Higgs Boson Searches at the Tevatron Collider

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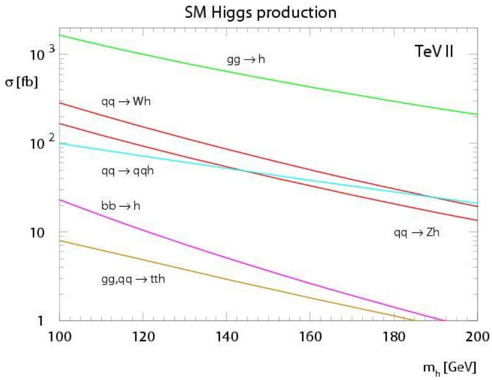
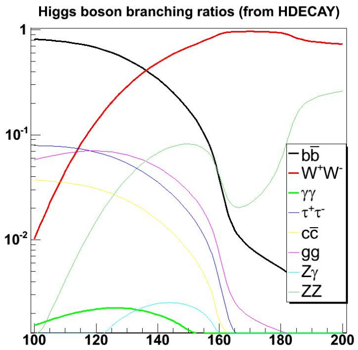
- Generalities
- Low-mass Higgs Boson Searches
- High-mass Higgs Boson Searches
- Exotics
- Perspectives

Higgs Boson Production Processes at the Tevatron

After the closure of LEP (establishing, within the SM, $M_H > 115$ GeV at 95% C.L.), and before LHC startup, the Tevatron is the unique place to look for the Higgs boson.



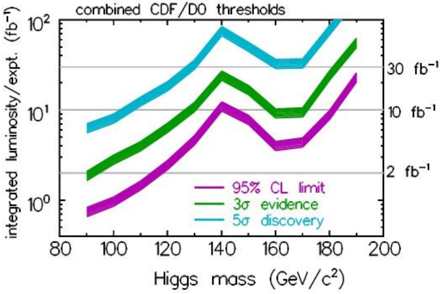


The Tevatron is (potentially) sensitive to both "low" and "high" masses
⇒ a wide range of processes to consider!

Expectations

Several studies carried out, one in '99 [hep-ph/0010338] and one in '03 [FERMILAB-PUB-03-320-E]

- implemented best understanding of object ID efficiencies etc.



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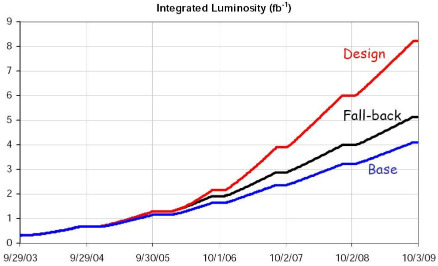
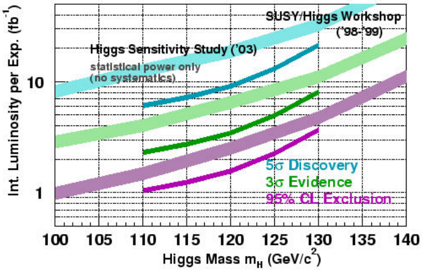
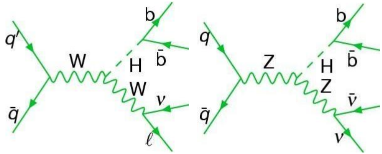




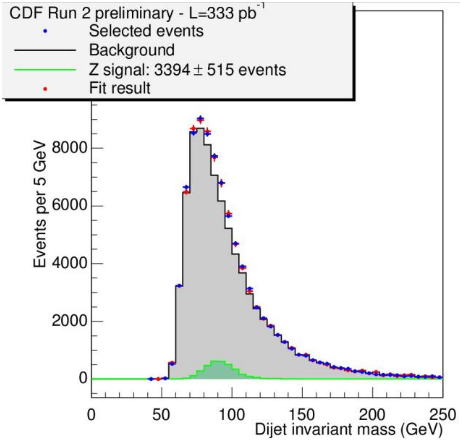
In this talk: focus on SM Higgs boson, but also consider non-SM alternatives

Low-mass search ($m_H < 135$ GeV) strategy:

- make use of large $H \rightarrow b\bar{b}$ branching ratio $\Rightarrow$ b-tagging
- but this signature drowns in QCD b production background $\Rightarrow$ need associated production:



- requires good b-jet E resolution

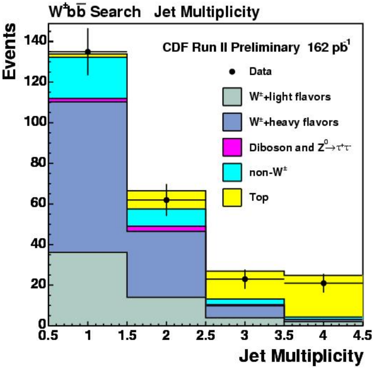


$W(\to \ell\nu)H(\to b\bar{b})$

This is the benchmark channel: $\ell^{\pm}$, $\not{E}_T$, b jets, large ($\sim 20\%$) $W \to \ell\nu$ branching ratios

CDF analysis:

- start from "standard" W+jets sample ($p_T^{\ell} > 20$ GeV, $\not{E}_T > 20$ GeV)
- require exactly 2 jets (reduce $t\bar{t}$ background)
- apply b-tagging and reconstruct invariant mass
- look for a resonance in the invariant mass distribution, set limits



Important issues: efficiency optimisation, understanding of (instrumental) backgrounds (background dominated by W+jets, fakes)

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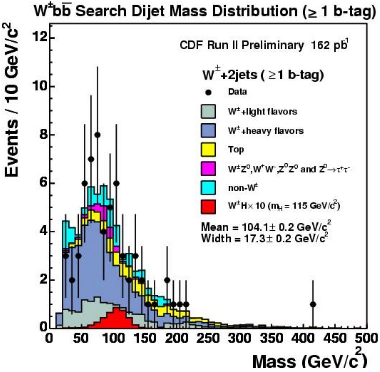

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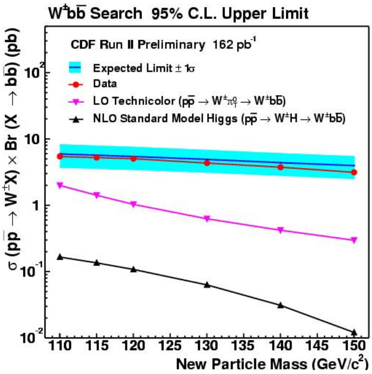

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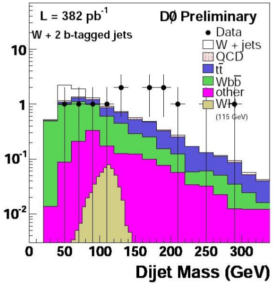
Results:

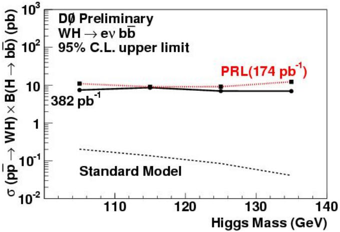
- cross section limits ($\sim$ 5 pb) clearly above SM predictions ($\sim$ 0.1 pb); however, they are becoming interesting for other models (with similar signatures), *e.g.* $\rho_T^{\pm} \to W^{\pm}\pi_T^0 (\to b\bar{b})$
- this sort of benchmark analysis also constitutes a reality check, lending confidence to the Higgs Sensitivity workshop projections:

	Run2	Run1		Run2 Higgs sensitivity report	
	This Analysis	Cut Based	NN	CASE 0	
Mass Resolution	17%	15%		15%	10%
S	0.24	0.31	0.24	0.13	0.13
B	18.2	50.7	18.3	3.2	2.1
$S/\sqrt{B}$	0.057	0.04	0.056	0.075	0.09

Table 1: The significance comparison of different analyses for $m_H = 115$ GeV/c^2. The "CASE 0" in Run2 Higgs sensitivity report uses the same lepton selection and SECVTX b-tagging as this analysis. There is no extension of higher η for either lepton identification or b-tagging. Both jets are required to be b-tagged, but allowing that the second b-tag be significantly looser(SECVTX or JPB) than the first one (SECVTX).

Similar results available from DØ (but using $W \to e\nu$ only):





$Z(\to \nu\bar{\nu})H(\to b\bar{b})$

Similar production cross section and $(Z \to \nu\bar{\nu})$ branching ratio... but no charged lepton!

DØ analysis strategy:

- select events with $\not{E}_T > 25$ GeV, ≥ 2 jets with $E_T > 20$ GeV
- select well-measured events using $\Delta\phi(\not{E}_T, \phi_{jets})$, $\not{H}_T \equiv |\sum_{jets} \vec{p}_T|$, $P_T^{trk} \equiv |\sum_{trk} \vec{p}_T|$, $P_{T,2}^{trk} \equiv |\sum_{trk\ in\ jets} \vec{p}_T|$, estimate fake background
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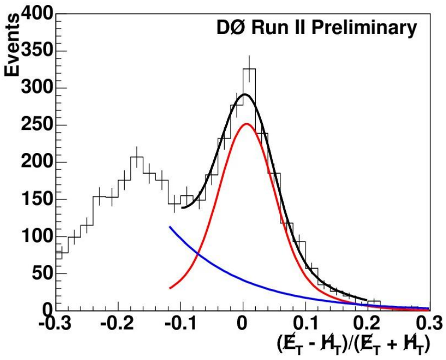

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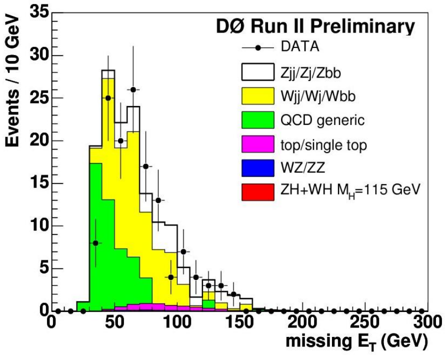

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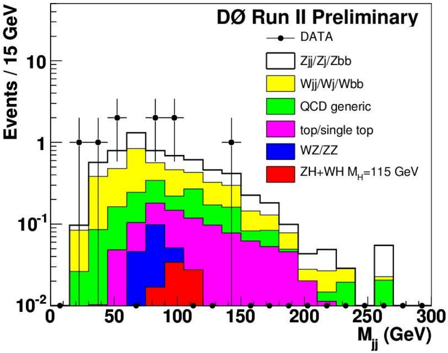

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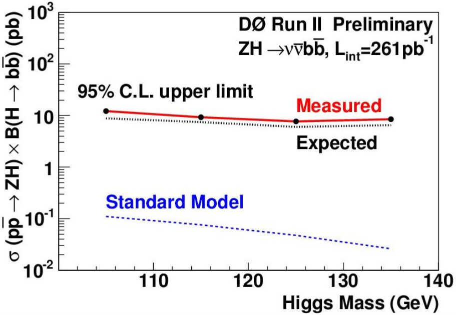
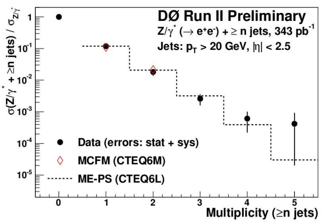
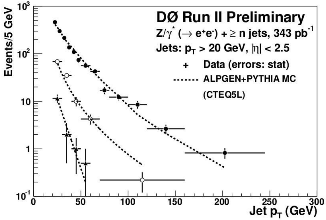


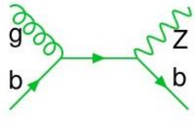
Cross-checks using $Z \to \ell^+\ell^-$ samples

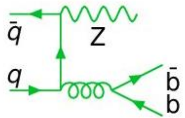
$Z \to e^+e^-$: jet radiation

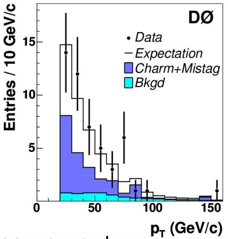


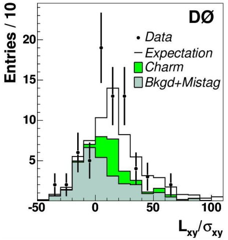


$R \equiv \sigma(Z+b)/\sigma(Z+\text{jet})$: sensitive to b-quark density in proton (not very well constrained):









Measurement
$(R = 0.021 \pm 0.004(\text{stat.})^{+0.002}_{-0.003}(\text{syst.}))$
compatible with (and of similar accuracy to)
NLO prediction ($R = 0.018 \pm 0.004$)

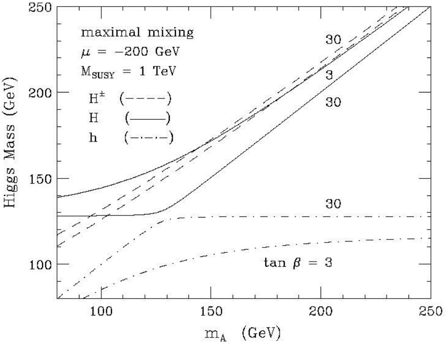
MSSM Higgs Boson Searches

Knowing the b-quark density in the proton is useful for other purposes, too!

In the MSSM:

- two Higgs doublets, VEVs $v_u / v_d \equiv \tan\beta$
- five Higgs bosons: h, H, A, $H^{\pm}$
- for large $\tan\beta$ (theoretical prejudice):
  - A and (h or H) degenerate in mass
  - coupling of these two Higgs bosons to down-type fermions $\sim \tan\beta$ times SM couplings

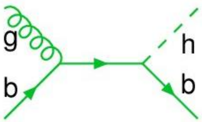
from [hep-ph/0010338]



Relatively straightforward signatures: SM-like but strongly enhanced for $\tan\beta \gg 1$

MSSM $h(b\bar{b})b$

Use enhanced $hb\bar{b}$ coupling to look for increased h/A production from initial state b quarks. Signature: resonance in leading jets' m_{jj} in bbb events



DØ analysis: data driven

- three-jet events w/ $E_{T,1} > 35$ GeV, $E_{T,2} > 20$ GeV, $E_{T,3} > 15$ GeV
- start from m_{jj} distribution in double-tagged events (dominated by $b\bar{b}jj$)
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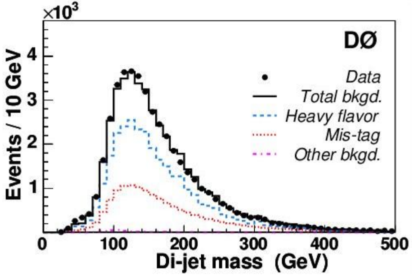

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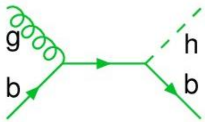

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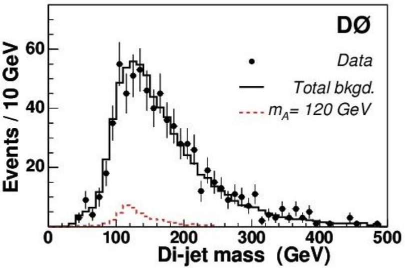

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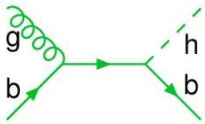

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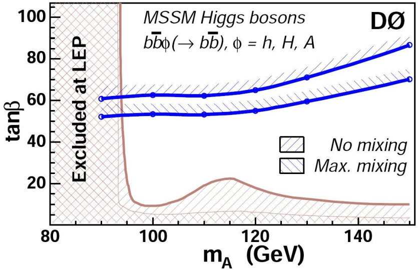

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MSSM A$\rightarrow \tau^+\tau^-$

Despite the large branching h/A$\rightarrow$ b$\bar{\text{b}}$ ratio, the analysis of this final state suffers from a large multi-jet background. Alternative: gg/b$\bar{\text{b}}$ $\rightarrow$h/A$\rightarrow \tau^+\tau^-$

CDF analysis using $\tau(\ell)\tau(\text{h})$ final states:

- clean reconstruction of hadronic τ decay
- apply cut on $\hat{H}_\text{T} \equiv |\vec{p}^{\,\text{vis}}_{\text{T},1}| + |\vec{p}^{\,\text{vis}}_{\text{T},2}| + \not{E}_\text{T}$, require $\vec{\not{E}}_\text{T}$ to be consistent w/ τ decays
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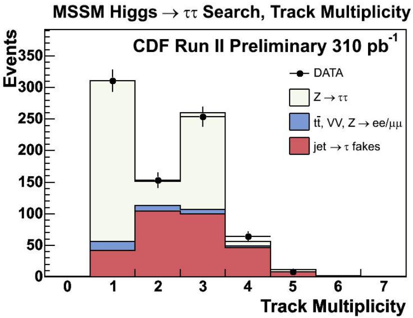

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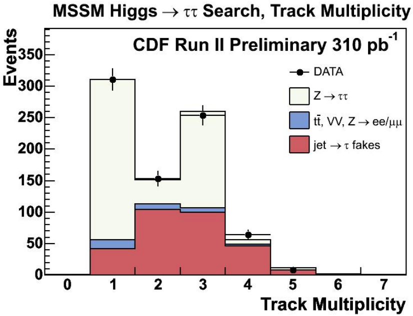

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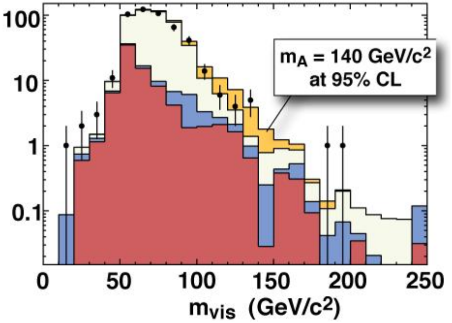

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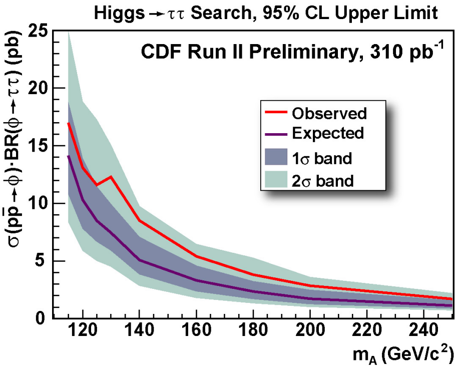

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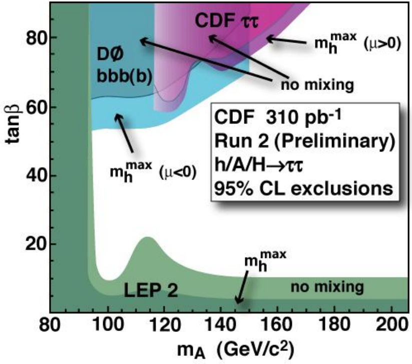


High-Mass Higgs Boson Searches

When $m_{\mathrm{H}} > 135$ GeV, branching ratio to $\mathrm{W}^{\pm}\mathrm{W}^{\mp(*)}$ becomes dominant
$\Rightarrow$ leptonic decay modes allow to use gg$\rightarrow$H production.
However, this requires good knowledge of the non-resonant WW background, which itself has a small production cross section
$\Rightarrow$ first need to measure this process accurately.

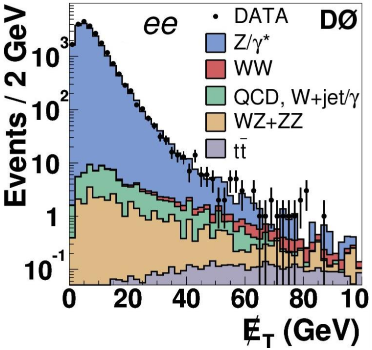
DØ analysis:

- require $\ell^{\pm}\ell'^{\mp}$ with $p_{\mathrm{T},1(2)} > 20(15)$ GeV
- require $\not{E}_{\mathrm{T}} > 30, 20, 40$ GeV for ee, eμ, $\mu\mu$ final states

Further Z/γ^* suppression through cuts specific for final states. For ee:

- suppress jet mis-measurement: $H_{\mathrm{T}} < 50$ GeV and

$$\frac{\not{E}_{\mathrm{T}}}{\sqrt{\sum_j ((E_j)^{1/2} \sin\theta_j \cos\Delta\phi(j, \not{E}))^2}} > 15$$



- require $|m_{\mathrm{ee}} - m_{\mathrm{Z}}| > 15$ GeV

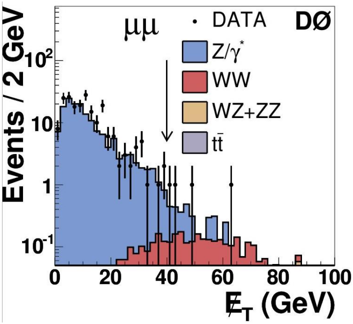
For $\mu\mu$:

- $20\ \text{GeV} < m_{\mu\mu} < 80\ \text{GeV}$
- $H_T < 100\ \text{GeV}$

For eμ:

- $\not\!\!E_T$ significance cut as for ee
- $m_T^e, m_T^\mu > 20$ GeV:

$$m_T^\ell \equiv \sqrt{2 p_T^\ell \not\!\!E_T (1 - \cos\Delta\phi(\ell, \not\!\!E_T))}$$



Result: $\sigma(p\bar{p} \to W^+W^-) = 13.8^{+4.3}_{-3.8}(\text{stat.})^{+1.2}_{-0.9}(\text{syst.}) \pm 0.9(\text{lum.})$ pb
CDF: $\sigma(p\bar{p} \to W^+W^-) = 24.2 \pm 6.9(\text{stat.})^{+5.2}_{-5.7}(\text{syst.}) \pm 1.5(\text{lum.})$ pb
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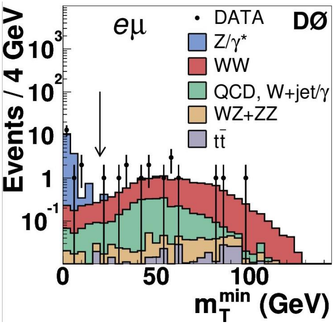

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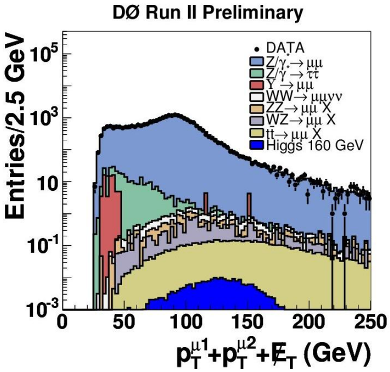
$H \rightarrow W^{\pm}W^{\mp(*)}$

Higgs searches largely build on WW cross section measurements. However, the nice possibility to look for resonances doesn't exist
$\Rightarrow$ exploit spin correlations in decays.

In the DØ case (NB slight mods. for $\mu\mu$):

- (slightly) relax cuts on $p_{T,\ell}$, $\not{E}_T$
- $m_H/2 + x < p_{T,1} + p_{T,2} + \not{E}_T < m_H$, $x = 10$ (20) GeV for $\mu\mu$ (ee, eμ)
- $m_{\ell\ell} < m_H/2$
- $\Delta\phi_{\ell\ell} < 2$
- $m_H/2 < m_T^{\ell\ell} < m_H - 10$ GeV
- extract cross section limits as function of m_H

Similar limits available from CDF



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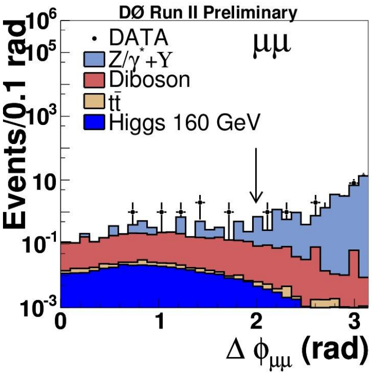

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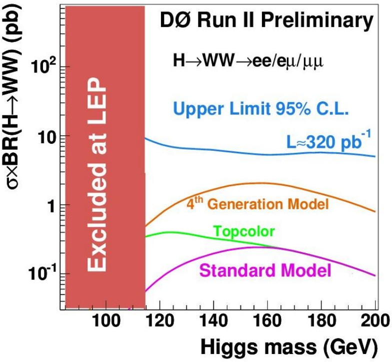

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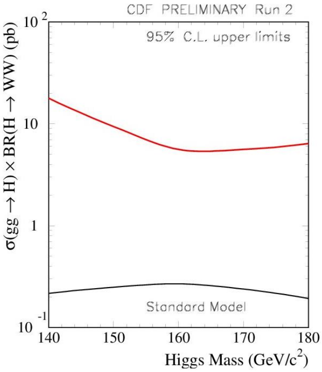
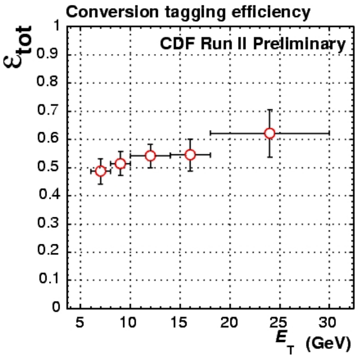


$H \to W^{\pm}W^{\pm(*)}X$

Alternative approach taken in nice analysis by CDF: study this same decay but in associated production $\Rightarrow$ like-sign dileptons

An almost background-free analysis. . . provided lepton charges can be identified unambiguously:

- require $p_{T,1(2)} > 20(6)$ GeV
- estimate lepton "fake rate", photon conversion rate
- cross-check w/ agreement in variables not very sensitive to signal
- define signal region and search for signal
- extract cross section limits



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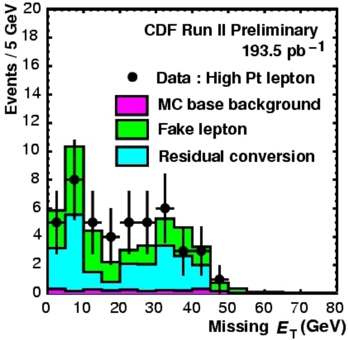

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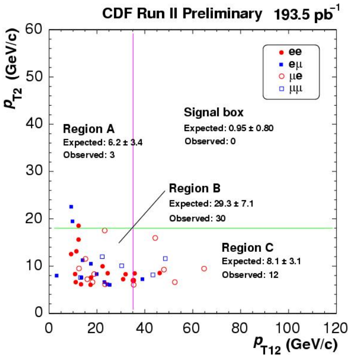

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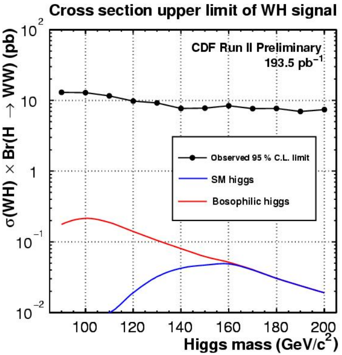


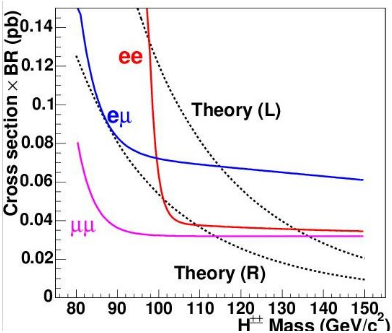
Doubly-Charged Higgs Bosons

While the exact symmetry breaking mechanism chosen by Nature has not been identified. . . consider alternative models.

In the left-right symmetric model, $H^{\pm\pm}_{L,R}$ bosons couple to left/right-handed fermions. At the Tevatron, they would be predominantly produced in pairs ($p\bar{p} \to Z/\gamma^* \to H^{++}H^{--}$) and (for relatively light $H^{\pm\pm}$) decay predominantly to charged leptons.

CDF Search strategy: attempt to identify only a single Higgs boson $\Rightarrow$ a signature like that of the $H \to W^{\pm}W^{\pm(*)}X$ search, apart from the resonant dilepton invariant mass spectrum.

- require two isolated leptons (e, μ)
- search in 10 GeV mass window around hypothesized mass, set cross section limits
- set lower limits on mass (assuming exclusive decay to given final state)



(similar DØ analysis, using only $\mu\mu$)

Perspectives

The Tevatron Higgs Search programme is now in full swing.

- "basics" (lepton ID, b-tagging, $\not{E}_T$) understood, but no use has yet been made of "advanced analysis techniques"
- present limits substantially above SM predictions
- . . . but close to probing other models
- also, Tevatron integrated luminosity is increasing rapidly
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Stay tuned!