Beyond the Standard Model Higgs Searches at the Tevatron

presented by

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on behalf of the DØ and CDF Collaborations

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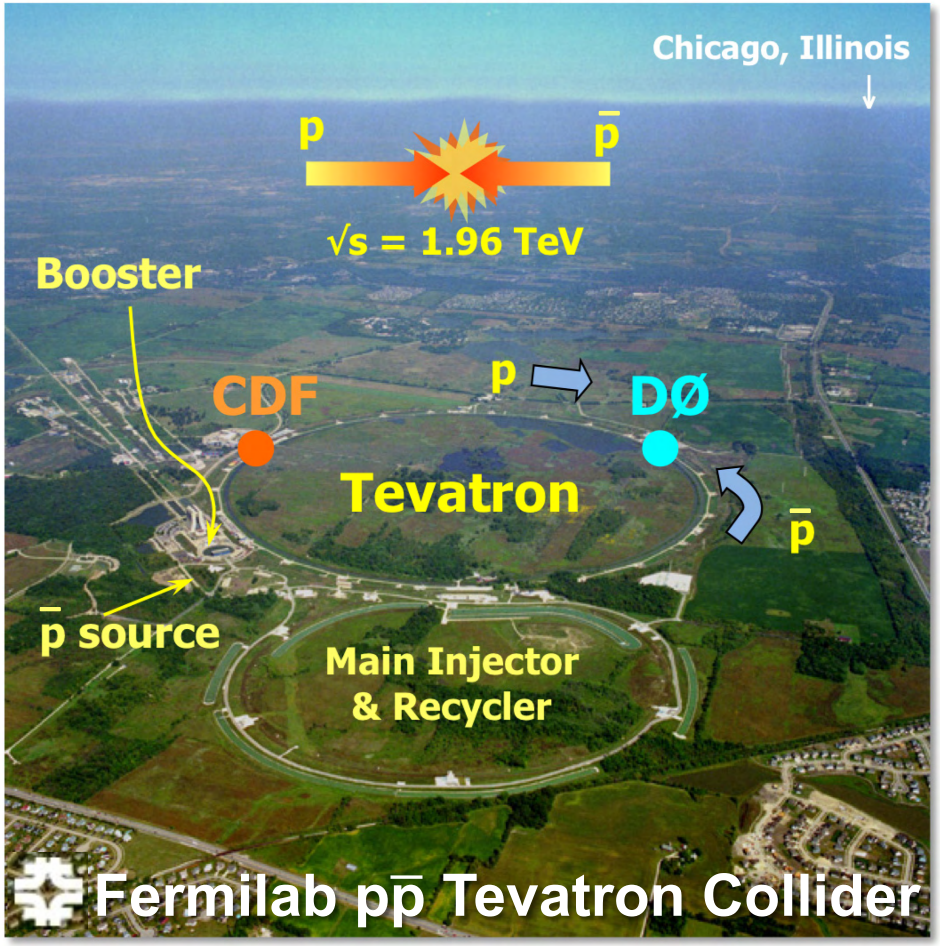
BSM Higgs: Outline

- In addition to SM searches, several extensions to SM predict Higgs
  - behave similar to SM Higgs, but exhibit different couplings
  - branching ratio of various Higgs decays can be enhanced significantly

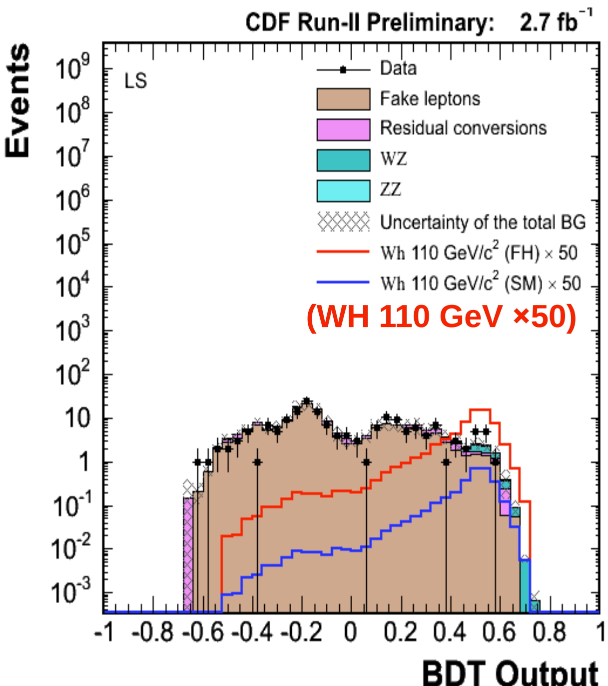
I. Fermiophobic Higgs Search
  - Higgs primarily couples to bosons and branching ratios to fermions substantially suppressed
  - depending on mass: decays mostly to γ or W bosons
    - $h_f \to \gamma\gamma$, $WH \to WWW^*$

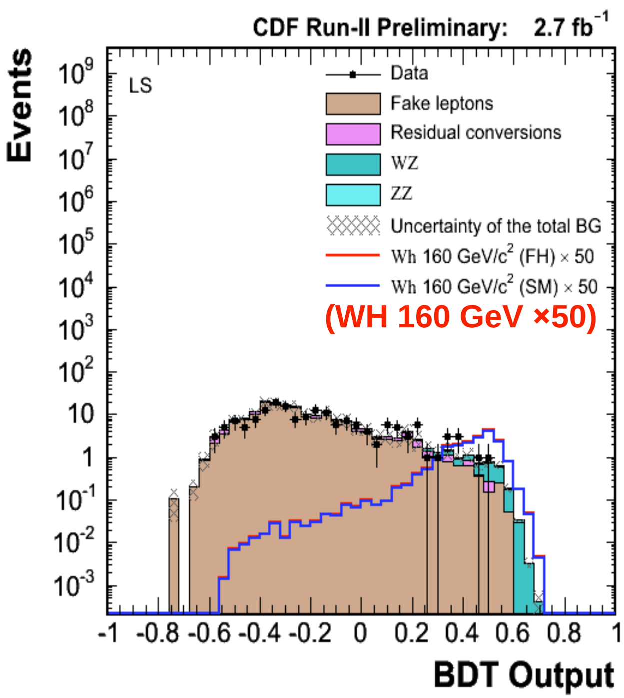
II. MSSM Higgs Search
  - 5 physical Higgs bosons
    - ϕ (= h^0, H^0, A^0) and $H^\pm$
  - main searches
    - $\phi b \to b\bar{b}b$
    - $\phi \to \tau\tau$ and $\phi b \to \tau\tau b$
    - charged Higgs in top decays (see talk on Tevatron $t\bar{t}$ Prod. results)

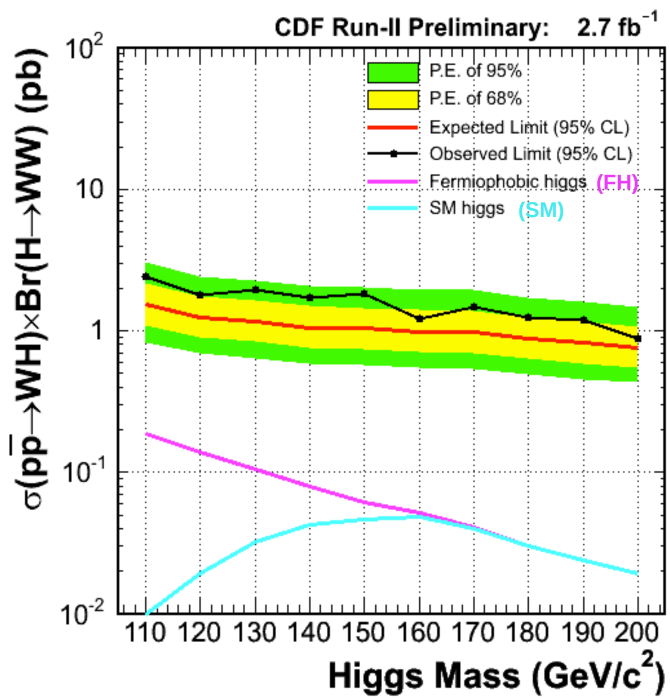


$WH \rightarrow WWW^* \rightarrow \ell^{\pm}\nu\,\ell^{\pm}\nu + X$ Search

- For Fermiophobic Higgs: $M_h > 110$ GeV $\Rightarrow$ Br($h \rightarrow WW^*$) supersedes Br($h \rightarrow \gamma\gamma$)
- Signature of associated Higgs production requires like-sign dileptons (e, μ)
  - sign from one of W's via Higgs = sign from associated W
- [updated since ICHEP '08] 2.7 fb^{-1} search: use data-driven methods in control regions to estimate fake leptons and residual photon-conversion backgrounds
- Implement Boosted Decision Tree to improve search sensitivity
  - BDT outputs: data agrees with expected background
  - ratio of $\sigma \times$ BR limit to theory prediction ~ 8.8 at $M_h = 120$ GeV (at 95% CL)

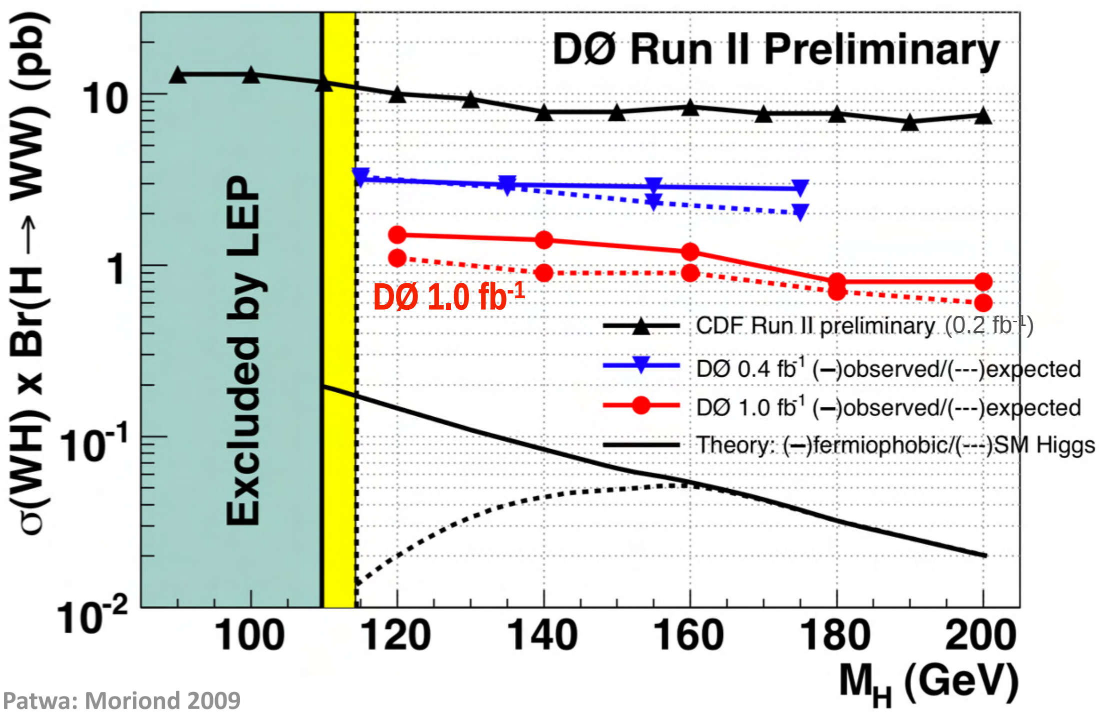


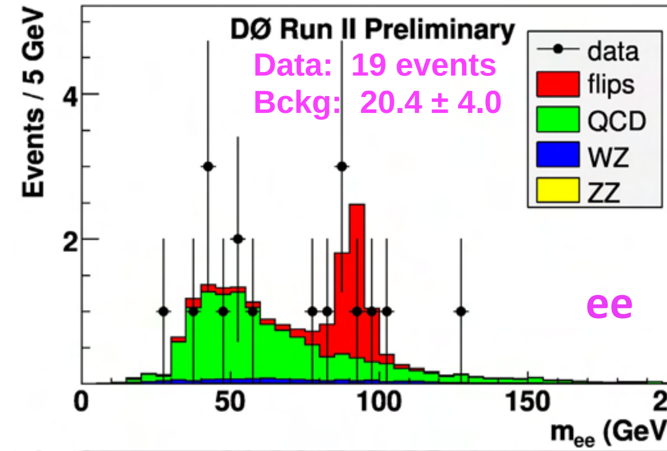


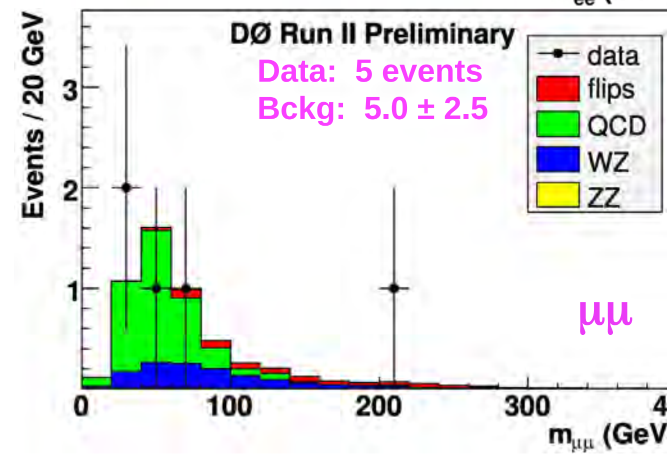


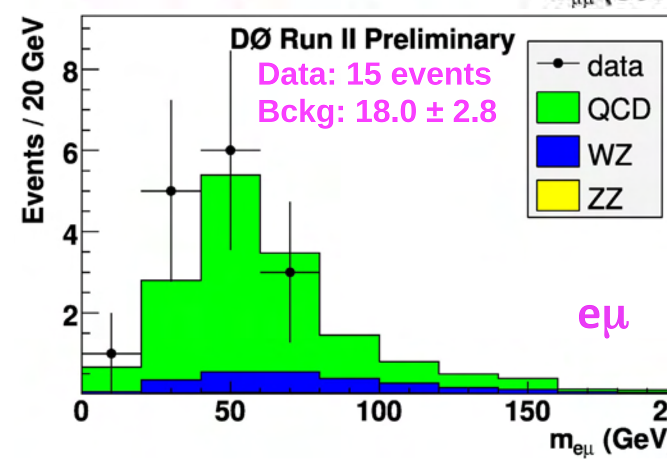
$WH \rightarrow WWW^* \rightarrow \ell^\pm\nu\,\ell^\pm\nu + X$

- Similarly, DØ considers like-sign isolated dileptons with 1.0 fb^{-1} dataset
- Likelihood discriminant used to separate signal from physics backgrounds:
  - physics: $WZ \rightarrow \ell\nu\ell\ell$, with lost lepton from Z
  - QCD: b-jets, punch-throughs, $\gamma \rightarrow e$
  - charge flips: mainly from $Z/\gamma^* \rightarrow \ell\ell$
- For each final state, data agrees with expected backgrounds $\Rightarrow$ similar sensitivity for $\sigma \times Br$





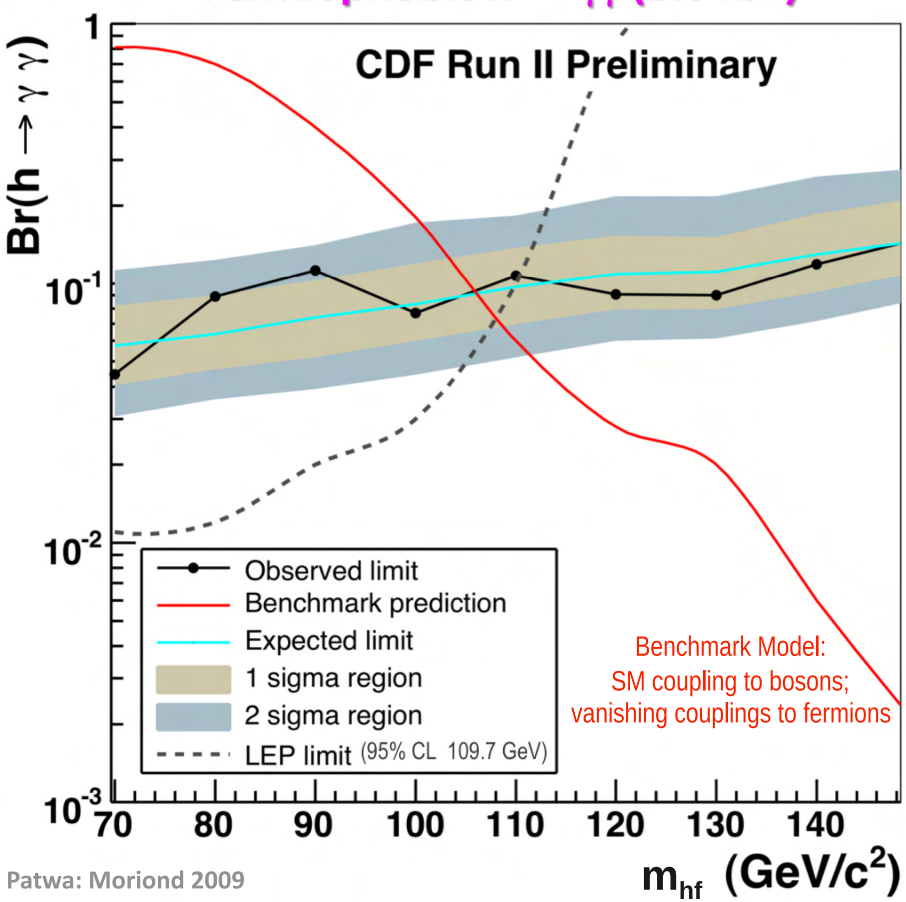


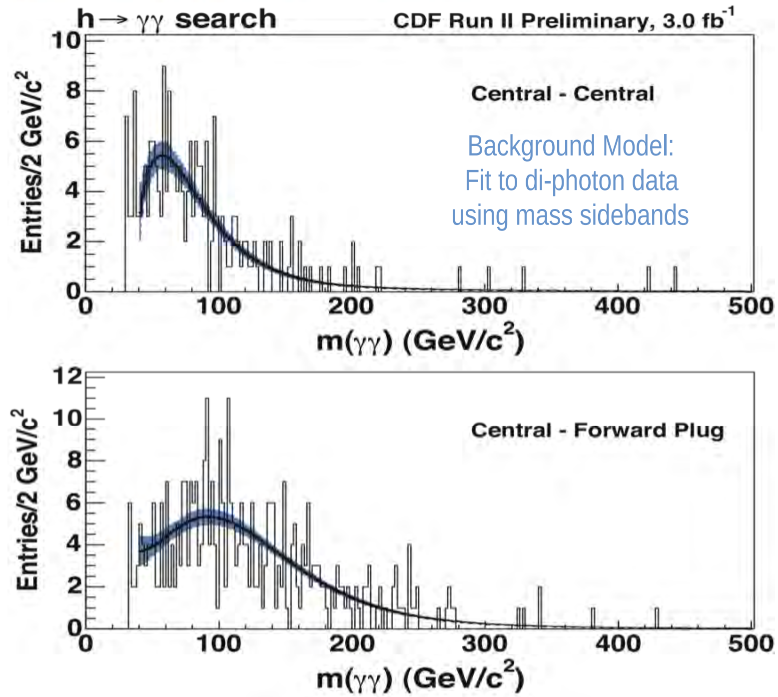


Fermiophobic $h_f \rightarrow \gamma\gamma$ Search

- [updated] 3.0 fb^{-1} result roughly doubles acceptance by including one forward γ
- $M_{\gamma\gamma}$ fitted with smooth function
  - peak hunt: no evidence of narrow resonance in di-photon data spectrum

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

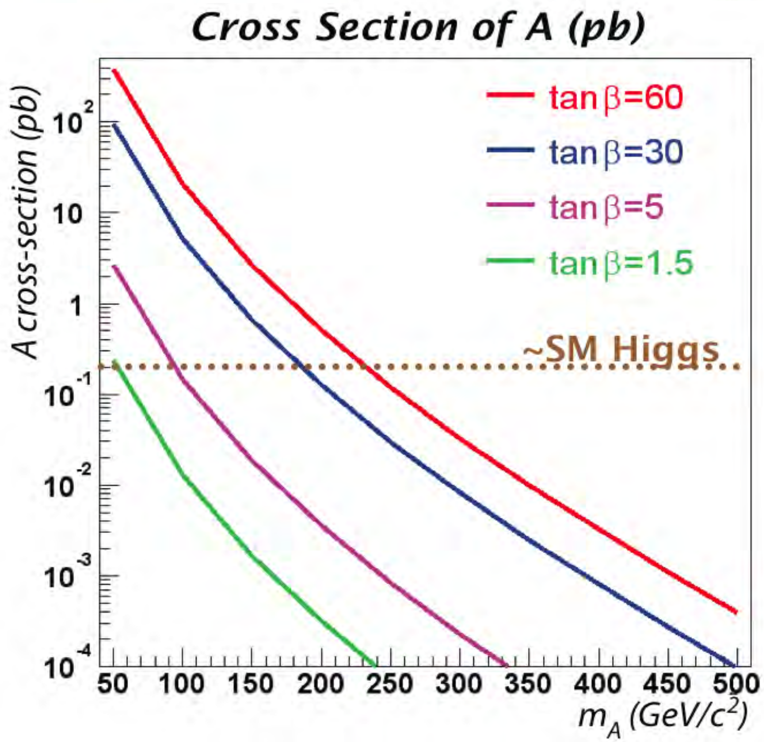


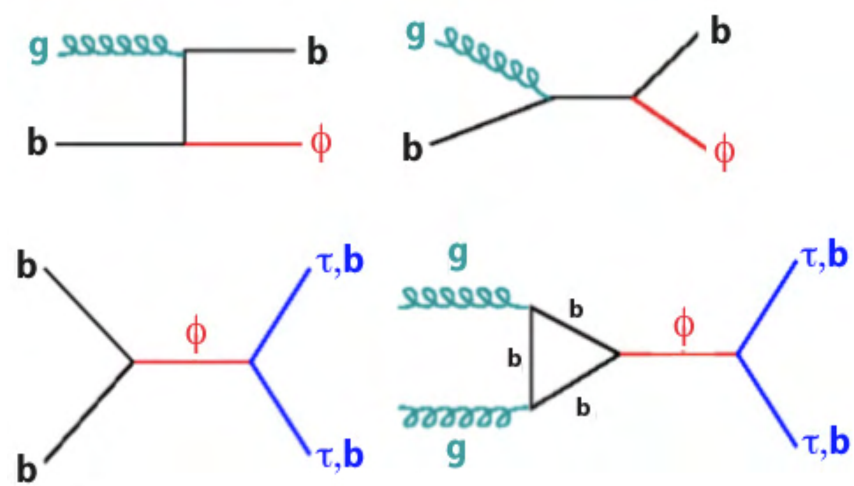


- For Fermiophobic couplings, limit set at 95% CL: $m_{hf} > 106$ GeV
  - for model, strongest limit to date by hadron collider
- DØ (1.1 fb^{-1}): $m_{hf} > 100$ GeV
  - new result expected soon
- Tevatron results: extend sensitivity for $Br(h_f \rightarrow \gamma\gamma)$ into $m_{hf} > 130$ GeV region, not accessible by LEP

Higgs bosons in the MSSM

- MSSM Higgs requires 2 doublets
  - yields: ϕ (= 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 doublet)
- Radiative corrections introduce dependence on additional SUSY parameters
- $\sigma(p\bar{p} \rightarrow h/H/A) \propto \tan^2 \beta$
  - at large $\tan\beta$ (low M_A) $\Rightarrow$ enhanced production cross-section
- 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)



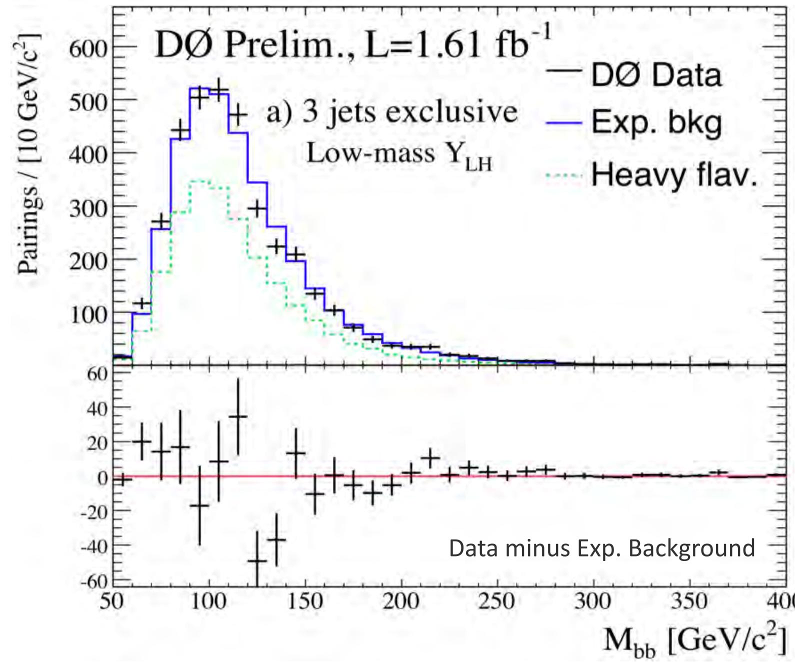


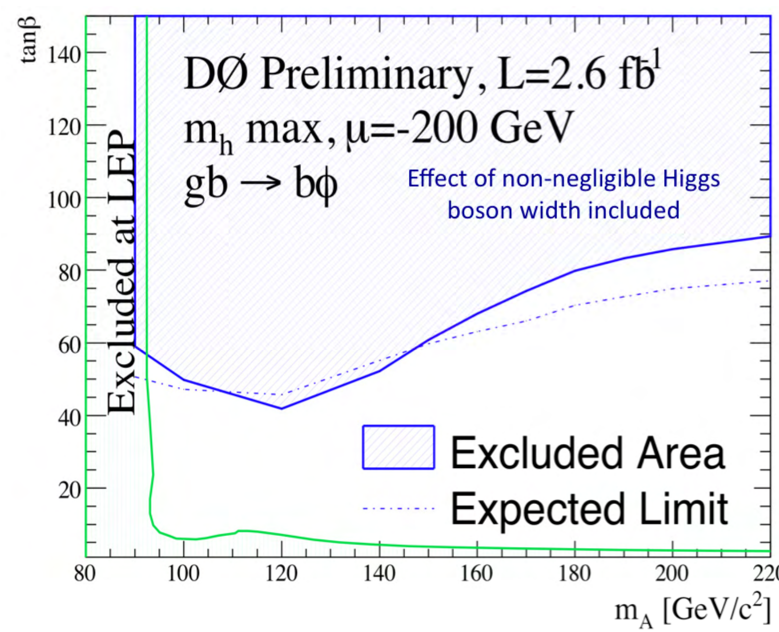
φ = h/H & A

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

- $\phi \rightarrow b\bar{b}$ search difficult due to large multi-jet background
  - consider ϕ produced in association with at least one b-jet
- 2.6 fb^{-1} data requires 3 b-tagged jets via NN b-tagger
  - likelihood discriminates b-jets via Higgs signal from multi-jet backgrounds
- Improve sensitivity by separating into 3, 4, and 5-jet channels
- No excess in di-jet invariant mass: 95% C.L. exclusion limits in MSSM benchmark parameter space

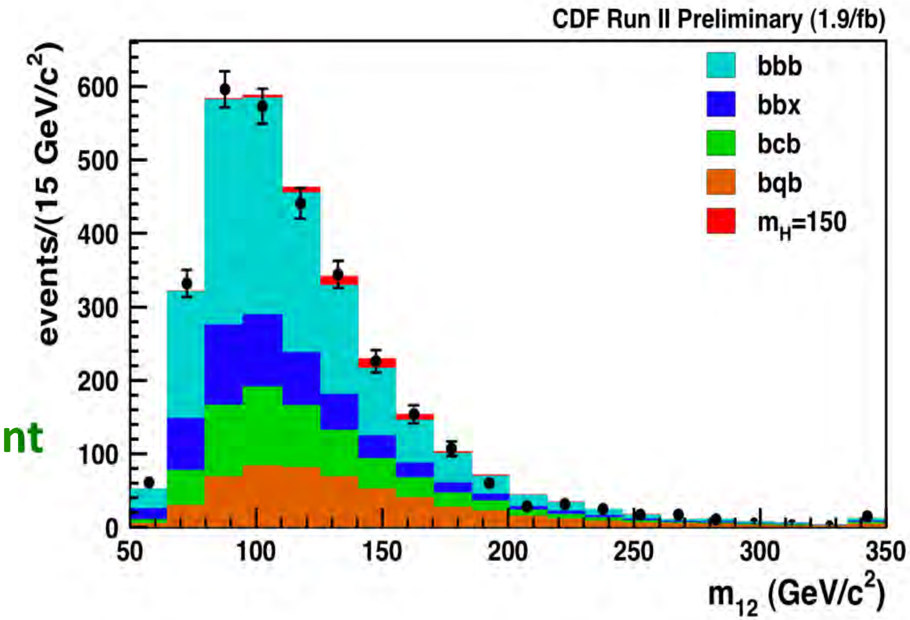
Higgs mass term, $\mu < 0$: enhanced production for 3b mode gives strongest limits

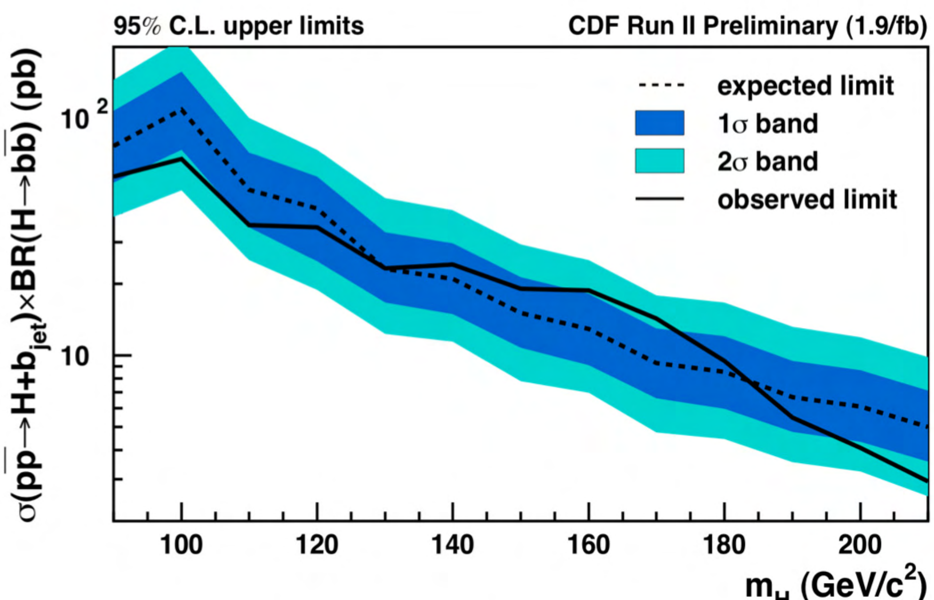


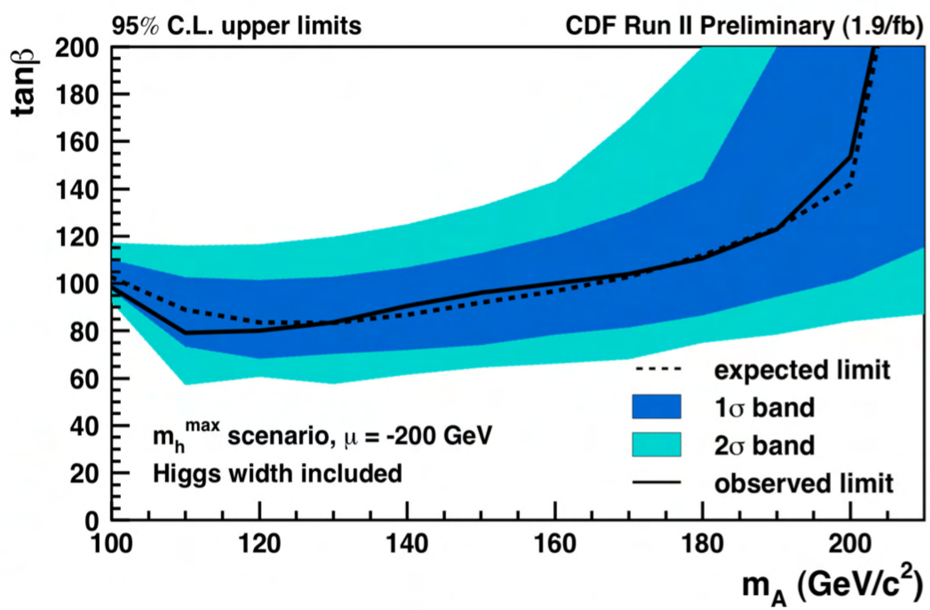


CDF: $\phi b \rightarrow b\bar{b}b$ Search

- Require 3 b-tagged jets with 1.9 fb^{-1} data
- Search for enhancements in mass of 2 lead jets, m_{12}
- Fit 2- and 3-tag distributions to estimate quark content from heavy-flavor multi-jet backgrounds
  - vertex mass fits $\Rightarrow$ set mass-dependent cross section limits
  - translate limits in (M_A, $\tan\beta$) plane





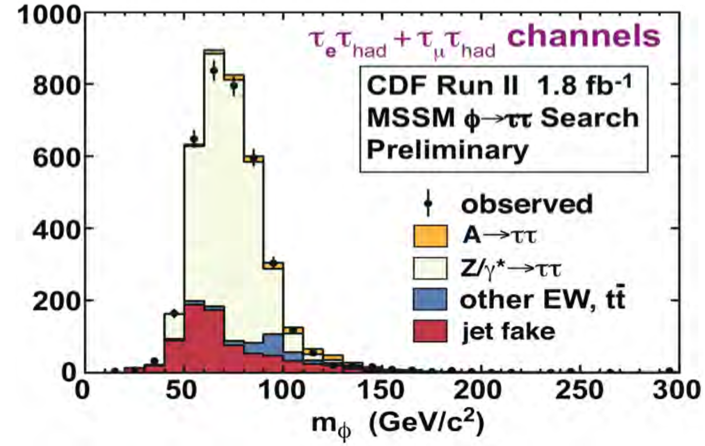


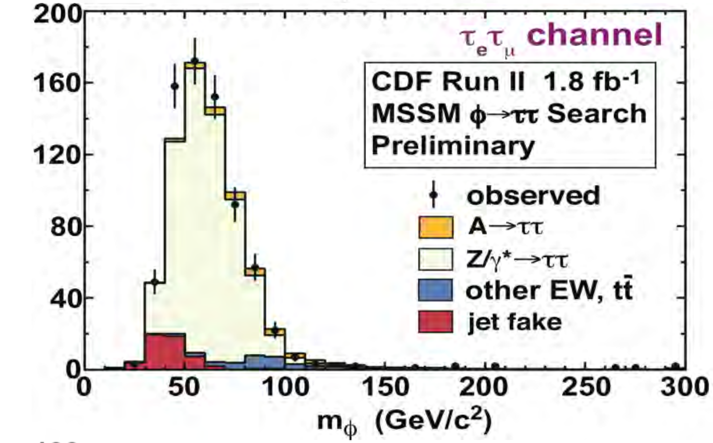
CDF: $\phi \rightarrow \tau\tau$ Search

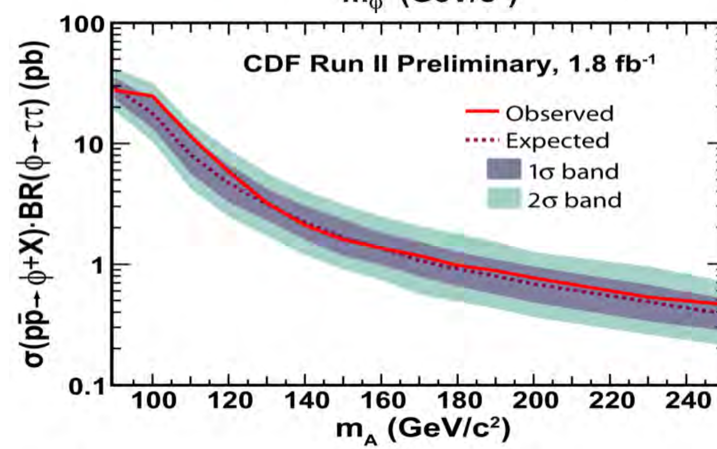
- CDF considers $\tau_e\tau_{had}$, $\tau_\mu\tau_{had}$, and $\tau_e\tau_\mu$ channels with 1.8 fb^{-1} data, selected by:
  - isolated e or μ: opposite sign (OS) from hadronic τ
  - τ's selected using variable-size cone algorithm
  - W+jets background removed by requirement on relative direction of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

Final State: (1.8 fb^{-1})	Sum Background	Data
$\tau_\mu\tau_{had}$	1750.8 ± 41.8	1666 ± 41
$\tau_e\tau_{had}$	1921.1 ± 43.8	1979 ± 45
$\tau_e\tau_\mu$	701.9 ± 26.5	726 ± 27

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

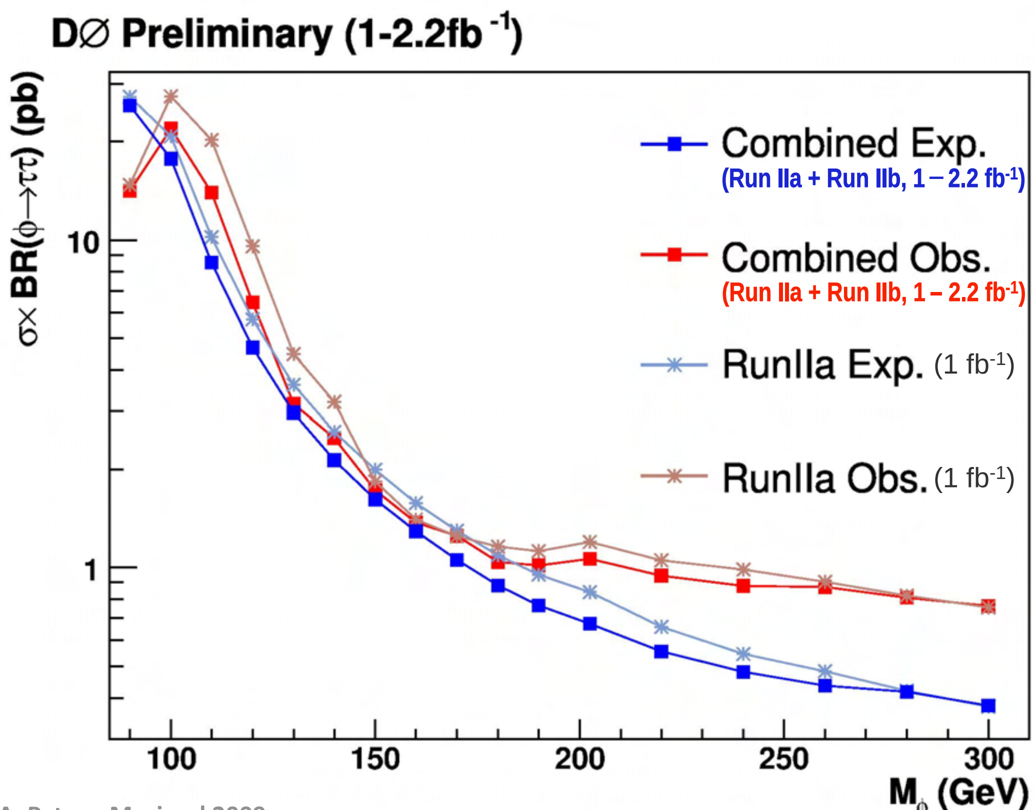


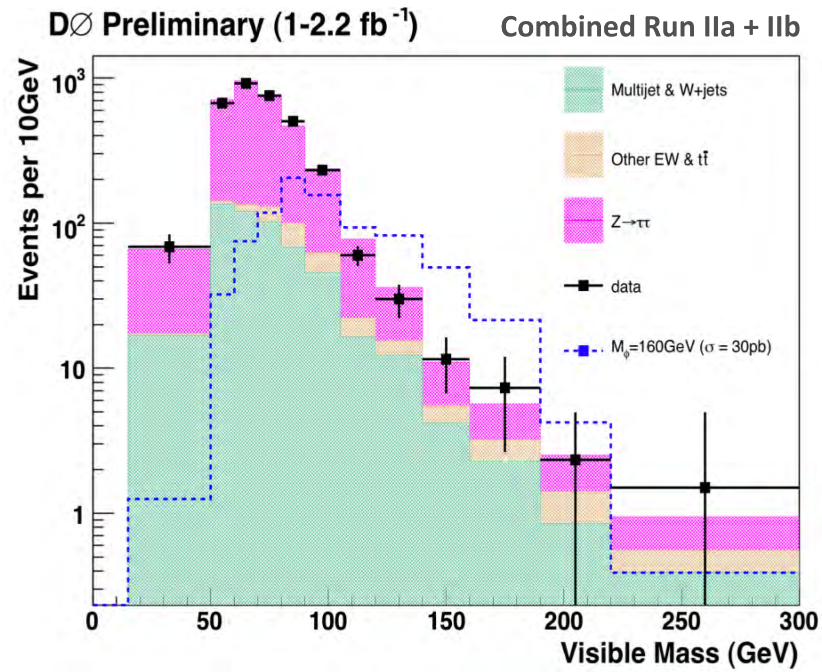




DØ: Inclusive ττ Search

- 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 ⇒ reject W+jets

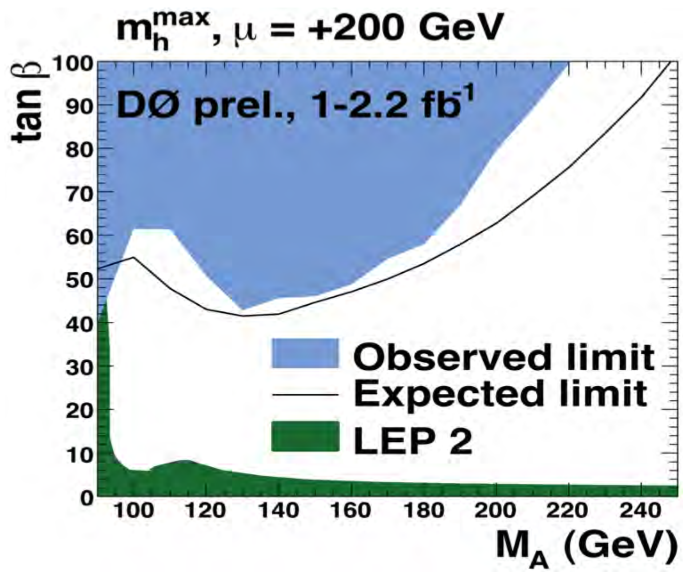


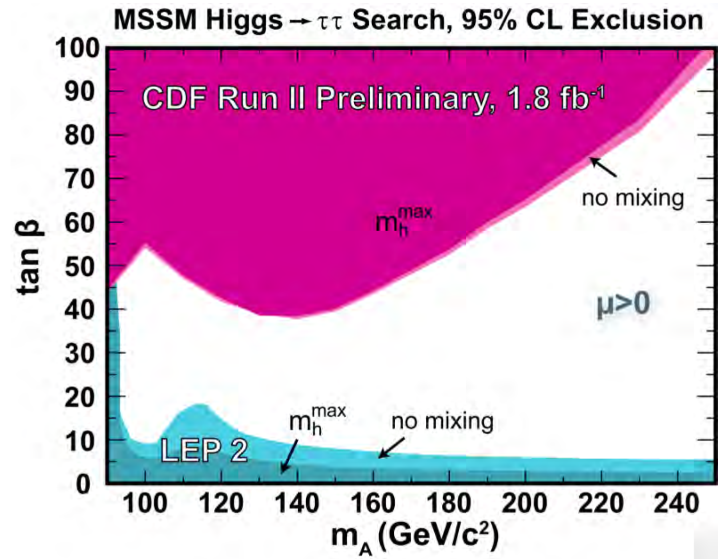


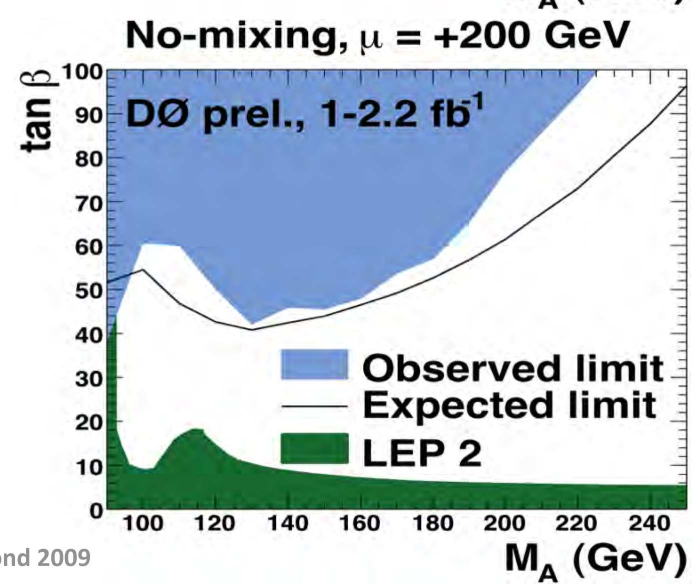
- No excess in data across visible mass spectrum
  - extract upper limits on σ × BR as function of φ mass
    - 2.2 fb^{-1} result: ~10 - 20% improvement
    - dominant systematic: τ-ID (4 - 8%)

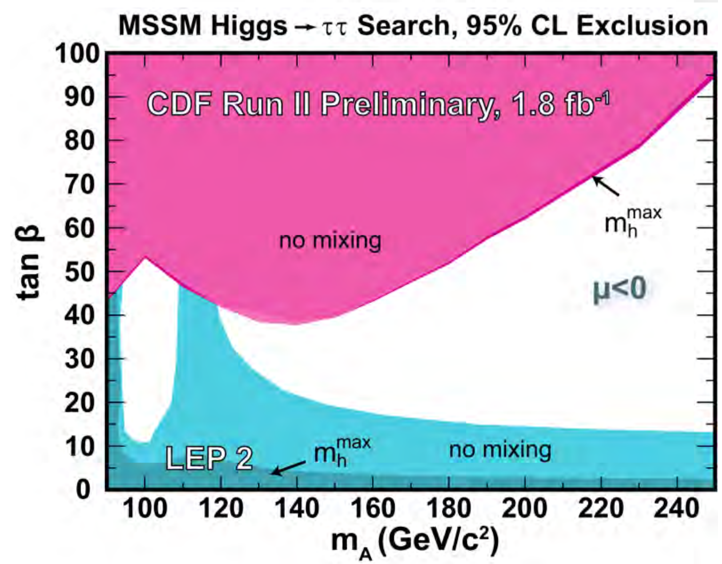
$\tau\tau$ Search: MSSM Interpretation

- Interpret limits into MSSM m_h^{max} and no-mixing benchmark scenarios
- Exclusion results similar for each experiment
  - reached sensitivity $\tan\beta \sim 40 - 50$ for $M_A < 180$ GeV



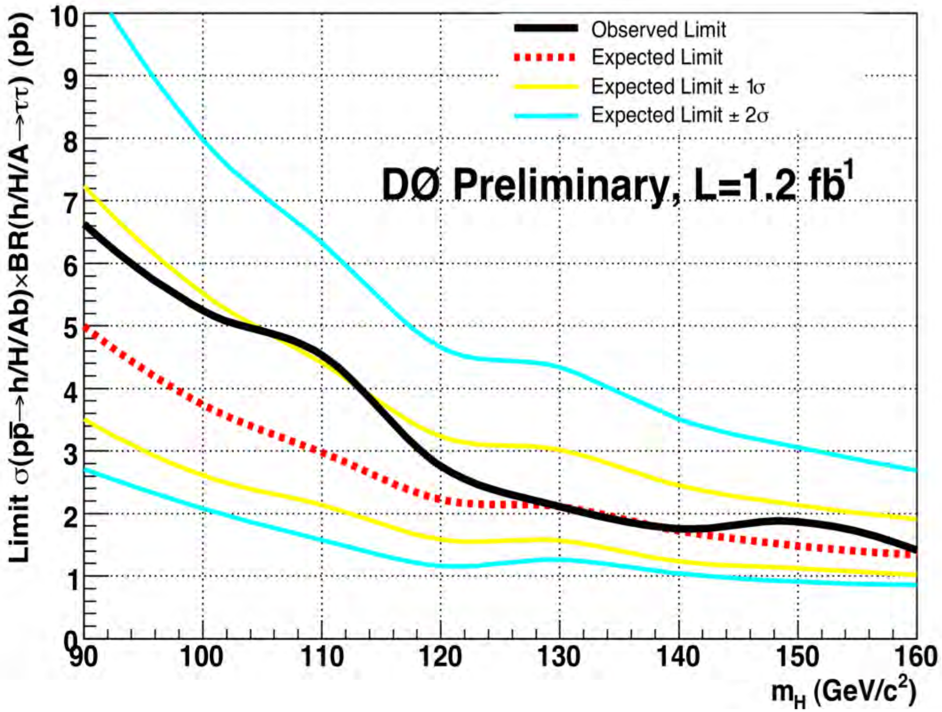


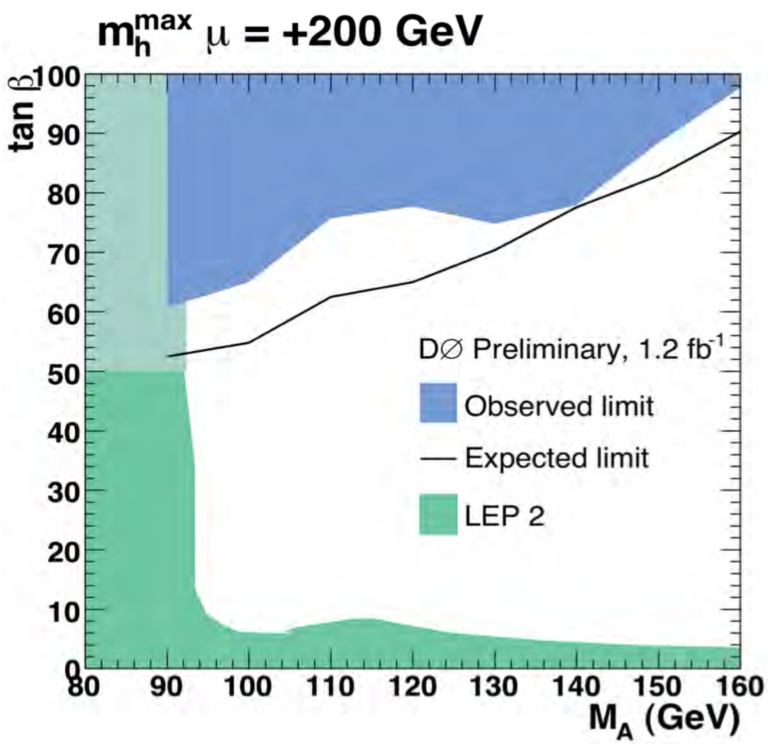




$\phi b \to \tau\tau b$ Search: $\sigma \times BR$ and MSSM Limits

- 1.2 fb^{-1} search considers $\phi b \to \tau_\mu \tau_{had} b$
  - use developed techniques from both $\phi \to \tau\tau$ and $\phi b \to b\bar{b}b$ searches
    [published 330 pb^{-1} result: PRL 102, 051804 (2009)]
- Pre b-tag: dominated by QCD multi-jet and $Z \to \tau\tau$, $\mu\mu$ backgrounds
- Post b-tag: dominated by QCD multi-jet and top events
- Limits calculated for $\sigma \times BR$ and translated into MSSM exclusions
  - complementary to $\phi \to \tau\tau$ channel as it does not suffer from $Z \to \tau\tau$ background





Contribute to overall Tevatron Sensitivity: $\mu > 0$, τ mode competitive to b mode despite 1:9 BR

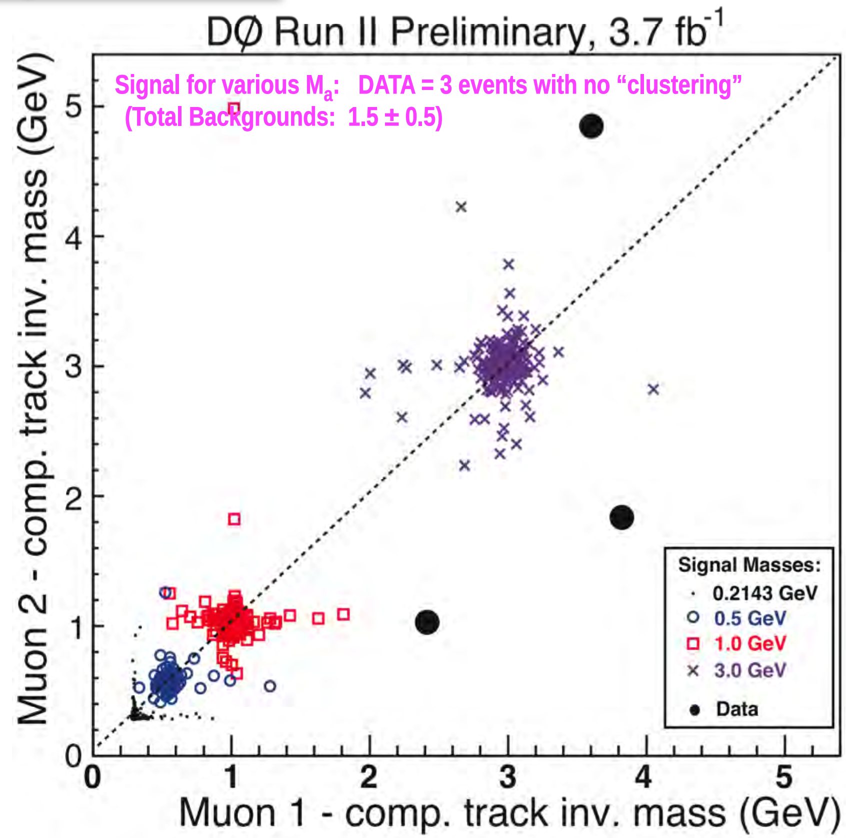
DØ: NMSSM $h \rightarrow aa$ Search (I)

- [new search] next-to-MSSM Higgs decay search, 3.7 fb^{-1} data [Theory: Nucl. Phys. B 492, 21 (1997)]
  - $h \rightarrow b\bar{b}$ branching ratio greatly reduced
  - h dominantly decays to pair of pseudo-scalar Higgs "a": $h \rightarrow aa$
  - general LEP search sets limit: $M_h > 82$ GeV [Eur. Phys. J. C27, 311 (2003)]

For Masses: $2M_\mu < M_a < \sim 2M_\tau$ (~3.6 GeV)

- $BR(a \rightarrow \mu^+\mu^-) \sim 100\%$: 4μ final state
  - signature: two pairs of extremely collinear muons due to low M_a
- Require "companion-track" for each of two μ's
  ⇒ redefine object ID: μ isolation for "pair"

Background Events	4μ Final State
QCD background [μ's from π/K in-flight decays or μ's from heavy-flavor decays]	1.2 ± 0.4
$Z/\gamma^* \rightarrow \mu\mu$ + jets	0.25 ± 0.03
Data	3

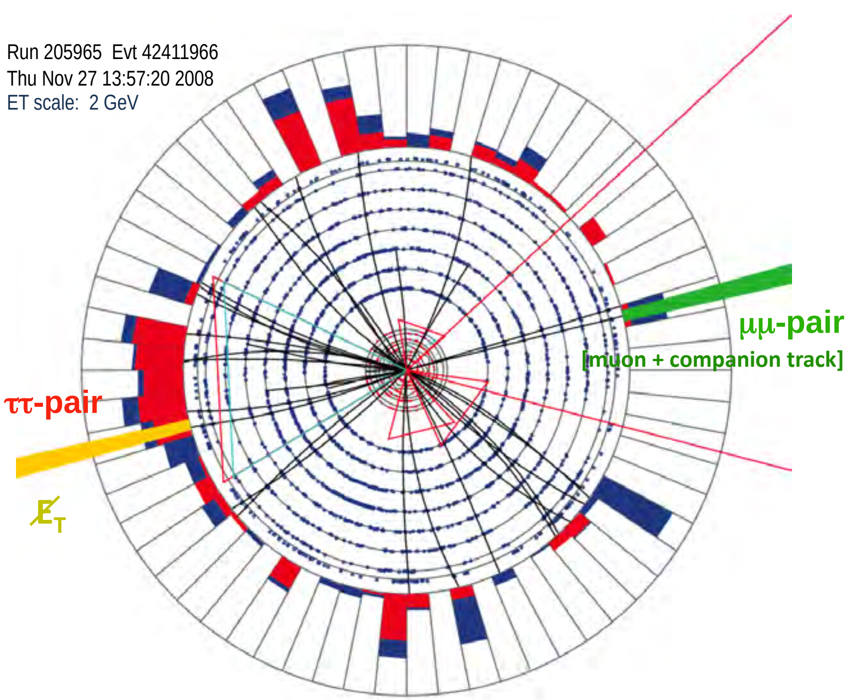


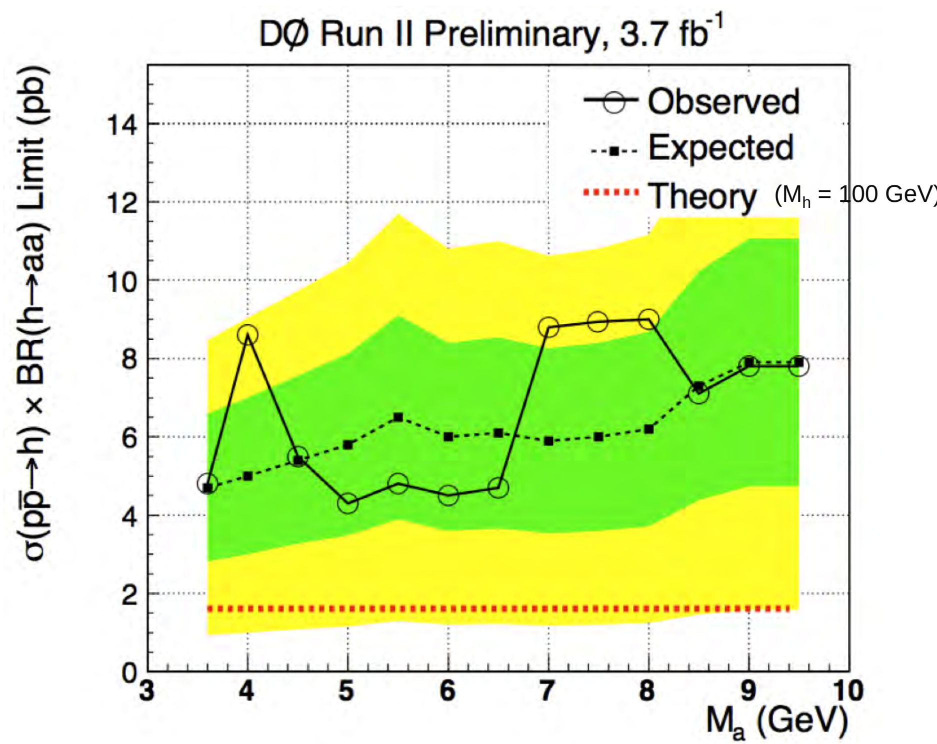
Assume Higgs cross-section of ~1000 fb at M_h = 120 GeV and $BR(h \rightarrow aa) \sim 1$ ⇒ 95% CL exclude: $BR(a \rightarrow \mu\mu) \gtrsim 10\%$

DØ: NMSSM $h \rightarrow aa$ Search (II)

For Masses: $2M_\tau < M_a < 2M_b$ (~9.0 GeV)

- BR($a \rightarrow \mu^+\mu^-$) suppressed and "a" dominantly decays to tau pairs
  - $2\mu 2\tau$ final state: one pair of collinear muons and large $\not{E}_T$ from $a \rightarrow \tau^+\tau^-$ decay
- Select back-to-back $\mu\mu$- and $\tau\tau$-paired topologies: $\Delta\phi(\not{E}_T, 2\mu) > 2.5$
- Fit signal di-muon mass: data consistent with expected backgrounds within $\pm 2\sigma$ window





Current Tevatron limit: × ~4 larger than expected Higgs production
Tevatron: requires $\mathcal{O}$(~40 fb^{-1}) data to reach sensitivity at expected signal level
LHC: need $\mathcal{O}$(~1 fb^{-1}) due to × ~50 larger Higgs cross section

Closing Summary

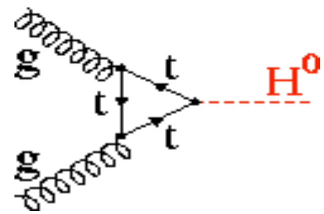
- CDF and DØ actively searching for Higgs boson in models beyond SM
  - results with up to 3.7 fb^{-1} reported with no excess observed in data
- Fermiophobic Higgs
  - strong mass-dependent limits established for $h_f \rightarrow \gamma\gamma$, $WH \rightarrow WWW^*$ searches
    - Higgs decays also contribute to SM Higgs searches
- MSSM Higgs
  - 95% CL exclusions in MSSM parameter space calculated for neutral Higgs search
    - reached sensitivity $\tan\beta \sim 40 - 50$ for $M_A < 180$ GeV
    - combination of different channels and with experiments is in progress
- NMSSM Higgs
  - new search at Tevatron, offers promising prospects for Higgs physics at LHC
- Tevatron delivered > 6.0 fb^{-1} of Run II data ...and more coming
  - updated results from searches expected soon
  - expect sensitivity to continually improve
    - if a key value of (M_A, $\tan\beta$) achieved, aim for observation

CDF: *http://www-cdf.fnal.gov/physics/new/hdg/hdg.html*
DØ: *http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm*

Reference Slides

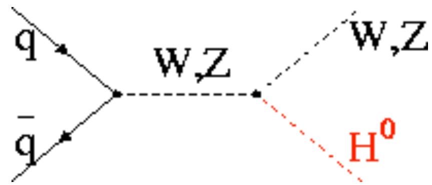
Ref: SM Higgs Production at Tevatron

- Gluon fusion: $gg \rightarrow H$



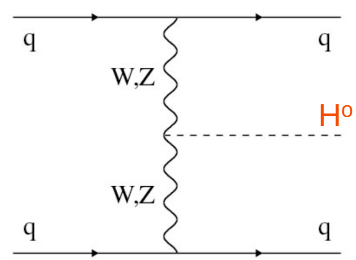
σ = 0.70 pb
for M(H) = 120 Gev/c^2
with QCD NLO correction

- Higgsstrahlung: $q\bar{q} \rightarrow VH$
  (V=W, Z)



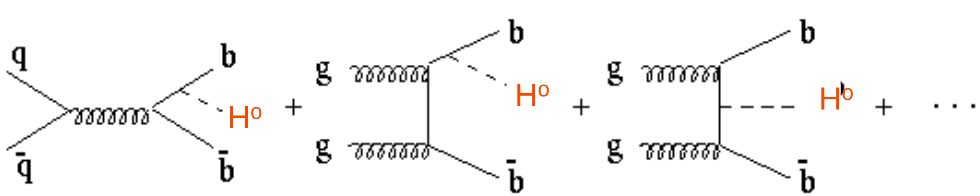
WH: σ = 0.16 pb
ZH: σ = 0.10 pb

- Vector Boson Fusion: $q\bar{q} \rightarrow q\bar{q}H$



σ = 0.10 pb

- Radiation off heavy quark: $q\bar{q} \rightarrow t\bar{t}H,\ b\bar{b}H$



σ = 0.004 pb

τ properties

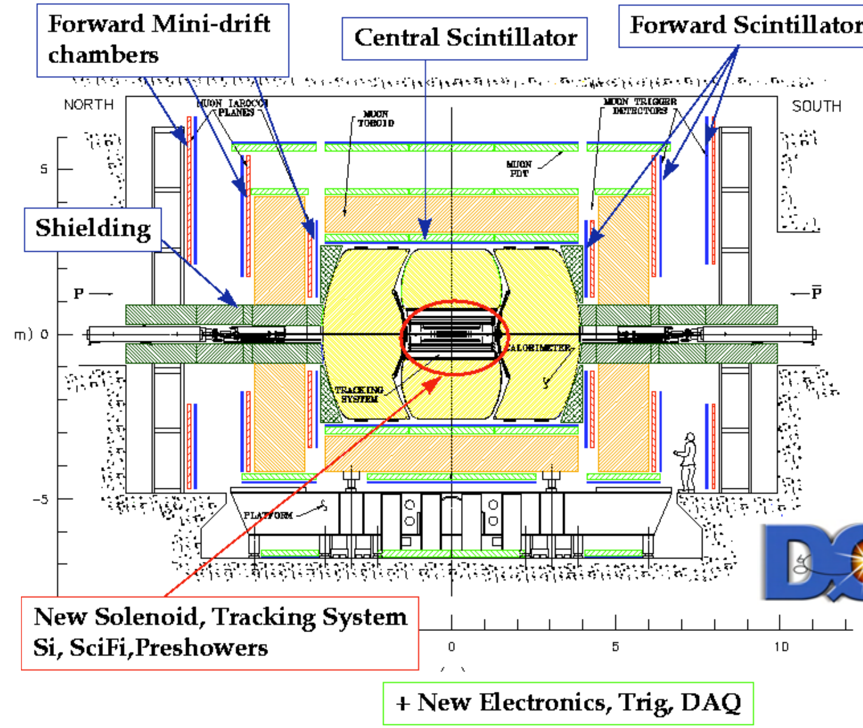
- Mass = 1.78 GeV; Short lifetime, $c\tau$ = 87.11 μm
  - $\mathcal{O}(10^{-13}$ s)
  - taus decay prior to reaching any detector active element
- Main decay channels:

τ Decay Final State	BR (%)	Decay Type		
$e + \nu_e + \nu_\tau$	17.8	Leptonic (35.2%)	τ_e	Detect using standard electron / muon ID algorithms
$\mu + \nu_\mu + \nu_\tau$	17.4		τ_μ	
$\pi(/K) + \nu_\tau$	11.8	1-prong (48.7%)	τ_h	Need dedicated tau ID to measure "narrow", low multiplicity jet objects
$\pi(/K) + \nu_\tau + \geq 1\pi^0$	36.9			
$\pi\pi\pi + \geq 0\pi^0 + \nu_\tau$	13.9	3-prong		

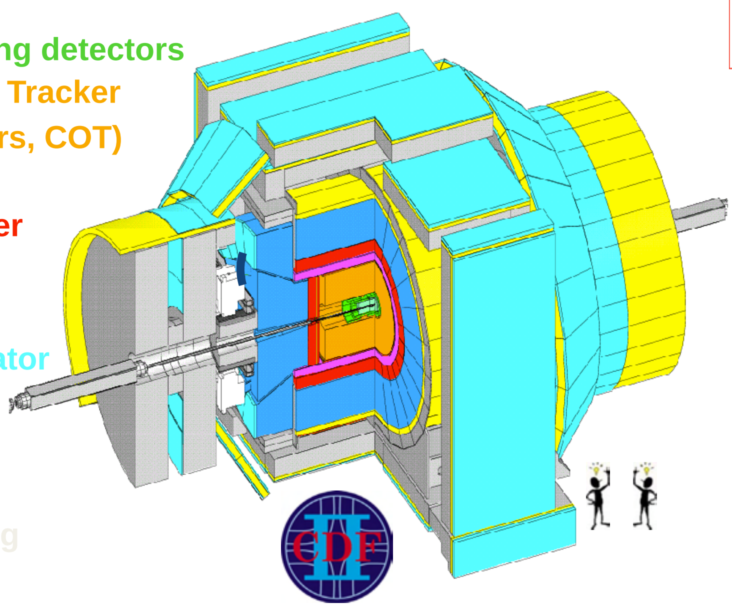
- Taus decay ~17% to e, μ; ~65% to hadrons
- For Higgs to di-tau final state, three channels studied
  - $\tau \rightarrow \mu\,\nu\nu$ + $\tau \rightarrow$ hadrons ν : $\tau_\mu\tau_h$
  - $\tau \rightarrow e\,\nu\nu$ + $\tau \rightarrow$ hadrons ν : $\tau_e\tau_h$
  - $\tau \rightarrow e\,\nu\nu$ + $\tau \rightarrow \mu\,\nu\nu$: $\tau_e\tau_\mu$

Detectors

- silicon detector and scintillating fiber tracker in 2.0 T solenoidal field
- liquid argon/uranium calorimeters: central (CC) and two forward, end (EC) calorimeters
- muons: scintillators and mini-drift tubes, coverage up to $\eta = 2.0$



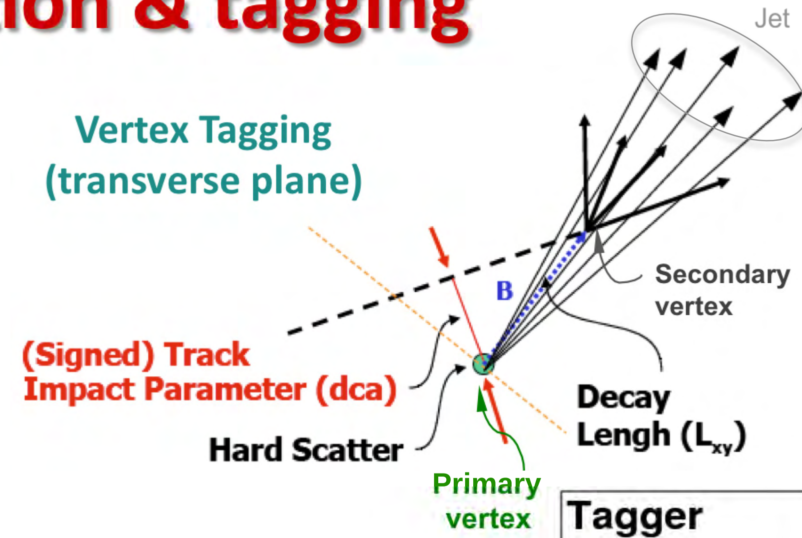
- Silicon tracking detectors
- Central Outer Tracker (drift chambers, COT)
- Solenoid Coil
- EM calorimeter
- Hadronic calorimeter
- Muon scintillator counters
- Muon drift chambers
- Steel shielding



- silicon and central outer tracker system in 1.4 T magnetic field
- lead (iron) scintillating calorimeter for EM (hadronic) showering
- forward end-plug cal, $\eta \rightarrow 3.0$
- muon coverage to $\eta = 1.0$

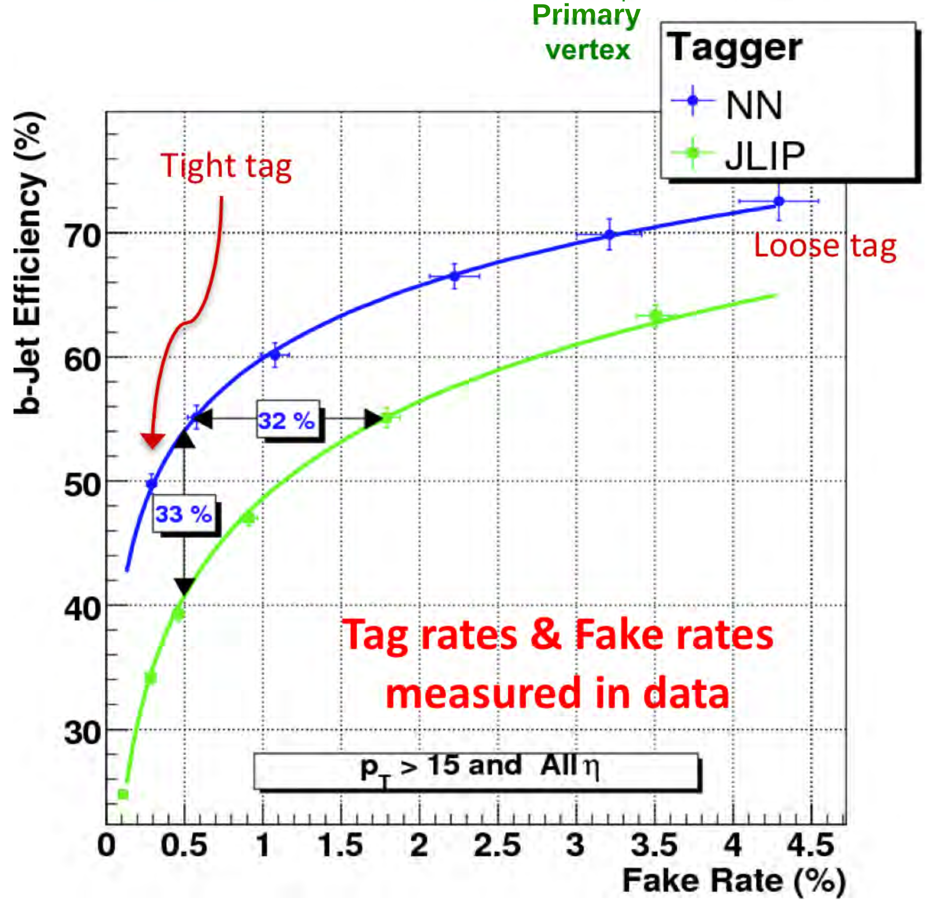
b-jet identification & tagging

- B-hadrons are long lived
  - search for displaced vertices & tracks with large impact parameters
- Tag via neural network (NN) tagger
  - combines several dca & vertex based tagging algorithms



Neural Network Input Variables

- vertex mass
- number of tracks for vertex
- vertex decay length significance
- χ^2/d.o.f. of vertex
- number of vertices
- combined impact parameter significances from two methods

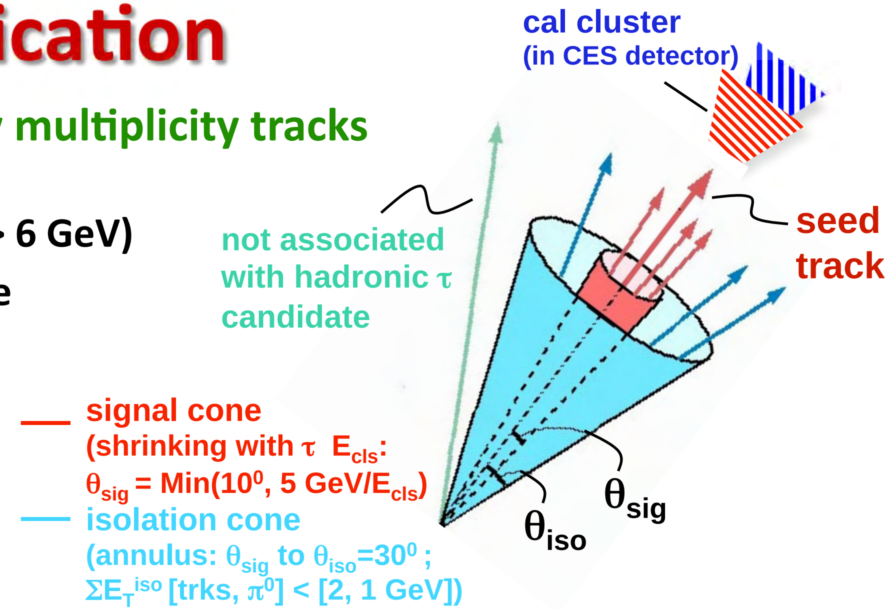


Loose tag: ~70% eff; ~4.5% mis-tag
Tight tag: ~48% eff; ~0.3% mis-tag

τ Identification

— narrow calorimeter clusters matched to low multiplicity tracks

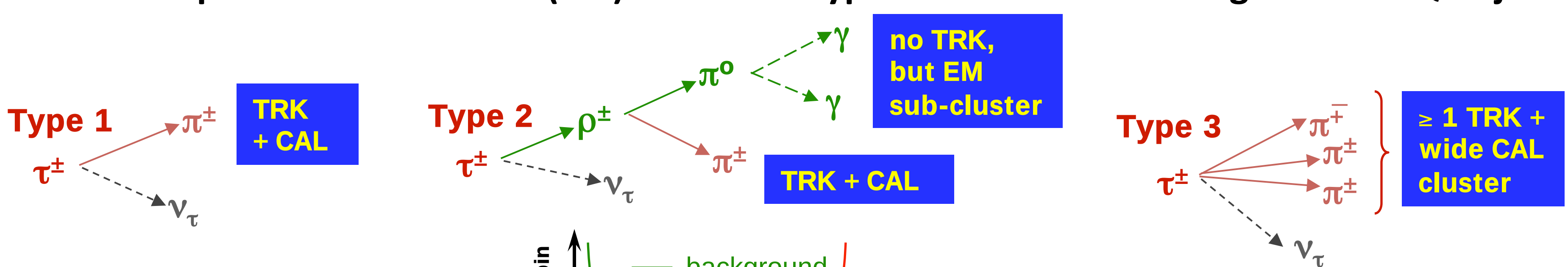
- define [shrinking] signal and isolation cones around seed track's axis (= highest p_T track; > 6 GeV)
- # of tracks inside signal cone = τ decay mode
- add π^o info to track-cal cluster $\Rightarrow$ consistent with τ mass
- EM-fraction < 0.8 $\Rightarrow$ remove electrons
- τ-id based on "cuts" to key variables (e.g., sum of isolation E_T, p_T tracks inside cone)

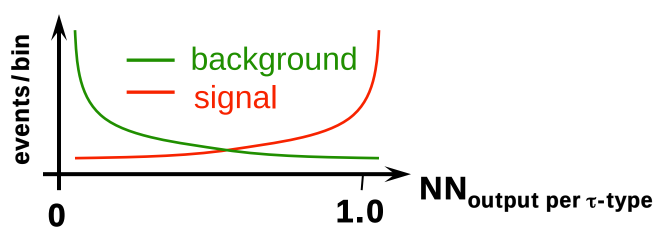


— narrow calorimeter energy clusters matched to tracks, with or without EM subclusters

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

- $\pi\nu$-like (type 1), $\rho\nu$-like (type 2), and 3-prongs (type 3)
- implement neural nets (NN) for each τ-type to discriminate τ signal from QCD jets





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
  - $m_{\tilde{g}}$ 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

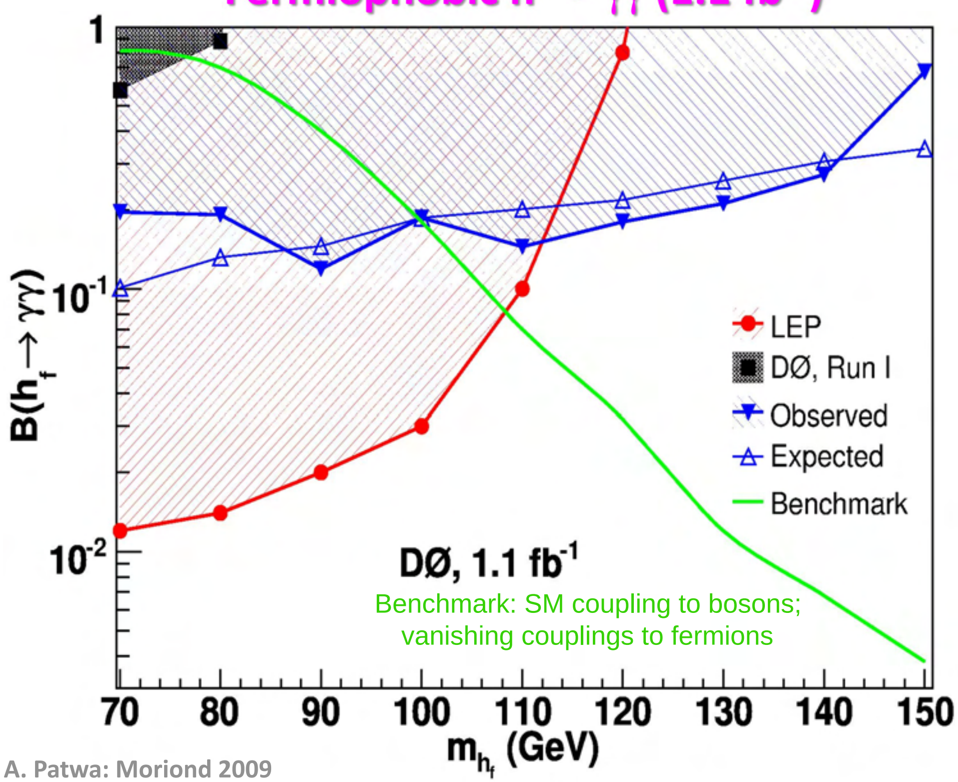
Constrained Model: Unification of SU(2) and U(1) gaugino masses

	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

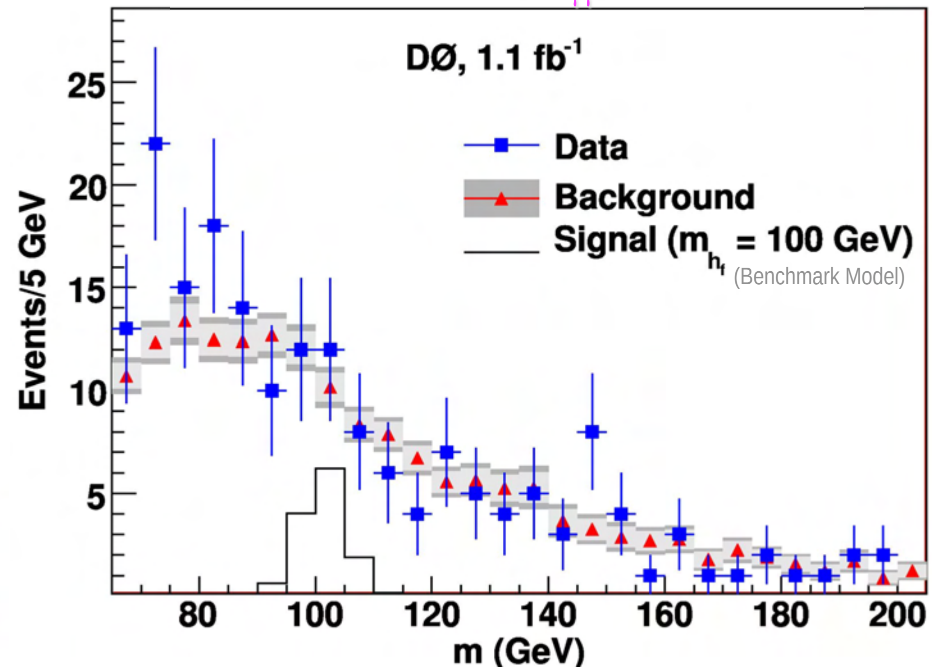
Fermiophobic $h_f \rightarrow \gamma\gamma$ Search

- 1.1 fb^{-1} result: PRL 101, 051801 (2008)
- Distinguish photons with misidentified jet backgrounds by using NN
  - implement energy-weighted width of DØ central preshower clusters
    - ✦ exploit fact that preshower width narrower for photons than for jets

Fermiophobic h → γγ (1.1 fb^{-1})



Di-photon Mass ($M_{\gamma\gamma}$) Distribution



- Search for excess of events in γγ mass spectrum
- Exclude Fermiophobic Higgs of mass up to 100 GeV at 95% C.L.
- Extends sensitivity for $Br(h_f \rightarrow \gamma\gamma)$ into m_{hf} > 130 GeV region, not accessible by LEP

A. Patwa: Moriond 2009

Multivariate Methods: Variables

CDF: $WH \rightarrow WWW^*$ Search

8-variable Boosted Decision Tree (BDT)
1^{st} lepton p_T (p_{T1})
2^{nd} lepton p_T (p_{T2})
Dilepton System p_T (p_{T12})
Missing E_T (MET)
Dilepton Mass
MetSpec: MET if $\Delta\phi$(MET, ℓ or jet) > $\pi/2$ MET*sin($\Delta\phi$(MET, ℓ or jet)); otherwise
H_T (sum of p_{T1}, p_{T2}, jets E_T, MET)
N_{jets} for jet's E_T > 15 GeV

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

6-variable Likelihood Discriminant
$\Delta\eta$ of 2-jets in the pair
$\Delta\phi$ of 2-jets in the pair
angle: ϕ(lead jet, total pT of jet)
Momentum balance: $\lvert p_{b1}-p_{b2}\rvert / \lvert p_{b1}+p_{b2}\rvert$
combined rapidity of jet pair
event sphericity

DØ: $WH \rightarrow WWW^*$ Search

2D-Likelihood Discriminant
$\Delta\phi(l_1,l_2)$ = opening angle between leptons
MET [for ee and eμ], Hadronic MET (for all)
Min Angle: $\Delta\phi$(l, MET) [for $\mu\mu$]
$M(l_1,l_2)$ = Invariant mass between leptons

DØ: $h_f \rightarrow \gamma\gamma$ Search

5-variable Artificial NN
Σp_T(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 associated CPS clusters with EM
Energy-weighted width of CPS clusters

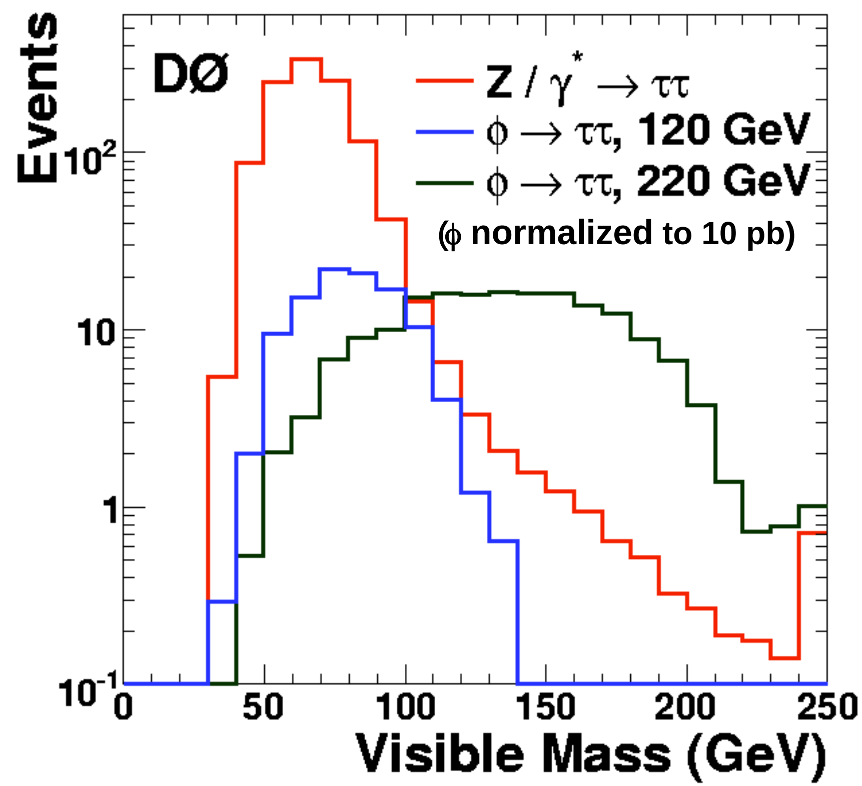
DØ: $\phi b \rightarrow \tau\tau b$ Search

kNN (anti-top)	Log-Likelihood (anti-QCD)
N_{jets}	Muon p_T
H_T	Tau p_T
$E(\tau + \mu + j)$	$\Delta R(\mu, \tau)$
$\Delta\phi(\mu, \tau)$	$M_{\mu\tau}$: $\mu-\tau$ Mass
	Visible Mass, M_{vis}

Visible Mass

- After final event selections for $\phi \to \tau\tau$, irreducible background from $Z \to \tau\tau$
  - small contribution from EW and QCD multi-jet
- 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 $Z \to \tau\tau$

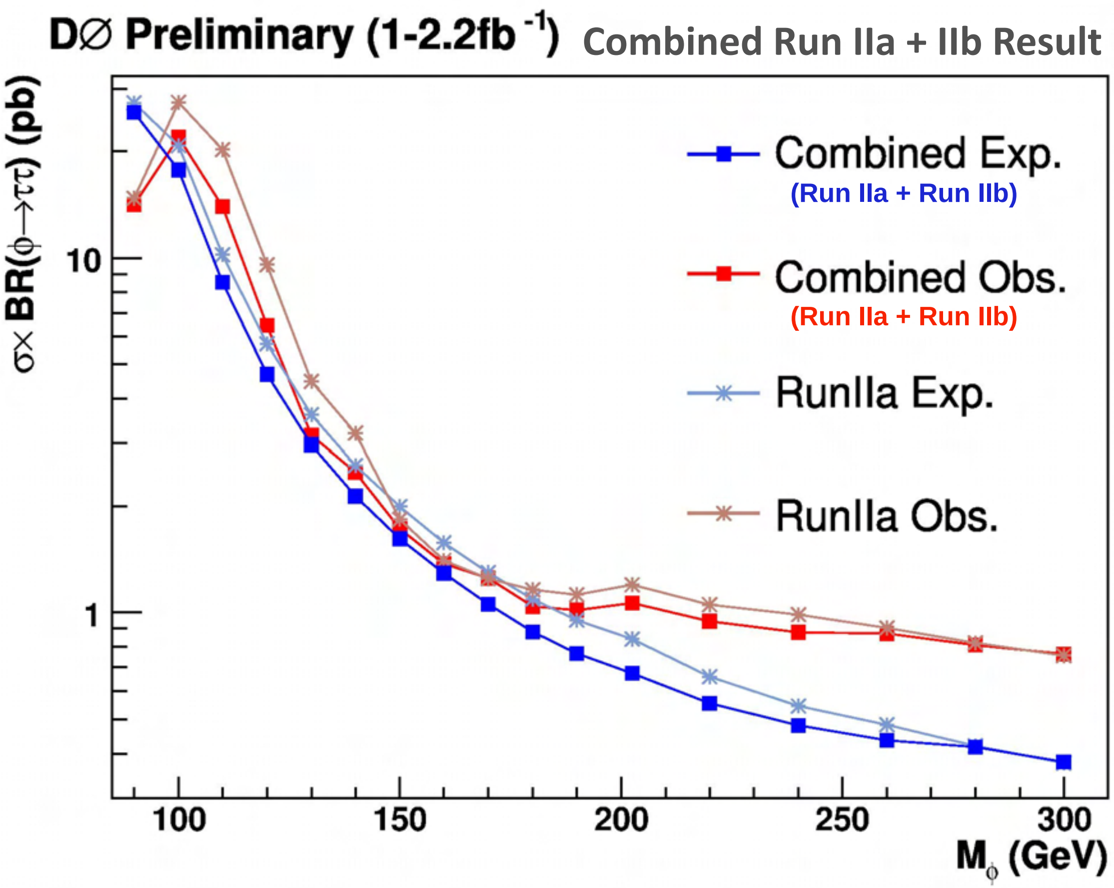
$$M_{VIS} = \sqrt{(P^{\tau 1} + P^{\tau 2} + \not{P}_T)^2}$$

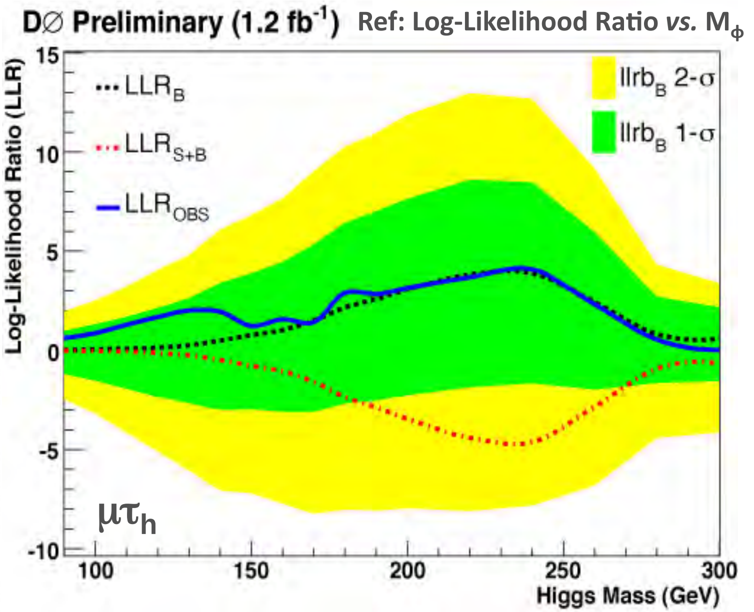


- Use 4-vectors of:
  - $P^{\tau 1}$, $P^{\tau 2}$ of visible tau decay products
  - $\not{P}_T = (\not{E}_T, \not{E}_x, \not{E}_y, 0)$, where $\not{E}_x$ and $\not{E}_y$ indicate components of $\not{E}_T$

$\phi \to \tau\tau$: $\sigma \times$BR Limit

- Study M_{vis} for Higgs boson masses from 90 to 300 GeV
  - no significant evidence for Higgs production observed
    - modified frequentist (CL_s) method used to extract upper limits on $\sigma \times$ BR
    - M_{vis} used as input to limit calculation





2.2 fb[-1] DØ Combination in Run II:
10 – 20% improvement in $\sigma \times$BR from PRL result

Major Systematic Uncertainties

Luminosity (6.1%)

τ-ID (4-8%, τ−type dependent)

τ energy scale (shape)

Z cross section (5%)

Trigger efficiency (shape)

DØ: $\phi b \to \tau\tau b$ Channel

- 1.2 fb^{-1} search considers $\phi b \to \tau_\mu \tau_{had} b$
  - isolated muon, $p_T > 12$ GeV; hadronic τ selected via τ-ID NN
  - one b-tagged jet using NN b-tagger: $p_T > 15$ GeV, $\Delta R(\ell_{\mu,\tau}, j) > 0.5$
- Pre b-tag: dominated by QCD multi-jet and $Z \to \tau\tau$, $\mu\mu$ backgrounds
- Post b-tag: dominated by QCD multi-jet and top events

(★ = largest contribution)

All τ_h-decay types	$Z \to (\tau\tau\,;\,\mu\mu)$	Top	Multi-jet	Other EW	Total Pred.	DATA
PRE b-tag	532.3 ± 5.6 ★	26.5 ± 1.0	252.7 ± 17.0 ★	56.0 ± 2.1	867.4 ± 24.8	906 ± 30
POST b-tag	7.8 ± 0.1	16.0 ± 0.6 ★	16.8 ± 1.4 ★	1.0 ± 0.1	41.7 ± 1.5	54 ± 7.4