Imperial College London

Fermilab

Beyond the Standard Model Higgs Searches at the Tevatron

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On behalf of the CDF and DØ Collaborations

CDF II

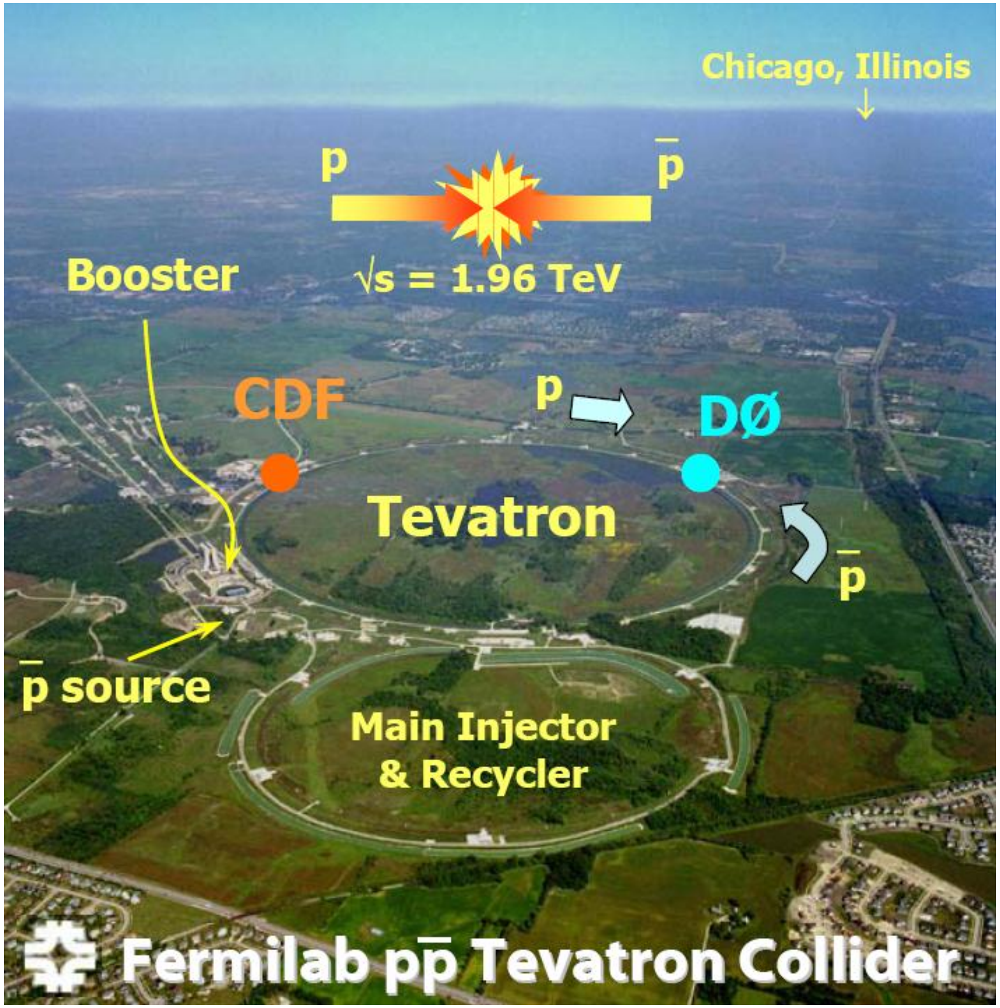
DØ

Outline

Results up to 8.2 fb^{-1}

Delivered > 10.5 fb^{-1}

- Minimal SUSY SM (MSSM)
- Next-to-MSSM
- Hidden Valley Higgs
- Fermiophobic Higgs
- Conclusions



[Thanks to all my Tevatron colleagues]

Neutral SUSY Higgs

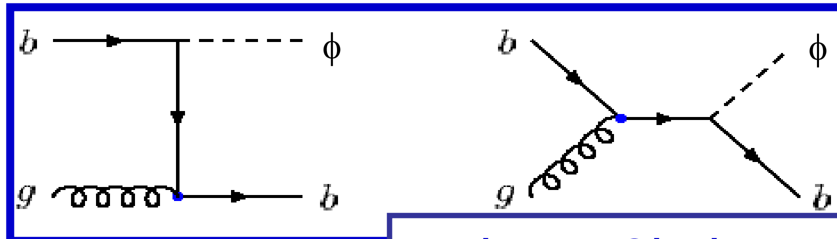
- Minimal Supersymmetric Standard Model (MSSM)
  - Introduction
  - Neutral Higgs bosons (ϕ) searches
    - $b\phi \rightarrow bbb$
    - $b\phi \rightarrow b\tau\tau$
    - $\phi \rightarrow \tau\tau$
    - Combination
    - Prospects
- Next-to-MSSM
- Hidden Valley Higgs
- Fermiophobic Higgs
- Conclusions

MSSM Higgs boson production

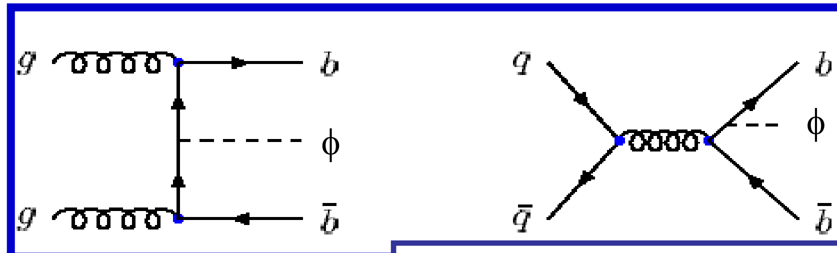
- MSSM - 5 Physical Higgs bosons
  - 3 Neutral: (A, h and H) $\rightarrow \phi$
    - BR(bb) ~ 90%
    - BR($\tau\tau$) ~ 10%
  - 2 Charged: $H^{\pm}$

- Coupling of neutral Higgs to b-quarks enhanced by tan(β)
  - tan(β) = ratio of vacuum expectation values of 2 Higgs fields
  - Production enhanced by $\tan^2(\beta)$

- 3 channels best suited to benefit from enhanced b-quark coupling
  - $\phi b \rightarrow bbb$
  - $\phi b \rightarrow \tau\tau b$
  - $\phi \rightarrow \tau\tau$



$b\phi \rightarrow 3b/b\tau\tau$



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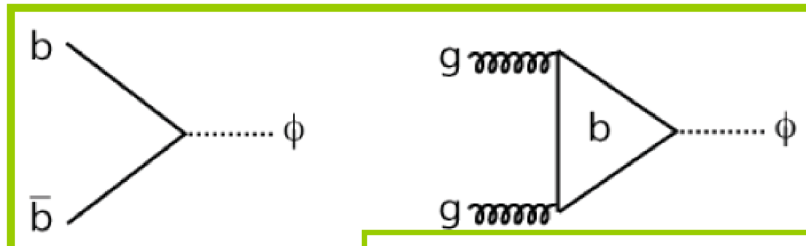
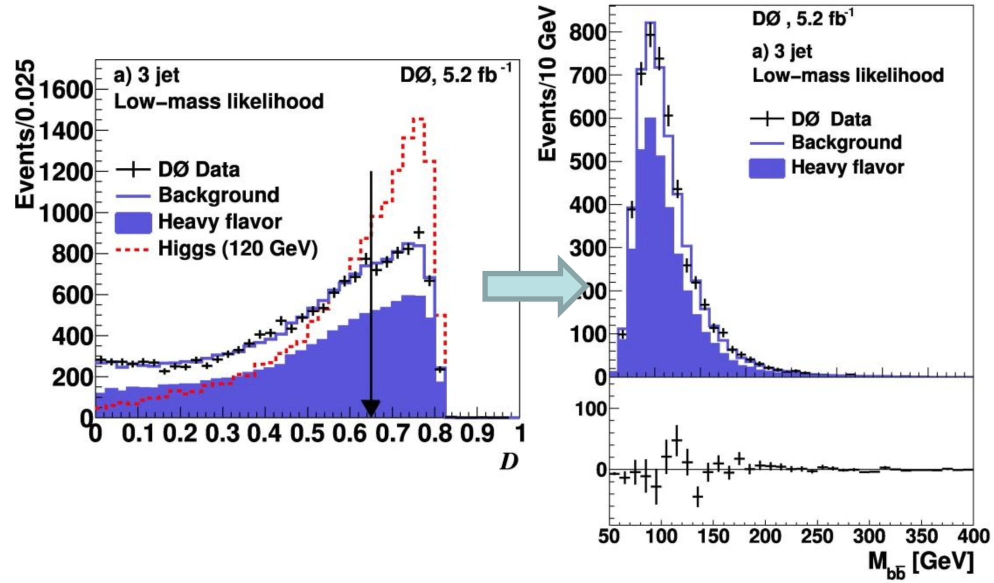


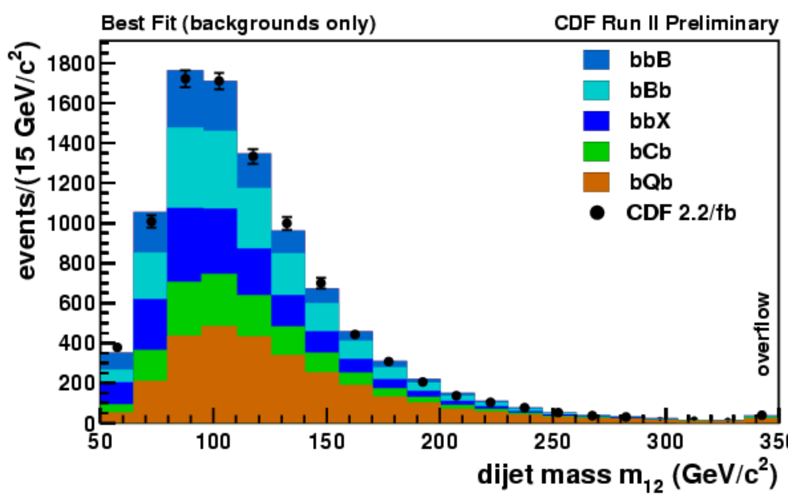
$\phi \rightarrow \tau\tau$

Similar overall sensitivities → Combine

Neutral MSSM Higgs → bb + b[b]

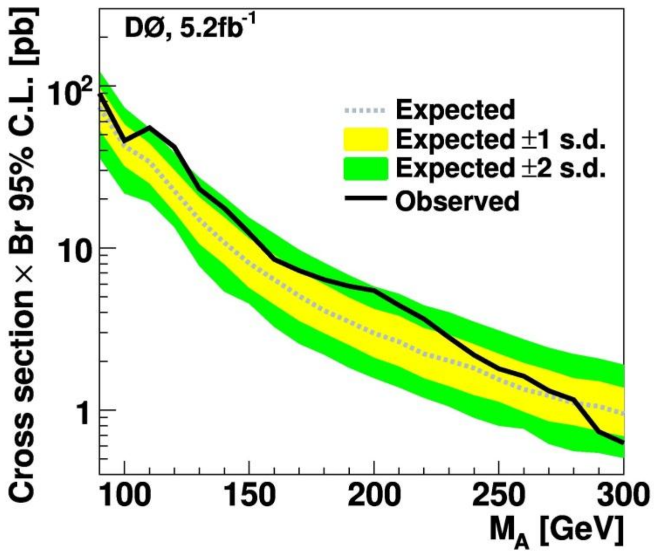
- Signal
  - At least 3 b-tagged jets
  - Peak in dijet mass spectrum
- Background
  - Heavy flavour multi-jet
  - Predicted from data/MC
- DØ: 5.2 fb^{-1} Published 2011
  - Consider multiple jet pairings
  - Kinematic likelihood
- CDF: 2.2 fb^{-1} Prelim. Winter 2010
  - Secondary vertex b-tagger
  - 2D fit m_{12} vs vertex mass variable
- Set limits using dijet invariant mass

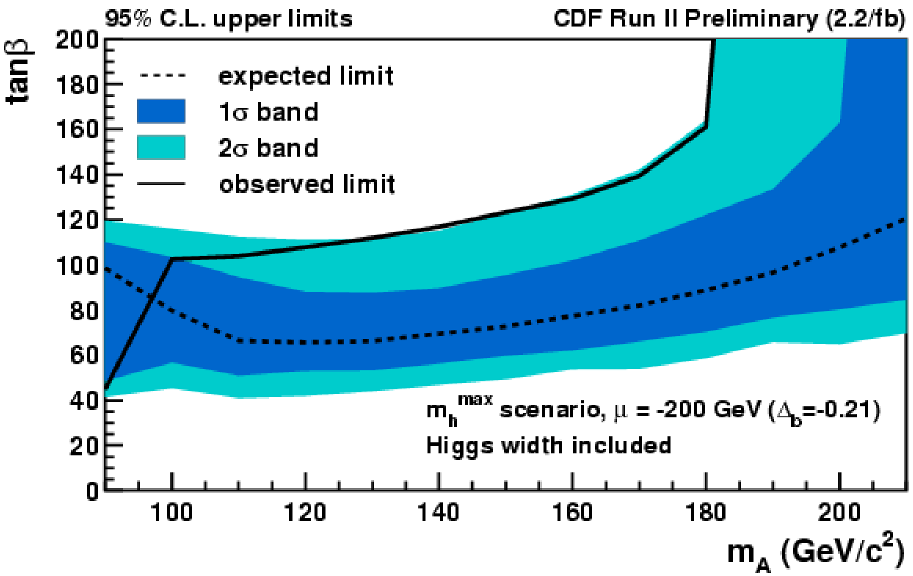


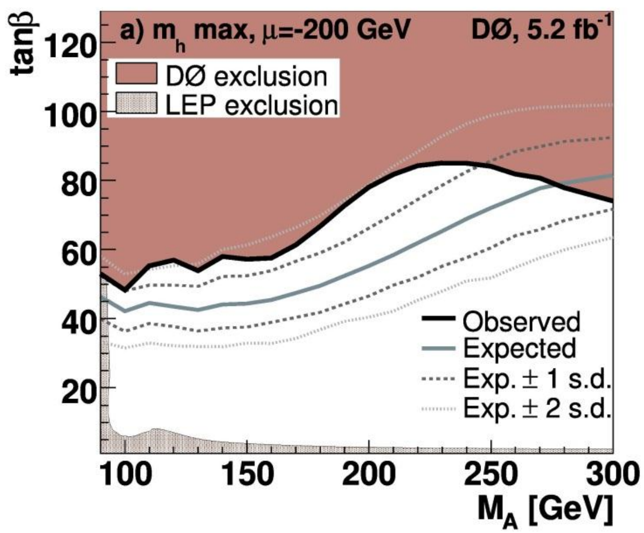


Neutral MSSM Higgs → bb + b[b]

- Set limits
  - σ x BR(φ→bb) @ 95% confidence level (CL)
  - 90 < m_A < 300 GeV
- MSSM scenarios
  - No-mixing & m_h^{max} benchmark scenarios

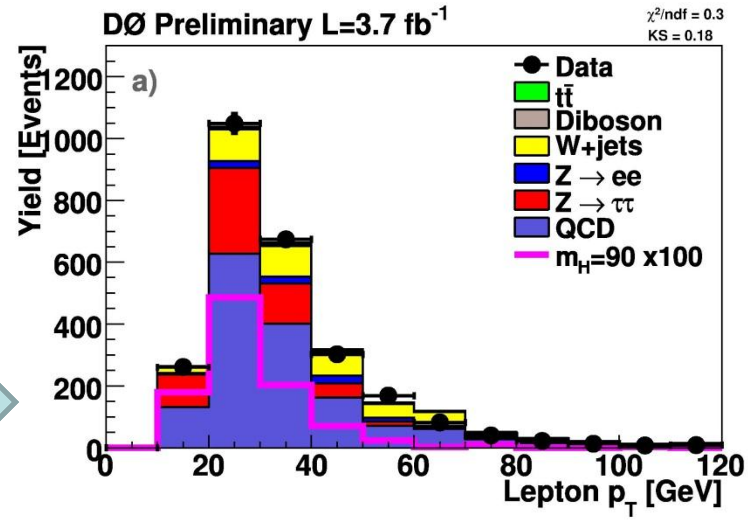


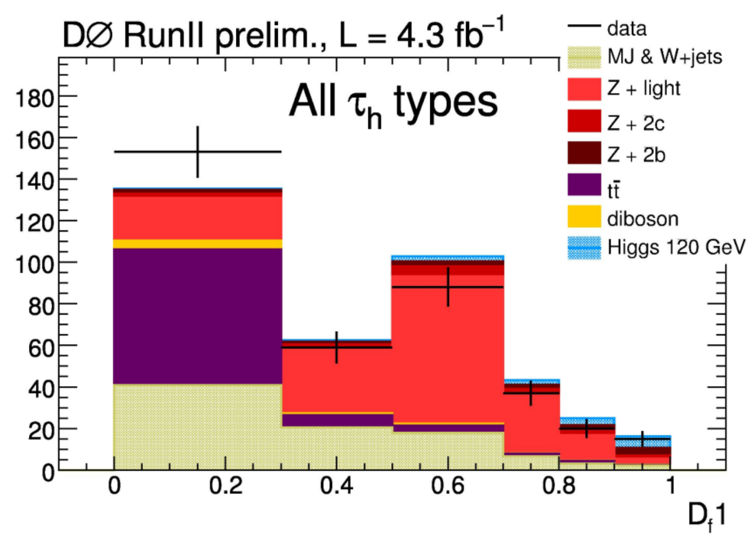




Neutral MSSM Higgs → $\tau_l\tau_{had}$ + b

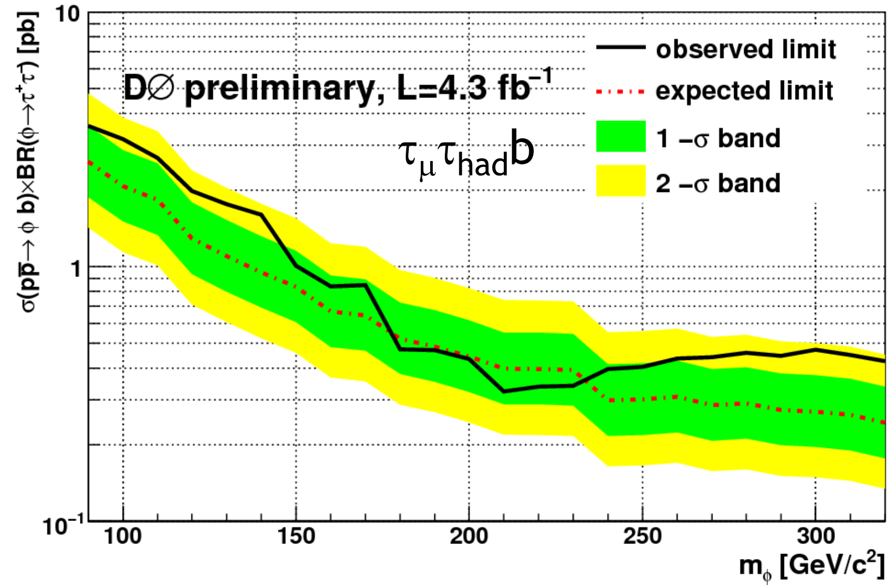
- Signal: $\tau_\mu\tau_{had}/\tau_e\tau_{had}$ + b-jet
- Lower branching ratio
  - Cleaner final state
    - Similar sensitivity
  - DØ e: Prelim. 3.7 fb^{-1}
  - DØ μ: Published 2.7 fb^{-1}/Prelim. 4.3 fb^{-1}
- Main bkgs.: Z+jets, multi-jets, tt
- Selection:
  - Isolated lepton separated from opposite sign τ_{had}
  - Multivariate classifiers (MVAs) trained vs Z+jets/tt/multi-jets

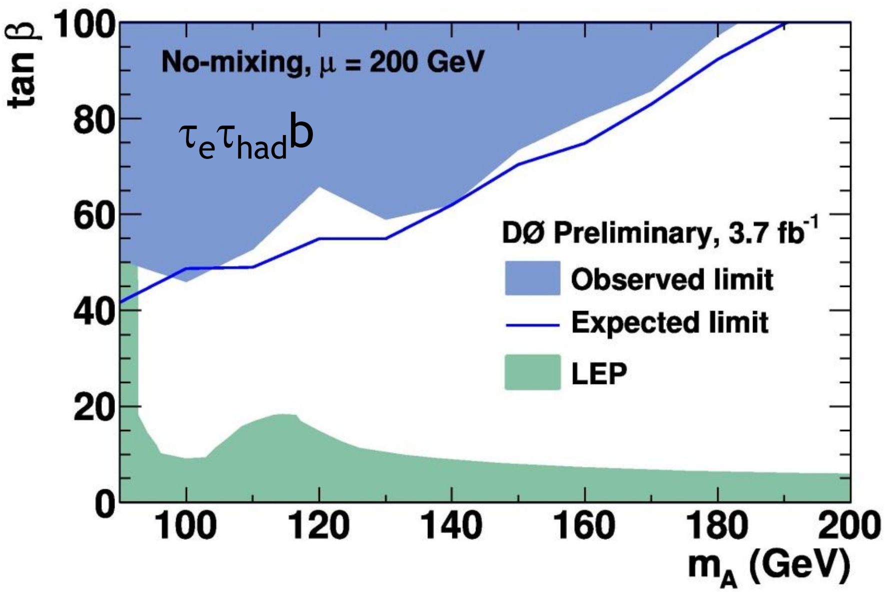


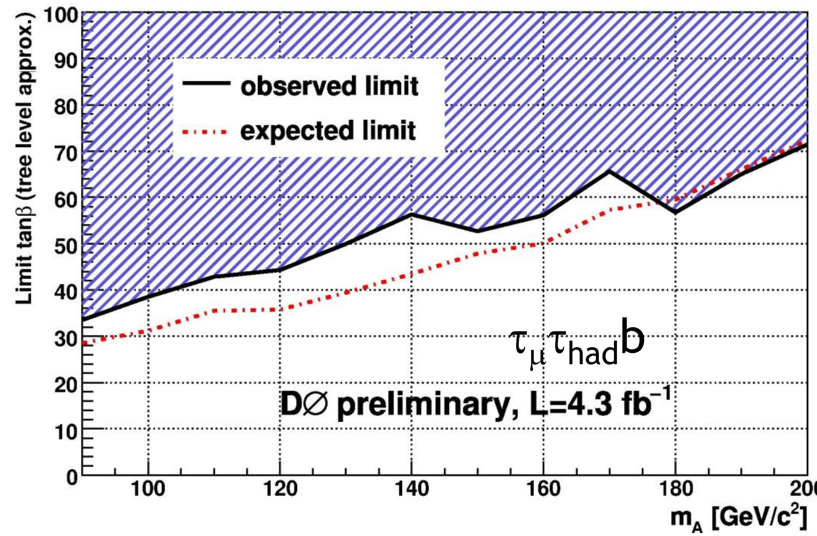


Neutral MSSM Higgs $\rightarrow \tau_l \tau_{had}$ + b

- Set limits
  - **σ x** BR($\phi \rightarrow \tau\tau$) @ 95% confidence level (CL)
  - $\tau_\mu \tau_{had}$b
    - Interpreted @ tree level
    - Most sensitive Tevatron MSSM search channel at low mass





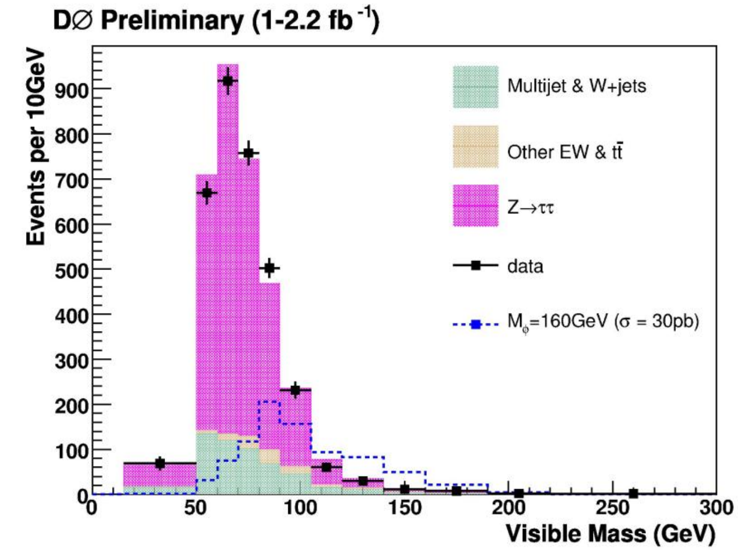


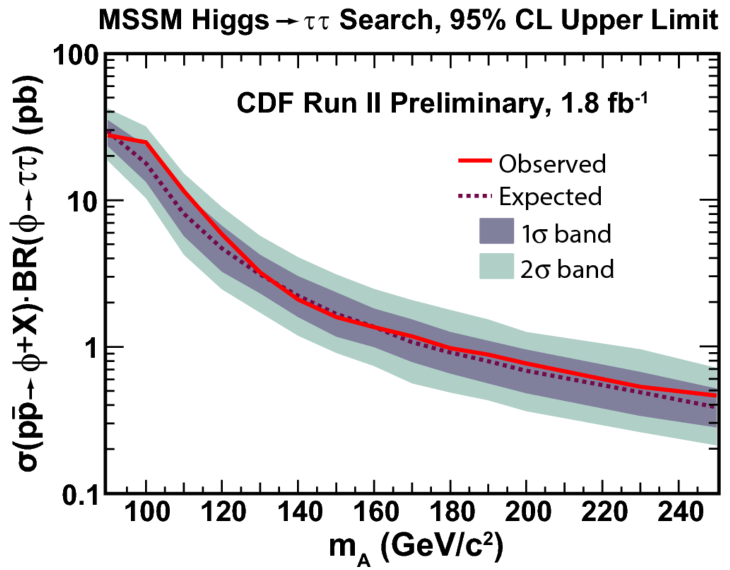
Neutral MSSM Higgs → $\tau_l\tau_{had/l}$

- Signal: Three possible search channels
  - ➢ $\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$, $\tau_e\tau_\mu$ channels
  - ➢ Isolated lepton with opposite sign
- Main bkgs.: $Z\rightarrow\tau\tau$ (irreducible), multi-jet, W+jets
- Visible mass used to derive limits

$$m_{vis} = \sqrt{(P_{\tau_1}+P_{\tau_2}+P_{MET})^2}$$

- DØ ($\tau_\mu\tau_{had}$): 2.2 fb^{-1} Summer 2008
  - ➢ Combined with published 1 fb^{-1} channels : $\tau_e\tau_{had}$, $\tau_\mu\tau_{had}$, $\tau_\mu\tau_e$
  - ➢ 5.4 fb^{-1} publication imminent
- CDF ($\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$, $\tau_e\tau_\mu$ channels):
  - ➢ 1.8 fb^{-1} published 2009





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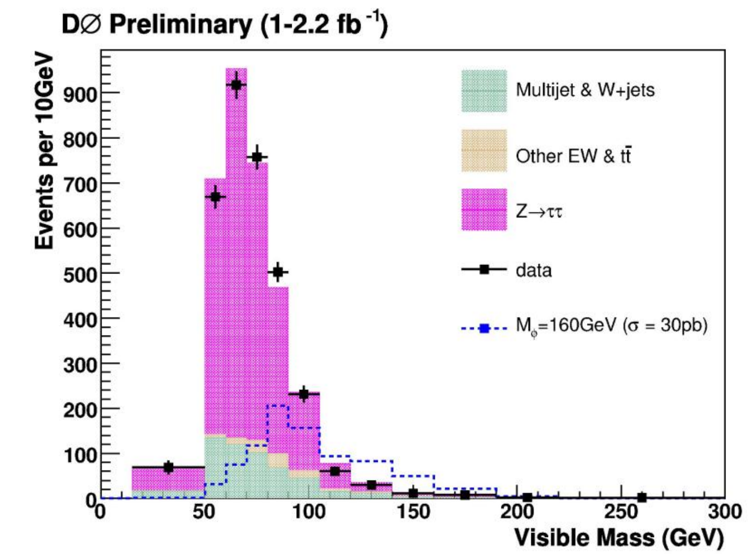
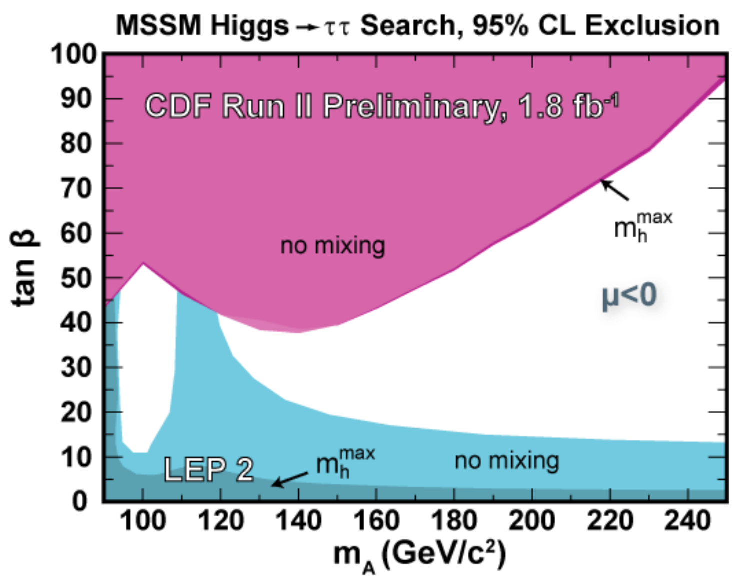
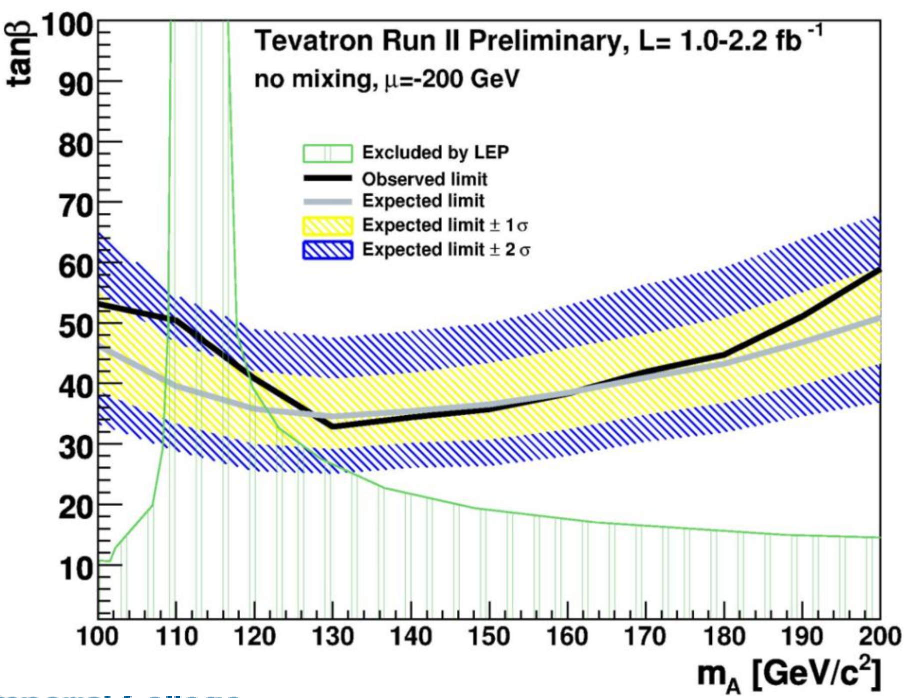
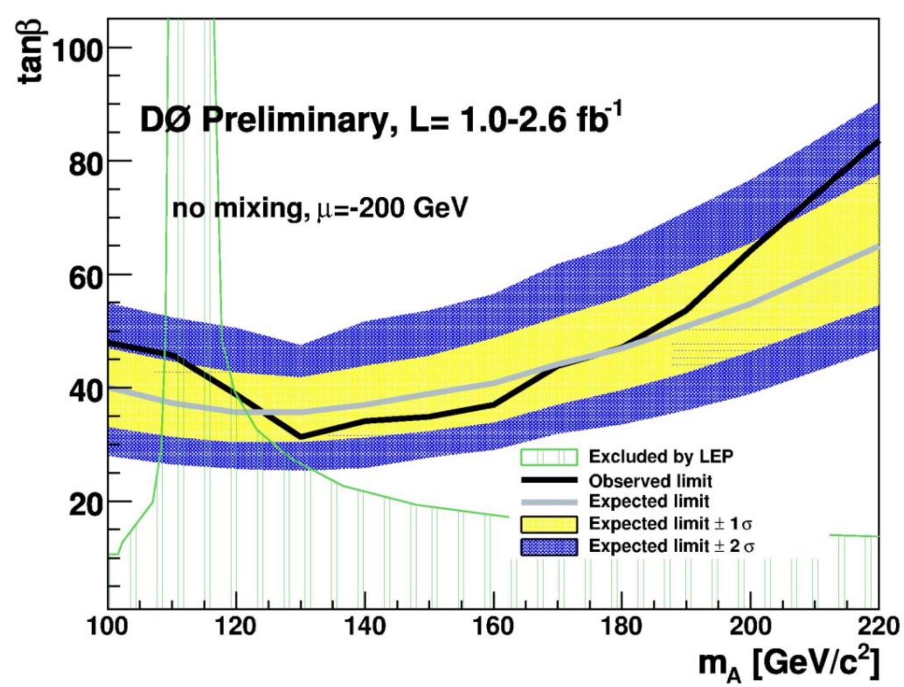




Neutral MSSM Combinations

- Tevatron combination: $\varphi \rightarrow \tau\tau$ results CDF ($1.8fb^{-1}$)+ DØ ($2.2fb^{-1}$)
- DØ combination: $\phi \rightarrow \tau\tau$ ($2.2fb^{-1}$) , $b\phi \rightarrow b\tau\tau$ ($1.2fb^{-1}$), $b\phi \rightarrow bbb$ ($2.6fb^{-1}$)
  - tan(β) > 30 @ 130 GeV



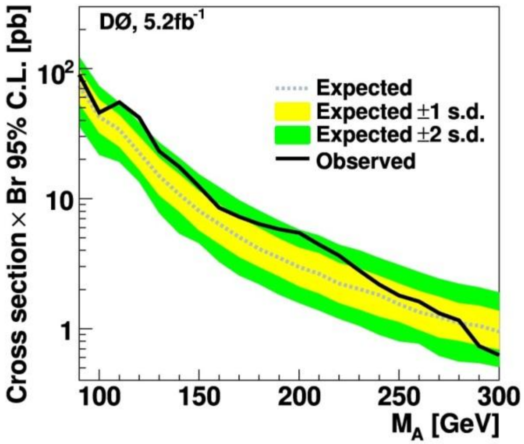


Prospects

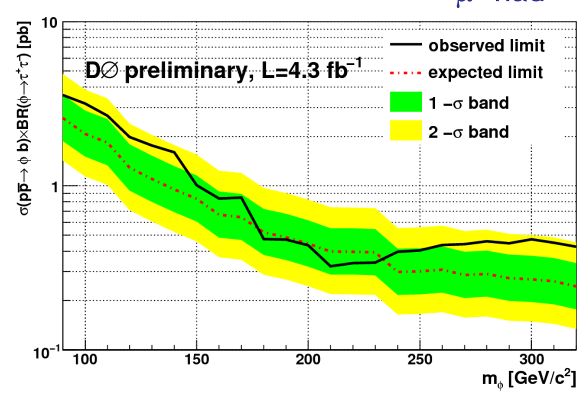
- Probing very interesting regions
  - > 9 fb^{-1} data now available
    - Aiming for rapid inclusion into analyses
  - Stable and well developed analyses
    - Further algorithmic/analysis improvements

- Short term (early summer)
  - Updated searches (> 8 fb^{-1}):
    - $\phi \rightarrow bb + b(b)$ & $\phi \rightarrow \tau\tau$ & $b\phi \rightarrow b\tau\tau$
  - New combinations
  - Down to tanβ ~20 for low m_A
  - Or discovery

bbb



$b\tau_\mu\tau_{had}$

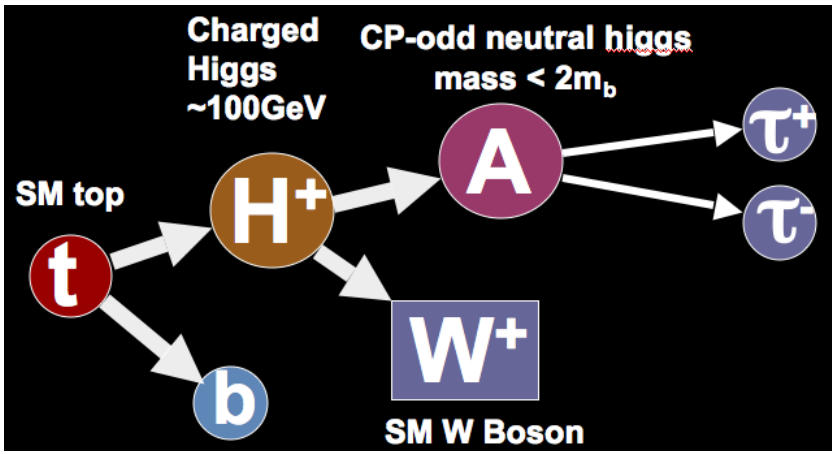


Next-to-MSSM

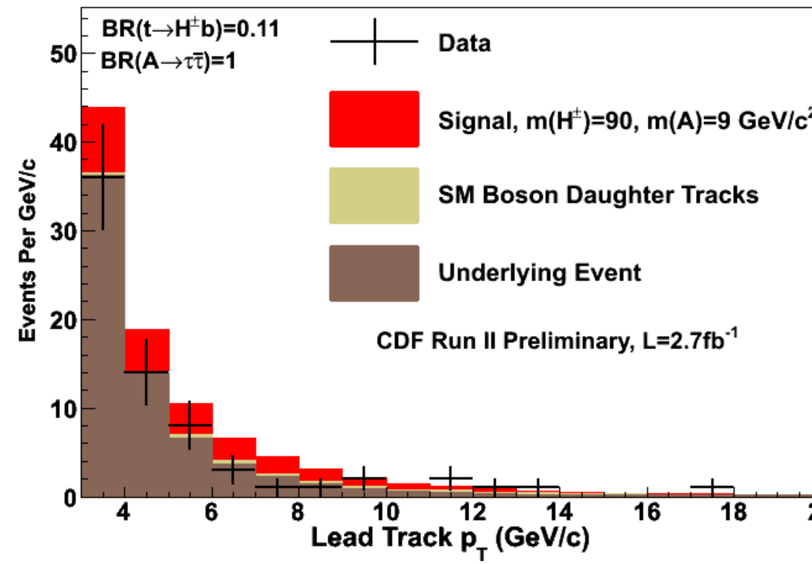
- Minimal Supersymmetric Standard Model (MSSM)
- Next-to-MSSM (NMSSM)
- Hidden Valley (HV) Higgs
- Fermiophobic Higgs
- Conclusions

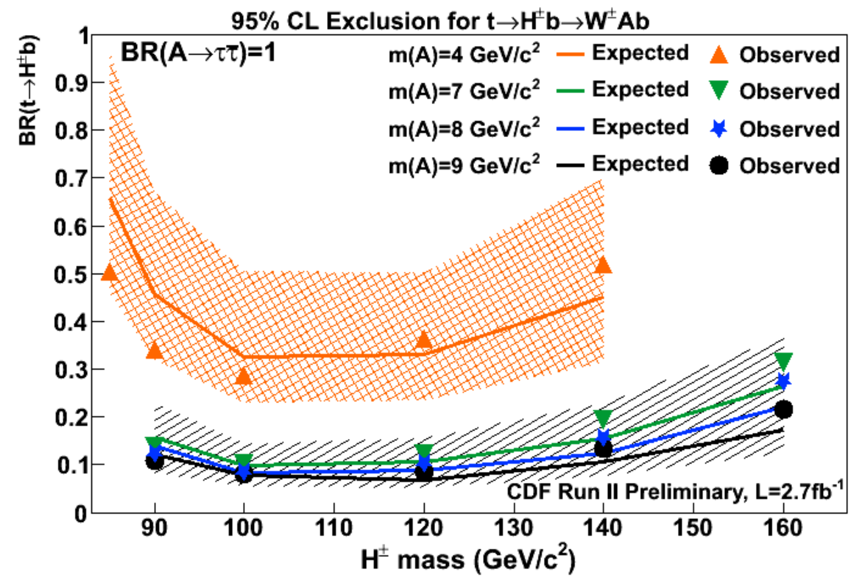
NMSSM Charged Higgs → a → ττ

- Search for NMSSM A boson ($m_A < 2\ m_b$)
  - ➢ Search in b-tagged, lepton, ≥ 3 jets
  - ➢ CDF 2.7 fb^{-1} Winter 2010



- Signature
  - ➢ Additional isolated tracks in event
- Fit p_T spectrum isolated tracks
  - ➢ Method validated using Z decays
  - ➢ World's 1st limits in this mode



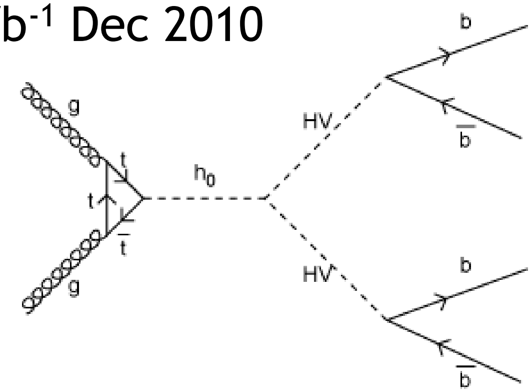


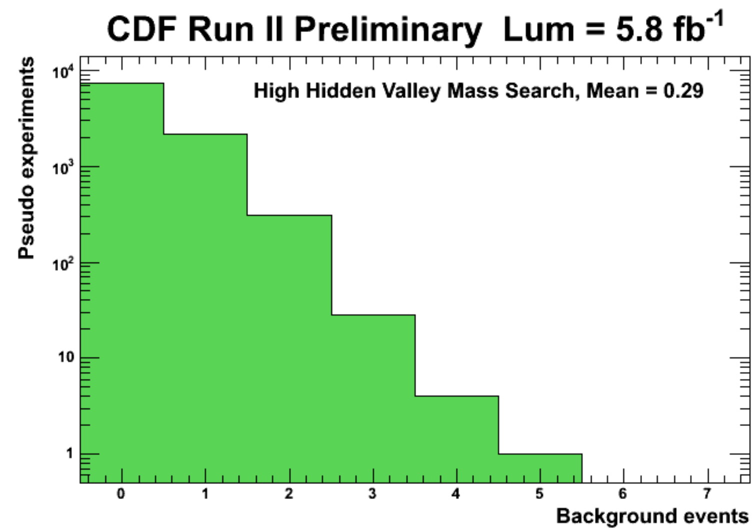
Hidden Valley Higgs

- Minimal Supersymmetric Standard Model (MSSM)
- Next-to-MSSM Higgs
- Hidden Valley (HV) Higgs
- Fermiophobic Higgs
- Prospects & Conclusions

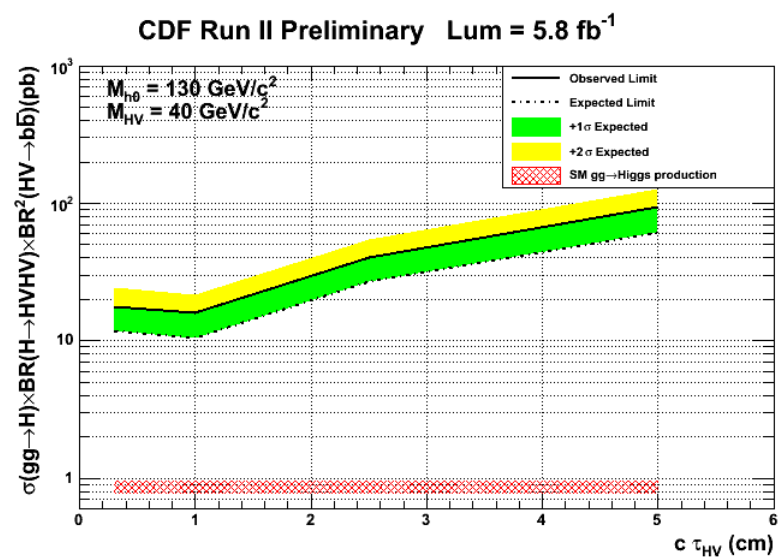
HV Higgs → HVHV → bbbb

- Search for long lived heavy particles with displaced secondary vertex (SV)
  - Hidden valley (HV) model
  - CDF 5.8 fb^{-1} Dec 2010





- Signature
  - 3+ jets, 2 SV tagged, large HV decay length



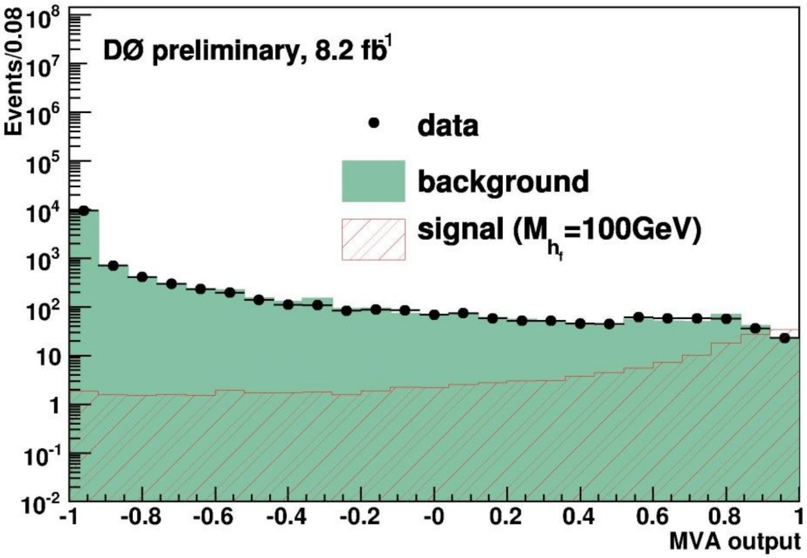
- Model background from data
  - Probability density functions models SM SV background
  - 10k pseudo-events generated for each data event

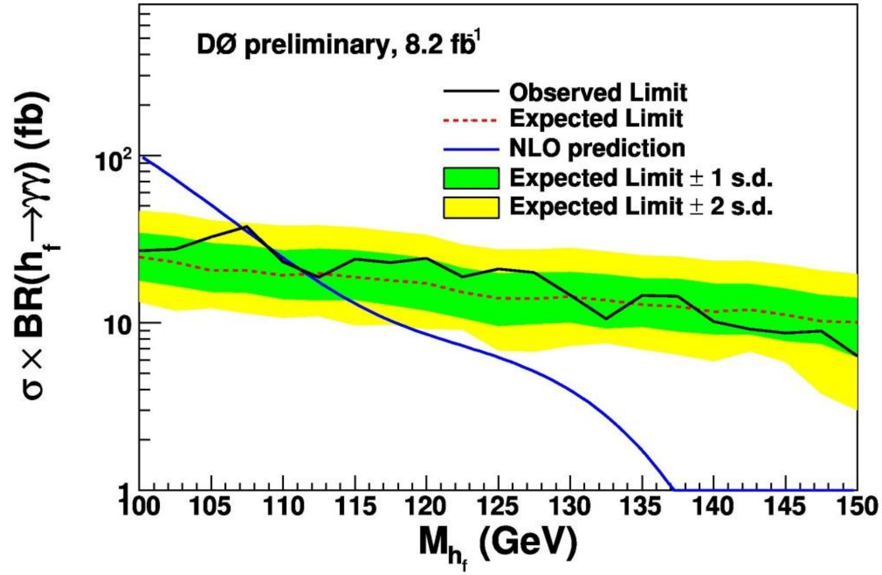
Fermiophobic Higgs

- Minimal Supersymmetric Standard Model (MSSM)
- Next-to-MSSM
- Hidden Valley (HV) Higgs
- Fermiophobic Higgs
- Conclusions

Fermiophobic Higgs→ $\gamma\gamma$

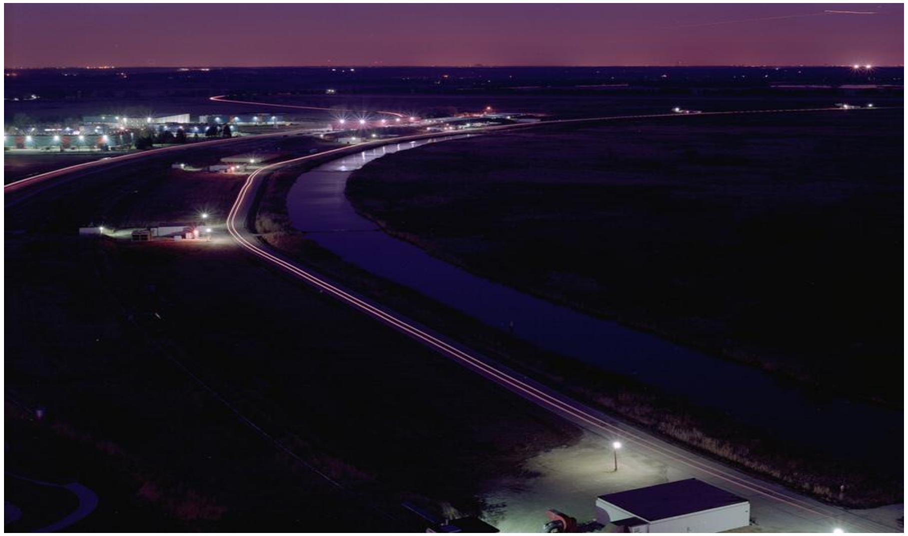
- Coupling to fermions highly suppressed
- Search for diphoton signature
  - ~3% mass resolution
- Backgrounds
  - Direct production, γ+jets/dijets, Drell-Yan
- DØ 8.2 fb-1 preliminary result
  - Two photons in central calorimeter
    - 5 variable MVA to separate signal/bkg
    - 20% improvement in limit
- Excluded m_{hf} < 112.5 GeV
  - Better than LEP limit
  - CDF: 4.2 fb^{-1} excludes m_{hf} < 106 GeV





Conclusions

- Minimal Supersymmetric Standard Model (MSSM)
- Next-to-MSSM
- Hidden Valley Higgs
- Fermiphobic Higgs
- **Conclusions**



Conclusions

- Wide range of beyond SM Higgs searches performed by CDF & DØ with up to 8.2 fb^{-1} Run II data
  - No signal observed (yet)
  - Probing theoretically very interesting regions
- Updated CDF and DØ analyses
  - x2-5 additional data being analysed
  - Improvements in analysis techniques
  - Combinations
  - Expect to be sensitive beyond $\tan\beta \sim 20$
- Updates on short timescale
  - Rapid increase in sensitivity in coming months

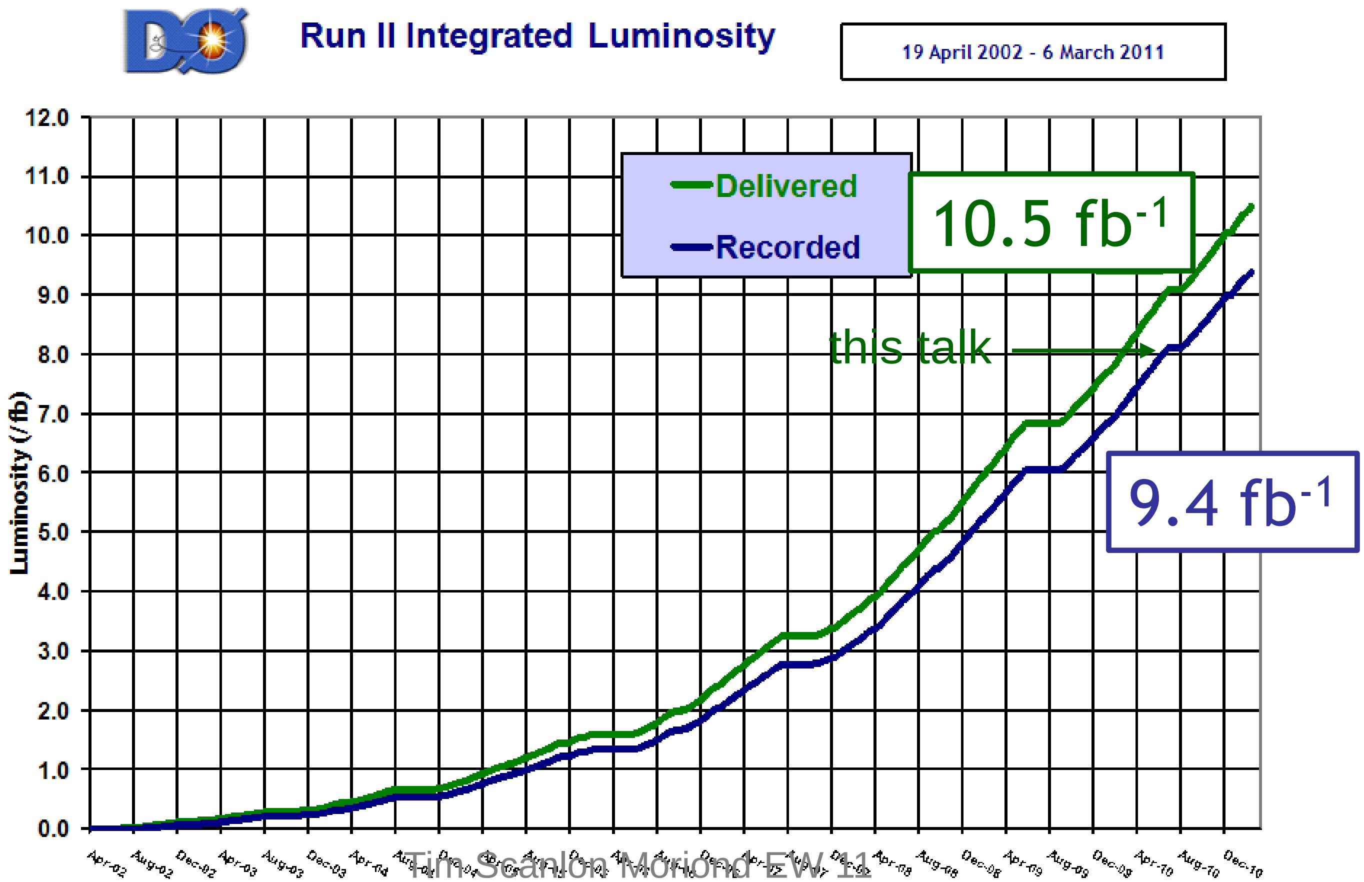
Very exciting times ahead –watch this space!

Backup slides

Tevatron Performance

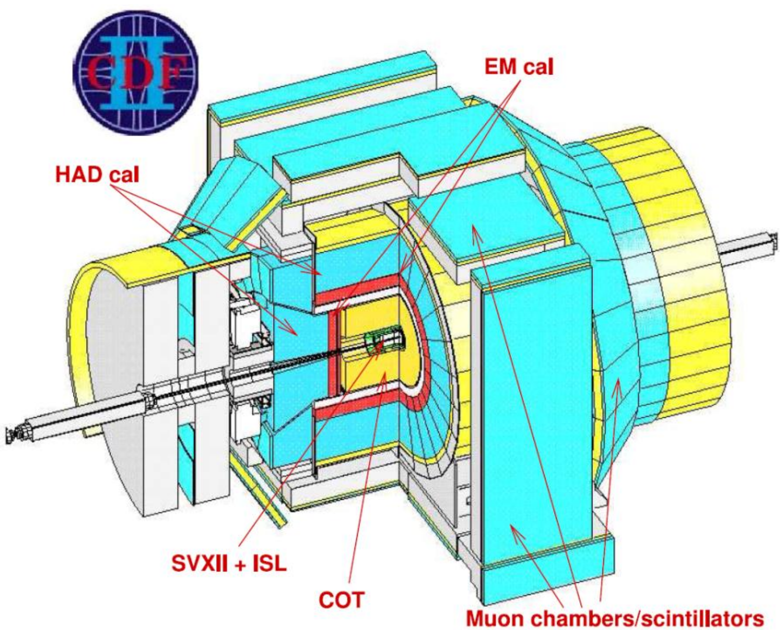
Tevatron continues to perform well

- Over 10.5 fb^{-1} delivered to each experiment
- Deliver ~2.5 fb^{-1} per year

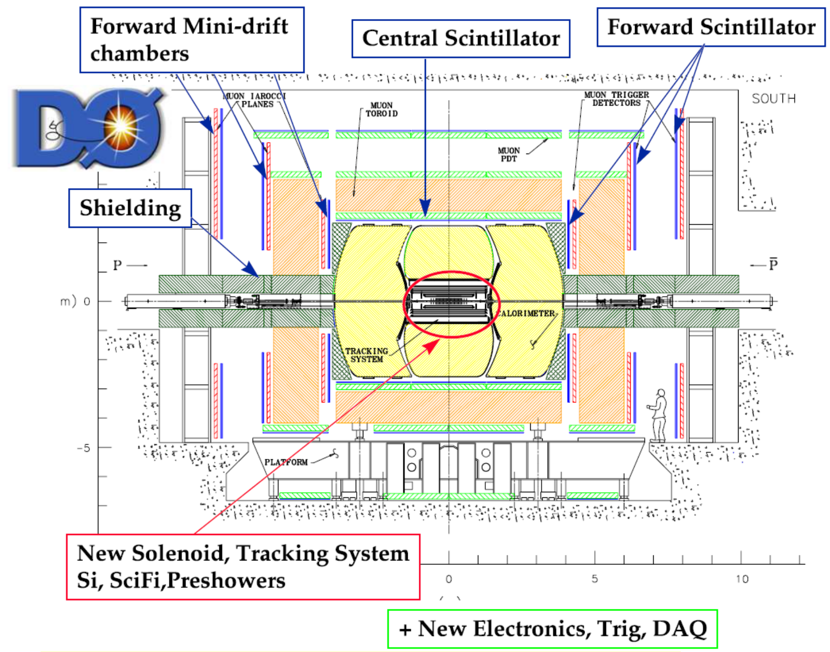


CDF and DØ experiments

- Both detectors extensively upgraded for Run IIa
  - ➢ New silicon vertex detector
  - ➢ New tracking system
  - ➢ Upgraded μ chambers



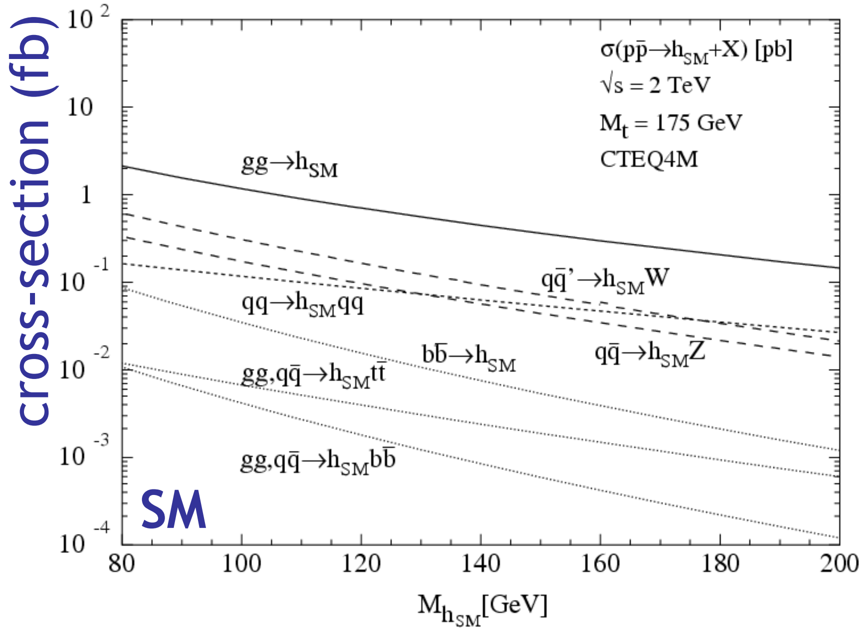
- CDF: New plug calorimeter & ToF

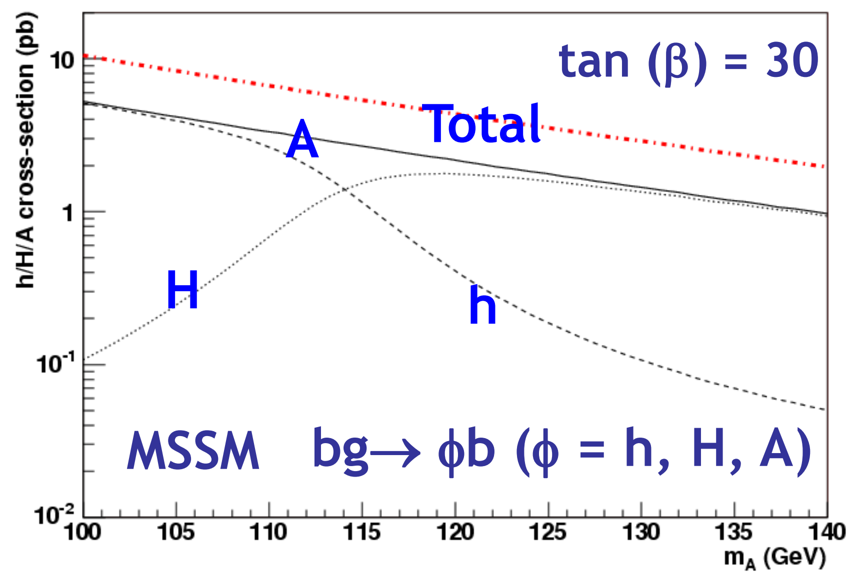


- DØ
  - – New solenoid & preshowers
  - – **Run IIb: New inner layer in SMT & L1 trigger**

Supersymmetric Higgs Sector

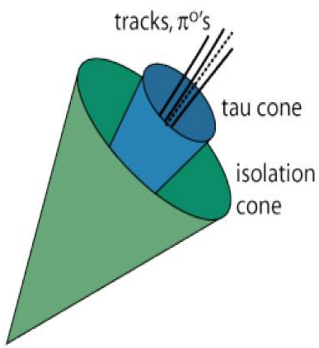
- Minimal Supersymmetric Standard Model (MSSM)
  - ➢ 2 Higgs doublets
  - ➢ 5 Physical Higgs bosons
    - ▪ 3 Neutral: (A, h and H) → ϕ
    - ▪ 2 Charged: $H^{\pm}$
- Need 2 parameters to calculate all Higgs masses and couplings at tree level
  - ➢ m_A
  - ➢ $\tan(\beta)$ = ratio of vacuum expectation values of two Higgs fields
- Coupling of neutral Higgs to b-quarks enhanced by $\tan(\beta)$
  - ➢ Production enhanced by $\tan^2(\beta)$





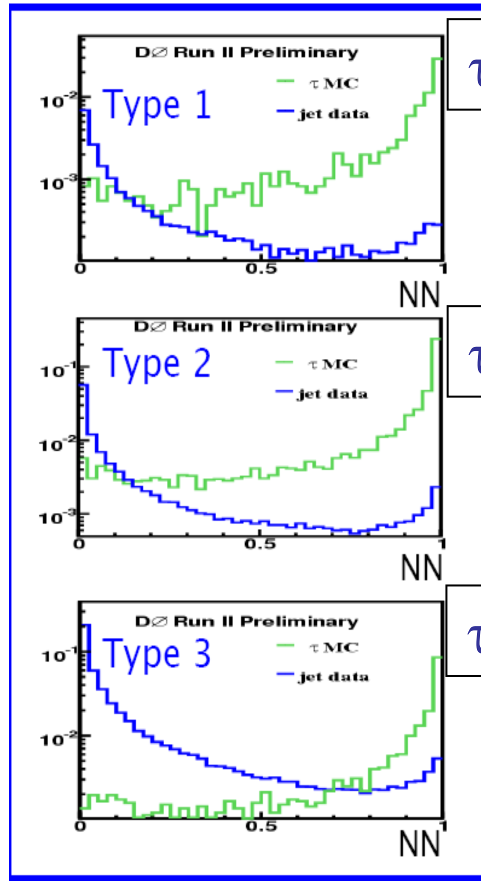
τ_{had}-Identification

- CDF: Isolation based



- 1 or 3 tracks in variable size and isolation cone
- Validated via W/Z measurements
  - Efficiency ~ 40-50%
  - Jet fake rate < 1%

- DØ: 3 NN's for each τ type
  - Validated via Z's



$\tau^{\pm} \rightarrow \pi^{\pm} \upsilon$

$\tau^{\pm} \rightarrow \pi^{\pm} \pi^{0} \upsilon$

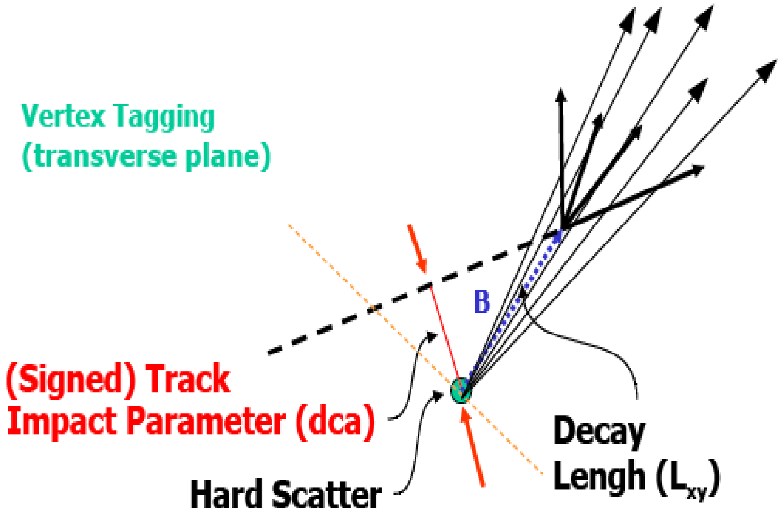
$\tau^{\pm} \rightarrow \pi^{\pm} \pi^{\pm} \pi^{\pm} (\pi^{0}) \upsilon$

Eff

Tau Type	1	2	3
Reconstruction			
Jets	1.5	10	38
Taus	9.1	50	20
NN > 0.9			
Jets	0.04	0.2	0.8
Taus	5.8	37	13

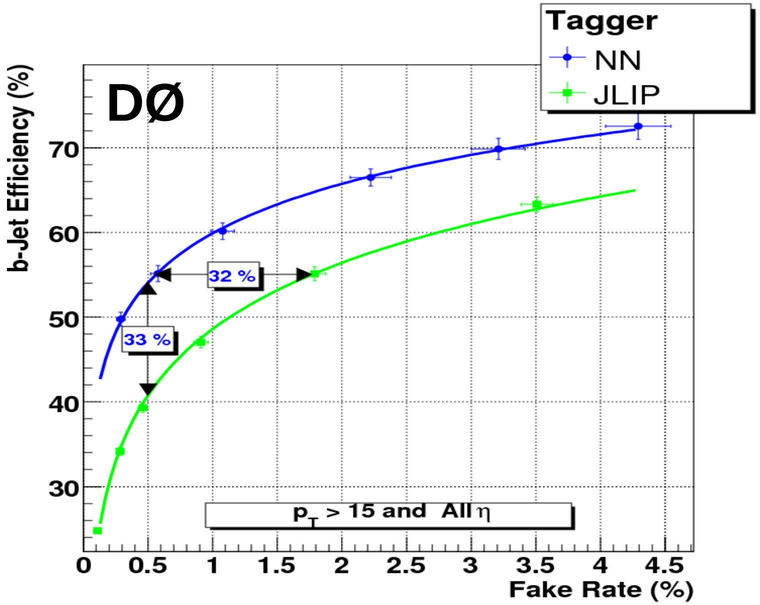
b-jet Identification

- MSSM Higgs → bb ~90% of time
  - ➢ Improves S/B by > 10
- Use lifetime information
  - ➢ Correct for MC/data differences
    - Measured at given operating points



CDF: Secondary vertex reconstruction
- ➢ Neutral network increases purity
- ➢ **Tight = 40% eff, 0.5 % mis-tag**

DØ: Neural Net tagger
- ➢ Secondary vertex & dca based inputs, derived from basic b-tagging tools
- ➢ High efficiency, purity →
- ➢ **Tight = 50% eff, 0.5% mis-tag**



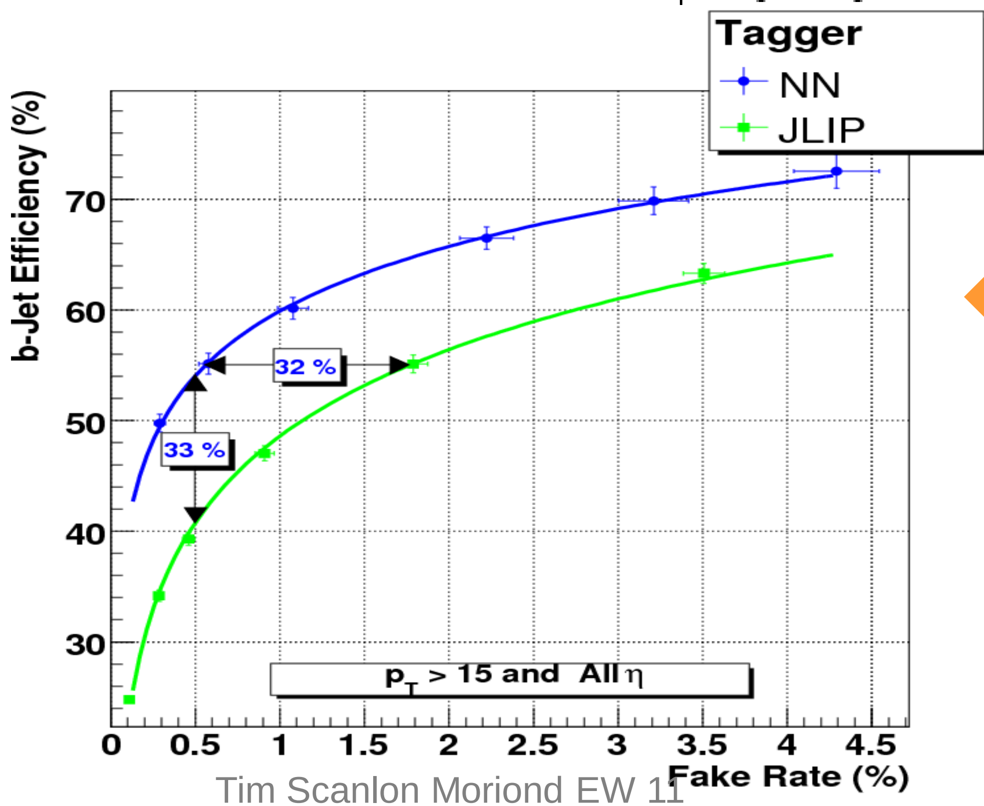
DØ B-tagging

Several mature algorithms used:

- 3 main categories:
  - Soft-lepton tagging
  - Impact Parameter based
  - Secondary Vertex reconstruction

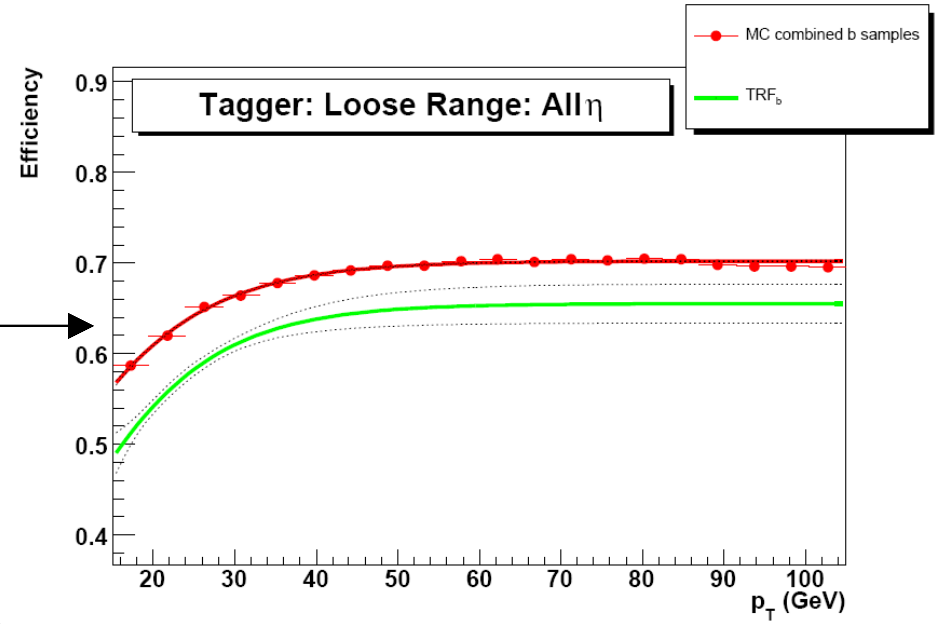
Combine in Neural Network:

- vertex mass
- vertex number of tracks
- vertex decay length significance
- chi2/DOF of vertex
- number of vertices
- two methods of combined track impact parameter significances

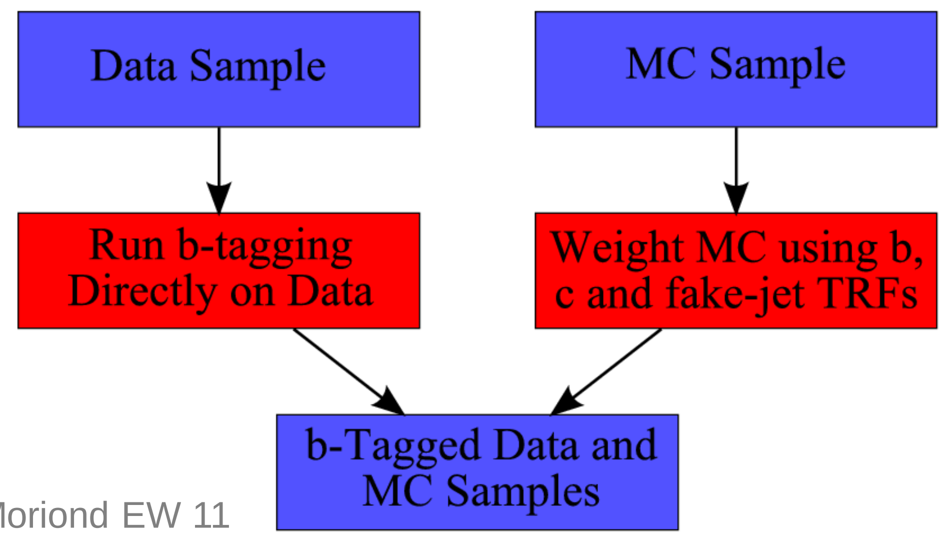


B-tagging - (DØ) Certification

- Have MC / data differences - particularly at a hadron machine
  - Measure performance on data
    - Tag Rate Function (TRF) Parameterized efficiency & fake-rate as function of p_T and η
  - Use to correct MC b-tagging rate



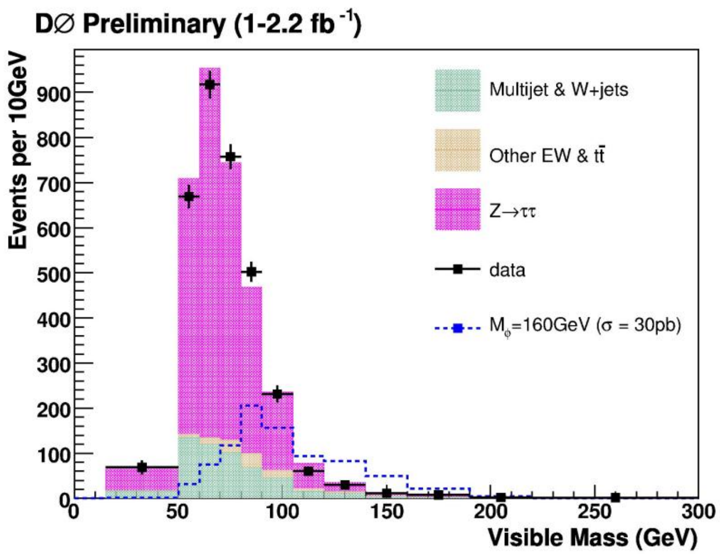
- b and c-efficiencies
  - Measured using a b-enriched data sample
- Fake-rate
  - Measured using multi-jet data

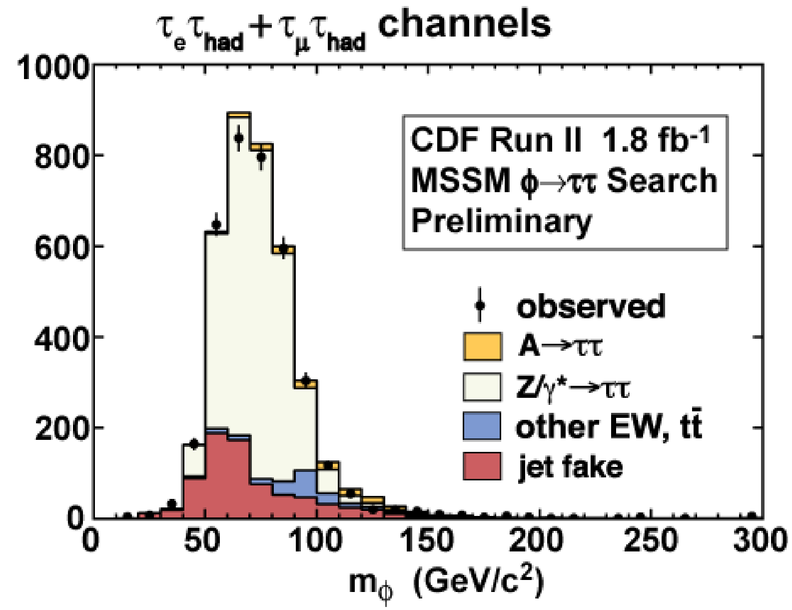


Neutral MSSM Higgs → $\tau_l\tau_{had}$

- m_{vis} used to derive cross section limits $\sqrt{(P_{\tau_1} + P_{\tau_2} + P_{MET})^2}$

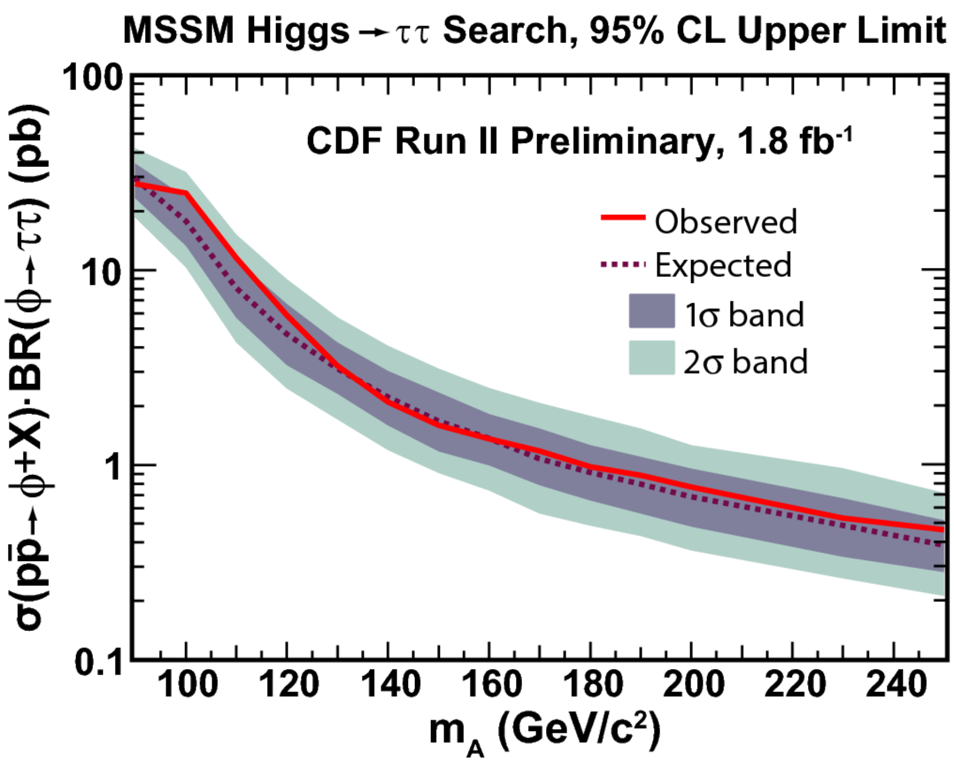
μτ, eτ, eμ

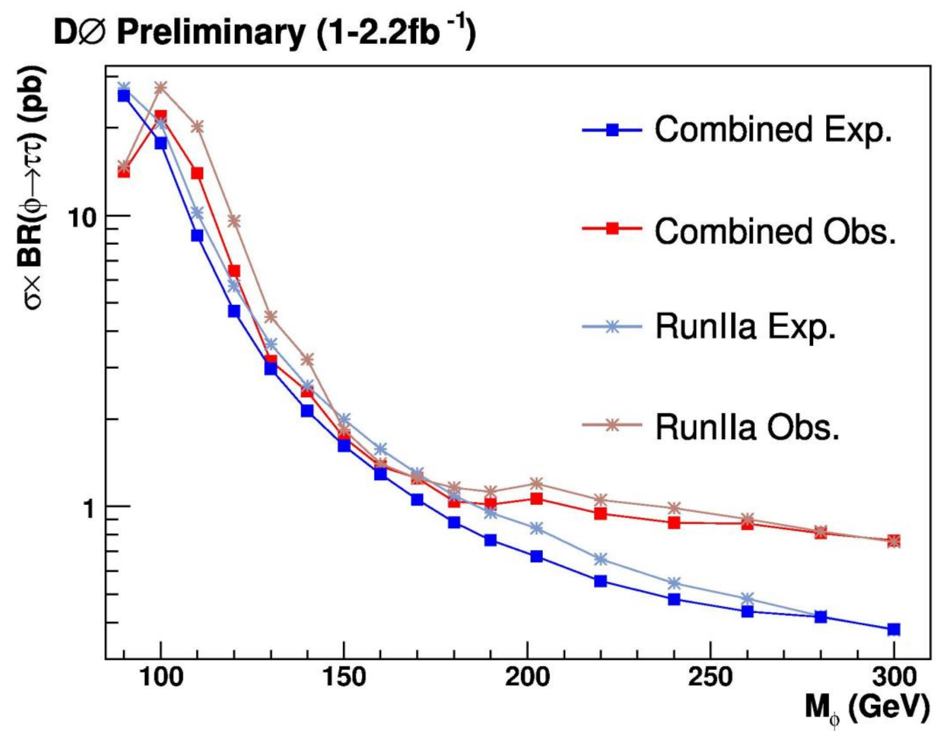




Neutral MSSM Higgs → $\tau_l \tau_{had}$

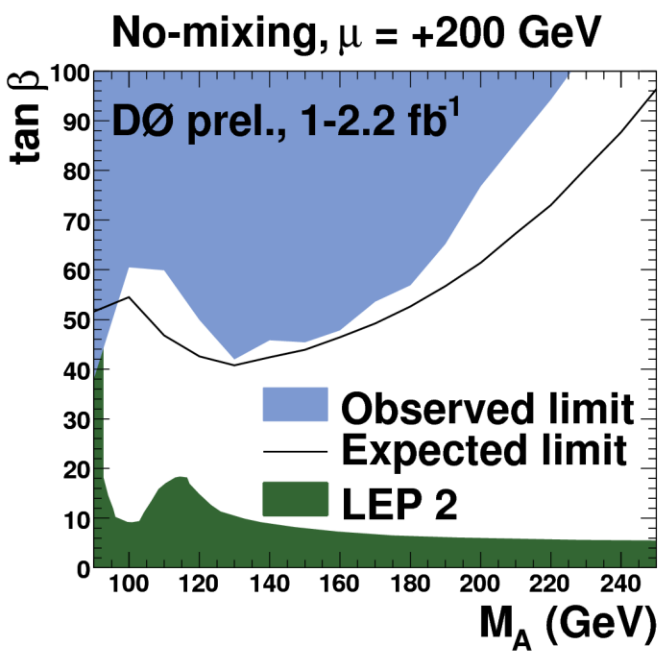
- Set limits
  - σ x Br ($\phi \rightarrow \tau\tau$) @ 95% confidence level (CL)

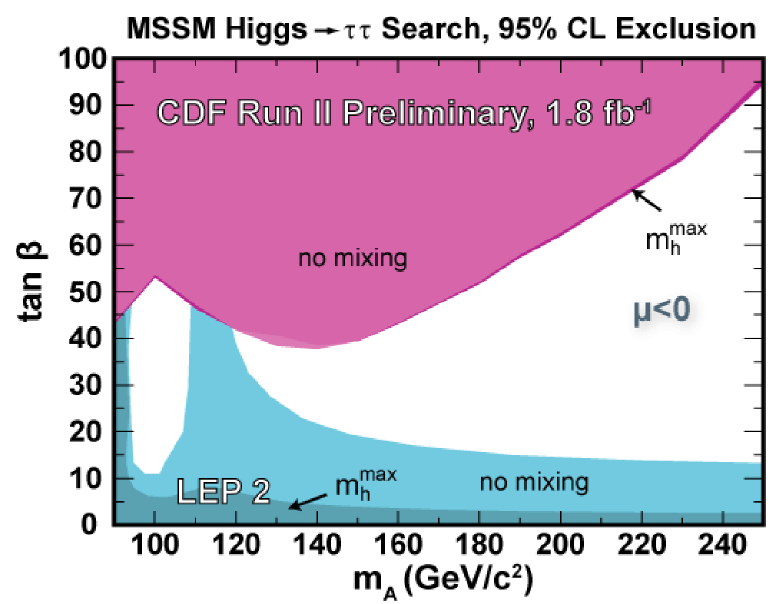




Neutral MSSM Higgs → $\tau_l \tau_{had}$

- Set limits
  - σ x BR(ϕ→ττ) @ 95% confidence level (CL)
  - $90 < m_A < 250$ GeV
- MSSM scenarios
  - No-mixing & m_h^{max} benchmark scenarios
  - tan(β) > 40 - 60 excluded for m_A < 180 GeV



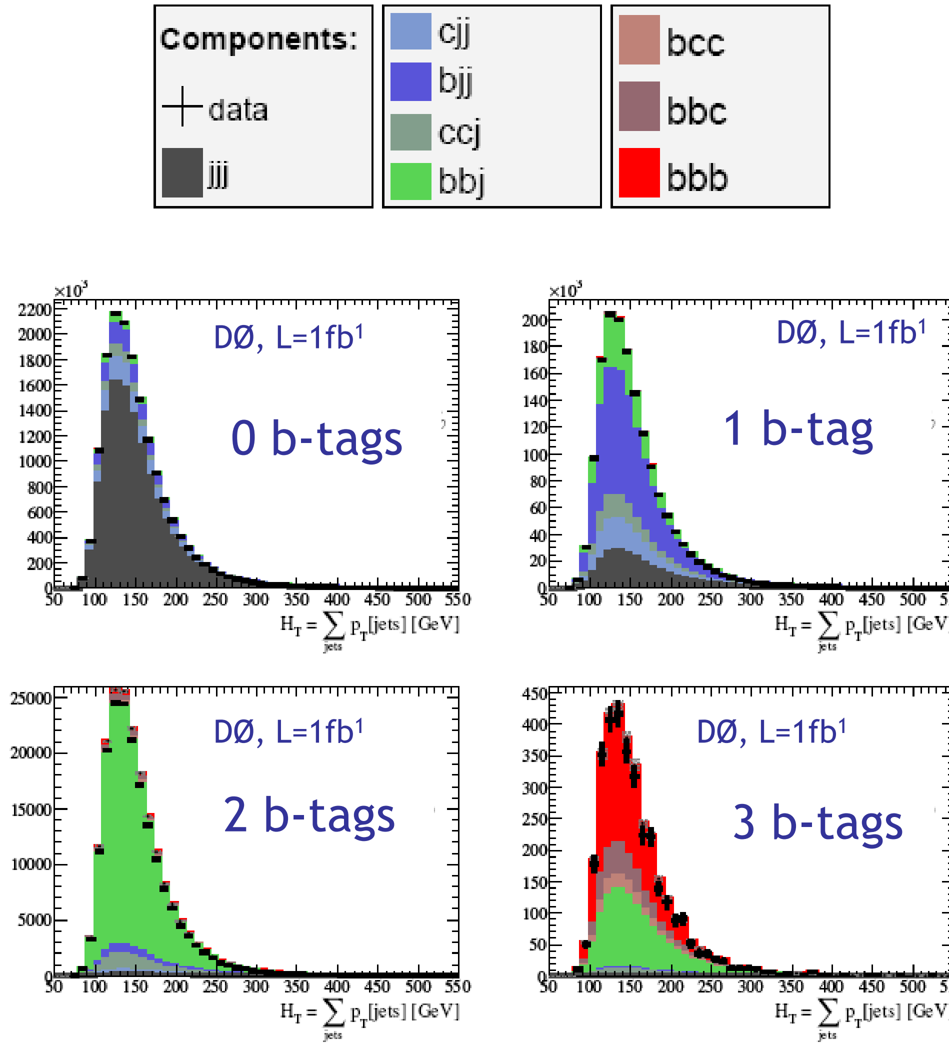


Neutral MSSM Higgs → bb + b[b]

- Background Prediction
  - Large multijet background
  - Theoretical cross sections very large errors
- DØ: Sample Composition
  - Fit MC to data over several b-tagging points
- DØ: Background Shape
  - Use double b-tagged data to predict triple b-tagged background

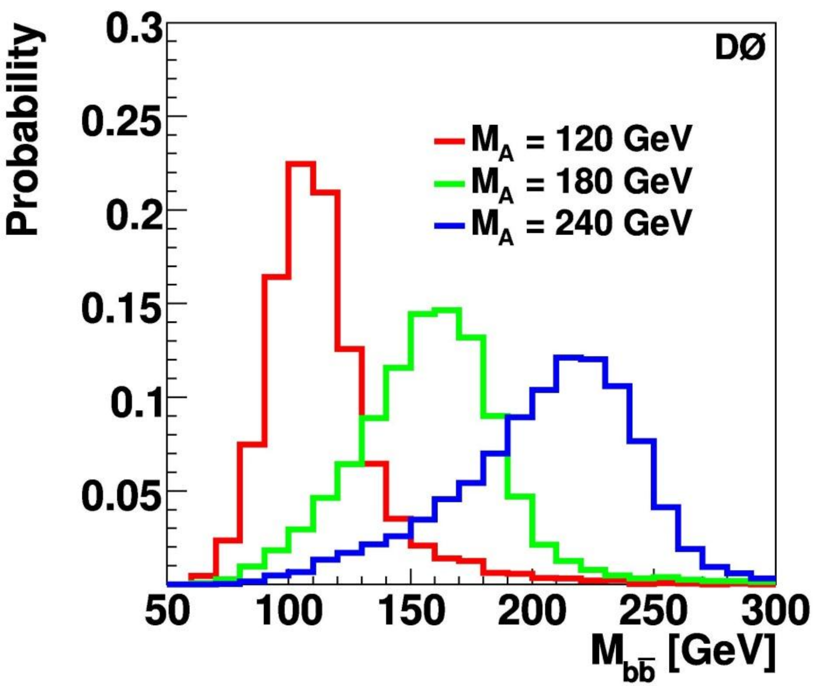
$$S^{exp}_{3\mathrm{Tag}}(\mathcal{D}, M_{bb}) = \frac{S^{MC}_{3\mathrm{Tag}}(\mathcal{D}, M_{bb})}{S^{MC}_{2\mathrm{Tag}}(\mathcal{D}, M_{bb})} S^{data}_{2\mathrm{Tag}}(\mathcal{D}, M_{bb}).$$

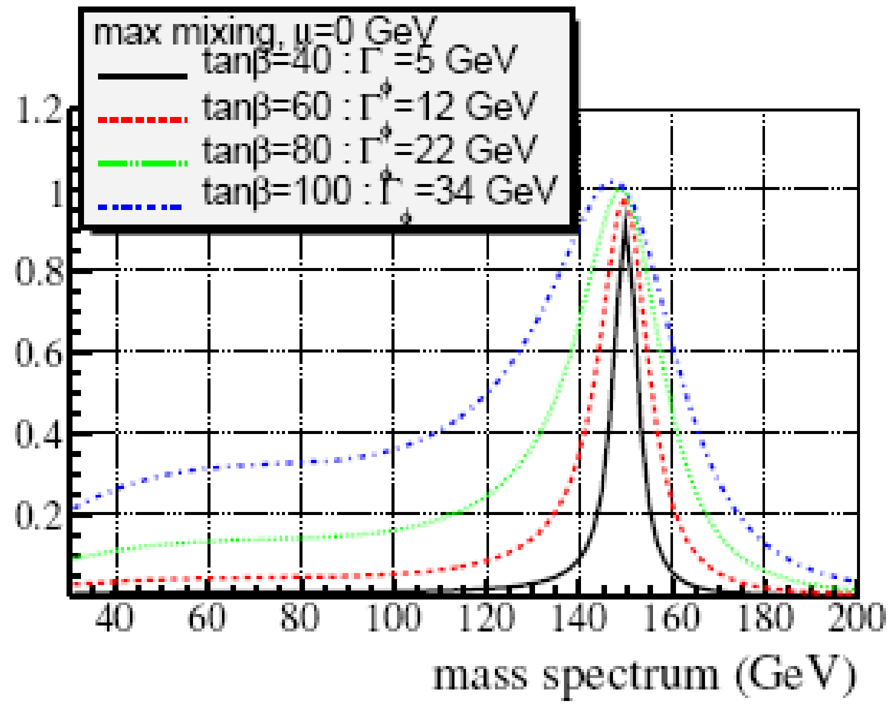
3 b-tag background | MC correction factor | 2 b-tag data



Neutral MSSM Higgs → bb + b[b]

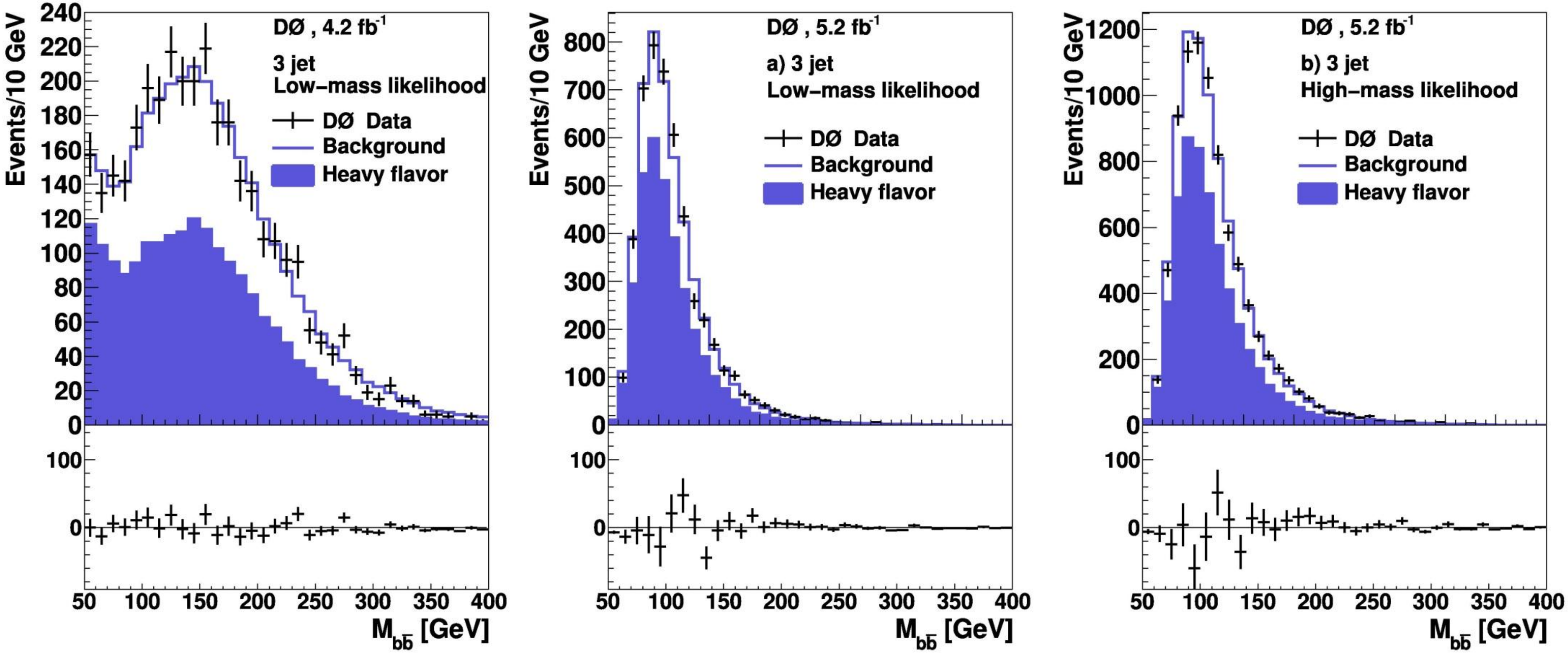
- Final limits corrected for width
  - ➢ Not negligible at high tanβ





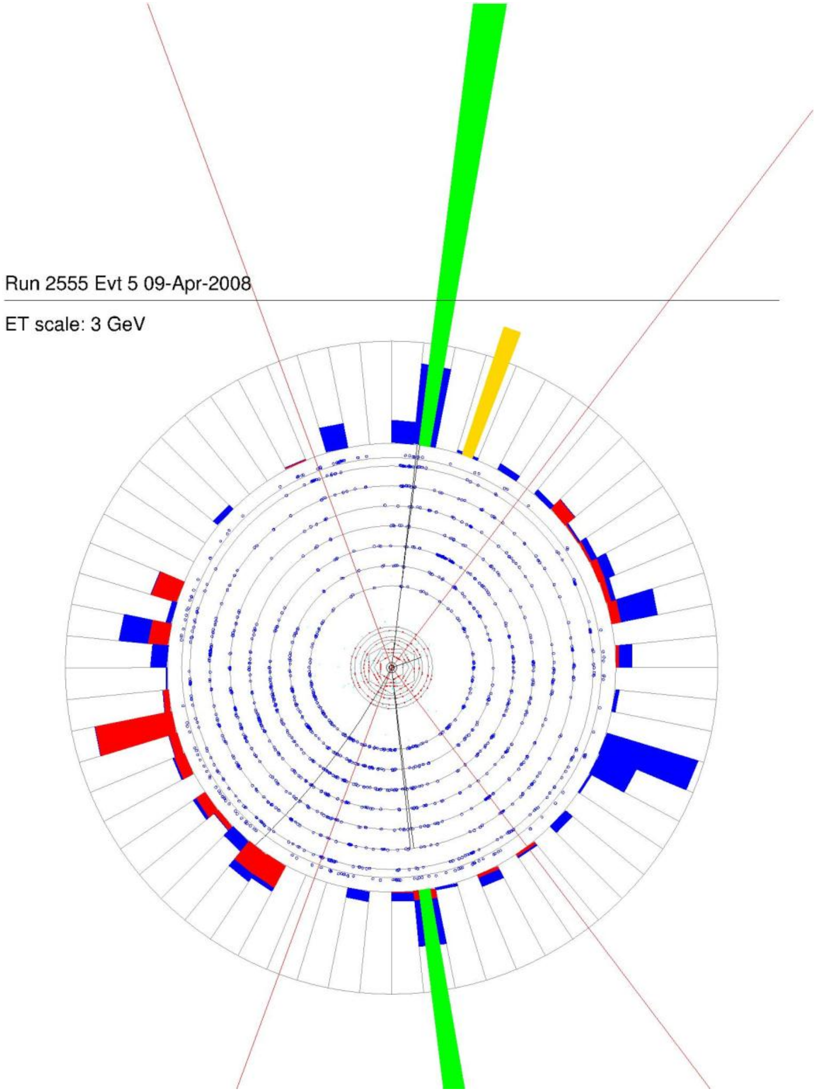
Neutral MSSM Higgs → bb + b[b]

- Mass plots
  - Low likelihood cross check, low and high mass likelihoods



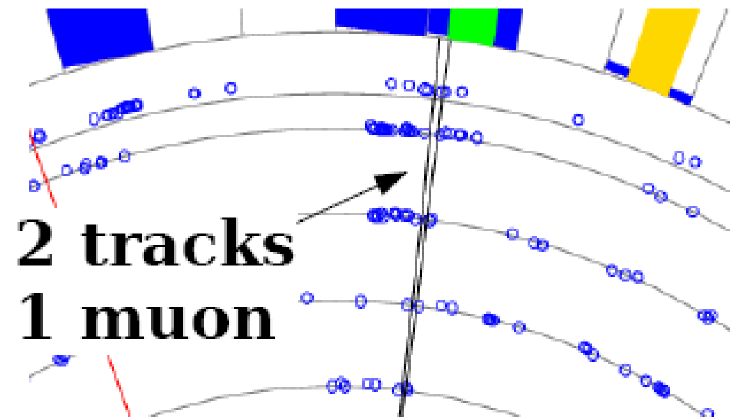
NMSSM Higgs → aa

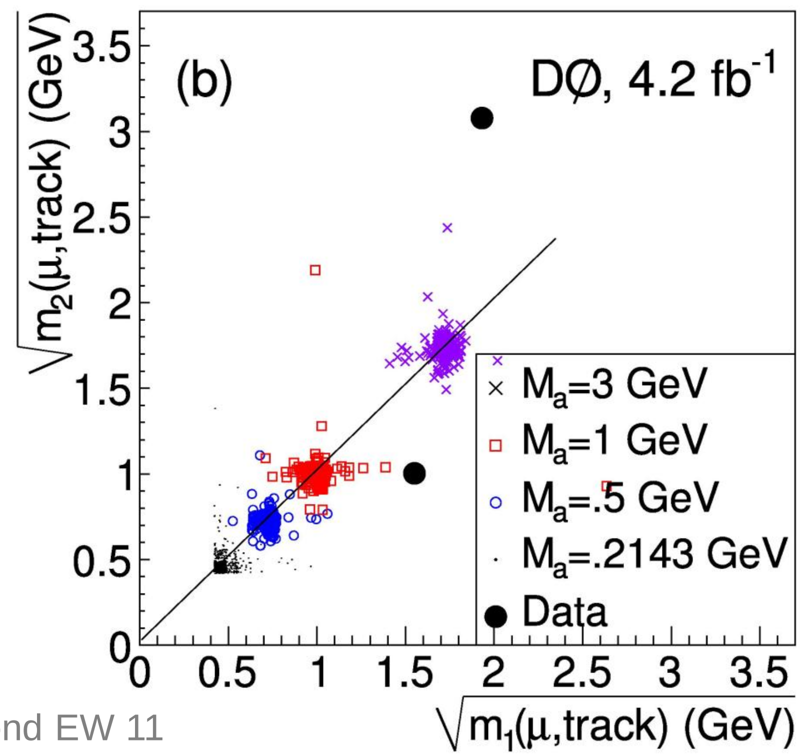
- Next-to-MSSM Higgs Sector
  - Two additional pseudo-scalar Higgs bosons (s and a)
    - $h \rightarrow aa$ dominates
  - If $m_a < 2m_\tau$
    - Dominant decay $a \rightarrow \mu\mu$
    - Limit $m_h > 82$ GeV
  - If $2m_\tau < m_a < 2m_b$
    - Dominant decay $a \rightarrow \tau\tau$
    - Limit $m_h > 86$ GeV
- Published 4.2 fb^{-1} search



NMSSM Higgs → aa

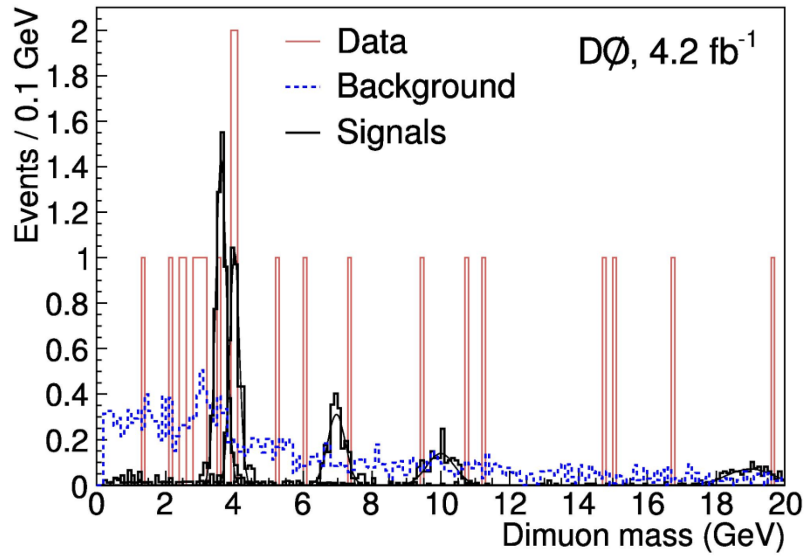
- Next-to-MSSM Higgs Sector
  - ➢ Two additional pseudo-scalar Higgs bosons (s and a)
    - ▪ h → aa dominates
- $m_a < 2m_\tau$: h → aa → μμμμ
  - ➢ Two pairs of collinear muons
- Event Selection
  - ➢ Two muons ΔR(μ,μ) > 1
  - ➢ ‘Companion’ tracks ΔR(μ,track) < 1
- Backgrounds: Multi-jet, $Z/\gamma^* \rightarrow \mu\mu$
- Set 95% limits in 2D mass window
  - ➢ σ x BR < 10-5.6 fb (m_h = 100 GeV)





NMSSM Higgs → aa

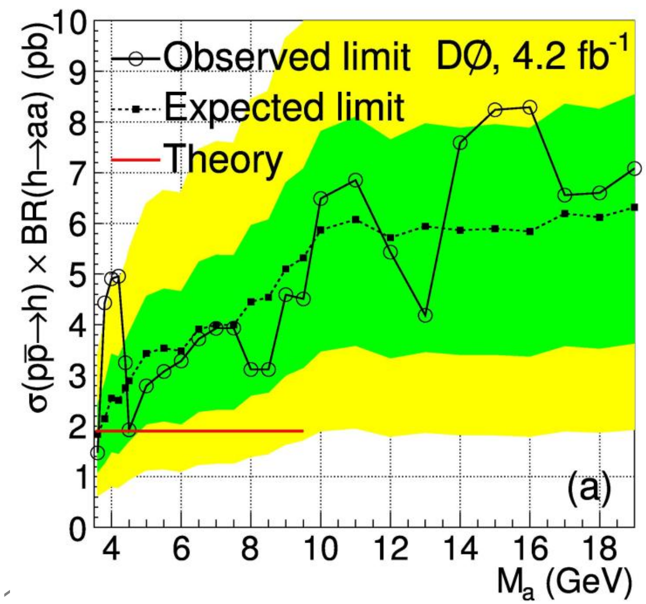
- $2m_\tau < m_a < 2m_b$: $h \to aa \to \mu\mu\tau\tau$
  - ➢ μ decay suppressed
  - ➢ τ decay dominates
  - ➢ Back-to-back μ and τ pairs



- Backgrounds: Multi-jet, Z/γ^*+jets→ μμ+jets

- Event Selection
  - ➢ μ pair $\Delta R(\mu,\mu) < 1$
  - ➢ Opposite missing E_T/μ/e

- Set limits @ 95% using dimuon mass



MSSM benchmarks

- Five additional parameters due to radiative correction
  - M_{SUSY} (parameterizes squark, gaugino masses)
  - X_t (related to the trilinear coupling $A_t \rightarrow$ stop mixing)
  - M_2 (gaugino mass term)
  - μ (Higgs mass parameter)
  - M_{gluino} (comes in via loops)

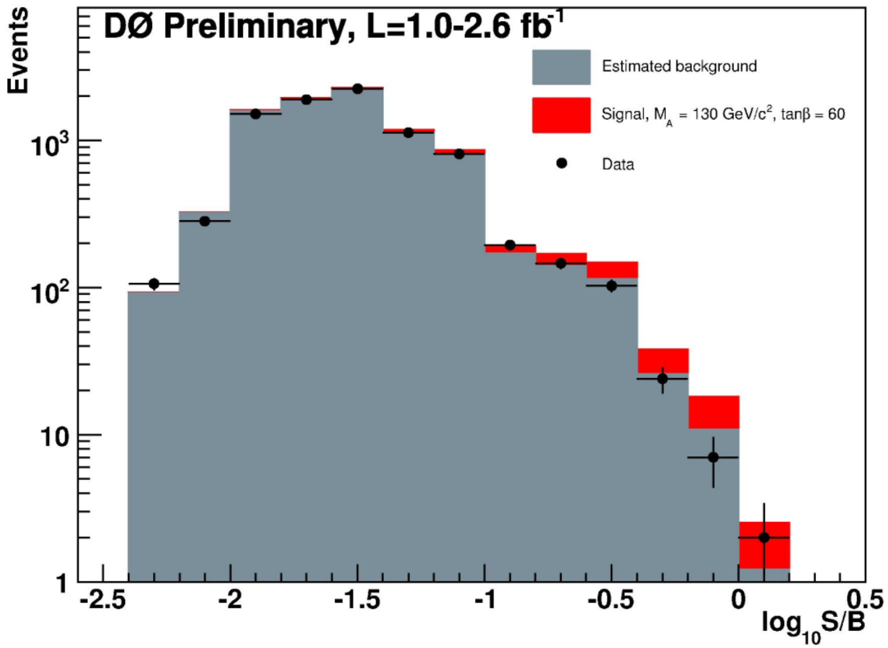
	m_h-max	no-mixing
M_{SUSY}	1 TeV	2 TeV
X_t	2 TeV	0
M_2	200 GeV	200 GeV
μ	±200 GeV	±200 GeV
$m_{\tilde{g}}$	800 GeV	1600 GeV

- Two common benchmarks
  - Max-mixing - Higgs boson mass m_h close to max possible value for a given tanβ
  - No-mixing - vanishing mixing in stop sector → small mass for h

DØ MSSM Combination

- Combine three neutral Higgs searches
  - 19 sub-channels

Channel	Integrated Luminosity / fb^{-1} Run IIa	Run IIb	Final Variable
$h \to \tau_e \tau_{had}$	1.0	-	visible mass
$h \to \tau_\mu \tau_{had}$	1.0	1.2	visible mass
$h \to \tau_e \tau_\mu$	1.0	-	visible mass
$bh \to b\tau_\mu \tau_{had}$	-	1.2	1D-discriminant
$bh \to bb\bar{b}$	1.0	1.6	M_{bb}

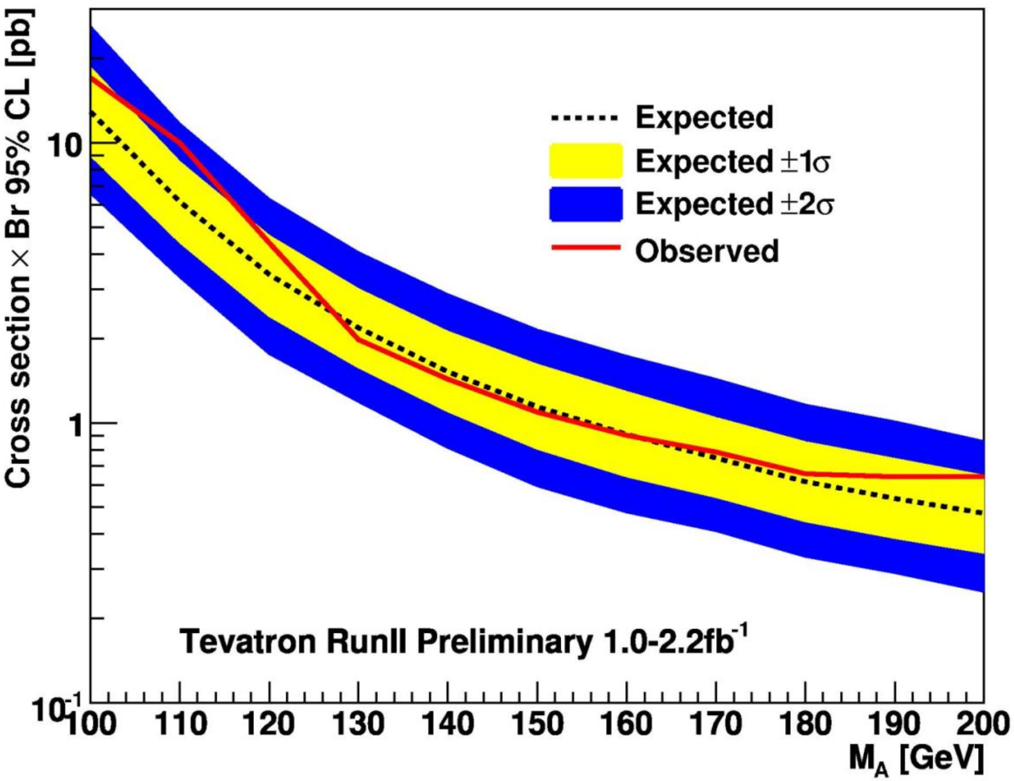


- Large number systematic errors
  - Assumed 0 or 100% correlated

- Uses ~7 times luminosity of previous combination

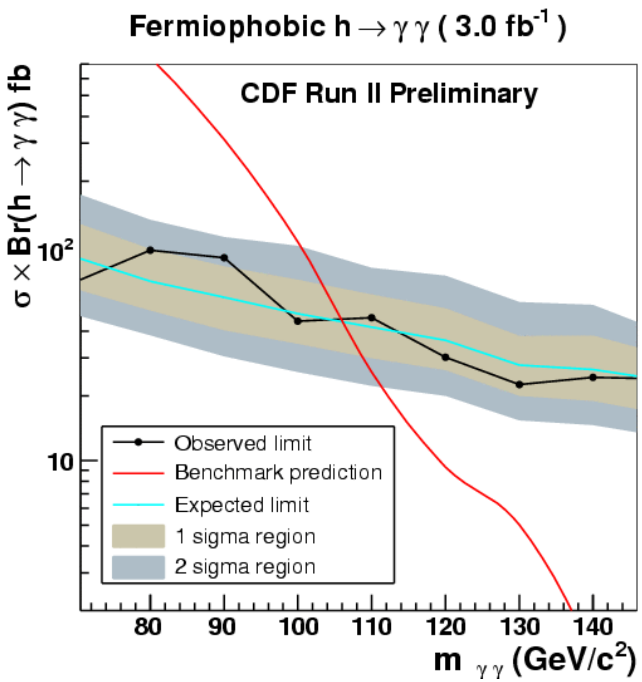
Neutral MSSM Combinations

- Combine results across experiments
  - $\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$, $\tau_e\tau_\mu$
    - DØ: up to 2.2 fb^{-1}
    - CDF: 1.8 fb^{-1}
- Combinations performed with Bayesian and Modified Frequentist
  - Most conservative result chosen

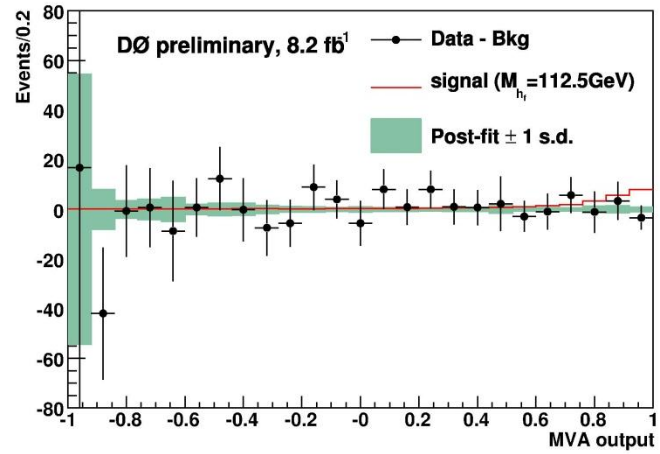


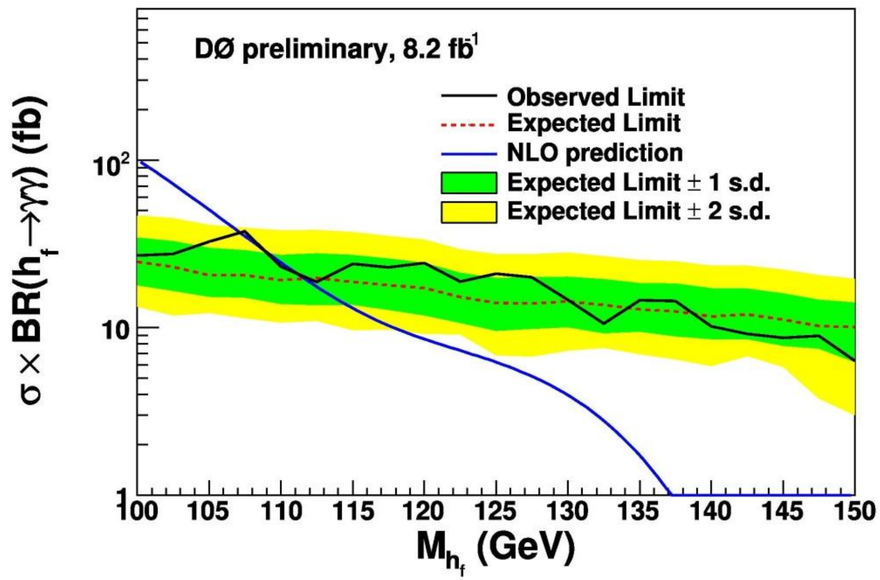
Fermiophobic Higgs → γγ

- No excess, set limits:
  - ➢ 95% CL limit



Excluded m_{hf} < 106 GeV

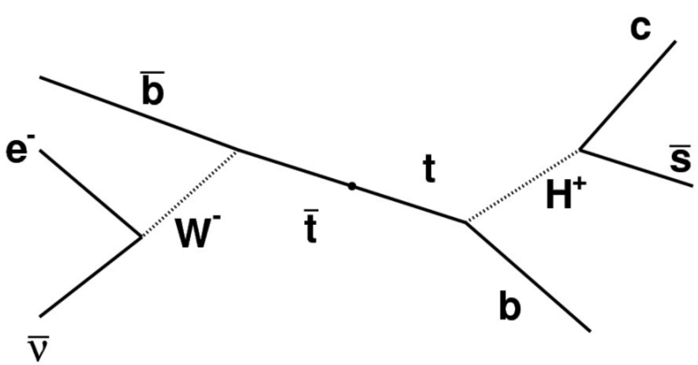




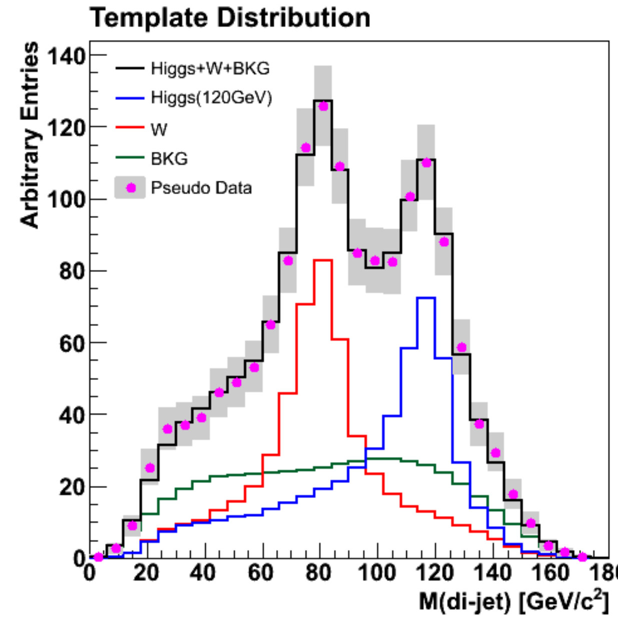
Excluded m_{hf} < 112.5 GeV
Better than LEP limit

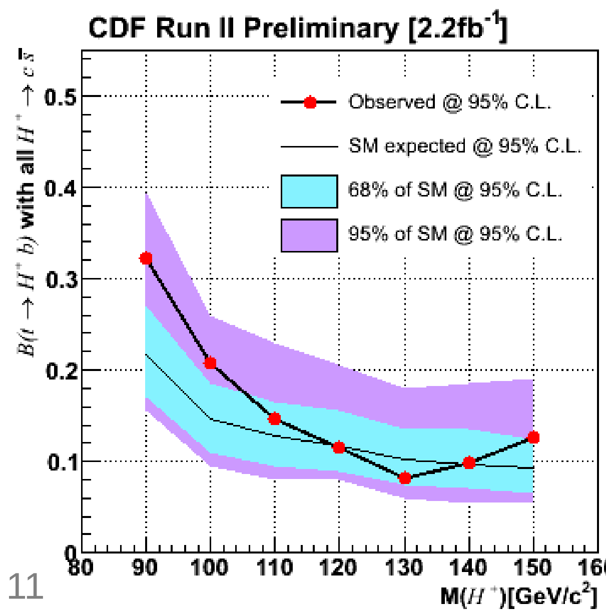
Charged Higgs → cs

- Search for $H^{\pm}$ in top decays
- CDF: Summer 2008 $2.2fb^{-1}$
  - ➢ Lepton + jet channel
  - ➢ $H^{\pm} \rightarrow cs$
    - MSSM: $\tan(\beta) < 1$ and $m_{H\pm} < 130$ GeV



- Di-jet mass used to set limits
  - ➢ Assume $BR(H^{\pm}\rightarrow cs) = 1$





Charged Higgs → cs/τν

- Search top decays in dilepton, lepton+jets, lepton+tau channels
  - ➢ Compare predicted/observed yields
  - ➢ DØ: Published 2009 1fb^{-1}
- Two models:
  - ➢ Tauonic: $H^{\pm} \rightarrow \tau\nu$
    - MSSM: tan(β) > 1
  - ➢ Leptophobic: $H^{\pm} \rightarrow cs$
    - MSSM: tan(β) < 1 and $m_{H\pm}$ < 130 GeV