Imperial College London

Search for Beyond the Standard Model Higgs Bosons at the Tevatron

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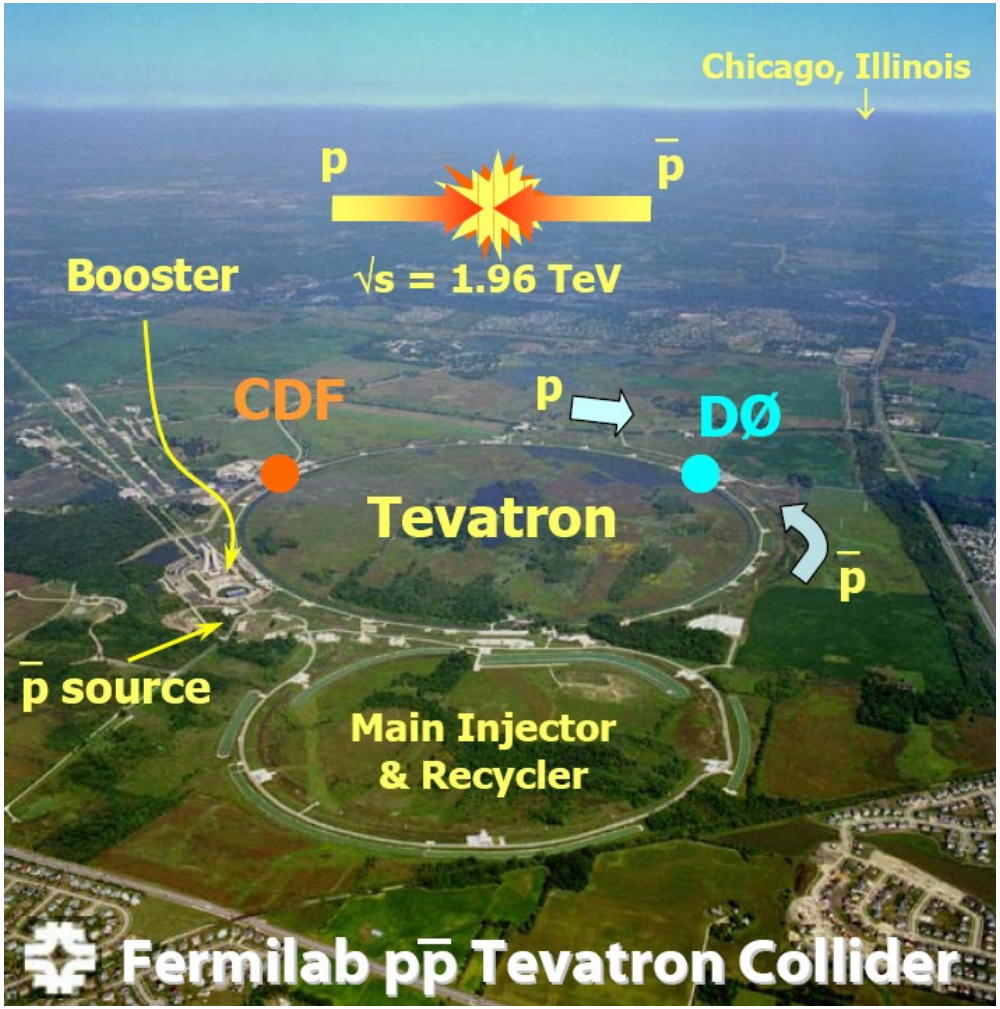
On behalf of the CDF and DØ Collaborations

Outline

- Introduction
  - Tevatron performance
- Neutral Higgs Searches
  - Minimal SUSY SM (MSSM)
  - Next-to-MSSM
  - Fermiophobic Higgs
- Charged Higgs Searches
- Prospects & Conclusions

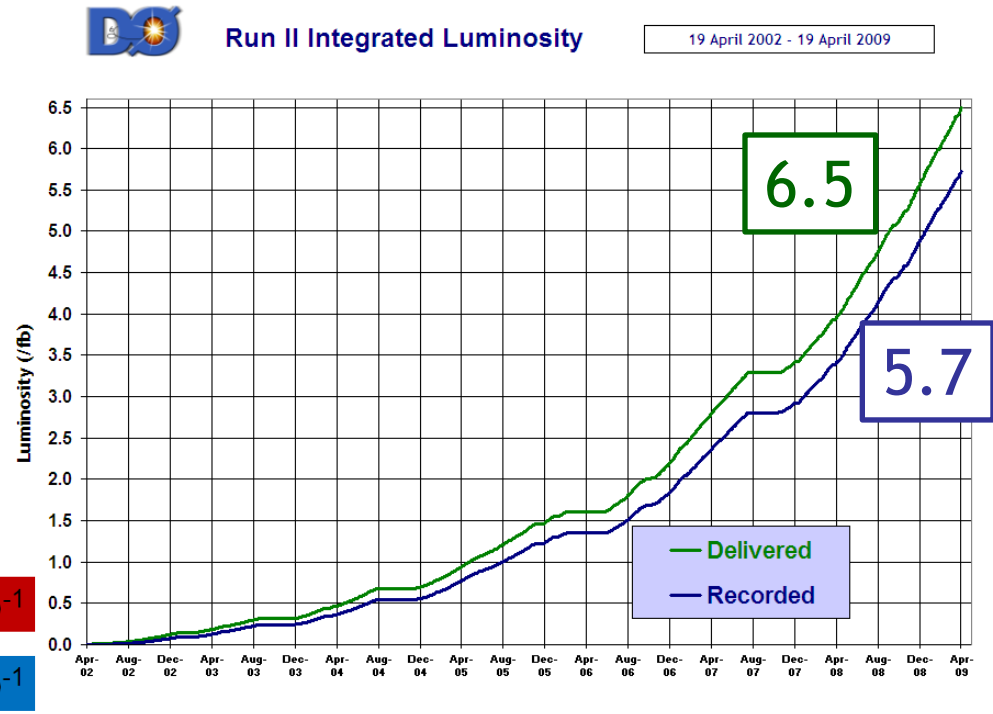


[Thanks to all my Tevatron colleagues]

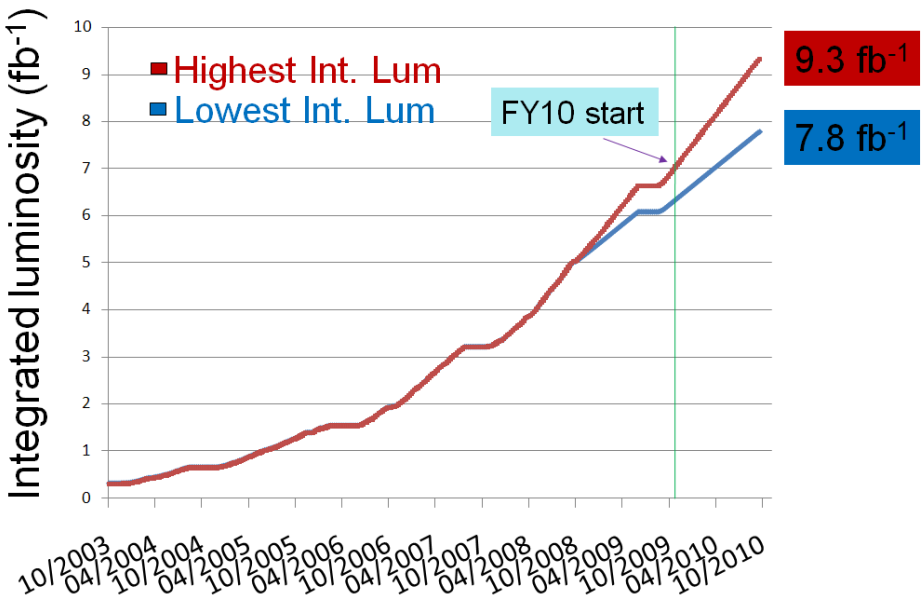
Tevatron Performance

Tevatron continues to perform well

- Over 6.5 fb^{-1} delivered to each experiment
- Peak luminosities of >3.5×10^{32}



Luminosity projection curves for Run II



- Performance matching design integrated luminosity of > 7 fb^{-1} by 2009

Neutral SUSY Higgs

- Introduction
- Minimal Supersymmetric Standard Model (MSSM)
  - Introduction
  - Neutral Higgs bosons (ϕ) searches

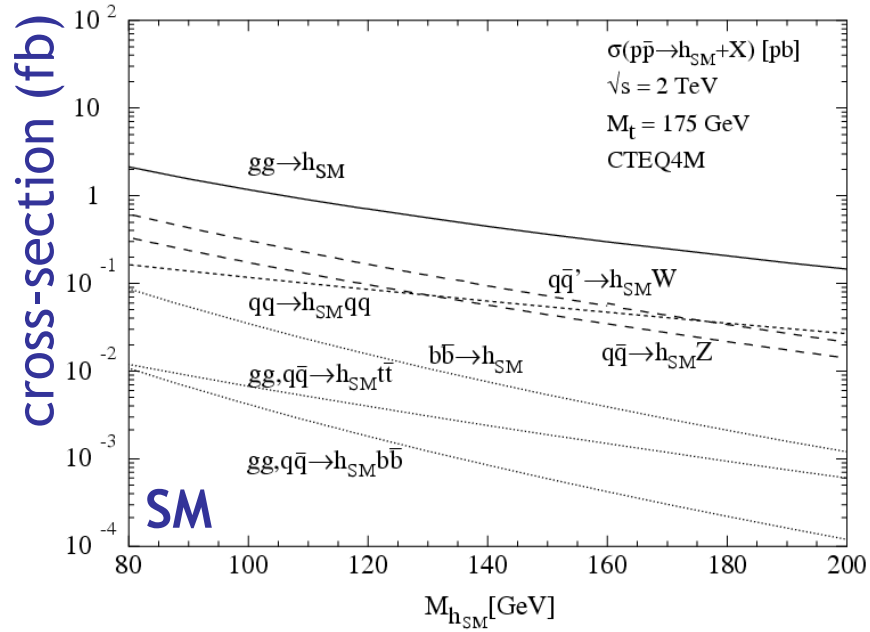
    $\phi \rightarrow \tau\tau$

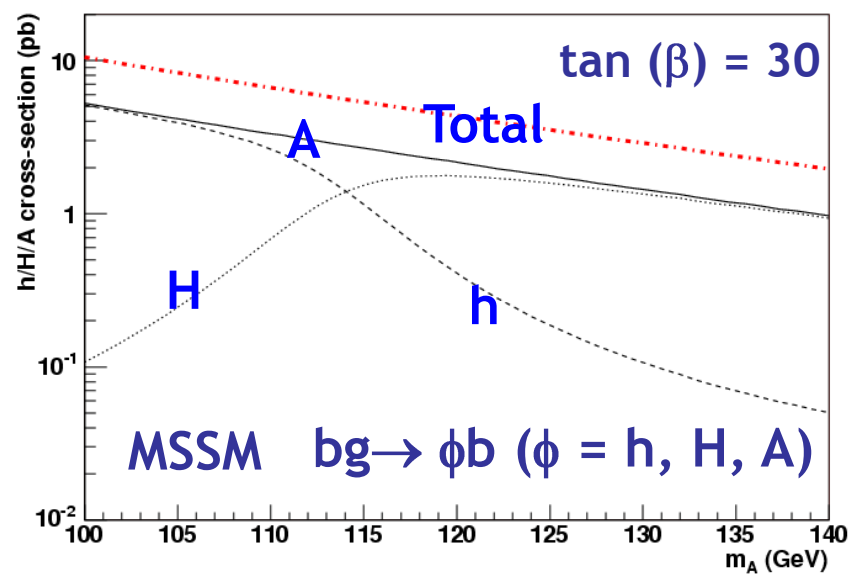
    $b\phi \rightarrow bbb$

    $b\phi \rightarrow b\tau\tau$
  - Next-to-MSSM search
- Fermiophobic Higgs
- Charged Higgs
- Prospects & Conclusions

Supersymmetric Higgs Sector

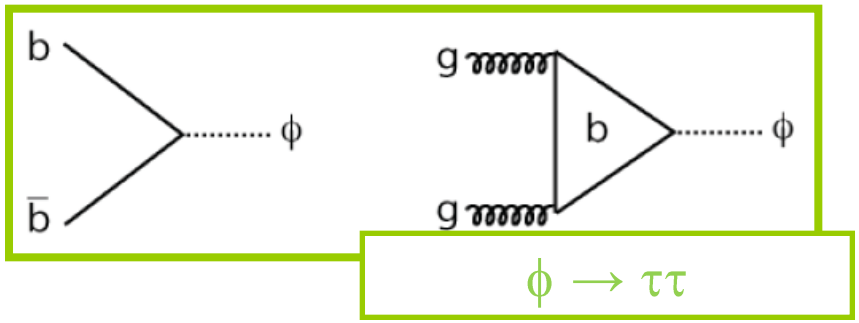
- Minimal Supersymmetric Standard Model (MSSM)
  - 2 Higgs doublets
  - 5 Physical Higgs bosons
    - 3 Neutral: (A, h and H) → ϕ
    - 2 Charged: $H^{\pm}$
- Need 2 parameters to calculate all Higgs masses and couplings at tree level
  - m_A
  - $\tan(\beta)$ = ratio of vacuum expectation values of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



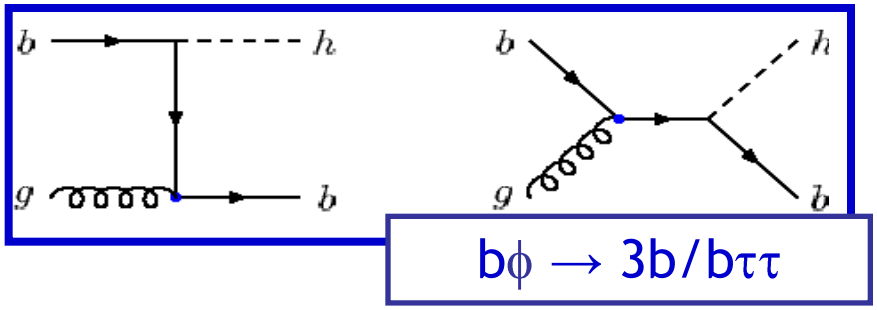


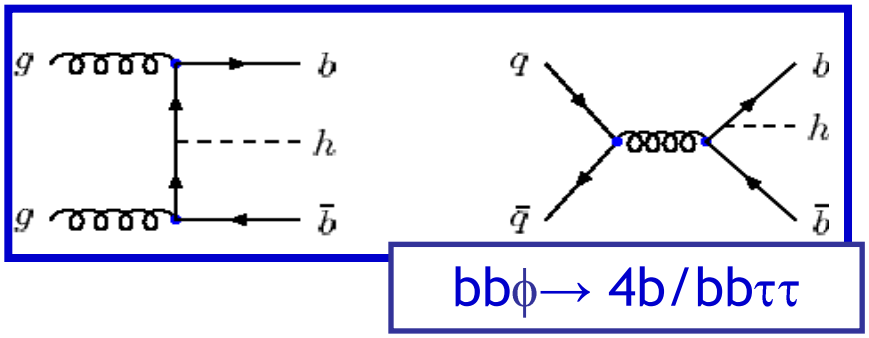
MSSM Higgs boson production

- Neutral MSSM Higgs decays
  - bb ~ 90%
    - Large background
  - ττ ~ 10%
    - More distinct signature



- 3 channels best suited to benefit from enhanced b-quark coupling
  - ϕ → ττ
  - ϕb → bbb
  - ϕb → ττb





- Good b-jet and τ identification vital

Similar overall sensitivities → Combine

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 separated from $\mu/e/\tau_{had}$ with opposite sign

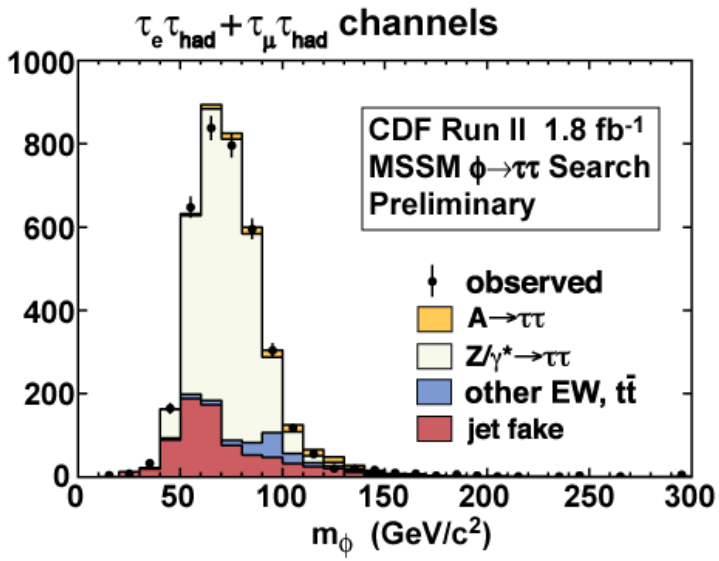
- Main bkgs.: $Z \rightarrow \tau\tau$ (irreducible), QCD multi-jet, W+jets

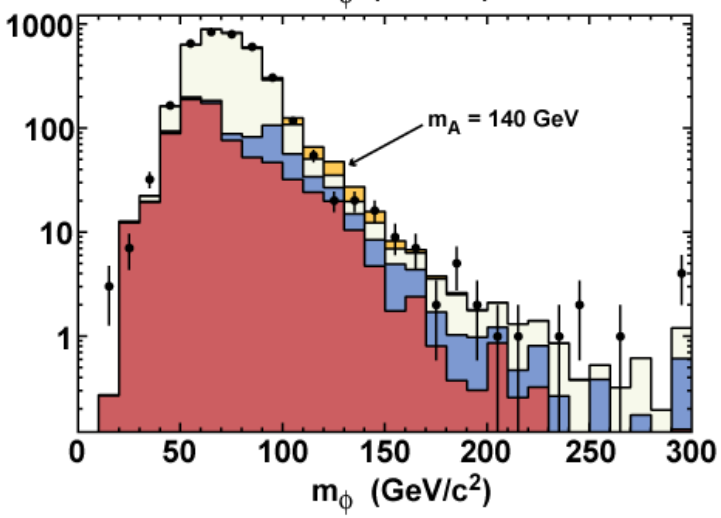
- DØ (μ): 2.2 fb^{-1} Summer 2008
  - Combined with published 1 fb^{-1} channels
  - τ_{had} identified using NNs
  - Remove W+jets: Transverse momentum < 40 GeV

- CDF (μ, e, e+μ channels): 1.8 fb^{-1} Summer 2007
  - τ_{had} identified using variable size cone
  - Remove QCD multi-jet: $|p_T^\tau| + |p_T^l| + |\text{missing } E_T| > 55$ GeV
  - Remove W+jets: Cut on relative directions of τ decay and missing E_T

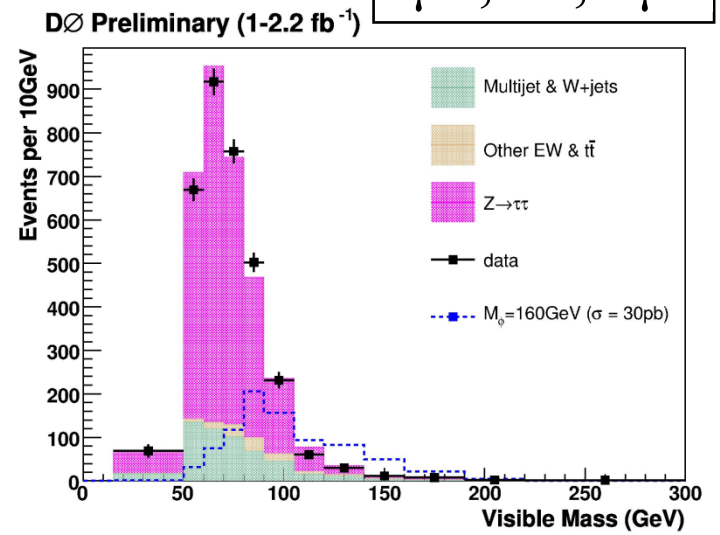
Neutral MSSM Higgs → $\tau_l\tau_{had}$

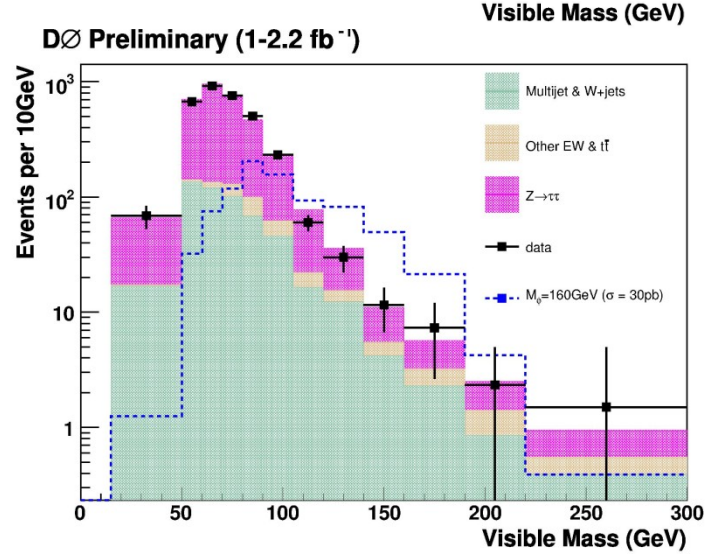
- m_{vis} used to derive cross section limits





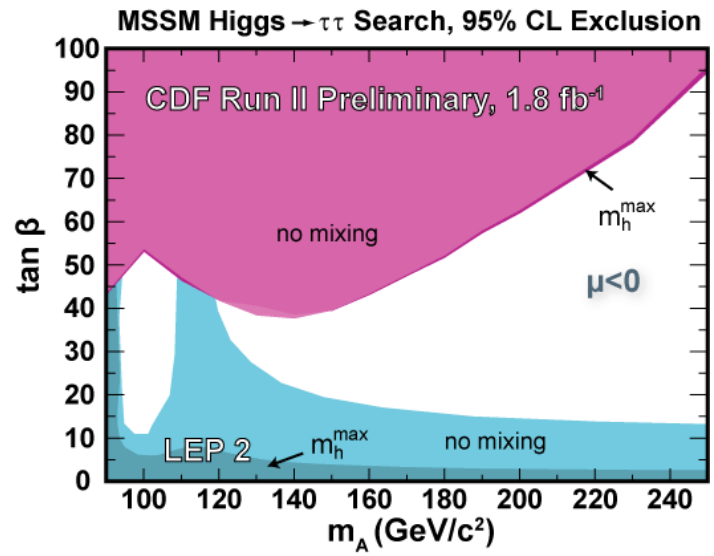
$\mu\tau$, $e\tau$, $e\mu$

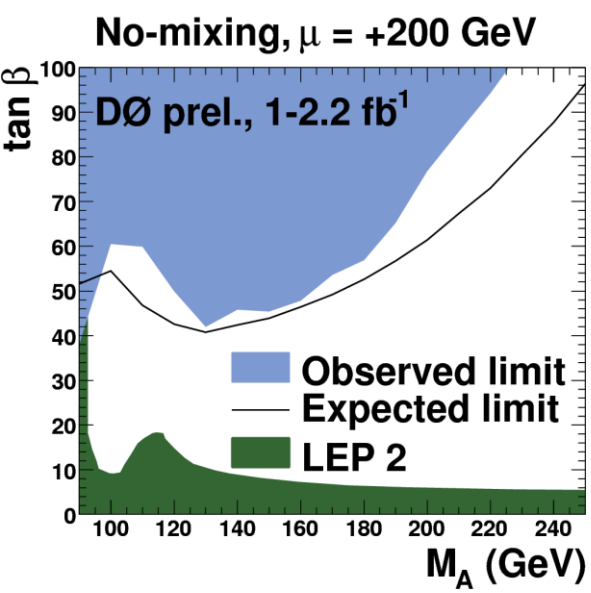


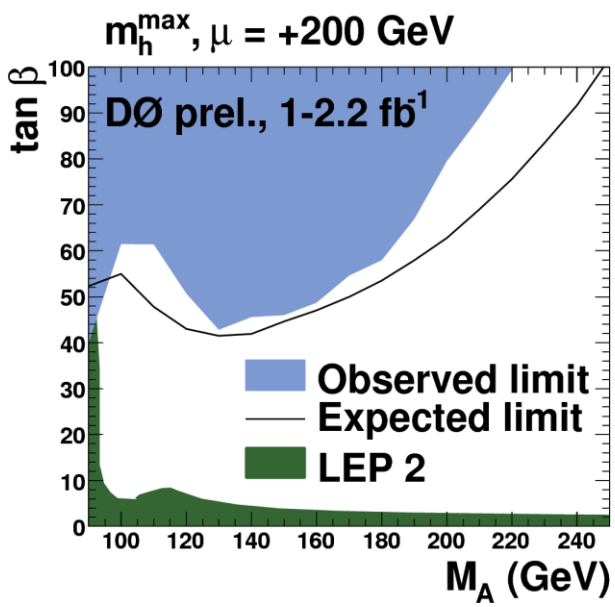


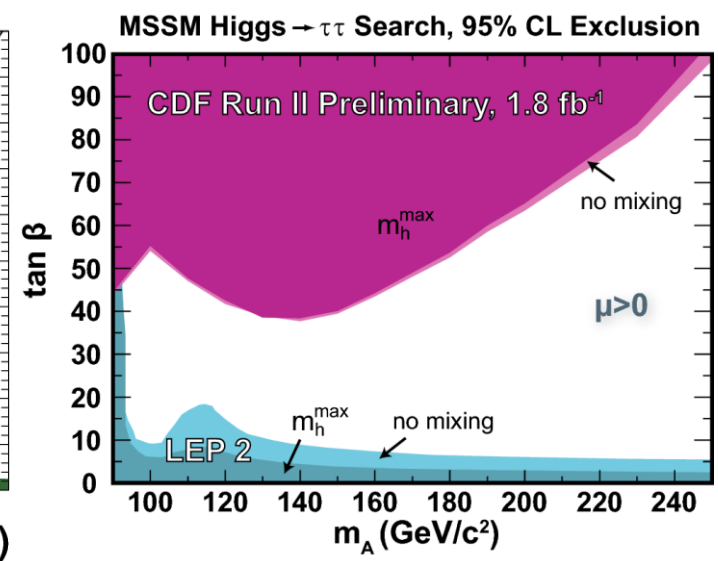
Neutral MSSM Higgs → $\tau_l\tau_{had}$

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



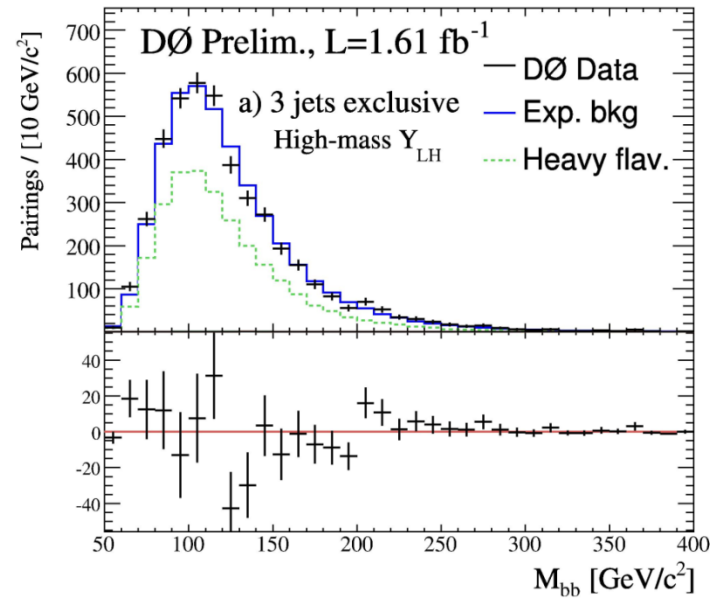


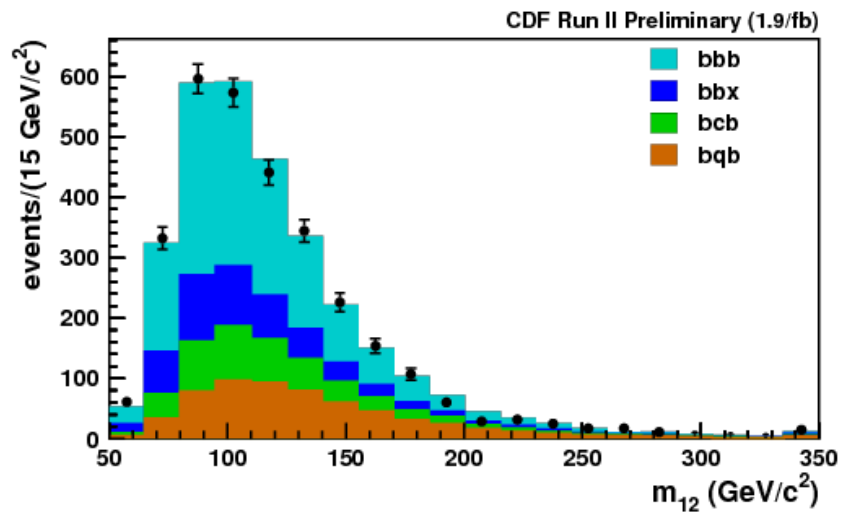




Neutral MSSM Higgs → bb + b[b]

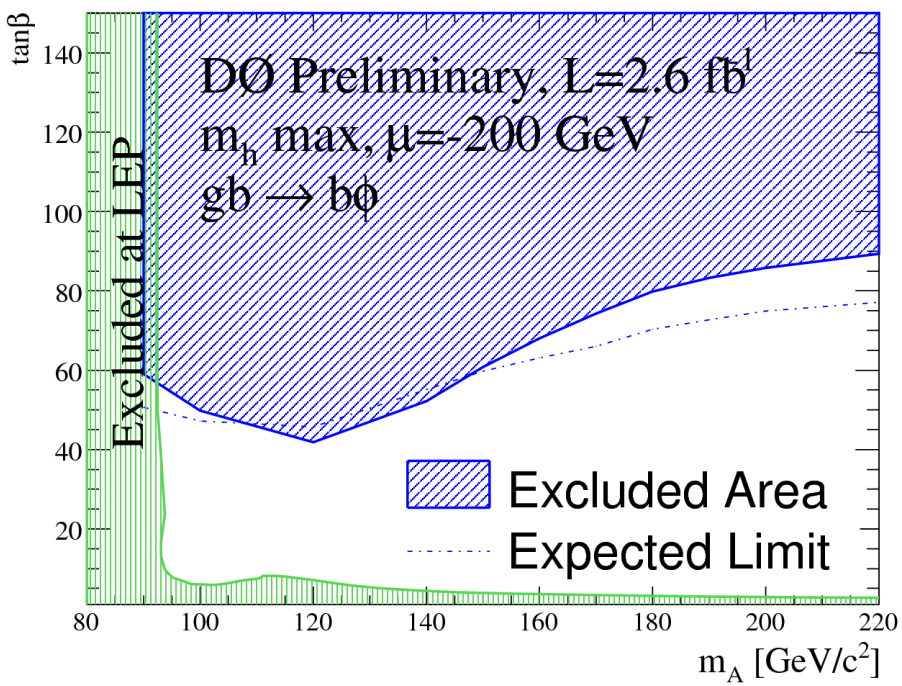
- Signal
  - At least 3 b-tagged jets
  - Peak in dijet mass spectrum
- Background
  - Heavy flavour QCD
  - Predicted from data/MC
- D0: 2.6 fb^{-1} Summer 2008
  - Neural network b-tagger
  - Separate 3, 4 and 5-jet channels
  - Keep multiple jet pairings
  - Train kinematic likelihood
    - Cut on likelihood
  - Use dijet invariant mass to set limits
- CDF: 2 fb^{-1} Winter 2008
  - Secondary vertex b-tagger

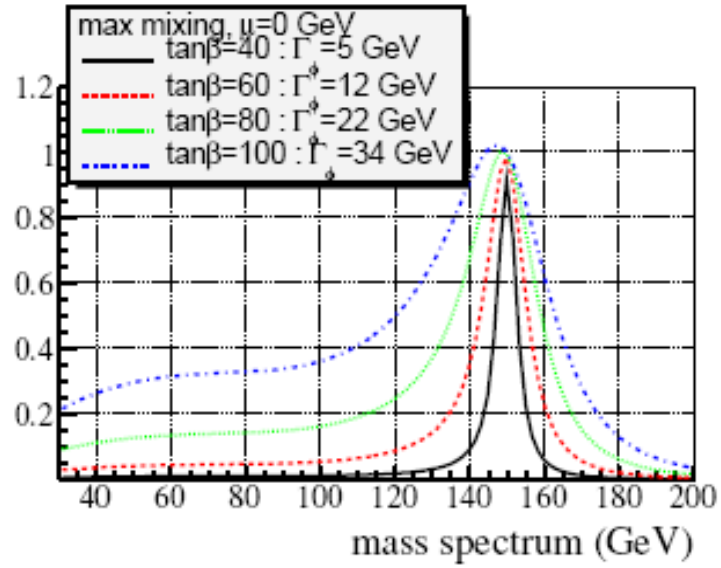


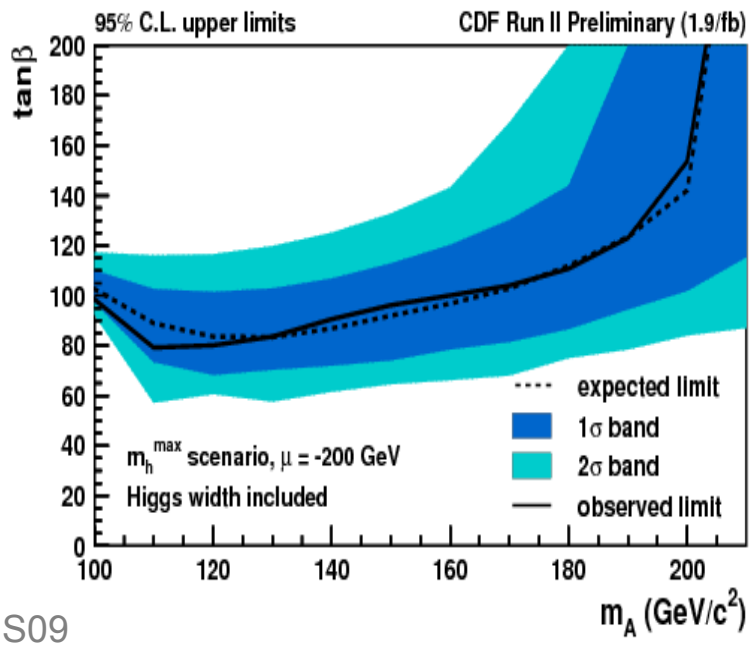


Neutral MSSM Higgs → bb + b[b]

- Final limits corrected for:
  - Width: Not negligible at high tanβ
  - MSSM NLO Corrections: Strongest limits for Higgs mass term, $\mu < 0$

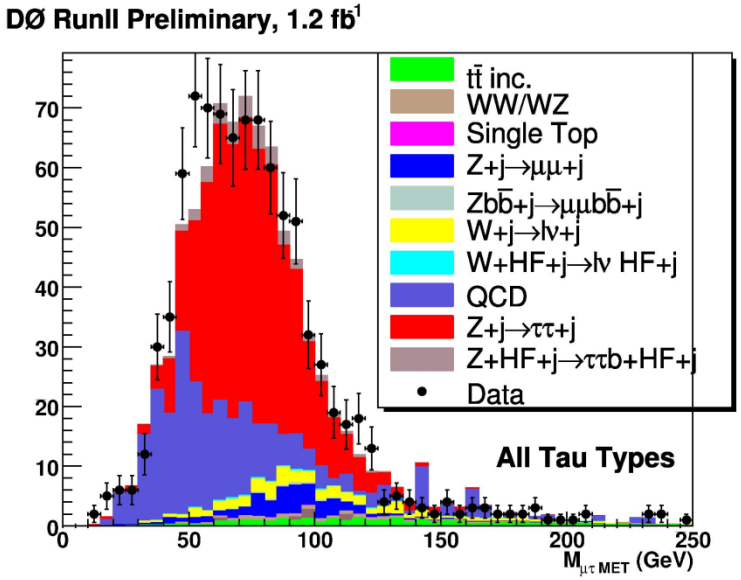


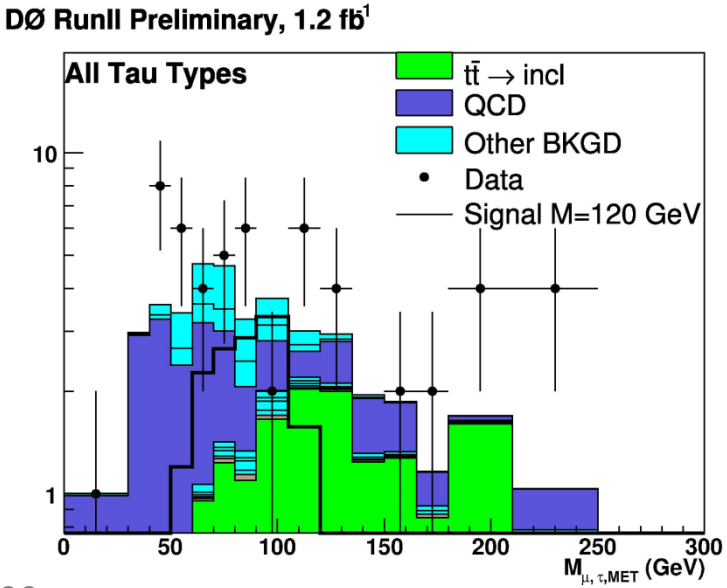




Neutral MSSM Higgs → $\tau_l \tau_{had}$ + b

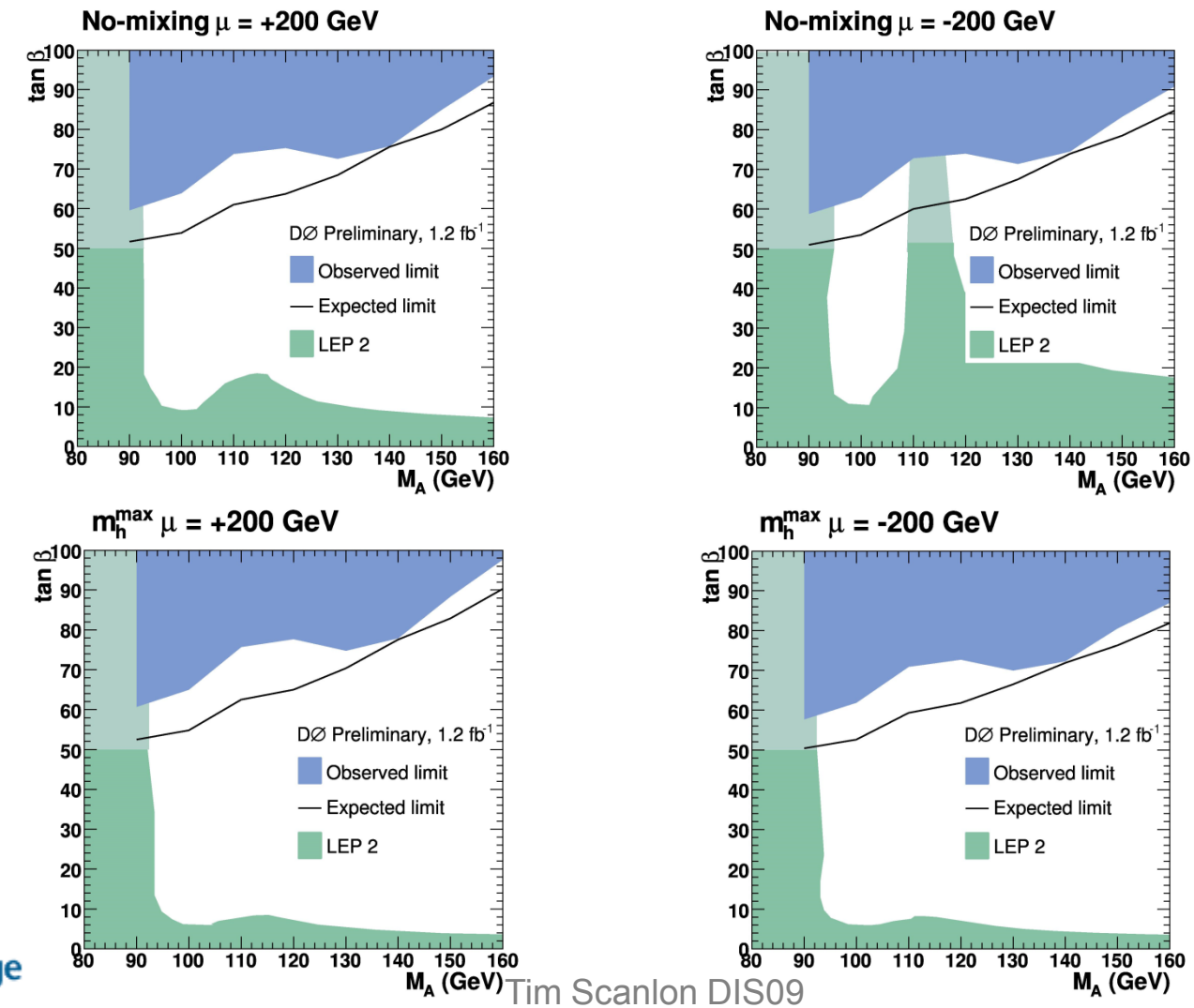
- Lower branching ratio/cross section
  - Cleaner final state
  - Similar sensitivity
  - Updated summer 2008
- Signal: τ_μ, τ_{had} + b-jet
- Main bkgs.: Z+jets, QCD multi-jets, *tt*
- Selection:
  - Isolated μ separated from opposite sign τ_{had}
  - τ_{had} identification: NN
  - 1 NN b-tagged jet
  - NN(tt) vs likelihood(QCD) used to set limits





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

- Limits in MSSM parameter space
  - No-mixing & m_h^{max} benchmark scenarios



Neutral SUSY Higgs

- Introduction
- Minimal Supersymmetric Standard Model (MSSM)
  - Introduction
  - Neutral Higgs bosons (ϕ) searches

    $\phi \rightarrow \tau\tau$

    $b\phi \rightarrow bbb$

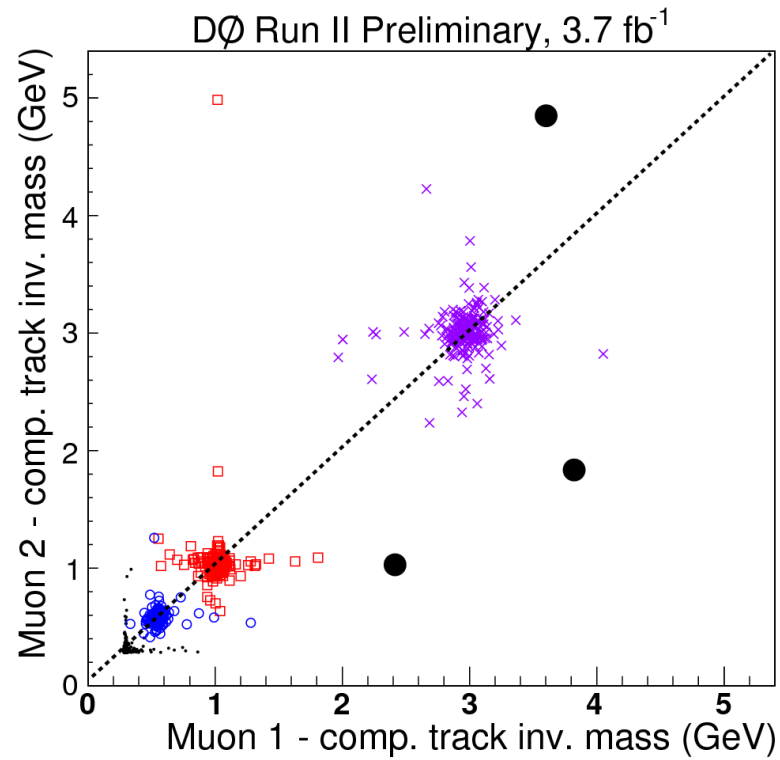
    $b\phi \rightarrow b\tau\tau$
  - Next-to-MSSM search
- Fermiophobic Higgs
- Charged Higgs
- Prospects & Conclusions

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 on $m_h > 82$ GeV
  - If $2m_\tau < m_a < 2m_b$
    - Dominant decay $a \rightarrow \tau\tau$
    - Limit on $m_h > 86$ GeV

NMSSM Higgs → aa

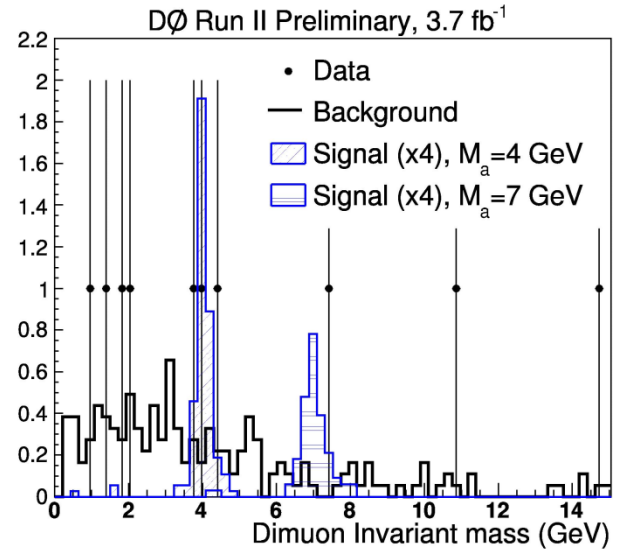
- $m_a < 2m_\tau$: $h \rightarrow aa \rightarrow \mu\mu\mu\mu$
  - Two pairs of collinear muons
- Backgrounds: QCD, $Z/\gamma^* \rightarrow \mu\mu$
- Event Selection
  - Two muons $\Delta R(\mu,\mu) > 1$
  - 'Companion' tracks $\Delta R(\mu,\text{track}) < 1$
- Set 95% limits in 2D mass window
  - $\sigma \times BR < 10\ fb^{-1}$
    - σ_h ~1000 fb
    - m_h = 120 GeV
    - $BR(h \rightarrow aa) \sim 1$)
  - $BR(a \rightarrow \mu\mu) < 10\%$

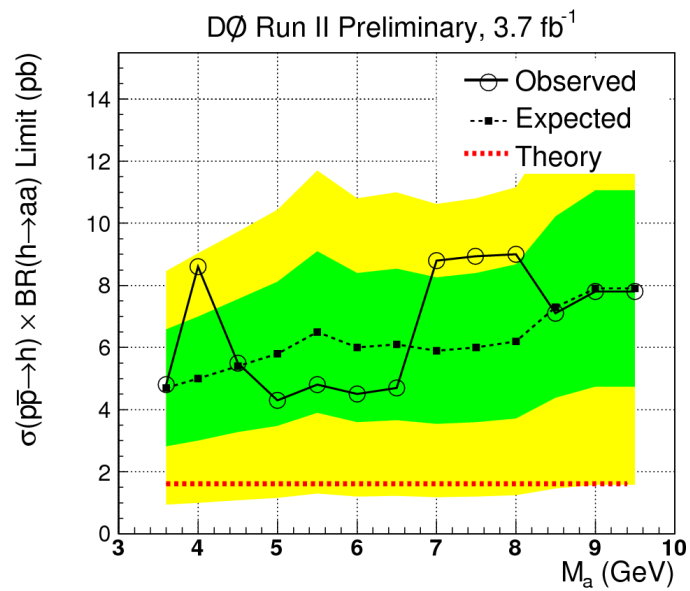


× M_a=3 GeV
□ M_a=1 GeV
○ M_a=.5 GeV
· M_a=.2143 GeV
● Data

NMSSM Higgs → aa

- $2m_b > m_a > 2m_\tau$: $h \rightarrow aa \rightarrow \mu\mu\tau\tau$
  - μ decay suppressed
  - τ decay dominates
  - Back-to-back μ and τ pairs
- Backgrounds: QCD, Z/γ^*+jets$\rightarrow \mu\mu$+jets
- Event Selection
  - μ pair $\Delta R(\mu,\mu) < 0.5$, $m_{\mu\mu} < 20$ GeV
  - Missing $E_T > 25$ GeV
- Set limits @ 95% using dimuon mass
  - Limit ~4 times larger than Higgs production



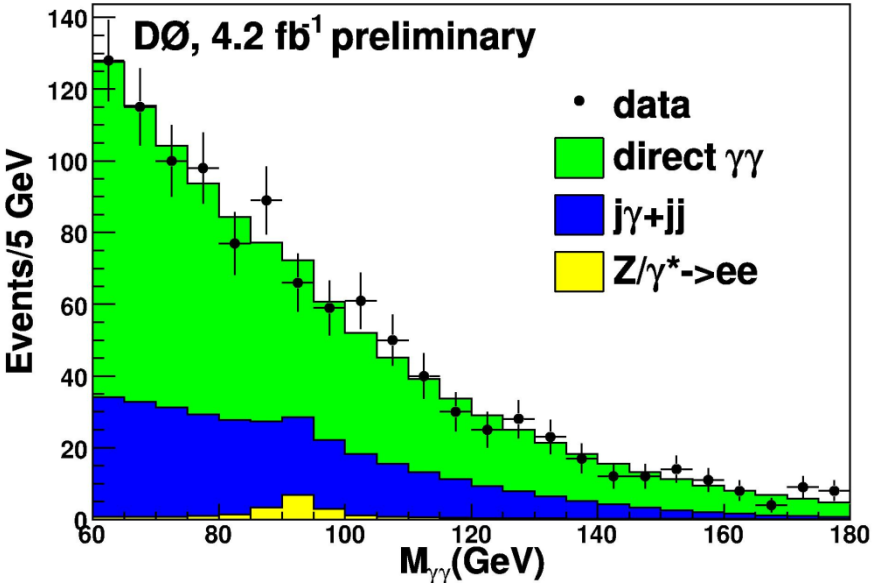


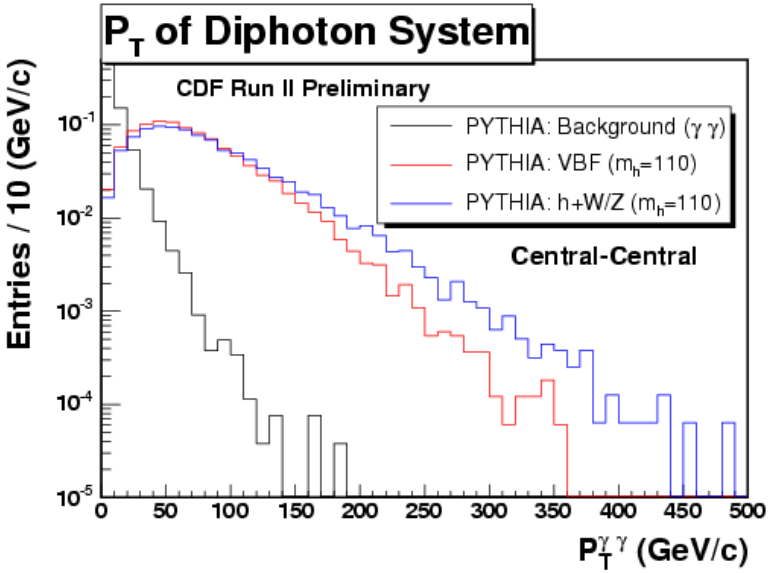
Fermiophobic Higgs

- Introduction
- Minimal Supersymmetric Standard Model (MSSM)
- Fermiophobic Higgs
- Charged Higgs
- Prospects & Conclusions

Fermiophobic Higgs→ γγ

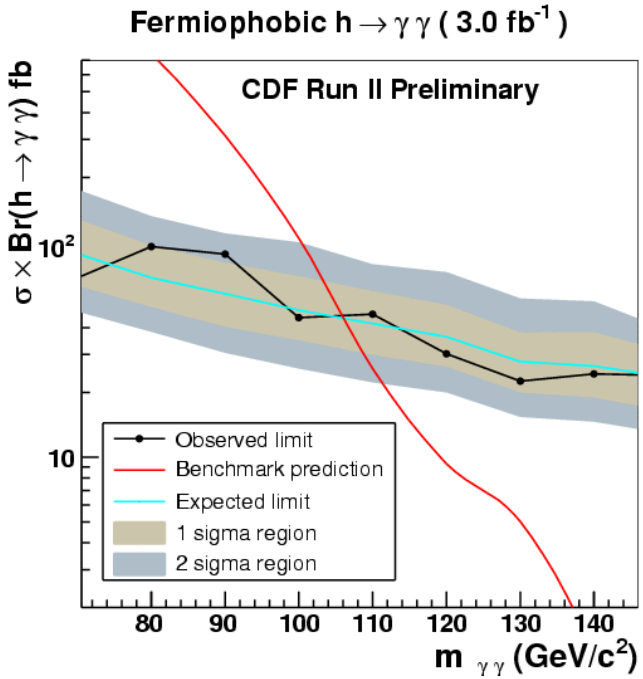
- Coupling to fermions highly suppressed
- Search for diphoton mass peak
  - ~3% resolution
- Backgrounds
  - Direct production, γ+jets/dijets, Drell-Yan
- Selection: 2 photons
  - D0: Central, $p_T^{\gamma\gamma} > 35$ GeV
  - CDF: Central or endcap, $p_T^{\gamma\gamma} > 75$ GeV
    - Allowing one endcap electron ~doubles acceptance



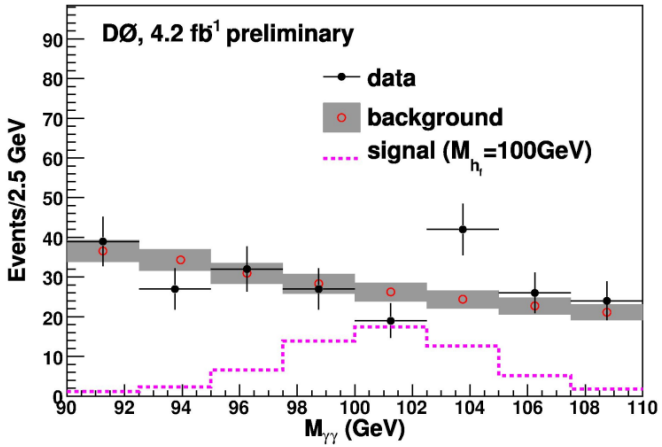


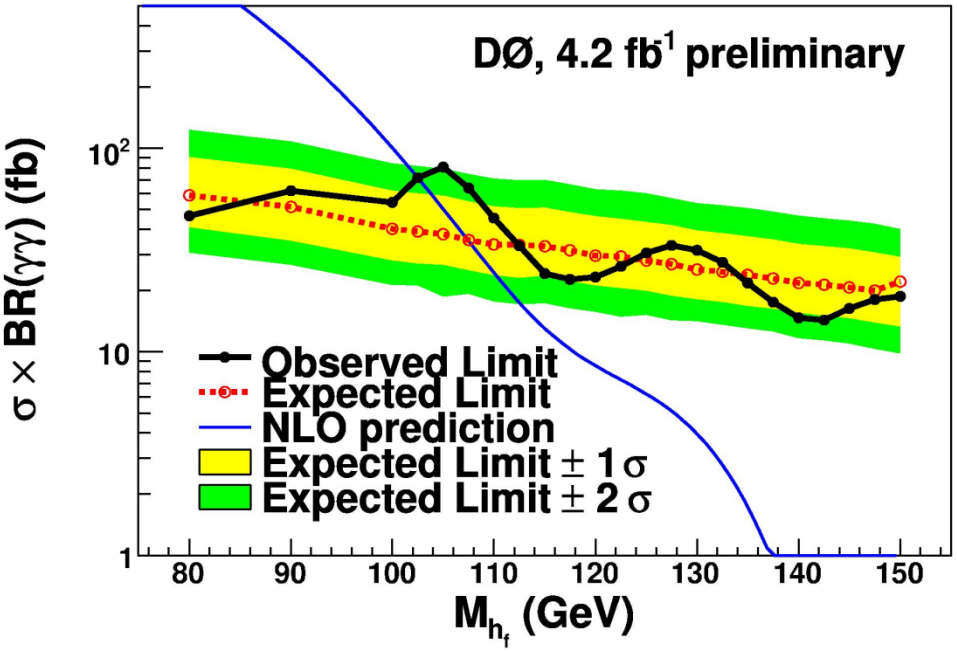
Fermiophobic Higgs → γγ

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



Excluded m_{hf} < 106 GeV





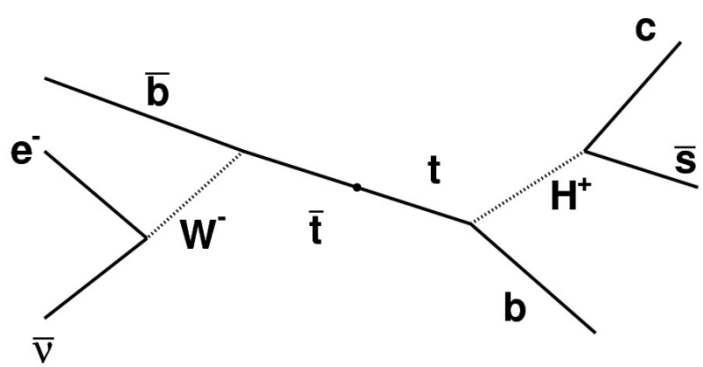
Excluded m_{hf} < 102.5 GeV

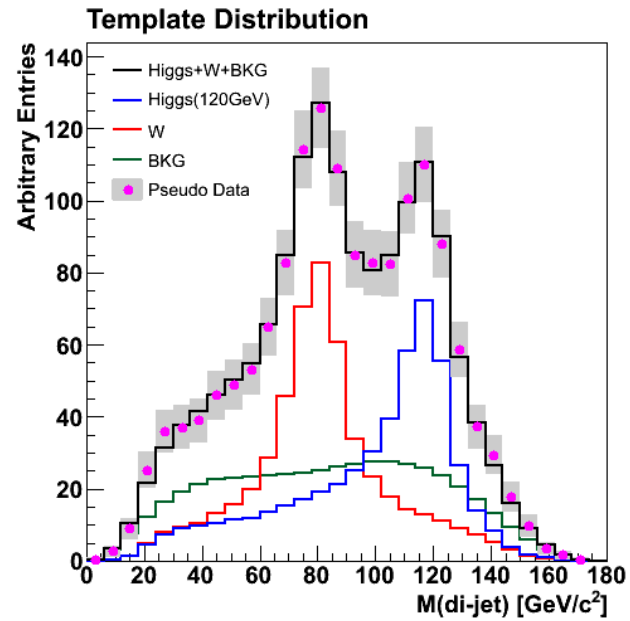
Charged Higgs

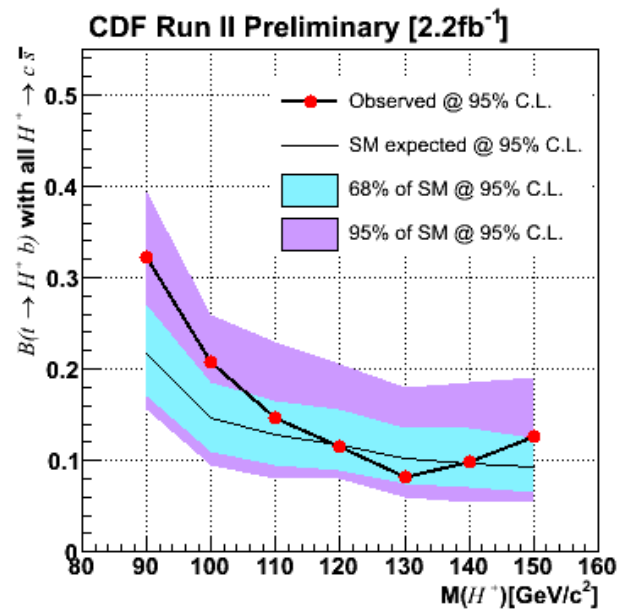
- Introduction
- Minimal Supersymmetric Standard Model (MSSM)
- Fermiophobic Higgs
- Charged Higgs
- Prospects & Conclusions

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



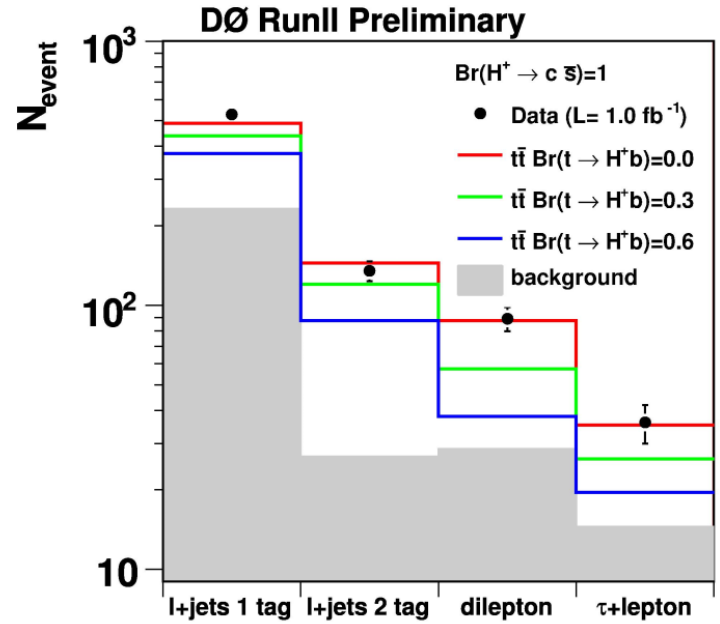


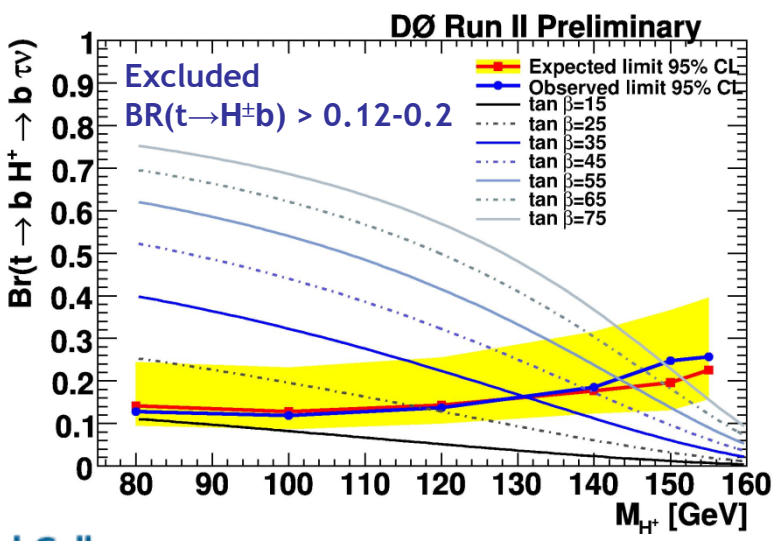


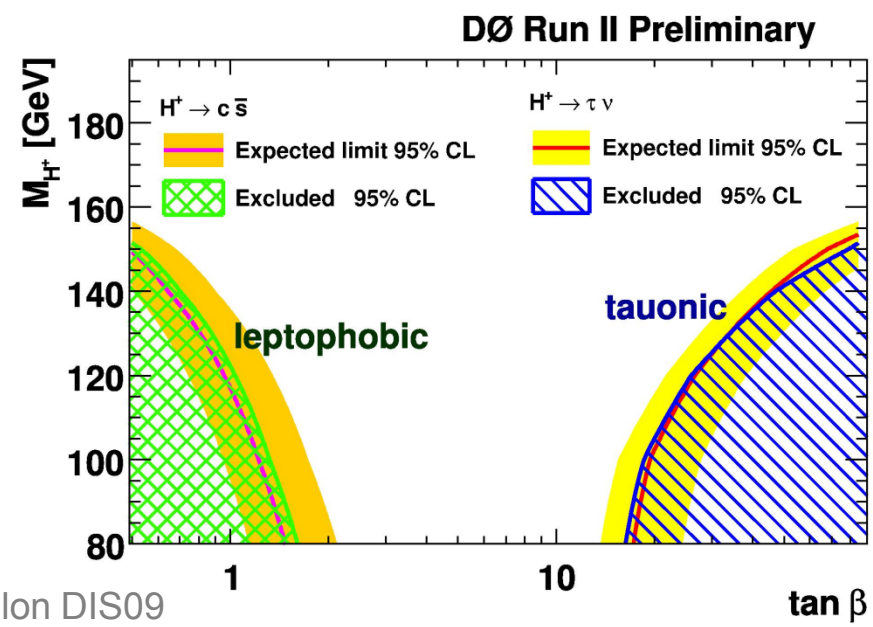
- Di-jet mass used to set limits
  - Assume $BR(H^{\pm} \rightarrow cs) = 1$

Charged Higgs → cs/τν

- DØ: Summer 2008 1fb^{-1}
- Search top decays in dilepton, lepton+jets, lepton+tau channels
  - Compare predicted/observed yields
- 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

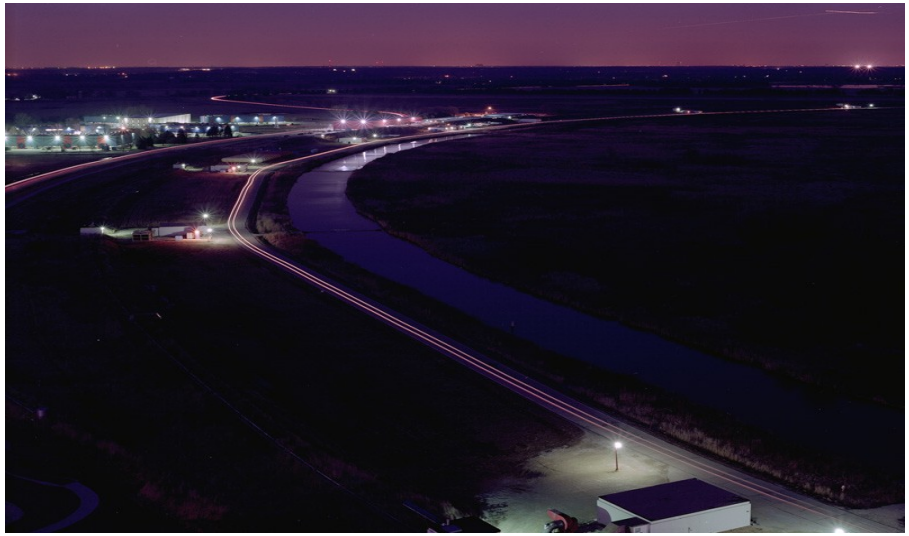






Prospects and Conclusions

- Introduction
- Neutral SUSY Higgs
- Fermiphobic Higgs
- Charged Higgs
- Prospects and Conclusions



Prospects – MSSM Higgs

- Probing very interesting regions
  - > 5.5 fb^{-1} data available
    - Aiming for rapid inclusion of new data
  - Stable and well developed analyses
    - Algorithmic/analysis improvements

- Short term (this summer)
  - Updated searches:
    - $\phi \rightarrow bb + b(b)$ & $\phi \rightarrow \tau\tau$ & $b\phi \rightarrow b\tau\tau$
  - New MSSM combination

- Longer term
  - Down to $\tan\beta$ ~20 for low m_A
  - Or discovery

Conclusions

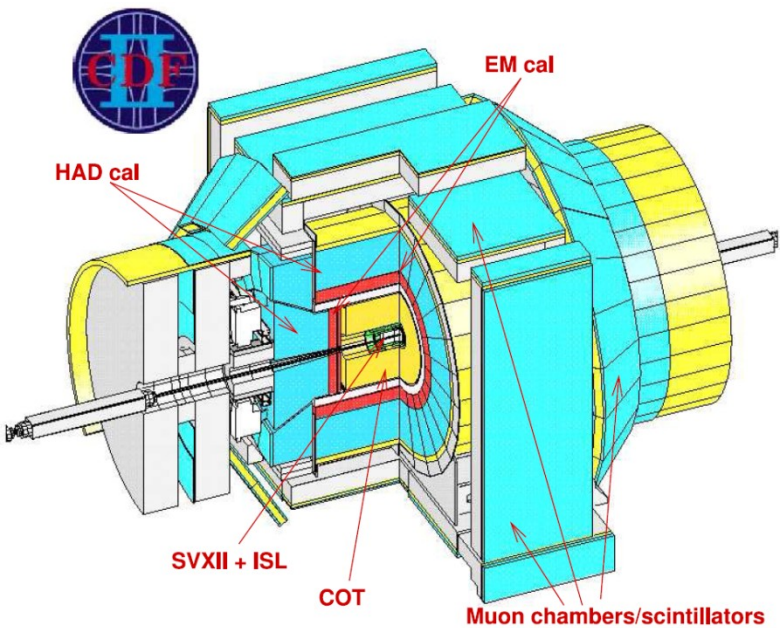
- Tevatron and CDF/ DØ experiments performing very well
- Wide range of beyond SM Higgs searches performed by CDF & DØ with up to 4.2 fb^{-1} Run II data:
  - No signal observed, but already powerful!
- Updated CDF and DØ analyses soon
  - Rapid accumulation in new data
  - Improvements in analysis techniques
  - MSSM Combination

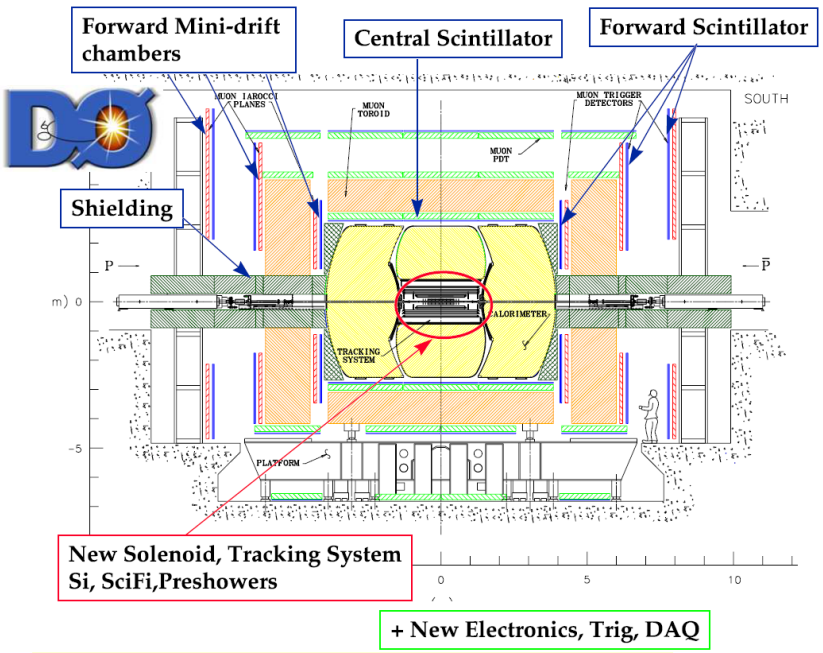
Very exciting times ahead!

Backup slides

CDF and DØ experiments

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



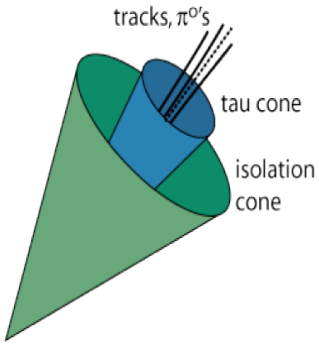


- DØ
  - New solenoid & preshowers
  - **Run IIb: New inner layer in SMT & L1 trigger**

- CDF: New plug calorimeter & ToF

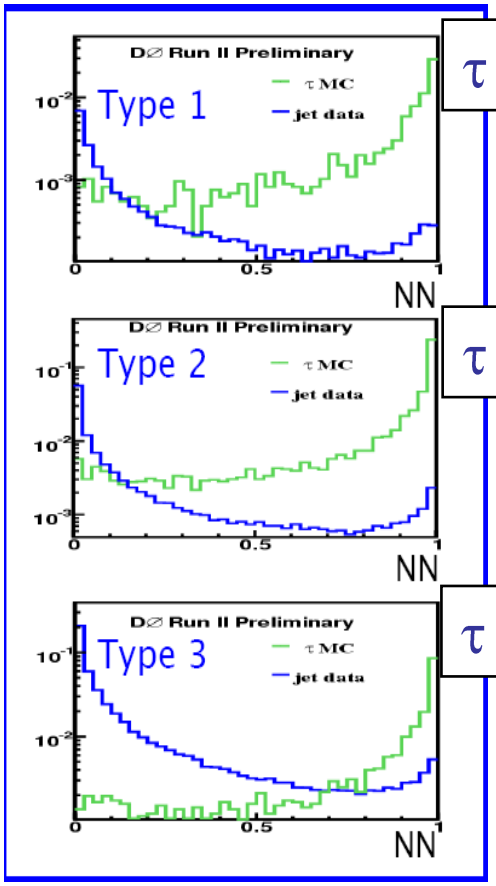
τ_{had}-Identification

- 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



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

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

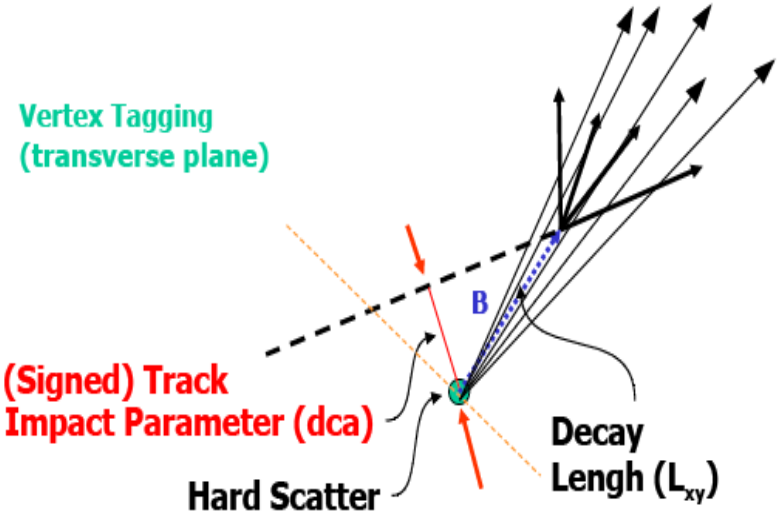
$\tau \rightarrow \pi^{\pm} \pi^{\pm} \pi^{\pm} (\pi^{0}) \upsilon$

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

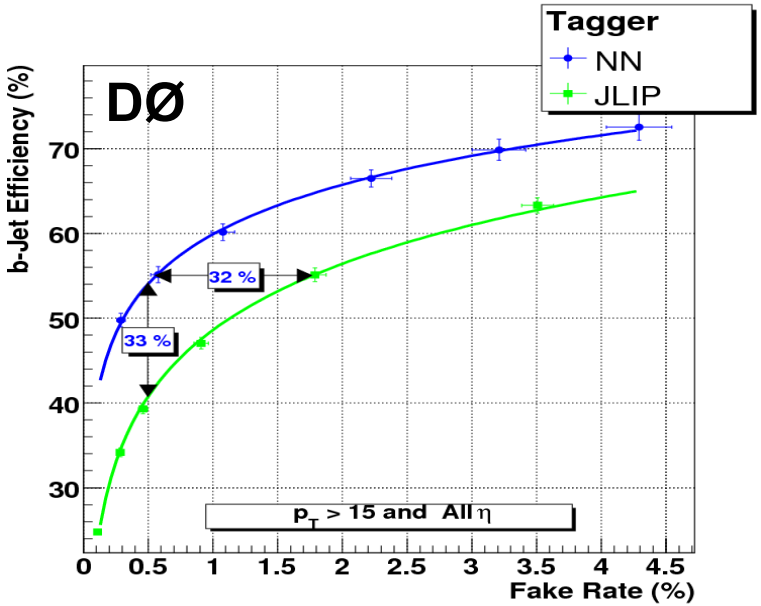
b-jet Identification

- 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**



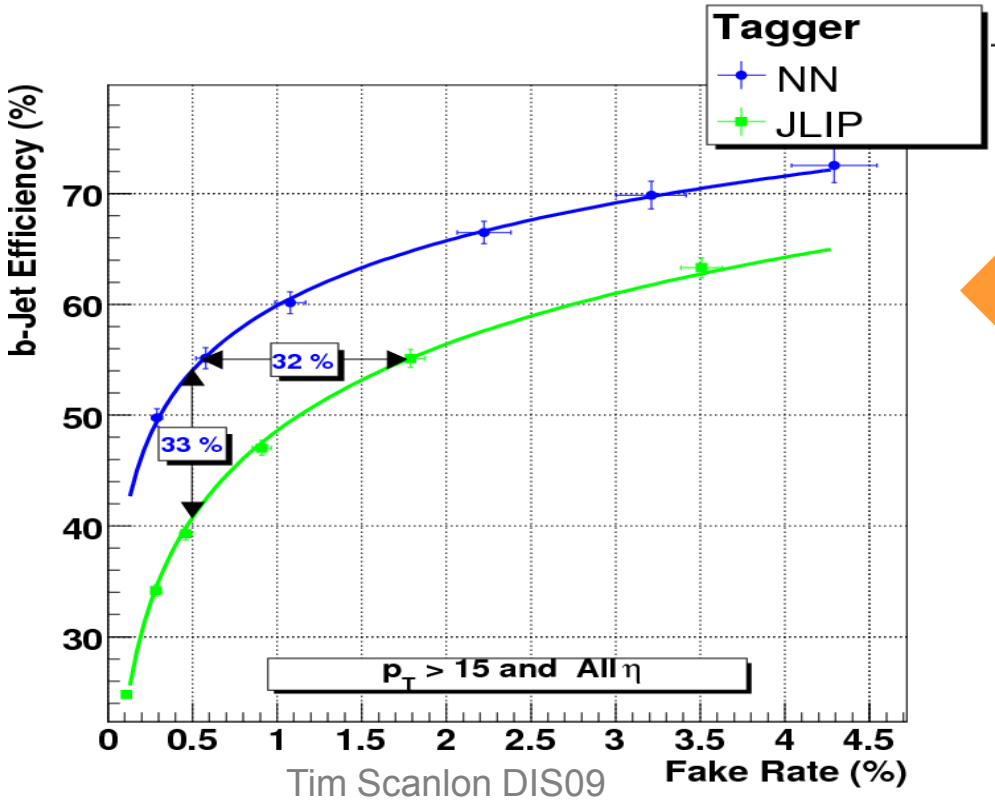
DØ B-tagging

Several mature algorithms used:

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

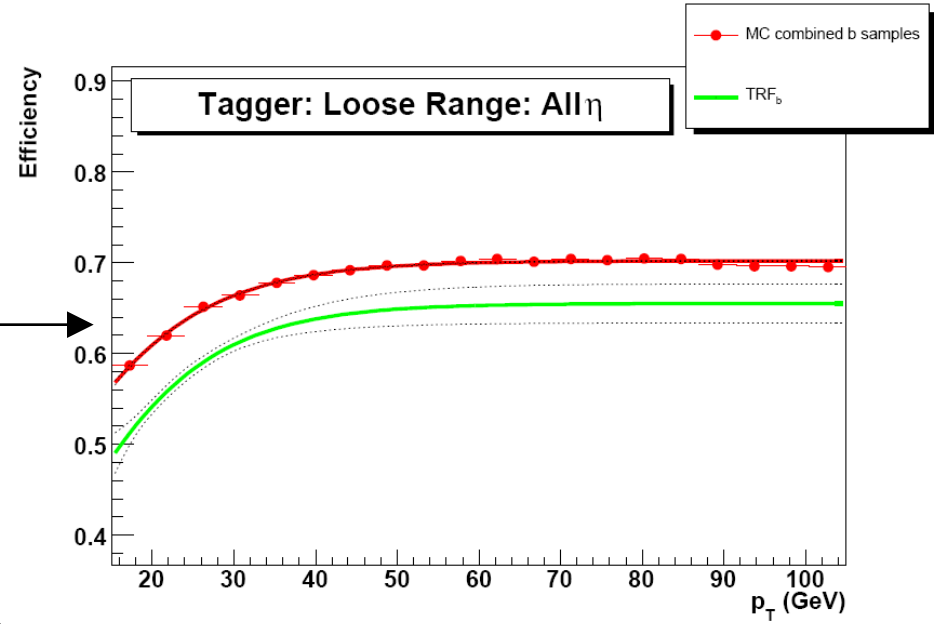
Combine in Neural Network:

- 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

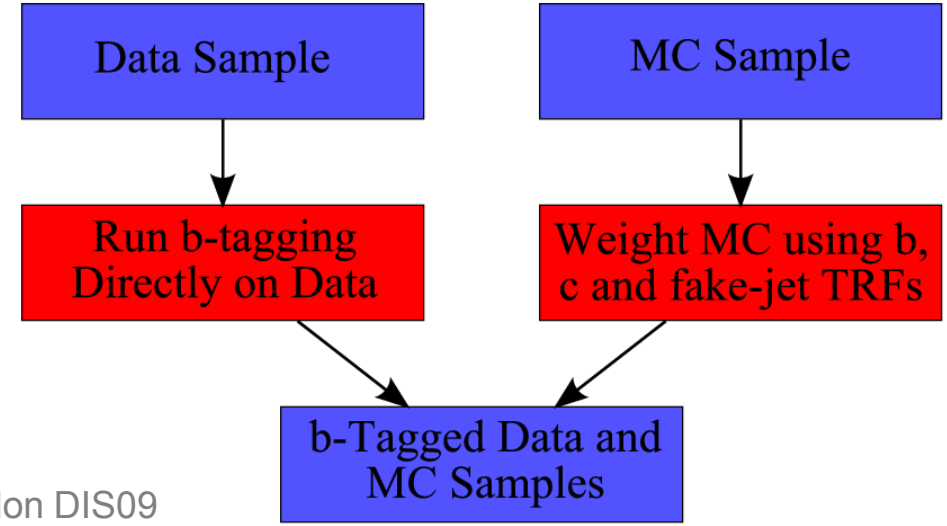


B-tagging – (DØ) Certification

- 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

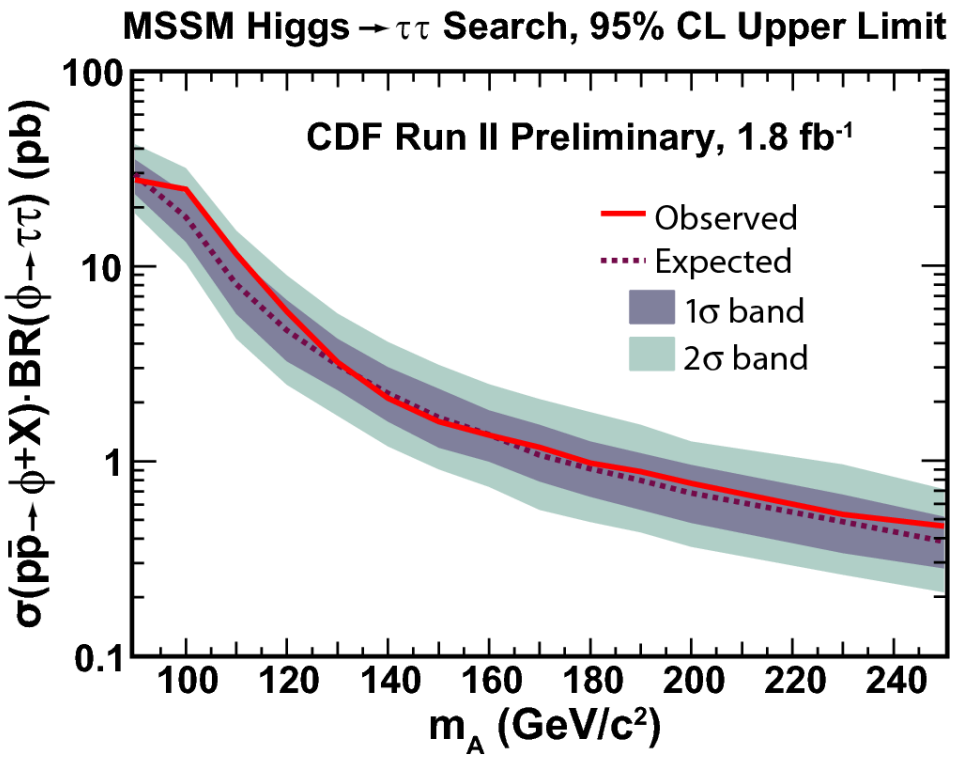


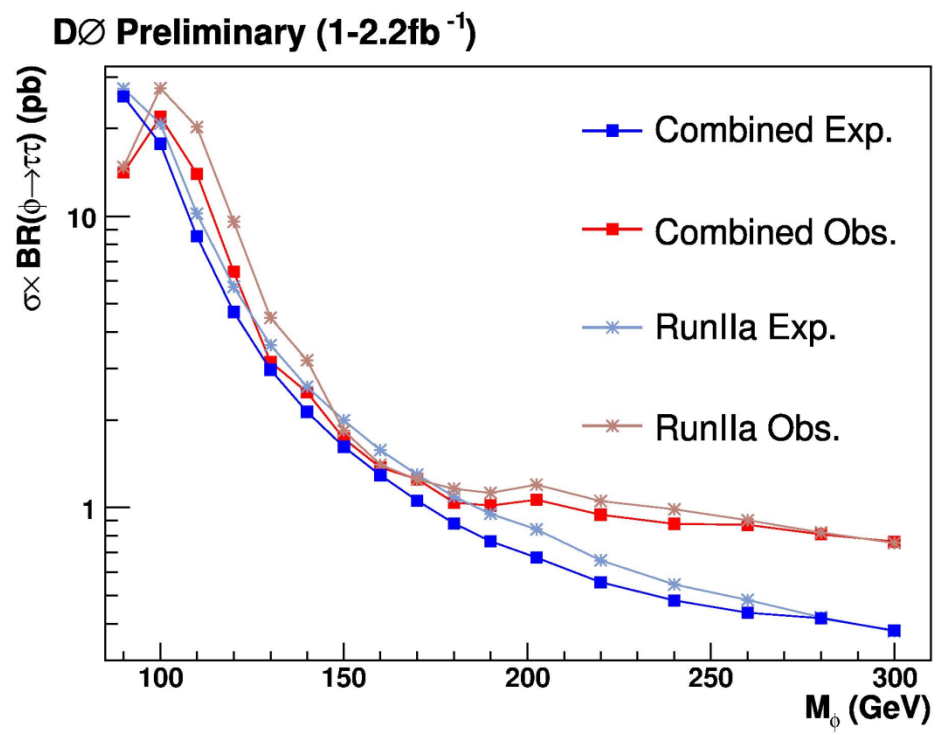
- b and c-efficiencies
  - Measured using a b-enriched data sample
- Fake-rate
  - Measured using QCD data



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

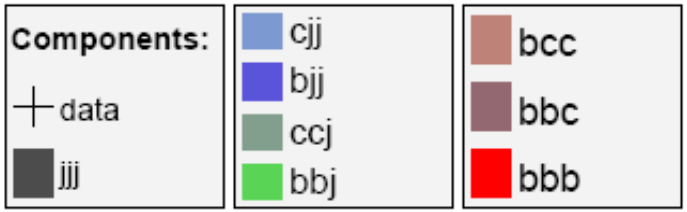
- Set limits
  - σ x Br ($\phi \rightarrow \tau\tau$) @ 95% confidence level (CL)



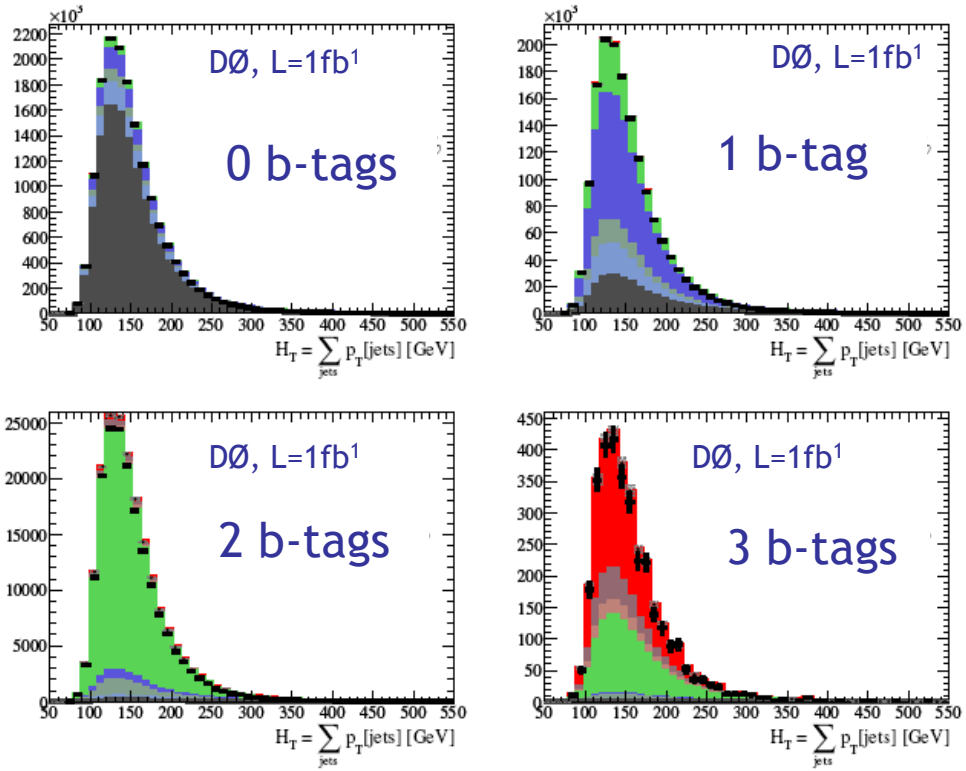


Neutral MSSM Higgs → bb + b[b]

- Background Prediction
  - Large multijet background
  - Theoretical cross sections very large errors



- DØ: Sample Composition
  - Fit MC to data over several b-tagging points



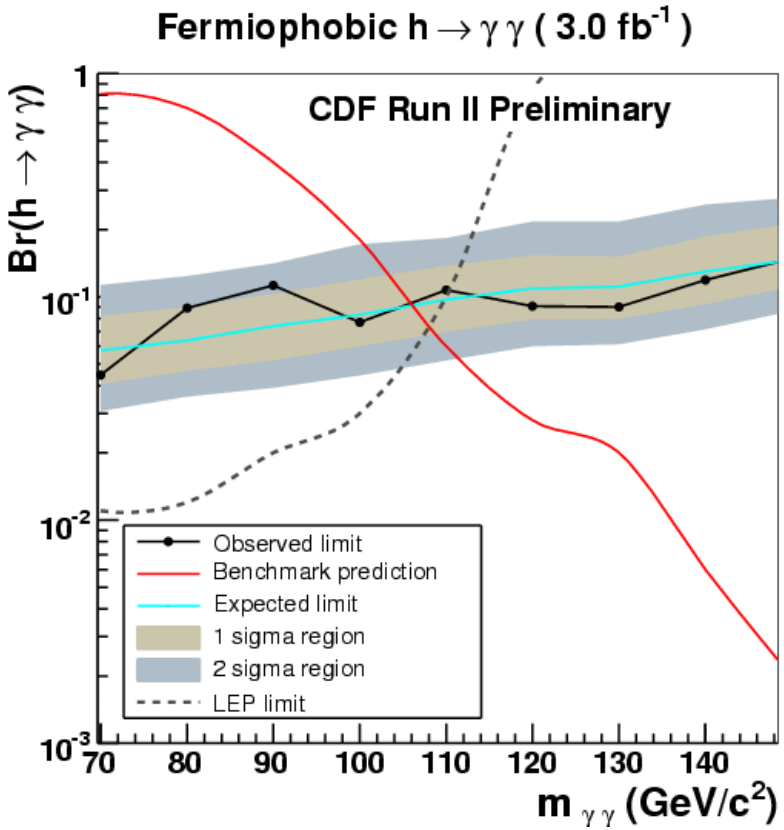
- DØ: Background Shape
  - Use double b-tagged data to predict triple b-tagged background

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

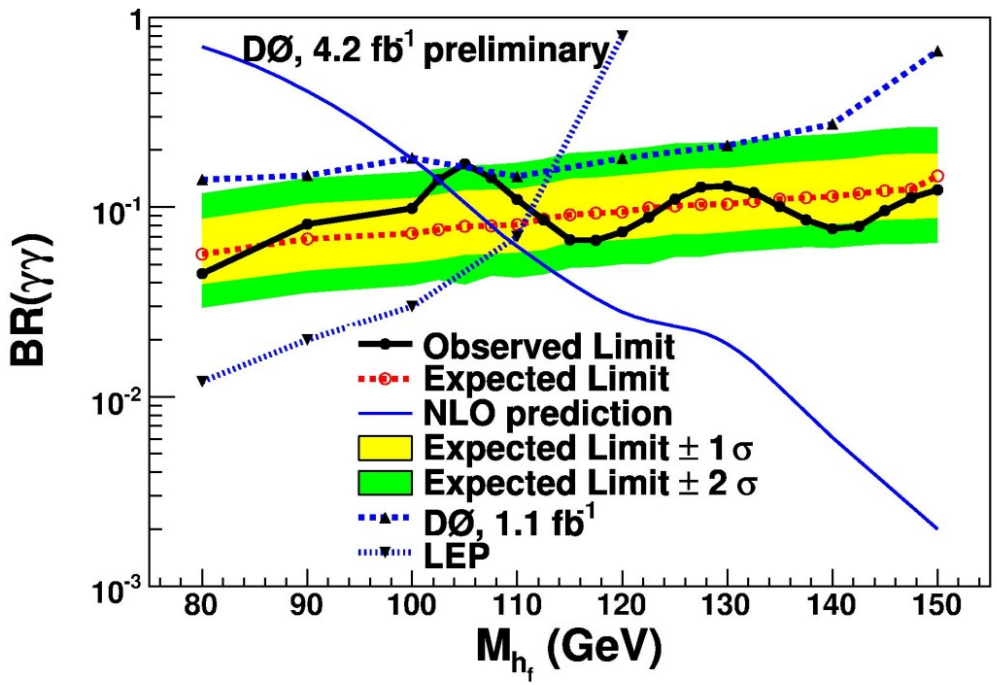
3 b-tag background — MC correction factor — 2 b-tag data

Fermiophobic Higgs → γγ

- 95% CL limits on branching ratio
  - Extend sensitivity into m_{hf} > 130 GeV
    - Not accessible by LEP



Excluded m_{hf} < 106 GeV

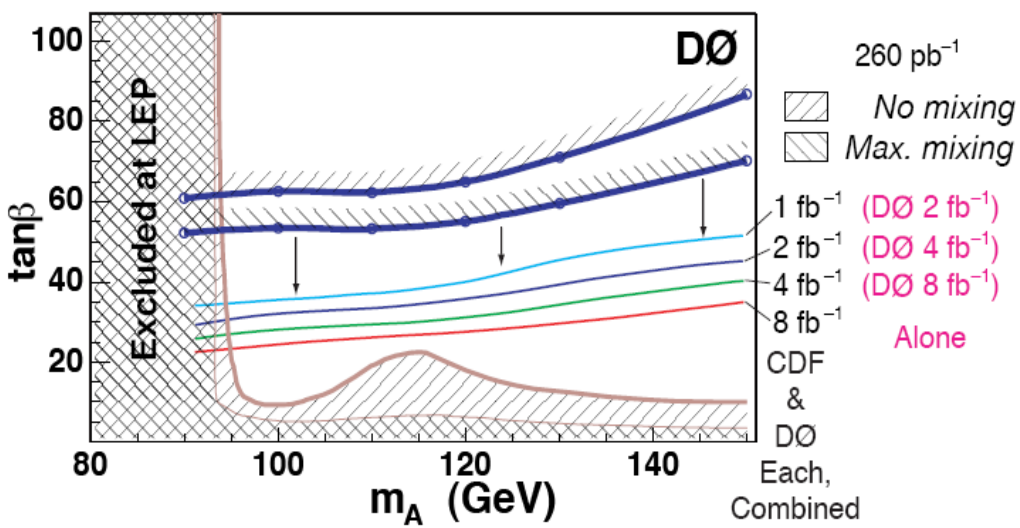
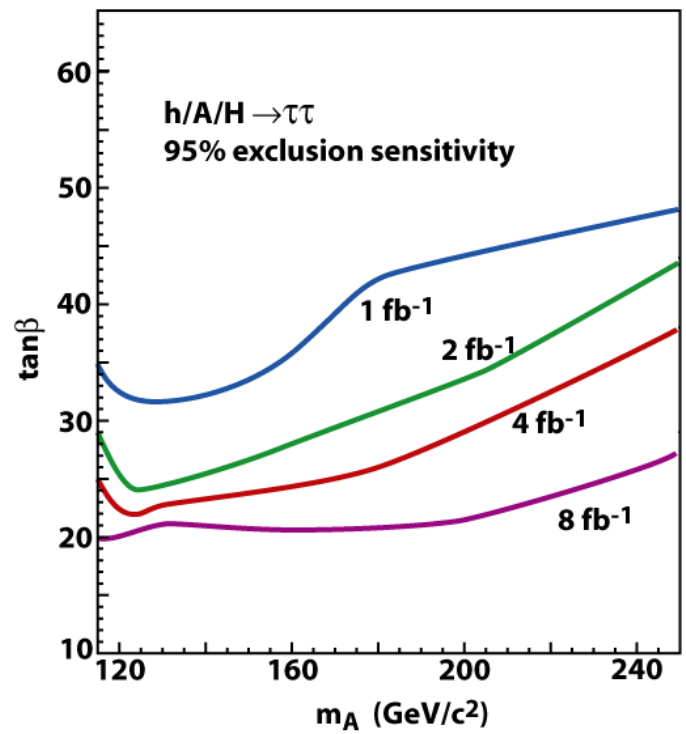


Excluded m_{hf} < 102.5 GeV

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_g	800 GeV	1600 GeV

- Two common benchmarks
  - Max-mixing - Higgs boson mass m_h close to max possible value for a given $\tan\beta$
  - No-mixing - vanishing mixing in stop sector $\rightarrow$ small mass for h

MSSM evolution