Beyond Standard Model Higgs Searches at the Tevatron

presented by
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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
  - ϕ (= 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. next-to-MSSM Higgs (NMSSM)

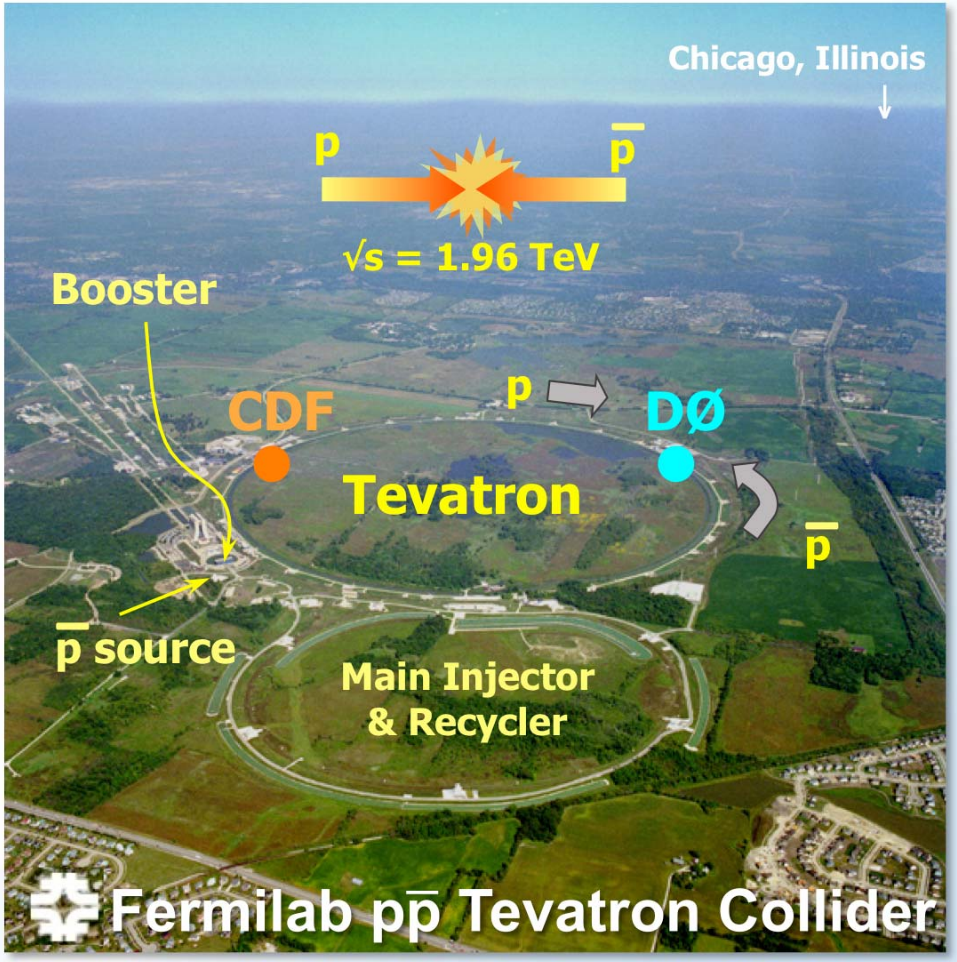
- neutral CP-even Higgs boson ($h_{1,2,3}$)
- neutral CP-odd Higgs boson ($a_{1,2}$)
- charged Higgs pair ($h^\pm$)

III. Extended Higgs sector models

- doubly charged Higgs ($H^{\pm\pm}$)
- Hidden Valley particles

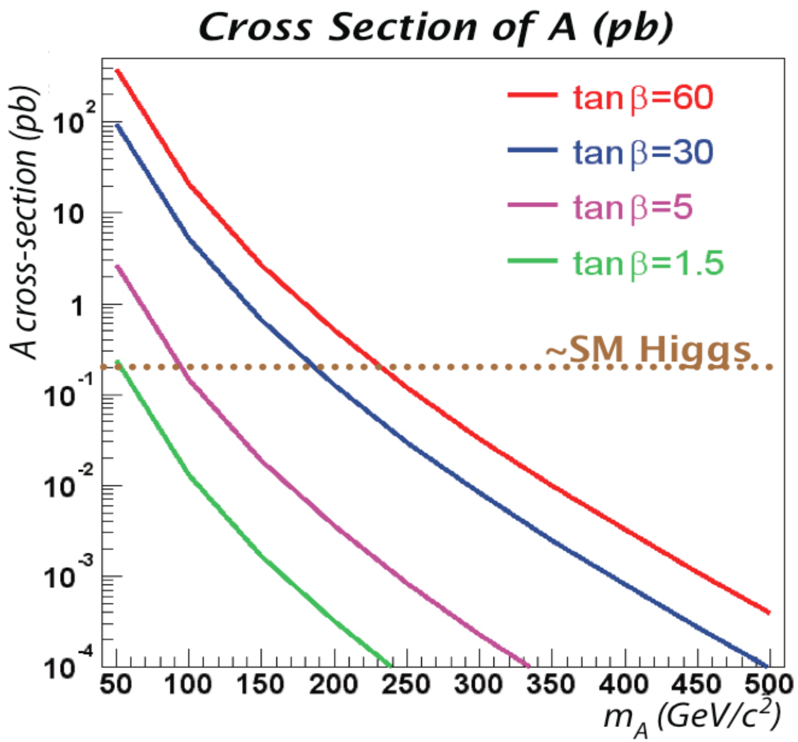
IV. Fermiophobic Higgs Search

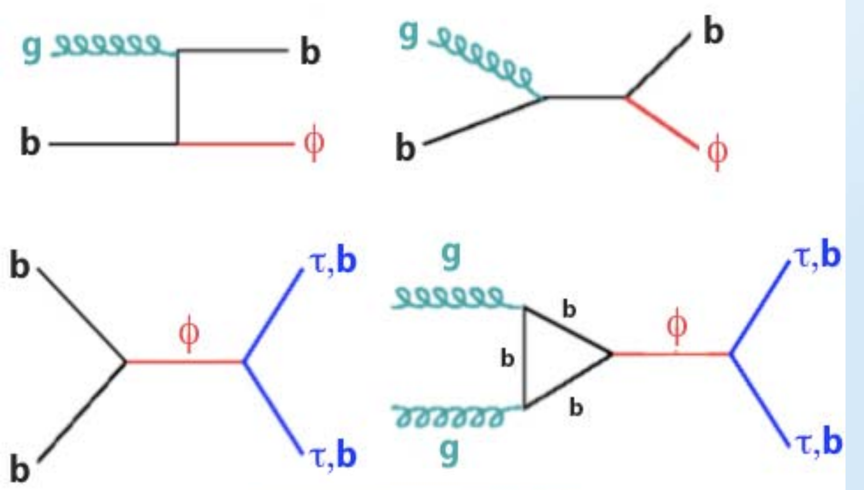
- Higgs primarily couples to bosons, BR to fermions suppressed



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 $\sigma(p\bar{p} \rightarrow h/H/A)$ is enhanced**
  - enhancement depends on $\tan\beta$
- **h/H/A decays, in most parameter space:**
  - $\phi \rightarrow b\bar{b}$ (~90%)
  - $\phi \rightarrow \tau\tau$ (~10%)
    - smaller BR but cleaner signature
      (*vs.* large QCD background in b mode)

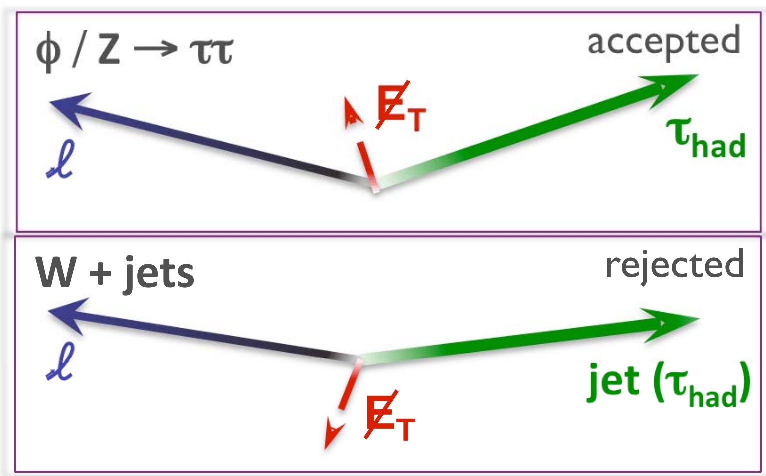




ϕ = h/H & A

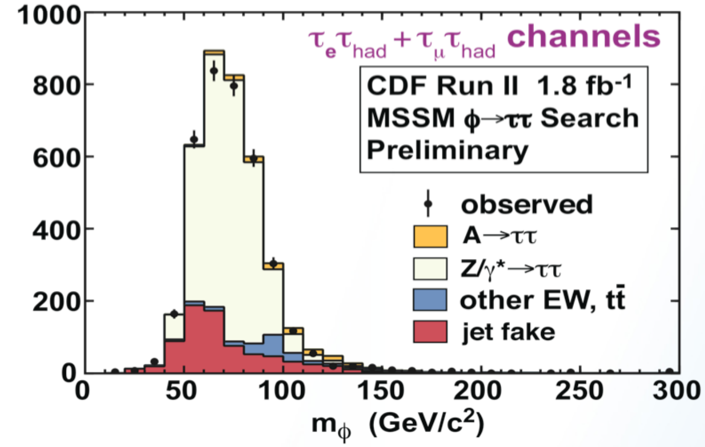
CDF: $\phi \rightarrow \tau\tau$ Search

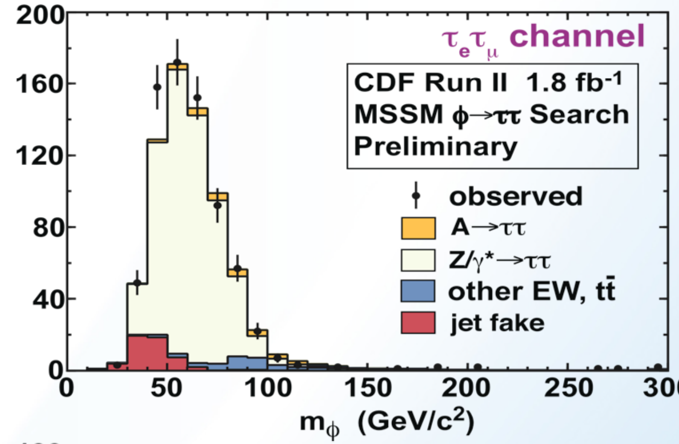
- CDF considers $\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$, and $\tau_e\tau_\mu$ channels with 1.8 fb^{-1} data, selected by:
  - isolated e or μ: opposite-sign (OS) from hadronic τ
  - τ's selected using variable-size cone algorithm
  - suppress W+jets background by requirement on relative direction of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

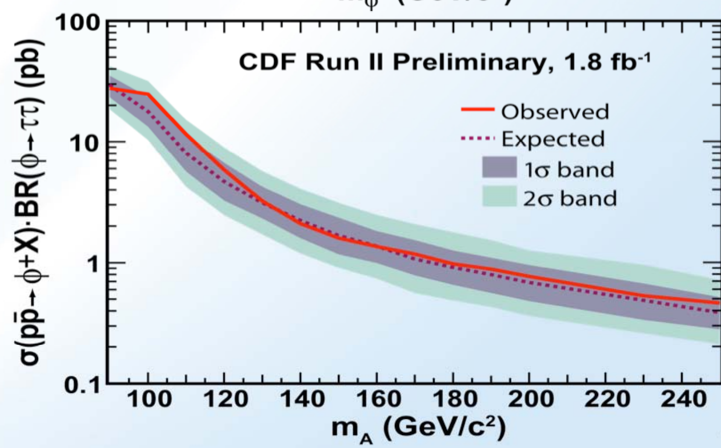


- Data agrees with backgrounds for visible mass
  - set σ × BR limits for 90 GeV < m_A < 250 GeV

CDF: PRL 103, 201801 (2009)

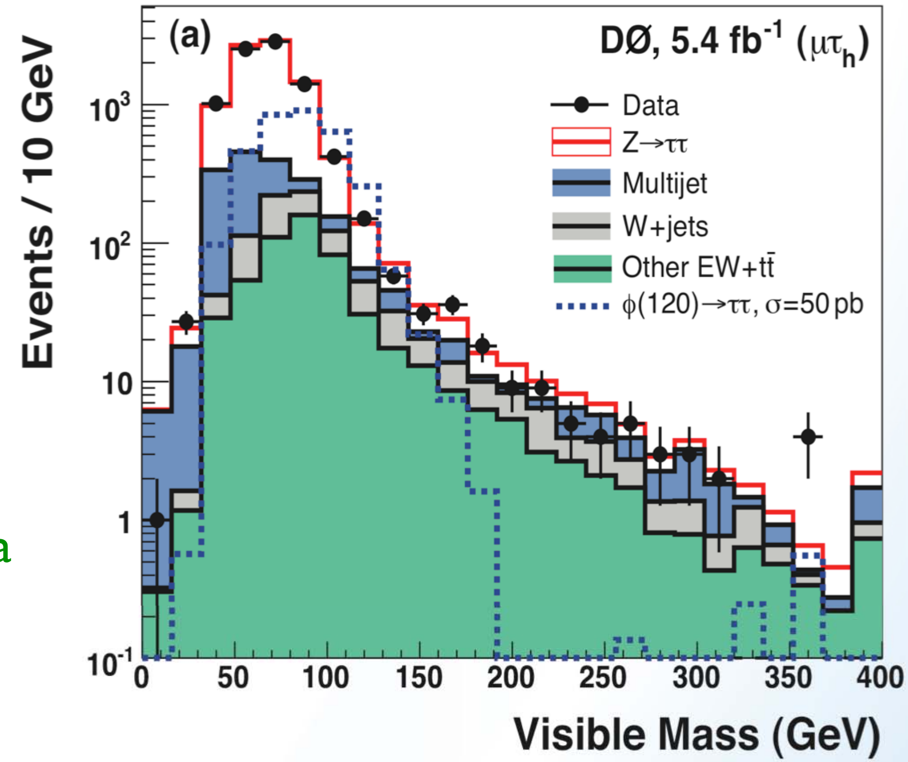


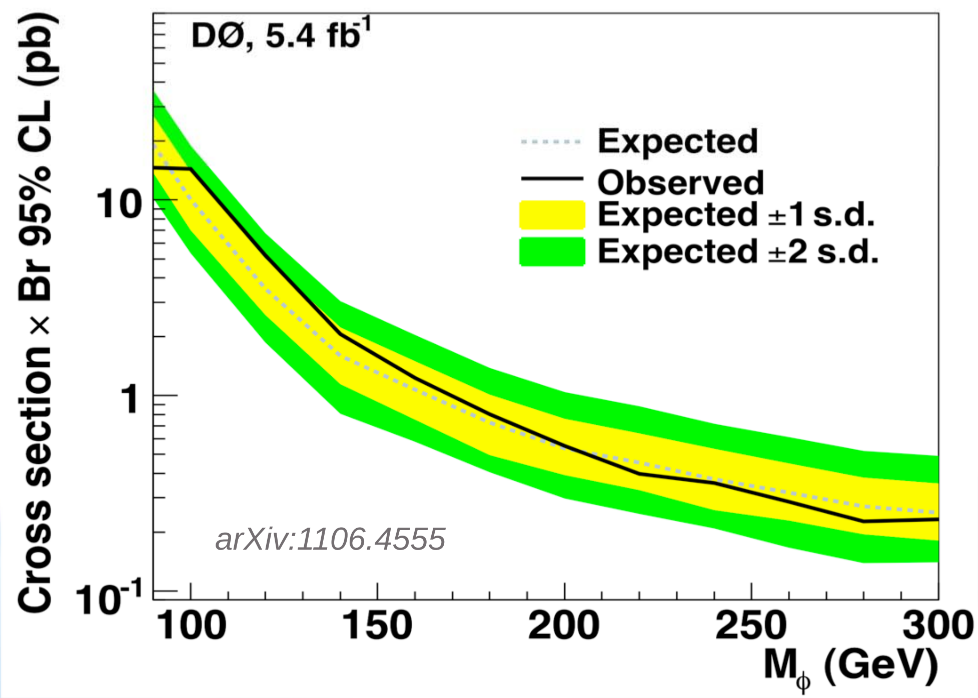




DØ: Inclusive ττ Search

- **[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**
  - τ_{had} discriminated from jets via τ-ID NN
  - $M_T < 50$ GeV ⇒ reject W+jets
  - estimate multijet bkgnd directly from data

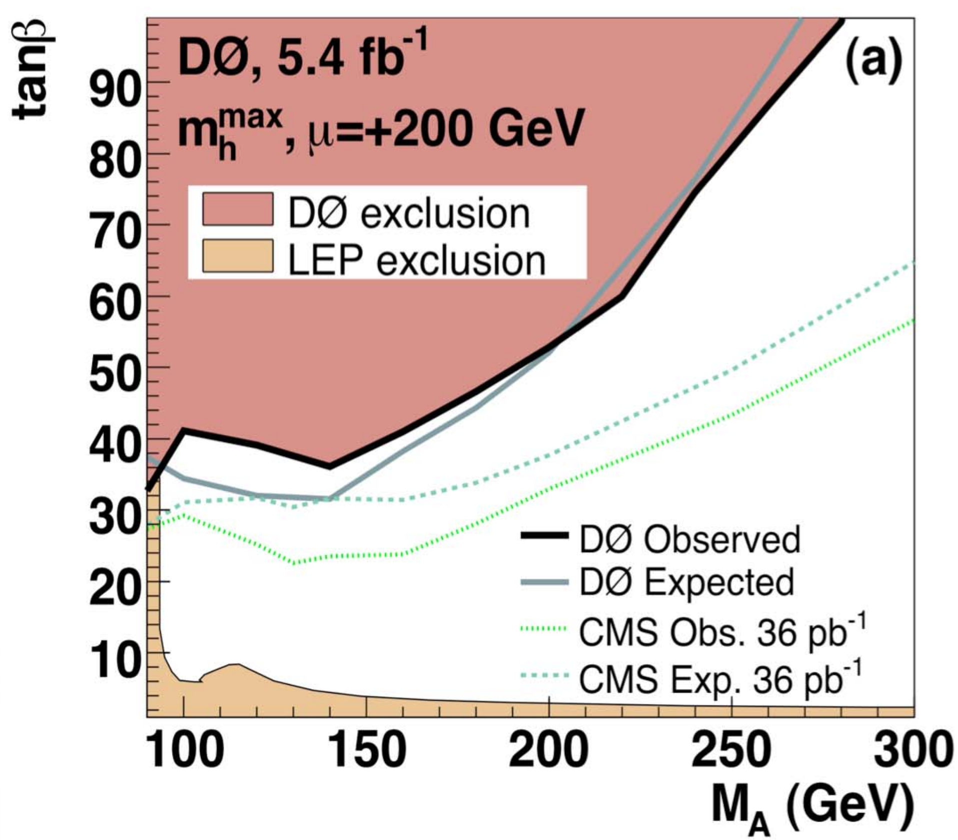


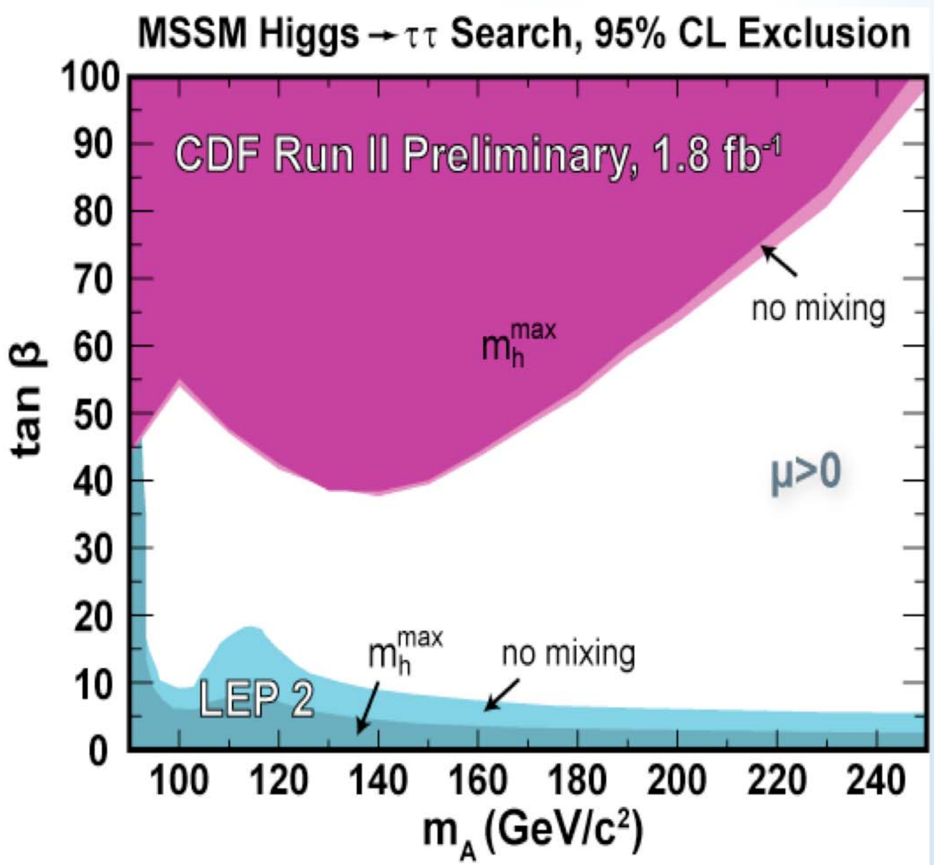


- **No excess in data across visible mass spectrum**
  - upper limits on σ × BR as function of φ mass
    - extended search range up to 300 GeV

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

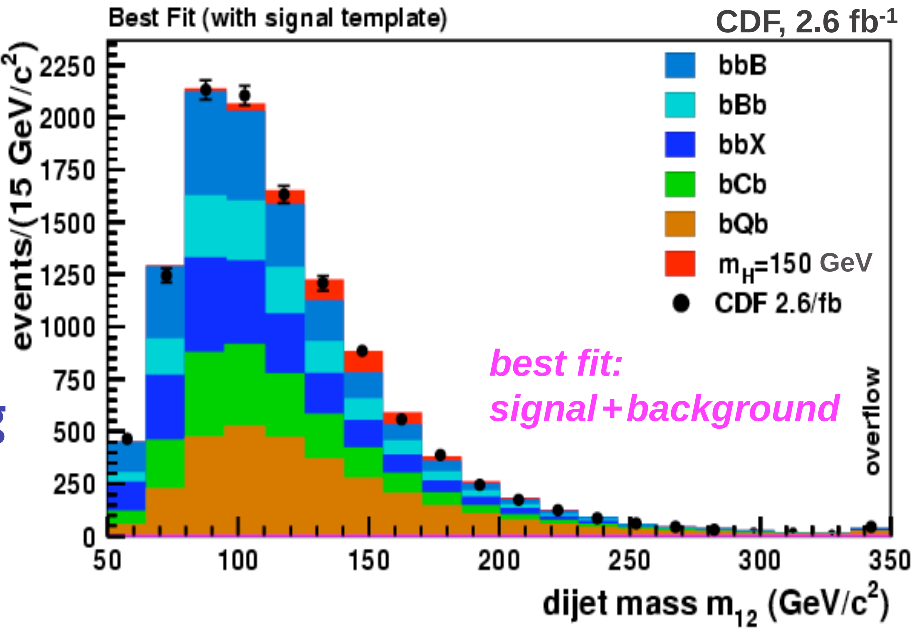
- **Translate limits in representative MSSM scenarios**
  - m_h^{max} and no-mixing for $\mu = \pm 200$ GeV
  - DØ 5.4 fb^{-1} result: FeynHiggs *v*2.8.1
    - includes updated bbH PDFs at NNLO (MSTW2008)
- **Reach expected sensitivity of tanβ ~ 30 at low M_A ~ 140 GeV**
  - comparable to recent limits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

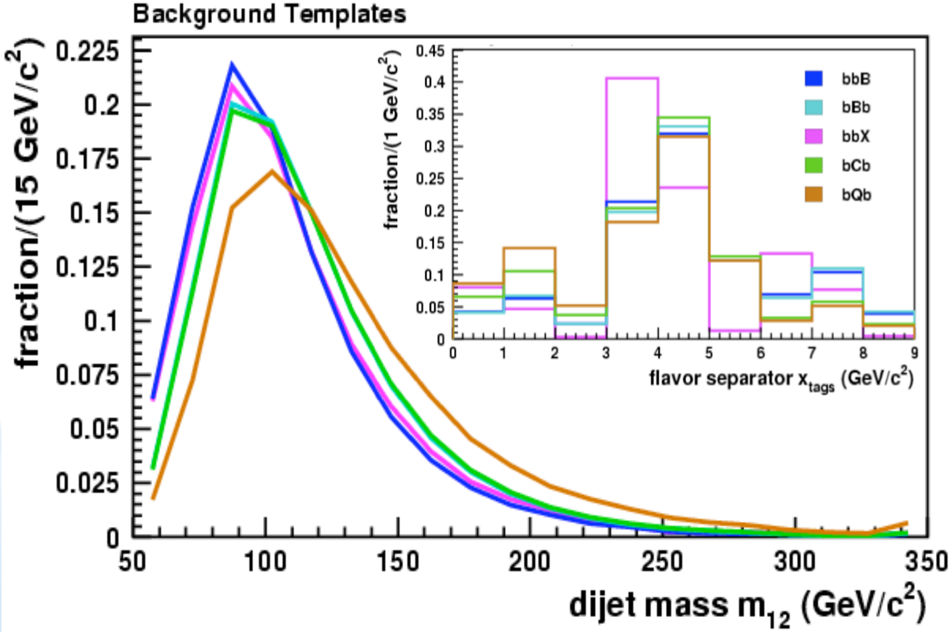


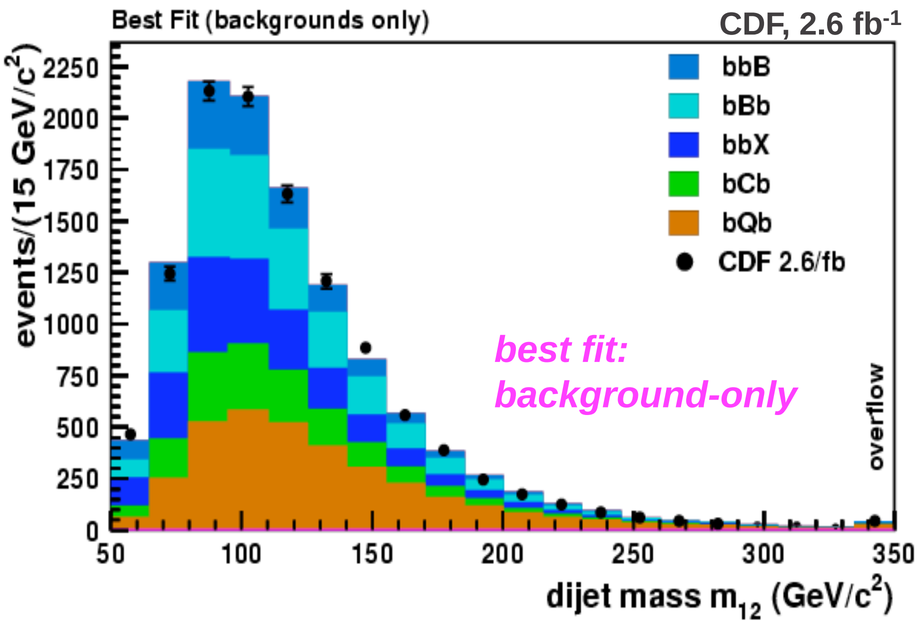


CDF: $\phi b \to b\bar{b}b$ Search

- $\phi \to b\bar{b}$ search difficult due to large multijet background
  - consider ϕ 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}



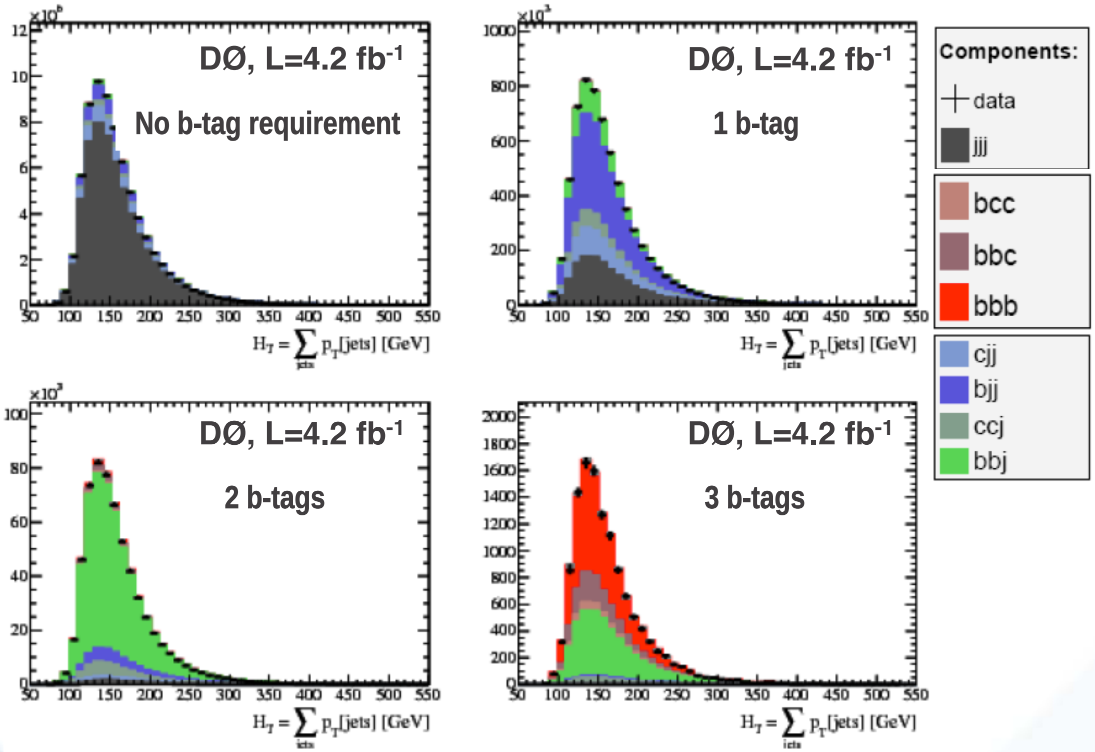


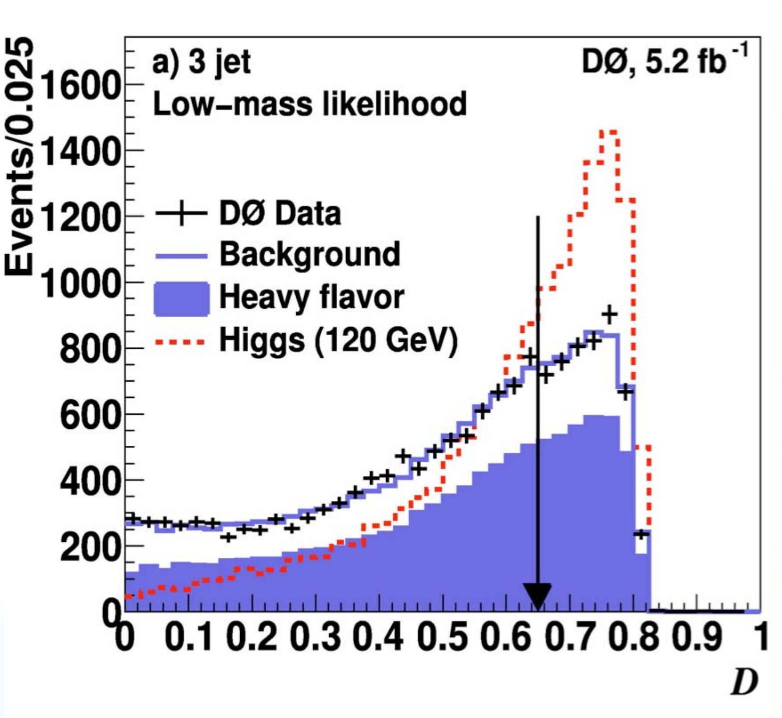


DØ: $\phi b \to b\bar{b}b$ Search

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

$$S_{3tag}^{exp}(M_{bb},\mathcal{D}) = \frac{S_{3tag}^{MC}(M_{bb},\mathcal{D})}{S_{2tag}^{MC}(M_{bb},\mathcal{D})} \times S_{2tag}^{DATA}(M_{bb},\mathcal{D})$$

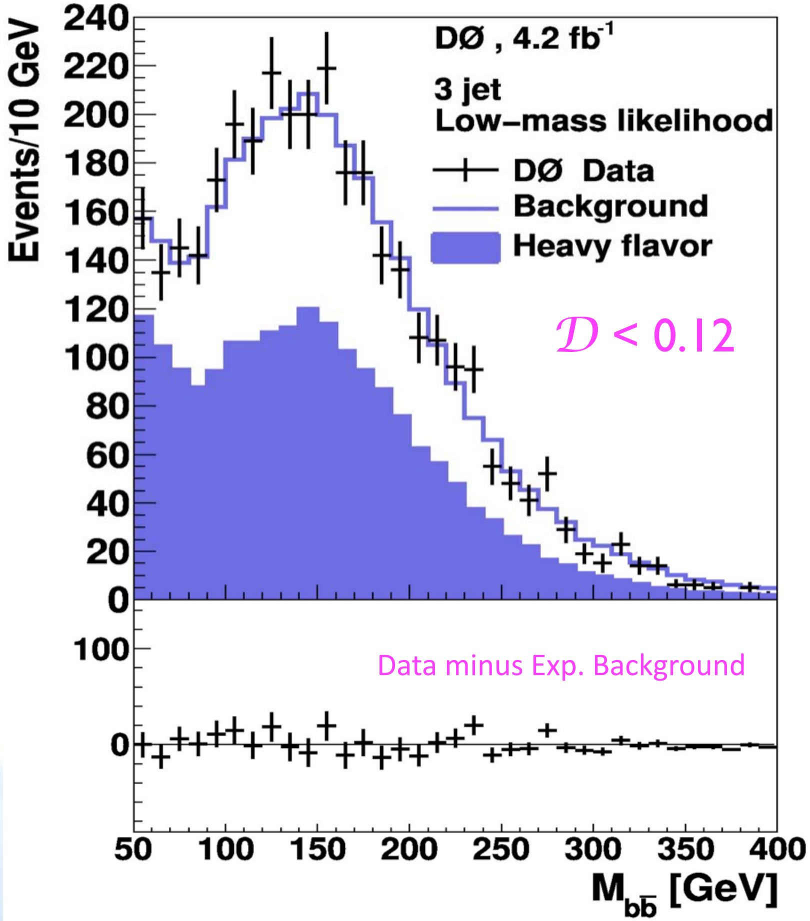


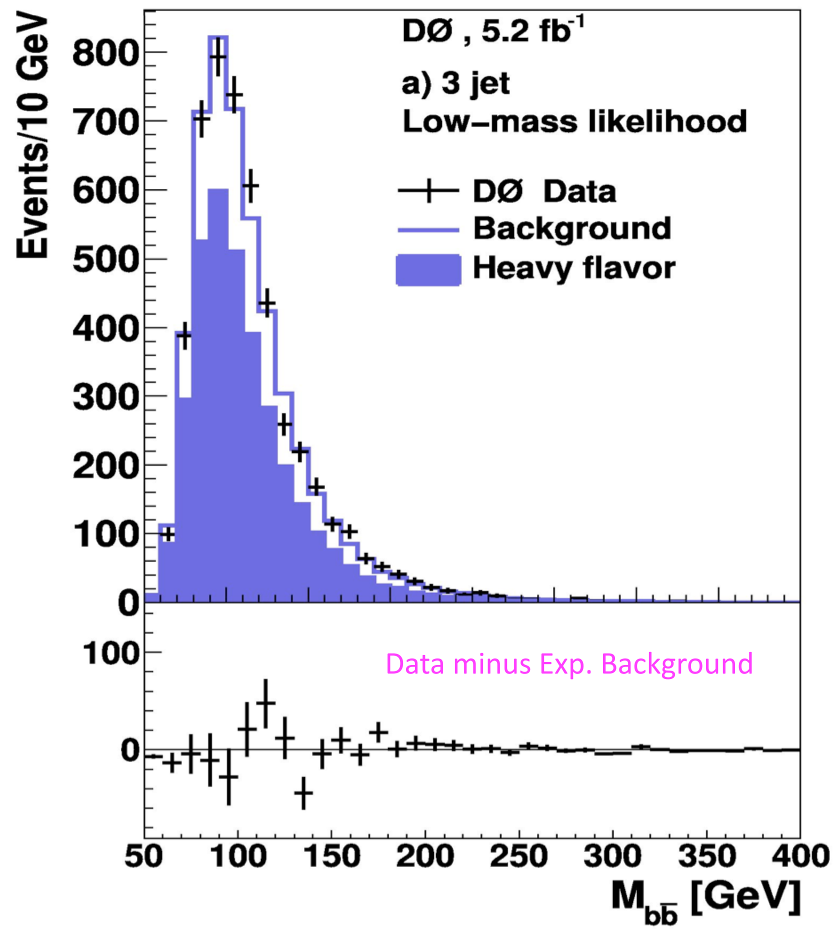


- **Improve sensitivity by separating into 3- and 4-jet channels**
  - likelihood discriminates b-jet pair via Higgs signal from multijet backgrounds
    - separate low-mass (<130 GeV) and high-mass (>130 GeV) likelihoods

DØ: $\phi b \rightarrow b\bar{b}b$ Search *(cont.)*

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

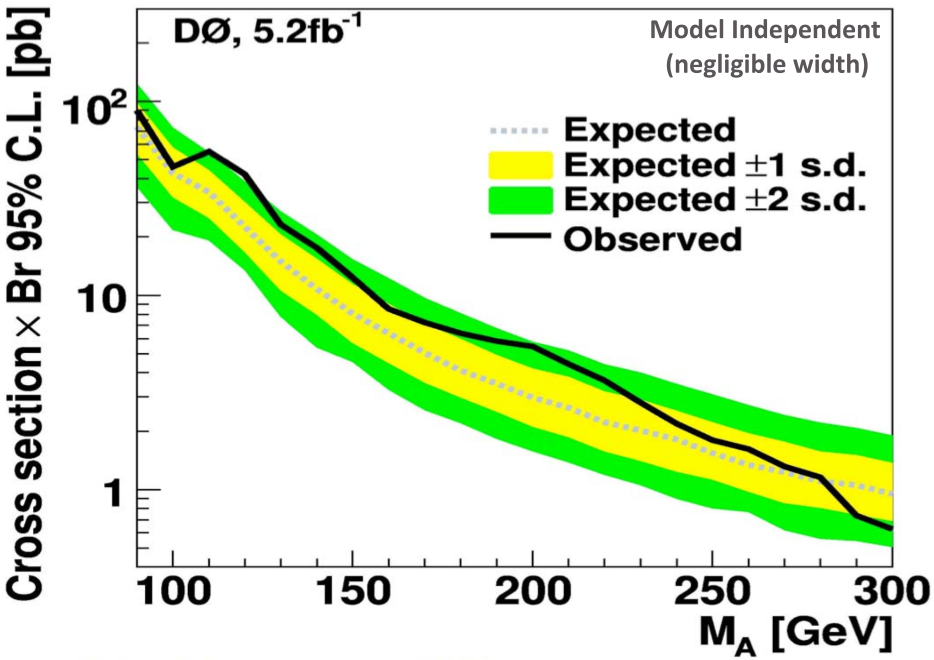


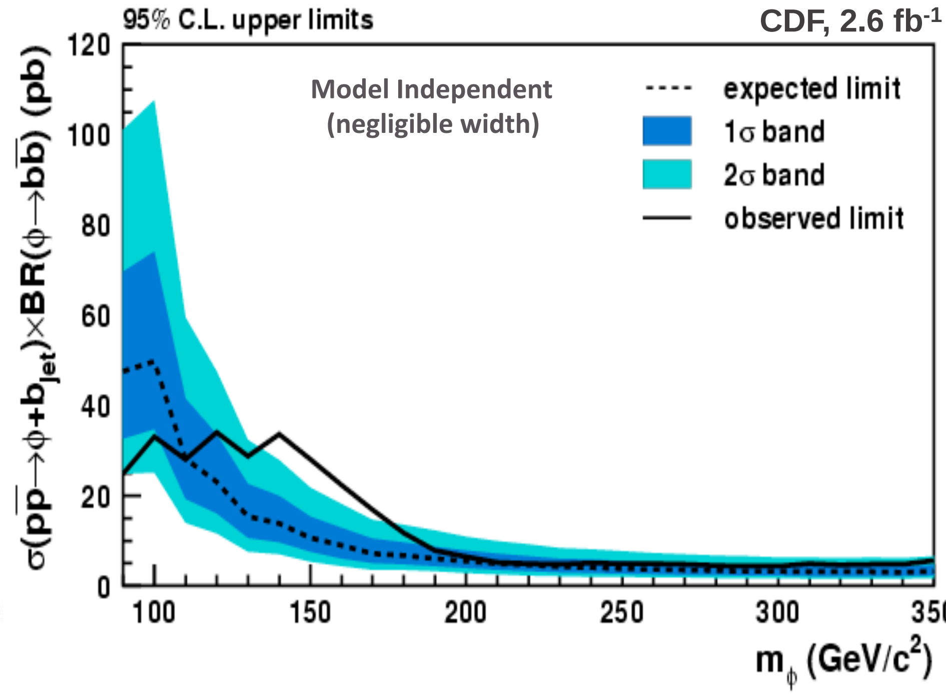


- **Dijet invariant mass of two leading jets used as input to $\sigma \times$ BR limit**
  - limit calculated using only the shape difference between signal and background

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

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

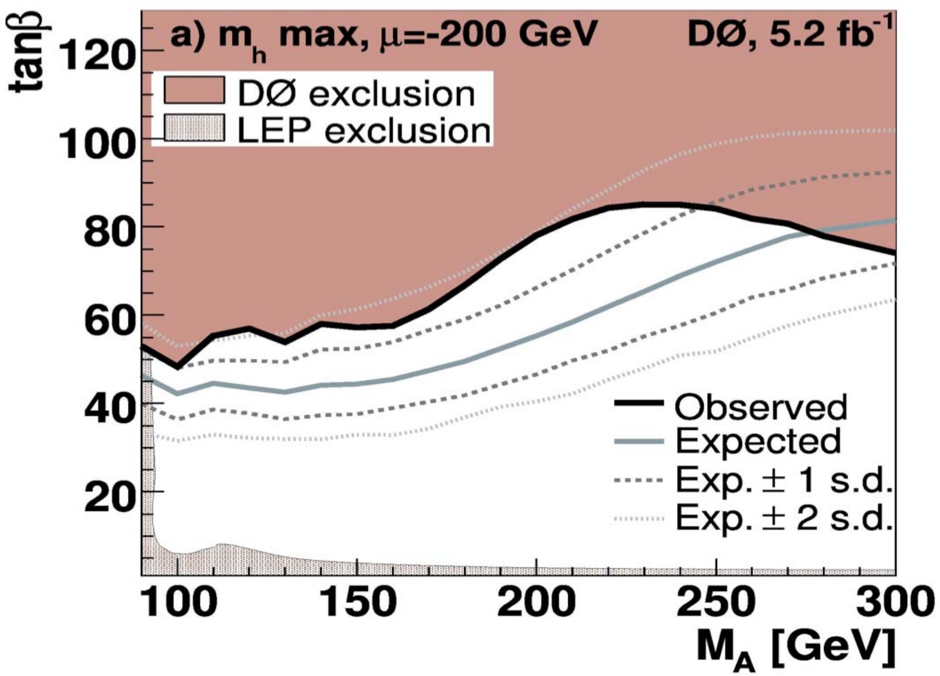




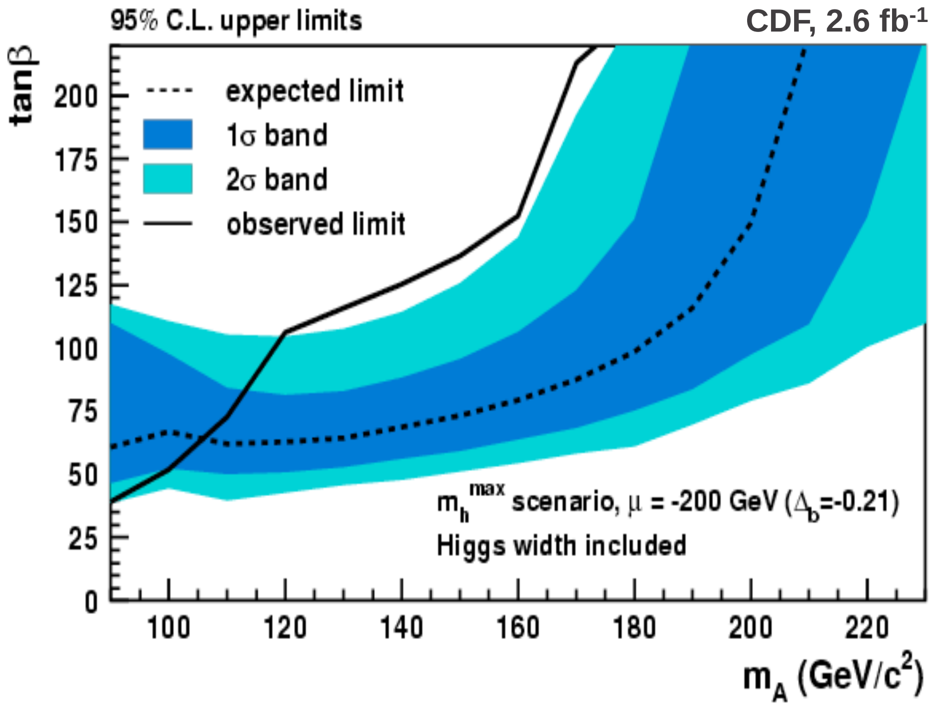
- **Limits on $\sigma \times$ BR**
  - DØ: observe ~2.5σ deviation at ~120 GeV for narrow-width case [after trial factors, significance of ~2.0σ]
  - CDF: deviation at ~150 GeV, with p-value = 0.23% (~2.8σ) [trial factors, 1.9σ significance to observe such an excess at any masses]
- **General limits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

$\phi b \rightarrow b\bar{b}b$: MSSM interpretation

MSSM Exclusions in (M_A, tanβ) Parameter Space



DØ: PLB 698, 97 (2011)

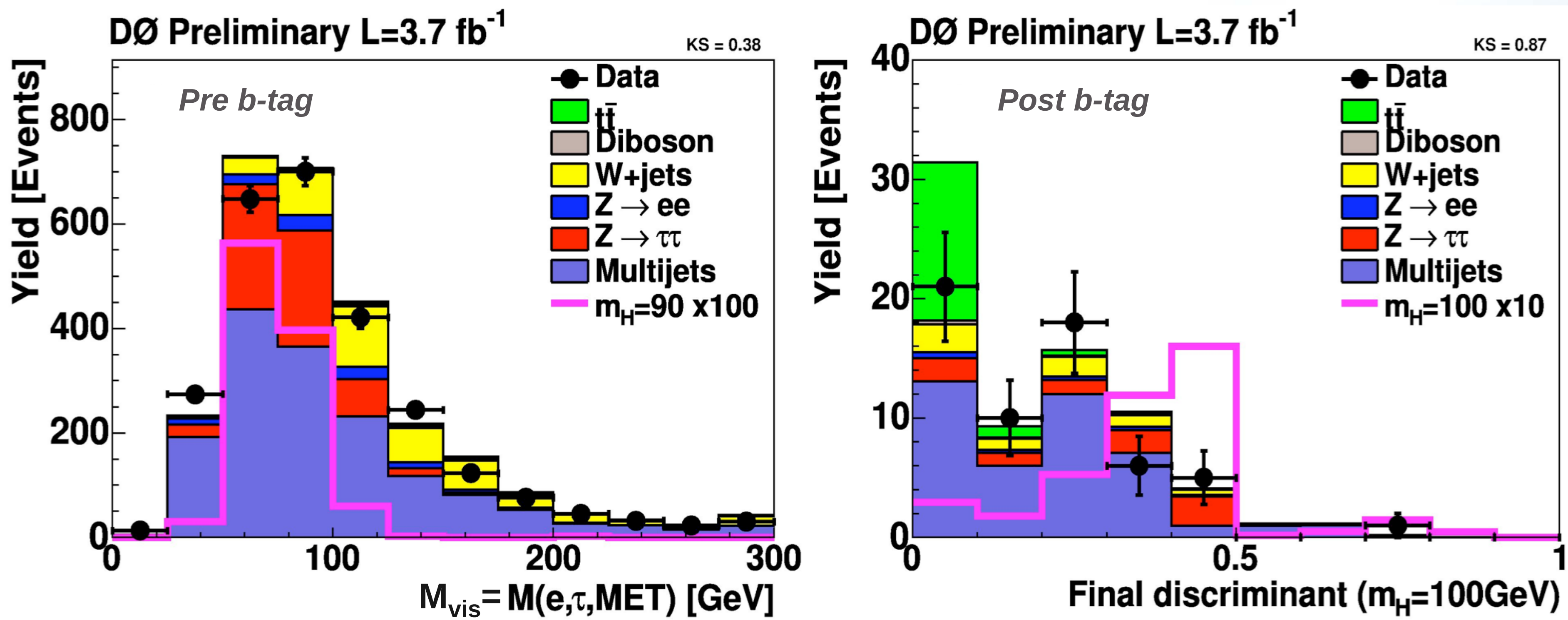


CDF: arXiv:1106.4782 (submitted to PRD)

- **Translate limits in MSSM benchmark scenarios in (M_A, tanβ) parameter space**
  - Higgs 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

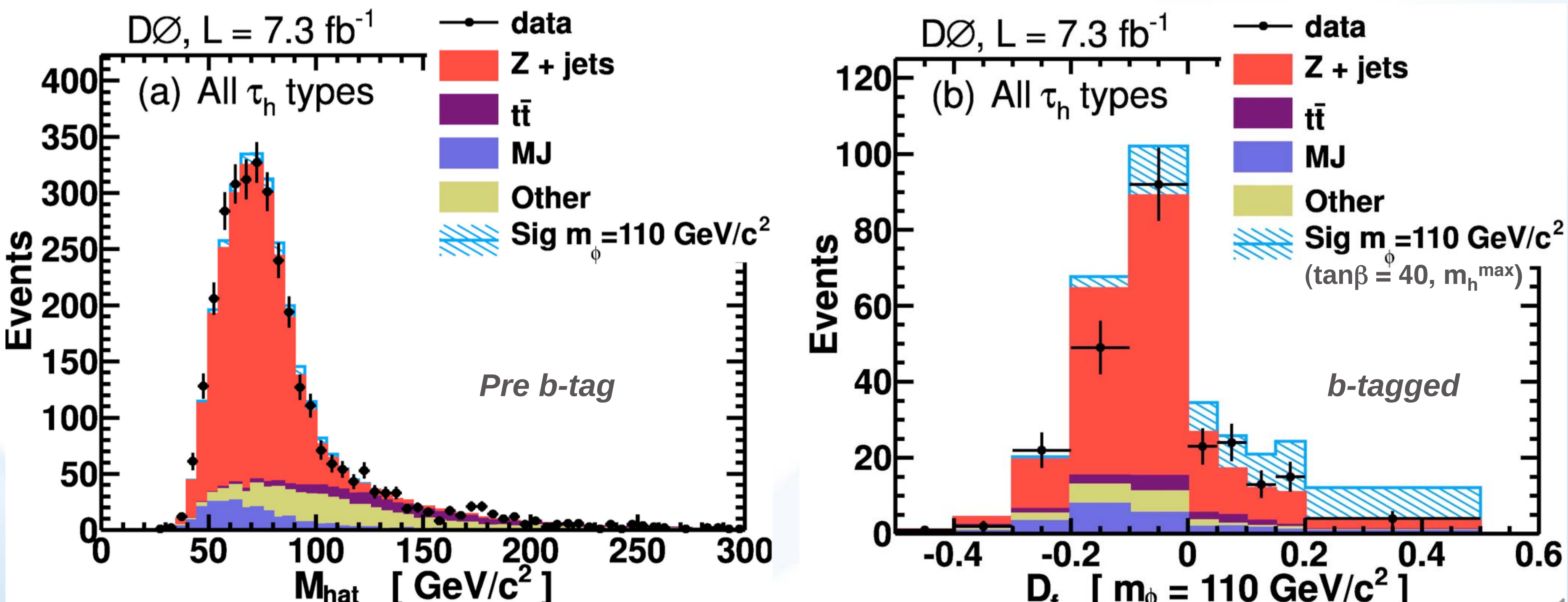
- **[New] 3.7 fb^{-1} search considers $\phi b \to \tau_e \tau_{had} b$**
  - use developed techniques from both $\phi \to \tau\tau$ and $\phi b \to b\bar{b}b$ searches
  - complimentary to $\phi \to \tau\tau$ channel as it does not suffer from $Z \to \tau\tau$ backgrounds
- **Discriminate against different backgrounds via MVA techniques**
  - suppress $Z \to \tau\tau$ (Z+jets) $\Rightarrow$ 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:** $[(D_{MJ} + 10)/20] \times D_{top}$

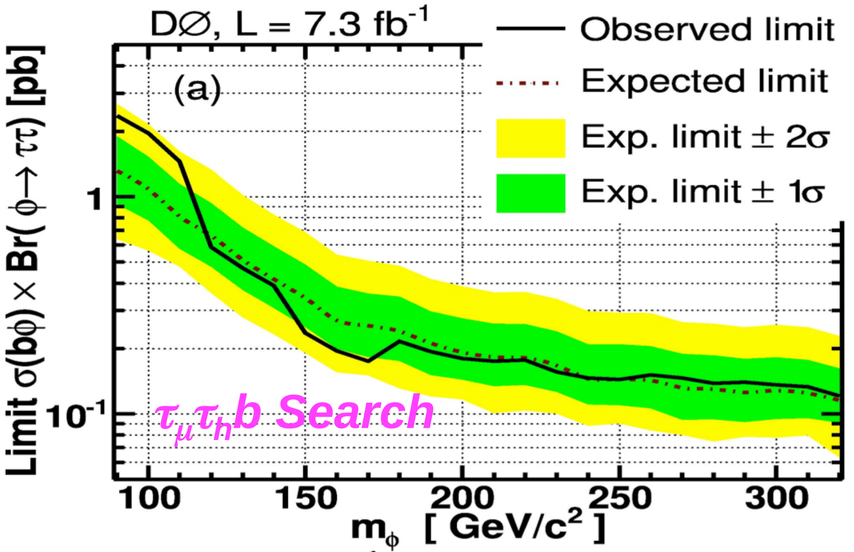
$\phi b \rightarrow \tau_\mu \tau_{had} b$ Search

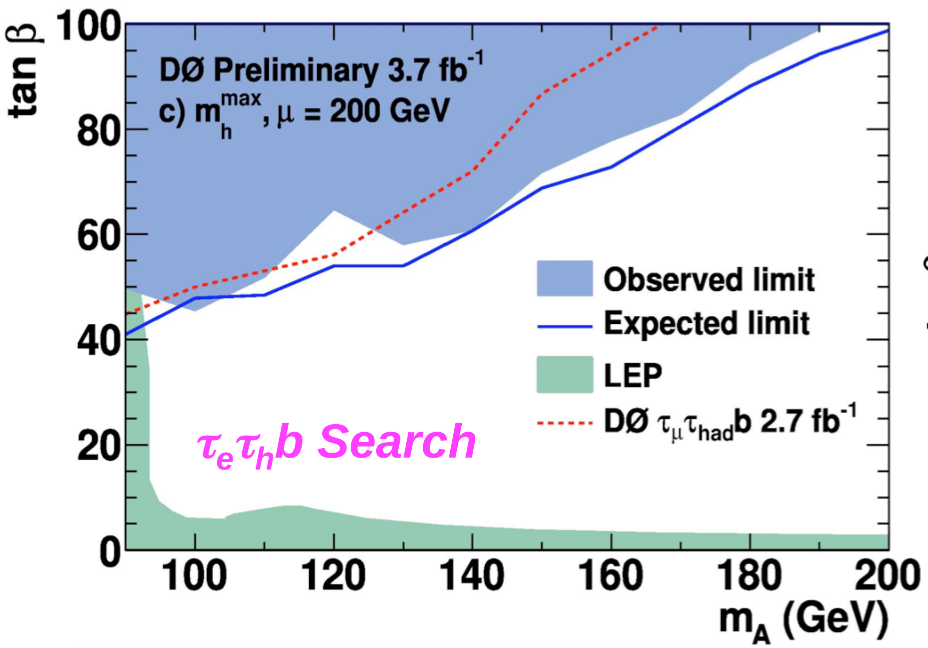
- **[New: submitted to PRL] 7.3 fb^{-1} search considers $\phi b \rightarrow \tau_\mu \tau_{had} b$**
  - supersedes earlier 2.7 fb^{-1} published result: PRL 104, 151801 (2010)
  - improved sensitivity
    - inclusive trigger approach
    - high-performance signal-to-background discriminants
- **Form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

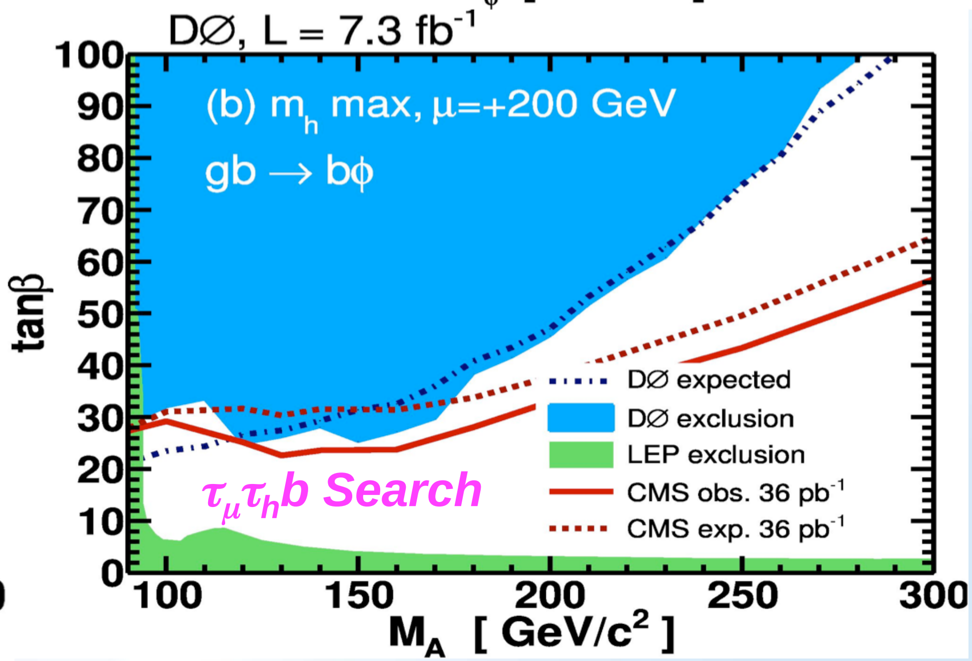


$\phi b \rightarrow \tau_{e,\mu}\tau_{had} b$ Results

- **Observe no significant excess in data over expected backgrounds**
  - model-independent limits on Higgs production cross section
  - translate to MSSM exclusions in $(M_A, \tan\beta)$ plane



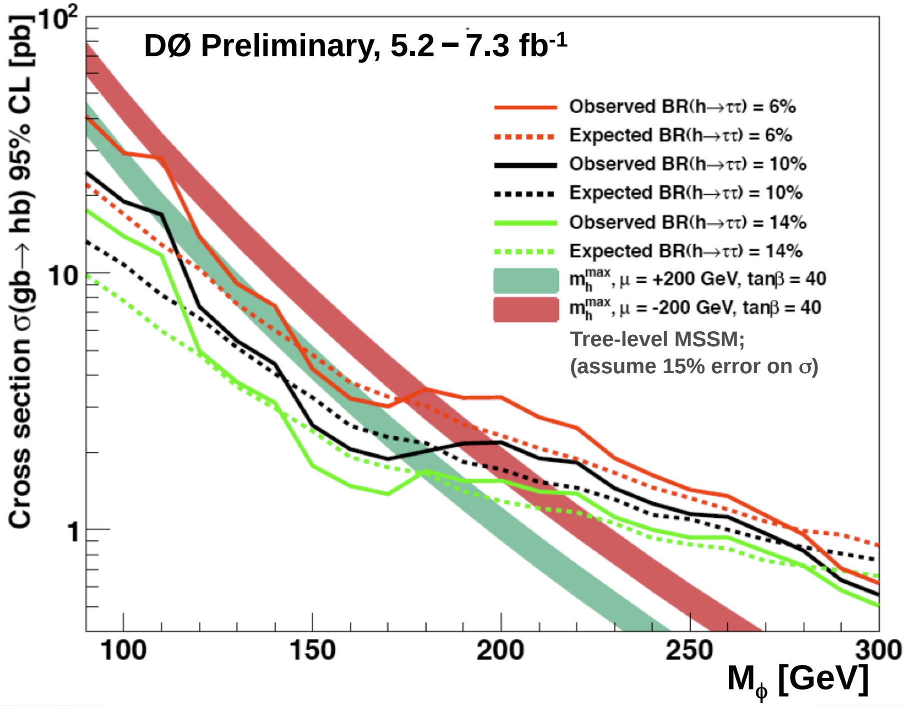


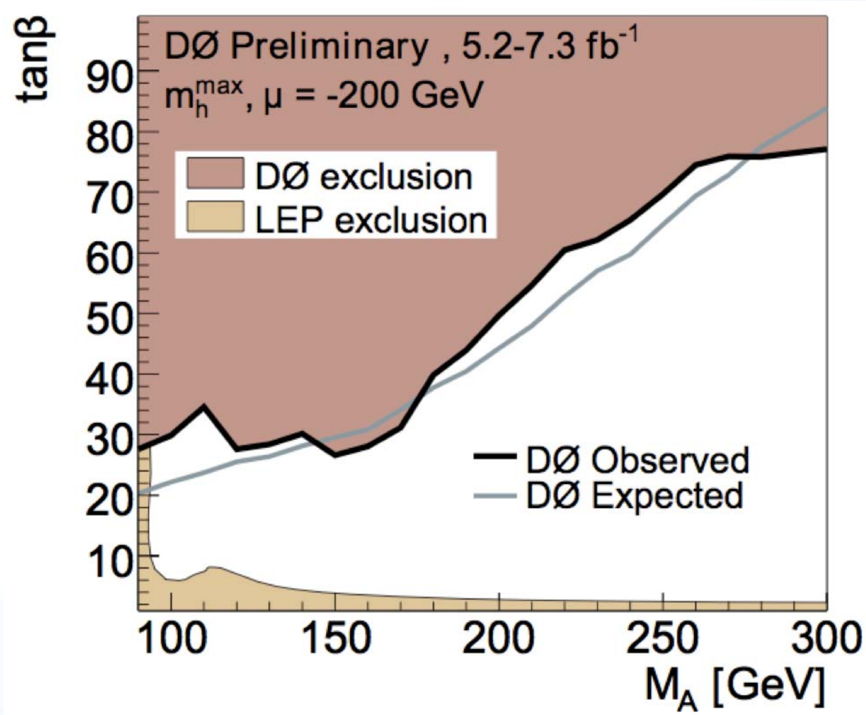


$\tau_\mu\tau_h$b: at low M_A, most stringent limit to-date in a direct search at the Tevatron

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

- **[New for Summer 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 exclusions in (M_A, $\tan\beta$) plane**

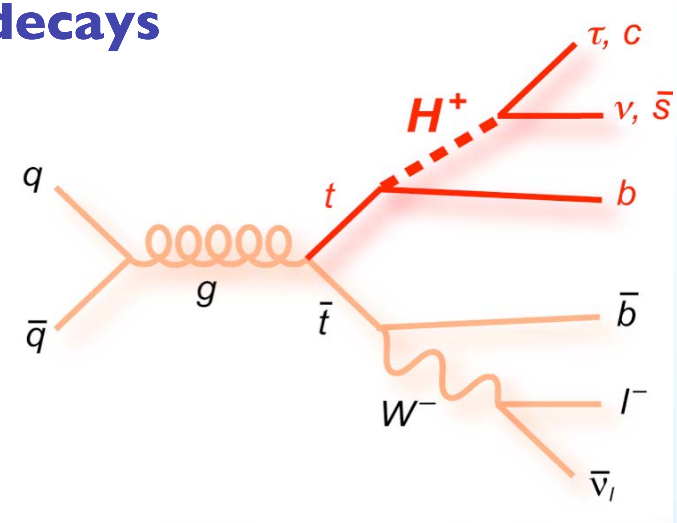


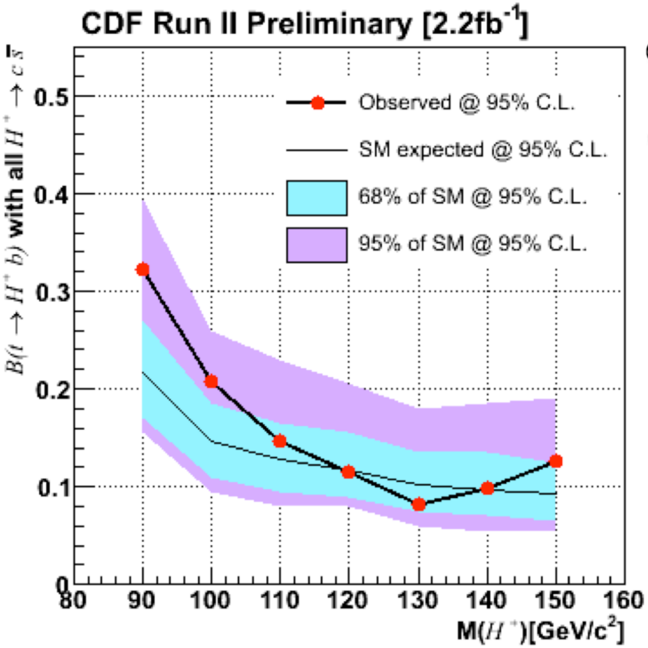


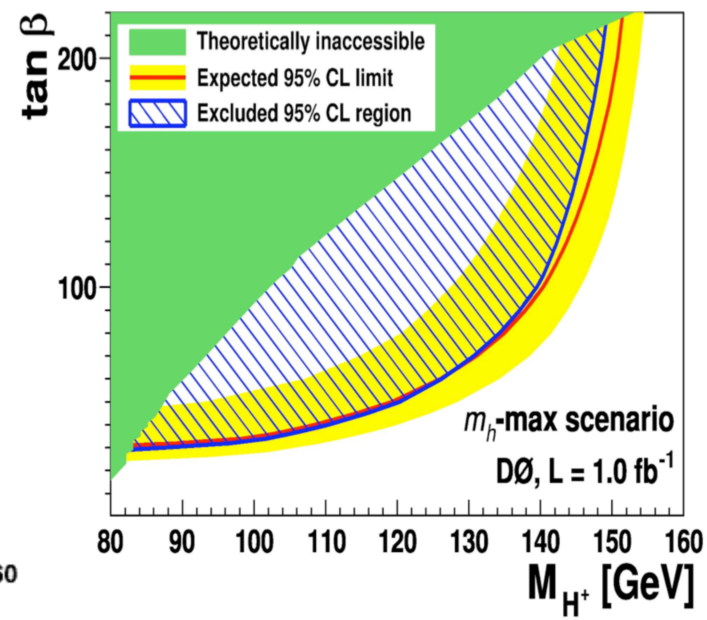
Tevatron combination from MSSM Higgs searches expected imminently…

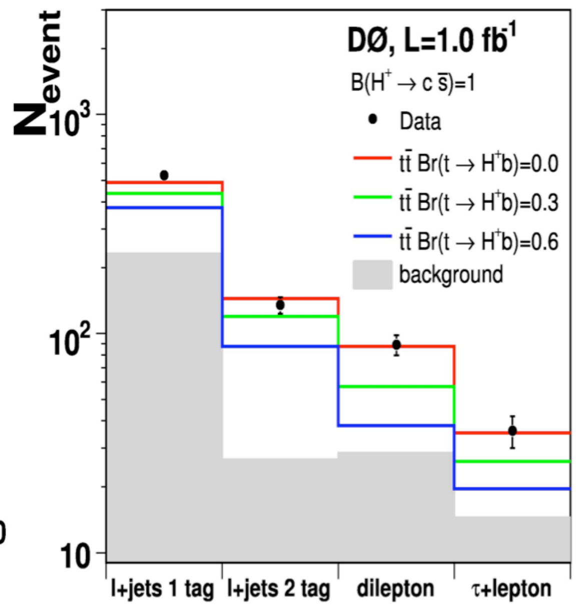
MSSM Charged Higgs Search

- 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: $H^\pm \to \tau\nu$ (high tanβ)
  - Leptophobic model: $H^\pm \to c\bar{s}$ (low tanβ)
- Search dilepton, ℓ+jets, $\ell+\tau$ top channels
- Select high-p_T leptons, $\not{E}_T$, and b-tag
- 95% CL limits on $BR(t \to H^+ b)$
  - DØ 1.0 fb^{-1}: PLB 682, 278 (2009)
  - CDF 2.2 fb^{-1}: PRL 103, 101803 (2009)



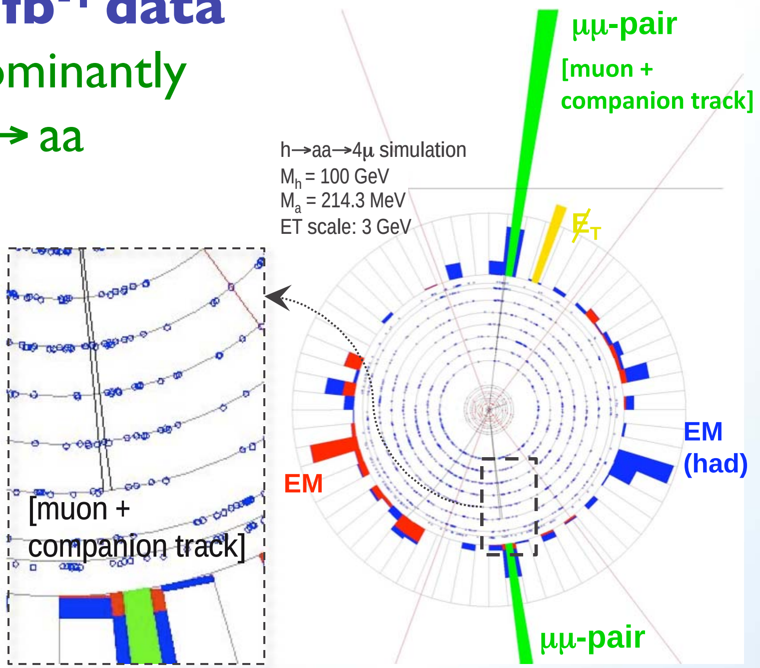






DØ: NMSSM $h \rightarrow aa$ Search

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

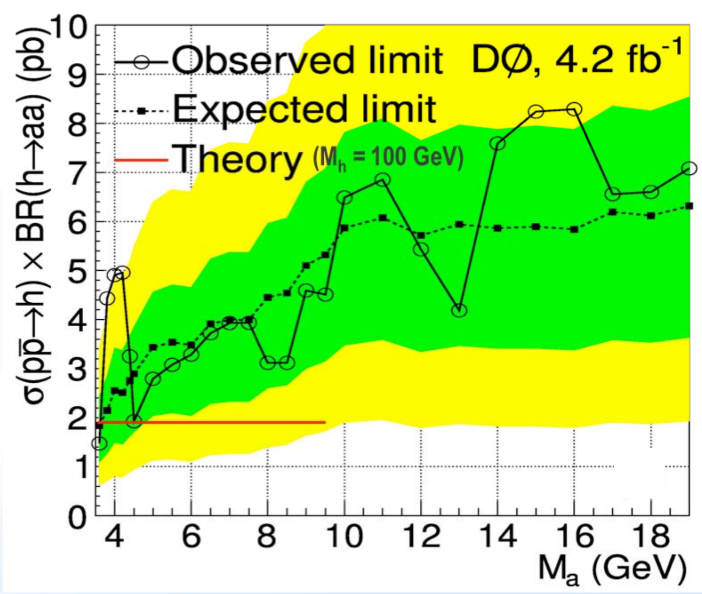


For masses: $2m_\mu < M_a <$ ~$2m_\tau$ (~3.6 GeV)

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

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

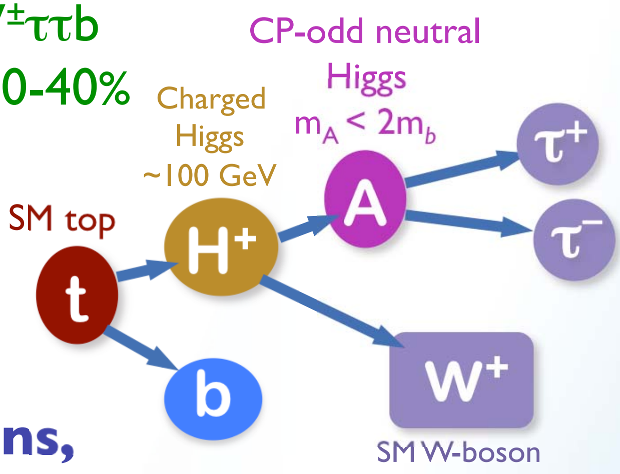
- **dominant decay: $aa \rightarrow 2\mu 2\tau$**
  - signature: one pair of collinear muons and large $\not{E}_T$ from $a \rightarrow \tau\tau$ decay
  - $\sigma \times BR$ limits: currently are factor of ≈1−4 larger than expected Higgs production

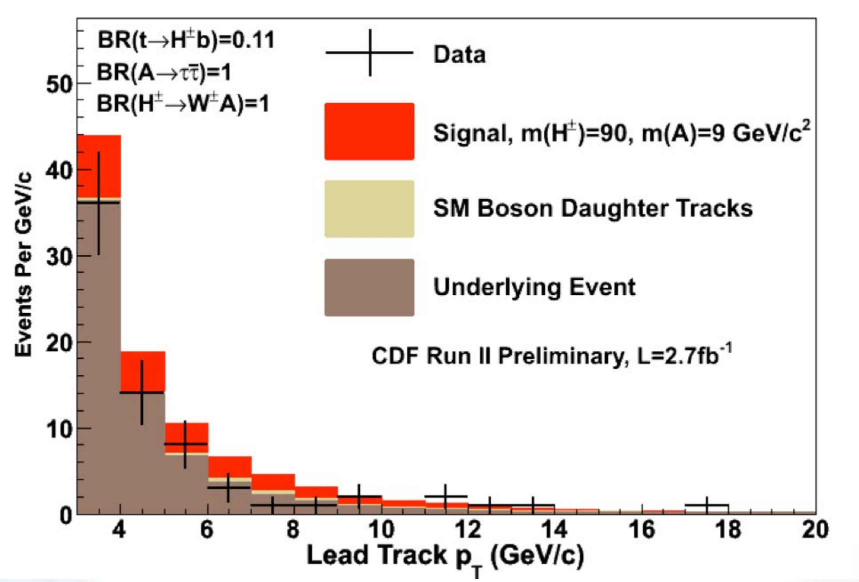


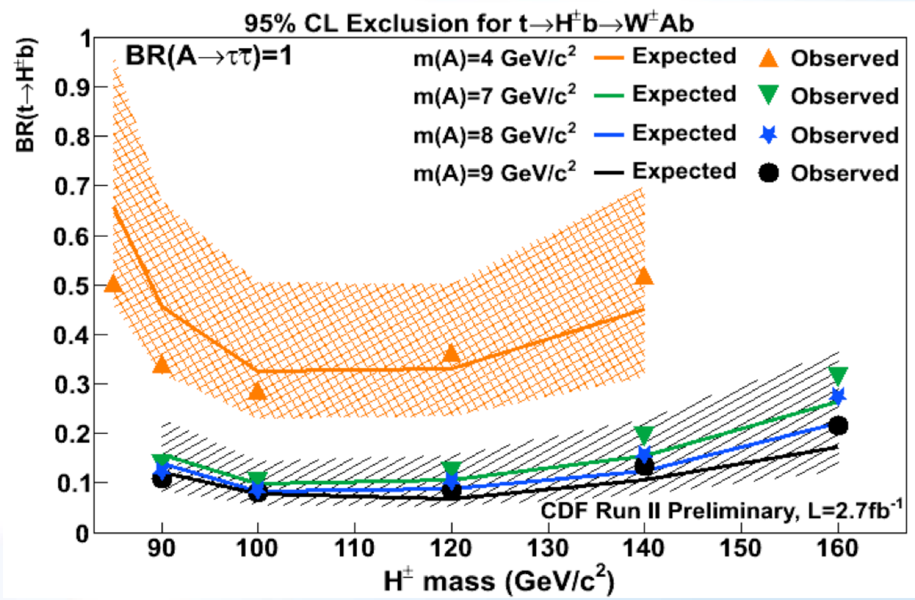
PRL, 103 061801 (2009)

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**



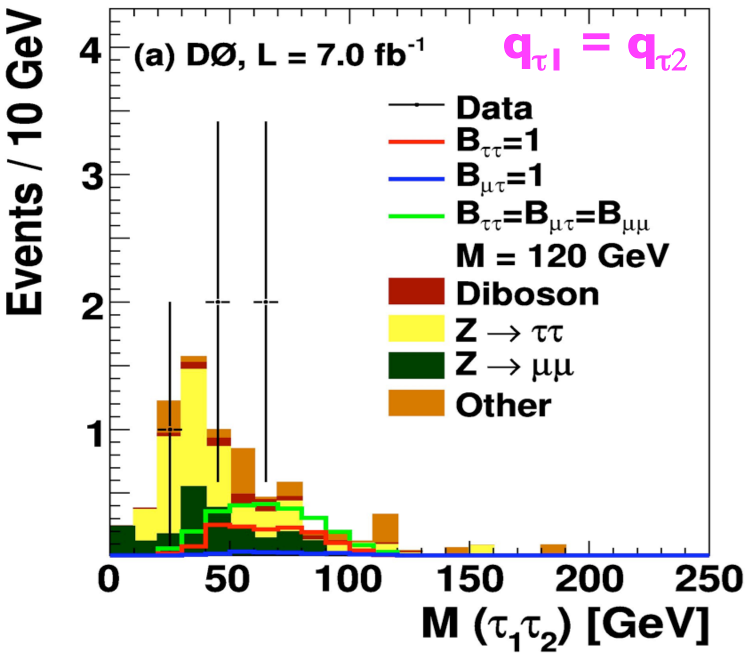




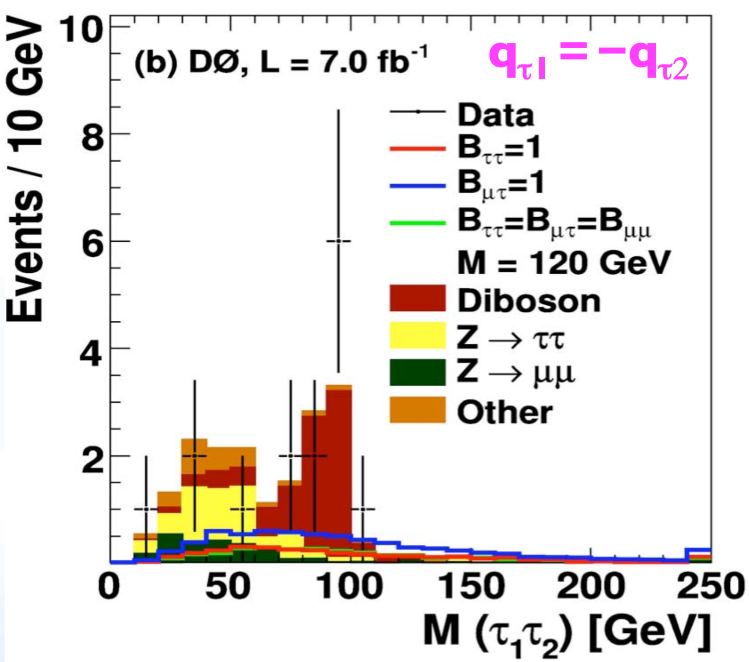
First such limits in the parameter space of top quark decays

Doubly Charged Higgs Search

- **Models with extended Higgs sector predict $H^{\pm\pm}$**
  - $H^{\pm\pm} \to \tau^{\pm}\tau^{\pm}$ 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 mechanism
    - hierarchy of neutrino masses yields equal BR for $H^{\pm\pm} \to \tau\tau, \mu\tau, \mu\mu$ (if mass of lightest neutrino < 10 meV)

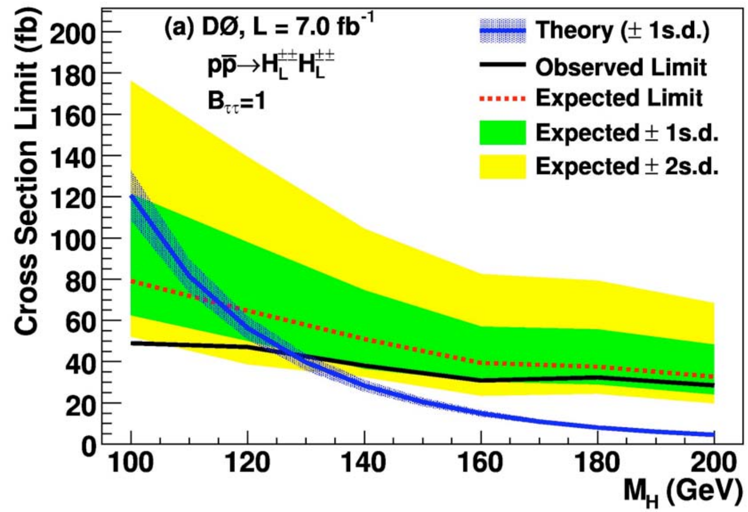


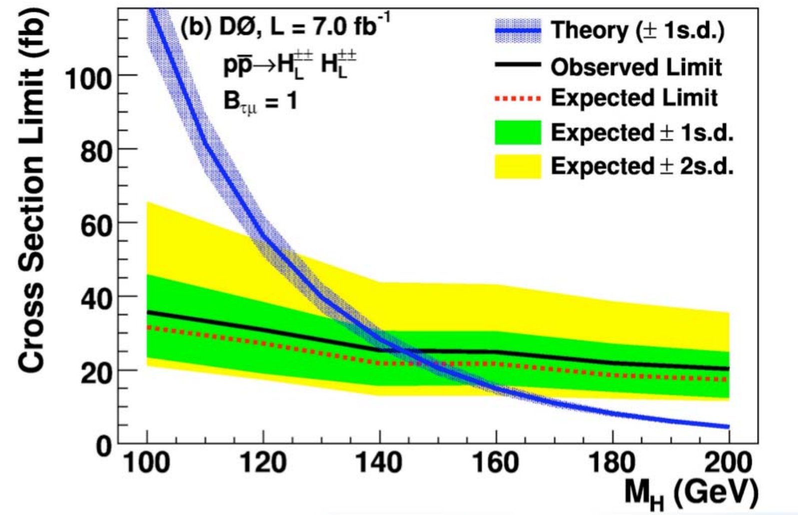
- **[New: submitted to PRL] 1st search for $H^{\pm\pm} \to \tau^{\pm}\tau^{\pm}$ at hadron collider, 7 fb^{-1}**
  - select events with at least one μ & two τ_{had}
  - increase sensitivity to signal by categorizing samples with different backgrounds
    - $q_{\tau 1} = q_{\tau 2}$ with $N_\mu = 1, N_\tau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

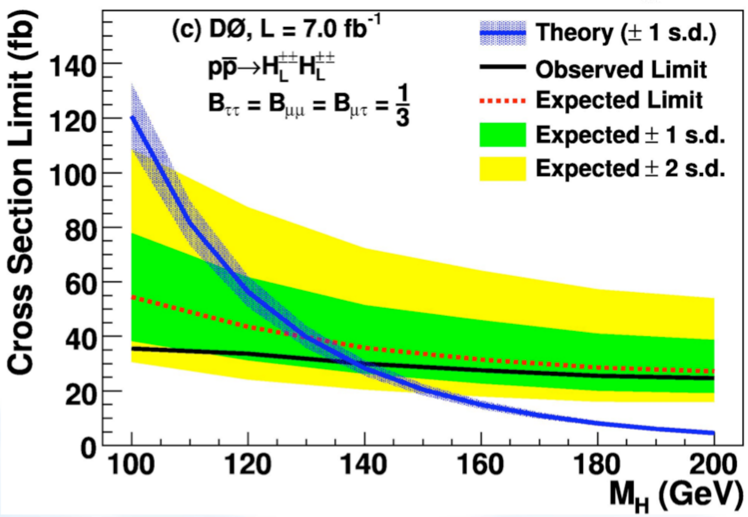


Doubly Charged Higgs: Results

- **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
  - $BR(H_L^{\pm\pm}\to\tau^\pm\tau^\pm) = BR(H_L^{\pm\pm}\to\mu^\pm\tau^\pm) = BR(H_L^{\pm\pm}\to\mu^\pm\mu^\pm) = ⅓$: $M[H_L^{\pm\pm}] > 138$ (130) GeV



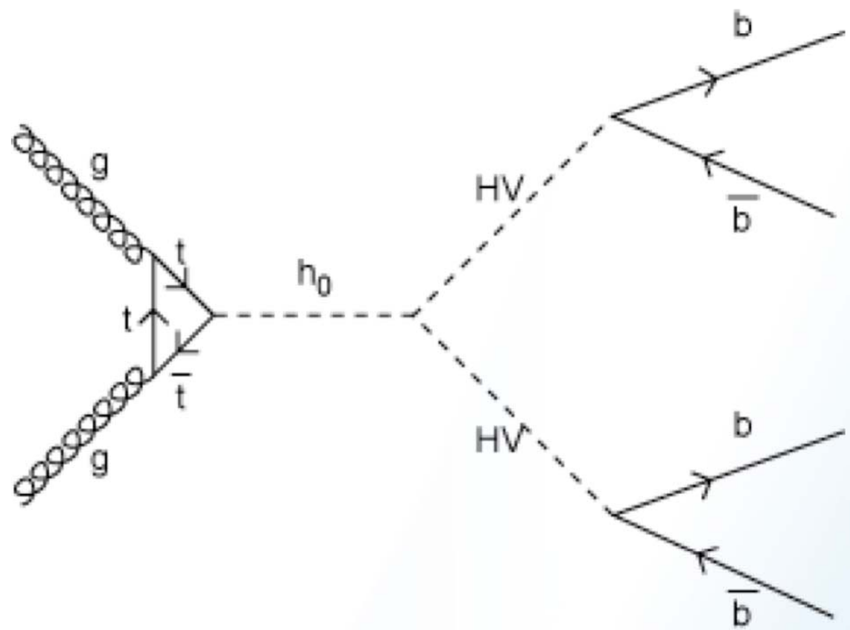


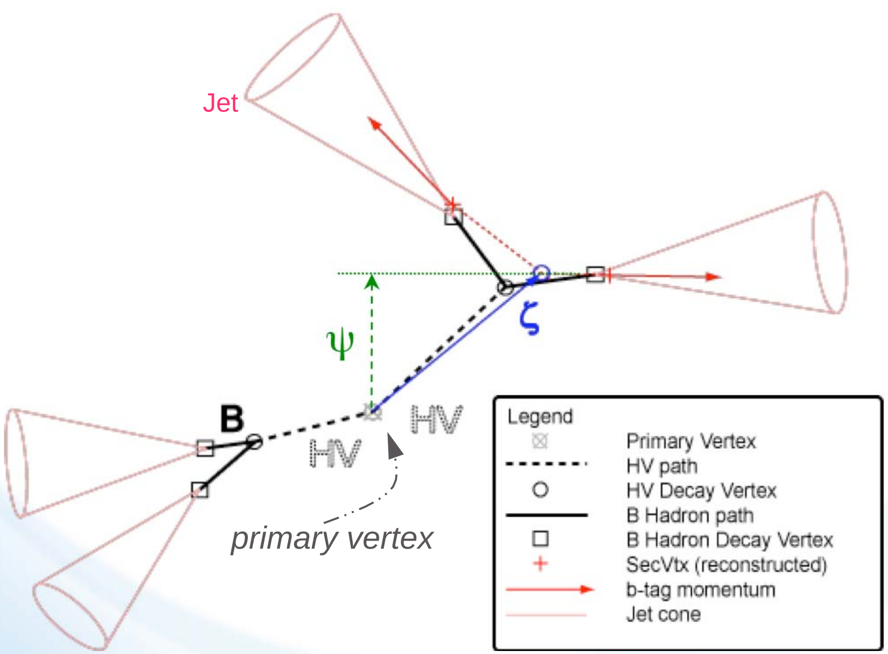


Most stringent limits on $H^{\pm\pm}$ masses in the hadronic ττ final states

arXiv:1106.4250
(Submitted to PRL)

- **5.8 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)]
- **Model backgrounds from data**

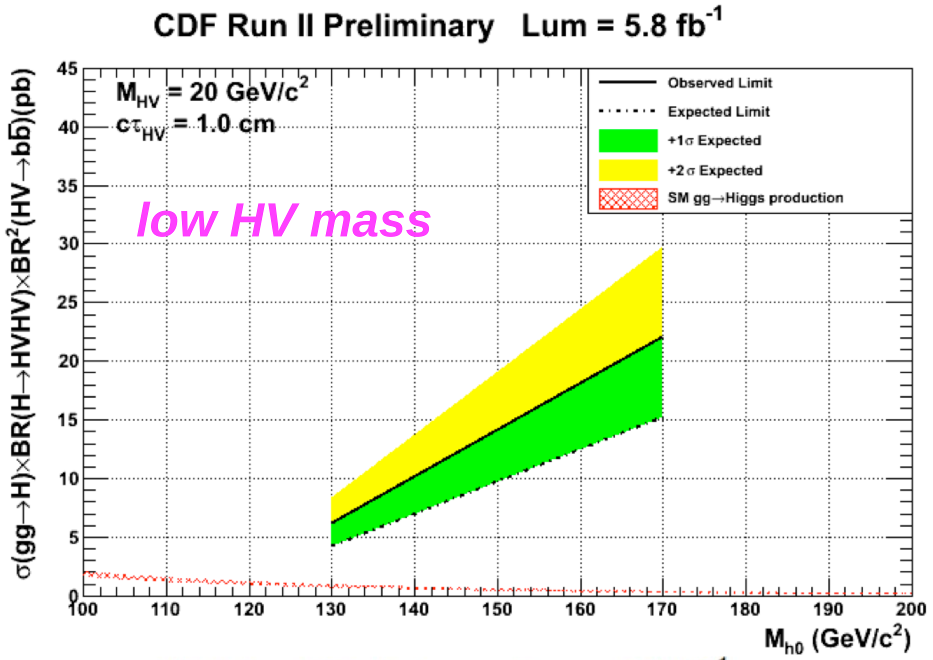


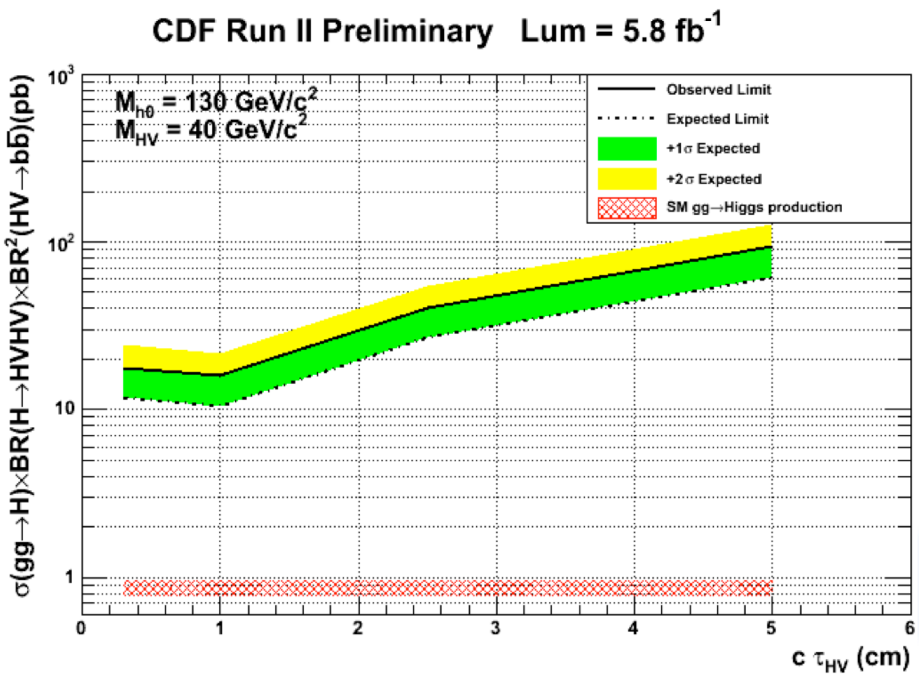


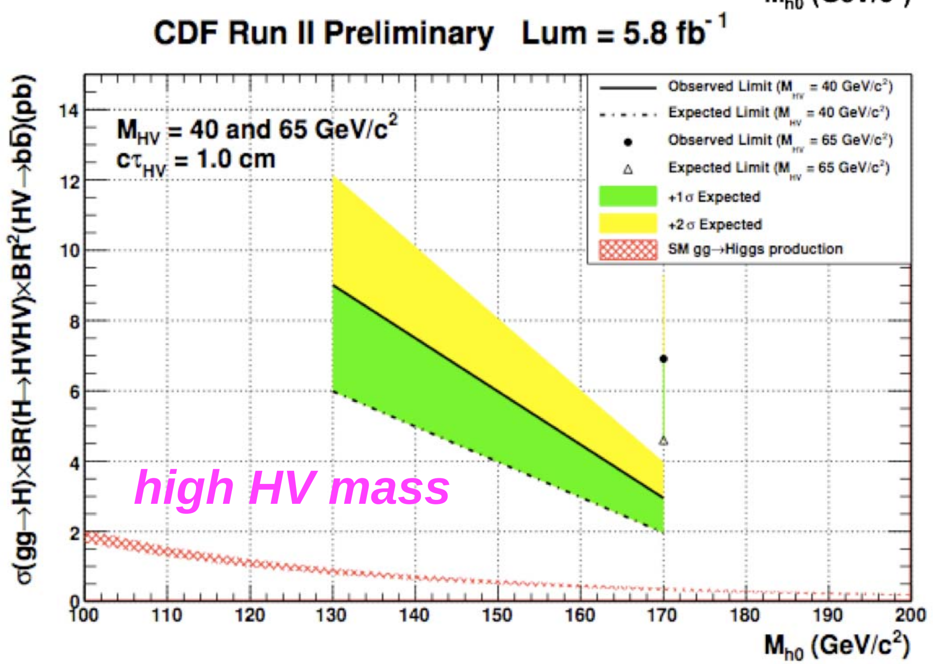
- **Optimize signal vs. background with variables based on reconstructed vertex**
  - ψ : Jet impact parameter
  - ζ : Decay vertex of HV particle
- **Signal: $\psi, \zeta > 0$**
- **multijet background: ψ, ζ uniformly distributed ~ 0**

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

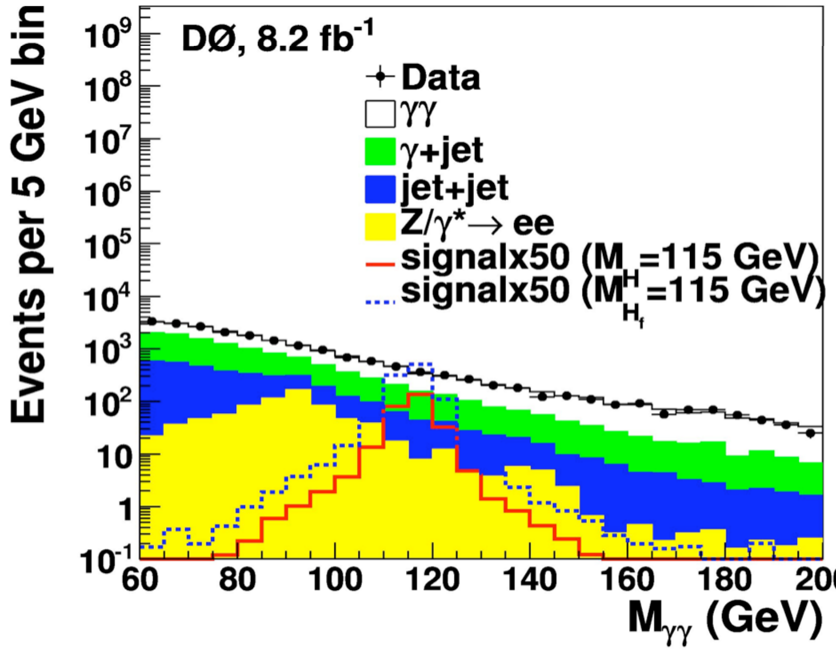




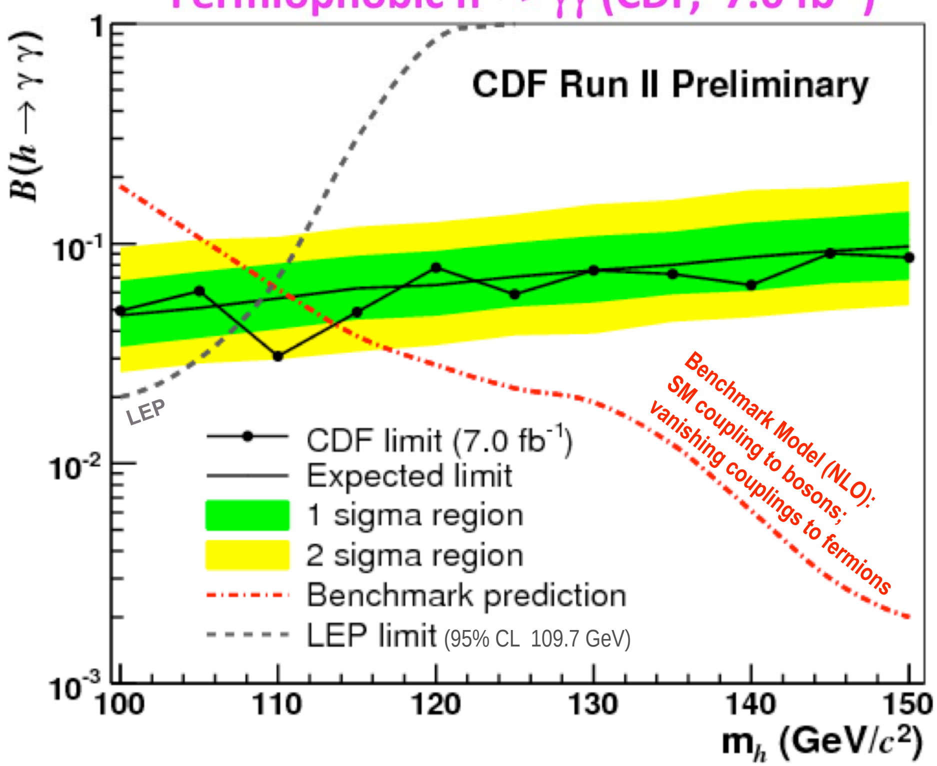


Fermiophobic $h_f \to \gamma\gamma$ Search

- **CDF: 7.0 fb^{-1} search**
  DØ: 8.2 fb^{-1} [submitted to PRL]
- **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 h → γγ (CDF, 7.0 fb^{-1})



- **Search for excess of events in γγ mass spectrum**
- **DØ, for Fermiophobic couplings, exclude at 95% CL: $m_{hf} < 112.9$ GeV**
- **CDF exclude: $m_{hf} < 114$ GeV**
- **Tevatron results: sensitivity beyond that of combined LEP experiments**
  - currently best limits on Fermiophobic Higgs mass

Summary

- **CDF and DØ actively searching for Higgs in models beyond SM**
  - results with up to 8.2 fb^{-1} of data reported here
  - probing theoretically very interesting regions
- **MSSM Higgs**
  - (M_A, $\tan\beta$) exclusions from (b)$\phi \rightarrow$(b)$\tau\tau$ searches comparable to Moriond 2011 limits from CMS and ATLAS
  - forthcoming searches with larger datasets should provide further insight into deviations from expectation in 3b search at low M_A
  - updated Tevatron combination expected soon
- **Models with Extended Higgs sector**
  - DØ: first search for $H^{\pm\pm} \rightarrow \tau^{\pm}\tau^{\pm}$ 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

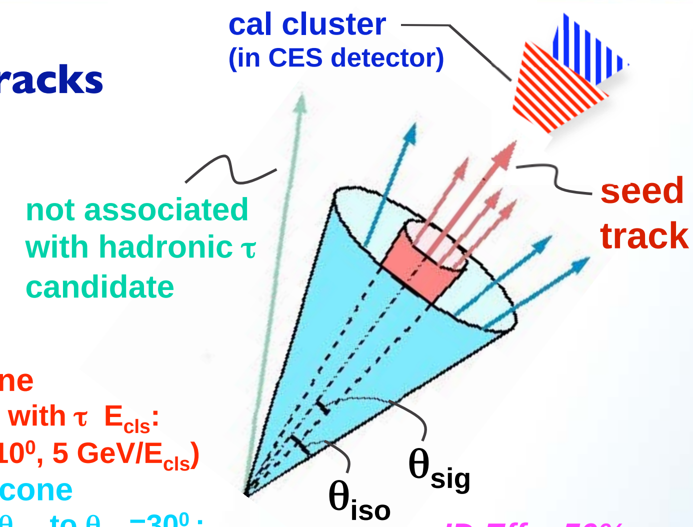
Tevatron delivered > 11.5 fb^{-1} of data;
Stay tuned for updates and combinations expected soon!

Reference Slides

τ-Identification

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 π^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)



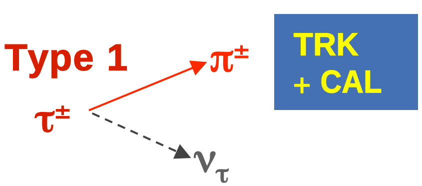
signal cone (shrinking with τ E_{cls}: θ_{sig} = Min(10^0, 5 GeV/E_{cls}))

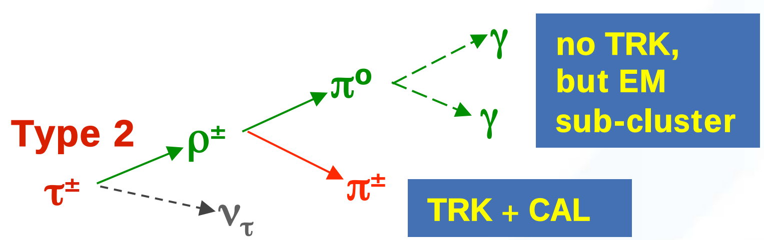
isolation cone (annulus: θ_{sig} to θ_{iso}=30^0 ; ΣE_T^{iso} [trks, π^0] < [2, 1 GeV])

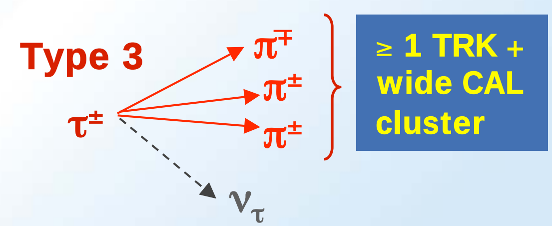
τ-ID Eff = 50% vs. fake rate < 1%

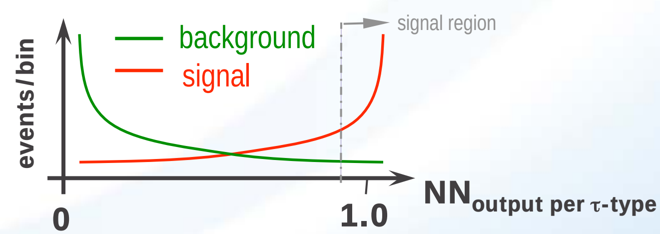
narrow cal energy clusters matched to tracks, with or without EM subclusters ⇒ separate τ's into 3 categories, defined by their decay mode

- 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









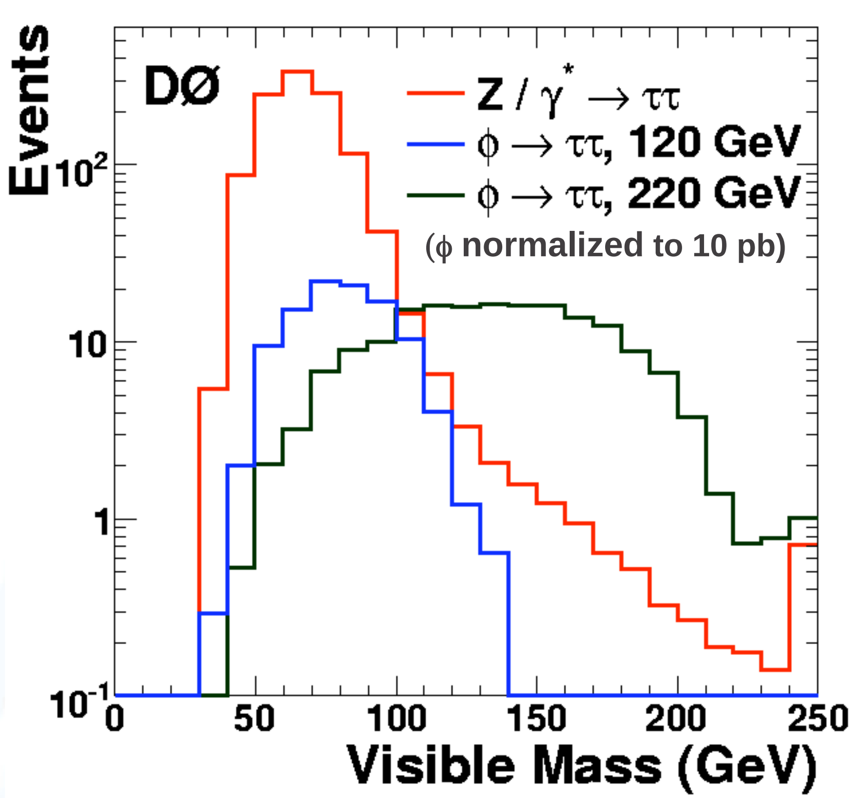
τ-ID Eff = 65% vs. fake rate ~ 2.5%

Visible Mass

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

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

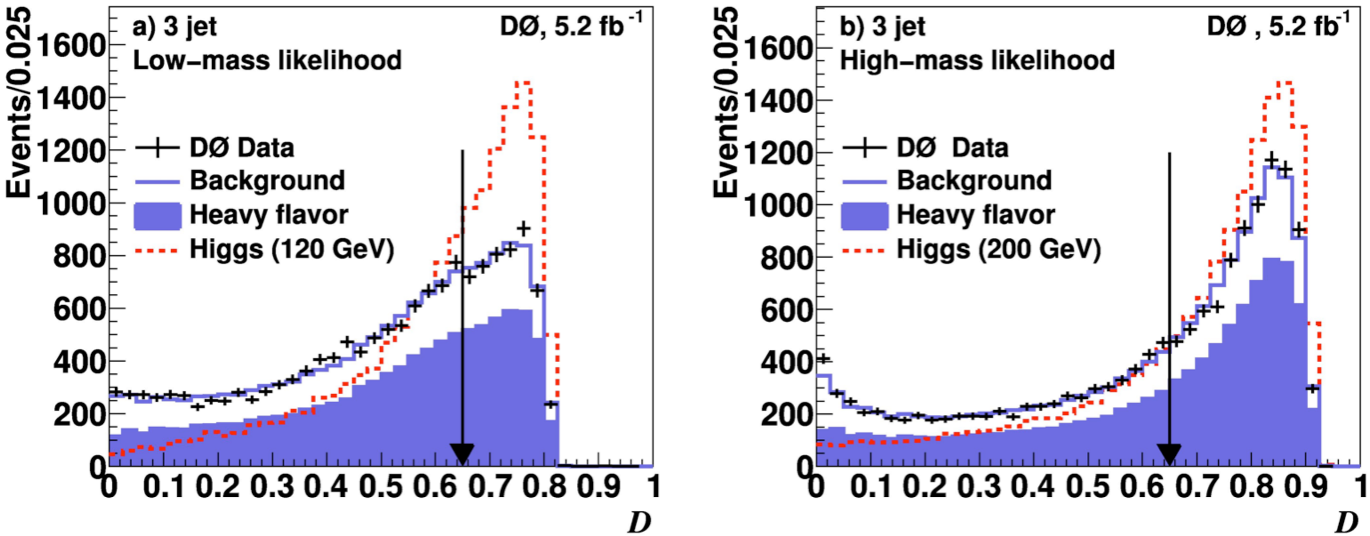
- **Use 4-vectors of:**
  - $P^{\tau 1}$, $P^{\tau 2}$ of visible tau decay products
  - $\not{P}_T = (\not{E}_T, \not{E}_x, \not{E}_y, 0)$, where $\not{E}_x$ and $\not{E}_y$ indicate components of $\not{E}_T$
- **M_{vis} used as input to $\sigma \times BR$ limit calculation in inclusive $\tau\tau$ search**



DØ: $\phi b \to b\bar{b}b$ 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 based b-tagger, with 2 jets in pair: $p_T^{jet1,2} > 25$ GeV
- **6-variable likelihood discriminant [$\mathcal{D}$]**

low-mass (3-jets, $m_\phi < 130$ GeV) high-mass (3-jets, $m_\phi > 130$ GeV)



Background Composition	
(3 b-tag Sample)	
$b\bar{b}b$	~50%
$b\bar{b}j$	~30%
$b\bar{b}c+bc\bar{c}$	~17%
$c\bar{c}j$	~2%

- **Background composition determined from 3-jet sample**
  - fit MC simulated events to data over b-tagging points: 0-, 1-, 2-, and 3-tag
- **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

Multivariate Methods: Variables

$h_f \to \gamma\gamma$ Search

5-variable γ-Neural Network (NN)
$\Sigma_{trks} p_T(\text{trks})$
N_{cells} in CAL Layer 1 within $\Delta R < 0.2$
N_{cells} in CAL Layer 1 within $0.2 < \Delta R < 0.4$
number of assoc. CPS clusters with EM_{CAL}
energy-weighted width of CPS clusters

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

6-variable Likelihood Discriminant *(for jet pair with 1st and 2nd leading jets)*
$\Delta\eta$ 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
$E_T = p_T^\tau + p_T^\mu + H_T$	$\lvert\Delta\phi[\mu, \tau]\rvert$
$\lvert\Delta\phi[\mu, \tau]\rvert$	$H_T = \Sigma_{jets} p_T[\text{jets}]$
$\lvert\Delta\phi[\mu, \text{MET}]\rvert$	MET
$\mathcal{A}_T = [p_T^\mu - p_T^\tau]/p_T^\tau$	$m_T[\mu, \tau, \text{MET}, \text{jet}]$
MET	$M_{collinear}$
$m_T[\mu, \text{MET}]$	M_{hat}
$m_T[\mu, \tau, \text{MET}, \text{jet}]$	–
$M_{collinear}$	–
M_{hat}	–

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

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 term
  - μ Higgs sector bilinear coupling (mass parameter, where $\Delta_b \propto \mu \times \tan\beta$)
  - $m_{\tilde{g}}$ 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

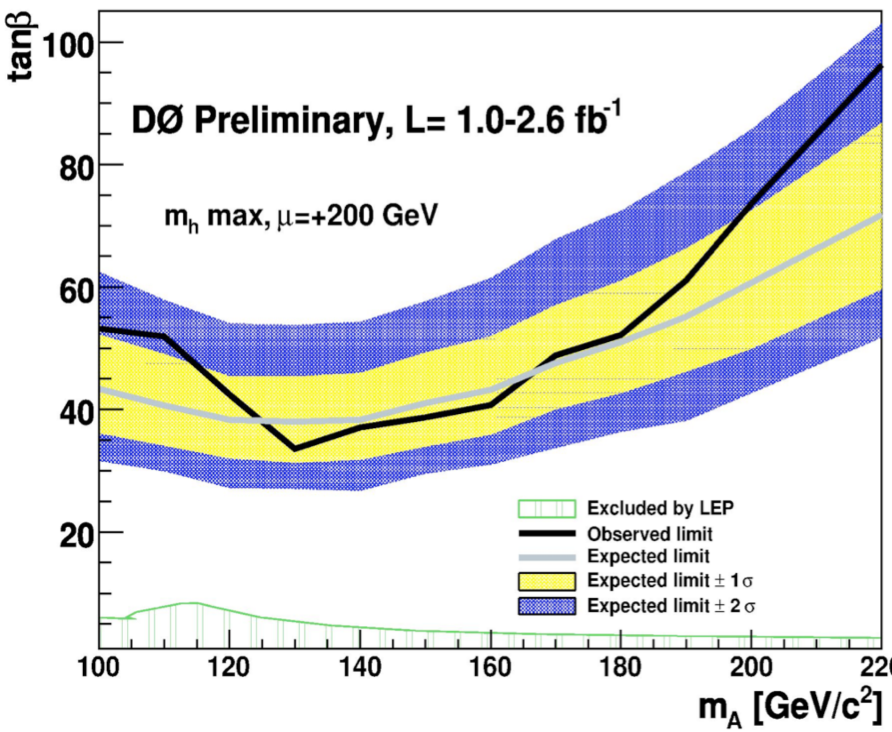
Constrained Model: Unification of SU(2) and U(1) gaugino masses

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

MSSM: Tevatron & DØ Combined Limits

- **DØ combination across search channels $\Rightarrow$ $\tan\beta$ vs. m_A exclusions**
  - $\phi \to \tau\tau$ (1.0−2.2 fb^{-1}), $\phi b \to \tau\tau b$ (1.2 fb^{-1}), and $\phi b \to b\bar{b}b$ (2.6 fb^{-1})
  - does not include recent 7.3 fb^{-1} $\phi b \to \tau\tau b$, 5.4 fb^{-1} $\phi \to \tau\tau$, 5.2 fb^{-1} $\phi b \to 3b$ search
- **Reach similar sensitivity as Tevatron combination**
  - inputs: CDF's $\phi \to \tau\tau$ (1.8 fb^{-1}) and DØ's $\phi \to \tau\tau$ (2.2 fb^{-1}) searches
  - sensitivity at low m_A: $\tan\beta \sim 30$ [$\mathcal{O}(m_{top}/m_b)$]

DØ MSSM Combination



Tevatron MSSM Combination