Physics at the LHC
Lecture 4: Higgs Physics at the LHC

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Reminder: Higgs mechanism in the Standard Model

- One complex Higgs doublet $\Phi = \begin{pmatrix} \Phi_1 + i\Phi_2 \\ H + i\Phi_3 \end{pmatrix}$ with vacuum expectation value $\begin{pmatrix} 0 \\ v \end{pmatrix}$, $v = 246\,\mathrm{GeV}$.
- Higgs potential $V(\Phi) = \lambda(\Phi^*\Phi - v^2/2)^2$
- Gauge couplings of Higgs doublet give gauge boson masses:

$$m_\mathrm{W}^2 = \frac{g^2 v^2}{4} \quad m_\mathrm{Z}^2 = \frac{g^2 v^2}{4\cos^2\theta_W}$$

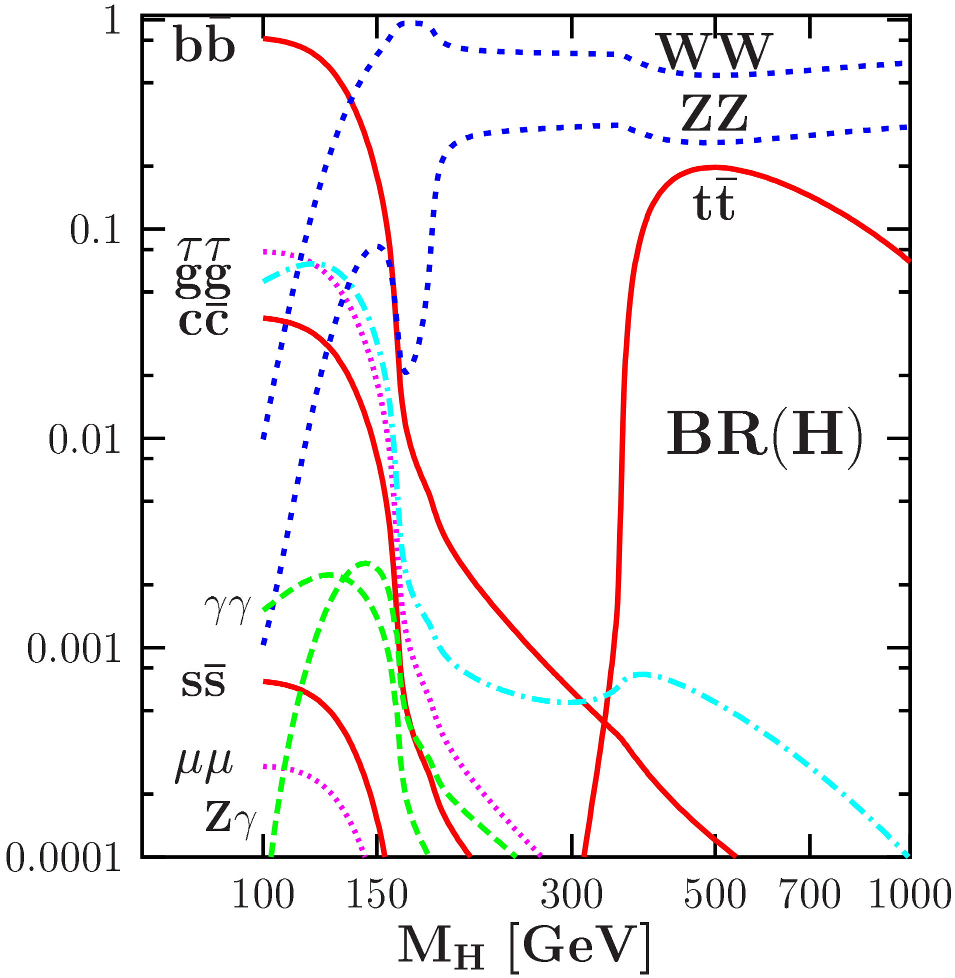
- Φ_i get absorbed in longitudinal d.o.f. of W,Z
- One Higgs particle H remains from fluctuations around v
  $\Rightarrow$ Higgs couplings to gauge bosons fixed by gauge boson mass
- Higgs mass $m_\mathrm{H}^2 = 2\lambda v^2$ free parameter

- Higgs couplings to fermions: $c_f \left[\tilde{F}_l(\Phi+v)f_r + \tilde{f}_r(\Phi+v)F_l\right]$
  $\Rightarrow$ Higgs coupling $\propto$ mass
- Partial widths:

$$\begin{aligned}\Gamma(H\to \mathrm{f\bar{f}}) &= \frac{N_c^{(f)}G_\mu}{4\sqrt{2}\pi} m_f^2(m_H)m_H(1+\delta_{QCD}^{(f)}) \\ \Gamma(H\to VV) &= \frac{3G_\mu^2 m_\mathrm{Z}^4}{16\pi^3} m_\mathrm{H} R_V(m_V^2/m_\mathrm{H}^2) \\ &\to 2(1)\frac{\sqrt{2}G_\mu}{32\pi} m_\mathrm{H}^3 \quad [V=W(Z)]\end{aligned}$$

- Higgs couplings to photons and gluons via loops

Partial and total widths of a Standard Model Higgs



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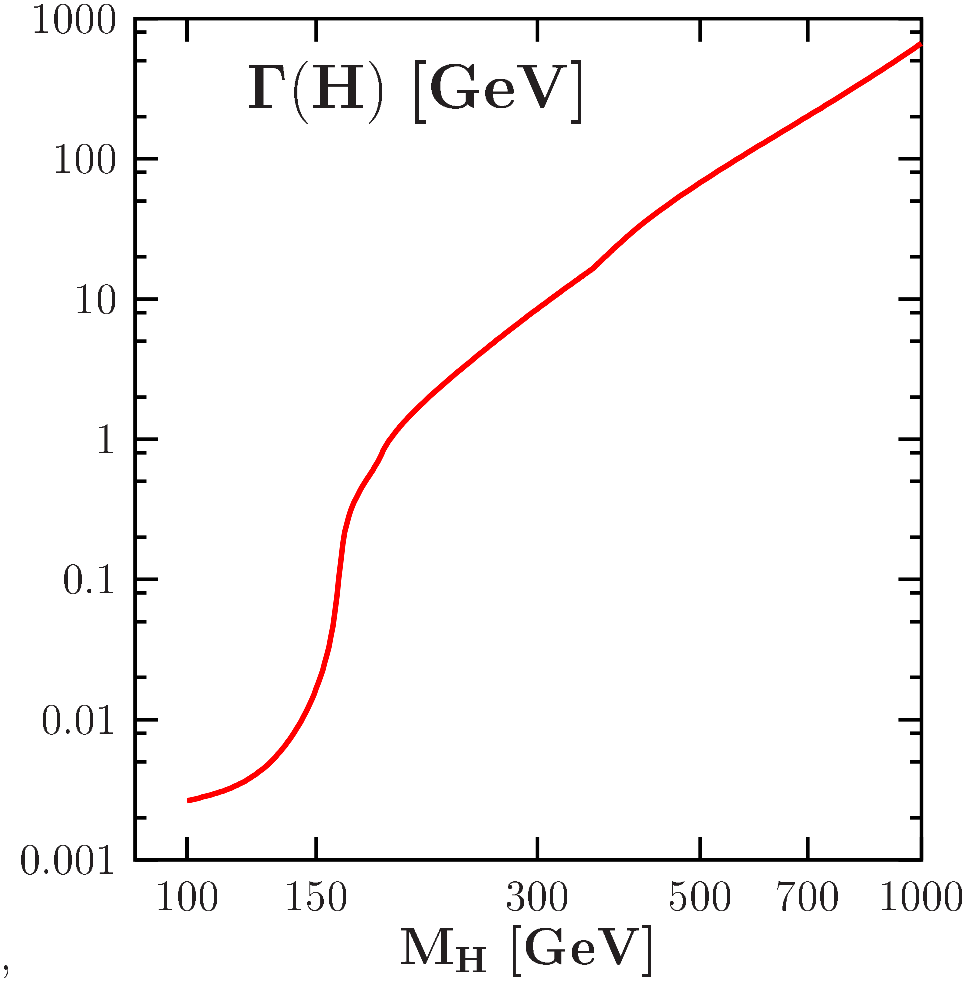


- Light Higgs: $b\bar{b}$ is dominant
- Heavy Higgs: Mostly WW and ZZ
- Higgs width large above WW threshold

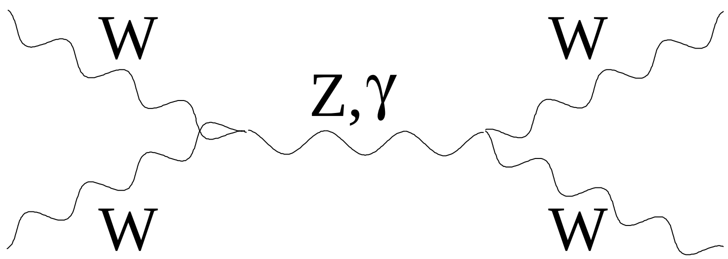
How the Higgs creates mass

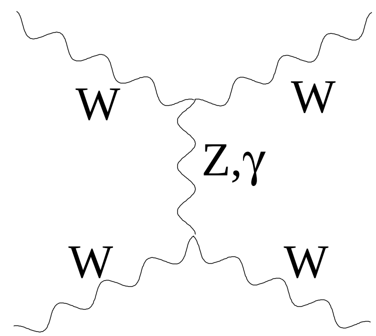
and how it creates itself

Limits on m_H

Theory:

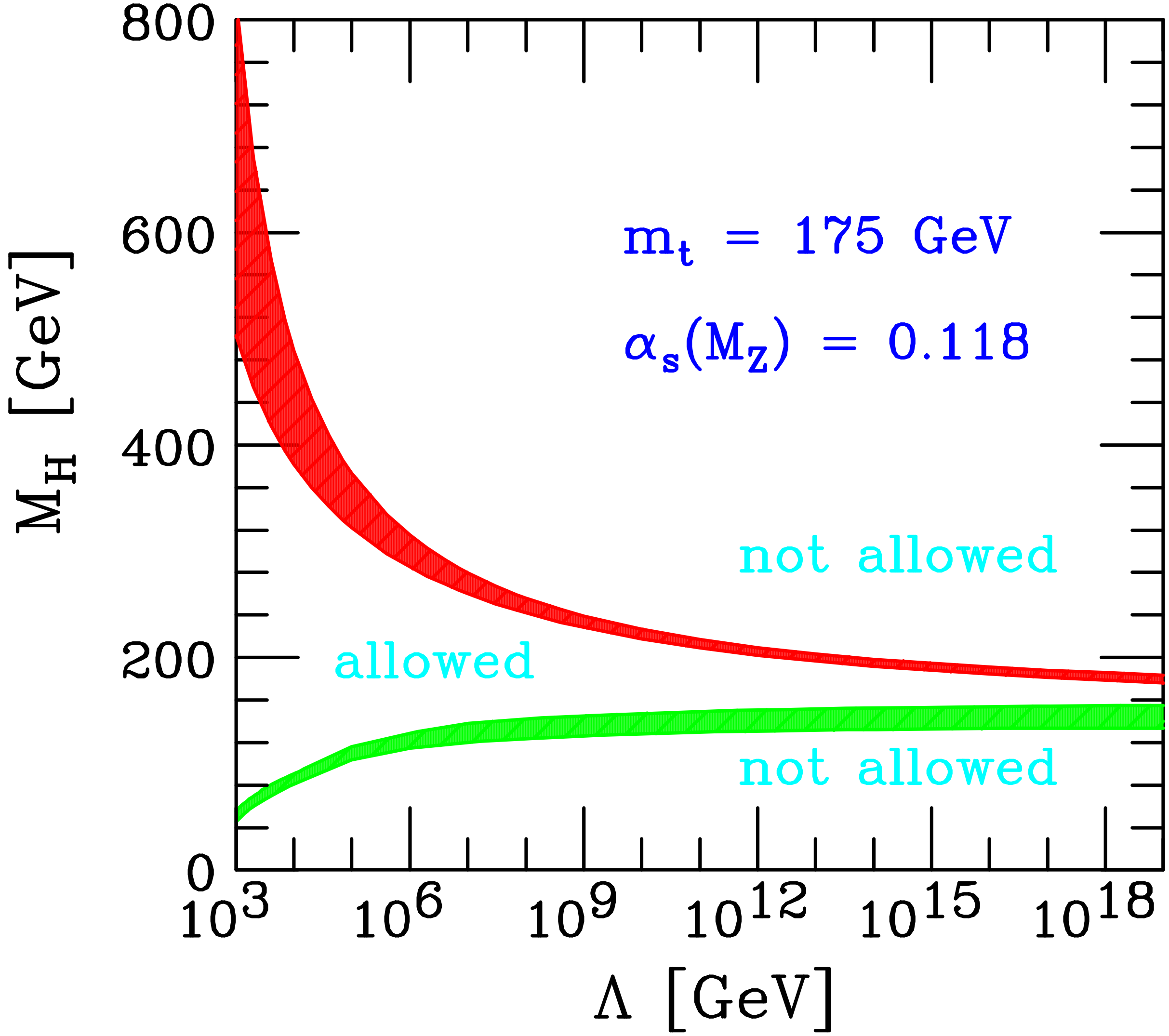
- No useful lower limit
- Upper limit from WW scattering:
  - Polarisation vector for longitudinally polarised particles $\propto p^2$
  - ➠ WW scattering without Higgs violates unitarity at 1.2 TeV





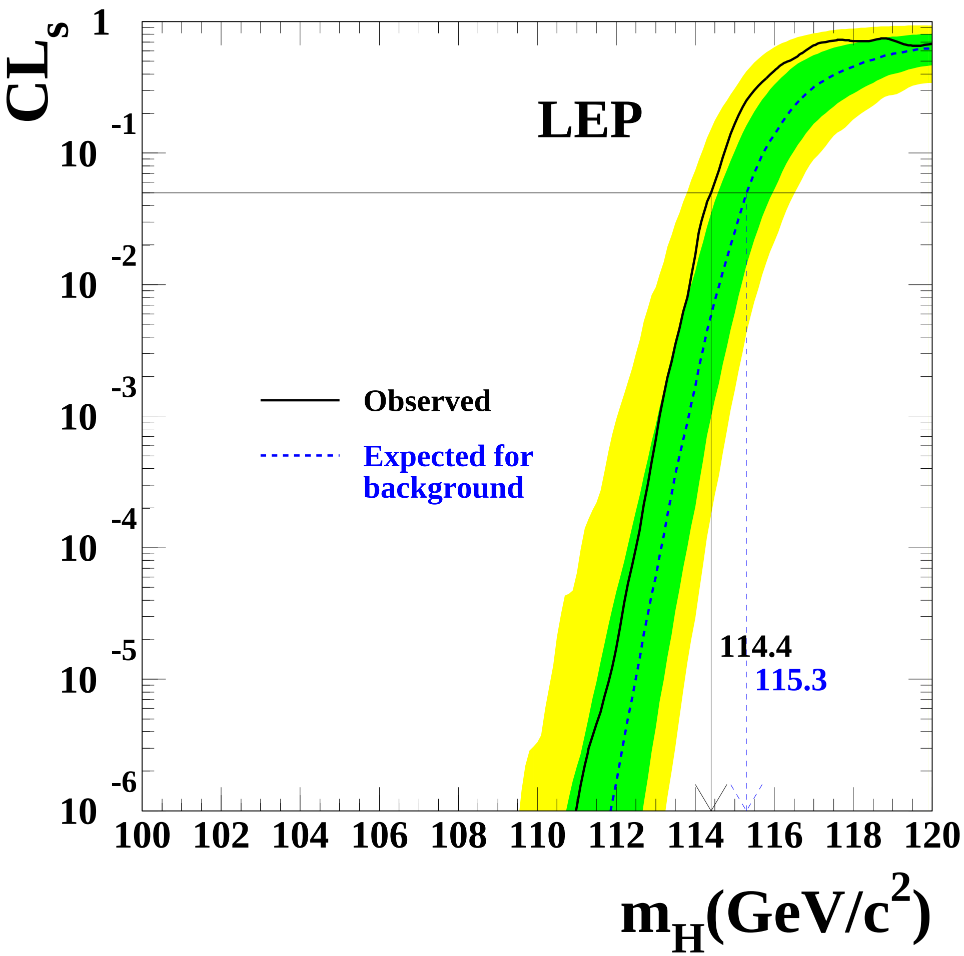
- Cross section gets regularised by the Higgs $\Rightarrow m_H \lesssim 1\,\text{TeV}$

- Perturbativity and vacuum stability give Higgs-mass limit as a function of the cutoff parameter
- If the SM is the final theory up to the Planck scale $\Lambda \sim 10^{19}\,\mathrm{GeV} \Rightarrow m_{\mathrm{H}} \sim 120 - 180\,\mathrm{GeV}$

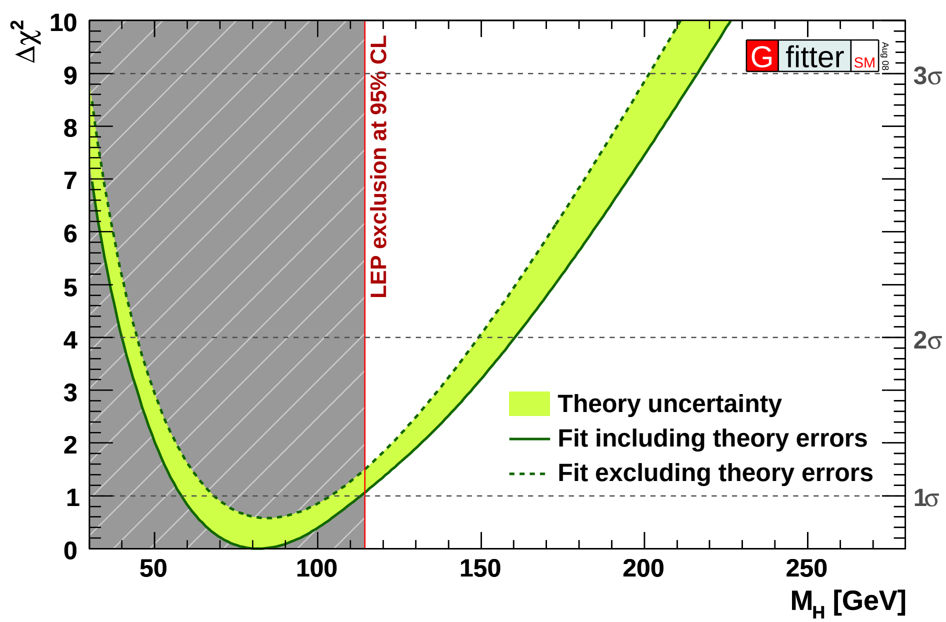


Experimental:

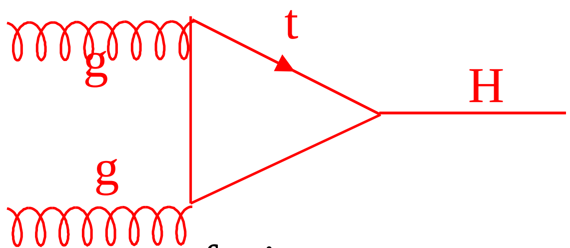
- Direct searches at LEP exclude a Higgs below 114 GeV
- This limit is valid for couplings significantly smaller than in the SM



- Analyses of electroweak precision data suggest $m_{\mathrm{H}} < 200\,\mathrm{GeV}$
- These analyses are only valid in the Standard Model without additional particles coupling to the gauge bosons

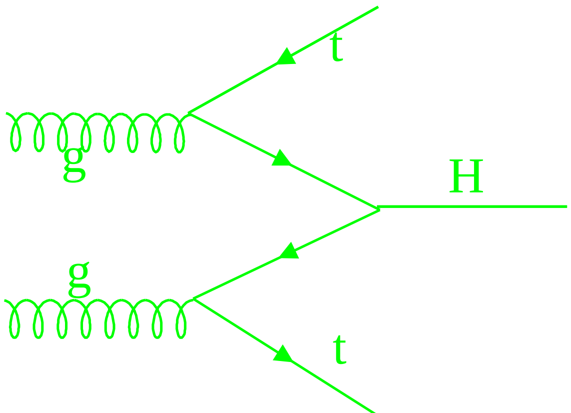


Higgs production at hadron colliders

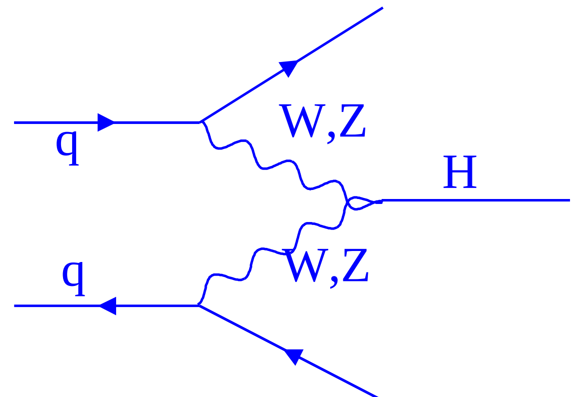


gg fusion

W,Z Bremsstrahlung



tt fusion

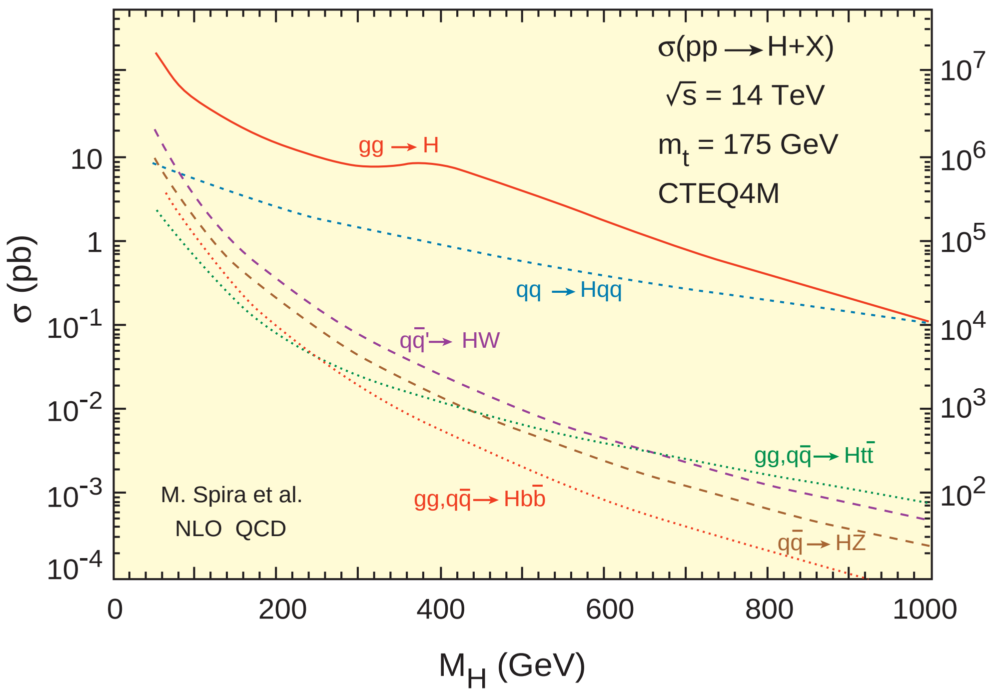


WW, ZZ fusion

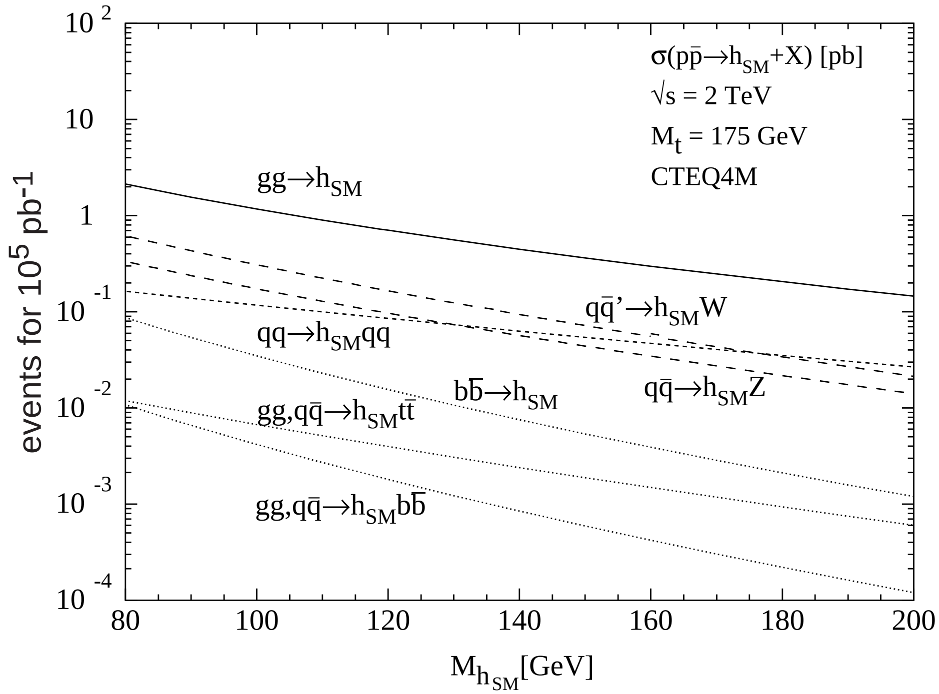
- gg fusion produces a Higgs and nothing else in the detector
- All other graphs have associated particles that help in the tagging

Higgs production cross section

LHC



Tevatron



- gg fusion dominates in both cases
- At LHC WW-fusion significant, rest small
- At Tevatron WW-fusion and W,Z Bremsstrahlung relevant
- Total cross section large at LHC, factor 100 smaller at Tevatron

How to discover a signal?

Assume background is known from somewhere

Number of events follows a Poisson distribution

➠ variance σ for mean value n: $\sigma = \sqrt{n}$

For a given mass expect $n_t = n_s + n_b$ events

Require that signal is $> 5\sigma$ above background (corresponds to a probability of 10^{-7} for a background fluctuation)

➠ need significance $S = n_s/\sqrt{n_b} > 5$

Influence of detector resolution: Gaussian signal with variance σ_D over linear background: $S \propto 1/\sqrt{\sigma_D}$

Dependence on Luminosity: $S \propto \sqrt{\mathcal{L}}$

Higgs searches at the Tevatron

Light Higgs:

- Main decay to $b\bar{b}$
- Main channel $gg \to H \to b\bar{b}$ hopeless
- Possible channels $WH \to \ell\nu b\bar{b}$, $ZH \to \ell\ell b\bar{b}$, $ZH \to \nu\nu b\bar{b}$,

Medium Higgs

- $gg \to WW \to \ell\nu\ell\nu$ becomes accessible
- In addition some signal from $WH \to \ell\nu\ell\nu + ...$

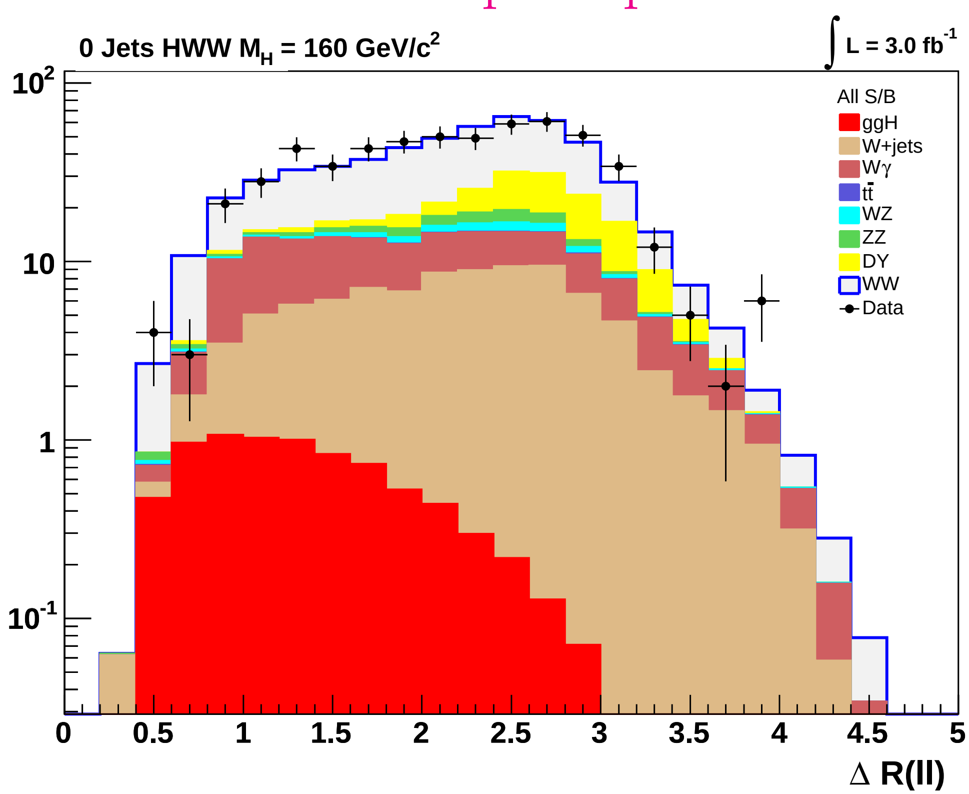
Heavy Higgs ($m_H > 200\,\mathrm{GeV}$)

- No chance because cross section too low

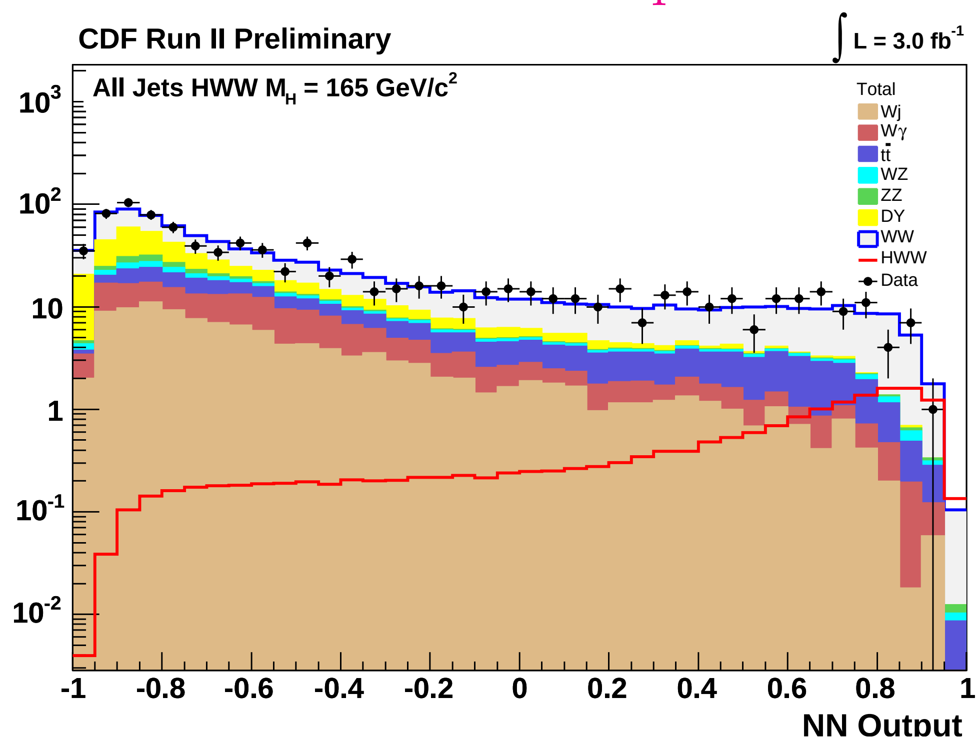
Search for $gg \to WW \to \ell\nu\ell\nu$

- Many variables with low separation power
- E.g. leptons correlated because of Higgs spin (=0)
- Combined with multivariate techniques, here NN
- Small signal under huge bg, WW and Drell-Yan dominant

ΔR for lepton pairs



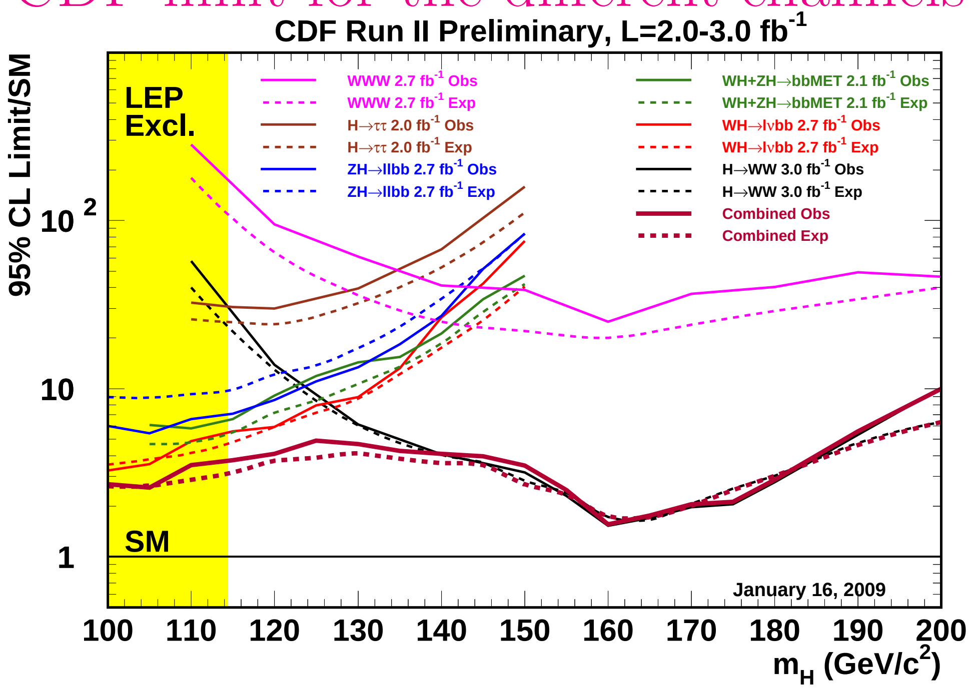
Neural Net output



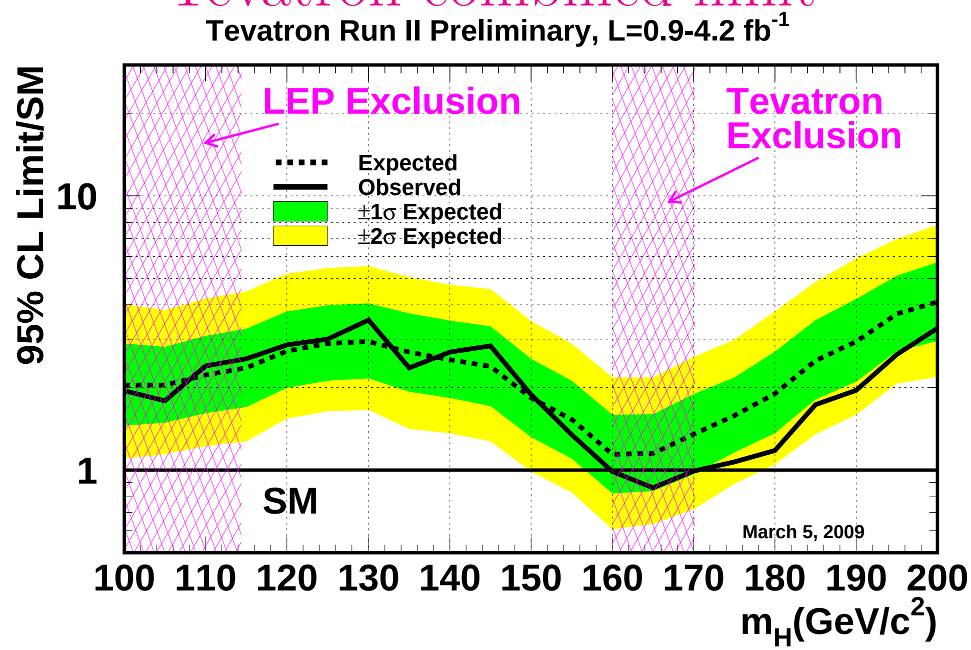
Results

- Low mass region dominated by $WH \to \ell\nu b\bar{b}$ and $WH, ZH \to \mathrm{MET}\, b\bar{b}$
- Higher masses only $H \to \ell\nu\ell\nu$
- Exclusion at low masses still around $2 - 3\sigma(SM)$
- At $160\,\mathrm{GeV} < m_{\mathrm{H}} < 170\,\mathrm{GeV}$ SM-Higgs excluded!

CDF limit for the different channels



Tevatron combined limit



Higgs search at the LHC

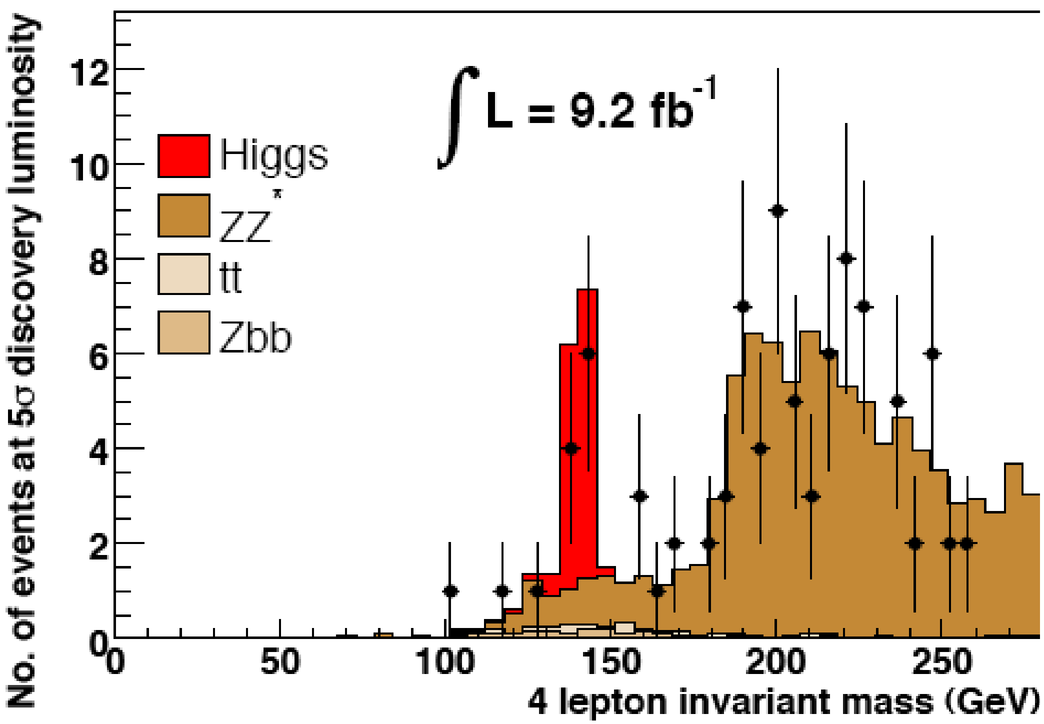
Easiest channel: $H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$

$\sigma \times BR \sim 10\,\mathrm{fb}$ for $m_{\mathrm{H}} = 130\,\mathrm{GeV}$

Largest background $\mathrm{t\bar{t}} \to WbW\bar{b} \to \ell\nu\,\ell\nu c\,\ell\nu\,\ell\nu c$: $\sigma \times BR = 1300\,\mathrm{fb}$

Best handle: lepton isolation and b-tagging

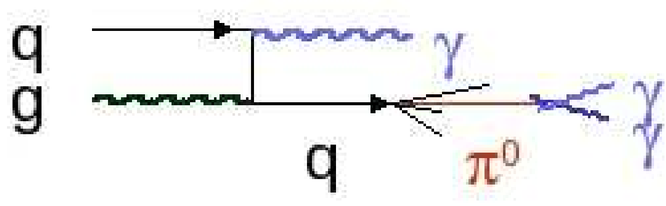
Dominant background after selection: ZZ



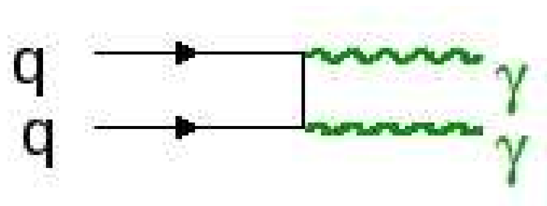
Channel can be used for discovery for $130\,\mathrm{GeV} < m_{\mathrm{H}} < 600\,\mathrm{GeV}$

Discovery channel for light Higgs: $H \to \gamma\gamma$

Main backgrounds:



reducible



irreducible

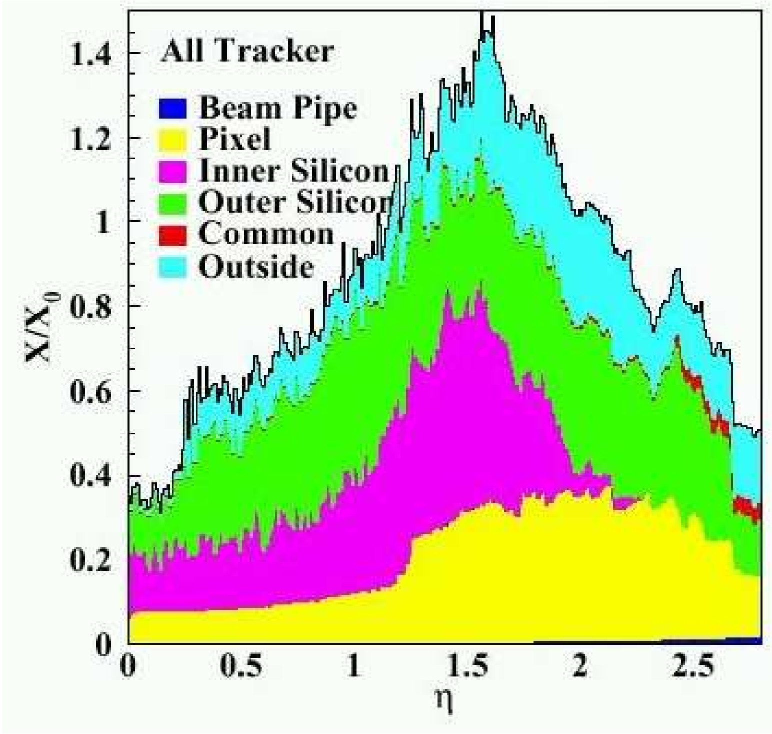
Start with $S/B = 10^{-6}$

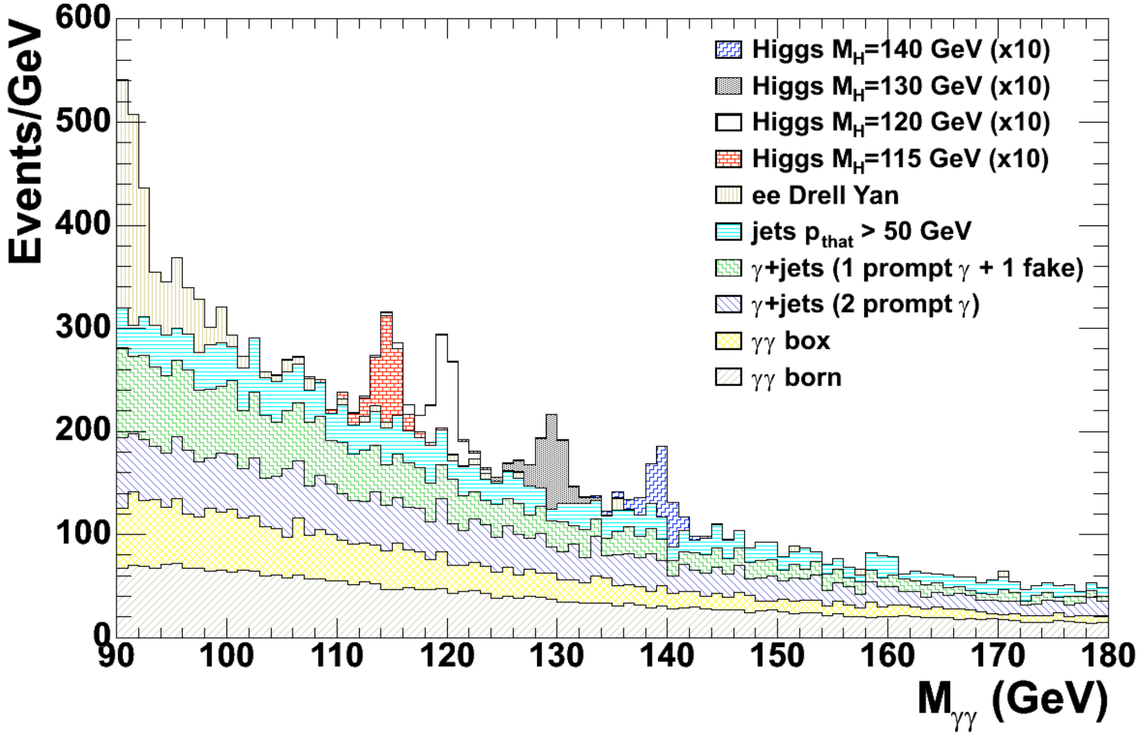
➡ need to reduce background by at least a factor 1000

Strategy:

- Effective selection of isolated photons (calorimeter granularity)
- Very good mass resolution (calorimeter energy resolution)

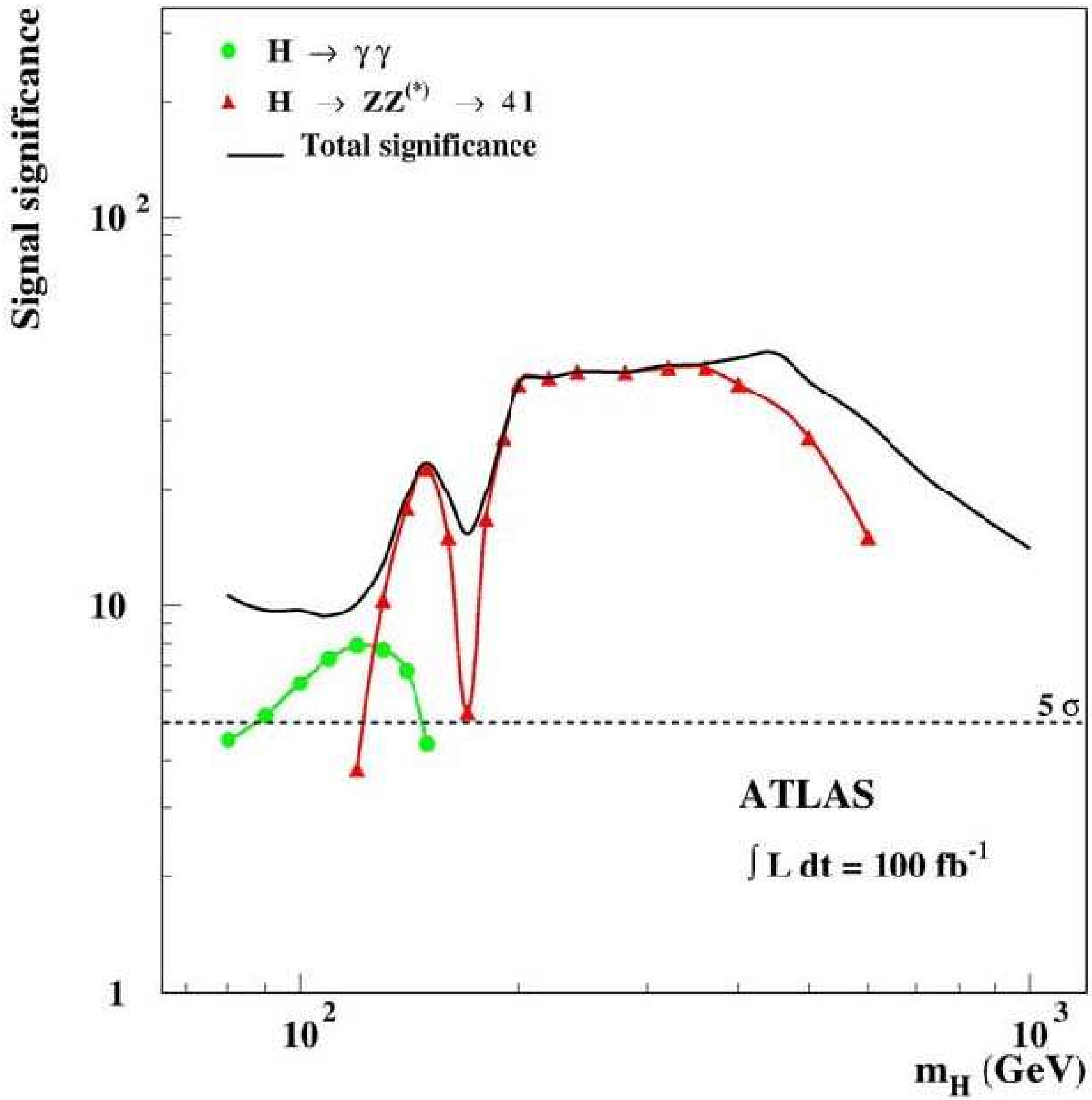
Complication: Experiments have ∼ 1 radiation length in from of tracker
➠ about 50% of photons convert before they reach calorimeter
➠ have to include converted photons to keep high efficiency



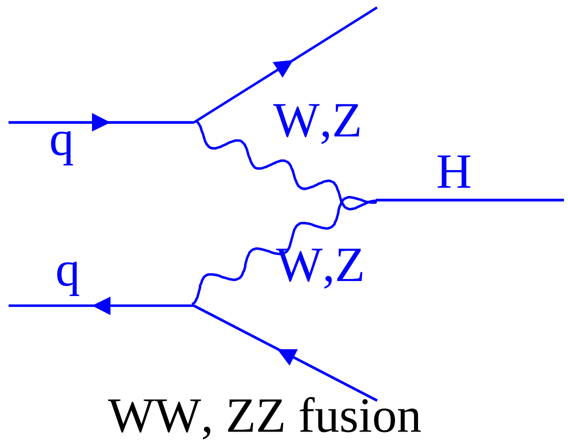


The final signal is small, however visible with few fb^{-1} for a light Higgs

These two channels are sufficient to discover the Higgs over the fill mass range



The Higgs in the VV-fusion channel



W-propagator:

$\frac{1}{t-m_W^2}$ with $t = (p-p')^2 \approx 4pp' \sin^2\frac{\theta}{2}$

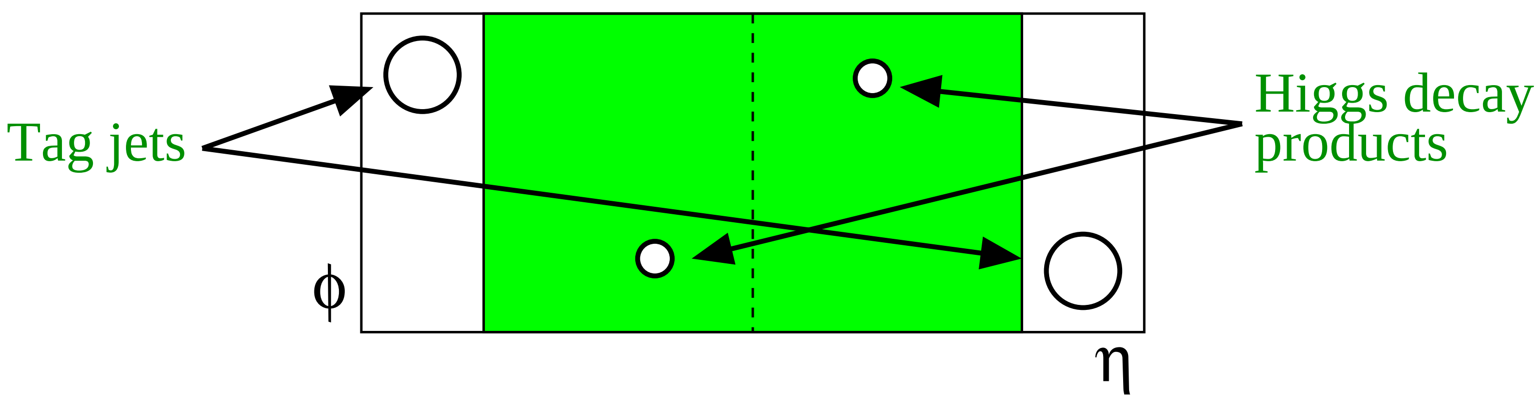
➠ propagator ∼constant as long as $2p' \sin\frac{\theta}{2} \lesssim m_W$

➠ forward jets should be visible in the detector

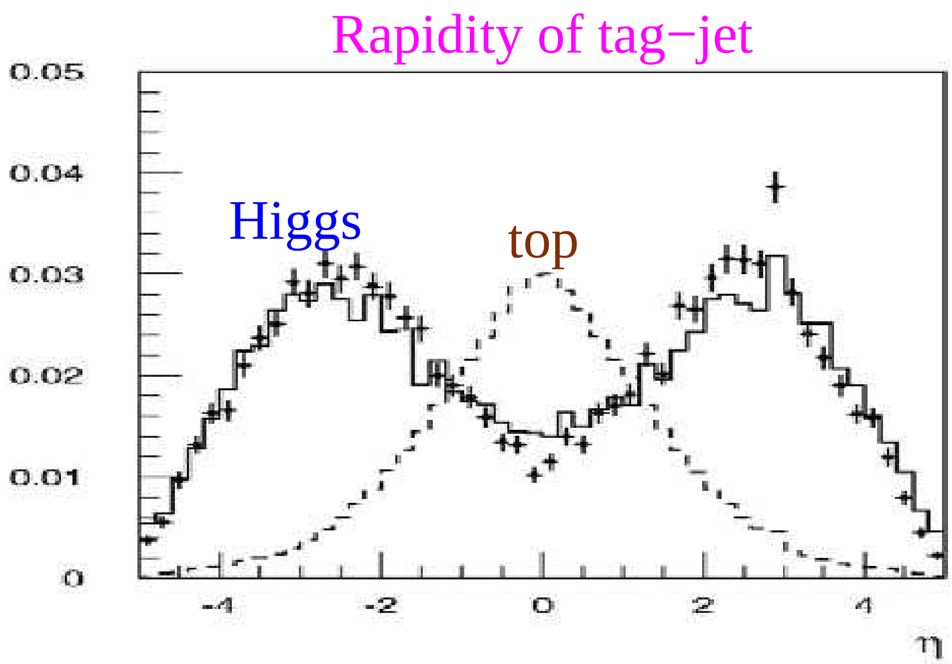
Higgs is colour singlet

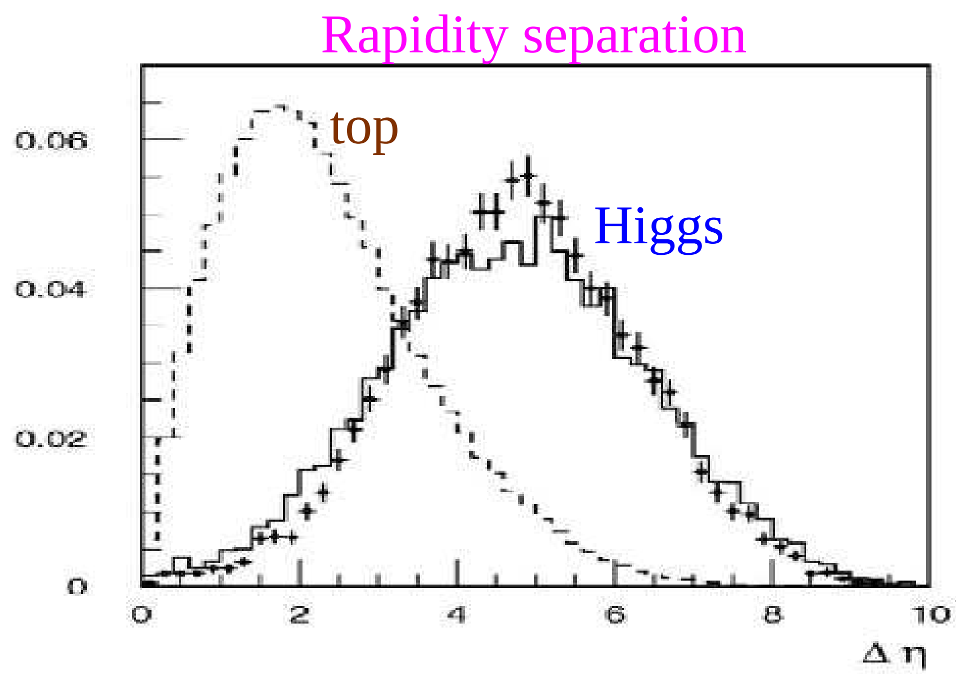
➠ colour connection between forward jet and proton remnant

➠ rapidity gaps between forward jets and Higgs-jets



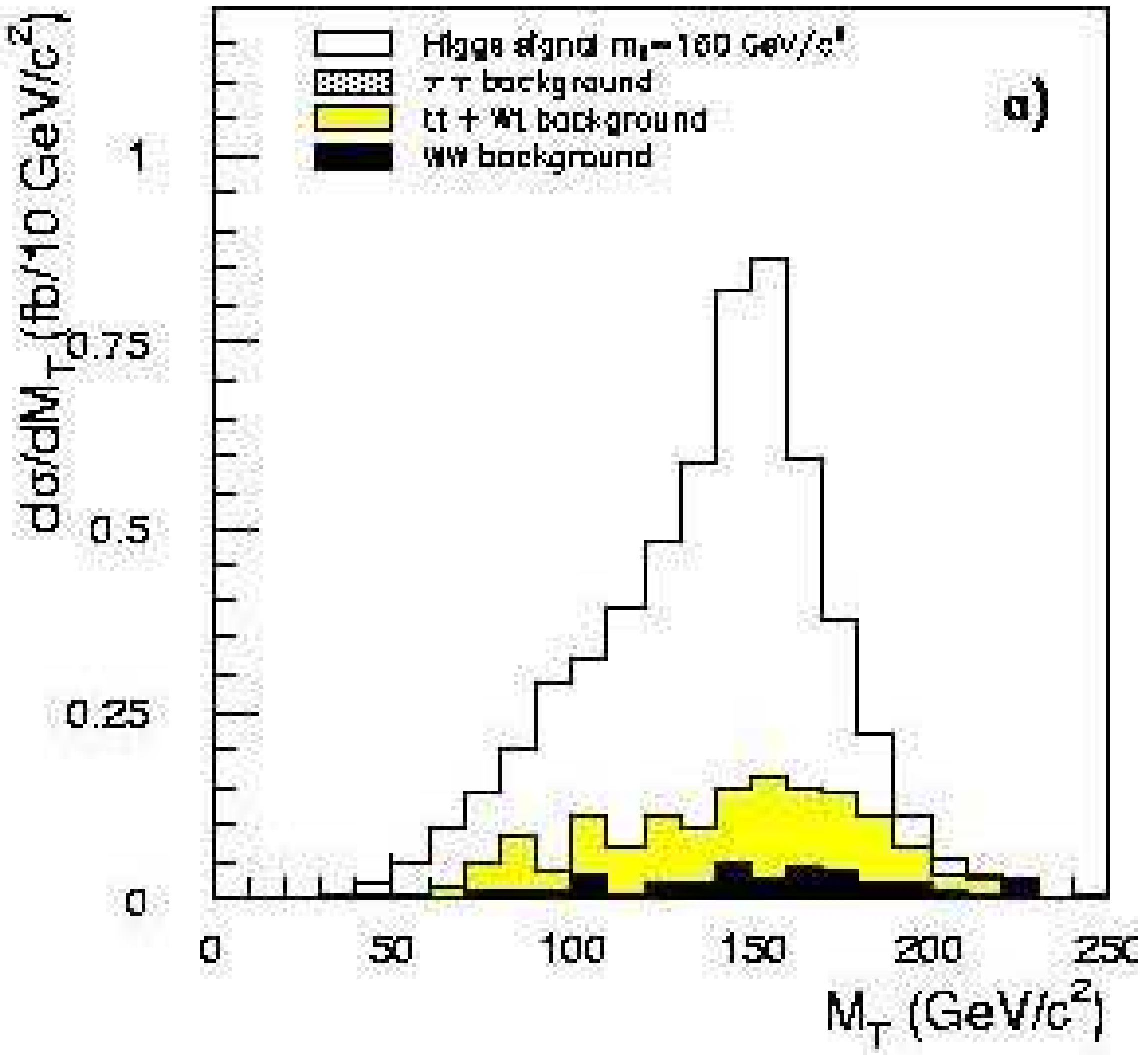
Largest background is $t\bar{t}$





Can be separated with rapidity cuts

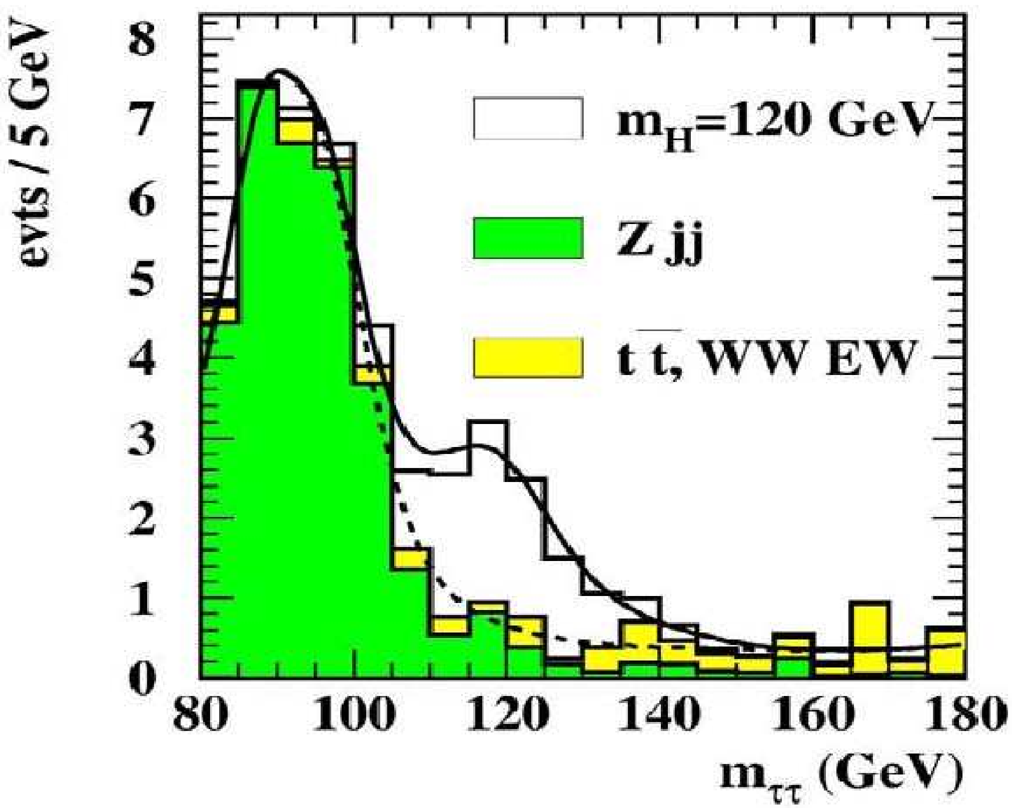
With transverse mass $M_T = \sqrt{(E_{T,\ell\ell} + E_{T,miss})^2 - (\vec{p}_{T,\ell\ell} - \vec{p}_{T,miss})^2}$
a clean signal can be separated



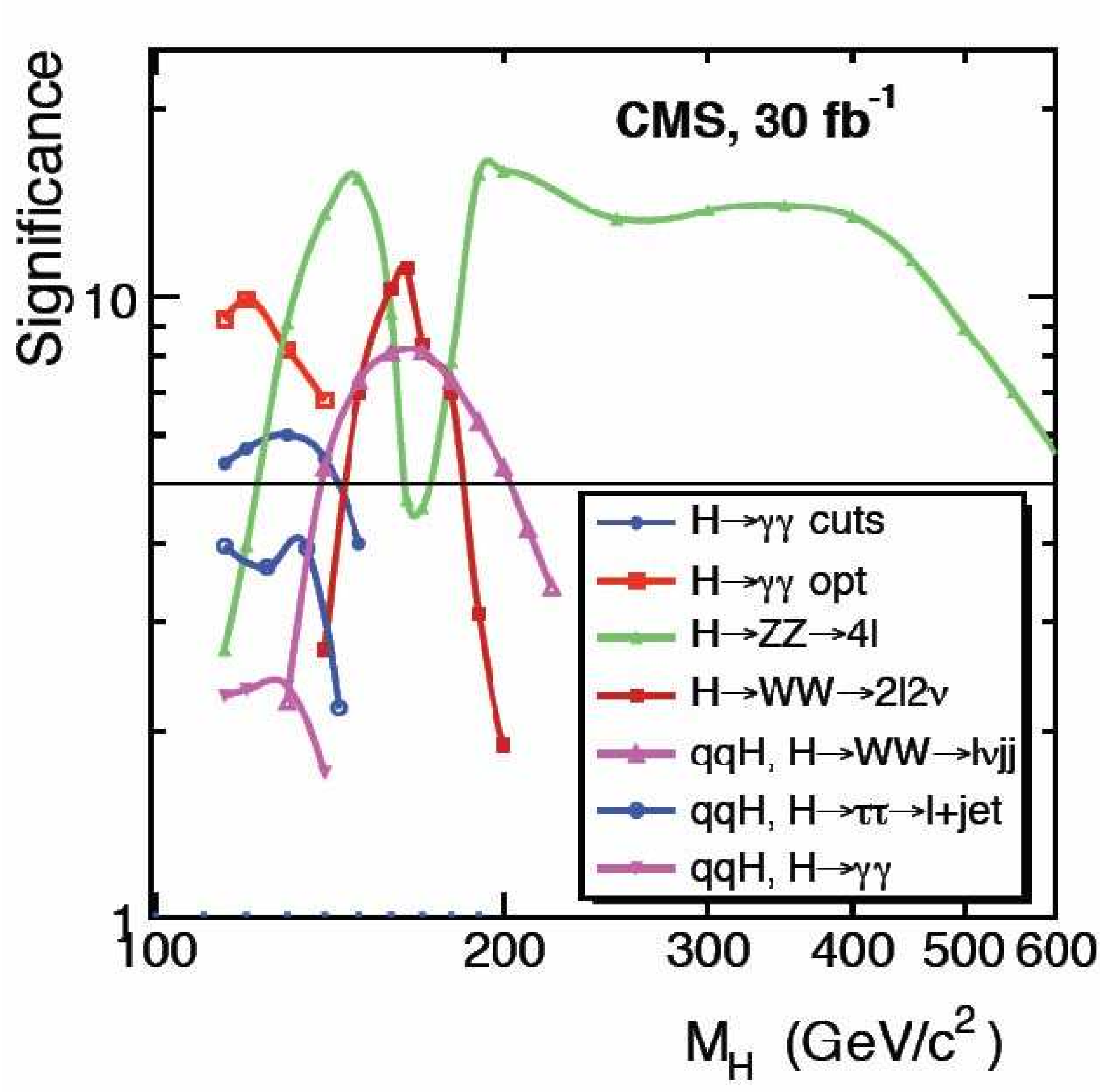
$H \to \tau\tau$:

- τs have large energy
- Can assume that neutrinos go in direction of visible decay products
- τ energy can be reconstructed from kinematic constraints

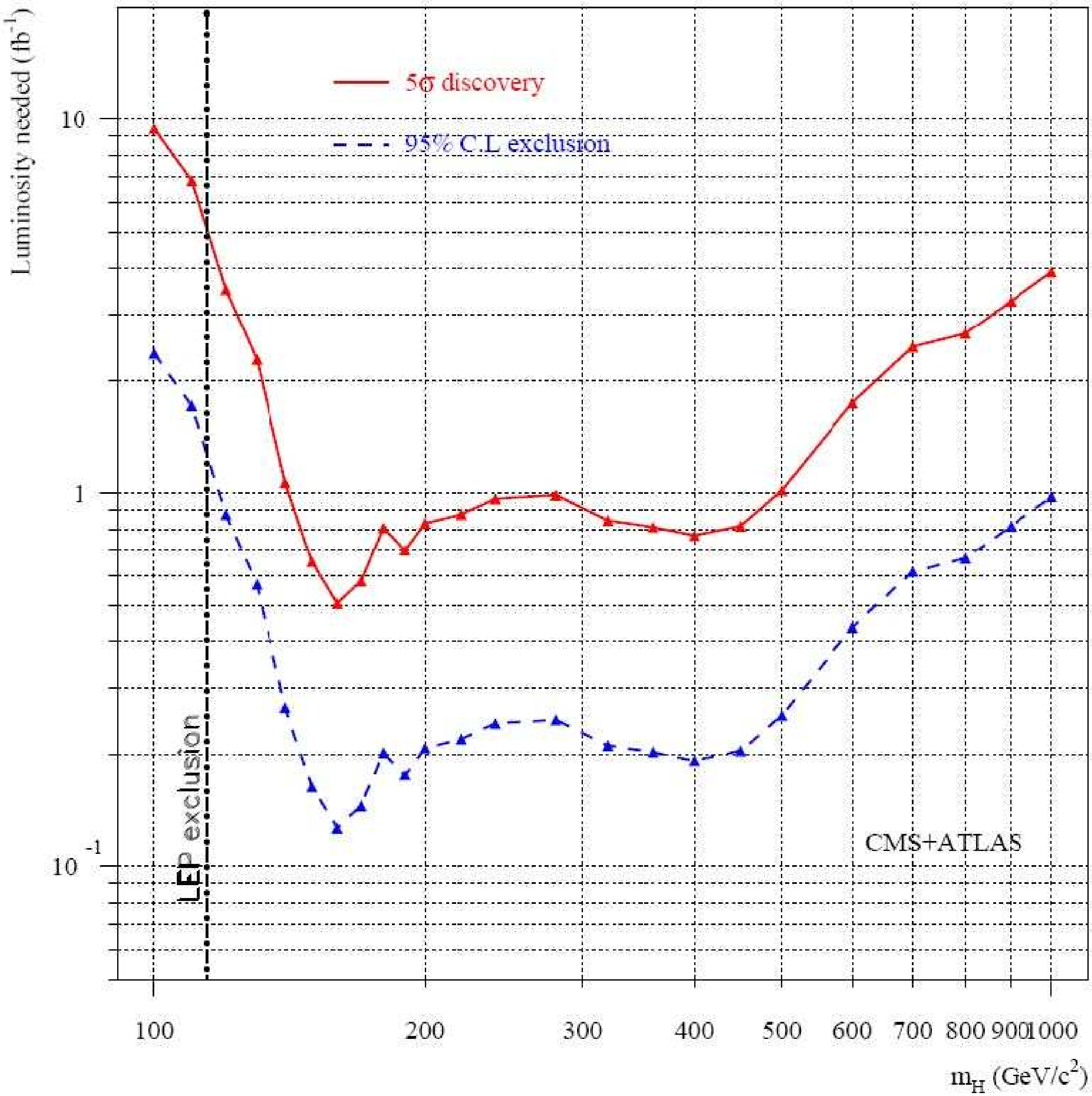
This allows $H \to \tau\tau$ reconstruction in the presence of tagging jets



With fusion channel the Higgs discovery will be assured in significantly more channels



Minimum luminosity needed for a Higgs discovery/exclusion

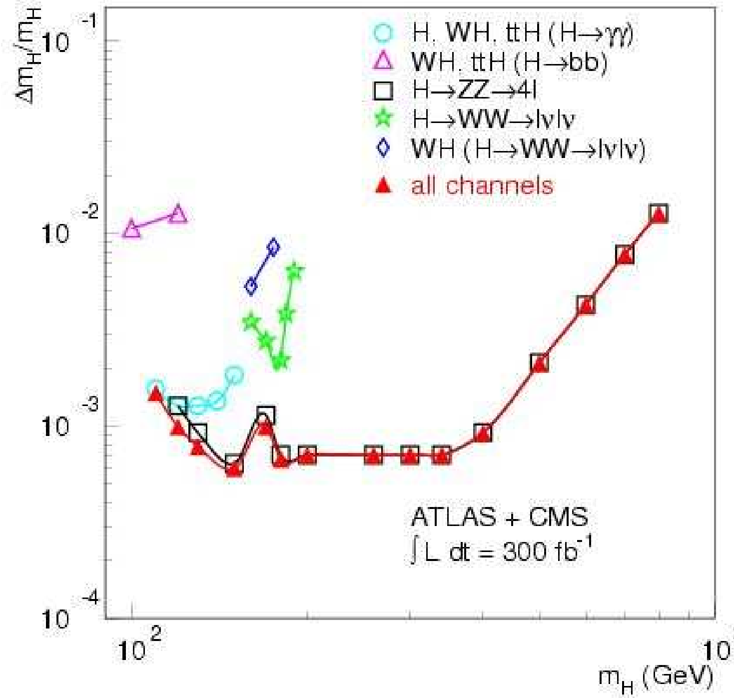


Higgs properties

LHC has discovered a particle compatible with a Higgs, what can be measured?

Mass:

Modes with complete Higgs reconstruction ($H \to \gamma\gamma$, $H \to ZZ \to 4\ell$) allow mass measurement with 0.1% precision.

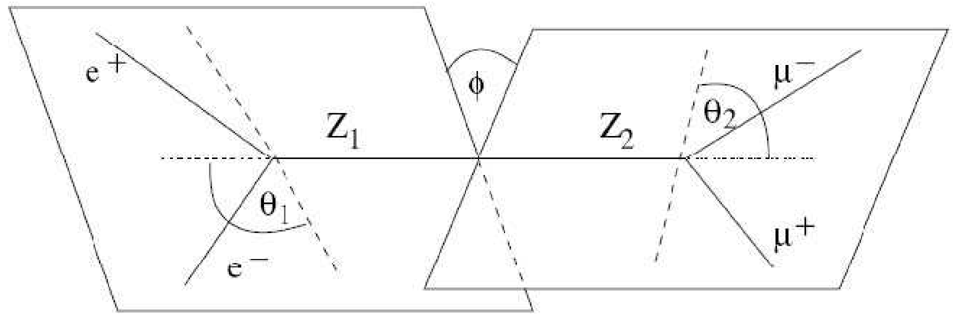


Spin:

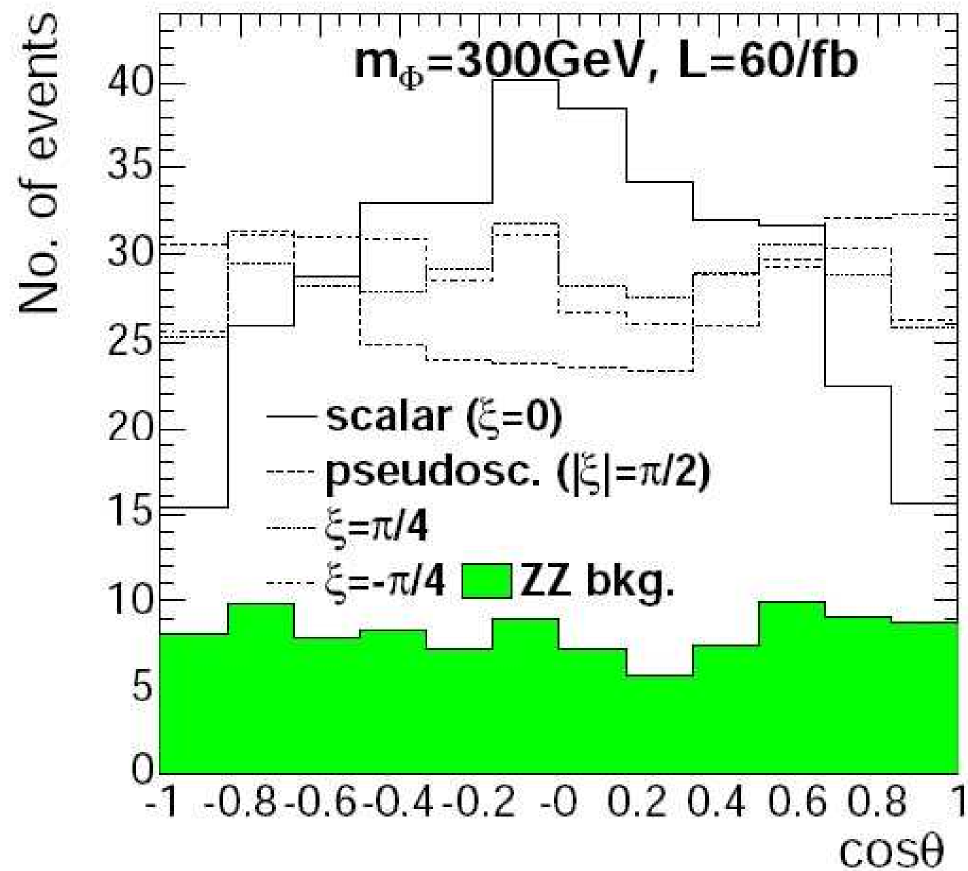
Coupling Hvv forbidden if H has spin 1 and v is massless vector particle (e.g. g or γ) (angular momentum conservation and Pauli principle)

➡ visibility of $H \to \gamma\gamma$ or $gg \to H$ excludes spin 1

If $H \to ZZ \to 4\ell$ is visible spin/CP can be obtained from decay angle distributions:

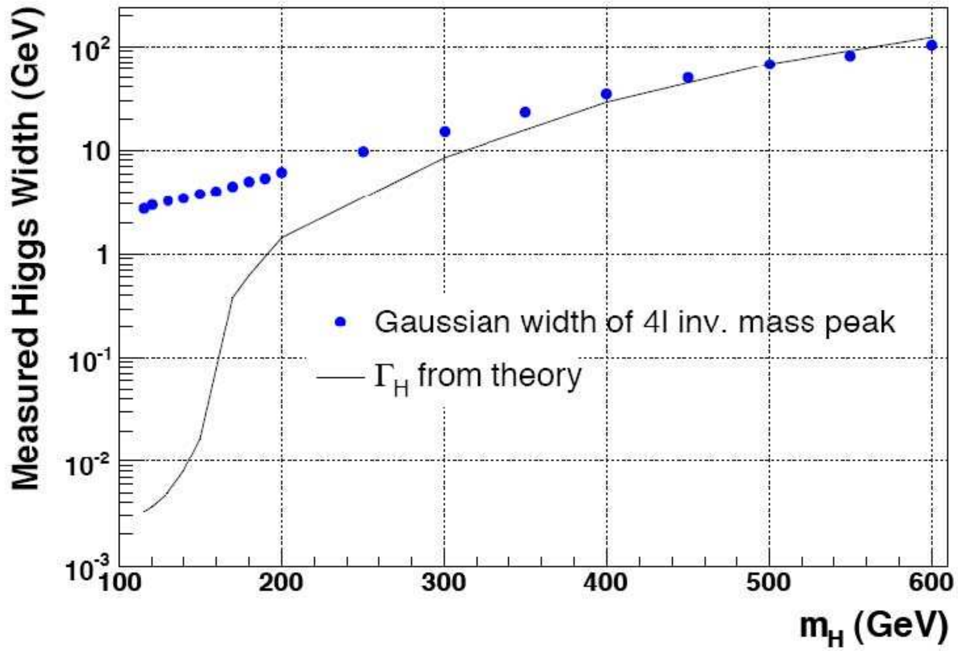


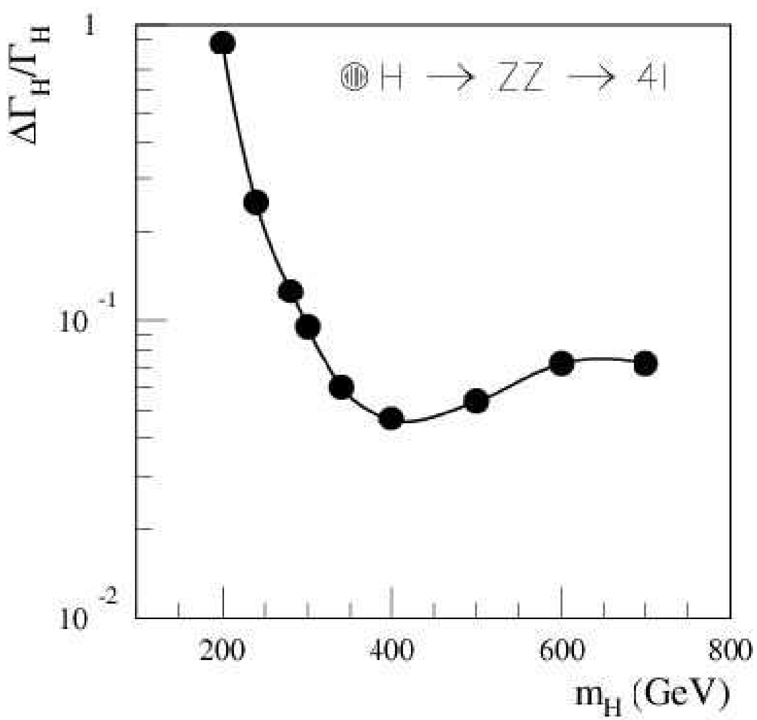
- Take $H \to ZZ \to 2e2\mu$
- Add CP odd coupling to SM coupling with strength $\tan\xi/m_V^2$
- Most backgrounds can be suppressed by cuts
- Can distinguish the extreme cases



The width of the Higgs

- For a light Higgs the width is much smaller than the detector resolution
- If $m_\mathrm{H} > 2m_\mathrm{W}$ the width gets much larger and can be measured

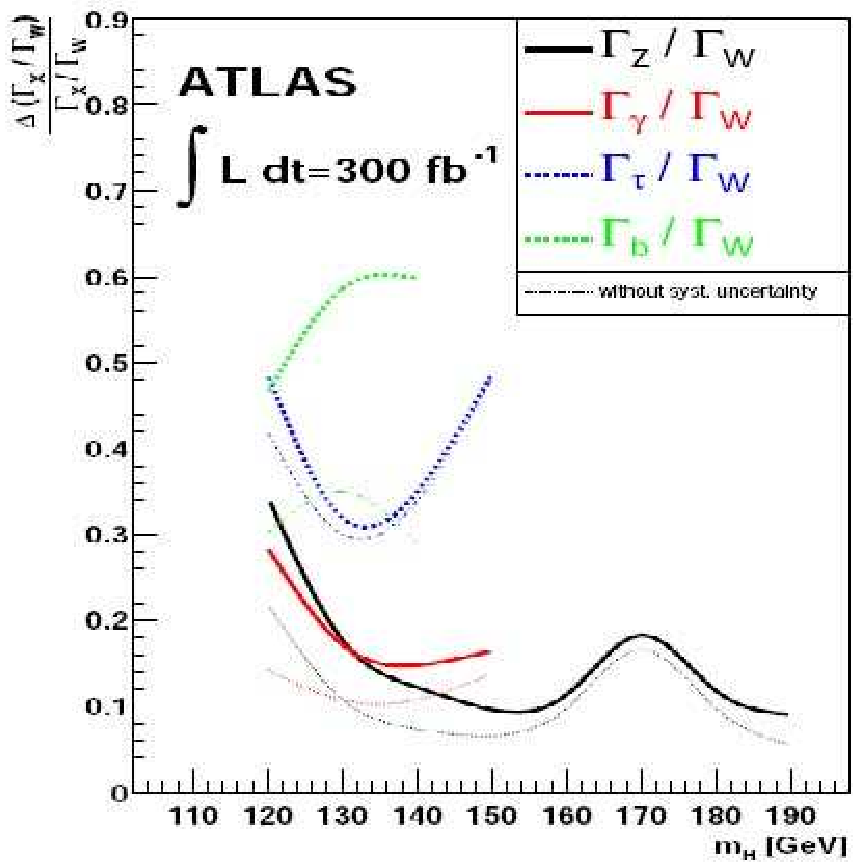




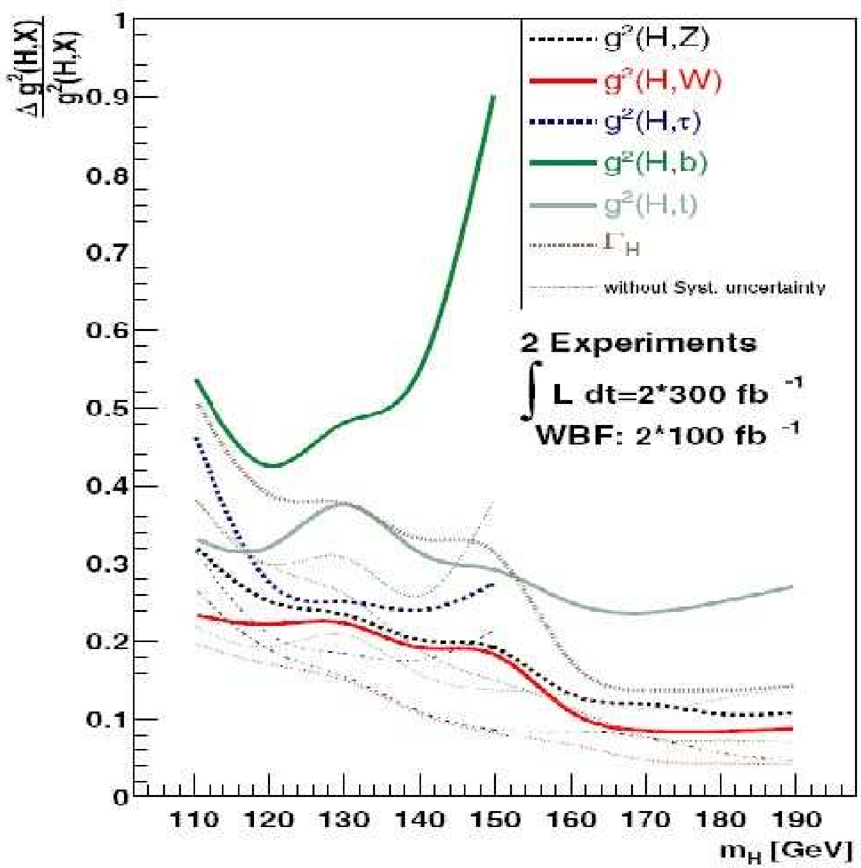
For $m_\mathrm{H} > 200\,\mathrm{GeV}$ a precision $<$ 10% is possible

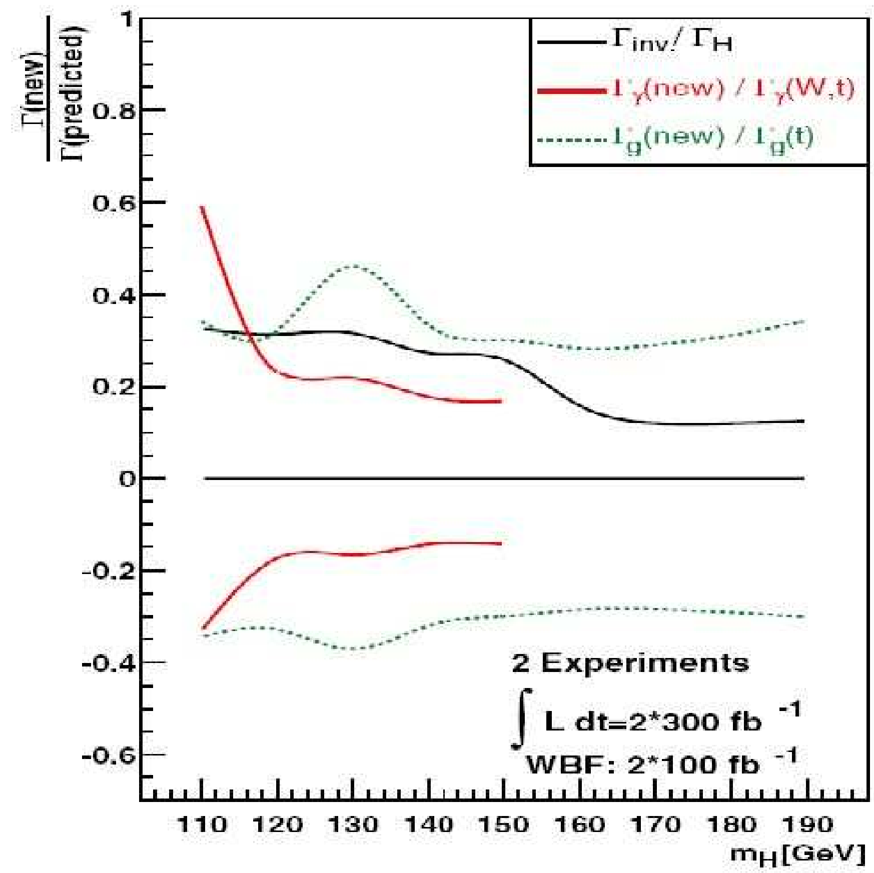
Higgs couplings

- $\sigma \times BR \propto \frac{\Gamma_{prod}\Gamma_{dec}}{\Gamma_H}$
- Ratios of production rates measure ratios of partial widths
- Can obtain ratios of decay widths with $> 10\%$ accuracy



- For absolute partial widths need additional assumptions.
- Precisions of couplings depend on assumptions
- Minimal assumption $\Gamma_V < \Gamma_V^{SM}$ $V = W, Z$
- Again precision $> 10 - 20\%$
- Better precision with additional assumptions





The Higgs in supersymmetric models

SUSY needs at least two Higgs-doublets (H_1, H_2) to generate masses of down- and up-type particles

Physical particles:

$$\begin{aligned} h &= H_2 \cos\alpha - H_1 \sin\alpha \\ H &= H_2 \sin\alpha + H_1 \cos\alpha \\ A & \quad \mathrm{CP-odd} \\ H^{\pm} & \quad \text{charged Higgses} \end{aligned}$$

Define $\tan\beta = \frac{v_2}{v_1}$ = ratio of expectation values $(v_1^2 + v_2^2 = v_{SM}^2)$

Born Formulae:

$$m_{h,H}^2 = \frac{1}{2}\left[m_A^2 + m_Z^2 \mp \sqrt{\left(m_A^2 + m_Z^2\right)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}\right]$$

$$m_h < m_Z$$

$$m_H > m_Z$$

$$m_{H^\pm}^2 = m_A^2 + m_{\mathrm{W}}^2$$

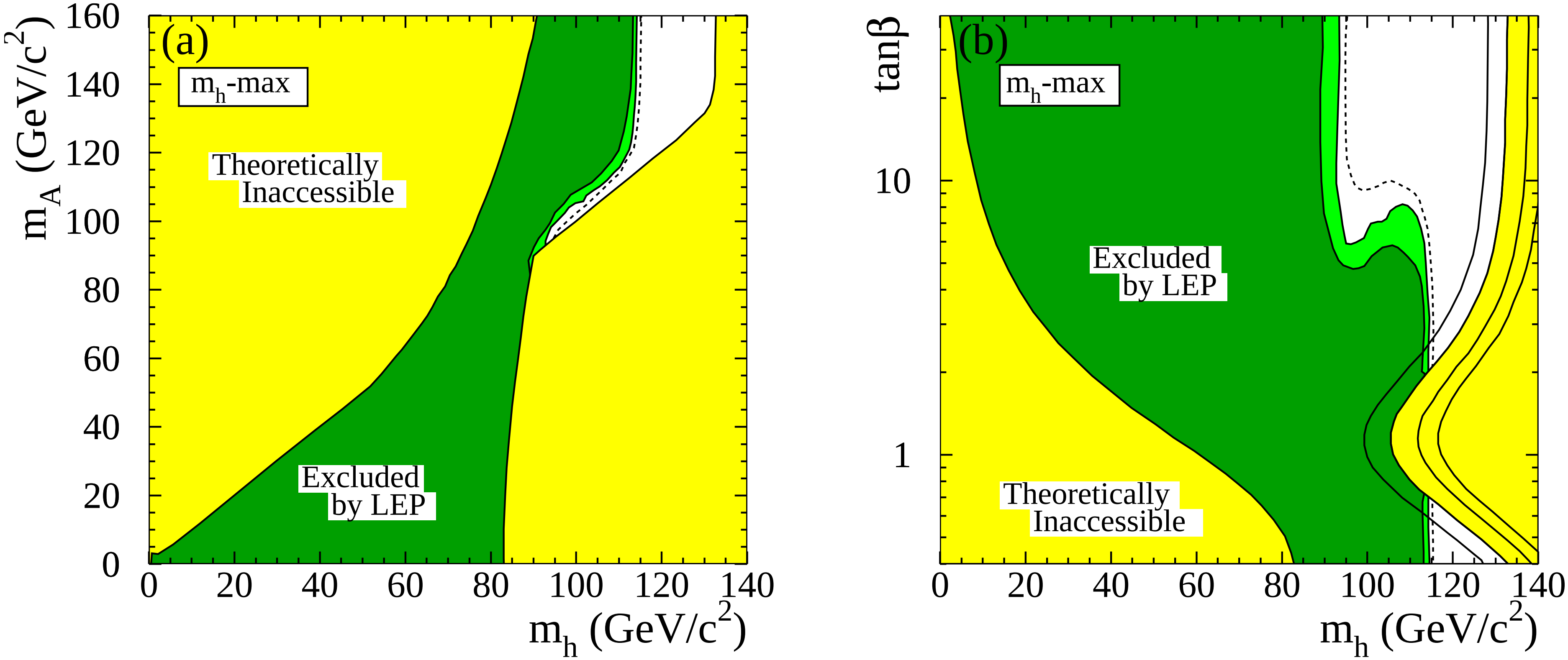
$$\tan 2\alpha = \tan 2\beta \frac{m_A^2 + m_{\mathrm{Z}}^2}{m_A^2 - m_{\mathrm{Z}}^2} \; (-\frac{\pi}{2} < \alpha < 0 < \beta < \frac{\pi}{2})$$

Higgs sector described by two free parameters

However large radiative corrections:

- shift of m_h up to $\sim 130\,\mathrm{GeV}$
- prediction gets dependent on other SUSY parameters, especially on mixing in stop sector
- strong dependence on top mass: $\Delta m_h/\Delta m_t \approx 1$

Currently allowed region:



$\tan\beta > 2$ preferred!

If m_A large:

- $\beta - \alpha = \pi/2$
- $m_H \approx m_{H^\pm} \approx m_A$

➡ Only one light Higgs can be seen

Branching ratios:

$$\Gamma(h \to VV) = \sin^2(\beta-\alpha)\Gamma_{\mathrm{SM}}(h \to VV)$$
$$\Gamma(h \to U\overline{U}) = \frac{\cos^2\alpha}{\sin^2\beta}\Gamma_{\mathrm{SM}}(h \to U\overline{U})$$
$$\Gamma(h \to D\overline{D}) = \frac{\sin^2\alpha}{\cos^2\beta}\Gamma_{\mathrm{SM}}(h \to D\overline{D})$$

- For m_A large the light Higgs becomes SM like

Heavy Higgses at the LHC

For small $\tan\beta$ (disfavoured by LEP)

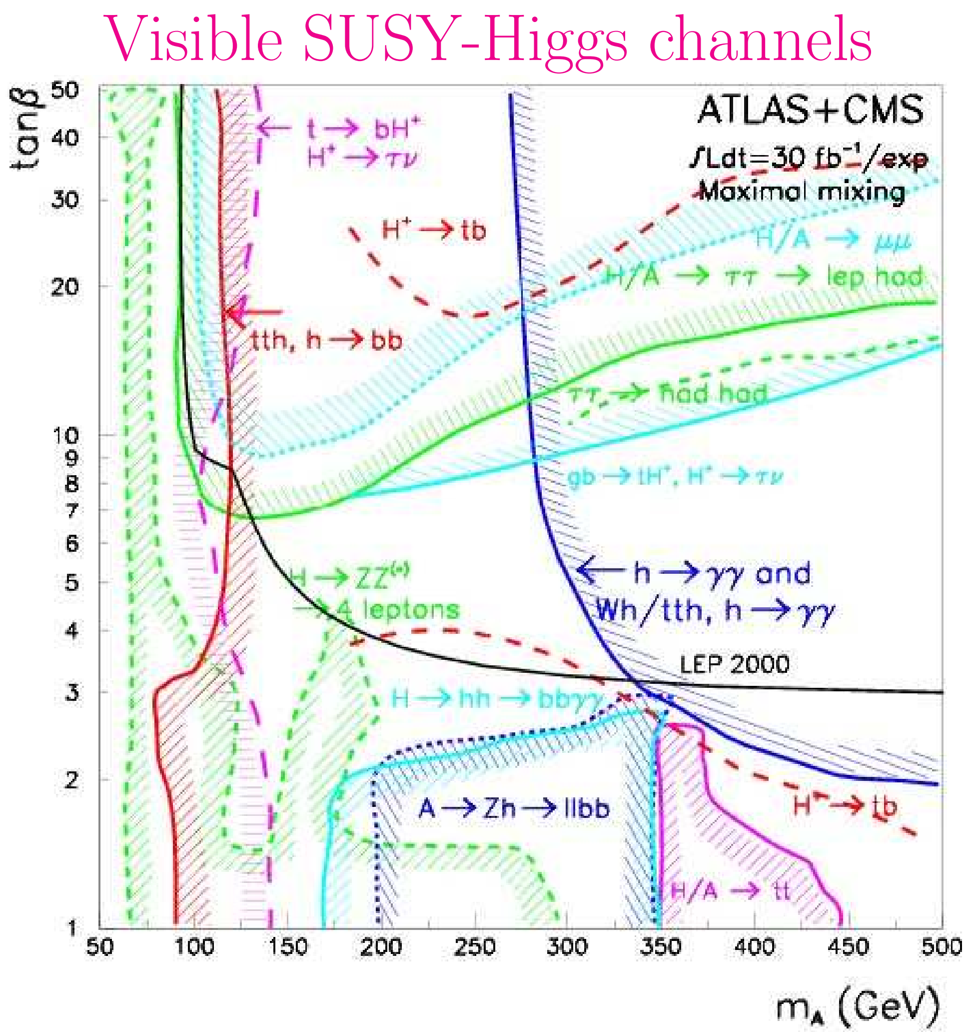
- $gg \rightarrow H, A$ production gets enhanced due to stronger $\mathrm{t\bar{t}}H$ coupling
- $H, A \rightarrow \mathrm{t\bar{t}}$ gets enhanced

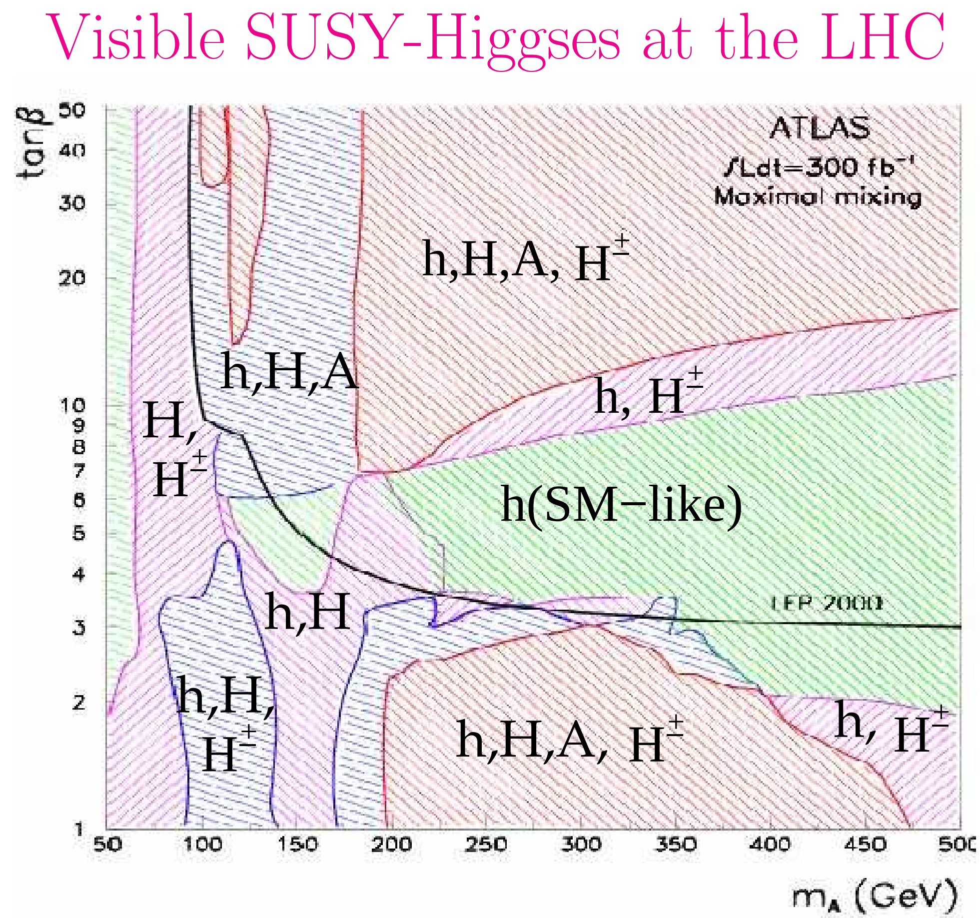
For large $\tan\beta$

- H, A production from $\mathrm{b\bar{b}}$-fusion gets enhanced
- Large branching ratio $H \rightarrow \tau\tau$

Medium $\tan\beta$

- Only SM-like h visible



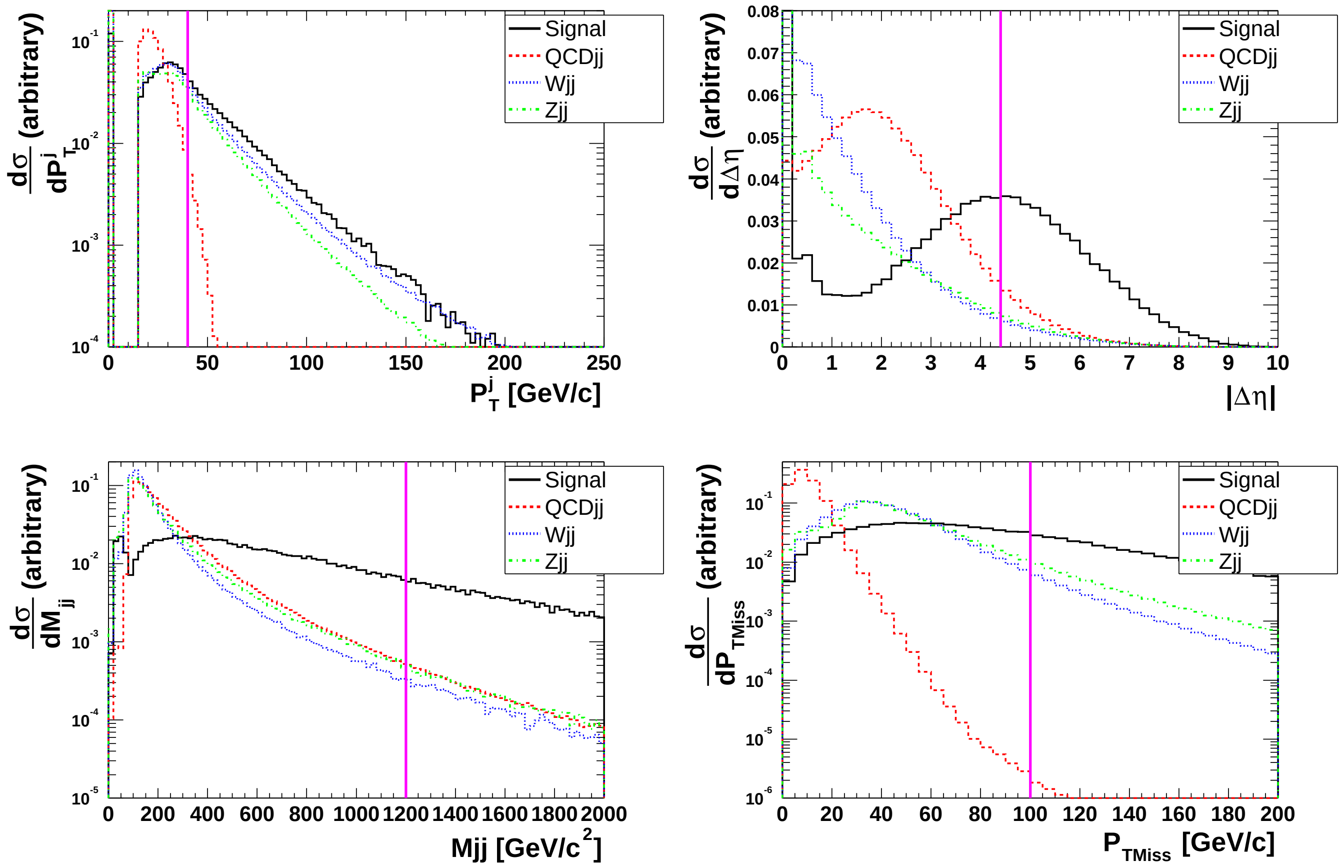


- At least a SM-like h can always be seen
- However there is a significant chance that the rest of the SUSY Higgs sector remains invisible
- This does not include decays into SUSY particles (strongly model dependent!)

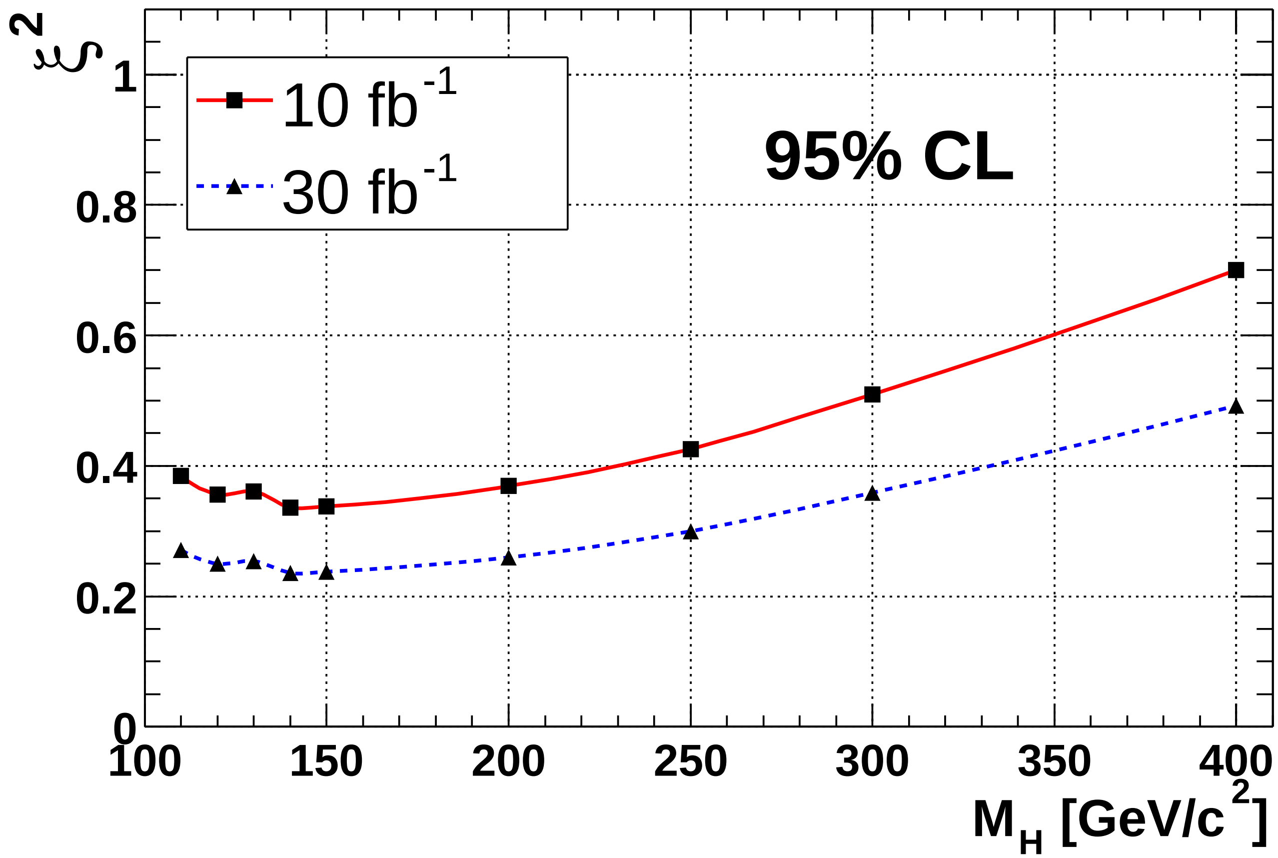
Invisible Higgs

- E.g. in SUSY models it is possible that the Higgs decays into invisible particles (e.g. the LSP)

- The properties of the VV-fusion process allows even in this case to separate the Higgs from the background



This allows to set a limit on $\xi^2 = BR(H \to \mathrm{inv})\sigma(qq \to qqH)/\sigma(qq \to qqH, SM))$ in the 0.2-0.5 range



The Higgs thus cannot be missed because it decays invisible!

Conclusions of lecture 4

- A roughly SM like Higgs cannot be missed at the LHC
- A precise mass measurement is almost included in the discovery
- Spin and CP properties may be measured to some extend
- In SUSY the light h will be seen, the rest is questionable