Beyond Standard Model Higgs Searches at the Tevatron

presented by

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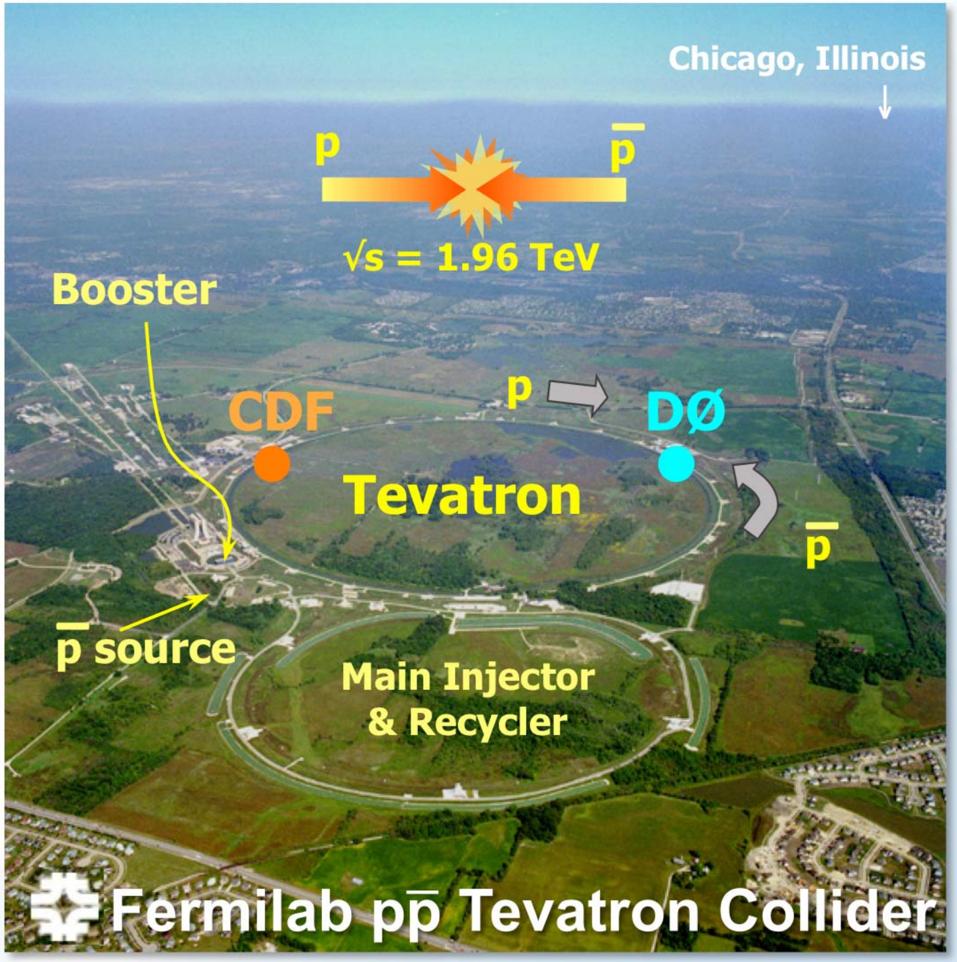
BSM Higgs: Outline

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

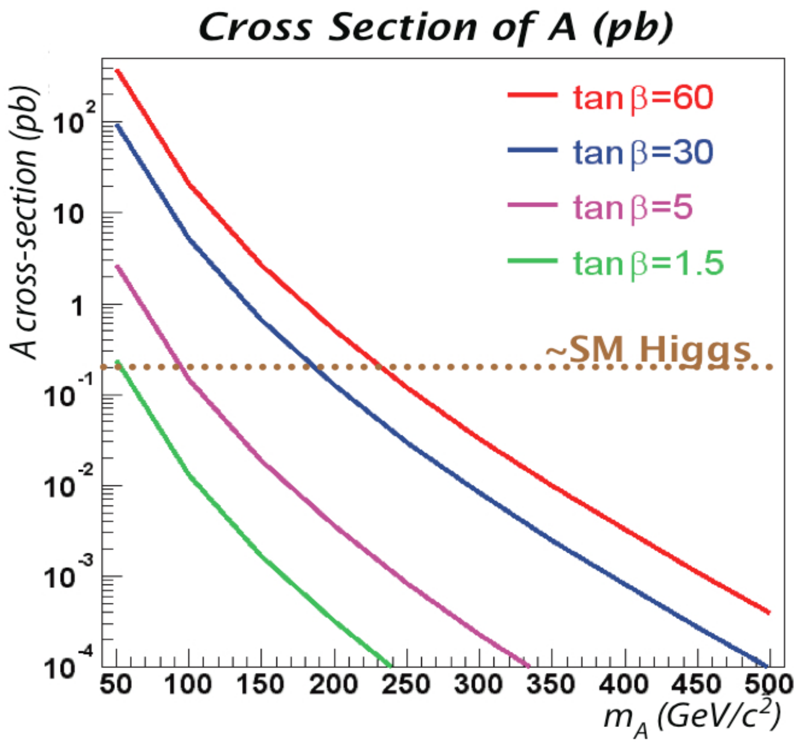
I. MSSM Higgs Search
- 5 physical Higgs bosons
  - $\phi (= h^0, H^0, A^0)$ and $H^\pm$
- main searches
  - $\phi b \rightarrow b\bar{b}b$
  - $\phi \rightarrow \tau\tau$ and $\phi b \rightarrow \tau\tau b$
  - charged Higgs in top decays

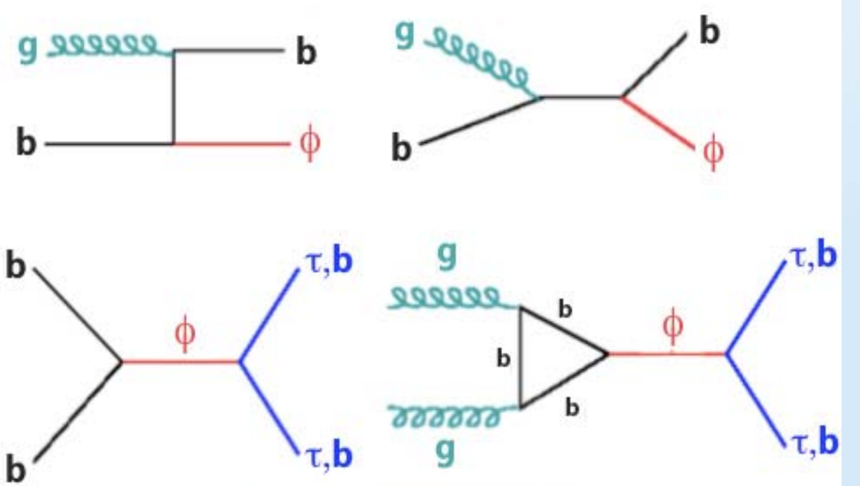
II. next-to-MSSM Higgs (NMSSM)
- neutral CP-even Higgs boson $(h_{1,2,3})$
- neutral CP-odd Higgs boson $(a_{1,2})$
- charged Higgs pair $(h^\pm)$

III. Fermiophobic Higgs Search
- not covered here… see talk by K. Peters, this conference



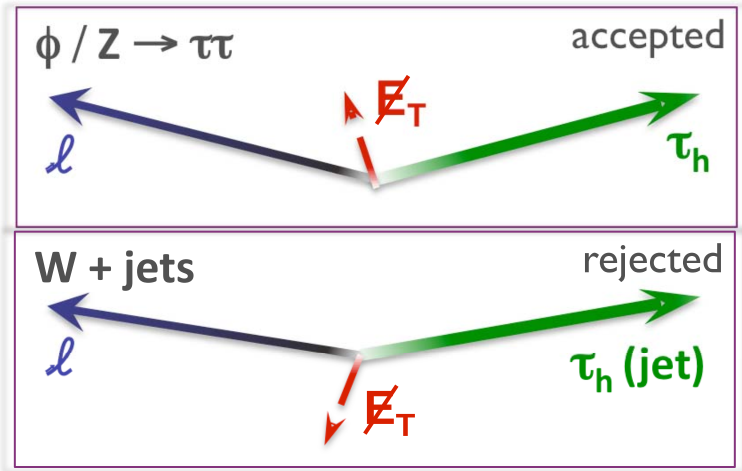
- **MSSM Higgs requires 2 doublets**
  - yields: $\phi(= h^0, H^0, A^0)$ and $H^\pm$
- **At tree-level, MSSM Higgs fully specified by two free parameters**
  - m_A
  - $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$
    (ratio of v.e.v. of 2 Higgs doublets)
- **Radiative corrections introduce 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)





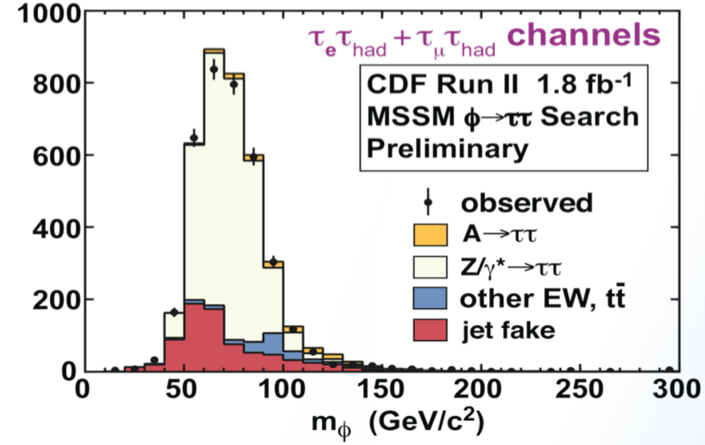
φ = h/H & A

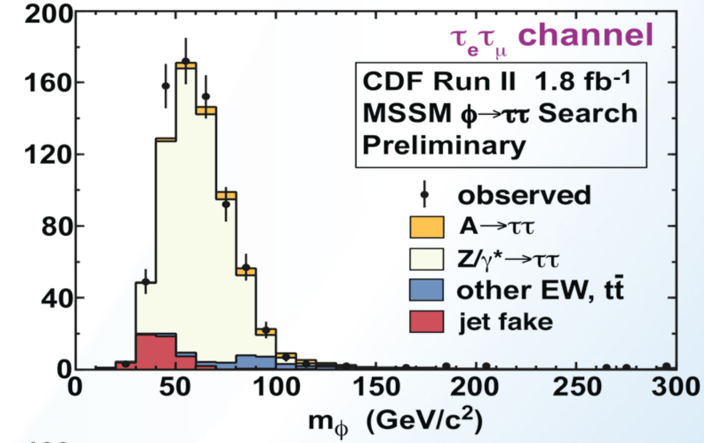
- CDF considers $\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$, and $\tau_e\tau_\mu$ channels with 1.8 fb^{-1} data, selected by:
  - isolated e or μ: opposite-sign (OS) from hadronic τ
  - τ's selected using variable-size cone algorithm
  - Suppress W+jets background by requirement on relative direction of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

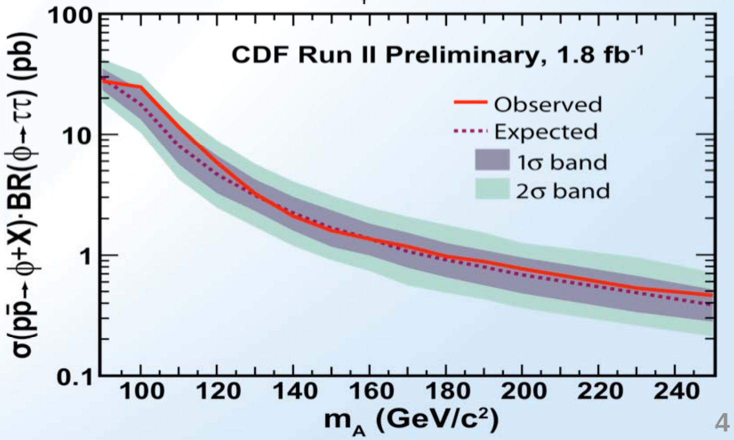


- Data agrees with backgrounds for visible mass
  - set $\sigma \times$ BR limits for 90 GeV < m_A < 250 GeV

CDF: PRL 103, 201801 (2009)

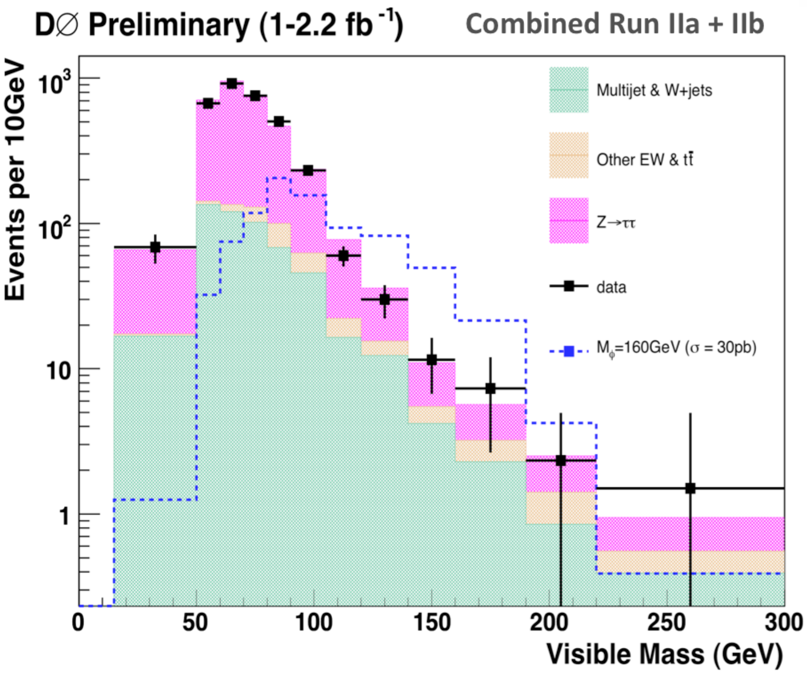


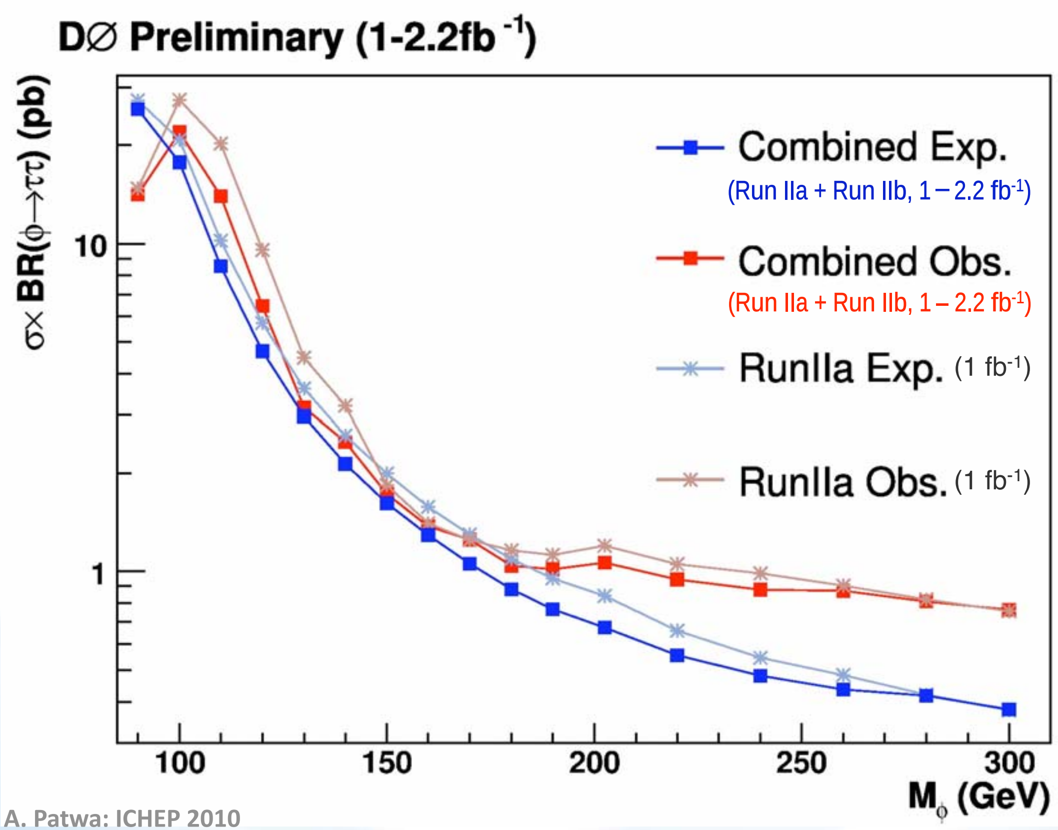




DØ: Inclusive $\tau\tau$ Search

- Result using 1.0 fb^{-1} dataset for $\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$, and $\tau_e\tau_\mu$: PRL 101, 071804 (2008)
- 2.2 fb^{-1} of Run II data considers $\tau_\mu\tau_{had}$
  - isolated μ separated from τ: opposite-sign
  - hadronic τ categorized by decay types
    - discriminated from jets using τ-ID NN
  - M_T < 40 GeV $\Rightarrow$ reject W+jets

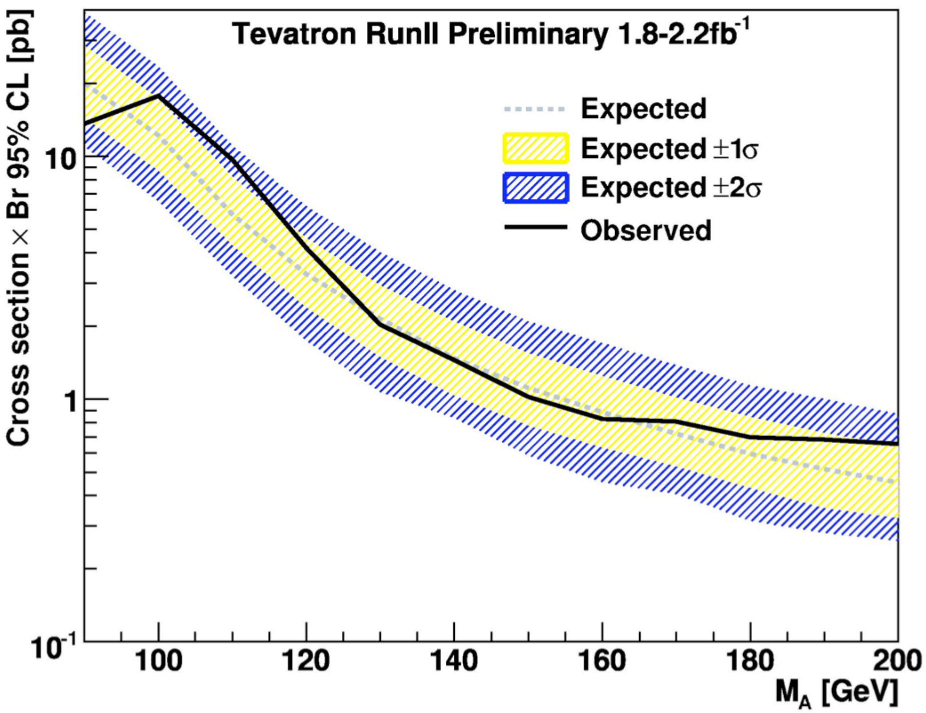


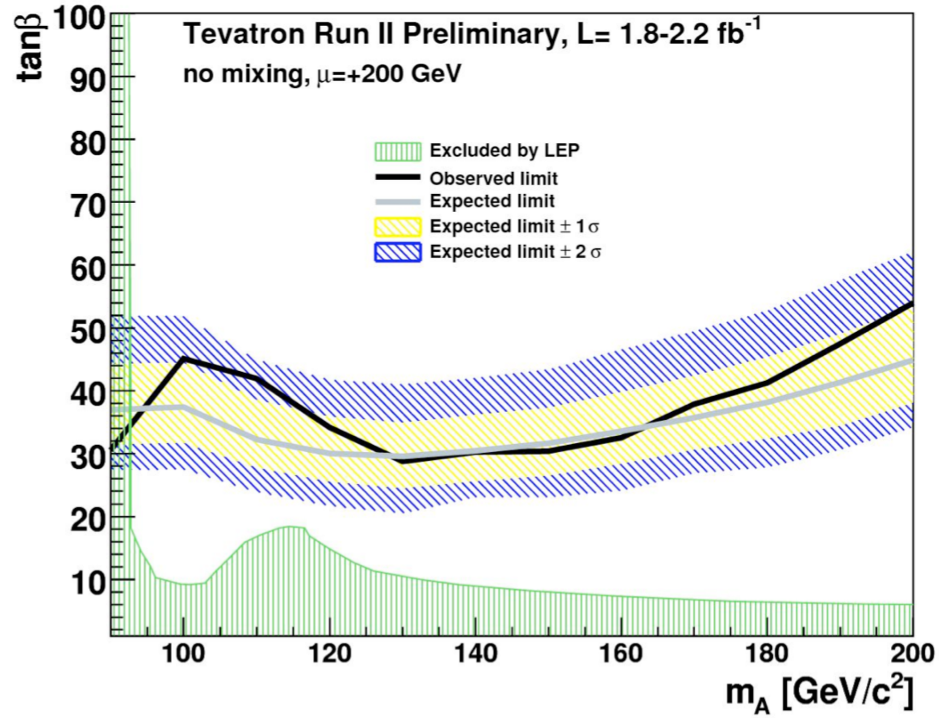


- No excess in data across visible mass spectrum
  - upper limits on $\sigma\times$ BR as function of ϕ mass
    - 2.2 fb^{-1} result: ~10 – 20% improvement over 1.0 fb^{-1} search

$\phi \to \tau\tau$: DØ and CDF Combined Limits

- **95% CL exclusion results similar for each experiment**
  - each reach sensitivity $\tan\beta \sim 40-50$ for $m_A < 180$ GeV
- **Tevatron combination**
  - with only a fraction of available dataset, probing interesting region of $\tan\beta \sim 30$ [$\mathcal{O}(m_{top}/m_b)$]

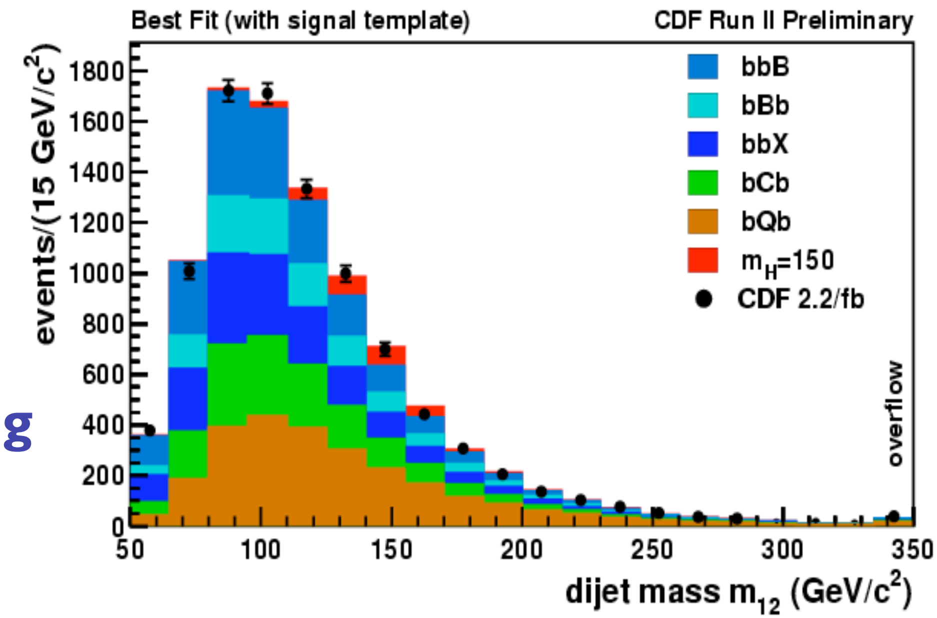


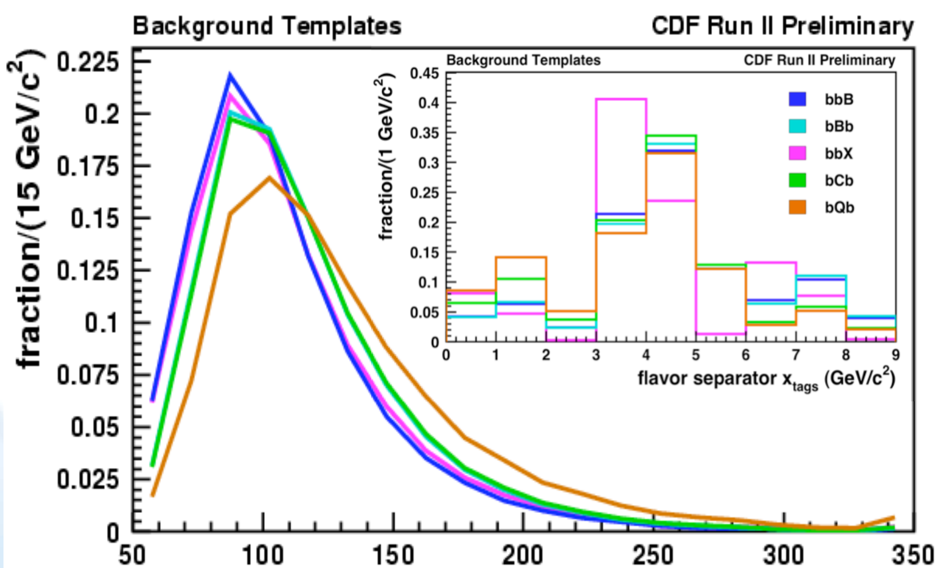


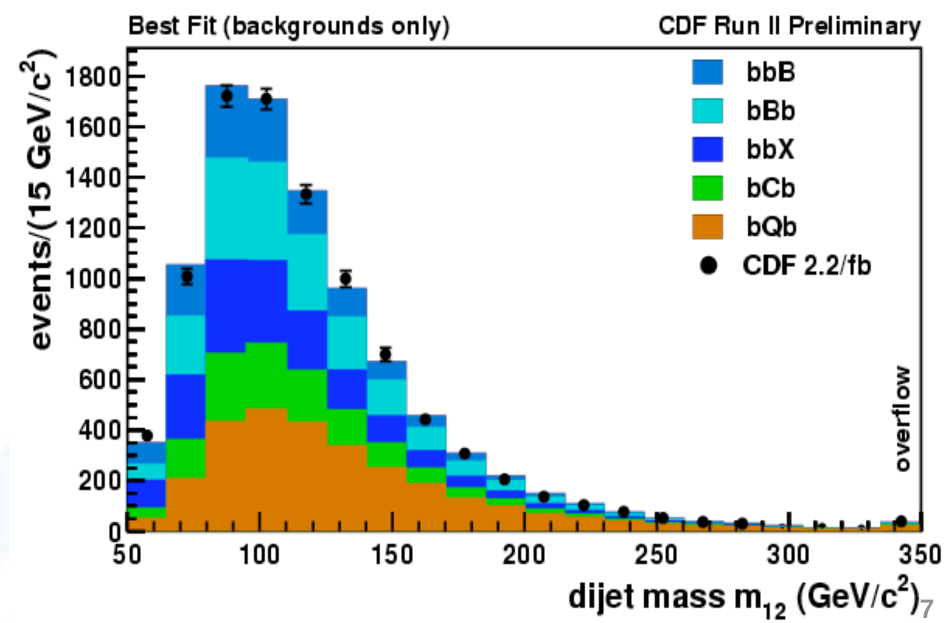
Tevatron Combination

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
- **[updated]** 2.2 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}

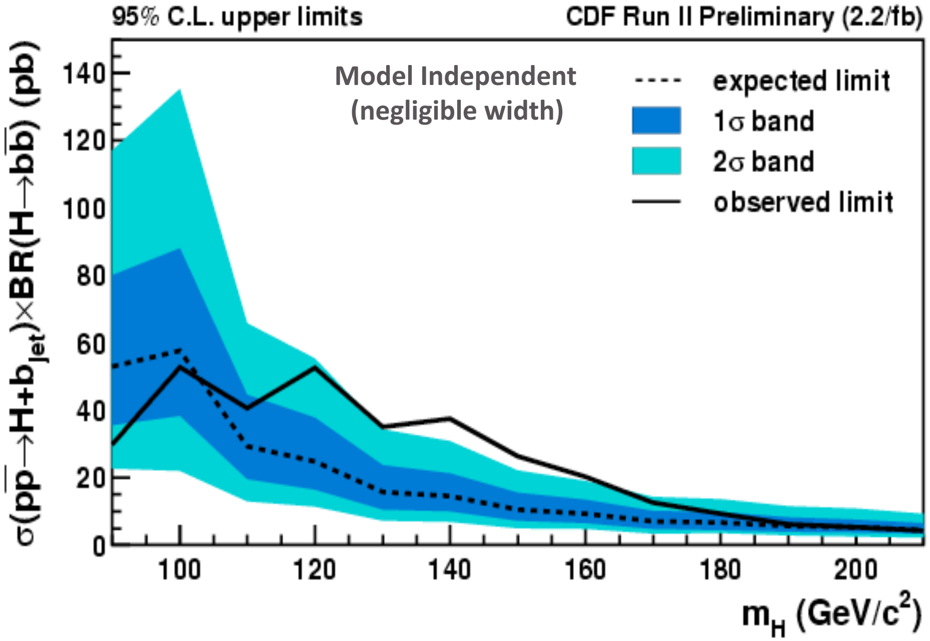


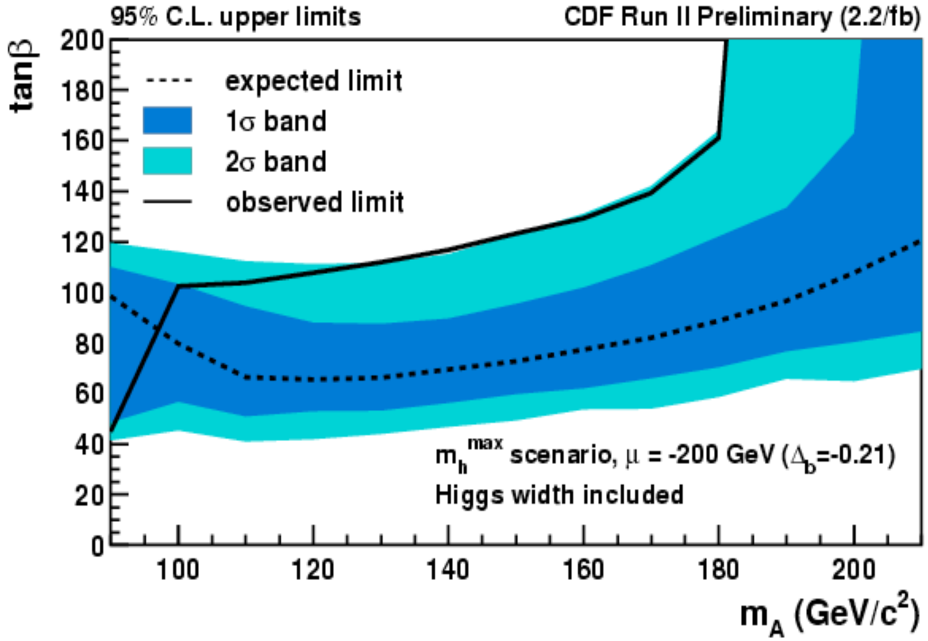




CDF: $\phi b \rightarrow b\bar{b}b$ Search *(cont.)*

95% C.L. Mass-Dependent Cross Section Limits and MSSM Exclusions

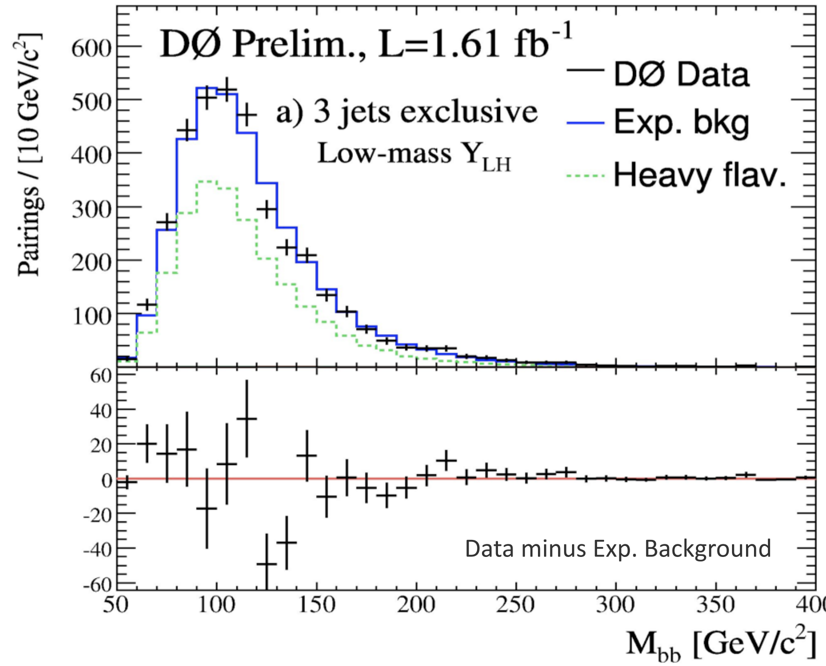


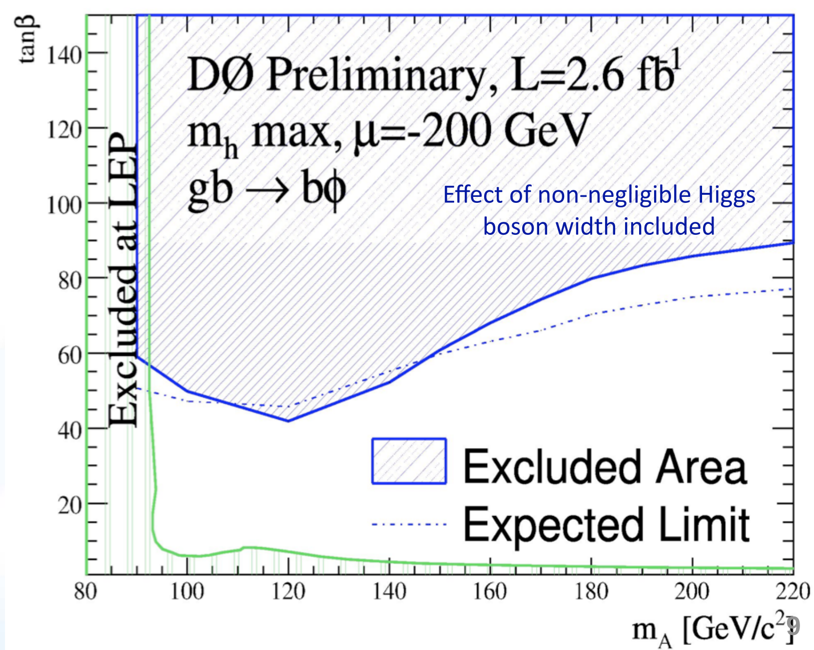


- **Limits on $\sigma \times$ BR**
  - positive deviation at ~140 GeV for narrow-width case, with *p*-value = 0.9% (trial factors, 5.7% probability to observe such an excess at any masses)
  - general limits applicable to any narrow scalar with $b\bar{b}$ final states produced in association with b-jet
- **Translate limits in MSSM benchmark scenarios in (m_A, tanβ) parameter space**
  - large tanβ ⇒ enhances the bbH coupling as well as increases width of the Higgs

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

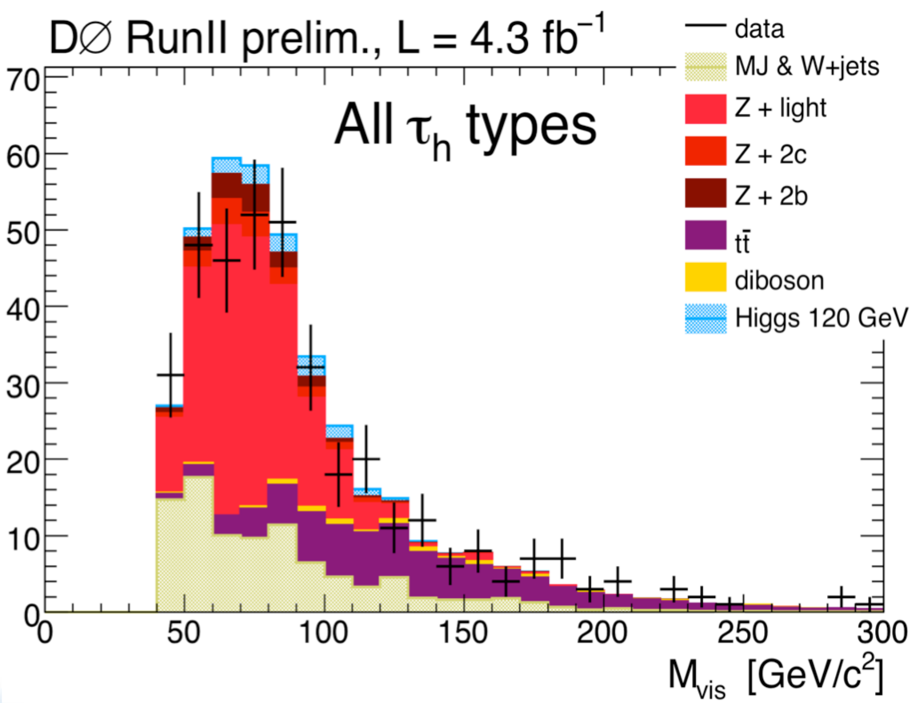
- 2.6 fb^{-1} search requires 3 b-tagged jets via NN b-tagger
- Improve sensitivity by separating into 3- and 4-jet channels
  - likelihood discriminates b-jet pair via Higgs signal from multijet backgrounds
    - separate low-mass (<130 GeV) and high-mass (>130 GeV) likelihoods
  - analysis relies on shape difference between signal & background
    - use double b-tagged data to predict triple b-tagged background shape
- No excess in dijet invariant mass: set exclusion limits in MSSM benchmark parameter space
  - Higgs mass term, $\mu < 0 \Rightarrow$ enhanced production for 3b mode gives strongest limits

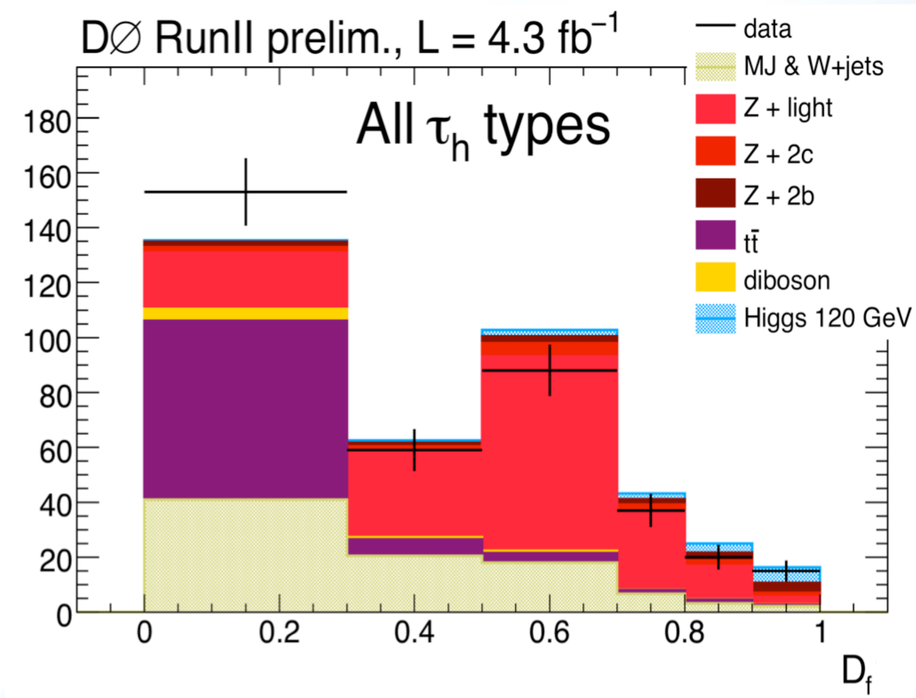




$\phi b \rightarrow \tau_\mu \tau_{had} b$ Search

- **[updated] 4.3 fb^{-1} search considers $\phi b \rightarrow \tau_\mu \tau_{had} b$**
  - use developed techniques from both $\phi \rightarrow \tau\tau$ and $\phi b \rightarrow b\bar{b}b$ searches
  - 2.7 fb^{-1} dataset result: PRL 104, 151801 (2010)
- **Discriminate against different backgrounds via MVA techniques**
  - NN based b-tagging algorithm of leading b-tag jet $\Rightarrow$ suppress $Z \rightarrow \tau\tau$ (Z+jets)
  - construct $t\bar{t}$ and QCD multijet discriminants per Higgs mass point

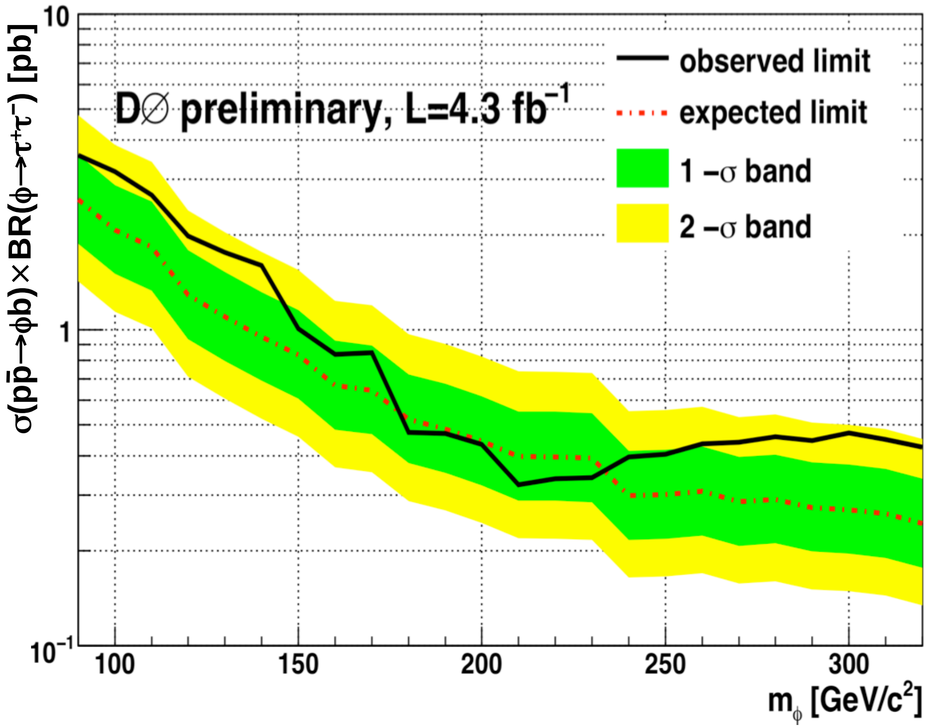


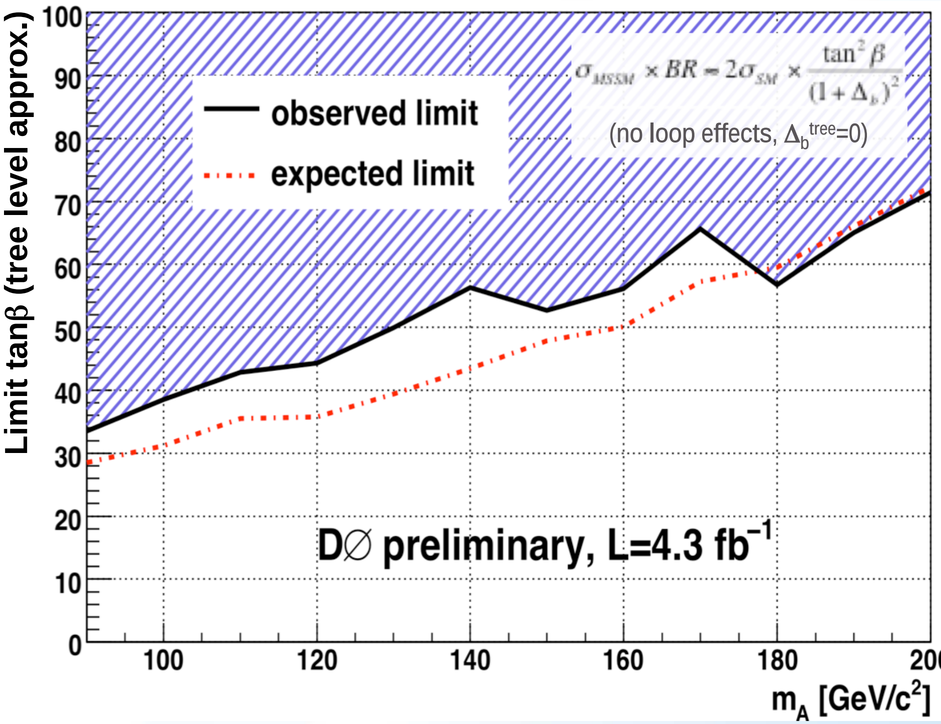


- **Take geometrical mean of top, multijet, and b-tag discriminants for final discriminant, D_f**

$\phi b \rightarrow \tau_\mu \tau_{had} b$ Search *(cont.)*

- **95% C.L. mass-dependent limits calculated for $\sigma \times$ BR**
- **Translate into MSSM exclusions in $\tan\beta$ vs. m_A space**

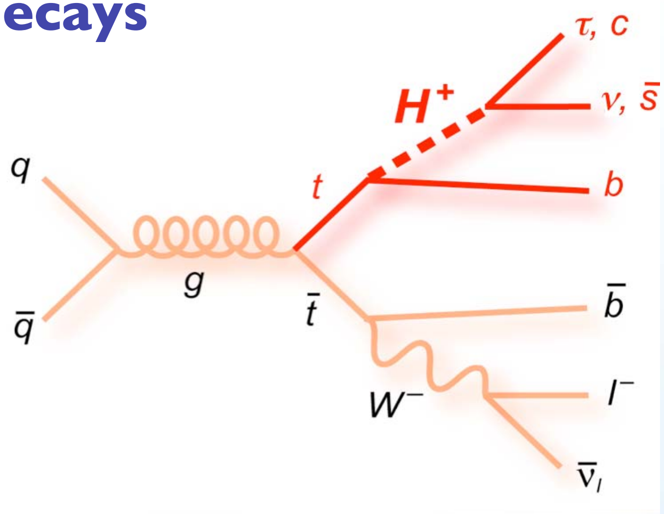


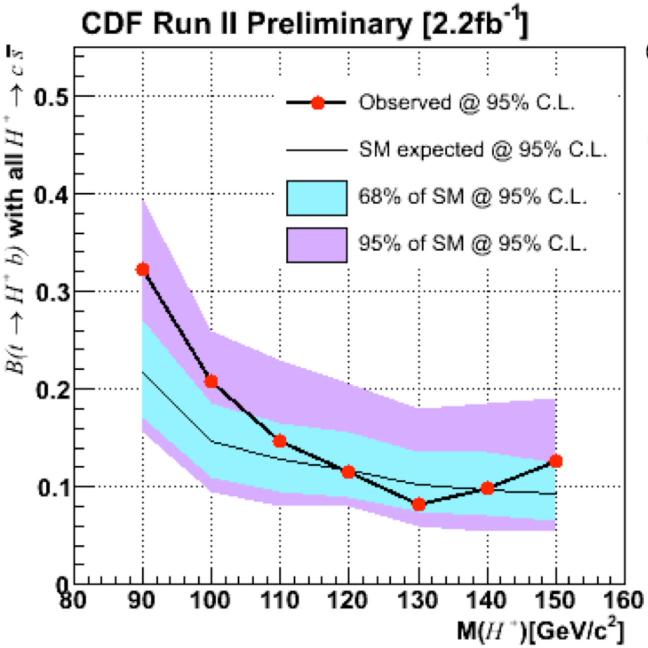


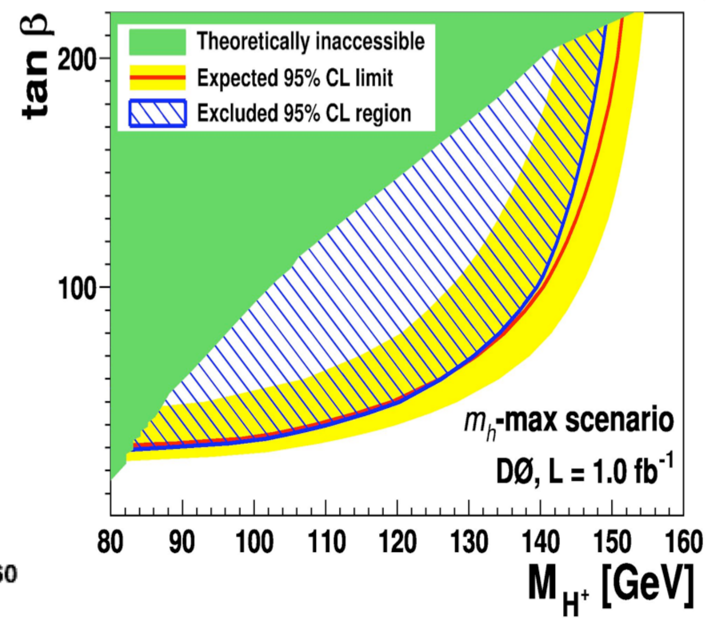
Search complimentary to $\phi \rightarrow \tau\tau$ channel as it does not suffer from $Z \rightarrow \tau\tau$ background

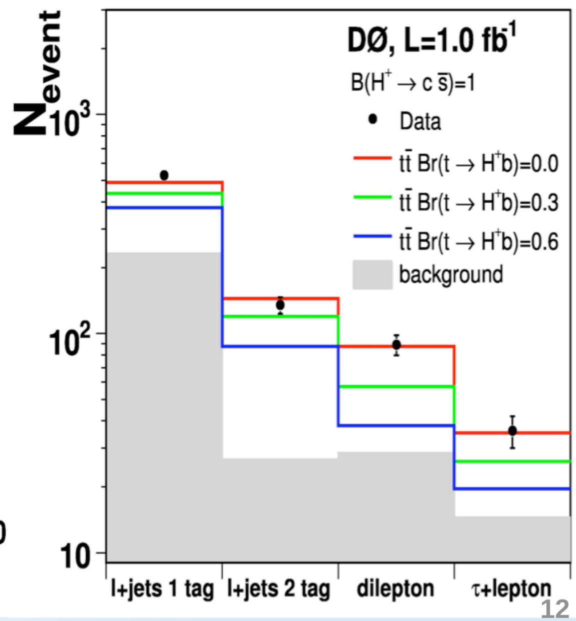
MSSM Charged Higgs Search

- 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 $\tan\beta$)
  - Leptophobic model: $H^\pm \to c\bar{s}$ (low $\tan\beta$)
- 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)







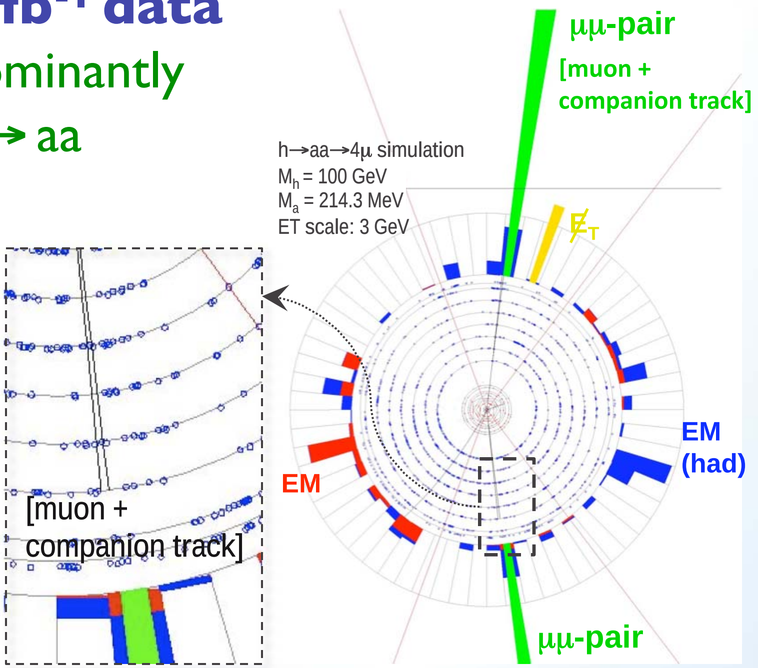


DØ: NMSSM $h \rightarrow aa$ Search

- **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

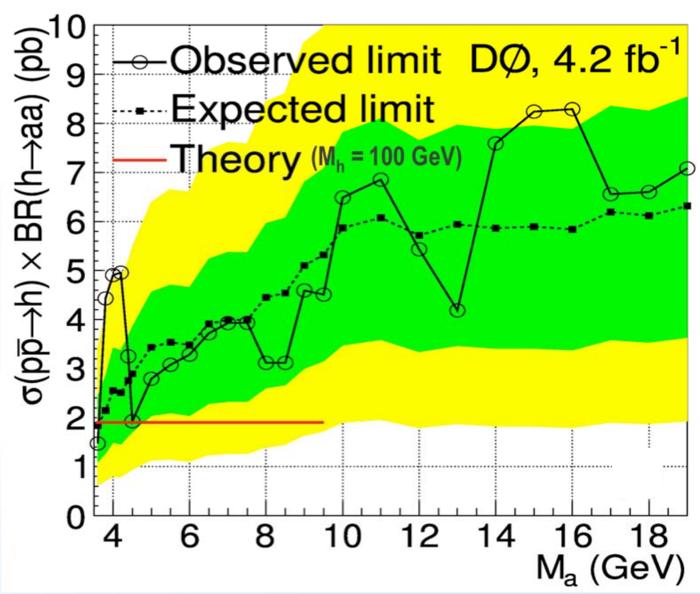
For masses: $2m_\mu < M_a < \sim 2m_\tau$ (~3.6 GeV)

- **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)

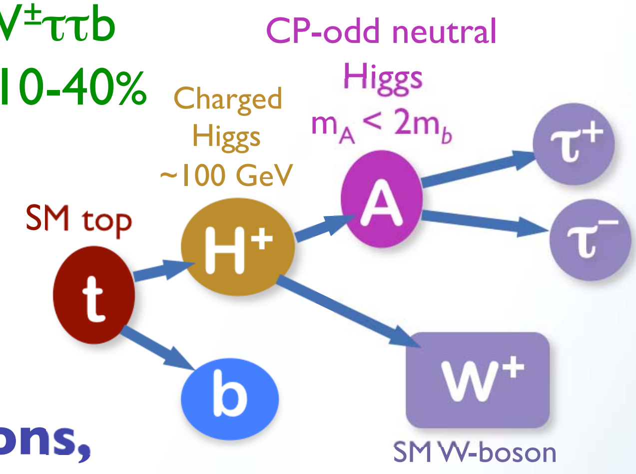
- **dominant decay: $aa \rightarrow 2\mu 2\tau$**
  - signature: one pair of collinear muons and large $\not{E}_T$ from $a \rightarrow \tau\tau$ decay
  - $\sigma \times$ BR limits: currently are factor of ≈1−4 larger than expected Higgs production

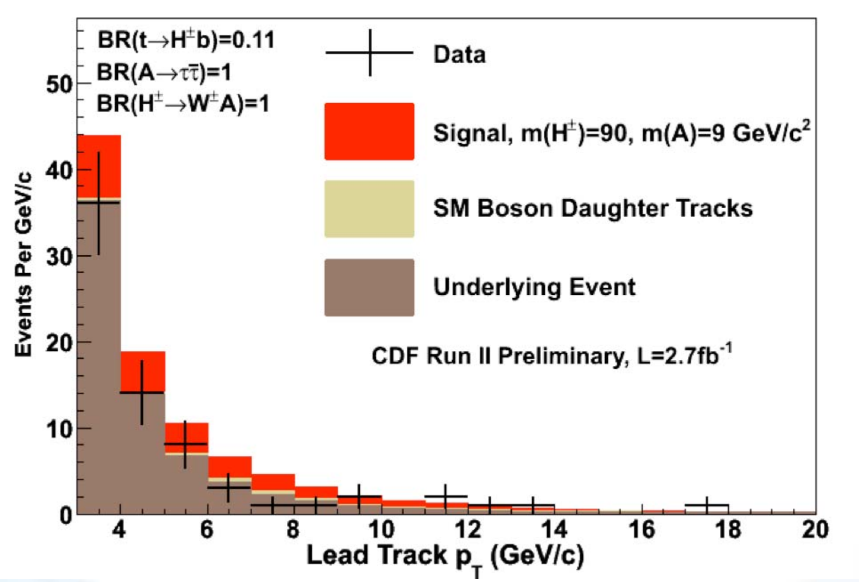


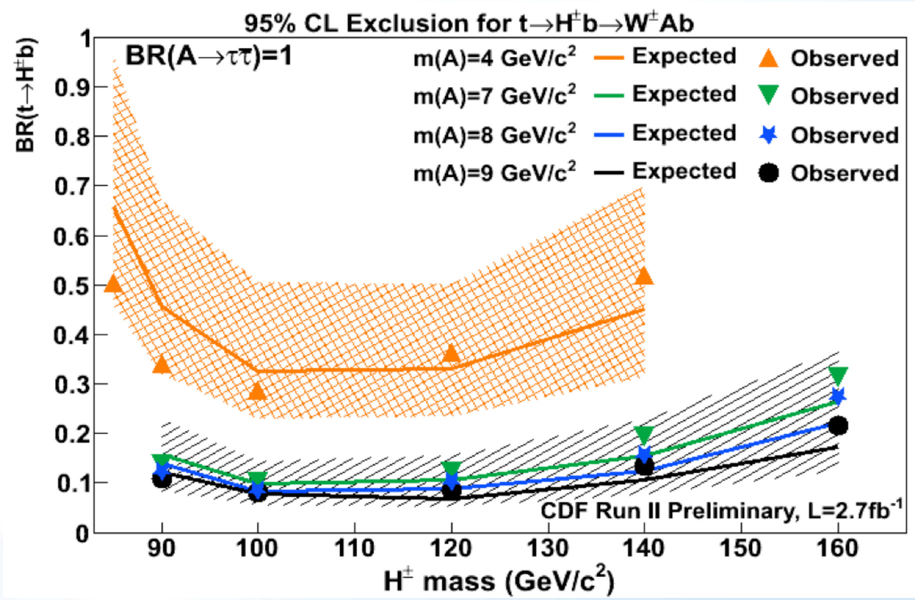
PRL, 103 061801 (2009)

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 $\Rightarrow$ 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**



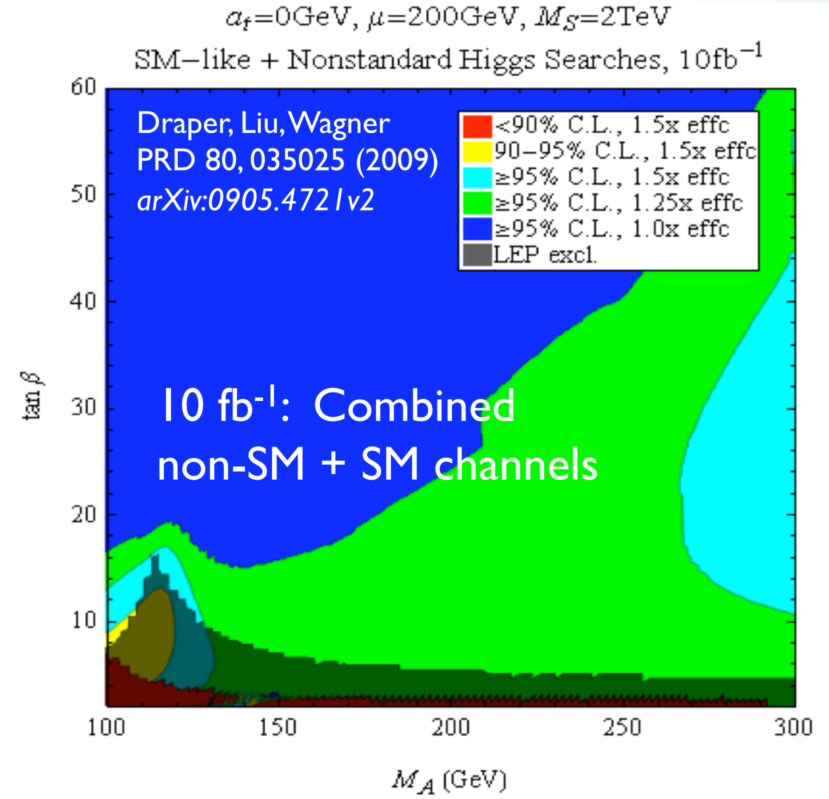




First such limits in the parameter space of top quark decays

Prospects and Conclusions

- **CDF and DØ actively searching for Higgs in models beyond SM**
  - results with up to 4.3 fb^{-1} of data reported here
- **MSSM Higgs**
  - Tevatron reaching sensitivity of $\tan\beta \sim 30$ for low m_A
  - forthcoming searches with larger datasets should provide further insight into deviations from expectation at low m_A
  - updated results with new combination expected soon
- **SM Higgs searches (*for e.g.,* $H \rightarrow WW$) could be used to constrain the SM-like Higgs in MSSM**
  - see P. Draper *et al.*, arXiv:0905.4721v2
  - potential to probe significant regions of MSSM parameter space



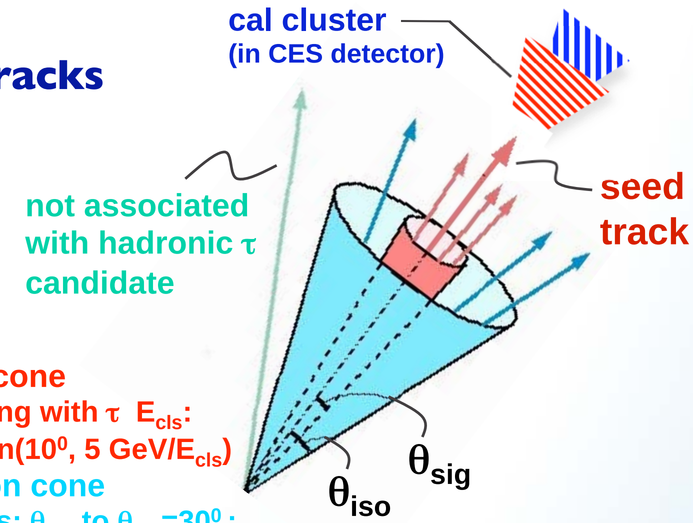
Tevatron delivered > 9 fb^{-1} of data
and more coming…
Stay tuned for exciting results ahead!

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 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)



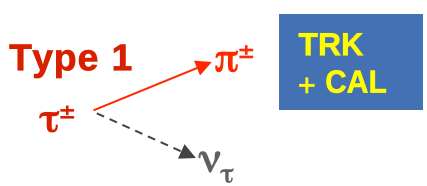
— signal cone (shrinking with τ E_{cls}: $\theta_{sig} = \text{Min}(10^0, 5\ \text{GeV}/E_{cls})$)

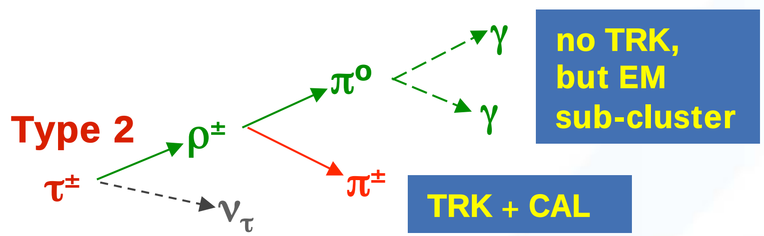
— isolation cone (annulus: θ_{sig} to $\theta_{iso}=30^0$; ΣE_T^{iso} [trks, π^0] < [2, 1 GeV])

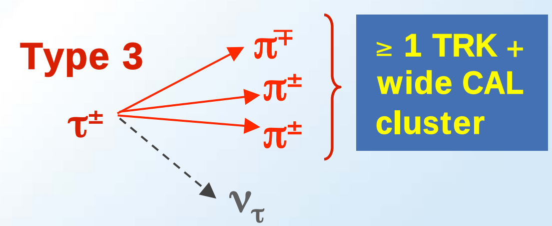
DØ: narrow cal energy clusters matched to tracks, with or without EM subclusters

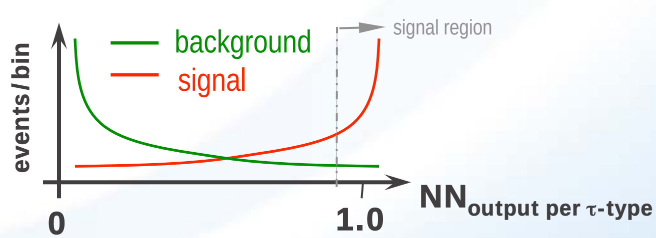
⇒ separate τ's into 3 categories, defined by their decay mode

- 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







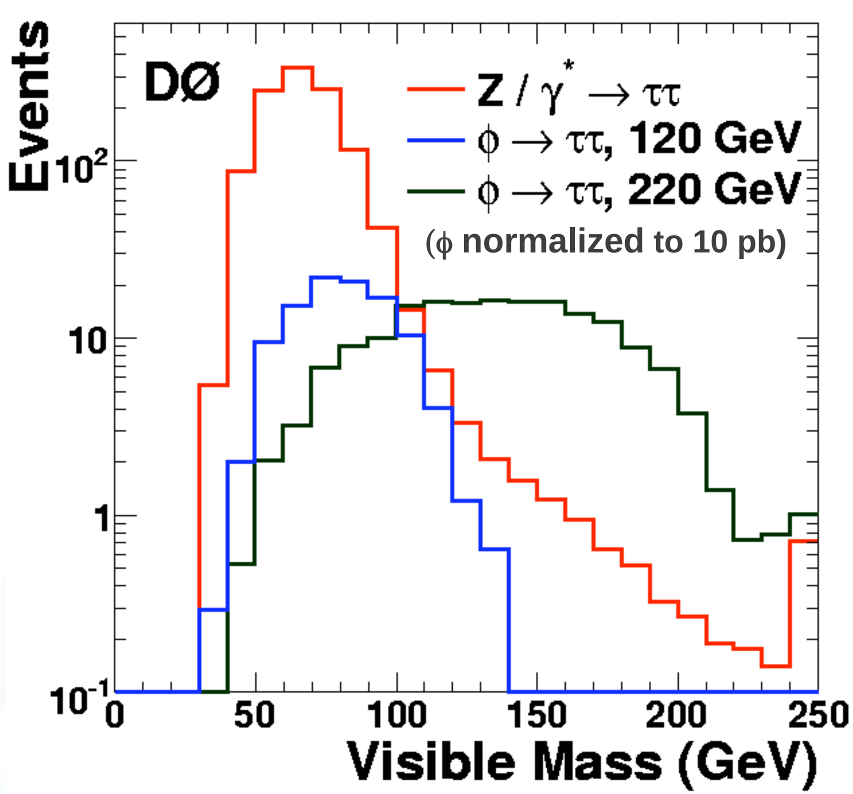


Visible Mass

- 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 τ decay plus missing transverse energies
    - exploit fact that signal appears as an enhancement above $Z\to\tau\tau$

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

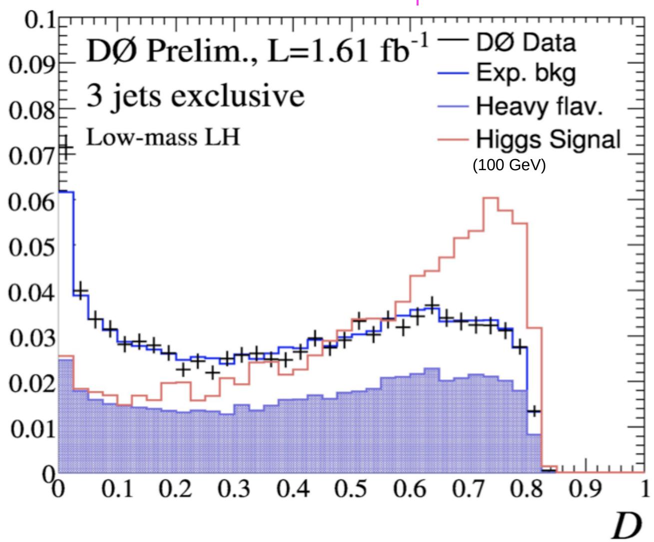
- Use 4-vectors of:
  - $P^{\tau 1}$, $P^{\tau 2}$ of visible tau decay products
  - $\not{P}_T = (\not{E}_T, \not{E}_x, \not{E}_y, 0)$, where $\not{E}_x$ and $\not{E}_y$ indicate components of $\not{E}_T$
- M_{vis} used as input to $\sigma\times BR$ limit calculation



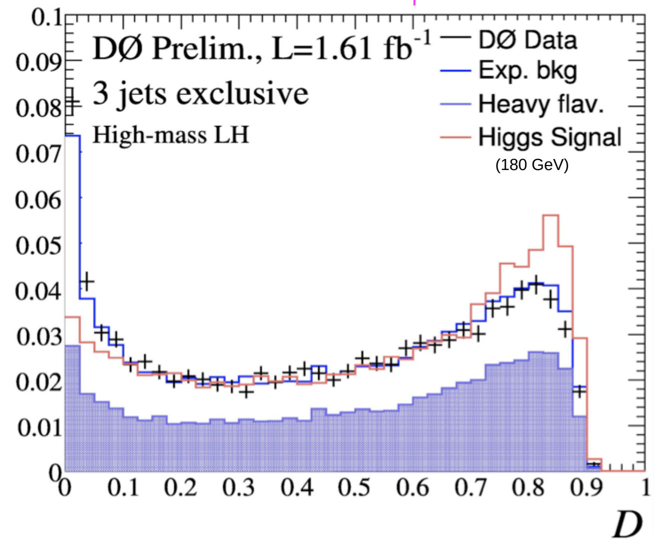
DØ: $\phi b \rightarrow b\bar{b}b$ Analysis Overview

- **2.6 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 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 Discriminant (D_{top})	anti-multijet Discriminant (D_{MJ})
$D_{final} = (D_{top} + D_{MJ} + D_{lead\ b\text{-}tag})^{1/3}$	
N_{jets}	Muon p_T
$H_T = \Sigma_{jets} p_T[\text{jets}]$	Tau p_T
$E_T = p_T^\tau + p_T^\mu + H_T$	$\lvert\Delta\phi[\mu, \tau]\rvert$
$\lvert\Delta\phi[\mu, \tau]\rvert$	$\lvert\Delta\phi[\mu, \text{MET}]\rvert$
$\lvert\Delta\phi[\mu, \text{MET}]\rvert$	$H_T = \Sigma_{jets} p_T[\text{jets}]$
$\mathcal{A}_T = [p_T^\mu - p_T^\tau]/p_T^\tau$	$m_T[\mu, \tau, \text{MET}]$
MET	$m_T[\mu, \tau, \text{MET, jet}]$
$m_T[\mu, \text{MET}]$	–
$m_T[\mu, \tau, \text{MET}]$	–
$m_T[\mu, \tau, \text{MET, jet}]$	–

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

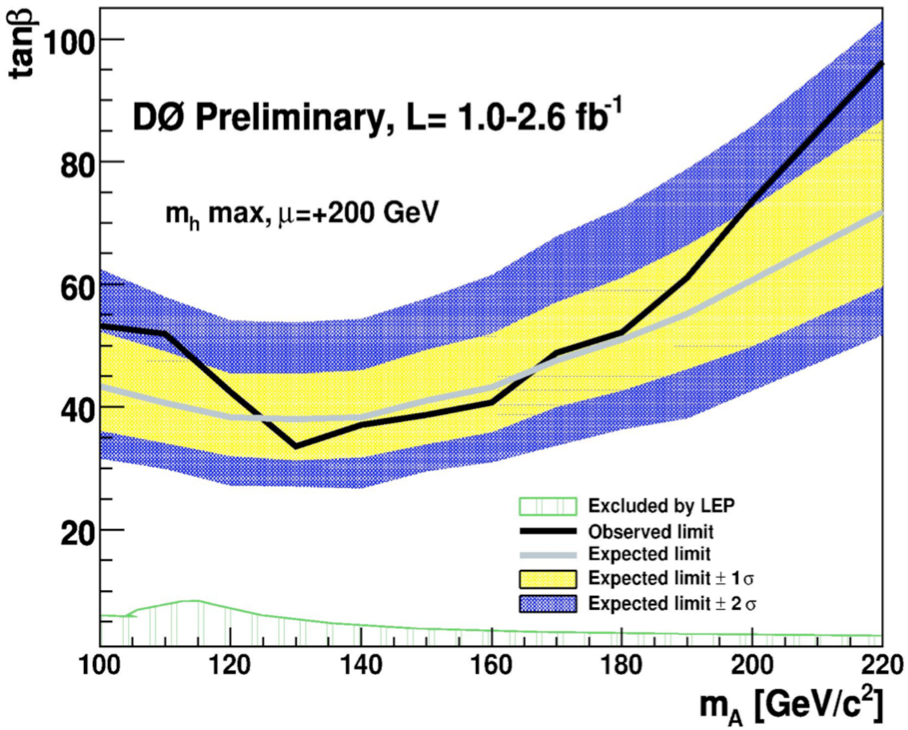
- **For neutral Higgs searches: $\sigma \times$ BR limits $\Rightarrow$ interpreted in MSSM**
- **Tree-level: Higgs sector of MSSM described by m_A & $\tan\beta$**
  - radiative corrections introduce dependence on additional SUSY parameters
- **Five additional, relevant parameters**
  - M_{SUSY} Common 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 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

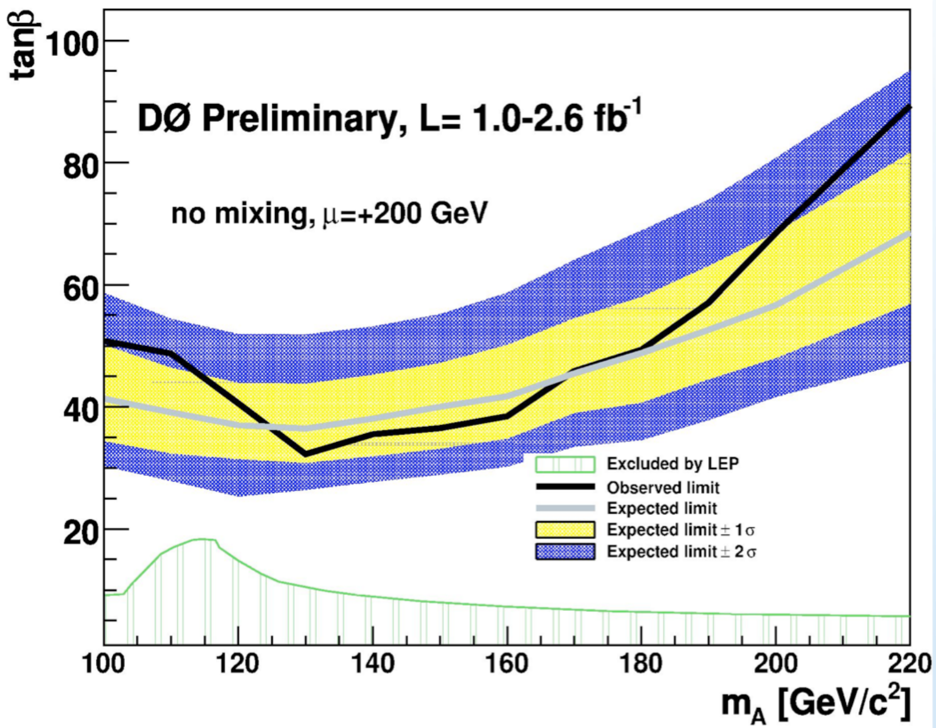
Constrained Model: Unification of SU(2) and U(1) gaugino masses

	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: 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 4.3 fb^{-1} $\phi b \to \tau\tau b$ search
    - expect new combination soon
- **Reach similar sensitivity as Tevatron combination on $\tau\tau$ searches**



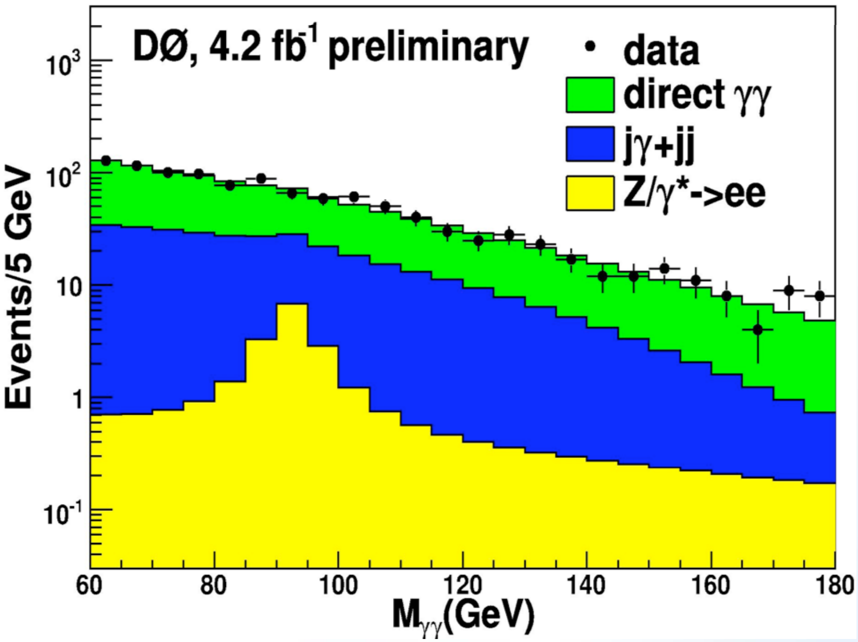


DØ Combination with 3 Search Channels

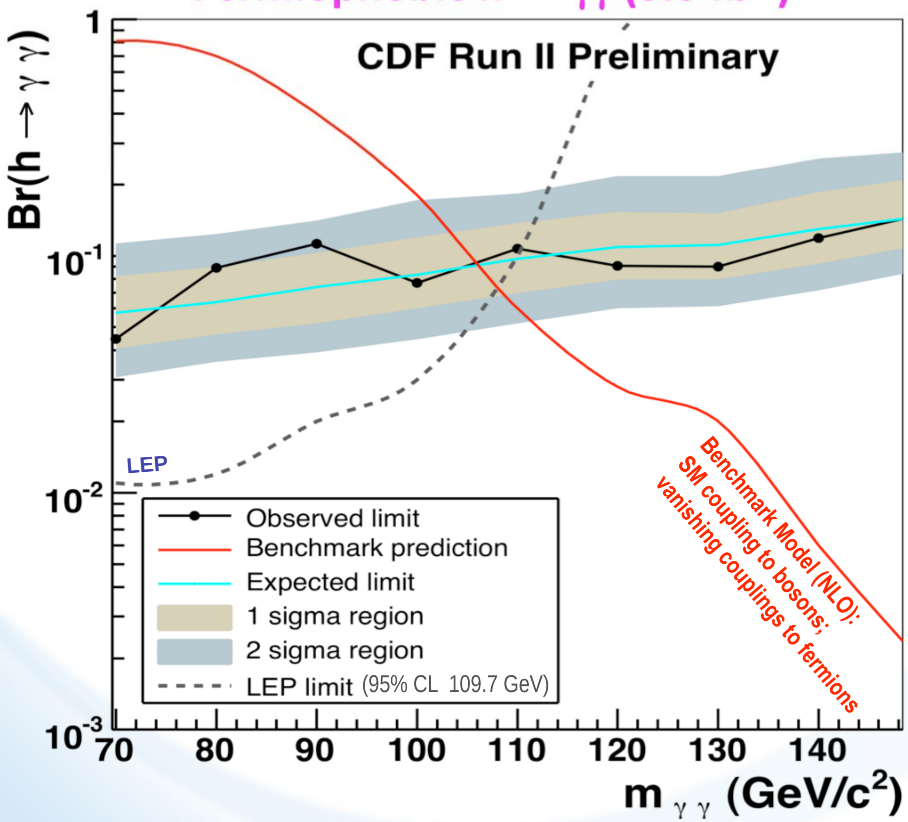
…see also M. Mulhearn's talk, this conference

Fermiophobic $h_f \to \gamma\gamma$ Search

- **DØ 4.2 fb^{-1} result**
- **Distinguish photons with misidentified jet backgrounds using NN**
  - implement energy-weighted width of DØ central preshower clusters
- **Search for excess of events in $\gamma\gamma$ mass spectrum**



Fermiophobic $h \to \gamma\gamma$ (3.0 fb^{-1})



- **For Fermiophobic couplings, limit set at 95% CL: $m_{hf} > 102.5$ GeV**
- **CDF (3.0 fb^{-1}): $m_{hf} > 106$ GeV**
  - each result has reached similar sensitivity as a single LEP experiment
- **Tevatron results: extend sensitivity for $Br(h_f \to \gamma\gamma)$ into $m_{hf} > 125$ GeV region, not accessible by LEP**