# Searches for BSM Higgs at the Tevatron

Luca Scodellaro
Instituto de Fisica de Cantabria – CSIC

On behalf of the CDF and DØ Collaborations

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QCD and High Energy Interactions
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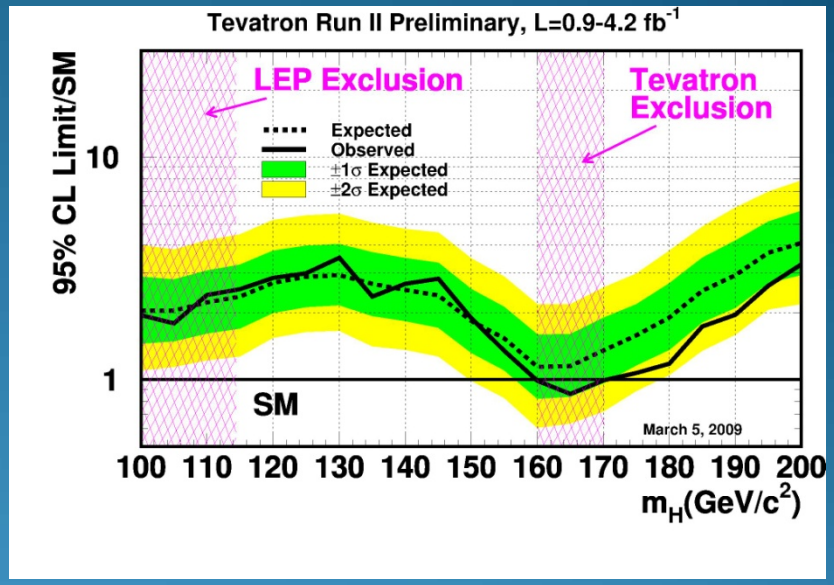
# Introduction and Outline

- CDF and DØ experiments finally sensitive to SM Higgs
  - Large mass windows not yet reachable at the Tevatron
  - Standard model incomplete: extensions required
- Neutral Higgs bosons
  - Enhanced cross sections in MSSM
- Charged Higgs bosons
  - Searched in top decays $t \rightarrow H^{\pm} b$
- Higgs bosons in nMSSM
- Fermiophobic Higgs
  - Greater sensitivity in the low mass region



# Neutral Higgs Bosons in the MSSM

# The Higgs Sector in the MSSM

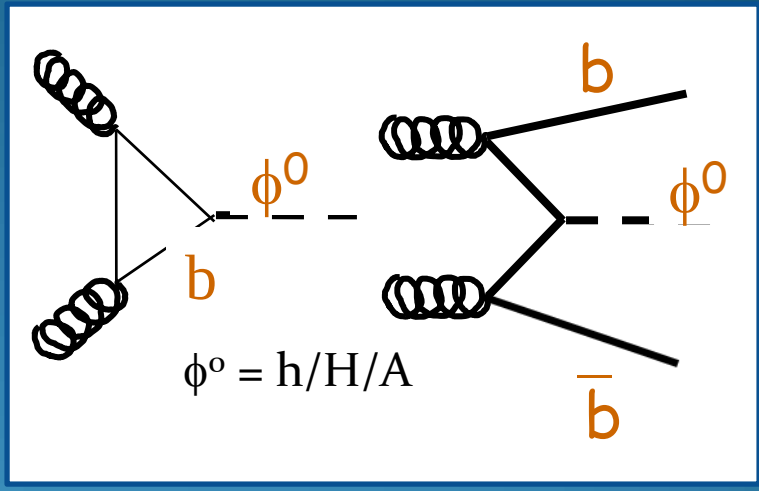
- MSSM requires two complex doublet fields:
  - One couples to up-type fermions, the other to down-type ones
  - Eight dof, three absorbed by W/Z masses → five physical fields
  - Three neutral scalars (h, H, A), and two charged ($H^{\pm}$)

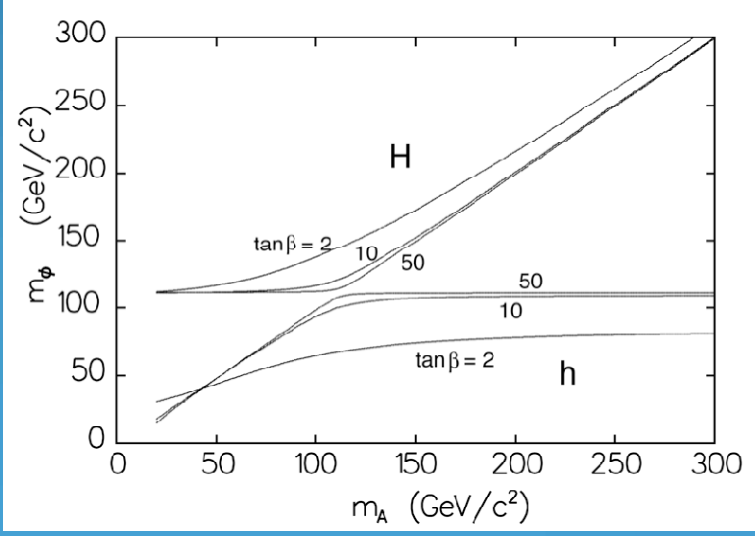
- At three level, Higgs properties described by:
  - $\tan\beta$: ratio of vacuum expectation values of Higgs doublets
  - $m_A$: mass of the pseudoscalar boson A

- At higher orders, other parameters become important:
  - $m_h^{max}$ and no-mixing scenarios, $\mu=\pm 200$ (EPJ C26:601)
  - Typically, $m_h<m_A<m_H$, and $m_{H\pm}\sim m_A$

# Neutral Higgs in the MSSM

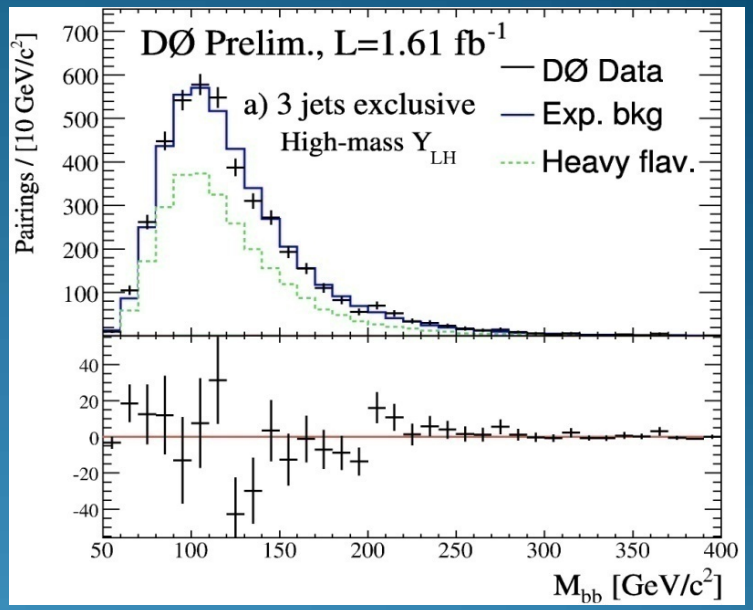
- Neutral Higgs couplings to b and τ (down-type) goes as tanβ
- At tanβ~1, h becomes SM-like
  - See limits on SM Higgs
- At high tanβ, processes involving b quarks enhanced (~tan²β)
- A becomes degenerate with h or H
  - Further enhancement of the signal
- Dominant decays into $b\bar{b}$ (~90%) and $\tau\bar{\tau}$ (~5-13%)
  - $\phi^o b(\bar{b}) \rightarrow b\bar{b}b(\bar{b})$
  - $\phi^o \rightarrow \tau\bar{\tau}$, $\phi^o \rightarrow \tau\bar{\tau}b(\bar{b})$

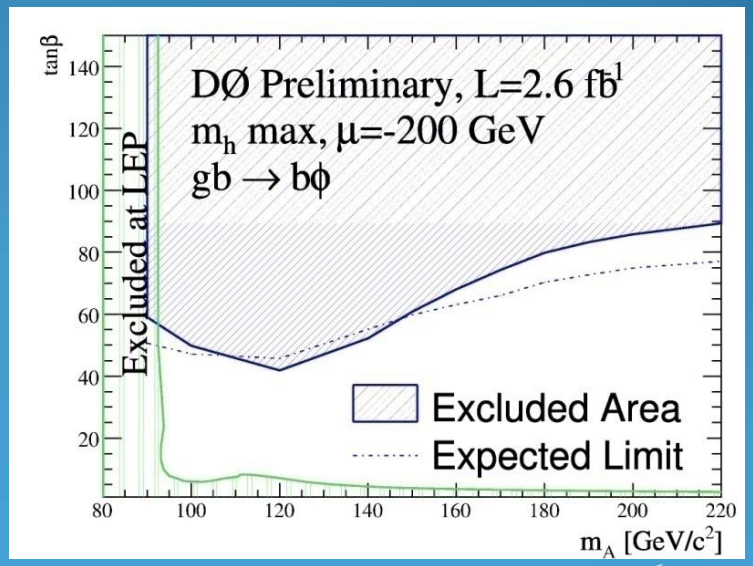


# $\Phi^0 b \rightarrow bbb$

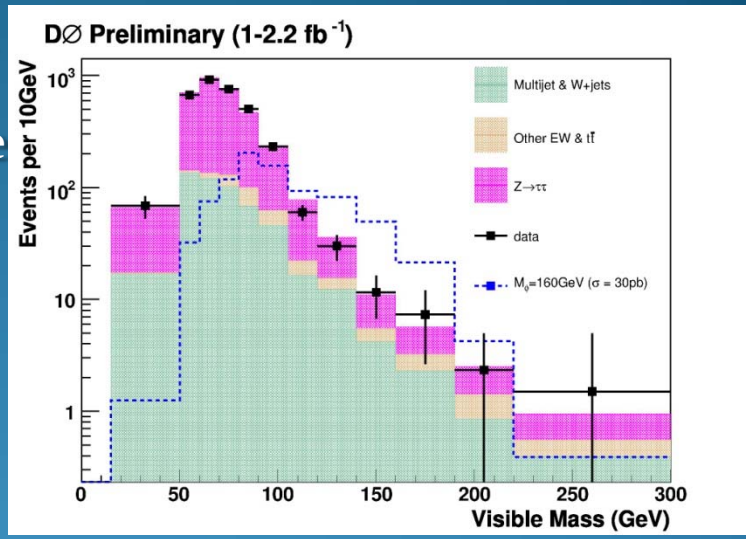
- $\Phi^o \rightarrow bb$ too hard due to QCD processes
- Updated DØ analysis
- Look for $\Phi^o b \rightarrow bbb$ in triple-tagged events to reduce background
  - › NN tagger (vertex and tracks in the jet)
- Event selection based on dijet kinamatics likelihood
- Use $M_{bb}$ to set upper limits on $\Phi^o$ production
  - › Background shape from two tags events tuned by a 3tag/2tag correction from MC
- Combination with analysis on earlier data:
  - › exclusion region in the $\tan\beta$-$m_A$ plane in the $m_h^{max}$ scenario

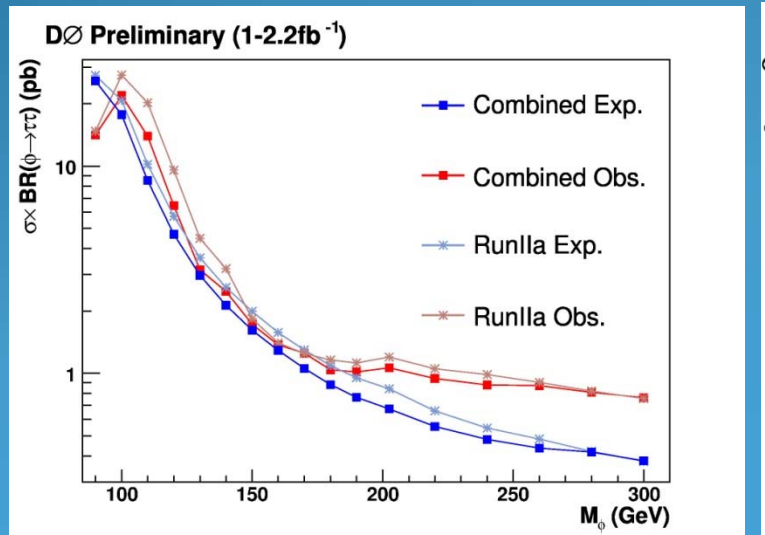


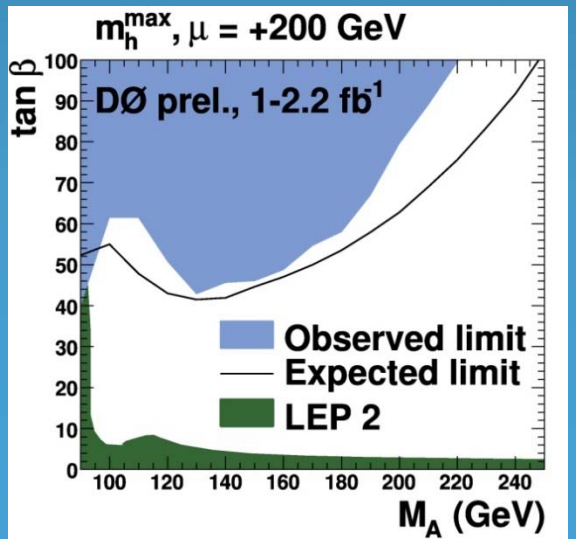



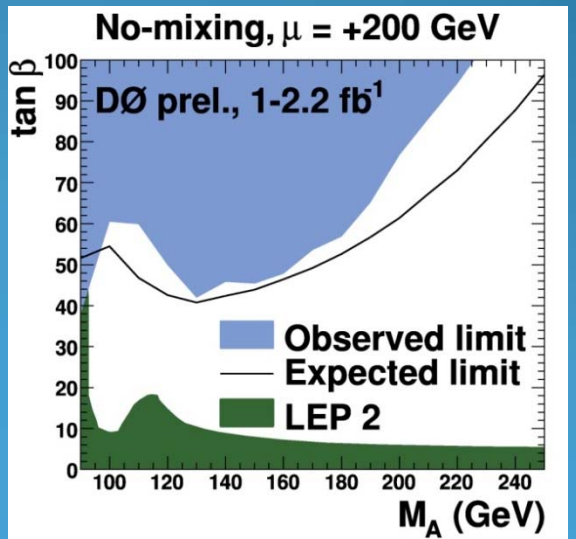
# $\phi^0 \rightarrow \tau\tau$

- Lower BR, but higher cross section
- Inclusive decays: $\phi^o \rightarrow \tau_e\tau_\mu$, $\tau_h\tau_\mu$, $\tau_h\tau_e$
- Challenge: hadronic $\tau$ decay ID
  - EM clusters and tracks, NN enforced
  - Three type: $\tau \rightarrow \pi^\pm\nu$, $\pi^\pm\pi^o\nu$, $\pi^\pm\pi^\pm\pi^\pm\nu$
- Visible mass $M_{vis}(\tau_1+\tau_1+\not{E}_T)$ to set limits on $\sigma$xBR



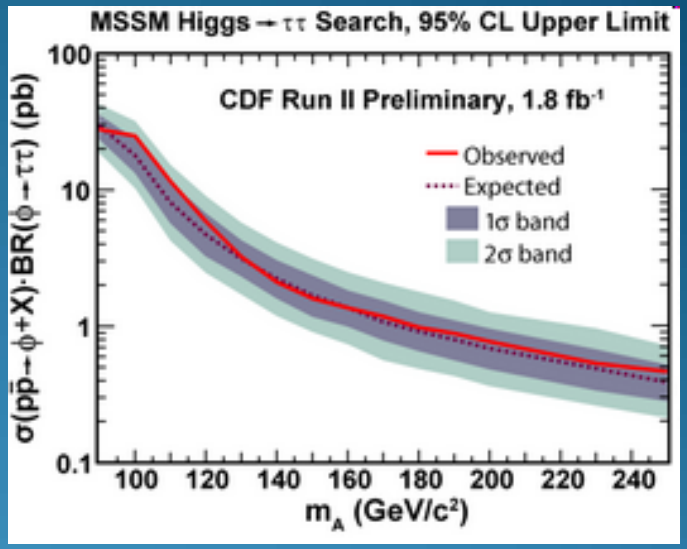



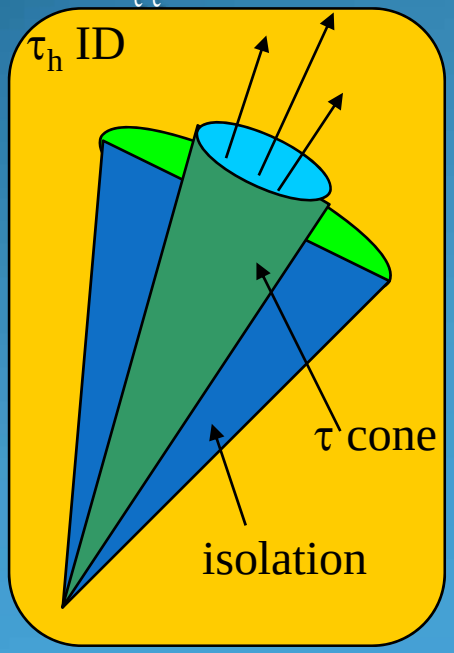



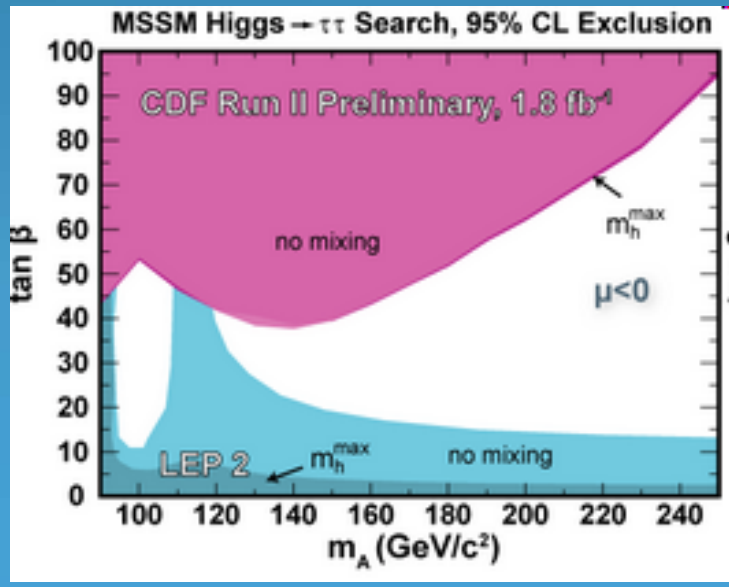



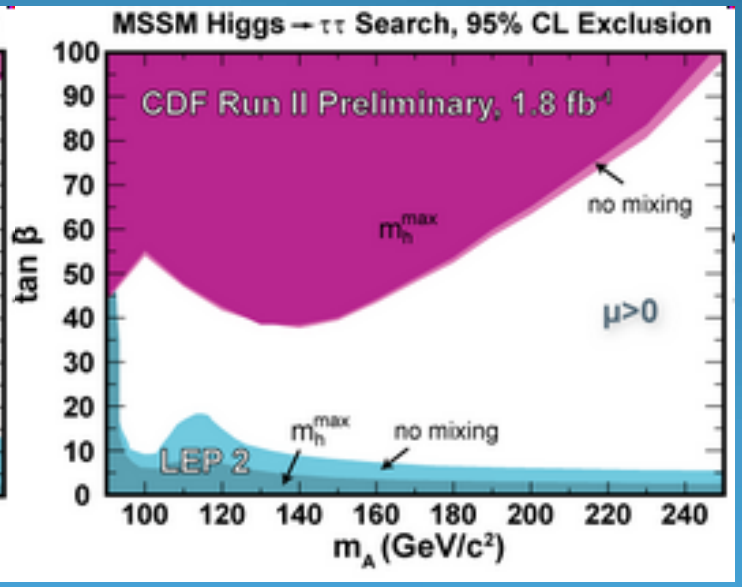
# $\phi^0 \rightarrow \tau\tau$

- CDF result from 2007
- Hadronic τ reconstruction:
  - One or three tracks from $\pi^{\pm}$ } "τ cone"
  - EM clusters from $\pi^0$ } (3-10°)
  - Isolation cone 30°
- $M_{\tau\tau}$ fit to set limits on σxBR



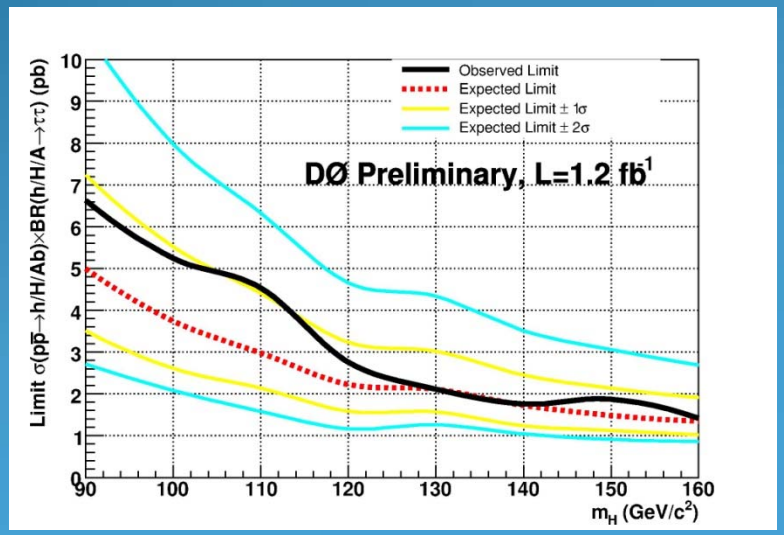



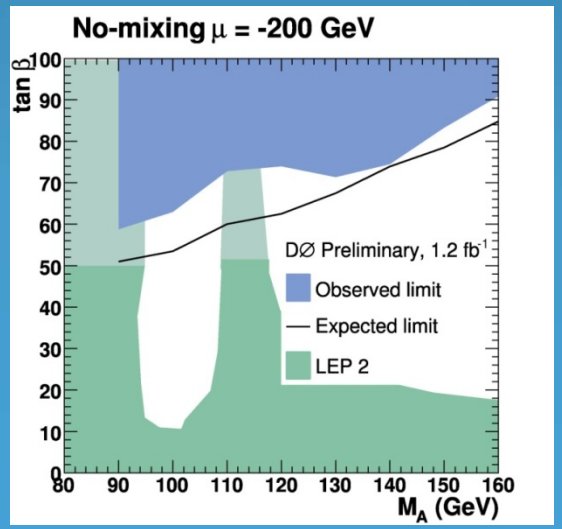



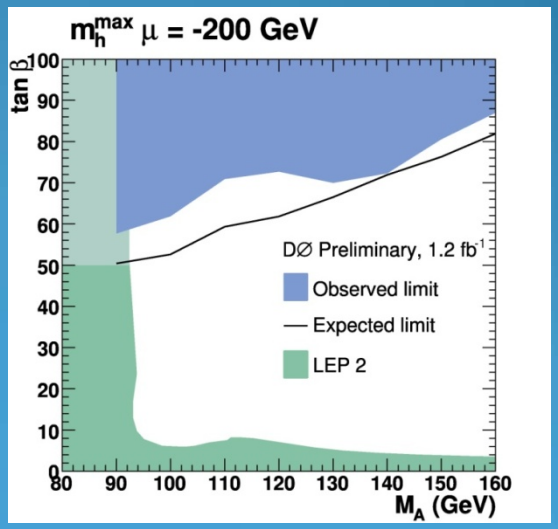



# $\phi^0 b \rightarrow \tau\tau b$

- Lower cross section, but smaller background
- Search in $\phi^0 b \rightarrow \tau_\mu \tau_{had} b$ channel
- Multivariate methods to discriminate main backgrounds
  - Kinematic NN to separate signal from $t\bar{t}$ events
  - Signal/Back. likelihood ratio against QCD multijet production
- No excess, limits on $\sigma$xBR($\phi^0 \rightarrow \tau\tau$)
- Improvement expected from other decay channels



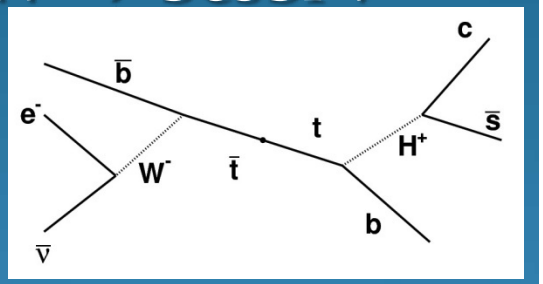



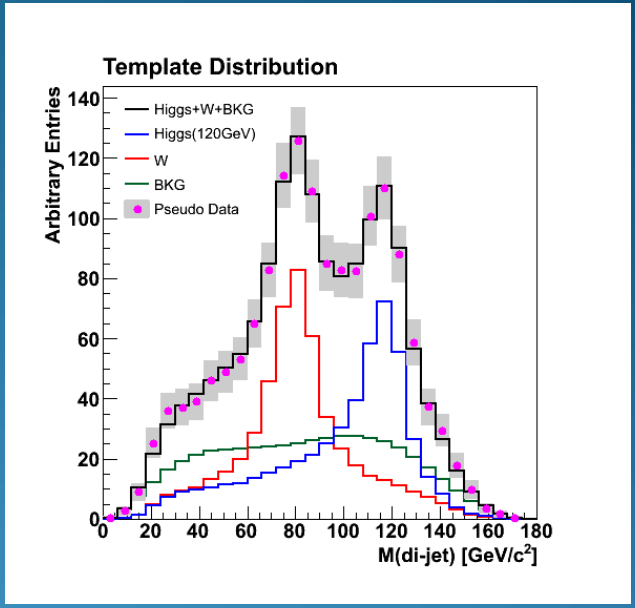



# Charged Higgs Bosons

# Searches for $H^{\pm}$

- Search for $t\bar{t} \rightarrow bH^{+}\bar{b}W^{-} \rightarrow bc\bar{s}\bar{b}l^{-}\bar{\nu}$
  - $W \rightarrow l\nu$ reconstructed
  - Two tagged jets

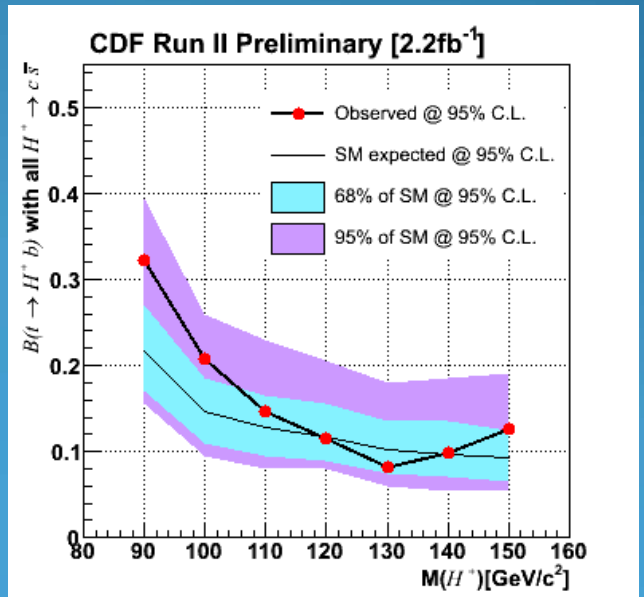



- Sensitive to MSSM production if $\tan\beta \leq 1$ and $M_{H\pm} \leq 130$ GeV/c²

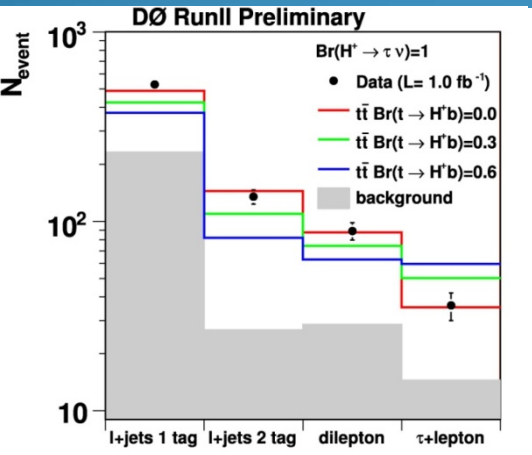
- Dijet mass to separate $H^{\pm} \rightarrow cs$ from $W^{\pm} \rightarrow qq$ and backgrounds

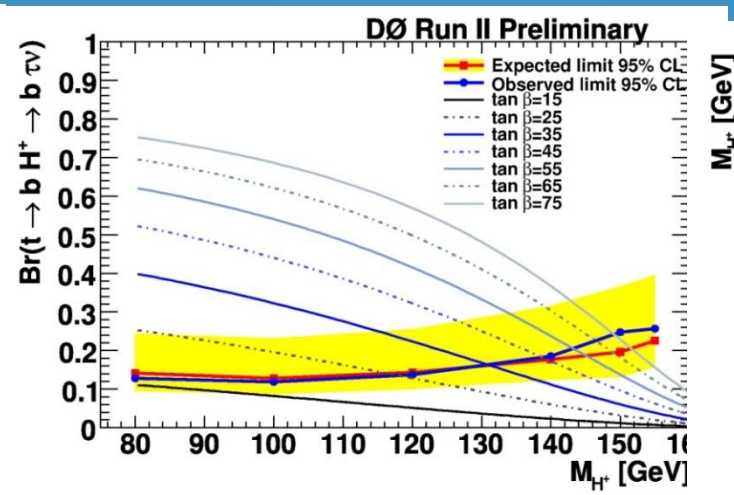
- No excess, limits on $BR(t \rightarrow H^{\pm} b)$
  - $BR(H^{\pm} \rightarrow cs) = 100\%$ assumed

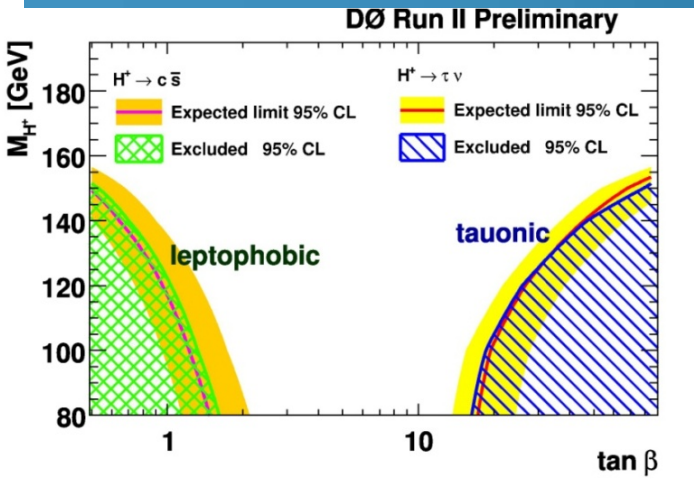


# Searches for $H^{\pm}$

- Compute effects of $t \to H^{\pm} b$ on yields of $t\bar{t}$ decay channels
  - $t\bar{t} \to b\bar{b}q\bar{q}l\not{E}_T$, $t\bar{t} \to b\bar{b}l^+l^-\not{E}_T$, $t\bar{t} \to b\bar{b}l\tau\not{E}_T$ channels studied
- Considered two scenarios for $H^{\pm}$ decays
  - Tauonic model: $H^{\pm} \to \tau\nu$ (MSSM with $\tan\beta >> 1$)
  - Leptophobic model: $H^{\pm} \to cs$ (MHDM, SUSY at $\tan\beta << 1$)
- Compare to observed events to set limits on $BR(t \to H^{\pm} b)$
  - Exclusion regions on $M_{H^{\pm}}$-$\tan\beta$ plane



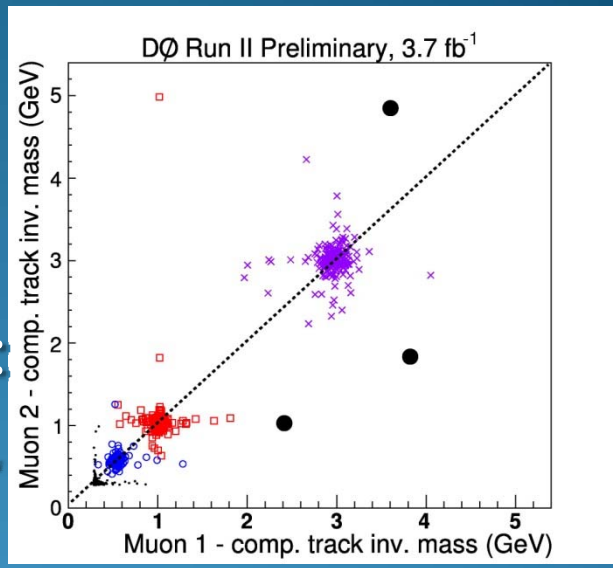
# Higgs Bosons in the nMSSM

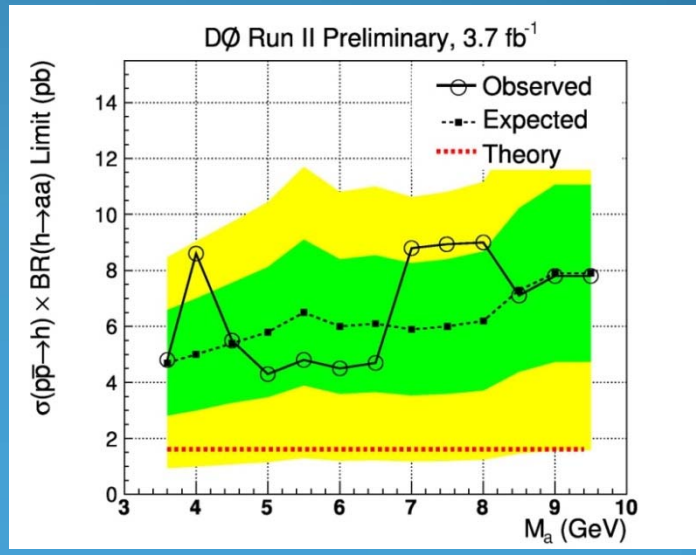
# Higgs Bosons in the nMSSM

- Add a singlet superfield to MSSM:
  - Dynamically generated μ-term: $\mu H_u H_d$
  - Simplest SUSY model in which EW scale originates from SUSY breaking scale only
- Two additional Higgs bosons: CP-even s and CP-odd a
- Lightest Higgs in nMSSM can be the CP-odd one:
  - Lightest SM-like Higgs dominant decay: $h \rightarrow aa$
- Avoid LEP limit on $M_h$ if $M_a < 2m_b$:
  - No fine-tuning of fundamental parameters necessary

# Higgs Bosons in the nMSSM

- $M_a \leq 2m_\tau$: $h \rightarrow aa \rightarrow \mu^+\mu^-\mu^+\mu^-$
  - Two reconstructed muons $\Delta R(\mu,\mu)>1$
  - Two "companion" tracks $\Delta R(\mu,\text{track})<1$
- Counting events in 2D mass windows:
  - $\sigma(pp\rightarrow hX) \times BR(h\rightarrow aa) \times BR(a\rightarrow\mu\mu)^2<10\text{fb}$ 95%CL
  - $BR(a\rightarrow\mu\mu)<0.1$ for $M_h<120\text{GeV}$, $BR(h\rightarrow aa)\sim1$ expected $BR(a\rightarrow\mu\mu)>0.1$ for $M_a<2m_c$
- $M_a>2m_\tau$: $h \rightarrow aa \rightarrow \mu^+\mu^-\tau^+\tau^-$
  - Muon pair $\Delta R(\mu,\mu)<0.5$ and $M_{\mu\mu}<20\text{GeV}$
  - $\not{E}_T>25$ GeV
- Looking in dimuon mass windows:
  - Limits on $\sigma \times BR \sim 4$ larger than theory

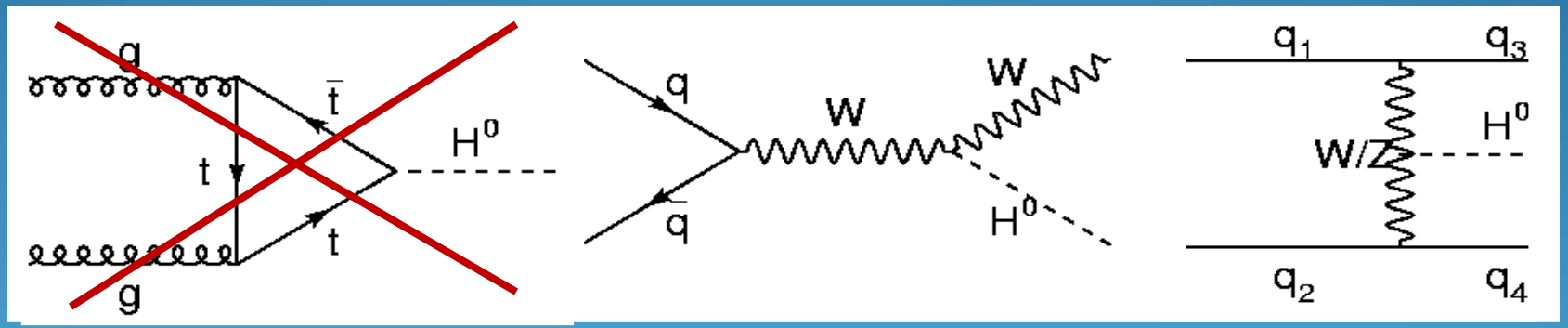


# Fermiophobic Higgs

# Fermiophobic Higgs

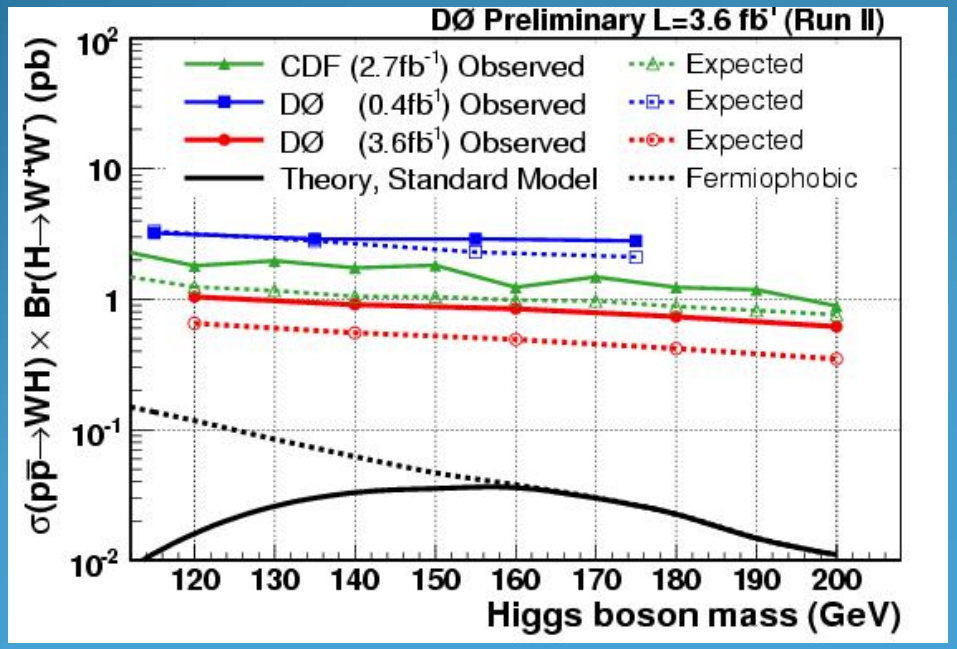
- Coupling to fermions null (or highly suppressed)
  - Would indicate different origin for masses of fermions and bosons
- Benchmark fermiophobic model:
  - Couplings to gauge bosons as SM, no coupling to fermions
  - Only associated W/ZH and vector boson fusion productions

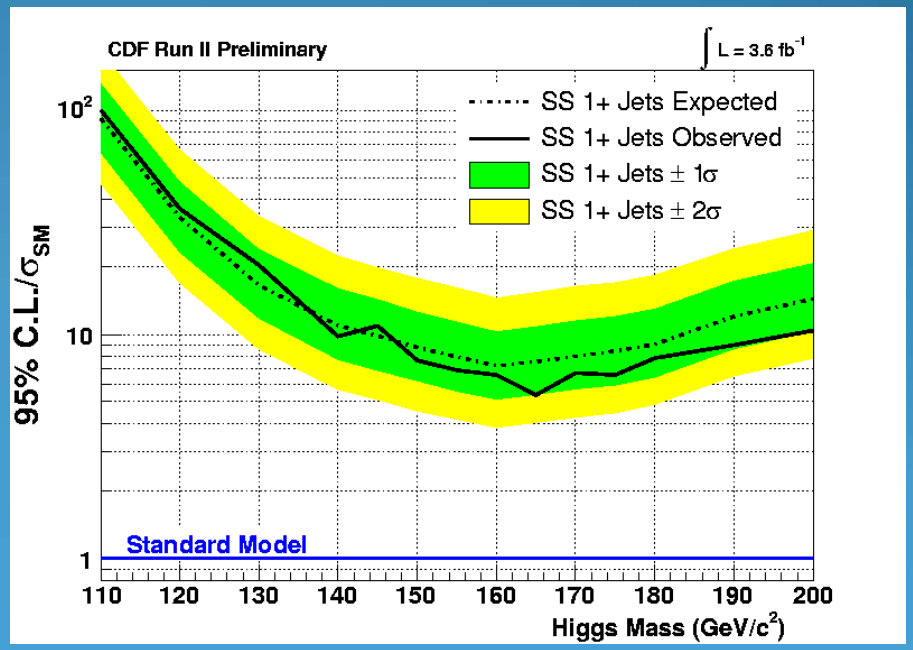



- Most promising channels:
  - Associated production of H decaying to W: WH → WWW*
  - Inclusive production of H decaying to photons: H → γγ

# WH → WWW*

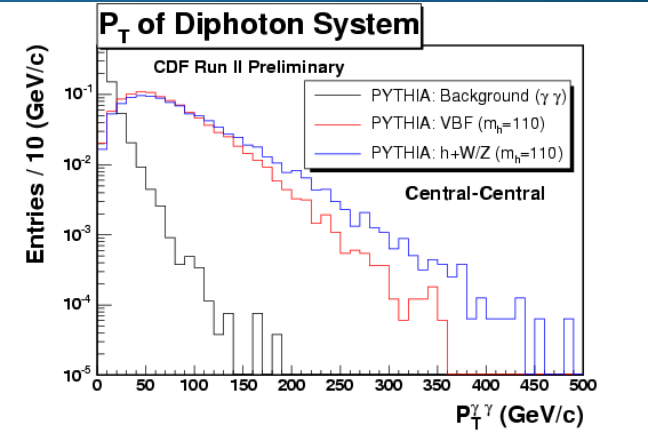
- Look for events with same sign leptons
  - WH → $l^{\pm}l^{\pm}\not{E}_T$+X
- Also some sensitive to SH Higgs
- More details on SM Higgs talks
- Set upper limits on σxBR

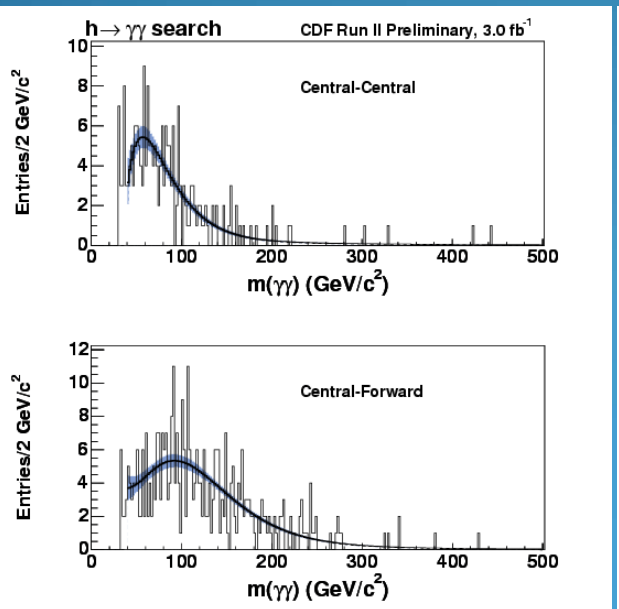


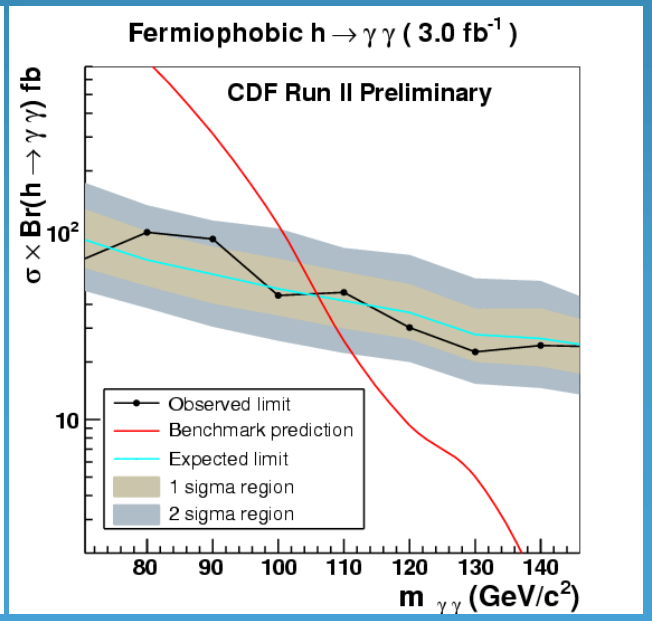



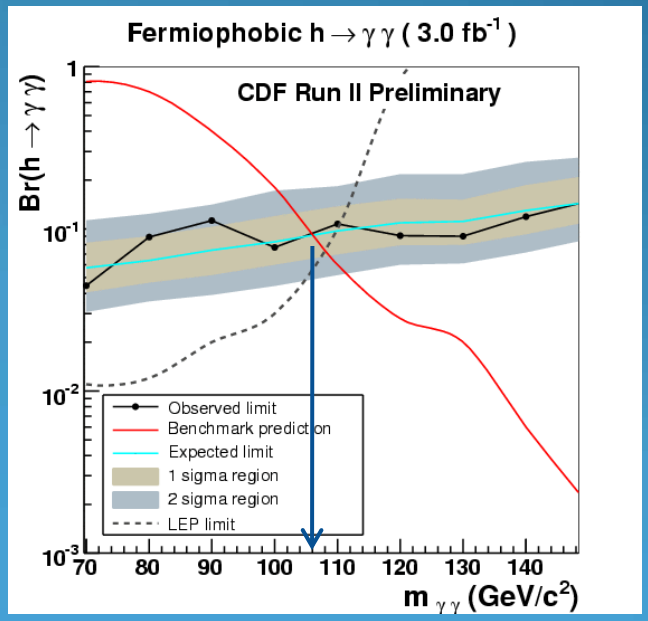
# H → γγ

- Search for di-photon mass peak:
  - Better energy resolution than jets (~3%)
- Strong cut $P_T^{\gamma\gamma}$>75GeV:
  - Background shape from sidebands
- No excess observed in mass spectrum:
  - Excluded $M_H$<106 GeV/c² @95%CL in the benchmark model



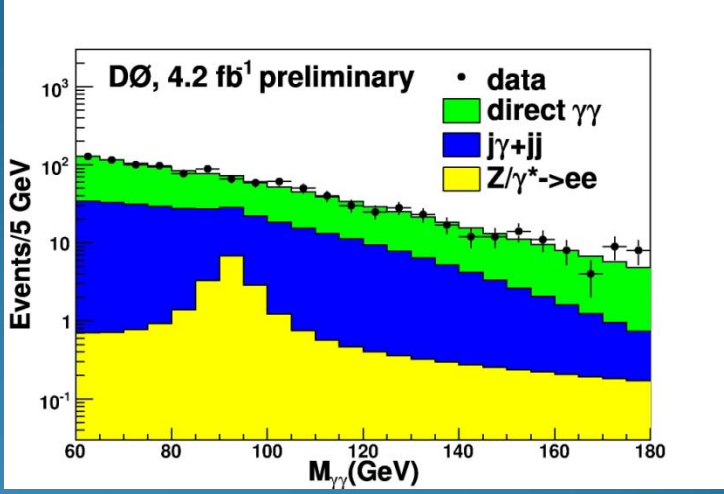



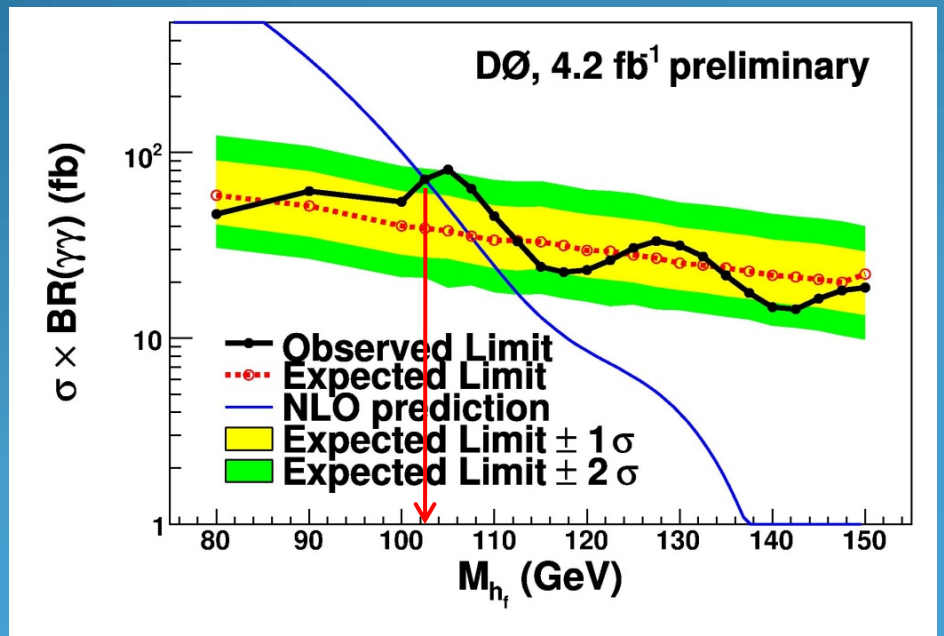



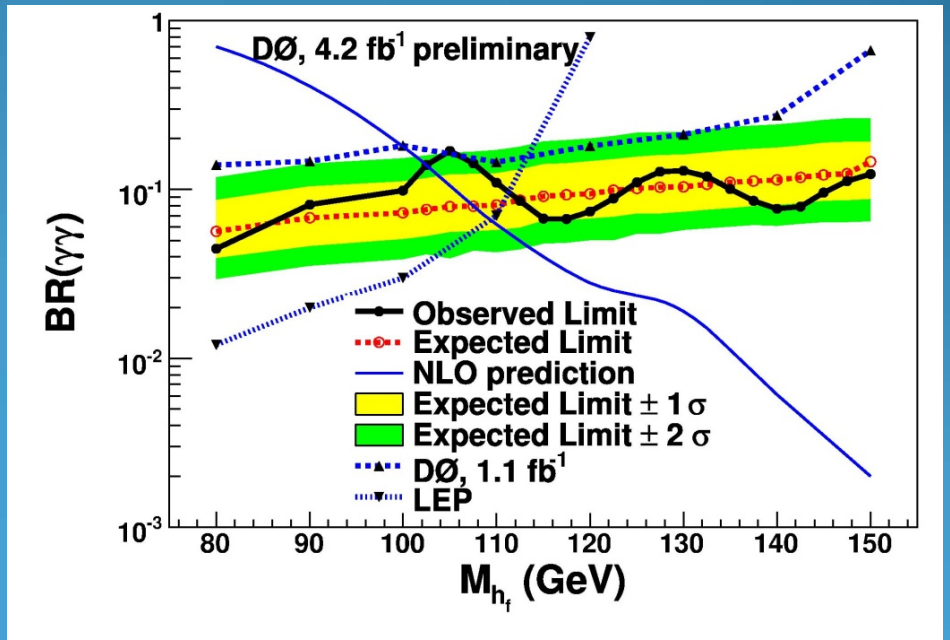



# H → γγ

- Search for di-photon mass peak:
  - Mass resolution ~ 3 GeV/c²
- Looser selection $P_T^{\gamma\gamma}$>35GeV:
  - Backgrounds from MC and data
- No excess observed:
  - Excluded $M_H$<102.5 GeV/c² @95%CL



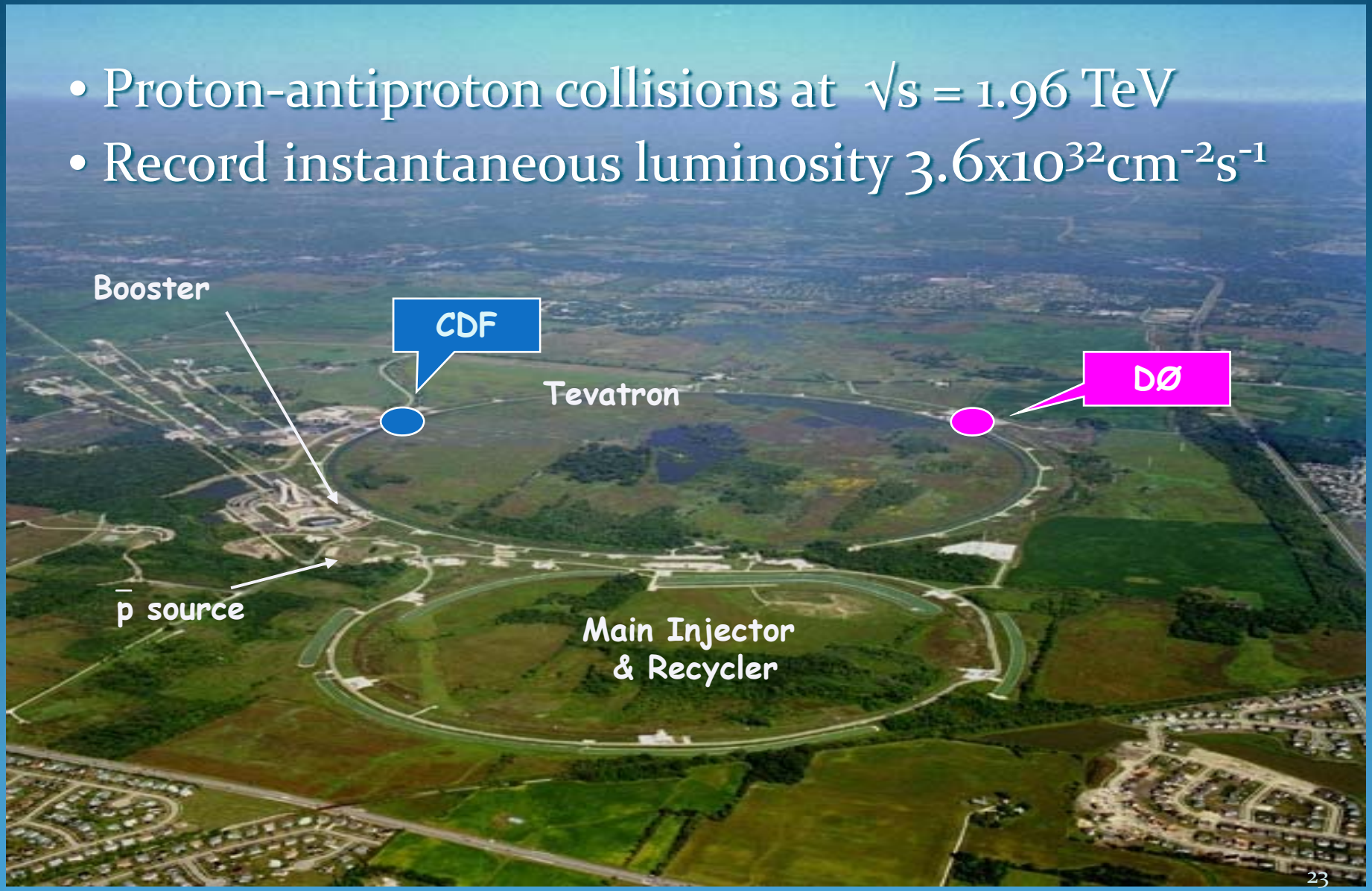
# Summary

- CDF and DØ are looking actively for Higgs bosons in the context of physics beyond the standard model:
  - Well advanced techniques
  - Several limits and exclusion regions have been set
  - No signal for Higgs production yet
- Lot of improvements coming:
  - More data to come: 5 $fb^{-1}$ per experiment already on tape
  - Combination of channels and experiments is planned
- New physics models are being investigated:
  - Search for Higgs in nMSSM at CDF coming soon

# Backup Material

# The Tevatron Collider

- Proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV
- Record instantaneous luminosity $3.6 \times 10^{32} cm^{-2} s^{-1}$



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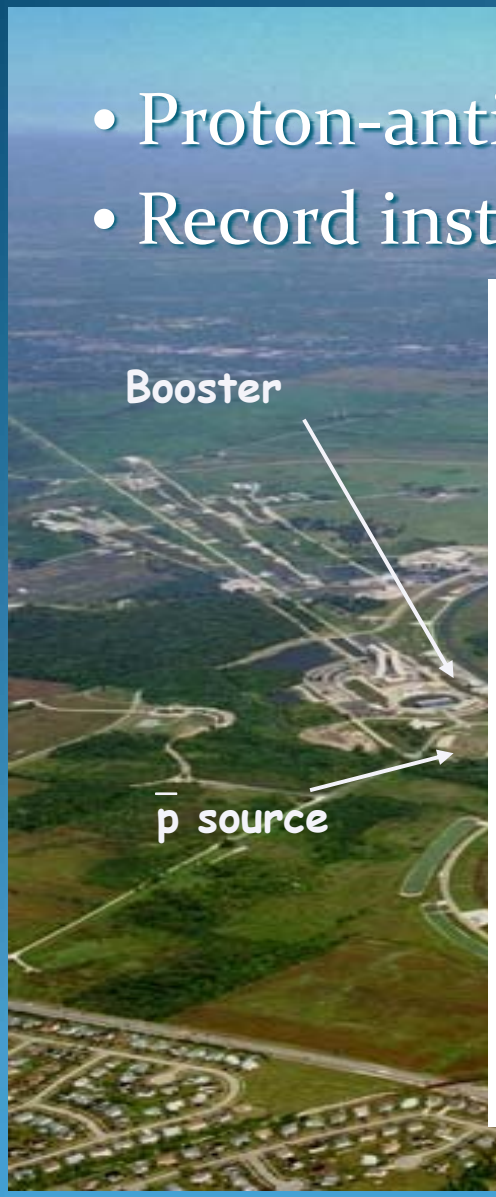
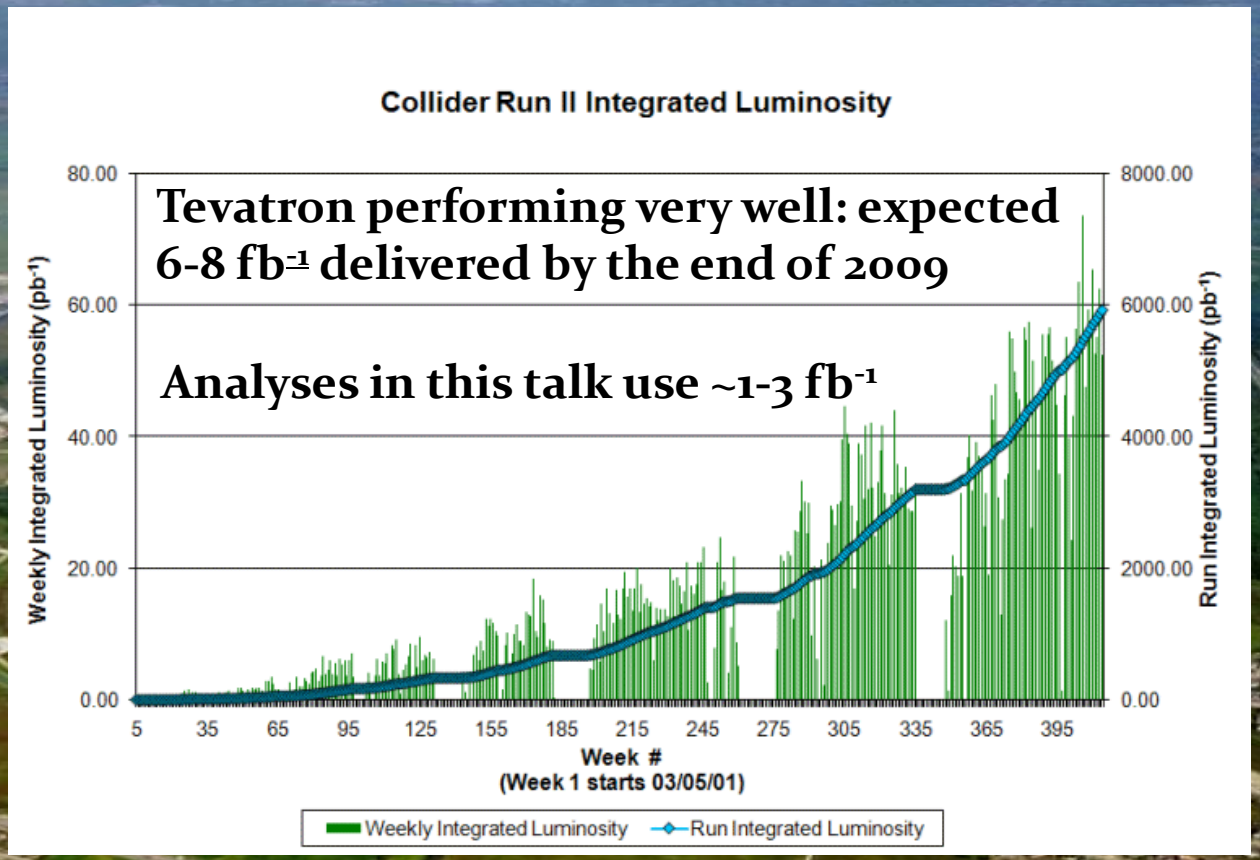
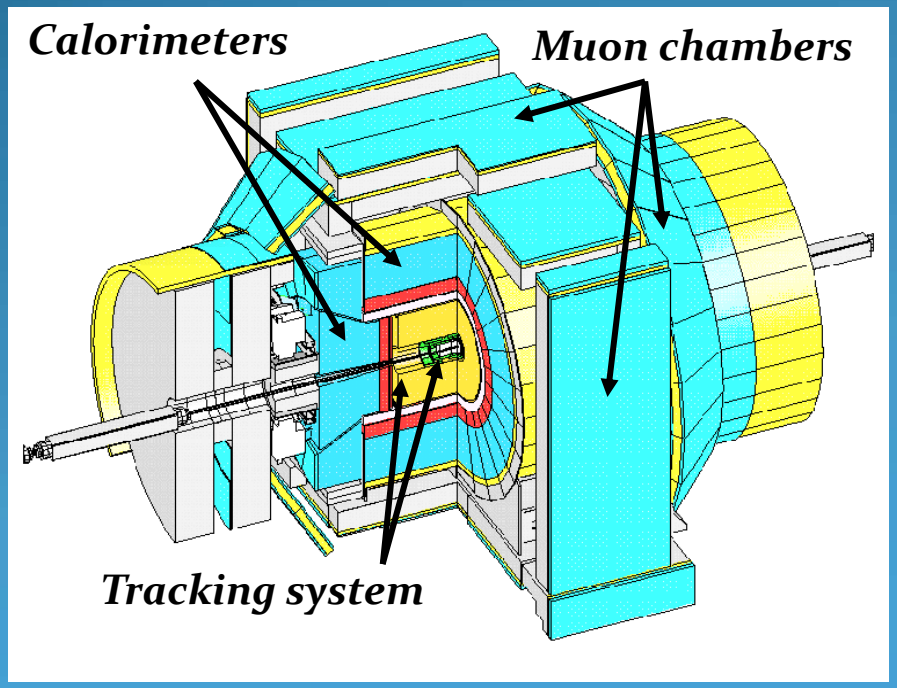


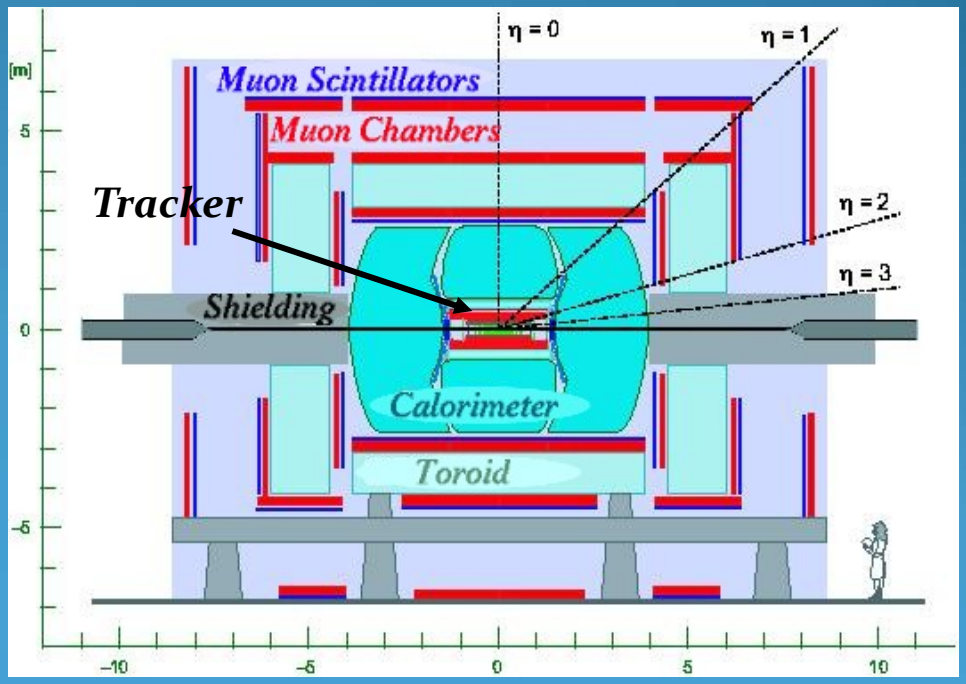



# The CDF and D0 Experiments

Multipurpose experiments collecting data at high efficiency

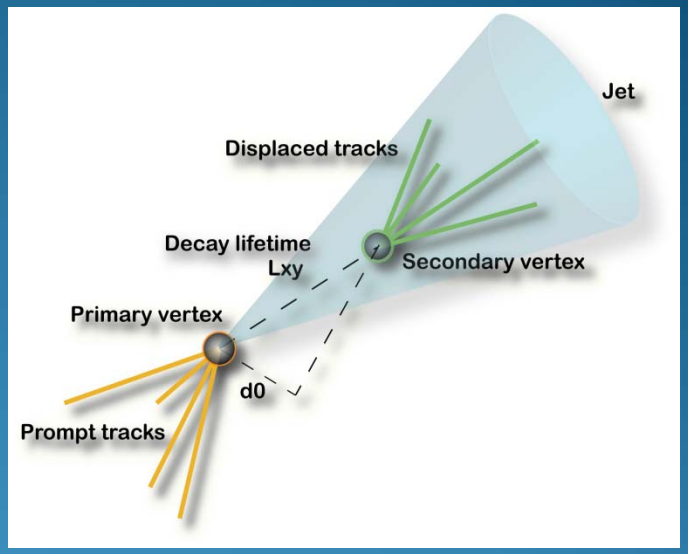
- Muon chambers, EM calorimeter and tracking for lepton ID
- Calorimeters for jet reconstruction
- Silicon detectors for b quark tagging

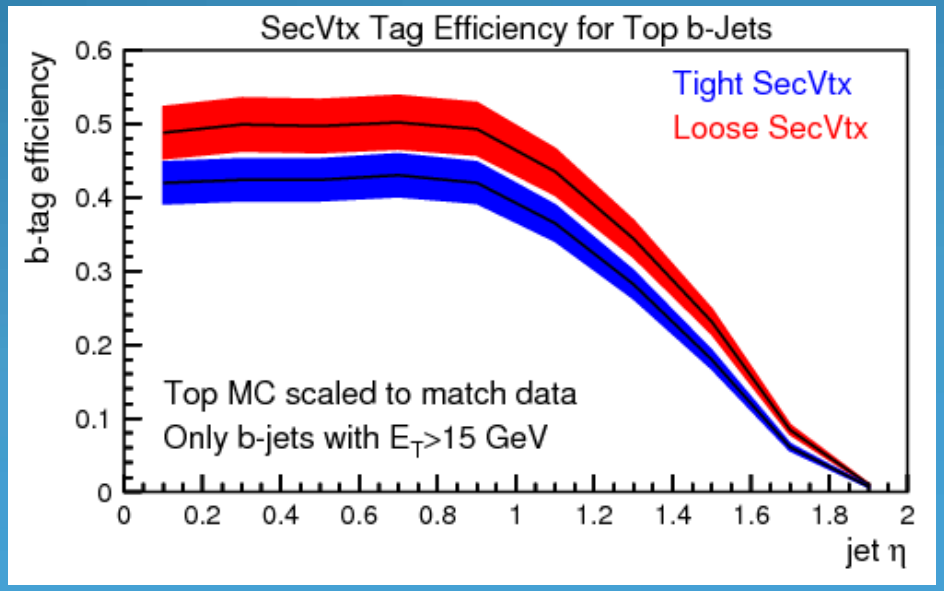


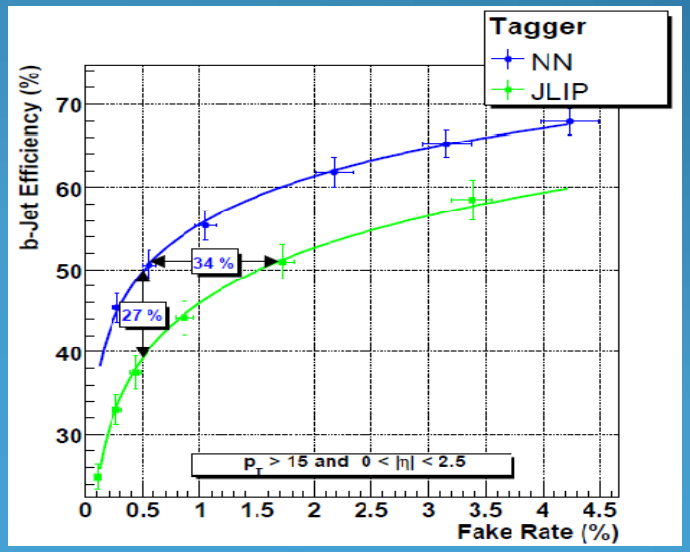



# B Tagging

- CDF: reconstruct displaced vertices with cut on $L_{xy}/\sigma$
  - Vertex mass separation
- DØ: use NN to combine vertex properties and displaced track info
  - Tag in $|\eta|>2$ region

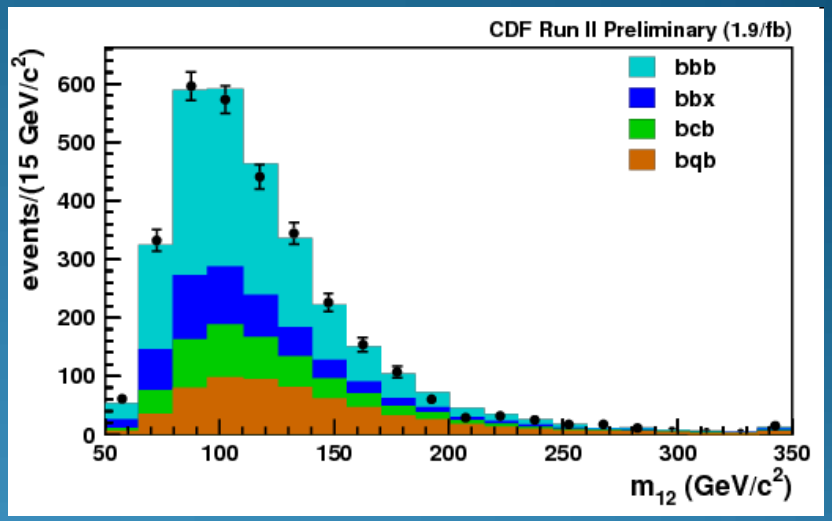


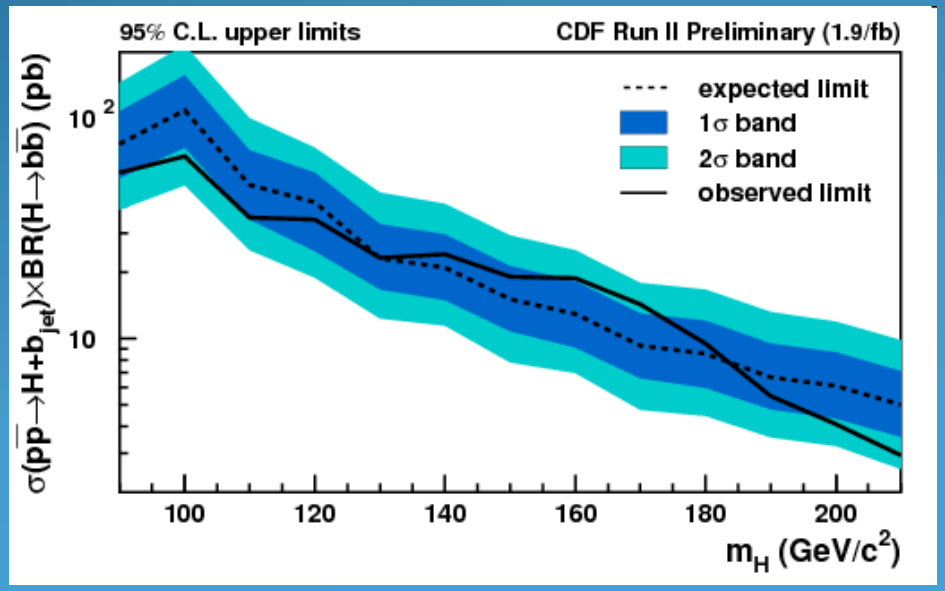



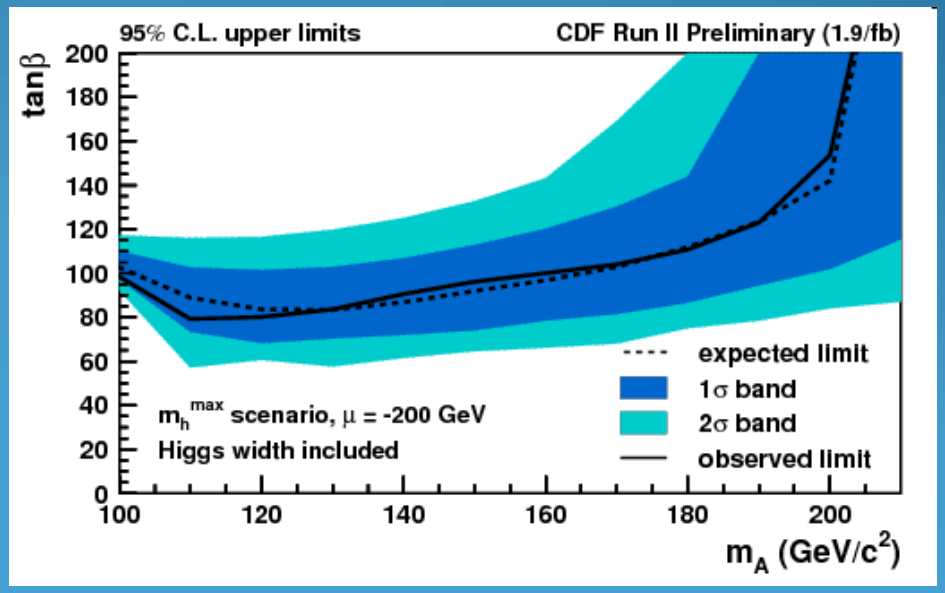



# $\Phi^0 b \rightarrow bbb$

- CDF result from Moriond 2008
- B tagging: reconstruct secondary vertex
  - › Cut on $L_{xy}/\sigma$
- Signal to background discrimination:
  - › Invariant mass of two leading jets
  - › Vertex mass information
- No excess: limits on σxBR
  - › exclusion region in the $m_h^{max}$ scenario

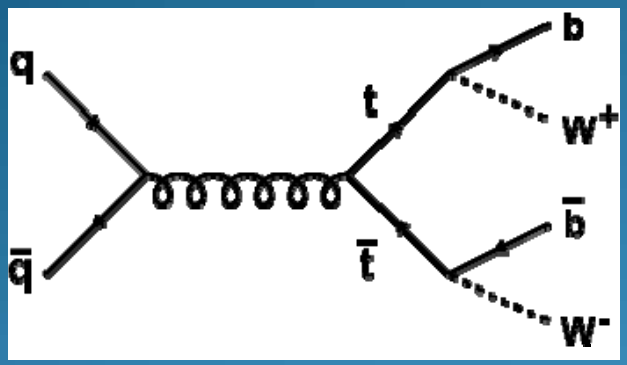


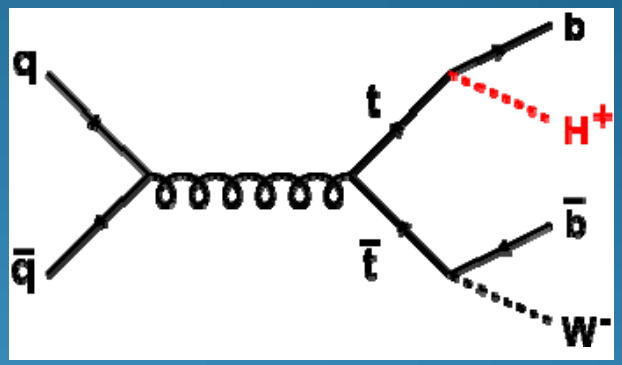



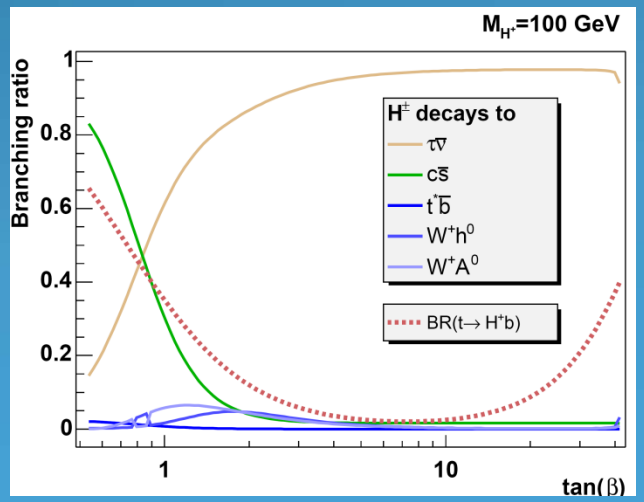
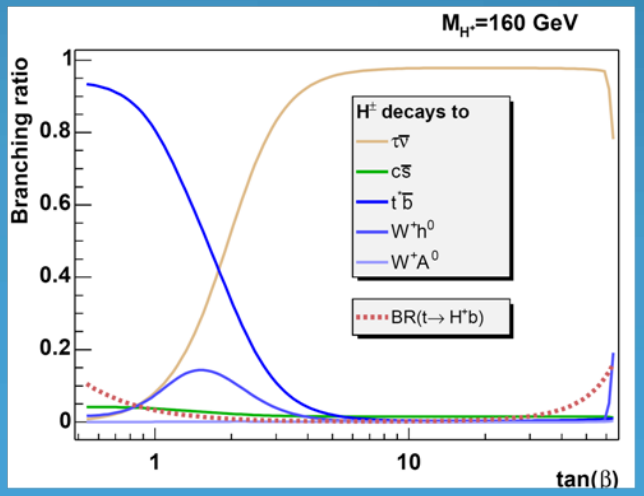



# Searches for $H^{\pm}$

- Look for $H^{\pm}$ production in top decays:




- MSSM: BR for $H^{\pm}$ decays depend on $M_{H\pm}$ and $\tan\beta$