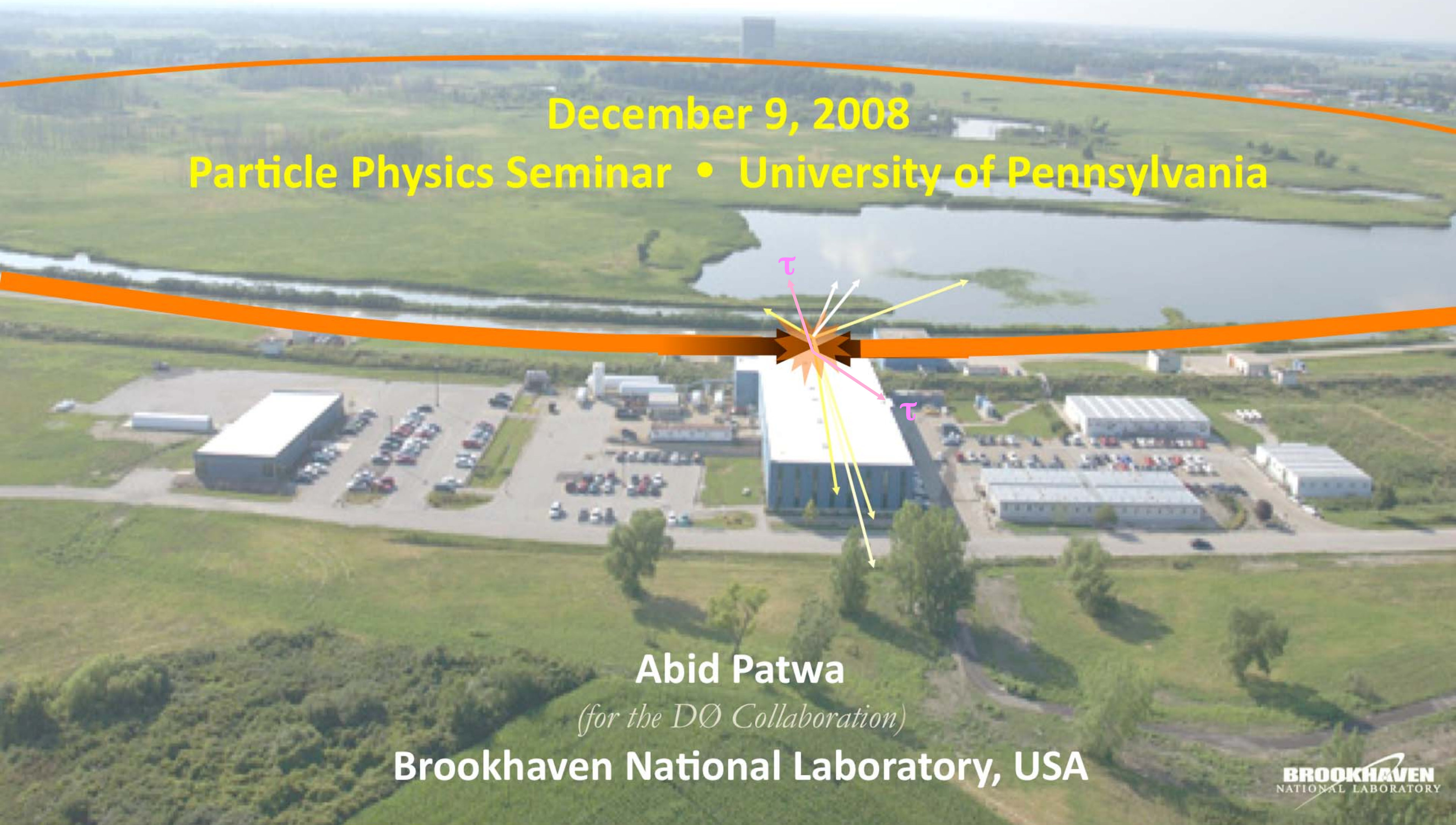
Search for MSSM Higgs Boson Production in di-tau Final States at DØ

December 9, 2008

Particle Physics Seminar • University of Pennsylvania



Abid Patwa

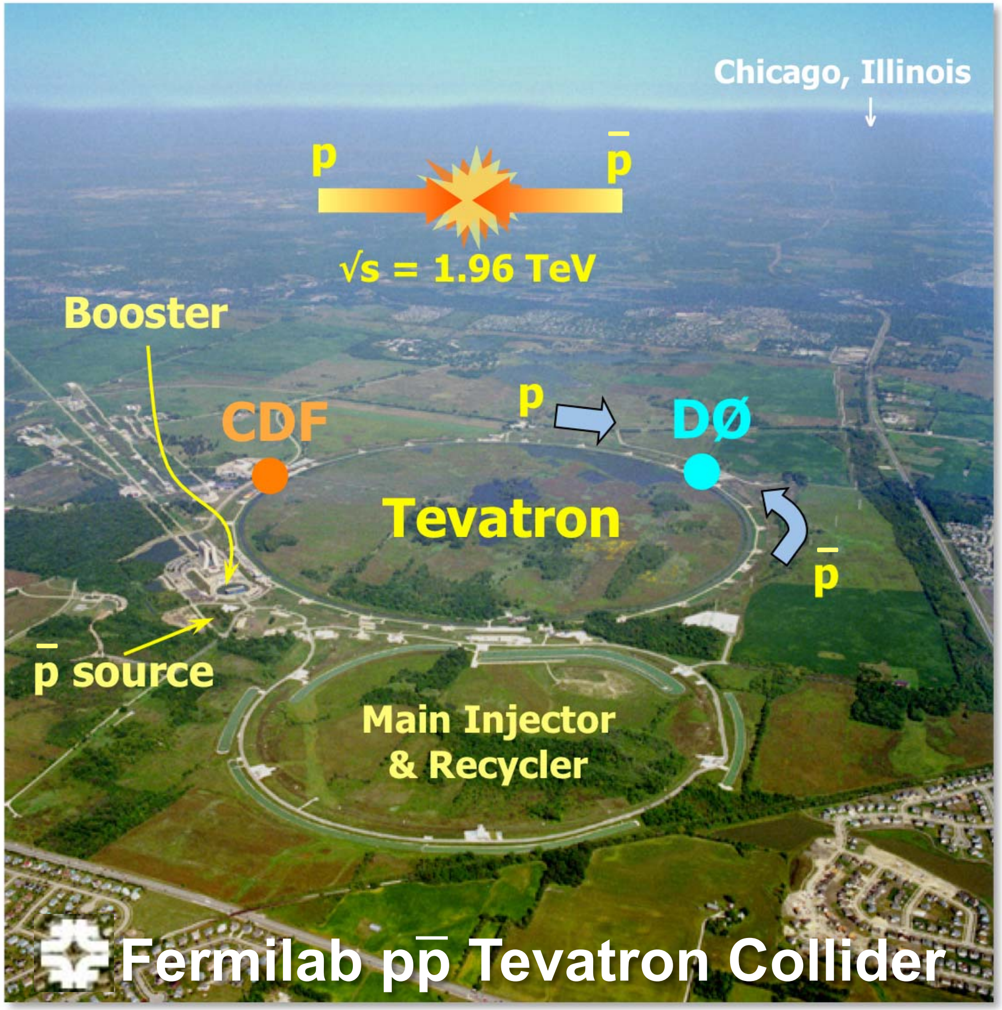
(for the DØ Collaboration)

Brookhaven National Laboratory, USA

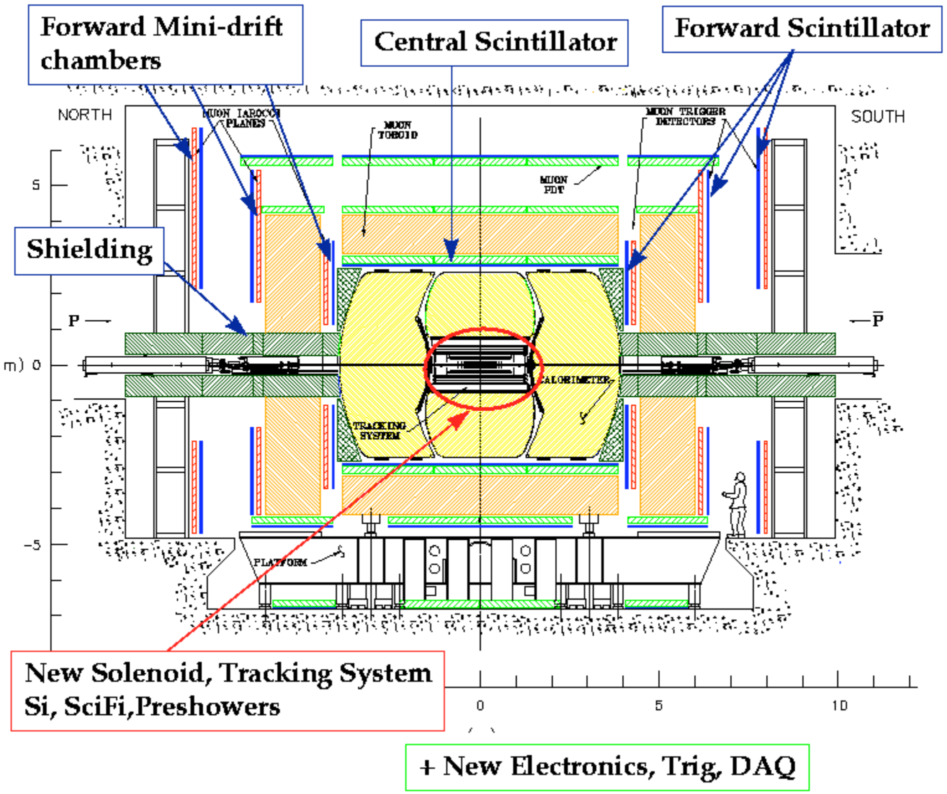
BROOKHAVEN NATIONAL LABORATORY

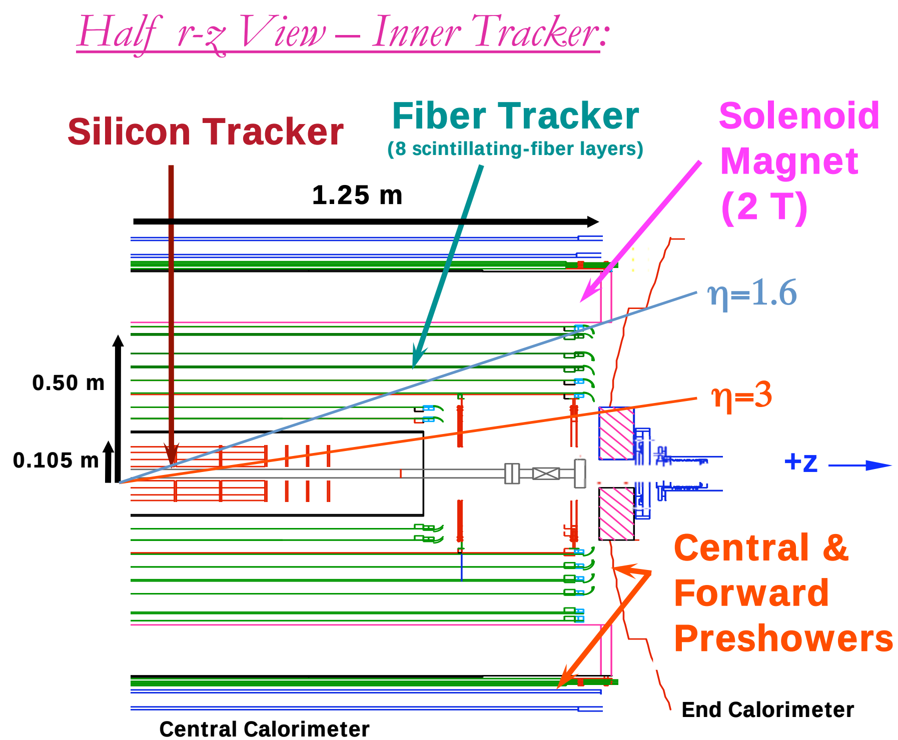
Outline

- Overview: DØ at Fermilab Tevatron
- Higgs Bosons in MSSM
- DØ τ reconstruction & identification
- Search for Neutral $\phi \rightarrow \tau\tau$
- Search for Neutral $\phi b \rightarrow \tau\tau b$
- Interpretation of Results in MSSM
- Prospects & Summary



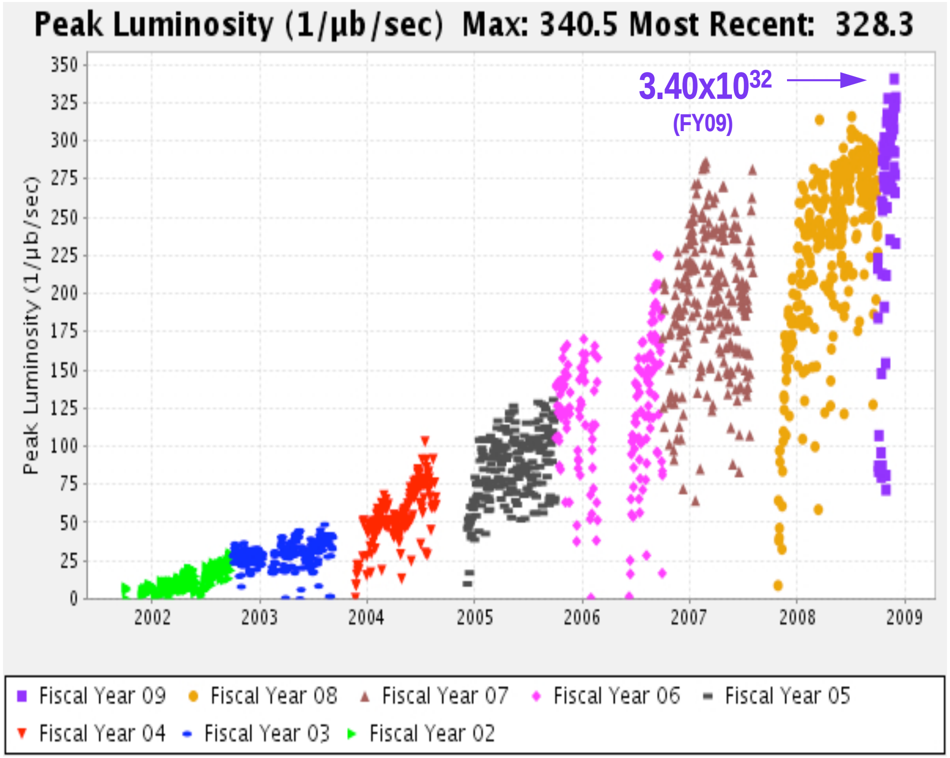
Detector

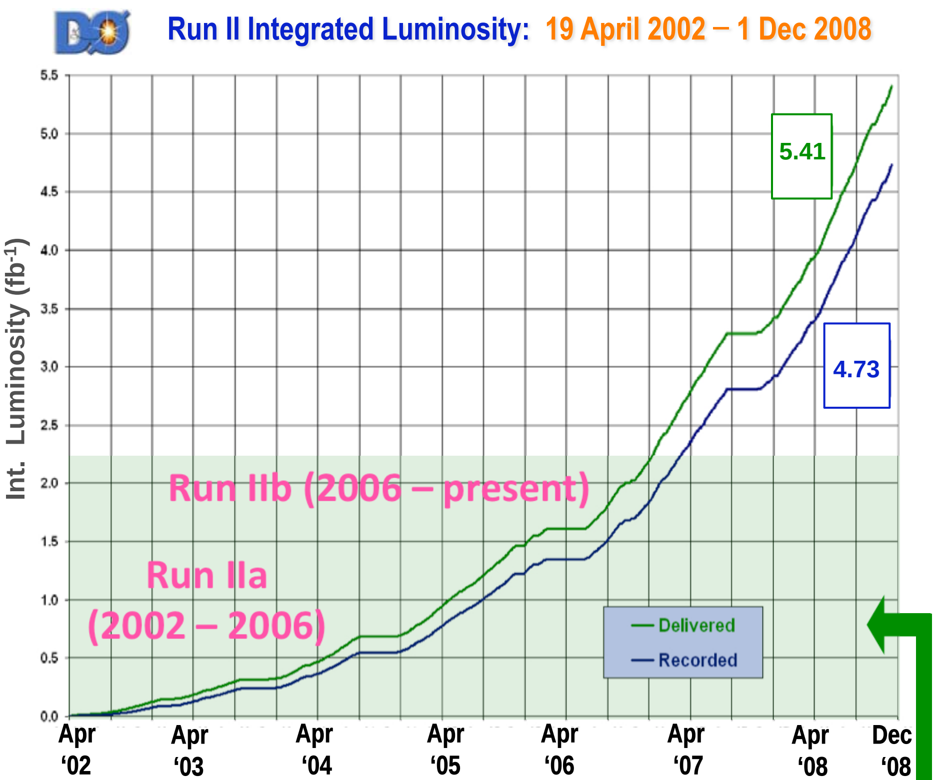




- silicon detector and scintillating fiber tracker in 2.0 T solenoidal field
- liquid argon/uranium calorimeters: central (CC) and two forward, end (EC) calorimeters
- muons: scintillators and mini-drift tubes ⇒ coverage up to $\eta = 2.0$
- upgraded trigger & electronics for Run IIb

Tevatron Performance

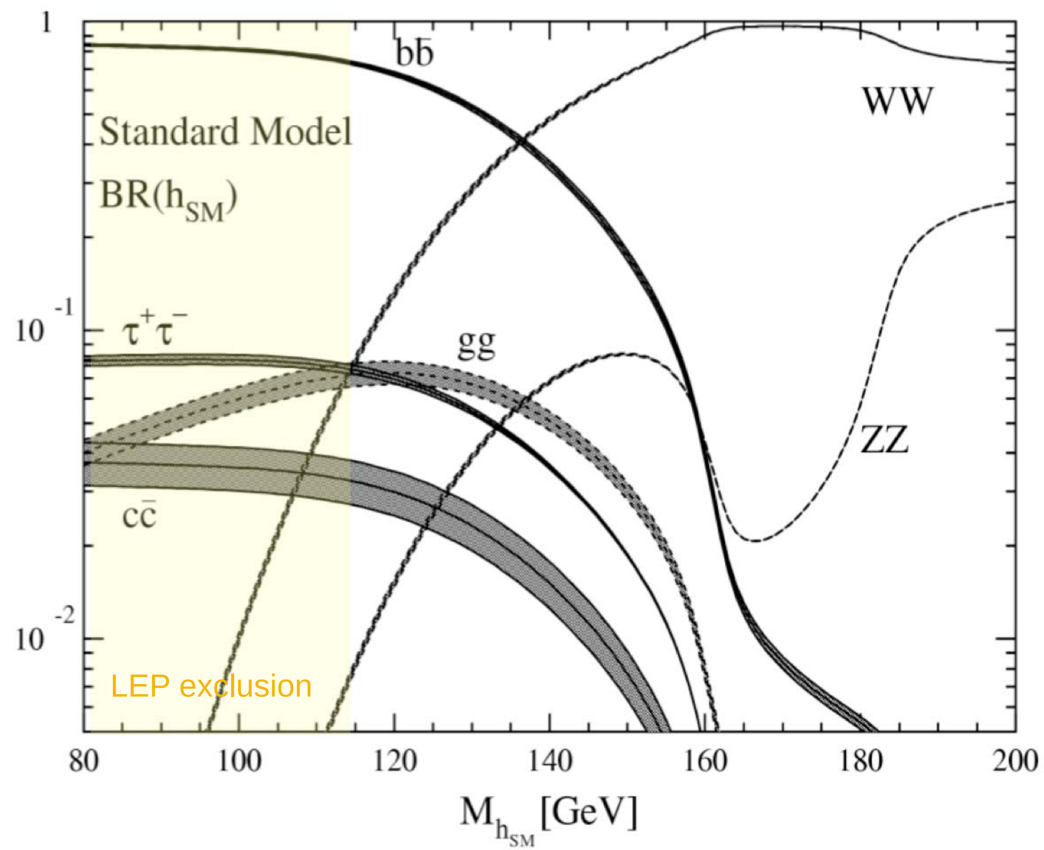




- **Tevatron Collider and DØ operating successfully in Run II**
- **Tevatron delivered $\int \mathcal{L}\, dt \rightarrow 5.4\ \text{fb}^{-1}$**
  - DØ recorded $> 4.7\ \text{fb}^{-1}$
  - reached peak luminosities $> 3.40 \times 10^{32}\ \text{cm}^{-2}\,\text{s}^{-1}$
  - weekly integrated luminosity $\sim 50\ \text{pb}^{-1}$/week
- **Projections through end-FY09 (FY10): $\sim 7\ \text{fb}^{-1}$ ($\sim 9\ \text{fb}^{-1}$)**
  - In this talk, report on up to $2.2\ \text{fb}^{-1}$ dataset *(Run IIa and Run IIb)*

Higgs boson decay to taus in SM

- Largest coupling of SM Higgs to leptons is via τ's
- SM Higgs exclusion $M_H > 114.4$ GeV limits search in di-tau final states
  - BR ($H \to \tau\tau$) < 10% compared to $b\bar{b}$ or WW decay
  - interesting (low mass) region further suffers from large irreducible $Z/\gamma \to \tau\tau$ background



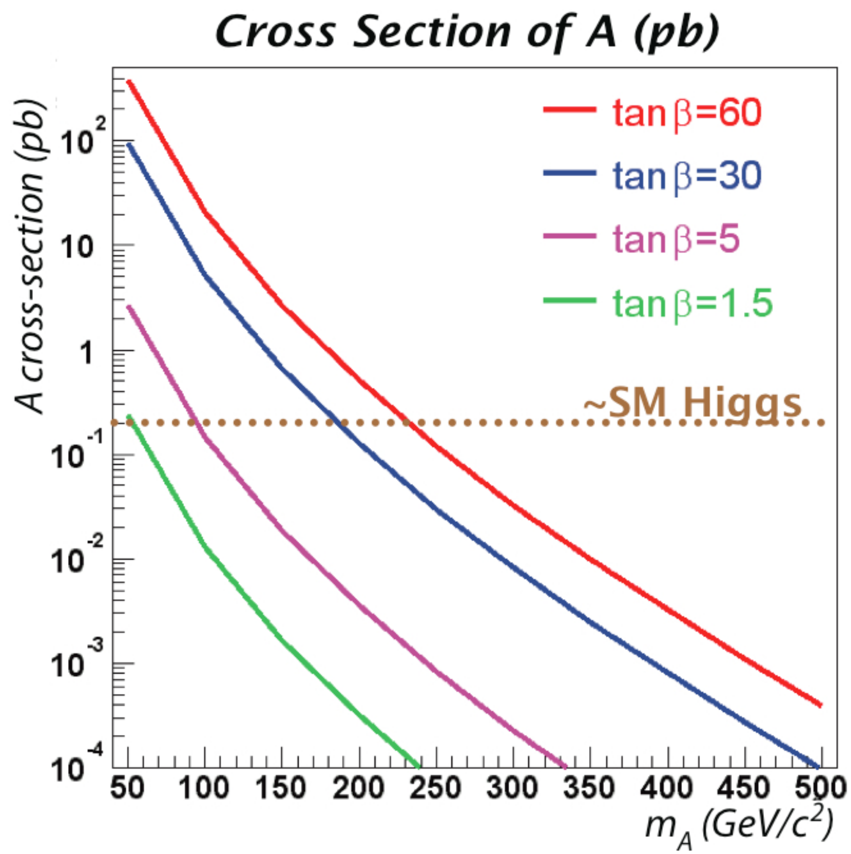
- But several DØ analyses exist for SM Higgs search considering taus
  - rely on associated production of Higgs with W, Z
    - ⁎ $WH \to \tau\nu b\bar{b}$ (2008 preliminary result, 1.0 fb^{-1})
    - ⁎ $ZH \to \tau\tau b\bar{b}$ (in progress)

Higgs bosons in the MSSM

- MSSM Higgs requires 2 doublets
  - H_u (H_d) couple to up- (down-) type fermions
  - ratio of their vacuum expectation values: $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$

⇒ 5 physical Higgs bosons after EWSB
  - two neutral CP-even: h^o, H^o
  - one neutral CP-odd: A^o
  - charged pair: H^+ and H^- (not in this talk)

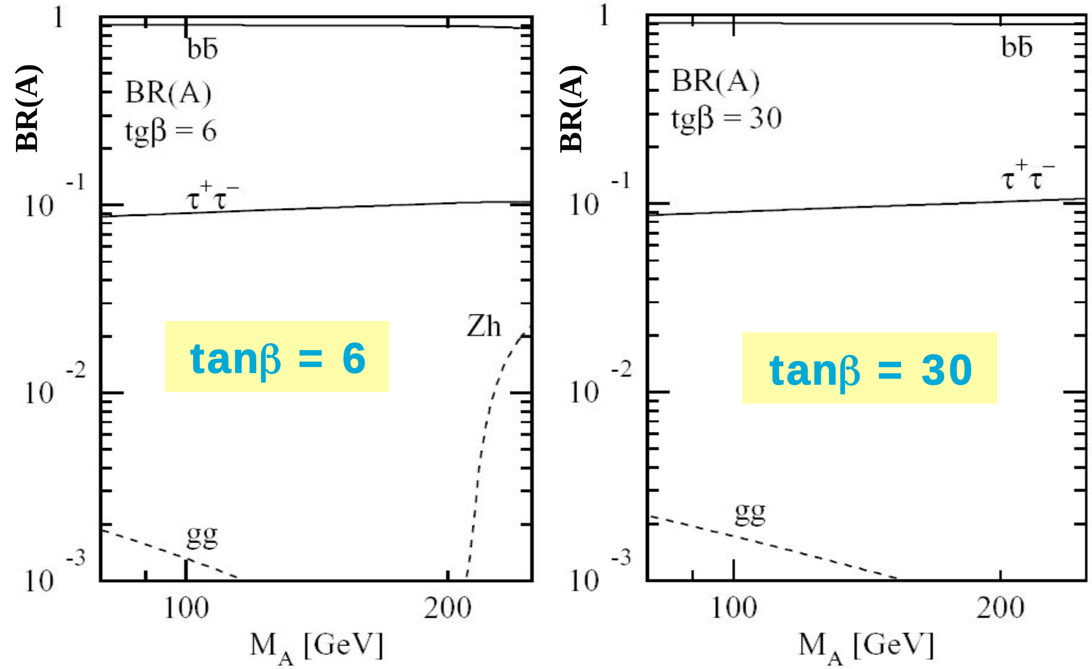
- at tree-level, MSSM Higgs fully specified by two free parameters
  - M_A and $\tan\beta$
- $\sigma(p\bar{p} \rightarrow h/H/A) \propto \tan^2\beta$
  - at large $\tan\beta$, (low M_A) ⇒ enhanced coupling of A, h/H to down-type fermions ⇒ enhanced production cross-section
  - provides a golden search mode
- at large $\tan\beta$, ϕ (= h/H & A) ~ degenerate in mass
  - further increase in cross-section



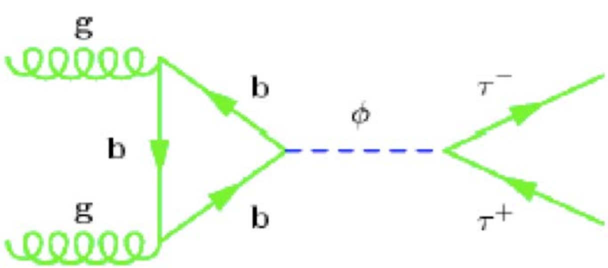
Low M_A, high $\tan\beta$:
Tevatron extend Higgs search region

Signatures: MSSM Neutral Higgs to di-tau

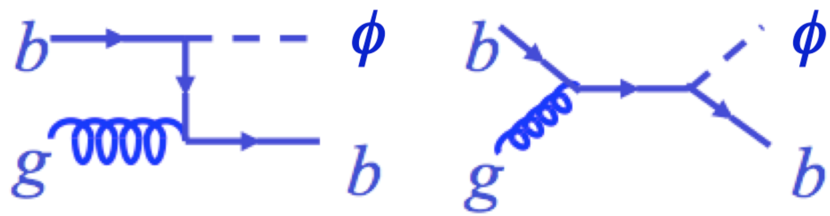
- **h/H/A decays, in most parameter space:**
  - **h/H/A → $b\bar{b}$ (~90%)**
  - **h/H/A → ττ (~10%)**
    - ∗ smaller BR but cleaner signature (*vs.* large QCD background in b mode)



- **Signatures**
  - a) inclusive production mode: Higgs decay to 2 opposite sign τ's
    - ∗ subsequent leptonic or hadronic decay of τ's define final states
  - b) production in association with at least one b-quark
    - ∗ same as (a) + additional jet from b-quark



φ → $\tau^+\tau^-$ (Gluon fusion)

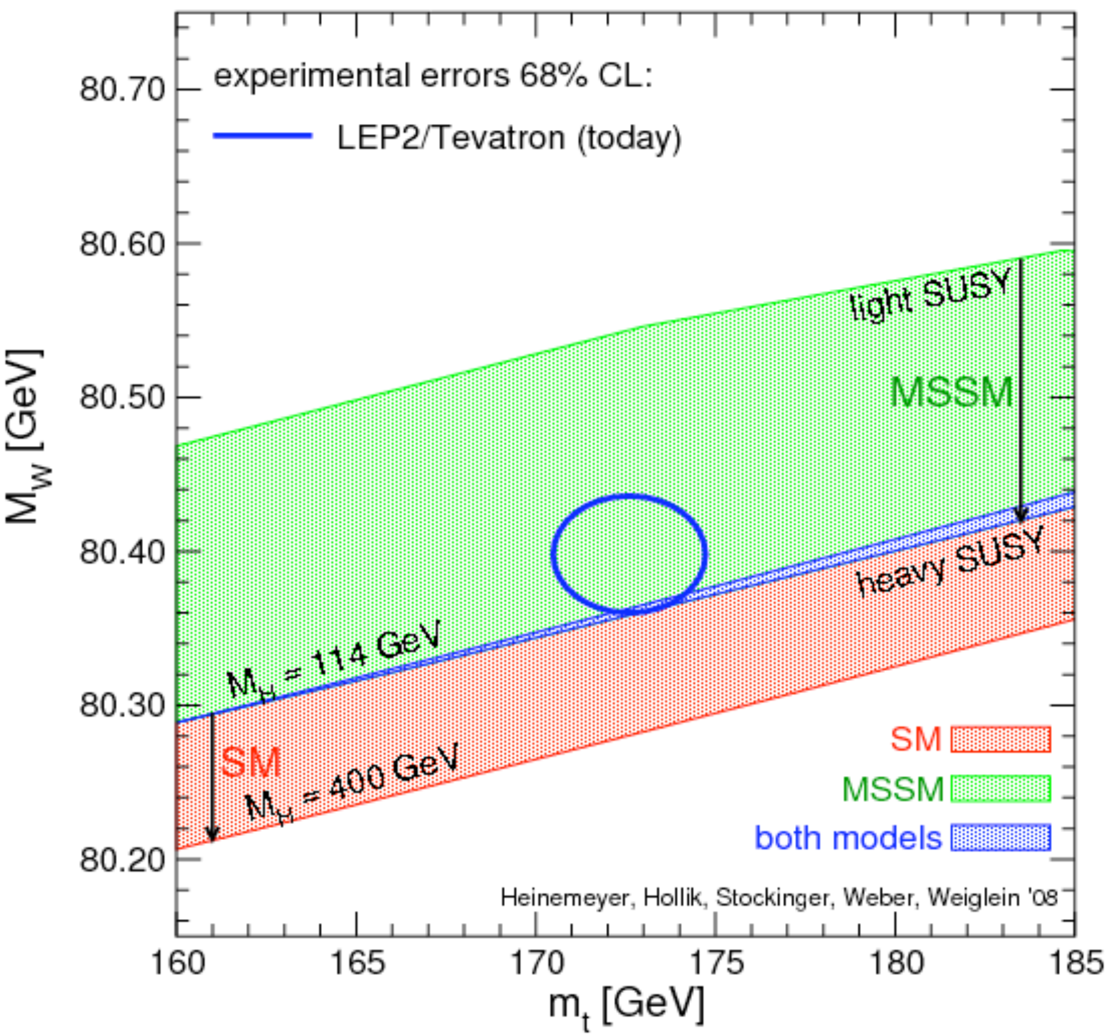


φb → $\tau^+\tau^-$b (in association with b)

Why these channels?

- Current experimental 68% C.L. region for m_t and M_W
  - slight preference of MSSM over SM
- Real discovery potential before we reach SM sensitivity
- The experimental challenge:
  - identifying a τ signal from far more copious jets produced by strong interaction processes
  - efficient b-tagging for $\phi b \rightarrow \tau\tau b$ search

Ref: Heinemeyer, Hollick, Stockinger, Weber, Weiglein '08



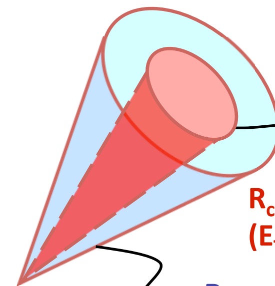
τ properties

- 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
$\pi(/K) + \nu_\tau + \geq 1\pi^o$	36.9			
$\pi\pi\pi + \geq 0\pi^o + \nu_\tau$	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 : $\tau_e\tau_h$
  - $\tau \rightarrow e\nu\nu + \tau \rightarrow \mu\nu\nu$: $\tau_e\tau_\mu$

DØ: τ reconstructed candidate



- **Begin with Calorimeter Cluster**
  - Tau calorimeter clusters found using Simple Cone Algorithm

    (core cone size R = 0.3, isolation cone size $R_{iso} = 0.5$)
  - require CAL cluster rms < 0.25
    - * rms = energy weighted width of cluster = $\sqrt{\sum_{i=1}^{n}(\Delta\phi_i^2 E_{T_i}/E_T + \Delta\eta_i^2 E_{T_i}/E_T)}$

- **Associate EM Sub-clusters**
  - Nearest Neighbor Algorithm in 3rd EM layer (= shower max); EM_3 cluster energy > 800 MeV
  - attach EM cells in other layers and preshower hits to the found EM_3 cluster

- **Associate up to 3 tracks with $p_T > 1.5$ GeV to the τ candidate**
  - track within 0.3 cone around CAL cluster
  - if more than one track, associate highest p_T track with τ candidate
  - add 2nd (3rd) track if invariant mass calculated from tracks < 1.1 (1.7) GeV and $Q_{tot} \neq \pm 3$

τ Reconstruction & ID

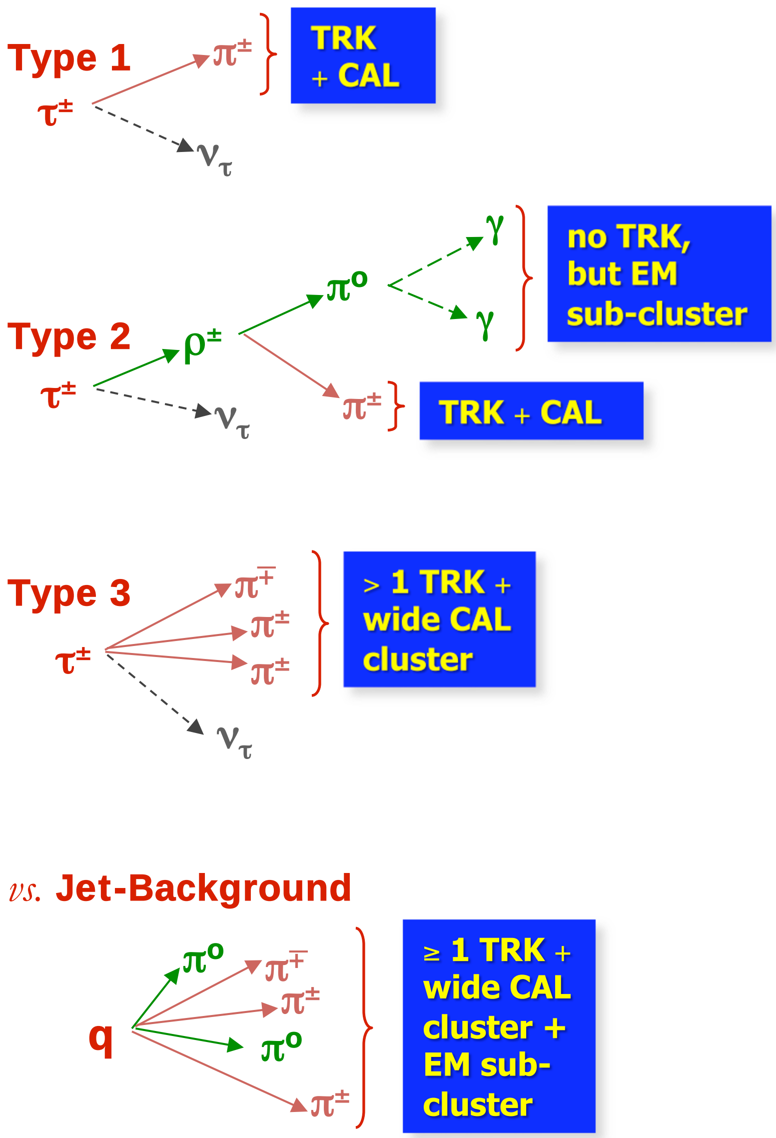
- Categorize hadronic τ candidates into 3 types, based on their detector signature

τ-type 1 (πν-like): one track + calorimeter cluster, no EM sub-clusters

τ-type 2 (ρν-like): one track + calorimeter cluster and > 0 EM sub-clusters

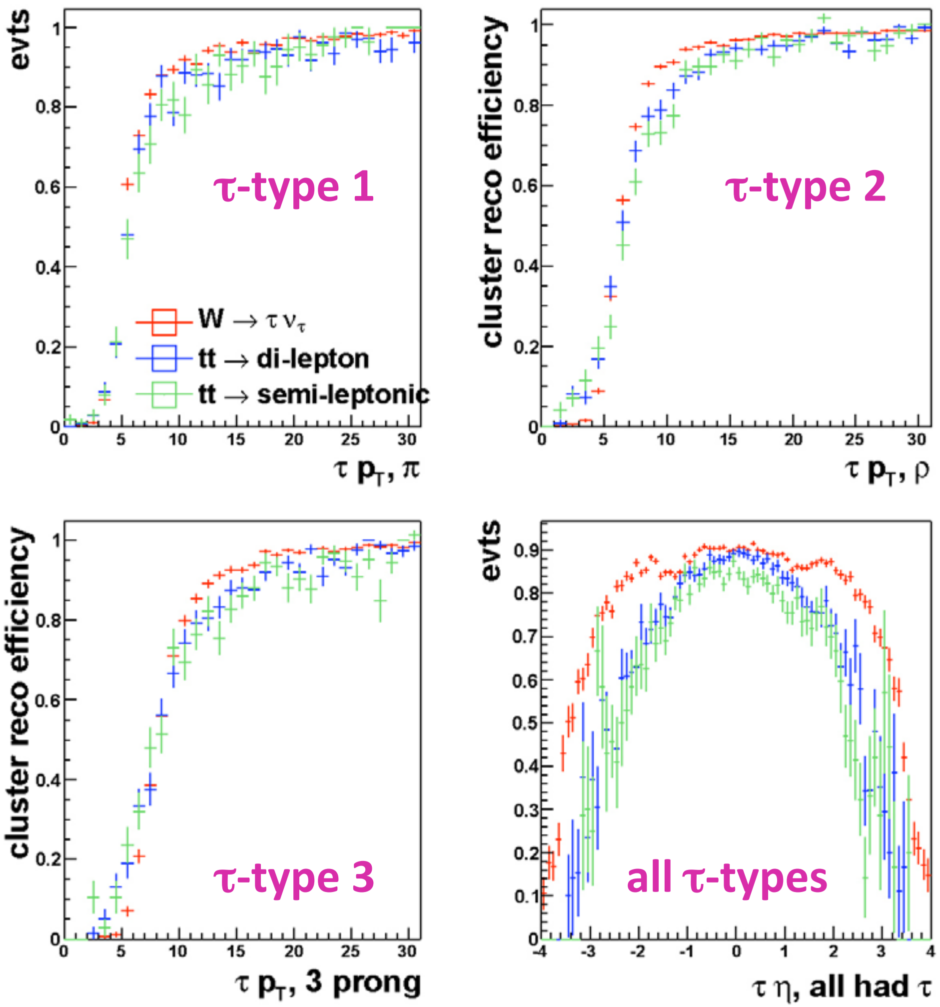
τ-type 3 (3-prong): > one track + calorimeter cluster and ≥ 0 EM sub-clusters

- Reduce backgrounds from τ's with Neural Network (NN) techniques

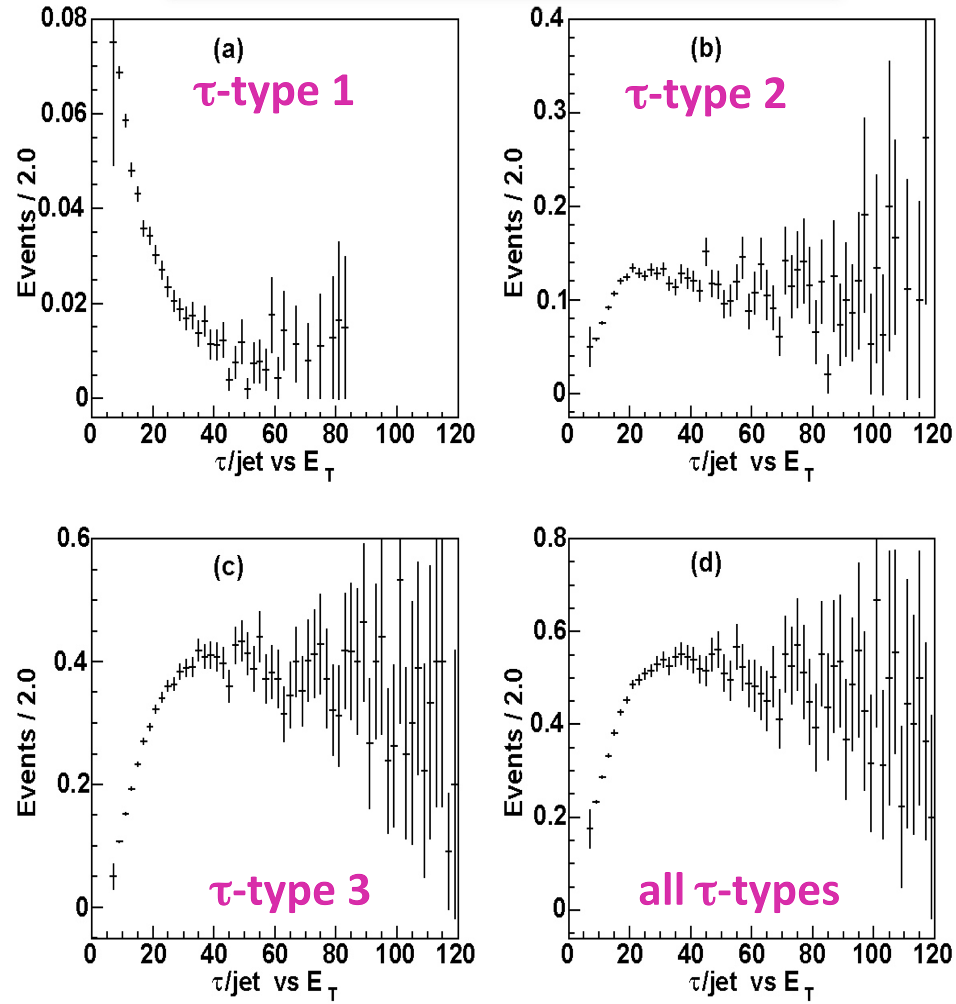


τ candidates: Reconstruction Efficiencies

Taus (MC)



Jets faking taus (data)

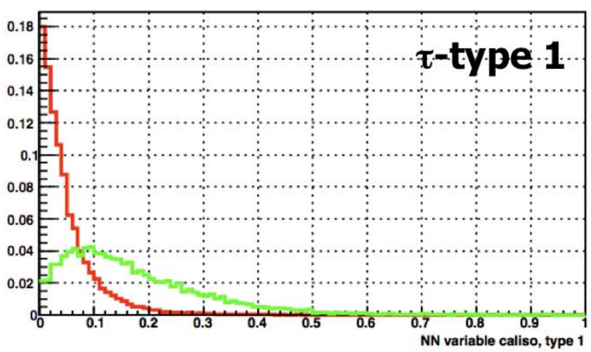


- Overall τ reconstruction efficiency > 90% can be achieved for E_T > 15 GeV, but rejection of jets is low ⇒ further discrimination needed
  - depends on τ-type and E_T

τ-ID Neural Network

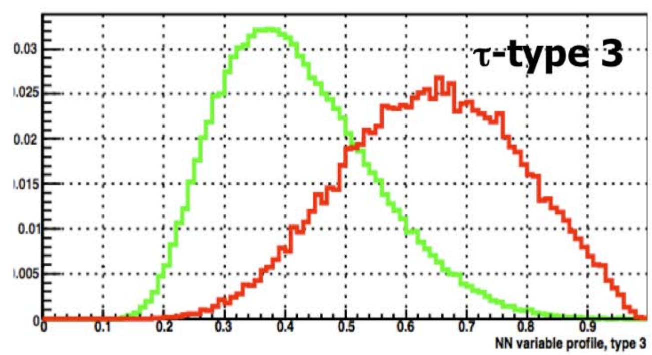
- three separate anti-jet Neural Networks ⇒ one for each τ-type
- one additional NN to reject electrons, NN_e
  - effective in separating τ-type 2 and electrons
- training samples for NN's:
  - signal: τ's from $Z \to \tau\tau$ MC
  - background: recoiling jets in events with a non-isolated μ from data
    - * for NN_e: electrons from $Z \to ee$ MC
- NN input variables based on isolation & shower shape parameters, and correlations built from calorimeter clusters and tracks

Signal (MC τ) and Background (jets from data)



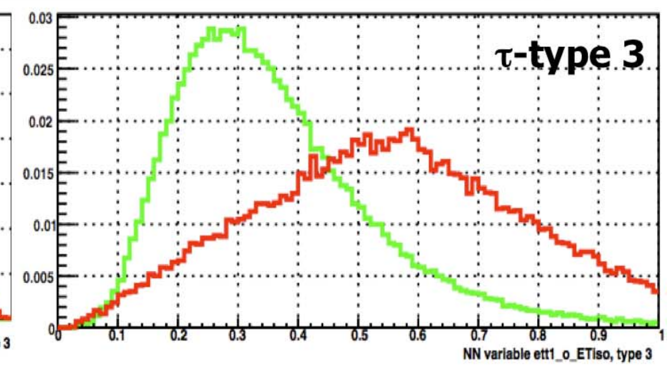
CAL isolation =

$$\frac{E_T^{\Delta R<0.5} - E_T^{\Delta R<0.3}}{E_T^{\Delta R<0.3}}$$



CAL profile=

$$\frac{E_T^{Tower1} + E_T^{Tower2}}{E_T^{\tau}}$$



Ett1=

$$\frac{p_T^{lead-tautrk}}{E_T^{\tau}}$$

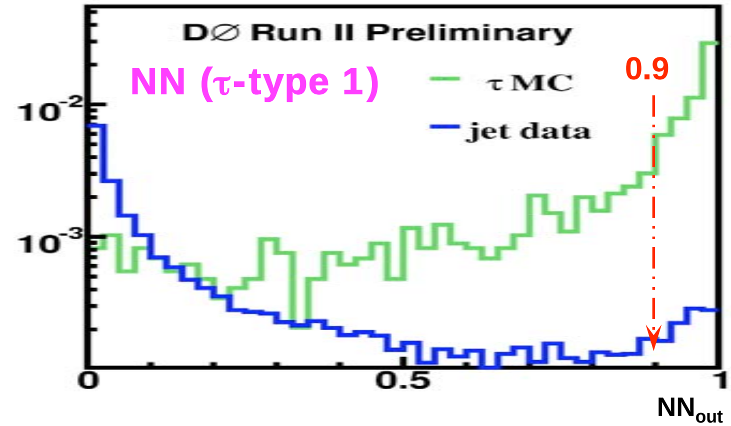
NN's for τ-ID (cont.)

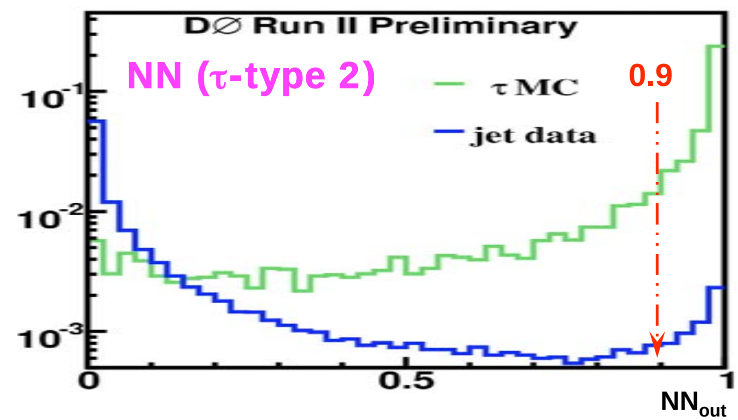
- apply NN to separate QCD jets from τ's

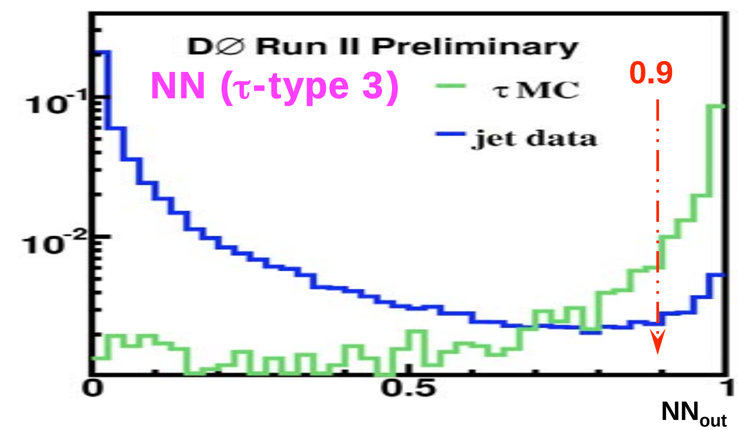
Efficiencies (%)

$$20 < E_T^{\tau} < 40\ \mathrm{GeV},\ |\eta^{\tau}| < 2.5$$

τ-type	1	2	3	all
Jets	2	12	38	52
τ	11	60	24	95
NN > 0.9				
Jets	0.06	0.24	0.80	1.1
τ	7	44	16	67







- NN > 0.9 reduces jet background by × ~50 while keeping total τ efficiency near 70%
- if exclude τ-type 3 ⇒ × ~3 increase in S/B, with only 16% loss in efficiency

Summary of DØ Analyses

- Run IIa (2002 – 2006), Run IIb (2006 – present)
- Search for $\phi \rightarrow \tau\tau$
  - ★ – Result using 1.0 fb^{-1} Run IIa dataset for $\tau_\mu\tau_h$, $\tau_e\tau_h$, and $\tau_e\tau_\mu$
    - PRL 101, 071804 (2008)
  - ★ – Preliminary Result using 1.2 fb^{-1} Run IIb dataset for $\tau_\mu\tau_h$
    - DØ CONF-Note 5728 (2008) ← recent
  - ★ – For limits, combined results for Run IIa and Run IIb ⇒ 2.2 fb^{-1}
    - DØ CONF-Note 5740 (2008) ← recent
  - Run IIb results for $\tau_e\tau_h$ and $\tau_e\tau_\mu$ … in progress
- Search for $\phi b \rightarrow \tau\tau b$
  - Result using 328 pb^{-1} Run IIa dataset for $\tau_\mu\tau_h b$
    - Submitted to PRL (2008); FERMILAB-PUB-08/451-E
  - Run IIa results using 1.0 fb^{-1} dataset for $\tau_\mu\tau_h b$ … in progress
  - ★ – Preliminary Result using 1.2 fb^{-1} Run IIb dataset for $\tau_\mu\tau_h b$
    - DØ CONF-Note 5727 (2008) ← recent
  - Run IIa and Run IIb results for $\tau_e\tau_h b$ … in progress

Ref: www-d0.fnal.gov/Run2Physics/WWW/results.htm

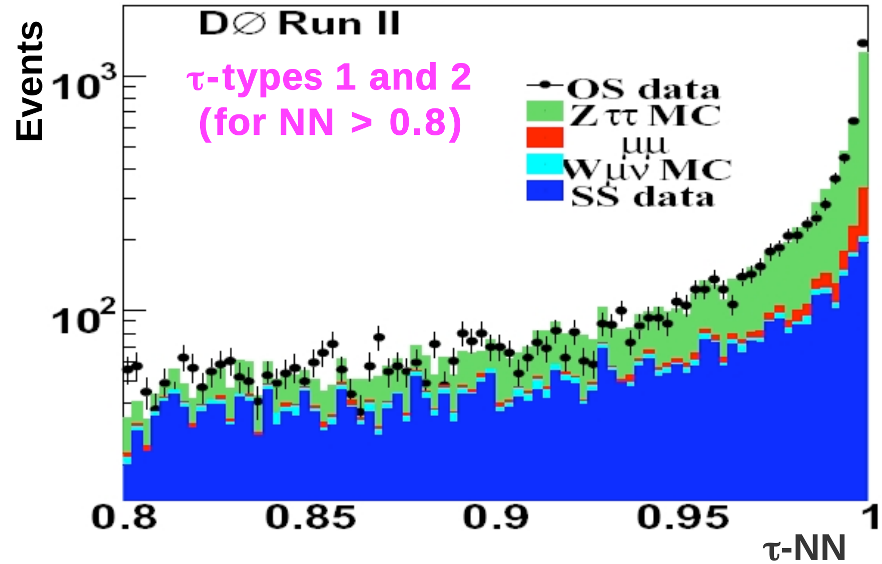
★ Will be the focus in this talk…

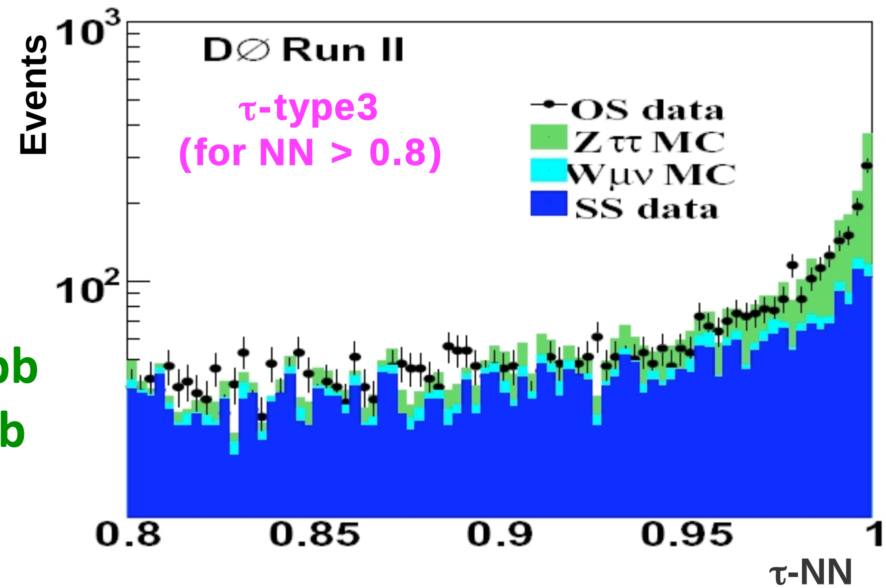
Precursor to ϕ: τ-NN and $Z \to \tau^+\tau^-$

- Published $Z \to \tau\tau$ cross section: $\tau_\mu \tau_h$
  - PRD 71, 072004 (2005): 226 pb^{-1}
    - * benchmark study for testing and certifying τ-ID algorithm
  - accepted by PLB (2008): 1.0 fb^{-1}
  - extend developed method to other τ physics channels

- Basic selections
  - $p_T^\mu > 15$ GeV
  - $p_T^\tau > 10, 10, 5$ GeV for τ-types 1, 2, 3
  - opposite sign (OS) and back-to-back ($|\phi_\mu - \phi_\tau| > 2.5$) $\mu\tau$ pairs

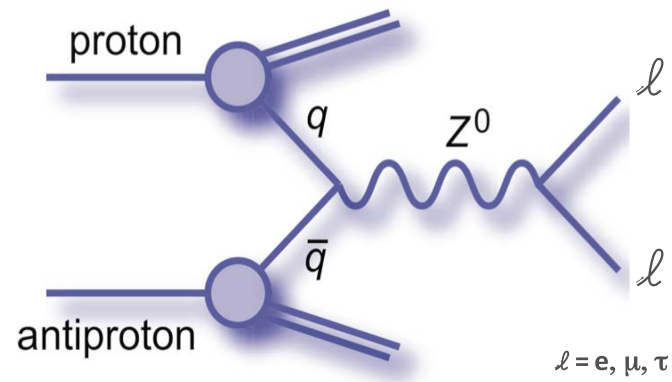
- $\sigma(p\bar{p} \to Z + X) \cdot Br(Z \to \tau^+\tau^-)$
  - PRD: 237 ± 15 (stat) ± 18 (sys) ± 15 (lum) pb
  - PLB: 240 ± 8 (stat) ± 12 (sys) ± 15 (lum) pb
  - SM theory (NNLO): $241.6^{+3.6}_{-3.2}$ pb

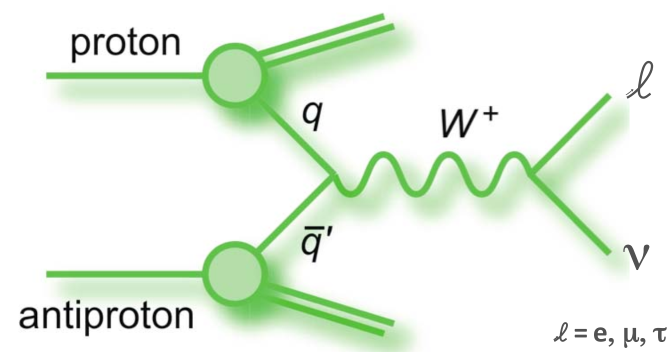




Dominant Backgrounds

- $\phi \rightarrow \tau^+\tau^-$ search
  - $Z/\gamma^* \rightarrow \tau^+\tau^-$
    - irreducible; similar final state
  - $Z/\gamma^* \rightarrow \ell\ell$, where ℓ = e, μ with mis-identified 2nd lepton
  - W + jets, where a jet is mis-identified as τ, μ or e
  - QCD multi-jets with mis-identified leptons/jets from heavy flavors (jets fake τ's)
  - Diboson, top decays to real taus
    - small cross section
- $\phi b \rightarrow \tau^+\tau^- b$ search
  - similar to inclusive ττ channel
    - but after b-tag, dominated by top events and QCD multi-jets





Strategy In Presenting Results

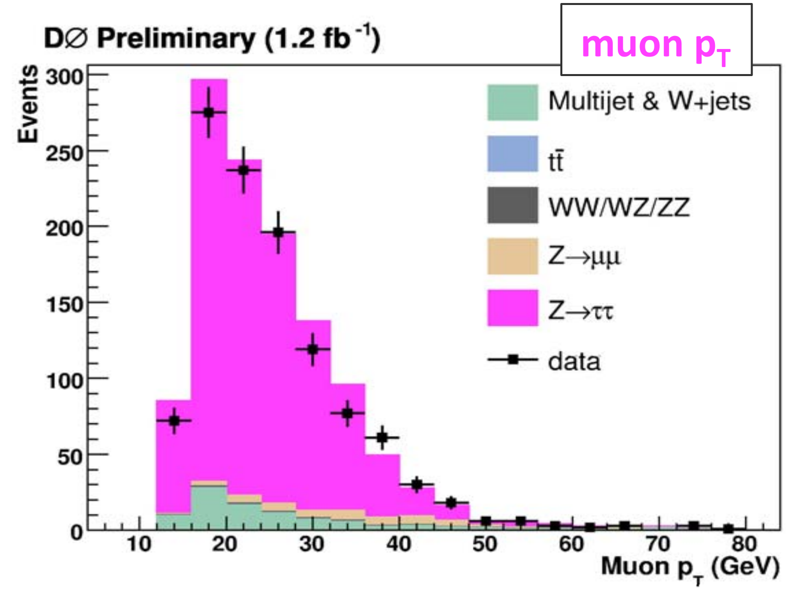
- Search for $\phi \rightarrow \tau\tau$ using selections for e, μ, and τ_h
  - per each tau pair decay channel and τ-type
    - require b-tag for associated ϕb mode
  - help suppress dominant backgrounds

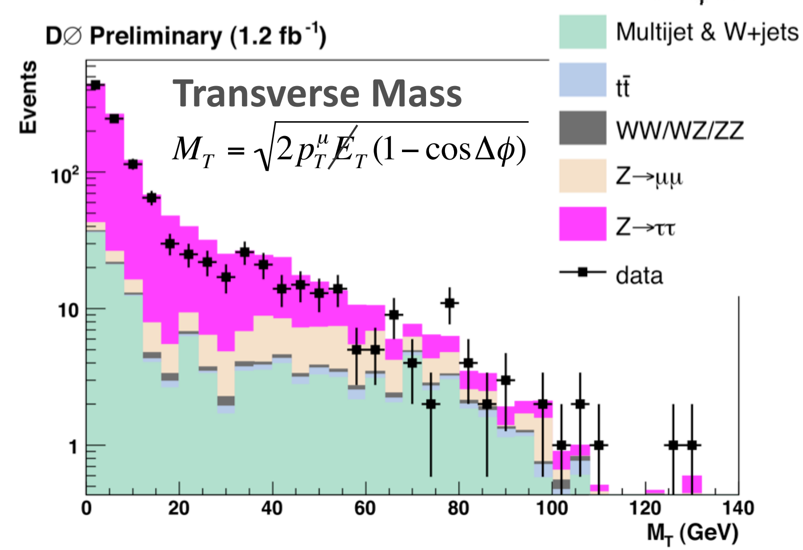
- Look for excess of Higgs signal in data over background; if no significant excess, first calculate:
  - 95% C.L. limit for production cross section times branching ratio, $\sigma \times$ BR

- Translate & interpret results in MSSM
  - calculate exclusion in (m_A , tanβ) plane for two MSSM benchmark scenarios

$\phi \to \tau^+\tau^-$ Search Channel

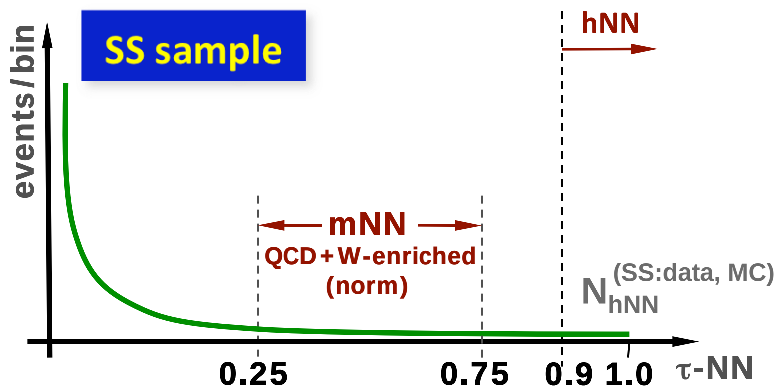
- $h/H/A \to \tau\tau$ search considers final states: $\tau_\mu\tau_h$, $\tau_e\tau_h$, and $\tau_e\tau_\mu$
  - di-τ decays to ee, $\mu\mu$ not considered
    - * large $Z/\gamma^* \to \mu\mu$ or $Z/\gamma^* \to ee$ background $\Rightarrow$ small S/B
- $\tau_\mu\tau_h$ event selections
  - recent, updated 1.2 fb^{-1} Run IIb result
  - one isolated μ: $p_T > 15$ GeV, $|\eta^\mu| < 1.6$
    - * veto events with more than one μ $\Rightarrow$ suppress $Z \to \mu\mu$
  - one τ, opposite sign (OS) from μ
    - * $E_T > 15, 15, 20$ GeV (types 1, 2, 3)
    - * $p_T^{\tau\text{-trk}} > 15, 5, 5$ GeV (types 1, 2, 3)
    - * $\Sigma p_T^{\tau\text{-trk}} > 15$ GeV (type 3)
    - * separated from muon: $\Delta R(\mu, \tau) > 0.5$
    - * NN > 0.9, 0.9, 0.95 (types 1, 2, 3)
  - correct MC tau energy such that E_T/p_T^{trk} matches data in $Z \to \tau\tau$ events
  - veto events: electron $p_T^e > 12$ GeV for orthogonality with eμ channel
  - $M_T < 40$ GeV $\Rightarrow$ reject W+jets

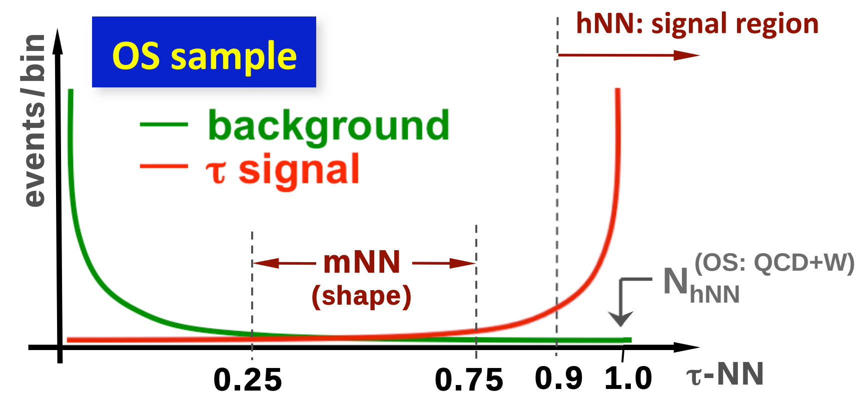




Background Modeling

- Backgrounds estimated by a combination of MC and controlled data samples
  - Z/γ^*, diboson, and $t\bar{t}$ taken from PYTHIA MC
  - QCD multi-jet + W determined from data
  - divide data in opposite-sign (OS) & same-sign (SS) events (any signal ⇔ OS events)
    - ∗ medium NN (mNN, QCD-enriched region): $0.25 < \tau\text{-NN} < 0.75$
    - ∗ high NN (hNN, signal region): NN > 0.9 (0.95) for τ-types 1, 2 (3)





- After MC bkg subtraction, OS & mNN region determines QCD+W shape
  - relatively flat region of τ-NN space
  - $N_{hNN}^{OS:QCD+W} = \rho \times (N_{mNN}^{OS:data} - N_{mNN}^{OS:MC})$
- Normalize using ratio of hNN to mNN in SS sample:

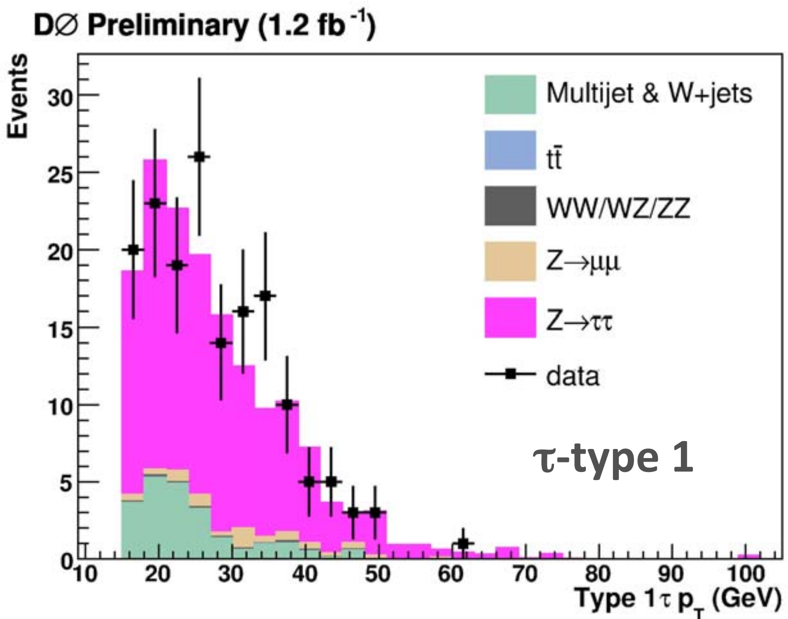
$$\rho = \frac{N_{hNN}^{SS:data} - N_{hNN}^{SS:MC}}{N_{mNN}^{SS:data} - N_{mNN}^{SS:MC}}$$

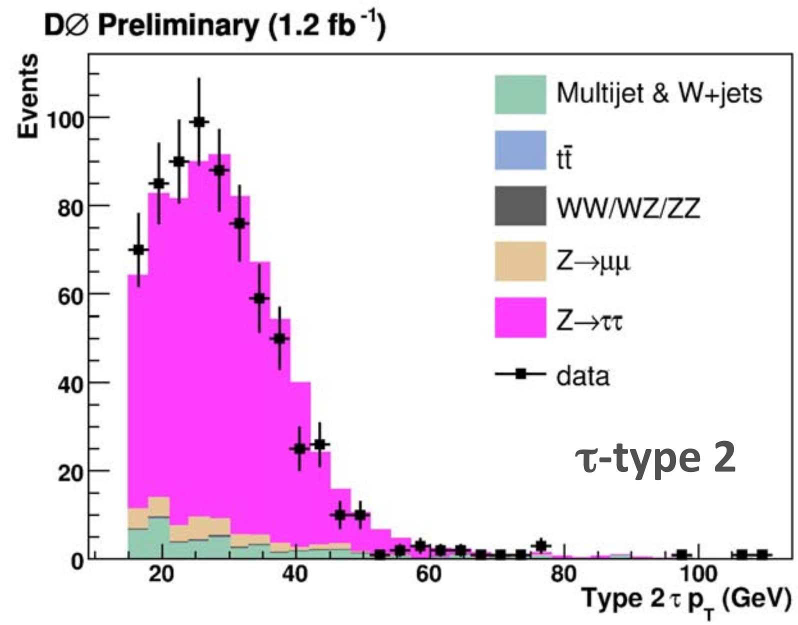
QCD Multi-jet + W+jets Control Regions

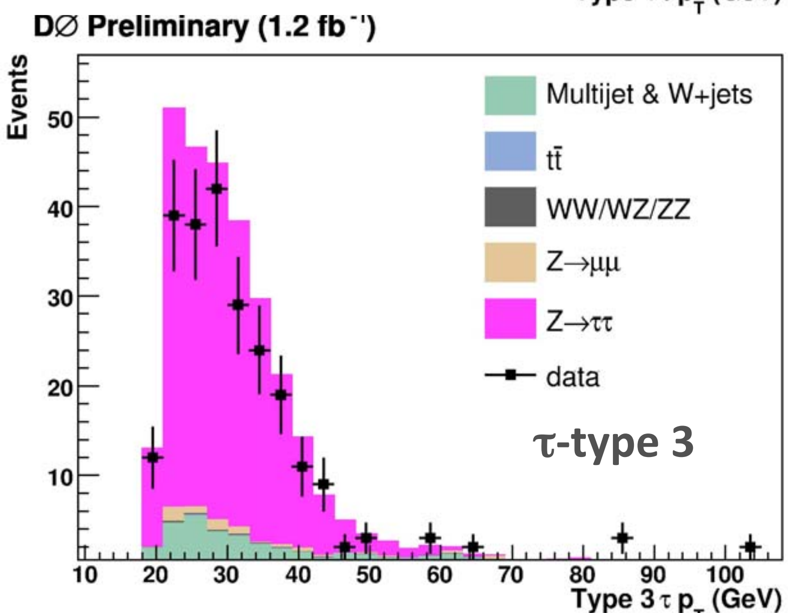
	mNN (data, MC)	hNN (data, MC)
OS (data, MC)	QCD+W [Shape]	Signal Region
SS (data, MC)	Normalize Distributions [ρ, via ratio]	

$\phi \rightarrow \tau_\mu \tau_h$ 1.2 fb^{-1} Result: p_T^τ

- **Predicted backgrounds consistent with events in data**



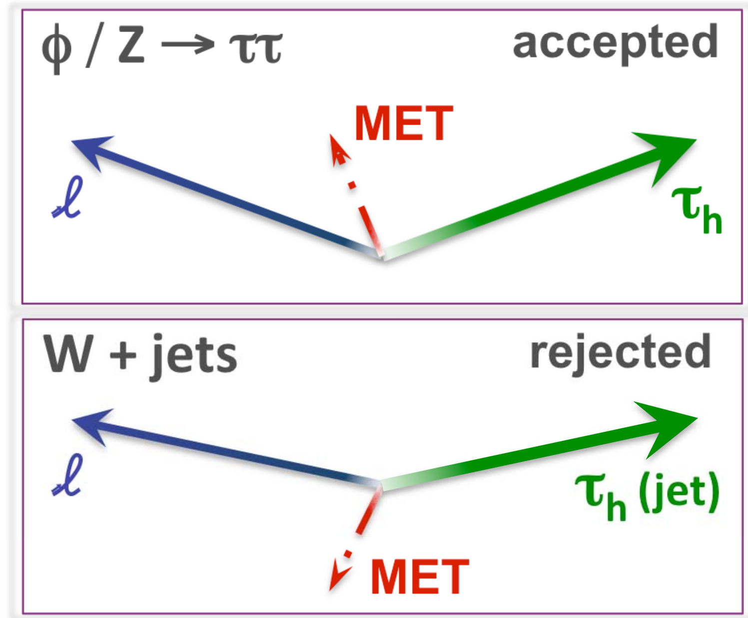




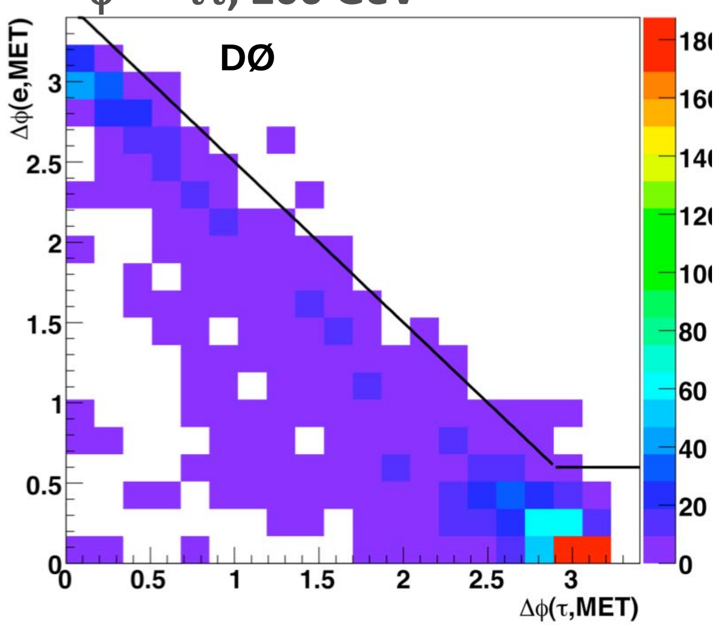
Process	Events (all τ–types)
$Z/\gamma^* \rightarrow \tau\tau, \mu\mu$	1078 ± 33
QCD Multi-jet + W	96 ± 9
Diboson	6 ± 2
Top	2.7 ± 1.6
Total Expected	1189 ± 34
Data	1109

$\phi \rightarrow \tau_e \tau_h$ Selections

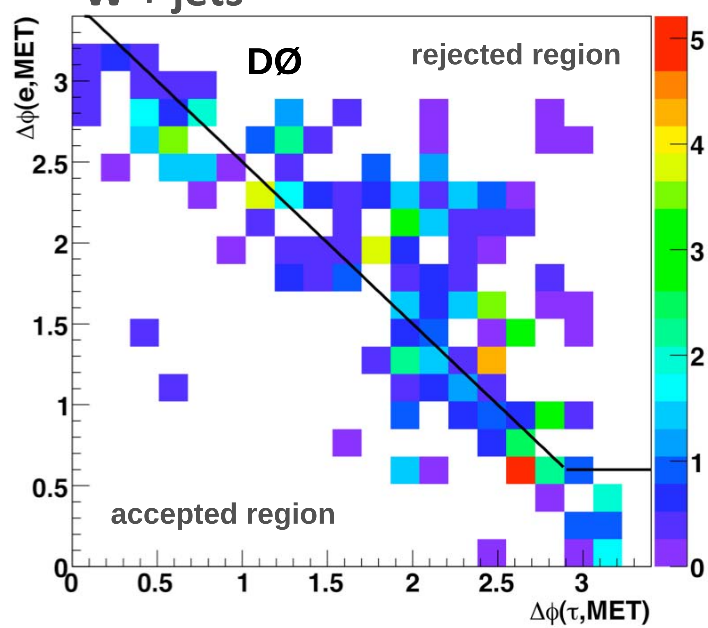
- Consider $\tau_e \tau_h$ final state
  - suppress electrons from $Z/\gamma^* \rightarrow ee$ decays that reconstructed as τ-type 2
    - ∗ e *vs.* τ-ID discriminant: $NN_e > 0.8$
  - remove larger multi-jet background with $\Delta\phi(e, \tau) > 1.6$
  - reject W+jet events
    - ∗ $M_T < 50$ GeV
    - ∗ cut in 2D $\Delta\phi(e, \not{E}_T) - \Delta\phi(\tau, \not{E}_T)$ plane



$\phi \rightarrow \tau\tau$, 200 GeV



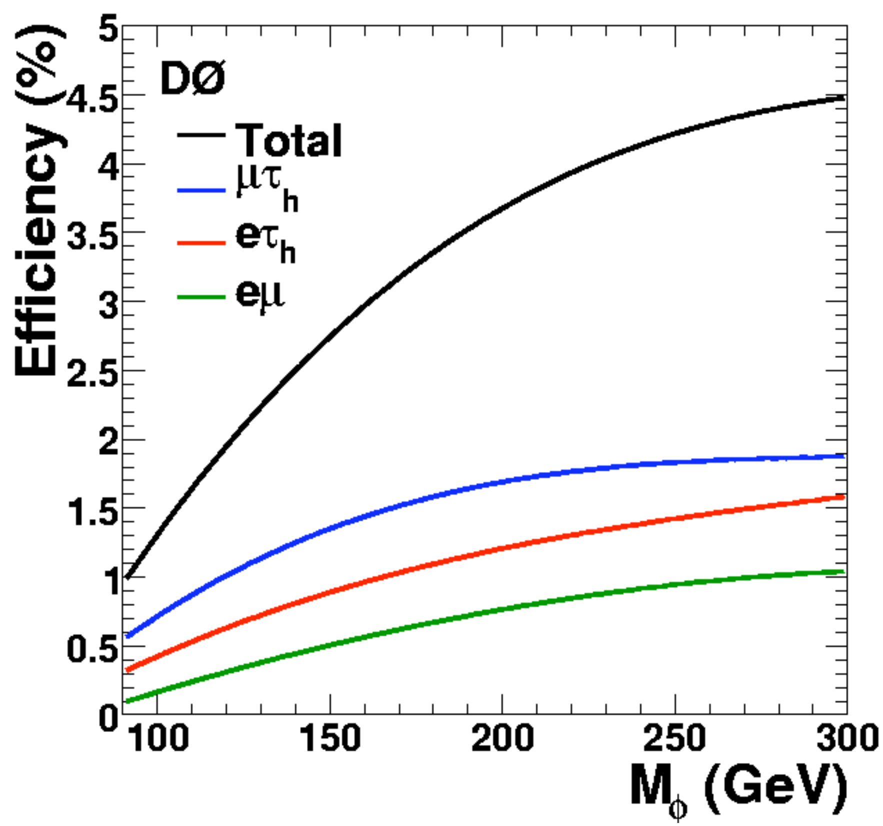
W + jets



$\phi \to \tau_e \tau_\mu$ Selections

- **Consider $\tau_e \tau_\mu$ final state**
  - isolated e ($p_T^e > 12$ GeV) and μ ($p_T^\mu > 8$ GeV) with $m_{\ell\ell} > 15$ GeV
  - impose kinematic selections based on leptons and $\not\!\!E_T$ to remove QCD multi-jet and W backgrounds
    - $p_T^e + p_T^\mu + \not\!\!E_T > 65$ GeV
    - $M_T^{min}(\ell, \not\!\!E_T) = \min(M_T(e, \not\!\!E_T), M_T(\mu, \not\!\!E_T)) < 10$ GeV
  - cut on scalar sum of jet p_T to remove top events
    - $H_T < 70$ GeV

- **Final efficiency for a signal**
  - summing channels: 1 – 4.5% across Higgs boson masses analyzed
  - comparable efficiencies but $\tau_e\tau_h$ suffers from larger multi-jet backgrounds (× ~3.5 higher than $\tau_\mu\tau_h$ mode)

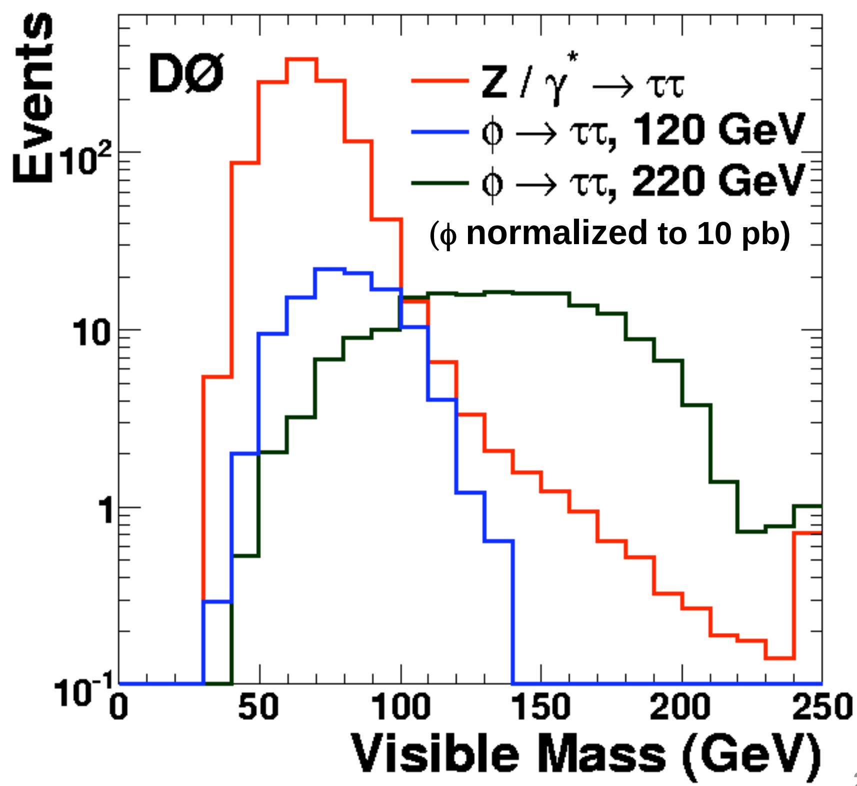


Visible Mass

- After final event selections, dominant background is Z
  - small contribution from EW and QCD multi-jet
- 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 $Z \rightarrow \tau\tau$

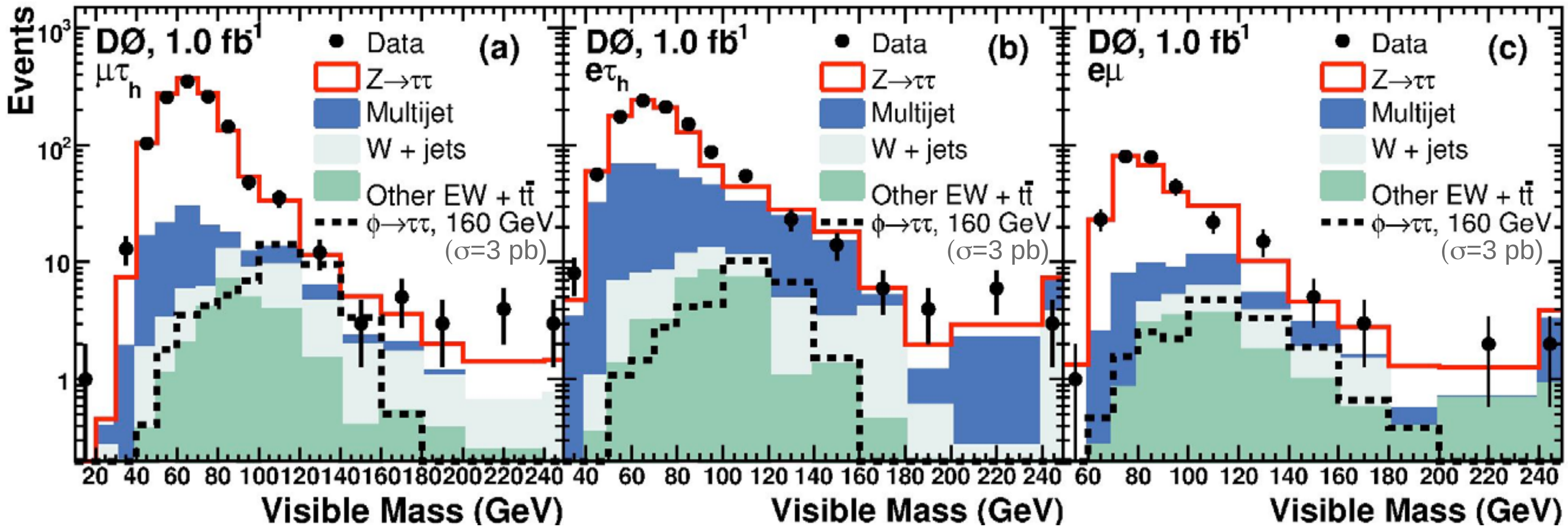
$$M_{VIS} = \sqrt{(P^{\tau 1} + P^{\tau 2} + \not{P}_T)^2}$$

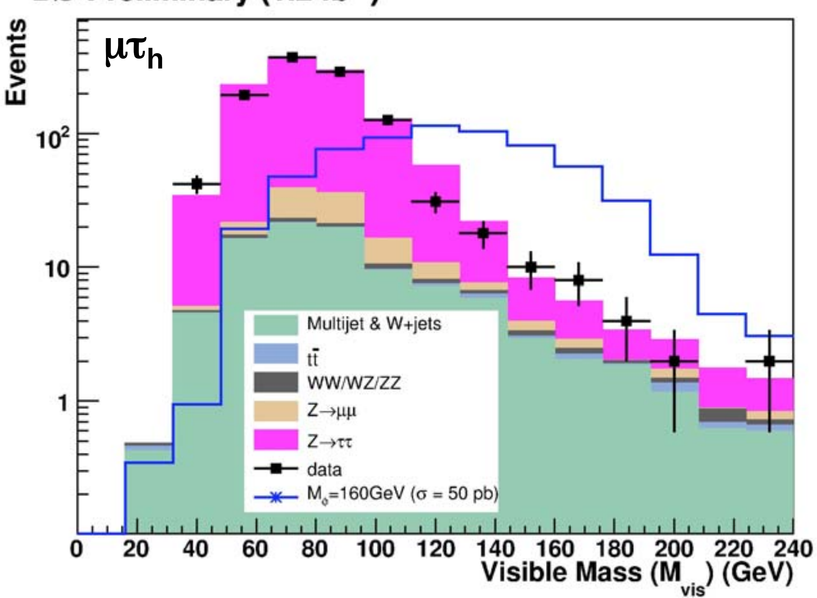
- Use 4-vectors of:
  - $P^{\tau 1}$, $P^{\tau 2}$ of visible tau decay products
  - $\not{P}_T = (\not{E}_T, \not{E}_x, \not{E}_y, 0)$, where $\not{E}_x$ and $\not{E}_y$ indicate components of $\not{E}_T$

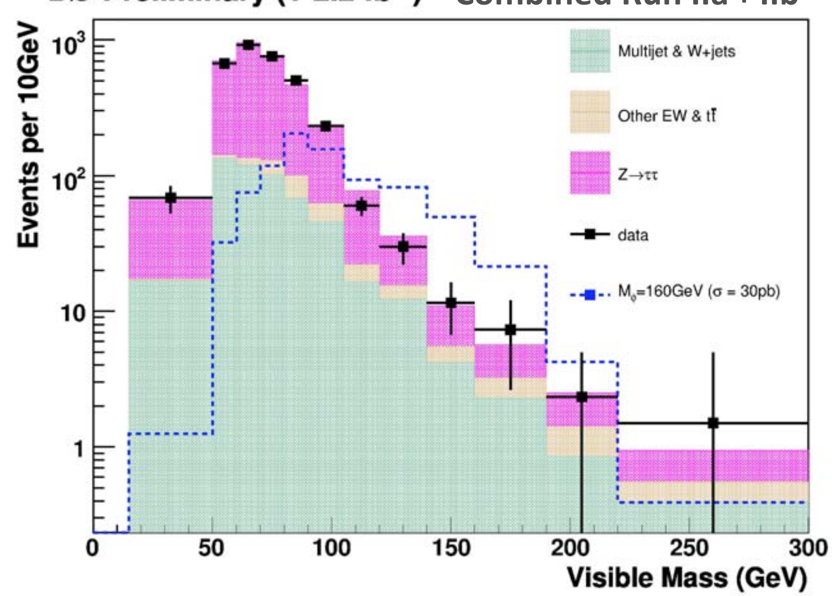


M_{vis}: 1–2.2 fb^{-1} Results

M_{vis}: Run IIa 1.0 fb^{-1} per decay channel ◆ Run IIb 1.2 fb^{-1} $\tau_\mu\tau_h$ ◆ Combined Run IIa + IIb

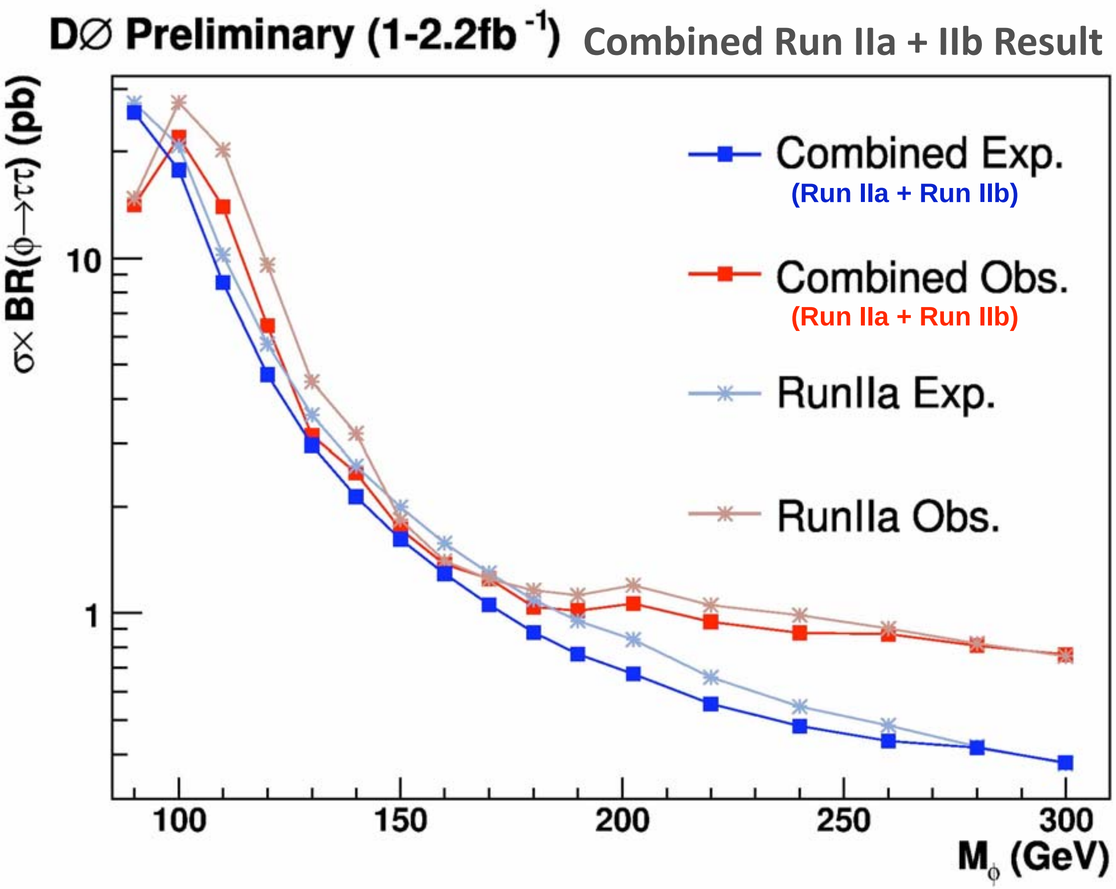


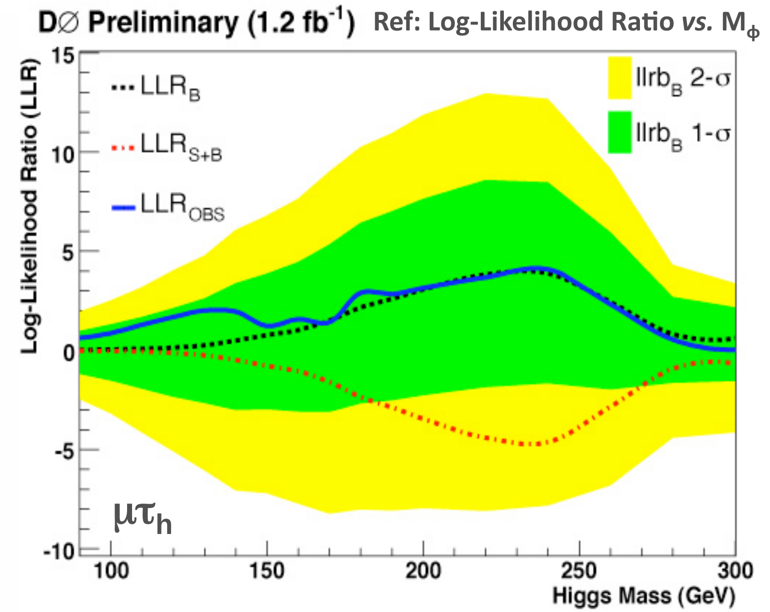




$\phi \rightarrow \tau\tau$: $\sigma \times$BR Limit

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





Major Systematic Uncertainties

Luminosity (6.1%)

τ-ID (4-8%, τ−type dependent)

τ energy scale (2-4%, type dependent)

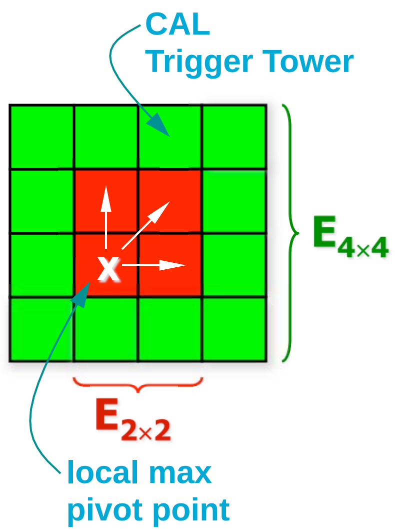
Z cross section (5%)

Trigger efficiency (shape)

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

$\phi b \rightarrow \tau^+\tau^- b$ Search ...Few Words on Triggers

- $\phi \rightarrow \tau_\mu \tau_h$ channel triggered on logical "OR" of single muon triggers
  - mainly adapted from Run IIa triggers
    - focused on muon trigger terms at all three levels of DØ Trigger (L1→L3)
    - essentially no tau trigger terms at L1 and L2 (L3 used basic τ NN algorithm)
  - increasing Run IIb luminosity (> 2×10^{32} cm^{-2} s^{-1}) required tightening conditions to avoid trigger pre-scales
    - offline selection cuts restricted to $p_T^\mu > 15$ GeV and $|\eta^\mu| < 1.6$
- Run IIb: implement L1Cal2b trigger upgrade
  - introduced suite of τ triggers
  - L1: τ's are "narrow jets"
    - pass E_T thresholds and CAL isolation (= $E_{2\times2}/E_{4\times4}$)
    - efficiency ~ 90%; background rejection > 75%
  - μ-τ triggers un-prescaled up to L ~ 2.8×10^{32} cm^{-2} s^{-1}
    - built on combination of muon and tau terms
  - allows using full DØ muon system coverage: $\eta^\mu \rightarrow 2.0$

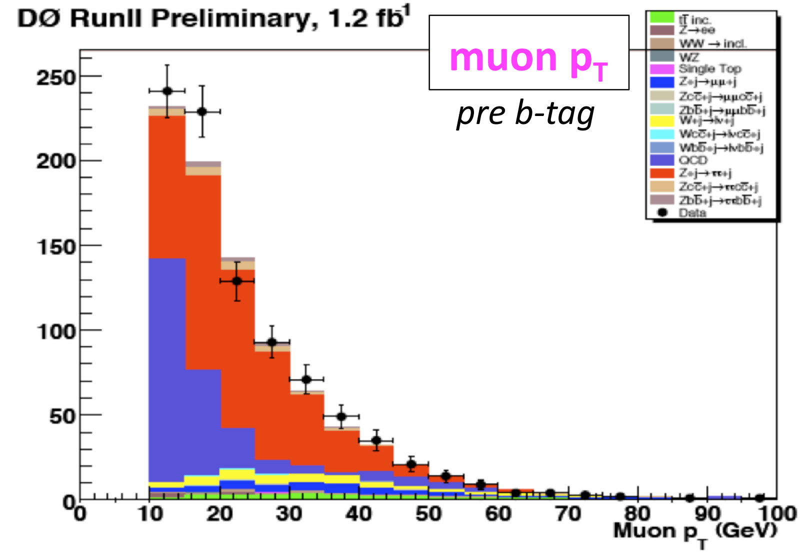


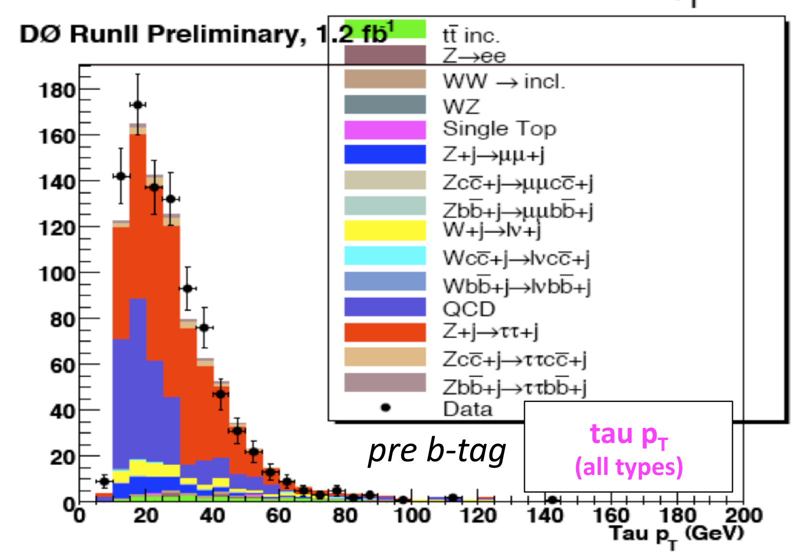
- $\phi b \rightarrow \tau_\mu \tau_h b$ search
  - trigger on logical "OR" of single muon triggers (9 total, ε_{tot} ~ 50-60%)
  - trigger on logical "OR" of new μ-τ triggers (24 total, ε_{tot} ~ 60-70%)

$\phi b \rightarrow \tau_\mu \tau_h b$ Search Channel

- **Use similar search techniques as those in $\tau_\mu\tau_h$ mode**
  - advantages: inclusion of μ-τ triggers plus a b-jet allows for looser cuts
  - but limited statistics available in channel after imposing final b-tag

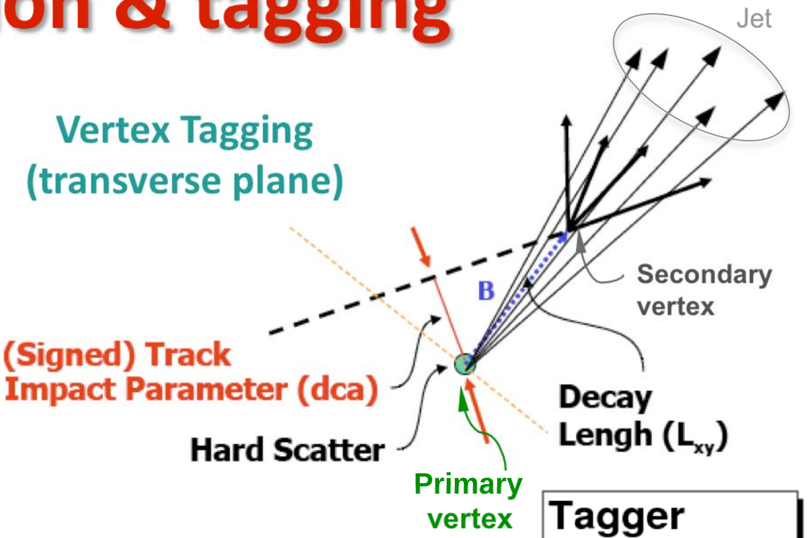
- **Event Selections**
  - one isolated μ: $p_T > 12$ GeV, $|\eta^\mu| < 2.0$
    - ⁎ suppress $Z \rightarrow \mu\mu$ by veto events with more than one μ
  - one τ, opposite sign (OS) from μ
    - ⁎ $E_T > 10, 10, 15$ GeV (types 1, 2, 3)
    - ⁎ $p_T^{\tau\text{-trk}} > 7, 5, 5$ GeV (types 1, 2, 3)
    - ⁎ $\Sigma\, p_T^{\tau\text{-trk}} > 10$ GeV (type 3)
    - ⁎ separated from muon: $\Delta R(\mu, \tau) > 0.5$
    - ⁎ NN > 0.9, 0.9, 0.95 (types 1, 2, 3)
  - at least one jet, $p_T > 15$ GeV
    - ⁎ separated from muon and tau: $\Delta R(\mu, j) > 0.5$ and $\Delta R(\tau, j) > 0.5$
  - final selections
    - ⁎ $M_W < 60$ GeV ⇒ suppress W+jets bkg
    - ⁎ one b-tagged jet





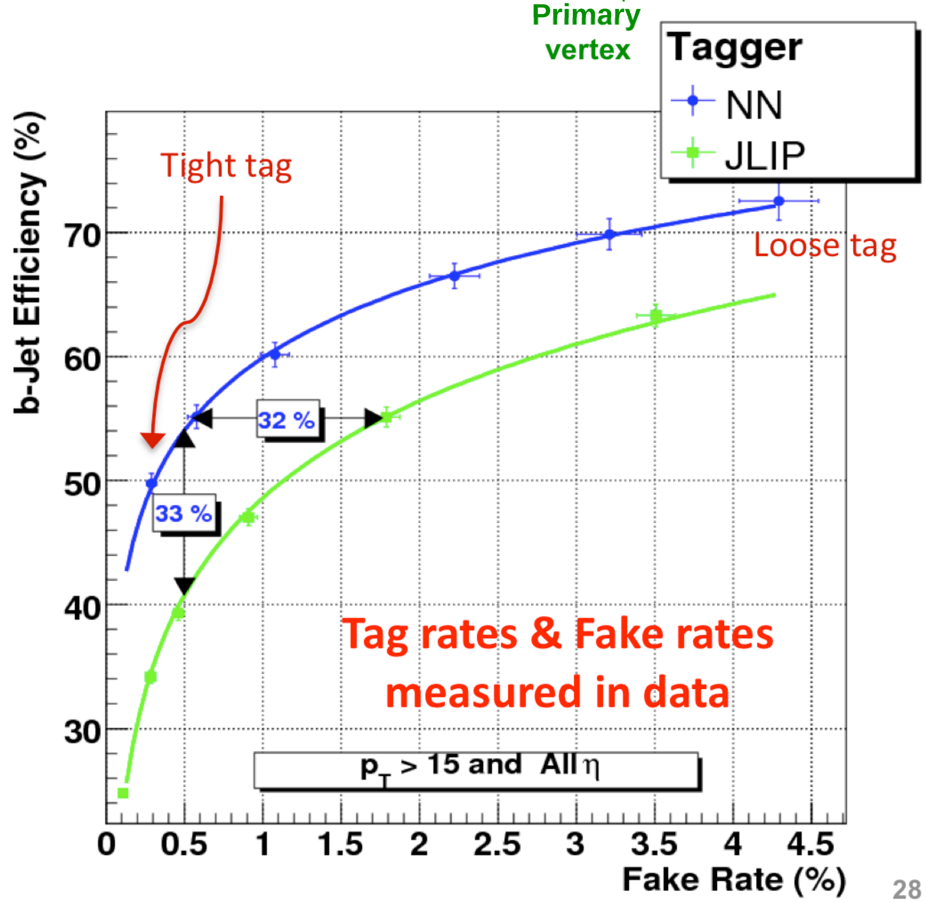
b-jet identification & tagging

- 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

Background Estimation

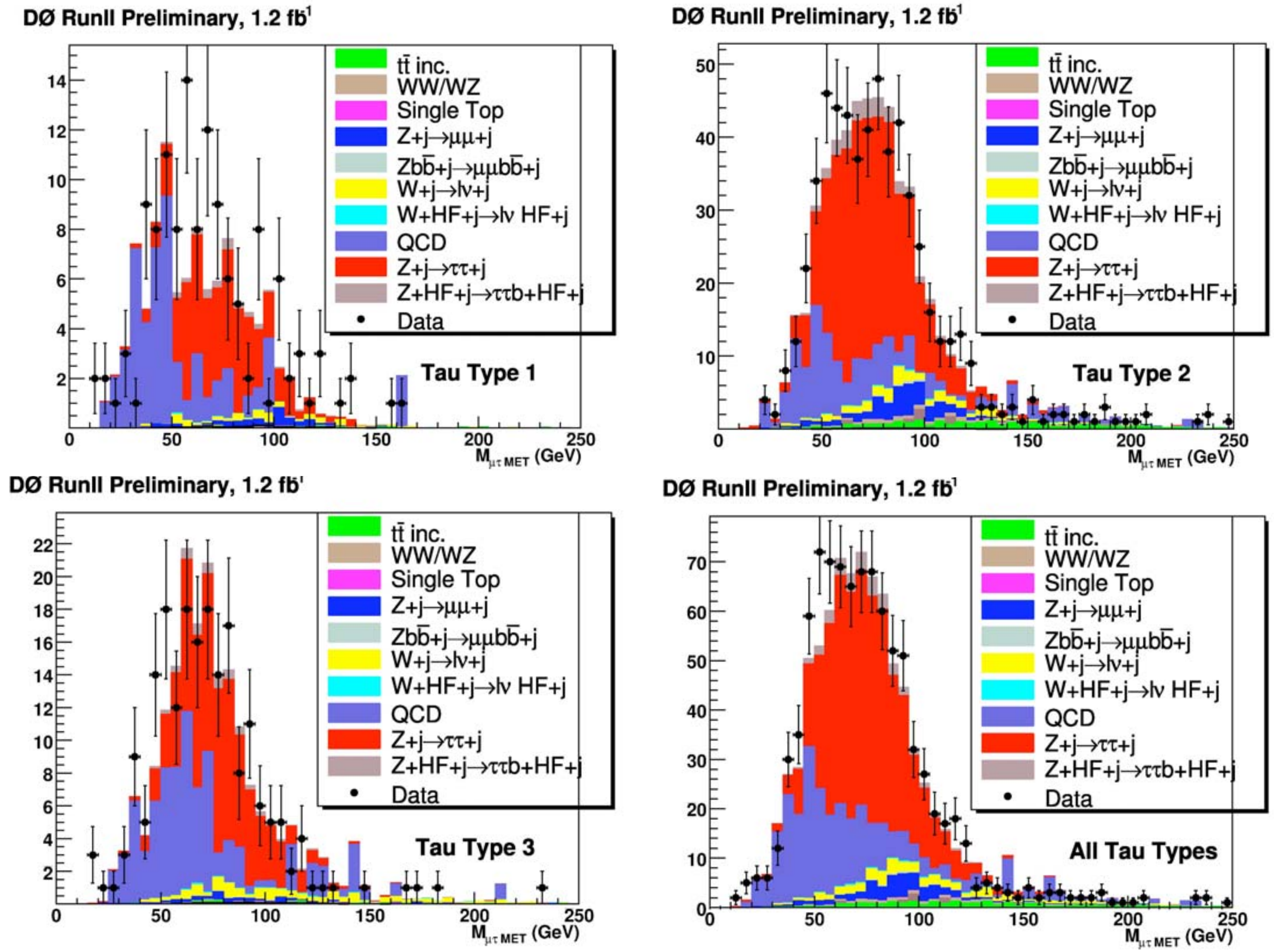
- Similar to $\phi \to \tau\tau$ search, backgrounds estimated from combination of simulated events and control data samples
  - top and diboson processes take from PYTHIA
  - (W, Z) + jets; (W, Z) + heavy flavor + jets events generated with ALPGEN
  - multi-jet "QCD" events difficult to simulate and hence, estimated from data
- QCD-enriched sample: pre-tag
  - use a strategy similar to the $\phi \to \tau\tau$ search
    - * invert muon isolation and select mNN events: $0.3 < \tau\text{-NN} < 0.8$
  - QCD in signal region extrapolated via ratio of OS to SS events in QCD-enriched sample
- Multi-jets: post b-tag
  - poor stats from b-tag require two methods
  - Tag-rate Function (TRF) method
    - * measure probability for jet to be b-tagged in QCD-enriched sample in terms of jet p_T and apply to pre-tag sample
  - Fake Rate Method
    - * determine muon isolation fake rate in events with $\not{E}_T < 20$ GeV
    - * further measure jet-to-tau fake rate from independent $W \to \mu\nu$ + jets sample
    - * apply both on control b-tag + mNN sample

Total # of Events: QCD			
τ-type	TRF Method (QCD shape)	Fake Rate Method	Avg.
1	4.94	1.73	3.34
2	9.27	6.10	7.69
3	7.17	4.22	5.69
Total	21.38	12.05	16.72

TRF method ⇒ QCD shape
Avg. of two methods ⇒ Normalization
Half the difference ⇒ Systematic Error

$\phi b \rightarrow \tau\tau b$: Pre b-tagging

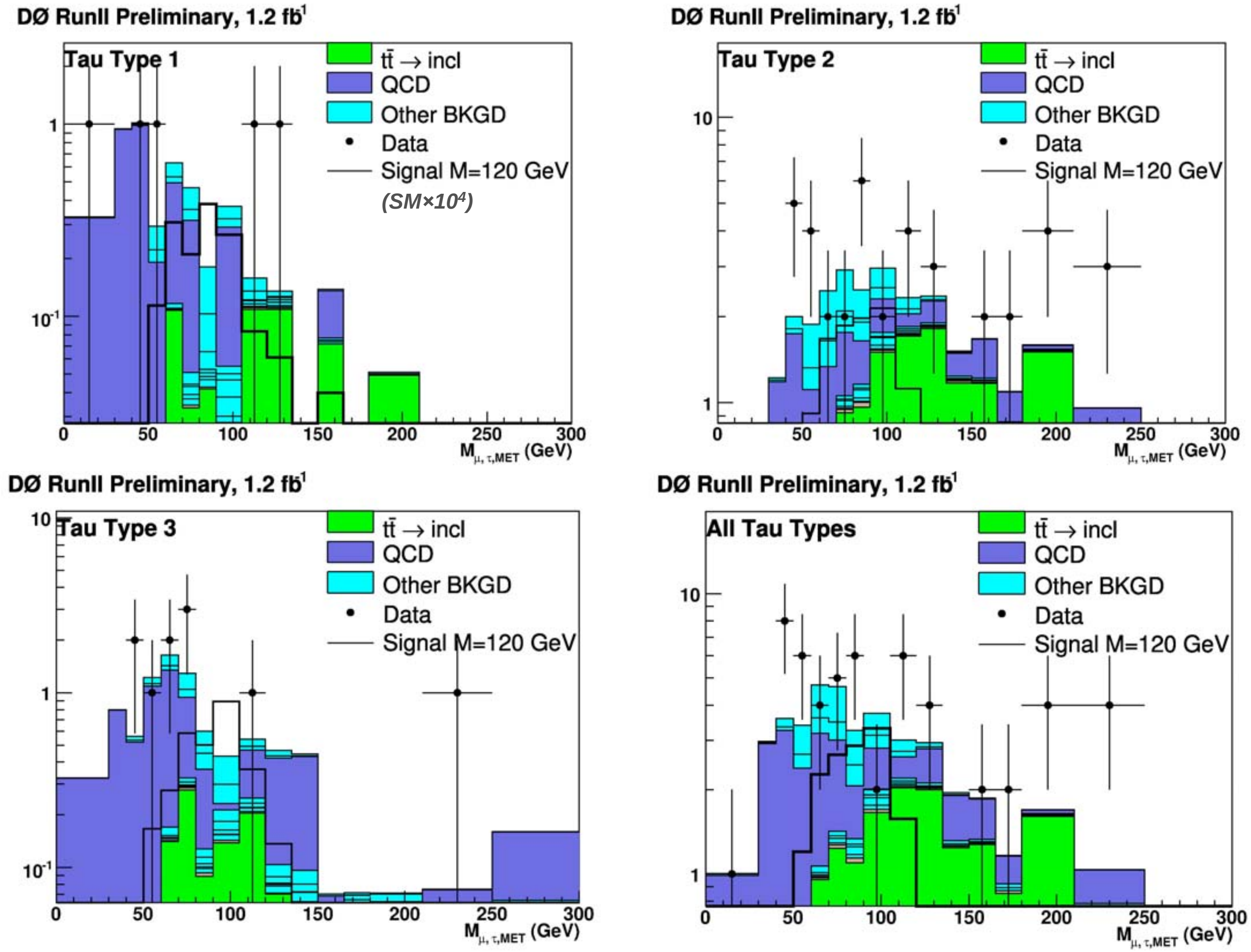
- Invariant mass of μ, τ, $\not{E}_T$ system ⇒ data in agreement with pred. backgrounds
  - dominant backgrounds: Z + jet & QCD multi-jet events



PRE b-tag	Z (μμ,ττ)	Top	Multi-jet	Other EW	Total Pred.	DATA
all τ-types	532.3 ± 5.6	26.5 ± 1.0	252.7 ± 17.0	56.0 ± 2.1	867.4 ± 24.8	906 ± 30

$\phi b \rightarrow \tau\tau b$: Post b-tagging

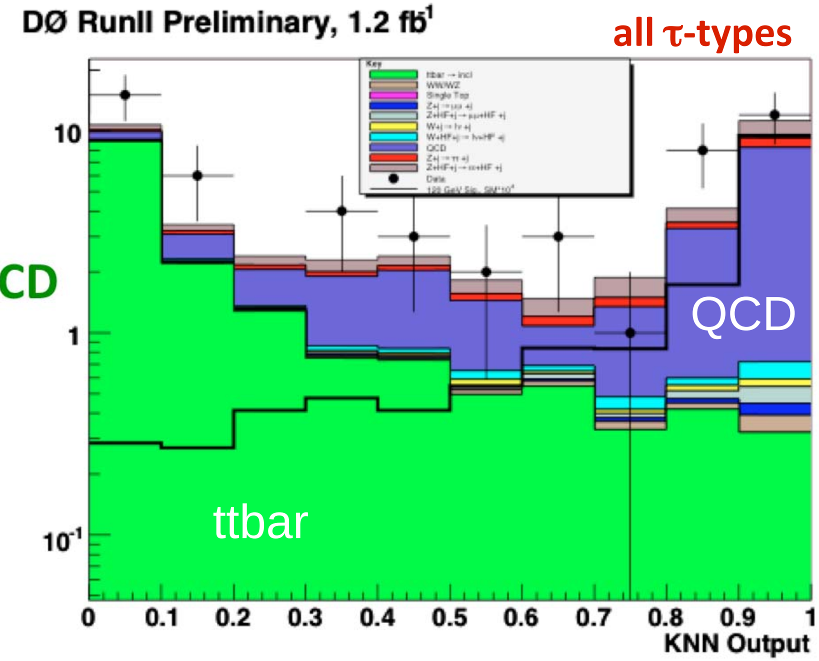
- After (NN tight) b-tag, dominant backgrounds: top & QCD multi-jet events
  - motivates constructing techniques to further discriminate against each

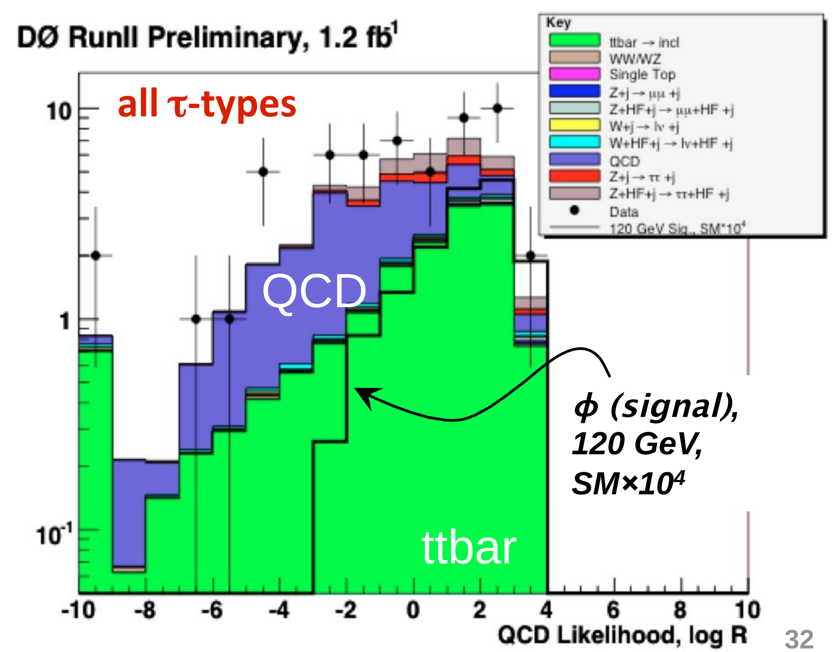


POST b-tag	Z ($\mu\mu,\tau\tau$)	Top	Multi-jet	Other EW	Total Pred.	DATA
all τ-types	7.8 ± 0.1	16.0 ± 0.6	16.8 ± 1.4	1.0 ± 0.1	41.7 ± 1.5	54 ± 7.4

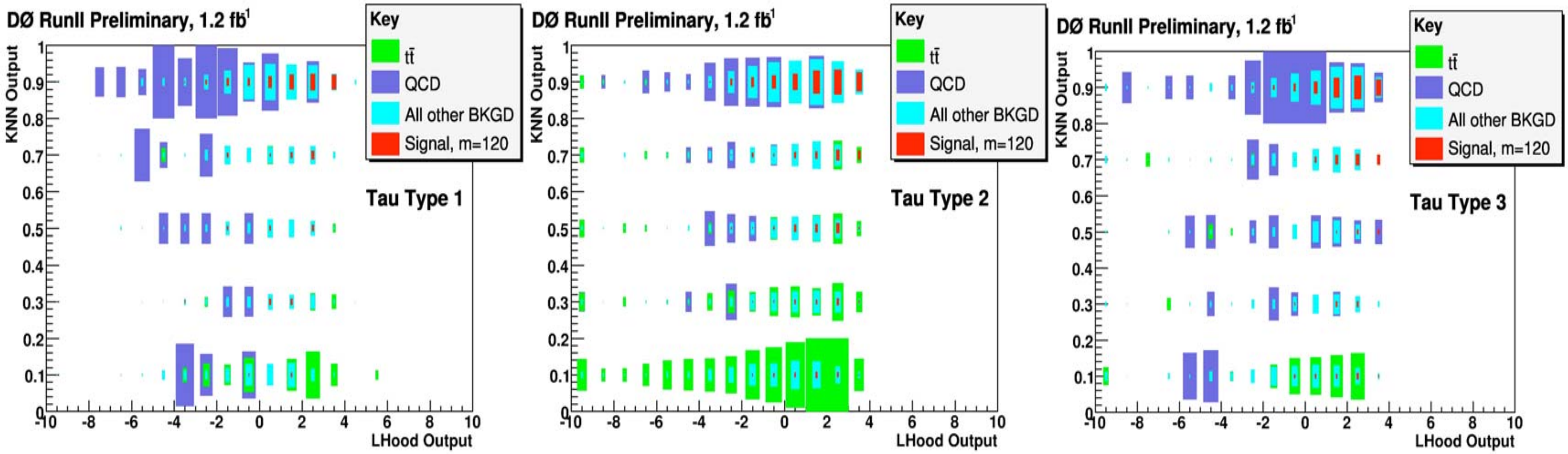
Multivariate Methods

- Post b-tag: two techniques used to suppress $t\bar{t}$ and QCD multi-jet events
  - Kinematic NN (KNN) ⇒ rejects top
  - Log-Likelihood Ratio (LHood) ⇒ rejects QCD
- KNN input variables
  - Jet multiplicity, H_T=scalar sum of jet p_T's, energy sum of (μ, τ, jets), and $\Delta\varphi(\tau, \mu)$
  - KNN > 0.3 offers ~75% rejection of top events with only ~4% signal loss
- LHood trained separately for each signal mass point
  - p_T^{μ}, p_T^{τ}, $\Delta R(\mu, \tau)$, $\mu-\tau$ invariant mass, and M_{vis}
  - compute likelihood of event to be signal-like or QCD-like & take ratio
    - higher LHood value ⇒ signal-like; lower LHood value ⇒ QCD-like





KNN vs. LHood

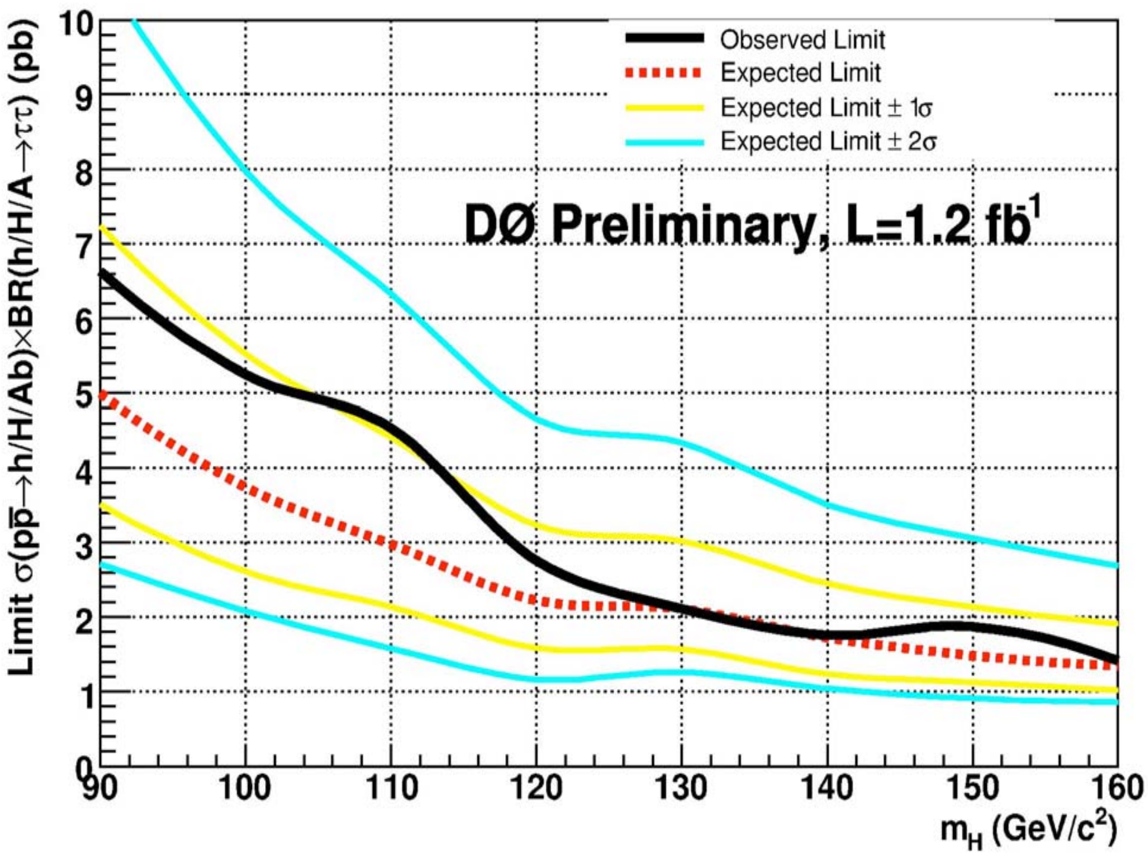


- KNN vs. LHood 2D distributions
  - apply cuts in (LHood, KNN) plane ⇒ chosen at values that optimize the expected significance
    - dependent on M_ϕ and τ-type
- no significant excess in data over predicted backgrounds
  - 2D signal and background distributions used to set limit on $\sigma \times BR$

M_ϕ (GeV)	τ-type 1		τ-type 2		τ-type 3	
	KNN	LHood	KNN	LHood	KNN	LHood
90	0.2	-1	0.3	-1	0.2	-1
100	0.3	-2	0.3	-1	0.2	0
110	0.3	-2	0.4	-2	0.2	-1
120	0.2	-2	0.35	-2	0.2	-1
130	0.2	-2	0.35	-2	0.2	-1
140	0.3	-2	0.35	-2	0.2	0
150	0.3	-2	0.35	-2	0.2	-1
160	0.2	-2	0.3	-3	0.2	-1

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

- Limits on $\sigma \times BR$ calculated using modified frequentist approach
- Study within Higgs boson mass range from 90 to 160 GeV in 10 GeV intervals
- Presently limited by large systematics on: $Z \to \tau\tau + b(c)$ scale factor (NNLO heavy-quark enhancements), $t\bar{t}$ cross section, and QCD estimate



DØ-CONF 5727 (2008)

Summary of Systematic Uncertainties

Luminosity (6.1%)

τ-ID (4-8%, type dependent)

τ energy scale (2-4%, type dependent)

QCD (40%, 21%, 26%, type dependent)

MC cross sections

Single top (12%)

$t\bar{t}$ (11%)

Diboson (6%)

W + lp (10%)

W + HF + lp (50%, from K-factor)

$Z \to \mu\mu, \tau\tau$ + lp (+2/-5%, NNLO theory)

$Z \to \mu\mu, \tau\tau$ + HF (50%, from K-factor)

Jet Energy Scale (shape)

b-tag (shape)

Trigger efficiency (shape)

MSSM Benchmark Scenarios

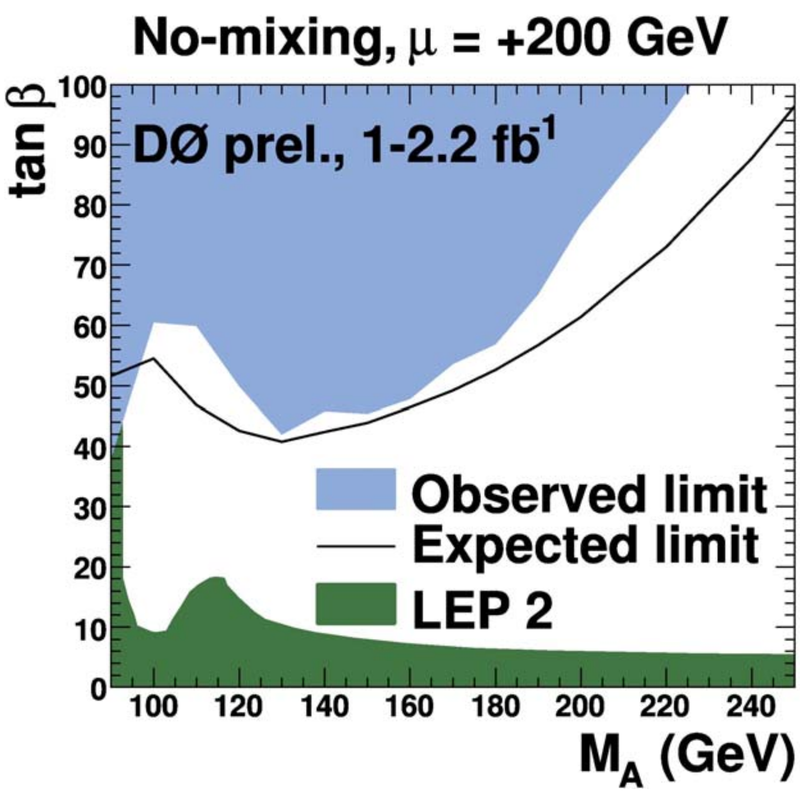
- $\sigma \times$ BR Limits $\Rightarrow$ interpreted in MSSM
- Tree-level: Higgs sector of MSSM described by M_A & $\tan\beta$
  - radiative corrections introduce dependence on additional SUSY parameters
- Five additional, relevant parameters
  - M_{SUSY} Common Scalar mass: parameterizes squark, gaugino 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

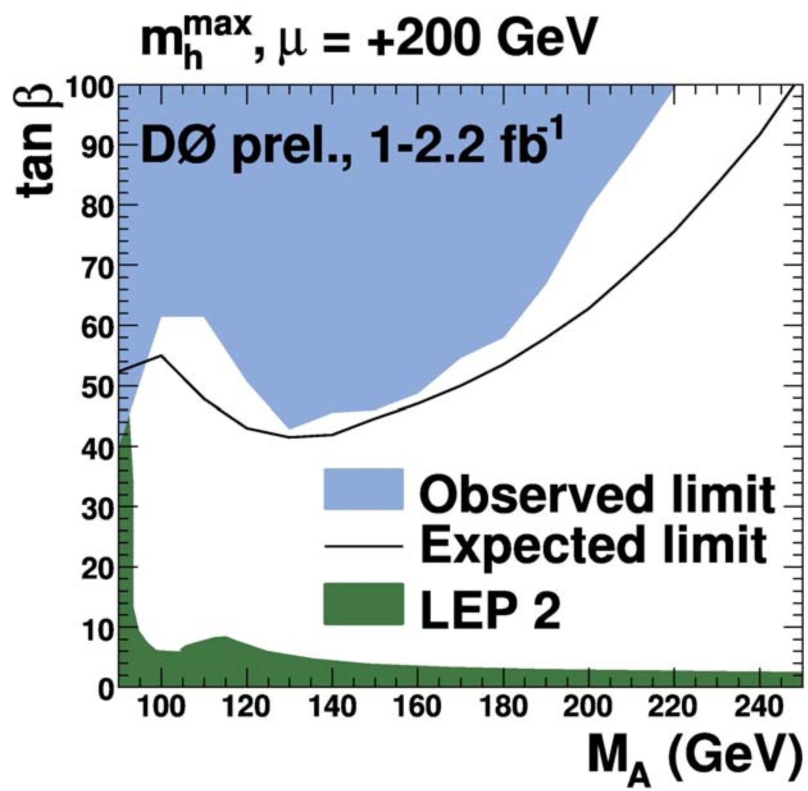
Constrained Model: Unification of SU(2) and U(1) gaugino masses		
	m_h^{max}	no-mixing
M_{SUSY}	1 TeV	2 TeV
X_t	2 TeV	0
M_2	200 GeV	200 GeV
μ	±200 GeV	±200 GeV
$m_{\tilde{g}}$	800 GeV	1600 GeV

$\phi \rightarrow \tau\tau$: Interpretation within MSSM

- From cross section limits, (M_A, $\tan\beta$) parameter space scanned & regions excluded in MSSM benchmark scenarios
  - cross sections taken from FeynHiggs v.2.6.4
  - h/H degenerate with A $\Rightarrow$ production cross section for $gg \rightarrow \phi$ and $b\bar{b} \rightarrow \phi$ added at each (M_A, $\tan\beta$) point
- Reach sensitivity for $M_A < 180$ GeV: $\tan\beta \sim 40 - 50$

MSSM: 95% CL Exclusion Limits ($\mu > 0$)

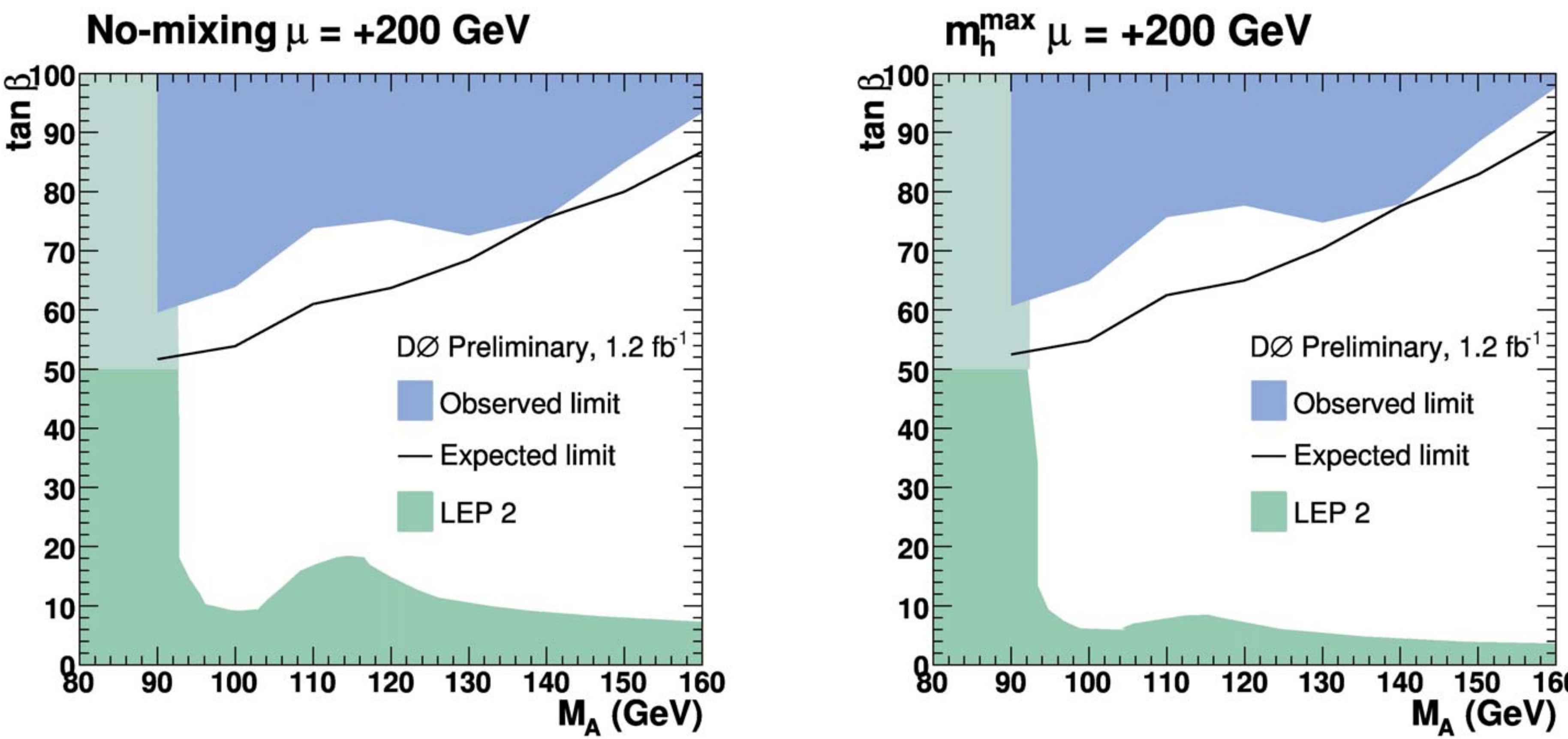




$\phi b \rightarrow \tau\tau b$: Interpretation within MSSM (I)

- Similarly, limits interpreted for ϕb in MSSM parameter space using FeynHiggs
  - expect sensitivity to continually improve with increased datasets
  - and gain from better understanding of systematics

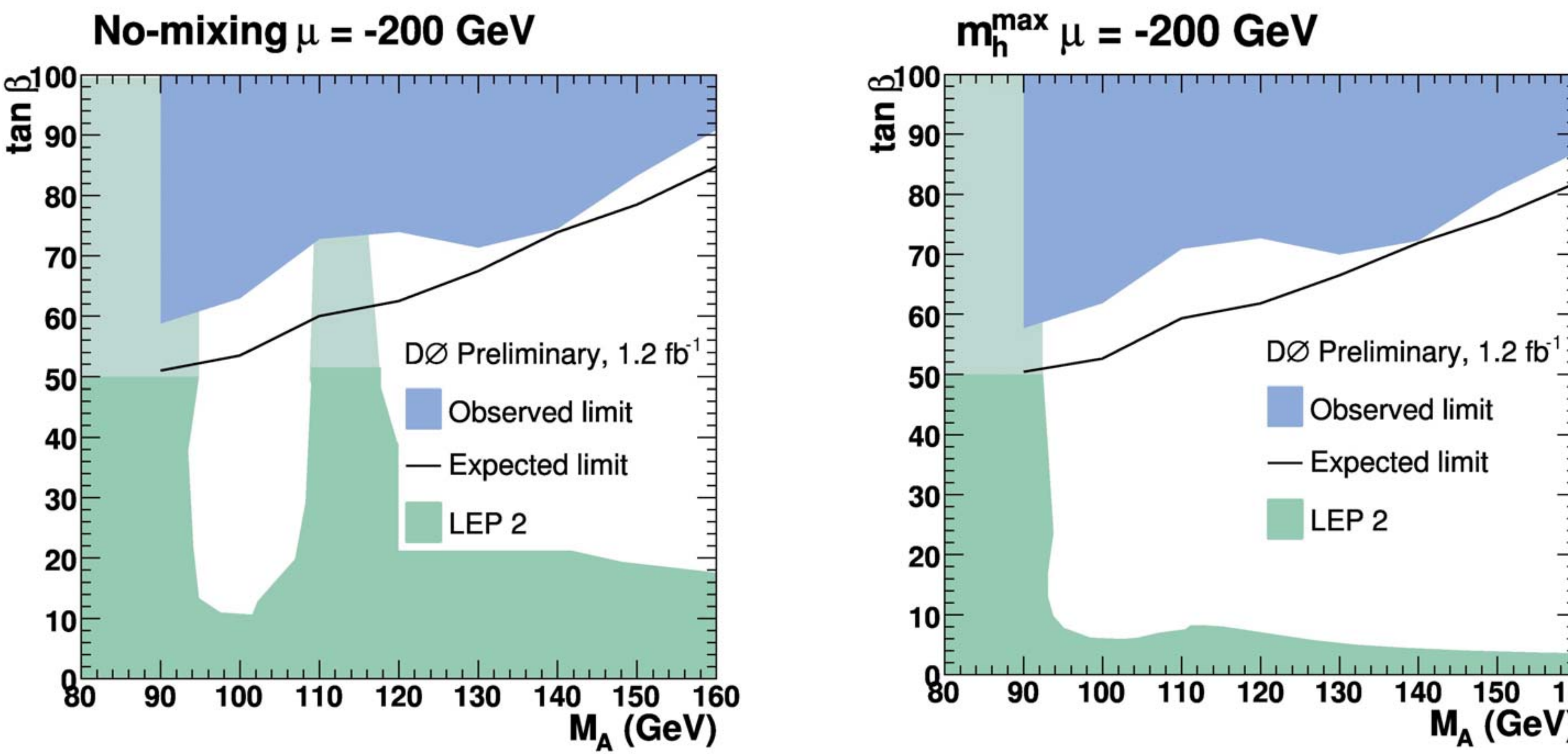
MSSM: 95% CL Exclusion Limits (μ > 0)



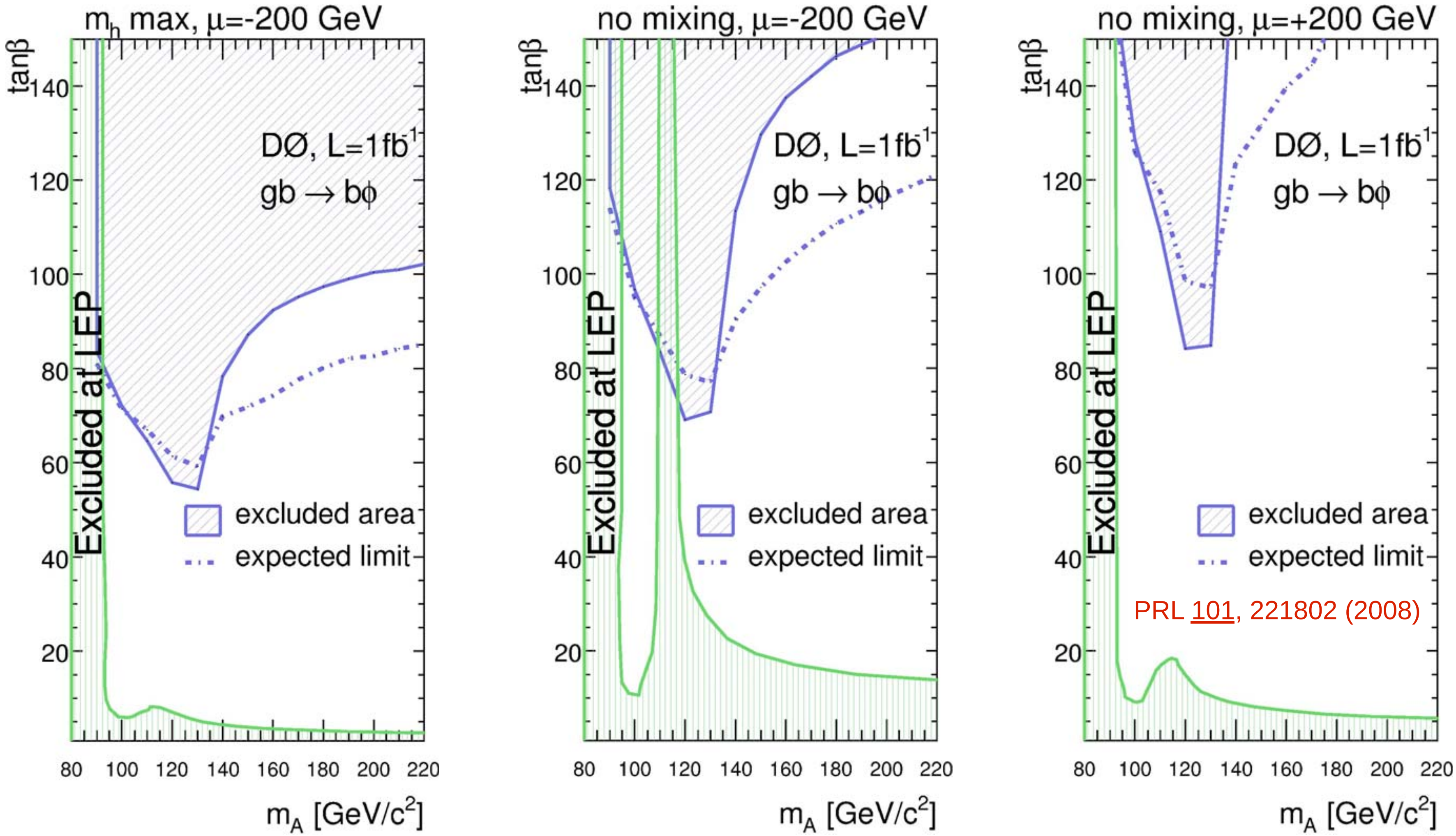
$\phi b \rightarrow \tau\tau b$: Interpretation within MSSM (II)

- Similarly, constraints for $\mu < 0$
- General, complementary to inclusive $\phi \rightarrow \tau\tau$ channel: helps contribute to overall Tevatron sensitivity, at low M_A $\Rightarrow$ does not suffer from $Z \rightarrow \tau\tau$ background
- Excluded regions largely insensitive to MSSM scenario and μ
  - different from $b\phi \rightarrow bb\bar{b}$ final state (i.e., "3b" Channel)

MSSM: 95% CL Exclusion Limits (μ < 0)



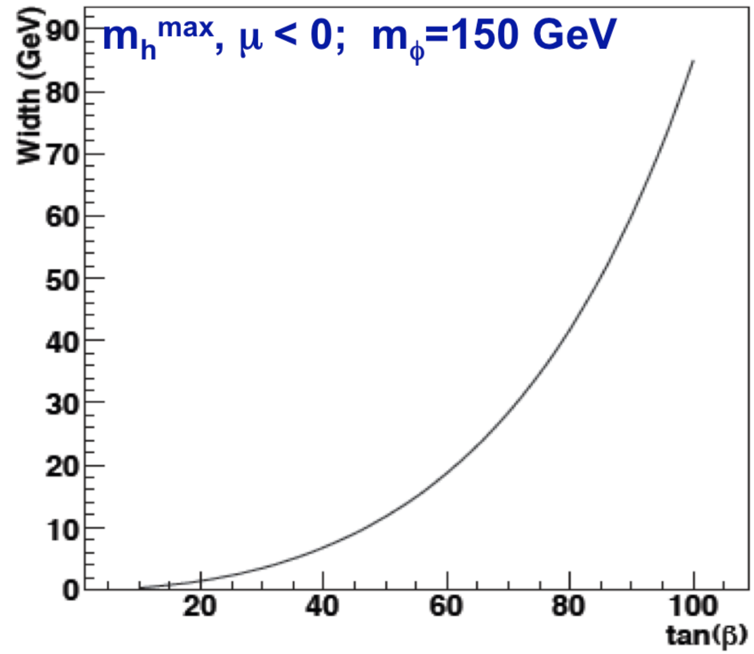
Comparisons with $\phi b \to bb\bar{b}$

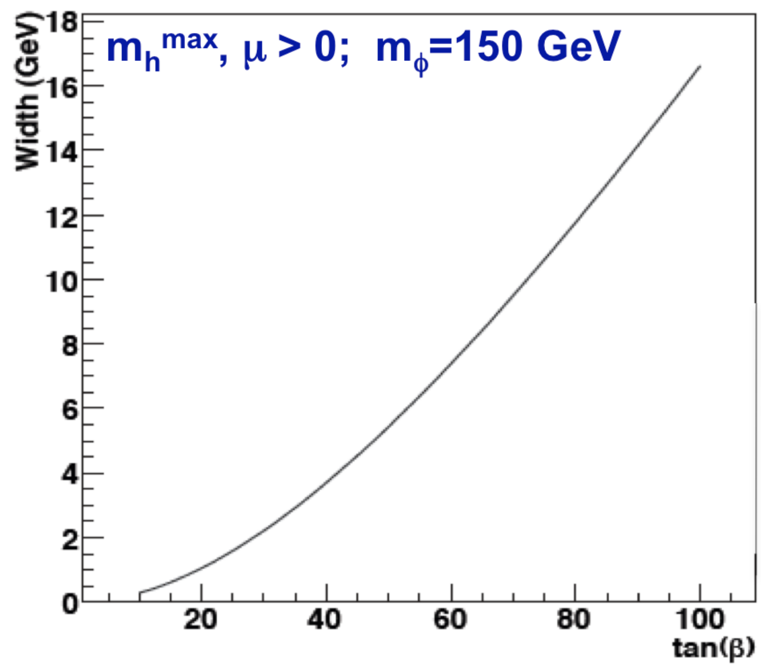


- **3b channel gives strong limits for m_h^{max} scenario with $\mu < 0$**
  - **radiative corrections give large sensitivity to μ and its sign**
    - **negative μ gives enhanced production**
  - **positive μ: tau mode competitive especially at low masses despite 1:9 BR**

Higgs Width

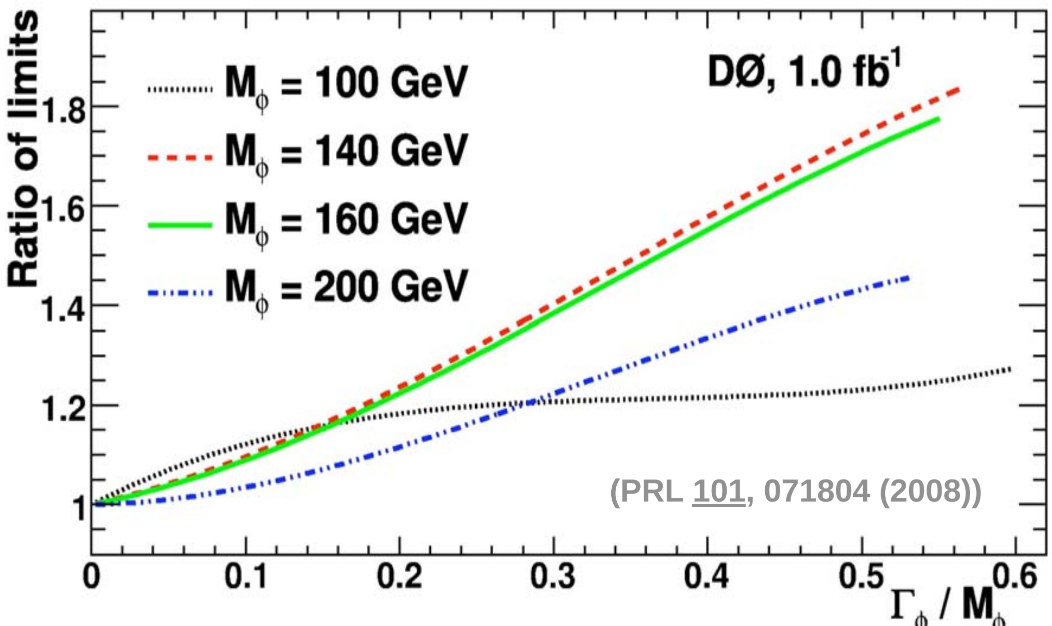
- Limit on $\sigma \times$ BR calculated assuming SM Higgs boson width
  - negligible compared to experimental resolution on M_{vis}
- In MSSM models, Higgs width can be larger than value in SM
  - increases with tanβ
  - also large dependence on other parameters… for e.g., μ
- e.g., factor ~ 2 or more difference for fixed tanβ in models with $\mu > 0$ *vs.* $\mu < 0$





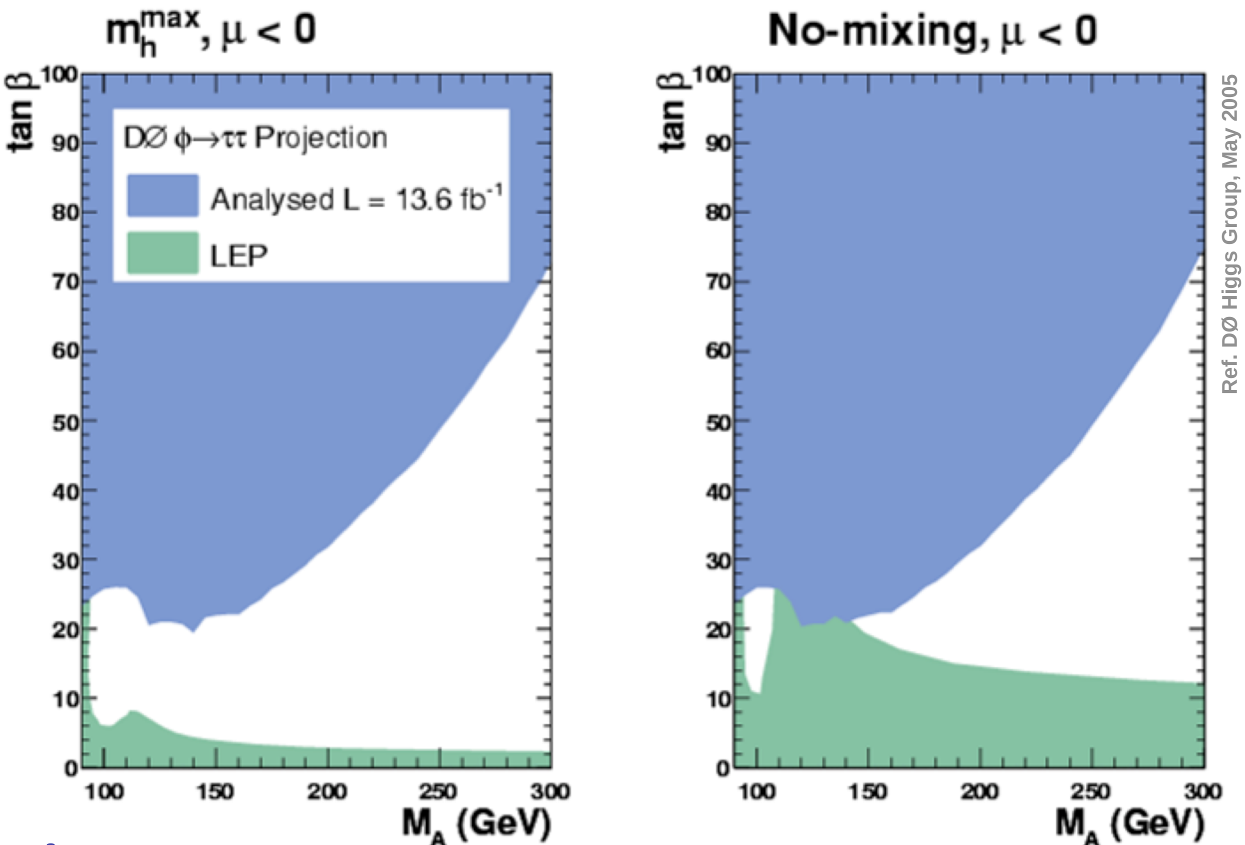
$\phi \to \tau\tau$ Result & Width

- 1.0 fb^{-1} PRL result $\Rightarrow$ provide a 'model-independent' correction for effect of a large Higgs boson width
  - simulate effect by adding together neighbouring Higgs boson signal samples with correct weights
- Build wide signal templates of M_{vis} distribution for Higgs mass M_ϕ and width Γ_ϕ
  - re-calculate cross section limits corresponding to various values of Γ_ϕ
  - take ratio of limits for wide Higgs boson with SM Higgs boson width ($=\Gamma_\phi / \Gamma_{SM}$)
  - study ratio as function of width and 4 different Higgs masses
- Can be used to obtain cross section limits for non-SM relative to limit for a Higgs with SM width
  - must specify M_ϕ and Γ_ϕ
  - for e.g., model with (Γ_ϕ , M_ϕ) = (16 GeV, 160 GeV) $\Rightarrow$ correct limits by 8%



Projections

- MSSM projections for full 2010 dataset
  - both experiments
  - if no Higgs boson observed, exclusions reach $\tan\beta \sim 20$ for $M_A \sim 120$-160 GeV



- LHC experiments
  - exclude the entire M_A – $\tan\beta$ plane
    - eliminate MSSM Higgs sector as a viable model
  - or achieve 5σ discovery of at least one MSSM Higgs boson

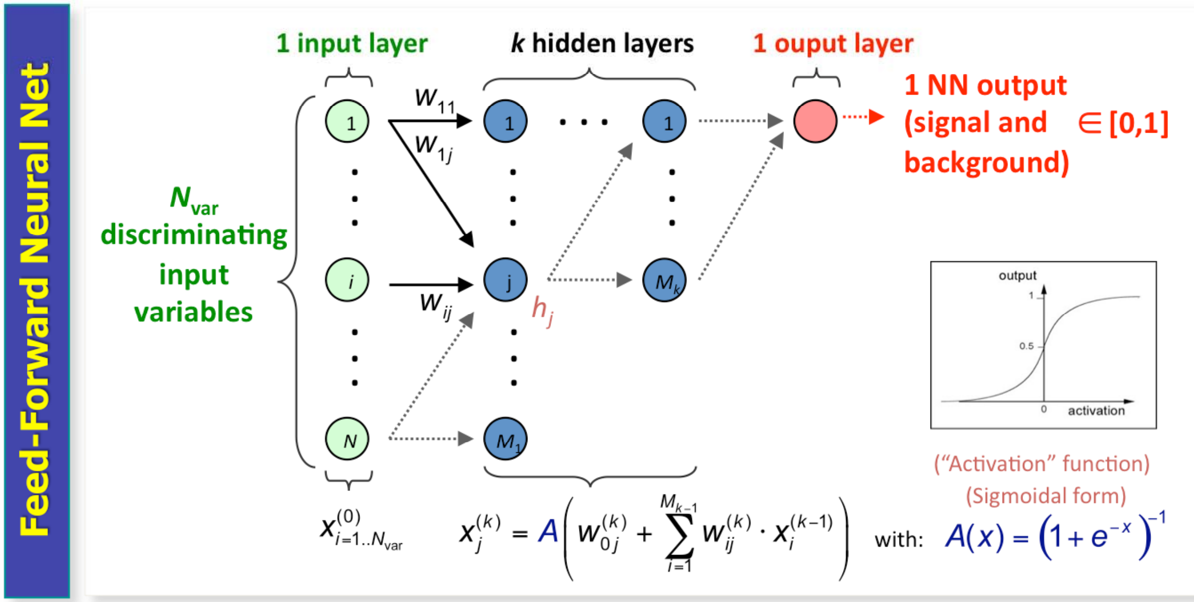
Closing Summary

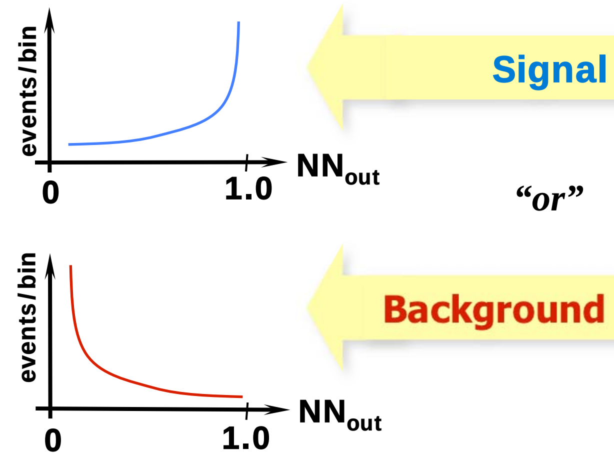
- DØ searches for neutral MSSM Higgs boson at high tanβ in two major di-tau decay channels
  - 3b channel and charged Higgs bosons in top decays also studied
  - analyses well-developed;   results with up to 2.2 fb^{-1} of Run II data
- No signal observed in data over expected backgrounds
- Upper limits set for $\sigma \times$BR and subsequently translated into 95% CL exclusions in MSSM parameter space
  - reached sensitivity tanβ ~ 40 – 50 for M_A < 180 GeV
  - combination of different channels studied at DØ is in progress and with CDF (Tevatron result)
- Tevatron delivered > 5.4 fb^{-1} of Run II data   …and more coming
  - updated results from other channels decaying to tau pairs expected soon…
  - expect sensitivity to continually improve

Reference Slides

Neural Networks and τ-ID

- multivariate analysis method ⇒ Neural Networks (NN)
  - parallel operation with neurons (nodes) arranged in series per layer connected via links

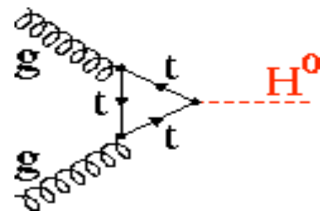




- input nodes, one for each measured variable (x_i)
- hidden nodes (h_j) ⇔ neuron performs a linear combination of input signals ~ $\sum_{i=1}^{n_i} \omega_{ij} x_i$, x_i = i^{th} input
  - weights (ω_{ij}) for links between node *i* to node *j*
- signal and background control samples
  - ⇒ adjust weights and biases using iterative back-propagation technique (training)
  - ⇒ optimize signal at $NN_{out} \rightarrow 1.0$ and produce weight file (kernel)
  - ⇒ apply kernels to τ-physics analysis

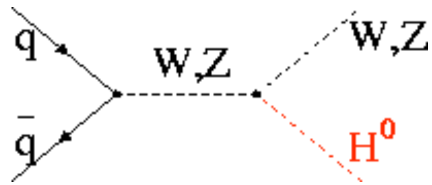
SM Higgs Production at Tevatron

- Gluon fusion: $gg \rightarrow H$



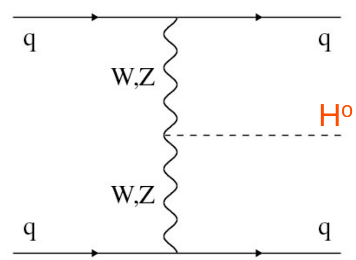
$\sigma = 0.70$ pb
for M(H) = 120 Gev/c^2
with QCD NLO correction

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



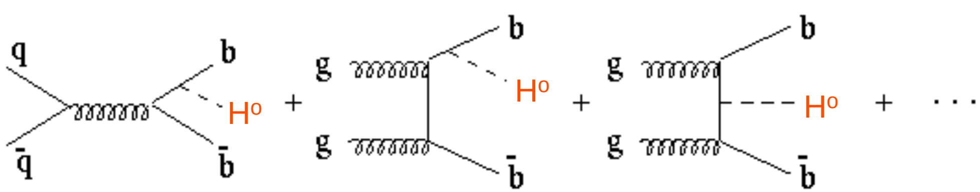
WH: $\sigma = 0.16$ pb
ZH: $\sigma = 0.10$ pb

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



$\sigma = 0.10$ pb

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



$\sigma = 0.004$ pb

MSSM $\phi \rightarrow \tau^+\tau^-$: Yields

- Observed & expected number of events for backgrounds
  - given efficiencies for a signal relative to M_ϕ = 160 GeV

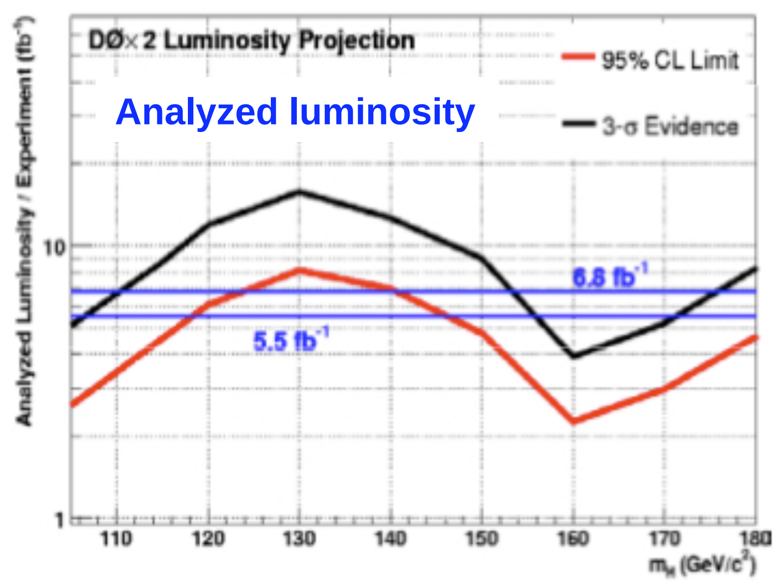
Channel	$e\tau_h$ (Run IIa, 1 fb^{-1}) PRL RESULT	$\mu\tau_h$ (Run IIa, 1 fb^{-1}) PRL RESULT	$e\mu$ (Run IIa, 1 fb^{-1}) PRL RESULT	$\mu\tau_h$ (Run IIb, 1.2 fb^{-1}) PRELIM RESULT
$Z/\gamma^* \rightarrow \tau\tau$	581 ± 5	1130 ± 7	212 ± 3	1030 ± 32
$Z/\gamma^* \rightarrow \mu\mu$, ee	31 ± 2	19 ± 1	12 ± 1	48 ± 6
QCD Multi-jet + W	374 ± 21	118 ± 6	38 ± 2	96 ± 9
Diboson + Top	3.0 ± 0.1	7.0 ± 0.4	6.1 ± 0.1	8.7 ± 2.6
Total Prediction	989 ± 23	1274 ± 9	269 ± 3	1189 ± 34
Data	1034	1231	274	1109
Efficiency (%)	1.04 ± 0.03	1.46 ± 0.04	0.57 ± 0.03	1.40 ± 0.05

- Data consistent with expected backgrounds
  - M_{vis} spectrum used in limit calculation
  - Modified frequentist approach using likelihood-fitter
    - confidence level $CL_s = CL_{s+b}/CL_b$; where CL_{s+b} = signal-plus-background & CL_b = background-only hypothesis
    - calculate expected & observed limits by scaling signal until $1-CL_s = 0.95$

Tevatron Projections & SM Higgs

- Recent Tevatron luminosity projections
  - plan on ~7 fb^{-1} (up to ~9 fb^{-1}) delivered for end-FY09 (end-FY10) running

- Tevatron expected SM Higgs reach
  - up to 6.8 fb^{-1} analyzed: 2σ exclusion for M_H > 125 GeV or 3σ evidence for M_H = 154-175 GeV
  - low mass region more difficult



CDF: MSSM Higgs Decay to di-tau

- CDF 1.8 fb^{-1} result: observe no significant excess in data above backgrounds
  - exclusion limits set for M_A = 90 – 250 GeV