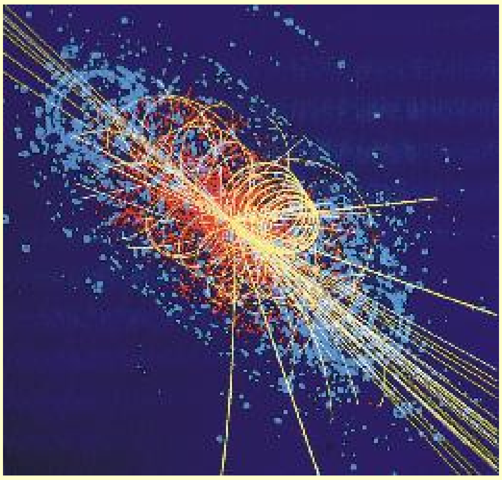
Higgs Boson Searches at Hadron Colliders



- **Introduction**
  - The Standard Model Higgs boson and its properties
- **Higgs boson production at Hadron Colliders**
- **Search for the Standard Model Higgs boson**
  - Overview on the LHC potential
  - Status and prospects at the Tevatron
- **Measurement of Higgs boson parameters**
- **Higgs bosons in the MSSM**
  - Potential at the LHC, various benchmark scenarios
  - Status and prospects at the Tevatron
  - Can invisibly decaying Higgs bosons be seen ?

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The Higgs Boson

Peter Higgs

**„The last missing piece of the Standard Model….,
the only particle not detected yet.“**

“Revealing the physical mechanism that is responsible for the breaking of electroweak symmetry is one of the key problems in particle physics”

„Particle Physicists know everything about this particle, the only thing they don‘t know is whether it exists.”

Preface / Disclaimer :

1. The subject I am talking about is sort of an „old topic“
   many talks about this subject, extensively discussed in the literature,
   many theorists and experimentalists working on it,
   overwhelming wealth of material

   → selection of material, will not be complete,....
   → tutorial

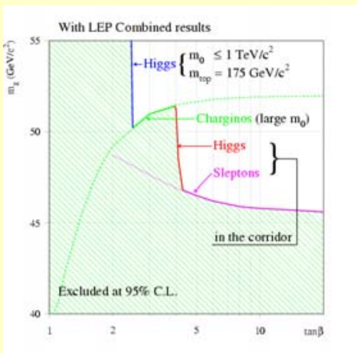
2. LHC is only 1.5 years away !!! (Detectors + machine → Steinar Stapnes)
   Focus of experimental studies is shifting
   → more full simulations, need to understand backgrounds,
   more sophisticated studies, incl. NLO calculations / Monte Carlos
   → point to new studies

3. Review the Tevatron situation in situ (Detectors, data taking, more physics,... → John Womersley)
   Discuss LHC first,
   where relevant, compare to the situation at the Tevatron
   → what can be done there?

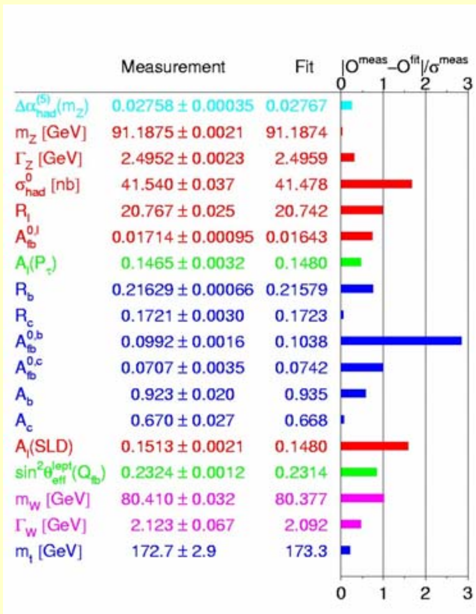
Where do we stand today?

e^+e^- colliders LEP at CERN and SLC at SLAC + the Tevatron pp collider
+ many other experiments (HERA, fixed target…….)
have explored the energy range up to **~100 GeV** with incredible precision

- The Standard Model is consistent with all experimental data !
- No Physics Beyond the SM observed



example:
Supersymmetry,
$m(\chi)$ > ~ 45 GeV



- No Higgs boson seen (yet)

Why do we need the Higgs Boson?

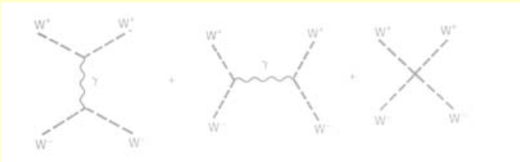
The Higgs boson enters the Standard Model to solve two fundamental problems:

- **Masses of the vector bosons W and Z:**

Experimental results: $M_W = 80.426 \pm 0.034$ GeV / c^2
$M_Z = 91.1875 \pm 0.0021$ GeV / c^2

A local gauge invariant theory requires massless gauge fields

- **Divergences in the theory** **(scattering of W bosons)**



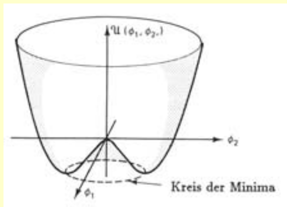
$$-i\,M\;(W^+W^- \rightarrow W^+W^-) \sim s / M_W^2$$

The Higgs mechanism

Spontaneous breaking of the SU(2) x U(1) gauge symmetry

- Scalar fields are introduced $\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Potential : $\mathcal{U}(\phi) = \mu^2(\phi^*\phi) + \lambda(\phi^*\phi)^2$



- For $\mu^2 < 0$, $\lambda > 0$, minimum of potential: $\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = v^2$ $\quad v^2 = -\mu^2/\lambda$

- Perturbation theory around ground state:

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \Rightarrow$$

3 massive vector fields: $M_{W^\pm} = \frac{1}{2} v g$

$M_Z = \frac{1}{2} v g / \cos\theta_W = M_W / \cos\theta_W$

1 massless vector field: $M_\gamma = 0$

1 massive scalar field: **The Higgs boson H**

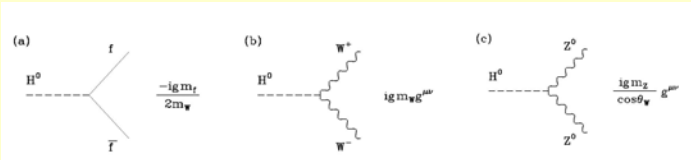
$M_H = \sqrt{\lambda\, v^2}$

Mass terms result from interaction of gauge bosons with Higgs field

v = vacuum expectation value $v = (\sqrt{2}\, G_F)^{-1/2} = 246$ GeV

The Higgs mechanism (cont.)

- Coupling terms of W- and Z-bosons and fermions to the Higgs field:



$$g_{ffH} = (\sqrt{2}G_F)^{1/2}\ m_f$$

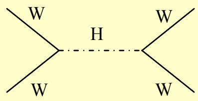
$$g_{VVH} = 2\,(\sqrt{2}G_F)^{1/2}\ M_V^2$$

- The introduced scalar fields can also be used to generate fermions masses $m_f = g_f\, v/\sqrt{2} \;\Rightarrow\; g_f = m_f \sqrt{2}/v$ (where g_f is the coupling of the Higgs field to the fermion)

- Higgs boson self-coupling $L = \ldots\ldots - \lambda v h^3 - \frac{1}{4}\lambda h^4$

and finally:

- Higgs boson regulates divergences in the WW scattering cross section



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Properties of the Higgs Boson

The decay properties of the Higgs boson are fixed, if the **mass** is known:

H → W^+, Z, t, b, c, τ^+,.........., g, γ
H → W^-, Z, t, b, c, τ ,.........., g, γ

$$\Gamma(H\to f\bar f) = N_C \frac{G_F}{4\sqrt{2}\pi}\, m_f^2(M_H^2)\, M_H$$

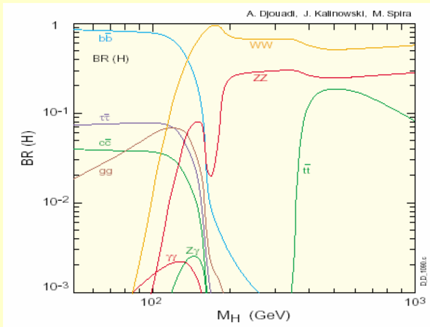
$$\Gamma(H\to VV) = \delta_V \frac{G_F}{16\sqrt{2}\pi}\, M_H^3\,(1-4x+12x^2)\,\beta_V$$

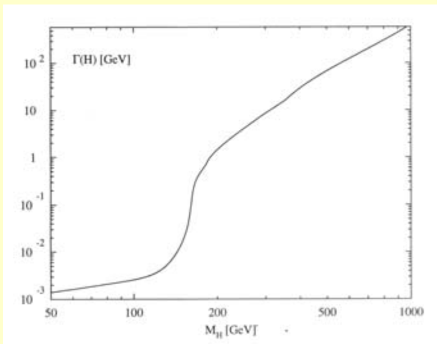
where: $\delta_Z = 1, \delta_W = 2$, $x = M_V^2/M_V^2$, β = velocity

$$\Gamma(H\to gg) = \frac{G_F\,\alpha_s^2(M_H^2)}{36\sqrt{2}\pi^3}\, M_H^3\left[1+\left(\frac{95}{4}-\frac{7N_f}{6}\right)\frac{\alpha_s}{\pi}\right]$$

$$\Gamma(H\to\gamma\gamma) = \frac{G_F\,\alpha^2}{128\sqrt{2}\pi^3}\, M_H^3\left[\frac{4}{3}N_C e_t^2 - 7\right]^2$$

(+ W-loop contributions)





Upper limit on Higgs boson mass, from unitarity of WW scattering: $M_H < 1$ TeV/c^2

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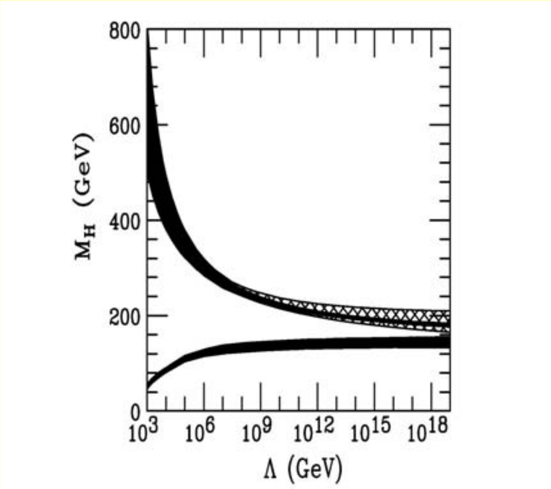
Higgs mass constraints (from theory):

Stronger bounds on the Higgs-boson mass result from the energy dependence of the Higgs coupling λ (Q^2)
(if the SM is assumed to be valid up to some scale Λ)

$$\lambda(Q^2) = \lambda_0 \{ 1 + 3\lambda_0/2\pi^2 \log(2Q^2/v^2) + \ldots - 3g_t^4/32\pi^2 \log(2Q^2/v^2) + \ldots \} \qquad \lambda_0 = M_H^2/v^2$$



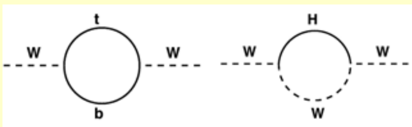
Hambye, Risselmann et al.

Upper bound: diverging coupling (Landau Pole)
Lower bound: stability of the vacuum (neg. contribution from top quark dominates)

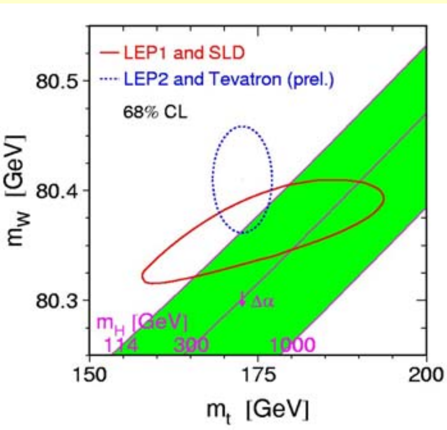
Mass bounds depend on scale Λ up to which the Standard Model should be valid

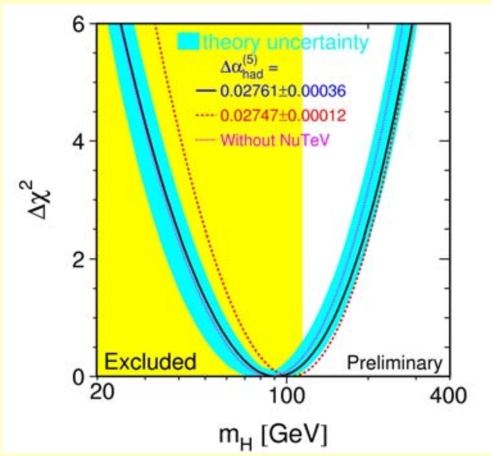
Indirect Limits via radiative corrections (exp + theory):

W-mass depends on top-quark mass and Higgs boson mass via radiative corrections:



$\Delta M_W \sim m_t^2 \qquad \Delta M_W \sim \ln M_H$



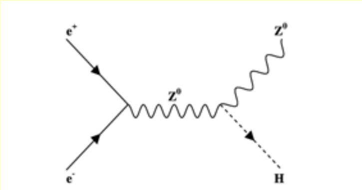


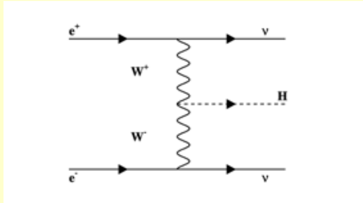
Results of the precision el.weak measurements: (LEWWG-2005):

M_H = 91 (+45) (-32) GeV/c²
M_H < 186 GeV/c² (95 % CL)

Results on Direct Higgs bosons searches at LEP (exp)

Higgs-Strahlung: $e^+ e^- \rightarrow Z\,H$ WW-Fusion: $e^+ e^- \rightarrow \nu\nu\,H$





Higgs decay branching ratios for m_H=115 GeV/c^2:
BR (H → bb) = 74%, BR (H→ ττ, WW, gg) = 7% each, BR(H → cc) = 4%

Decay modes searched for:

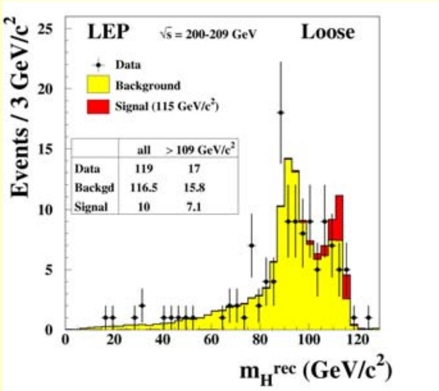
- Four Jet channel: HZ → bb qq
- Missing energy channel: → bb νν
- Leptonic channel: → bb ee, bb μμ
- Tau channels: → bb ττ, and ττ qq

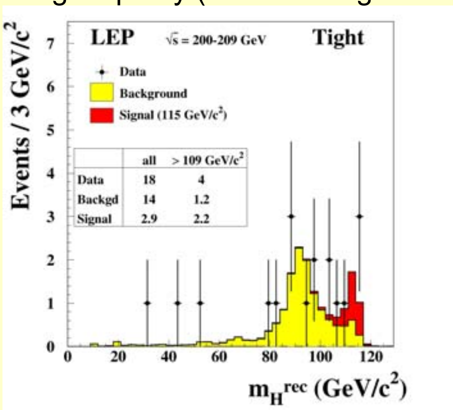
Results of the final LEP analysis:

Final results have been published: CERN-EP / 2003-011:

Based on final calibrations of the detectors, LEP-beam energies, final Monte Carlo simulations and analysis procedures.

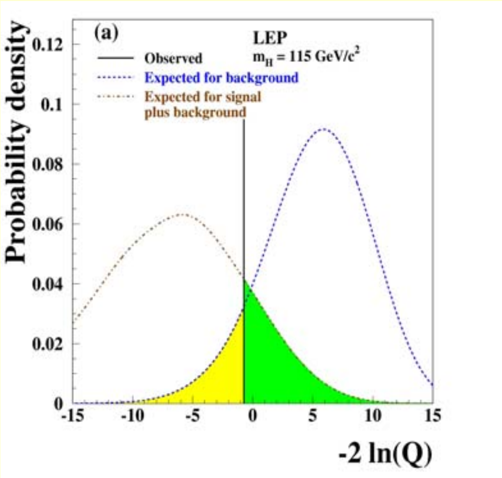
The reconstructed bb mass for two levels of signal purity (loose and tight cuts):





Clear peak in the background prediction in the vicinity of m_Z due to the $e^+e^- \rightarrow ZZ$ background, which is consistent with the data.

Final combined LEP result



	$1-CL_b$	CL_{s+b}
LEP	0.09	0.15
ALEPH	3.3×10^{-3}	0.87
DELPHI	0.79	0.03
L3	0.33	0.30
OPAL	0.50	0.14
Four-jet	0.05	0.44
All but four-jet	0.37	0.10

$1- CL_B = 0.09 \quad \leftrightarrow$

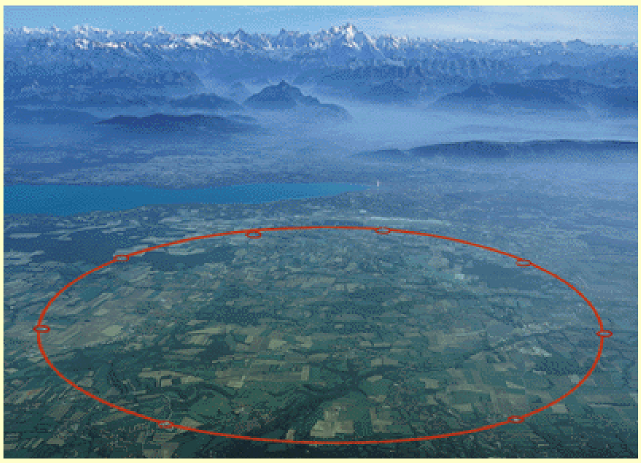
Signal significance = 1.7 σ

Likelihood ratio $Q := L_{S+B} / L_B$
Test statistics: $-2 \ln Q$

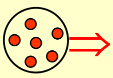
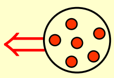
M_H > 114.4 GeV/c² (95% CL)

expected mass limit: 115.3 GeV/c²
(sensitivity)

The Large Hadron Collider (LHC)



- Proton-proton accelerator in the LEP tunnel at CERN

p   p
7 TeV 7 TeV

- Four experiments:
  ATLAS, CMS (pp physics)
  LHC-B (physics of b-quarks)
  ALICE (Pb-Pb collisions)

- Startup planned for 2007

- **Luminosities: Early phase, "low luminosity":** **$L = 1\times10^{33}$ cm^{-2} sec^{-1}**
  10 fb^{-1} / year

  After 2-3 years, "high luminosity": **$L = 1\times10^{34}$ cm^{-2} sec^{-1}**
  100 fb^{-1} / year

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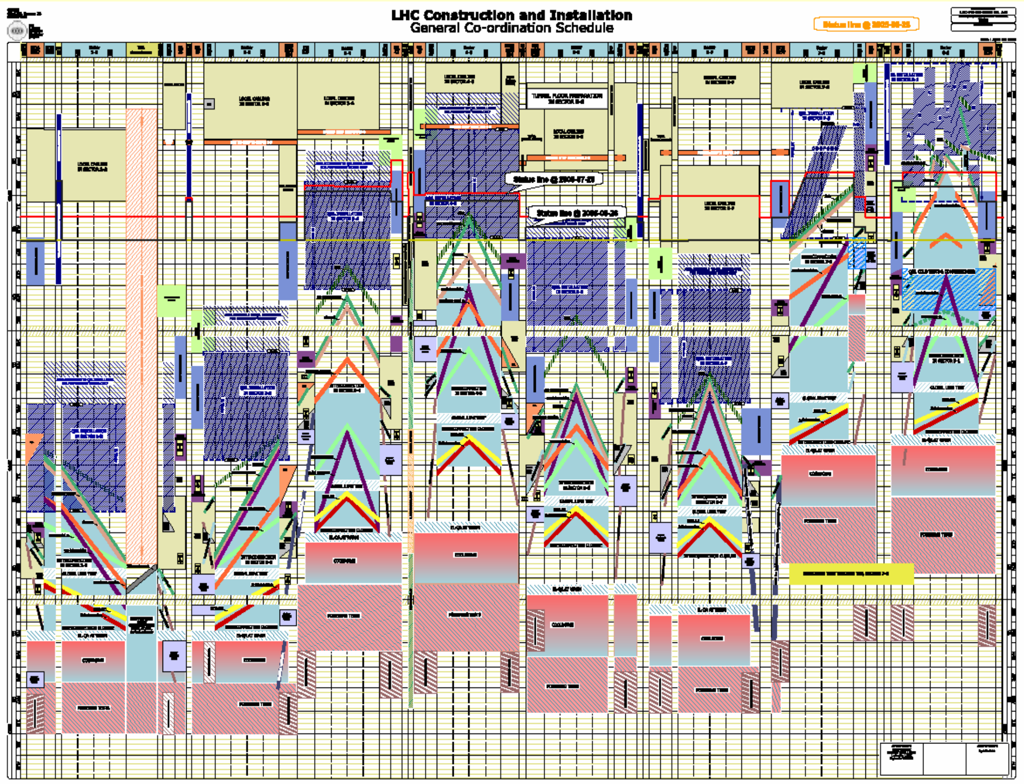
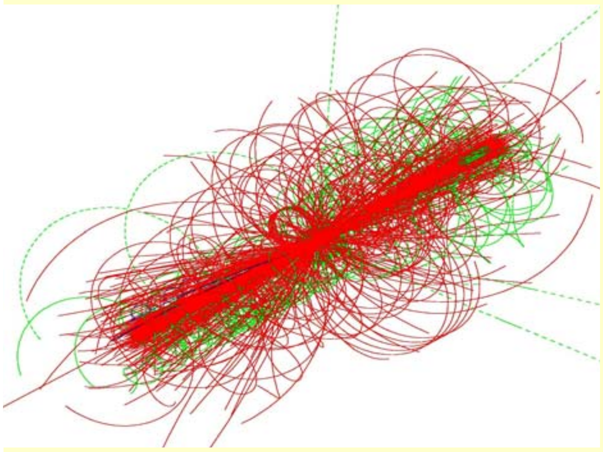
Official LHC installation schedule – *"a piece of art"*-

we are here →



June 07 →

Proton-Proton Collisions at the LHC



Proton – Proton:

2835 x 2835 bunches
separation: 7.5 m (25 ns)

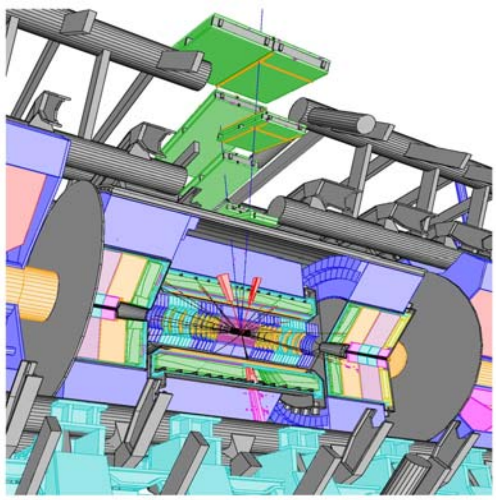
10^{11} Protons / bunch
Bunch crossing rate: 40 MHz
Luminosity: L = 10^{34} cm^{-2} sec^{-1}

Proton-Proton collisions: ~10^9 / sec
(superposition of 23 pp-interactions
per bunch crossing)

~1600 charged particles in the detector

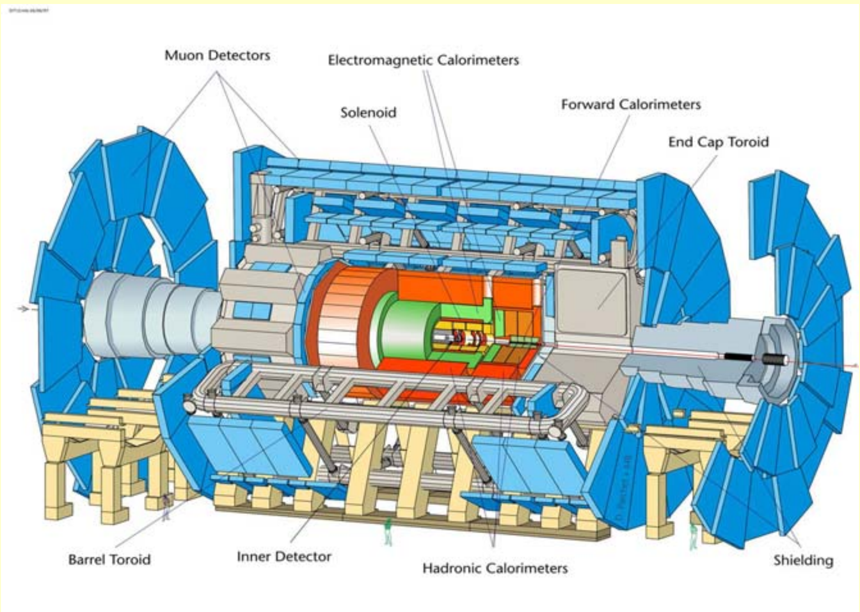
⇒ high particle densities
high requirements on the detectors

Detector requirements from physics



- Good measurement of leptons and photons with large transverse momentum P_T
- Good measurement of missing transverse energy (E_T^{miss})
  and
  energy measurements in the forward regions
  $\Rightarrow$ calorimeter coverage down to $\eta \sim 5$
- Efficient b-tagging and τ identification (silicon strip and pixel detectors)

The ATLAS experiment



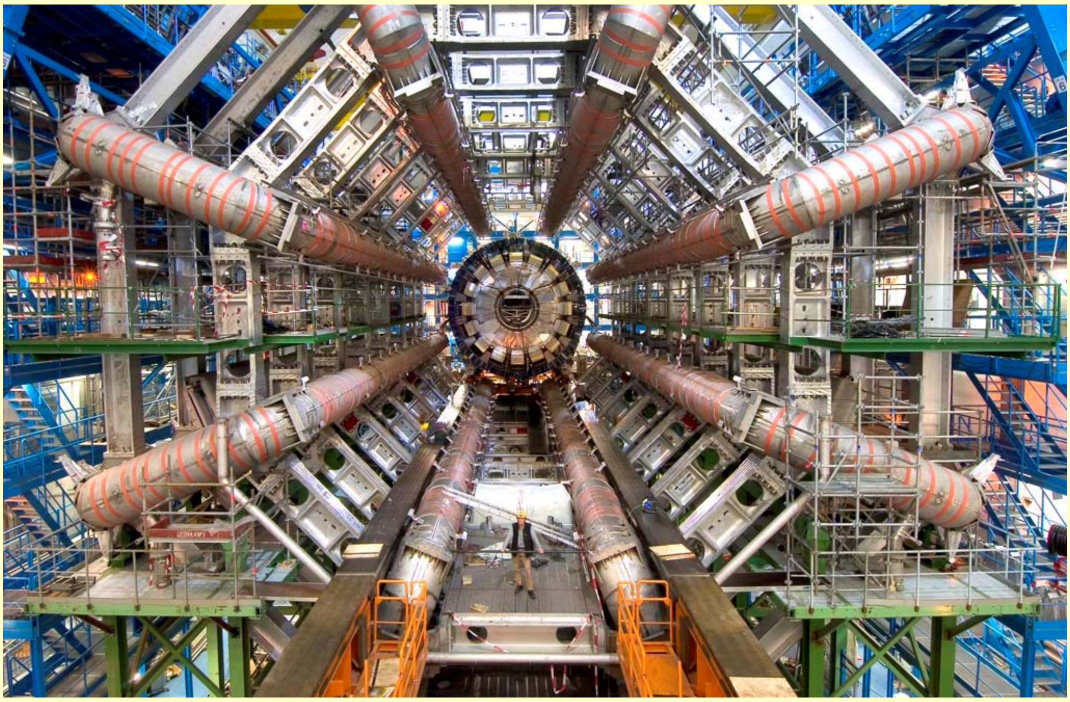
Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons

- Solenoidal magnetic field (2T) in the central region (momentum measurement)

  High resolution silicon detectors:
  - 6 Mio. channels (80 μm x 12 cm)
  - 100 Mio. channels (50 μm x 400 μm)

  space resolution: ~ 15 μm
- Energy measurement down to 1º to the beam line
- Independent muon spectrometer (supercond. toroid system)

ATLAS Installation

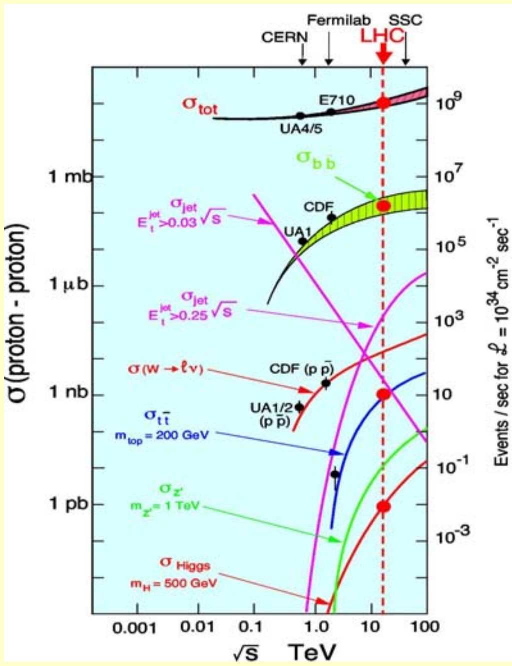


October 2005

Physics during the first year(s) ?

Expected event rates in ATLAS and CMS at L = 10^{33} cm^{-2} s^{-1}:

Process	Events / sec	Events for 10 fb^{-1} (1 year)	Total stat. collected at previous machines by 2007
$W \rightarrow e \nu$	15	10^8	10^4 (LEP) 10^7 (TeV)
$Z \rightarrow e e$	1.5	10^7	10^7 (LEP)
tt	1	10^7	10^4 (Tevatron)
bb	10^6	10^{12}-10^{13}	10^9 (BaBar/Belle)
Higgs M_H = 130 GeV/ c^2	0.02	10^5	?
Squarks, Gluinos M ~ 1 TeV /c^2	0.001	10^4	--



Already in the first year:
large statistics expected from known SM processes

First goals …. (2007/08) (?)

1. Understand and calibrate detector and trigger

in situ using well-known physics samples

e.g. - $Z \rightarrow ee, \mu\mu$ tracker, calorimeter, muon chambers calibration and alignment

- $tt \rightarrow b\ell\nu\, bjj$ 10^4 events/day after cuts

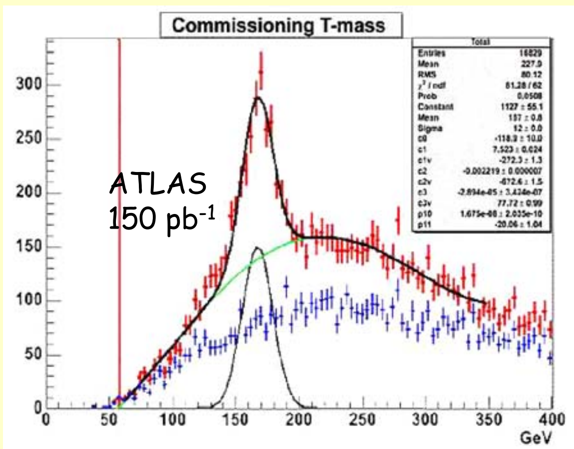
→ jet scale from W→jj
→ b-tag performance

⇒ defines t_0 !!

Early Physics: Top quark without b-tag

Extremely simple selection:

- Use $tt \rightarrow Wb\, Wb \rightarrow \ell\nu b\, qqb$ decays
- 1 isolated lepton (P_T>20 GeV/c)
- Exactly 4 jets (P_T > 40 GeV/c)
- no kinematic fit, no b-tagging (!)
- invariant mass of 3 highest P_T jets

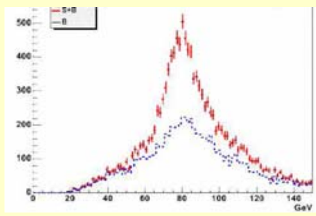


$M(j_1j_2j_3)$

Signal visible after few days at 10^{33}

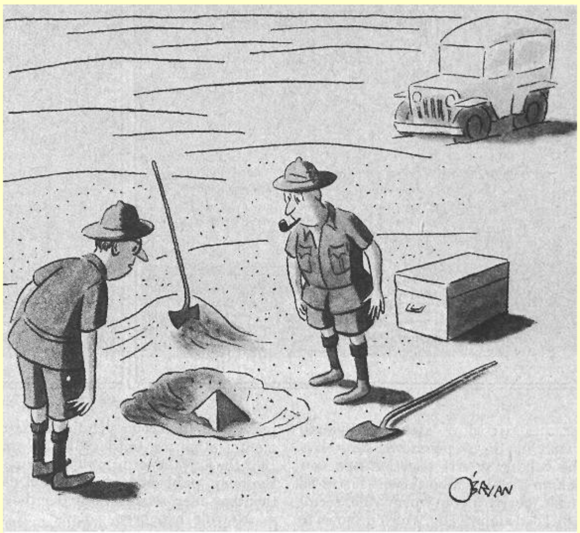
- stat. error on m_{top} ~ 400 MeV after one week
- Δm_{top} = 7 GeV (assuming 10% b-jet-scale error)
- use for jet energy calibration
- ideal to commission b-tagging!

also: hadronic W-mass peak (→jet E-scale)



......and in parallel.....

....2. prepare the road for discovery



"This could be the discovery of the century. Depending, of course, on how far down it goes."

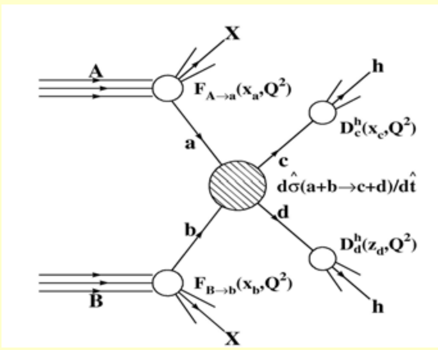
- Understand basic SM physics at $\sqrt{s}$ = 14 TeV

→ first checks of Monte Carlos
(very important input from the Tevatron)

e.g. measure cross sections for W, Z, tt, QCD jets,
and event features (P_T spectra etc.)

(tt and W/Z+ jets are omnipresent in Searches for New Physics)

Search for the Higgs Boson at Hadron Colliders

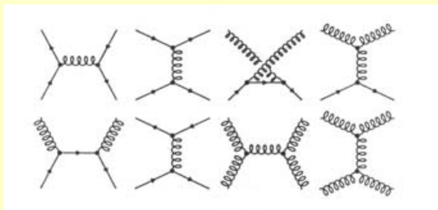


$$\sigma = \sum_{ij}\int dx_1 dx_2\, f_i\left(x_1,\mu_F^2\right) f_j\left(x_2,\mu_F^2\right)\hat{\sigma}_{ij}\left(\alpha_s^m\left(\mu_R^2\right), x_1P_1, x_2P_2, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

Sum over initial states — *Parton Distributions* — *Factorization Scale* — *Point Cross Section* — *Order α_s^n* — *Renormalization Scale*

Dominant hard scattering cross section:

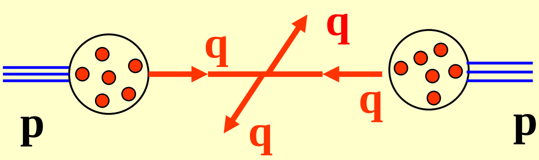
„QCD Jet Production"
quark/gluon scattering



Detection of Higgs boson decays into qq (bb) final states (without associated signatures) are hopeless !!

What experimental signatures can be used ?

Quark-quark scattering:

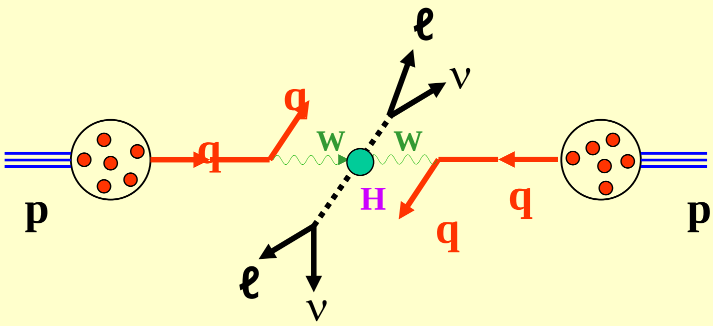


No leptons / photons in the initial and final state

If leptons with large transverse momentum are observed:

⇒ **interesting physics !**

Example: Higgs boson production and decay



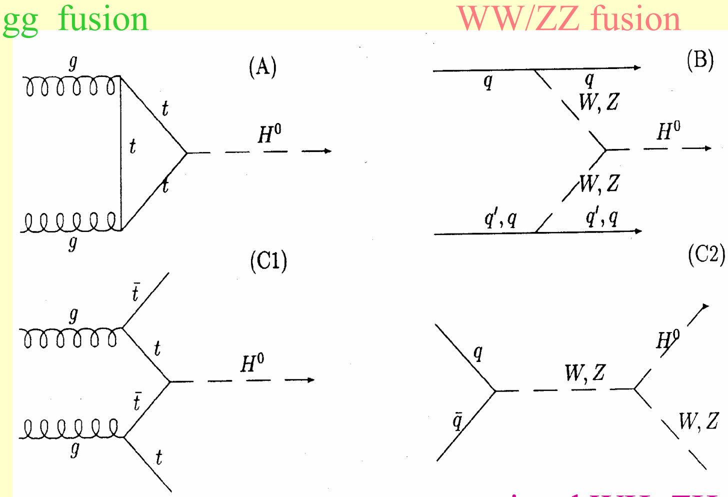
Important signatures:

- **Leptons und photons**
- **Missing transverse energy**

Higgs Boson production processes at Hadron Colliders

gg fusion

WW/ZZ fusion

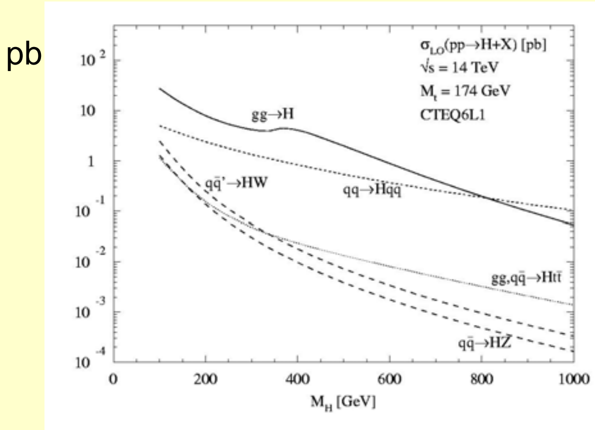


associated $t\bar{t}H$

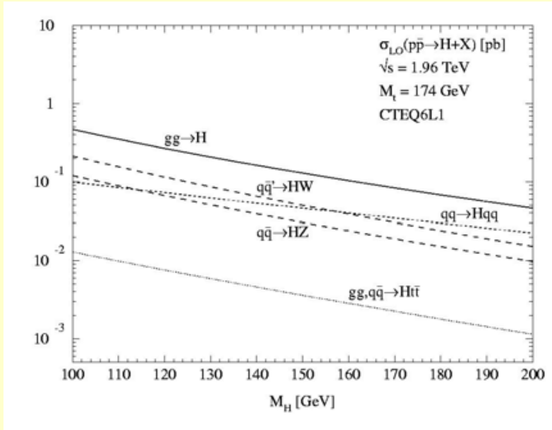
associated WH, ZH

Leading Order Higgs Boson Production cross sections

LHC — M. Spira et al.



Tevatron — M.Spira et al.



Dominant production modes:

1. Gluon fusion
2. Vector boson fusion

 .....

1. Gluon fusion

2./3. W/Z H associated production
 (Vector boson fusion at high mass)

4. ttH (very small cross section)

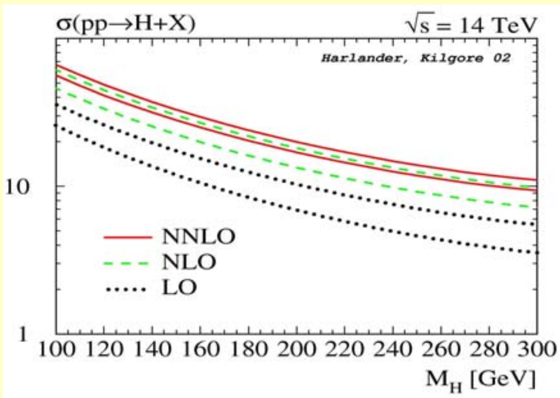
Note the difference in mass range !

Status of higher order corrections

NLO corrections (K-factors) have meanwhile been calculated for all Higgs production processes (huge theoretical effort !)

1. gg fusion:

- large NLO QCD correction **K ~ 1.7 – 2.0**
 [Djouadi, Spira, Zerwas (91)] [Dawson (91)]
- complete NNLO calculation ⇒
 evidence for nicely converging pQCD series
 (infinite top mass limit)
 [Harlander, Kilgore (02)] [Anastasiou, Melnikov (02)]



(similar behaviour for the Tevatron)

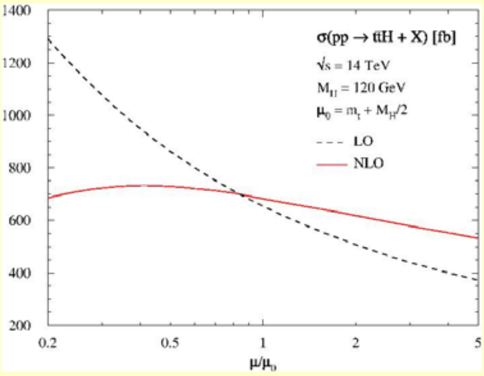
2. Weak boson fusion: K ~1.1
[Han, Valencia, Willenbrock (92)] [Spira (98)]

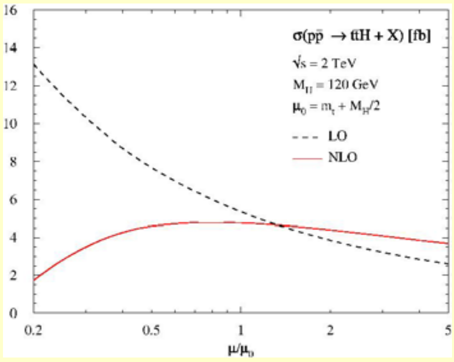
3. WH associated production: K ~ 1.3
(QCD corrections from Drell-Yan process)

Status of higher order corrections (cont.)

4. ttH associated production:

- full NLO calculation LHC: K ~ 1.2 scale: $\mu_0 = m_t + M_H/2$
  Tevatron: K ~ 0.8
- scale uncertainty drastically reduced
  [Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas (01)] [Dawson, Reina (01)]

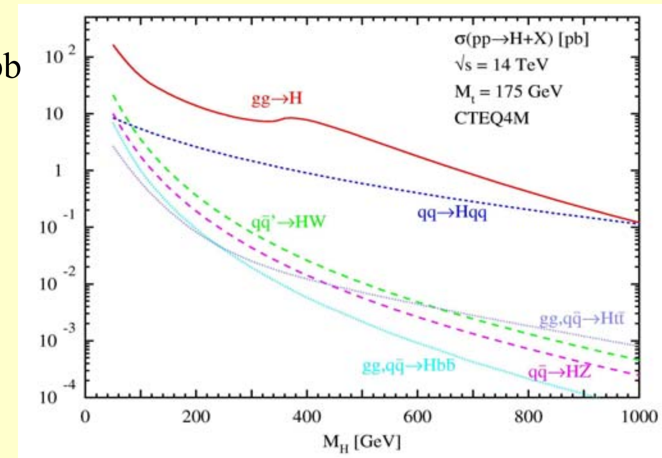




Higgs Boson Production cross sections at NLO

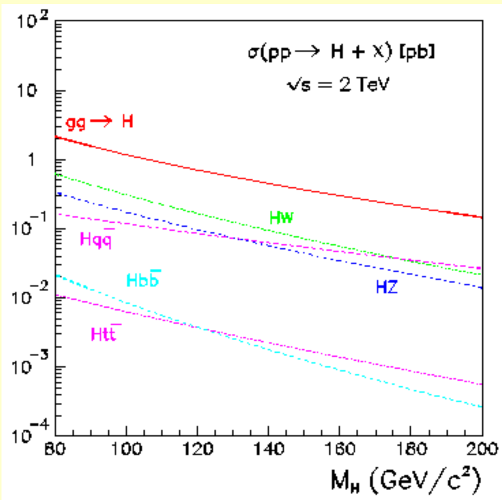
LHC M. Spira et al.

pb



Tevatron M.Spira et al.

pb



qq → W/Z + H cross sections ~10 x larger at the LHC
gg → H ~70-80 x larger at the LHC

Some important comments:

- huge theoretical effort !!

- so far, LHC experimentalists (at least from one experiment) have refrained from systematically using these higher order corrections („no K factors“)

  main arguments: K-factors are not known for all background processes,
  → consistent treatment between signal and background,
  most likely a conservative approach

- New Tools → Experimentalists are about to use/familiarize + validate them:

(i) New (N)NLO Monte Carlos (also for backgrounds):

- MCFM Monte Carlo, J. Campbell and K. Ellis, http://mcfm.fnal.gov
- MC@NLO Monte Carlo, S.Frixione and B. Webber, wwwweb.phy.cam.ar.uk/theory/webber/MCatNLO
- T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. D68, 073005 (2003)
- E.L.Berger and J. Campbell, Phys. Rev. D70, 073011 (2004)
- C. Anastasiou, K. Melnikov and F. Petriello, hep-ph/0409088 and hep-ph/0501130 (differential cross sections through NNLO)

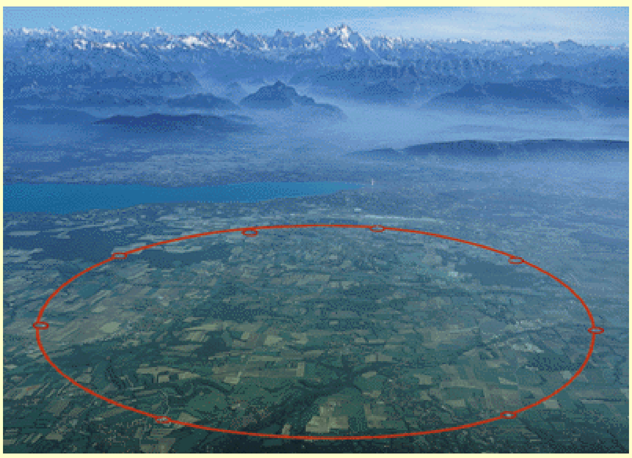
(ii) New approaches to match parton showers and matrix elements:
(based on algorithm developed by Catani, Krauss, Kuhn and Webber (CKKW)*)

- ALPGEN Monte Carlo + MLM matching, M. Mangano et al.
- PYTHIA, adapted by S. Mrenna
- SHERPA Monte Carlo, F. Krauss et al., www.physik.tu-dresden.de/~krauss/hep/index.html

Tevatron data are extremely important for validation,
work has started, see e.g., TeV4LHC workshops

*) S. Catani, F. Krauss, R. Kuhn, B. R. Webber, JHEP 0111 (2001) 063.

The Search for the



Standard Model Higgs Boson

at the LHC

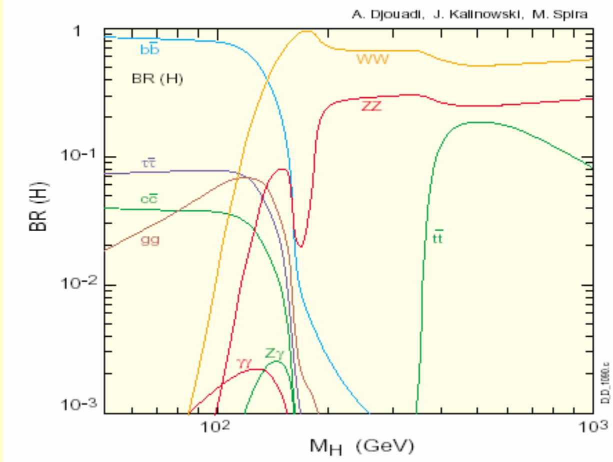
K. Jakobs

19^{th} Nordic Particle Physics Meeting, Spatind/Norway, Jan. 2006

Higgs boson search in the

gluon fusion

channel



no accompanying particles (except high-P_T Higgs + jet production)

→ lepton or photon final states (the „classical" channels)

$H \to Z Z^{(*)} \to \ell\ell\,\ell\ell$

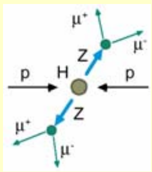
$H \to \gamma\gamma$

$H \to WW^{(*)} \to \ell\nu\,\ell\nu$

- large production rates, compensate for small leptons / photonic branching ratios
- jet vetos can be applied to suppress large tt and other backgrounds

(i) $H \to ZZ^{(*)} \to \ell\ell\ell\ell$

Signal: σ BR = 5.7 fb (m_H = 100 GeV)



Background: Top production

$tt \to Wb\,Wb \to \ell\nu\, c\ell\nu\, \ell\nu\, c\ell\nu$

σ BR ≈ 1300 fb

Associated production Z bb

$Z\,bb \to \ell\ell\, c\ell\nu\, c\ell\nu$

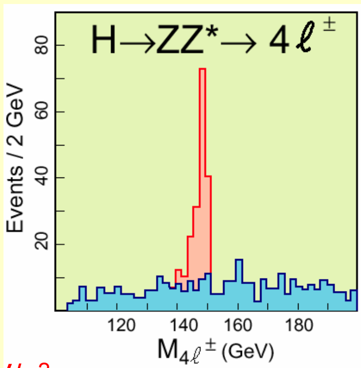
Background rejection: Leptons from b-quark decays
→ non isolated
→ do not originate from primary vertex
(B-meson lifetime: ~ 1.5 ps)

Dominant background after isolation cuts: ZZ continuum

P_T (1,2) > 20 GeV/c
P_T (3,4) > 7 GeV/c
$|\eta|$ < 2.5
Isolated leptons

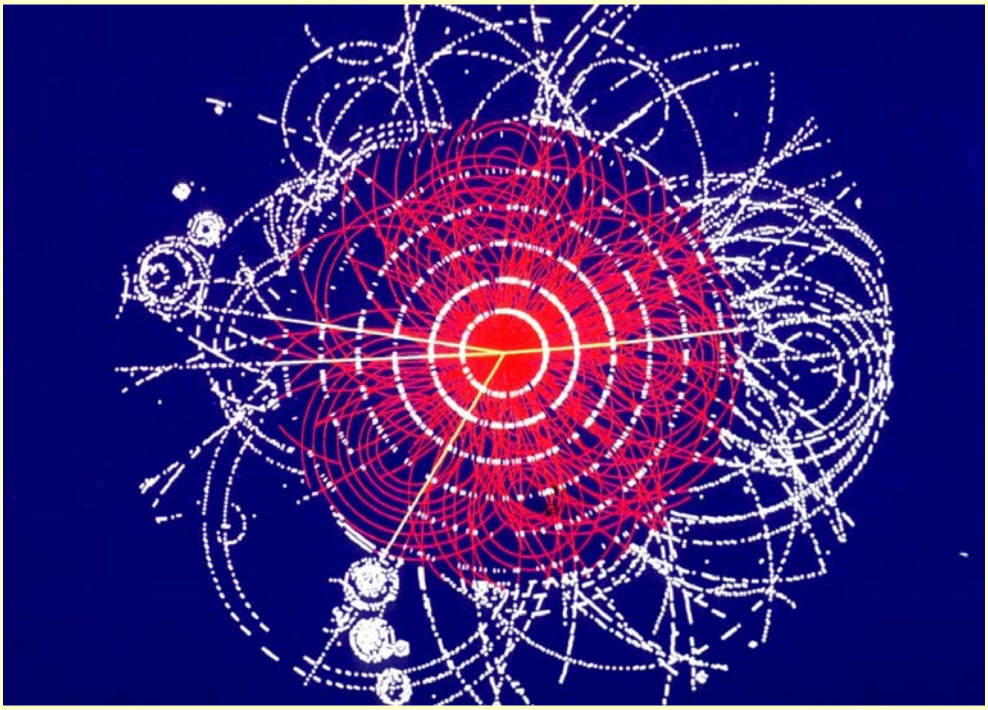
M(ll) ~ M_Z
M(l'l') ~ < M_Z

L = 100 fb^{-1}

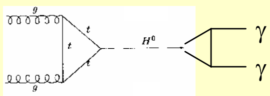


Discovery potential in mass range from ~130 to ~600 GeV/c^2

A simulated $H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$ event

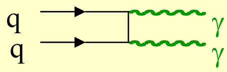


(ii) $H \rightarrow \gamma\gamma$

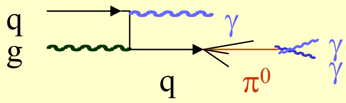


$m_H \leq 150$ GeV

- σ x BR $\approx$ 50 fb (BR $\approx 10^{-3}$)
- Backgrounds : - $\gamma\gamma$ (irreducible): e.g.



$\sigma_{\gamma\gamma} \approx$ 2 pb / GeV
$\Gamma_H \approx$ MeV
} $\rightarrow$ need $\sigma(m)/m \approx 1\%$



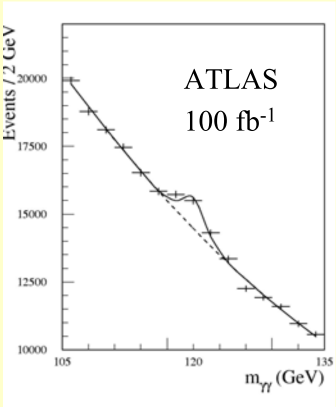
– γj+ jj (reducible):

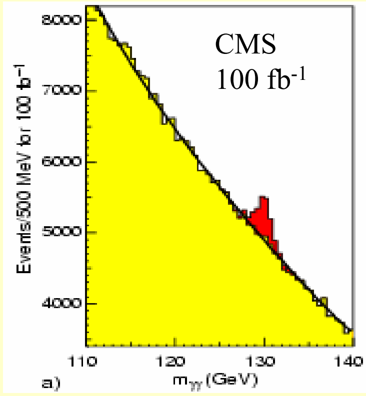
$\sigma_{\gamma j+jj} \sim 10^6\, \sigma_{\gamma\gamma}$ with large uncertainties
$\rightarrow$ need $R_j > 10^3$ for $\varepsilon_\gamma \approx$ 80% to get $\sigma_{\gamma j+jj} << \sigma_{\gamma\gamma}$

$\rightarrow$ most demanding channel for EM calorimeter performance :
energy and angle resolution, acceptance, γ /jet and γ / π^0 separation

ATLAS and CMS: complementary performance

H→ γγ (cont.)





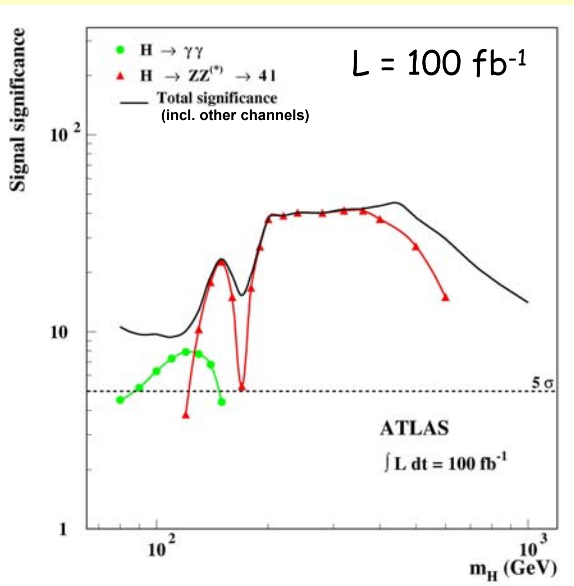
Two isolated photons:
$P_T(\gamma_1)$ > 40 GeV/c
$P_T(\gamma_2)$ > 25 GeV/c
$|\eta|$ < 2.5

Mass resolution: m_H = 100 GeV/c^2

ATLAS : 1.1 GeV/c^2 (LAr-Pb)
CMS : 0.6 GeV/c^2 (crystals)

Signal / background ~ 4% (Sensitivity in mass range 100 – 140 GeV/c^2)
background (dominated by γγ events*⁾ can be determined from side bands
important: γγ-mass resolution in the calorimeters, γ / jet separation

*⁾ detailed simulations indicate that the γ-jet and jet-jet background can be suppressed to the level of 10-20% of the irreducible γγ-background



The full allowed mass range

from the LEP limit (~114 GeV/c^2)
up to
theoretical upper bound of ~1000 GeV/c^2

can be covered using the two “safe” channels

H → ZZ → ℓℓ ℓℓ and
H → γγ

(iii) $H \to WW^{(*)} \to \ell\nu\ \ell\nu$

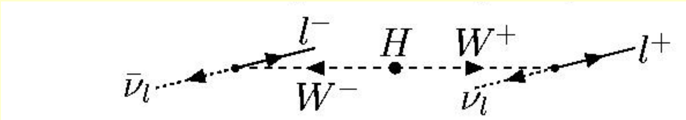
- Branching ratio for $H \to WW$ is nearly 98% for m_H ~ 160 GeV/c^2
  (dip in the $H \to ZZ$ sensitivity)
  BR ($H \to WW \to \ell\nu\ \ell\nu$) / BR ($H \to ZZ \to \ell\ell\ \ell\ell$) ~ 100

- However: neutrinos present in final state, no mass peak can be reconstructed
  → use transverse mass

- Large backgrounds: σ ($t\bar{t} \to WbWb \to \ell\nu\ \ell\nu$ + ...) = 32.9 pb
  σ ($WW \to \ell\nu\ \ell\nu$ + ...) = 4.8 pb

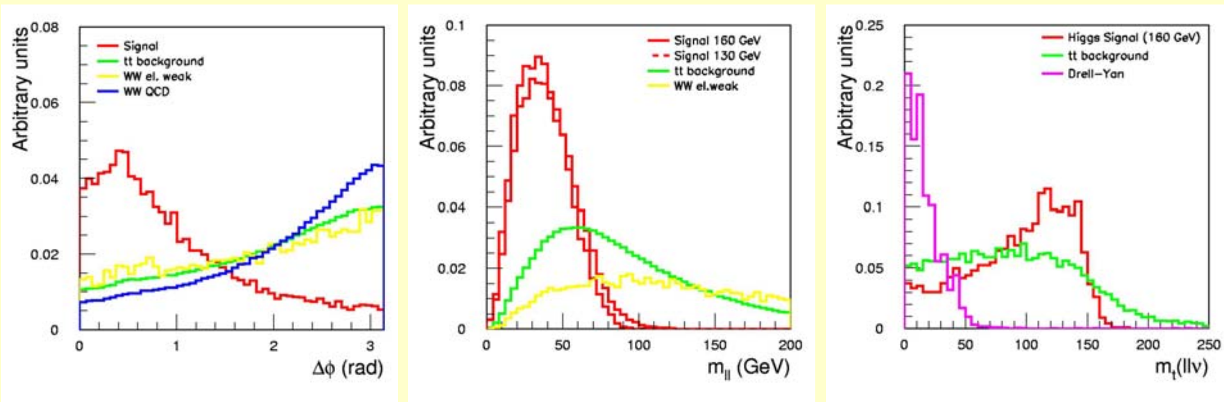
Two main discriminants:

(i) Lepton-lepton angular correlation: expect small angular separation between leptons from Higgs decays



(ii) Jet veto: no jet activity (P_T > 20 GeV/c) in the central detector region ($|\eta|$ < 3.2)

Discrimination between signal and background in $H \to WW \to \ell\nu\ \ell\nu$ using the lepton variables



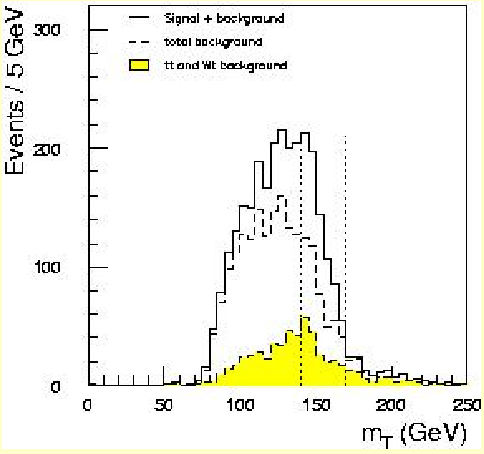
$\Delta\phi$ ($\ell\ell$)

Spin 0 → W W
expect charged leptons to be close by in space

m ($\ell\ell$)

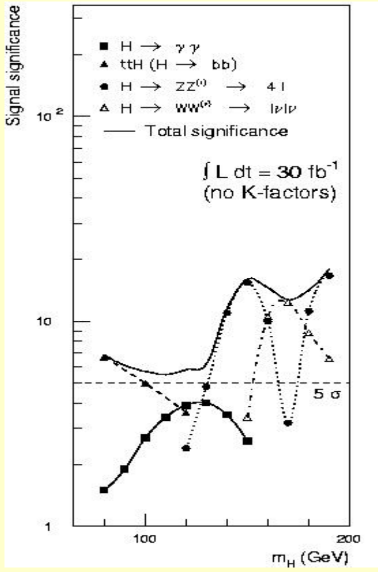
Transverse mass $m_T(\ell\ell\nu)$

reconstructed transverse mass distribution: m_H = 170 GeV/c^2, L = 30 fb^{-1}



- Signal and background shapes are similar
- Background (size and shape) need to be precisely known (for high signal significance)

Sensitivity including H → WW



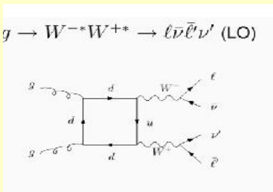
ATLAS experiment: no K-factors, L = 30 fb^{-1}, 5% syst. uncertainty on the background

---

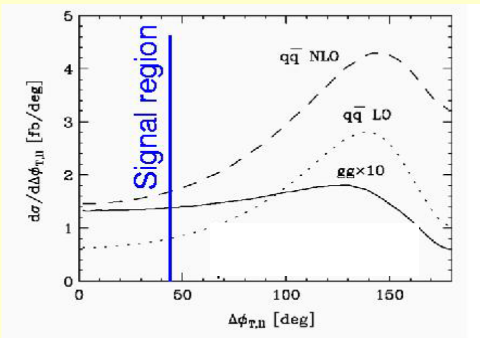
new

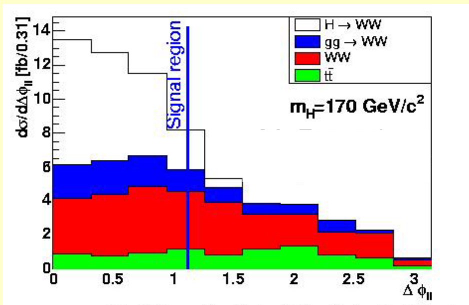
more work on the backgrounds.....

Main theoretical challenge: - need to know the shape of the WW background
- need to know the contributions from higher orders
e.g., gg → WW



σ(gg → WW): only 5% of σ(WW) before cuts,
but ~ 30% of σ(WW) after cuts

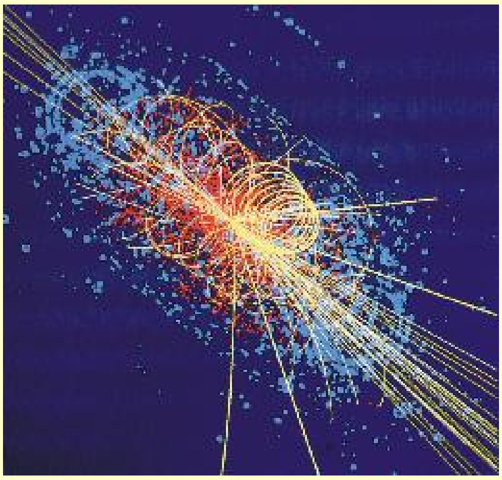




WW measurements at the Tevatron are important, but gg contribution too small;

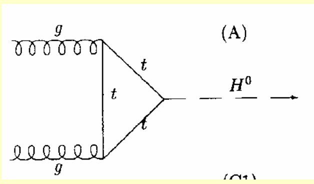
Higgs Boson Searches at Hadron Colliders

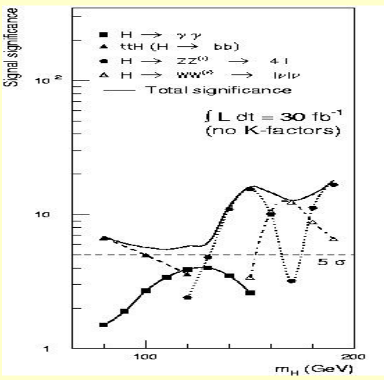
Lecture 2

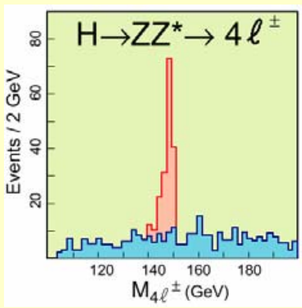


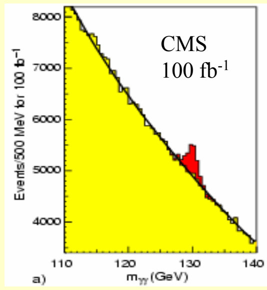
- **Search for the SM Higgs boson at the LHC (cont.)**
- **Status and perspectives at the Tevatron**
- **Measurement of Higgs boson parameters**
  (mass, spin, couplings, self-coupling)

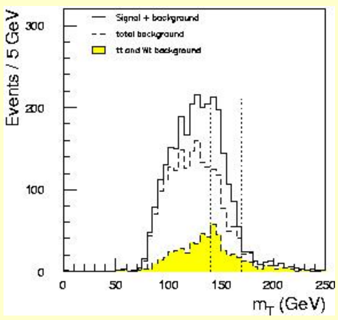
Gluon fusion









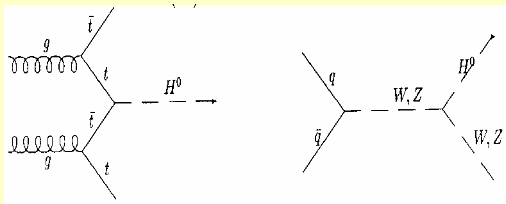


- Higgs boson can be discovered over the full mass range with 30 fb^{-1}
- What about the other production modes ?

Higgs boson search in the

associated production

modes



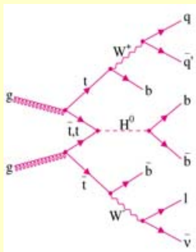
require leptons from W/Z or top decays
→ Trigger, suppression of background from QCD jet production

→ H → bb decay mode becomes accessible
tt H → ℓνb qqb bb
W H → ℓν bb (not a „discovery channel“ at the LHC)

- very challenging at the LHC !!
- large tt, ttj, ttjj, ttbb,..... Wqq, Wqqq,..... backgrounds
- high performing b-tagging is absolutely necessary

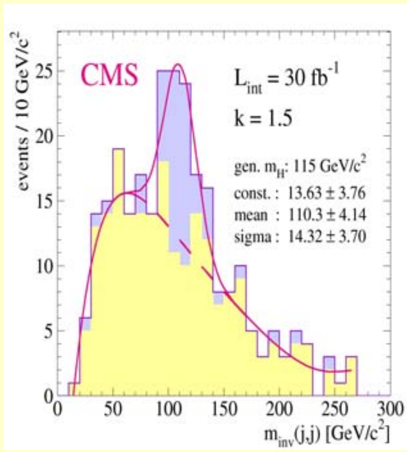
$t\bar{t}\,H \rightarrow t\bar{t}\,b\bar{b}$

σ x BR ≈ 300 fb
Complex final state: H→bb , t → bjj, t → bℓν



• Main backgrounds:
  - combinatorial from signal (4b in final state)
  - Wjjjjj, WWbbjj, etc.
  - ttjj (dominant, non-resonant)

• b-tagging performance is crucial
  ATLAS results for 2D-b-tag from full simulation
  (ε_b =60% R_j (uds)~ 100 at low L)



S = 38 events
B = 52 events
S/B ~ 0.73

S/ √B = 3.5
for K = 1.0

• Shape of background must be known;
  60% (from ttbb) can be measured from ttjj using anti-b tag
• LHC experiments need a better understanding of the signal and the backgrounds (K-factors for backgrounds)

new

and finally, a new channel: W/Z H + ttH $\rightarrow$ $\gamma\gamma$ + E_T^{miss}
use H $\rightarrow$ $\gamma\gamma$ decay mode again

$\gamma\gamma$ signature: background suppression, trigger, good mass resolution

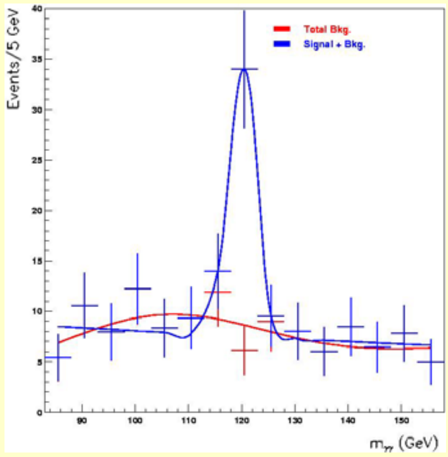
E_T^{miss} signature: additional background suppression
E_T^{miss} from $W \rightarrow \ell\nu$, $Z \rightarrow \nu\nu$ or $t \rightarrow \ell\nu b$ decays

Recent study:

- ATLAS fast simulation
- γ selection as for inclusive case
- E_T^{miss} > 65 GeV

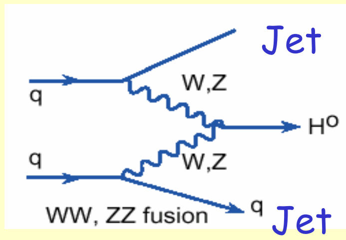
- For 100 fb^{-1}: expect

20.9 signal events (mass peak)
5.4 background (flat)



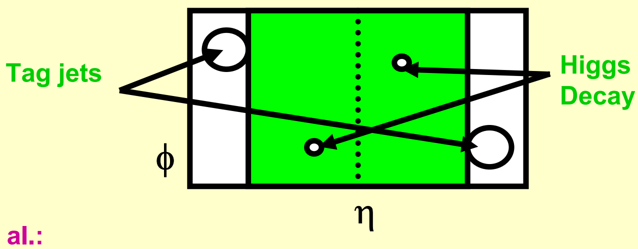
Higgs boson search in

vector boson fusion



Distinctive Signature of:

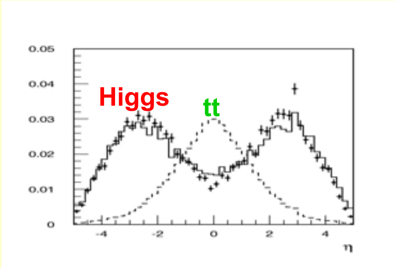
- **two high P_T forward jets ("tag jets")**
- **little jet activity in the central region**
  $\Rightarrow$ central jet Veto
- **leptons from Higgs decay products (WW,$\tau\tau$,...)**



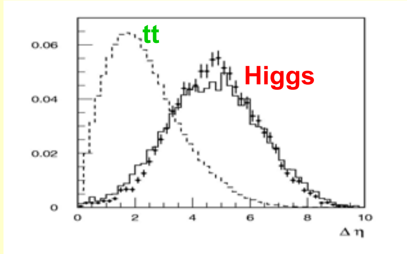
proposed by D.Rainwater and D.Zeppenfeld et al.:
(hep-ph/9712271, hep-ph/9808468 and hep-ph/9906218)

Forward jet tagging

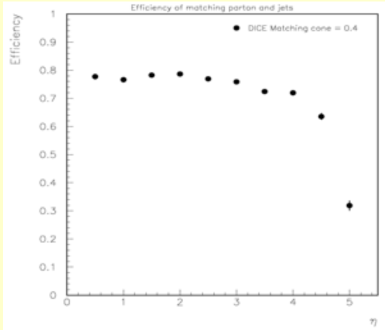
Rapidity distribution of tag jets
VBF Higgs events vs. tt background



Rapidity separation



Forward tag jet reconstruction has been studied in full simulation in ATLAS and CMS



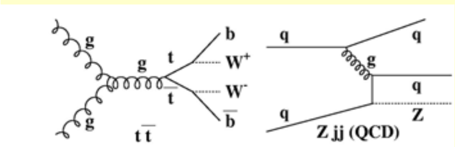
ATLAS results:
kin. eff. for tag jets = 51.9%
(P_T > 40/20 GeV/c, $\Delta\eta > 3.6$)

tag eff. per jet: around 75%

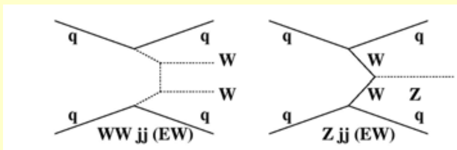
qq H → qq WW* → qq ℓν ℓν

Background:

QCD backgrounds:
tt production Z + 2 jets

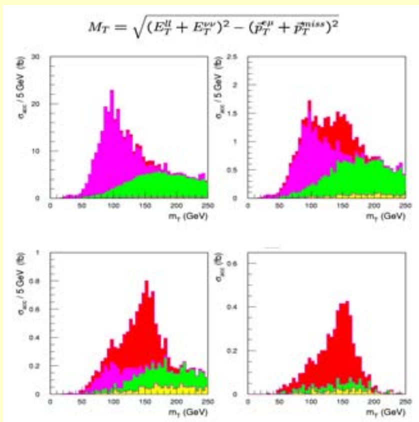


el.weak background:
WW jj production Z + 2 jets



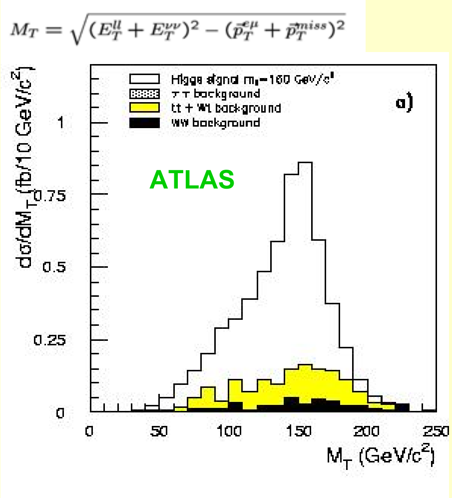
Background rejection:

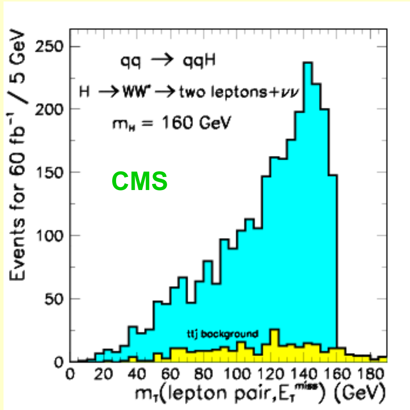
- Lepton P_T cuts and tag jet requirements ($\Delta\eta$, P_T)
- Require large mass of tag jet system
- Jet veto (important)
- Lepton angular and mass cuts



Higgs boson (m_H = 160 GeV)
tt background
γ* / Z + jets
el.weak WW jj

qq H → qq W W*
→ qq ℓν ℓν





Transverse mass distributions: clear excess of events above the background from tt-production

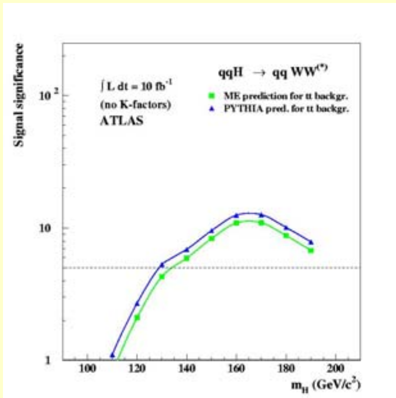
However: background shape is similar to signal ?? robustness of signal ?

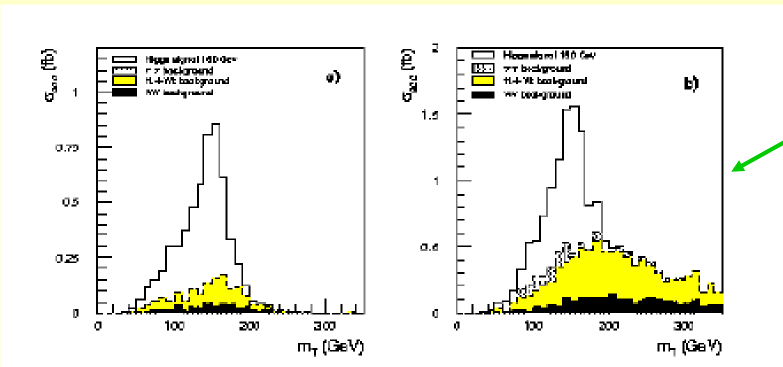
How reliable is this signal ?

- Factor of two uncertainty found on the tt background calculation (PYTHIA vs. ttj + ttjj matrix element calculation, issue of parton shower matching)
  ATLAS-SN-2003-024, Les Houches (2005)

  However: large (S : B) ratio,
  discovery significance is stable

- Cuts can be relaxed, to get background shape from the data:



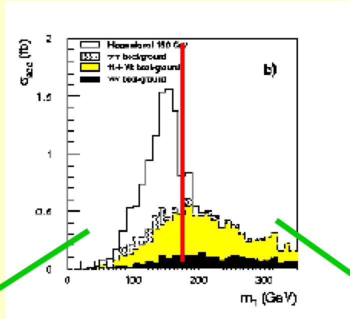


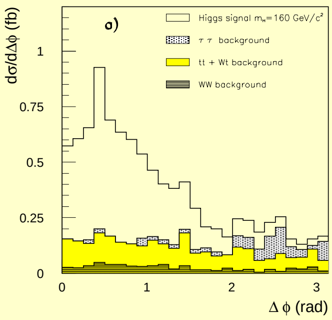
No kinematical cuts on leptons applied: (ATLAS study)

Presence of a signal can also be demonstrated in the $\Delta\phi$ distribution
(i.e. azimuthal difference between the two leptons)

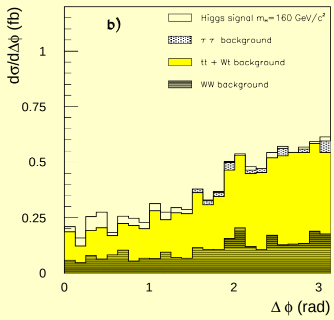
Evidence for spin-0 of the Higgs boson

Spin-0 → WW → $\ell\nu\ell\nu$ expect leptons to be close by in space





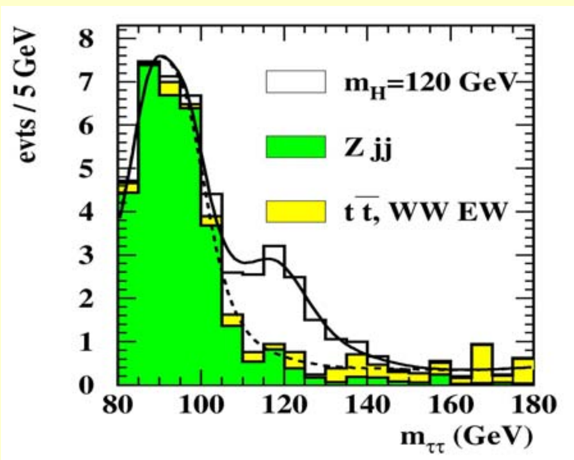
signal region



background region

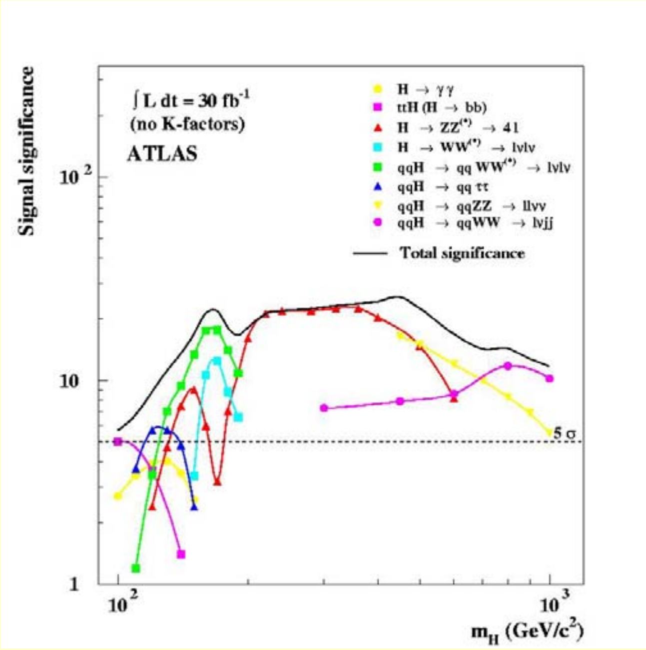
$H \rightarrow \tau\tau$ decay modes visible for a SM Higgs boson in vector boson fusion (not visible in gluon fusion mode)

qq H → qq τ τ
→ qq ℓνν ℓνν
→ qq ℓνν hν



- large boost (high-P_T Higgs)
  - → collinear approximation: assume neutrinos go in the direction of the visible decay products
  - → Higgs mass can be reconstructed
- main background: Z jj, $Z \rightarrow \tau\tau$

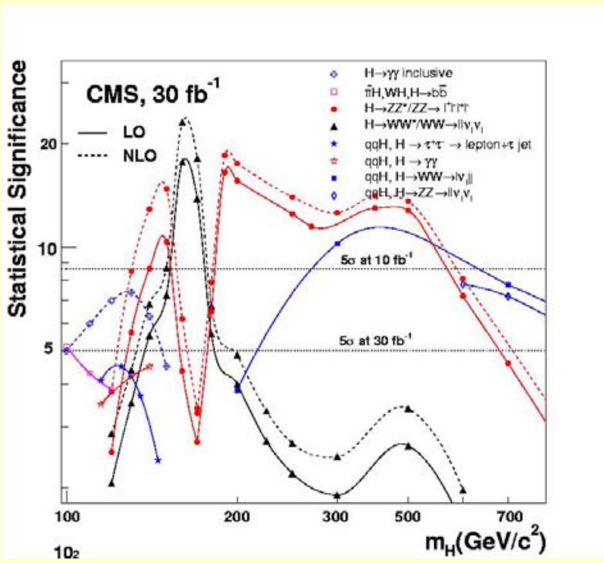
ATLAS Higgs discovery potential for 30 fb^{-1}



- Full mass range can already be covered after a few years at low luminosity
- Several channels available over a large range of masses

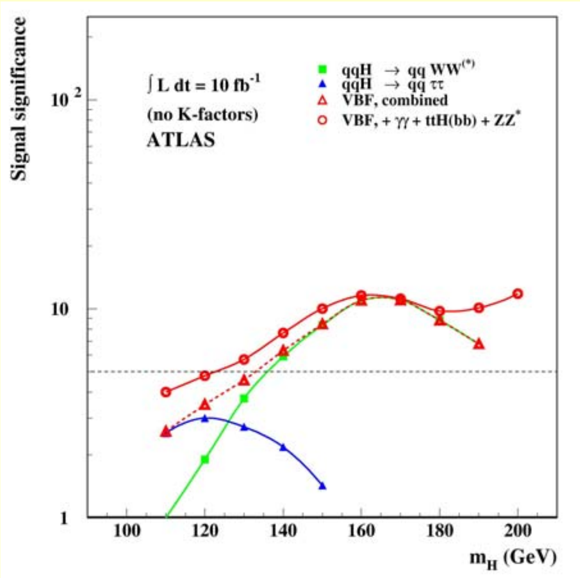
Vector boson fusion channels play an important role at low mass !

Comparable situation for the CMS experiment



Effects of NLO contributions are shown for several channels

Combined significance of VBF channels for 10 fb^{-1}



For 10 fb^{-1} in ATLAS
(1 year -after t_0- at low luminosity):

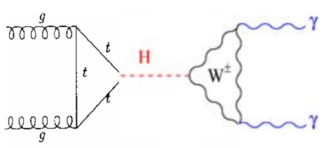
5 σ significance for
$120 \leq m_H \leq 190$ GeV/c^2

Remarks for a light Higgs with m_H < 120 GeV/c^2 and 10 fb^{-1}:

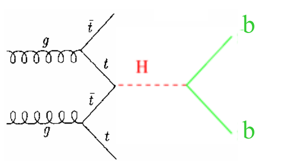
Three channels with ~ 2-3 σ each → observation of all channels important to extract convincing signal in first year(s)

The 3 channels are complementary → robustness:

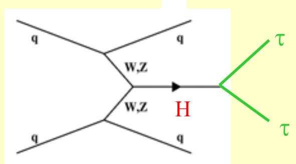
$H \to \gamma\gamma$



$ttH \to tt\ bb \to b\ell\nu\ bjj\ bb$



$qqH \to qq\tau\tau$



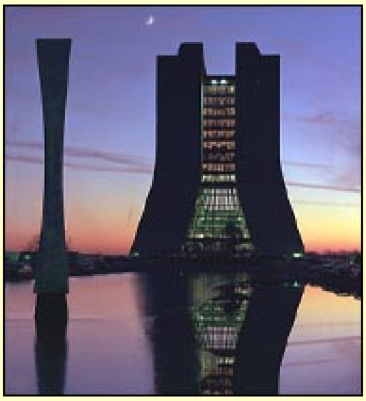
- different production and decay modes
- different backgrounds
- different detector/performance requirements:
  - -- ECAL crucial for $H \to \gamma\gamma$ (σ/m ~ 1% needed)
  - -- b-tagging is crucial for ttH : (4 b-tagged jets needed to reduce combinatorics)
  - -- efficient jet reconstruction over $|\eta| < 5$ crucial for qq H → qq ττ

Note : -- all require "low" trigger thresholds

e.g. ttH analysis cuts : p_T (ℓ) > 20 GeV, p_T (jets) > 15-30 GeV

-- ttH requires very good understanding (5 -10%) of the backgrounds

The Search for the



Standard Model Higgs Boson

at Fermilab

Search channels at the Tevatron

- important production modes: associated WH and ZH
  gluon fusion with $H \rightarrow WW \rightarrow \ell\nu\ \ell\nu$
- hopeless: gluon fusion in $H \rightarrow \gamma\gamma$, 4 ℓ (rate limited)
  σ BR ($H \rightarrow ZZ \rightarrow 4\ \ell$) = 0.07 fb ($M_H$=150 GeV/$c^2$)

Mass range 110 - 130 GeV:	LHC
WH $\rightarrow$ lν bb	(✓) weak
ZH $\rightarrow$ l^+l^- bb	weak
ZH $\rightarrow$ νν bb	∅ (trigger)
ZH $\rightarrow$ bb bb	∅ (trigger)
ttH $\rightarrow$ lν b jjb bb	✓

Triggering:
is easier at the Tevatron:
- better E_T^{miss}-resolution
- track trigger at Level-1

Mass range 150 - 180 GeV:	LHC
H $\rightarrow$ WW$^{(*)}$ $\rightarrow$ lν lν	✓
WH $\rightarrow$ WWW$^{(*)}$ $\rightarrow$ lν lν lν	✓
WH $\rightarrow$ WWW$^{(*)}$ $\rightarrow$ l^+ν l^+ν jj	✓

Background:
electroweak production:
~10 x larger at the LHC
QCD production (e.g, tt):
~ 100 x larger at the LHC

Detector acceptance: larger at Fermilab (central production)

Signal and background ratios after detector acceptance:

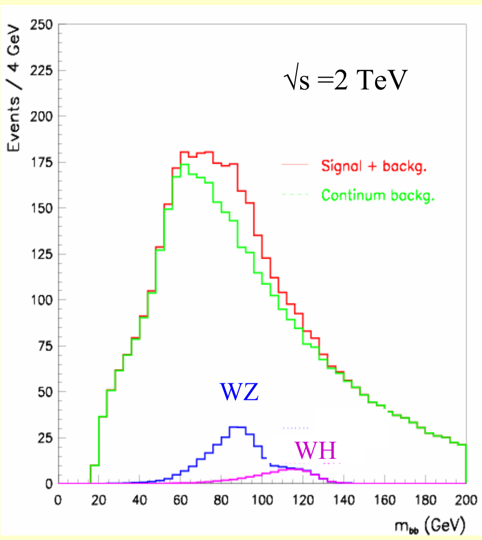
	low mass	high mass
	$WH \to \ell\nu\ b\bar{b}$ $ZH \to \ell\ell\ b\bar{b}$	$H \to WW^{(*)} \to \ell\nu\ \ell\nu$ (M_H = 160 GeV/c^2)
S (14 TeV) / S (2 TeV)	≈ 5	≈ 30
B (14 TeV) / B (2 TeV)	≈ 25	≈ 6
S/B (14 TeV) / S/B (2 TeV)	≈ 0.2	≈ 5
S/√B (14 TeV) / S/√B (2 TeV)	≈ 1	≈ 10

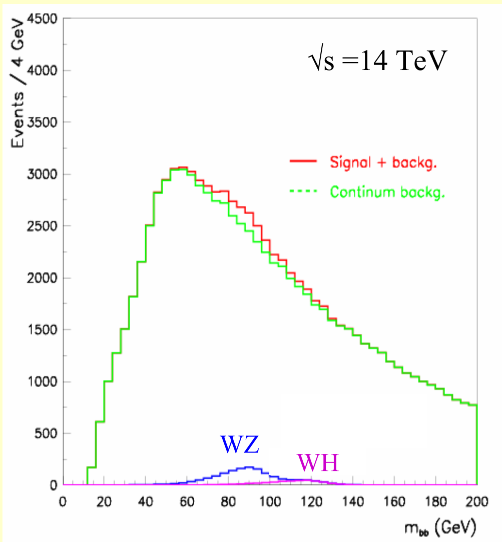
→ - comparable discovery potential for WH and ZH:
  - larger signal at the LHC
  - better S/B-ratio at theTevatron
  - difficult at both colliders

- significantly better LHC potential for $H \to WW^{(*)} \to \ell\nu\ \ell\nu$

WH Signals at the LHC and the Tevatron

M_H = 120 GeV, 30 fb^{-1}

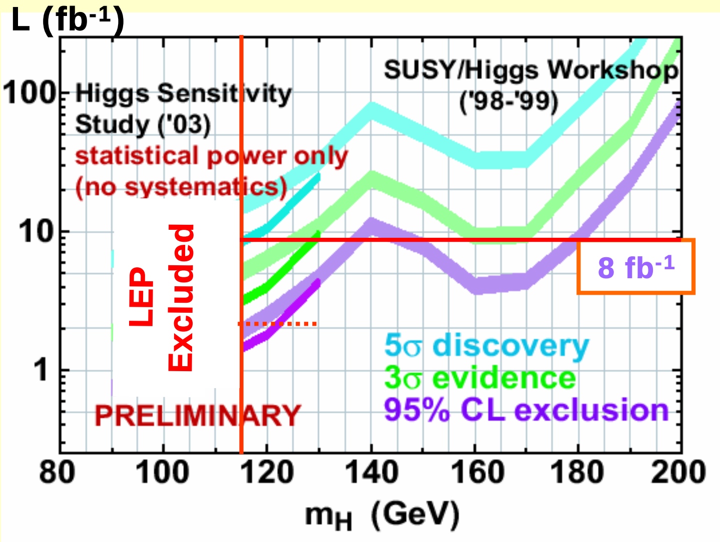




most important: control of the background shapes !!

Tevatron discovery potential for a light Higgs Boson

combination of both experiments and all channels
(discovery in a single channel not possible)



For 8 fb^{-1} :

(i) 95% CL exclusion of a SM Higgs boson is possible up to 135 GeV/c^2 and for 150 – 180 GeV/c^2

(ii) 3-σ evidence for M_H < 130 GeV/c^2

(iii) Sensitivity at low mass starts with an int. luminosity of 2 fb^{-1} (end 2006)

Results from the

present

Run II data

typically, data corresponding to 300 – 350 pb^{-1} analyzed

Low Mass: WH → e/μ ν bb

Data sample: 320 pb^{-1}

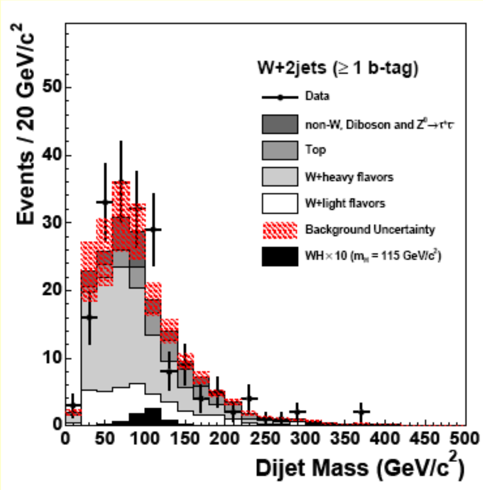
Event selection:

- 1 high P_T central e or μ
- P_T^{miss} > 20 GeV/c
- 2 jets, at least 1 b-tagged
- veto events with > 1 lepton

Backgrounds:

- Wbb, Wcc, Wjj (mistags)
- WW, WZ, ZZ, Z→ ττ
- tt, single top
- QCD multijet

for details, see: hep-ex / 0512051

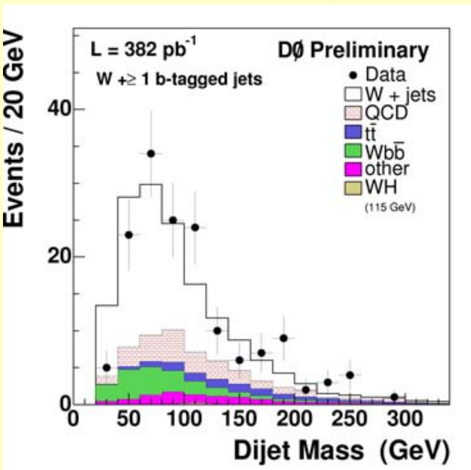


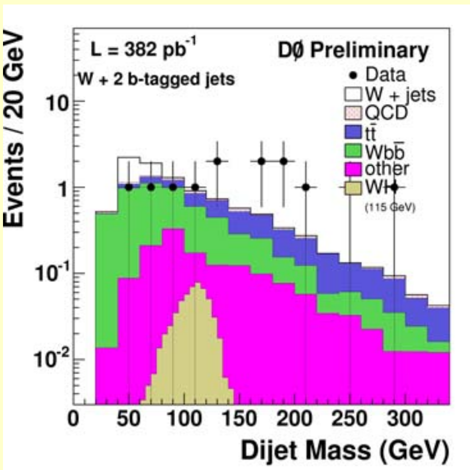
Number of tags:	$\geq$ 1 tags	$\geq$ 2 tags
False tags	39.3 ± 3.1	1.0 ± 0.1
$Wb\bar{b}$	54.0 ± 18.4	8.0 ± 3.0
$Wc\bar{c}$	19.5 ± 6.6	0.4 ± 0.2
Wc	16.8 ± 4.3	$0.0^{+0.1}_{-0.1}$
Diboson/$Z \to \tau^+\tau^-$	5.0 ± 1.1	0.3 ± 0.1
non-W	16.5 ± 3.2	0.4 ± 0.1
Single top	9.6 ± 2.0	1.3 ± 0.3
$t\bar{t}$	14.6 ± 2.5	3.1 ± 0.5
Total background	175 ± 26	15 ± 3
Observed positive tagged events	187	14

Low Mass: WH → eν bb

Data sample: 382 pb^{-1}

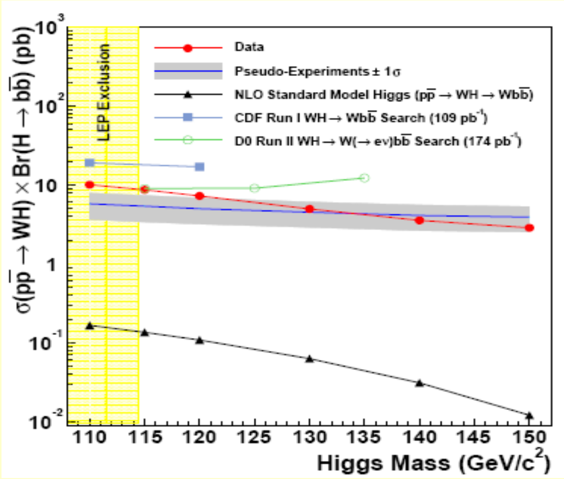
Event selection: 1 e, (|η| < 1.1, E_T>20 GeV), E_T^{miss} > 20 GeV, 2 jets (E_T > 20 GeV) add b-tags

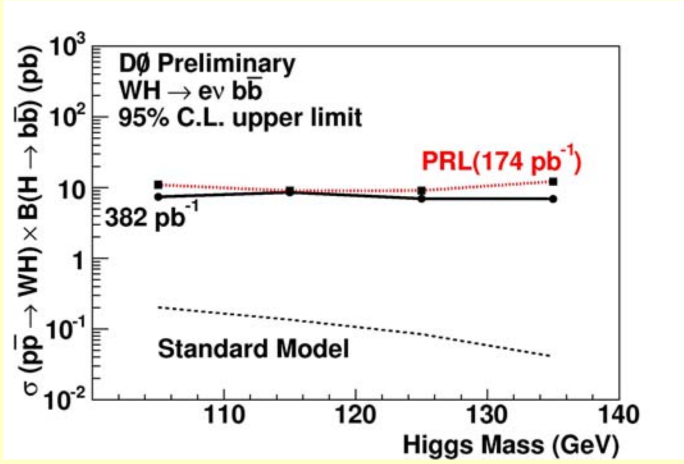




Data:	**153 events**	**13 events**
Tot. expectation	**153.6**	**10.2**
Wbb:	18.1	4.29
WH:	0.4	0.14
Backgrounds:	135.5	5.73

Low mass: WH cross section limits:



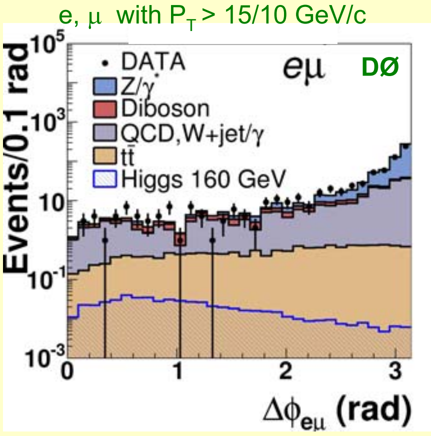


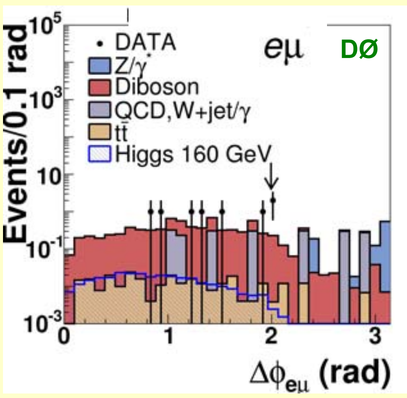
High mass: $H \to WW \to \ell\nu\ \ell\nu$

- Analyses have been performed by both CDF and DØ
- based on data corresponding to an int. luminosity of ~ 350 pb^{-1}

Search for $\ell\ell$ + P_T^{miss} events (ℓ = e, μ)

e, μ with P_T > 15/10 GeV/c



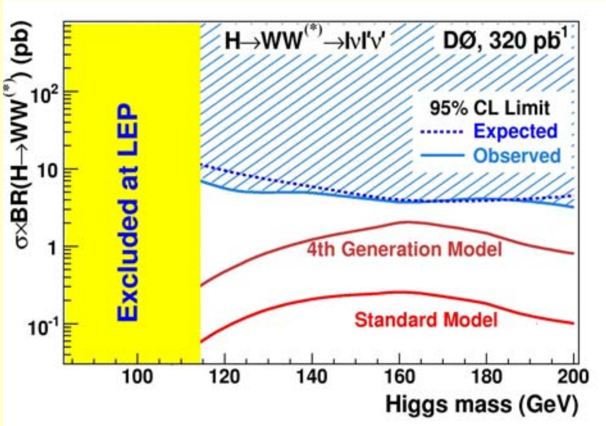


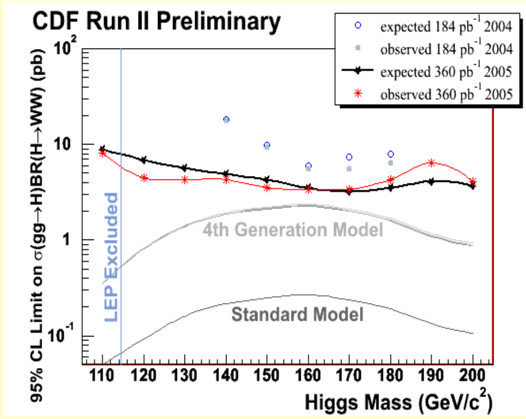
additional cuts:

E_T^{miss} > 20 GeV
$M(\ell\ell) < m_H/2$
$M_T(\ell\ell E_T^{miss}) < m_H - 10$ GeV

Data are consistent with expectations from SM backgrounds

Limits on H $\rightarrow$ WW $\rightarrow$ ℓν ℓν cross sections



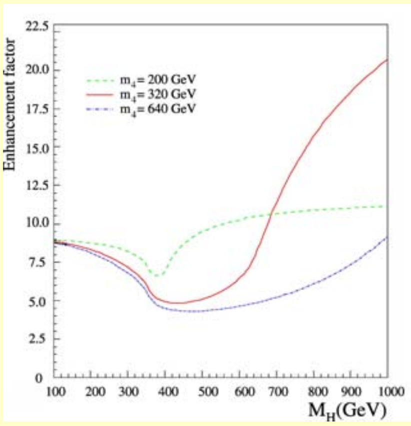


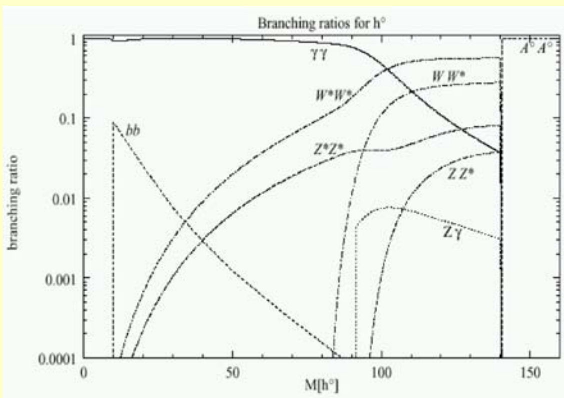
Larger Higgs boson cross sections in exotic models

Higgs boson production rates can be enhanced in Exotic Models:

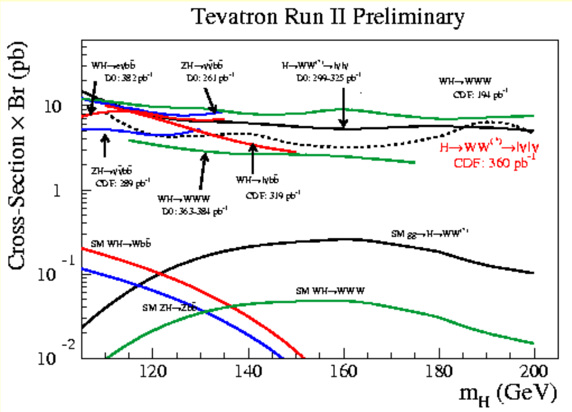
* 4th SM family enhance Higgs cross sections by a factor of ~8.5 for a Higgs boson mass between 100-200 GeV

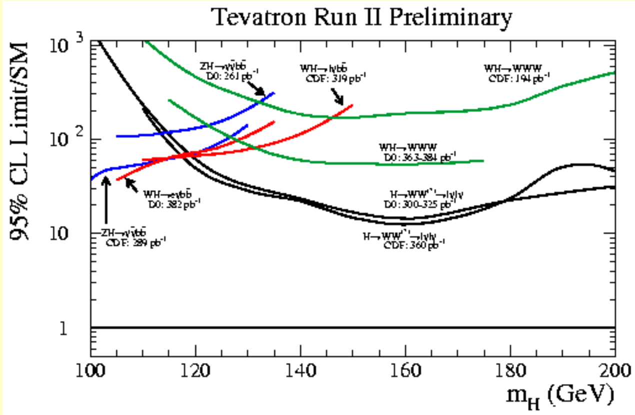
* Fermiophobic Higgs: BR (H $\rightarrow$ V V) >98% for $m_H \geq$ 100 GeV





Summary of current results from CDF and DØ





Combination of current analyses (CDF + DØ): for ~300 – 350 pb^{-1}

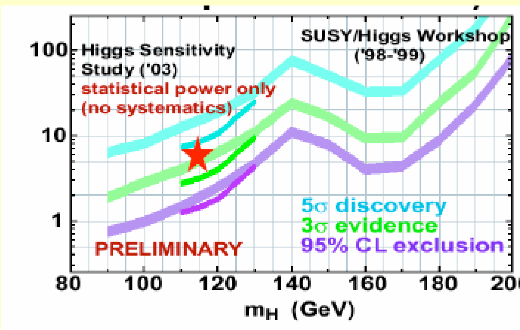
- upper limit about ~ 14 times larger than SM prediction at 115 GeV/c^2
- for L = 2 fb^{-1}: → gain = √ L / 0.3 → still a factor 5 missing

- Are the estimates from 1999 / 2003 credible ?
  Can the missing factors be gained ??

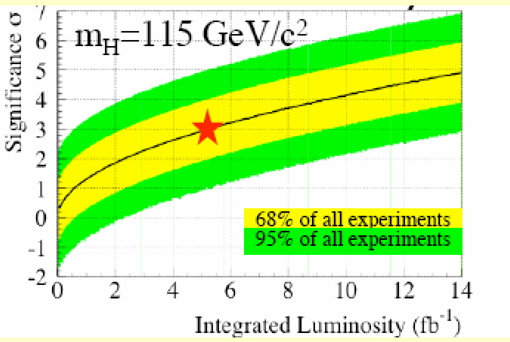
Anticipated improvements: (B. Heinemann, P5-meeting, Fermilab Sep. 05)

- increase acceptance (forward leptons, forward b-tagging)
- improvements in b-tagging (neural network)
- improvements in selection efficiencies (track-only leptons, neural networks)
- improved di-jet mass resolution
- ....

based on pre-RunII analyses



based on RunII analyses



95% CL exclusion: 2 – 2.5 fb^{-1}: 115 GeV/c^2
4 fb^{-1}: 130 GeV/c^2
8 fb^{-1}: 135 GeV/c^2

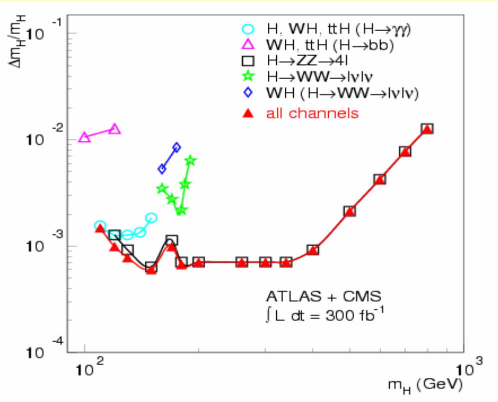
3 σ evidence: ★ 5 fb^{-1}: 115 GeV/c^2

improvements not demonstrated yet, no guarantee, but there is a chance.......

Determination of Higgs Boson Parameters

1. **Mass**
2. **Couplings to bosons and fermions**
3. **Spin**
4. **Higgs self coupling**

Measurement of the Higgs boson mass



Dominated by 4ℓ and γγ channels (mass peak, good mass resolution)

Dominant systematic uncertainty: γ / ℓ E scale.
Assumed 1‰
Goal 0.2‰
Scale from $Z \to \ell\ell$ (close to light Higgs)

Higgs boson mass can be measured with a precision of 0.1% over a large mass range (130 - ~450 GeV / c^2)

Note: no theoretical error, e.g. mass shift for large Γ_H (interference resonant/non-resonant production) taken into account

Measurement of the Higgs boson couplings

For a given Higgs boson mass: use the full information available,
i.e. rates in various production modes
→ **global fit**

Production mode	Decay mode	Mass range (GeV/c²)
Gluon fusion	$H \to ZZ^{(*)} \to \ell\ell\,\ell\ell$	110 200
	$H \to WW^{(*)} \to \ell\nu\,\ell\nu$	110 200
	$H \to \gamma\gamma$	110 150
Vector boson fusion	$H \to ZZ^{(*)} \to \ell\ell\,\ell\ell$	110 200
	$H \to WW^{(*)} \to \ell\nu\,\ell\nu$	110 190
	$H \to \tau\tau \to \ell\nu\nu\,\ell\nu\nu$	110 150
	$H \to \tau\tau \to \ell\nu\nu\ had\ \nu$	110 150
	$H \to \gamma\gamma$	110 150
$t\bar{t}$ H production	$H \to WW^{(*)} \to \ell\nu\,\ell\nu\,(\ell\nu)$	120 200
	$H \to b\bar{b}$	110 140
	$H \to \gamma\gamma$	110 120
WH production	$H \to WW^{(*)} \to \ell\nu\,\ell\nu\,(\ell\nu)$	150 190
	$H \to \gamma\gamma$	110 120
ZH production	$H \to \gamma\gamma$	110 120

Production cross sections:

$$\sigma_{ggH} = \alpha_{ggH} \bullet g_t^2$$
$$\sigma_{VBF} = \alpha_{WF} \bullet g_w^2 + \alpha_{ZF} \bullet g_Z^2$$
$$\sigma_{ttH} = \alpha_{ttH} \bullet g_t^2$$
$$\sigma_{WH} = \alpha_{WH} \bullet g_W^2$$
$$\sigma_{ZH} = \alpha_{ZH} \bullet g_Z^2$$

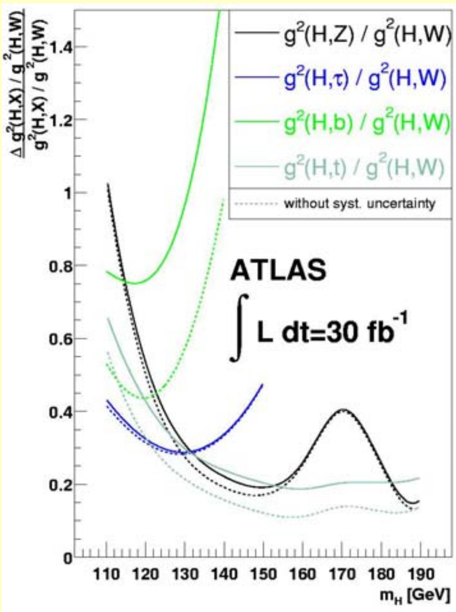
α from theory with assumed uncertainty $\Delta\alpha$

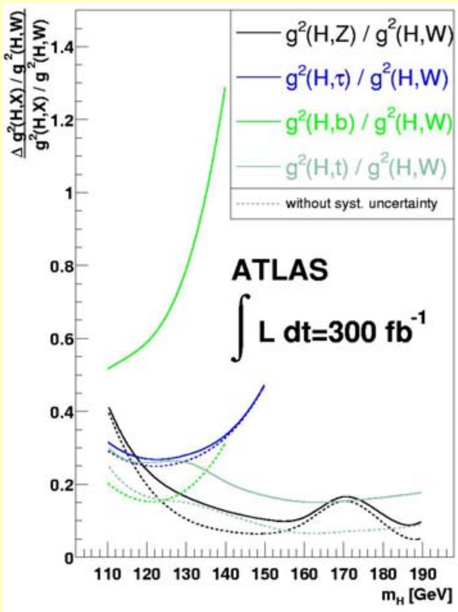
$$\Delta\alpha_{ggH} = 20\%$$
$$\Delta\alpha_{WF} = \alpha_{ZF} = 4\%$$
$$\Delta\alpha_{ttH} = 15\%$$
$$\Delta\alpha_{WH} = \Delta\alpha_{ZH} = 7\%$$

Fit parameters:

$$\frac{g_Z^2}{g_W^2} \quad \frac{g_\tau^2}{g_W^2} \quad \frac{g_b^2}{g_W^2} \quad \frac{g_t^2}{g_W^2}$$

Measurement of Higgs Boson Couplings

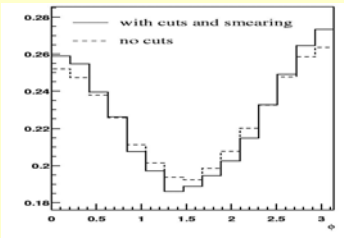


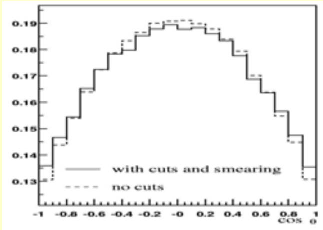


Relative couplings can be measured with a precision of 10-20% (for 300 fb^{-1})

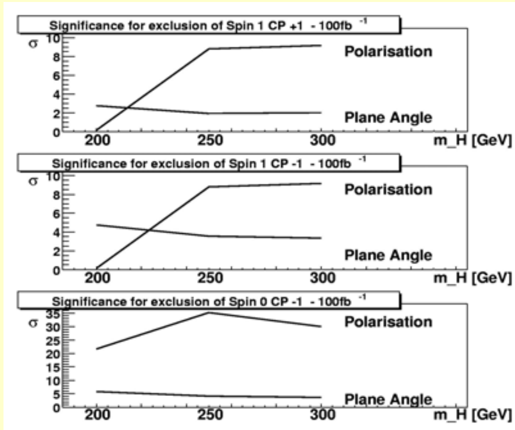
Higgs Boson spin ?

- Angular distributions in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4\ \ell$ are sensitive to spin and CP eigenvalue
- azimuthal angle ϕ, defined as angle between the decay planes of the two Z-bosons in the restframe of the Higgs
- polar angle θ, defined as angle of neg. charged lepton in the restframe of the Z to the direction of motion of the Z in the restframe of the Higgs



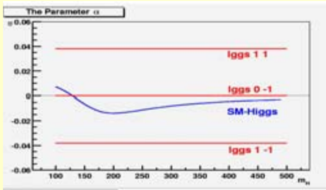


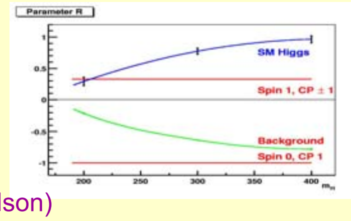
Expected results:



Fit to $F(\phi) = \alpha \cos(\phi) + \beta \cos(2\phi)$

$F(\theta) = T\,(1+\cos^2\theta) + L \sin^2\theta \qquad R = (L-T)/(L+T)$



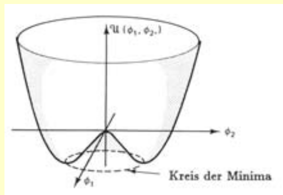


(J.R. Dell´Aquila, C.A. Nelson)

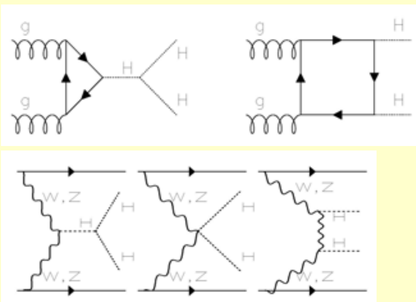
Higgs Bosons Self-coupling ?

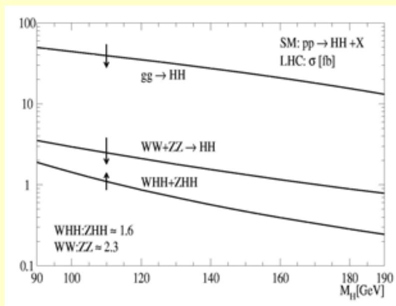
to establish the Higgs mechanism the Higgs boson self-coupling has to be measured:

$$\lambda_{HHH}^{SM} = 3\,\frac{m_H^2}{v}\ , \qquad \lambda_{HHHH}^{SM} = 3\,\frac{m_H^2}{v^2}$$



Cross sections for HH production:





small signal cross sections, large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

$\Rightarrow$ no significant measurement possible at the LHC

need Super LHC $L = 10^{35}\ cm^{-2}\ sec^{-1}$, 6000 fb^{-1}

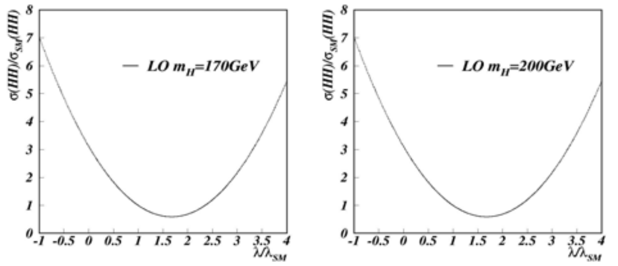
Most sensitive channel: **$gg \to HH \to WW\,WW \to \ell\nu\, jj\;\; \ell\nu\, jj$**

- accessible in mass range 160 GeV - 200 GeV
- bb-decay mode at lower masses is hopeless

Selection:

- 2 isolated, high P_T, like sign leptons (from different Higgs bosons)
- 4 high P_T jets, compatible with W-mass

m_H	Signal	$t\bar{t}$	$W^{\pm}Z$	$W^{\pm}W^{+}W^{-}$	$t\bar{t}W^{\pm}$	$t\bar{t}t\bar{t}$	$S/\sqrt{B}$
170 GeV	350	90	60	2400	1600	30	5.4
200 GeV	220	90	60	1500	1600	30	3.8



6000 fb $^{-1}$ $\Rightarrow$ $\Delta\lambda_{HHH} / \lambda_{HHH}$ = 19 % (stat.) (for m_H = 170 GeV)
$\Delta\lambda_{HHH} / \lambda_{HHH}$ = 25 % (stat.) (for m_H = 200 GeV)

Higgs Boson Searches at Hadron Colliders

Lecture 3

Higgs Bosons

in Supersymmetry

The Higgs Sector in the MSSM

Two Higgs doublets: 5 Higgs particles **H, h, A** **H^+, H^-**

determined by two parameters: m_A, $\tan\beta$

fixed mass relations at tree level:
(Higgs self coupling in MSSM fixed by gauge couplings)

$$m^2_{H,h} = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2+m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta}\right)$$

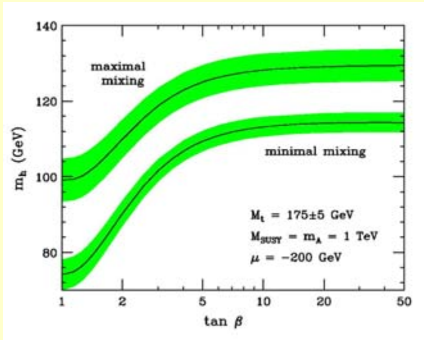
$$m_h^2 \le m_Z^2 \cos^2 2\beta \le m_Z^2$$

Important radiative corrections !! (tree level relations are significantly modified)

→ upper mass bound depends on top mass and mixing in the stop sector

$$m_h^2 \le m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + x_t^2\left(1-\frac{x_t^2}{12}\right)\right]$$

where: $M_S^2 = \frac{1}{2}\left(M_{\tilde{t}_1}^2 + M_{\tilde{t}_2}^2\right)$ and $x_t = (A_t - \mu\cot\beta)\ /\ M_S$



→ m_h < 115 GeV for no mixing

→ m_h < 135 GeV for maximal mixing

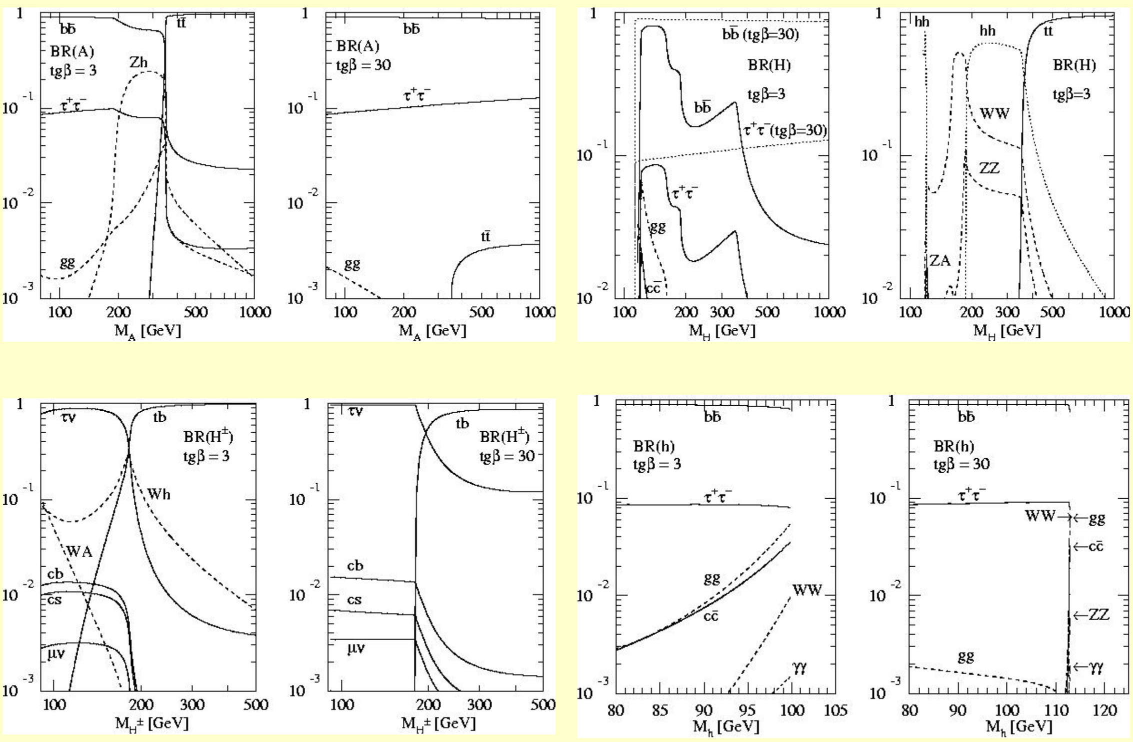
i.e., no mixing scenario: in LEP reach

max. mixing: easier to address at the LHC

Branching ratios of MSSM Higgs bosons

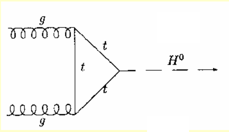
A *H*

H±



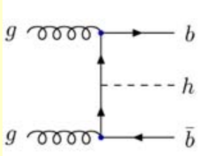
Production of MSSM Higgs bosons

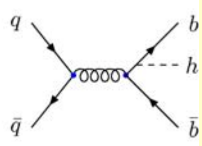
At large tan β: enhanced couplings of Higgs bosons H and A to down-type fermions
$\rightarrow$ important production processes:



gg $\rightarrow$ bb H/A
qq $\rightarrow$ bb H/A

gg $\rightarrow$ H/A
(**b**, t quarks and **SUSY-particles** in loop)





Cross section calculation:*)
- associated bbH production becomes dominant process
- NLO calculations are available

  two approaches –long discussions among theorists-
  - four flavour scheme (bb from gluon splitting) K ~ 1.3 – 1.5 (Tevatron – LHC)
  - five flavour scheme (use b-quark parton distributions, bb $\rightarrow$h, gb $\rightarrow$ bh)
- Finally: reasonable agreement (within respective scale uncertainties) between the NLO four-** and the NNLO five-flavour*** calculation is found for the inclusive (no b-tags) cross section.

*) For a review, see: J. Campbell et al. Proc. Les Houches 2003, hep-ph/0405302.
**) S. Dittmaier, M. Krämer and M. Spira, Phys. Rev. D70 (2004) 074010; S. Dawson et al., Phys. Rev. D69 (2004) 0740027.
***) D. Dicus,T.Stelzer, Z. Sullivan and S. Willenbrock, Phys. Rev. D59 (1999) 094016; R. Harlander and W.B. Kilgore Phys. Rev. D68 (2003) 013001.

MSSM benchmark scenarios

Masses and couplings of the Higgs bosons depend –in addition to tanβ and m_A- on the SUSY parameters through radiative corrections

Most relevant parameters: A_t = trilinear coupling in the stop sector ($X_t = A_t - \mu \cot \beta$)
μ = Higgs mass parameter
M_2 = gaugino mass term (M_1 from gauge unification)
m_g = gluino mass
m_{SUSY} = common scalar mass

m_h-max: SUSY parameters chosen such that max mass value for h achieved;
No mixing: vanishing mixing in the stop sector, $X_t = 0$;
Gluophobic: coupling to gluons strongly suppressed, large stop mixing, cancellation between top-quark and stop loop contributions;
Small α: effective mixing angle between CP-even Higgs bosons is small, reduced BR into bb and $\tau\tau$ for large tanβ and intermediate values of m_A.

M. Carena, S. Heinemeyer, C.E.Wagner, G. Weiglein, Eur.Phys. J. C26 (2003) 601.

	m_{SUSY} (GeV/c^2)	μ (GeV/c^2)	M_2 (GeV/c^2)	X_t (GeV/c^2)	m_g (GeV/c^2)
m_h-max	1000	200	200	2000	800
No mixing	1000	200	200	0	800
Gluophobic	350	300	300	−750	500
Small α	800	2000	500	−1100	500

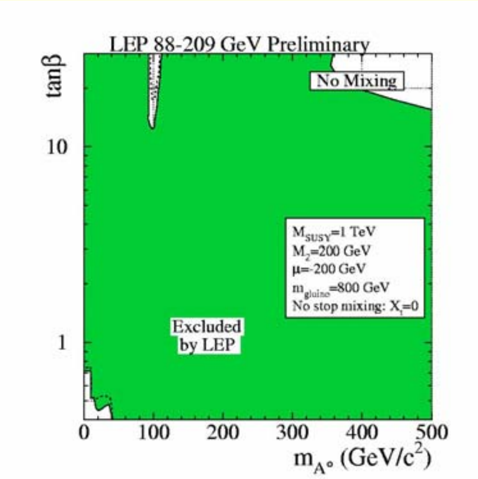
LEP results for the no-mixing scenario:

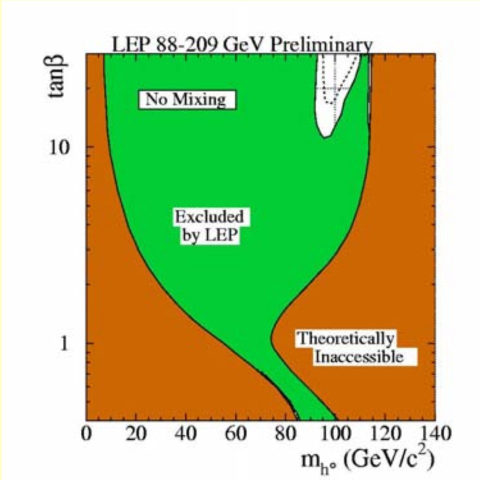
Search for $e^+e^- \rightarrow h\,A \rightarrow bb\;bb$ and $e^+e^- \rightarrow h\,Z$

$\rightarrow bb\;\tau\tau$

No significant excess found $\rightarrow$

set limits in MSSM Higgs boson parameter space (M_A-tan β)



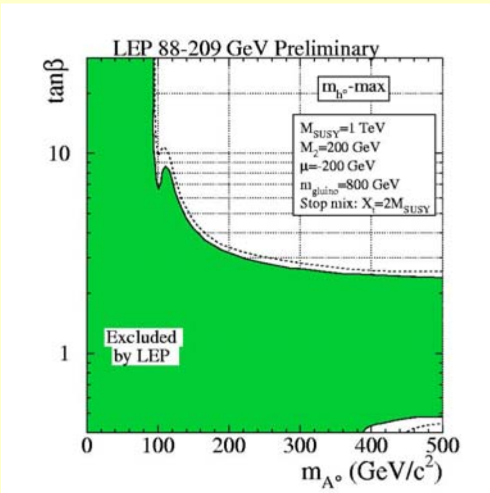


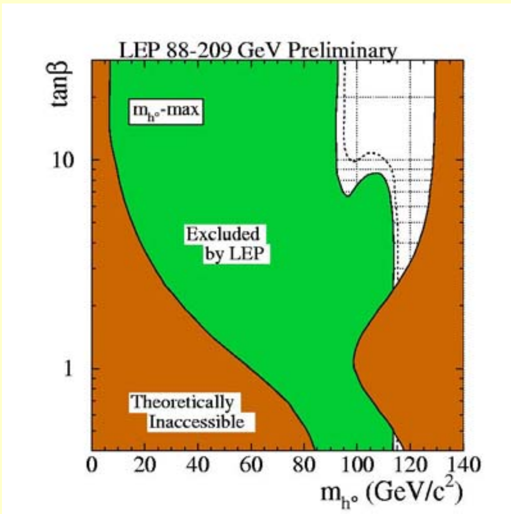
$M_h > 91.5$ GeV/c^2

$m_A > 92.2$ GeV/c^2

Excluded tan β range: $0.7 < \tan\beta < 10.5$

Results for the m_h-max scenario:





$M_h > 91.0$ GeV/c^2

$m_A > 91.9$ GeV/c^2

Excluded tan β range: $0.5 < \tan\beta < 2.4$ (m_t =175 GeV/c^2)

< 1.9 (m_t = 179 GeV/c^2)

MSSM Higgs Boson Search at the LHC

Important channels in the MSSM Higgs boson search:

1. The Standard Model decay channels
   - h $\rightarrow$ $\gamma\gamma$
   - tt h, h $\rightarrow$ bb
   - qq h, h $\rightarrow$ $\tau\tau$

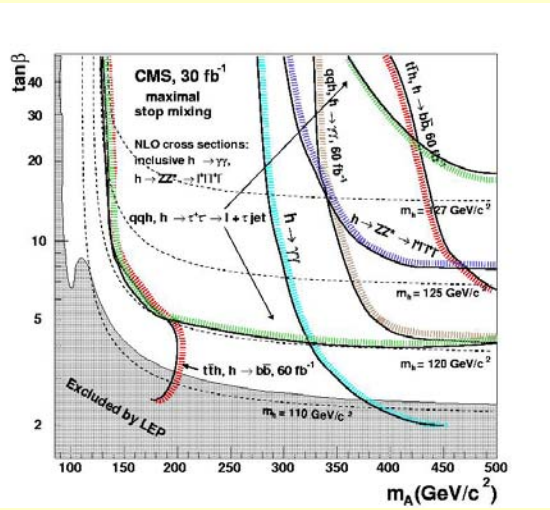
   evaluation of performance is based on SM results

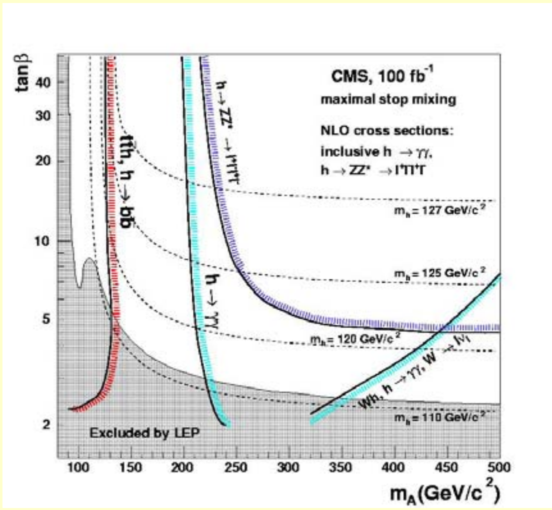
2. Modes strongly enhanced at large tan β:
   - **H/A** $\rightarrow$ $\tau^+ \tau^-$ $\quad$ $H^+ \rightarrow \tau \nu$
   - **H/A** $\rightarrow$ $\mu^+ \mu^-$

3. Other interesting channels:
   - H/A $\rightarrow$ tt
   - H/A $\rightarrow$ Zh $\rightarrow$ $\ell\ell$ $\gamma\gamma$
     $\rightarrow$ $\ell\ell$ bb
   - H $\rightarrow$ hh

Search for the light CP-even Higgs boson h

- Standard search channels can be used
- Vector boson fusion channels contribute significantly



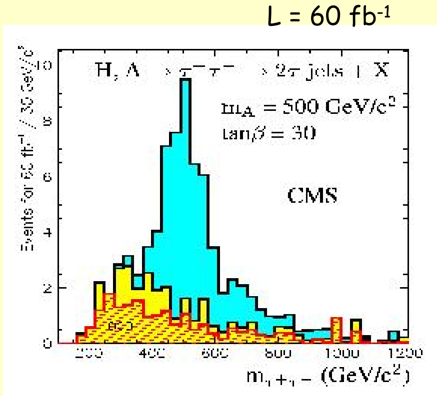


uncovered region at small m_A $\rightarrow$ look for heavier Higgs bosons

Search for the heavy Higgs bosons H and A

at large tan β: **bb H/A $\rightarrow$ bb $\tau\tau$** plays a key role
in addition: bb H/A $\rightarrow$ $\mu\mu$,
bb H/A $\rightarrow$ bb bb very difficult at the LHC
(trigger, backgrounds,....)

L = 60 fb^{-1}



- Selection requires excellent b and τ identification
- detailed studies $\rightarrow$ both leptonic and hadronic tau decays can be used

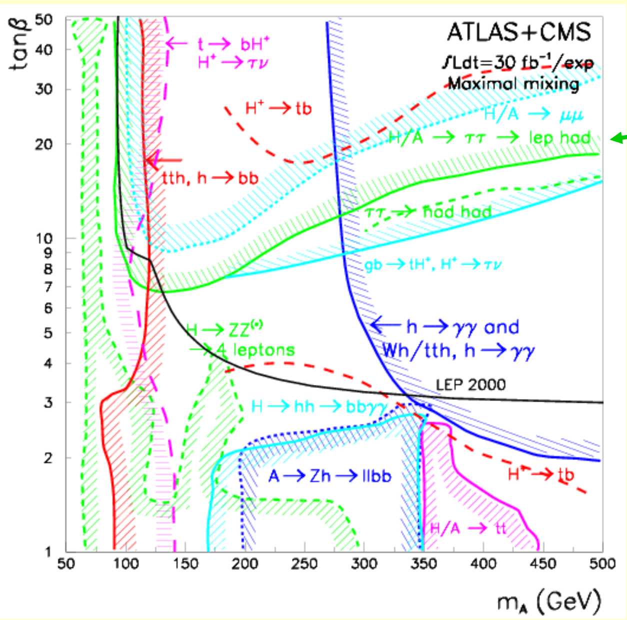
$m_{H/A}$ < 400 GeV/c^2 (ℓ -τ_{had}) dominates
\> 400 GeV/c^2 (τ_{had}-τ_{had}) contributes significantly

- H/A mass can be reconstructed, collinear approx.
- Dominant backgrounds: W+jet, tt production

at small tan β: add. modes: search for H/A $\rightarrow$ h decays
allows for simultaneous observation for two Higgs bosons
examples: H $\rightarrow$ hh, A $\rightarrow$ Zh

MSSM Higgs bosons h, H, A, H $^{\pm}$

m_h < 135 GeV
$m_A \approx m_H \approx m_{H\pm}$ at large m_A



A, H cross-section ~ tan$^2\beta$ (tree level)

- best sensitivity from A/H $\rightarrow$ $\tau\tau$,
(not easy the first year ..)

- A/H → $\mu\mu$ experimentally easier
(esp. at the beginning)

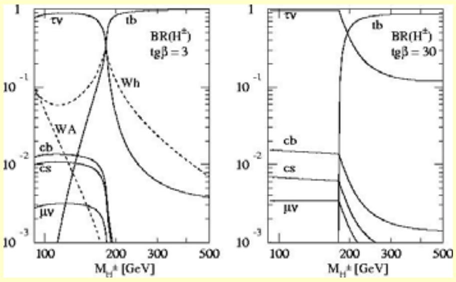
Search for the Charged Higgs Boson

Detection of a charged Higgs boson $\rightarrow$ ***Physics Beyond the Standard Model***

Production: depends strongly on $m_{H\pm}$

(i) via top decays: $t \rightarrow H^{\pm} b$
(ii) $gg \rightarrow H^{\pm} tb$ or $gb \rightarrow H^{\pm} t$
(iii) $gg, qq \rightarrow H^{\pm} W$
(iv) $qq \rightarrow H^{+} H^{-}$

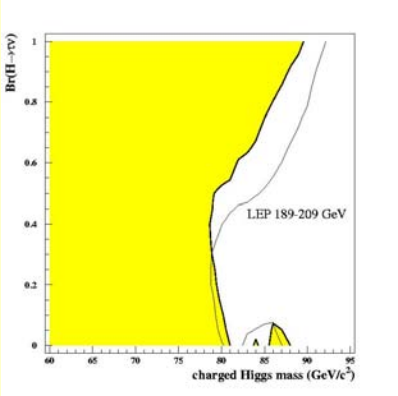
Decays: depend strongly on $m_{H\pm}$



$\tau\nu$ decay mode significant at large tan β

LEP results on m_{H+}:

search for $H^{+} \rightarrow cs$ and $\tau\nu$

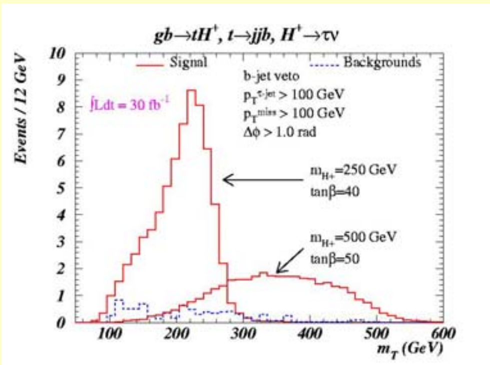


$M_{H^+} > 78.6$ GeV/c^2 (95% CL)

Search for the charged Higgs bosons $H^{\pm}$ at large mass

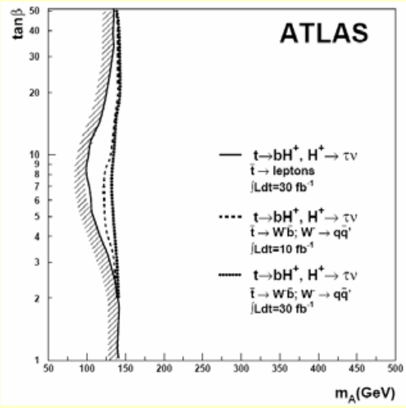
Both the tb and the $\tau\nu$ decay modes can be used

- $H^{\pm} \rightarrow tb$ decays:
  - promising channel: (i) $gb \rightarrow H^{\pm} t \rightarrow tb\ t \rightarrow \ell\nu bb\ qqb$
    require three b-tags + t-reconstruction $\rightarrow$ large background suppression
  - more difficult: (ii) $gg \rightarrow H^{\pm}tb \rightarrow tb\ tb \rightarrow \ell\nu bb\ qqbb$
    require four b-tags + t-reconstruction (larger comb. background in rec. of $H^{\pm}$)
- $H^{\pm} \rightarrow \tau\nu$ decays:
  - promising channel: (i) $gb \rightarrow H^{\pm} t \rightarrow \tau\nu\ t \rightarrow h\nu\nu\ qqb$
    exploit hadronic decays of the τ and t quark
    $\rightarrow$ transverse mass distribution (τ_{had} + E_T^{miss}) can be used to reconstruct the $H^{\pm}$ mass
  - additional channel:
    (ii) $gg \rightarrow H^{\pm}tb \rightarrow \tau\nu\ tb \rightarrow h\nu\nu\ qqbb$
    require two b-tags
- Other decay modes ($H^{\pm} \rightarrow Wh$, WH)
  marginal - hopeless in MSSM



LHC discovery potential for charged Higgs bosons

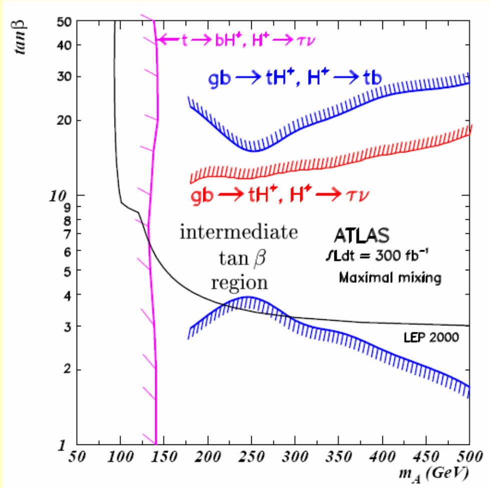
for $m_H < m_t - m_b$:
use $t \to H^{\pm}b$, $H^{\pm} \to \tau\nu$ decays



both leptonic and hadronic decays of the top quark can be used

closes gap at small m_A

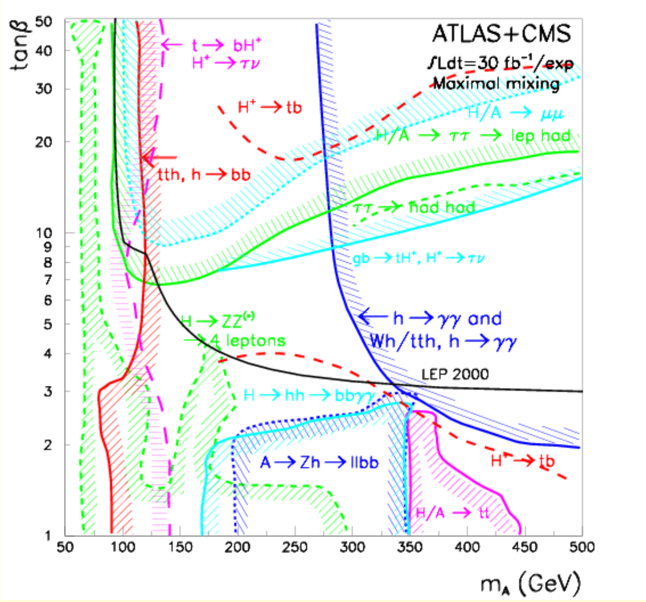
combined discovery reach:



- **good discovery potential, except moderate tanβ region at high mass**
- transition region around m_t can also be covered

LHC discovery potential for MSSM Higgs bosons

5σ discovery in m_A – tan β plane

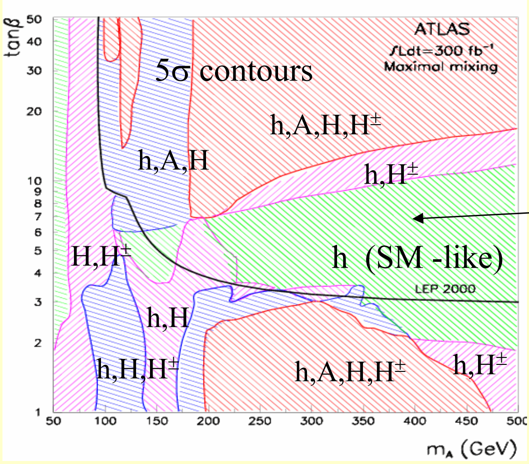


m_{SUSY} = 1 TeV, m_{top} = 175 GeV/c^2

Two or more Higgs can be observed over most of the parameter space → disentangle SM / MSSM

- Plane fully covered (no holes) at low L (30 fb^{-1})
- **Main channels : h → γγ , tth h → bb, A/H → μμ, ττ , H± → τ ν**

LHC discovery potential for MSSM Higgs bosons



4 Higgs observable
3 Higgs observable
2 Higgs observable
1 Higgs observable

Here only SM-like h observable if SUSY particles neglected.

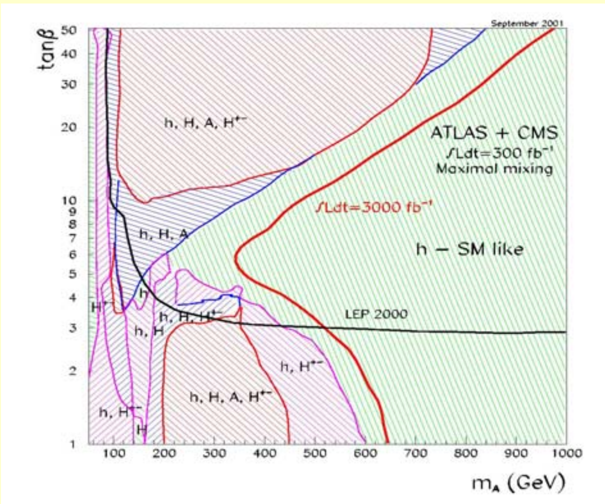
Assuming decays to SM particles only

- Region at large m_A and moderate tan β only covered by h; difficult to detect other Higgs bosons

Possible coverage: * via SUSY decays (model dependent, see below)
* luminosity (only moderate improvement)

MSSM discovery potential for Super-LHC

ATLAS + CMS, 2 x 3000 fb^{-1}



- Situation can be improved, in particular for m_A < ~400 GeV
- But: (S)LHC can not promise a complete observation of the heavy part of the MSSM Higgs spectrum ....

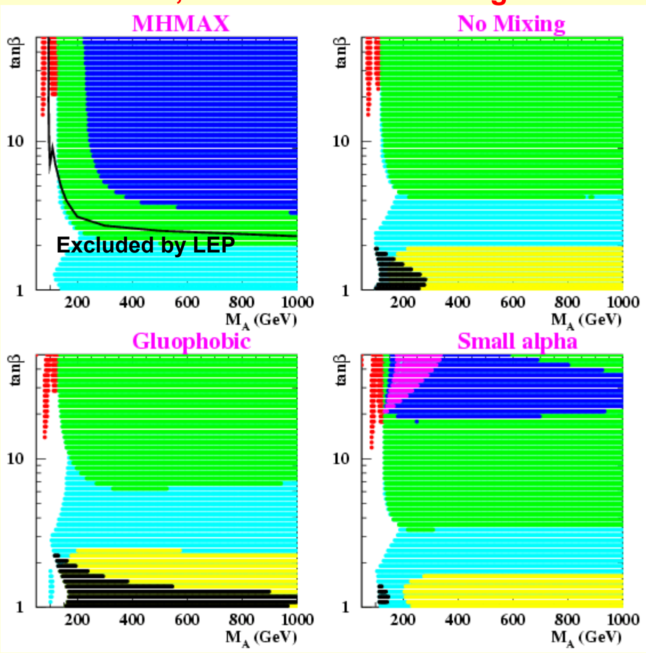
.... although the observation of sparticles will clearly indicate that additional Higgs bosons should exist.

K. Jakobs 19th Nordic Particle Physics Meeting, Spatind/Norway, Jan. 2006

MSSM scan for different benchmark sceanarios

- Vector boson channels included
- Benchmark scenarios as defined by M.Carena et al. (h mainly affected)

ATLAS, 30 fb^{-1}, 5σ coverage for h



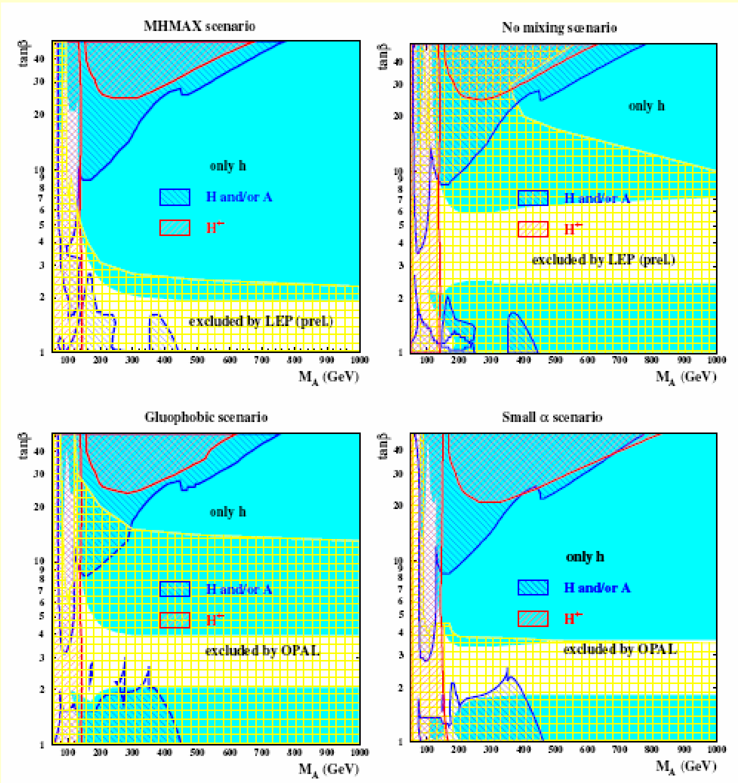
MHMAX scenario (M_{SUSY}=1 TeV)
maximal theoretically allowed region for m_h

Nomixing scenario (M_{SUSY}= 2TeV)
(1TeV almost excl. by LEP)
small m_h → difficult for LHC

Gluophobic scenario (M_{SUSY} = 350 GeV)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for g g → H, H→γγ and Z→4 ℓ

Small α scenario (M_{SUSY} = 800 GeV)
coupling to b (and **t**) suppressed
(cancellation of sbottom, gluino loops) for large tan β and M_A 100 to 500 GeV

MSSM discovery potential for various benchmark scenarios



- Full parameter range can be covered with modest luminosity, 30 fb^{-1}, for all benchmark scenarios !
- Only one Higgs boson, h, in some regions
  (moderate tanβ – large m_A wedge)

Can SUSY particles be used to detect
Higgs bosons ??

or

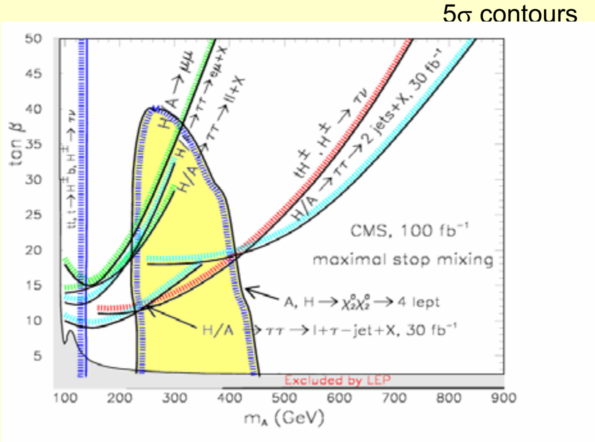
the interplay between the
Higgs sector and SUSY particles

so far: SUSY particles have been assumed to be
too heavy to play a role in Higgs boson decay phenomenology

CMS study: MSSM scenario

$H/A \to \chi^0_2 \chi^0_2 \to \ell\ell\chi^0_1 \ \ell\ell\chi^0_1$

5σ contours



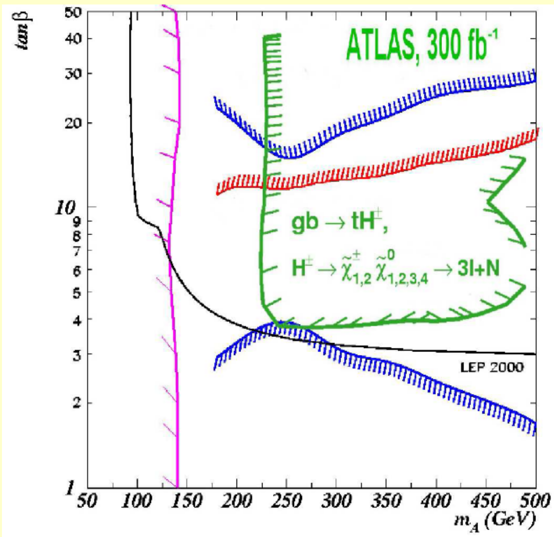
special choice in MSSM (no scan)
M_1 = 60 GeV
M_2 = 110 GeV
μ = -500 GeV

Exclusions depend on MSSM parameters
(slepton masses, μ)

Search for $H^{\pm}$ decays into SUSY particles

$gb \rightarrow tH^{+}$, $H^{\pm} \rightarrow \chi_{2,3}^{0}\, \chi_{1,2}^{\pm} \rightarrow 3\ell + E_T^{miss}$

special choice in MSSM (no scan)
M_2 = 210 GeV
μ = 135 GeV
$m(s\text{-}\ell_R)$ = 110 GeV
$m(s\text{-}\tau_R)$ = 210 GeV
m_g = 800 GeV
m_{SUSY} = 1000 GeV



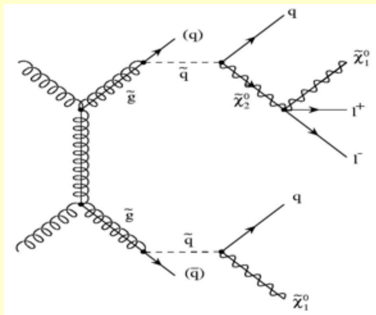
complementary discovery potential

Excursion: Search for Supersymmetry

• If SUSY exists at the electroweak scale, a discovery at the LHC should be easy

• Squarks and Gluinos are strongly produced

They decay through cascades to the lightest SUSY particle (LSP)



⇒ combination of Jets, Leptons, E_T^{miss}

⇒ **Heavy Higgs bosons might appear in cascades decays,**
e.g. cascade decays of squarks and gluinos via heavy charginos and neutralinos

$$pp \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g} \rightarrow \chi_2^{\pm}, \chi_3^0, \chi_4^0 + X$$
$$\rightarrow \chi_1^{\pm}, \chi_2^0, \chi_1^0 + h, H, A, H^{\pm} + X$$

$$pp \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g} \rightarrow \chi_1^{\pm}, \chi_2^0 + X$$
$$\rightarrow \chi_1^0 + h, H, A, H^{\pm} + X$$

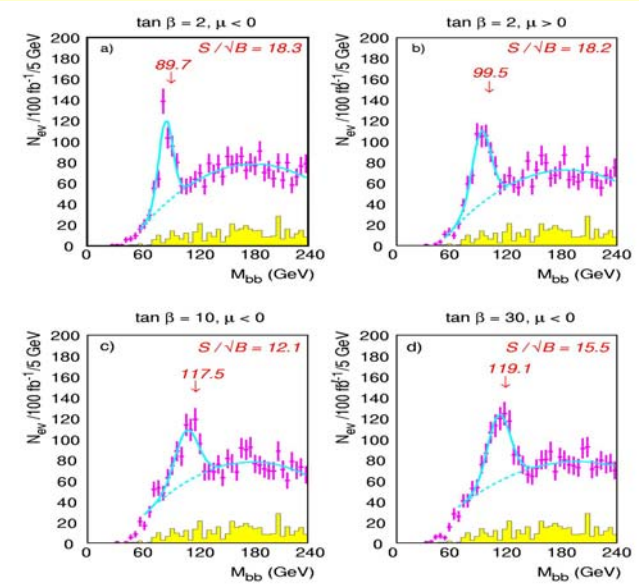
Search for Higgs decays in standard channels: bb, $\tau\tau$, $\tau\nu$

Search for h →bb in SUSY cascade decays

Applying a cut on E_T^{miss} ⇒ suppresses the Standard Model background (QCD-jets), dominant background from SUSY production

h → bb:

CMS study, mSUGRA



important if $\chi^0_2 \rightarrow \chi^0_1 h$ is open;

bb peak can be reconstructed in many cases

Could be a Higgs discovery mode !

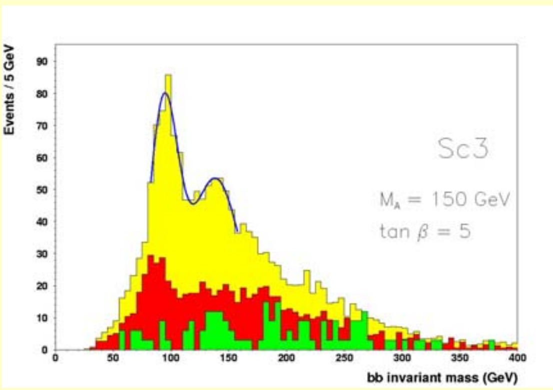
More complicated scenarios, an example (CMS):

$$pp \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g} \rightarrow \chi_2^{\pm}, \chi_3^0, \chi_4^0 + X$$
$$\rightarrow \chi_1^{\pm}, \chi_2^0, \chi_1^0 + h, H, A, H^{\pm} + X$$

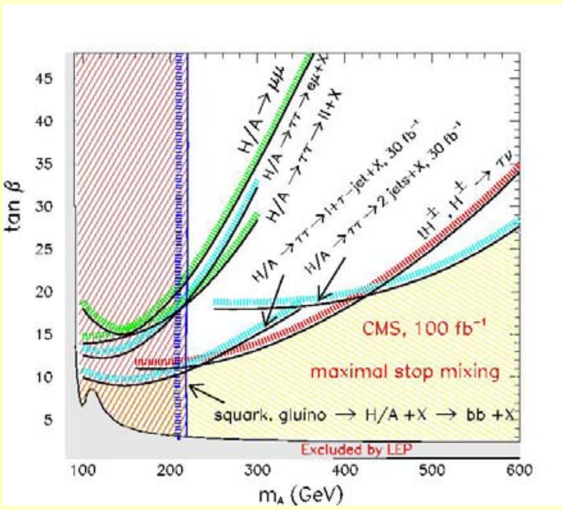
Search for final states with bb and large E_T^{miss}

m_g = 1200 GeV, m_q = 800 GeV, M_2 = 350 GeV, μ = 150 GeV

reconstructed bb mass



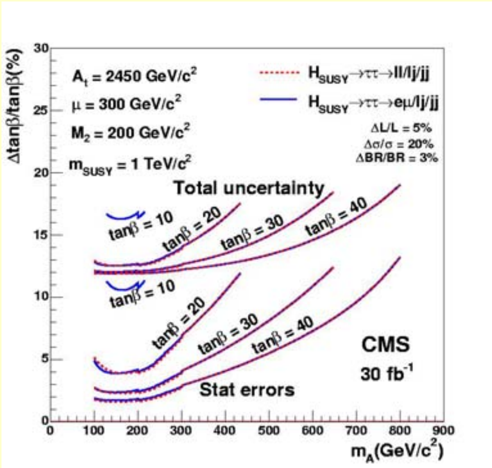
Two Higgs (H, h) bosons visible



tanβ measurement in the MSSM

- Strong dependence of production cross section of heavy Higgs bosons on tanβ (~ tanβ² at tree level) can be used to measure its value

- However, large radiative corrections at large tanβ, depend on SUSY particles
  ⇒ will need to be entered into a global fit of SUSY parameters



Status of

MSSM Higgs boson searches

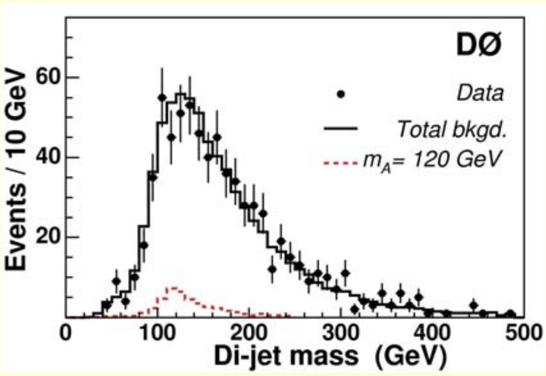
at the Tevatron

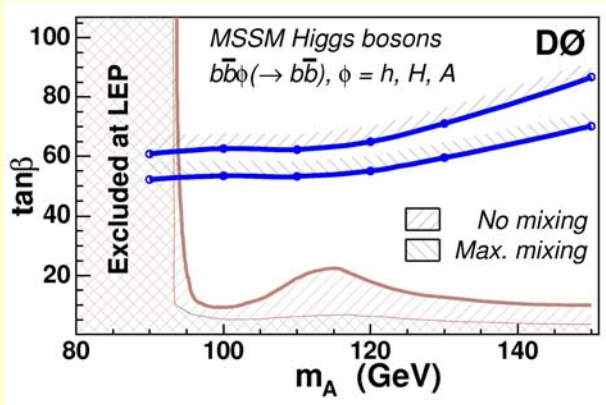
Search for Heavy Neutral Higgs Bosons $\Phi \rightarrow bb$

Data sample: 260 pb^{-1}

Search for bb A/H $\rightarrow$ bb bb

- dedicated trigger
- select four jet final states
- require three b-tagged jets



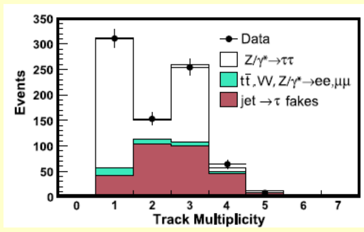


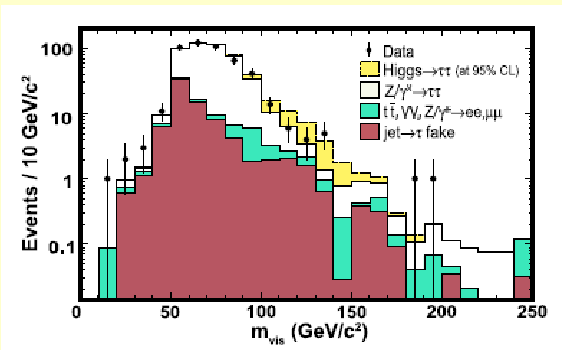
Search for the $\Phi \rightarrow \tau\tau$ decay mode

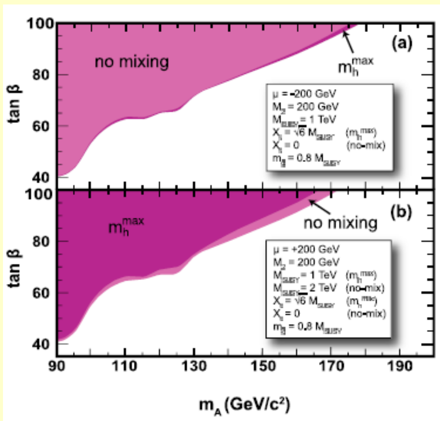
Data sample: 310 pb^{-1}

Search for A/H $\rightarrow \tau\tau$ and bb A/H $\rightarrow$ bb $\tau\tau$

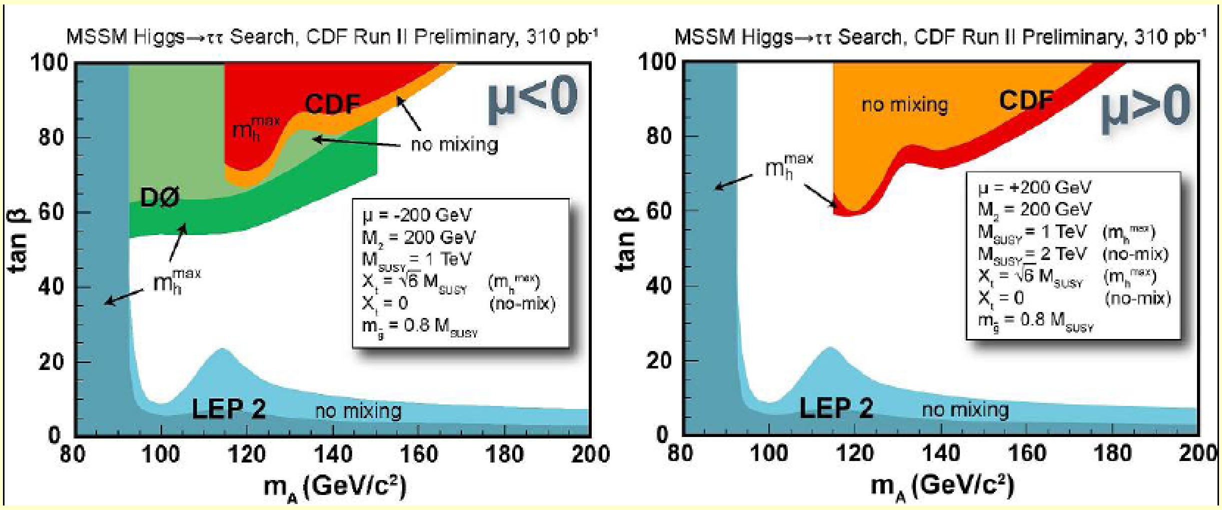
- select ℓ - τ_{had} decays with ℓ = e, μ
- reconstruct visible mass (ℓ- τ_{had})



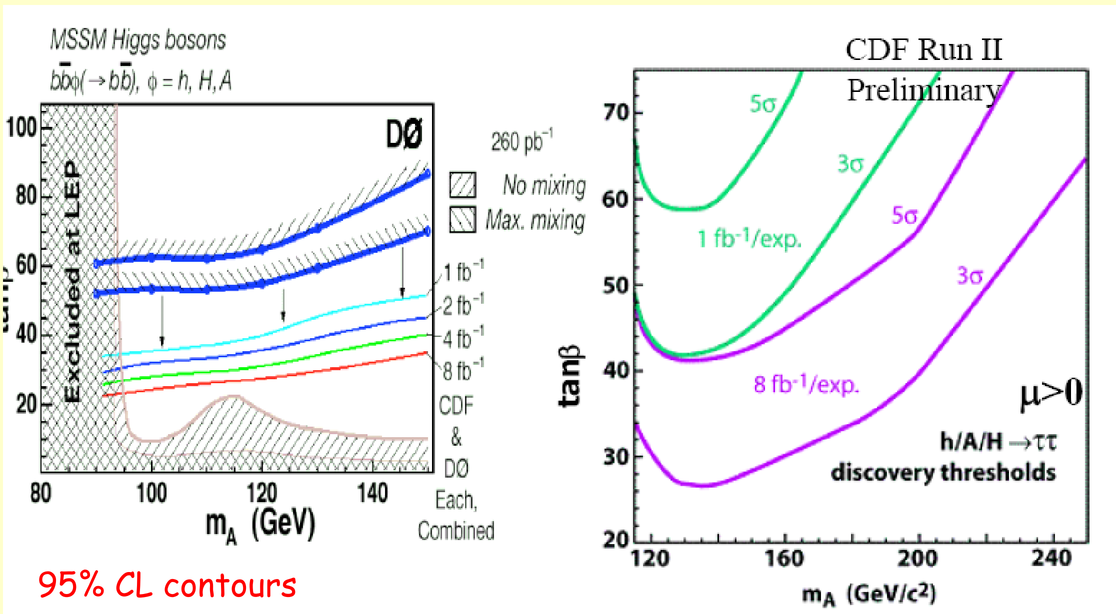




Combined excluded region

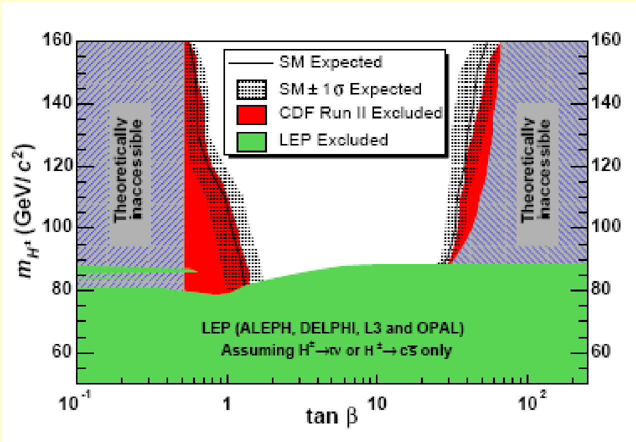


Prospects for MSSM Higgs boson searches at the Tevatron



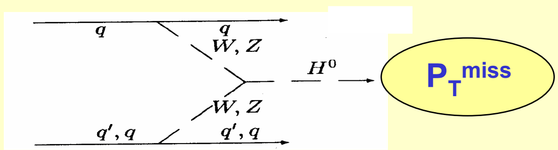
Search for Charged Higgs Bosons $H^{\pm}$

- Search for charged Higgs bosons in top decays,
- $H^{\pm} \rightarrow \tau\nu$ decays
- No excess of τ contributions found $\rightarrow$ limit



Invisible Higgs decays ?

Possible searches: tt H $\rightarrow$ ℓνb qqb + P_T^{miss}
W/Z H $\rightarrow$ ℓν (λλ) + P_T^{miss}
qq H $\rightarrow$ qq + P_T^{miss}



ATLAS study:

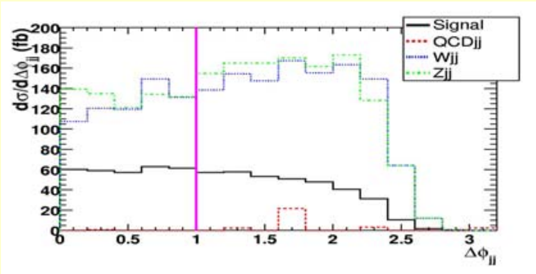
search for invisibly decaying Higgs boson in VBF mode

Event selection: 2 tag jets, (P_T, Δη, M_{jj}>1200 GeV)
P_T^{miss} > 100 GeV
Lepton and Jet veto (no jets with P_T> 20 GeV)

Main backgrounds: W jj production (W → ℓν)
Z jj production (Z → νν)
QCD jet production, fake P_T^{miss}

Requires special forward jet + P_T^{miss} trigger (under study)

Discriminating variable: $\Delta \phi_{jj}$ (separation between tag jets)
expect differences due to Higgs coupling structure:

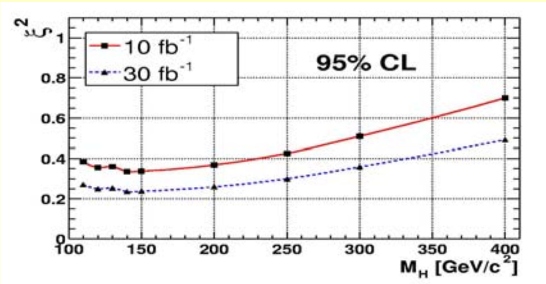


Expected rates for 10 fb^{-1}:

Signal: 590 events
W-background: 1215 events
Z -background: 1230 events

background normalization via $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\ell$ in region $\Delta\phi > 1$ needed, to constrain the background (estimated background uncertainty: 4-5%)

Sensitivity: $\xi^2 = Br(H \rightarrow Inv.) \frac{\sigma_{qq \rightarrow qqH}}{\sigma_{qq \rightarrow qqH}|_{SM}}$



- Needs confirmation from more detailed simulation (trigger)
- Non-Standard Model background ??
- Needs confirmation in ttH and/or WH channel to demonstrate presence of a Higgs boson

Conclusions

- **Should a SM Higgs boson exist, it cannot escape detection at the LHC**
- **MSSM parameter space can be covered for several benchmark scenarios (incl. LHC-phobic scenarios)**

Maybe celebration at Spatind 2010 ??

- **Tevatron might have a 3-σ discovery windows, however, much depends on the detector and accelerator performance.**
- **LHC can perform first, important measurements of Higgs boson parameters or help to constrain underlying SUSY models**

Exiting times ahead of us….

transparencies under: wwwhep.physik.uni-freiburg.de/~jakobs
$\rightarrow$ Physik-Schulen

writeup: V. Büscher and K. Jakobs, *Higgs Boson Searches at Hadron Colliders*, Int. Journal Mod. Phys. A Vol. 20 (2005) 2523-2602, hep-ph/0504099