Higgs Physics at Hadron Colliders

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Outline

- Introduction
  - The Higgs mechanism and the origin of mass
  - Higgs couplings: the test of the model
  - Other models where Higgs couplings can be nonstandard

- A Taste of Precision: the International Linear Collider (ILC)

- The Nearer Future: the Large Hadron Collider (LHC)
  - Higgs discovery (if Tevatron doesn't)
  - Our first shot at coupling measurements

- LHC Higgs physics beyond the Standard Model: an invisibly-decaying Higgs

- Conclusions

Introduction: the mystery of mass

If all we knew were QED and QCD, we could write down fermion masses as

$$\mathcal{L} = -m\bar{f}_R f_L + \text{h.c.}$$

• But in the Standard Model, fermions are chiral: f_L and f_R have different SU(2)×U(1) quantum numbers.

- The mass term above is not gauge invariant!

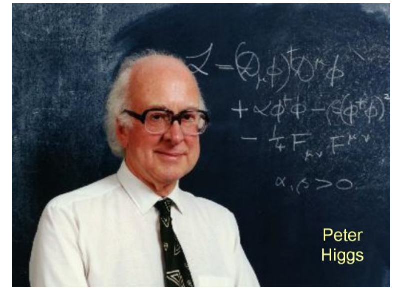
• We also know that the W and Z bosons have a nonzero mass.

- This also violates gauge invariance!

• Massless gauge bosons have two polarizations; massive ones have three:

- Where does the third polarization degree of freedom come from?

The simplest solution:



The Higgs mechanism

- Introduce a scalar "Higgs" field H
  - doublet under SU(2)
  - carries U(1) hypercharge

- Write down couplings of H to gauge bosons (via the covariant derivative, $\mathcal{L} = |\mathcal{D}_\mu H|^2$) and to fermions (Yukawa couplings, $\mathcal{L} = y_f \bar{f}_L H f_R$).
  - These are all gauge invariant.

- Write down a mass and self-interaction for H: the Higgs potential

$$V = m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

  - Also gauge invariant.

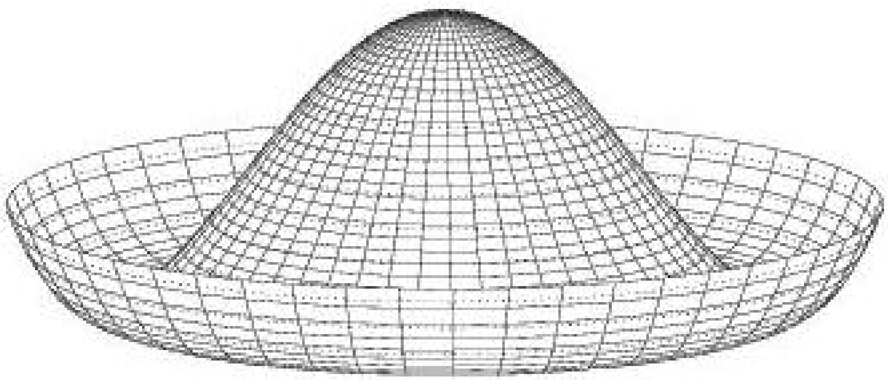
Now the trick:

Choose the signs of the terms in the Higgs potential.

$$V = m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

- m^2 is negative
- λ is positive (why? SM gives no explanation.)

The Higgs potential looks like this:



• The potential is symmetric under the SU(2)×U(1) gauge symmetry.

• The minimum of the potential is away from zero field value – must choose a particular (non-symmetric) configuration.

This is spontaneous symmetry breaking.

The “Higgs field” takes a nonzero value that fills all of space. This is what breaks electroweak symmetry in the Standard Model.

What does this mean?

Here’s an analogy...

(by David Miller; cartoons from CERN)

Imagine a cocktail party of political workers...

These represent the Higgs field filling space.

An ex-Prime Minister enters and crosses the room. Political workers cluster around her...

The Higgs field interacts with a particle, giving it a mass.

Now imagine that a rumor enters the room...

The rumor generates a cluster of people, which propagates across the room...

The Higgs boson is an “excitation” of the Higgs field.

(...back to the language of physics...)

At the minimum of the potential (the ground state), the Higgs field has a nonzero vacuum expectation value v. Write it as a constant plus perturbations:

$$H = \begin{pmatrix} G^+ \\ (h+v)/\sqrt{2} + iG^0/\sqrt{2} \end{pmatrix}$$

• h is the massive excitation of the field: the physical Higgs boson.

• G^0 and G^+ are the would-be Goldstone bosons: they become the third polarization degree of freedom of the Z and W^+ gauge bosons.

• Insert into the covariant derivative, $\mathcal{L} = |\mathcal{D}_\mu H|^2$:

- Gives the gauge bosons masses and couplings to the physical Higgs field:

$$\mathcal{L} = (g^2 v^2/4) W^+ W^- + (g^2 v/2) h W^+ W^- + (g^2/4) hh W^+ W^-$$

and similarly for the Z boson

• Insert into the Yukawa coupling, $\mathcal{L} = y_f \bar{f}_R H f_L + \text{h.c.}$:

- Gives the fermions masses and couplings to the physical Higgs field:

$$\mathcal{L} = (y_f v/\sqrt{2}) \bar{f}_R f_L + (y_f/\sqrt{2}) h \bar{f}_R f_L + \text{h.c.}$$

• Notice that the mass of each particle is proportional to its Higgs coupling!

• We know the proportionality constant since we know the gauge coupling g and the W boson mass: $v = 246$ GeV.

• Test of the Higgs mass-generation mechanism in the Standard Model: Measure the Higgs couplings to SM particles.

Insert the known masses of the SM particles to predict their couplings to the Higgs:

- Gauge boson couplings:

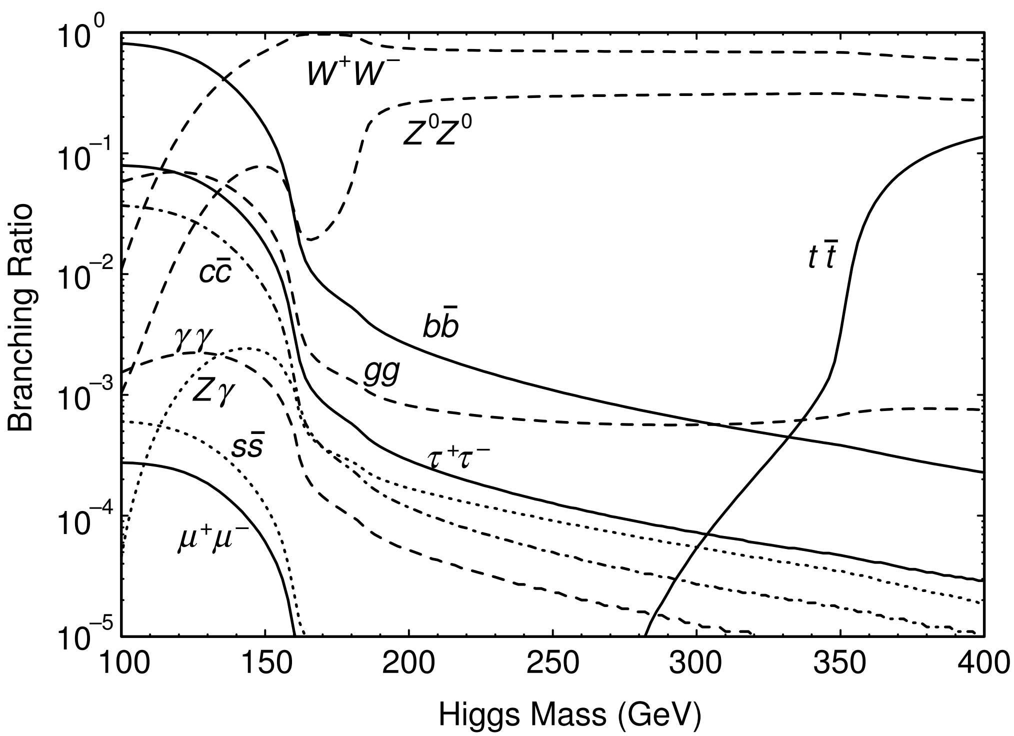
$$\mathcal{L} = (2m_W^2/v)hW^+W^- + (m_W^2/v^2)hhW^+W^-$$

and similarly for the Z boson

- Fermion couplings:

$$\mathcal{L} = (m_f/v)h\bar{f}f$$

We know $v = 246$ GeV in the SM.



Unique predictions for Higgs branching fractions in the SM, as a function of the (unknown) Higgs mass.

HDECAY

• This simple relation between masses and Higgs couplings holds in the Standard Model.
- Beyond the Standard Model, Higgs couplings could be different.

An example: the Minimal Supersymmetric Standard Model (MSSM)

• The MSSM has two Higgs doublets, H_1 and H_2
with two different vacuum expectation values, v_1 and v_2.

• The W boson mass comes from the combination of covariant derivatives: $\mathcal{L} = |\mathcal{D}_\mu H_1|^2 + |\mathcal{D}_\mu H_2|^2$

• This gives $m_W^2 = g^2 v_1^2/4 + g^2 v_2^2/4 = g^2 v_{SM}^2/4$

• So v_1 and v_2 must obey $v_1^2 + v_2^2 = v_{SM}^2$ to give the correct W boson mass. There is one unknown combination, $v_2/v_1 = \tan\beta$.

MSSM, continued

Two Higgs doublets: $\rightarrow$ the physical states are:

- h, the lightest CP-even Higgs
- H, A, and $H^{\pm}$, the heavier CP-even, CP-odd, and charged Higgses

• h is a linear combination of H_1 and H_2, with a mixing angle α.

• In most of SUSY parameter space, H, A, and $H^{\pm}$ are heavy and the couplings of h are quite similar to those of the SM Higgs – the decoupling limit.

• Any deviations of the h couplings from the SM expectations give us valuable information about the structure of the Higgs sector!

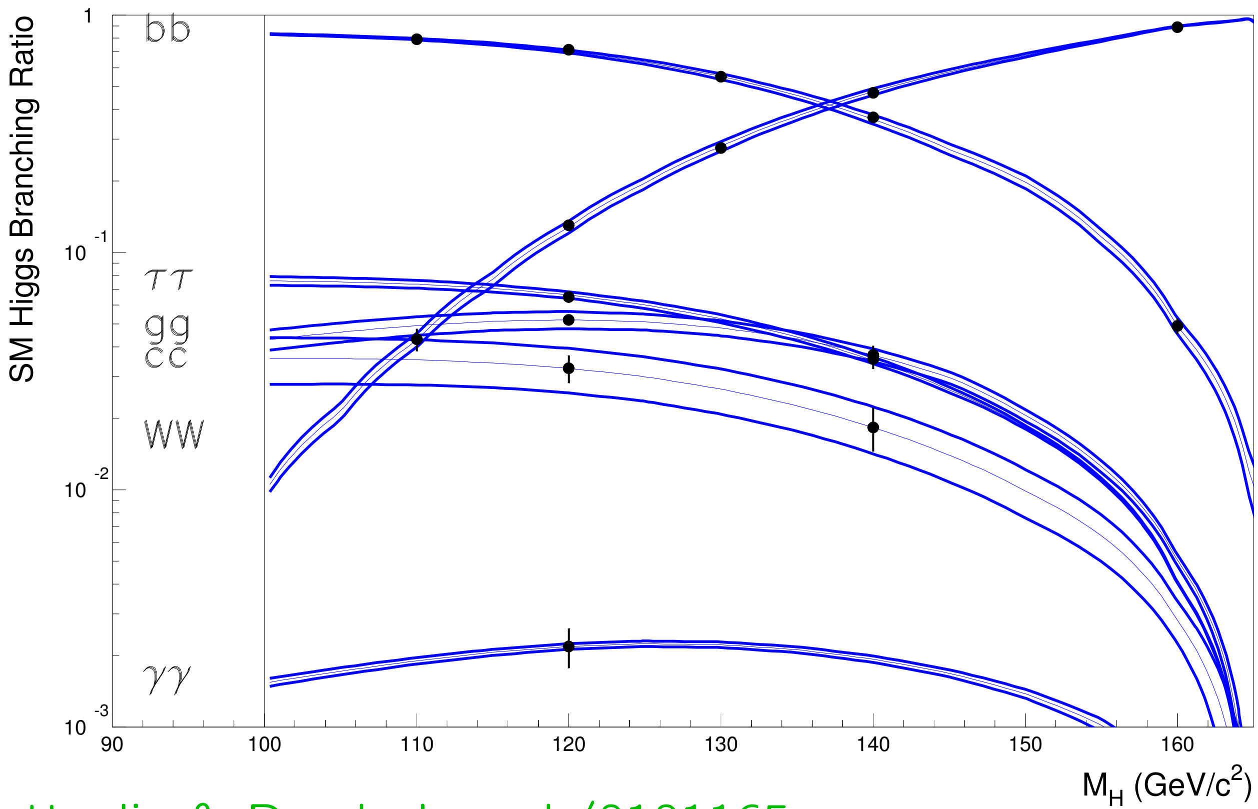
How can we measure all this?

A Taste of Precision: the International Linear Collider

An e^+e^- collider is a wonderful thing.

- Clean environment – no large QCD backgrounds
- Well-known initial state
  - no parton distributions: initial state particles are known
  - energy/momentum of initial state is known
- Model-independent techniques for measuring Higgs couplings
- High luminosity $\longrightarrow$ large statistics

Measure Higgs branching ratios to high precision!



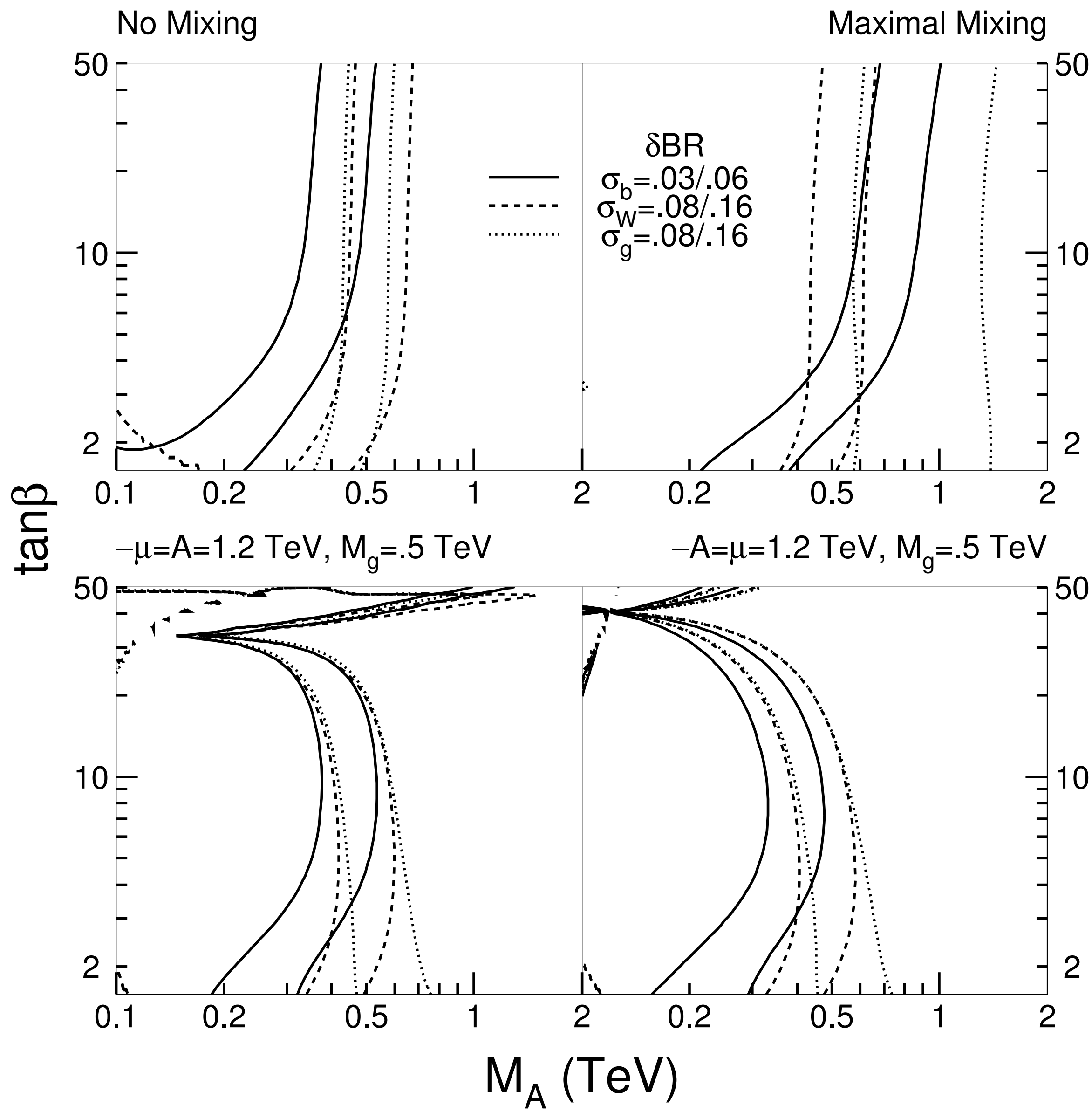
Battaglia & Desch, hep-ph/0101165

For a 120 GeV SM-like Higgs boson:

BR	$b\bar{b}$	WW^*	$\tau\tau$	$c\bar{c}$	gg	$\gamma\gamma$
Precision	2.4%	5.1%	5.0%	8.3%	5.5%	23%

K. Desch, hep-ph/0311092

Use the high-precision measurements of Higgs couplings to look for deviations from the Standard Model



Example:
MSSM benchmark scenarios

Contours of
$\delta BR(b) = 3\%,\ 6\%$
(solid),
$\delta BR(W) = 8\%,\ 16\%$
(long-dashed),
$\delta BR(g) = 8\%,\ 16\%$
(short-dashed)
($\sim$ 1, 2 sigma).

Carena, Haber, H.L., Mrenna (2002)

An e^+e^- collider is a wonderful thing...

... but it will be many years before ILC data is available.

- An expensive machine – need international cooperation
- Not yet approved
- 8 years (?) to build

The Large Hadron Collider (LHC) is already under construction – scheduled to start running in 2007!

Hadron collider:

  - Large QCD backgrounds
  - Initial-state kinematics unconstrained: PDFs

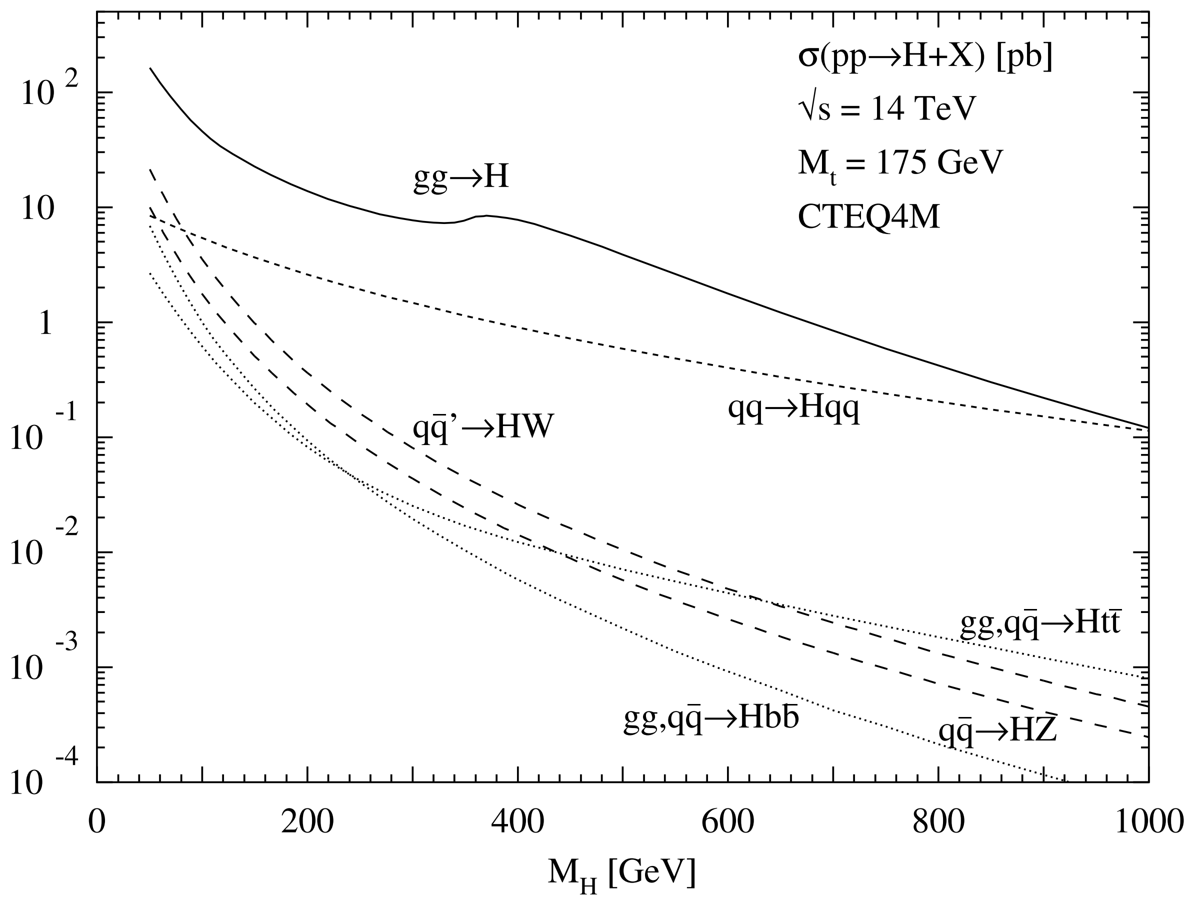
But!

  - Already under construction
  - A powerful machine with good reach for Higgs physics
  - We will have LHC data quite soon!

How can we use it to learn as much as possible about the Higgs?

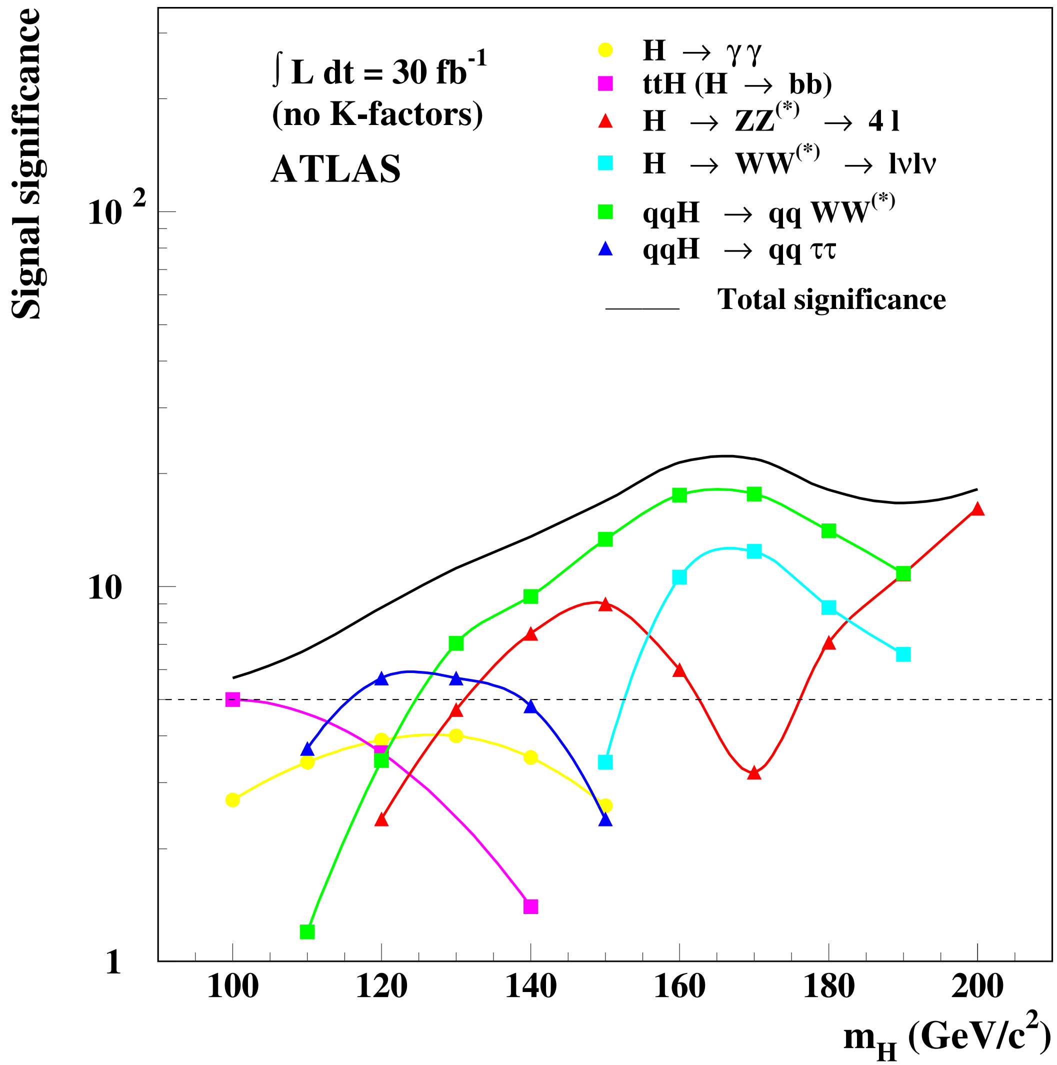
The near future: Large Hadron Collider

- Proton-proton collider, 14 TeV center-of-mass energy.
- Lots of data:
  - Initial "low luminosity" run, 10 fb^{-1}/year
  - Later "high luminosity" run, 100 fb^{-1}/year
- Higgs production cross sections are reasonably large:



M. Spira, Fortsch. Phys. 46, 203 (1998)

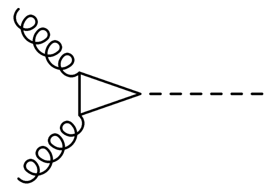
If the Higgs is Standard Model-like, LHC will discover it!



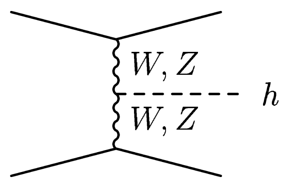
S. Asai et al., Eur.Phys.J.C 32S2, 19 (2004)

Higgs will be accessible via multiple production mechanisms

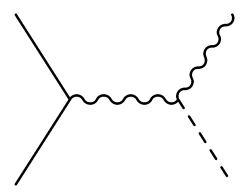
- Gluon fusion, $gg \to H$



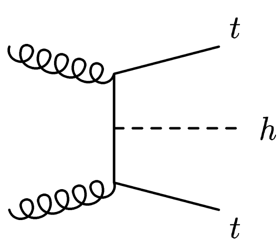
- Weak boson fusion, $qq \to Hqq$



- WH, ZH associated production



- ttH associated production



Higgs will be accessible in multiple decay channels

GF $gg \to H \to ZZ$

WBF $qqH \to qqZZ$

GF $gg \to H \to WW$

WBF $qqH \to qqWW$

$t\bar{t}H$, $H \to WW$

WH, $H \to WW$

Inclusive $H \to \gamma\gamma$

WBF $qqH \to qq\gamma\gamma$

$t\bar{t}H$, $H \to \gamma\gamma$

WH, $H \to \gamma\gamma$

ZH, $H \to \gamma\gamma$

WBF $qqH \to qq\tau\tau$

$t\bar{t}H$, $H \to b\bar{b}$

GF = gluon fusion
WBF = weak boson fusion

• The Higgs couplings fix the production cross sections and decay branching ratios $\longrightarrow$ determine the rates in each channel.

• By measuring rates in multiple channels, various combinations of couplings can be determined.

• Take ratios of rates with same production and different decays: production cross section and Higgs total width cancel out.

$$\frac{WBF \to H \to WW^*}{WBF \to H \to \tau\tau} = \frac{\Gamma(H \to WW^*)}{\Gamma(H \to \tau\tau)} \propto \frac{g_{HWW}^2}{g_{H\tau\tau}^2}$$

• Take ratios of rates with different production and same decay: decay BRs cancel out.

$$\frac{gg \to H \to \gamma\gamma}{WH, H \to \gamma\gamma} = \frac{\sigma(gg \to H)}{\sigma(q\bar{q} \to WH)} \propto \frac{g_{Hgg}^2}{g_{HWW}^2}$$

• Ratios of Higgs couplings-squared to WW^*, ZZ^*, $\gamma\gamma$, $\tau\tau$ and gg can be extracted to 15–30% for $M_H = 120$ GeV.

Zeppenfeld et al., PRD62, 013009 (2000)

Measuring ratios of couplings already tests the Higgs mechanism for mass generation.

But we want to go farther: measure each coupling independently if we can!

- Difficulties:
  - No measurement of inclusive production rate like at LC.
  - Some decays cannot be directly observed at LHC due to backgrounds: $H \to gg$, $H \to$ light quarks, ...

- Incomplete data: can't extract individual couplings in a totally model-independent way.

- To make progress, we have to make some theoretical assumptions.

The first step is model-independent:

- Observation of Higgs production
  $\longrightarrow$ lower bound on production couplings
    $\longrightarrow$ lower bound on Higgs total width.

But there is no model-independent upper bound on Higgs total width.

Some strategies:

- Assume no unexpected decay channels
  $\longrightarrow$ total width extraction from observed modes

- Assume SM ratio of Higgs couplings to $b\bar{b}$ and $\tau\tau$
  - $b\bar{b}$ channel suffers from large QCD background

    Zeppenfeld, Kinnunen, Nikitenko, Richter-Was (2000)
  - Not necessarily true in MSSM!
  - More model-independent: use ttH, $H \to b\bar{b}$ channel.

    Belyaev & Reina, (2002)

A new strategy:

Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld (2004)

- Consider Higgs models containing only SU(2) doublets/singlets
  - hWW and hZZ couplings are related by custodial SU(2)
  - hWW and hZZ couplings are bounded from above by their SM values

- A mild assumption!
  - True in most good models: MSSM, NMSSM, 2HDM, ...
  - Larger Higgs multiplets stringently constrained by ρ parameter

Theoretical constraint $\Gamma_V \leq \Gamma_V^{\rm SM}$
$\oplus$ measurement of $\Gamma_V^2/\Gamma_{\rm tot}$ from WBF $\to H \to VV$
$\longrightarrow$ upper bound on Higgs total width.

- Combine with lower bound on Higgs total width from production couplings
  - This interplay provides constraints on remaining Higgs couplings.
  - Make no assumptions on unexpected/unobserved Higgs decay modes.

- A second approach: fit the observed rates to a particular model. E.g., chi-squared fits in specific MSSM scenarios.

How well can Higgs couplings be extracted from LHC data using this method?

Do a fit of all the LHC Higgs analyses!

- Assume SM rates for statistics

- Allow additional unobserved Higgs decays
  - constrain using the fit

- Allow new particles running in the loops for $gg \to h$ and $h \to \gamma\gamma$
  - constrain using the fit

- Include correlated systematic uncertainties (next slide)

- Find 1σ uncertainty on each Higgs coupling

Systematic uncertainties:
correlated between the various channels.

5% overall Luminosity normalization

Theory uncertainties on Higgs production:

- 20% GF
- 15% $t\bar{t}H$
- 7% WH, ZH
- 4% WBF

Reconstruction/identification efficiencies:

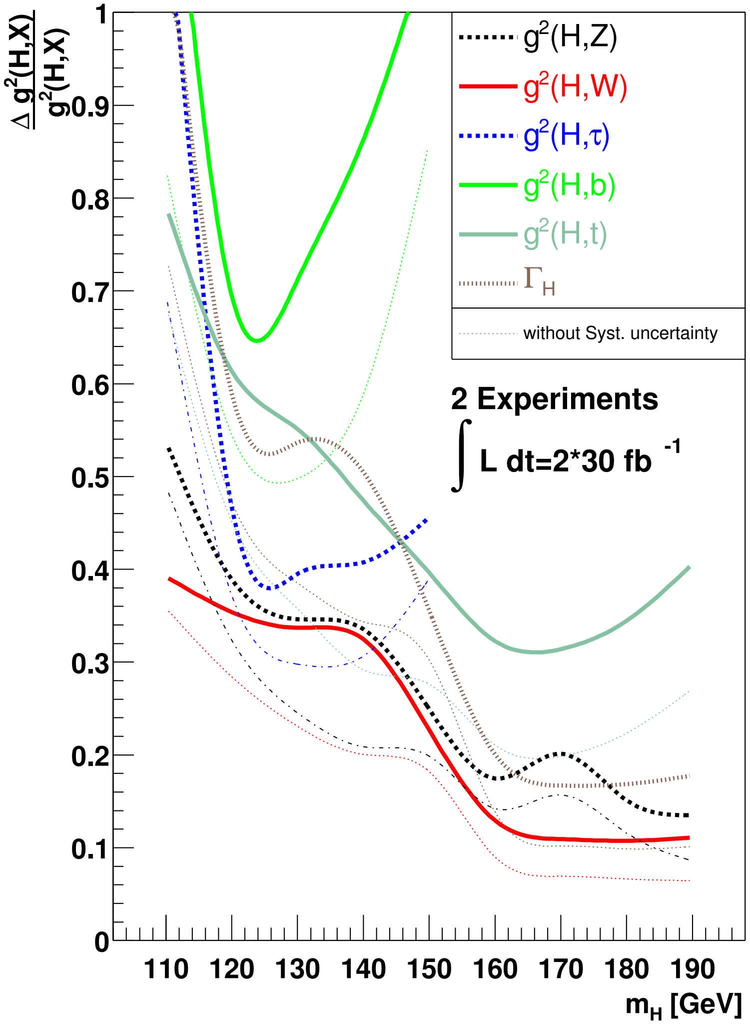
- 2% leptons
- 2% photons
- 3% b quarks
- 3% τ jets
- 5% forward tagging jets and veto jets (WBF)

Background extrapolation from side-bands (shape):

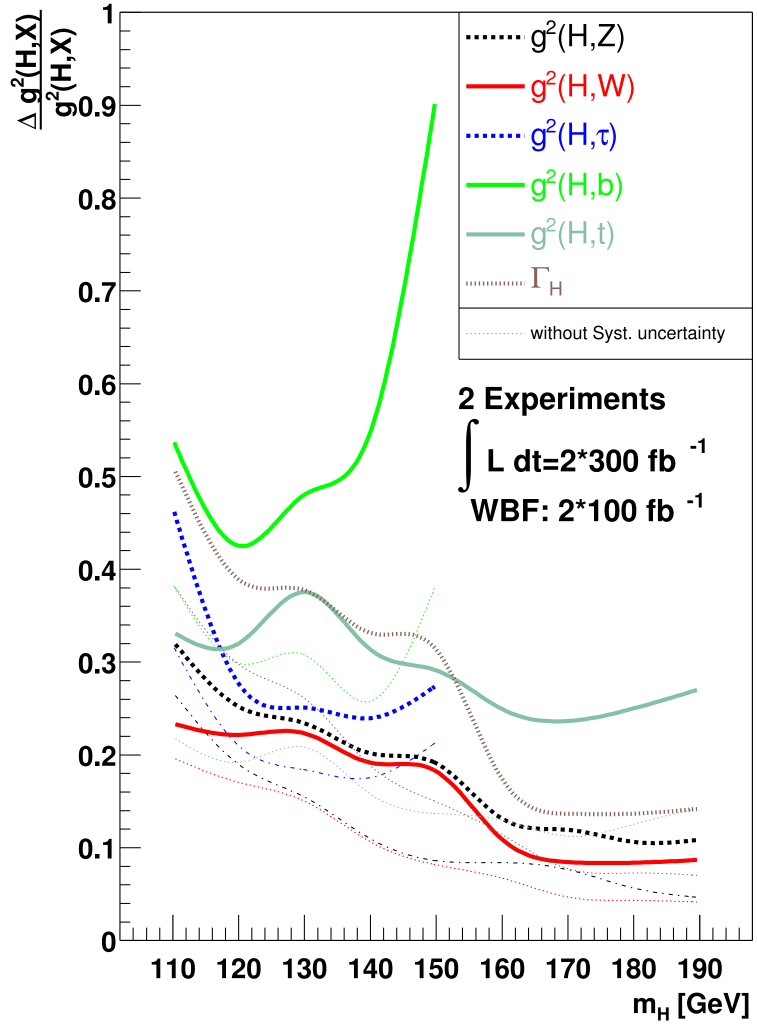
- from 0.1% for $H \to \gamma\gamma$
- to 5% for $H \to WW$ and $H \to \tau\tau$
- to 10% for $H \to b\bar{b}$

Results: fit of Higgs couplings-squared

$30\ \mathrm{fb}^{-1} \times 2$ detectors



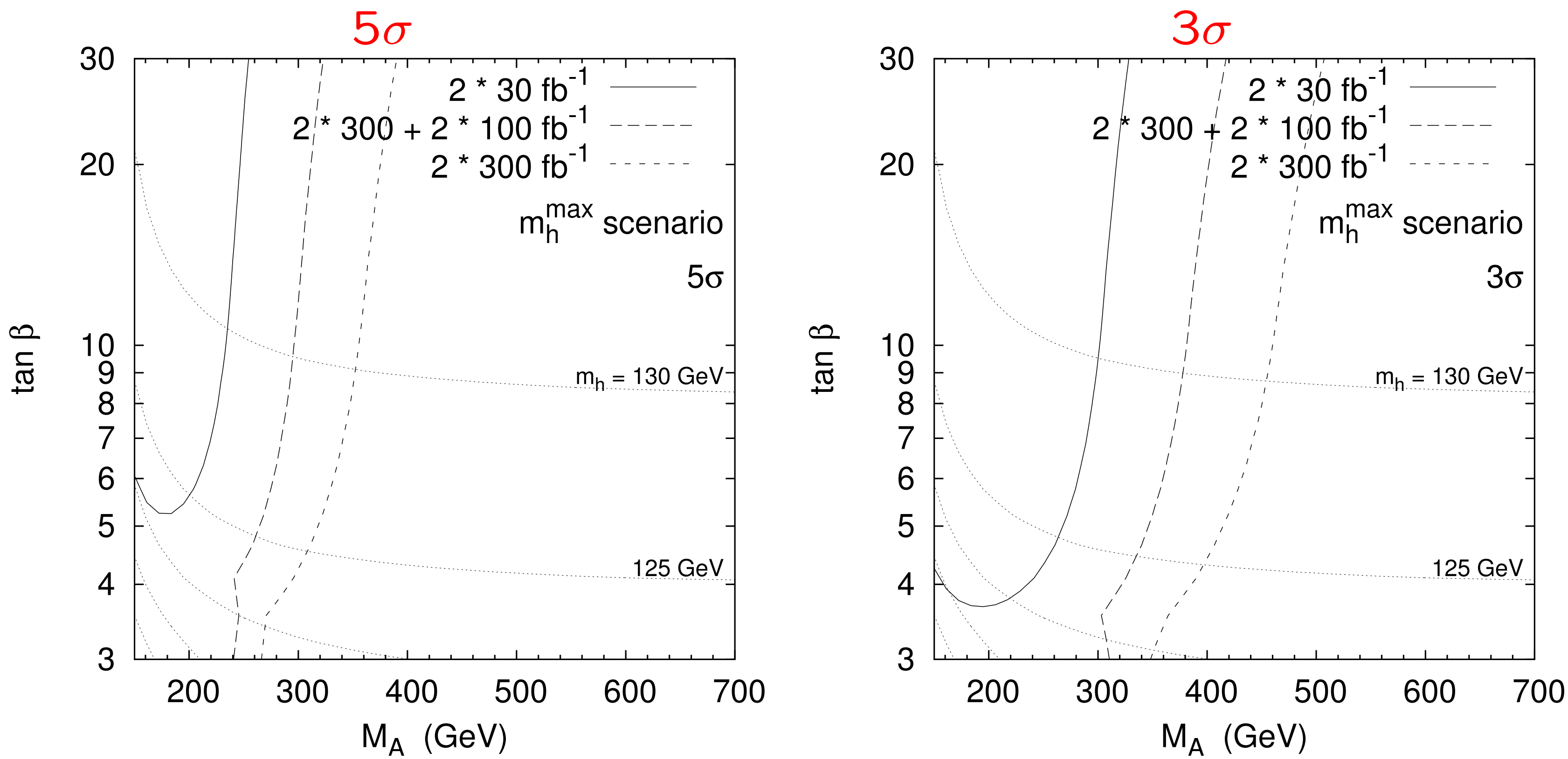
$300/100\ \mathrm{fb}^{-1} \times 2$ detectors



Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld (2004)

Use the sensitivity to Higgs couplings to look for deviations from the Standard Model

Example: MSSM, m_h^{max} scenario



Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld (2004)

Sensitive to MSSM nature of h up to $M_A \lesssim 350$ GeV!
(m_h^{max}, 5σ, high lumi)

Going further at the LHC: non-standard Higgs scenarios

• bbH associated production: could be visible in SUSY with large $\tan\beta$. Use together with $H \to b\bar{b}$.

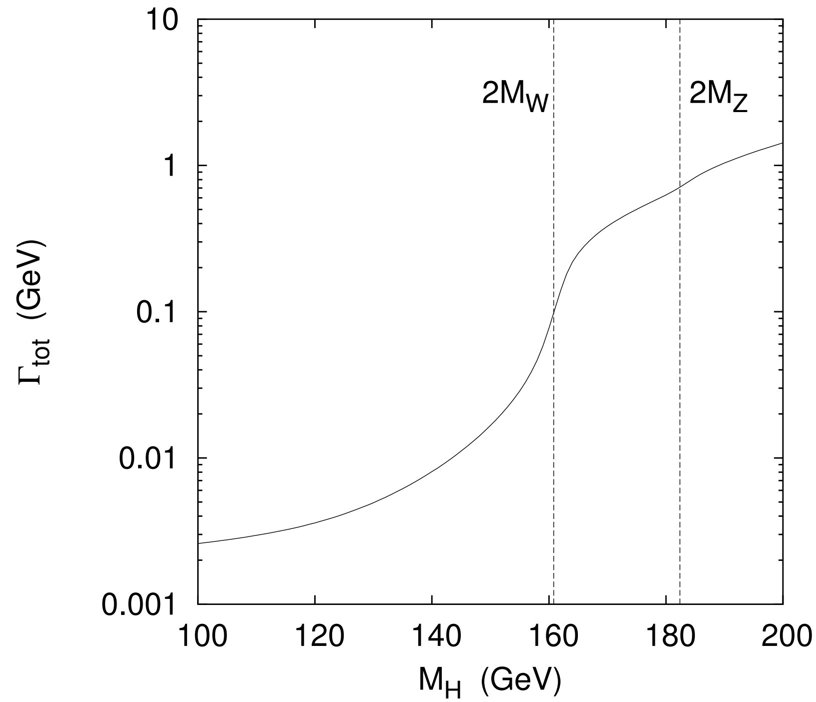
• $H \to \mu\mu$: could be visible at large $\tan\beta$ or if other decays are suppressed.

WBF Plehn & Rainwater; gluon fusion Han & McElrath

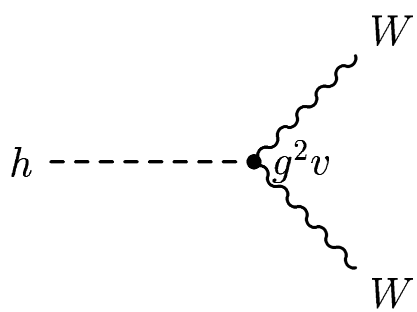
• $H \to$ invisible: could be significant in SUSY, or models with scalar dark matter.

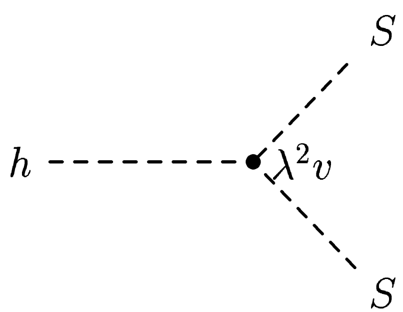
Why consider an invisible Higgs?

The SM Higgs is very narrow for $m_h \lesssim 160$ GeV.



If the Higgs couples with electroweak strength to a neutral (quasi)stable particle (e.g., dark matter) with mass $< m_h/2$, then $h \to$ invisible can be the dominant decay mode.





The Higgs *could* decay invisibly

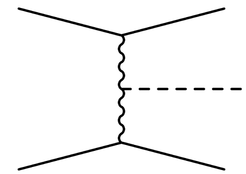
- $h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ in MSSM, NMSSM
- $h \to SS$ in simple models of scalar dark matter
- $h \to$ KK neutrinos in extra dimensions
- $h \to$ Majorons
- $\ldots$

$\longrightarrow$ Cover all our bases!
We shouldn't just assume the Higgs will be SM-like – even small additions (such as scalar singlet dark matter) can make BR($h \to$ invis.) large.

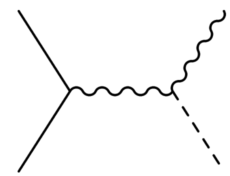
"Invisible" Higgs is not that hard to "see": $\not{p}_T$
$h \to jj$ is much harder.

An invisible Higgs at the LHC

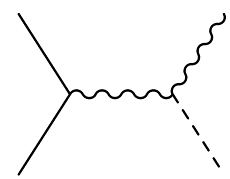
Search modes:



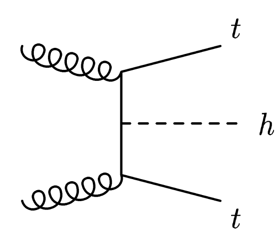
• WBF $\to h_{inv}$ Eboli & Zeppenfeld (2000)
Signal is $jj\not{p}_T$; jets are hard and forward



• $Z + h_{inv}$ Frederiksen, Johnson, Kane & Reid (1994); Choudhury & Roy (1994); Godbole, Guchait, Mazumdar, Moretti & Roy (2003); Davoudiasl, Han & H.L. (2004)
Signal is $\ell^+\ell^-\not{p}_T$, with $m(\ell^+\ell^-) = m_Z$ ($\ell = e, \mu$)

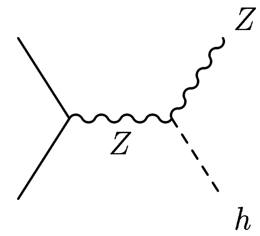


• $W + h_{inv}$ Choudhury & Roy (1994); Godbole, Guchait, Mazumdar, Moretti & Roy (2003)
Signal is $\ell\not{p}_T$; totally swamped by background.



• $t\bar{t}h_{inv}$ Gunion (1994); Kersevan, Malawski & Richter-Was (2002)
Signal is $bjj + b\ell + \not{p}_T$.

Associated $Z + h_{inv}$ production at LHC



Higgs decays invisibly; consider Z decays to leptons.
$\rightarrow$ Signal is $\ell^+\ell^-\not{p}_T$ $(\ell = e, \mu)$

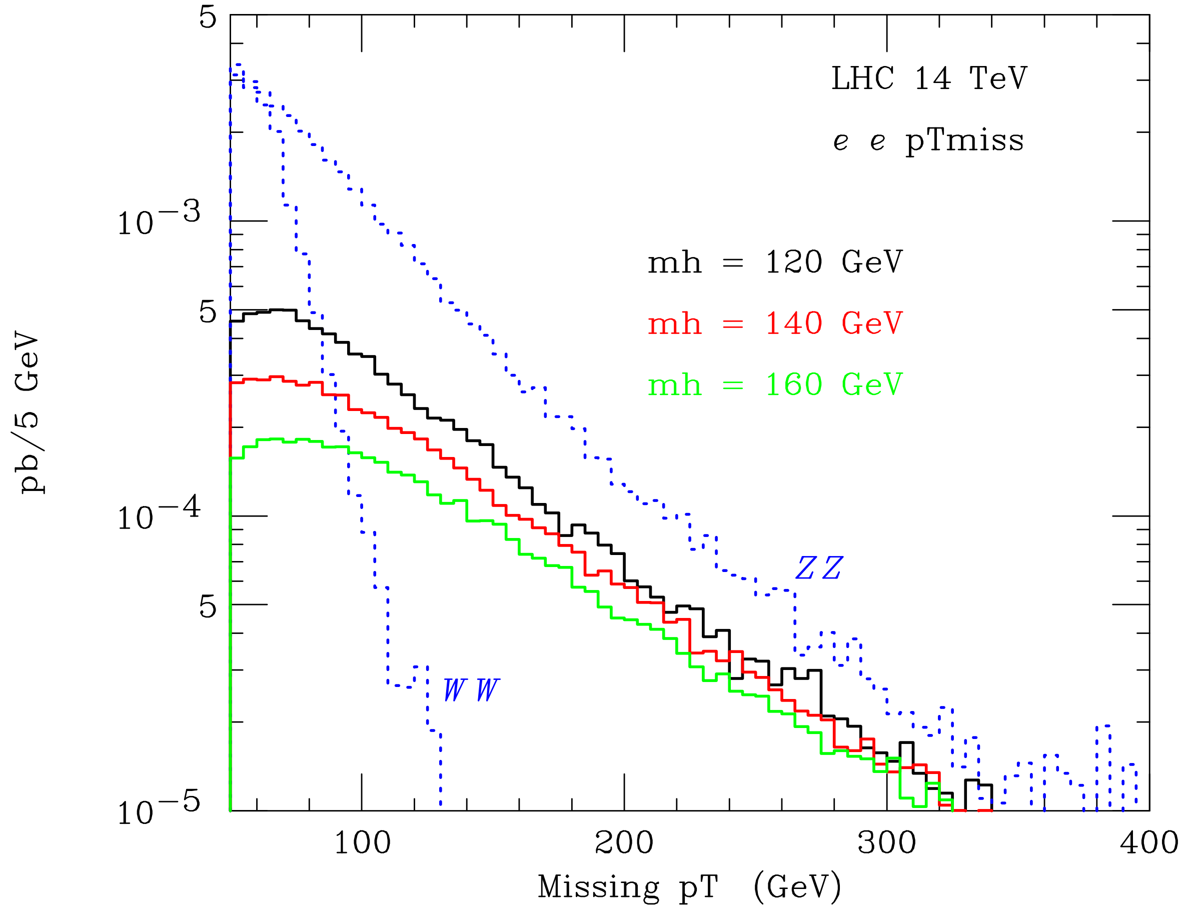
Major backgrounds:

- $Z(\rightarrow \ell^+\ell^-)Z(\rightarrow \nu\bar{\nu})$
- $W(\rightarrow \ell^+\nu)W(\rightarrow \ell^-\bar{\nu})$
- $W(\rightarrow \ell\nu)Z(\rightarrow \ell^+\ell^-)$ with missed lepton
- $Z(\rightarrow \ell^+\ell^-) + j$ with fake $\not{p}_T$

We simulated the $Z + h_{inv}$ signal and the ZZ, WW, and WZ backgrounds using Madgraph.

The $Z + j$ background with fake $\not{p}_T$ comes from $Z + j$ events in which the jet(s) are missed: either they are too soft or they go down the beampipe. We took results for this background from Frederiksen, Johnson, Kane & Reid.

- Apply cuts:
  - Require $\ell^+\ell^-$ reconstruct to Z mass
  - Veto events with jets or an extra lepton
  - Cut on missing p_T:



Including hadronization using PYTHIA/HERWIG [Godbole et al, 2003] does not significantly degrade the results.

Results (LHC, $ee + \mu\mu$)

Signal and background cross sections (after cuts):

$\not{p}_T$ cut	B(ZZ)	B(WW)	B(ZW)	B($Z+j$)*	S($Z + h_{inv}$) $m_h = 120$	140	160 GeV
65 GeV	48.0 fb	10.6 fb	10.2 fb	22 fb	14.8 fb		
75 GeV	38.5 fb	4.3 fb	7.4 fb	9 fb	12.8 fb	9.4 fb	7.0 fb
85 GeV	30.9 fb	1.8 fb	5.5 fb		11.1 fb	8.3 fb	6.3 fb
100 GeV	22.1 fb	0.6 fb	3.6 fb		8.7 fb	6.8 fb	5.3 fb

*B($Z + j$) extrapolated from Frederiksen, Johnson, Kane & Reid

Significance: (parentheses: includes $Z + j$)

$\not{p}_T$ cut	$m_h = 120$ GeV S/B	$m_h = 120$ GeV S/$\sqrt{\text{B}}$ (10 fb^{-1})	$m_h = 120$ GeV S/$\sqrt{\text{B}}$ (30 fb^{-1})	$m_h = 140$ GeV S/$\sqrt{\text{B}}$ (30 fb^{-1})	$m_h = 160$ GeV S/$\sqrt{\text{B}}$ (30 fb^{-1})
65 GeV	0.22 (0.16)	5.6 (4.9)	9.8 (8.5)		
75 GeV	0.25 (0.22)	5.7 (5.3)	9.9 (9.1)	7.3 (6.7)	5.4 (5.0)
85 GeV	0.29	5.7	9.8	7.4	5.6
100 GeV	0.33	5.4	9.3	7.3	5.7

$m_h = 120$ GeV: $> 5\sigma$ signal with 10 fb^{-1}.

With 30 fb^{-1}, 5σ discovery extends out to $m_h = 160$ GeV.

• $Z + h_{inv}$: $S/\sqrt{B} \gtrsim 5$ for $m_h = 120$ GeV and 10 fb^{-1}.

Comparison to WBF$\rightarrow h_{inv}$ process
[Eboli & Zeppenfeld]

• WBF $\rightarrow h_{inv}$ gives much better significance:
$S/\sqrt{B} \simeq 24$ for $m_h = 120$ GeV and 10 fb^{-1}.

• $Z + h_{inv}$ provides an independent discovery channel:
very different search with different systematics
independent handle on h_{inv} production

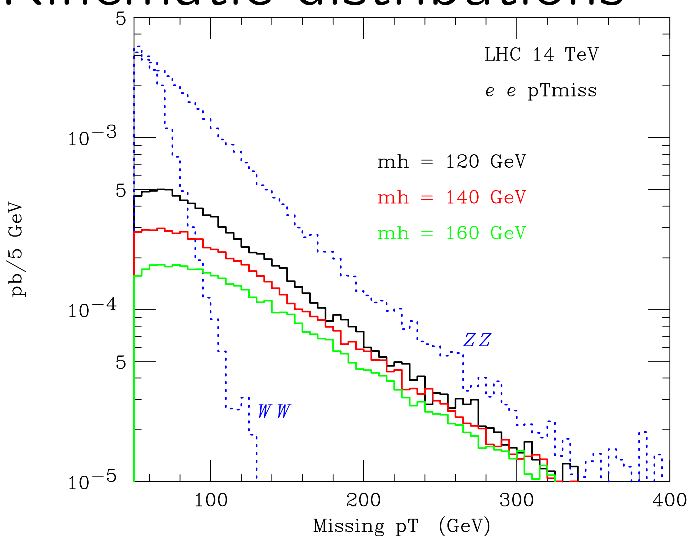
Comparison to $t\bar{t}h_{inv}$ process
[Gunion; Kersevan, Malawski & Richter-Was]

• $t\bar{t}h_{inv}$ is a complicated process – *many* particles in the final state and many backgrounds.
$S/\sqrt{B} \sim 4$ for $m_h = 120$ GeV and 10 fb^{-1}.

Extracting the mass of an invisible Higgs

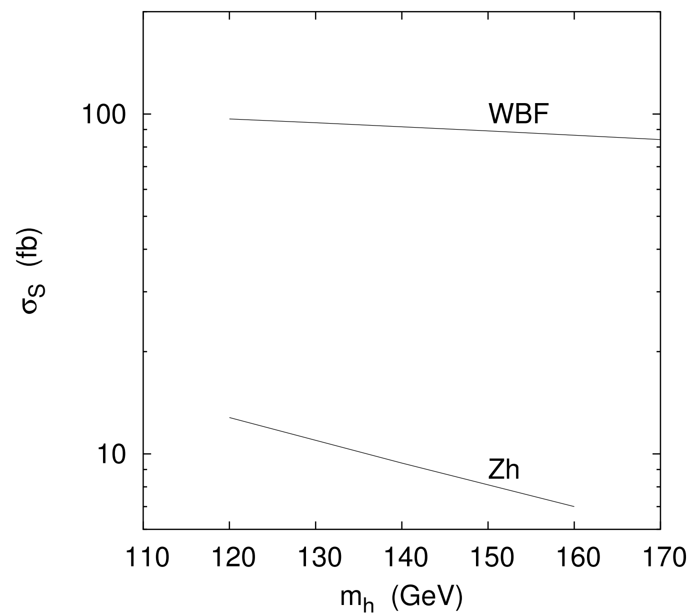
- Mass of h_{inv} accessible only through production process:

Kinematic distributions



(future direction)

Cross section



- Measure signal rate
- Assume SM production cross section, 100% invisible decay.*

$\longrightarrow$ Higgs mass.

*Will remove these assumptions later!

Uncertainties:

- Statistical uncertainty:

$\Delta\sigma_S/\sigma_S = \sqrt{S+B}/S$

- Background normalization:

Backgrounds for $Z + h_{inv}$ and WBF are dominated by $Z \to \nu\nu$.
Can *measure* background rates/shapes in $Z \to \ell\ell$ channel!
Less statistics: $\mathrm{BR}(Z \to \ell\ell)/\mathrm{BR}(Z \to \nu\nu) \simeq 0.28$.

$\Delta\sigma_S/\sigma_S = \sqrt{B \times \mathrm{BR}(\ell\ell)/\mathrm{BR}(\nu\nu)}/S$

- Theory uncertainty: QCD + PDFs

4% for WBF, 7% for $Z + h_{inv}$

- Uncertainty on experimental efficiencies:

5% for WBF forward-jet tag / central-jet veto
4% dilepton tagging (2% per lepton)

- Luminosity normalization: 5%

Higgs mass determination from $Z + h_{inv}$, with 10 (100) fb^{-1}:

m_h (GeV)	120	140	160
$(d\sigma_S/dm_h)/\sigma_S$ (1/GeV)	-0.013	-0.015	-0.017
Statistical uncert.	21% (6.6%)	28% (8.8%)	37% (12%)
Background normalization uncert.	33% (10%)	45% (14%)	60% (19%)
Total uncert.	40% (16%)	53% (19%)	71% (24%)
Δm_h (GeV)	30 (12)	35 (12)	41 (14)

$Z + h_{inv}$: $\Delta m_h = 30\text{–}40\ (12\text{–}14)$ GeV with 10 (100) fb^{-1}

Higgs mass determination from WBF$\to h_{inv}$, with 10 (100) fb^{-1}:

m_h (GeV)	120	130	150	200
$(d\sigma_S/dm_h)/\sigma_S$ (GeV^{-1})	-0.0026	-0.0026	-0.0028	-0.0029
Statistical uncert.	5.3% (1.7%)	5.4% (1.7%)	5.7% (1.8%)	6.4% (2.0%)
Background norm.	5.2% (2.1%)	5.3% (2.1%)	5.6% (2.2%)	6.5% (2.6%)
Total uncert.	11% (8.6%)	11% (8.6%)	11% (8.6%)	12% (8.8%)
Δm_h (GeV)	42 (32)	42 (33)	41 (31)	42 (30)

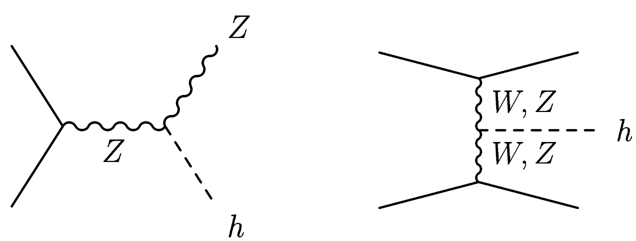
WBF: $\Delta m_h \simeq 40\ (30)$ GeV with 10 (100) fb^{-1}

$Z + h_{inv}$ cross section falls faster with m_h than WBF – more m_h dependence but less statistics.

Extracting m_h from a single cross section relies on SM assumption for production couplings.

- For a more model-independent m_h extraction, take the ratio of $Z + h_{inv}$ and WBF rates!

$Z + h_{inv} \sim hZZ$ coupling; WBF $\sim hWW, hZZ$ couplings – related by SU(2) in models with only Higgs doublets/singlets.



Example: MSSM (or 2HDM)

ZZh coup $= (g m_Z / \cos\theta_W) \sin(\beta - \alpha)$

WWh coup $= g m_W \sin(\beta - \alpha)$

Higgs mass determination from ratio method with 10 (100) fb^{-1}:

m_h (GeV)	120	140	160
$r = \sigma_S(Zh)/\sigma_S(\text{WBF})$	0.132	0.102	0.0807
$(dr/dm_h)/r$ (1/GeV)	-0.011	-0.013	-0.013
Total uncert., $\Delta r/r$	41% (16%)	54% (20%)	72% (25%)
Δm_h (GeV)	36 (14)	43 (16)	53 (18)

Can now learn more about the Higgs!

Test 100% invisible decay:

- Look for visible decays in all detectable channels $\rightarrow$ upper bounds on BRs
- $\sum \mathrm{BR}_i = 1 \longrightarrow \mathrm{BR}_{inv} = 1 - \sum \mathrm{BR}_{other}$
- Cannot exclude certain decays, e.g. $h \rightarrow$ light quarks, $h \rightarrow gg$: background is overwhelming

Assume SU(2) doublets and/or singlets only
(same assumption as we made for ratio method m_h extraction):
hWW and hZZ couplings $\leq$ SM values.
$Z + h$ and WBF *production* cross sections bounded from above by SM values.
$\longrightarrow$ Relatively model-independent *lower bound* on BR_{inv} to produce observed rates in $Z + h_{inv}$ and WBF$\rightarrow h_{inv}$.

Test the assumption of SM production cross section:

- Measure m_h using ratio method
- Compute SM prediction for $\sigma_S(Z+h)$ and σ_S(WBF)
- Compare to measured $\sigma_S(Z+h_{inv})$ and σ_S(WBF)

$\rightarrow$ Probe hZZ, hWW couplings! (modulo BR_{inv})

If we assume no significant branching fraction for $h \rightarrow gg, jj$ (so that $\mathrm{BR}_{inv} + \mathrm{BR}_{SM\ decays} \simeq 1$), then:

- Compute $\Gamma(h \rightarrow WW)$ from hWW coupling and m_h
- Add upper bound on $\mathrm{BR}(h \rightarrow WW)$ from non-observation in WBF$\rightarrow h \rightarrow WW$

$\longrightarrow$ *lower* bound on total Higgs width Γ_{tot}

$\longrightarrow$ lower bound on $\Gamma(h \rightarrow invis)$.

$\rightarrow$ Test models of invisibly-decaying Higgs.

Test the top quark Yukawa coupling:

- Compute SM prediction for $\sigma_S(t\bar{t}h)$
- Compare to measured $\sigma_S(t\bar{t}h_{inv})$

$\rightarrow$ Probe htt coupling! (again modulo BR_{inv})

Conclusions

• Upcoming high-energy physics experiments will illuminate the twin mysteries of electroweak symmetry breaking and particle mass.

• The LHC will provide plentiful Higgs data, but care must be taken in its interpretation

- Combining channels allows more information to be extracted
- Theory assumptions are needed to overcome correlations caused by incomplete data.

10–40%-level measurements of SM couplings-squared

Nonstandard decays can also be probed – e.g., invisible Higgs

• The next step: refine the LHC studies, improve understanding of signals and backgrounds, add more channels for standard and nonstandard Higgs decays.