Higgs physics at the LHC

Heather Logan
(Carleton University)

Colloquium – York University
February 20, 2007

Outline:

- Introduction
  - The Higgs mechanism and the origin of mass
  - How to test the model
  - Standard Model versus New Physics

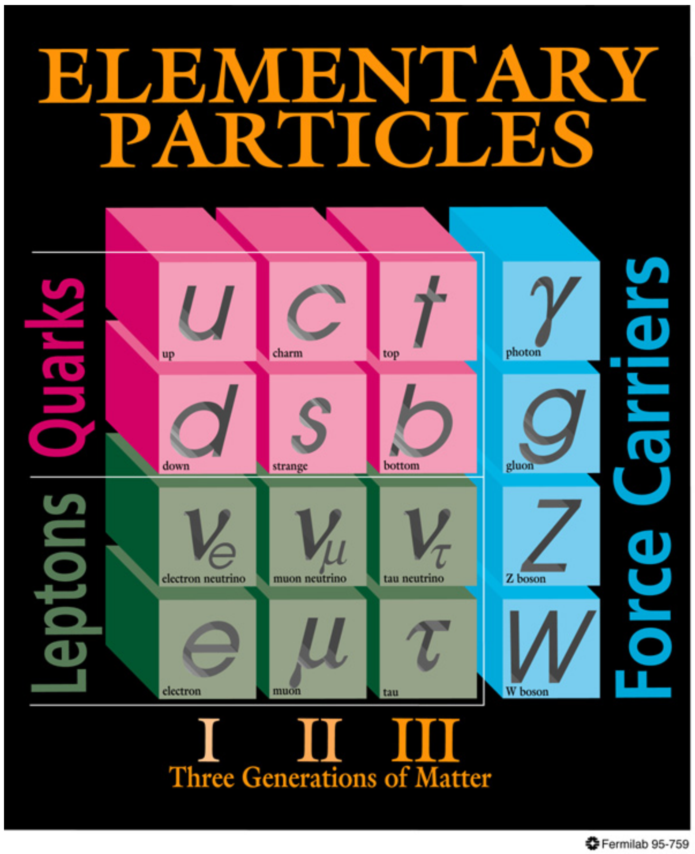
- The Large Hadron Collider

- Higgs at the LHC
  - Discovering the Higgs
  - Measuring Higgs couplings

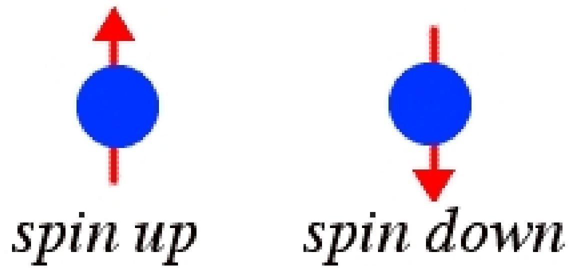
- Beyond the Standard Model: Exotic Higgs

- Conclusions

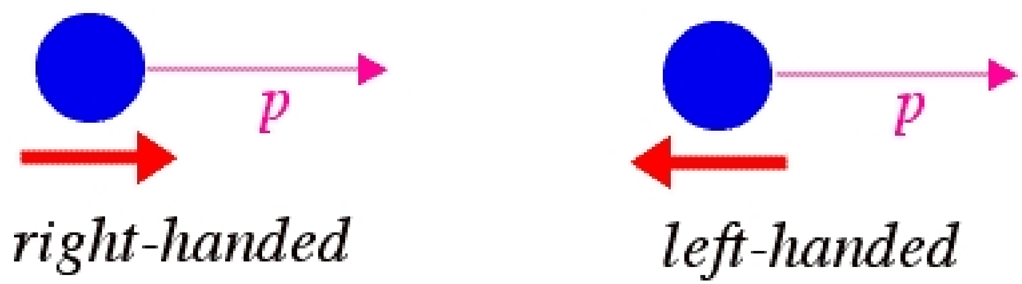
Introduction: the mystery of mass



Standard Model matter particles are fermions: spin-1/2.



For fast-moving particles: convenient to quantize spin along direction of motion: helicity states.



Can transform a right-handed particle into a left-handed particle by Lorentz-boosting past it:

Only possible for particles with mass $\neq 0$.
Massless particles move at the speed of light: the two helicity states are physically distinct.

If all we knew were QED and QCD, this would be fine:
LH and RH particles have the same quantum numbers.

But weak interactions distinguish between left- and right-handed!
– $W^\pm$ bosons couple only to left-handed fermions
– Z bosons couple differently to LH and RH fermions

How can this be??

Under weak interactions, left- and right-handed particles are fundamentally different!

We can't Lorentz boost a particle with one set of quantum numbers into a particle with different quantum numbers!

Standard Model fermions have to be massless!

This is a problem, to say the least. We know the SM fermions have mass.

In mathematical terms:

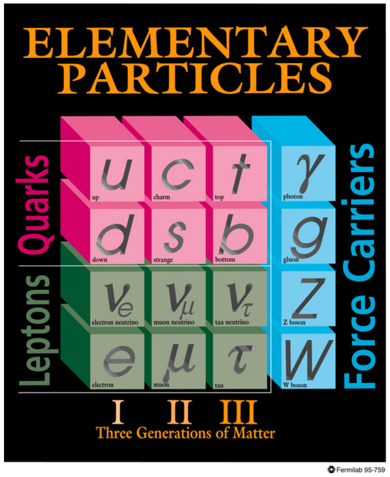
The mass of a fermion is written like this:

$$\mathcal{L} = -m\overline{f_R}f_L + \text{h.c.}$$

This is fine if f_L and f_R have the same quantum numbers.

But in the Standard Model, fermions are chiral: f_L and f_R have different $\text{SU}(2)_L \times \text{U}(1)_Y$ quantum numbers.

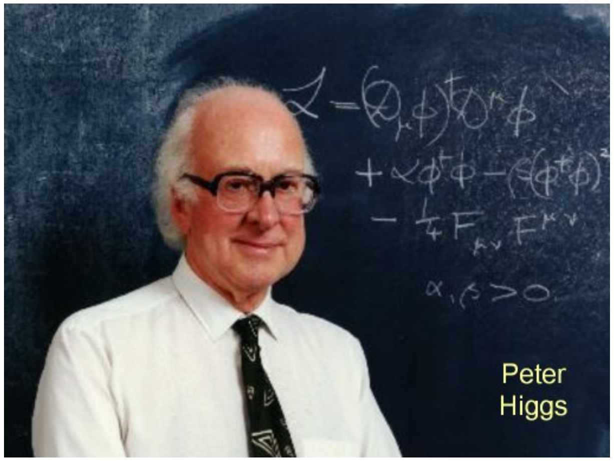
The mass term above is not gauge invariant!



From experiment we know that the $W^{\pm}$ and Z bosons have mass.
In field theory, just sticking in a gauge boson mass violates gauge invariance.

Massless gauge bosons have two polarizations (left- and right-circular); massive ones have three:
Where do the third polarization degrees of freedom of $W^{\pm}$ and Z come from?

Simplest solution: the Higgs mechanism.



Introduce a scalar "Higgs" field H
- Doublet under SU(2)$_L$: $H = (\phi^+, \phi^0)^T$
- Carries U(1)$_Y$ hypercharge

Write down couplings of H:
- To gauge bosons via the covariant derivative, $\mathcal{L} = |\mathcal{D}_\mu H|^2$.
- To itself via the Higgs potential, $-\mathcal{L} = V = m^2 H^\dagger H + \lambda (H^\dagger H)^2$.
- To fermions via Yukawa couplings, $\mathcal{L} = y_f \overline{f_R} H^\dagger F_L$.
  e.g., $F_L = (u_L, d_L)^T$, $f_R = d_R$.

These couplings are all gauge invariant.

Now the trick:

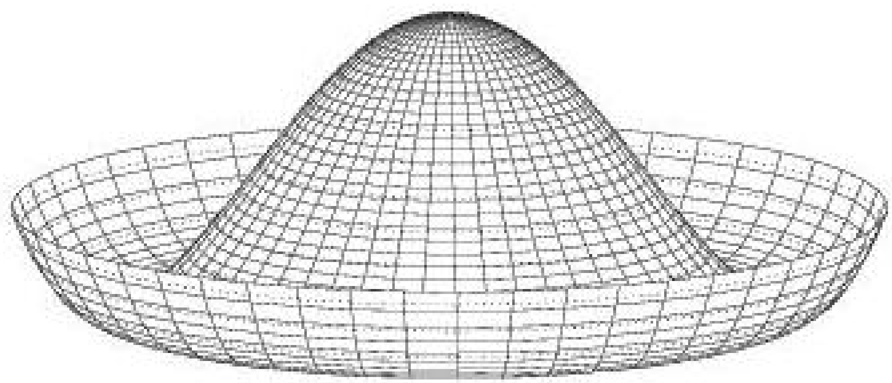
Choose the signs of the terms in the Higgs potential.

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

- m^2 is negative
- λ is positive

(why? SM gives no explanation.)

With these signs, the Higgs potential looks like this:



Potential is symmetric under SU(2)$_L$×U(1)$_Y$ gauge symmetry.

But the minimum of the potential is away from zero field value:
Universe must choose particular (non-symmetric) configuration.

This is spontaneous symmetry breaking.

At the minimum, Higgs field has a nonzero vacuum expectation value v.

Expand about the minimum:

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

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.

With $v \neq 0$, the Higgs couplings to gauge bosons and fermions give those particles mass.

Covariant derivative gives gauge boson masses and coups to h:

$$\mathcal{L} = (\mathcal{D}_\mu H)^\dagger (\mathcal{D}^\mu H) + \cdots$$

where $[Q = T_3 + Y/2]$

$$\begin{aligned} \mathcal{D}_\mu &= \partial_\mu - igW_\mu^a T^a - ig'\frac{Y}{2}B_\mu \\ &= \partial_\mu - i\frac{g}{\sqrt{2}}\left(W_\mu^+ T^+ + W_\mu^- T^-\right) \\ &\quad -i\frac{g}{\cos\theta_W} Z_\mu \left(T^3 - \sin^2\theta_W Q\right) - ieQA_\mu \end{aligned}$$

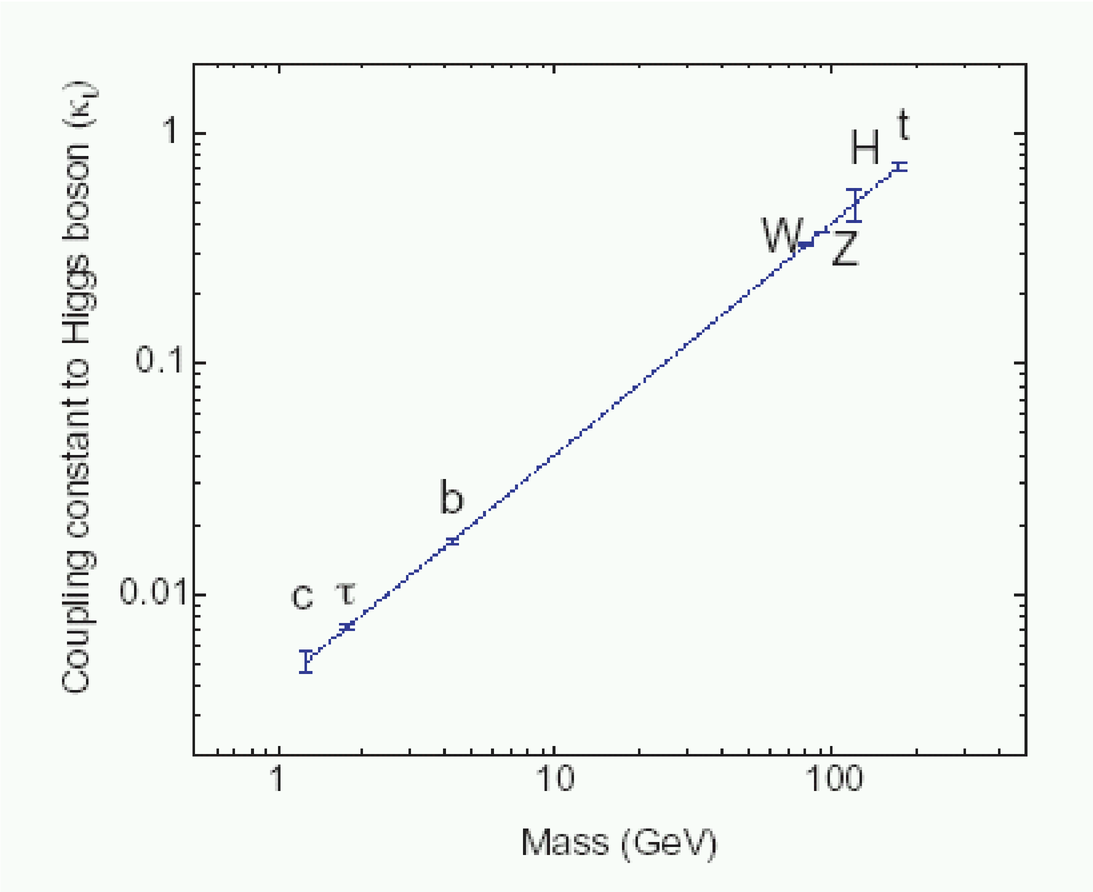
This gives: [extra 1/2 for the ZZ terms is a symmetry factor]

$$\begin{aligned} \mathcal{L} &= (g^2 v^2/4) W^+ W^- + (g^2 v/2) h W^+ W^- + (g^2/4) hh W^+ W^- \\ &\quad + (g_Z^2 v^2/8) ZZ + (g_Z^2 v/4) hZZ + (g_Z^2/8) hhZZ \end{aligned}$$

where $g_Z = \sqrt{g^2 + g'^2}$.

Yukawa couplings $y_f \overline{f_R} H^\dagger F_L$ give fermion masses and couplings to h:

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



Mass of each particle is proportional to its Higgs coupling!

Slope is predicted by $v = 2M_W/g = 246$ GeV.

Test the SM Higgs mechanism by measuring the Higgs couplings to SM particles.

This simple linear relation between masses and Higgs couplings holds in the Standard Model.
But beyond the Standard Model, Higgs couplings can vary.

An example: Minimal Supersymmetric Standard Model (MSSM)

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

W boson mass comes from sum of two covariant derivatives: $\mathcal{L} = |\mathcal{D}_\mu H_1|^2 + |\mathcal{D}_\mu H_2|^2$, which gives $M_W^2 = \frac{g^2 v_1^2}{4} + \frac{g^2 v_2^2}{4} = \frac{g^2 v_{SM}^2}{4}$.

So v_1 and v_2 must obey $v_1^2 + v_2^2 = v_{SM}^2 = 2M_W/g$.
One unknown combination is left free: $v_2/v_1 \equiv \tan\beta$.

Two complex doublets $\rightarrow$ 8 degrees of freedom
- h: lightest CP-even Higgs
- H, A, and $H^\pm$: heavier CP-even, CP-odd, and charged Higgses
- G^0 and $G^\pm$: unphysical Goldstone bosons

Mix to form mass eigenstates:

$$H_1 \cos\beta + H_2 \sin\beta = \begin{pmatrix} G^+ \\ [v_{SM} + iG^0 + h\sin(\beta-\alpha) + H\cos(\beta-\alpha)]/\sqrt{2} \end{pmatrix}$$

$$-H_1 \sin\beta + H_2 \cos\beta = \begin{pmatrix} H^+ \\ [iA^0 + h\cos(\beta-\alpha) - H\sin(\beta-\alpha)]/\sqrt{2} \end{pmatrix}$$

Couplings of h get modified from their SM values:

$g_{hWW} = \sin(\beta-\alpha) g_{H_{SM}WW}$ likewise Z
$g_{hb\bar{b}} = [\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)] g_{H_{SM}b\bar{b}}$ likewise d, s, e, μ, τ
$g_{ht\bar{t}} = [\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)] g_{H_{SM}t\bar{t}}$ likewise u, c

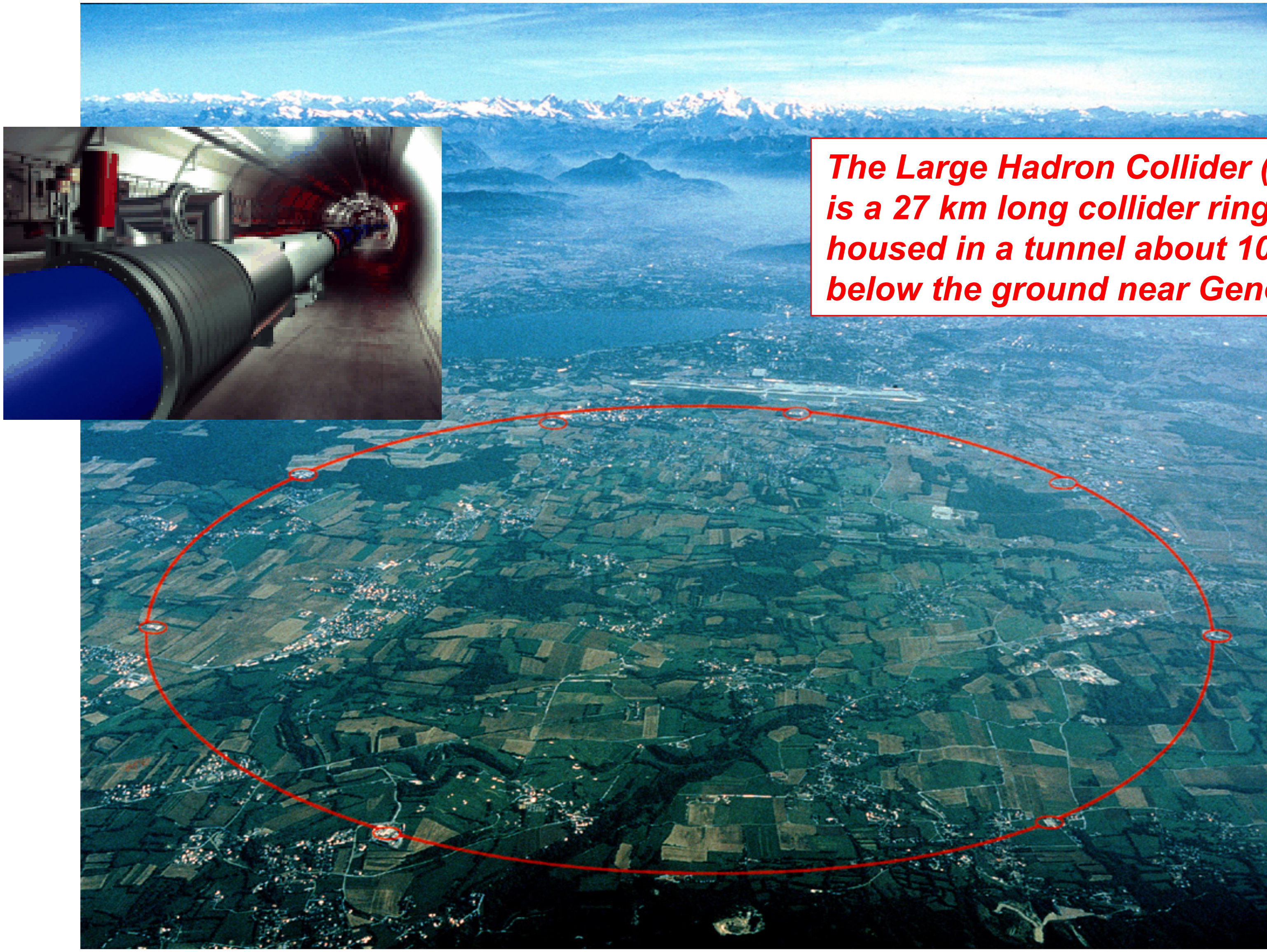
In most MSSM parameter space, H, A, and $H^\pm$ are fairly heavy.

Mixing angle: $\cos(\beta-\alpha) \simeq \frac{1}{2}\sin 4\beta \frac{M_Z^2}{M_A^2} \longrightarrow 0$ for $M_A \gg M_Z$

Couplings of h approach their SM values – the decoupling limit.

Search for coupling deviations → test Higgs sector structure!

The Large Hadron Collider



The Large Hadron Collider (LHC) is a 27 km long collider ring housed in a tunnel about 100 m below the ground near Geneva

LHC will collide protons with protons, at 14 TeV centre-of-mass energy.

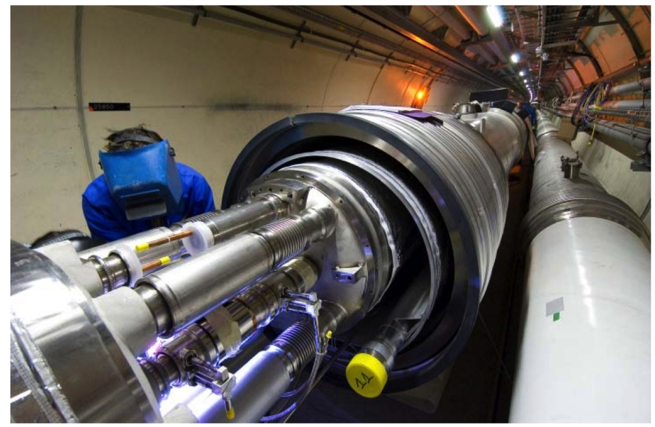
Initial operation – end of 2007 – at 900 GeV (450 on 450) to debug machine and detectors.

Full commissioning of the magnets up to 7 on 7 TeV will be done in the winter 2008 shutdown.

Ready for a high-energy run in June 2008.
Goal of first physics run is "a few" fb^{-1} by the end of 2008.

Longer-term design goals:
Initial "low luminosity" run, 10 fb^{-1}/year $\times$ 3 years $\rightarrow$ 30 fb^{-1}.
Later "high luminosity" run, 100 fb^{-1}/yr $\times$ 3 yrs $\rightarrow$ 300 fb^{-1}.

LHC – Current activity

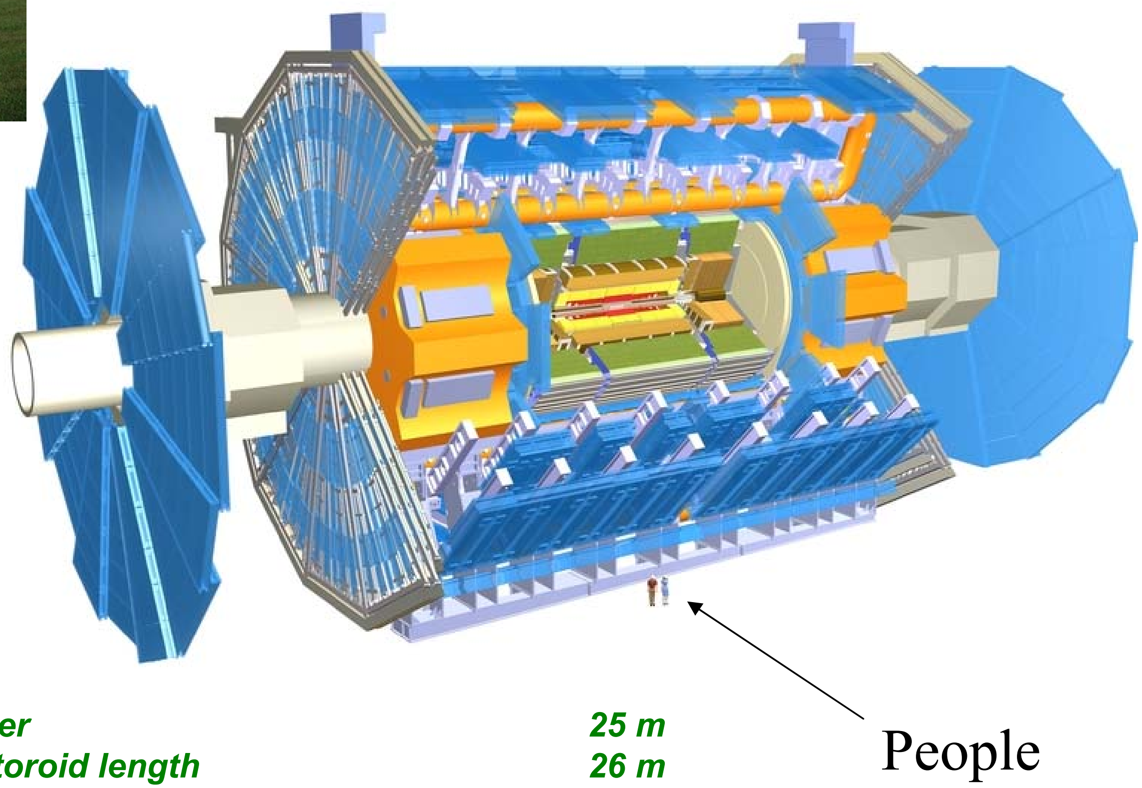


Canadian involvement: the ATLAS detector

Global collaboration, 1770 people!

ATLAS superimposed to
the 5 floors of building 40

The ATLAS detector is being installed 100 m underground on the LHC ring.

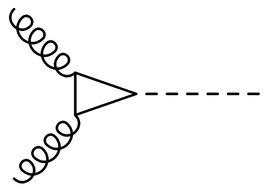


Diameter	*25 m*
Barrel toroid length	*26 m*
End-cap end-wall chamber span	*46 m*
Overall weight	*7000 Tons*

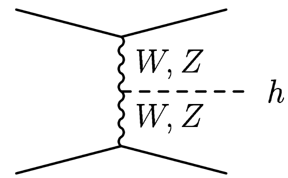
Higgs at the LHC

Higgs will be accessible via multiple production mechanisms:

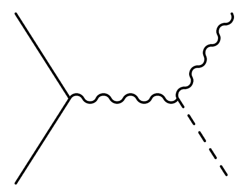
- Gluon fusion, $gg \to H$



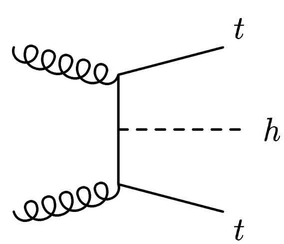
- Weak boson fusion, $qq \to Hqq$



- WH, ZH associated production

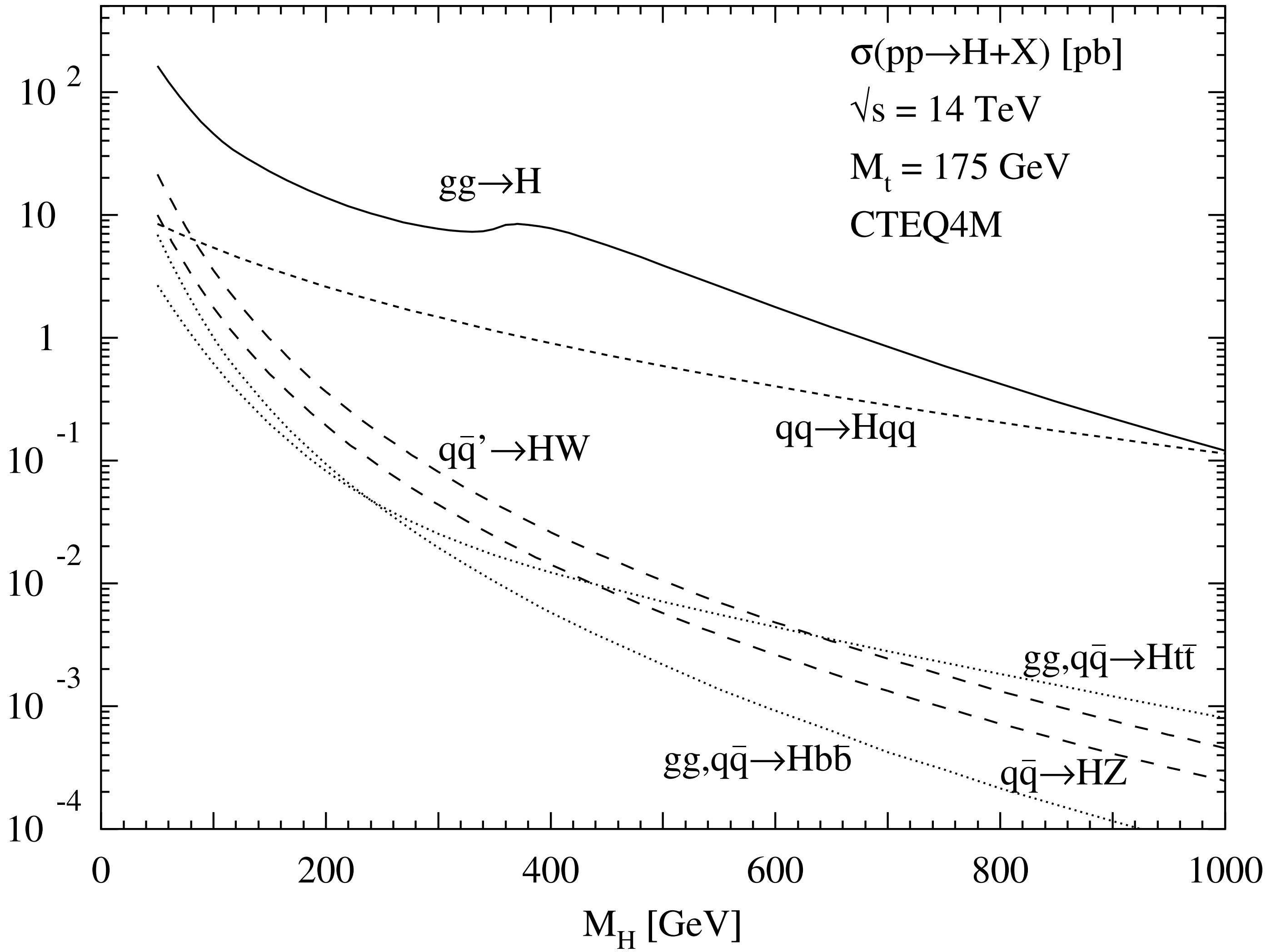


- ttH associated production



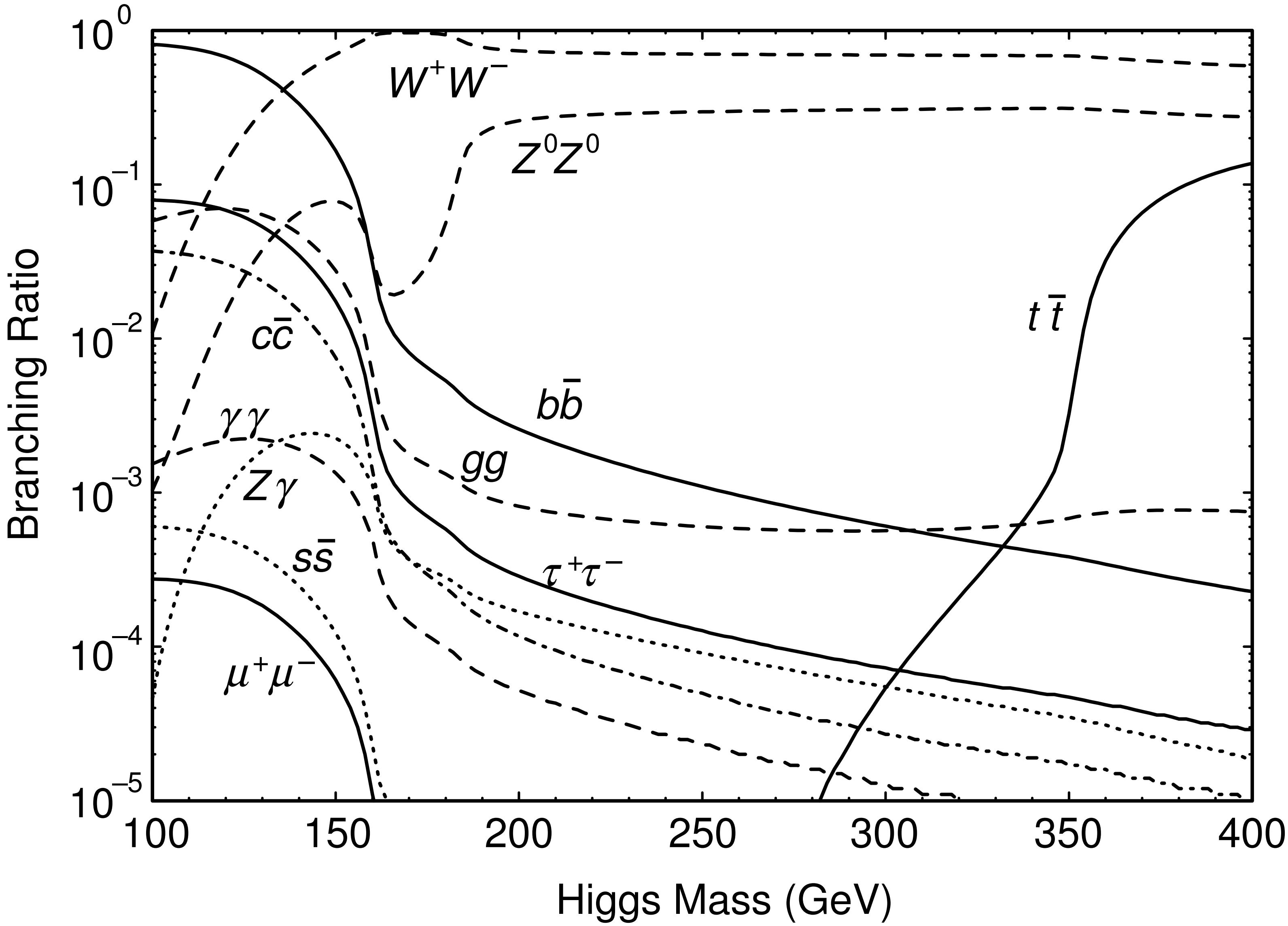
Higgs production cross sections are reasonably large:

$1\ \text{pb} \times 1\ \text{fb}^{-1} = 1000$ events



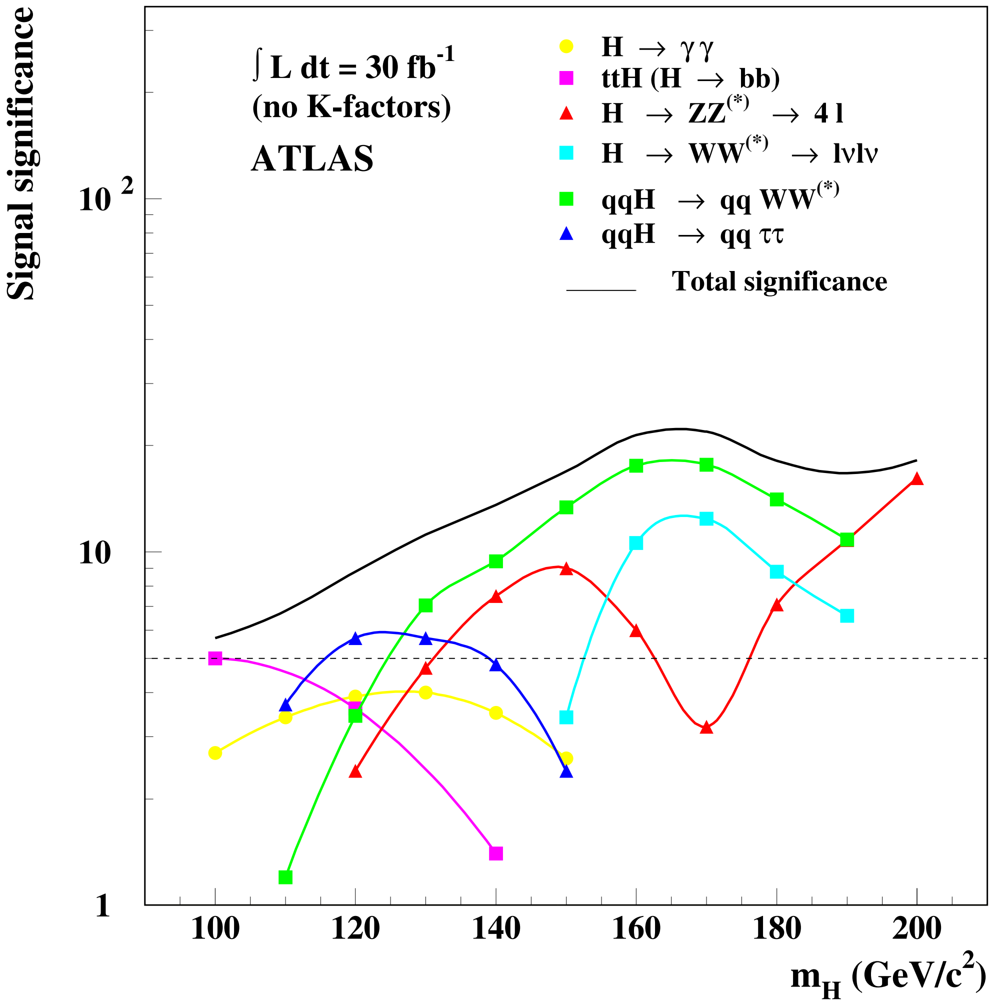
M. Spira, Fortsch. Phys. 46, 203 (1998)

Standard Model Higgs decay modes depend only on M_H:



HDECAY

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 in many production and decay channels:
(GF = gluon fusion, WBF = weak boson fusion)

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, $H \to \gamma\gamma$

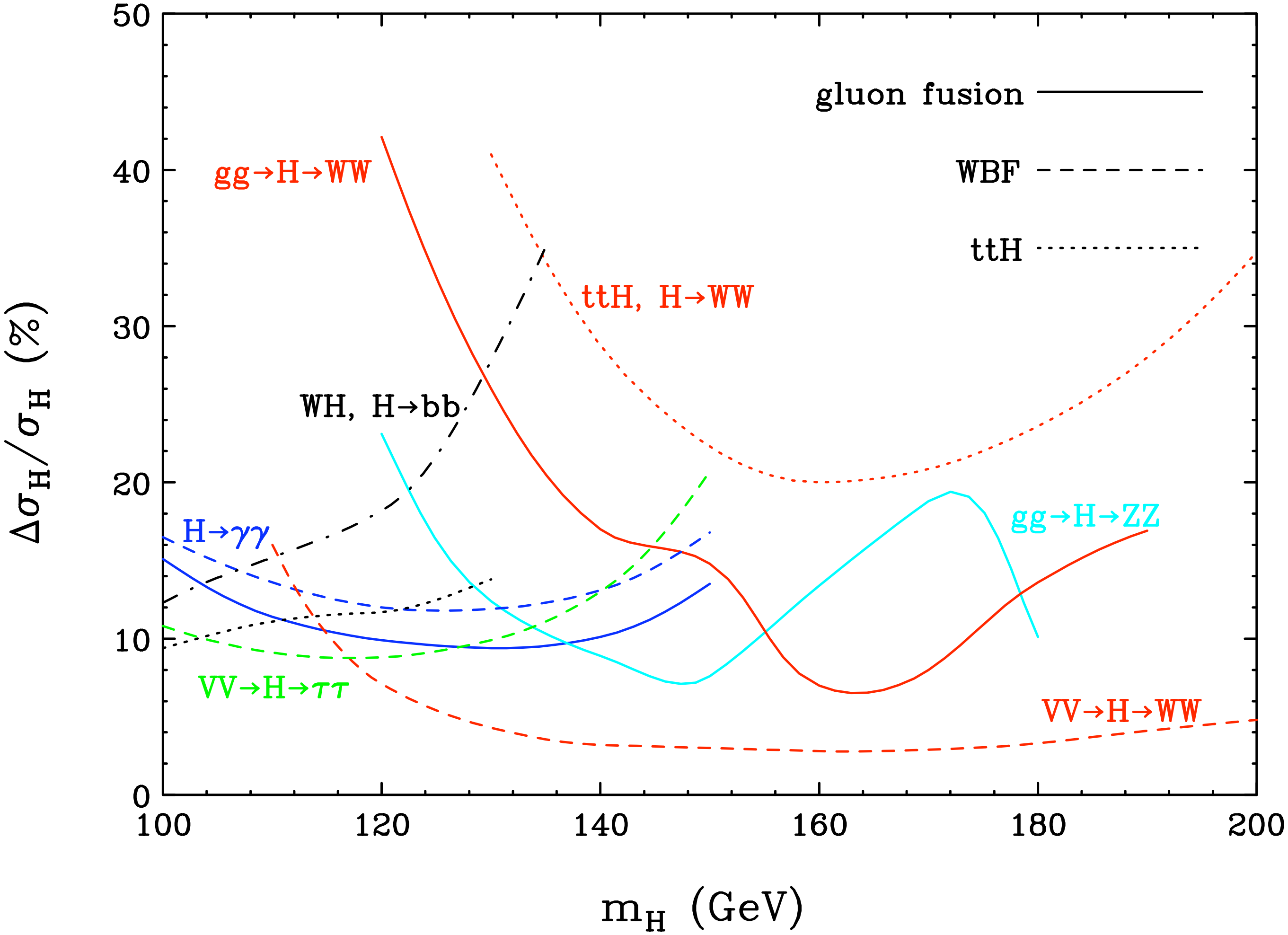
ZH, $H \to \gamma\gamma$

WBF $qqH \to qq\tau\tau$

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

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

Measure rates: test the SM!



LHC, 200 fb^{-1} (except 300 fb^{-1} for $ttH, H \to bb$, $WH, H \to bb$). Zeppenfeld, hep-ph/0203123

If there's a discrepancy, want to know where it comes from.

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

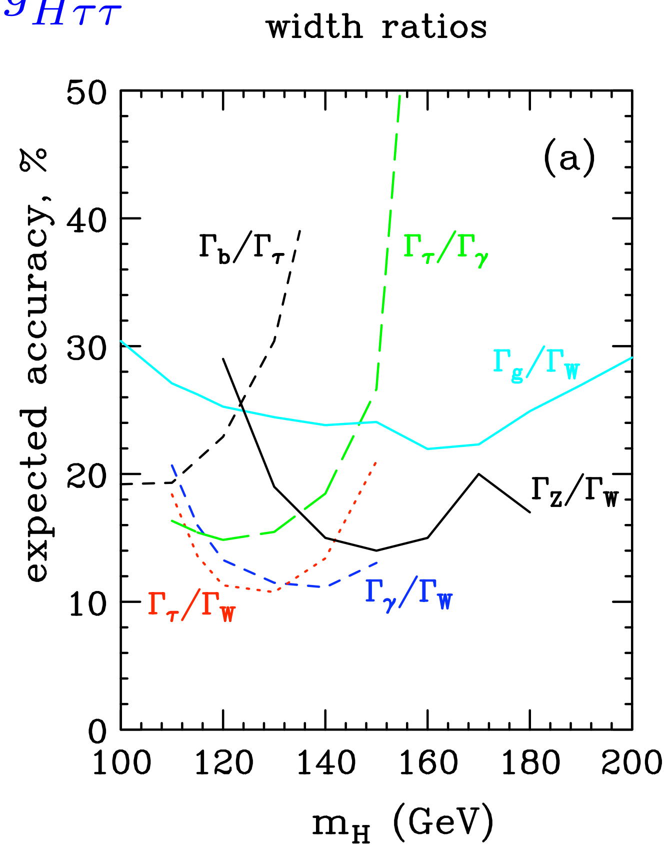
$$\frac{WBF \to H \to WW^*}{WBF \to H \to \tau\tau} = \frac{\Gamma(H \to WW^*)}{\Gamma(H \to \tau\tau)} \propto \frac{g^2_{HWW}}{g^2_{H\tau\tau}}$$

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

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

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)



LHC, 200 fb^{-1} (except 300 fb^{-1} for $ttH, H \to bb$, $WH, H \to bb$). Zeppenfeld, hep-ph/0203123

Ratios of couplings are nice.
But can we measure each coupling independently?

Difficulties:

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

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

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

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

To make progress, have to make some theoretical assumptions.

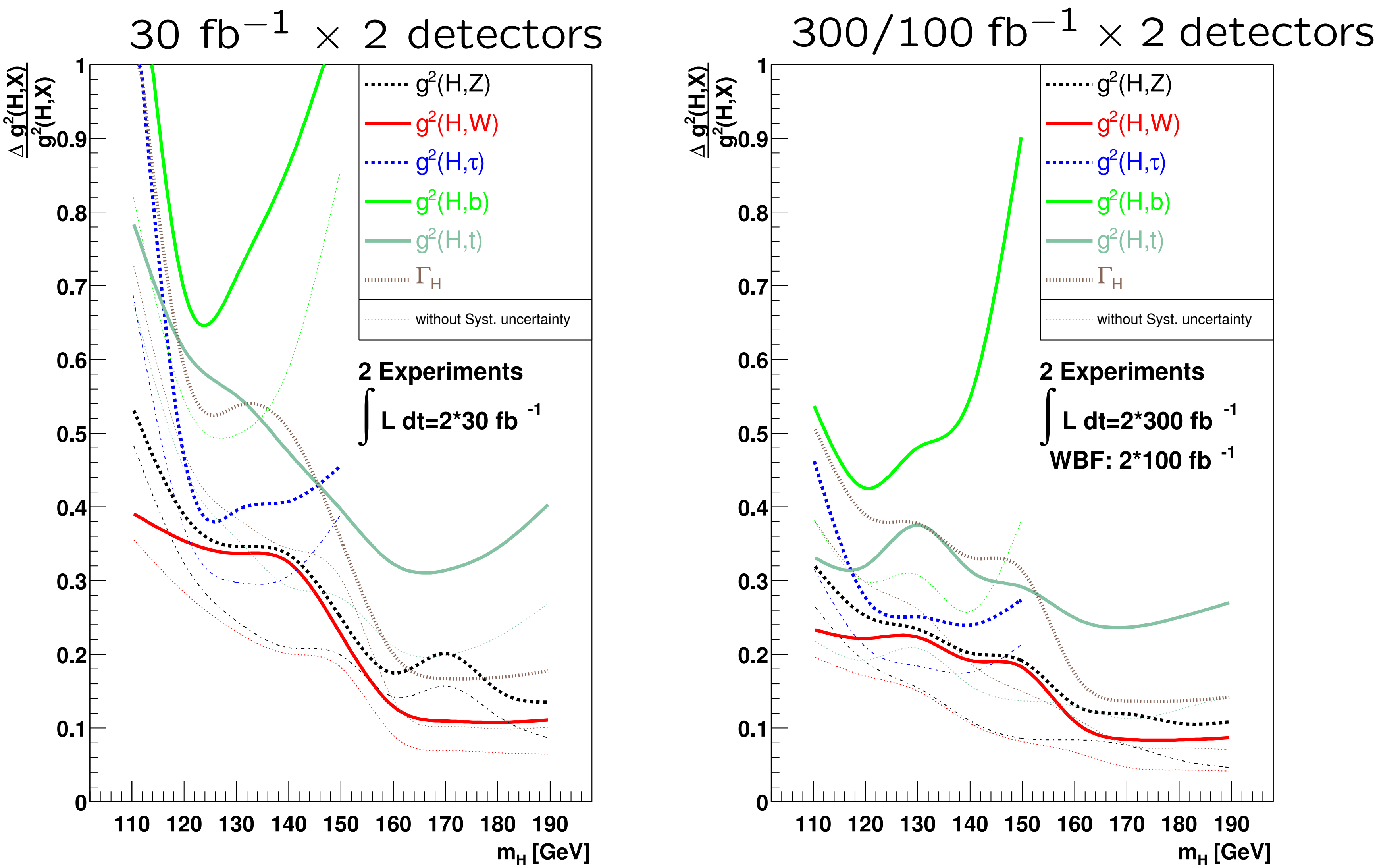
Consider Higgs models containing only SU(2) doublets/singlets.
- hWW, hZZ couplings related by custodial SU(2).
- hWW, hZZ couplings bounded from above by SM values.

This is a mild assumption!
- True in most good models: MSSM, NMSSM, 2HDM, etc.
- 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.
- Interplay constrains remaining Higgs couplings.
- Make no assumptions on unexpected/unobserved Higgs decay modes.

Result: fit of Higgs couplings-squared



Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld, hep-ph/0406323

Systematic uncertainties play an important role.

5% overall Luminosity normalization

Theory uncertainties on Higgs production:

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

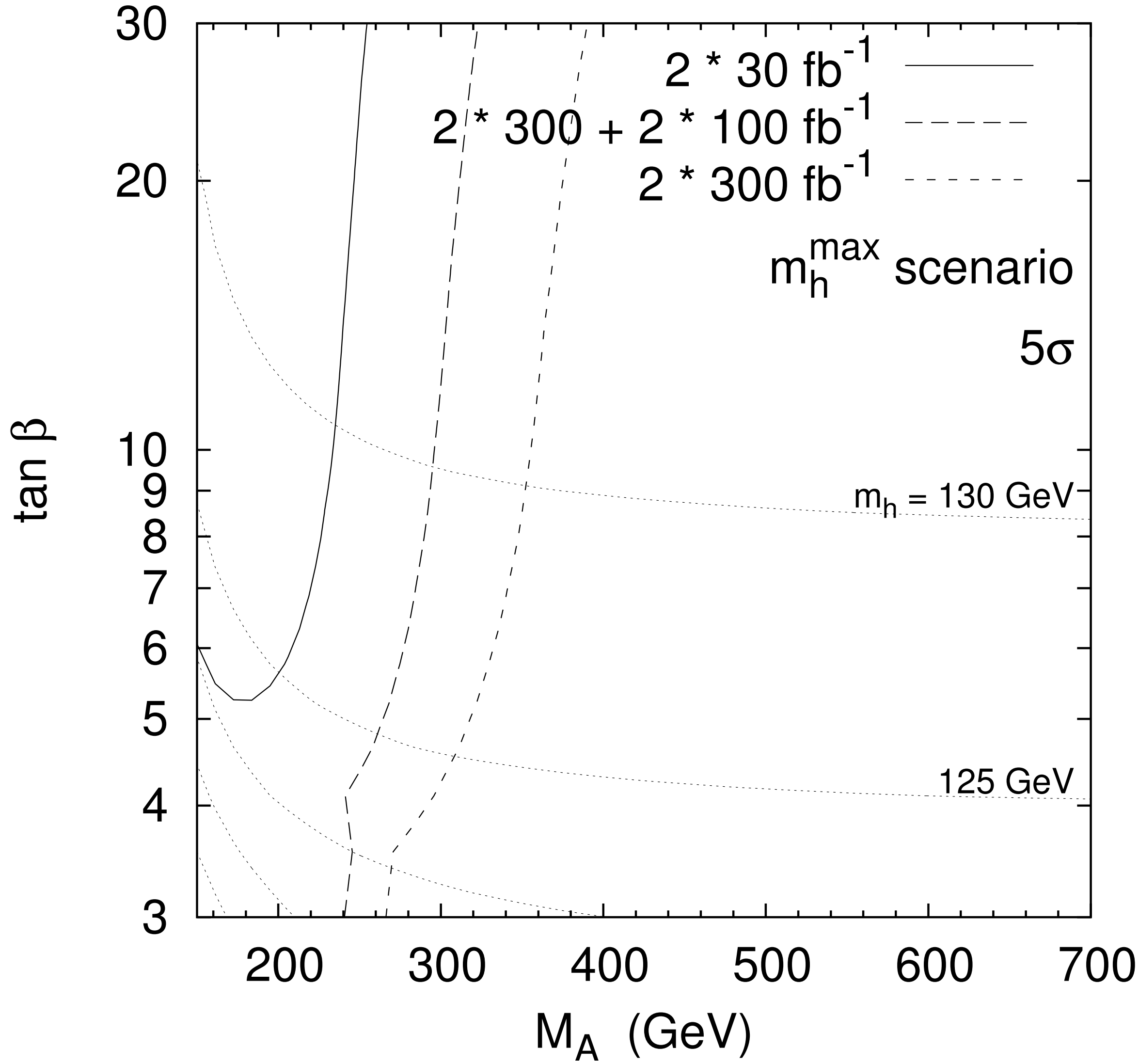
Reconstruction/identification efficiencies:

- 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 $H \to b\bar{b}$

Another approach: fit observed rates to a particular model.
Example: chi-squared fits in MSSM, $m_h^{\rm max}$ scenario



LHC sensitive to MSSM nature of h up to $M_A \lesssim 300$ GeV

from Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld, hep-ph/0406323

Exotic Higgs scenarios

Typical MSSM Higgs physics is fairly tame.

More exotic possibilities:

a) $H \to \mu^+\mu^-$. Rate too small in SM. Visible if $H\mu\mu$ coupling enhanced or other decays suppressed. Spectacular signal.

b) CP violation. Exotic effects on structure of Higgs couplings to WW, ZZ, $\bar{f}f$.

c) Invisibly-decaying Higgs. Can be significant in some SUSY models, etc. Higgs decays to dark matter!

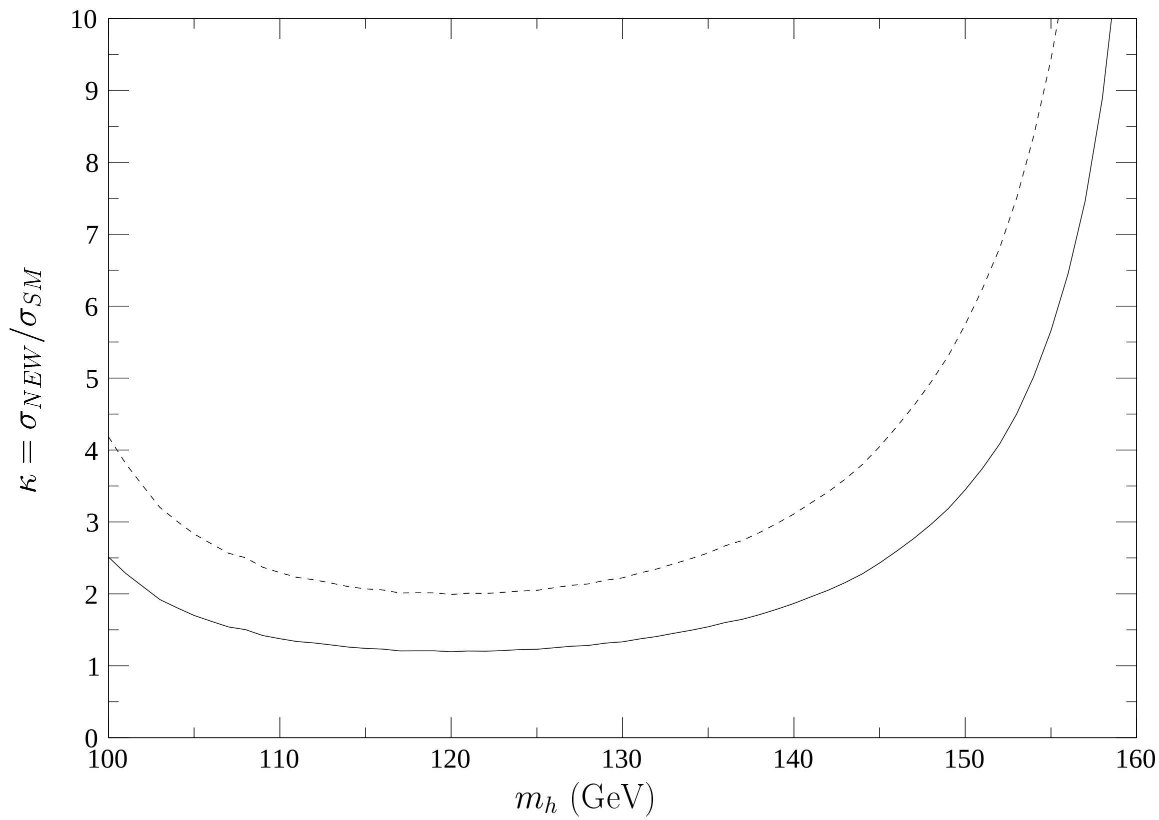
$H \to \mu^+\mu^-$: Do small fermion masses come from higher-dimensional operators?

$$\mathcal{L} = y \left(\frac{H^\dagger H}{\Lambda^2} \right)^n \mu_R H^\dagger L_L \qquad \to \qquad y_\mu^{\text{eff}} = (2n+1) m_\mu / v$$

Signal from $gg \to H \to \mu\mu$: [Han & McElrath, hep-ph/0201023]

Scaling factor on SM rate to see 3σ, 5σ signal.

Can probe $n \geq 1$!



Higgs mass [GeV]

Similar reach from VBF $\to H \to \mu\mu$ [Cranmer & Plehn, hep-ph/0605268]

CP violation and HWW, HZZ couplings:

Tensor structure of SM coupling is $HV_\mu V^\mu$.
- Normally such a coupling would not be gauge invariant!
- Works via Higgs mechanism: replace one H field with its vev.

Coupling is only nonzero for scalars with a vev.
- No AVV coupling for CP-odd state A: it would violate CP.

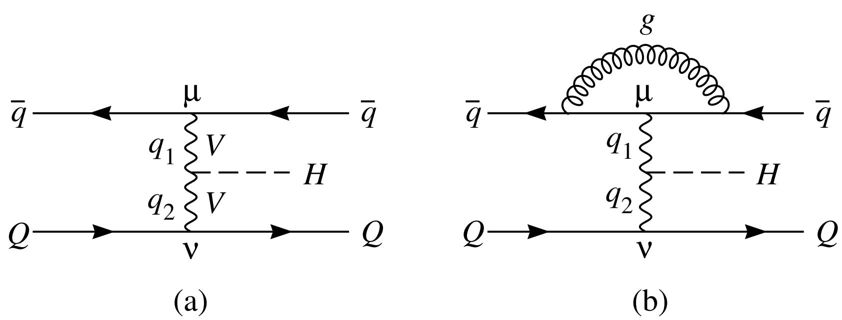
How else can a scalar couple to two vector bosons?
Construct gauge invariant couplings from field strength tensor:
- $HV_{\mu\nu}V^{\mu\nu}$ for CP-even scalar H.
- $AV_{\mu\nu}\widetilde{V}^{\mu\nu}$ for CP-odd scalar A.

These are dimension-5 operators: generated by a loop.
- Same operators that generate $H \to \gamma\gamma$, $gg \to H$, $gg \to A$ in MSSM, etc.
- The scalar need not have a vev.

Measure tensor structure of HVV coupling in VBF:

Slide from D. Zeppenfeld, plenary talk at SUSY'06 conference

Most general HVV vertex $T^{\mu\nu}(q_1, q_2)$



$$T^{\mu\nu} = a_1\, g^{\mu\nu} + a_2\, (q_1 \cdot q_2\, g^{\mu\nu} - q_1^{\nu} q_2^{\mu}) + a_3\, \varepsilon^{\mu\nu\rho\sigma}\, q_{1\rho} q_{2\sigma}$$

The $a_i = a_i(q_1, q_2)$ are scalar form factors

Physical interpretation of terms:

SM Higgs $\mathcal{L}_I \sim H V_\mu V^\mu \longrightarrow a_1$

loop induced couplings for neutral scalar

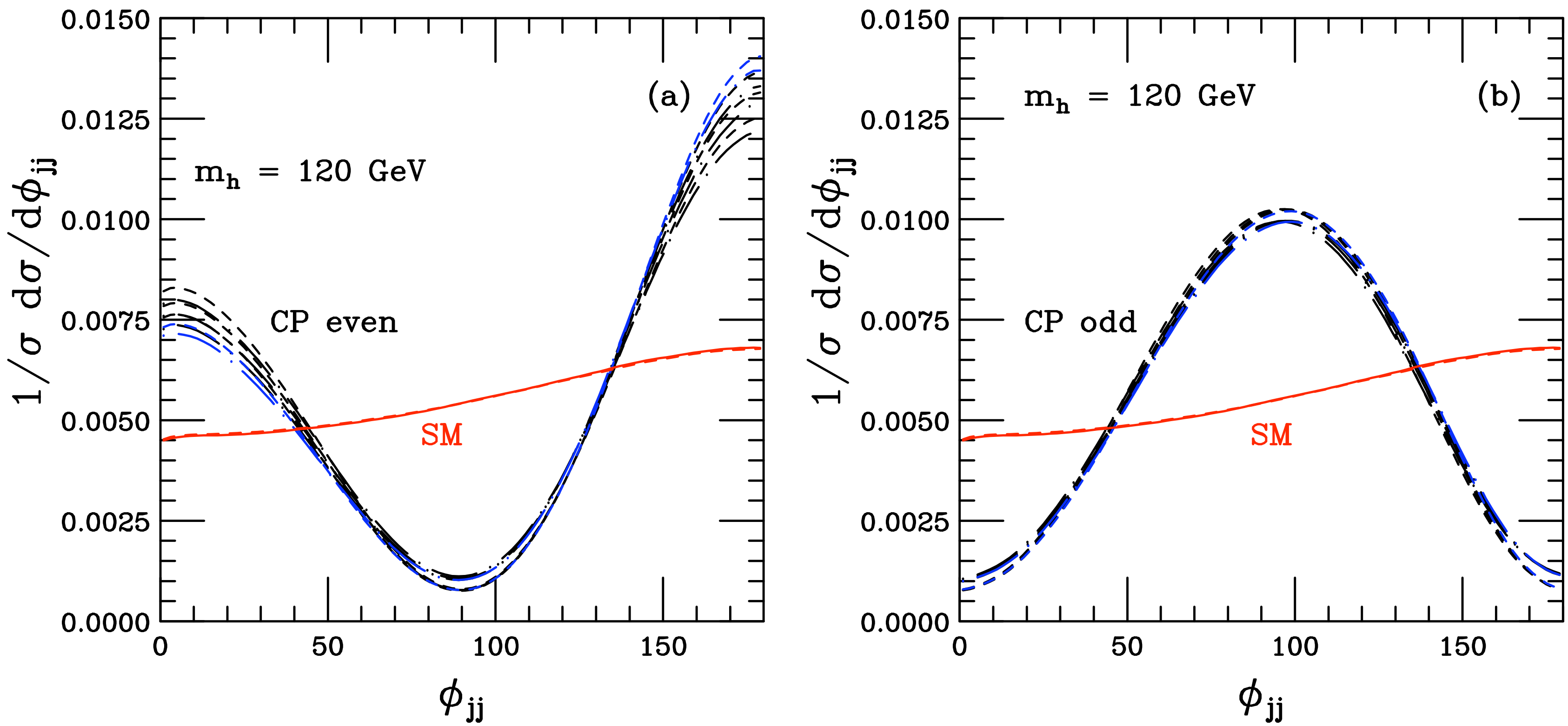
CP even $\mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

CP odd $\mathcal{L}_{eff} \sim H V_{\mu\nu} \tilde{V}^{\mu\nu} \longrightarrow a_3$

Must distinguish a_1, a_2, a_3 experimentally

Slide from D. Zeppenfeld, plenary talk at SUSY'06 conference

Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



Dip structure at 90° (CP even) or 0/180° (CP odd) only depends on tensor structure of HVV vertex. Very little dependence on form factor, LO vs. NLO, Higgs mass etc.

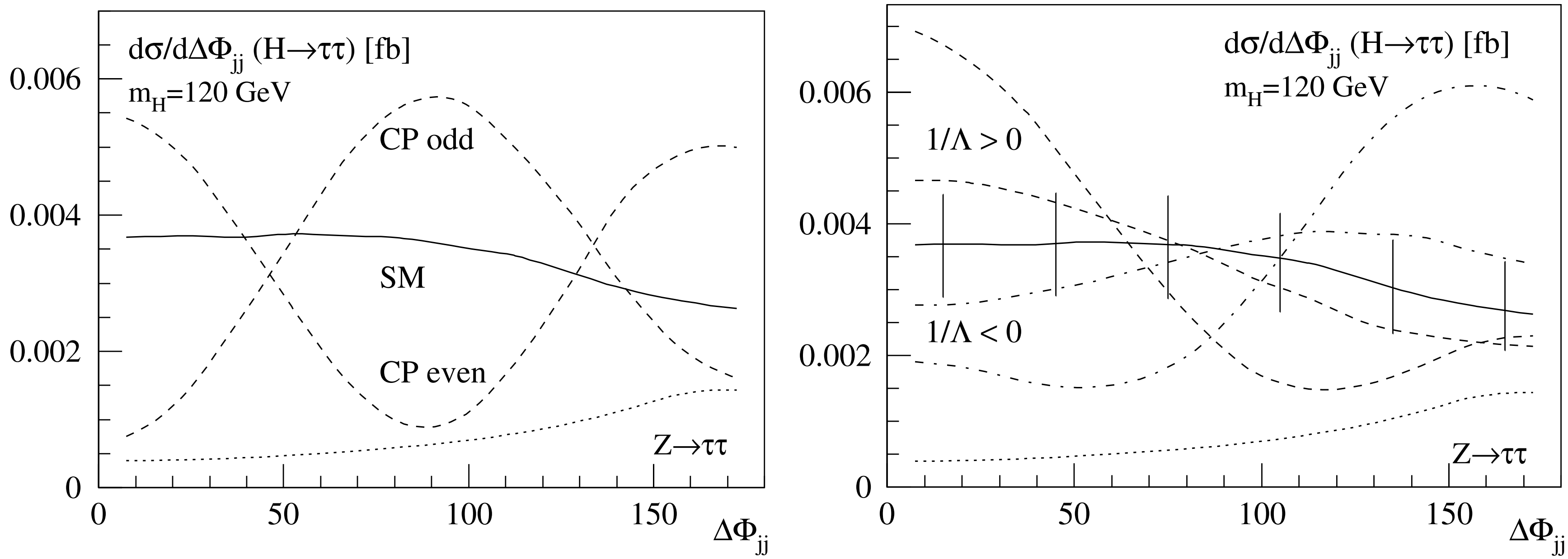
Dashed lines include LO vs NLO and formfactor effects for LHC. Plots from Figy & Zeppenfeld, hep-ph/0403297. See also Plehn, Rainwater & Zeppenfeld, hep-ph/0105325.

Standard Model $HV_\mu V^\mu$ coupling is tree-level.
- From covariant derivative $|\mathcal{D}_\mu H|^2$, with one H replaced by vev.

CP-odd $AV_{\mu\nu}\widetilde{V}^{\mu\nu}$ coupling is dimension-5 (e.g., loop-induced): gives only a tiny contribution to VBF rate.
- "CP-odd" rate is too small if A couples only through the loop.

CP-even $HV_{\mu\nu}V^{\mu\nu}$ coupling is also dimension-5.
- Get interference term between $HV_\mu V^\mu$ and $HV_{\mu\nu}V^{\mu\nu}$ production: "SM times dimension-5" gives better sensitivity to small CP-even dimension-5 contribution.

Interference term between $HV_\mu V^\mu$ and $HV_{\mu\nu}V^{\mu\nu}$:



[from Plehn, Rainwater & Zeppenfeld, hep-ph/0105325]

[Left] Curves are normalized to each give the SM cross section.

[Right] Shows interference effect for either sign of the $HV_{\mu\nu}V^{\mu\nu}$ operator coefficient, with $\sigma_{\rm new}/\sigma_{\rm SM} = 1.0$ and 0.04.

Error bars are statistical for 100 fb^{-1} times 2 experiments.

What about mixed CP states?
MSSM with CP violation: get mixing between A and H.

Look at a process where SM-like and CP-odd parts enter at the same level.

Couplings to fermions:

$$H^0 b\bar{b} = -\frac{igm_b}{2m_W}\left[\tan\beta\sin(\beta-\alpha)+\cos(\beta-\alpha)\right]$$
$$A^0 b\bar{b} = -\frac{gm_b}{2m_W}\tan\beta\gamma_5$$
$$H^0 t\bar{t} = -\frac{igm_t}{2m_W}\left[-\cot\beta\sin(\beta-\alpha)+\cos(\beta-\alpha)\right]$$
$$A^0 t\bar{t} = -\frac{gm_t}{2m_W}\cot\beta\gamma_5$$

Couplings to gluons/photons: loop-induced for both H and A.
CP-even: $HG_{\mu\nu}G^{\mu\nu}$ CP-odd: $AG_{\mu\nu}\tilde{G}^{\mu\nu}$

CP-even and CP-odd components of the coupling are a priori of the same order of magnitude!

Tensor structure of Hgg coupling at LHC:

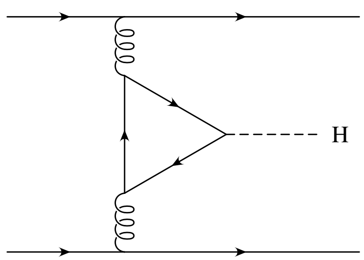
Slide from D. Zeppenfeld, plenary talk at SUSY'06 conference

Effective Hgg vertex is induced via top-quark loop

$$\text{CP} - \text{even}: \quad i\frac{m_t}{v} \quad \longrightarrow \quad H\, G^a_{\mu\nu} G^{\mu\nu,a} \text{ coupling}$$

$$\text{CP} - \text{odd}: \quad \frac{m_t}{v}\gamma_5 \quad \longrightarrow \quad H\, G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} \text{ coupling}$$

Consider Hjj production via gluon fusion, e.g.



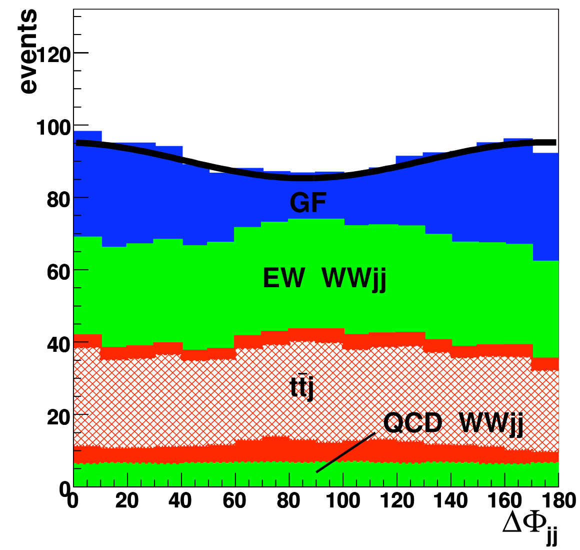
(a)

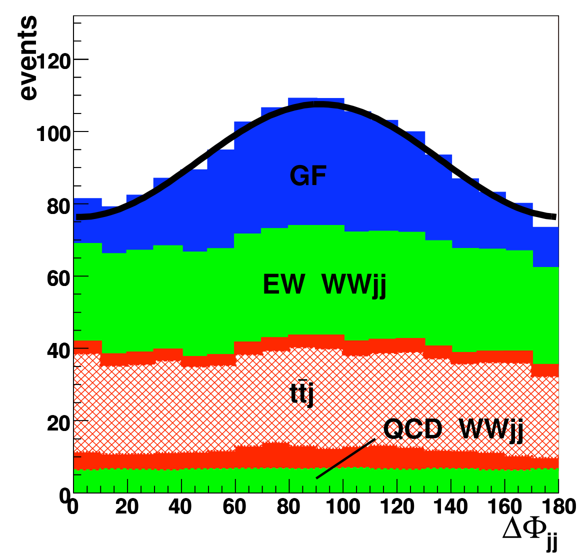
Parton level analysis with relevant backgrounds

(Hankele, Klämke, DZ, hep-ph/0605117)

$\Longrightarrow$ Difference visible in Hjj, $H \rightarrow WW \rightarrow l^+ l^- \not{p}_T$ events at $m_H \approx 160$ GeV with 30 fb^{-1} at 6σ level

Method can be generalized for any Higgs mass. Problem is lower signal rate for $h \rightarrow \tau\tau$ or $h \rightarrow \gamma\gamma$

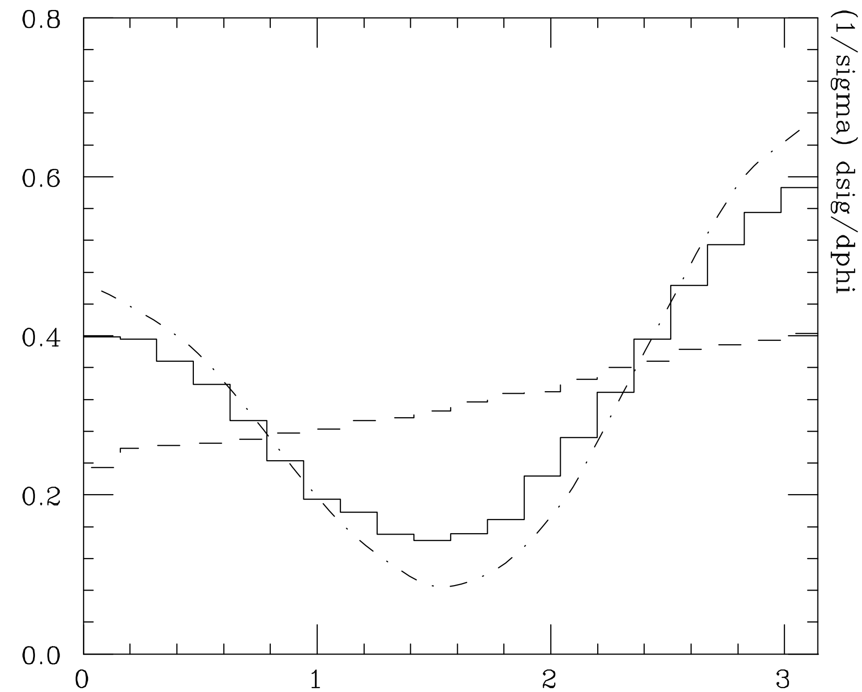




Monte Carlo simulations begun in Del Duca et al, hep-ph/0608158

Angular correlations survive the parton shower.

Shown is SM gluon fusion Hjj with and without parton shower, and SM VBF with parton shower.



[from Del Duca et al, hep-ph/0608158]

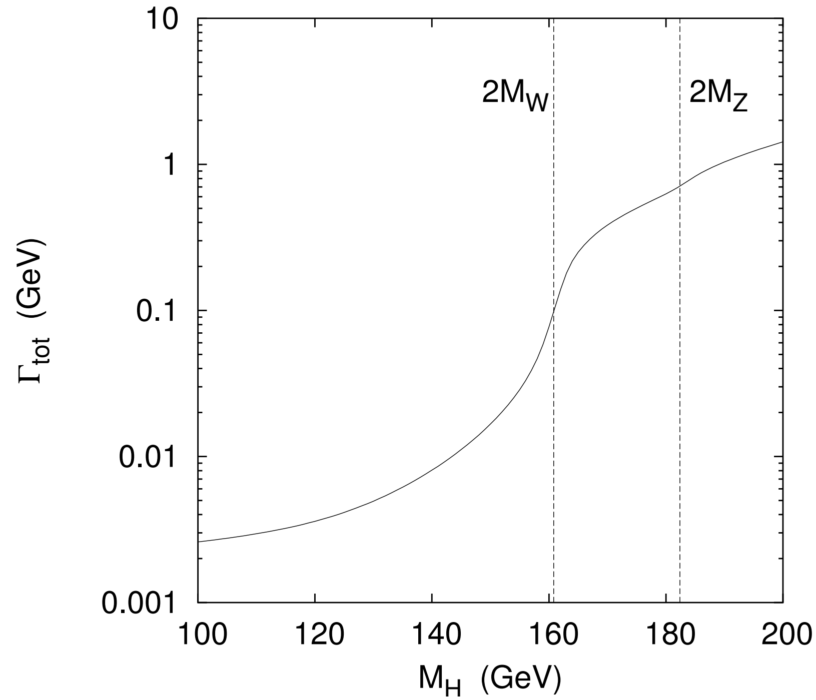
Can separate gluon fusion and VBF events using rapidity gap between two “tagging jets”.

Expectation in CP-mixed case:

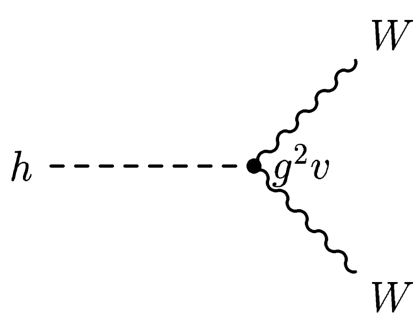
- See sum of CP-even and CP-odd shapes in gluon fusion.
- See SM-like shape in VBF Higgs production (CP-odd part much smaller; no interference term).

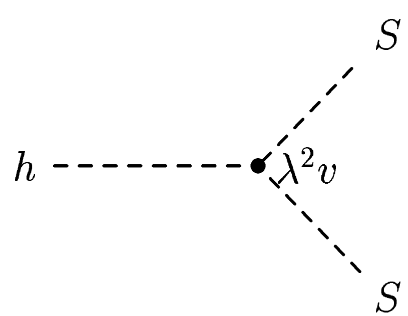
Invisibly-decaying Higgs

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



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





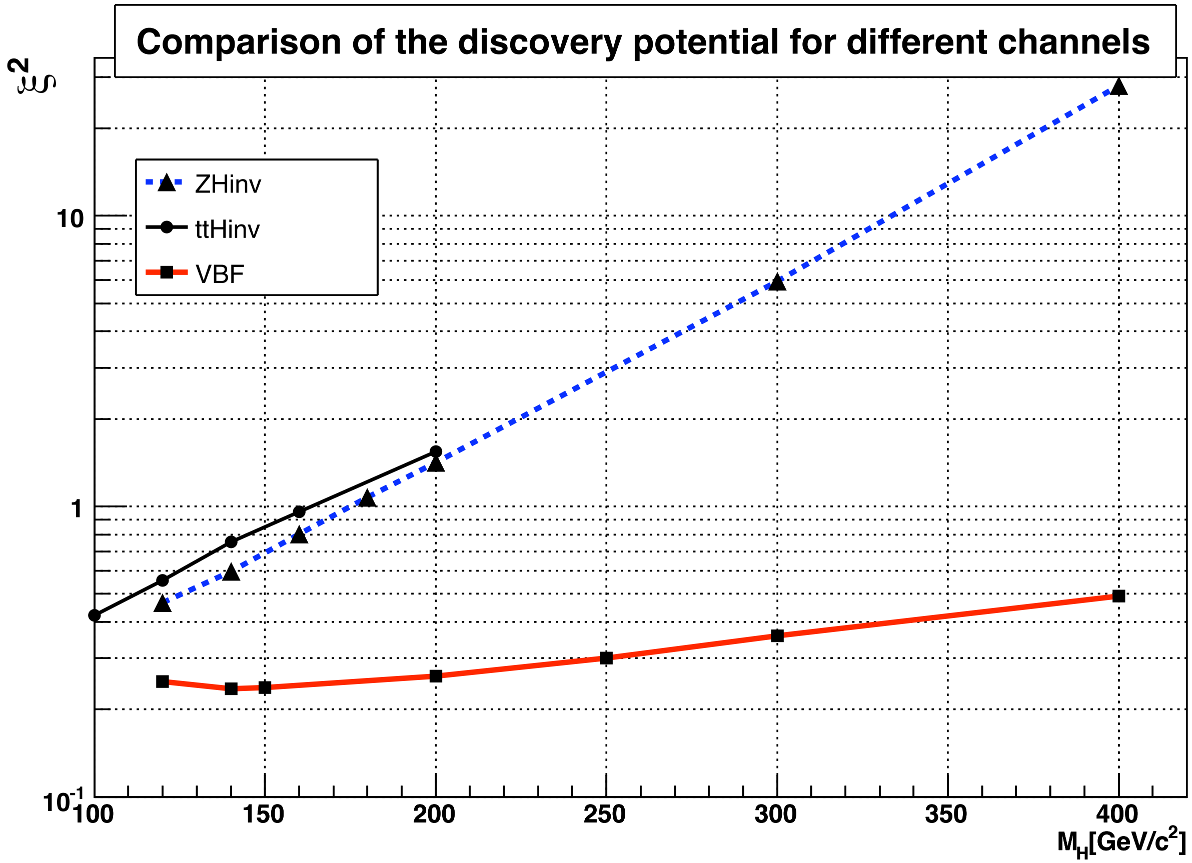
The Higgs *could* decay invisibly

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

Shouldn't just assume Higgs will be SM-like.
Even small additions (e.g., singlet scalar dark matter) can make BR($h \to$ invis.) large.
Let's cover all our bases!

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

Limits on invisible decay modes:



ZH_{inv} uses $Z \to \ell^+\ell^-$

VBF looks promising (but it's not clear how well those events can be triggered)

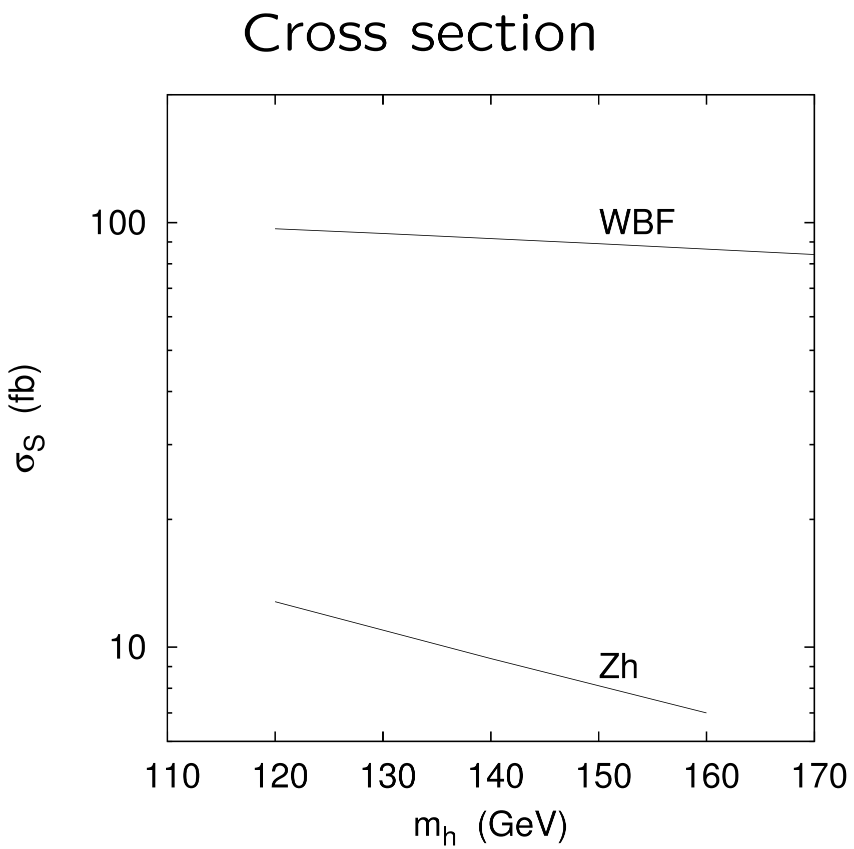
$t\bar{t}H_{\text{inv}}$ – may be room for improvement?

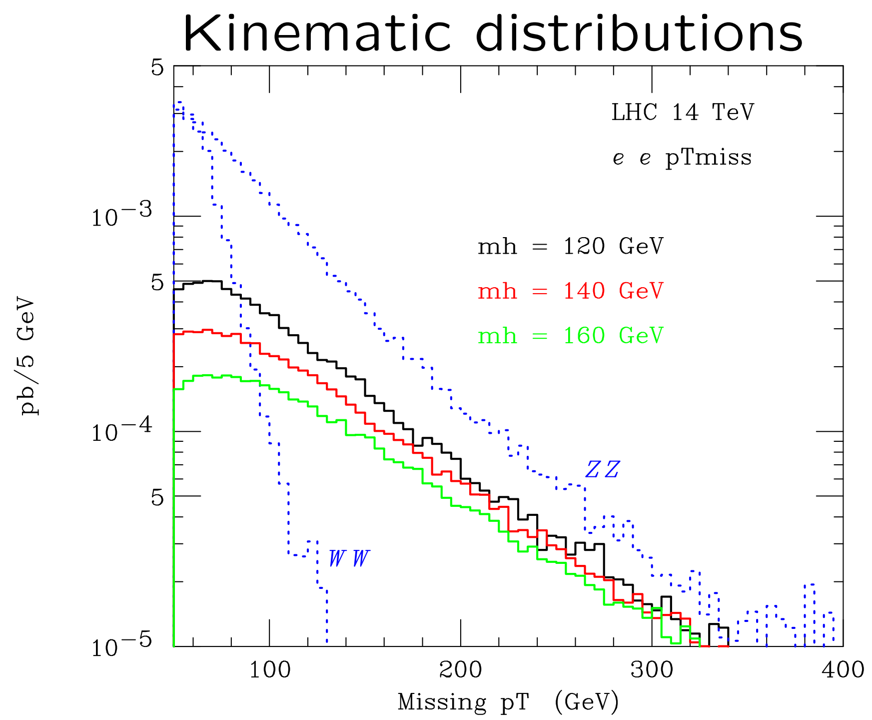
95% CL exclusion limits with 30 fb^{-1} at LHC [ATL-PHYS-PUB-2006-009]

ξ^2 is a scaling factor: $\sigma \times \text{BR}(H \to \text{invis}) \equiv \xi^2 \sigma_{\text{SM}}$

Extracting the mass of an invisible Higgs:

Mass of h_{inv} accessible only through production process.





(needs more study)

Davoudiasl, Han & H.L. (2004)

Measure signal rate.

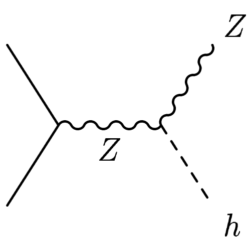
Assuming SM production cross section and 100% invisible decay:

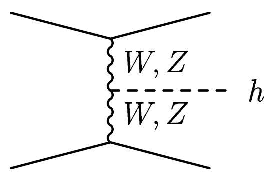
- $Z + h_{inv}$: Δm_h = 30–40 (12–14) GeV with 10 (100) fb^{-1}.
- WBF: $\Delta m_h \simeq$ 40 (30) GeV with 10 (100) fb^{-1}.

What if production rate is not SM-like?
What if decay is not 100% invisible?

For a more model-independent M_h extraction, take the ratio of $Z + h_{inv}$ and WBF rates. Davoudiasl, Han & H.L. (2004)

$Z + h_{inv} \sim hZZ$ 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 $= g m_W \sin(\beta - \alpha)$

Ratio method: $\Delta m_h \simeq$ 35–50 (15–20) GeV with 10 (100) fb^{-1}.

Not great, but rather model-independent.

Conclusions

The Higgs mechanism is the Standard Model's solution to the origin of mass. Upcoming Large Hadron Collider experiments will let us test this at last!

LHC will provide plentiful Higgs data: we must work hard to extract the maximum physics.
- Combining channels allows more information to be extracted.
- Theory assumptions are sometimes needed to overcome correlations caused by incomplete data.

The program:
- First, discover the Higgs.
- Measure couplings to test the SM: 10–40%-level precision on couplings-squared.
- Look for exotic effects, like rare or invisible decays, anomalous coupling structures.

LHC starts running in less than one year.
We'll soon learn what lies behind electroweak symmetry breaking.