# SUSY & Beyond Standard Model Higgs Searches at the Tevatron

*presented by*

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***on behalf of the CDF and DØ Collaborations***

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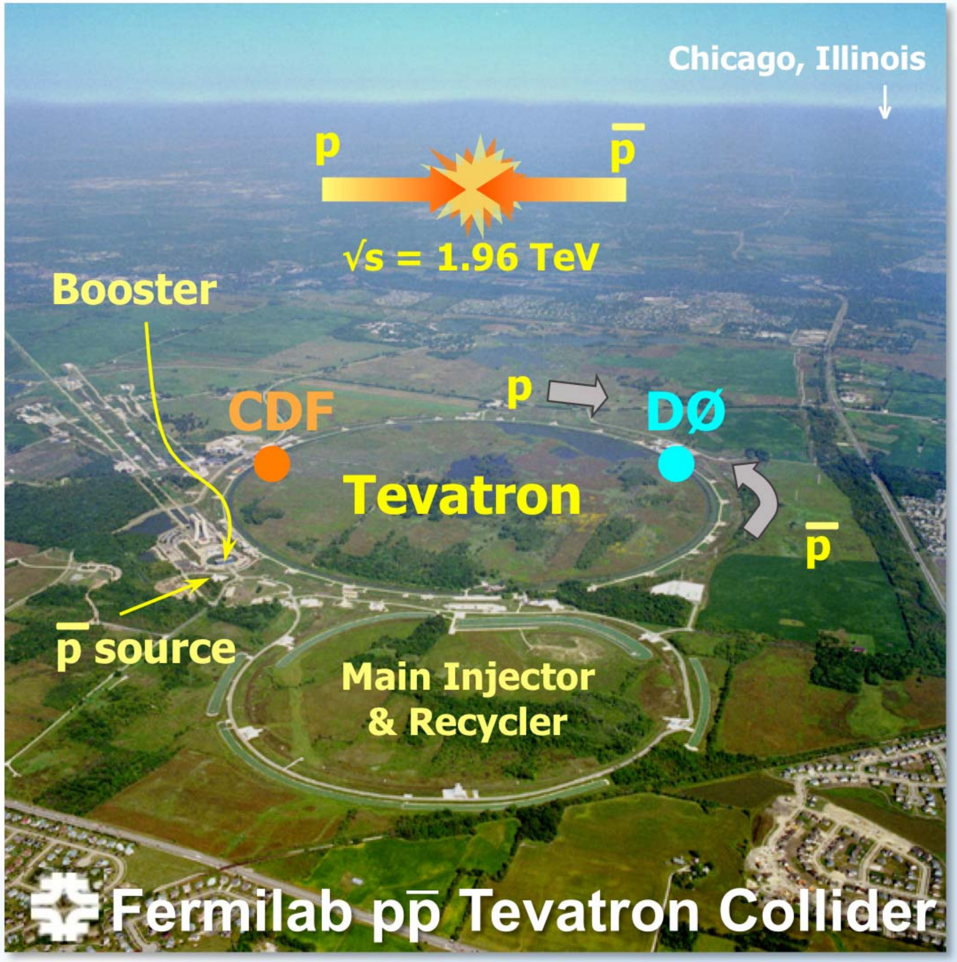
# [SUSY + BSM] Higgs: Outline

- **Several extensions to SM predict additional Higgs bosons**
  - behave similar to SM Higgs, but exhibit different couplings
  - branching ratio (BR) of various Higgs decays can be enhanced significantly

**I. MSSM Higgs Search**
- 5 physical Higgs bosons
  - $\phi (= h^0, H^0, A^0)$ and $H^\pm$
- main searches
  - $\phi b \rightarrow b\bar{b}b$ , $\phi \rightarrow \tau\tau$ , $\phi b \rightarrow \tau\tau b$
  - charged Higgs in top decays

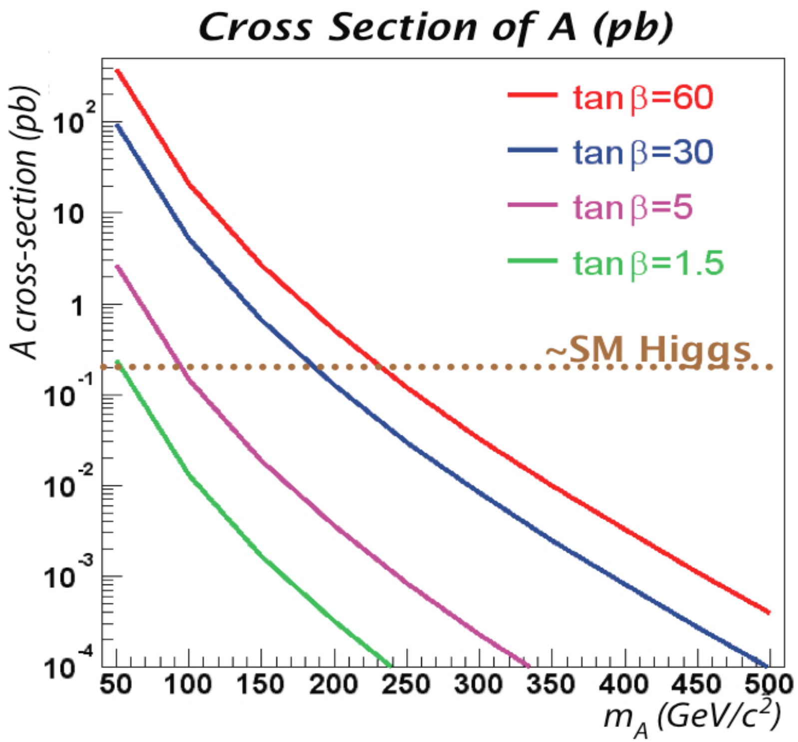
**II. Extended Higgs sector models**
- Doubly Charged Higgs ($H^{\pm\pm}$)
- Hidden Valley particles

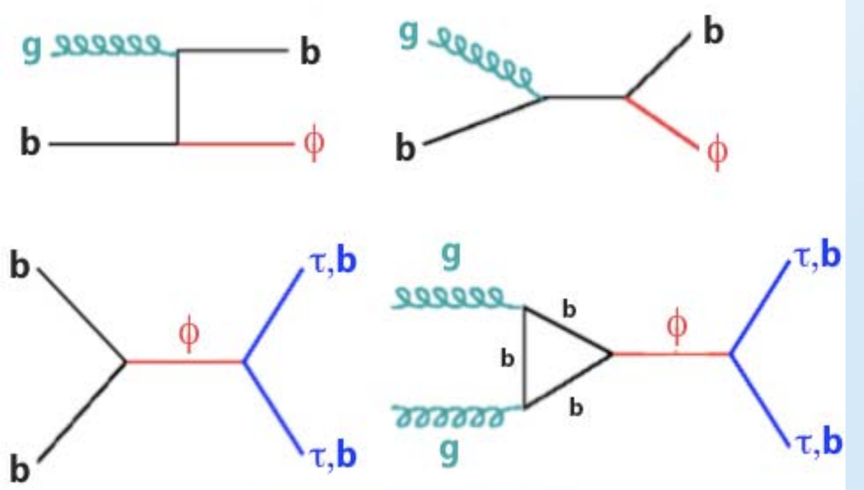
**III. Fermiophobic Higgs Model (FHM):**
- Higgs primarily couples to bosons, BR to fermions significantly suppressed



# Higgs bosons in the MSSM

- **MSSM Higgs requires 2 doublets**
  - yields: $\phi$ (= $h^0$, $H^0$, $A^0$) and $H^{\pm}$
- **At tree-level, MSSM Higgs fully specified by two free parameters**
  - $m_A$
  - $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$ (ratio of v.e.v. of 2 Higgs doublets)
- **Radiative corrections introduce dependence on additional SUSY parameters**
- **Inclusive production cross section $\sigma(p\bar{p} \to h/H/A)$ is enhanced**
  - enhancement depends on $\tan\beta$
- **h/H/A decays, in most parameter space:**
  - $\phi \to b\bar{b}$ (~90%)
  - $\phi \to \tau\tau$ (~10%)
    - smaller BR but cleaner signature (*vs.* large QCD background in b mode)

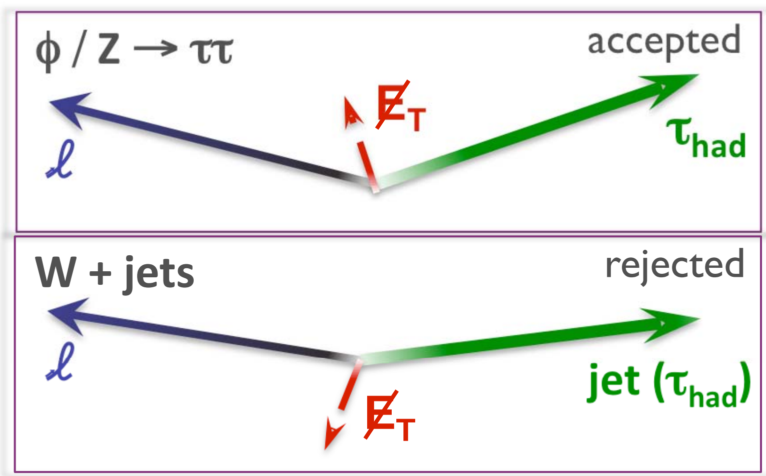



$\phi$ = h/H & A

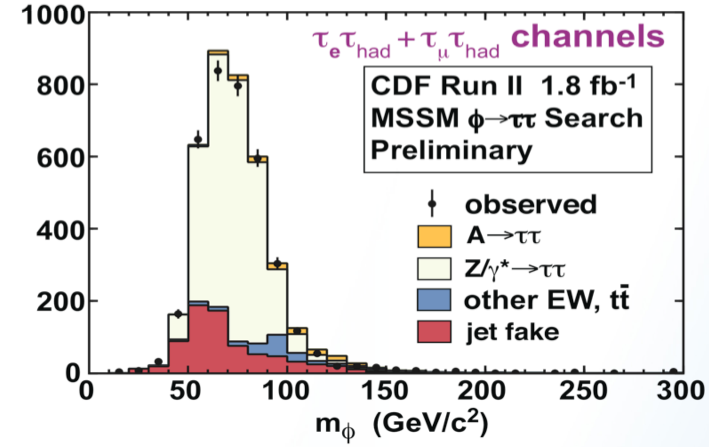
# CDF: $\phi \rightarrow \tau\tau$ Search

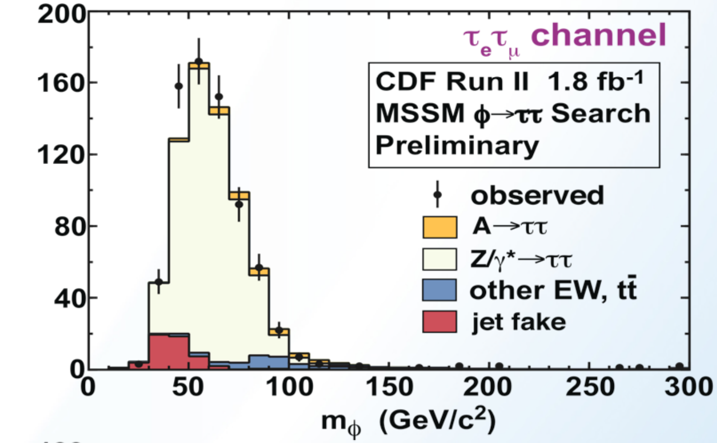
- CDF considers $\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$, and $\tau_e\tau_\mu$ channels with 1.8 fb$^{-1}$ data, selected by:
  - isolated e or μ: opposite-sign (OS) from hadronic τ
  - τ's selected using variable-size cone algorithm
  - suppress W+jets background by requirement on relative direction of visible τ decay products and $\not{E}_T$

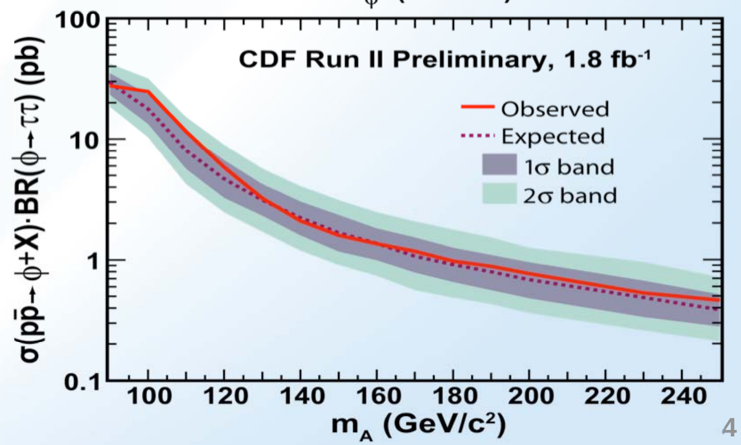



- Data agrees with backgrounds for visible mass
  - set σ × BR limits for 90 GeV < $m_A$ < 250 GeV

CDF: PRL 103, 201801 (2009)

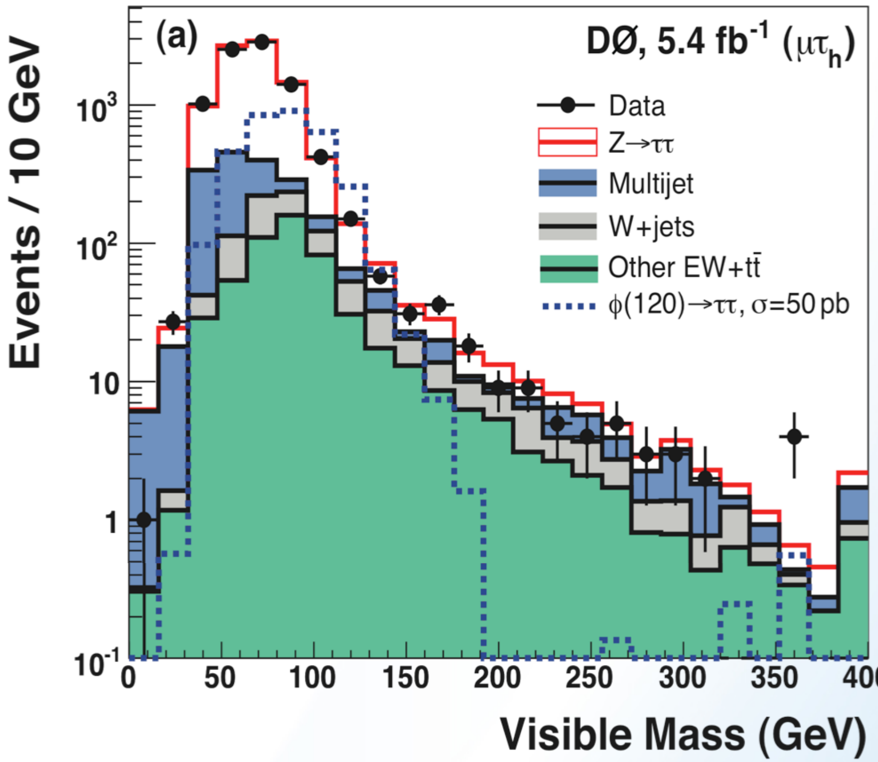


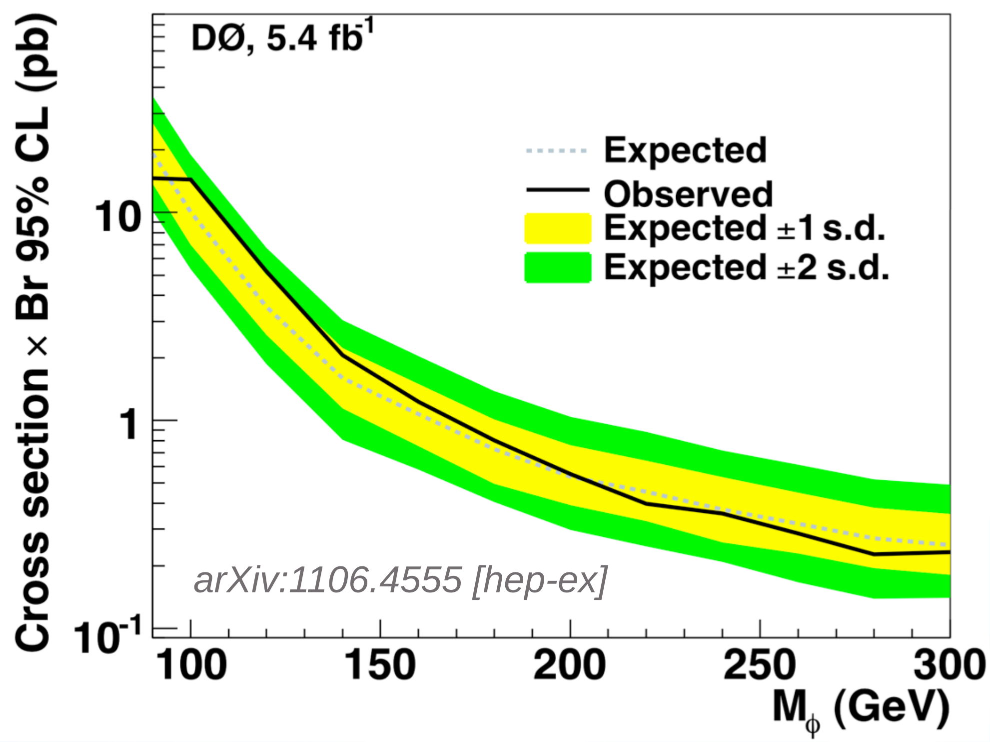



# DØ: Inclusive $\tau\tau$ Search

- **[New: submitted to PLB] result using 5.4 $fb^{-1}$ data for $\tau_\mu \tau_{had}$ and $\tau_e \tau_\mu$**
  - ~ 5 × more data than earlier 1.0 $fb^{-1}$ published result: PRL 101, 071804 (2008)
- **Search for two high-$p_T$ isolated leptons, opposite-sign**
  - $\tau_{had}$ discriminated from jets via $\tau$-ID NN
  - estimate multijet bkgnd directly from data

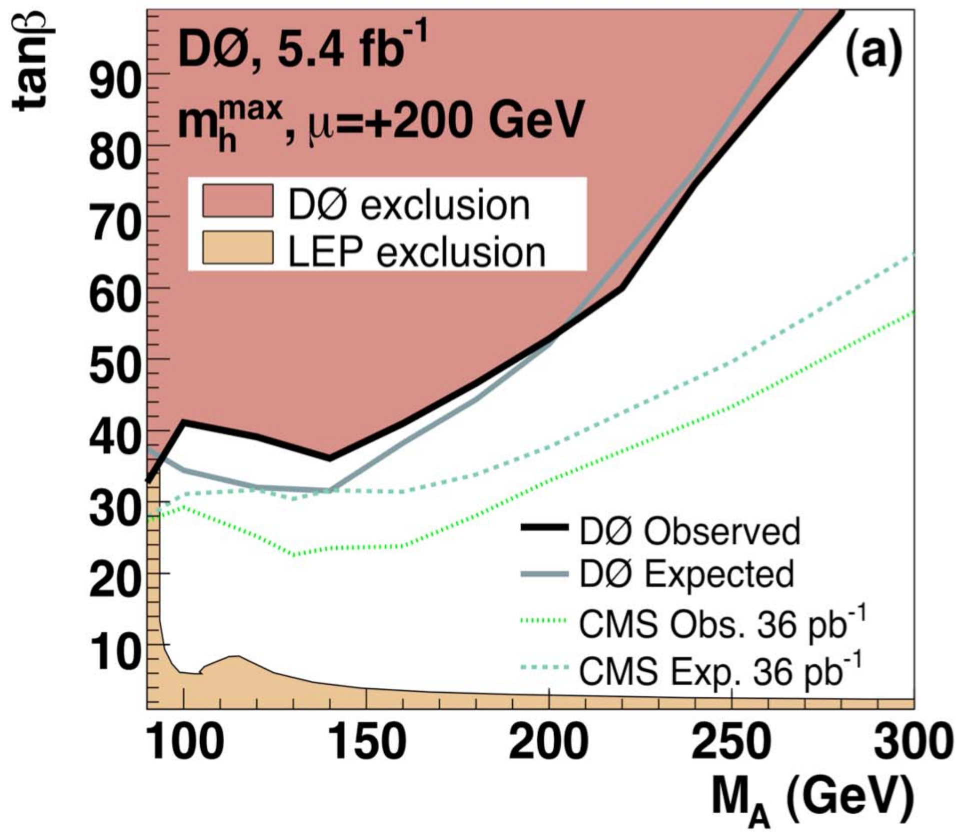


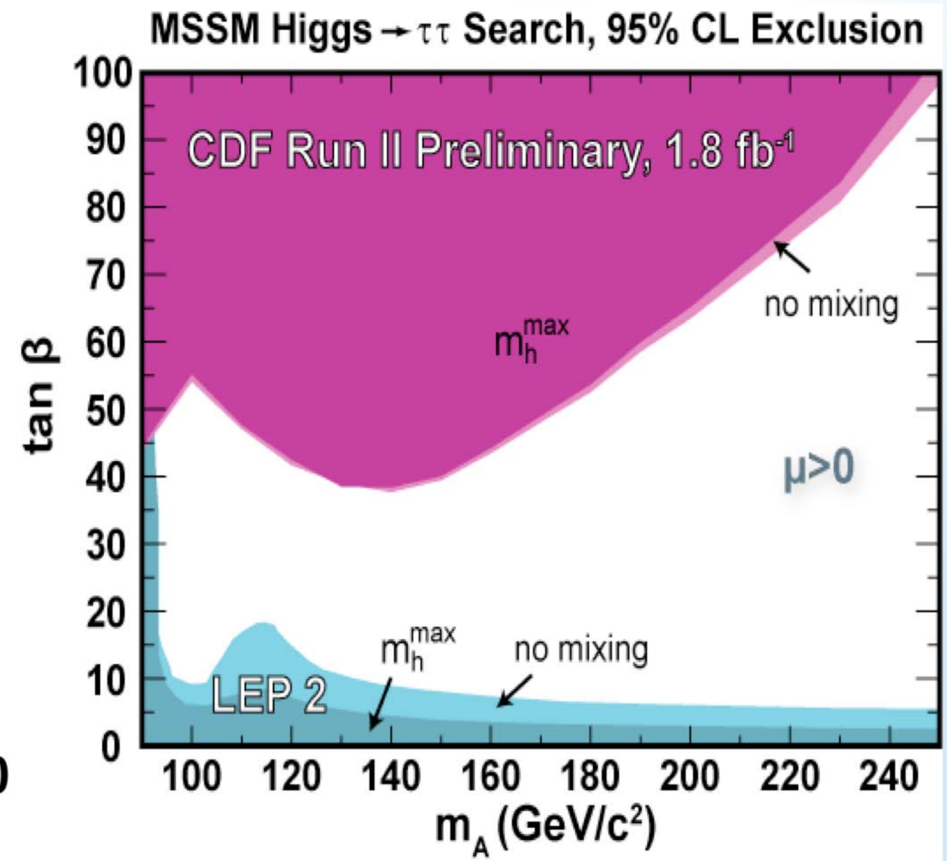




- **No excess in data across visible mass spectrum**
  - upper limits on $\sigma \times$ BR as function of $\phi$ mass
    - extended search range up to 300 GeV

# $\phi \rightarrow \tau\tau$: Results

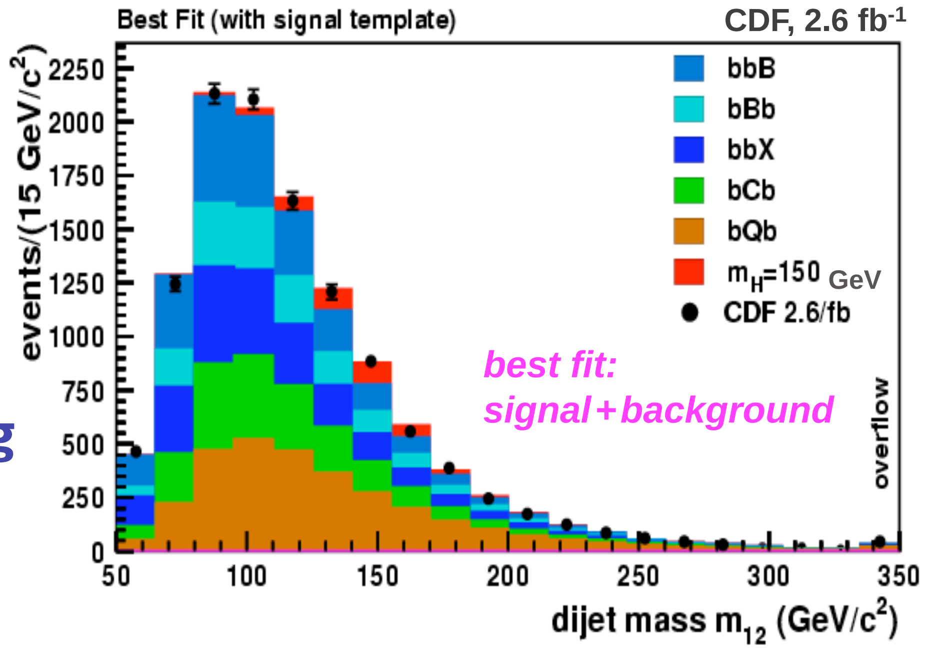
- **Interpret limits in representative MSSM scenarios**
  - $m_h^{max}$ and no-mixing for $\mu = \pm 200$ GeV
  - DØ 5.4 $fb^{-1}$ result: FeynHiggs *v*2.8.1
    - includes updated bbH PDFs at NNLO (MSTW2008)
- **Reach expected sensitivity of tanβ ~ 30 at low $M_A$ ~ 140 GeV**
  - comparable to limits from ATLAS and CMS using $\mathcal{L}$ = 36 $pb^{-1}$

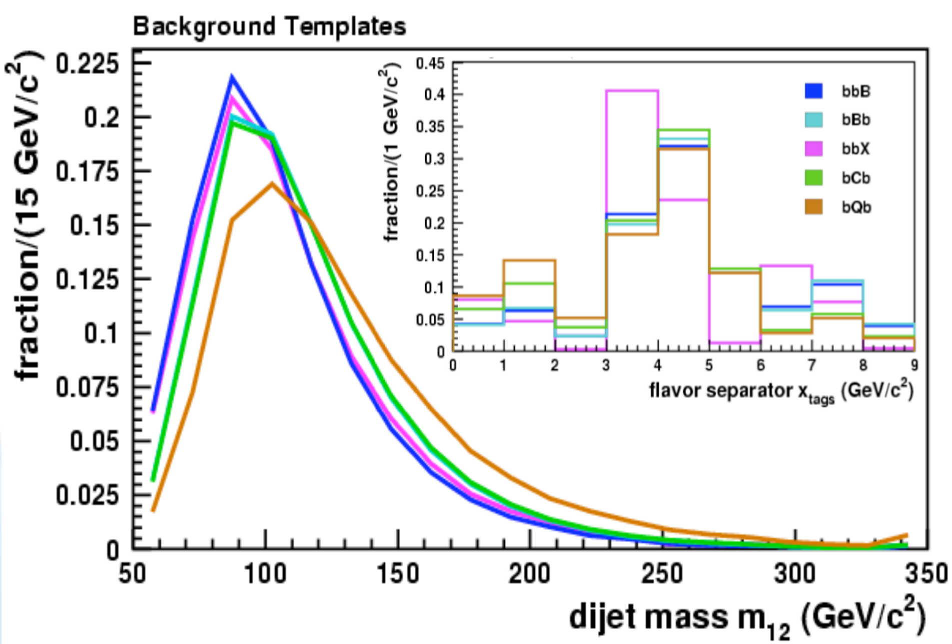


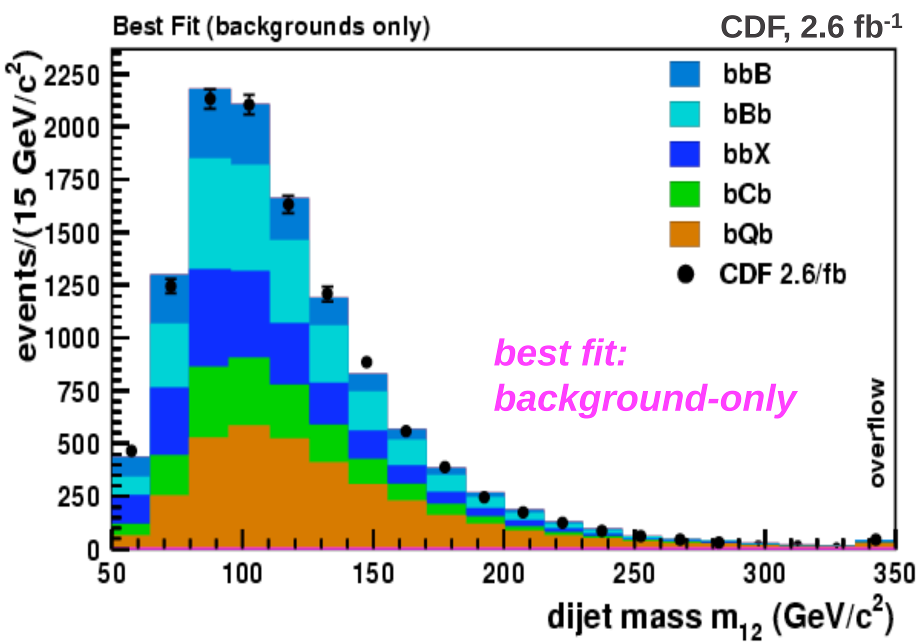



# CDF: $\phi b \rightarrow b\bar{b}b$ Search

- $\phi \rightarrow b\bar{b}$ **search difficult due to large multijet background**
  - consider $\phi$ produced in association with one b-jet
- **[New: submitted to PRD]** **2.6 fb$^{-1}$ data with 3 b-tagged jets**
- **Model multijet backgrounds using dijet mass of 2 lead jets ($m_{12}$) & flavor separator ($x_{tags}$)**
  - search for enhancements in $m_{12}$

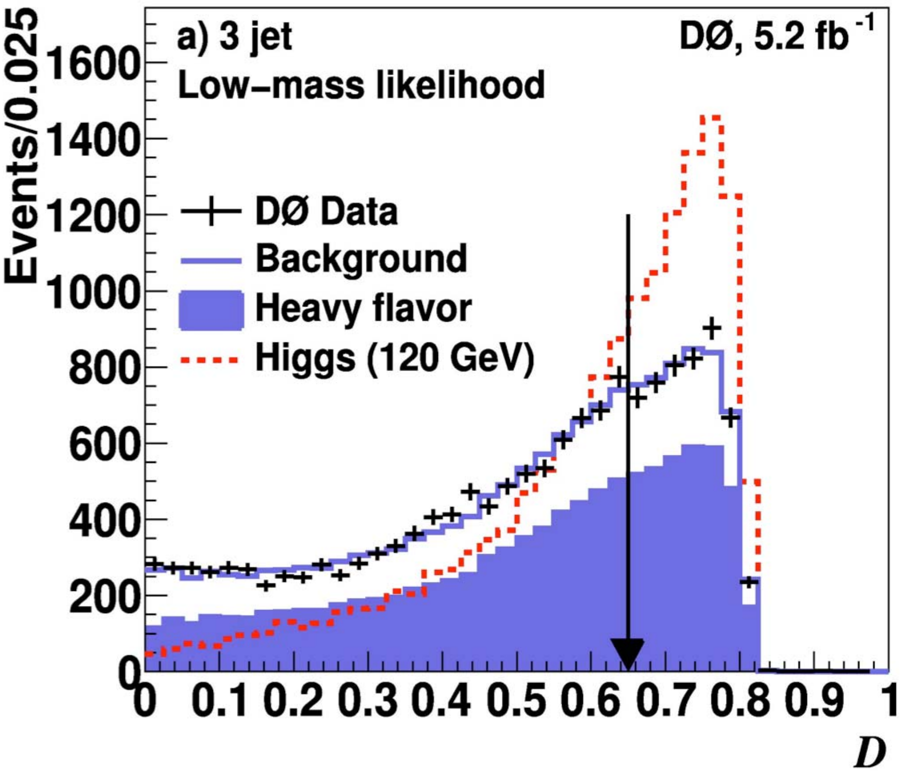


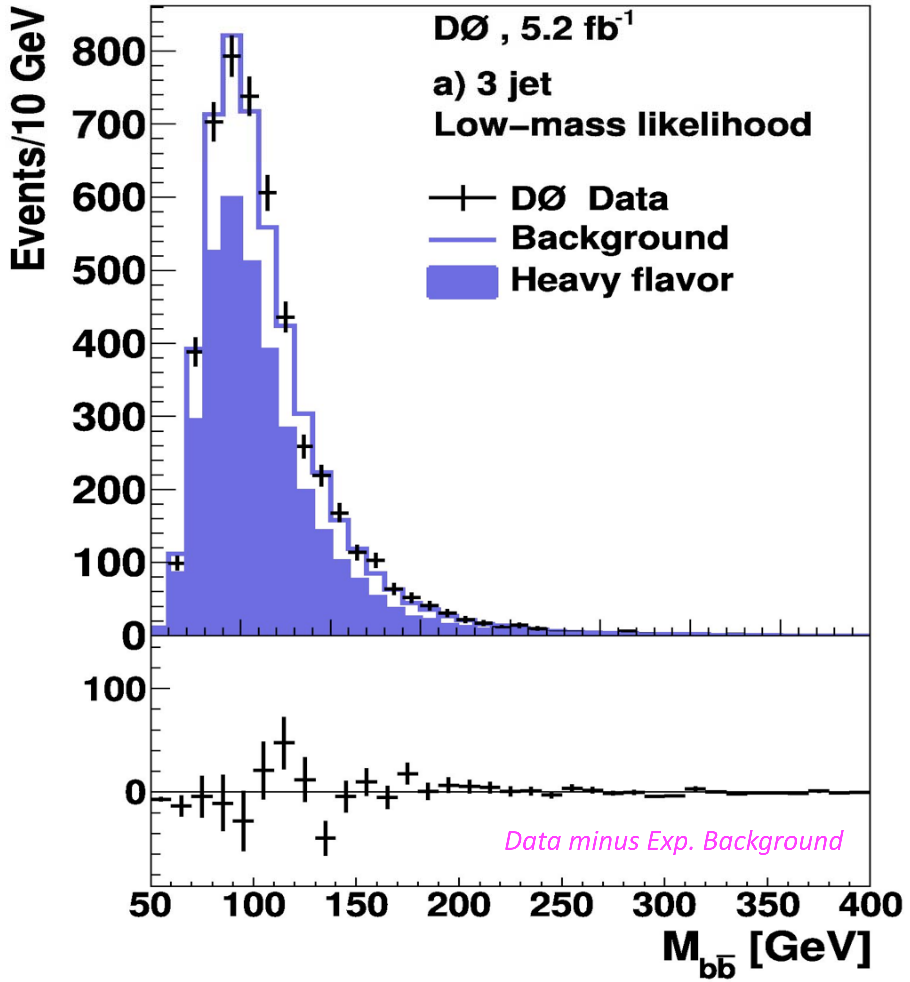



# DØ: $\phi b \rightarrow b\bar{b}b$ Search

- **5.2 fb$^{-1}$ search requires 3 b-tagged jets via NN b-tagger**
  - background composition from global fit over several b-tagging points

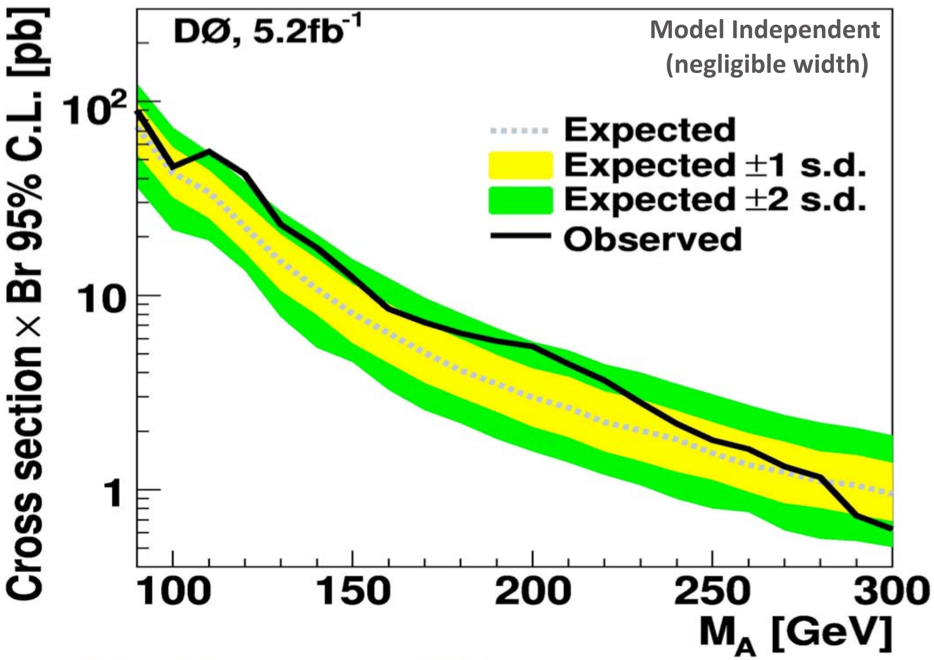


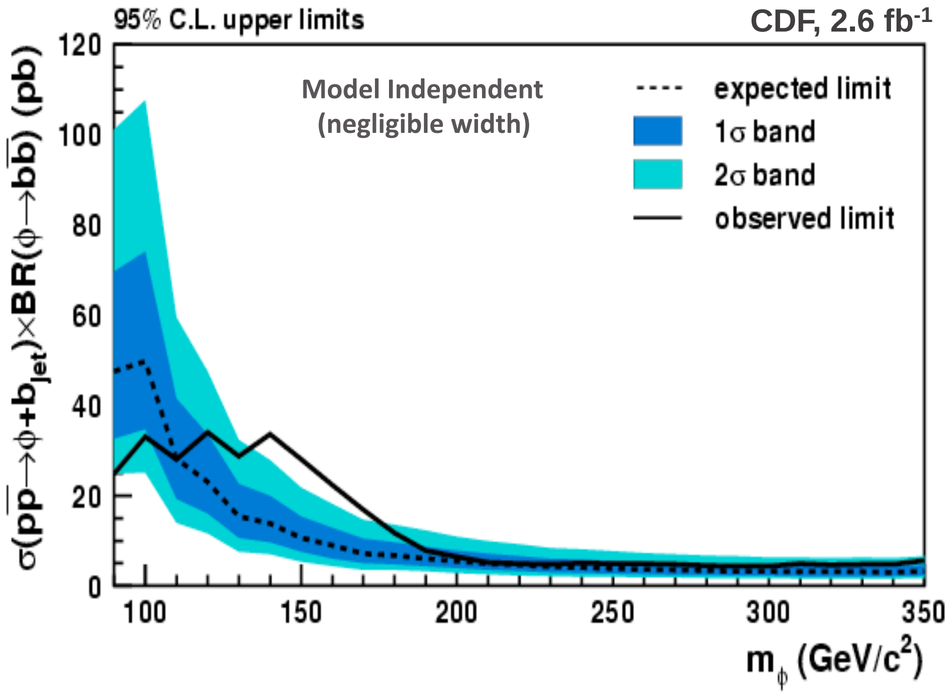




- **Improve sensitivity by separating into 3- and 4-jet channels**
  - likelihood discriminates b-jet pair via Higgs signal from multijet backgrounds
- **Dijet invariant mass of two leading jets used as input to limit**

# $\phi b \rightarrow b\bar{b}b$ Results: Limits

## 95% C.L. Mass-Dependent Cross Section Limits

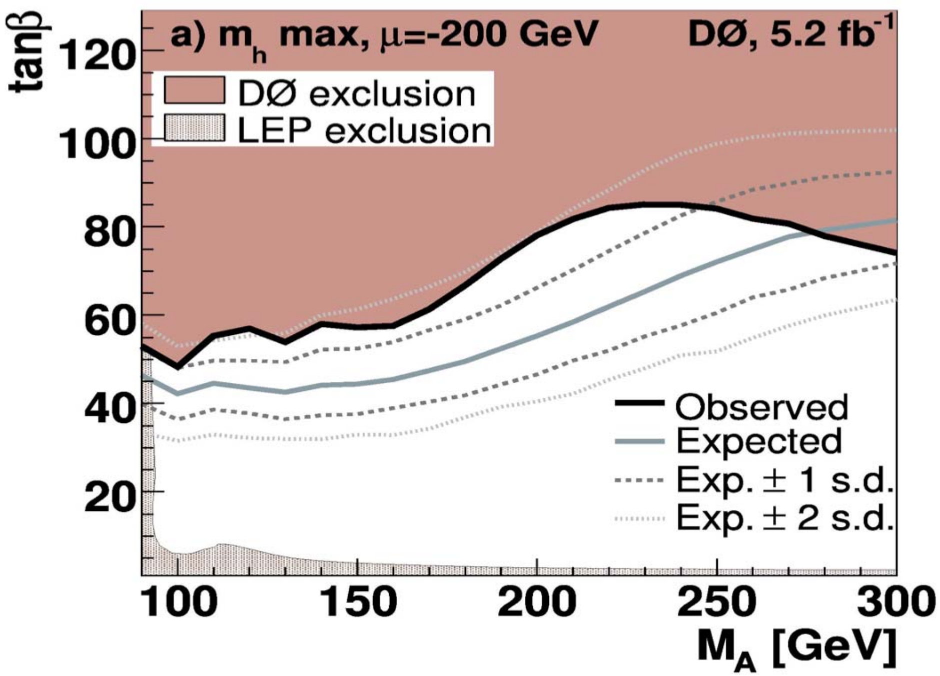


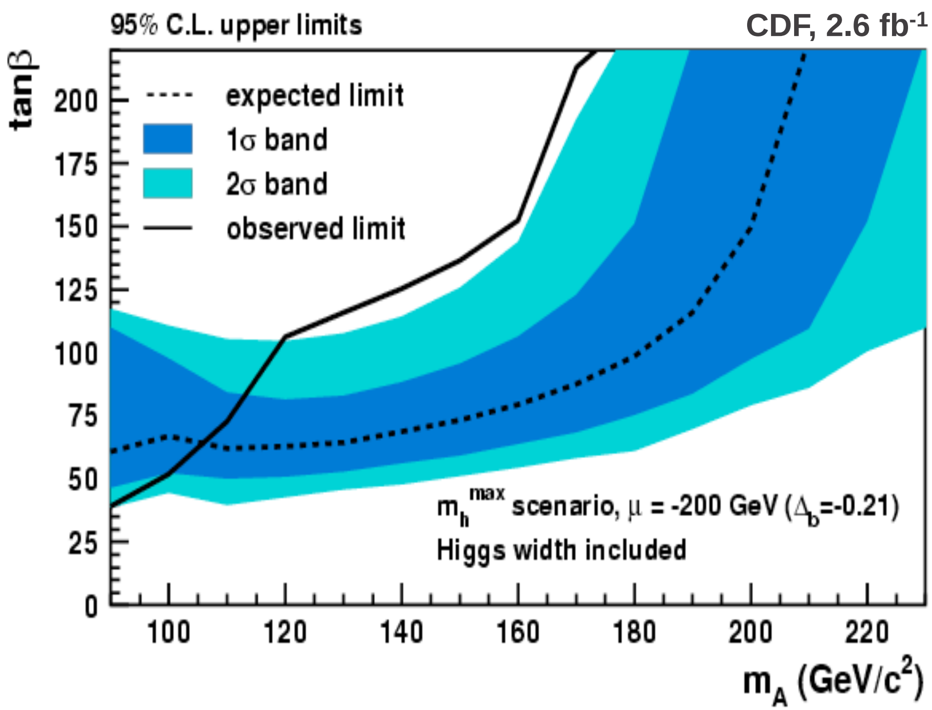

- **Limits on $\sigma \times$ BR**
  - DØ: observe ~2.5σ deviation at ~120 GeV for narrow-width case [after trial factors, significance of ~2.0σ]
  - CDF: deviation at ~150 GeV, with $1-CL_b$ $p$-value = 0.23% (~2.8σ) [trial factors, 1.9σ significance to observe such an excess at any masses]
- **General limits applicable to any narrow scalar with $b\bar{b}$ final states produced in association with b-jet**

# $\phi b \to b\bar{b}b$: MSSM interpretation

## MSSM Exclusions in ($M_A$, tanβ) Parameter Space




**DØ:** PLB 698, 97 (2011)

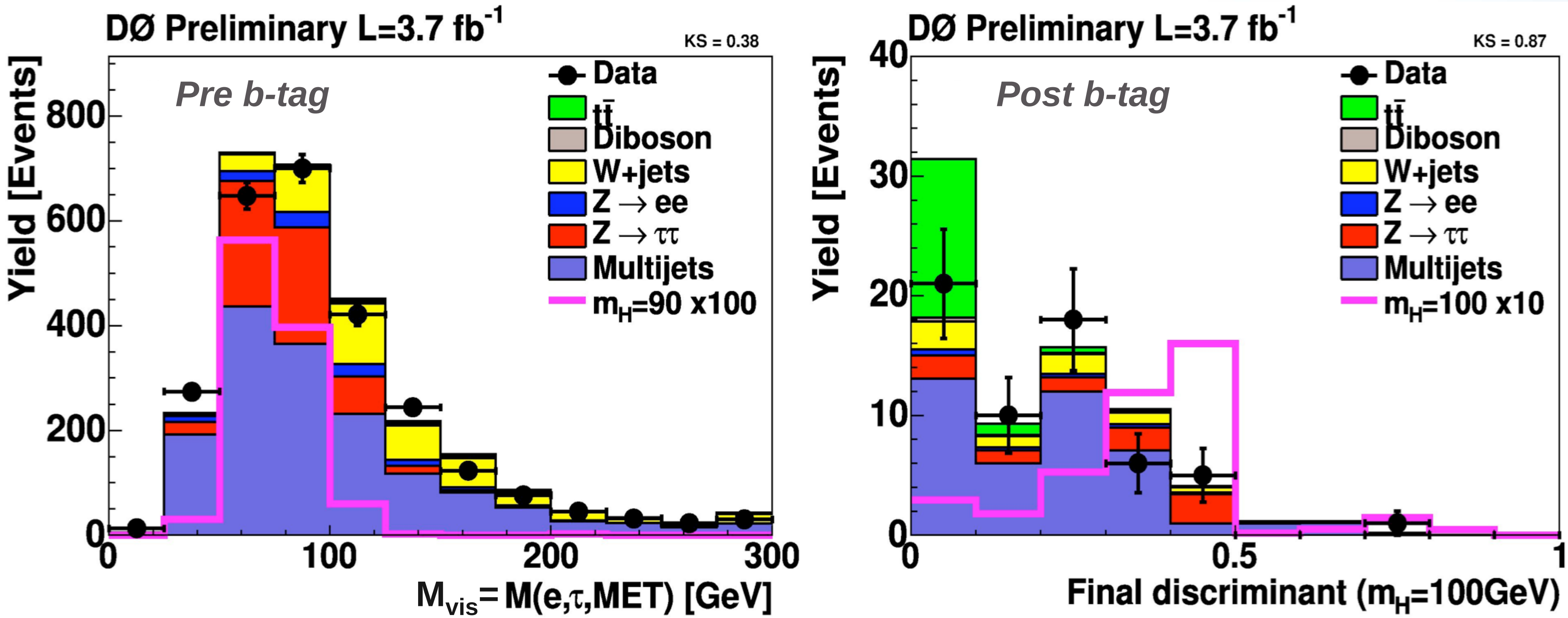



**CDF:** arXiv:1106.4782 [hep-ex]
(submitted to PRD)

- **Translate limits in MSSM benchmark scenarios in ($M_A$, tanβ) parameter space**
  - Higgsino mass term, $\mu < 0 \Rightarrow$ enhanced production for 3b
  - at large tanβ
    - enhances the bbH coupling as well as increases width of the Higgs

# $\phi b \to \tau_e \tau_{had} b$ Search

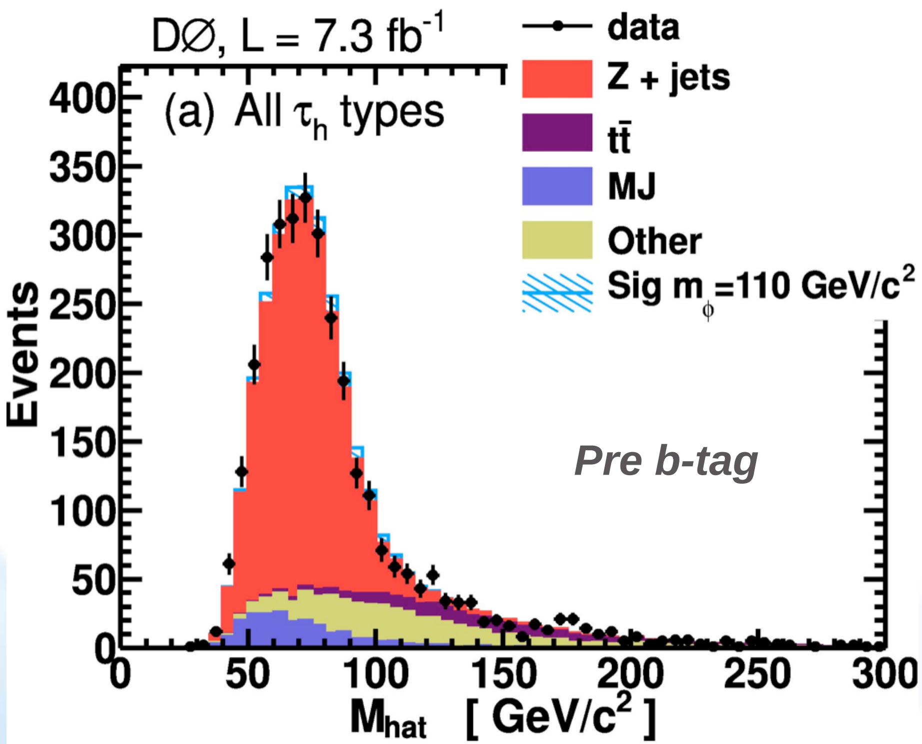
- **3.7 fb$^{-1}$ search considers $\phi b \to \tau_e \tau_{had} b$**
  - use developed techniques from both $\phi \to \tau\tau$ and $\phi b \to b\bar{b}b$ searches
  - complimentary to $\phi \to \tau\tau$ channel as it does not suffer from $Z \to \tau\tau$ backgrounds
- **Discriminate against different backgrounds via MVA techniques**
  - suppress $Z \to \tau\tau$ (Z+jets) ⇒ require one b-tag jet via NN b-tagger
  - construct $t\bar{t}$ ($D_{top}$) and multijet ($D_{MJ}$) discriminants per Higgs mass point

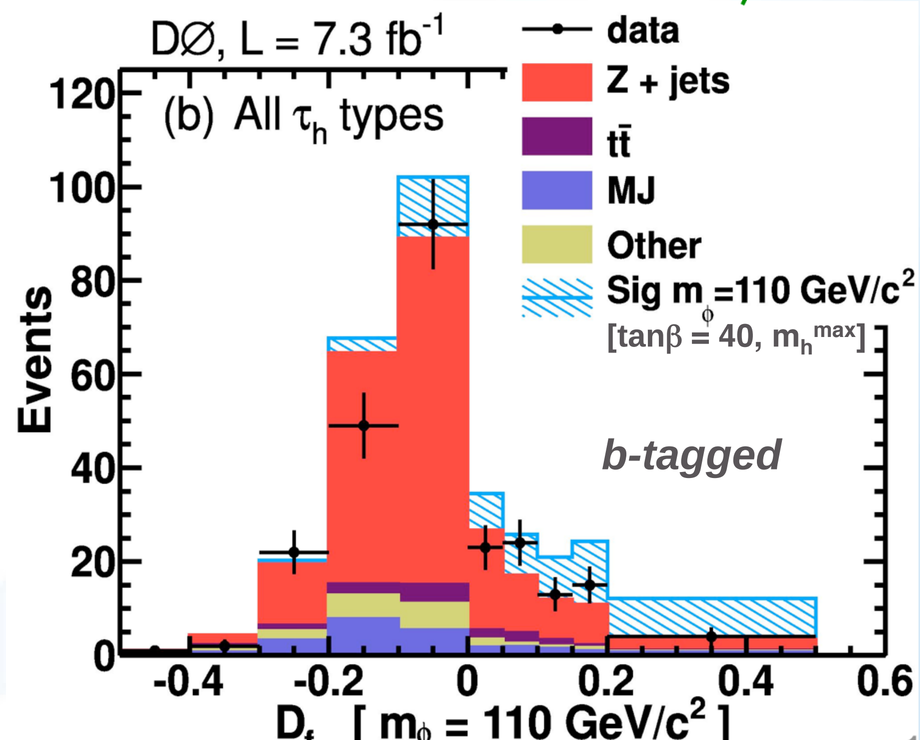



- **Combine for final discriminant:** $[(D_{MJ} + 10)/20] \times D_{top}$

# $\phi b \rightarrow \tau_\mu \tau_{had} b$ Search

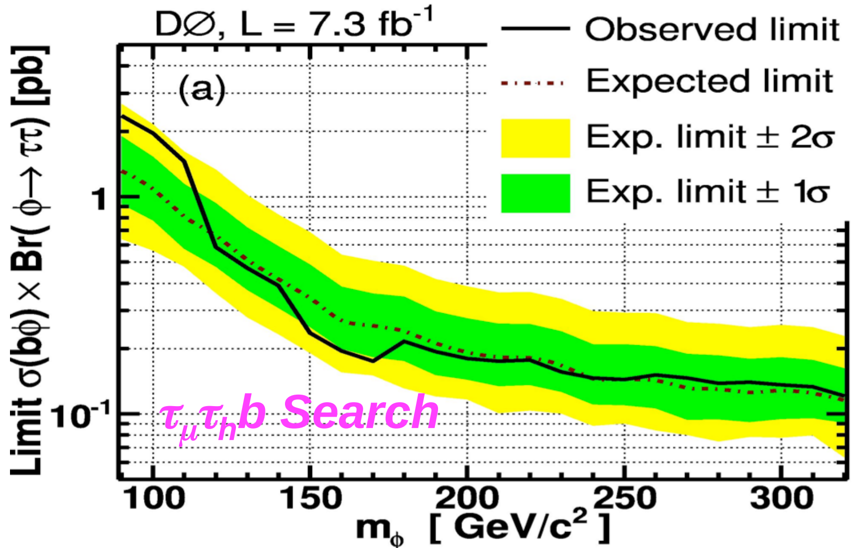
- **[New: PRL 107, 121801 (2011)]** **7.3 fb$^{-1}$ search considers** $\phi b \rightarrow \tau_\mu \tau_{had} b$
  - supersedes earlier 2.7 fb$^{-1}$ published result: PRL 104, 151801 (2010)
  - improve sensitivity
    - inclusive trigger: single $\mu$, $\mu+\tau_{had}$, $\mu$+jet, $\not{E}_T$+jet triggers
    - high-performance signal-to-background discriminants
- **Form likelihood for final discriminant:** $D_{MJ}$, $D_{top}$, $NN_b$, $M_{hat}$
  - $M_{\mathrm{hat}} \equiv \sqrt{\left(E^{\mu\tau_h} - p_z^{\mu\tau_h} + \not{E}_T\right)^2 - |\vec{p}_T^{\,\tau_h} + \vec{p}_T^{\,\mu} + \vec{\not{E}}_T|^2}$
  - minimal center-of-mass energy consistent with resonance: $R \rightarrow \tau\tau \rightarrow \mu\tau_{had}\not{E}_T$

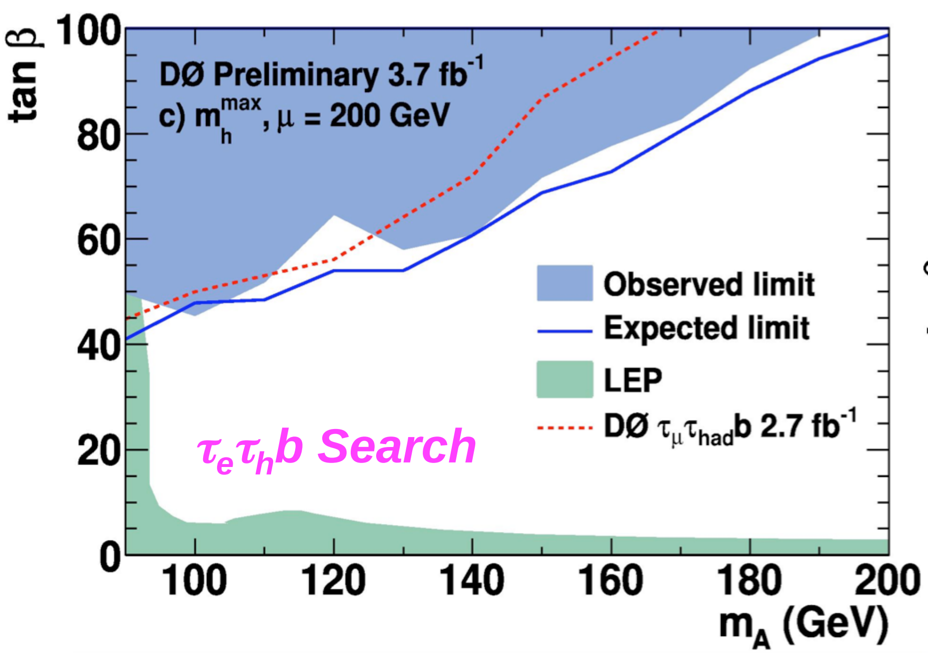


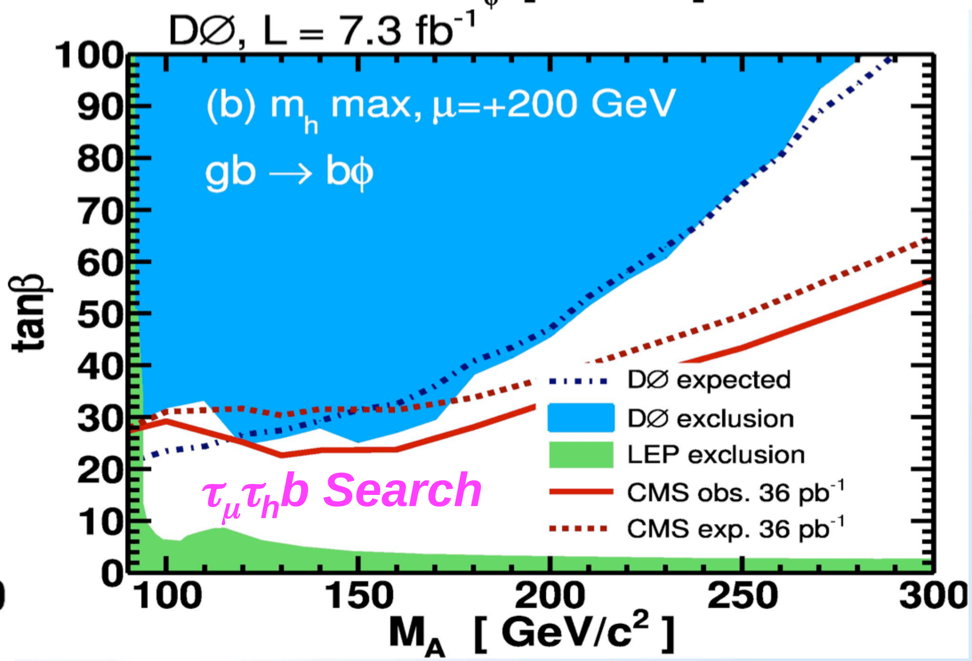



# $\phi b \to \tau_{e,\mu}\tau_{had} b$ Results

- **Observe no significant excess in data over expected backgrounds**
  - model-independent limits on Higgs production cross section
  - interpret as MSSM exclusions in $\tan\beta$ vs. $M_A$ plane



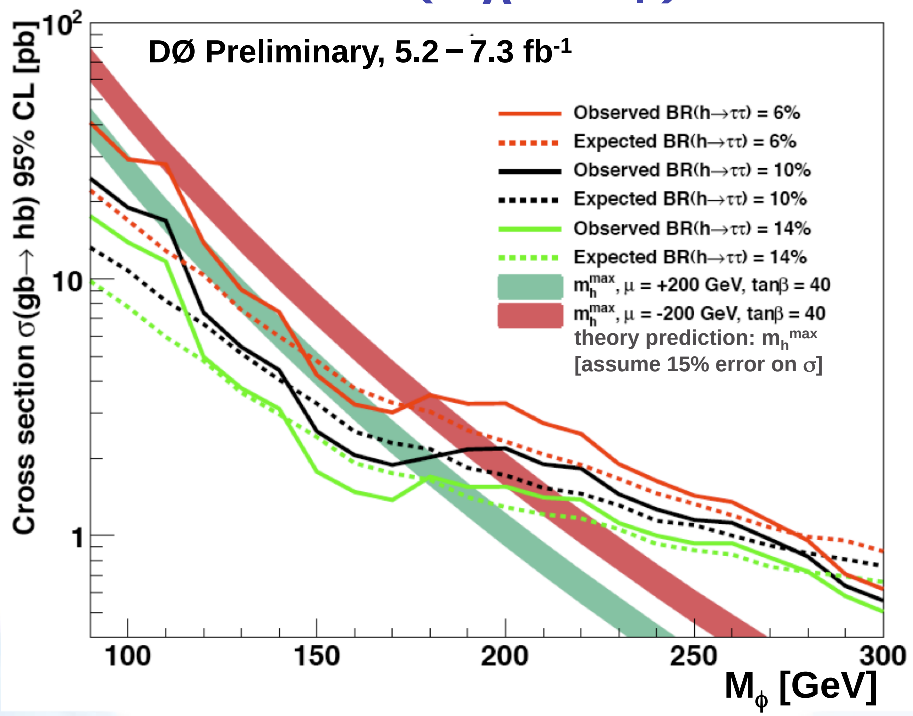



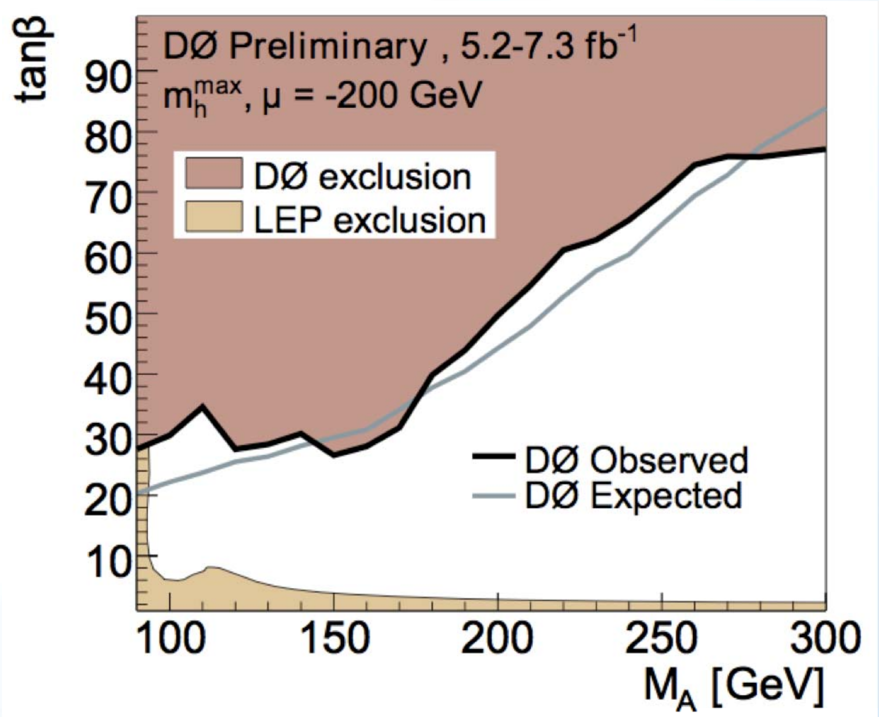




$\tau_\mu\tau_h b$: at low $M_A$, most stringent limit to-date in a direct search at the Tevatron

# DØ Combined Limits: $\phi b \to \tau\tau b$, $\phi b \to 3b$

- **[New in 2011] DØ MSSM Higgs combination**
- **Inputs to limits: 5.2 fb$^{-1}$ $\phi b \to b\bar{b}b$ and 7.3 fb$^{-1}$ $\phi b \to \tau_\mu \tau_{had} b$**
  - assume narrow Higgs and sum rule: BR($\phi \to b\bar{b}$) + BR($\phi \to \tau\tau$) = 1
    - for BR($\phi \to \tau\tau$) = 0.06, 0.10, and 0.14
  - correlate b-tag efficiency and jet modeling systematics between channels
  - up to $M_\phi \simeq$ 180 GeV: $\phi b \to \tau\tau b$ dominates limits;
    $\phi b \to 3b$ at higher mass as dependencies on the limit from tau BR decreases
- **Translate to ($M_A$, tanβ) exclusions**



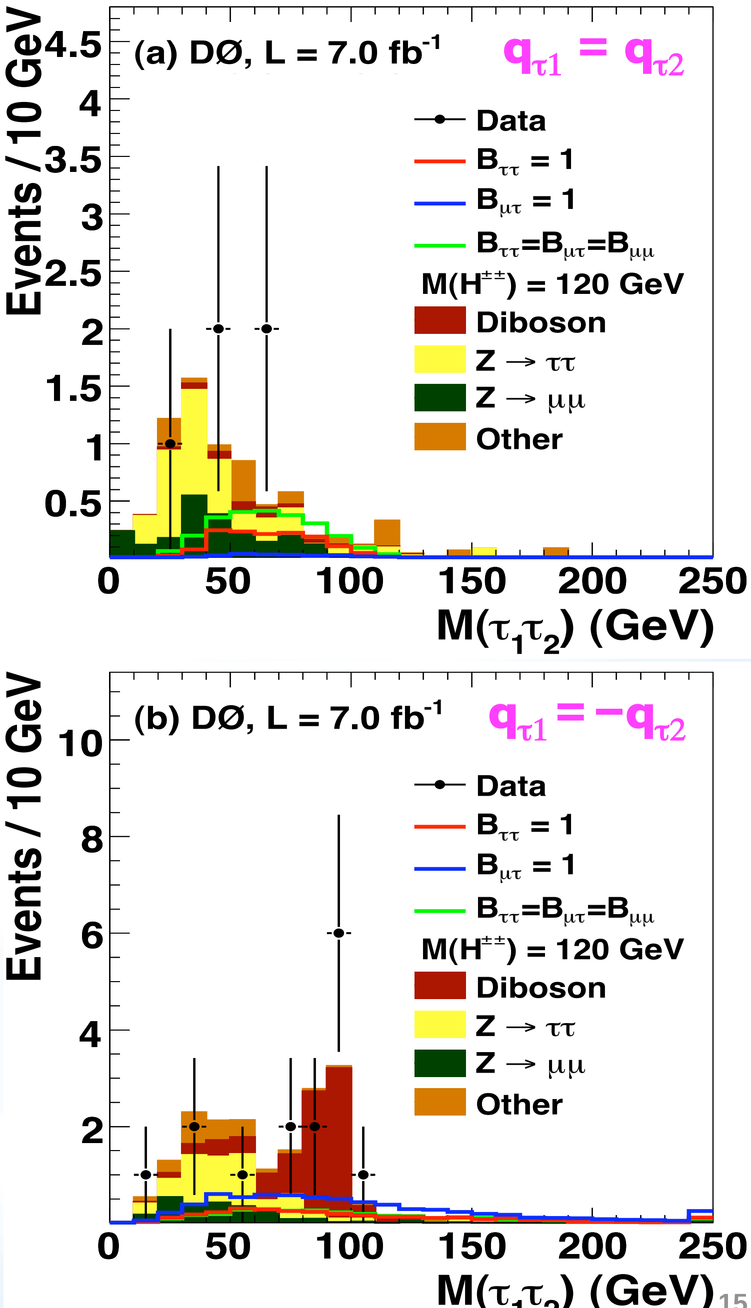




Tevatron combination from 3b searches in progress…

# Doubly Charged Higgs Search

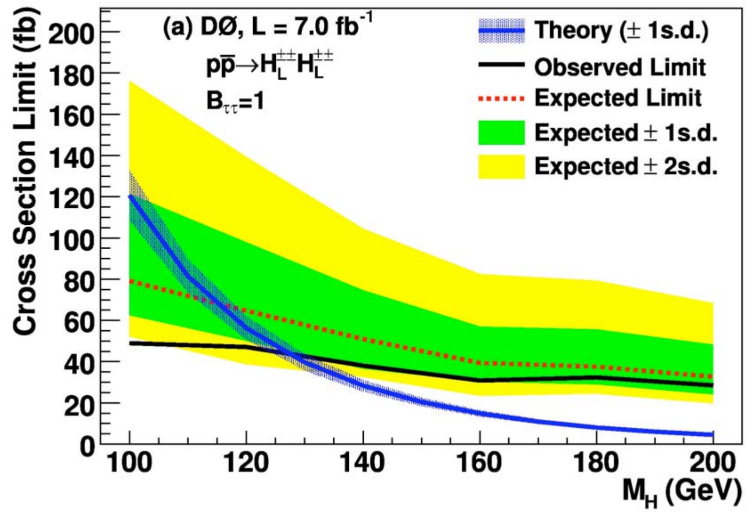
- **Models with extended Higgs sector predict $H^{\pm\pm}$**
  - $H^{\pm\pm} \rightarrow \tau^{\pm}\tau^{\pm}$ dominate in $SU(3)_c \times SU(3)_L \times U(1)_Y$ (3-3-1) gauge symmetric models
  - Higgs triplet model based on seesaw neutrino mass mechanism
    - hierarchy of neutrino masses yields equal BR for $H^{\pm\pm} \rightarrow \tau\tau, \mu\tau, \mu\mu$

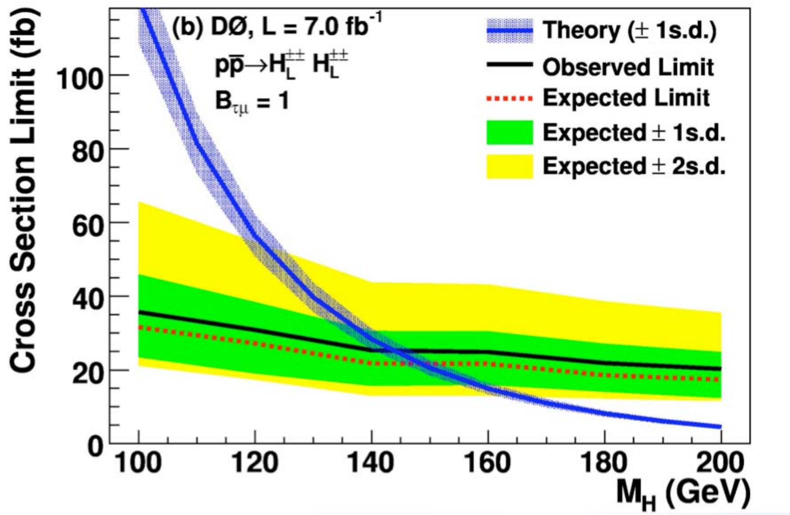
- **[New: accepted in PRL] 1st search for $H^{\pm\pm} \rightarrow \tau^{\pm}\tau^{\pm}$ at hadron collider, 7 fb$^{-1}$**
  - require at least one $\mu$ & two $\tau_{had}$
  - increase sensitivity to signal by categorizing samples with different backgrounds
    - $q_{\tau 1} = q_{\tau 2}$: $Z \rightarrow \tau\tau$ + jets, where jet mimics same-sign lepton
    - $q_{\tau 1} = -q_{\tau 2}$: $WZ \rightarrow \mu\nu e^{+}e^{-}$, where electrons misidentified as $\tau$ ($\rightarrow \rho\nu_{\tau}$)

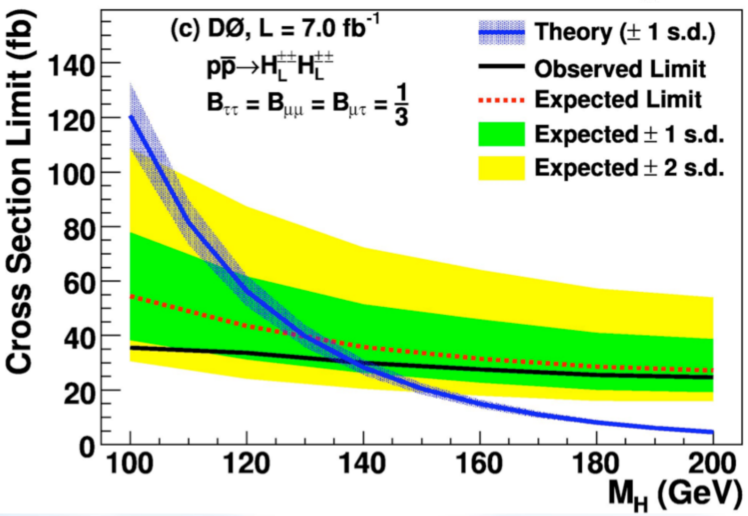


# Doubly Charged Higgs: Results

- **Set 95% C.L. observed (expected) lower limits of $M[H_L^{\pm\pm}]$**
  - $BR(H_L^{\pm\pm} \to \tau^\pm\tau^\pm) = 1$: $M[H_L^{\pm\pm}] > 128\ (116)$ GeV
  - $BR(H_L^{\pm\pm} \to \mu^\pm\tau^\pm) = 1$: $M[H_L^{\pm\pm}] > 144\ (149)$ GeV
  - $BR(H_L^{\pm\pm}\to\tau^\pm\tau^\pm) = BR(H_L^{\pm\pm}\to\mu^\pm\tau^\pm) = BR(H_L^{\pm\pm}\to\mu^\pm\mu^\pm) = 1/3$: $M[H_L^{\pm\pm}] > 138\ (130)$ GeV



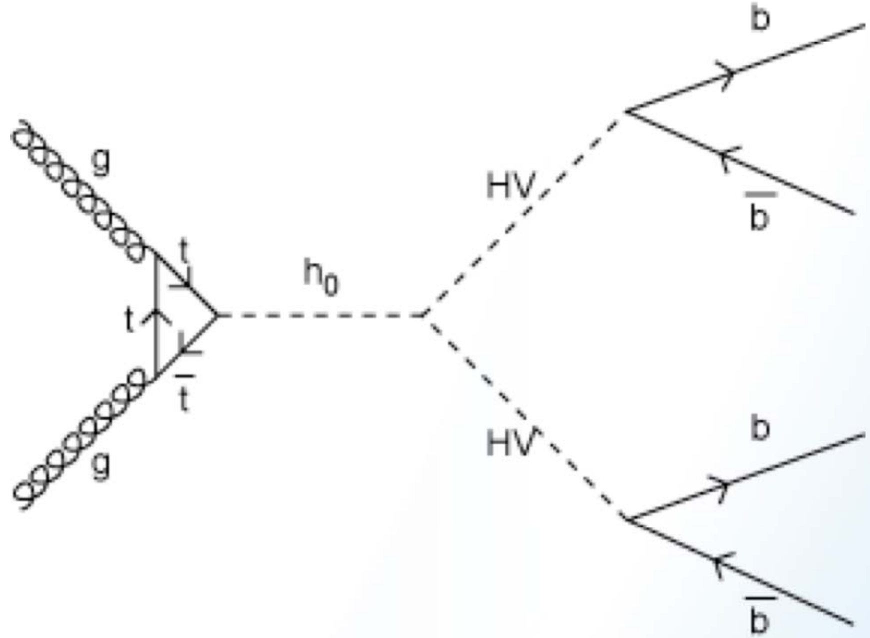



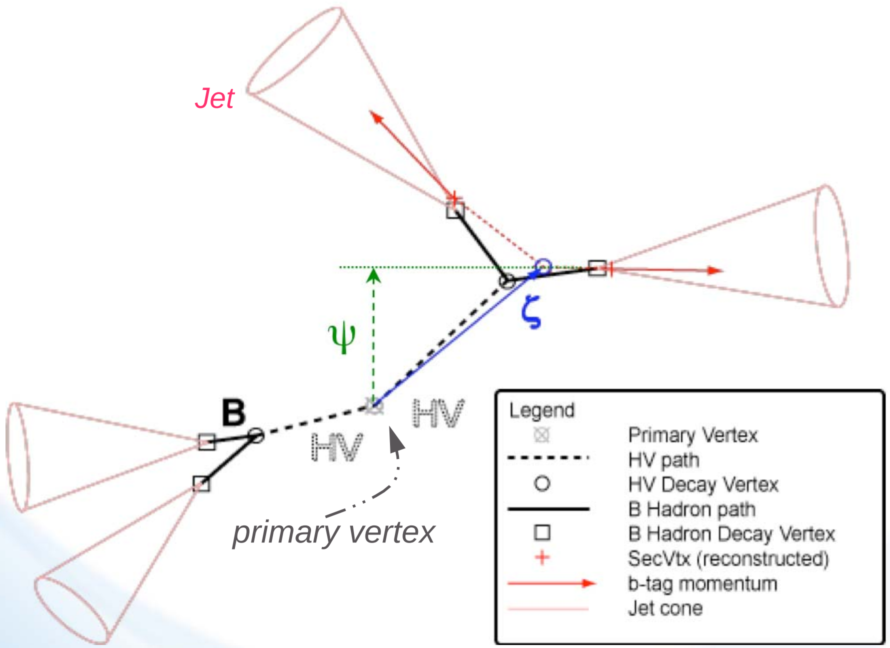

Most stringent limits on $H^{\pm\pm}$ masses in the hadronic $\tau\tau$ final states

*arXiv:1106.4250 [hep-ex]*

# CDF: Hidden Valley (HV)

- **[New: submitted to PRD]** **3.2 $fb^{-1}$ search: heavy particles with displaced secondary vertex (SV)**
  - Hidden Valley (HV) model
  - each HV decays into two b-quarks, with 4b final states
- **Signature**
  - 3+ jets with modified vertexing: large HV decay length [$\mathcal{O}$(~1 cm)]

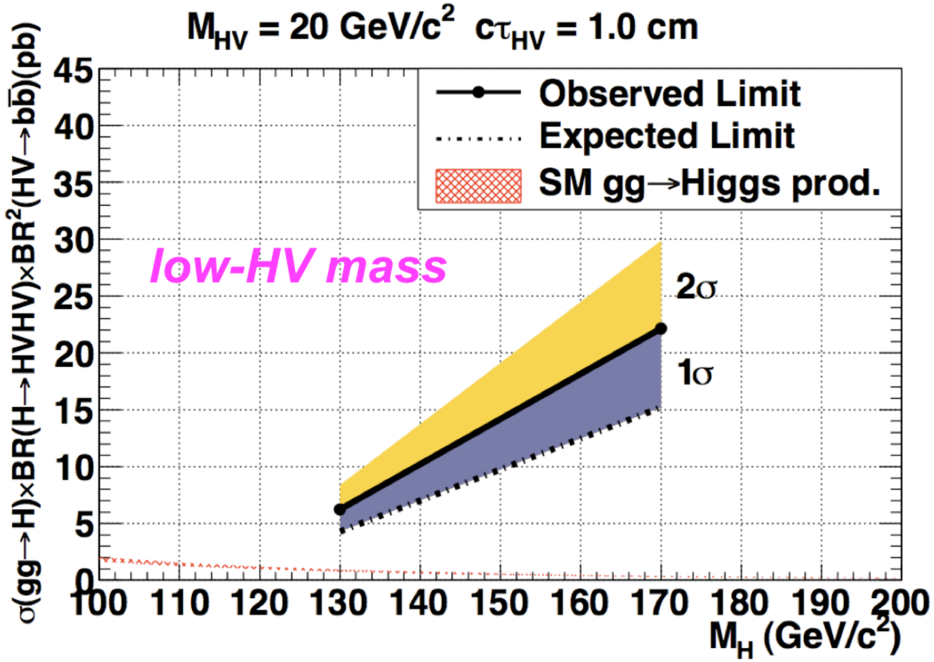


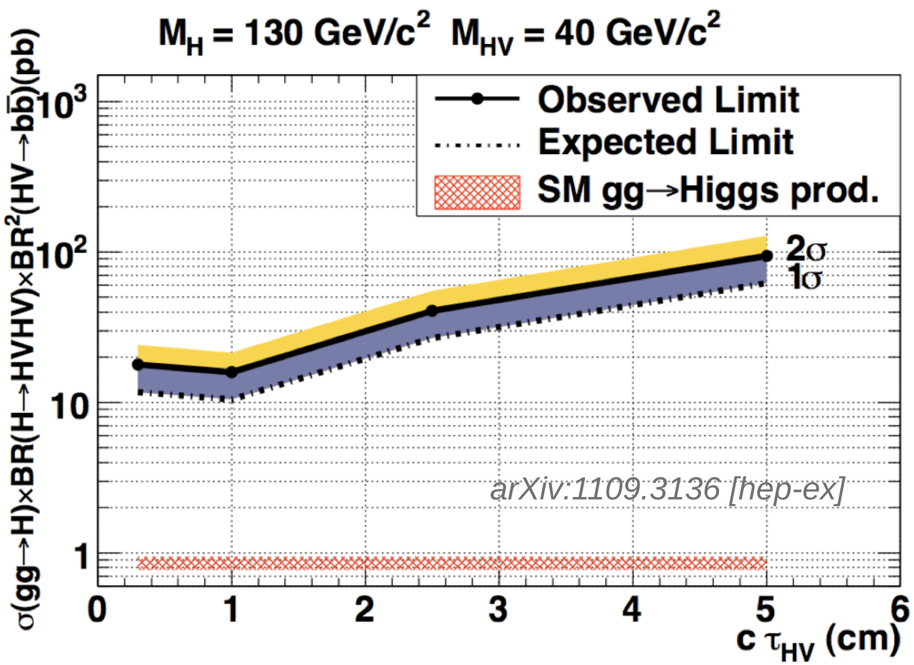



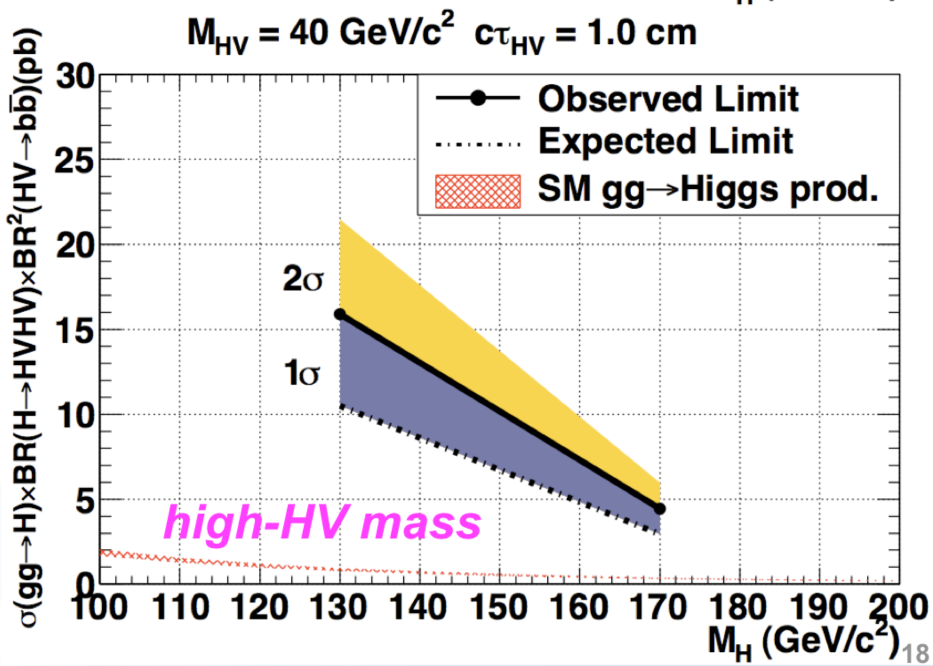

- **Optimize signal vs. background with variables based on reconstructed vertex**
  - $\psi$ : Jet impact parameter
  - $\zeta$ : Decay vertex of HV particle
- **Signal: $\psi, \zeta > 0$**
- **multijet background: $\psi, \zeta$ uniformly distributed ~ 0**

# Hidden Valley (HV): Results

- **Split into low- and high-HV mass search**
  - observe 1 event, 0.3 – 0.6 expected background events
- **set $\sigma \times BR$ limits in each HV mass search**
  - for various Higgs masses
  - for various HV particle lifetimes

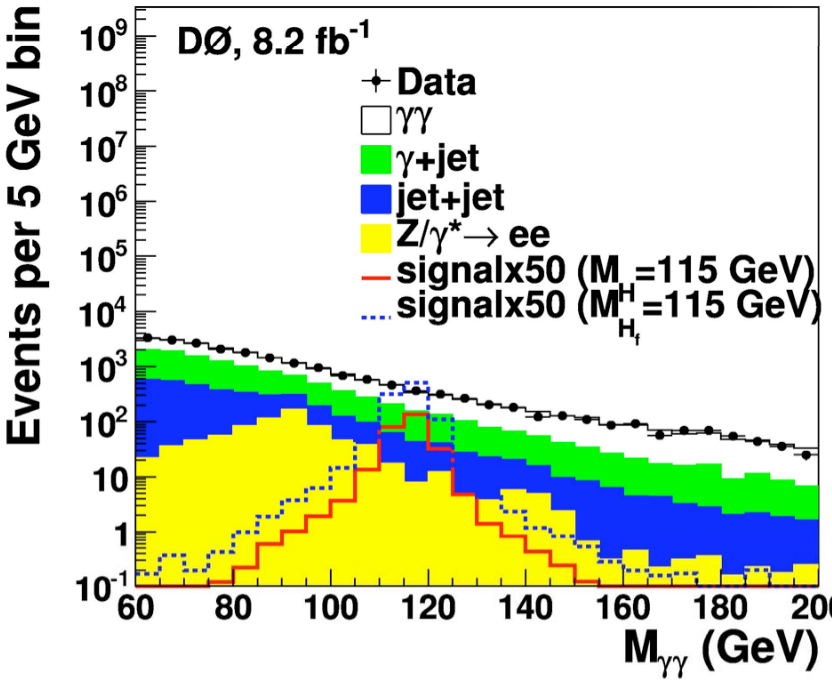


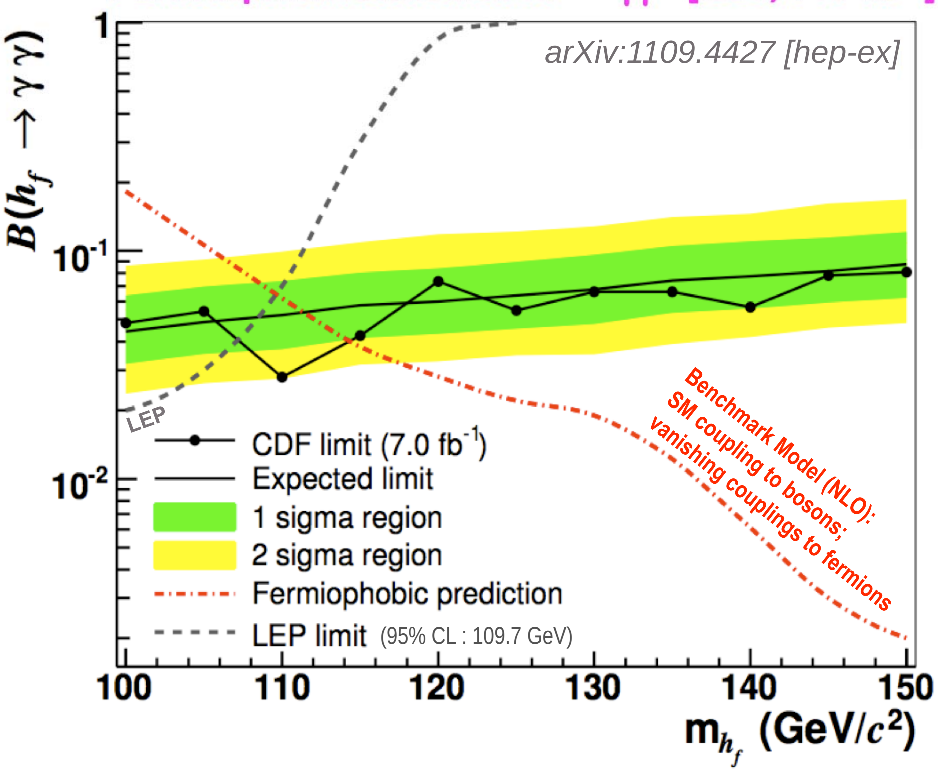



# Fermiophobic $H_f \rightarrow \gamma\gamma$ Search

- **CDF: 7.0 $fb^{-1}$: submitted to PRL**
  **DØ: 8.2 $fb^{-1}$: PRL 107, 151801 (2011)**
- **Distinguish photons with misidentified jet backgrounds using NN**
  - CDF: NN enhances central photon-ID as well as central + end-plug photons
  - DØ: implement energy-weighted width of central preshower clusters




Fermiophobic Model: H → γγ [CDF, 7.0 $fb^{-1}$]

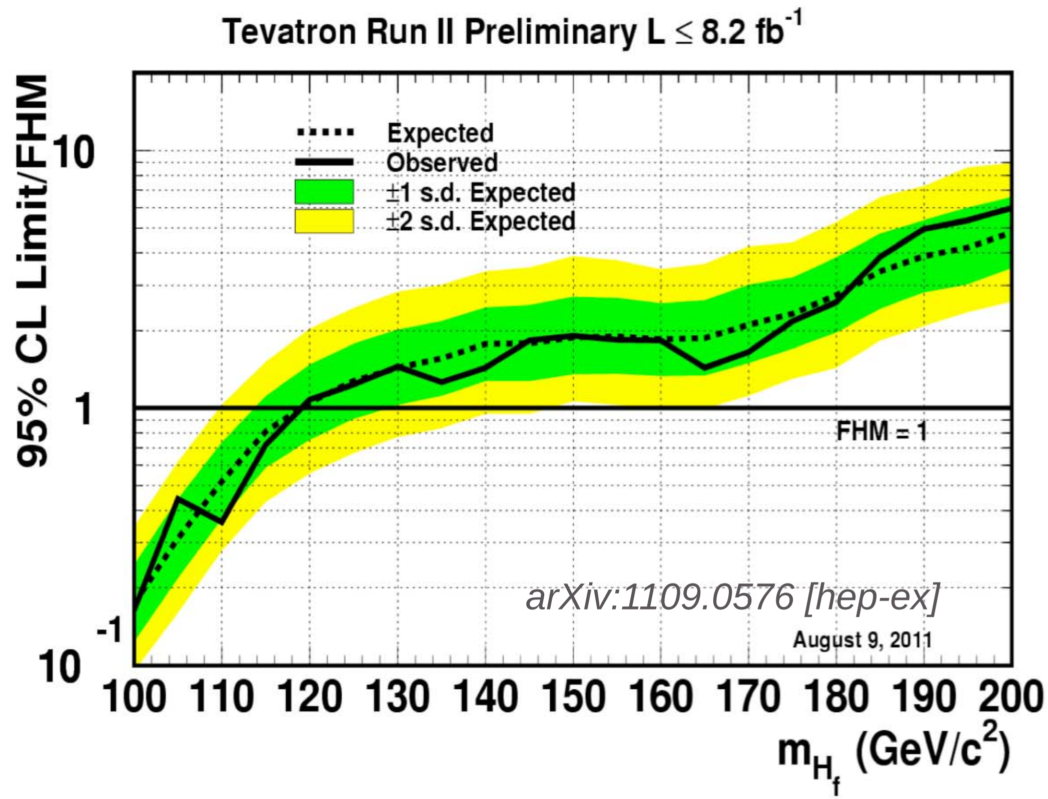



- **Search for excess of events in γγ mass spectrum**
  - CDF: separate search in 3 $p_T$ regions
    - $p_T^{\gamma\gamma} < 35$; 35 − 75; > 75 GeV
  - DØ: improve sensitivity using BDTs
- **DØ, for Fermiophobic couplings, exclude at 95% CL: $m_{Hf} < 112.9$ GeV**
- **CDF exclude: $m_{Hf} < 114$ GeV**

# Fermiophobic Higgs: Combined Limits

- **[New] Combined Tevatron search results on fermiophobic Higgs production**
  - $gg \rightarrow H_f$ suppressed; produced via $WH_f$, $ZH_f$, and Vector Boson Fusion processes
  - Higgs decays to $\gamma\gamma$ or $W^+W^-$
- **Search modes**

| Channel | $\mathcal{L}$ [fb$^{-1}$] | $m_{Hf}$ range [GeV] |
|---|---|---|
| CDF: $H_f \rightarrow \gamma\gamma$ | 7.0 | 100 – 150 |
| CDF: $H \rightarrow W^+W^-$ | 8.2 | 110 – 200 |
| CDF: $WH \rightarrow WW^+W^-$ *(SS leptons + Tri-leptons)* | 8.2 | 110 – 200 |
| CDF: $ZH \rightarrow ZW^+W^-$ *(Tri-leptons + 1, ≥2 jets)* | 8.2 | 110 – 200 |
| DØ: $H_f \rightarrow \gamma\gamma$ | 8.2 | 100 – 150 |
| DØ: $VH \rightarrow \ell^\pm\ell^\pm + X$ | 5.3 | 115 – 200 |




- **Tevatron exclusion: $m_{H_f}$ < 119 GeV**
  - sensitivity beyond that of combined LEP experiments
  - currently most restrictive limits on fermiophobic Higgs model

# Summary

- **CDF and DØ actively searching for Higgs in models beyond SM**
  - reported results with up to 8.2 $fb^{-1}$ of data
  - also $H^{\pm}$ and NMSSM searches [not covered here]
- **MSSM Higgs**
  - $(M_A, \tan\beta)$ exclusions from $(b)\phi \to (b)\tau\tau$ searches probing theoretically interesting regions of $\tan\beta \simeq 20-30$
  - forthcoming searches with larger datasets should provide further insight into deviations from expectation in 3b search at low $M_A$
  - updated DØ as well as Tevatron combinations expected imminently
- **Models with Extended Higgs sector**
  - DØ: first search for $H^{\pm\pm} \to \tau^{\pm}\tau^{\pm}$ decays at hadron collider
  - CDF's Hidden Valley results can be used to constrain other models
- **Fermiophobic Higgs**
  - most stringent limits on Fermiophobic Higgs mass

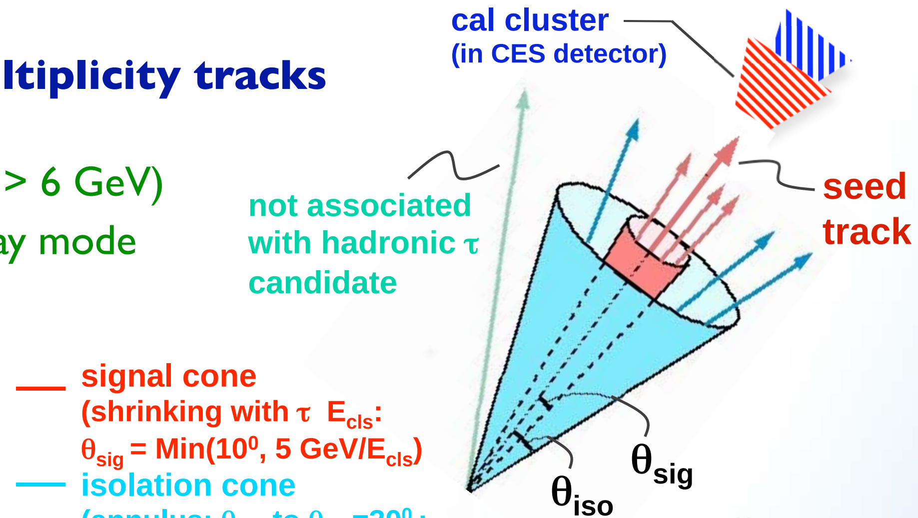
Tevatron delivered ~11.9 $fb^{-1}$ of data;
Stay tuned for updates and combinations expected soon!

# Reference Slides

# τ-Identification

## CDF: narrow cal clusters matched to low multiplicity tracks

- define [shrinking] signal and isolation cones around seed track's axis (≡ highest $p_T$ track; > 6 GeV)
- # of tracks inside signal cone defines τ decay mode
- add $\pi^o$ info to track-cal cluster ⇒ consistent with τ mass
- τ-ID based on "cuts" to key variables (e.g., sum of isolation $E_T$, $p_T$ tracks inside cone)

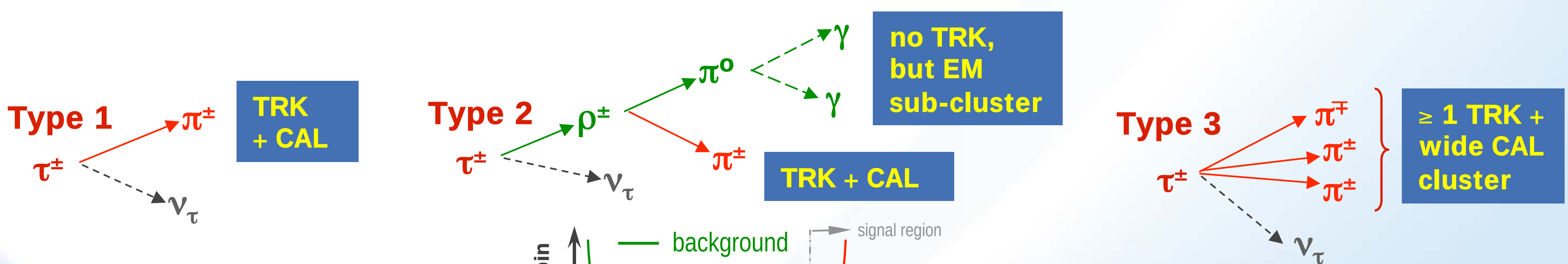


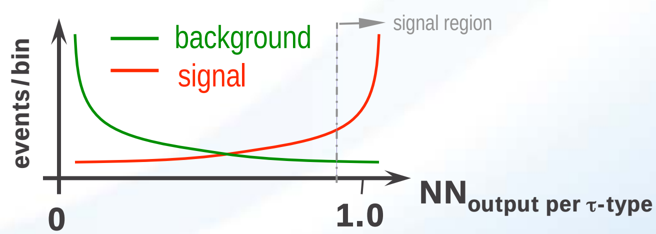

*τ-ID Eff = 50% vs. fake rate < 1%*

## DØ: narrow cal energy clusters matched to tracks, with or without EM subclusters

**⇒ separate τ's into 3 categories, defined by their decay mode**

- πν-like [type 1], ρν-like [type 2], and 3-prongs [type 3]
- implement Neural Nets (NN) per τ-type to discriminate τ signal from multijet background



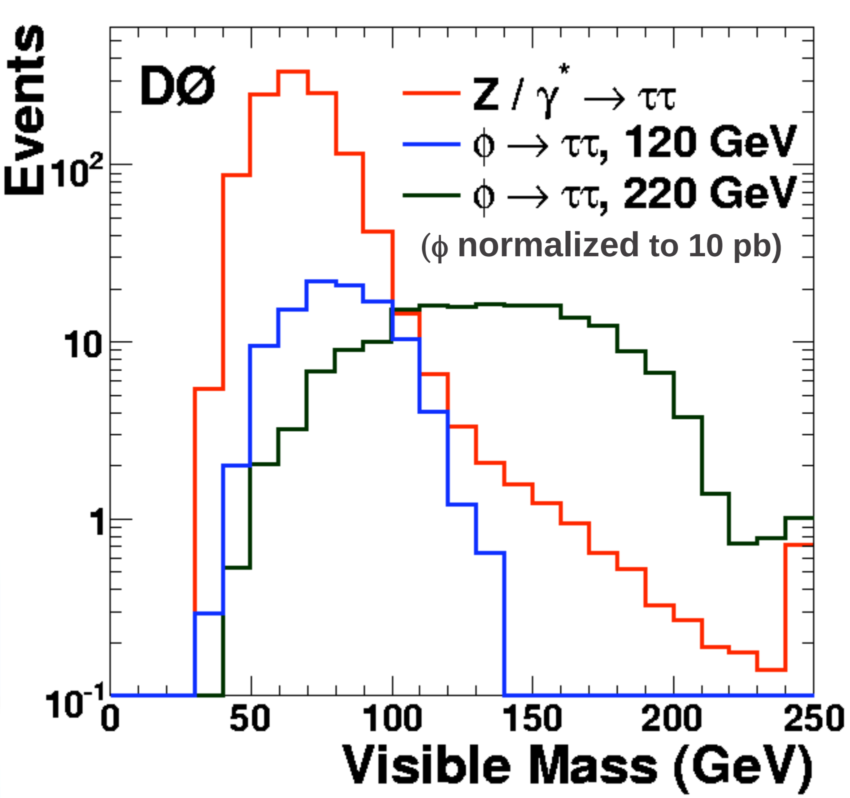




*τ-ID Eff = 65% vs. fake rate ~ 2.5%*

# Visible Mass

- **After final event selections for $\phi \to \tau\tau$, irreducible background from $Z \to \tau\tau$**
  - smaller contribution from EW and QCD multijet processes
- **Distinguish Higgs boson by its mass**
  - presence of neutrinos in final states $\Rightarrow$ not possible to reconstruct $\tau\tau$ mass
  - use visible mass: the invariant mass of the sum of the $\tau$ decay plus missing transverse energies
    - exploit fact that signal appears as an enhancement above $Z \to \tau\tau$

$$M_{VIS} = \sqrt{(P^{\tau 1} + P^{\tau 2} + \not{P}_T)^2}$$




- **Use 4-vectors of:**
  - $P^{\tau 1}$, $P^{\tau 2}$ of visible tau decay products
  - $\not{P}_T = (\not{E}_T, \not{E}_x, \not{E}_y, 0)$, where $\not{E}_x$ and $\not{E}_y$ indicate components of $\not{E}_T$
- **$M_{vis}$ used as input to $\sigma \times$ BR limit calculation in inclusive $\tau\tau$ search**

# MSSM Benchmark Scenarios

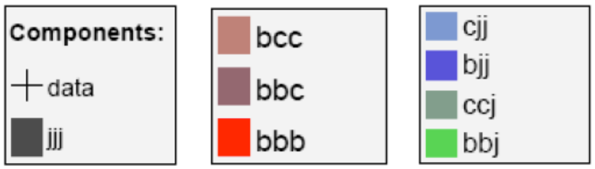
- **For neutral Higgs searches: $\sigma \times$ BR limits $\Rightarrow$ interpreted in MSSM**
- **Tree-level: Higgs sector of MSSM described by $m_A$ & $\tan\beta$**
  - radiative corrections introduce dependence on additional SUSY parameters
- **Five additional, relevant parameters**
  - $M_{SUSY}$ Common Scalar mass: parameterizes squark, gaugino masses
  - $X_t$ Mixing Parameter: related to the trilinear coupling $a_t \rightarrow$ stop mixing
  - $M_2$ SU(2) gaugino mass parameter
  - $\mu$ Higgs sector bilinear coupling (mass parameter; where $\Delta_b^{loop} \propto \mu \times \tan\beta$)
  - $m_{\tilde{g}}$ gluino mass: comes in via loops
- **Two common benchmarks**
  - $m_h^{max}$ (max-mixing): Higgs boson mass, $m_h$, close to maximum possible value for a given $\tan\beta$
  - no-mixing: vanishing mixing in stop sector $\Rightarrow$ small Higgs boson mass, $m_h$

Constrained Model: Unification of SU(2) and U(1) gaugino masses

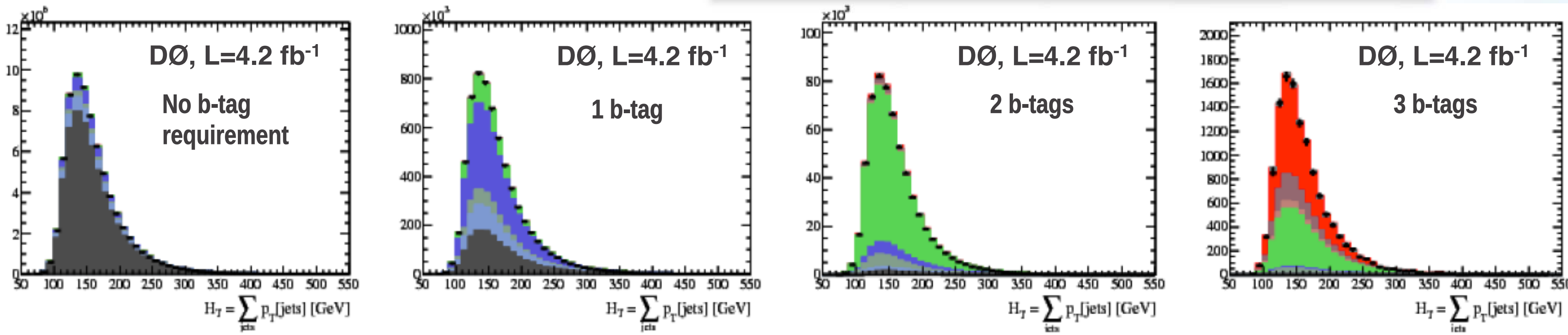
| | $m_h^{max}$ | no-mixing |
|---|---|---|
| $M_{SUSY}$ | 1 TeV | 2 TeV |
| $X_t$ | 2 TeV | 0 |
| $M_2$ | 200 GeV | 200 GeV |
| $\mu$ | ±200 GeV | ±200 GeV |
| $m_{\tilde{g}}$ | 800 GeV | 1600 GeV |

# DØ: $\phi b \rightarrow b\bar{b}b$ Analysis Overview

- **5.2 fb$^{-1}$ search requires**
  - separate into 3- and 4-jet channels: $p_T^{jet} > 20$ GeV, $|\eta| < 2.5$
  - 3 b-tagged jets with NN b-tagger (>0.775), with 2 jets in pair: $p_T^{jet1,2} > 25$ GeV
- **Background composition determined from 3-jet sample**
  - fit MC simulated events to data over b-tagging points: 0-, 1-, 2-, and 3-tags



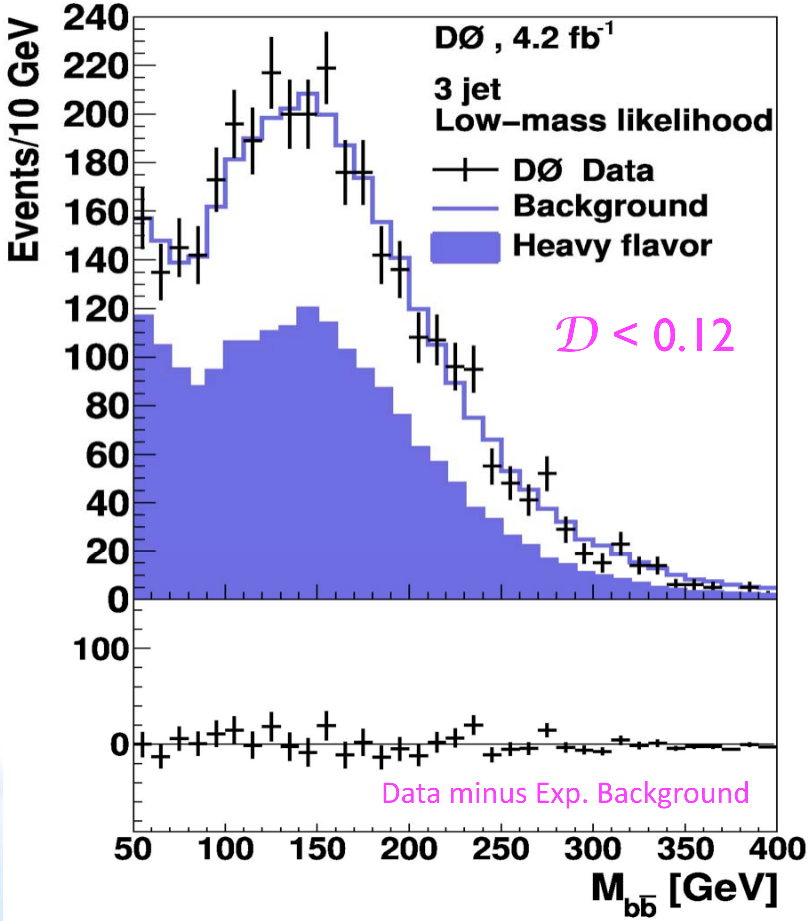

| Background Composition *(3 b-tagged sample)* | | | |
|---|---|---|---|
| $b\bar{b}b$ | $b\bar{b}j$ | $b\bar{b}c + bc\bar{c}$ | $c\bar{c}j + bjj + cjj$ |
| ~50% | ~30% | ~15% | ~4% |

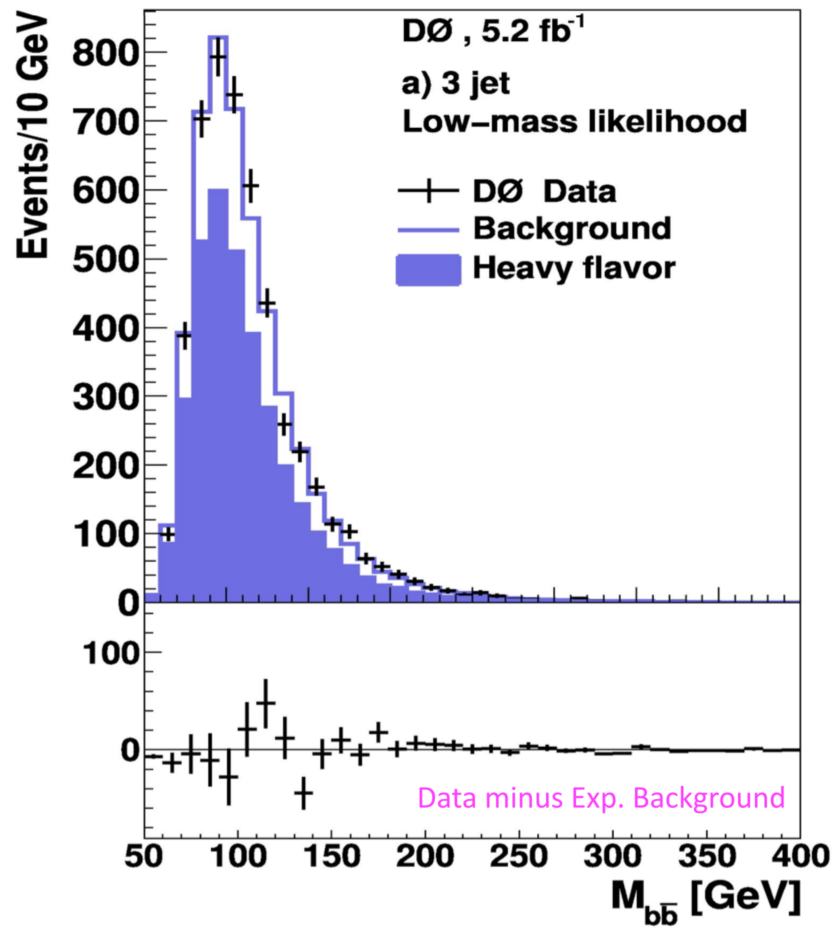



- **Background modeling**
  - irreducible $b\bar{b}b$ background $\Rightarrow$ indistinguishable from any possible signal
  - no control regions to normalize to data
    - model background shape using combination of data and simulation
    - predict 3 b-tag bkgnd shape from 2 b-tag data, scaled by simulated 3/2-tag ratio
- **6-variable jet-pair likelihood discriminant [$\mathcal{D}$]**

# DØ: $\phi b \to b\bar{b}b$ Search (cont.)

- **Background model verified in a signal-depleted region**
  - pick lower likelihood jet-pairing and select $\mathcal{D} < 0.12$
  - observe agreement [$\chi^2$/n.d.f. = 0.86] between data and background model




- **Dijet invariant mass of two leading jets used as input to $\sigma \times$ BR limit**
  - limit calculated using only the shape difference between signal and background

# Multivariate Methods: Variables

## $H_f \to \gamma\gamma$ Search (FHM)

| 5-variable $\gamma$-Neural Network ($NN_\gamma$) | BDT |
|---|---|
| $\Sigma_{trks} p_T(\text{trks})$ | $M_{\gamma\gamma}$ |
| $N_{cells}$ in CAL Layer I in $\Delta R < 0.2$ | $\Delta\phi_{\gamma\gamma}$ |
| $N_{cells}$ in CAL Layer I in $0.2 < \Delta R < 0.4$ | $p_T^{\gamma\gamma}$ |
| $N_{CPS}$ clusters assoc. with $EM_{CAL}$ | $p_T^{\gamma 1}$ |
| CPS cluster: energy-weighted width | $p_T^{\gamma 2}$ |

## $\phi b \to b\bar{b}b$ Search

| 6-variable Likelihood Discriminant<br>*( for "jet-pair" with 1st & 2nd leading jets: $max[\Sigma p_T^{j1,2}]$ )* |
|---|
| $\Delta\eta$ of 2-jets in the pair |
| $\Delta\phi$ of 2-jets in the pair |
| angle: $\phi = \text{acos}(\text{lead jet, total } p_T \text{ of jet pair})$ |
| momentum balance: $\lvert p_{b1} - p_{b2}\rvert / \lvert p_{b1} + p_{b2}\rvert$ |
| combined rapidity of jet pair |
| event sphericity |

## $\phi b \to \tau_\mu \tau_{had} b$ Search

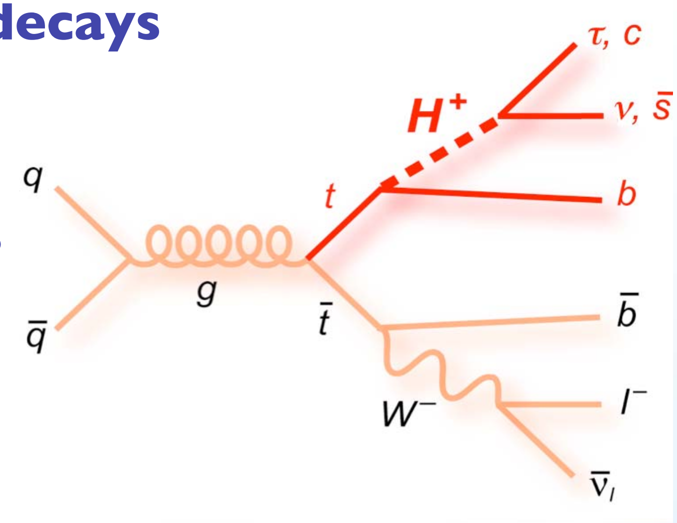
| anti-top NN Discriminant ($D_{top}$) | anti-multijet NN Discriminant ($D_{MJ}$) |
|---|---|
| $D_{final}$ = Likelihood $[D_{top}, D_{MJ}, NN_{b-tag}, M_{hat}]$ | |
| $N_{jets}$ (✳) | Muon $p_T$ (✳) |
| $H_T = \Sigma_{jets} p_T[\text{jets}]$ (✳) | Tau $p_T$ (✳) |
| $E_T = p_T^\tau + p_T^\mu + H_T$ (✳) | $\lvert\Delta\phi[\mu,\tau]\rvert$ |
| $\lvert\Delta\phi[\mu,\tau]\rvert$ (✳) | $H_T = \Sigma_{jets} p_T[\text{jets}]$ |
| $\lvert\Delta\phi[\mu, MET]\rvert$ | MET |
| $\mathcal{A}_T = [p_T^\mu - p_T^\tau]/p_T^\tau$ | $m_T[\mu, \tau, MET, jet]$ |
| MET | $M_{collinear}$ |
| $m_T[\mu, MET]$ | $M_{hat}$ |
| $m_T[\mu, \tau, MET, jet]$ | – |
| $M_{collinear}$ | – |
| $M_{hat}$ | – |

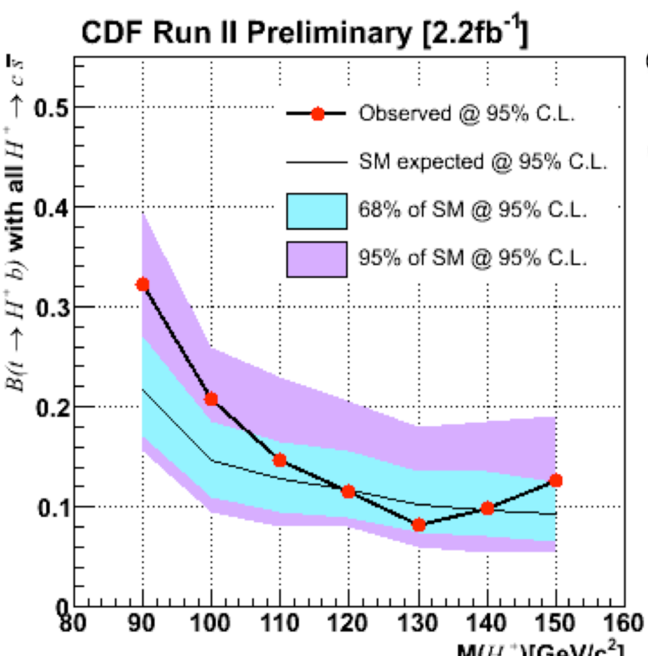
N-object $m_T$ defined by: $m_T[O_1,\ldots,O_k,\ldots,O_N] = \sqrt{\sum_{i=1}^{i\le N}\sum_{j=1}^{j\le N} p_T[O_i]\times p_T[O_j]\times(1-\cos\Delta\varphi[O_i;O_k])}$

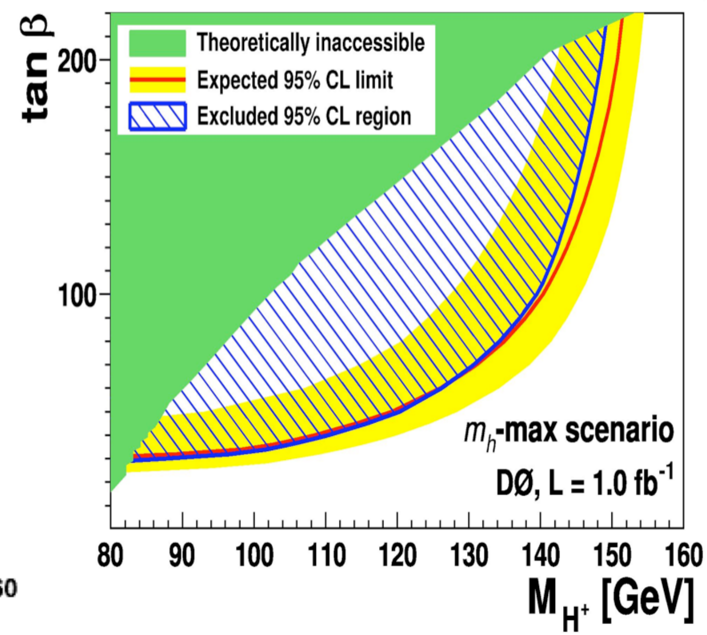
(✳) = Also used in 3.7 fb$^{-1}$ $e\tau_{had}$+b Search

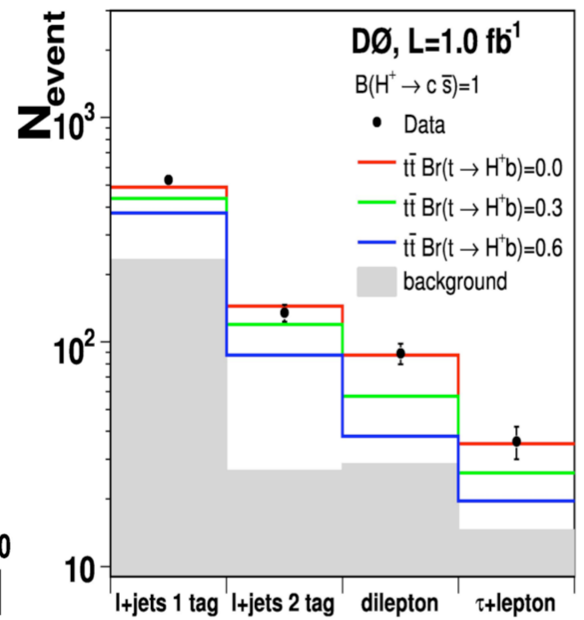
# MSSM Charged Higgs Search

- If $m_{H^\pm} < m_{top}$: search in top pair sample for decay to $H^\pm$
- Consider two search modes based on $H^\pm$ decays
  - Tauonic model: $H^\pm \rightarrow \tau\nu$ [high tanβ]
  - Leptophobic model: $H^\pm \rightarrow c\bar{s}$ [low tanβ]
- Search dilepton, $\ell$+jets, $\ell+\tau_h$ top channels
- Select high-$p_T$ leptons, $\not{E}_T$, and b-tag
- 95% CL limits on BR($t \rightarrow H^+ b$)
  - DØ 1.0 fb$^{-1}$: PLB 682, 278 (2009)
  - CDF 2.2 fb$^{-1}$: PRL 103, 101803 (2009)



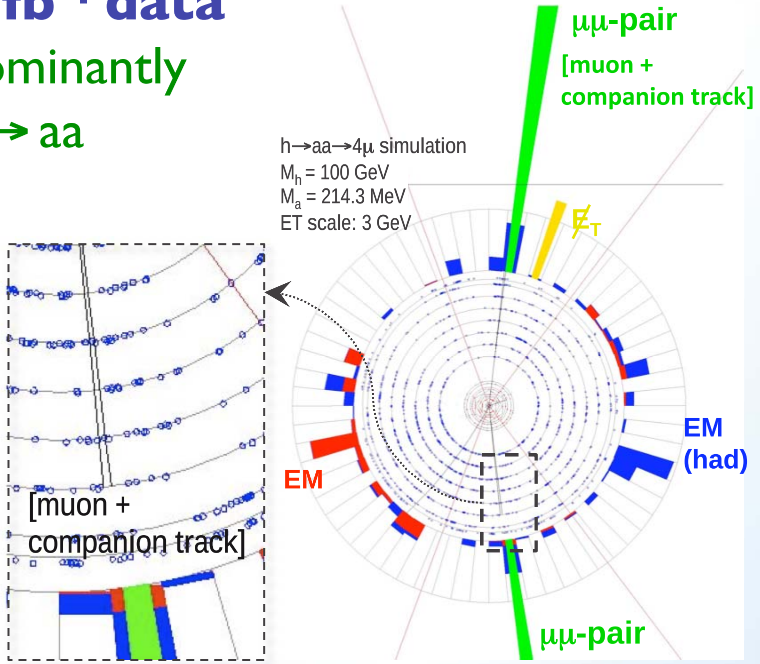



# DØ: NMSSM h→aa Search

- **next-to-MSSM Higgs decay search, 4.2 $fb^{-1}$ data**
  - $h \to b\bar{b}$ branching ratio greatly reduced and dominantly decays to pair of pseudo-scalar Higgs "a": $h \to aa$
  - general LEP search sets limit: $M_h > 82$ GeV

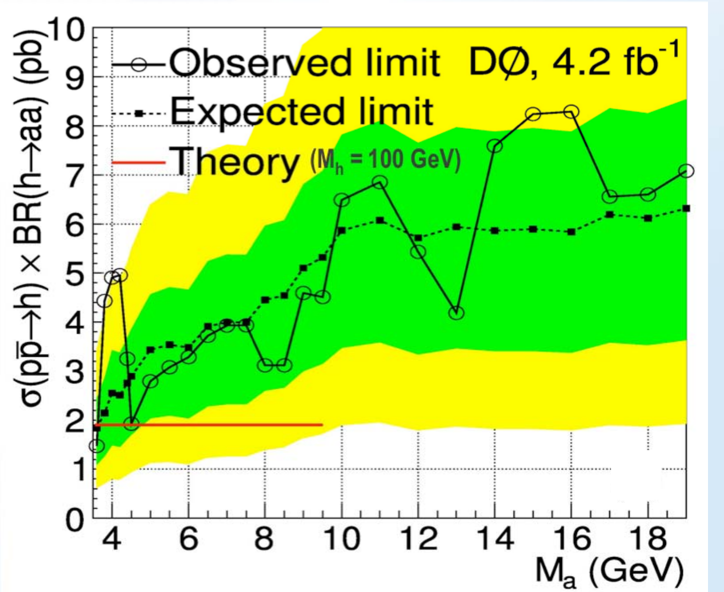
**For masses: $2m_\mu < M_a < \sim 2m_\tau$ (~3.6 GeV)**

- **dominant decay: $aa \to \mu\mu\mu\mu$**
  - signature: two pairs of extremely collinear muons due to low $M_a$
  - $\sigma \times$ BR limits $< 5-10$ fb (for $M_h = 100$ GeV)
  - BR($a \to \mu\mu$) < 7%, assuming BR($h \to aa$) ~ 1




**For masses: $2m_\tau < M_a < 2m_b$ (~9 GeV)**

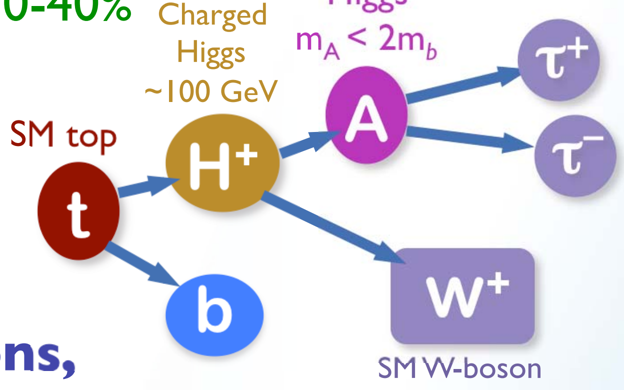
- **dominant decay: $aa \to 2\mu 2\tau$**
  - signature: one pair of collinear muons and large $\not{E}_T$ from $a \to \tau\tau$ decay
  - $\sigma \times$ BR limits: currently are factor of $\approx 1-4$ larger than expected Higgs production

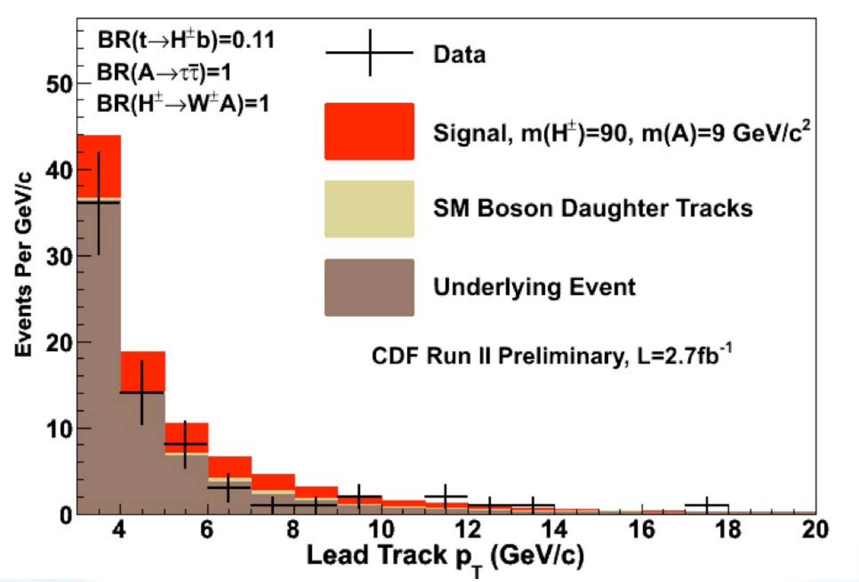


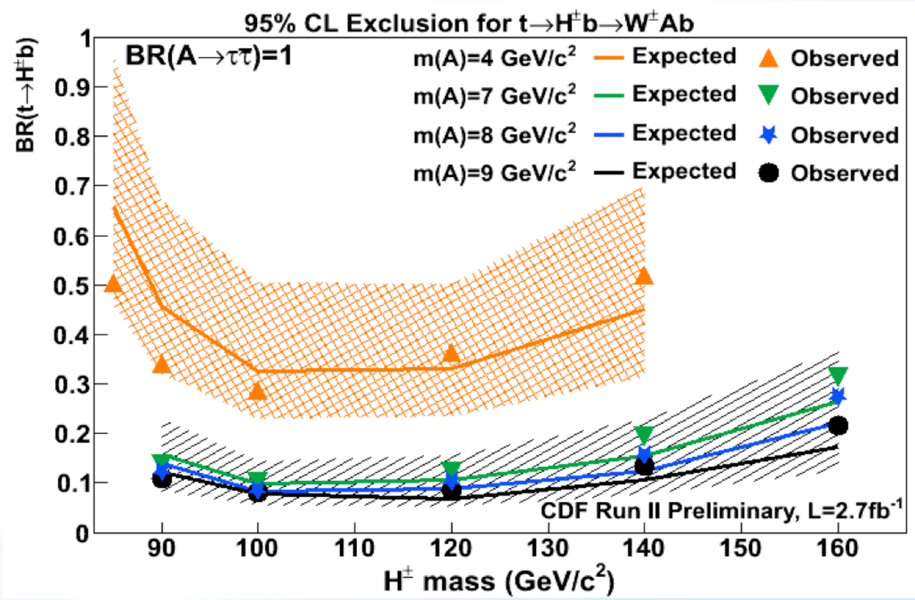

PRL, 103 061801 (2009)

# CDF: Charged Higgs Search in NMSSM

- **next-to-MSSM Higgs decay search, 2.7 $fb^{-1}$ data**
  - search in top quark decays: $t \to H^{\pm}b \to W^{\pm}Ab \to W^{\pm}\tau\tau b$
  - if charged Higgs ~100 GeV exists ⇒ $BR(t \to H^{\pm}b)$ ~10-40%
- **Search assumes mass of light pseudo-scalar Higgs (A) < $2m_b$**
  - region not experimentally excluded
  - select low-$p_T$ isolated tracks created by τ decay
- **Data in signal region agrees with expectations, set 95% CL limits for various $H^{\pm}$ and A masses**




**First such limits in the parameter space of top quark decays**