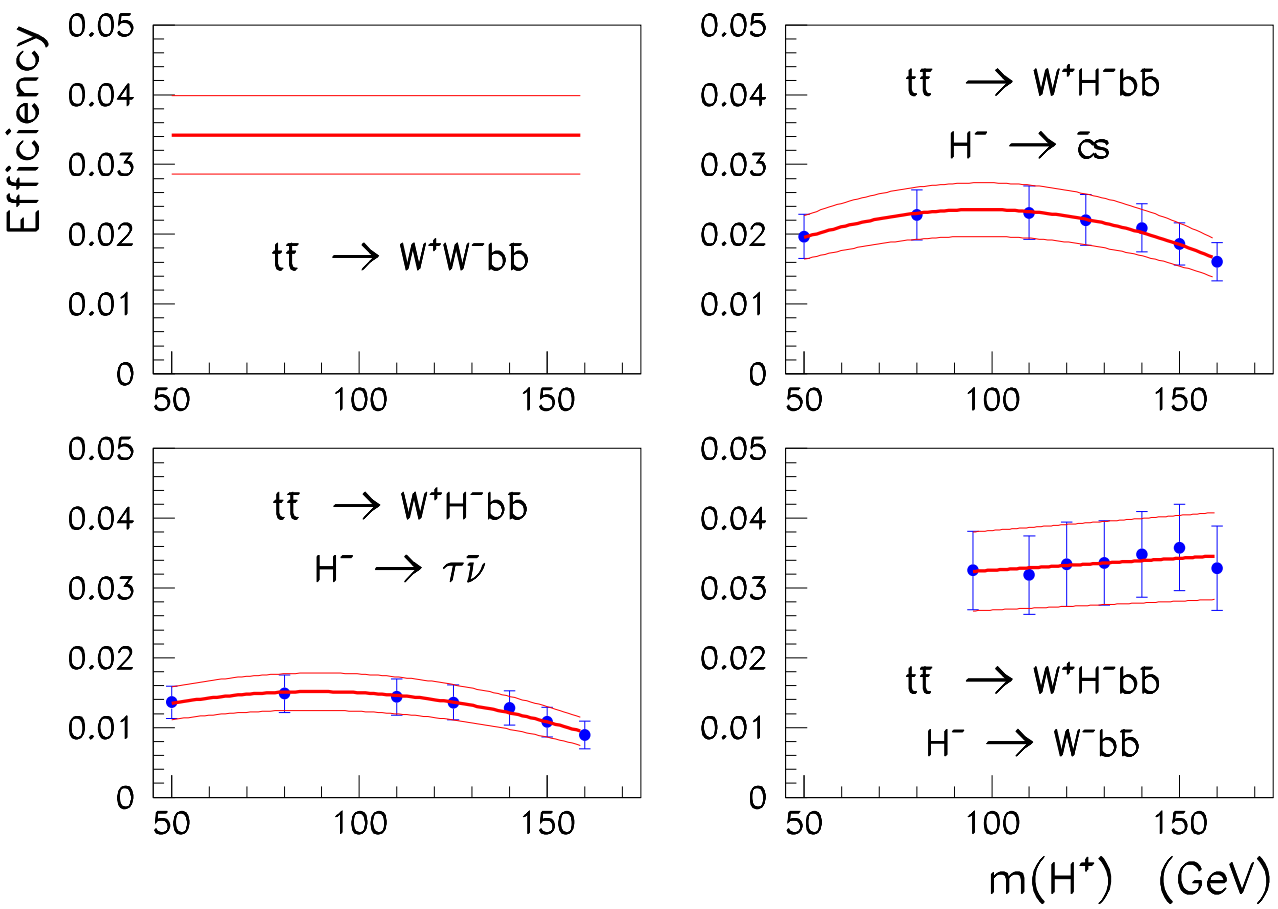
	Topological	b-tag
$p_T(l)$	> 20 GeV	> 20 GeV
$\lvert\eta(l)\rvert$	< 2.0 (1.7)	< 2.0 (1.7)
$\not{E}_T$	> 25 GeV	> 20 GeV
$E_T(j)$	> 15 GeV	> 20 GeV
$\lvert\eta(j)\rvert$	< 2.0	< 2.0
n_j	≥ 4	≥ 3
n_{tag}	0	≥ 1
A	> 0.065	> 0.040
H_T	> 180 GeV	> 110 GeV
$p_T(l) + E_T$	> 60 GeV	–
$\lvert\eta(W)\rvert$	< 2.0	–

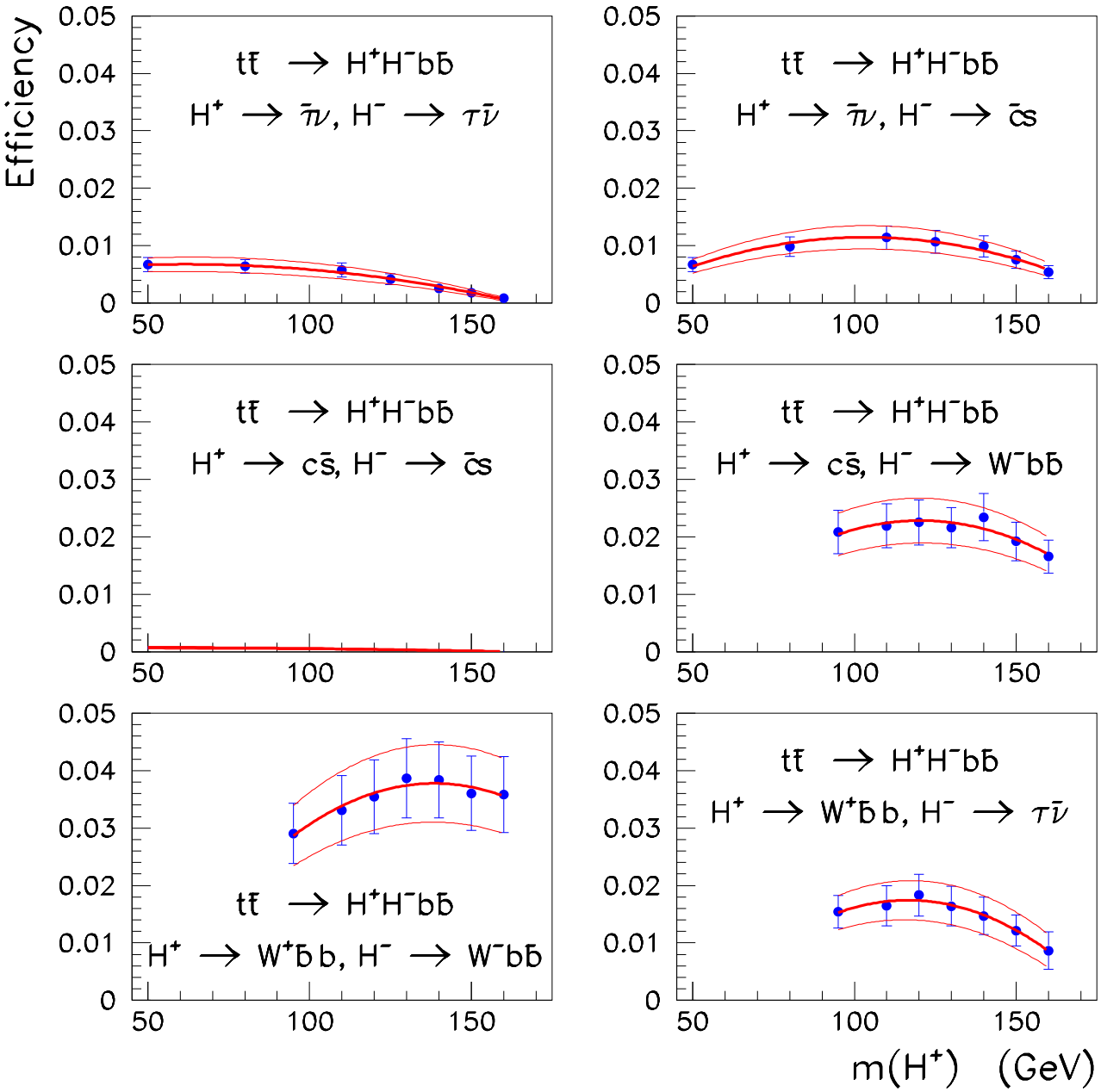
(plus a few other cuts to reject CR muons, $Z \to \mu\mu$ etc.)

Parametrization of effi ciencies as functions of M_{H+} (statistics)

Parabolic fits are adequate for all channels:

$$\epsilon_{i,j} = \sum_{k=0}^{2} p_{i,j,k} \cdot M_{H+}^{k} \qquad (8)$$




Efficiency
$t\bar{t} \to H^+H^-b\bar{b}$
$H^+ \to \bar{\tau}\nu$, $H^- \to \tau\bar{\nu}$
$t\bar{t} \to H^+H^-b\bar{b}$
$H^+ \to \bar{\tau}\nu$, $H^- \to \bar{c}s$
$t\bar{t} \to H^+H^-b\bar{b}$
$H^+ \to c\bar{s}$, $H^- \to \bar{c}s$
$t\bar{t} \to H^+H^-b\bar{b}$
$H^+ \to c\bar{s}$, $H^- \to W^-b\bar{b}$
$t\bar{t} \to H^+H^-b\bar{b}$
$H^+ \to W^+\bar{b}b$, $H^- \to W^-b\bar{b}$
$t\bar{t} \to H^+H^-b\bar{b}$
$H^+ \to W^+\bar{b}b$, $H^- \to \tau\bar{\nu}$
0
0.01
0.02
0.03
0.04
0.05
50
100
150
$m(H^+)$ (GeV)

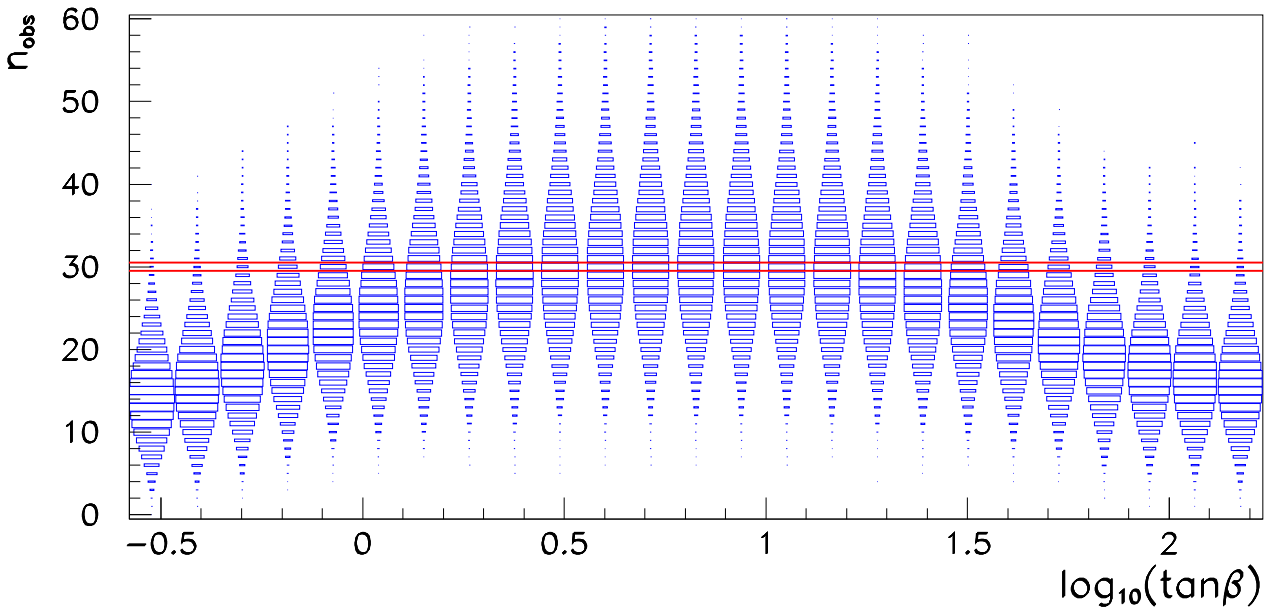
Limit calculation (Probability)

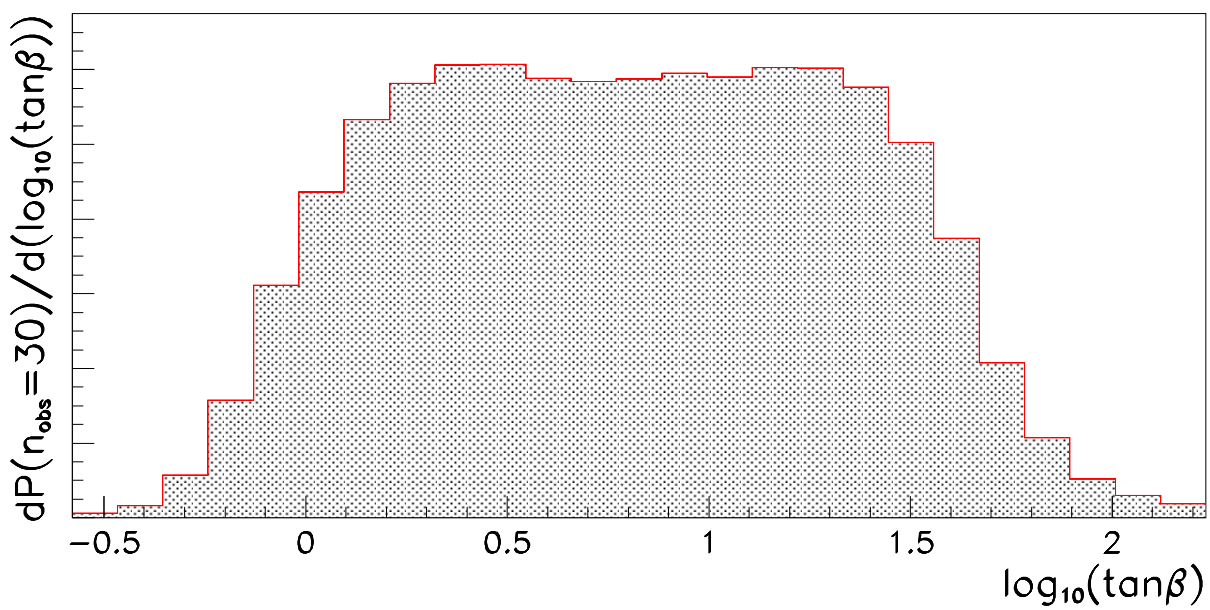
The DØ experiment is simulated a large number of times over the entire [M_{H^+},$\tan\beta$] window of interest:

- M_{H^+} from 50 GeV to 160 GeV in 5 GeV bins.
- $\tan\beta$ from 0.3 to 150 in 25 uniform bins in $\log_{10}(\tan\beta)$.
- 200,000 experiments in each bin of [M_{H^+},$\tan\beta$].

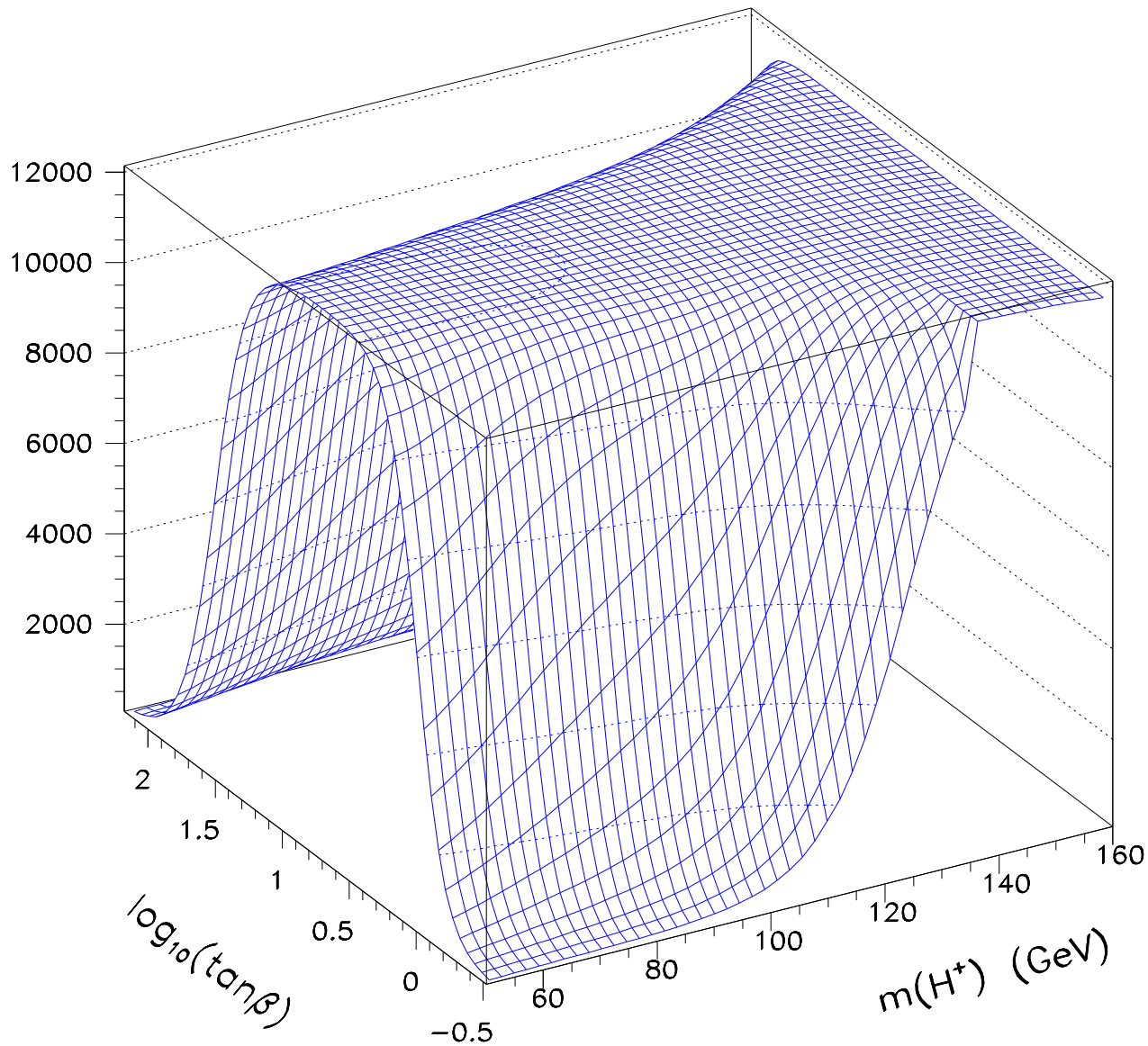
- $\int \mathcal{L}dt = 109.2 \pm 5.8$ pb$^-1$.
- $\sigma(t\bar{t})$ = 5.5 pb.
- m_t = 175 GeV.
- $\langle n_S \rangle = A \cdot \sigma(t\bar{t}) \cdot \int \mathcal{L}dt$.
- $\langle n_B \rangle = 11.12 \pm 1.95$.
- $n_{obs} = n_S + n_B$.

Frequency of n_{obs} and $P(n_{\text{obs}} = 30)$ vs. $\log_{10}(\tan\beta)$ for M_{H^+} =80 GeV

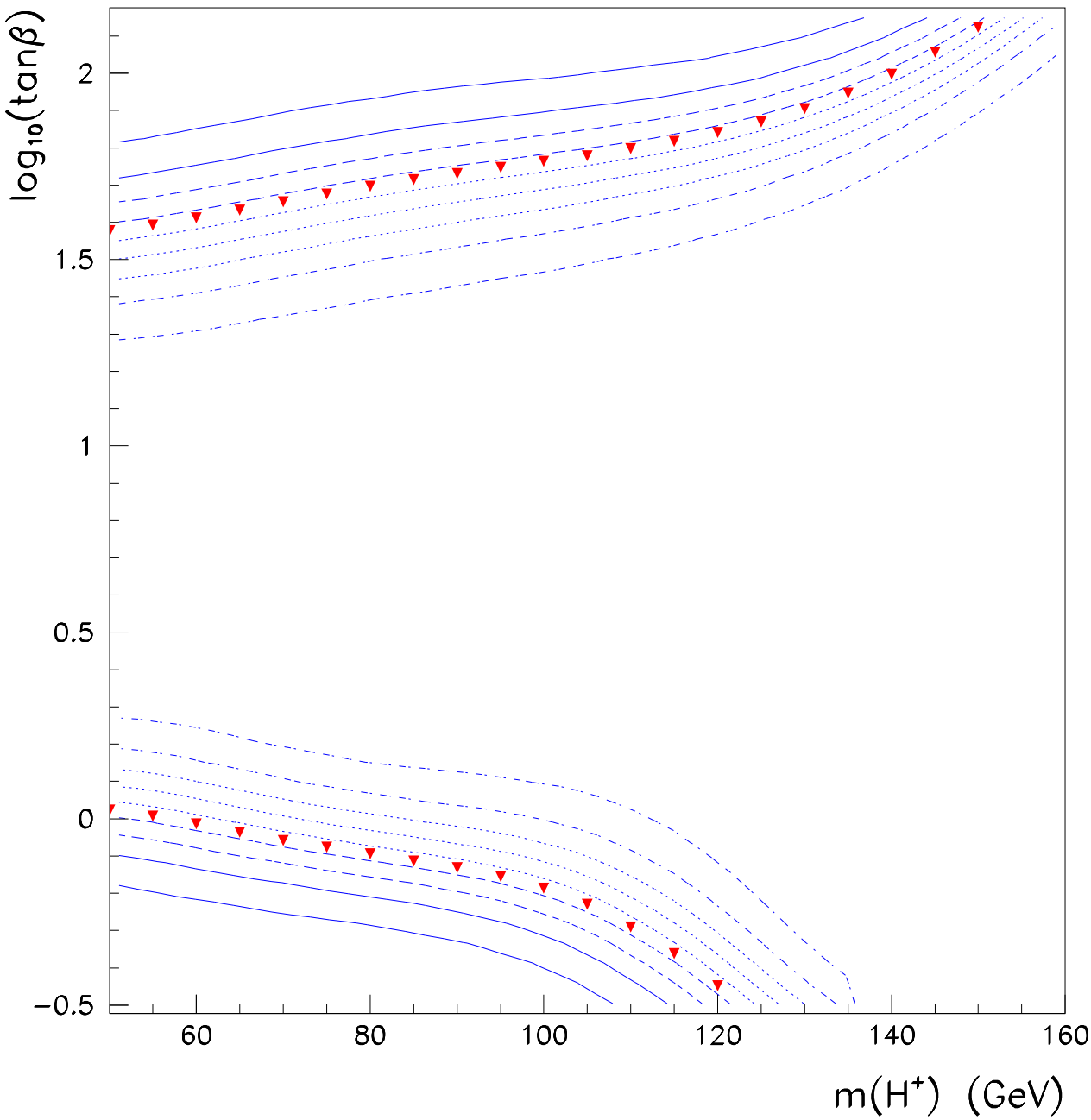




$P(\tan\beta, M_{H^+} | n_{obs} = 30)$ vs $[M_{H^+}, \tan\beta]$

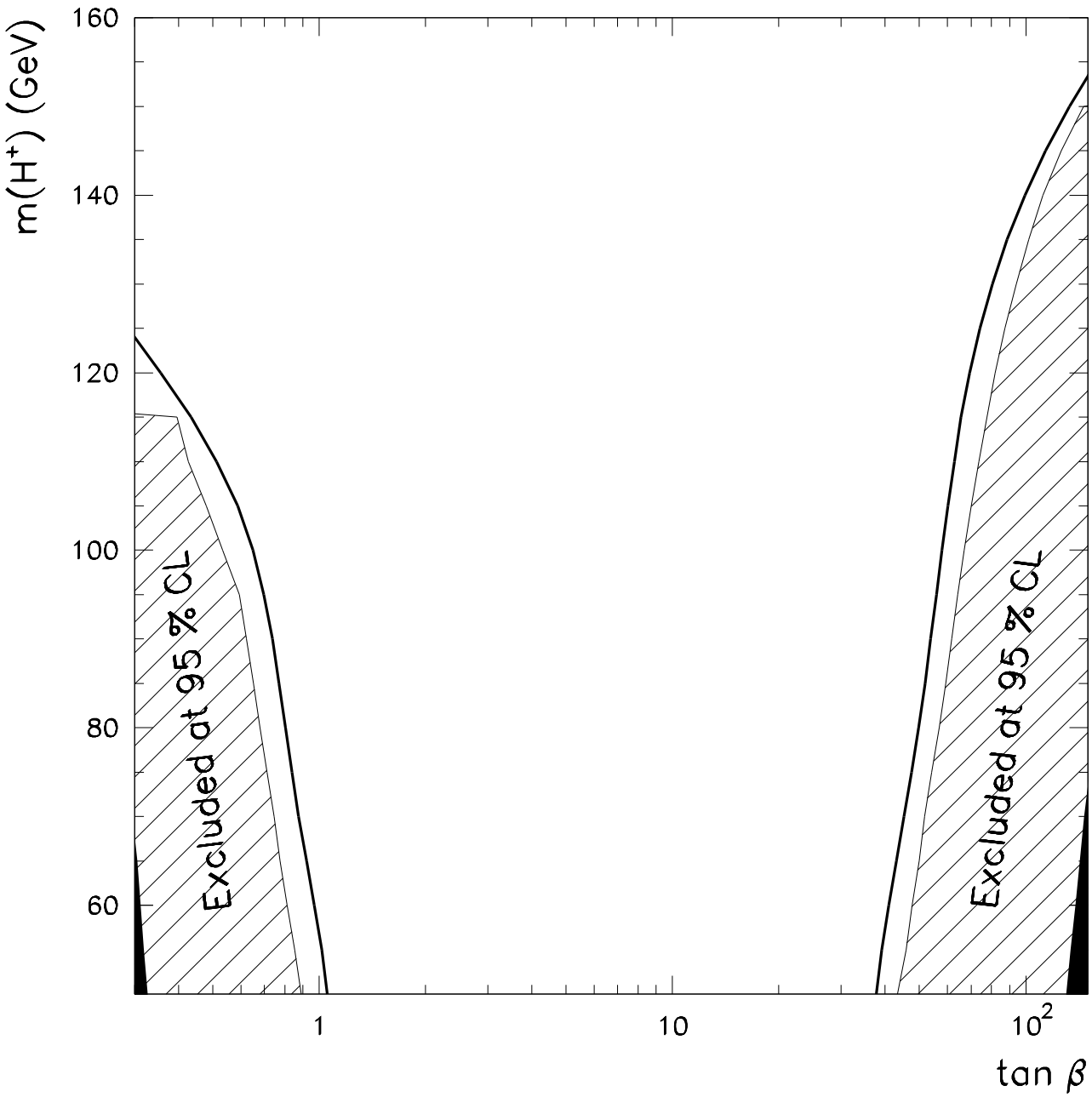


Contours of $P(\tan\beta, M_{H^+}|n_{obs} = 30) = const$



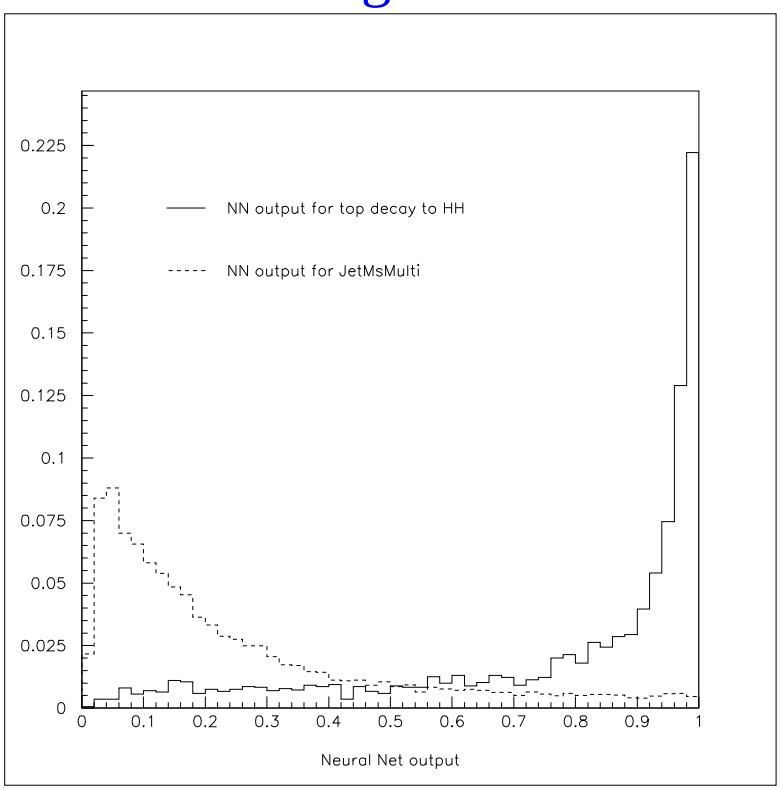
Results

Exclusion limits:
unshaded $\Rightarrow$ Bayesian,
shaded $\Rightarrow$ frequentist)

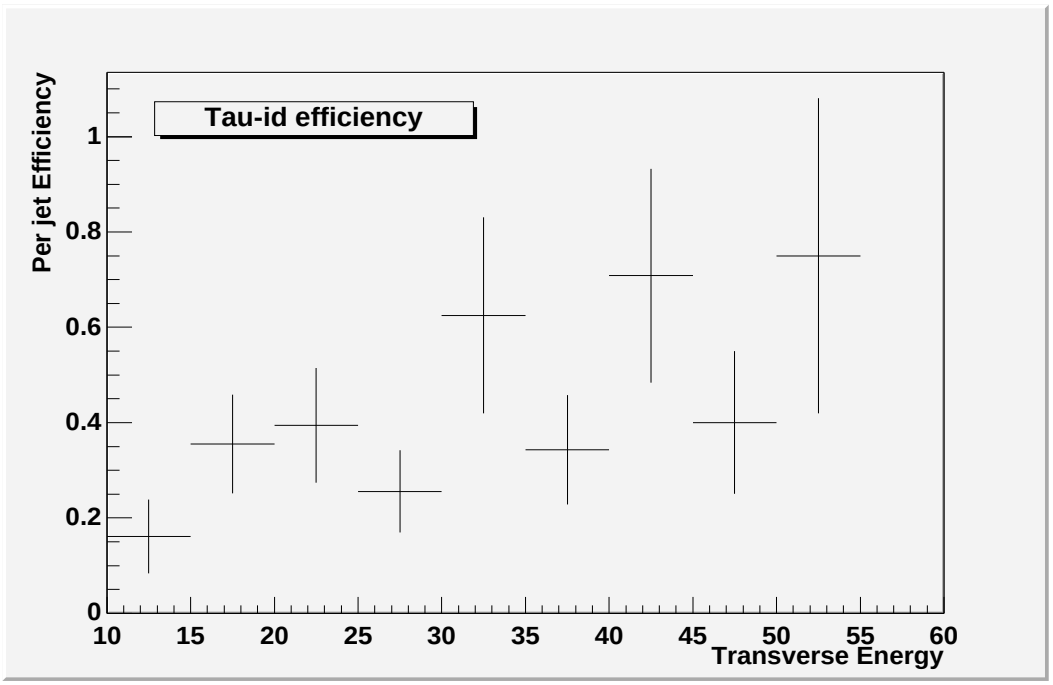


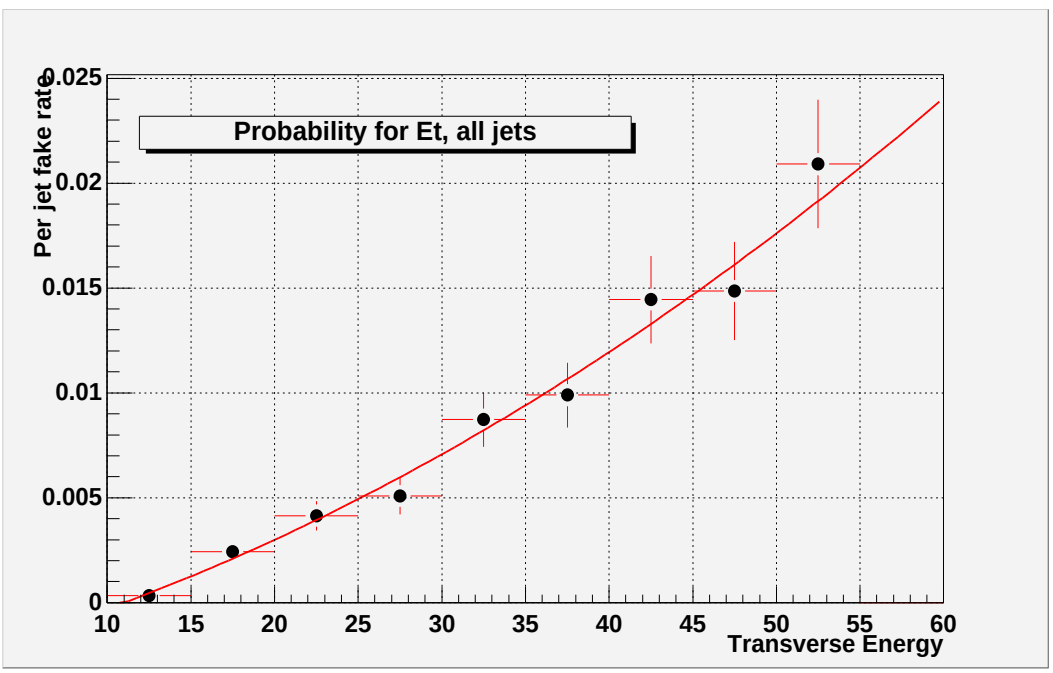
The Appearance Search (Run 1)

- Multijet + $\not{E}_T$ trigger: 4 jets with $E_T > 12$ GeV, $\not{E}_T > 10$ (14) GeV.
- $\int \mathcal{L} dt = 62.2$ pb[1].
- Artificial Neural Network used to reduce QCD background (no τ id yet)
- Require at least one good τ candidate.

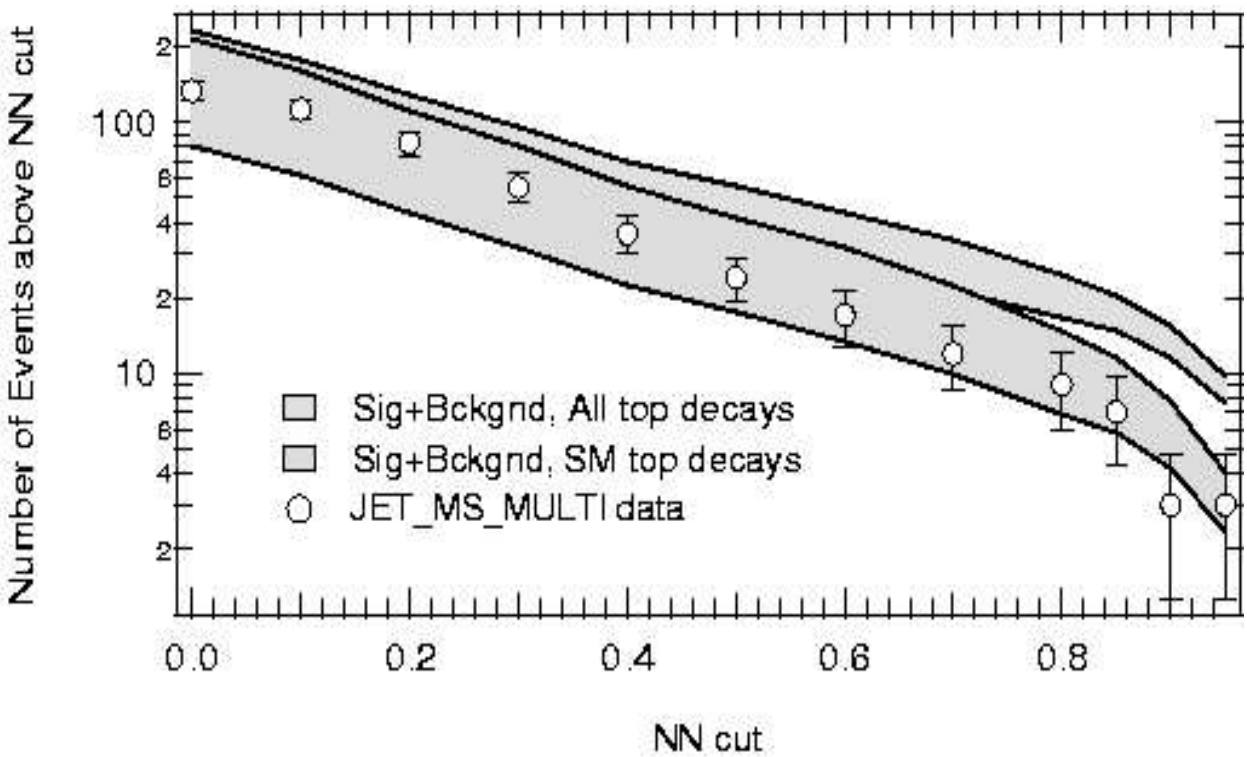


τ id effi ciency and fake rate

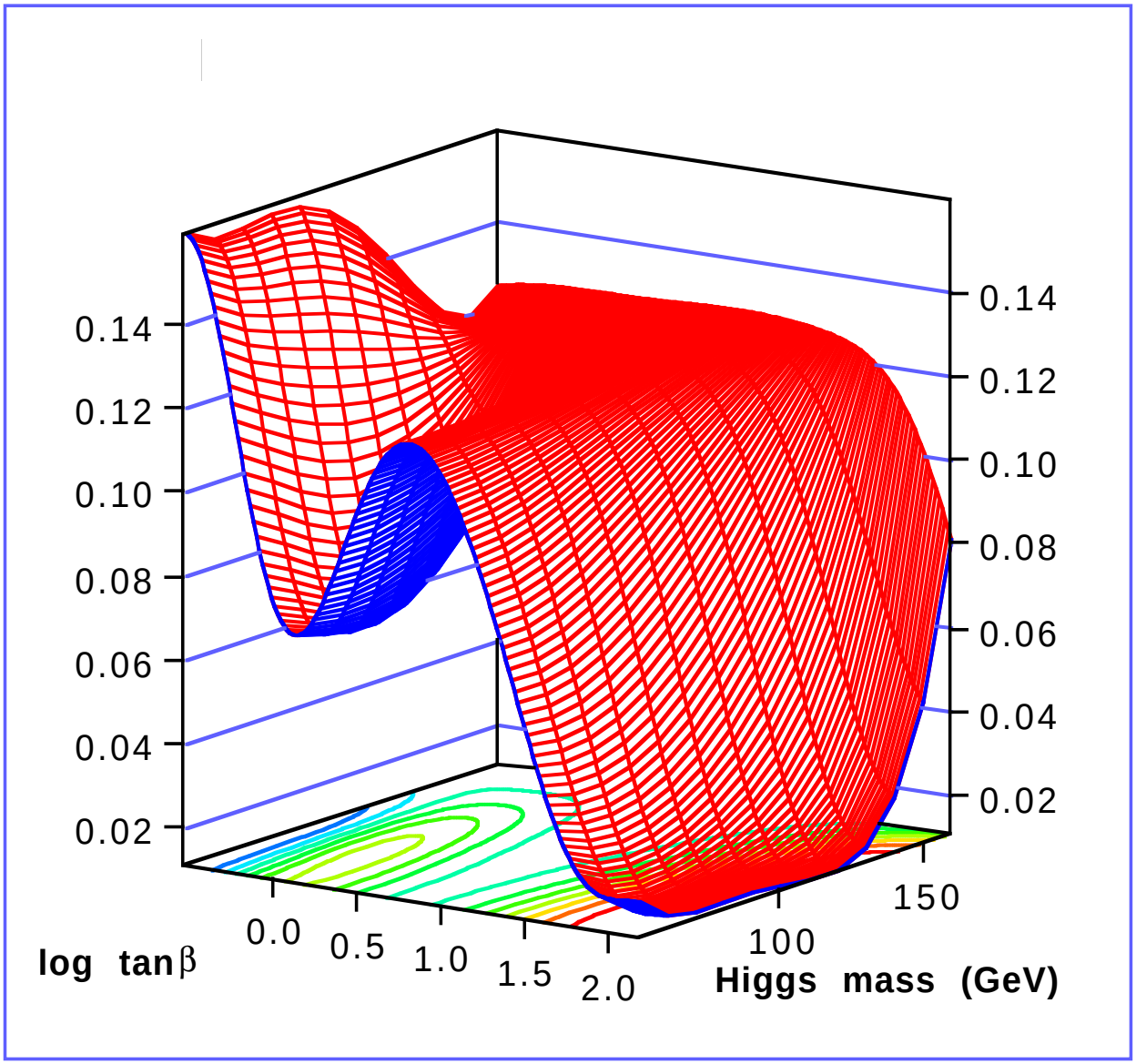




Predictions for $t\bar{t}$ with and without H^+, and DØdata

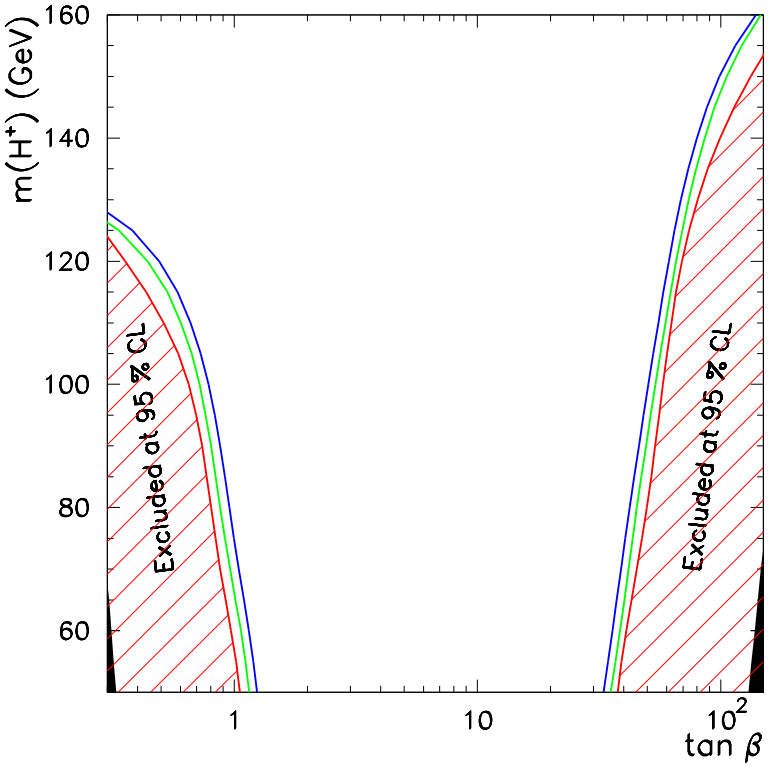


Likelihood over the parameter space

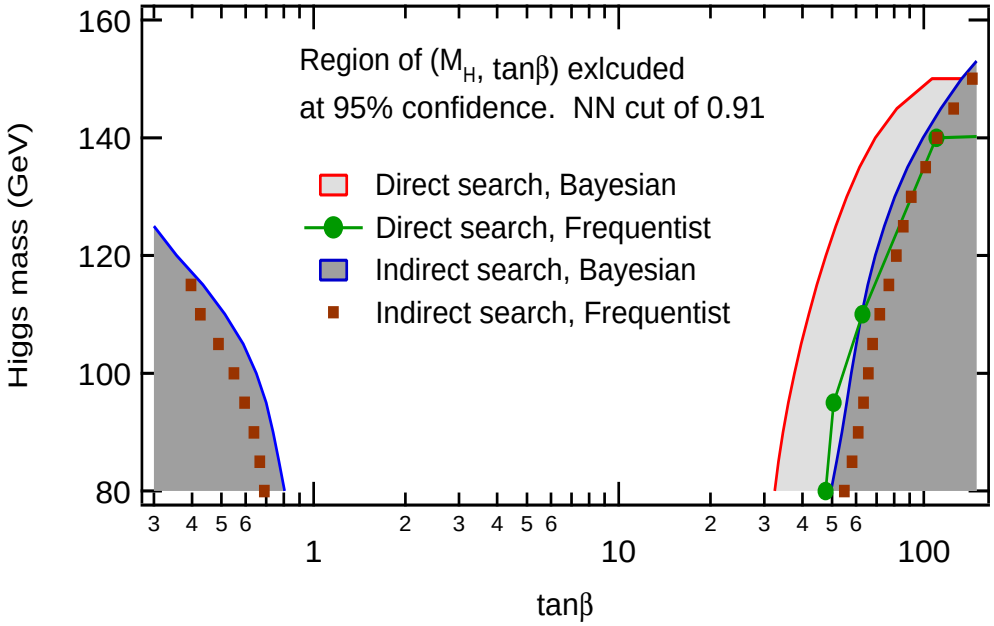


Search for $t \to H^+b$: DØ result

Exclusion boundaries ($\sigma(t\bar{t})$ = 5.5, 5.0, 4.5 pb)



Search for $t \to H^+b$, $H^+ \to \bar{\tau}\nu_\tau$:



Measurement of $\sigma(p\bar{p}) \to t\bar{t}$ at $\sqrt{s} = 1.96$ TeV (Run 2) using the $\tau + \not{E}_T$ + jets final state

(New preliminary) result

- This is based on SM, where one of the two W's from the top decays to two hadronic jets while the other decays to a τ lepton and the associated neutrino, followed by hadronic decay of the τ.

- It takes us a long way toward the appearance search for $t \to H^+b$ in the region of large $\tan\beta$. We can now apply essentially the same analysis to $t \to H^+b$ Monte Carlo.

- The observable final state is characterized by the hadronic remnants of the τ, large missing transverse momentum due to the neutrino-antineutrino pair, and 4 hadronic jets, two of which arise from b quarks. (see Mark Owen's talk for a detailed description of τ identification at DØ).

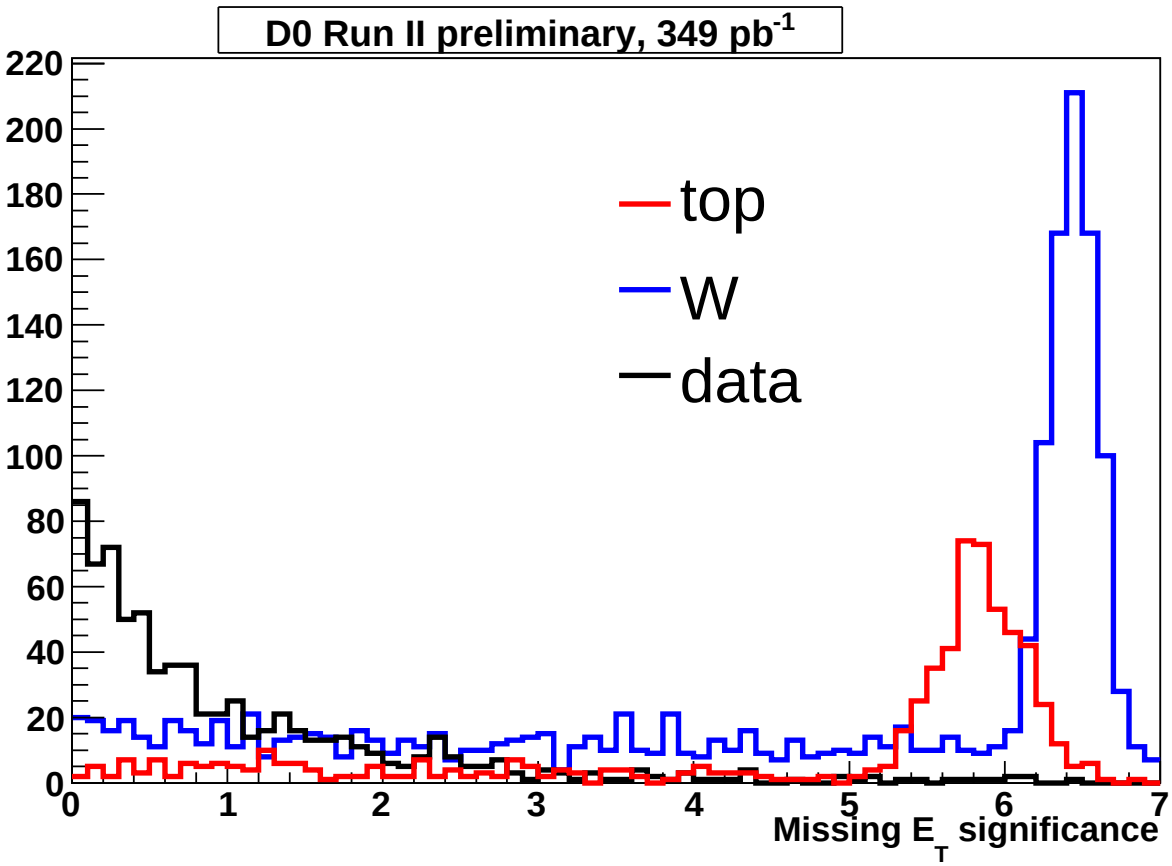
- Present report is based on $\int \mathcal{L} dt = 349 \pm 19$ pb^{-1}. Analysis of a ~ 0.9 fb^{-1} data sample is underway.

- Trigger: 4 jets with $E_T > 10$ GeV (same as the all-jets analysis).

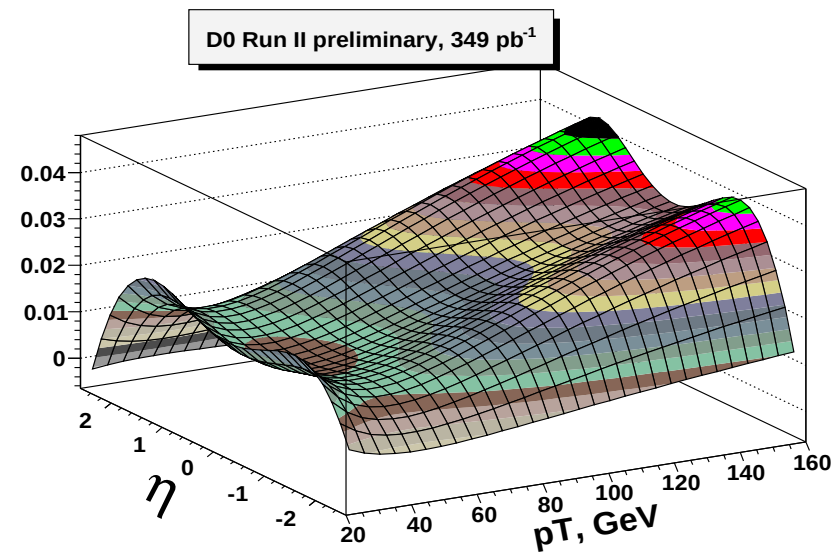
- Preselection:
  - $|z_{\rm PV}| < 60$ cm, $n_{\rm trk}({\rm PV}) > 3$,
  - No isolated electron or muon,
  - $\not{E}_T$ significance > 3,
  - $n_{\rm jets} \geq 4$.

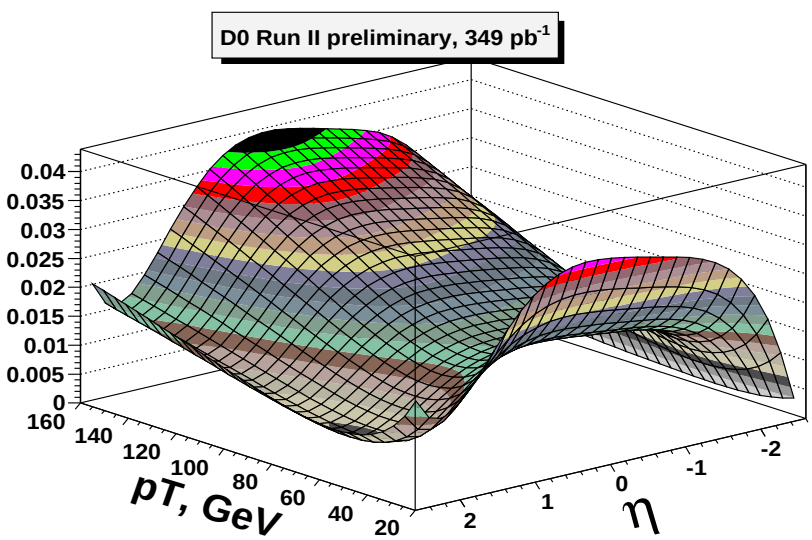
- τ and b id (the latter using secondary vertex tag) criteria are applied later.

$\not{E}_T$ significance: $L = \ln \frac{P(\not{E}_T)\text{max}}{P(\not{E}_T=0)}$



Probability of a QCD jet faking τ is determined from multijet trigger sample with a b veto. Single-prong decays without associated π^0's ("type 1") don't contribute much, and are ignored. Single-prong decays with associated π^0's ("type 2", top) and multi-prong decays ("type 3", bottom) are treated separately.





To suppress background to $t\bar{t}$ events, a 2-stage NN is used. Signal is modelled with Monte Carlo, background with same trigger data, but without a good τ candidate (fake rate parametrization is used instead).

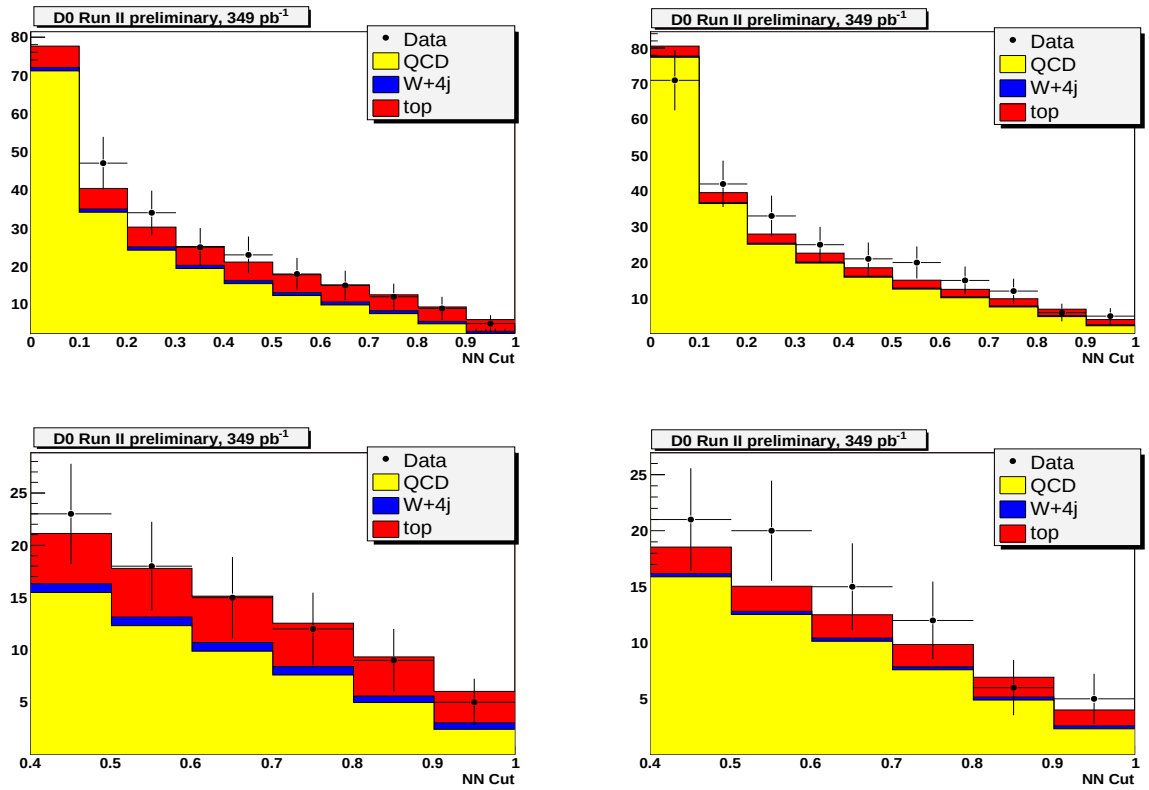
Stage 1:

- H_T (scalar sum of jet E_T's) and $\sqrt{s}$,
- Sphericity and Aplanarity,
- Centrality, defined as $\frac{H_T}{H}$.

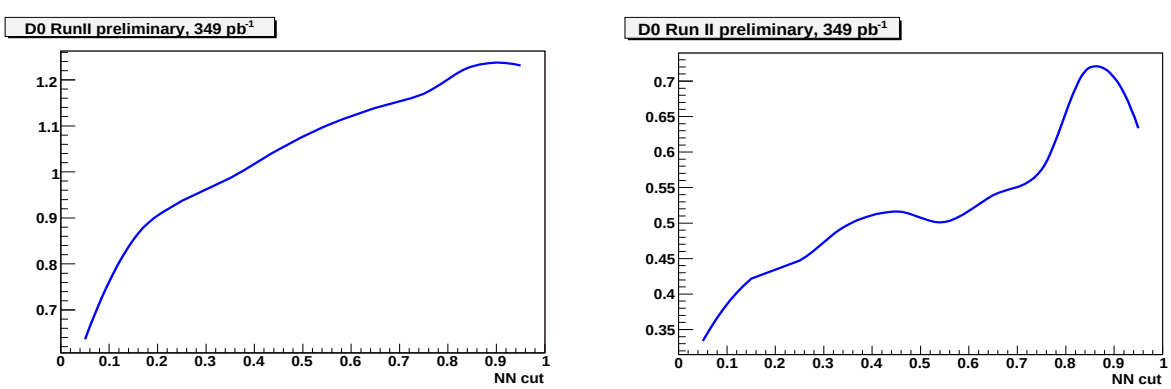
Stage 2:

- Output of Stage 1,
- Top and W mass likelihood - a χ^2-like variable, $L \equiv \left(\frac{m_{3j}-m_t}{\sigma_t}\right)^2 + \left(\frac{m_{2j}-m_W}{\sigma_W}\right)^2$, where $m_t, M_W, \sigma_t, \sigma_W$ are top and W masses (175 GeV and 80 GeV respectively) and resolution values (45 GeV and 10 GeV respectively). m_{3j} and m_{2j} are composed of the jet combinations, so as to minimize L,
- E_T and SVT significance of the leading b-tagged jet.

Acceptance as functions of the cut on the final NN output (left: type 2, right: type 3):



The signal significance, $\frac{S}{\sqrt{S+B}}$, as a function of thte NN cut (left: type 2, right: type 3):



Results of requiring NN output > 0.9

(uncertainties are statistical only):

	Type 2	Type 3
$W(\to \tau\nu)$	0.60 ± 0.03	0.27 ± 0.01
QCD fake	2.41 ± 0.09	2.33 ± 0.09
$\varepsilon(t\bar{t})$ (%)	1.57 ± 0.01	0.73 ± 0.01
$\langle S \rangle$ ($\sigma_{t\bar{t}}$ = 7 pb)	$3.83^{+0.46}_{-0.51}$	$1.80^{+0.22}_{-0.23}$
$\langle S + B \rangle$	$6.84^{+0.46}_{-0.51}$	$4.39^{+0.22}_{-0.23}$
N_{obs}	5	5

Systematic uncertainties: jet energy scale, MC statistics, $\sigma(W \to \tau\nu)$, τ fake rate parametrization, b id, etc.

$\sigma(p\bar{p}) \to t\bar{t}$ result

From "type 2" τ's only:

$$\sigma(t\bar{t}) = 3.63^{+4.72}_{-3.50}\ \text{(stat)}\ ^{+0.49}_{-0.48}\ \text{(syst)}\ \pm 0.14\ \text{(lumi)}\ \text{pb}$$

From "type 3" τ's only:

$$\sigma(t\bar{t}) = 9.39^{+10.10}_{-7.49}\ \text{(stat)}\ ^{+1.25}_{-1.18}\ \text{(systt)}\ \pm 0.61\ \text{(lumi)}\ \text{pb}$$

Combined ("type 2" and "type 3" τ's):

$$\sigma(t\bar{t}) = 5.05^{+4.31}_{-3.46}\ \text{(stat)}\ ^{+0.68}_{-0.67}\ \text{(sys)}\ \pm 0.33\ \text{(lumi)}\ \text{pb}$$

- We have a 1.5σ result.
- Hope to improve it very soon to 3σ, amounting to independent "evidence" of $t\bar{t}$ production using the $\tau + \not{E}_T$ +jets final state alone.
- Can already see that this will lead to a srong result on a search for $t \to H^+ b$.

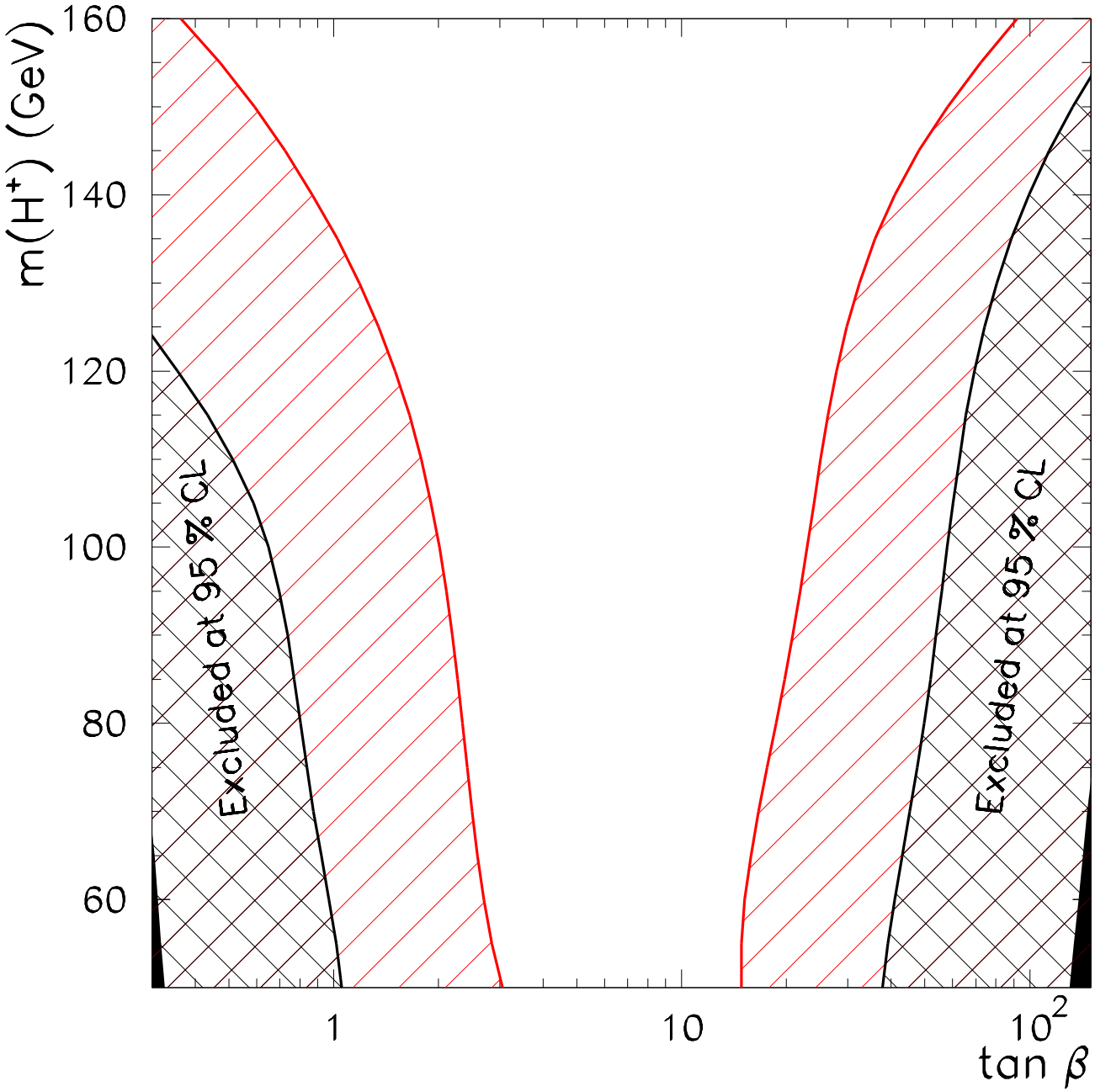
Expectations from disappearance search

- Accelerator upgrade ⇒more data.
  - Luminosity goal: 2 fb^{-1}.
  - $\sqrt{s} = 2$ TeV ⇒30-40% increase in $\sigma(t\bar{t})$ over $\sqrt{s} = 1.8$ TeV.
- Detector upgrade ⇒improvement in S/B.
  - Magnetic field in central tracker, preshower detectors ⇒ improvement in identification and momentum resolution of e, μ, τ. Also electron-tagging of b.
  - Silicon vertex detector ⇒b-tagging by separation of secondary vertex.

Quantity	Value
$\int \mathcal{L} dt$	2000 ± 100 pb^{-1}
m_t	175 GeV
$\sigma(t\bar{t})$	7.0 pb
ϵ_{SM}	4.0 ± 0.4 %
$\langle n_B \rangle$	50 ± 5
n_{obs}	600

Limits expected from Run 2

(if SM-based measurement of $\sigma(t\bar{t})$ continues to agree with QCD prediction)



Future plans

- Have all the analysis tools in hand for both appearance & disappearance searches in Run 2.
- Run 1 exerience $\Rightarrow$well-developed strategy.
- Now trying to understand issues of MC generation and presentation of results.
- New methods, e.g.ratio of 2-, 1-, and 0- lepton final states will be tried.
  - Advantage: $\sigma(t\bar{t})$ and some systematic uncertainties cancel out.
  - Disadvantage: statistical uncertainty is larger. Larger data set of Run 2 will help this method become competitive with the others
- Also, dilepton channels where one of the leptons is a τ will be included
- Combination of all channels should lead to rather strong results for a charged Higgs lighter than the top quark - good groundwork and warm-up exercise for LHC.