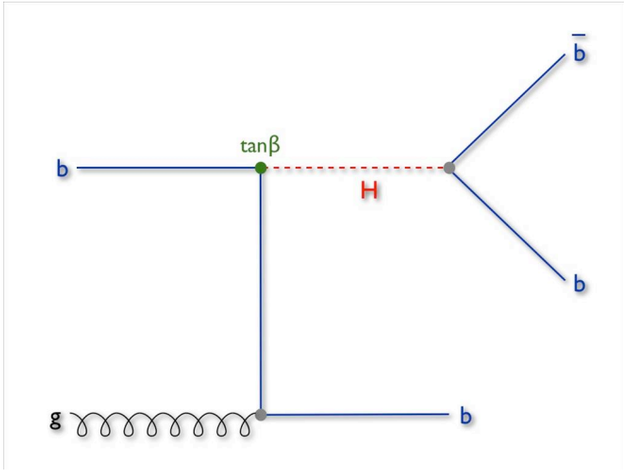
Beyond-the-Standard-Model Searches for Higgs Bosons at the Tevatron



Chris Hays,
Oxford University
on behalf of the CDF and D0 Collaborations

XVIII International Workshop on
Deep Inelastic Scattering and Related Subjects
Florence, Italy
20 April, 2010

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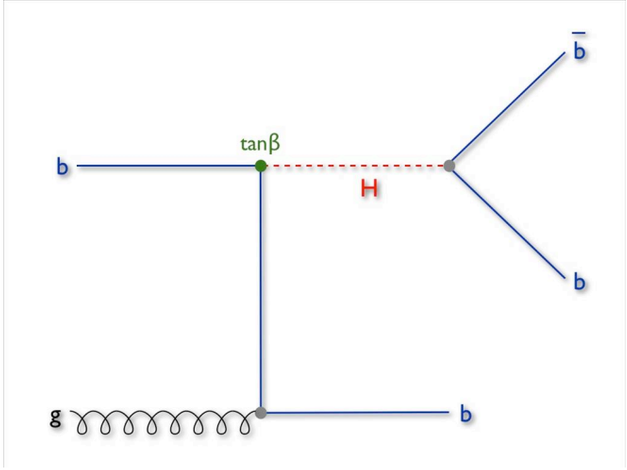

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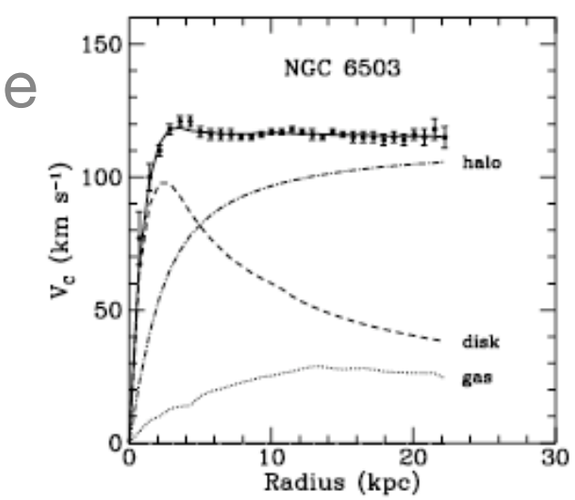
Higgs Bosons Beyond the Standard Model

- Likely to find new physics at the electroweak scale
  - Motivated by e.g. the density of dark matter



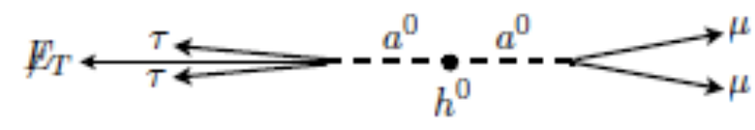
$$\Omega_{DM} \approx \frac{0.2\ \text{pb}}{\sigma_{\text{ann.}}}$$

- Additional Higgs bosons common in new-physics models
  - Two Higgs doublets (supersymmetry), Higgs triplet (LRSM)

$$(\phi^+, \phi^0)$$
$$(\phi^+, \phi^0)$$

$$\vec{\tau} \cdot \vec{\mathrm{H}} = \begin{pmatrix} H^+ & \sqrt{2}\, H^{++} \\ \sqrt{2}\, H^0 & -H^+ \end{pmatrix}$$

- Higgs properties can change significantly in the context of new physics
  - New decay modes



  - Modified couplings or branching ratios to fermions and/or gauge bosons

Higgs Bosons in Minimal Supersymmetry

- Eight degrees of freedom in Higgs supermultiplet
  - Z^0_L, $W^\pm_L$, H^0, $H^\pm$, h^0, A^0: requires two complex Higgs doublets (H_u and H_d)

- Vacuum expectation values of H_u and H_d give particles their masses
  - $m_u = \lambda_u v_u$; $m_d = -\lambda_d v_d$
  - Physical fields are rotations of H_u and H_d:

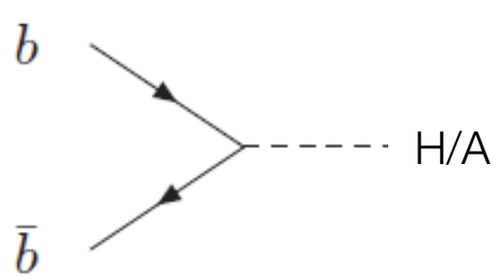
$$\begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix} = \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{\sqrt{2}} R_\alpha \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} + \frac{i}{\sqrt{2}} R_{\beta_0} \begin{pmatrix} G^0 \\ A^0 \end{pmatrix}$$

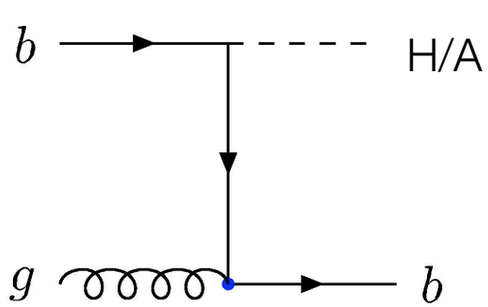
$$R_\alpha = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}, \quad R_{\beta_0} = \begin{pmatrix} \sin\beta_0 & \cos\beta_0 \\ -\cos\beta_0 & \sin\beta_0 \end{pmatrix}$$

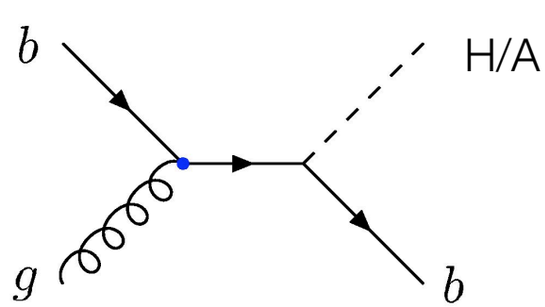
  - $\tan\beta = v_u / v_d$
    - $\lambda_t \sim 1$; if $\lambda_b \sim 1$ then $\tan\beta \sim 40$

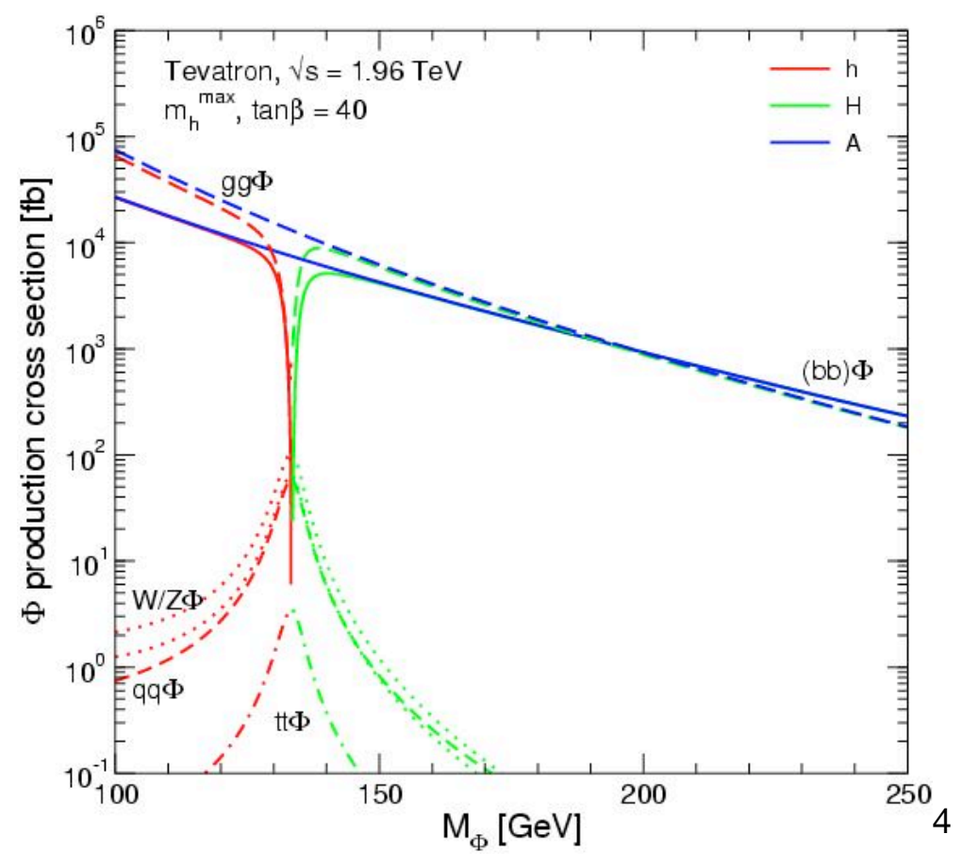
Higgs Bosons at High tanβ

- One Higgs boson has SM-like cross sections, possibly modified BRs
- New neutral Higgs bosons have similar masses ($m_A \sim m_H$), modified couplings
  - $\lambda_t \sim \lambda_t^{SM} \cot\beta$; $\lambda_b \sim \lambda_b^{SM} \tan\beta$
- Large $b\bar{b} \rightarrow H/A$ production cross section at the Tevatron for high tanβ
  - H/A decay almost exclusively to $b\bar{b}$ and $\tau\bar{\tau}$



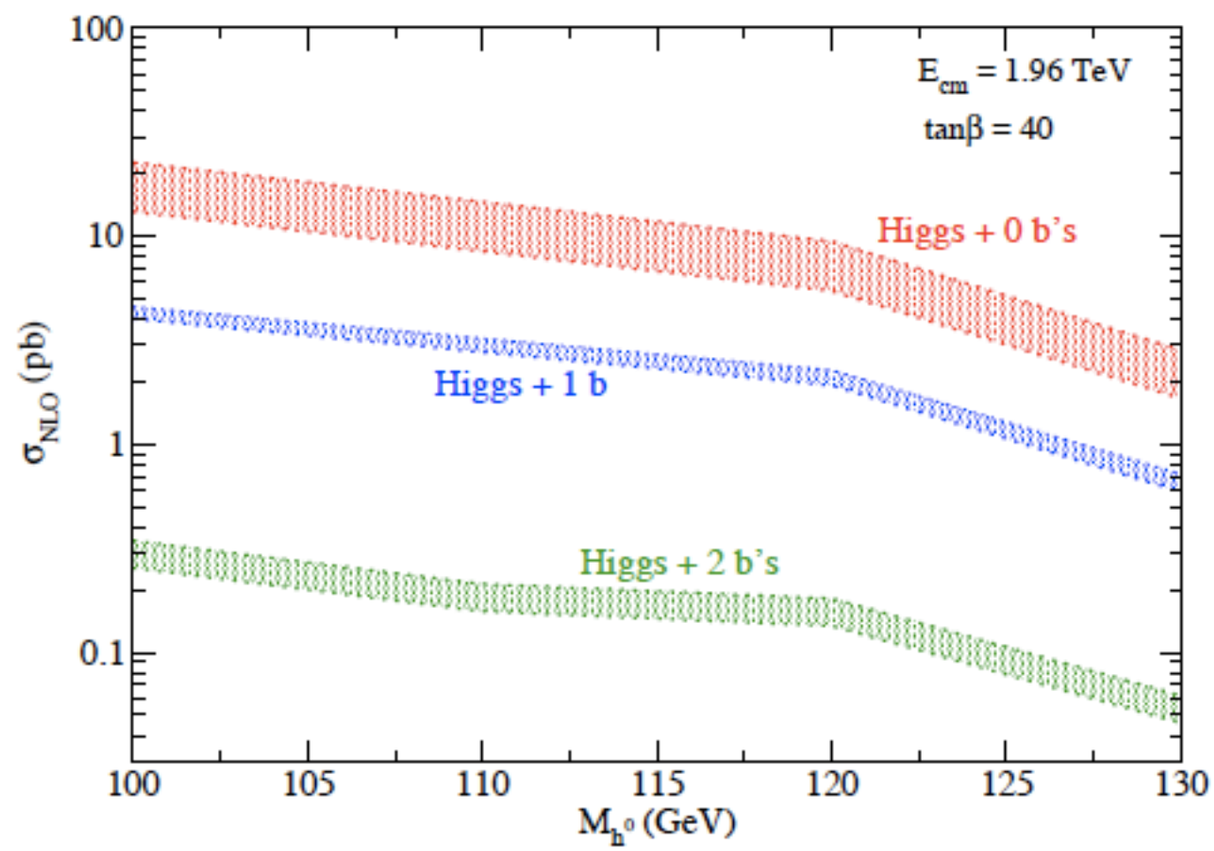






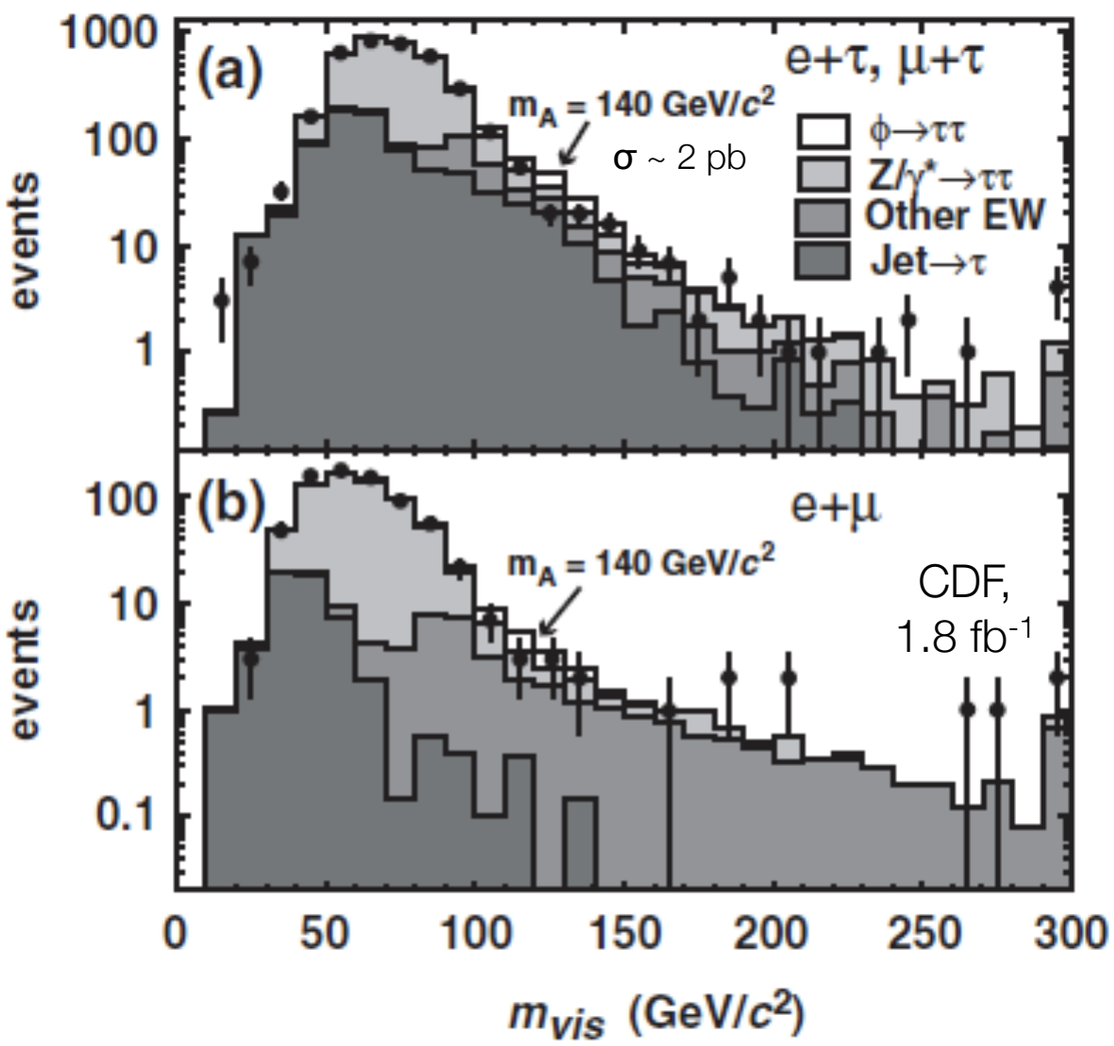
Higgs Boson Search Strategies at High tanβ

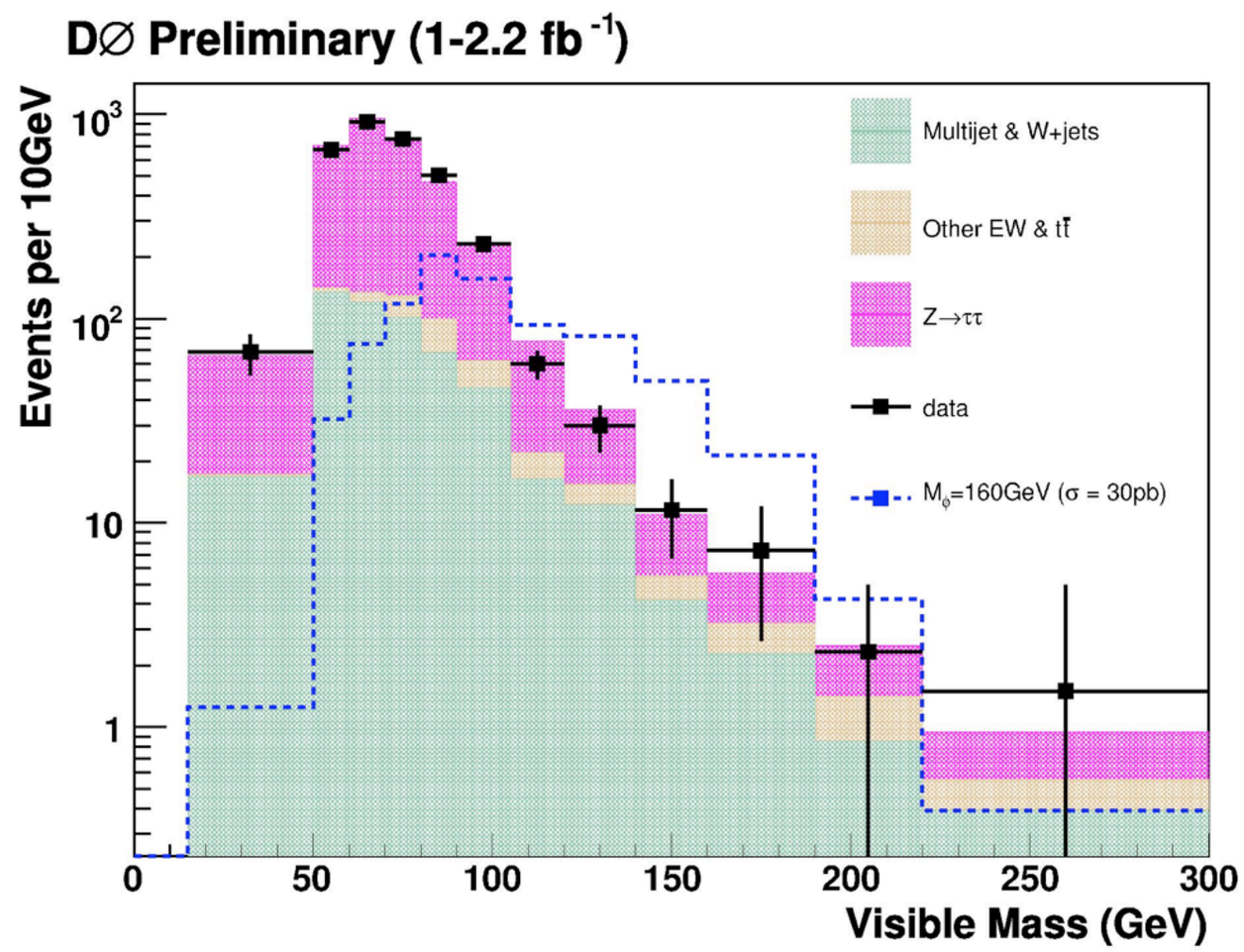
- Production cross section largest with no associated b-quarks
  - Negligible compared to QCD $b\bar{b}$ production, not to Drell-Yan ττ production
- Backgrounds significantly suppressed in production of Higgs + 1 b-quark
- ∴ search in the following modes:
  - H/A → ττ (+ b)
  - H/A → bb + b(b)



CDF & D0 Combined Search for H/A → ττ

- CDF and D0 have searched for H/A in $\tau_e\tau_{had}$, $\tau_\mu\tau_{had}$, and $\tau_e\tau_\mu$ final states
  - Both use visible mass to discriminate Higgs from Drell-Yan production





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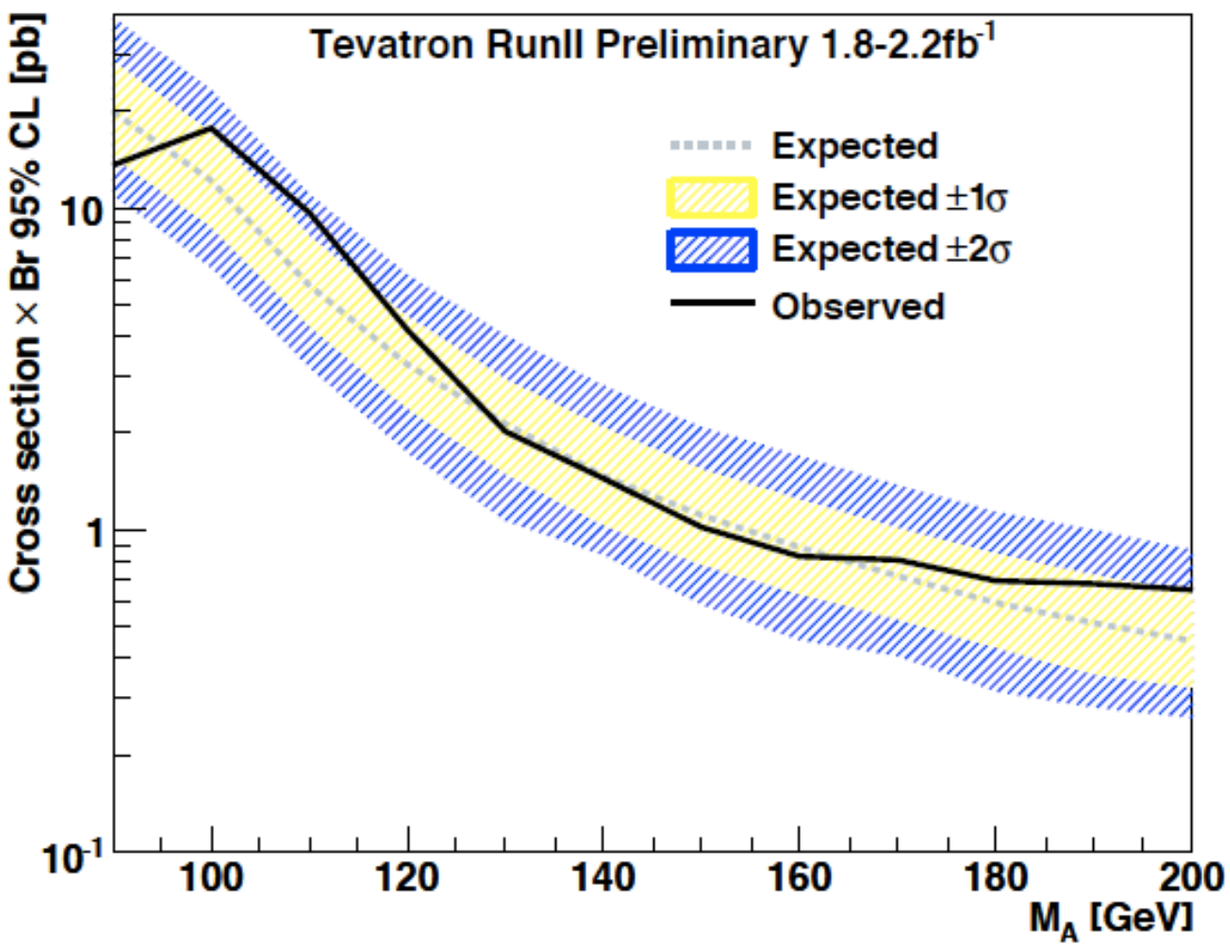
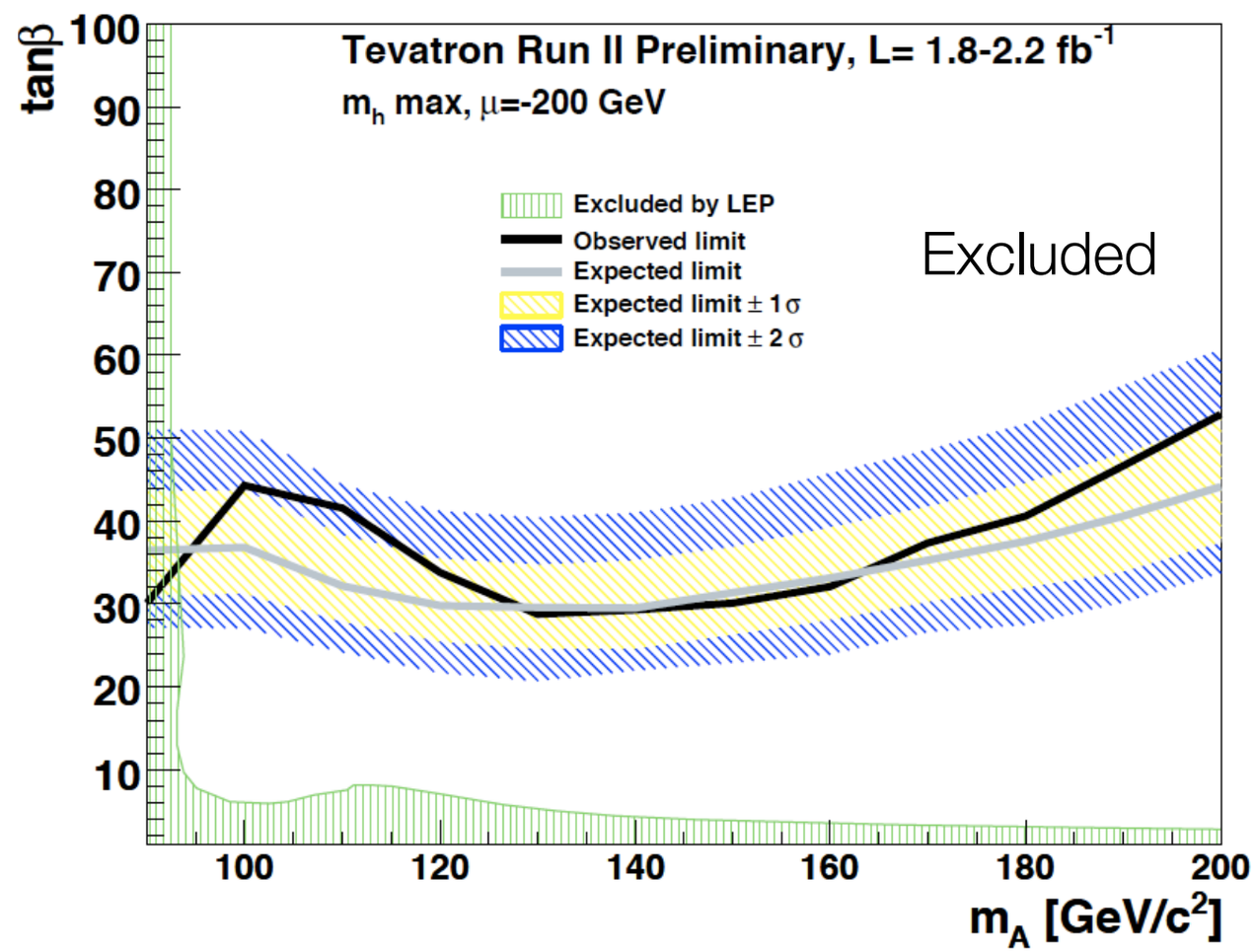
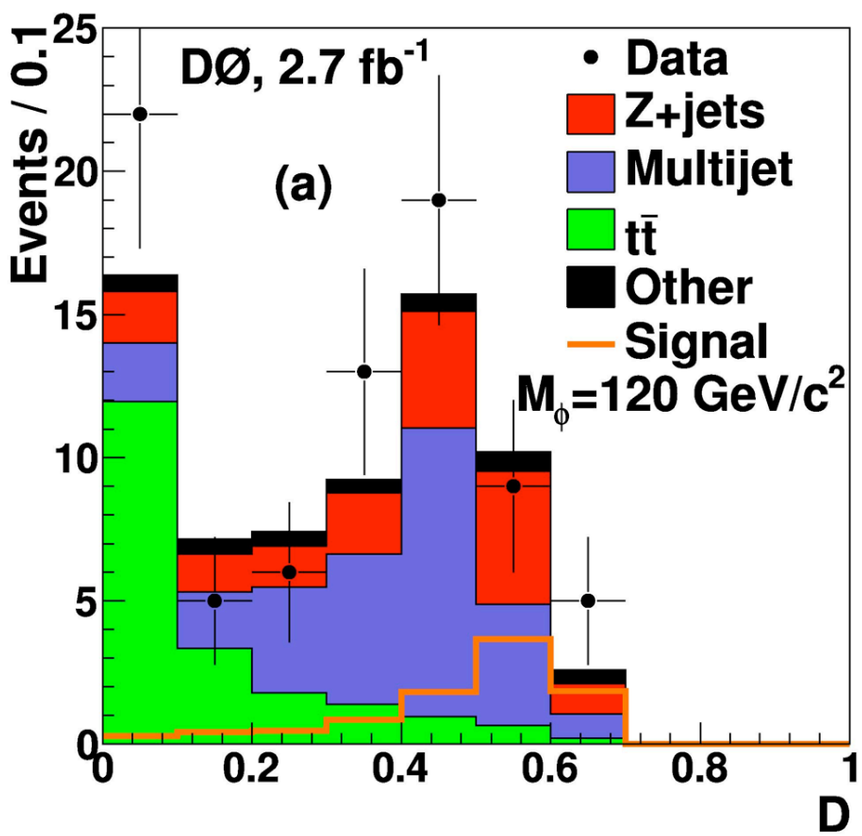




D0 Search for b(H/A → $\tau_\mu \tau_{had}$)

- Requirement of b-quark suppresses Drell-Yan
  - Improves sensitivity near Z boson peak
  - Discriminant based on NN ($t\bar{t}$ rejection) and likelihood (multijet rejection)

	Pre-tag	b-tagged	Final
$t\bar{t}$	66.0 ± 1.3	39.6 ± 0.8	20.3 ± 0.6
Multijet	549 ± 26	38.5 ± 2.3	28.1 ± 1.9
$Z(\rightarrow \tau\tau) + \text{jets}$	1241 ± 8	18.8 ± 0.3	16.3 ± 0.3
Other Bkg	267 ± 6	5.1 ± 0.1	4.1 ± 0.1
Total Bkg	2123 ± 28	102 ± 2.4	68.7 ± 2.0
Data	2077	112	79
Signal	26.5 ± 0.3	8.8 ± 0.1	8.4 ± 0.1



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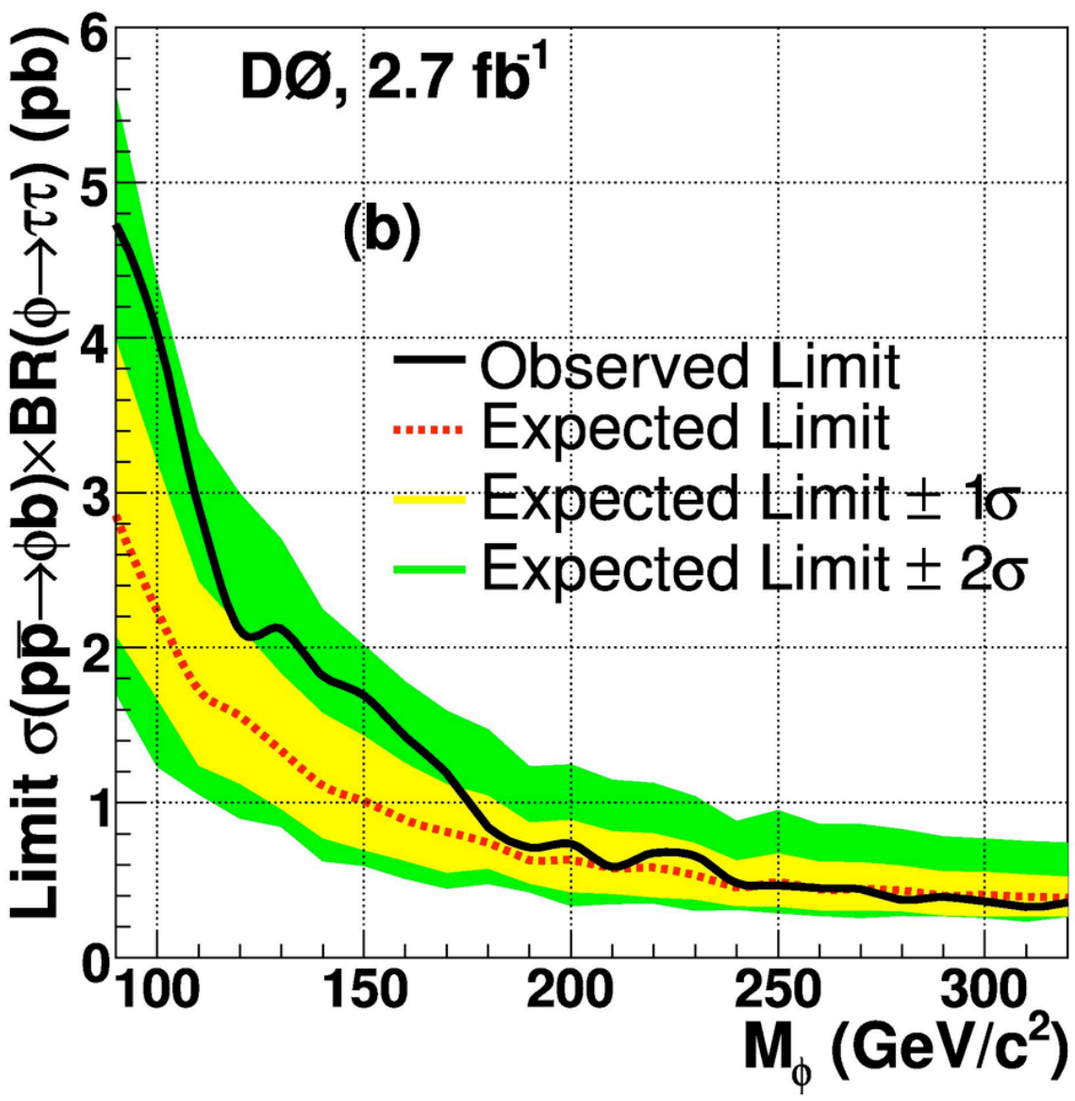
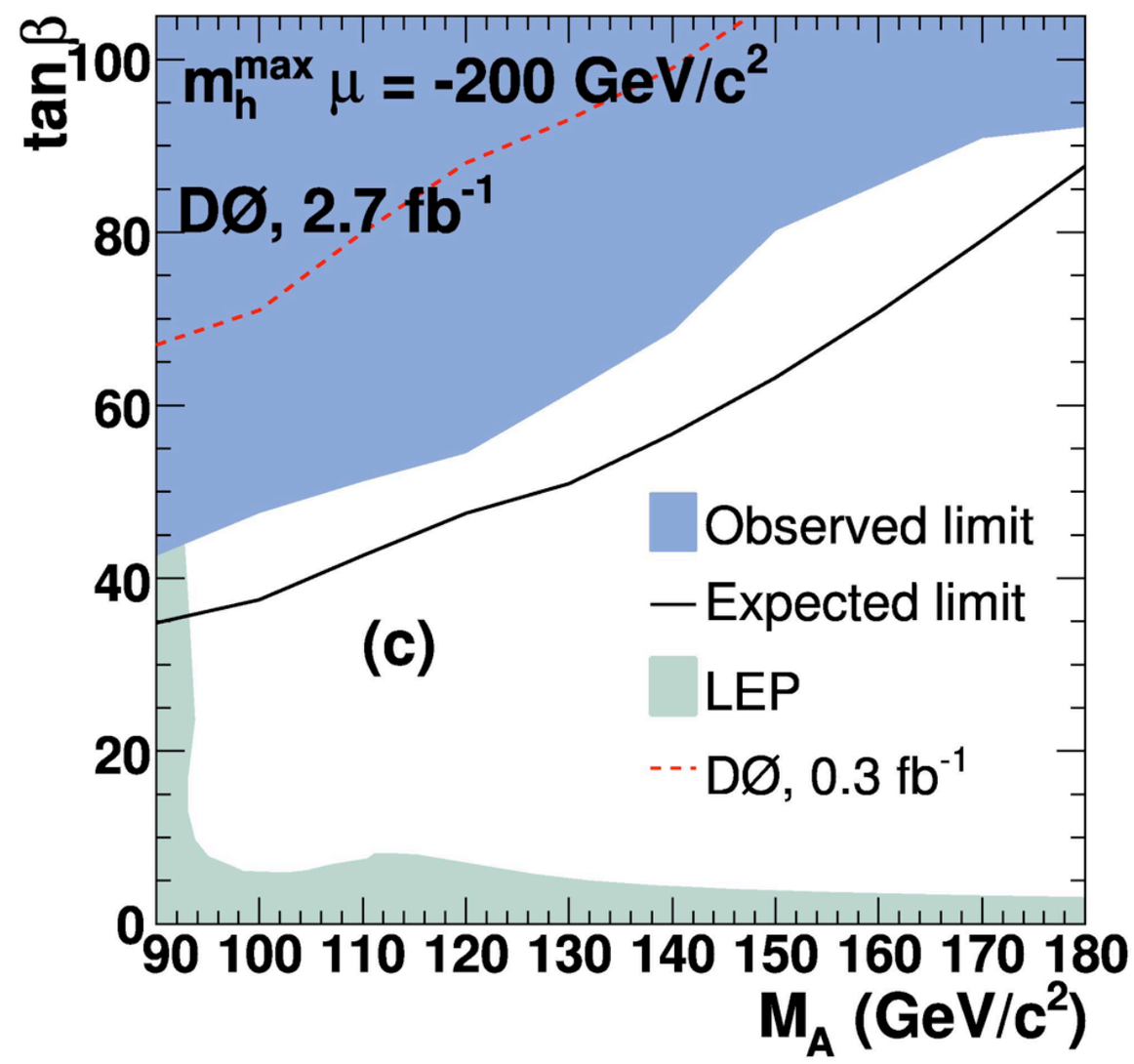
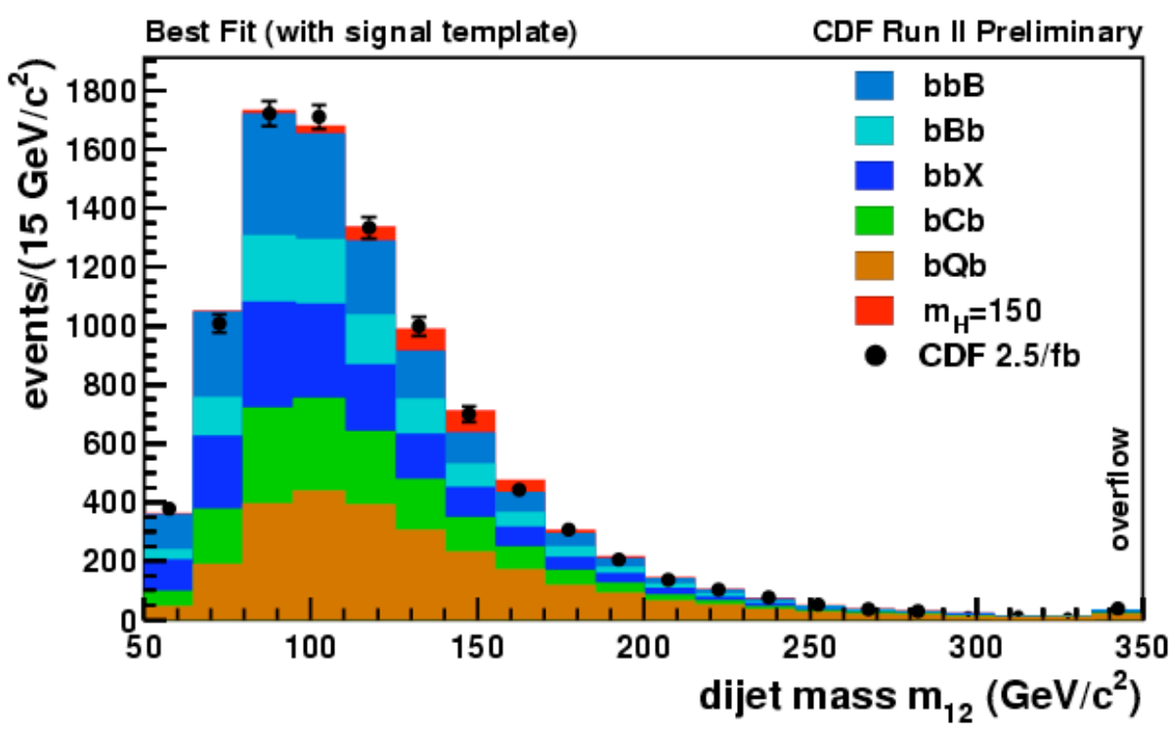
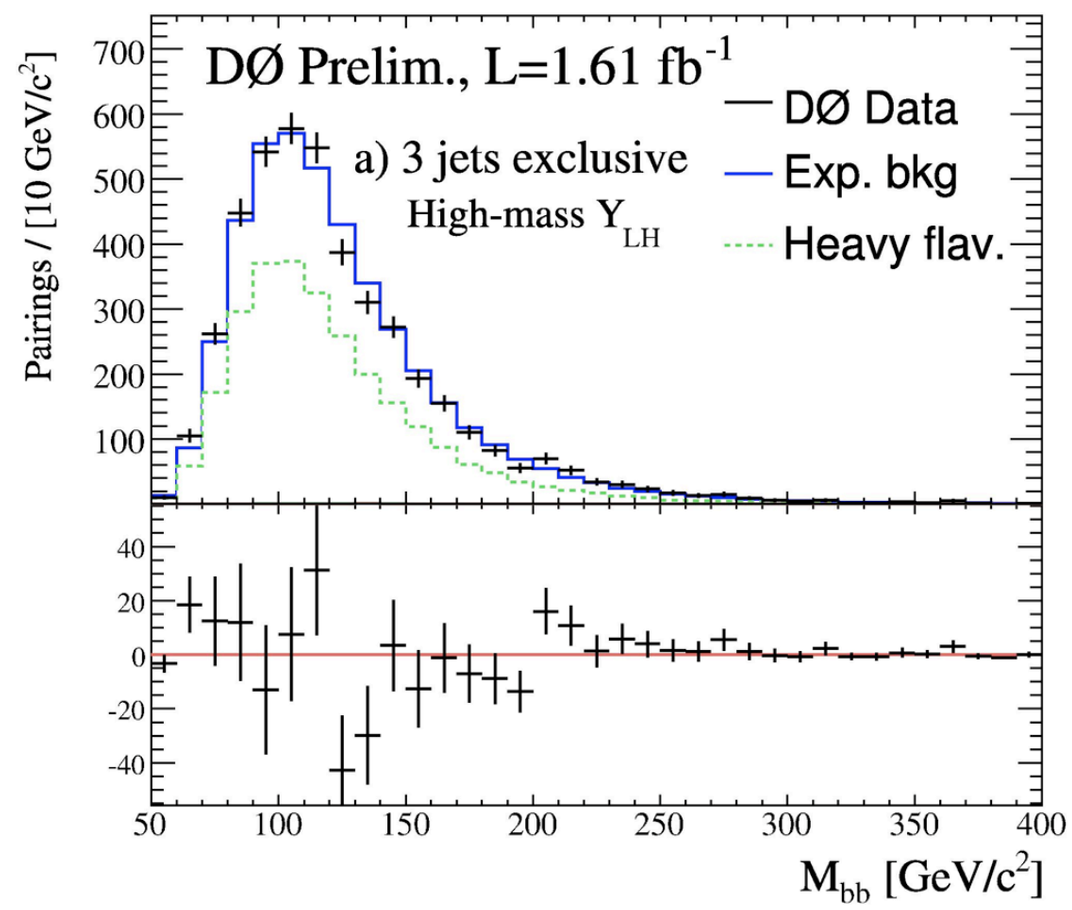




CDF & D0 Searches for b(b)(H/A → bb)

- Backgrounds fit using templates of individual components
  - Three b-quark jets and combinations of b-quark and light-quark jets
- D0 optimizes with likelihood of 6 variables; CDF fits $b\bar{b}$ mass





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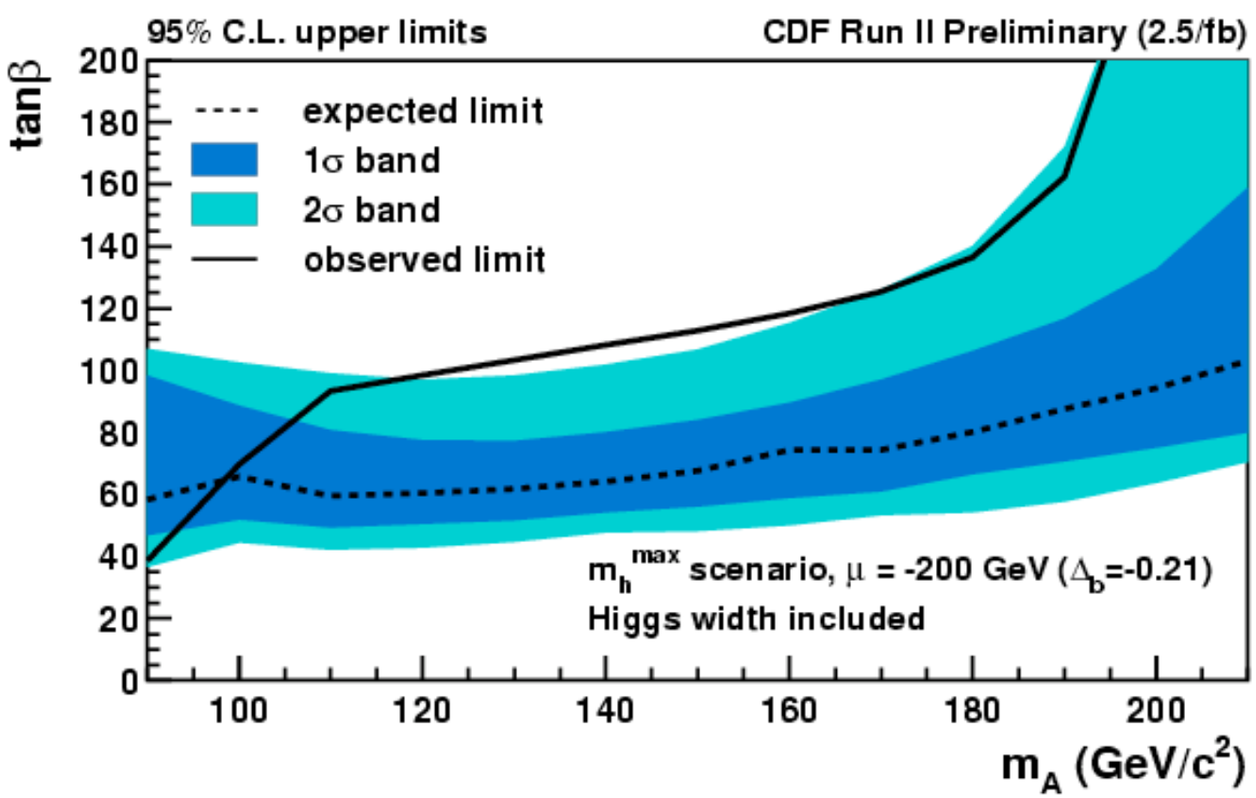
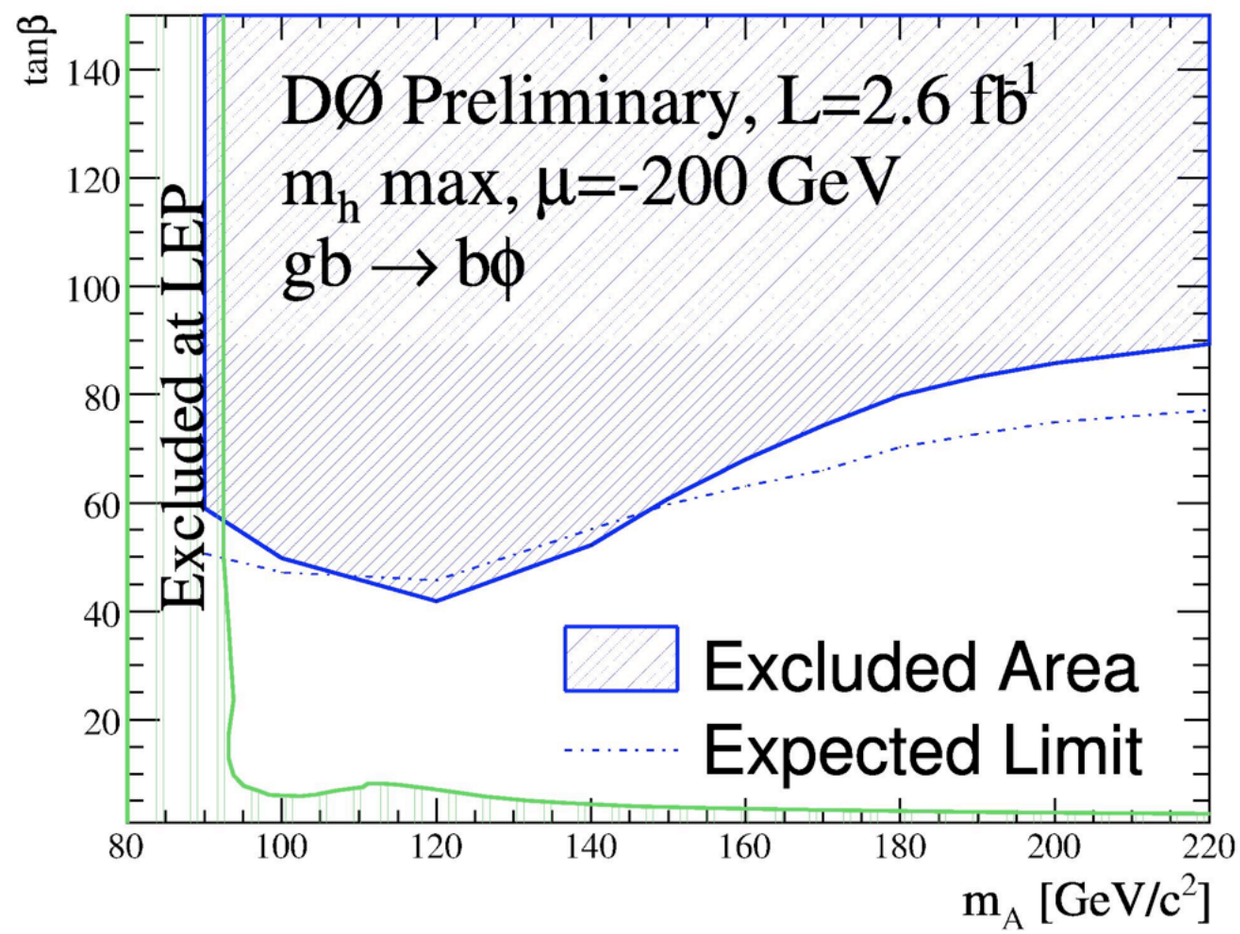
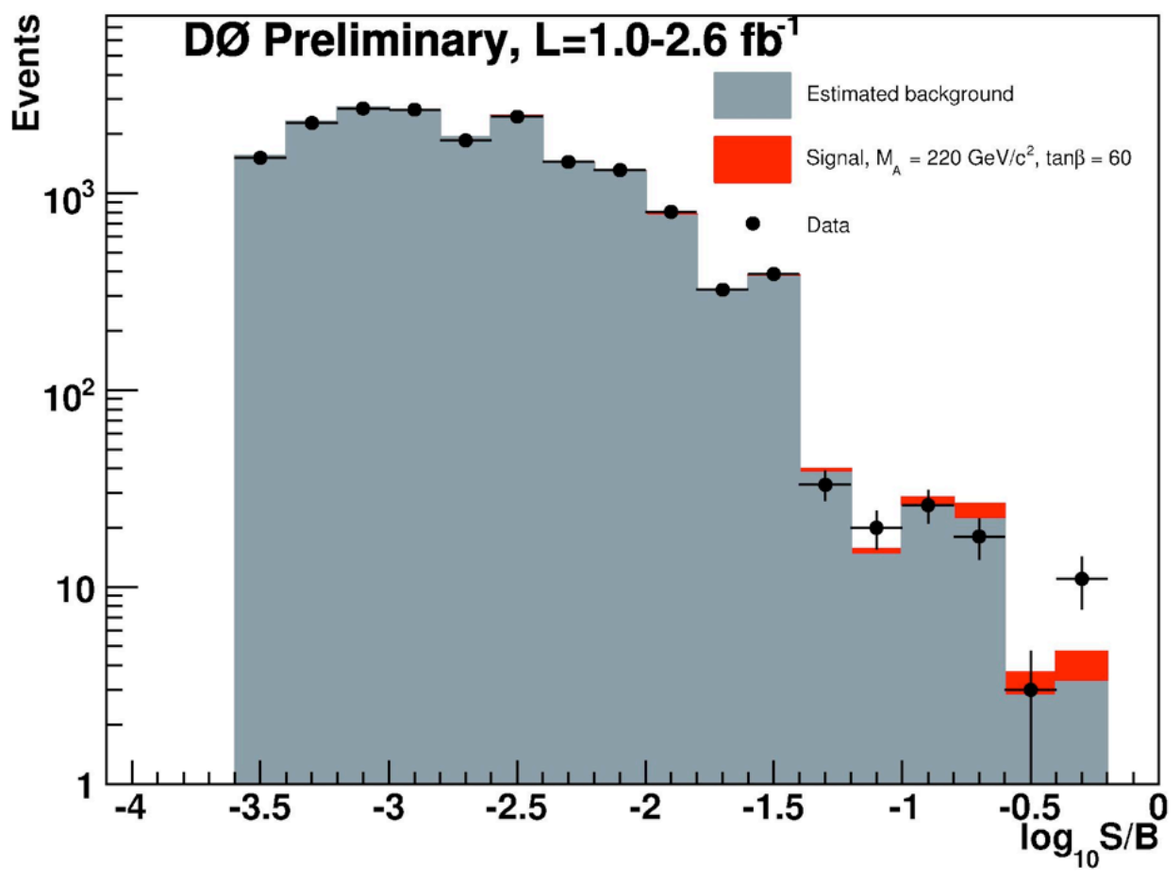
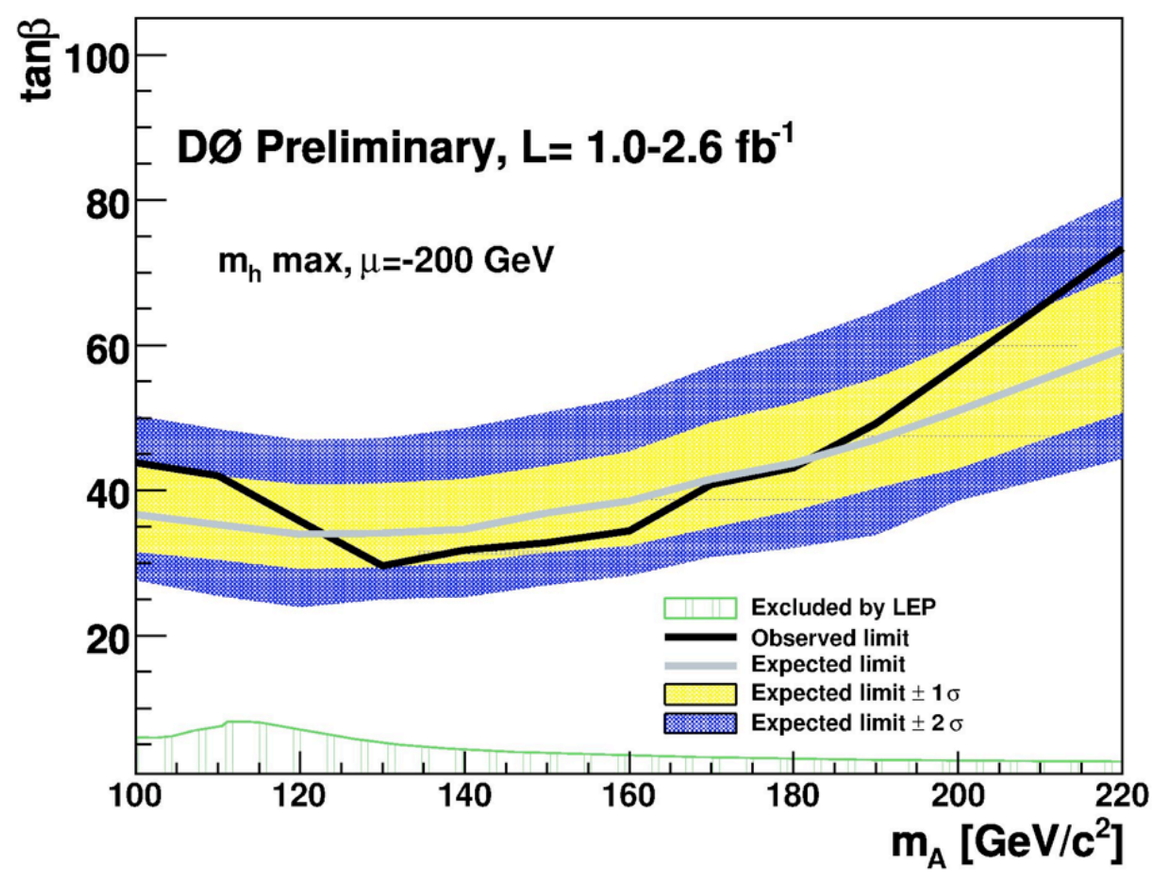




D0 Combined Search for H/A

- Includes ττ, ττb, bbb, and bbbb final states
- Combine 19 channels defined by tau decay and jet multiplicity

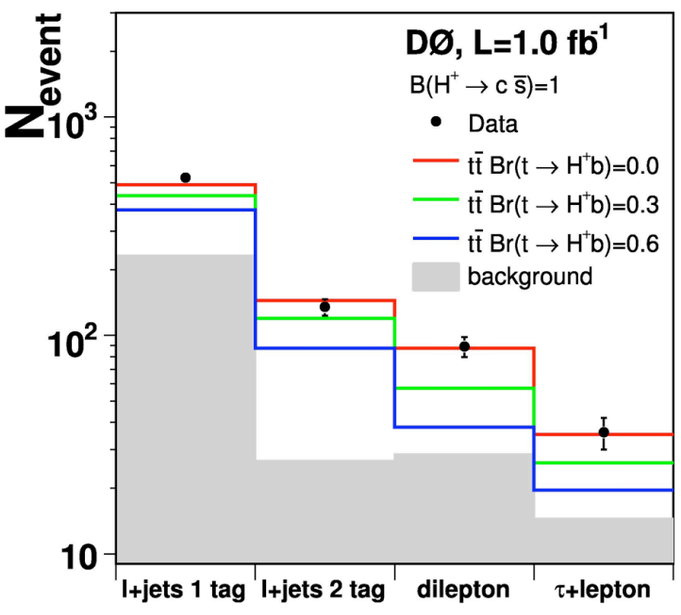


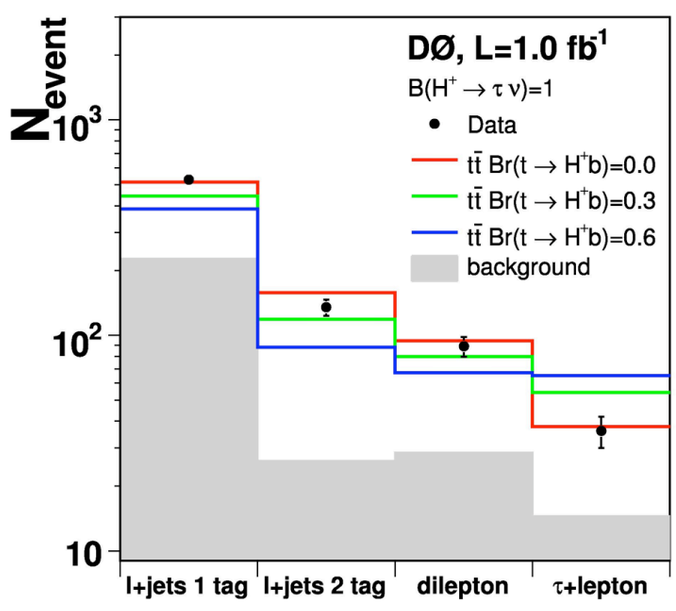


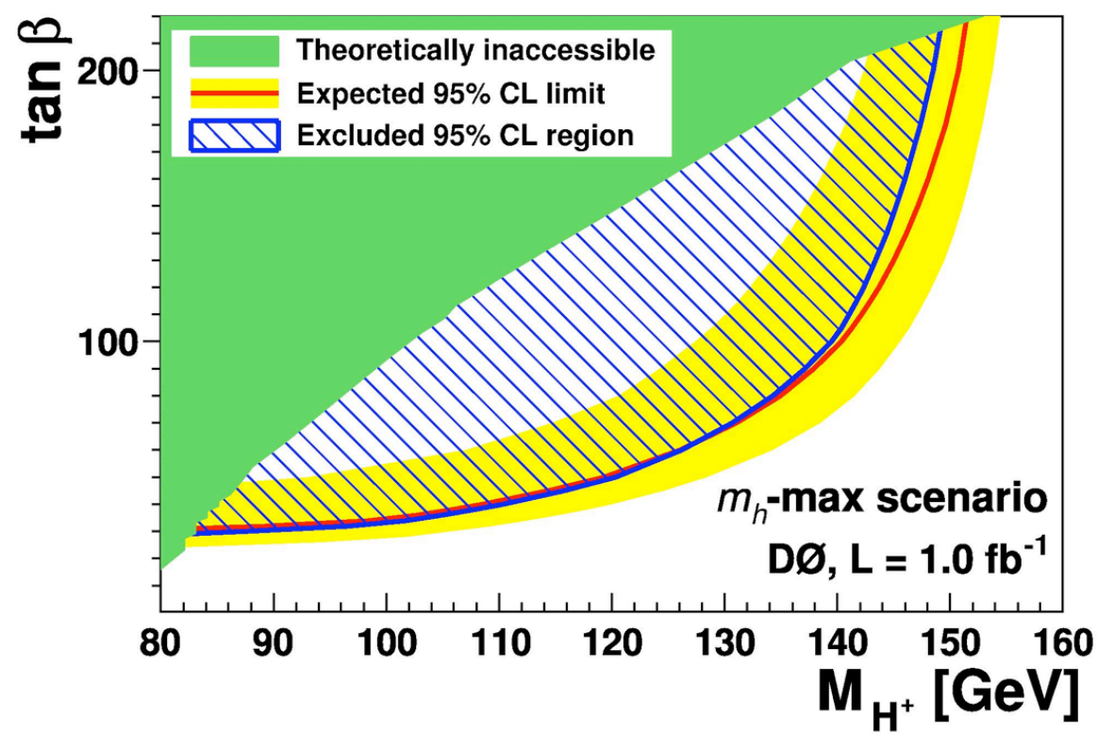
- Expect additional sensitivity when combining with CDF & including SM channels

CDF & D0 Searches for Charged Higgs

- If $m_{H\pm} < m_t + m_b$, top can decay to charged Higgs and a b-quark
- Charged Higgs can then decay to cs or τν
- Affects relative ratio of $t\bar{t}$ decays to e/μ + jets, eμ + jets, and (e/μ)τ + jets







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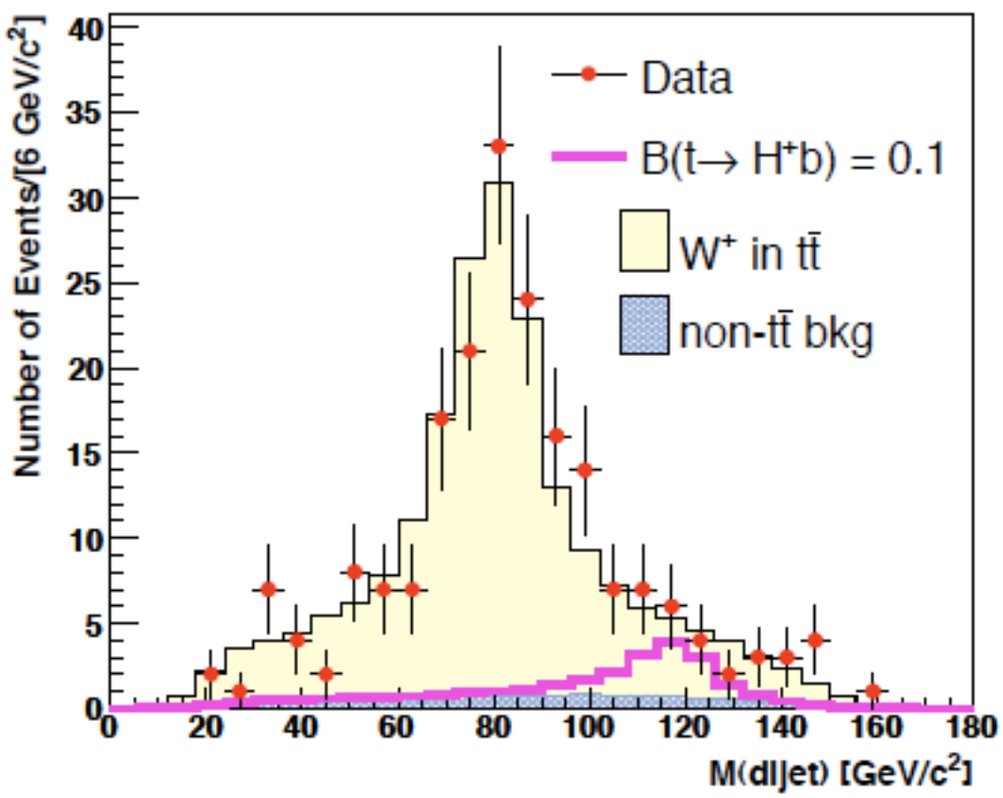
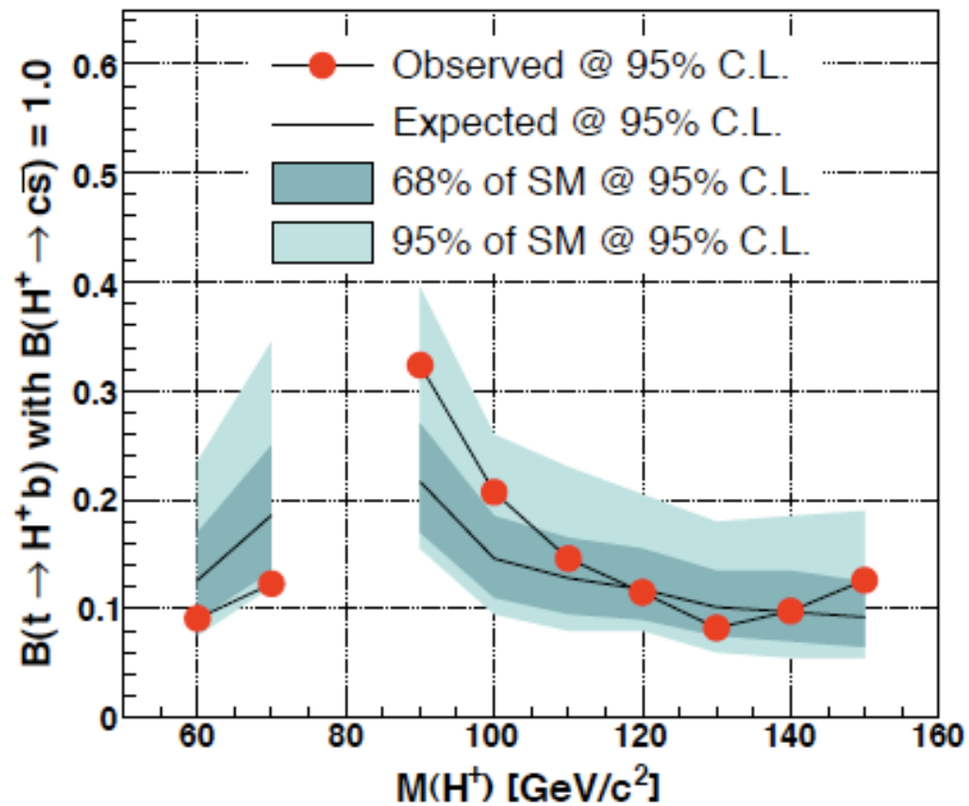




- Can also search for resonance in dijet mass spectrum from top decay

Higgs Bosons in Next-to-Minimal Supersymmetry

- Minimal supersymmetry Higgs mass terms have two components
  - $m_H^2 = m_{HSB}^2 + |\mu|^2$

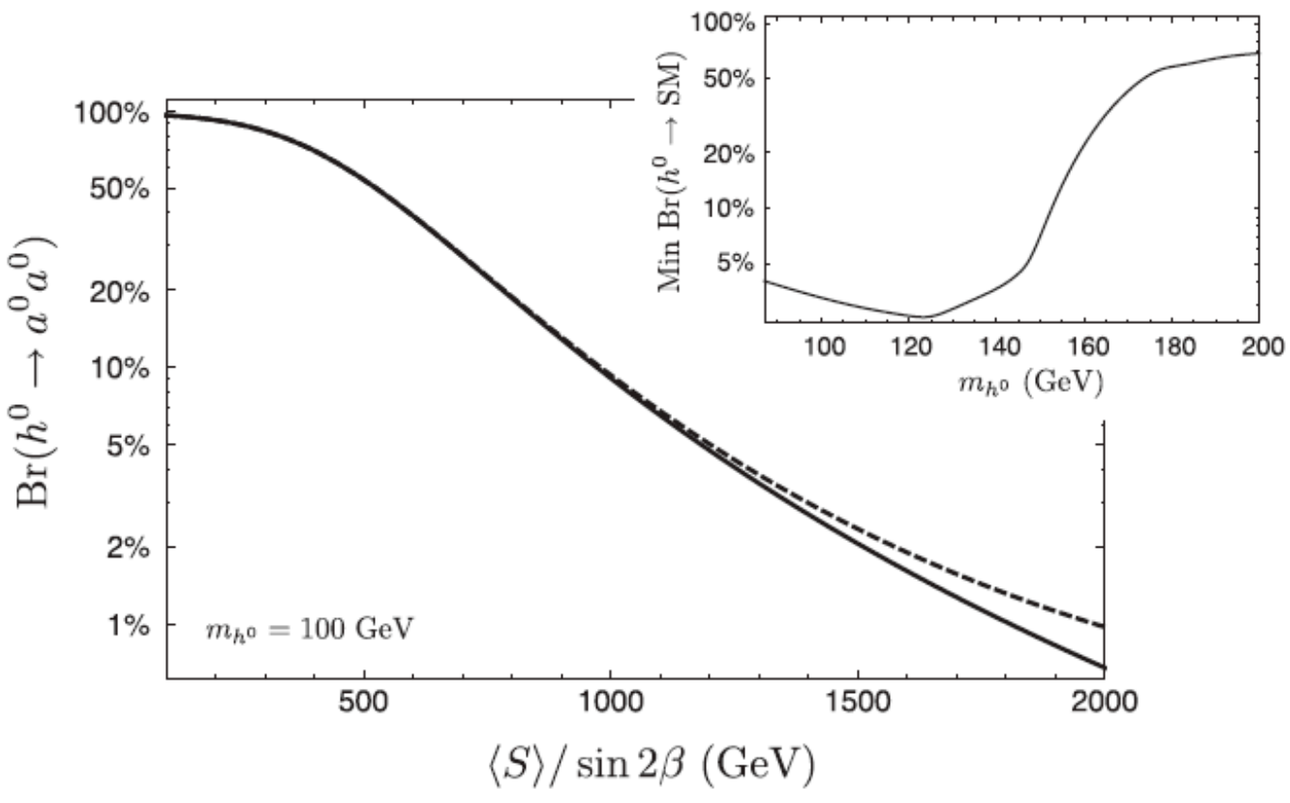
supersymmetry breaking scale

fundamental scale

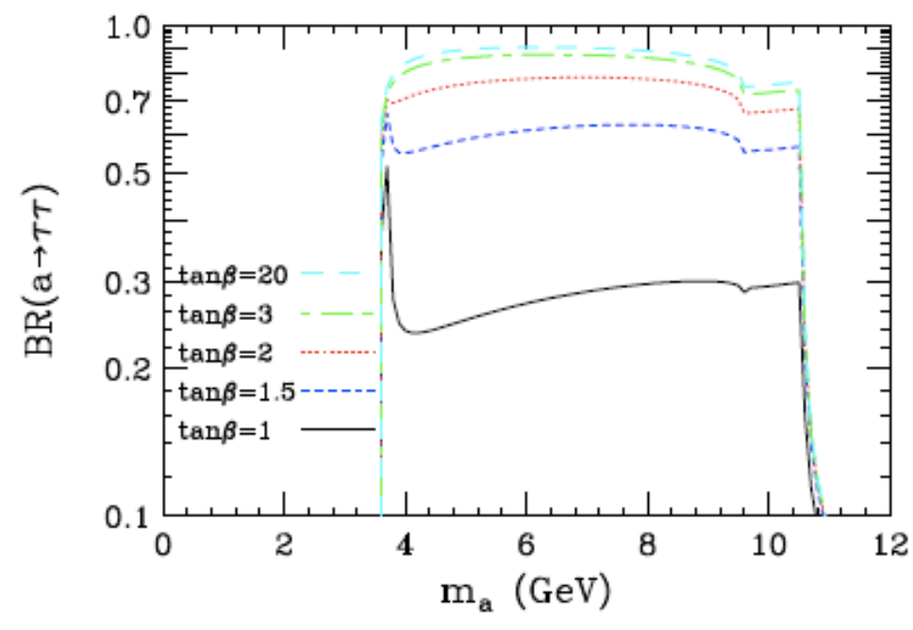
  - Why are the Higgs masses not at the Planck scale?
    - “mu problem”
  - One explanation: due to an underlying symmetry and an SM singlet S
    - Leads to additional Higgs terms in superpotential
      - $W_S = 1/2\mu_S S^2 + 1/6\kappa_S S^3 + \lambda_S S H_d H_u$
      - Then $\mu = \lambda_S \langle S \rangle$

Higgs Bosons in Next-to-Minimal Supersymmetry

- Additional singlet produces new Higgs bosons, a^0, h_S^0, and $h^\pm$
  - New decay modes for the Higgs

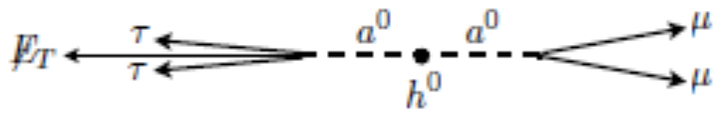


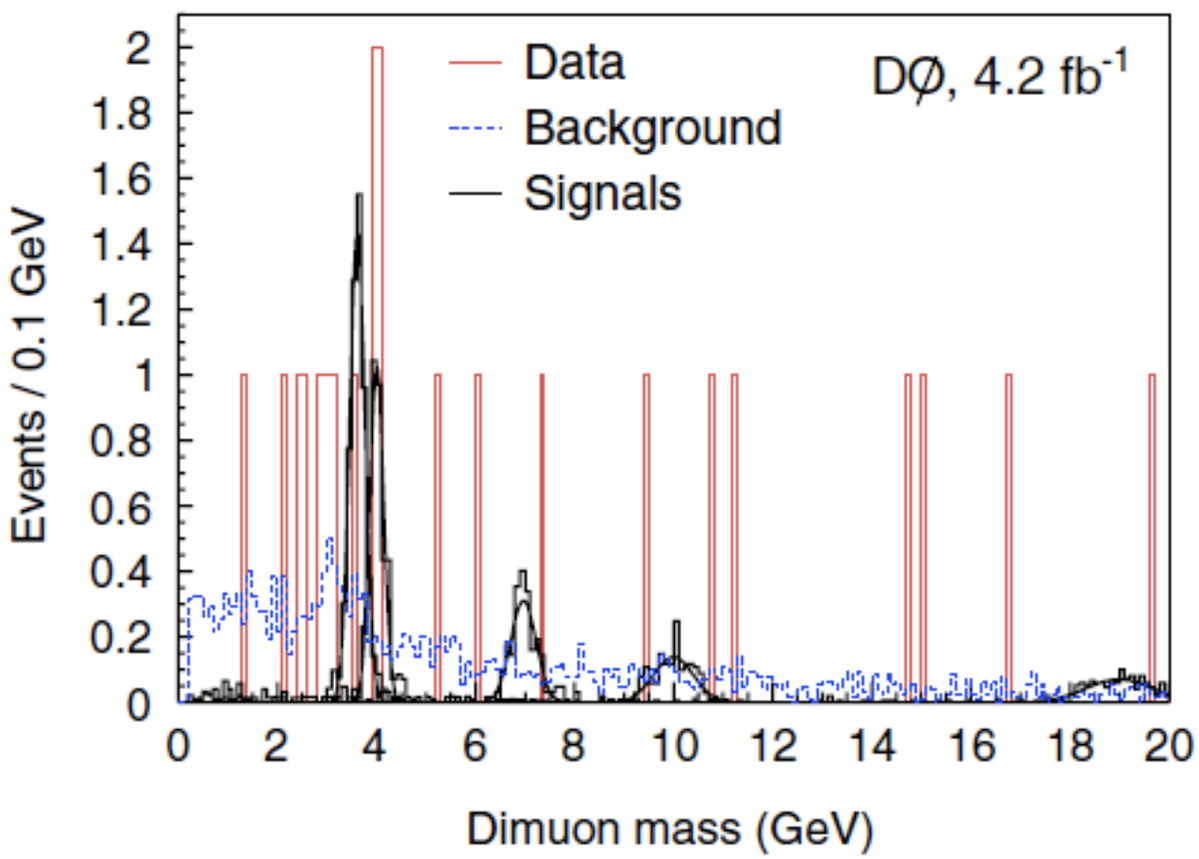
- $a^0 \lesssim 2\, m_b$ and $m_h \sim 100$ GeV not ruled out
  - Recent limits from BaBar and LEP constrain parameter space
  - Require $m_a \sim 2m_b$ or small $\tan\beta$ ($\lesssim 2$)

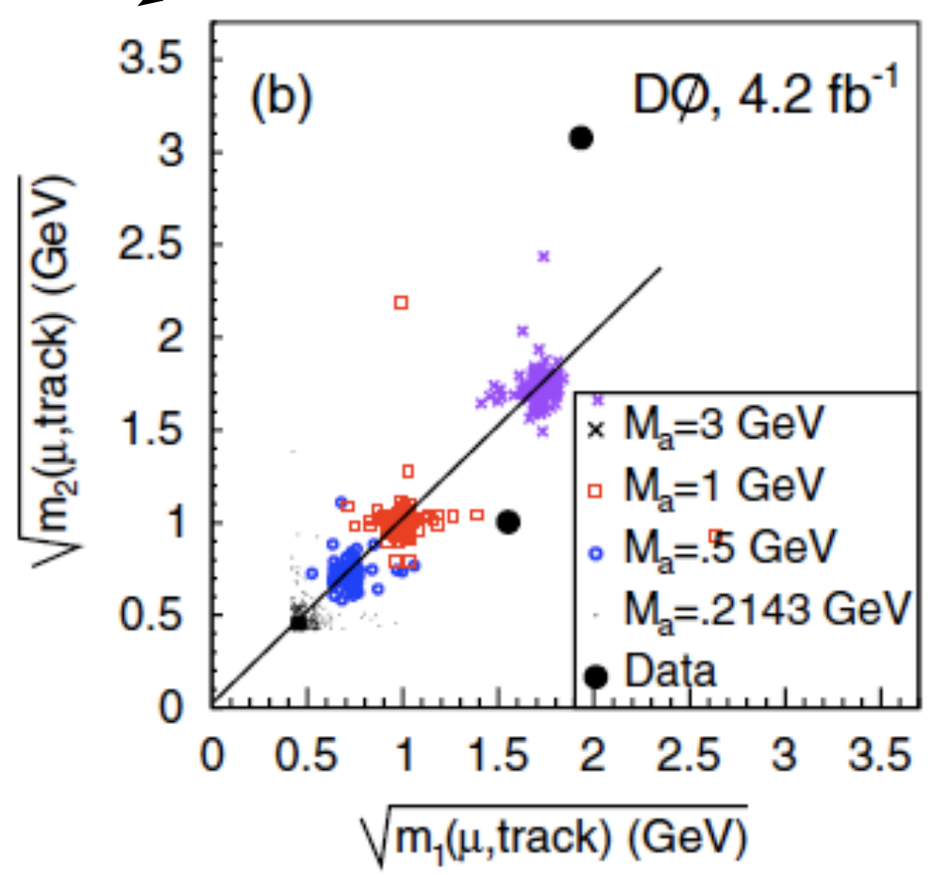


D0 Search for a^0

- Search for Higgs produced via gluon fusion and decaying to a^0 pairs
  - Probe final states where one or both a^0 decay to μμ







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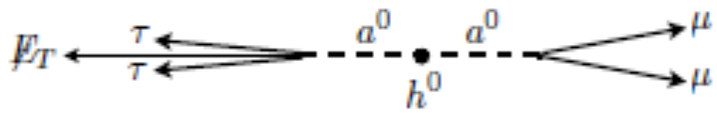
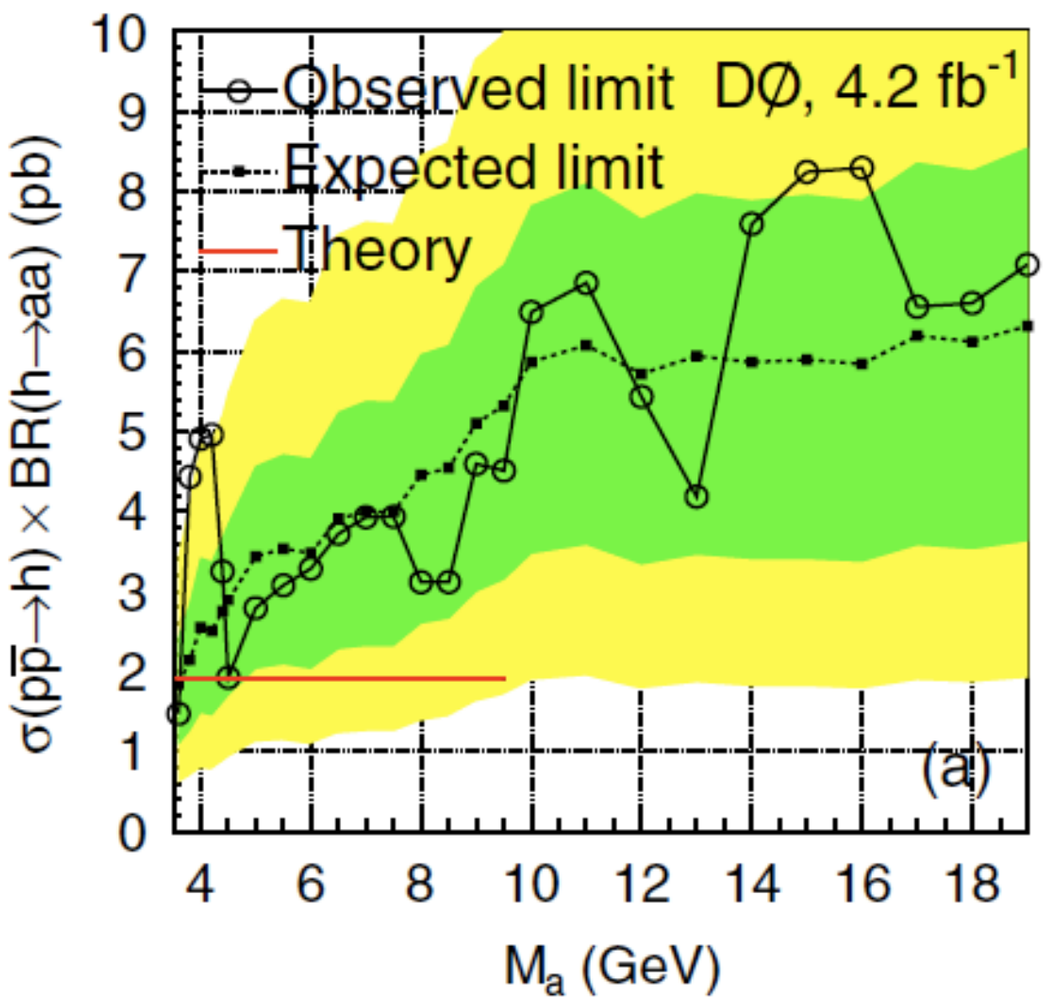
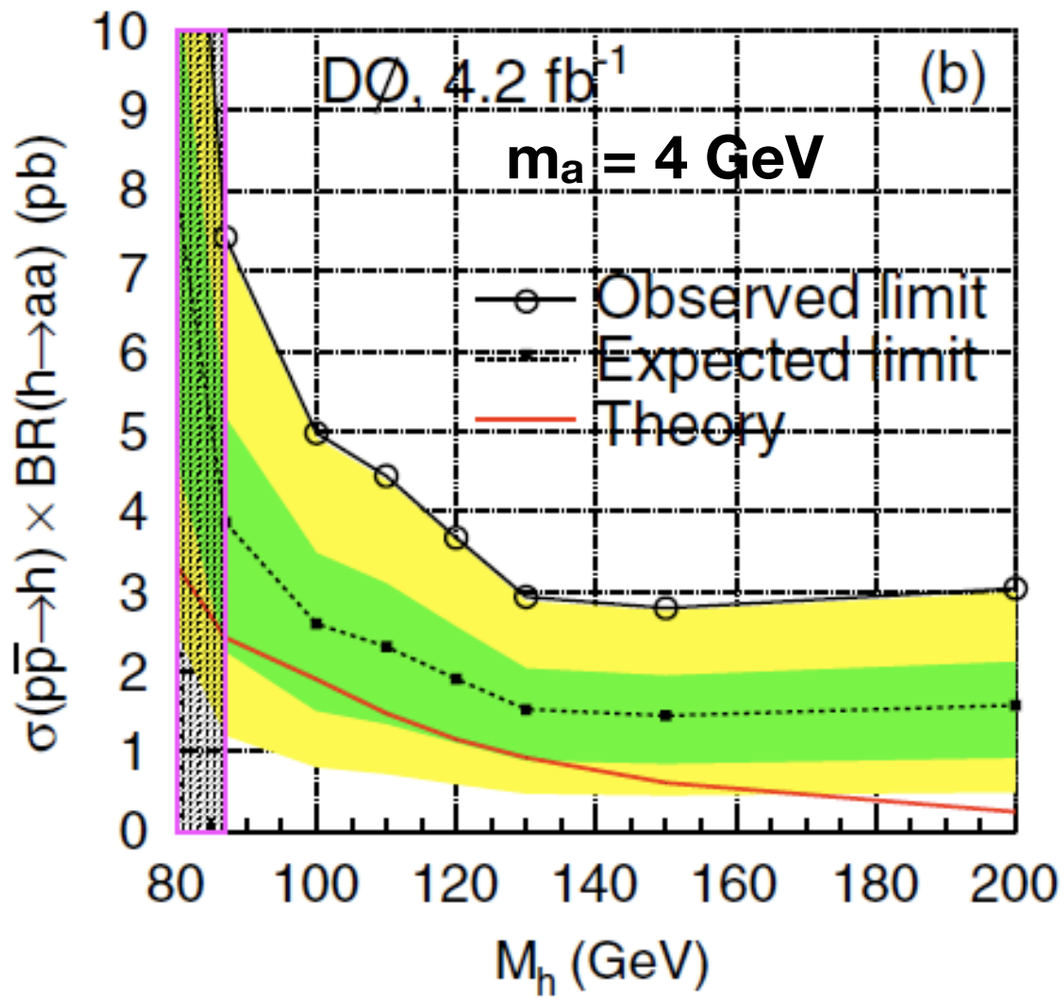
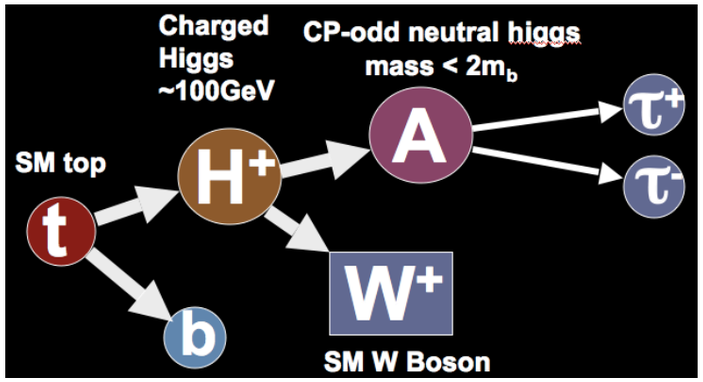






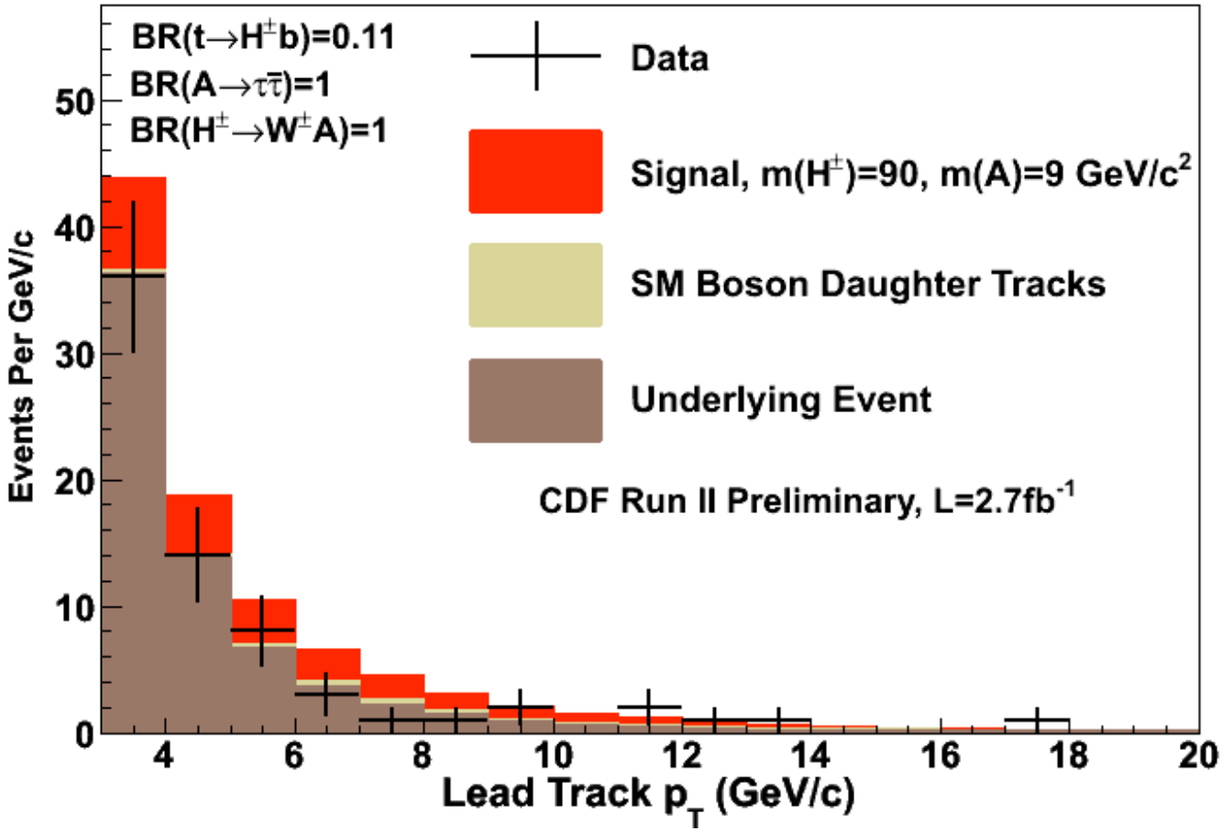
CDF Search for a^0

- Can also find a^0 in top decays if $H^{\pm}$ is sufficiently light
  - Could explain LEP 2.8σ deviation from expectation for lepton universality
- Search for isolated tracks in events with a lepton and 3 jets, one of which is b-tagged
  - Model isolated track rate using jet data
- Track requirement reduces background from 835 to 83 events



$$R_{\tau/l} \equiv 2B(W \to \tau\nu)/(B(W \to e\nu)+B(W \to \mu\nu)),$$

$$R^{exp}_{\tau/l} = 1.073 \pm 0.026,$$



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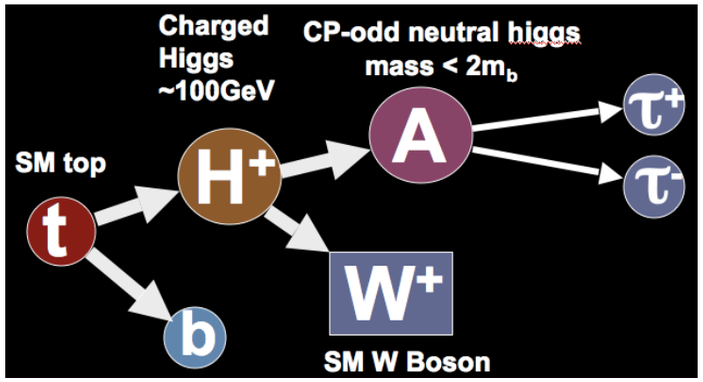

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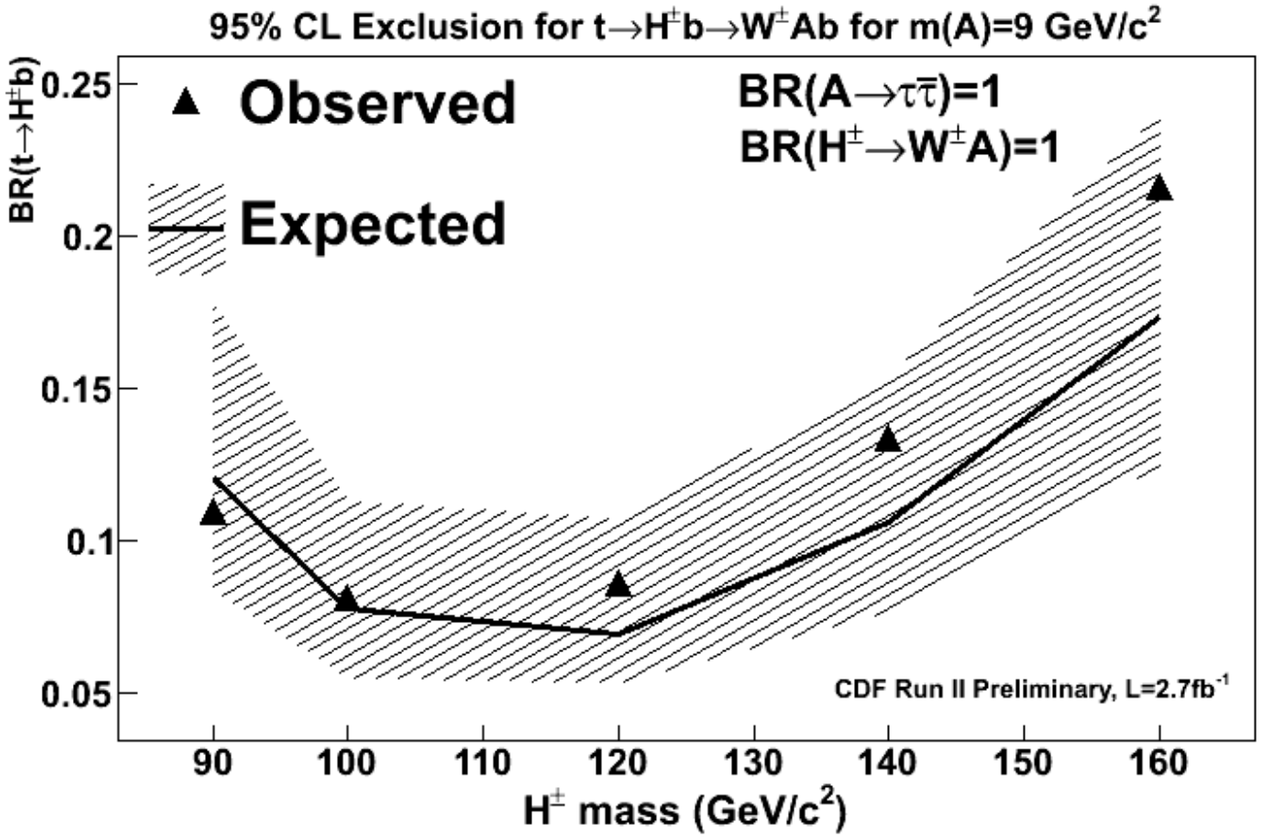
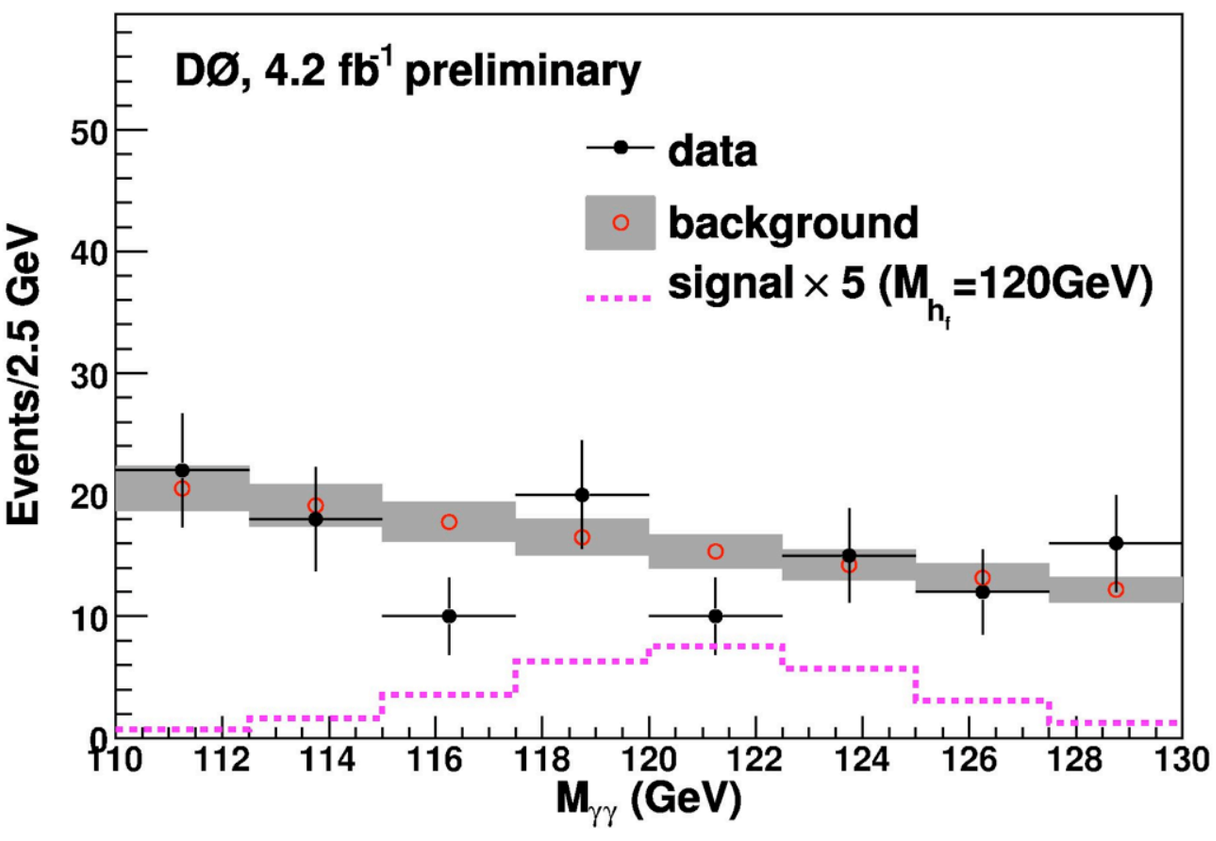
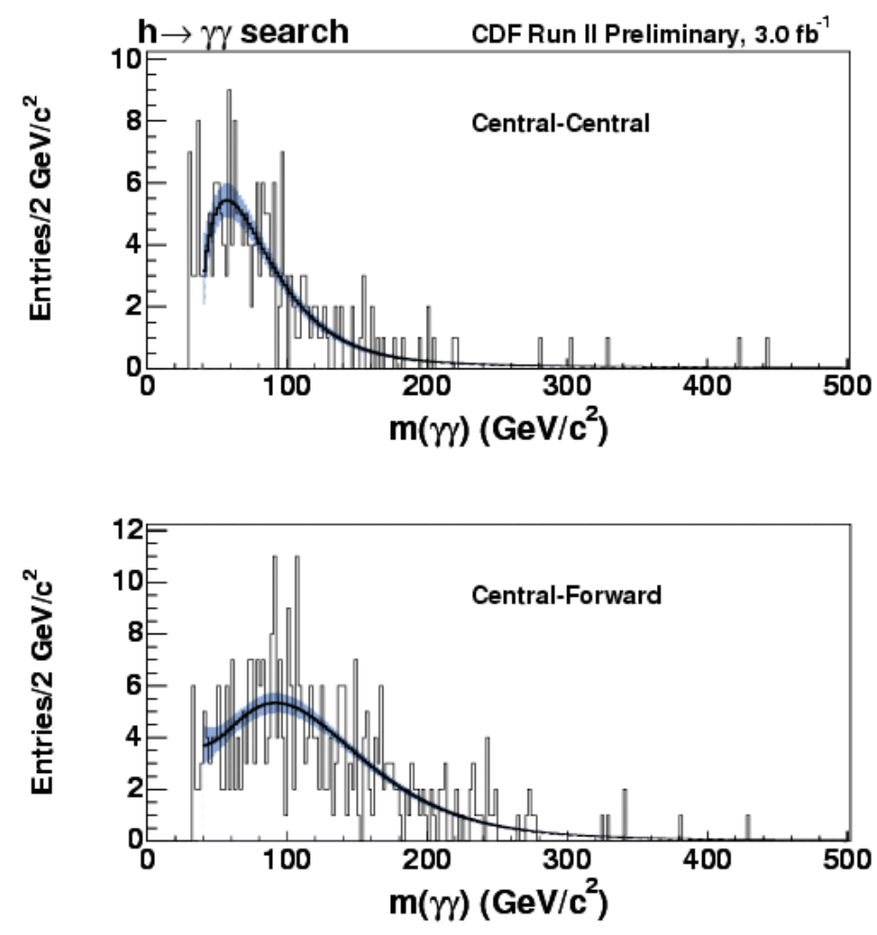


CDF & D0 Searches for a Fermiophobic Higgs

- Fermion and boson masses could result from different mechanisms
  - Removing Higgs couplings to fermions dramatically affects Higgs decay
  - Diphoton decay dominant for a low-mass Higgs (but no gluon fusion)





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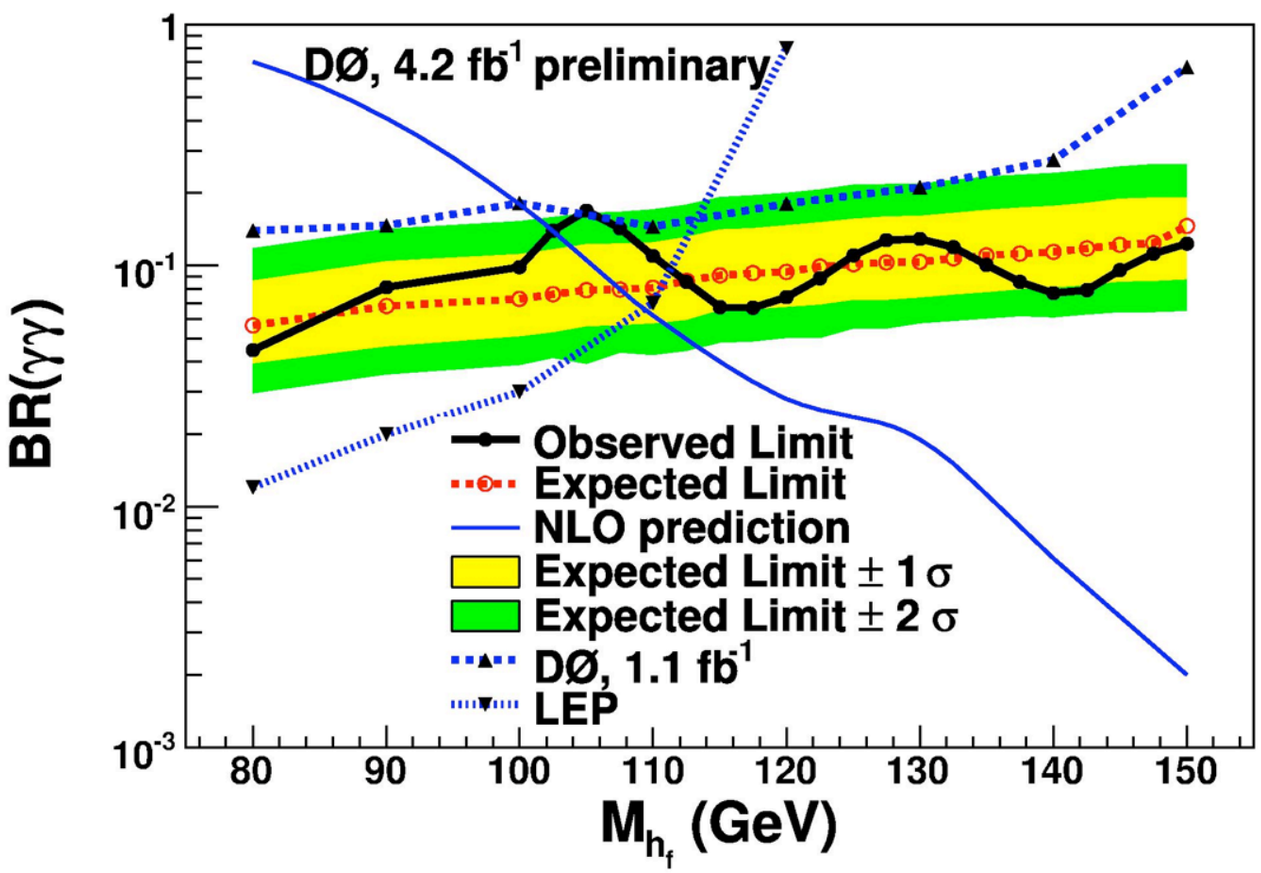
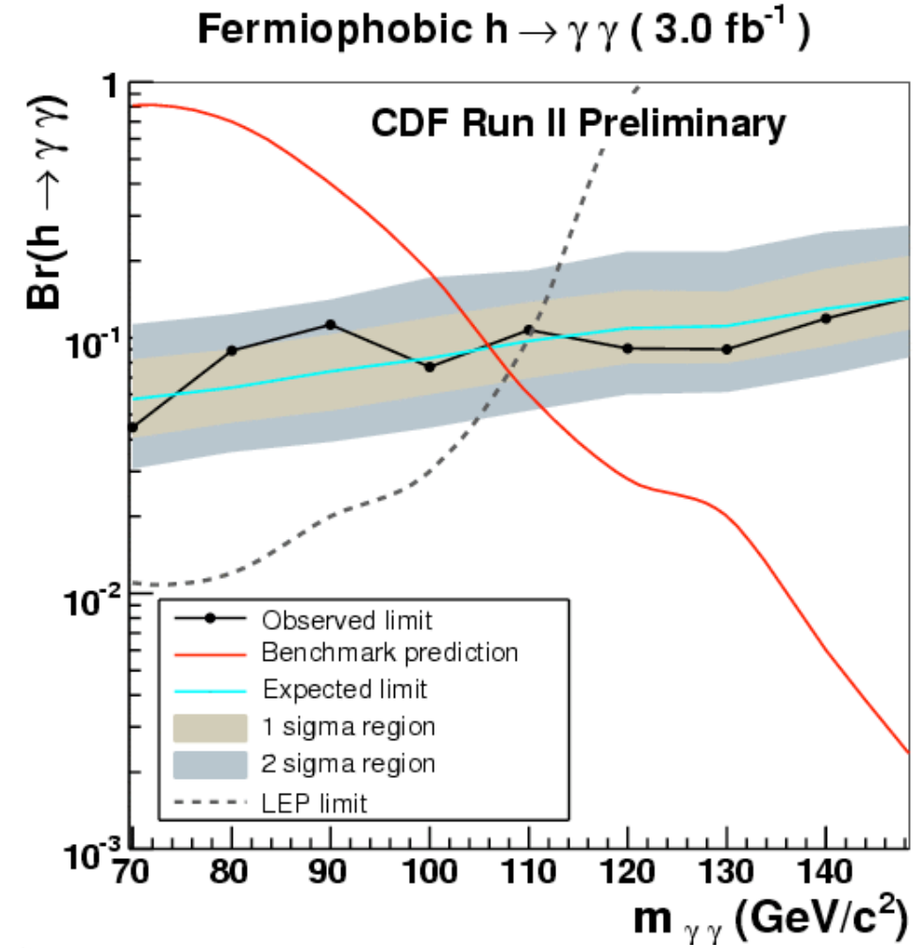
  - Diphoton decay dominant for a low-mass Higgs (but no gluon fusion)





Summary

- Expect non-standard Higgs bosons connected to new physics
- Tevatron searching broad range of Higgs bosons
  - Supersymmetric Higgs bosons at large tanβ
  - Charged Higgs bosons in top decays
  - Light Higgs in next-to-minimal supersymmetry
  - Fermiophobic Higgs bosons
  - Doubly charged Higgs bosons
- Factors of 2-4 more data available for analysis
  - Expect significant improvements in sensitivity in the near future