Higgs Boson Decay into a Pair of Leptons: Signal and Backgrounds

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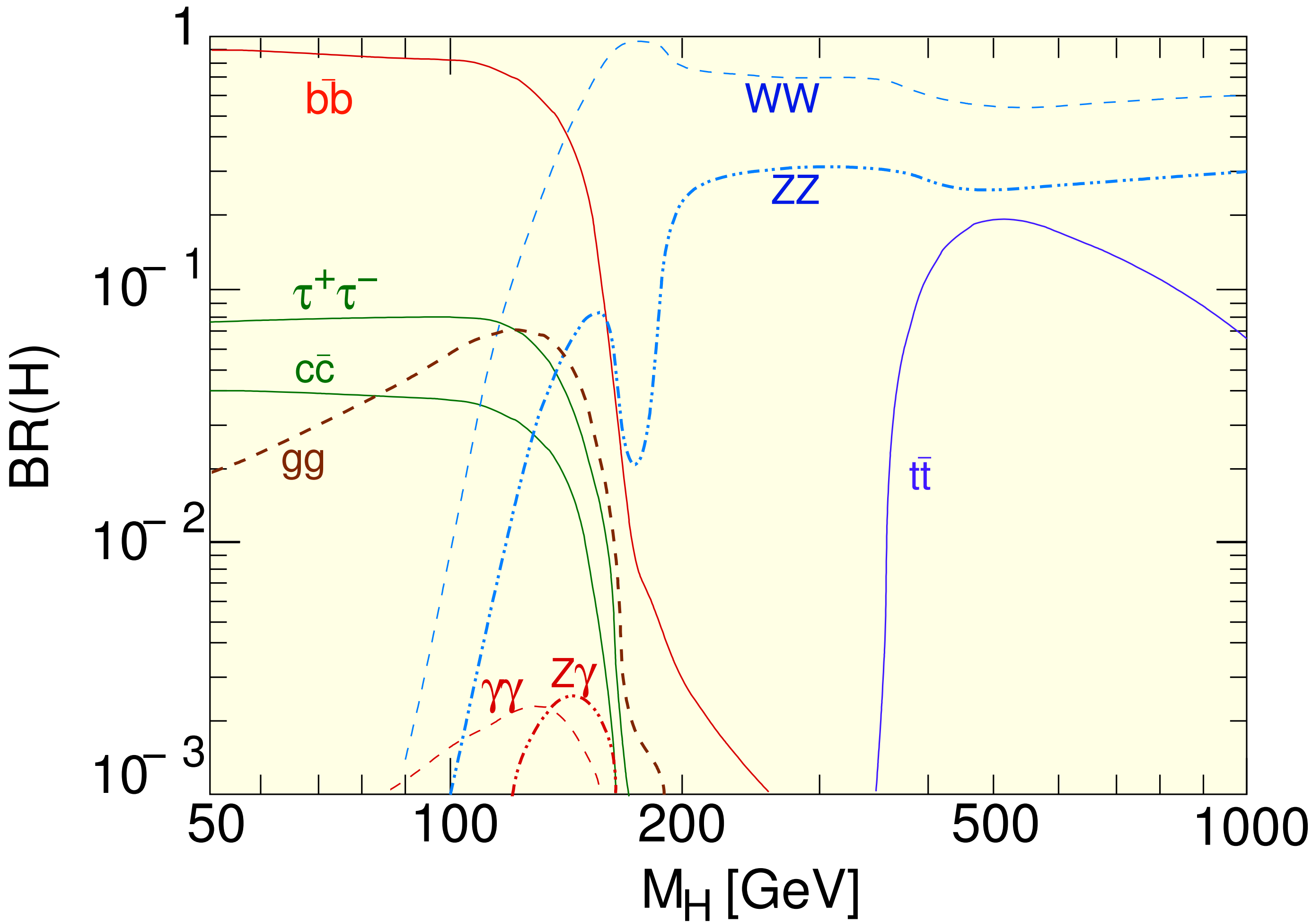
Higgs boson decay to W^+W^- to l^+l^- plus missing energy
and the standard model backgrounds

Based on research done with Zack Sullivan, hep-ph/0606271

Search for the Higgs Boson

- Discover/understand the mechanism for electroweak symmetry breaking: a clear goal of Tevatron, LHC, and ILC experiments during the next decade
- Experimental plans:
  - Thorough search for Higgs bosons
  - Measure their properties and determine their couplings
- Focus on the l^+l^- final state:
  - At LHC, examine signal $h \to W^+W^- \to l^+l^-X$ and backgrounds from a cocktail of standard model processes; including leptons from decays of heavy flavors produced in hard scattering subprocesses, e.g., $gg \to b\bar{b}X$
  - Comments on $h \to W^+W^- \to l^+l^-X$ at the ILC

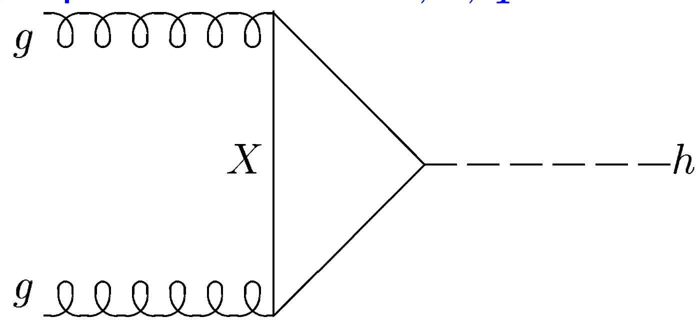
Higgs boson branching fractions



$h \to W^+W^-$ branching fraction takes over when $m_h > 135$ GeV

Higgs boson production and decay at the LHC $pp \to hX$; $h \to WW$

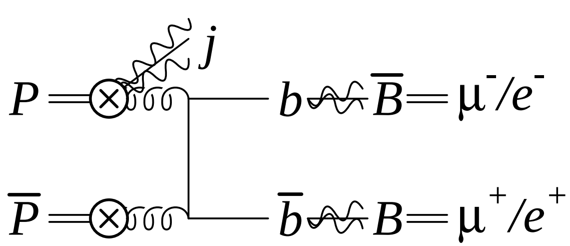
- glue-glue fusion is the dominant production mechanism; lowest order triangle graph with $X = t, b, \tilde{q}$

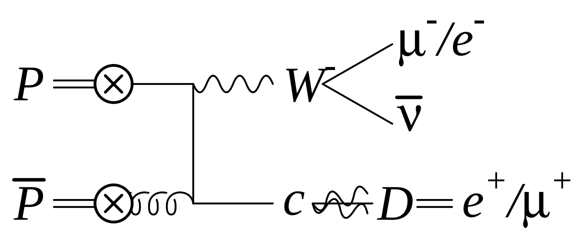


- Decay modes of the W include $W \to q\bar{q}$ and $W \to l\nu$
- Signals of $h \to WW \to 4$ jets and $h \to WW \to l\nu + 2$ jets are buried in the hadronic backgrounds at Tevatron and LHC energies
- Try to look at $WW \to l\bar{l}\nu\bar{\nu}$
- Information on the coupling g_{hWW} can be gained from the weak boson fusion process, $qq \to qqh$

Higgs boson decay $h \to W^+W^- \to l\bar{l}\nu\bar{\nu}$

- $h \to W^+W^-$ branching fraction dominant when $m_h > 135$ GeV; at $m_h = 170$ GeV, $BR(h \to WW^* \to l^+l^-\nu\bar{\nu}) \sim 100 BR(h \to ZZ^* \to 4l)$
- The 'signal' is an excess of events above backgrounds from processes that provide l^+l^- plus missing transverse energy ($\not{E}_T$)
- Standard model backgrounds:
  - 'irreducible' backgrounds have at least two 'isolated' leptons plus missing energy: continuum $WW^* \to l^+l^-\nu\bar{\nu}$; $WZ/ZZ \to l^+l^-\nu X$; $t\bar{t} \to WWb\bar{b}$; 'single top' $qg \to Wt \to WWb$;...
  - 'reducible' backgrounds in which the (second) lepton(s) and the missing energy arise from heavy flavor decay: $Wb\bar{b} \to l\nu b\bar{b}$; $Wc\bar{c}$, Wc,..., and inclusive $b\bar{b}/c\bar{c}$





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DØ study of $h \to W^+W^- \to l\bar{l} + \not{E}_T$

- Taken from a 1/3 fb^{-1} study of $e^+e^-, e^\pm\mu^\mp, \mu^+\mu^-$ pairs
  PRL 96, 011801 (2006)
- Table lists the number of expected signal and background events, after all cuts have been applied. Statistical uncertainties only [1]

M_H(GeV)	100	120	140	160	180	200
$H \to WW^{(*)}$	0.007 ± 0.001	0.125 ± 0.002	0.398 ± 0.008	0.68 ± 0.01	0.463 ± 0.009	0.210 ± 0.004
Z/γ^*	7.9 ± 1.1	7.5 ± 1.0	3.8 ± 0.6	4.0 ± 0.7	6.6 ± 0.9	9.9 ± 1.1
Diboson	4.4 ± 0.2	8.1 ± 0.2	11.7 ± 0.3	12.3 ± 0.3	11.6 ± 0.3	9.6 ± 0.3
$t\bar{t}$	0.03 ± 0.01	0.11 ± 0.02	0.29 ± 0.02	0.47 ± 0.03	0.66 ± 0.05	0.72 ± 0.05
W+jet/γ	16.9 ± 2.2	14.2 ± 2.1	5.8 ± 1.2	2.8 ± 0.9	0.7 ± 0.5	0.7 ± 0.5
Multi-jet	0.6 ± 0.3	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.3 ± 0.1	0.3 ± 0.1
Background sum	29.9 ± 2.5	30.1 ± 2.3	21.8 ± 1.4	19.7 ± 1.2	19.8 ± 1.1	21.2 ± 1.2
Data	27	21	20	19	19	14

- DØ included as relevant backgrounds: continuum WW, $t\bar{t}$, Drell-Yan, small rate from jets faking $e^\pm$, ...
  Note: Continuum WW is the largest background for $m_h = 160$ GeV
- Data consistent with the backgound estimate
- Not the end of the story. What about leptons from semi-leptonic decays of heavy flavors: b and c quarks?

Higgs boson decay $h \to W^+W^- \to l\bar{l}\nu\bar{\nu}$

- Heavy flavor backgrounds: issue is the extent to which lepton isolation and subsequent kinematic physics cuts can suppress them
- The problem: at the LHC energy,
  $\sigma B(h \to WW^* \to ll\nu\bar{\nu}) \sim 0.7$ pb for $m_h = 150$ to 190 GeV
  $\sigma^{b\bar{b}}_{\rm inclusive} \sim 5 \times 10^8$ pb
- 'Isolation' in $b \to lX$ (ΔR, $E_T^{\rm iso}$) even at the 0.5 % level leaves $l^+l^-\not{E}_T$ background that is 10^4 greater than the signal
- Questions of both magnitude and shape of the backgrounds
- Thorough (re)evaluation of the signal and backgrounds for $h \to WW^* \to ll\nu\bar{\nu}$: Berger and Sullivan,hep-ph/0606271
- Independent study of the DØ and ATLAS analysis chains but with all heavy flavor processes included

Detailed simulations for Tevatron and LHC

- DØ (PRL 96, 011801 (2006)) and CDF (hep-ex/0605124) have data and ongoing analyses, with $S/B \sim 1/30$
- ATLAS has done simulations and expects $S/B \sim 1$

Two classes of backgrounds with heavy-flavor leptons:

1. Wc, $Wb\bar{b}$, $Wc\bar{c}$, Wb, single-top — All have 1 real W plus 1 HFL
2. $b\bar{b}$, $c\bar{c}$ — have 2 HFL.
   Both have mb cross sections, w/ only 10^4 suppression from isolation

How our simulations were done

- $h \to WW$ and WW start with PYTHIA normalized with NLO K factors
- Wc/Wb use MadEvent fed through PYTHIA with NLO K factors
- Single-top, $Wb\bar{b}$, $Wc\bar{c}$, normalized to ZTOP/MCFM differential NLO

PYTHIA output is fed through **modified** PGS simulation that reproduces DØ and ATLAS full detector results to 10%

ATLAS-like search, $m_h = 160$ GeV

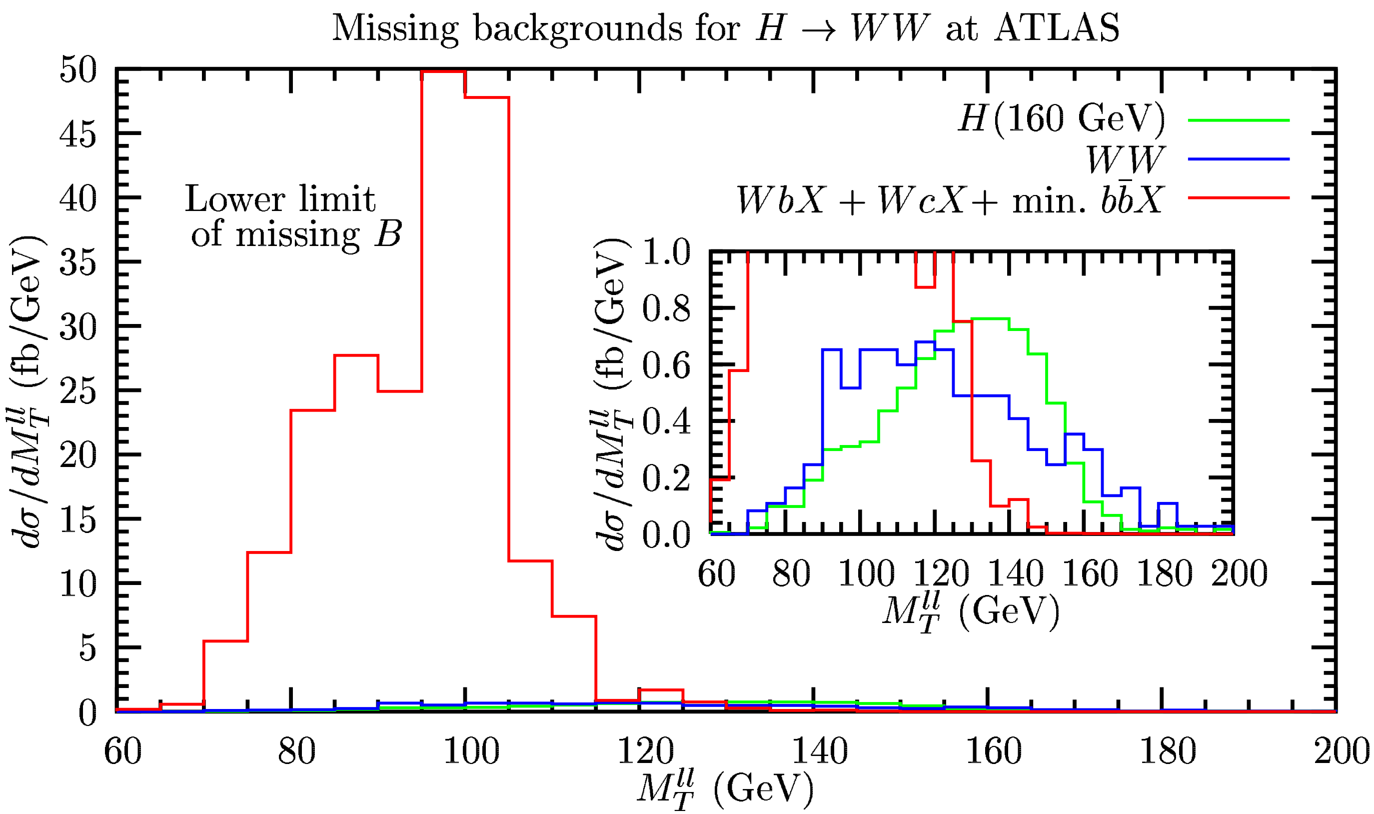
Series of isolation and physics cuts on reconstructed objects (Table shows $\sigma(\mathrm{fb})$ from our analysis.) ‘Isolated’ means $p_T^l > 10$ GeV, $\eta^l < 2.5$, plus generic ATLAS cone ΔR and E_T^{iso} choices

Cut level	$h \to WW$	WW	$b\bar{b}j^\star$	Wc	single-top	$Wb\bar{b}$	$Wc\bar{c}$
Isolated $l^+l^- > 10$ GeV	336	1270	> 35700	12200	3010	1500	1110
$E_{T l_1} > 20$ GeV	324	1210	> 5650	11300	2550	1270	963
$\not{E}_T > 40$ GeV	244	661	> 3280	2710	726	364	468
$M_{ll} < 80$ GeV	240	376	> 3270	2450	692	320	461
$\Delta\phi < 1.0$	136	124	> 1670	609	115	94	131
$\lvert\theta_{ll}\rvert < 0.9$	81	83	> 1290	393	68	49	115
$\lvert\eta_{l_1} - \eta_{l_2}\rvert < 1.5$	76	71	> 678	320	48	24	104
Jet veto	41	43	> 557	175	11	12	7.4
$130 < M_T^{ll} < 160$ GeV	18	11	—	0.21	1.3	0.04	0.09

- $b\bar{b}j^\star$ ME is preselected to pass $\not{E}_T$ cut
  Looser cuts indicate that “$>$” is at least a factor of 5
  This method allowed us to demand 2 reconstructed isolated leptons!
- After the $\not{E}_T$ cut, real power comes from the transverse mass M_T^{ll} cut

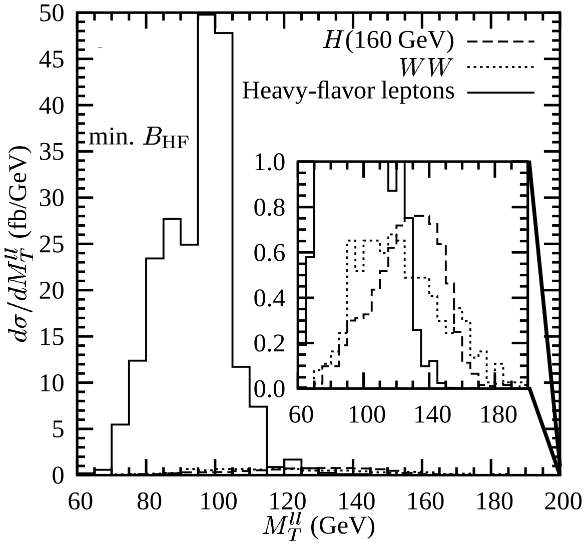
Transverse mass distribution after cuts

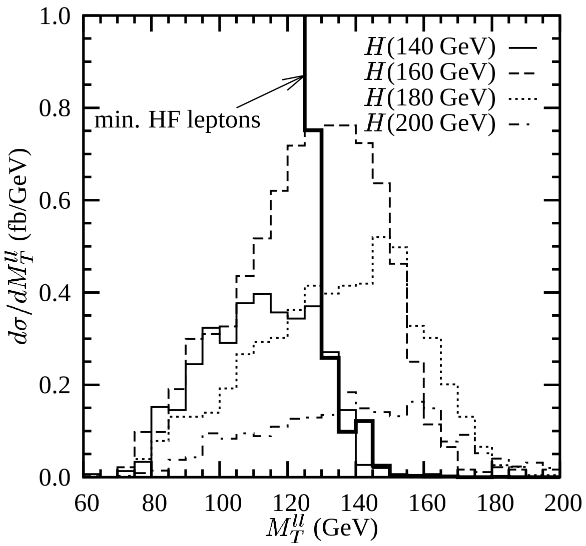
- Cannot reconstruct a Higgs boson mass peak from $h \to WW^* \to l^+l^-\nu\bar{\nu}$; use 'transverse mass' as an estimator; $M_T^{l\bar{l}} = \sqrt{2p_T^{l\bar{l}}E_T^{miss}(1-\cos(\Delta\phi))}$



- Heavy flavor background is more than 10 times previous estimates of backgrounds when $M_T^{l\bar{l}} < 110$ GeV; a tail extends into the signal region

Transverse mass distribution at ATLAS





The HF background starts off 50$\times$ the signal

The M_T^{ll} peak is $\sim 2/3\, b\bar{b}j^\star$, $\sim 1/4\, Wc$
$Wb\bar{b}$, $Wc\bar{c}$, single-top **all** are larger than continuum
WW

The leading edge in M_T^{ll} covers $m_h = 140$ GeV,
and bisects larger Higgs masses

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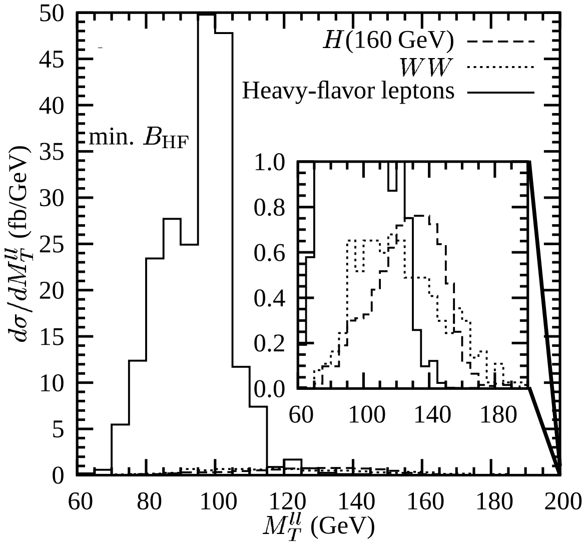

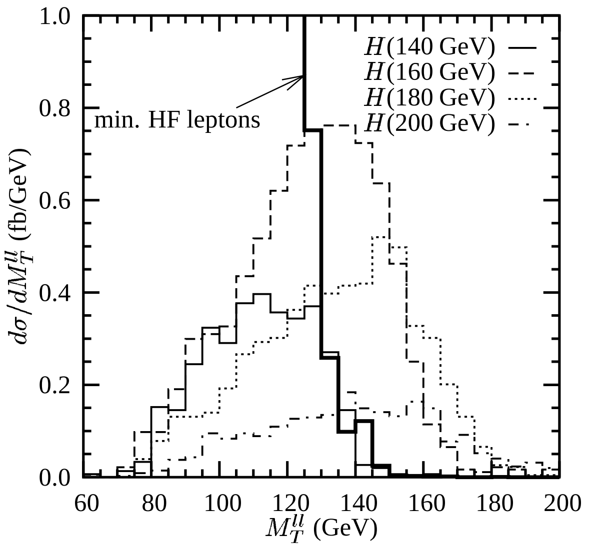

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ATLAS makes a very tight cut:

$m_h - 30(40)$ GeV $< M_T^{ll} < m_h$

in an attempt to extract the upper shoulder of $h \to WW$ from the upper shoulder of continuum WW

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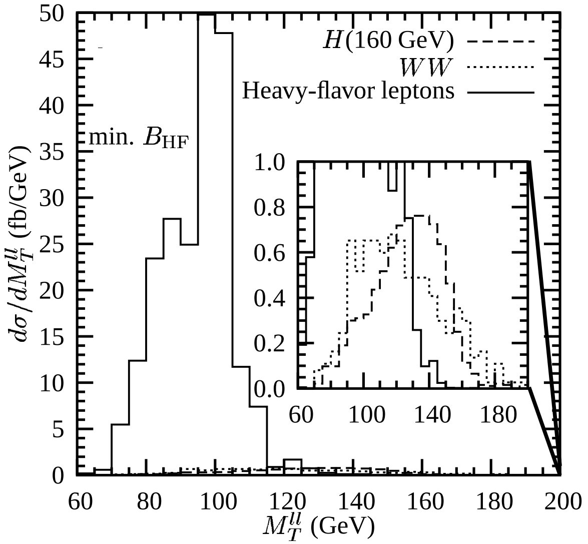

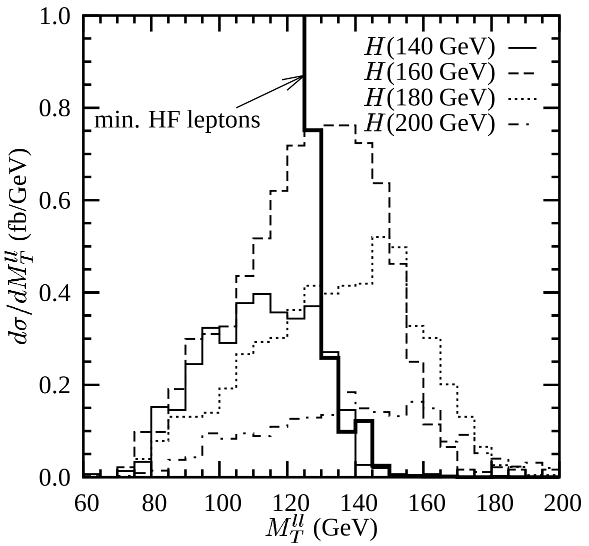

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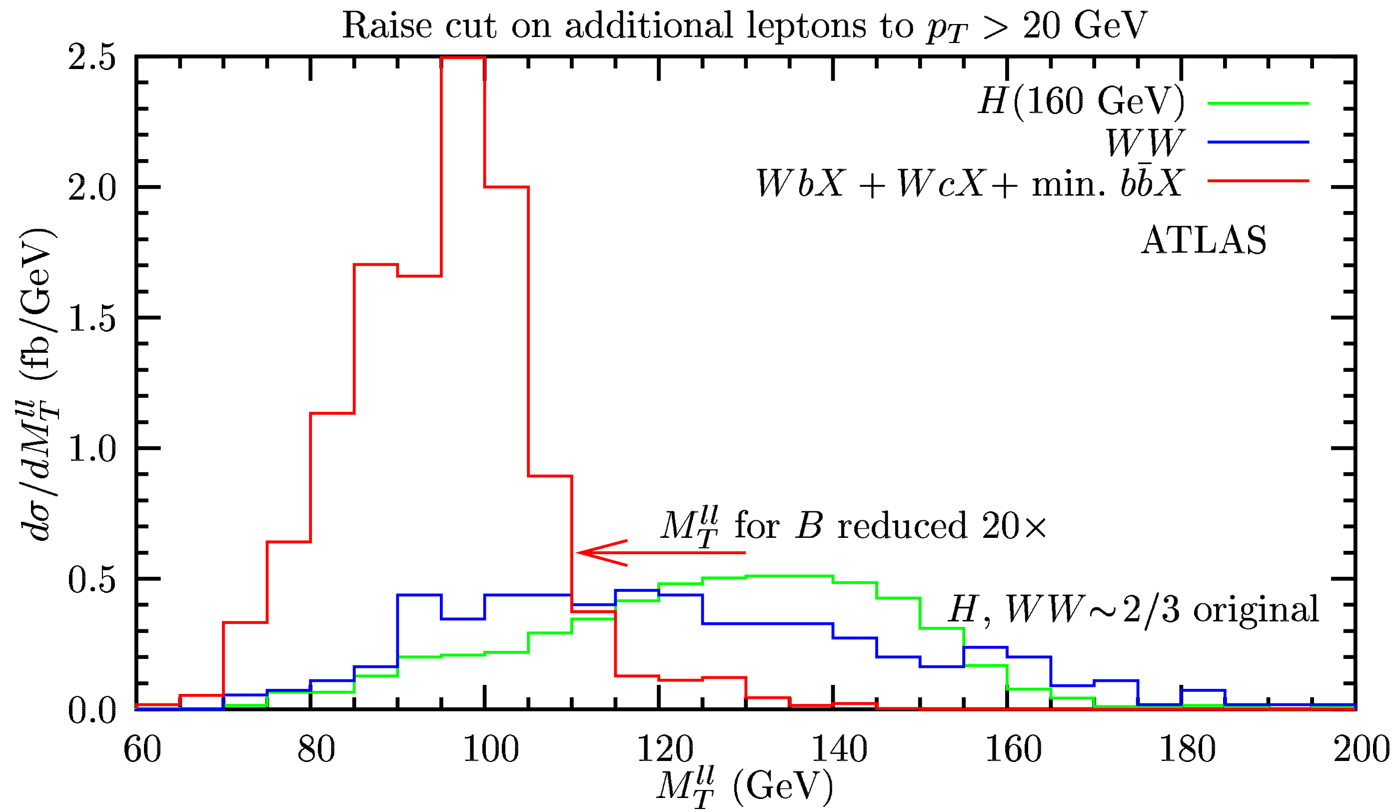
If WW were the only background, this might work

Cannot predict to 10–20 GeV the the position of HF leading edge

However, can measure the HF background . . . and maybe cut it

$M_T^{l\bar{l}}$ distribution with a harder p_T^l cut



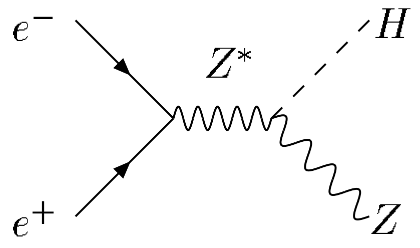
- Harder cut on the p_T of the second lepton suppresses the heavy flavor background, by a factor of about 20, but has only a small effect on the $h \to WW$ and continuum WW contributions.
- The leading edge of the heavy flavor contribution drops to lower $M_T^{l\bar{l}}$

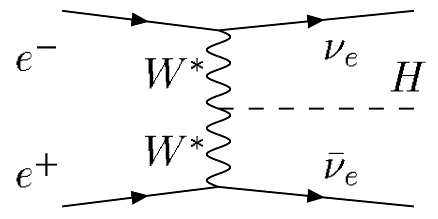
Summary for $h \to W^+W^- \to l\bar{l}\nu\bar{\nu}$ at LHC

- Previously omitted heavy flavor backgrounds are potentially huge: not killed by isolation
- Raising the p_T^l cut on the non-leading lepton appears essential
- Lepton identification criteria and isolation cuts will change once data are in-hand and real detector response is known
- Shape of the background is a limiting factor – not clear we can simulate tails well – could be worse
- 'Measure' the background in the transverse mass distribution?
- Can do a study now with a good sample of $b\bar{b}$ events in Tevatron data to measure what fraction of leptons from b decay pass isolation cuts
- Heavy flavor backgrounds are an issue for all BSM signals with leptons in the final state; e.g., requirement to raise the p_T^l cut will affect SUSY studies with multi-lepton final state signatures

$h \to W^+W^- \to l\bar{l}\nu\bar{\nu}$ at the ILC

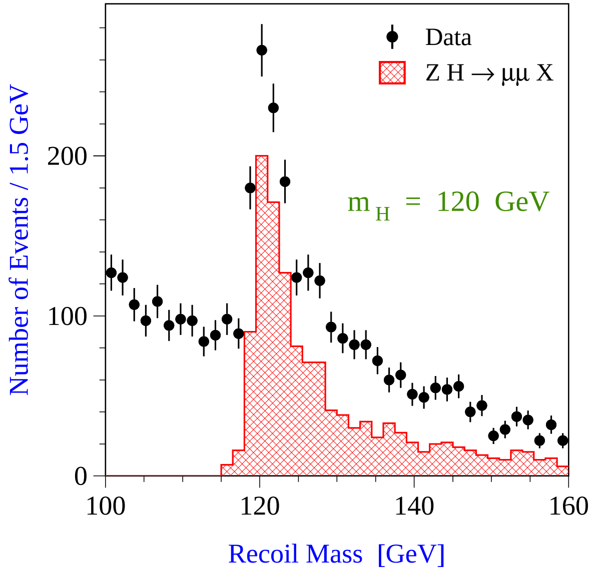
~~Higgs production mechanisms (Higgs-strahlung and WW fusion)~~





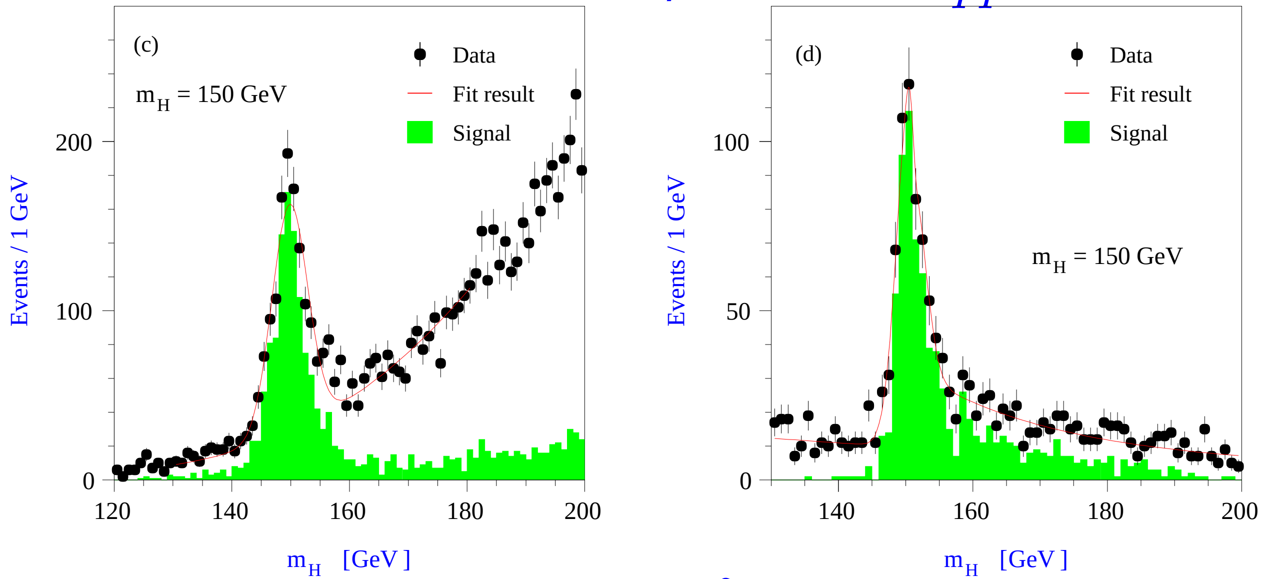
Also ZZ fusion

- Higgs boson mass is well determined ($\delta m/m \sim 100$ MeV), independently of decays, via the recoil mass from the Z from Tesla TDR



$h \to W^+W^-$ *final states at the ILC*

- $h \to W^+W^-$ decays dominate for $m_h > 150$ GeV
  Higgs boson decay can be fully reconstructed from hadronic W decays in $e^+e^- \to hZ \to W^+W^-Z$, with $Z \to q\bar{q}$ or $Z \to l\bar{l}$



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- (c), $Z \to q\bar{q}$; (d) $Z \to l\bar{l}$; $\sqrt{s} = 350$ GeV and $\int L dt = 500$ fb^{-1}
  Garcia-Abia, Lohmann, Raspereza, LC-PHSM-2000-062
- Branching fraction $BR(h \to WW^*)$ can be measured to $\sim 4\%$in $e^+e^- \to hZ \to WW^*Z$, with $WW^* \to 4$ jets or $WW^* \to l\nu + 2$ jets
- Can also use the Higgs-strahlung process to determine g_{hZZ} and the WW fusion process (plus a known branching fraction) for g_{hWW}

Anything (e.g., J^{PC}) to learn from $h \to W^+W^- \to l^+l^- + E_{\rm miss}$ at the ILC?

- $e^+e^- \to hZ$, with $Z \to l^+l^-$, with $h \to W^+W^- \to l^+l^- + E_{\rm miss}$, has interesting kinematic signatures in the 4 charged lepton final state, especially near threshold .
- In $W \to l\nu$ (unlike $W \to q\bar{q} \to 2$ jets), we can identify the electric charge of the lepton, whether l^+ or l^-. The electric charge tells us the helicity (right- or left-handed). In $W^- \to l^-\nu$, the decay l^- goes in the direction opposite to the spin orientation of the W
- Determination of the charges of the two leptons in $h \to W^+W^- \to l^+l^- + E_{\rm miss}$ tells us the spin orientations of each of the W's
- Work in progress
- Request to the audience: if anyone knows of studies of $h \to W^+W^- \to l^+l^- + E_{\rm miss}$ at the ILC, please let me know

BACKUPS

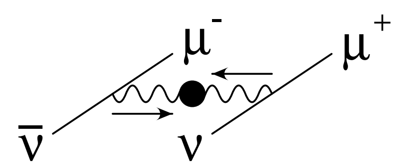
DØ-like search ($\mu^+\mu^-$), $m_h = 160$ GeV; $\sigma(\mathrm{fb})$

Cut level	WW	$b\bar{b}$	$c\bar{c}$	Wc	$Wb\bar{b}$	$Wc\bar{c}$
Inclusive	1.3×10^4	2.7×10^9	3.3×10^9	1.2×10^5	5.0×10^4	5.0×10^4
Isolated $\mu^+\mu^-$	62	7.8×10^6	5.3×10^4	85	36	16
$p_{T_{\mu_1}} > 15$ GeV	61	5.8×10^6	3.9×10^4	82	34	15
$\not{E}_T > 20$ GeV	49	208	5	51	19	7.5
$\not{E}_{T\,\mathrm{scaled}} > 15$	42	24	< 0.1	38	7.7	4.4
$H_T < 100$ GeV	42	24	< 0.1	38	7.7	4.3
$\Delta\phi_{ll} < 2.0$	19	24	< 0.1	12	3.3	1.8
Interval cuts	9.3	24	< 0.1	3.1	2.0	0.9

"Inclusive" $b\bar{b}$, $c\bar{c}$ already have some cuts applied: $E_T > 10$ GeV; $|\eta| < 3.25$

Isolated $\mu^+\mu^-$ means 2 reconstructed OS muons, $p_T > 10$ GeV

- $W + X$ is chipped away and finally reduced by "interval cuts" (the most effective of which is 20 GeV $< M_{ll} < m_h/2$)
- $b\bar{b}$, $c\bar{c}$ are reduced primarily by the $\not{E}_T$ cuts
- reason for $\Delta\phi_{ll}$ cut: spin correlations in h decay:



Once $\not{E}_T$ cut is applied, $b\bar{b}$ is already in a configuration that passes the rest of the cuts

Breakdown of LS/OS leptons at DØ

σ_{ll} (fb):	ee		$e\mu$		$\mu\mu$	
	LS	OS	LS	OS	LS	OS
$h \to WW$	—	0.73 ± 0.04	—	1.26 ± 0.05	—	0.60 ± 0.03
WW	—	12 ± 1	—	20 ± 1	—	9.3 ± 0.9
$b\bar{b}(j)$	—	2.1	—	5.6	—	24
Wc	0.8 ± 0.4	2.3 ± 1.1	1.1 ± 0.4	3.7 ± 1.8	—	3.1 ± 2.2
$Wb\bar{b}$	0.4 ± 0.2	0.4 ± 0.1	2.1 ± 1.6	1.3 ± 0.4	2.5 ± 1.6	2.0 ± 1.1
$Wc\bar{c}$	1.4 ± 0.5	1.1 ± 0.4	1.0 ± 0.2	1.6 ± 0.3	1.0 ± 0.4	0.9 ± 0.2
all else	0.1	1.6	0.3	0.3	0.04	0.1

$b\bar{b}$ contribution more than doubles the background to $\mu^+\mu^-$

Other channels see 50% increases

Is this consistent with the DØ result? Yes, to within 1–2σ

Should you trust this result as an absolute prediction? No

To understand all of the physical processes at play,
we must try to measure the backgrounds. . .

Why does varying isolation cuts have such a small impact?

Essentially, all experiments have tuned their isolation cuts to have high lepton acceptance, with reasonable rejection vs. jets faking leptons.

It is possible to get factors of 2–3 suppression of the heavy-flavor background by using tighter cuts.

- CDF did this in Note 7152 to get a very pure WW cross section.
- They got purity by sacrificing real signal leptons, and killing $H \to WW$.

The only question is whether the hadron remnant is seen.

Our simulations suggest:

- $\sim 1/2$ of the events pass the usual isolation cuts, because the remnant is just outside whatever cone is used for tracking/energy cuts.
- $\sim 1/2$ of the events pass because the lepton took nearly all of the energy. Hence, there is nothing left to reject on.

  These events are not good candidates to reject with impact parameter cuts — they tend to point back to the primary vertex.