Higgs at the LHC & SLHC

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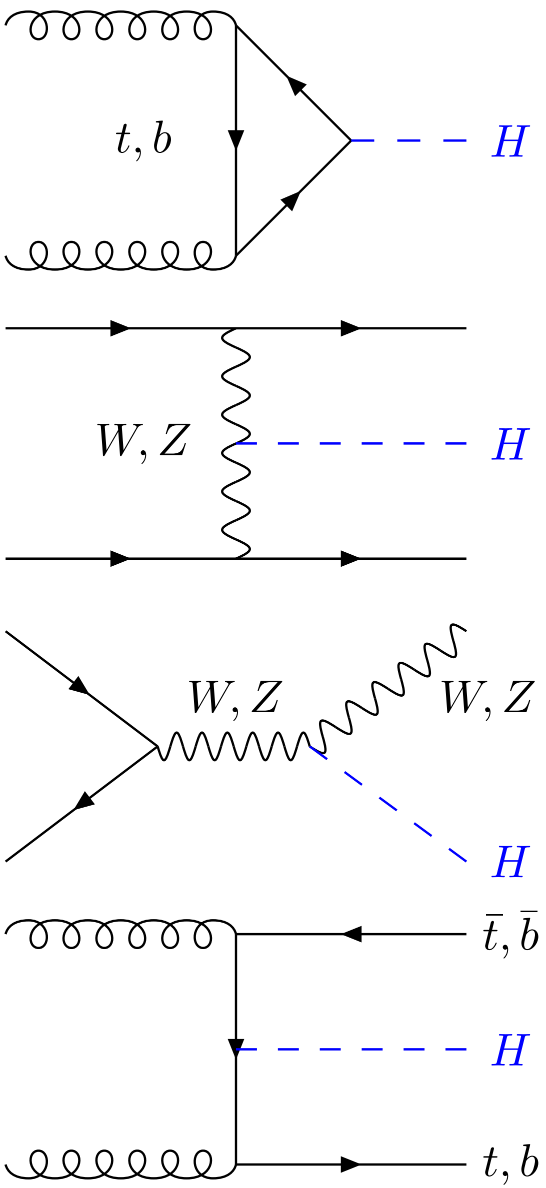
ALCWS, Snowmass, 2005

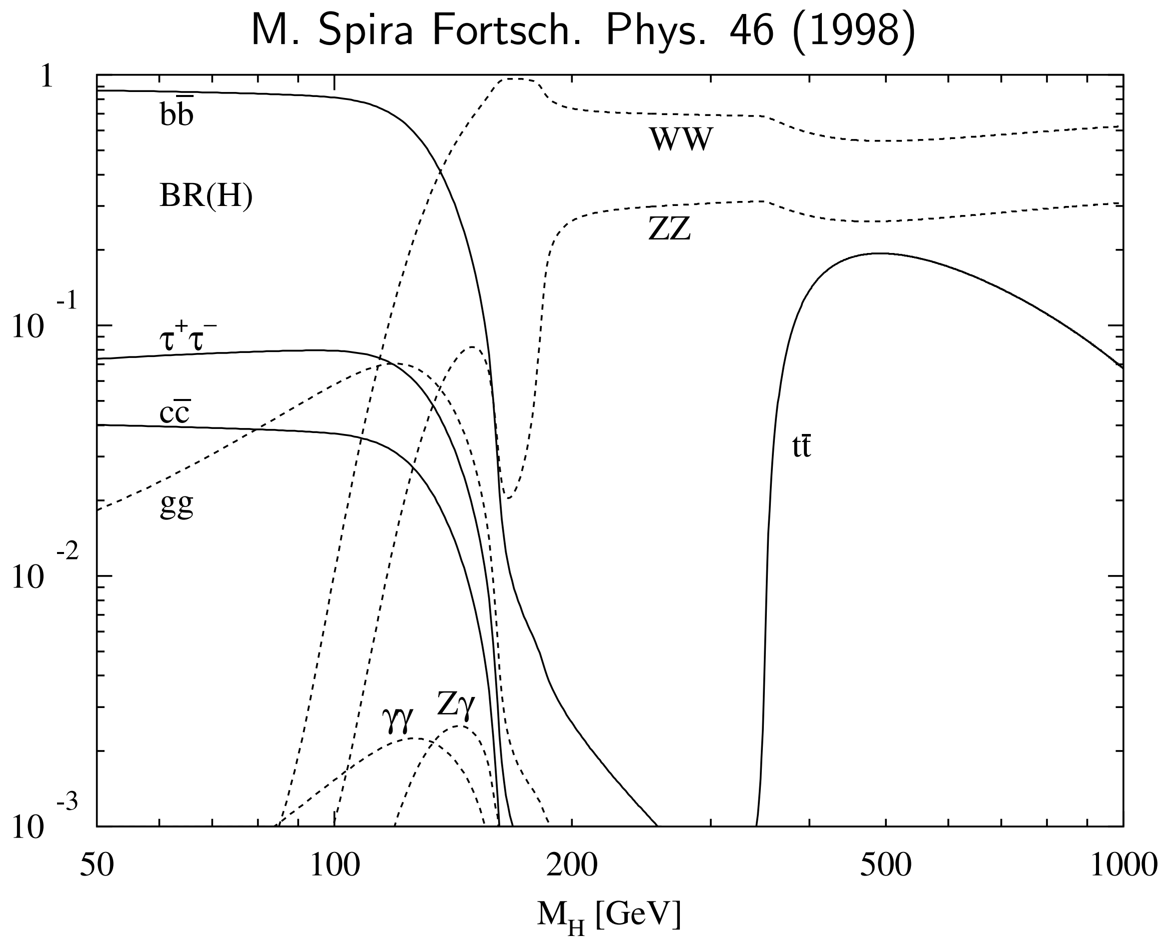
Outline

- Overview of Higgs progress in recent years
- LHC discovery and measurement potential
- $H \rightarrow \mu\mu$ at the LHC *?!*
- Motivation for a luminosity upgrade
- Higgs prospects for SLHC

Input from:
D. Rainwater, T. Plehn, S. Dawson,
W. Smith, M. Dührssen

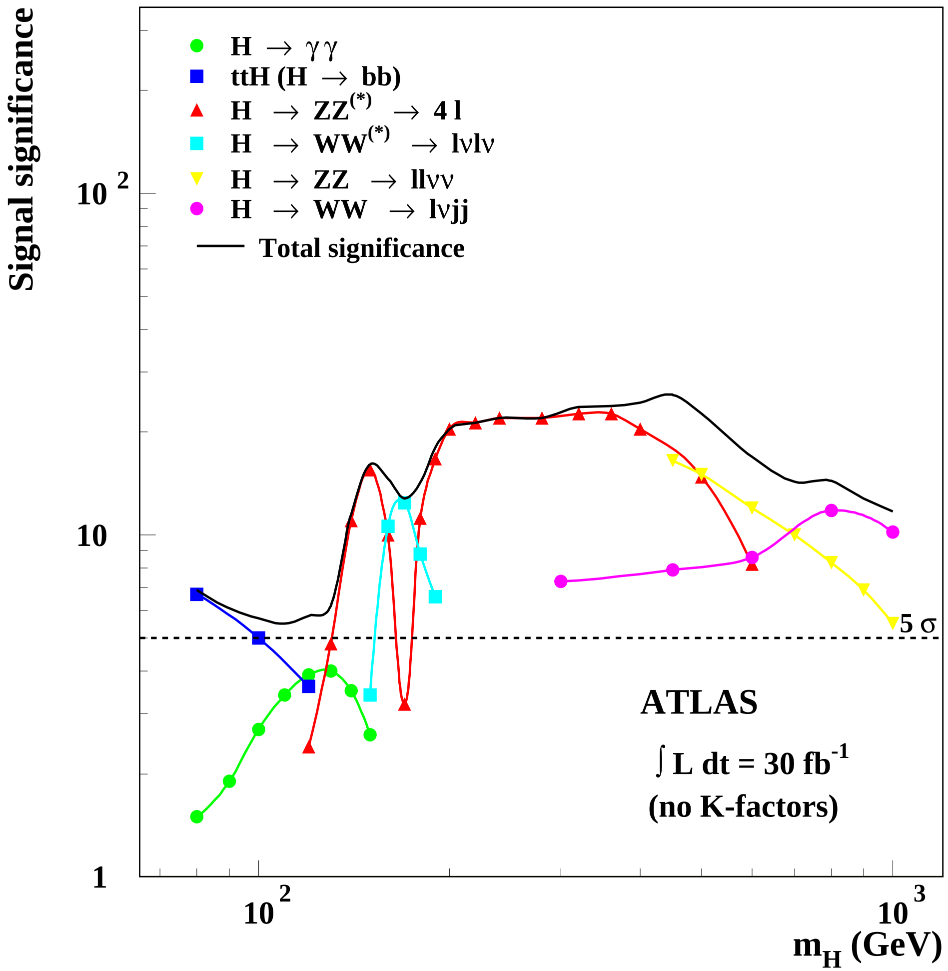
Production and Decay of the Standard Model Higgs



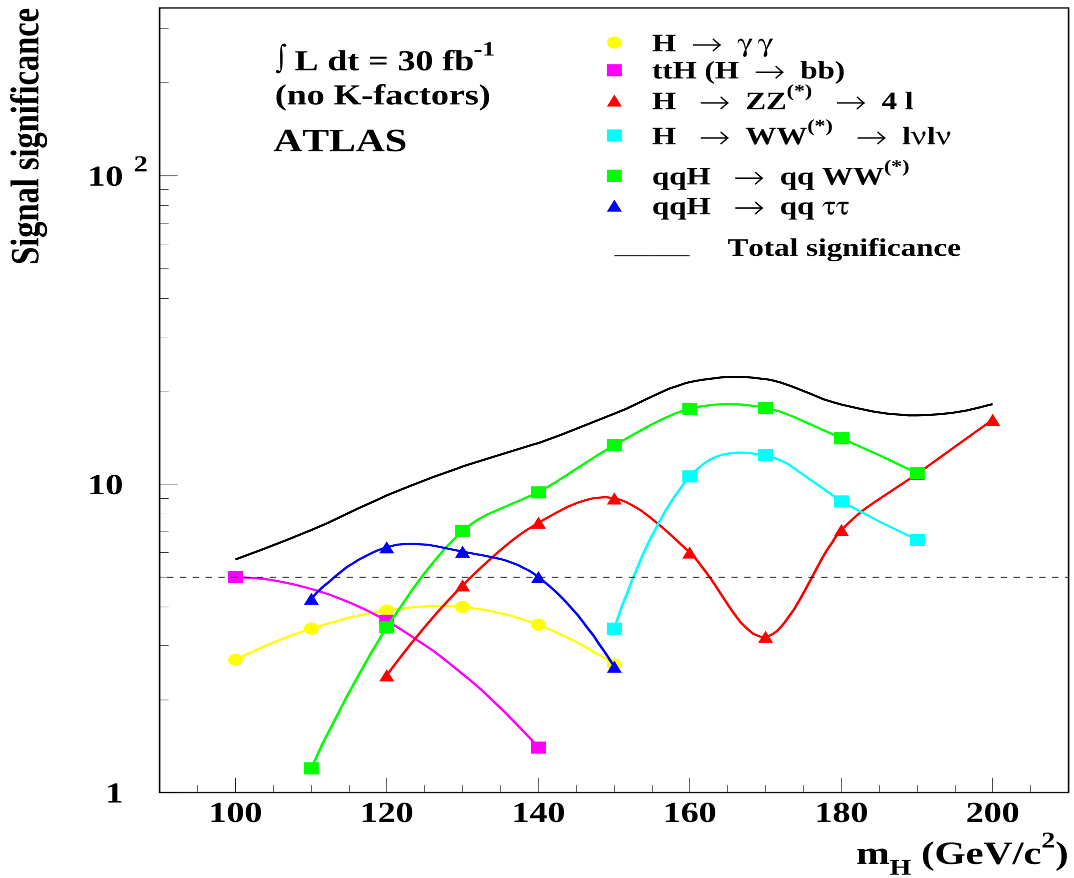


- Gluon-Gluon Fusion dominant production process ($\sim 10pb$).
- Vector Boson Fusion (VBF) $\approx 20\%$ of gg at 120 GeV
- $BR(H \to b\bar{b})$ dominant at low mass, but need trigger
- Forward Tagging Jets of VBF help S/B

Higgs Discovery Potential 1999 → 2003

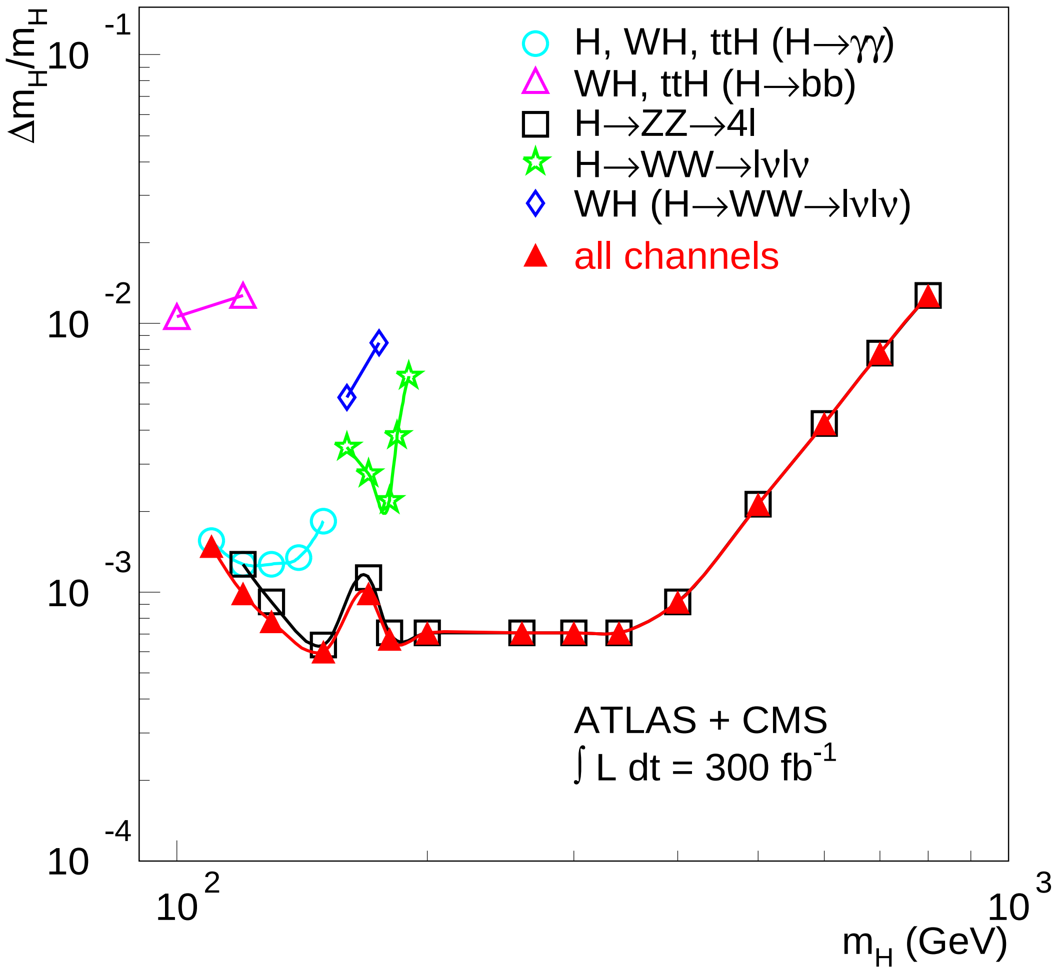


Higgs Potential in ATLAS TDR (1999)



Addition of Vector Boson Fusion Channels at Low mass SN-ATLAS-2003-024

Both ATLAS and CMS cover entire SM Higgs mass range early in LHC running



Eur. Phys. J. C 32, 209 (2004)

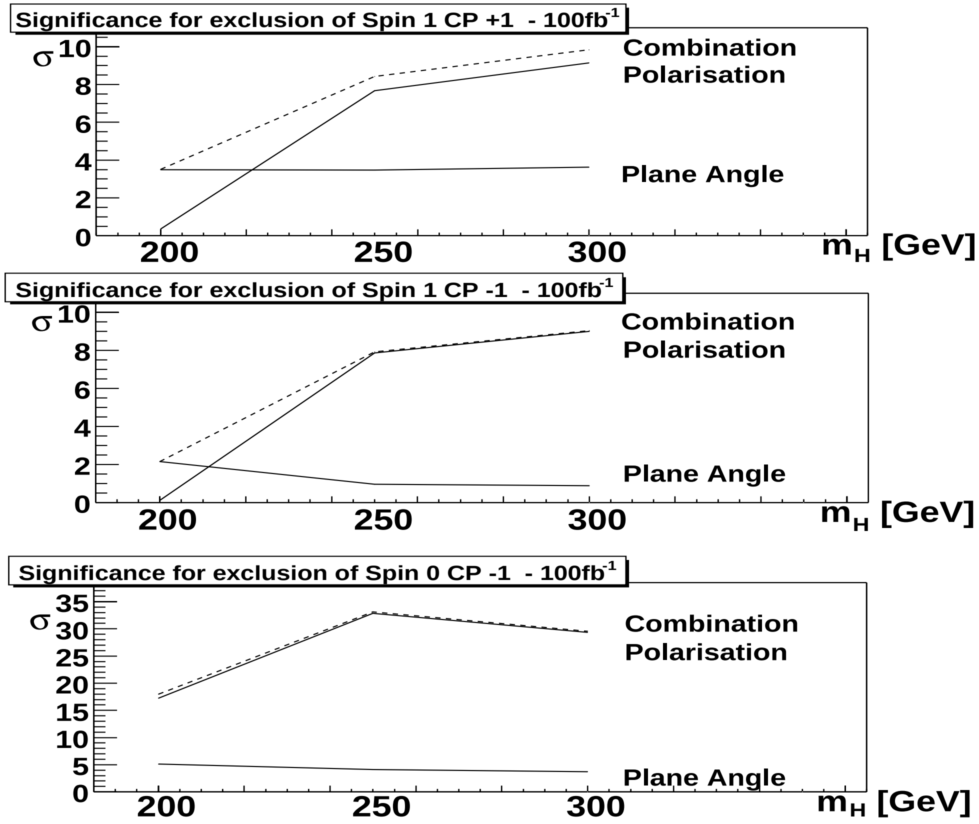


Figure 9: The overall significance for the exclusion of the non standard spin and CP-eigenvalue. The significance from the polar angle measurement and the decay-plane-correlation are plotted separately.

Basic properties of the Higgs should be covered by the LHC.

Figure does not indicate systematic error on mass scale (eg. $H \to \gamma\gamma$)

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Additional Channels:

- ATLAS & CMS included VBF $H \to WW$ and $H \to \tau\tau$ channels
- Corresponding updates to SUSY scans & coupling measurements (for LHC)
- Many new channels under investigation: $ttH(H \to WW, \tau\tau)$; $ZH(H \to \gamma\gamma)$; etc. !

Improved Monte Carlo:

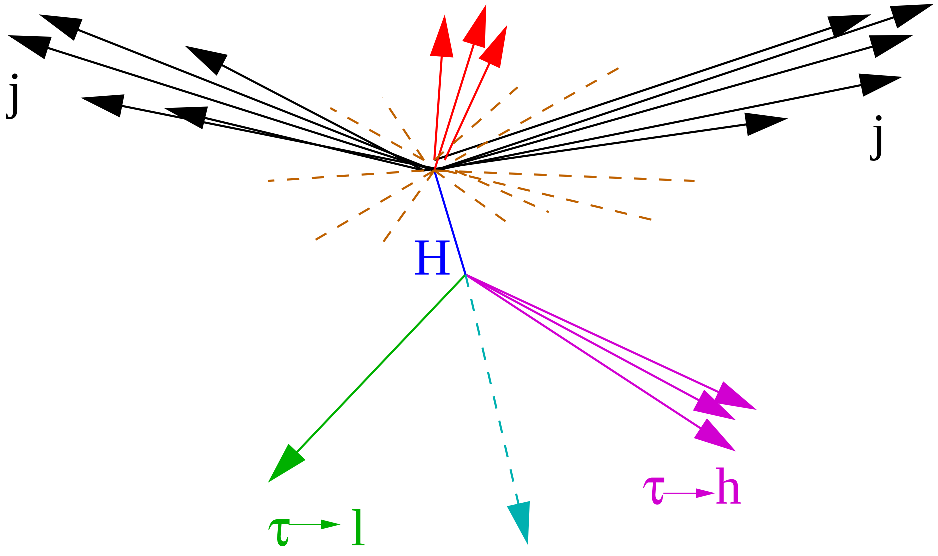
- NLO & NNLO x-sec. generators (MCFM, PHOX,etc.) and event generators (MC@NLO)
- Higher-order tree-level generators (MadEvent, Alpgen, etc.)
- Matrix Element - Parton Shower matching (CKKW, Sherpa, etc...)
- New Underlying Event & Min-Bias tunings (Pythia, Jimmy)

Improved Realism in Simulation:

- Most channels studied with Geant3 or Geant4 and use real reconstruction algorithms
- Studies with Pile-up, underlying event, electronic noise, etc.
- Determine background control samples from data, estimation of systematics, etc.

Studies of LHC/SLHC potential by experimentalists will probably slow when data comes

Weak Boson Fusion $H \to \tau\tau$



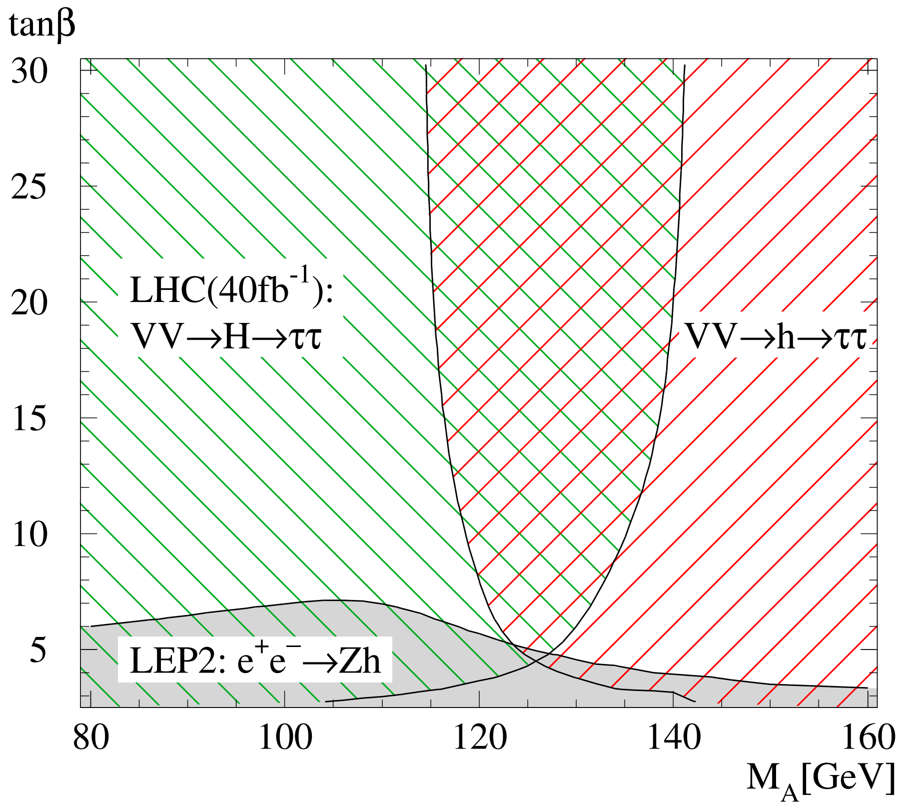
MissingET is the dominant experimental issue

Unexpected complications from finely segmented calorimeter and noise suppression

Several GeV of bias in MissingET if one simply cuts all cells with $E < 2\sigma_{noise}$

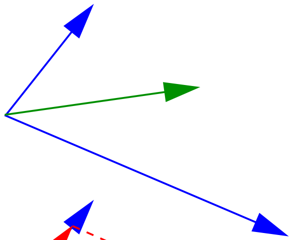
Translates into bias on $m_{\tau\tau}$

Complementarity of $h \to \tau\tau$ and $H \to \tau\tau$ allows this channel to cover most of the MSSM Higgs plane.



Plehn, et. al hep-ph/9911385

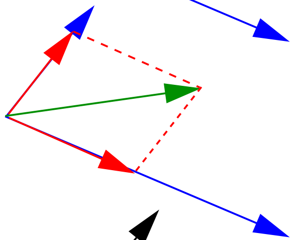
Mass Reconstruction:



Observe

missing transverse momentum

and visible Tau−decay products

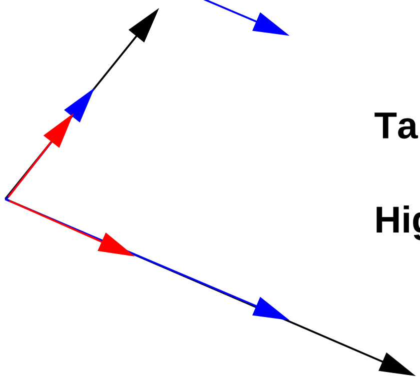


Assume Tau decay products

collinear with original Tau

Solve 2 linear equations

for the neutrinos



Taus can be reconstructed

Higgs can be reconstructed

$$x_{\tau h} = \frac{h_x l_y - h_y l_x}{h_x l_y + \not{p}_x l_y - h_y l_x - \not{p}_y l_x}$$

$$x_{\tau l} = \frac{h_x l_y - h_y l_x}{h_x l_y - \not{p}_x h_y - h_y l_x + \not{p}_y h_x}$$

Some Comments:

After jet cuts, $M_{\tau\tau}$ is the only discrimination we use between $Z \to \tau\tau$ and $H \to \tau\tau$

Collinear approximation doesn't take into account MissingET resolution

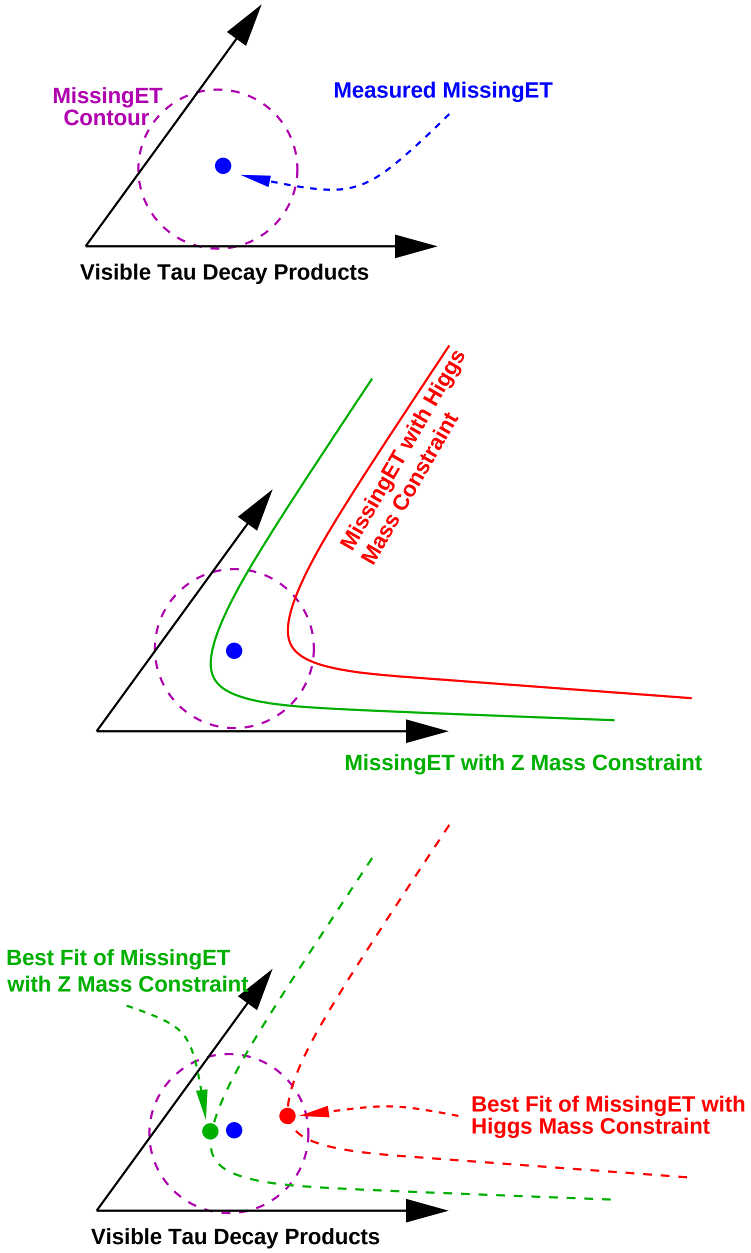
$$M_{\tau\tau} = \sqrt{2(E_h + E_{\nu h})(E_l + E_{\nu l})(1 - \cos\theta_{\tau\tau})}$$

is equivalent to $M_{\tau\tau} = \frac{M_{ll}}{\sqrt{x_{\tau l} x_{\tau h}}}$

only when $0 < x_\tau < 1$

Previously showed we can recover some signal lost by $0 < x_\tau < 1$ cut

Mass Constraints and $\Delta\chi^2$ (Cranmer)



We Observe MissingET and **visible τ decay products**.
From $\sum |E_T|$ we know 1σ MissingET contour

Assuming ν's collinear with τ's the MissingET can be

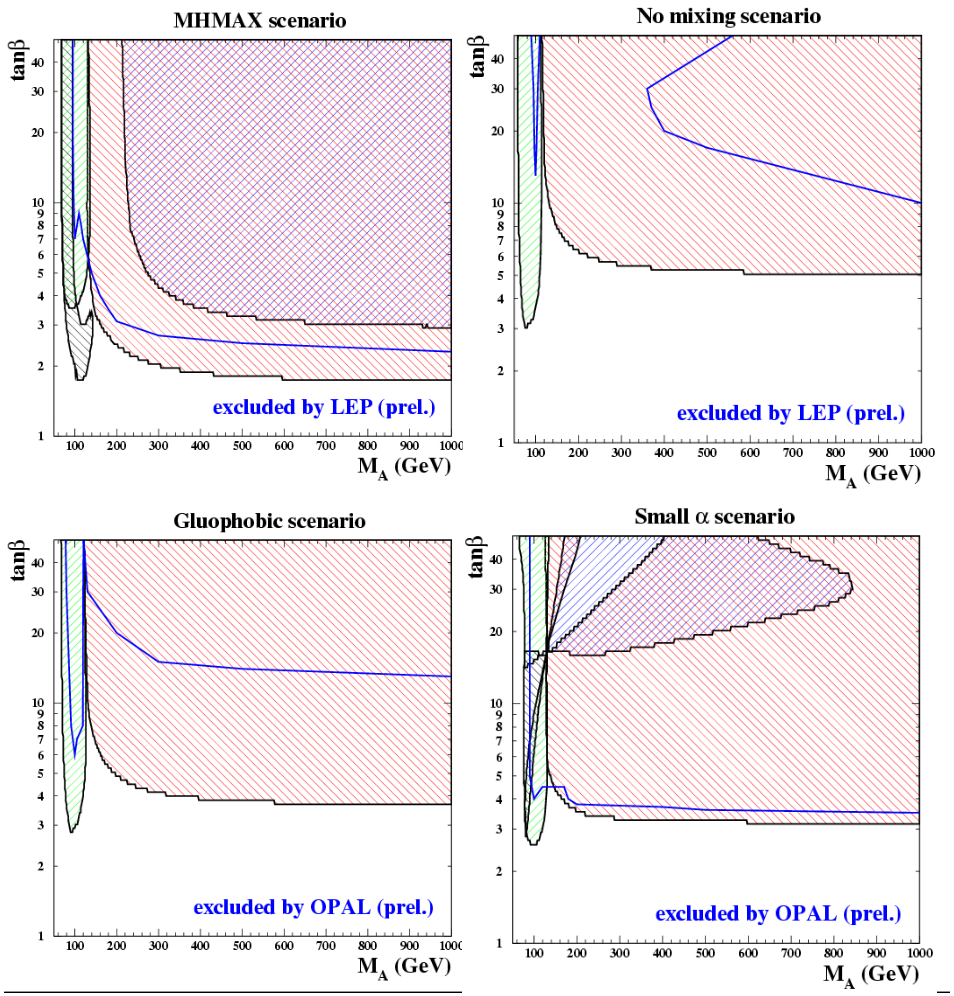
- Constrained to Hypothesized Higgs Mass
- Constrained to Z Mass
- $x_{\tau l} = \left(M_{ll}^2 / M_0^2\right) / x_{\tau h}$

Kinematic fits can be used to find hypothetical MissingET most consistent with observed MissingET and mass constraint. Each has it's own χ^2

Finally, $\Delta\chi^2$ quantifies if event is more consistent with $H \to \tau\tau$ or $Z \to \tau\tau$

Leads to a low- and high-purity sample. Preliminary results very promising.

The MSSM plane with 30 fb^{-1}



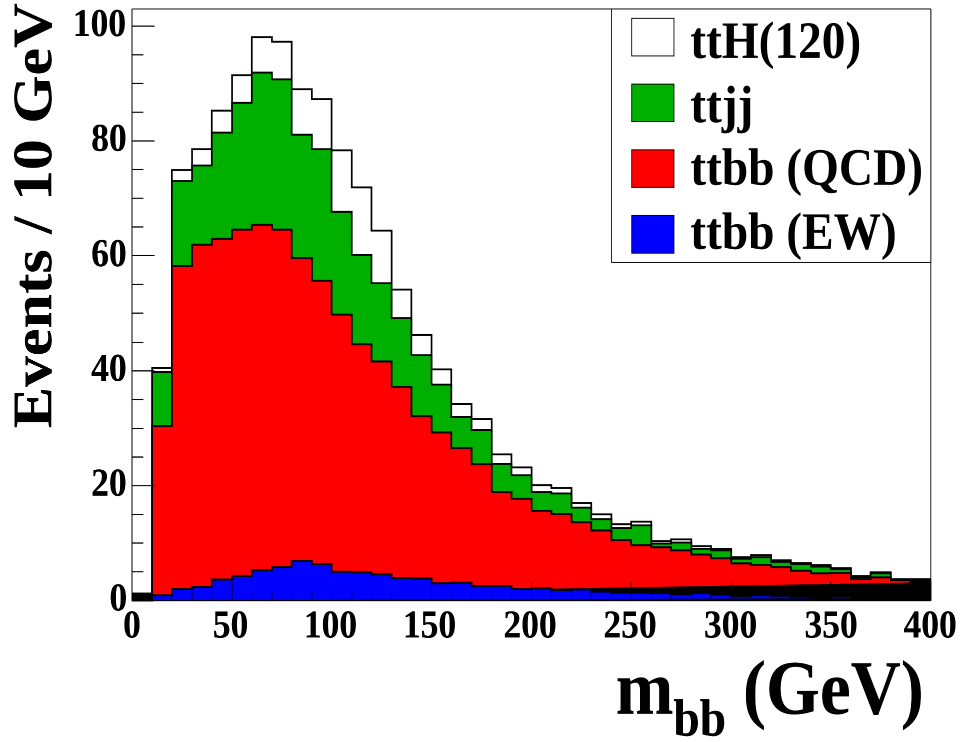
Complementarity of VBF $h \rightarrow \tau\tau$ and $H \rightarrow \tau\tau$ covers almost all the plane not excluded by LEP

Also shown:

- VBF $h \rightarrow WW$
- VBF $H \rightarrow WW$

There are more recent ATLAS results from M. Schumacher (with systematic errors), but they are still preliminary.

J. Cammin & M. Schumacher, ATL-PHYS-2003-024 (nice thesis by J. Cammin)



Combinatorial background is challenging with 4b-jets and ≥ 6 jets total

Signal efficiency goes like ϵ_b^4

Signal & bkgnd. have similar shape

Estimating $ttjj$ and $ttbb$ background from data difficult, large systematics

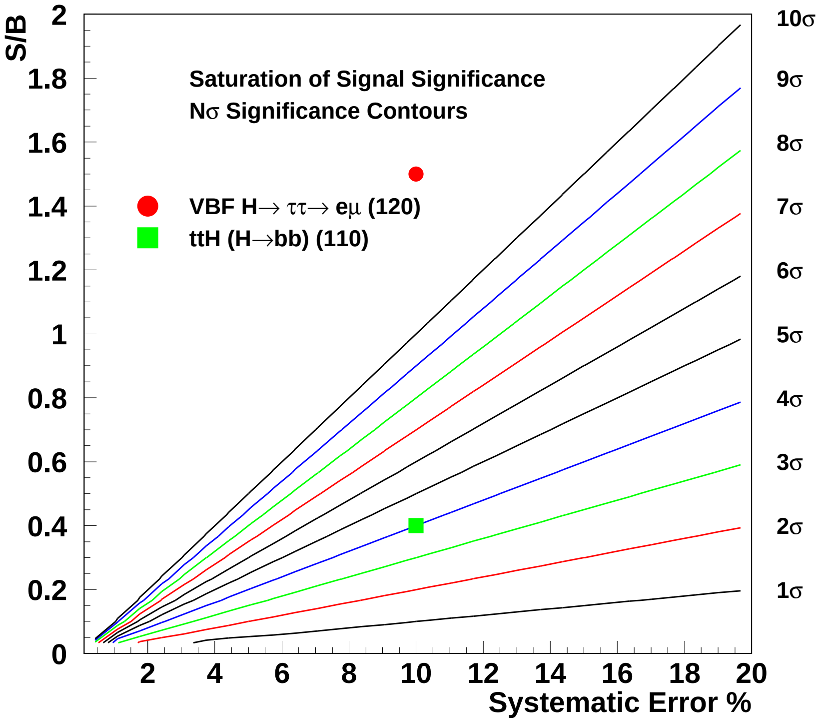
It's not clear if this channel will ever reach 5σ

- This is (was) one of the few powerful channels near the LEP limit
- Do ATLAS and CMS results agree?

Background determination from sidebands carries two sources of error:

- statistical error from sideband measurement
- systematic on extrapolation from sideband to signal-like area (shape systematic)

The shape systematic does not (necessarily) reduce with increased luminosity



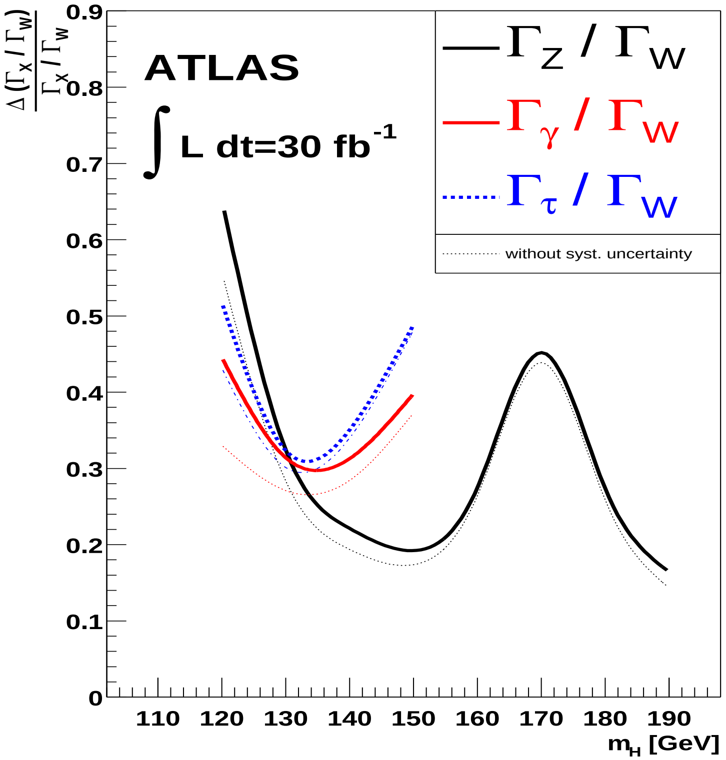
Normal significance measure $s/\sqrt{b}$ is replaced by $s/\sqrt{b(1+b\Delta^2)}$

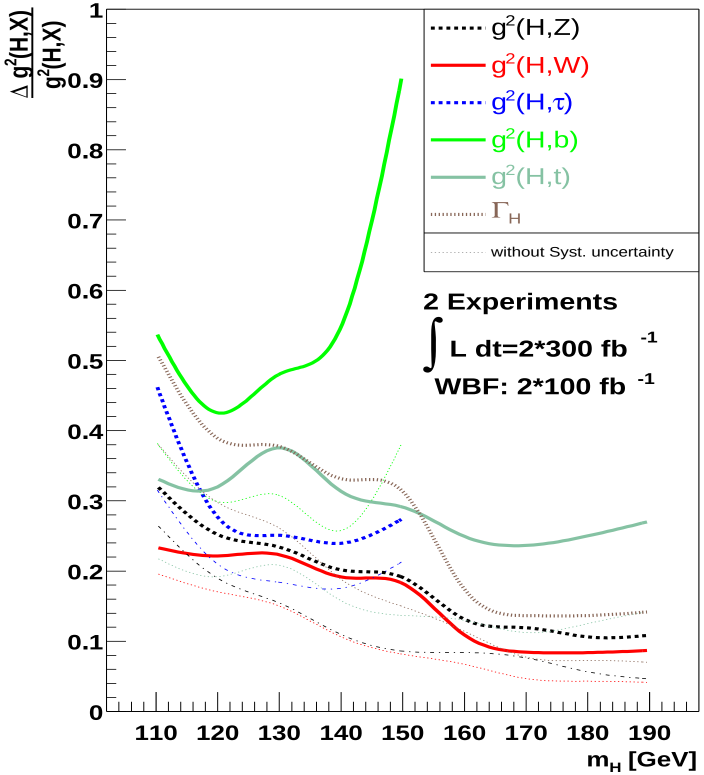
If s/b is fixed as we increase luminosity, the expected significance saturates:

$$\sigma_\infty = \frac{s/b}{\Delta_{shape}}$$

With its low S/B and 10% shape ystematic, $ttH(\rightarrow bb)$ can't get to 5σ even with $L \rightarrow \infty$

M. Dührssen, et. al. ATL-PHYS-2003-030 & Phys.Rev.D70:113009,2004 (hep-ph/0406323)





Assume CP-even, spin-0, only one Higgs

Ratios of partial widths
to within 20% with 30 fb^{-1}

Weak assumptions:
$g(H,V) < 105\% g(H,V,SM)$
allow for unobserved decays & new loops

Absolute couplings measured
to within 10% with 2×300 fb^{-1}

Overview of Systematic Uncertainties

L	5%	Measurement of luminosity
ϵ_D	2%	Detector efficiency
ϵ_L	2%	Lepton reconstruction efficiency
ϵ_γ	2%	Photon reconstruction efficiency
ϵ_b	3%	b-tagging efficiency
ϵ_τ	3%	hadronic τ-tagging efficiency
ϵ_{Tag}	5%	WBF tag-jets / jet-veto efficiency
ϵ_{Iso}	3%	Lepton isolation ($H \to ZZ \to 4\ell$)

Table 1: Estimated systematic uncertainties on luminosity and detector effects.

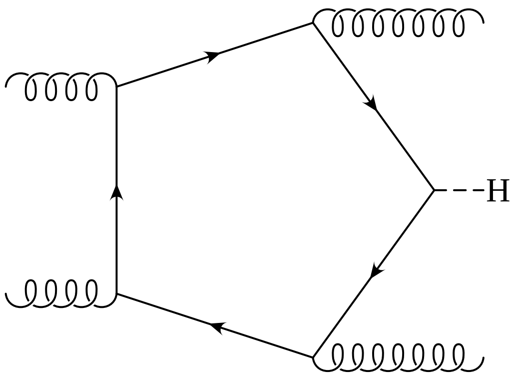
Decay	Shape	N_N/N_B
$H \to ZZ^{(*)} \to 4l$	1%	5
$H \to WW^{(*)} \to \ell\nu\,\ell\nu$	5%	1
$H \to \gamma\gamma$	0.1%	10
$H \to \tau\tau$	5%	2
$H \to b\bar{b}$	10%	1

Table 2: Estimated systematic uncertainties on background normalization.

Taken from Phys.Rev.D70:113009,2004 (hep-ph/0406323)

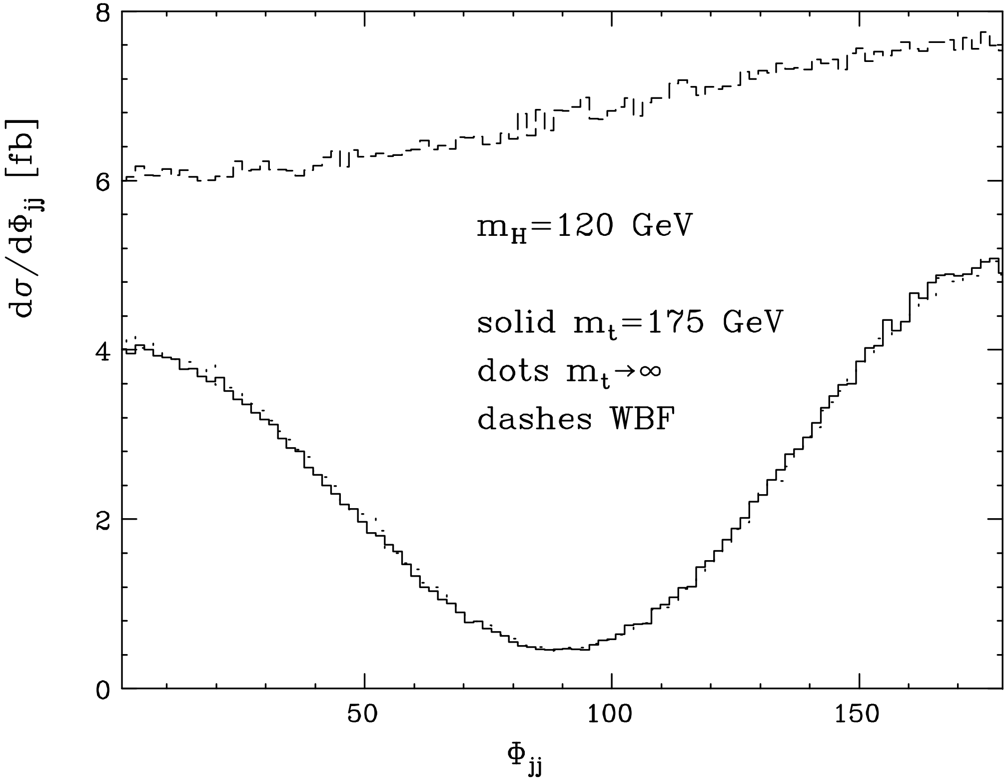
GF	20%
$t\bar{t}H$	15%
WH	7%
ZH	7%
WBF	4%
$gg \to Hgg$	100%

Table 3: Theoretical QCD and PDF uncertainties on the various Higgs boson production channels. The channel $gg \to Hgg$ was added to all WBF analyses at 10% of the WBF rate with an uncertainty of a factor 2.



(c)

V. Del Duca, C. Oleari, D. Zeppenfeld, et. al. hep-ph/0108030



$\Delta\phi_{jj}$ can be used to fit relative contribution from $gg \to Hgg$

Should reduce systematic error considerably.

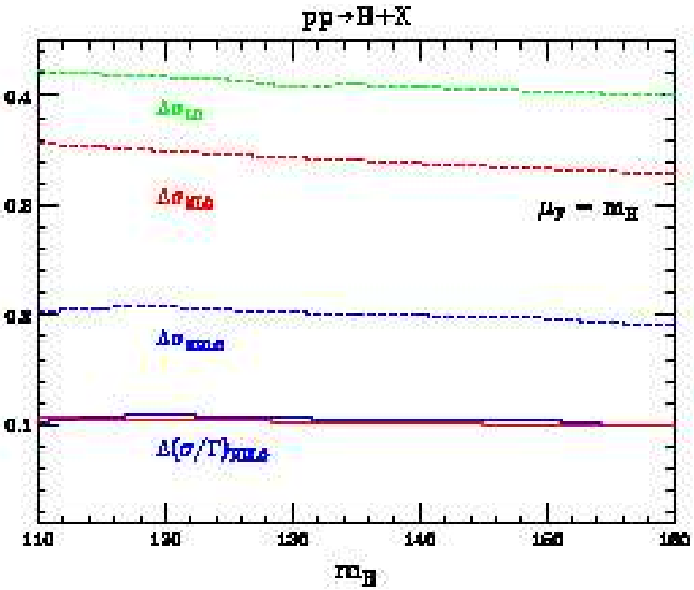
Petriello, Anastasiou, Melnikov

- Analyses of Higgs couplings use relation

$$\sigma(H) \times BR(H \to xx) = \frac{\sigma(H)^{SM}}{\Gamma_p^{SM}} \cdot \frac{\Gamma_p \Gamma_x}{\Gamma}$$

$\Rightarrow$ calculate and assign theoretical uncertainty to σ/Γ, extract $\Gamma_p \Gamma_x / \Gamma$

- Current studies assign $\approx 20\%$ theoretical uncertainty to σ/Γ for $gg \to H$ production mode (Duhrssen et. al.)



- $\Gamma \sim \alpha(\mu_R)^2 C_1(\mu_R)^2 \{1 + \alpha(\mu_R) X_1 + \ldots\}$
  $\sigma \sim \alpha(\mu_R)^2 C_1(\mu_R)^2 \{1 + \alpha(\mu_R) Y_1 + \ldots\}$
- Corrections to σ, Γ track each other

$\Rightarrow$ Large μ_R uncertainty in σ/Γ cancels

- At NNLO, should take $20\% \to 10\%$ theory error
- Effect on coupling extractions?

Very preliminary, more details to come

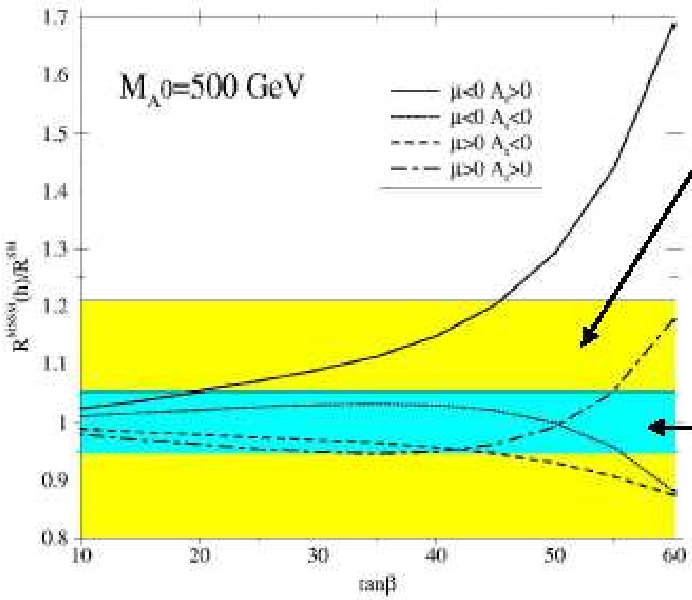
This will be included in Dührssen's next fits.

How well do we need to know the couplings?

Taken from Sally Dawson's 2003 wine & cheese lecture

- MSSM example:

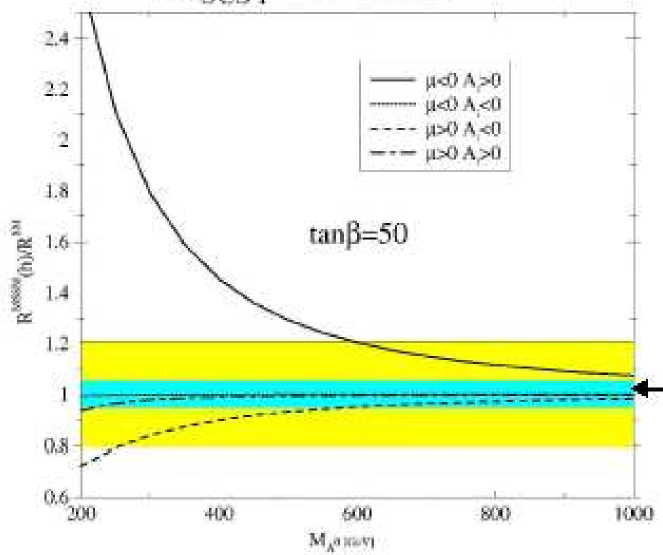
$$R = \frac{BR(h \to b\bar{b})}{BR(h \to \tau^+\tau^-)}$$



21% deviation from SM

5.4% deviation from SM

M_{SUSY}=1.5 TeV



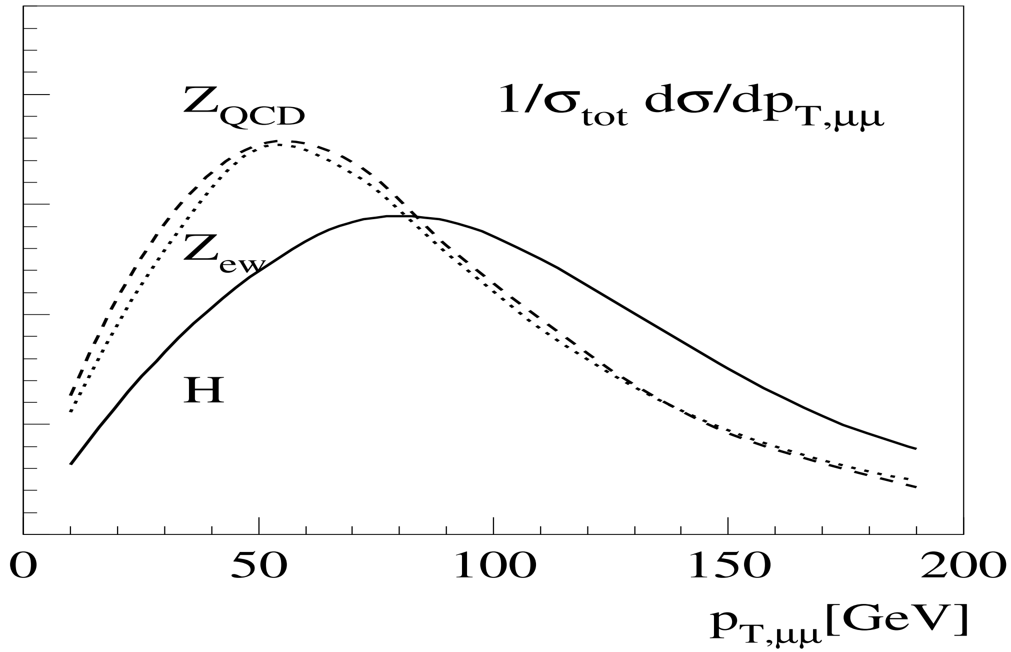
Note rapid approach to decoupling limit

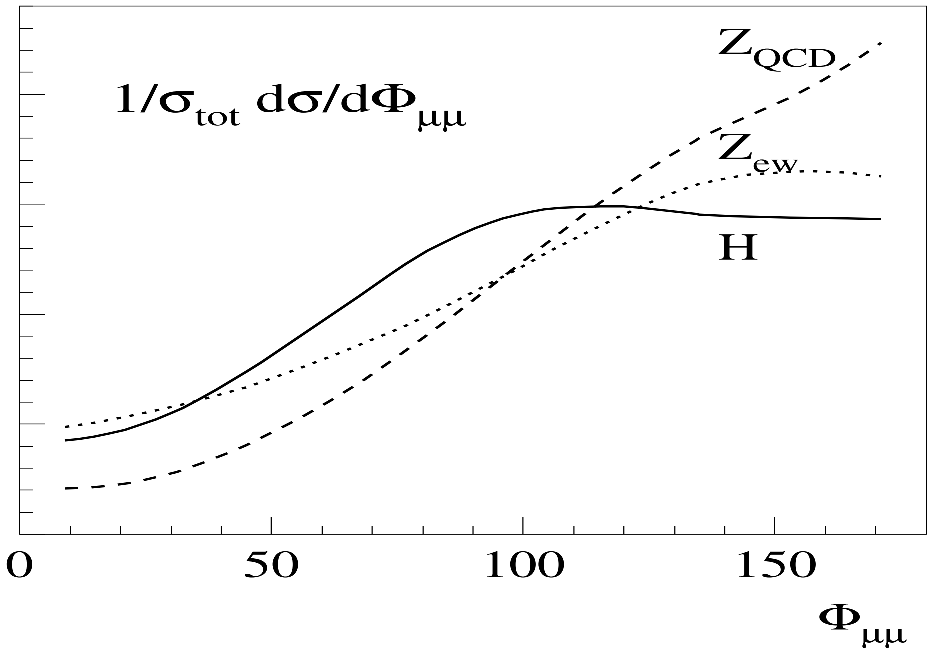
Guasch, Hollik, Penaranda, hep-ph/0307012

In hep-ph/0107180, Tilman Plehn and David Rainwater investigated the potential of VBF $H \to \mu\mu$ to measure Yukawa coupling to second-generation fermions at LHC.

Even with 300 fb^{-1}, best cuts only achieve 1.8σ significance for $M_H = 120$ GeV.

However, they note several other variables with discriminating power:





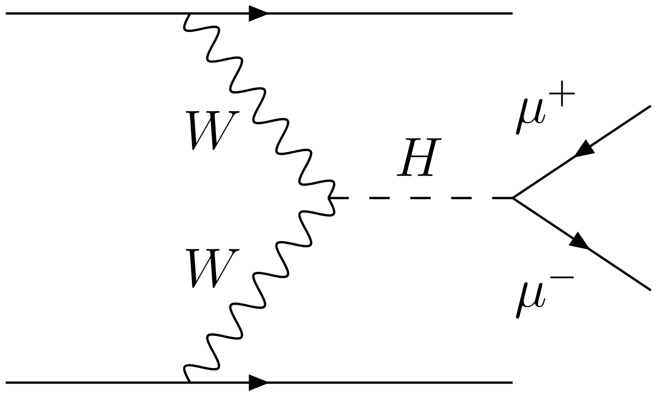
They suggested the use of Neural Networks or some multivariate algorithm

Tao Han & Bob McElrath (hep-ph/0201023) included gluon fusion, still no discovery.

In addition to multivariate techniques , *the most powerful search* considers:

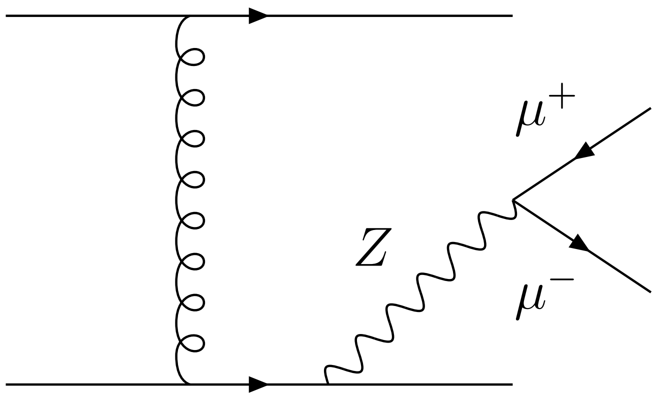
Likelihood of experiment $= \Pi$ likelihood of each event

With basic cuts, only need to consider signal and irreducible backgrounds



Phase Space:

2	for incoming quarks
$+(3 \times 4)$	for outgoing fermions
-4	for 4-momentum conservation
10	phase space dimensions



All other observables are a function of these. There is no more information available.

Re-write Higgs, EW Z, & QCD Z MC generators to run on same grid, sample same phase-space points

Changed Higgs width to 2.4 GeV to simulate mass res.

The Calculation in Words (Cranmer & Plehn)

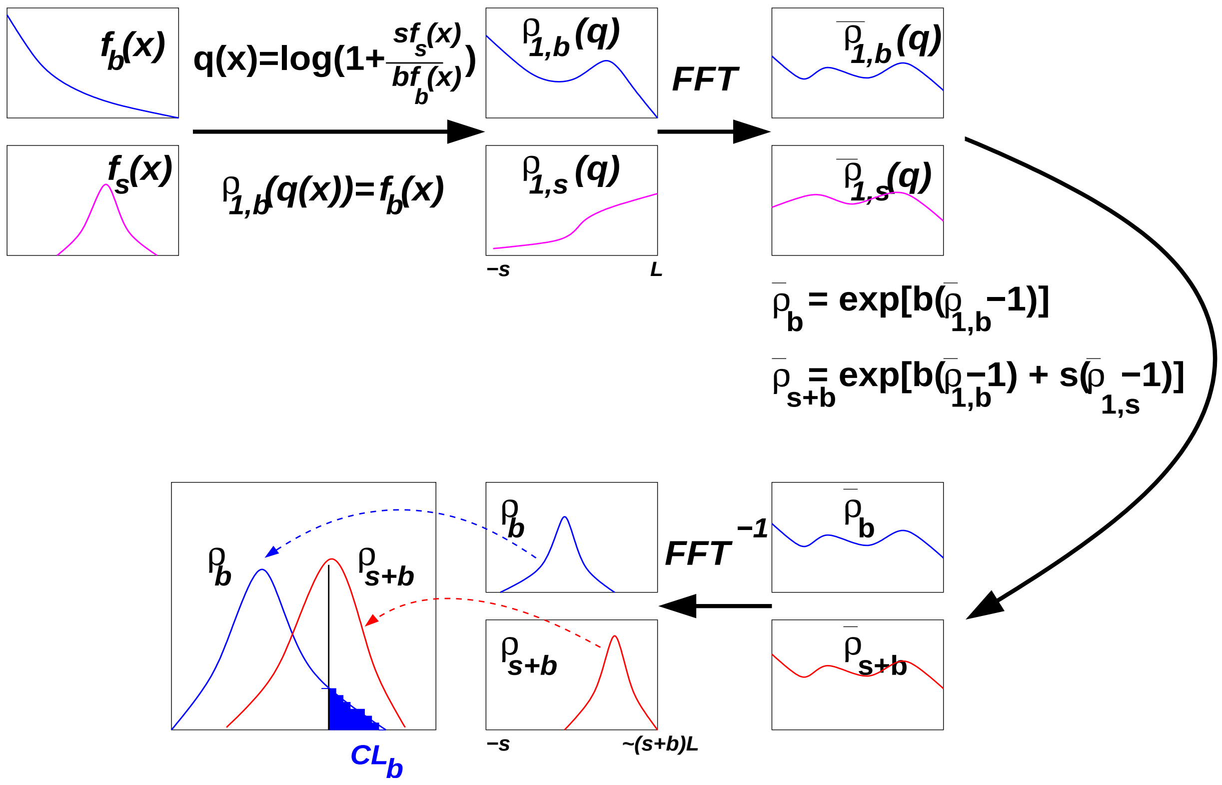
The problem for experimentalists is we don't know $L(x|H_0)$ & $L(x|H_1)$ – It's a convolution of $|\mathcal{M}|^2$ with detector

By neglecting/simplifying detector effects, we can **analytically calculate an upper limit** on the expected significance of a new particle search

From MC generator, we can calculate distribution of q for one event

Using Fourier Transform, we can easily calculate distribution of q for N events (N convolutions).

Using exponentiation trick, we can obtain distribution of q for a given luminosity including Poisson fluctuations of N



$H \to \mu\mu$ Results (Cranmer & Plehn)

The original cuts in hep-ph/0107180 give 1.8σ / experiment for 300 fb^{-1}.

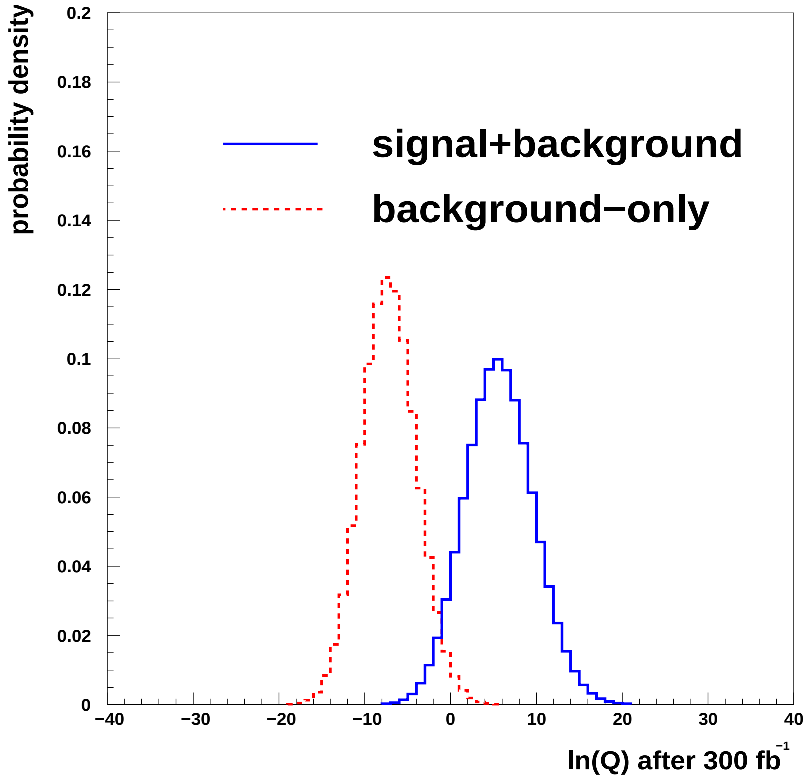
Using our technique with a 2.4 GeV (B.W.) mass resolution, we achieve:

3.7σ / experiment for 300 fb^{-1}

There's a 10% chance of a lucky 5σ discovery

CMS+ATLAS gives 5.2σ

Including CJV efficiencies from hep-ph/0107180, expect 4.2σ / experiment for 300 fb^{-1}.



Conclusion: the use of multivariate techniques and event weighting may make it possible to observe the Standard Model $H \to \mu\mu$ at the LHC!

Even if LHC can do it, a luminosity upgrade would improve $\lambda_{H\mu\mu}$ measurement

Will Do

Discovery of SM Higgs:

- ♢ SM Higgs could be discovered over full mass range with 30 fb^{-1}
- ♢ Several Channels Available, VBF a big improvement

Measurements of Higgs Parameters:

- ♢ Masses 0.1 - 1%
- ♢ Ratios of Widths 10-60%
- ♢ Couplings 15-50%

MSSM Higgs:

- ♢ Most of $M_A - \tan\beta$ plane covered in first year
- ♢ Many prospects to distinguish SM from MSSM Higgs sectors (eg. charged higgs)

Won't Do

At All:

- ♢ Measurements of Higgs Self-Coupling
- ♢ Observe/Discover $H \to \mu\mu$?

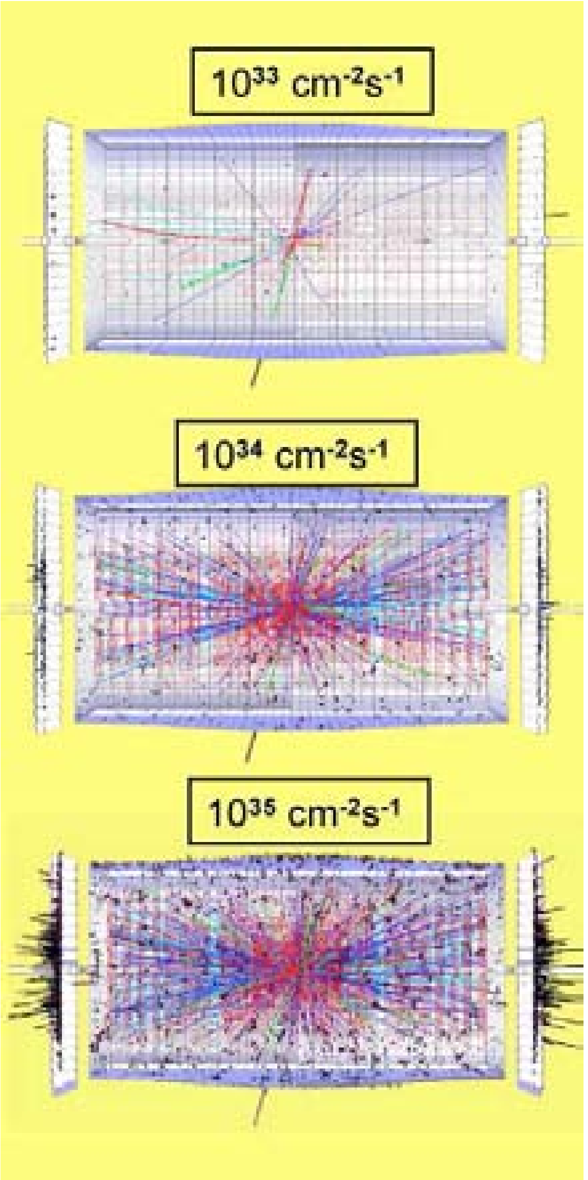
In Some Cases:

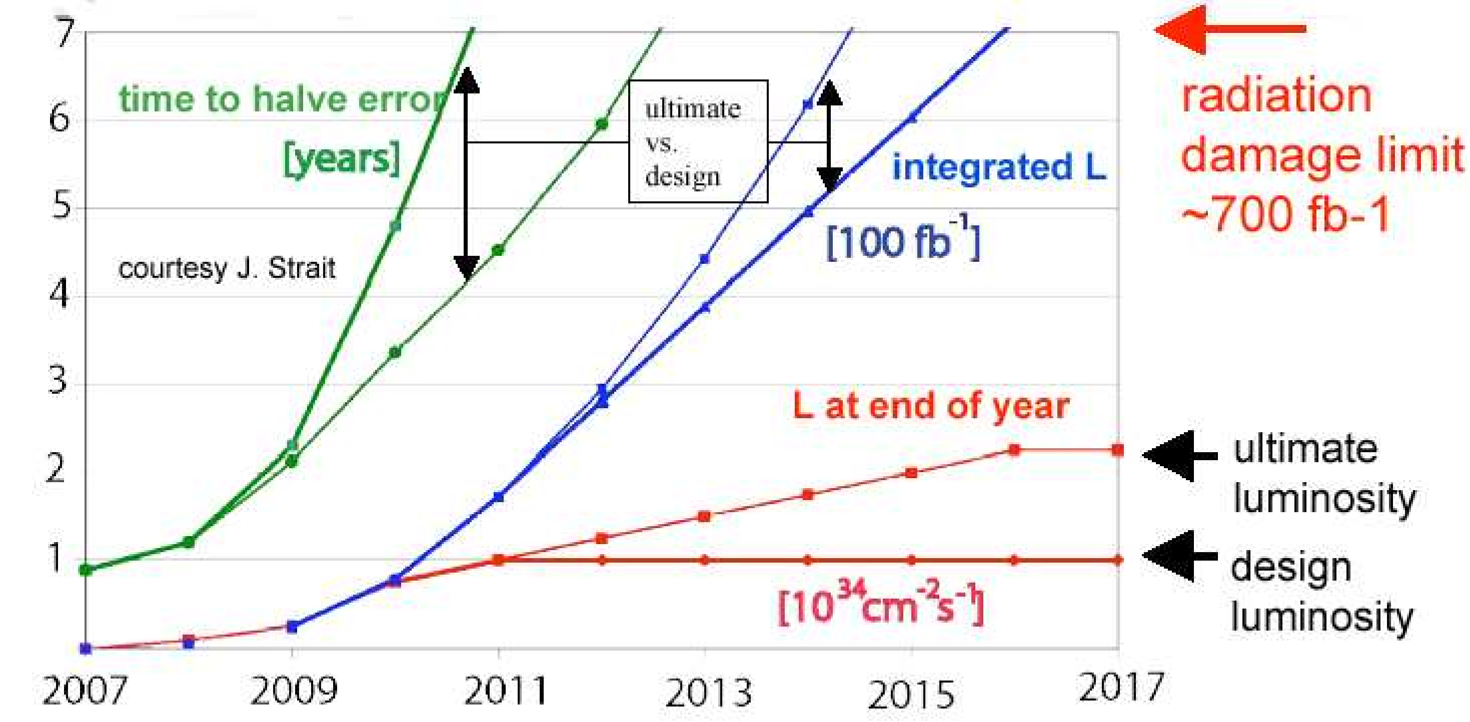
- ♢ Distinguish SM from MSSM Higgs Sector (small $\tan\beta$)

As Well as SLHC:

- ♢ Coupling Measurements
- ♢ Rare Decays $H \to \mu\mu$

$H \to ZZ \to ee\mu\mu$





(1) *LHC IR quads life expectancy* estimated <10 years from radiation dose

(2) the *statistical error halving time* will exceed 5 years by 2011-2012

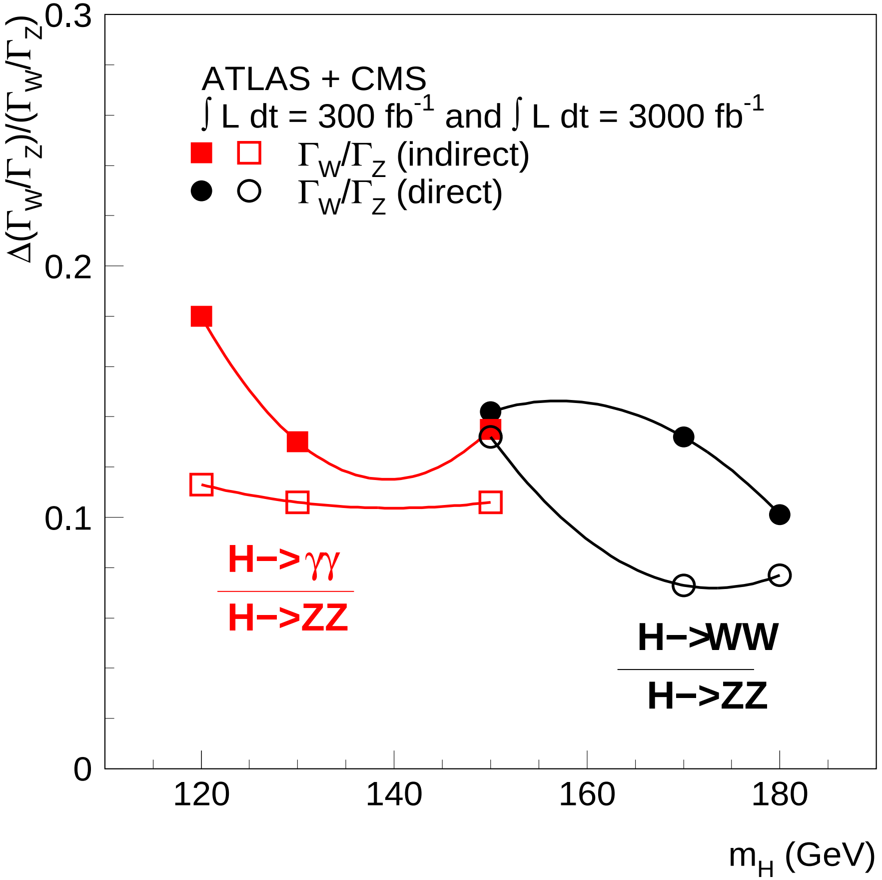
(3) therefore, it is reasonable to plan a ***machine luminosity upgrade based on new low-β IR magnets before ~2014***

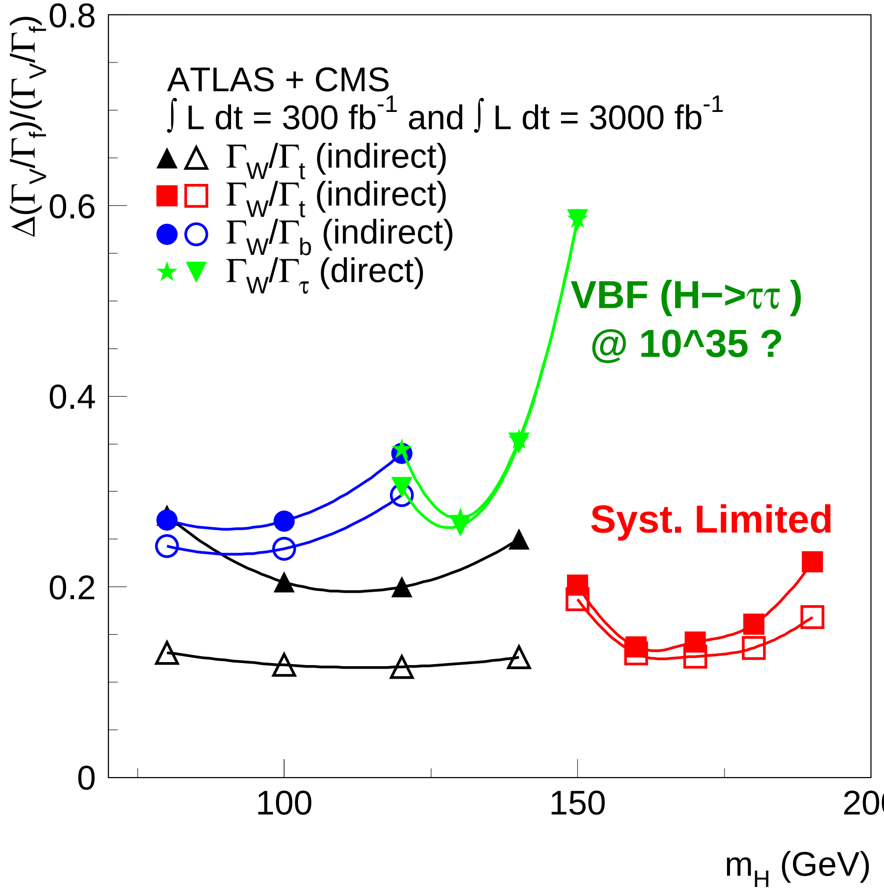
W. Smith, U. Wisconsin, ILC Workshop, Snowmass, August 17, 2005 — LHC & SLHC Physics & Detectors – 13

See Wesley Smith's talk:

http://cmsdoc.cern.ch/cms/TRIDAS/tr/0508/Smith_ILC_SLHC_Aug05.pdf

Results from main SLHC publication: hep-ph/0204087

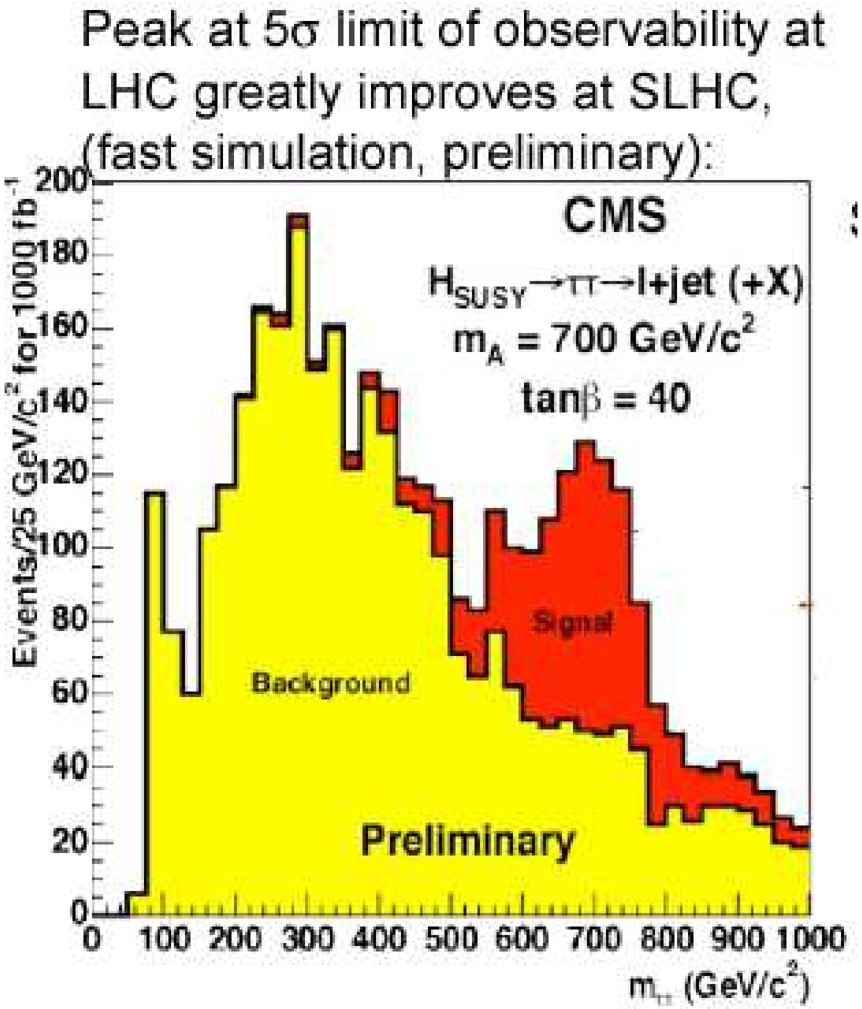


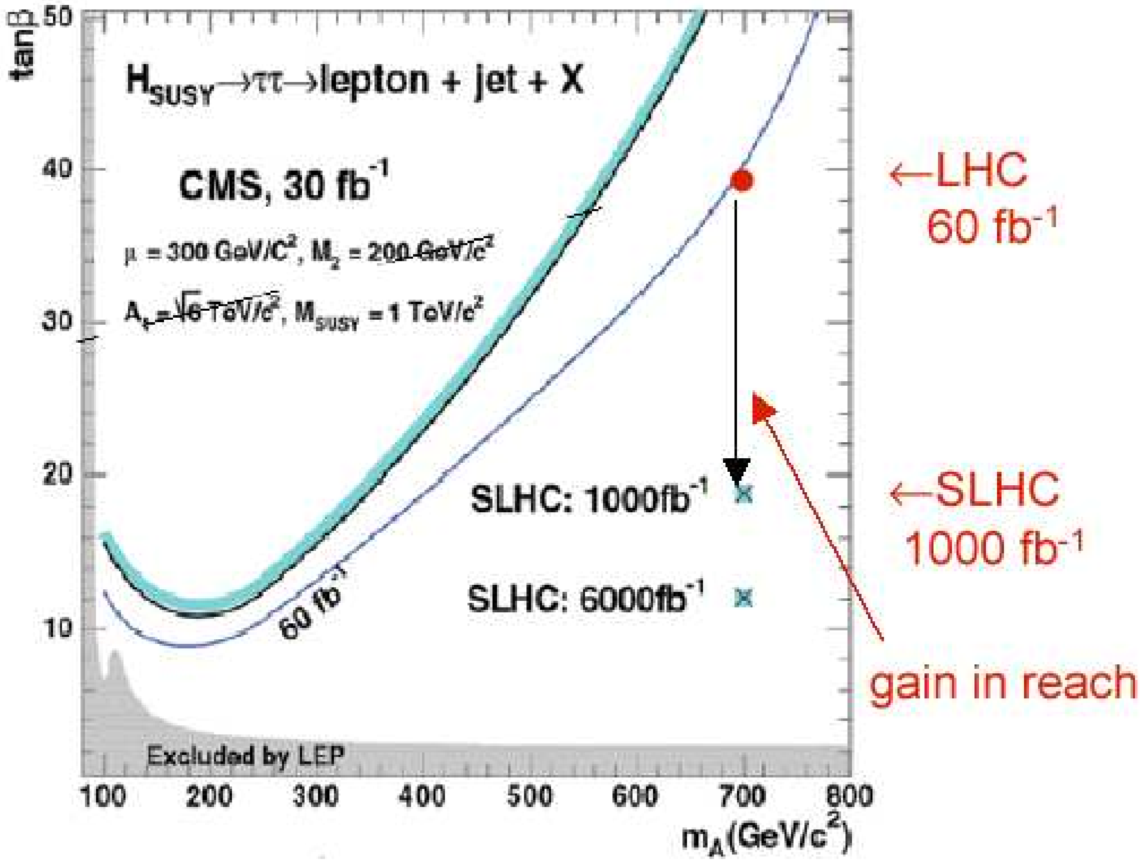


SLHC will significantly improve coupling measurements.

By the end of the LHC, we should understand forward jets and central jet veto much better!

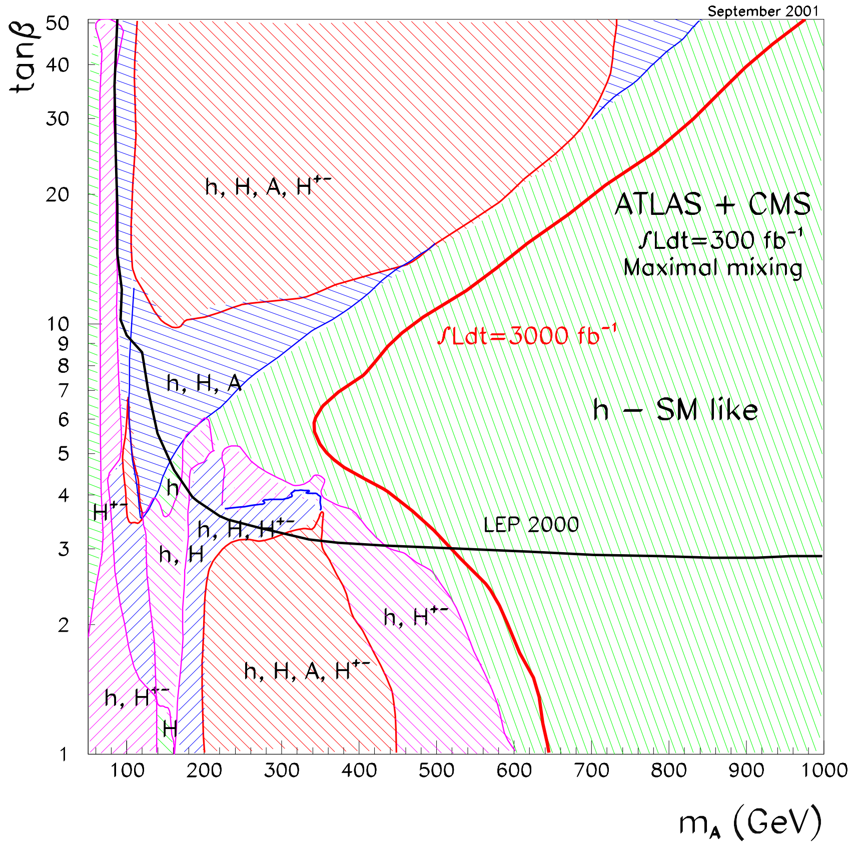
Many new channels since this study, should be revisited.





An order of magnitude increase in integrated luminosity can significantly improve discovery reach for heavy Higgs bosons

Extended SUSY Higgs



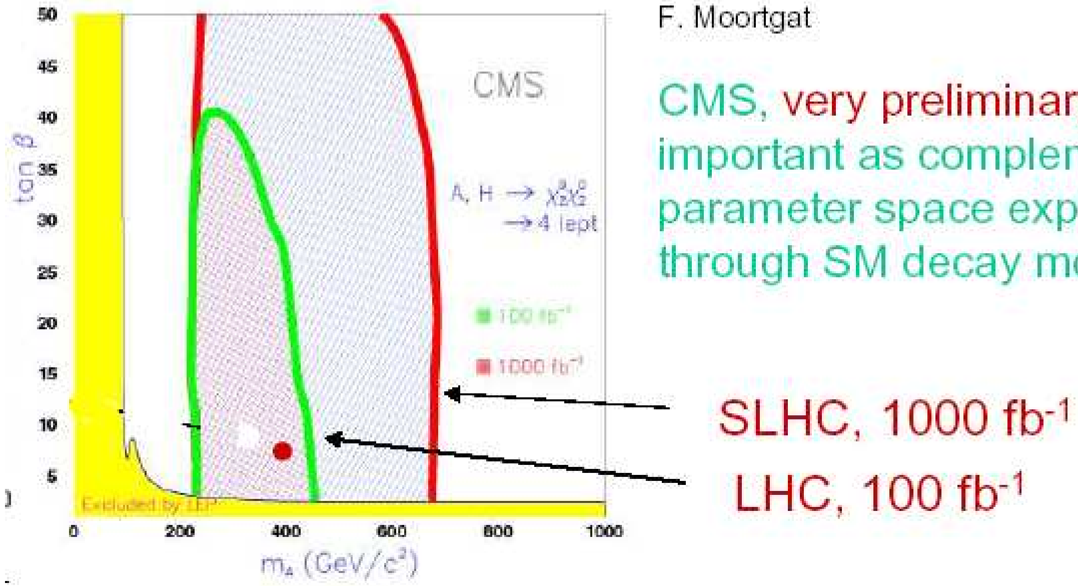
↑ SLHC extends discovery potential for Heavy Higgs.

Use of $H/A \rightarrow$ SUSY particles is model dependent.

$H/A \rightarrow \chi_2^0\chi_2^0 \rightarrow 4l$ contributes in the region where only h is seen decaying to SM particles

↓ SLHC can extend discovery potential for $H/A \rightarrow \chi_2^0\chi_2^0 \rightarrow 4l$

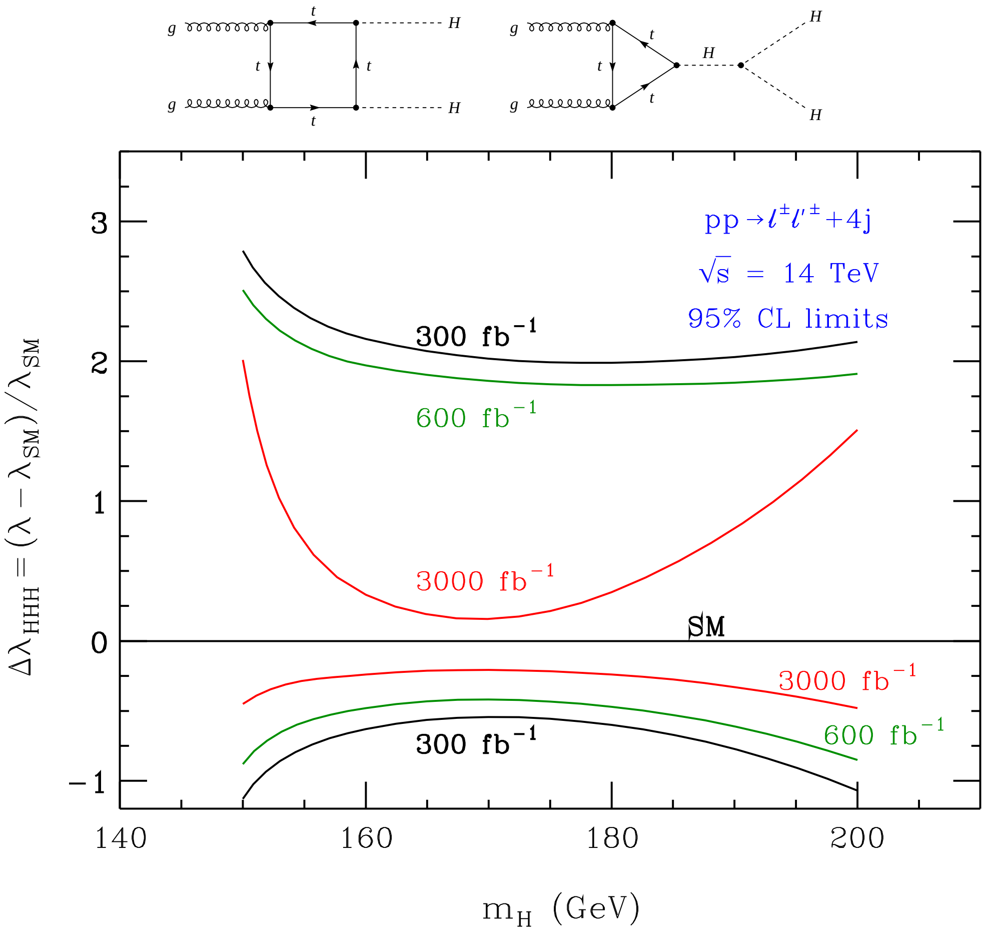
example:
MSSM parameters: M_2 = 120 GeV, M_1 = 60 GeV, μ = -500 GeV, m(sleptons) = 250 GeV, m(squarks, gluinos) = 1 TeV



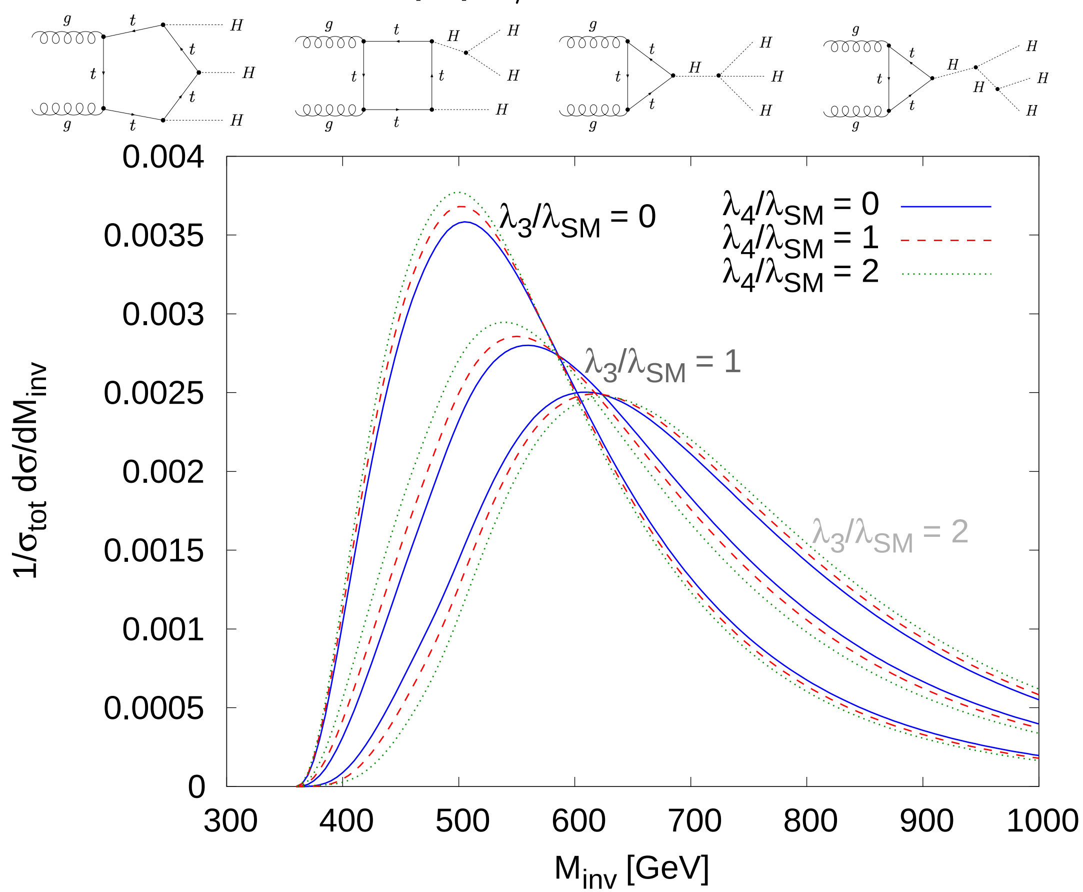
F. Moortgat

CMS, very preliminary
important as complements parameter space explorable through SM decay modes!

hep-ph/0211224



hep-ph/0507321



Parton-level:

- $\lambda_{HHH} = 0$ can be excluded at 95% CL
- λ_{HHH} determined at 20-30%

ATLAS and CMS studies still preliminary

Interference between diagrams important

Variation in trilinear self-coupling dominates

No hope of measuring quartic self-coupling at SLHC or VLHC

Summary

If the SM Higgs is there, we should discover it relatively early at the LHC

Several channels are available: provides an opportunity to measure Higgs couplings to 15-50%

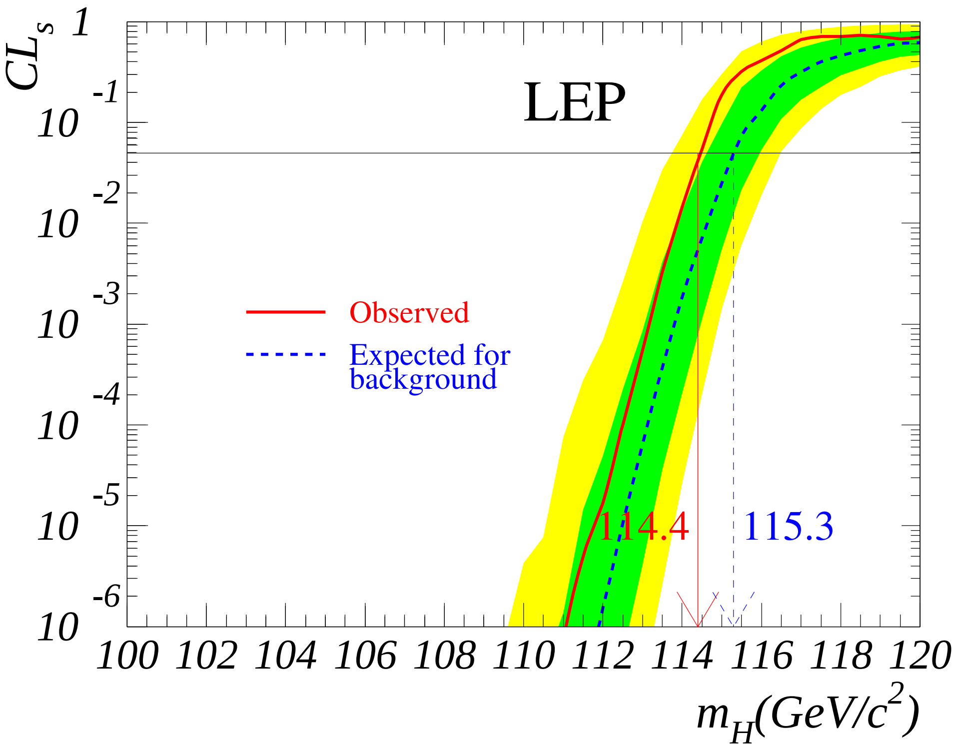
Most of the SUSY Higgs plane is covered by the LHC under most well-motivated scenarios.

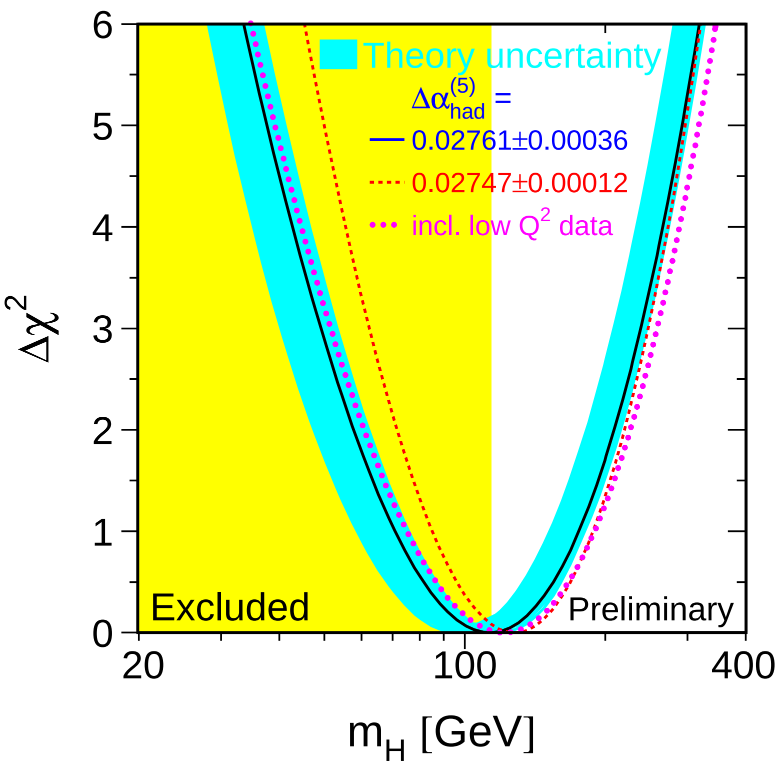
LHC will not observe Higgs self-coupling. Many measurements and discovery reach are statistics-limited. $\Rightarrow$ motivation for a luminosity upgrade: "SuperLHC"

An SLHC is sensitive to Higgs self-coupling and can improve on coupling measurements

Many opportunities to improve LHC analyses, extend feasibility studies for SLHC, and understand (S)LHC-LC connections

Backup



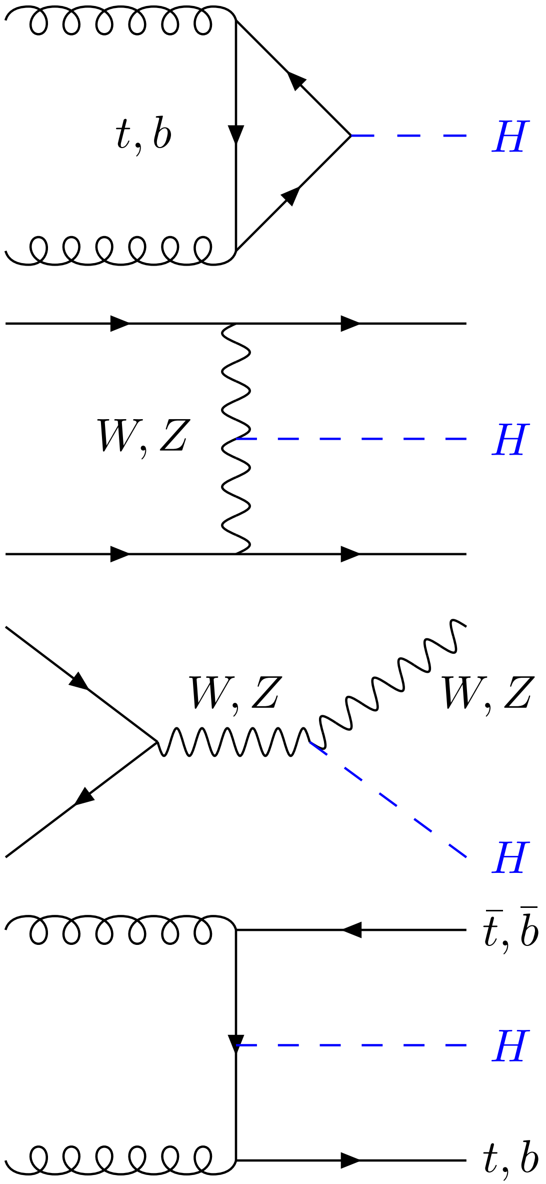


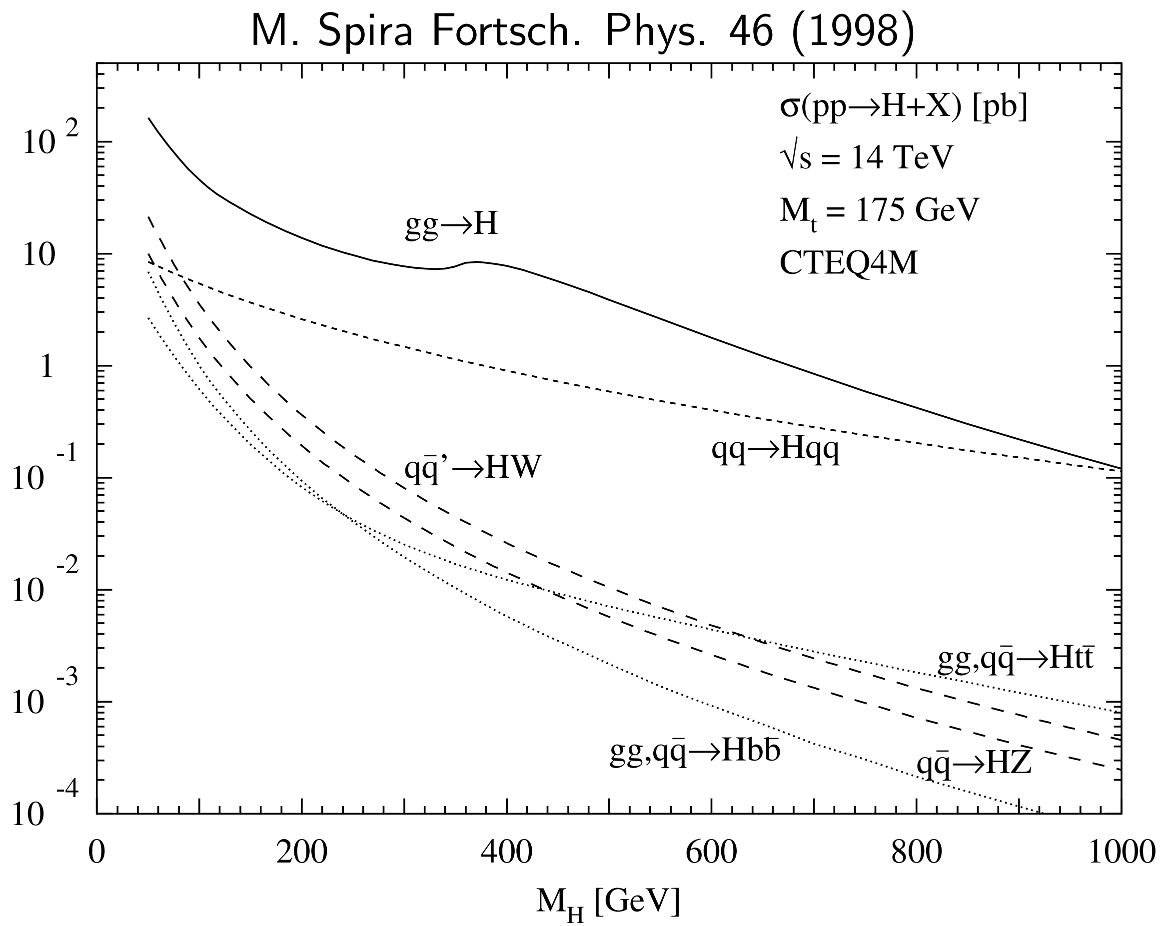
LEP direct search limit places
$M_H > 114.4$ GeV at 95% Confidence

LEP Electroweak Fits limit
$M_H < 237$ GeV at 95% Confidence

The MSSM predicts lightest Higgs to have $M_h < 135$ GeV

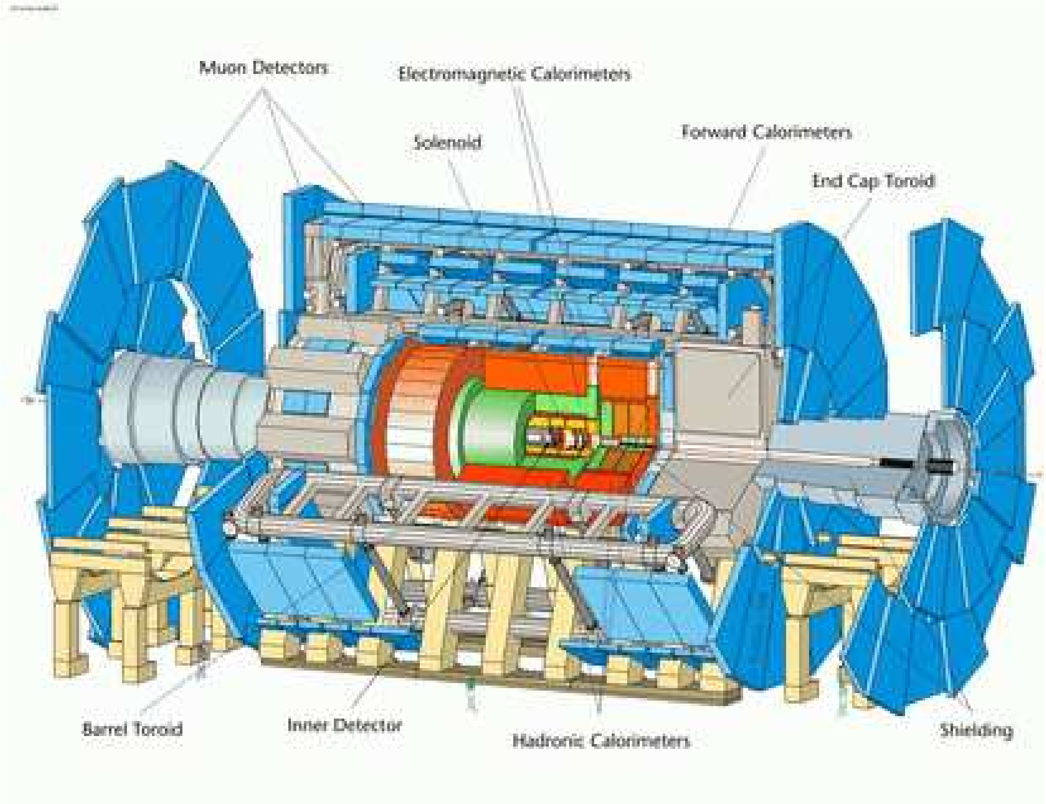
The low mass region is very exciting and very challenging!





- Gluon-Gluon Fusion dominant production process.
- Vector Boson Fusion (VBF) $\approx 20\%$ of gg at 120 GeV
- $BR(H \to b\bar{b})$ dominant at low mass, but need trigger
- Forward Tagging Jets of VBF help S/B

The ATLAS Detector



- Length $\approx$ 40 m
- Radius $\approx$ 10 m
- Weight $\approx$ 7000 tons
- El. Channels $\approx 10^8$

Sub-detector Highlights

- EM Calorimeter: Pb - liquid Ar
  $\sigma/E \approx 10\%/\sqrt{E}$
  uniform longitudinal segmentation
- Muon Detectors:
  $\sigma/p_T \approx 10\%$ at 1 TeV

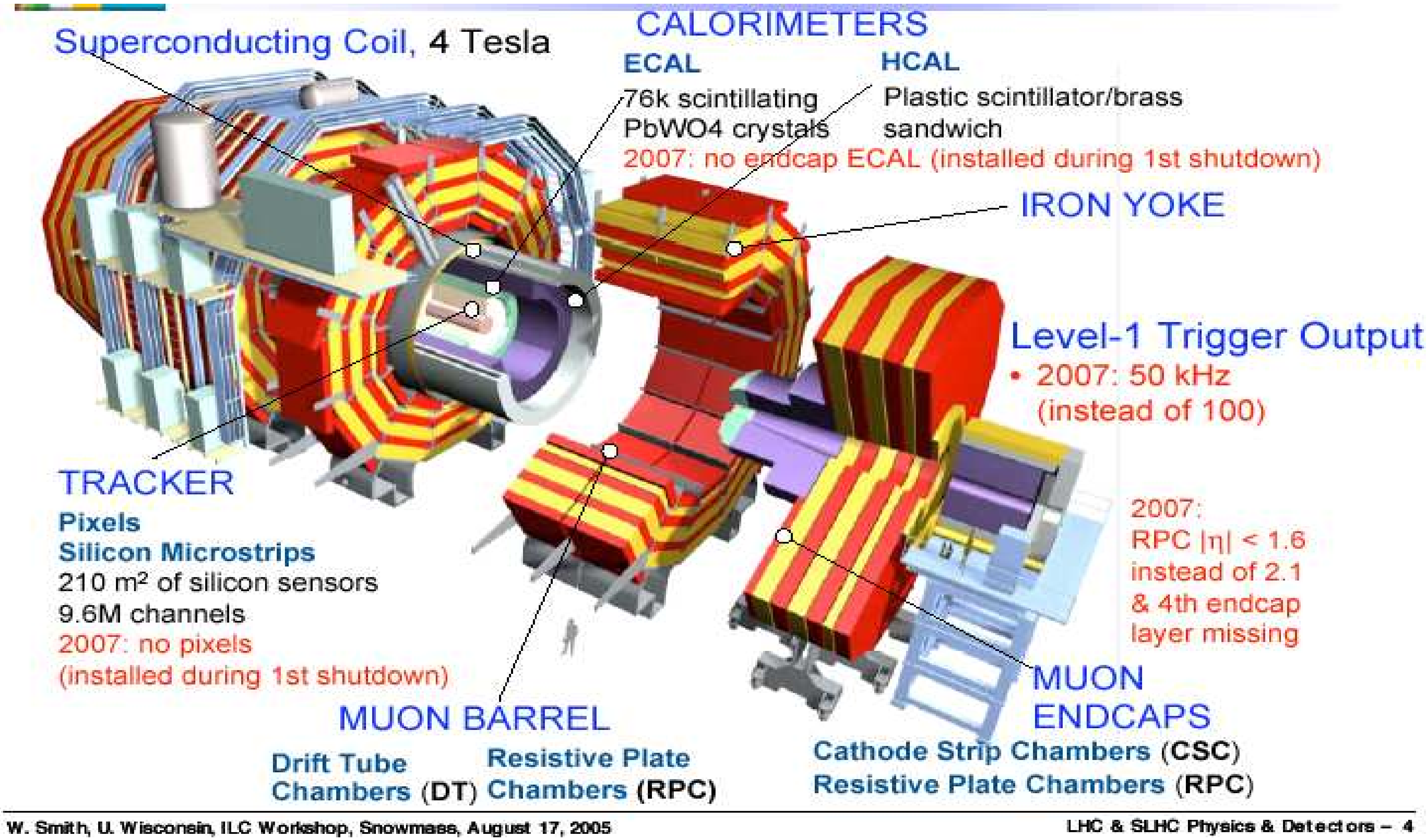
LHC Environment

- $\sqrt{s} = 14$ TeV
- Instantaneous Luminosity
  $\approx 10^{33} - 10^{34}$ cm^{-2}s^{-1}
- "pile-up" : 2-20 inelastic collisions

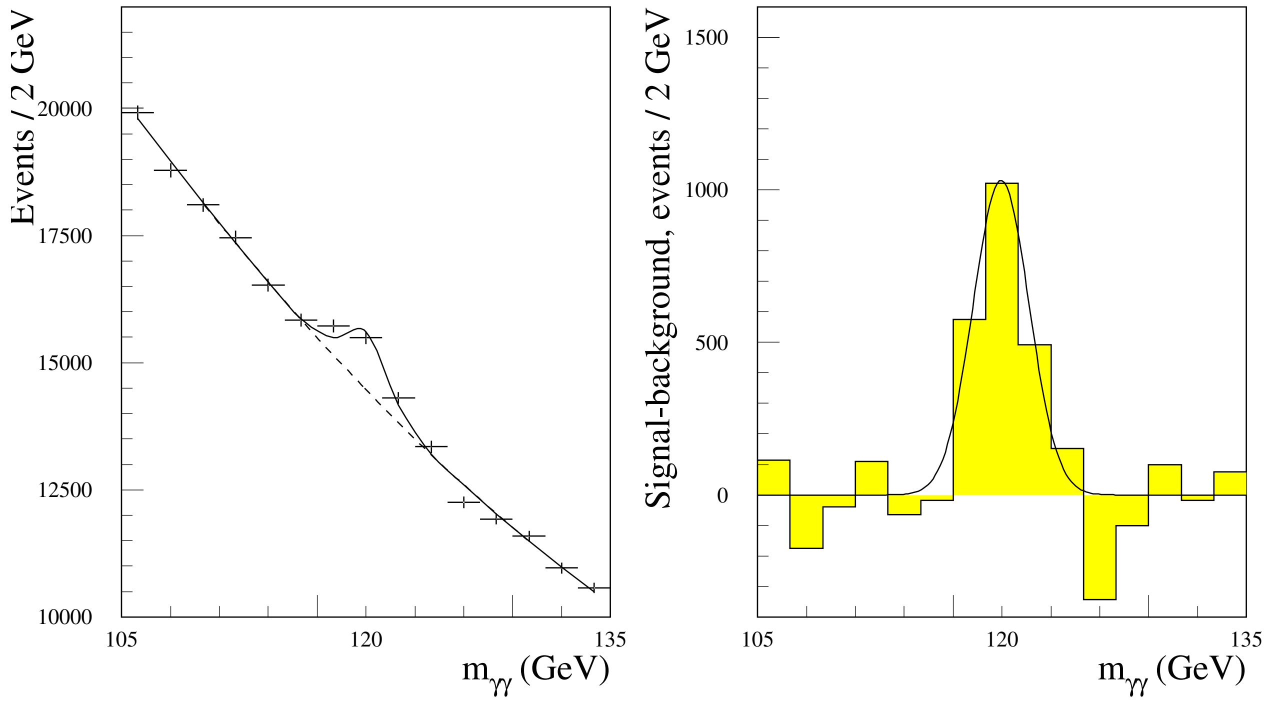
The ATLAS detector is a multipurpose detector...

flexible enough for the surprises which may lie ahead!

The CMS Detector



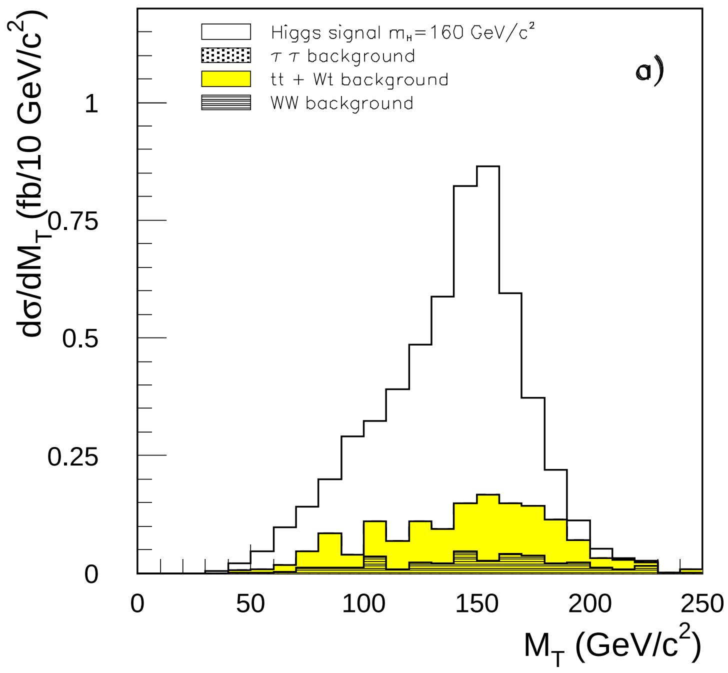
Example Analyses: $H \to \gamma\gamma + 0, 1, 2$ *jets*



- Excellent EM Calorimetry needed for $\Delta M_H / M_H \approx 1\%$
- Excellent γ/jet separation needed
- Convincing signal with sideband subtraction
- Often associated with a hard jet (or 2 *a lá* VBF), which can be used to improve S/B & reduce sensitivity to systematics

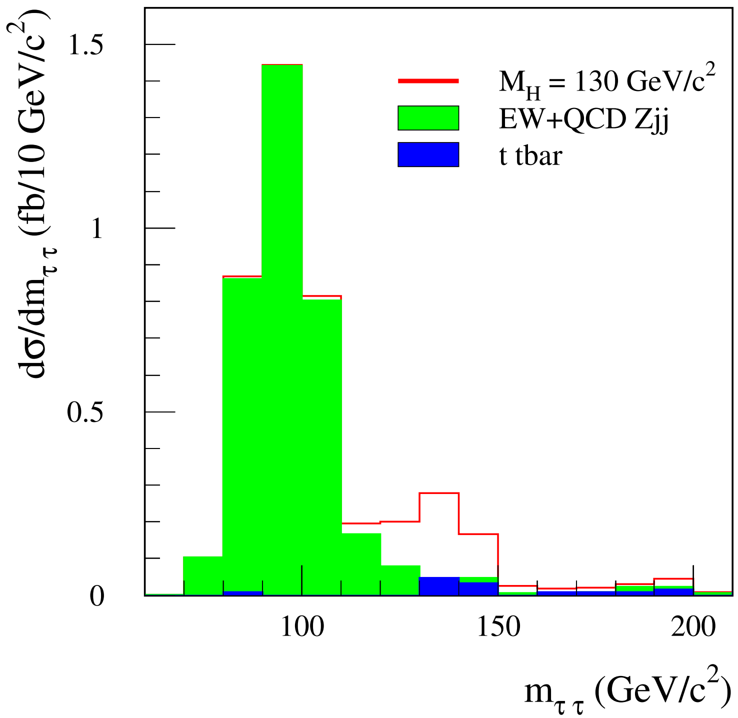
VBF $H \to WW$

- Forward jet tagging, b-jet veto, central jet veto
- Need at least 1 $W \to l\nu$ for trigger
- Only transverse mass, high S/B



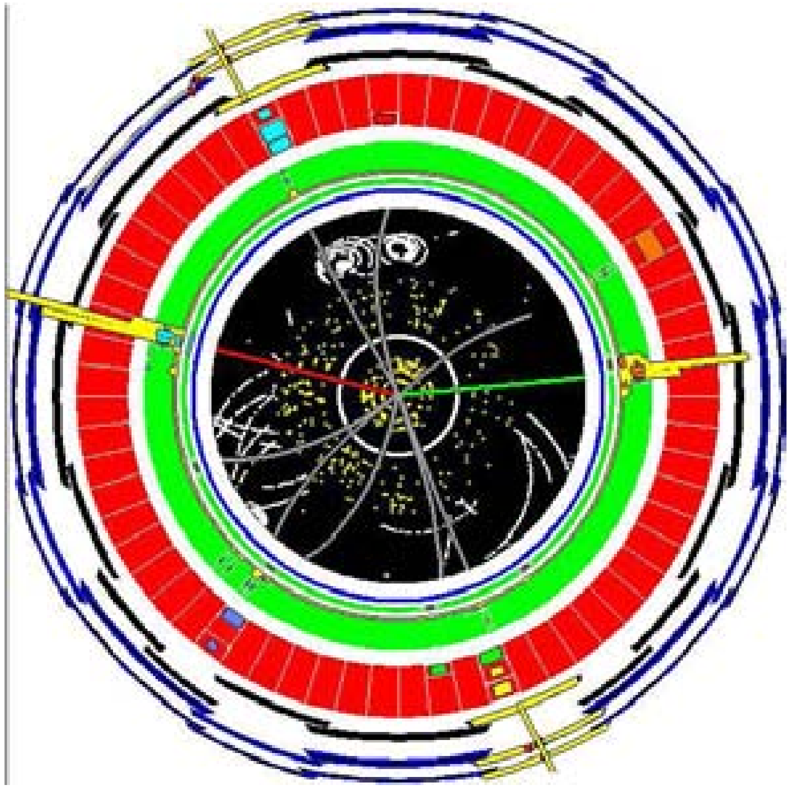
VBF $H \to \tau\tau$

- Forward jet tagging, b-jet veto, central jet veto
- Co-linear approximation for τ's
- $M_{\tau\tau}$ with ≈ 12 GeV resolution



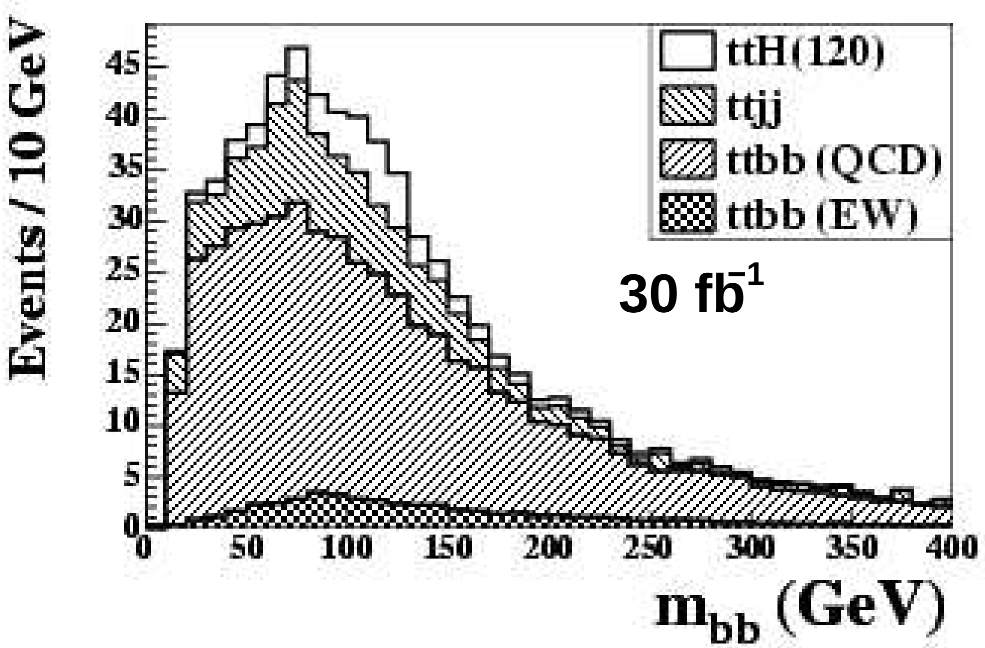
$H \to ZZ \to 4l$

- The "golden channel"
- Recent analyses use K-Factors for Signal & Background



$ttH(H \to bb)$

- This is one of the most powerful channels near the LEP limit
- Combinatoric background very challenging
- Multivariate analysis, low S/B

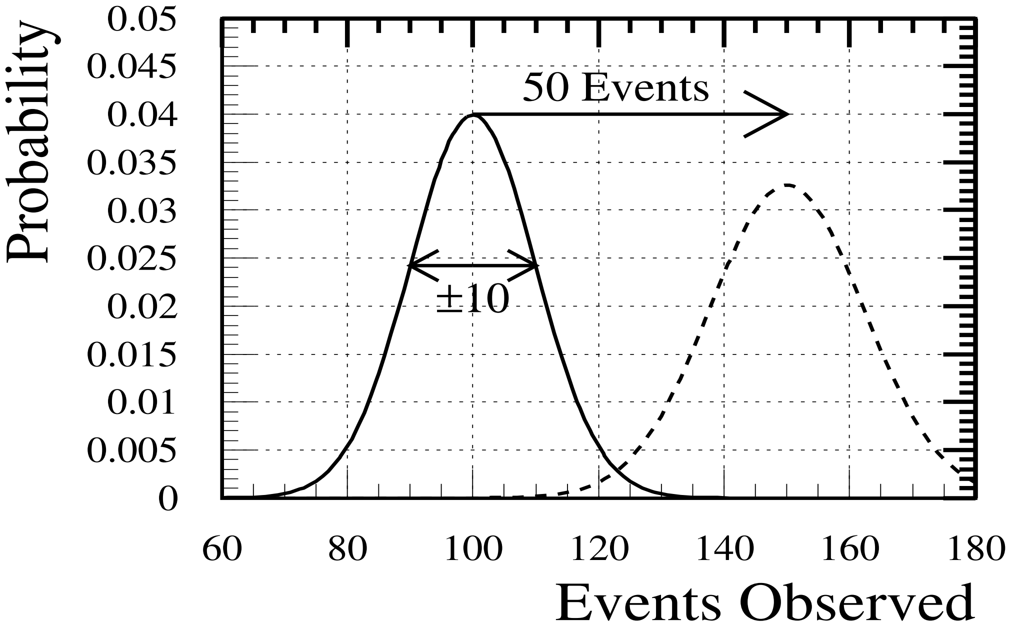


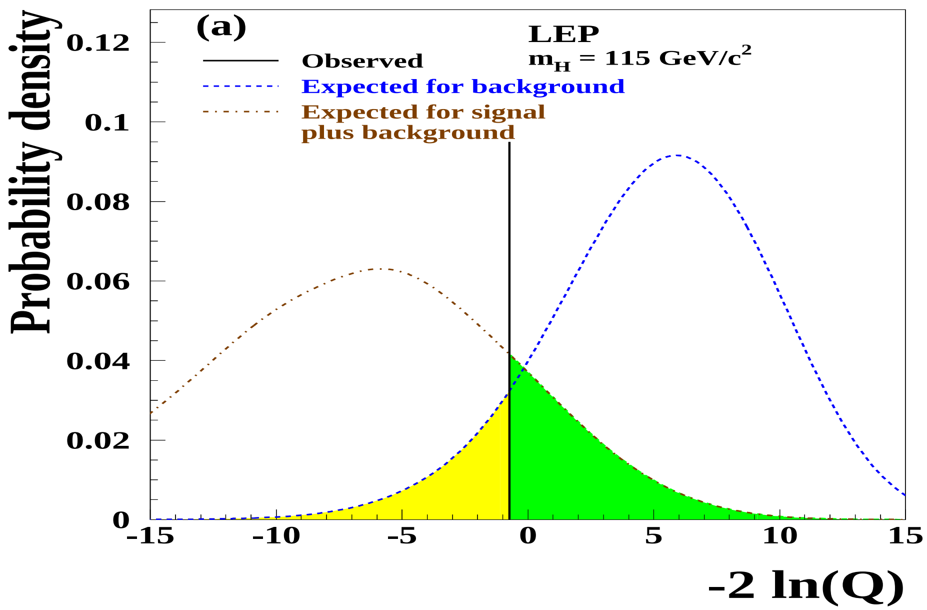
In addition to multivariate techniques , *the most powerful search* considers:

Likelihood of experiment $= \Pi$ likelihood of each event

This was done by LEP Higgs WG and follows from the Neyman-Pearson Lemma

Essentially, weight each event by $\log(1 + s/b)$





The Calculation in Equations

Define likelihood ratio for a single event at phase space x

$$q(x) = \ln\left(\frac{L(x|H_1)}{L(x|H_0)}\right) = \ln\left(1 + \frac{|\mathcal{M}_H|^2 \cdot d\mathrm{LIPS}}{|\mathcal{M}_Z|^2 \cdot d\mathrm{LIPS}}\right)_x$$

Define the distribution of these q-values for 1 signal (background) event

$$\rho_{1,s}(q_0) = \frac{1}{\sigma_H}\int_x d\mathrm{LIPS}\,|\mathcal{M}_H|^2 \cdot \delta(q_0 - q(x))$$

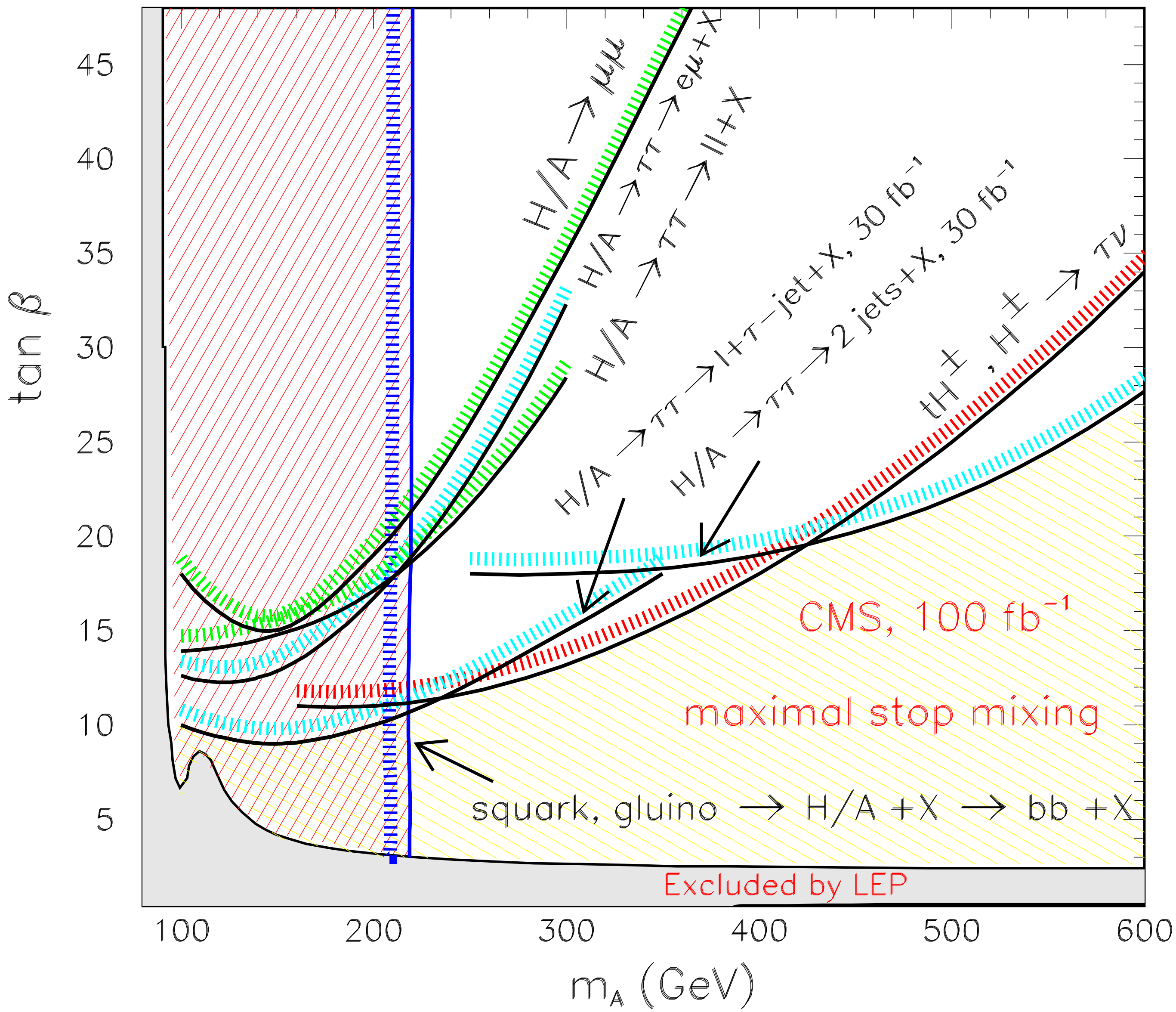
$$\rho_{1,b}(q_0) = \frac{1}{\sigma_Z}\int_x d\mathrm{LIPS}\,|\mathcal{M}_Z|^2 \cdot \delta(q_0 - q(x))$$

For N events, use Fourier transform to perform N convolutions

$$\rho_{N,i}(q) = \underbrace{\rho_{N,i}(q) \oplus \cdots \oplus \rho_{N,i}(q)}_{N \text{ times}} = \mathcal{F}^{-1}\left\{\left[\mathcal{F}\left(\rho_{1,i}\right)\right]^N\right\}$$

To include Poisson fluctuations on N for a given luminosity, one can exponentiate

$$\rho_i(q) = \sum_{N=0}^{\infty} P(N; L\sigma_i) \cdot \rho_{N,i}(q) = \mathcal{F}^{-1}\left\{e^{L\sigma_i\left[\mathcal{F}(\rho_{1,i}(q))-1\right]}\right\}$$



tan β
45
40
35
30
25
20
15
10
5
100
200
300
400
500
600
m_A (GeV)
H/A → μμ
H/A → ττ → eμ+X
H/A → ττ → ll+X
H/A → ττ → l+τ−jet+X, 30 fb⁻¹
H/A → ττ → 2 jets+X, 30 fb⁻¹
tH±, H± → τν
CMS, 100 fb⁻¹
maximal stop mixing
squark, gluino → H/A +X → bb +X
Excluded by LEP