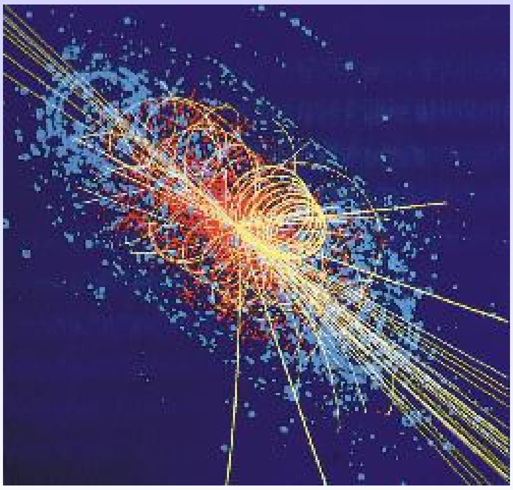
The Search for the Higgs Boson
- From LEP via Tevatron to the LHC -



- **Introduction**

  The Higgs Boson and its properties

- **The present knowledge from LEP/SLC**

  Was there a Higgs Boson at LEP ??

- **Search for the Higgs Boson at the LHC**
  - Overview on the standard channels
  - Potential in vector boson fusion
  - Measurement of Higgs boson parameters (mass, couplings)

- **What can be done at the Tevatron ?**

  incl. the present status

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The Higgs Boson

Peter Higgs

„The last missing piece of the Standard Model….“

“Experimental confirmation of the existence of this particle is eagerly awaited.”

“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.”

The structure of the Standard Model

Fundamental principle: Local gauge invariance
Prototype: **Quantum Electrodynamics (QED)**

Free Dirac equation: $i\gamma^\mu \partial_\mu \psi - m\psi = 0$

Lagrangian formalism: $\mathcal{L} = i\bar{\psi}\gamma^\mu \partial_\mu \psi - m\bar{\psi}\psi$

Invariance of L under local gauge transformations
$(\psi \rightarrow e^{i\alpha(x)}\psi)$

→ Introduction of a **massless vector field A_μ**
(gauge field → Photon)

Lagrangian of QED:

$$\mathcal{L} = i\bar{\psi}\gamma^\mu \partial_\mu \psi - m\,\bar{\psi}\psi + e\bar{\psi}\gamma^\mu \psi A_\mu - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Mass terms for A_μ violate gauge invariance

Similar for the SM interactions:

Quantum Chromodynamics (QCD):

SU(3) transformations,
8 gauge fields, 8 massless gluons

Electroweak Interaction (Glashow, Salam, Weinberg):

SU(2) x U(1) transformations,
4 gauge fields, (W_μ^1, W_μ^2, W_μ^3, B_μ)

Physical states:

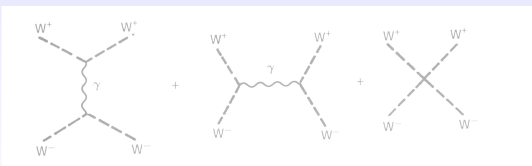
$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2)$$
$$Z_\mu = -\sin\theta_W B_\mu + \cos\theta_W W_\mu^3$$
$$A_\mu = \cos\theta_W B_\mu + \sin\theta_W W_\mu^3$$

Fundamental problems:

1. **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

2. **Divergences in the theory (scattering of W bosons)**



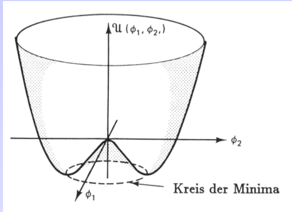
$$-i\,M\,(W^+W^- \rightarrow W^+W^-) \sim s / M_W^2$$

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: $\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = v^2 \qquad v^2 = -\mu^2/\lambda$

- 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**

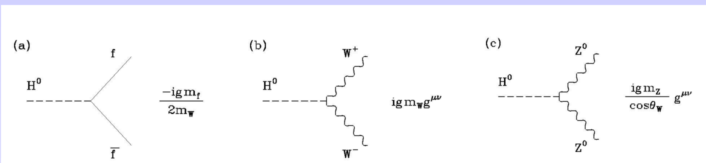
$M_H = \sqrt{\lambda\, v^2}$

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:



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

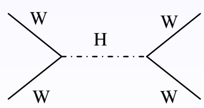
$$g_{VVH} = 2\left(\sqrt{2}G_F\right)^{1/2} M_V^2$$

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

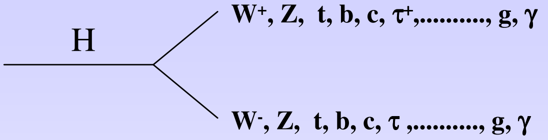
and finally:

- Higgs boson regulates divergences in the WW scattering cross section



Properties of the Higgs Boson

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



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

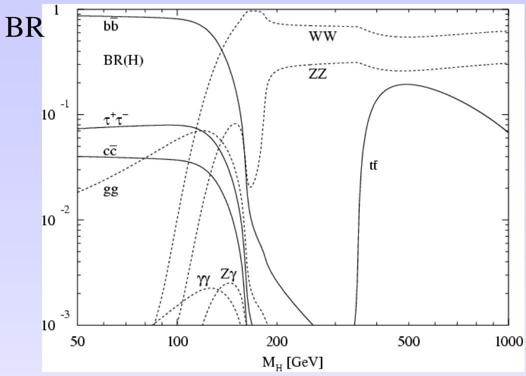
$$\Gamma(H \to VV) = \delta_V \frac{G_F}{16\sqrt{2}\pi} M_H^3 \,(1 - 4x + 12x^2)\, \beta_V$$

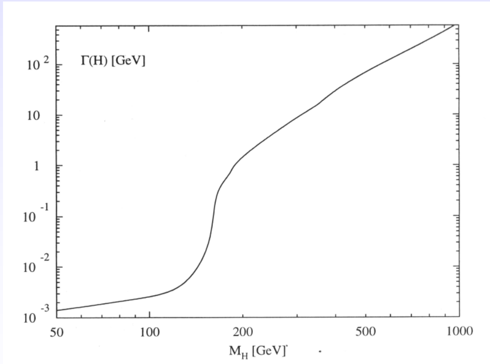
where: $\delta_Z = 1, \delta_W = 2, \quad x = M_V^2/M_H^2, \quad \beta =$ velocity

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

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

(+ W-loop contributions)





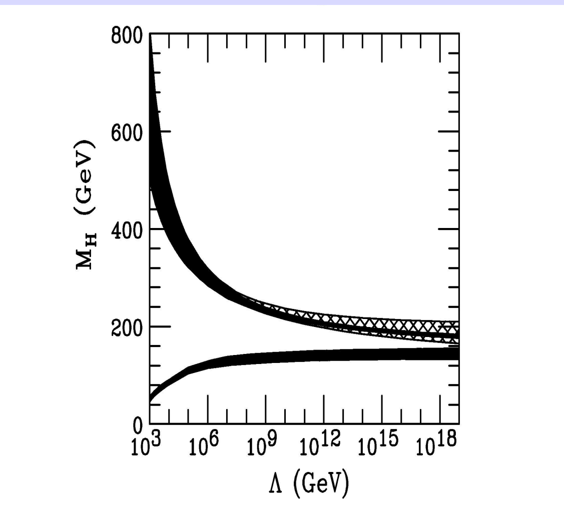
Upper limit on Higgs boson mass: from unitarity of WW scattering $M_H < 1$ TeV/c^2

Higgs mass constraints:

Stronger bounds on the Higgs-boson mass result from the energy dependence of the Higgs coupling $\lambda\,(Q^2)$

(if the SM is assumed to be valid up to some scale Λ)

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



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

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)

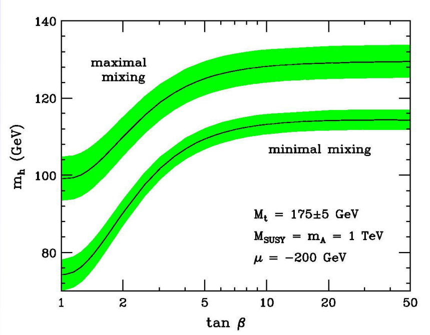
$$m^2_{H,h} = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2+m_Z^2)^2 - 4 m_Z^2 m_A^2 \cos^2 2\beta}\right)$$

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

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 $x_t = (A_t - \mu \cot\beta) \,/\, M_S$

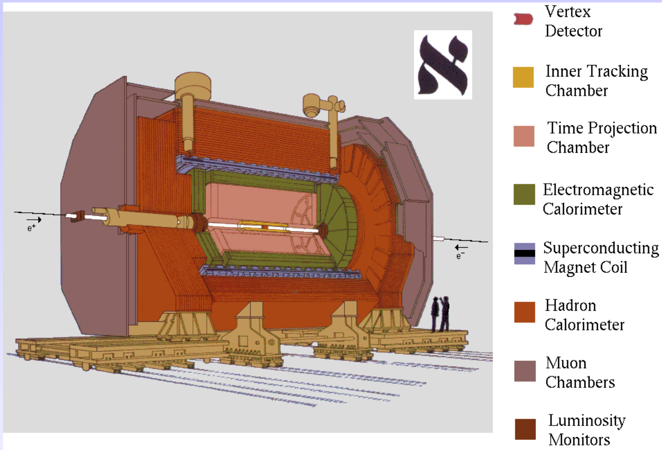


→ m_h < 115 GeV for minimal mixing
→ m_h < 135 GeV for maximal mixing

i.e., no mixing scenario: in LEP reach
max. mixing: easier to address at the LHC

Direct Higgs Searches at LEP

- e^+e^- collider, operating at CERN between 1989 and 2000
- √s between 91 GeV (1989 –1995) and up to 209 GeV (→2000)
- Four experiments: **ALEPH, DELPHI, L3, OPAL**



The ALEPH Detector

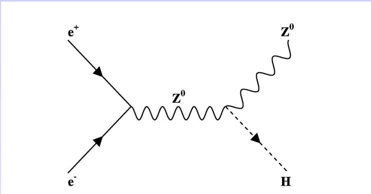
Different features, however, all experiments suited for Higgs boson searches

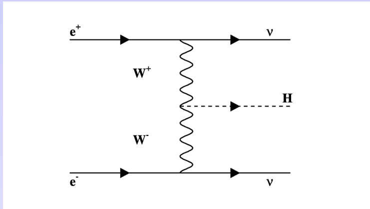
Integrated luminosities:

Integrated luminosities in pb^{-1}					
	ALEPH	DELPHI	L3	OPAL	LEP
$\sqrt{s} \ge 189$ GeV	629	608	627	596	2461
$\sqrt{s} \ge 206$ GeV	130	138	139	129	536
$\sqrt{s} \ge 208$ GeV	7.5	8.8	8.3	7.9	32.5

Higgs production at LEP

Higgs-Strahlung: e+ e- → Z H WW-Fusion: e+ e- → νν H





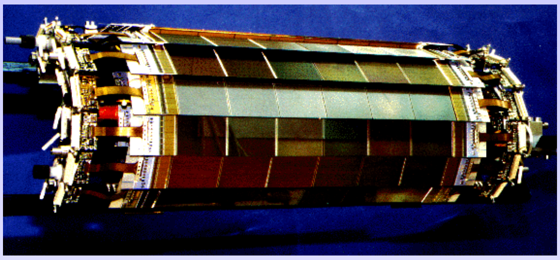
Higgs decay branching ratios for m_H=115 GeV:
BR (H → bb) = 74%, BR (H→ ττ, WW, gg) = 7% each, BR(H → cc) = 4%

Decay modes searched for:

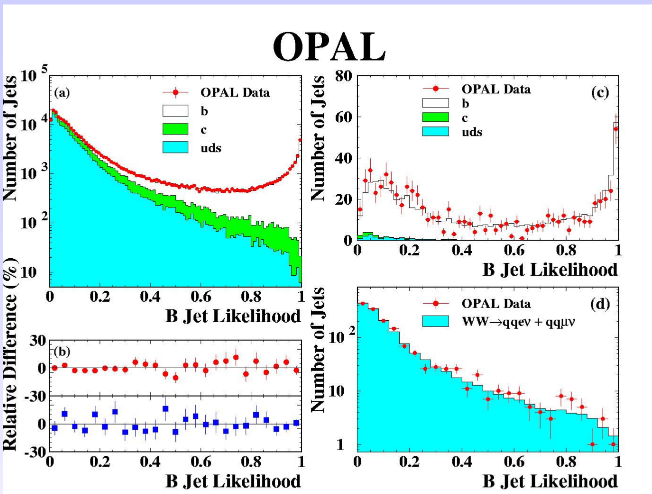
- Four Jet channel: HZ → bb qq
- Missing energy channel: → bb νν
- Leptonic channel: → bb ee, bb μμ
- Tau channels: → bb ττ, and ττ qq

Higgs boson candidate mass can be reconstructed

Essential analysis tool: b-tagging

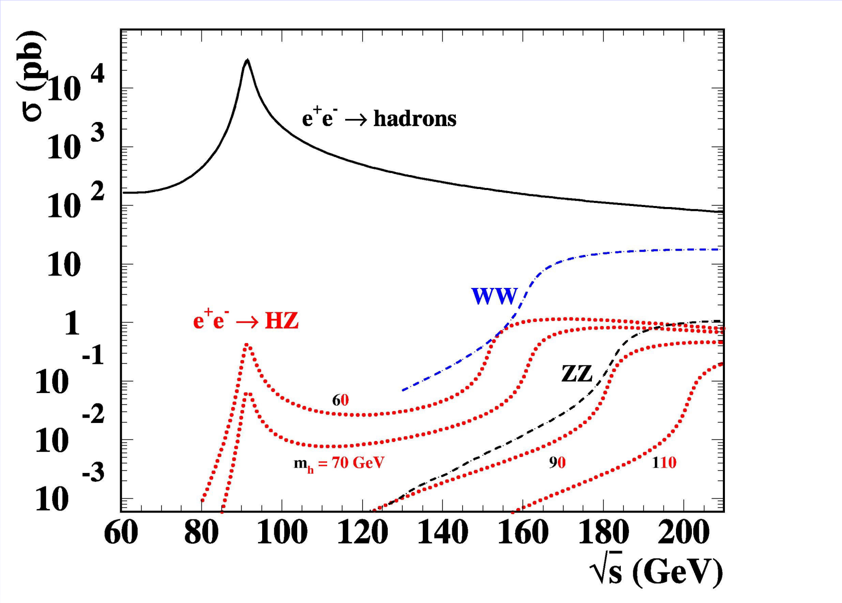


Silicon Vertex detectors



(a) Distribution of the b-tagging variable for jets in data compared to the MC expectations ($\sqrt{s} = m_Z$) in 2000
(b) Relative difference between data and MC for jets opp. non b-tagged jets (red circles) and for jets opp. b-tagged jets (blue squares).
(c) Distribution of the b-tagging variable for jets opp. to b-tagged jets in a sample of qqγ events.
(d) same, but for jets in a sample of $W^+W^- \to$ qq μ ν events

Signal and Background cross sections



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, and, in some cases, on improved Monte Carlo simulations and revised analysis procedures.

Pre-selection by each experiment: to reduce the main backgrounds from:
- two-photon processes
- radiative return to the Z boson ($e^+e^- \to Z\,\gamma\,(\gamma)$)

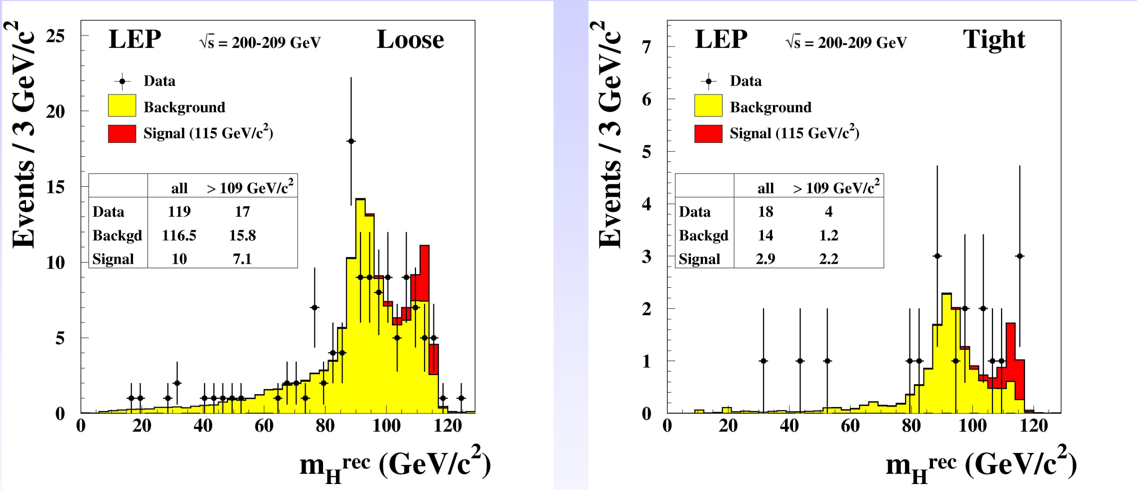
Main remaining background:
- Fermion pair production,
- WW and ZZ production

Further reduced by applying more selective cuts, multivariate techniques such as likelihood analyses and neural networks

Identification of b-quarks and the reconstructed Higgs boson candidate mass play an important role in the discrimination between signal and background

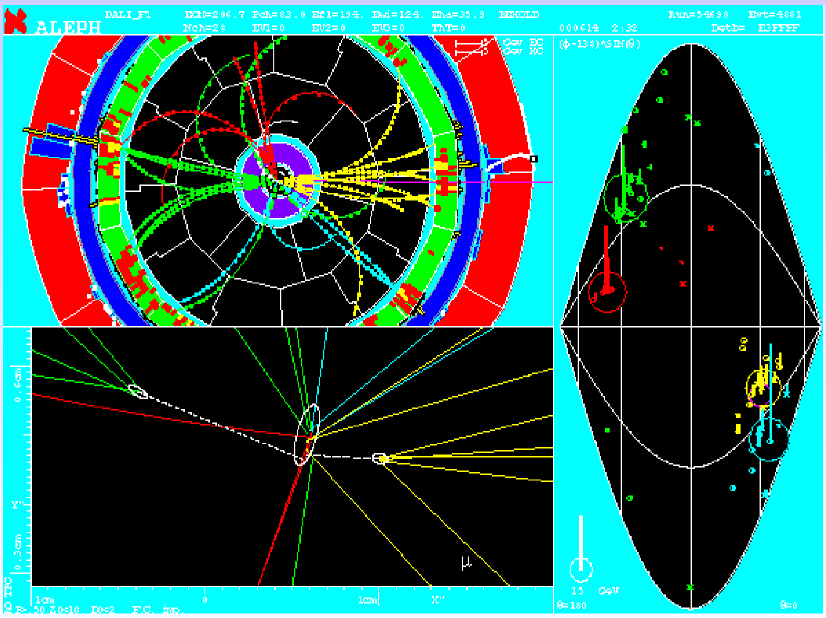
Reconstructed Higgs boson candidate mass:

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.

Higgs boson candidate event in ALEPH



B-tag output: $b_1 > 0.99$
$b_2 > 0.99$

m_H (rec.)= 114.3 GeV/c^2

m_Z(rec.) = 92.1 GeV/c^2

Hypothesis testing

The observed data are subjected to a likelihood ratio test of two hypothetical scenarios:

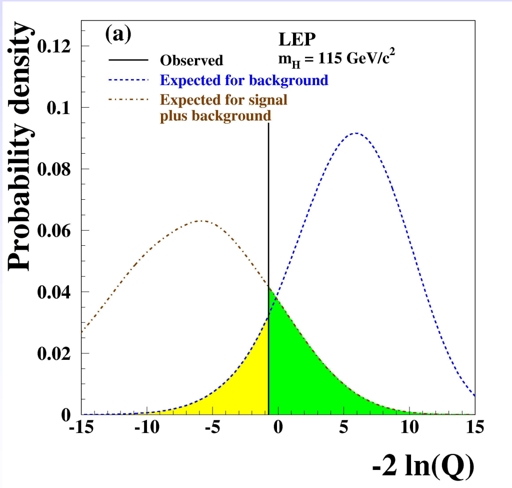
- Background scenario (no Higgs signal assumed)
- Signal + Background scenario (Higgs signal with assumed mass added)

Compute likelihood for B and (S+B) hypothesis

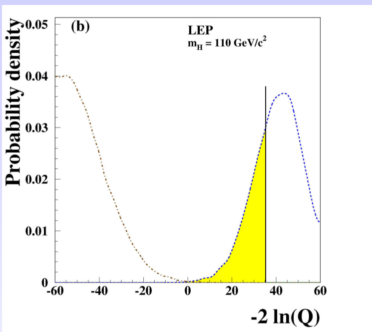
Likelihood ratio $Q := L_{S+B} / L_B$

Test statistics: $-2 \ln Q$

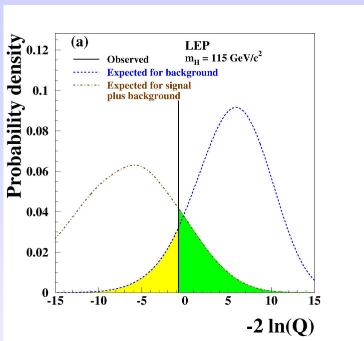
Distribution (pdf) of -2 ln Q can be calculated in MC experiments for (S+B) and B-hypothesis



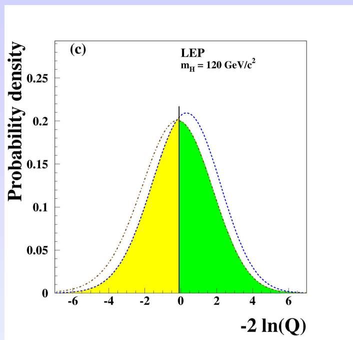
Likelihood ratio distributions for different assumed Higgs boson mass values



m_H = 110 GeV/c^2

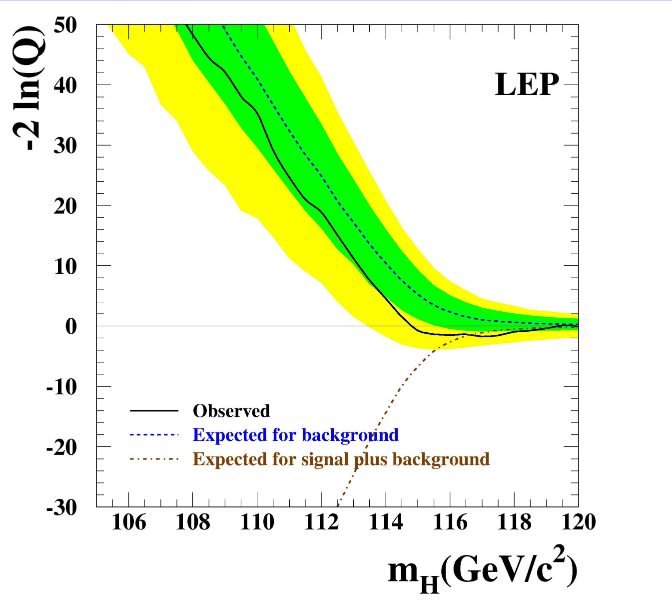


m_H = 115 GeV/c^2



m_H = 120 GeV/c^2

Observed and expected behavior of -2 ln Q

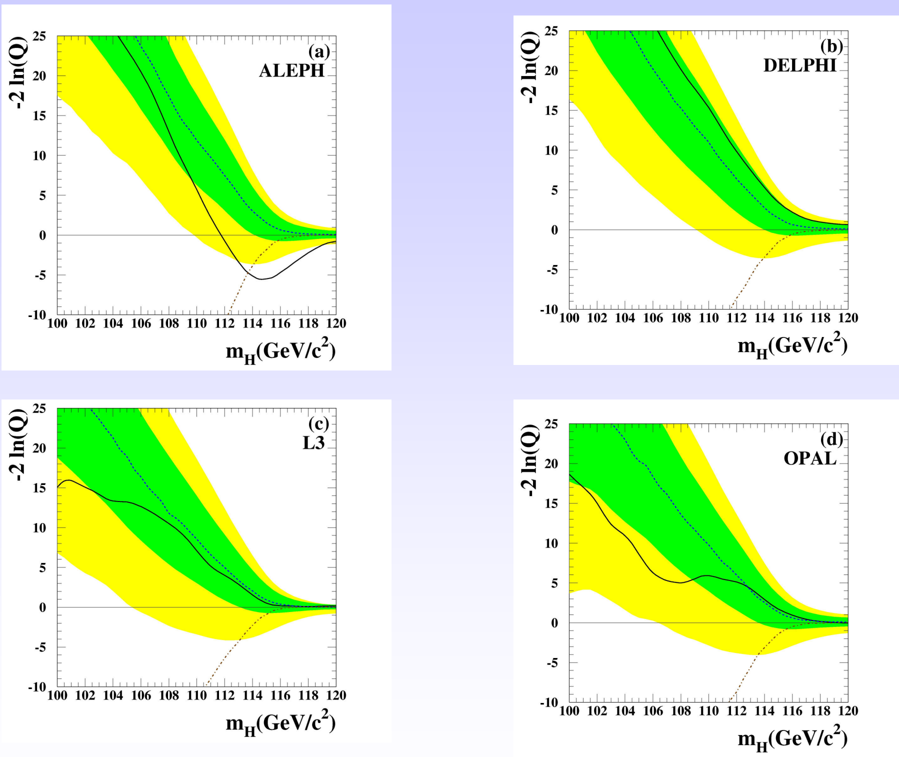


Broad minimum around 115 GeV/c^2

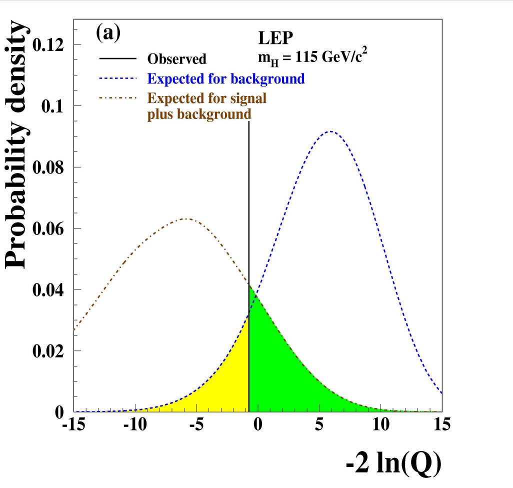
Neg. value of -2 ln Q in data indicates that the (S+B) hypothesis is more favored than the B-hypothesis,

however, at low significance

Comparison between experiments:



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

$1-CL_B = 0.09 \quad \leftrightarrow$

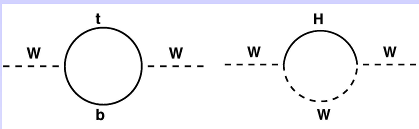
Signal significance = 1.7 σ

$M_H > 114.4$ GeV/c² (95% CL)

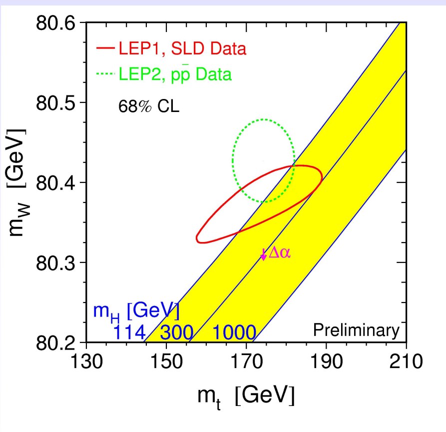
Expected mass limit: 115.3 GeV/c²

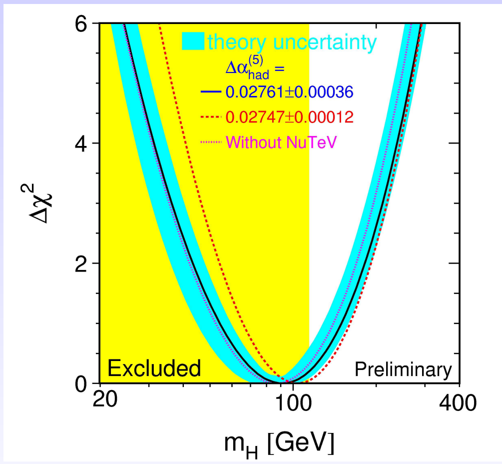
Indirect Limits via radiative corrections

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-2003):

M_H = 91 (+58) (-37) GeV/c²
M_H < 211 GeV/c² (95 % CL)

Search for MSSM Higgs Bosons at LEP

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

Same analysis techniques applied as for the Standard Model Higgs search

No significant excess found

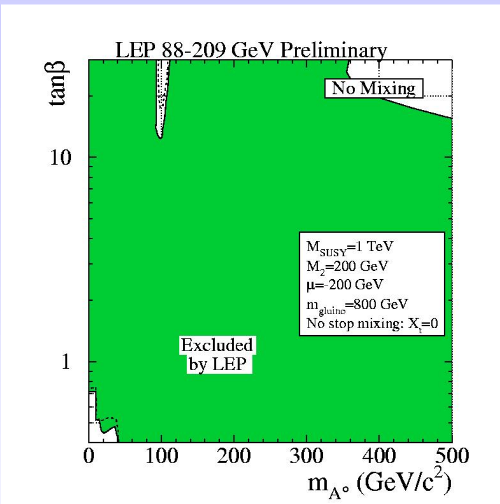
$\rightarrow$ set limits in MSSM Higgs boson parameter space (M_A-tan β)

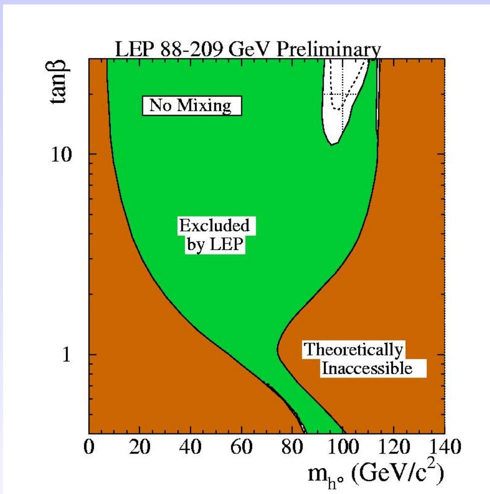
Two different assumptions on mixing in the stop sector:

a) The so called m_h-max scenario
Fermion masses at el.weak scale at M_{SUSY}=1 TeV
(designed to yield the largest value for m_h (most conservative for LEP))

b) The no-mixing scenario
Assumes that there is no mixing between the scalar partners of the left-handed and right-handed top quarks.

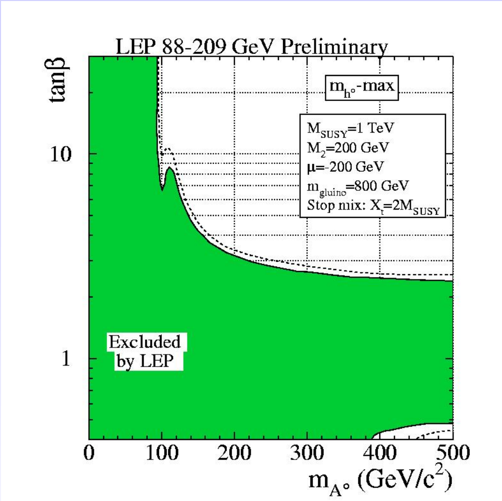
Results for the no-mixing scenario:

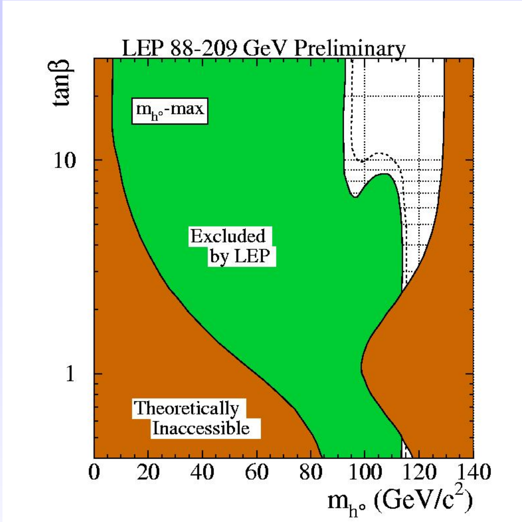




$M_h > 91.5$ GeV/c^2
$m_A > 92.2$ GeV/c^2
Excluded tan β range: $0.7 < \tan\beta < 10.5$

Results for the m_h-max scenario:





$M_h > 91.0$ GeV/c^2

$m_A > 91.9$ GeV/c^2

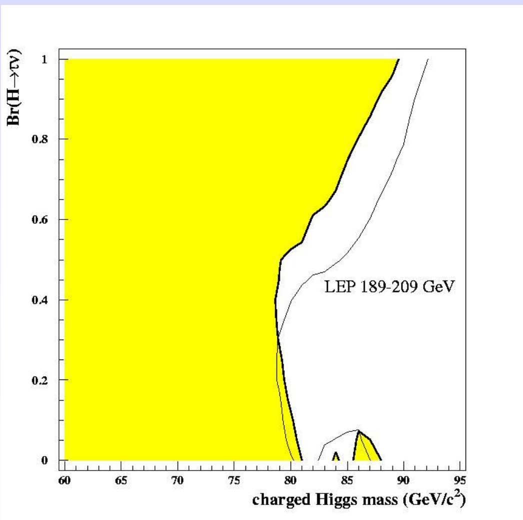
Excluded tan β range: $0.5 < \tan\beta < 2.4$ (m_t =175 GeV/c^2)

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

Limits on Charged Higgs Bosons

Search for the decays $H^+ \rightarrow cs$ and $\tau\nu$

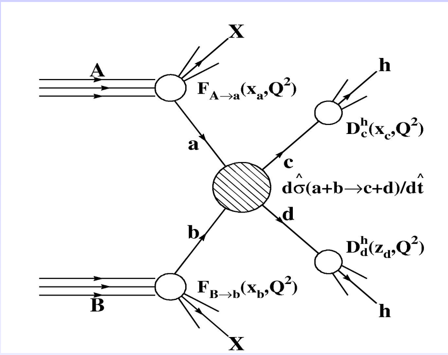
Mass limit as function of BR($H+ \rightarrow \tau\nu$)



Data are consistent with expectations from Standard Model background

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

Search for the Higgs Boson at Hadron Colliders

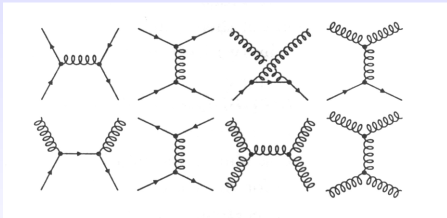


$$\sigma = \sum_{ij} \int dx_1 dx_2 f_i\left(x_1, \mu_F^2\right) f_j\left(x_2, \mu_F^2\right) \hat{\sigma}_{ij}\left(\alpha_s^m\left(\mu_R^2\right), x_1 P_1, x_2 P_2, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

Sum over initial states — *Parton distributions* — *Factorization Scale* — *Point Cross Section* — *Order* — *Renormalization Scale*

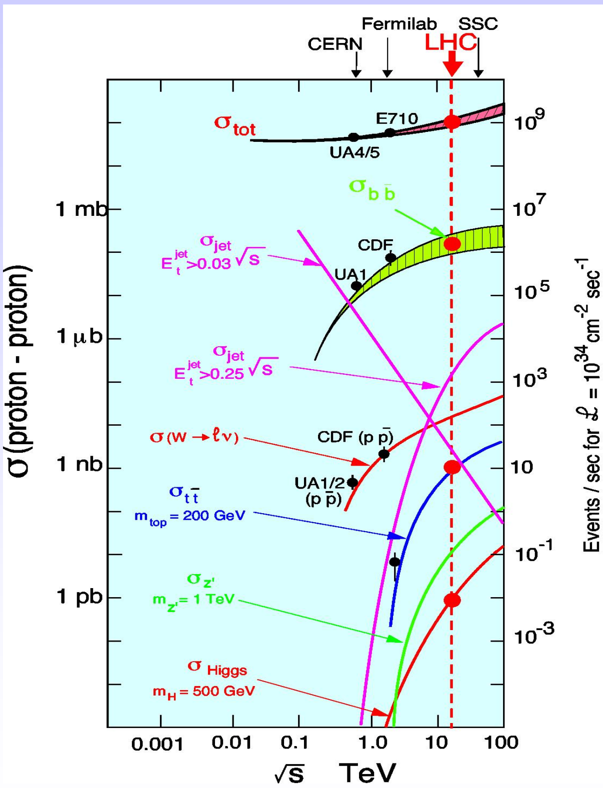
Dominant hard scattering cross section:

„QCD Jet Production“
quark/gluon scattering



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

Cross Sections and Production Rates



Rates for L = 10^{34} cm^{-2} sec^{-1}:

• Inelastic proton-proton reactions:	10^9 / sec
• bb pairs • tt pairs	5 10^6 / sec 8 / sec
• W → e ν • Z → e e	150 / sec 15 / sec
• Higgs (150 GeV) **• Gluino, Squarks (1 TeV)**	**0.2 / sec** **0.03 / sec**

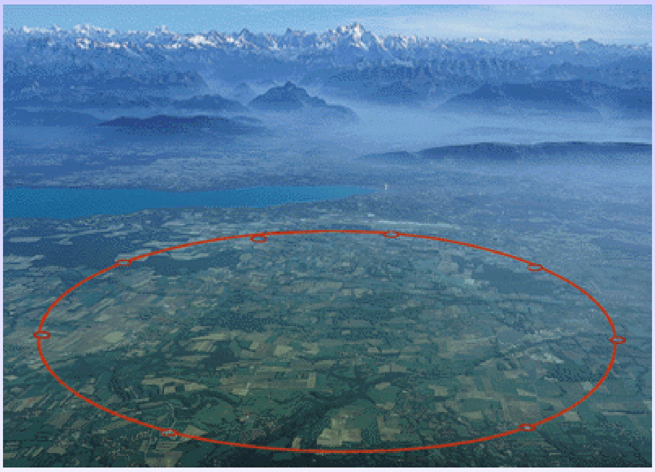
Interesting physics processes are rare:

⇒ high luminosity,
⇒ extremely challenging detectors
(to suppress the huge backgrounds)

The Large Hadron Collider (LHC)

- Proton-Proton accelerator in the LEP tunnel at CERN

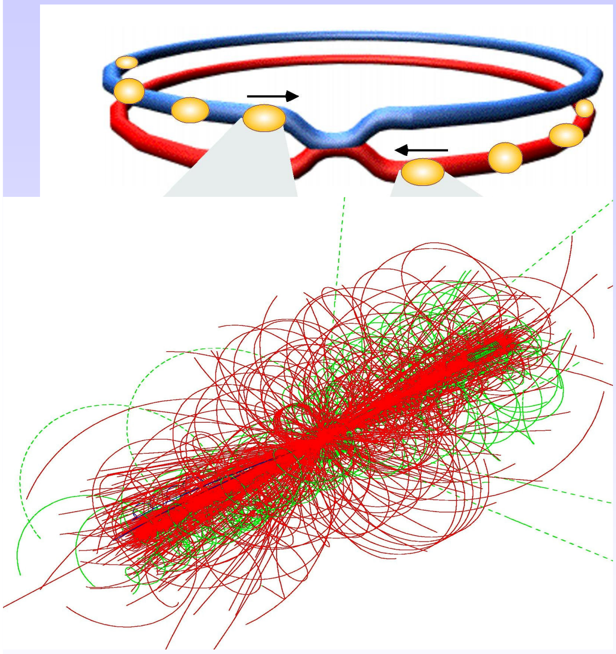
- Four experiments:
  ATLAS, CMS (pp-Physics)
  LHC-B (Physics of b-quarks)
  ALICE (Pb-Pb collisions)



- **Revised Time Schedule:**

Dec. 2006	Ring closed and cold
Jan. - Mar. 2007	Machine commissioning
Spring 2007	First collisions , pilot run. L=5×10^{32} to 2×10^{33} cm^{-2} sec^{-1}, ≤ 1 fb^{-1} Start detector commissioning, ~ 10^5 $Z \to \ell\ell$, $W \to \ell\nu$, tt events
June - Dec. 2007	Complete detector commissioning, Physics run
→ 2009	L=1-2 $\times 10^{34}$, 100 fb^{-1} per year (high luminosity LHC)

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}

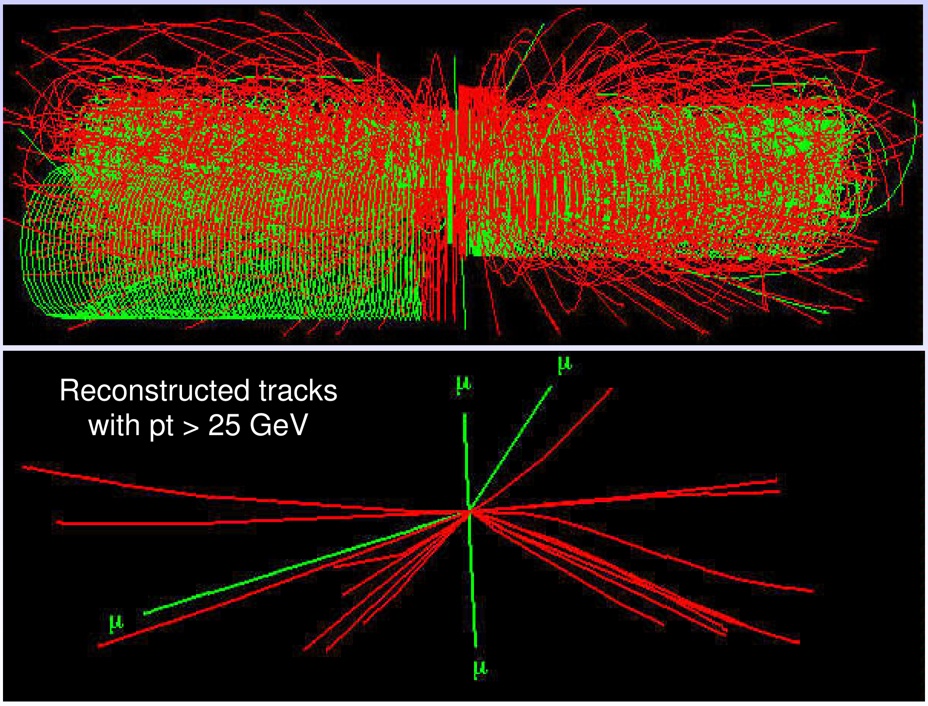
Proton-Proton collisions: ~10^9 / sec
(superposition of 23 pp-interactions per bunch crossing)

~1600 charged particles in the detector

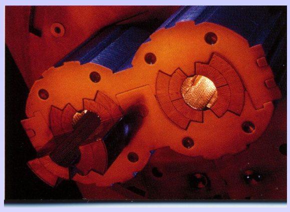
⇒ high particle densities
high requirements on the detectors

Addressed in many Research & Development projects

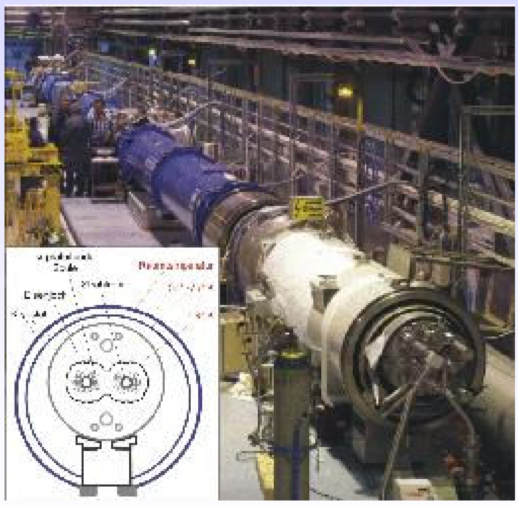
background rejection: Reconstruction of high-PT objects



Important components of the accelerator



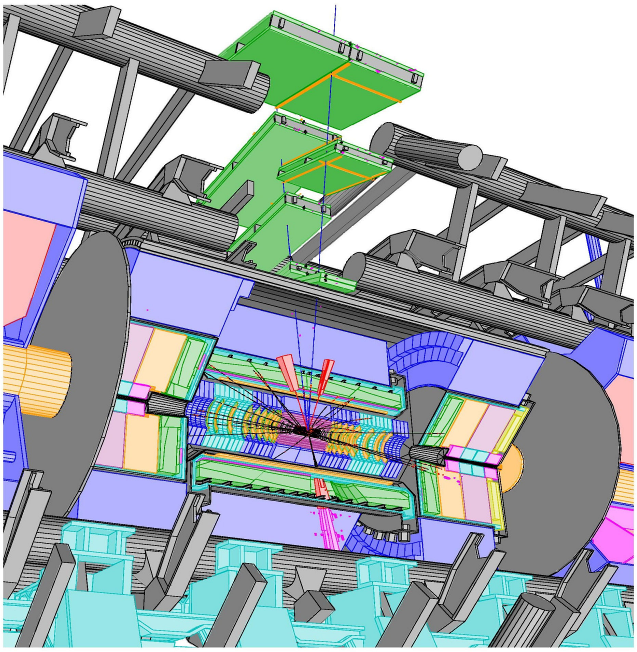
- Superconducting dipole magnets to define the circular orbit
  - biggest challenge: magnetic field of 9 Tesla
  - 1300 magnets in total, 15 m long
  - operated at a temperature of 1.9 K



- Eight superconducting accelerator structures, gradient of 5 MV/m
- Test of a complete LHC-cell has been successfully performed

LHC: the world largest superconducting facility

Detector Requirements

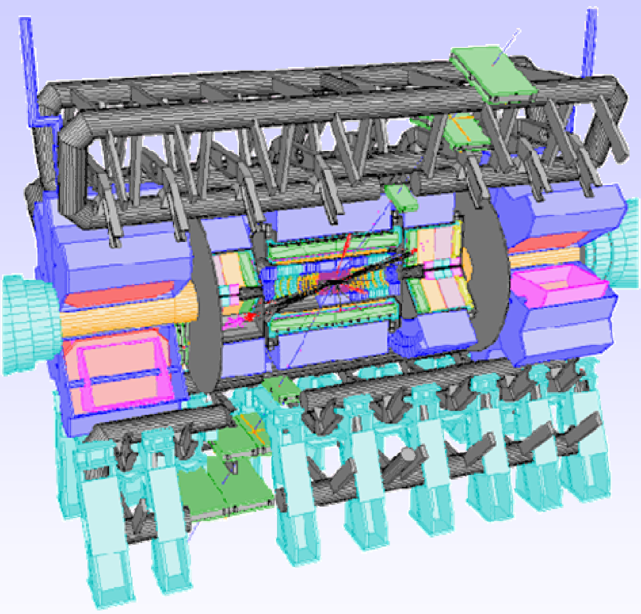


- Good measurement of:
  leptons and photons
  missing transverse energy (E_T^{miss})

- Jet energy measurements and jet-tagging in forward region
  $\Rightarrow$ calorimeter coverage down to η ~ 5

- Efficient **b-tagging** and **τ identification**
  (silicon strip and pixel detectors)

The ATLAS Experiment



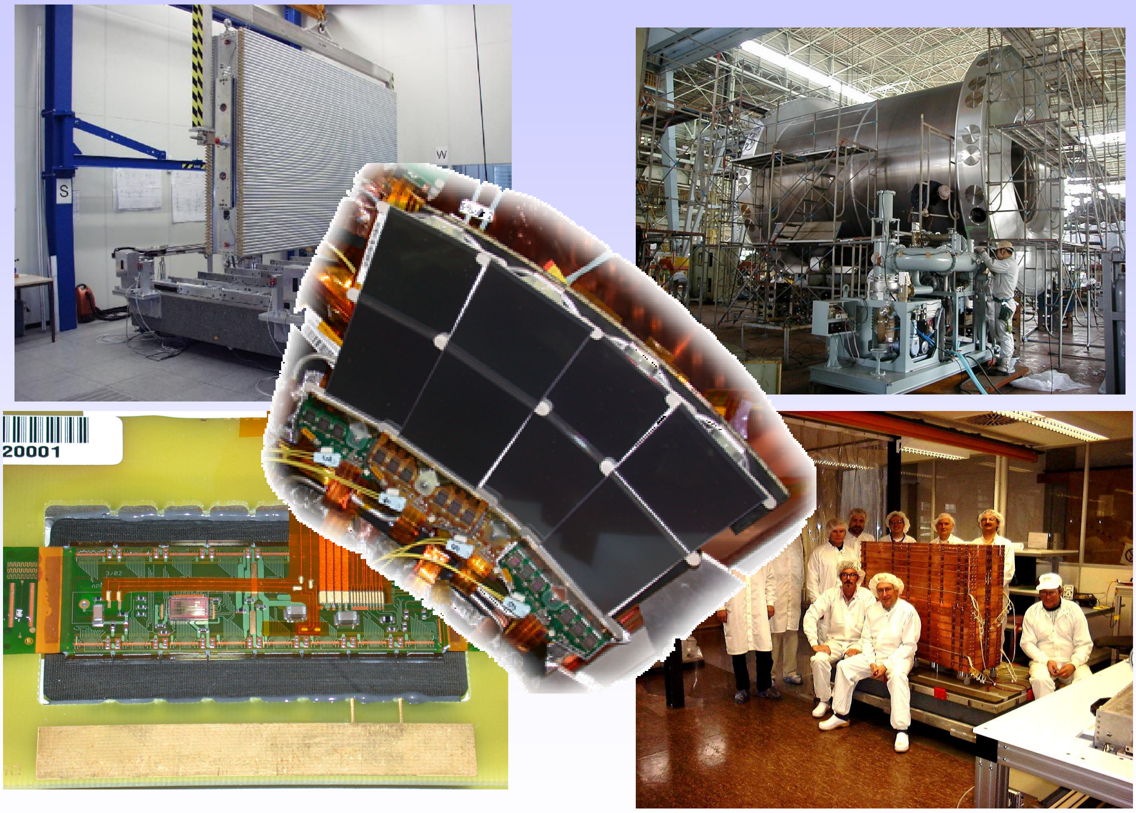
- Solenoidal magnetic field (2T) in the central region
  (measurement of particle momenta)

  high resolution silicon strip and pixel detectors:
  - 6 Mio. channels (80 µm x 12 cm)
  - 100 Mio. channels (50 µm x 400 µm)
  resolution: ~ 15 µm

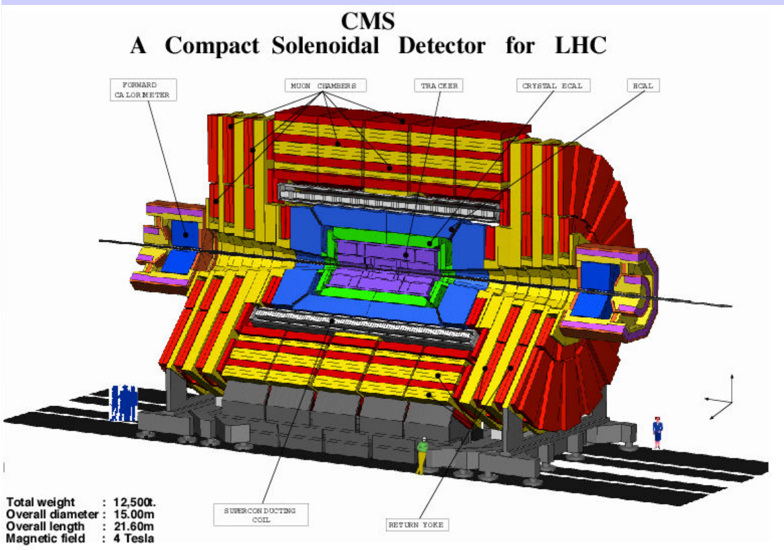
- Energy measurement in calorimeters down to ~1º to the beam line
  (liquid argon calorimeters, scintillator tiles)

- Independent muon spectrometer
  (superconducting toroid system)

ATLAS detector construction



The CMS experiment



- Solenoidal magnetic field (4T) in the central region
  (tracking, momentum measurement)

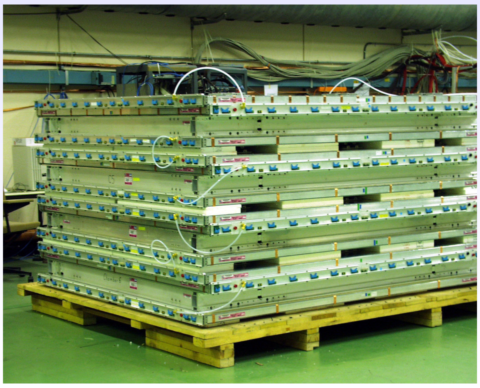
  One magnet system only !

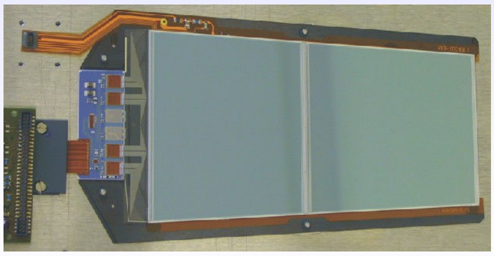
- High resolution silicon tracking detector
  - 9,7 Mio. channels, 210 m^2

- Energy measurement in a crystal calorimeter ($Pb WO_4$)

  (good electron/photon resolution)

CMS detector construction

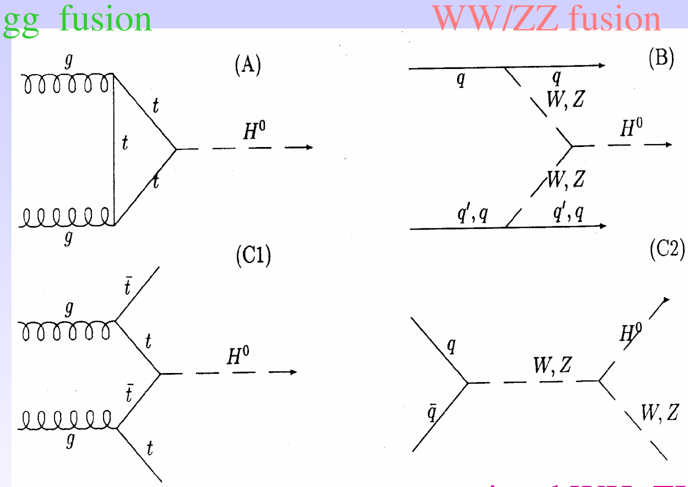




Higgs Boson Production at Hadron Colliders

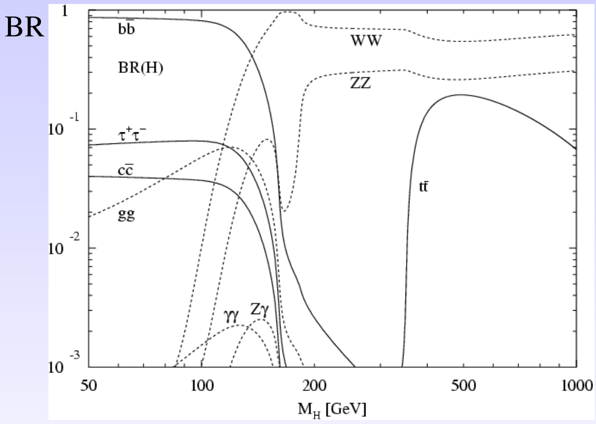
gg fusion

WW/ZZ fusion



associated $t\bar{t}H$

associated WH, ZH



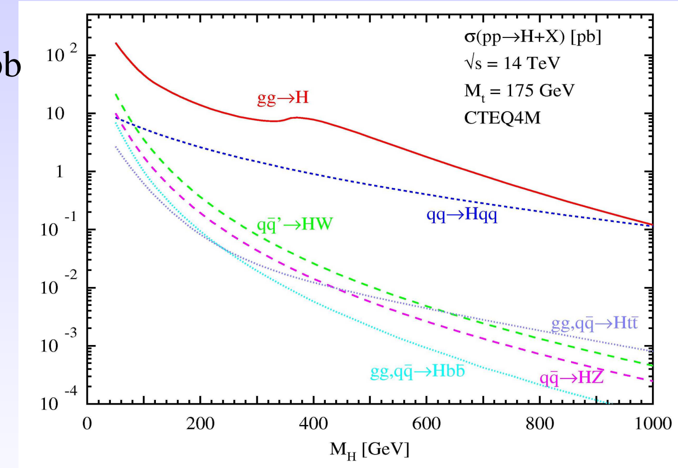
Lepton and Photon final states are essential (**via H → WW , ZZ, (ττ), γγ**) (QCD jet background)

bb decay mode only possible in associated production (W/Z, tt)

Higgs Boson Production cross sections

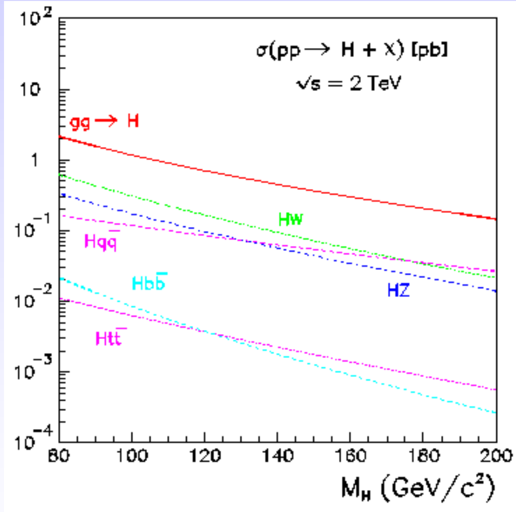
LHC M. Spira et al.

pb



Tevatron M.Spira et al.

pb



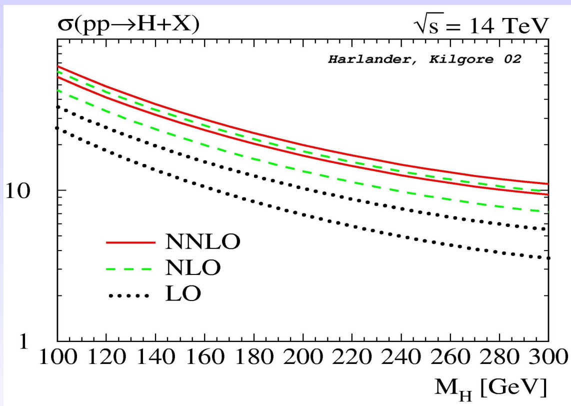
qq → W/Z + H cross sections ~10 x larger at the LHC
gg → H ~70-80 x larger at the LHC

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)]



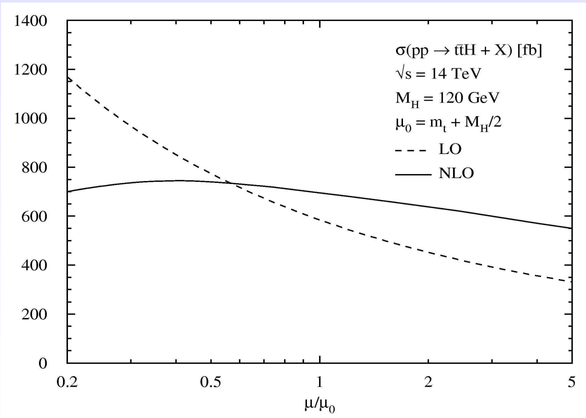
2. Weak boson fusion: K ~1.1
[Han, Valencia, Willenbrock (92)] [Spira (98)]

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

Status of higher order corrections (cont.)

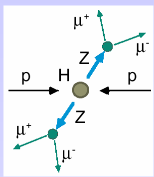
4. ttH associated production:

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



$H \rightarrow ZZ^{(*)} \rightarrow \ell\ell\ell\ell$

Signal: σ BR = 5.7 fb (m_H = 100 GeV)



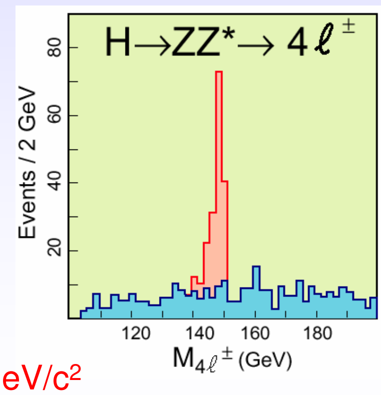
Background: Top production
$tt \rightarrow Wb\,Wb \rightarrow \ell\nu\; c\ell\nu\; \ell\nu\; c\ell\nu$
σ BR ≈ 1300 pb

Associated production Z bb
$Z\,bb \rightarrow \ell\ell\; c\ell\nu\; c\ell\nu$

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

$M(ll) \sim M_Z$
$M(l'l') \sim < M_Z$

$L = 100\ fb^{-1}$

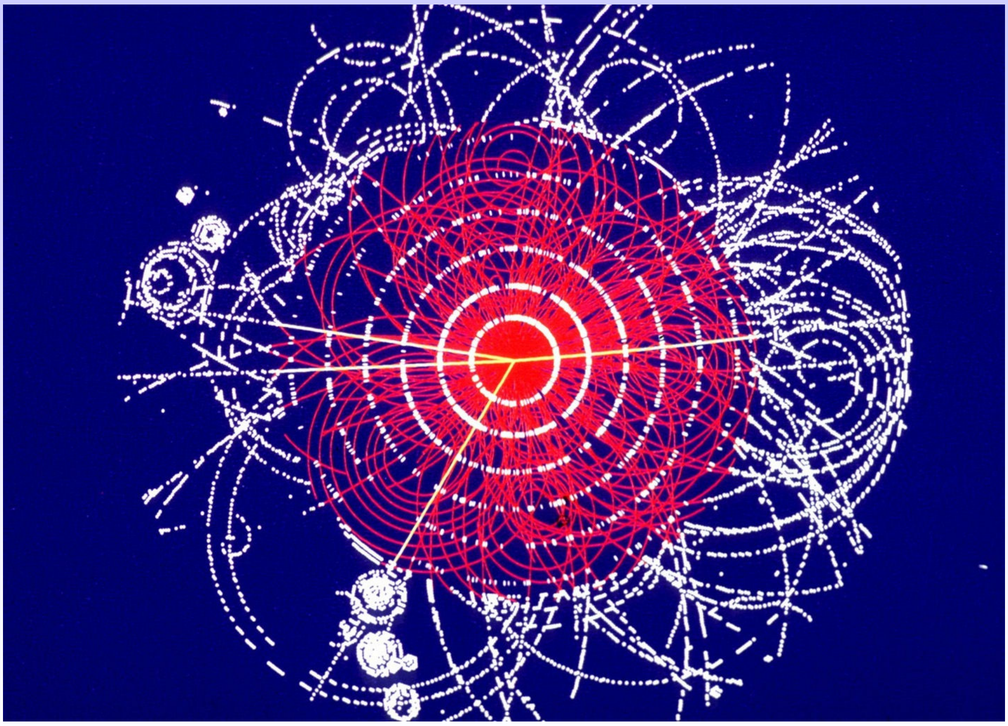


Background rejection: Leptons from b-quark decays
→ non isolated
→ do not originate from primary vertex
(B-meson lifetime: ~ 1.5 ps)

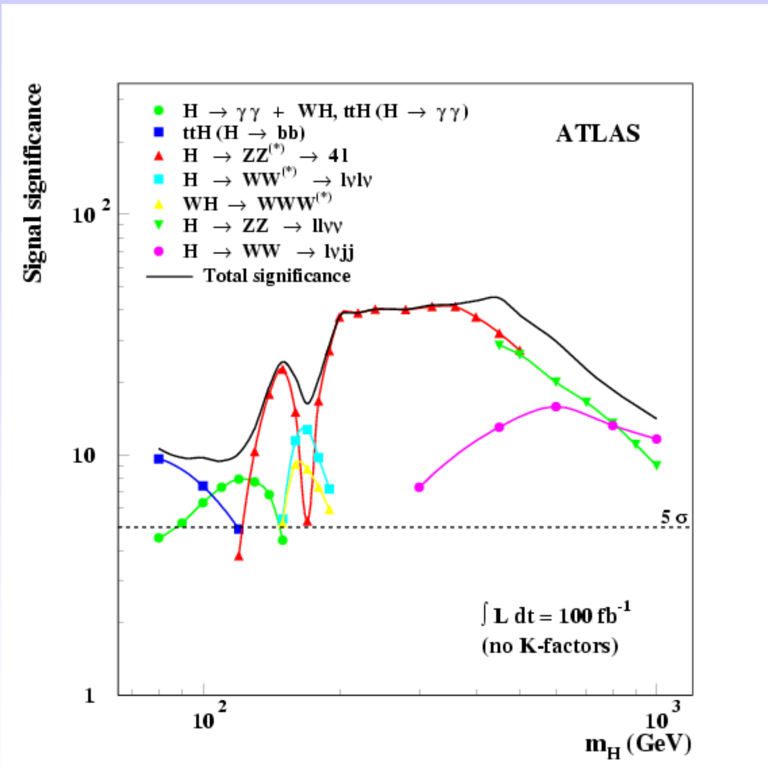
Dominant background after isolation cuts: ZZ continuum

Discovery potential in mass range from ~130 to ~600 GeV/c²

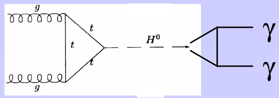
A simulated H → ZZ → ℓℓℓℓ event



$$\frac{S}{\sqrt{B}}$$

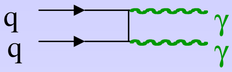


$H \to \gamma\gamma$

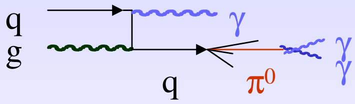


$m_H \leq 150$ GeV

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



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



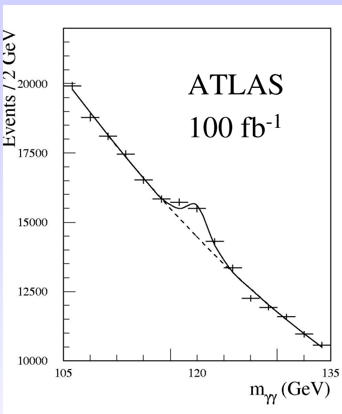
– γj+ jj (reducible):

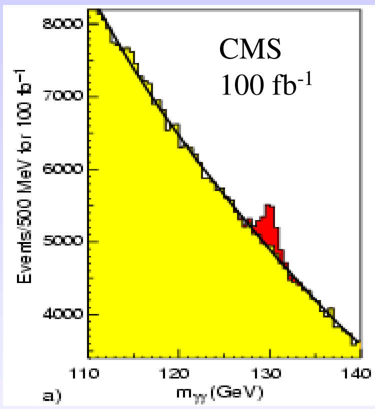
$\sigma_{\gamma j+jj} \sim 10^6\, \sigma_{\gamma\gamma}$ with large uncertainties
$\to$ need $R_j > 10^3$ for $\varepsilon_\gamma \approx 80\%$ to get $\sigma_{\gamma j+jj} << \sigma_{\gamma\gamma}$

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

ATLAS and CMS: complementary performance

$H \to \gamma\gamma$ (cont.)





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

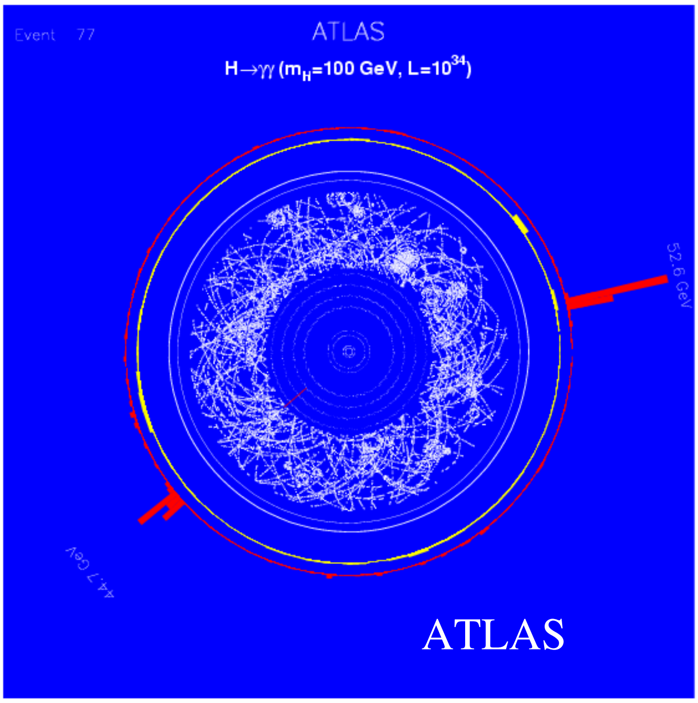
Mass resolution: $m_H = 100$ GeV/c²

ATLAS : 1.1 GeV (LAr-Pb)
CMS : 0.6 GeV (crystals)

Signal / background ~ 4% (Sensitivity in mass range 100 – 140 GeV/c²)
background (dominated by $\gamma\gamma$ events *) can be determined from side bands
important: $\gamma\gamma$-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 $\gamma\gamma$-background

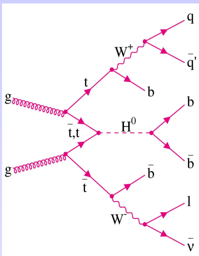
A simulated $H \to \gamma\gamma$ event in ATLAS



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

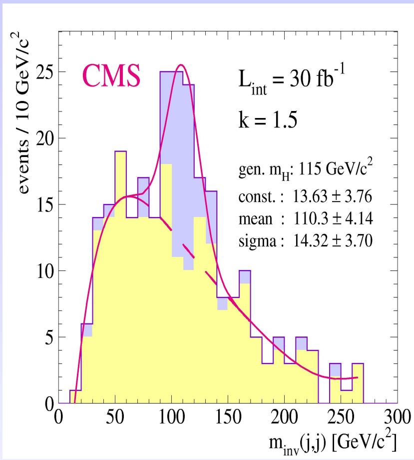
σ x BR ≈ 300 fb

Complex final state: $H \to bb$, $t \to bjj$, $t \to b\ell\nu$



- Main backgrounds:
  - -- combinatorial from signal (4b in final state)
  - -- Wjjjjjj, 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)



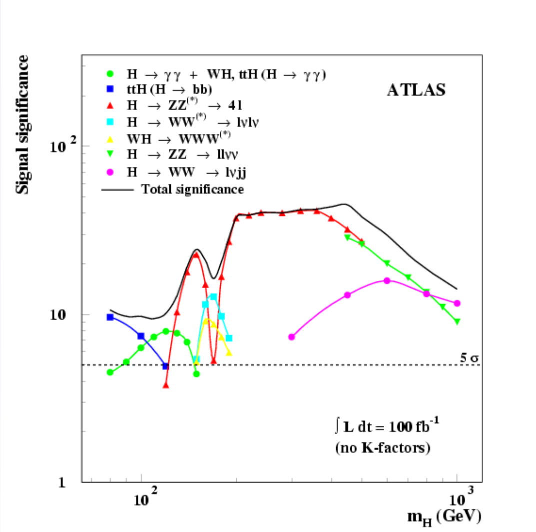
S = 38 events
B = 52 events
S/B ~ 0.73

$S/\sqrt{B}$ = 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)

The LHC Higgs discovery potential



$\frac{S}{\sqrt{B}}$

10 fb^{-1}: Discovery possible over the full mass range, however, needs combination of ATLAS + CMS

M_H = 115 GeV: $S/\sqrt{B}$ = 4.7

$m_H < 2\, m_Z$: $t\bar{t}H \rightarrow \ell b\bar{b} + X,\ \ H \rightarrow \gamma\gamma,$

$H \rightarrow ZZ^* \rightarrow 4\ell,\ \ H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$

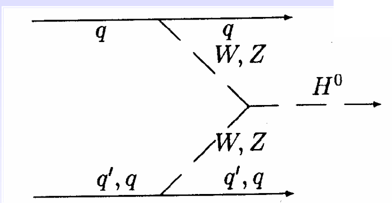
$m_H > 2\, m_Z$: $H \rightarrow ZZ \rightarrow 4\ell$

$qqH \rightarrow qq\, ZZ \rightarrow qq\, \ell\ell\, \nu\nu$
$qqH \rightarrow qq\, ZZ \rightarrow qq\, \ell\ell\, jj$
$qqH \rightarrow qqWW \rightarrow qq\, \ell\nu jj$
} m_H > 300 GeV **forward jet tag**

Higgs Boson Search using vector boson fusion at low mass

Motivation: Increase discovery potential at low mass
Improve measurement of Higgs boson parameter
(couplings to bosons, fermions (taus))

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



Distinctive Signature of:

- **two high P_T forward jets**
- **little jet activity in the central region**
  - ⇒ **Jet Veto**

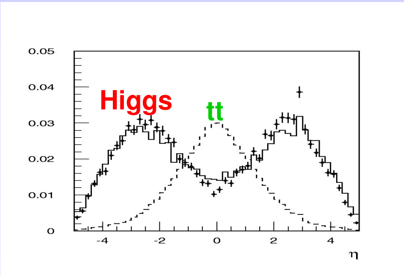
⇒ **Experimental Issues:**

- **Forward jet reconstruction**
- **Jets from pile-up in the central/forward region**

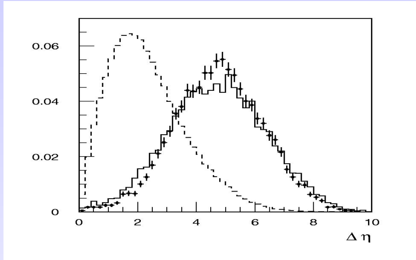
Channels studied: $qqH \rightarrow qqWW^* \rightarrow qq\ \ell\nu\ \ell\nu$
$qqH \rightarrow qq\ \tau\ \tau \rightarrow qq\ \ell\nu\nu\ \ell\nu\nu$
$\rightarrow qq\ \ell\nu\nu\ \text{had}\ \nu$

Forward jet tagging

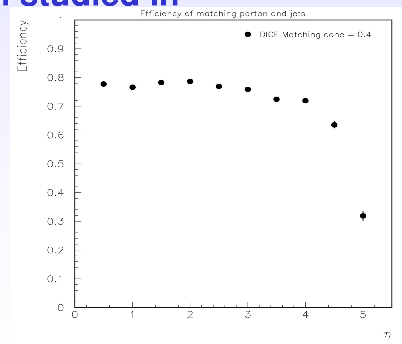
Rapidity distribution of tag jets
VBF Higgs events vs. tt-background



Rapidity separation



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



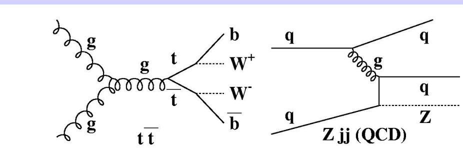
kin. eff. for tag jets = 51.9%
($P_T > 40/20$ GeV, $\Delta\eta > 3.6$)

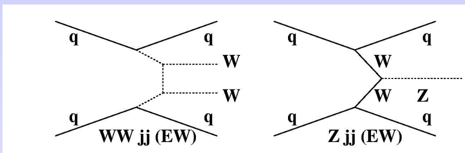
tag eff. per jet: around 75%

Background:

QCD backgrounds:
tt production Z + 2 jets

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

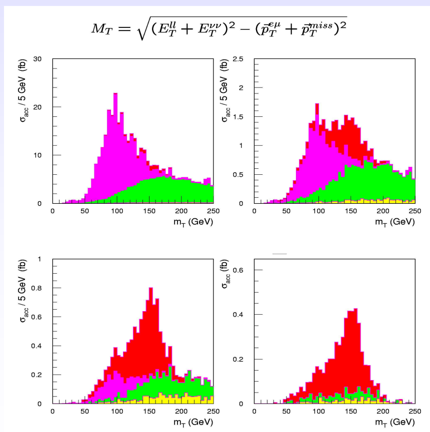




Background rejection:

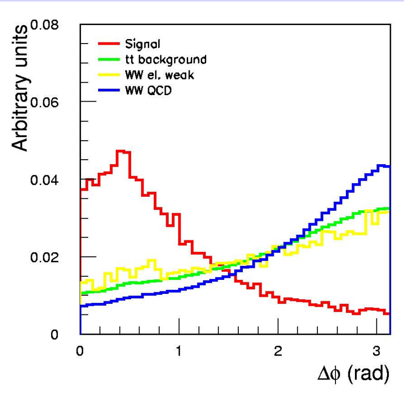
qqH → qqWW* → qq l ν l ν

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



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

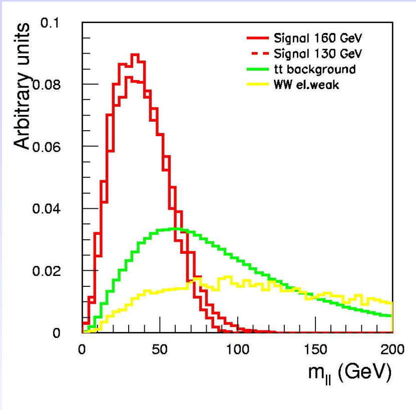
Discrimination between signal and background in $H \to WW \to \ell \nu \ell \nu$



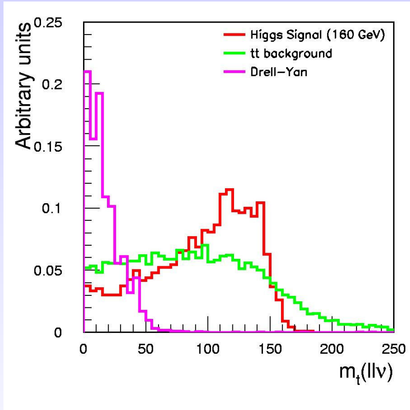
$\Delta\phi\ (\ell\ell)$

Spin 0 → W W

expect charged leptons to close by in space



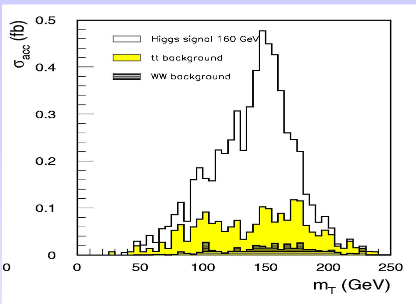
$m\ (\ell\ell)$



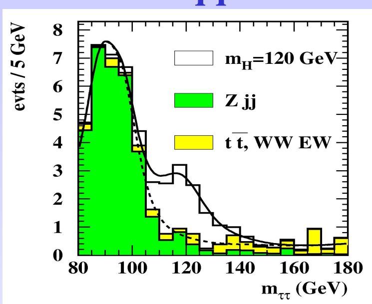
Transverse mass $m_T(\ell\ell\nu)$

---

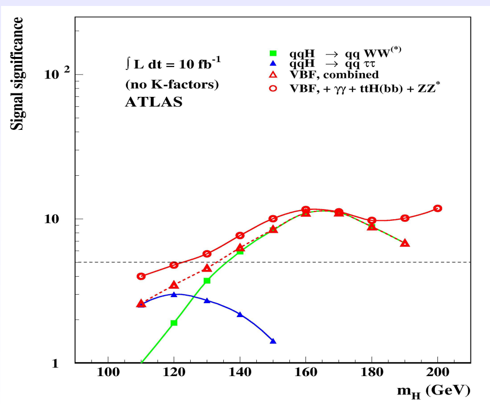
qq H → qq WW* → qq l ν l ν



qq H → qq τ τ → qq l ν ν l ν ν → qq l ν ν h ν



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

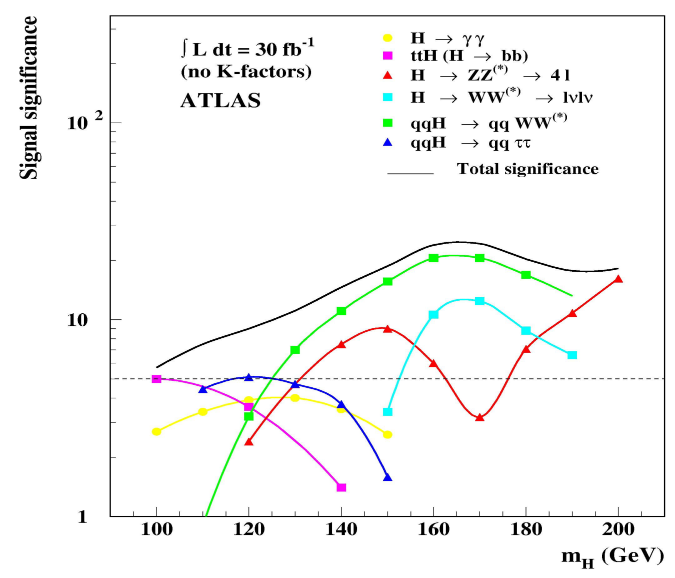


- VBF channels (in particular WW*) are discovery channels at low luminosity

- **For 10 fb^{-1} in ATLAS:**

5 σ significance for $120 \le m_H \le 190$ GeV

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



- Vector boson fusion channels improve the sensitivity significantly in the low mass region
- Several channels available over the full mass range

MSSM Higgs Boson Search at the LHC

Important channels in the MSSM Higgs boson search:

1. The Standard Model decay channels
   - h → γγ
   - tt h, h → bb

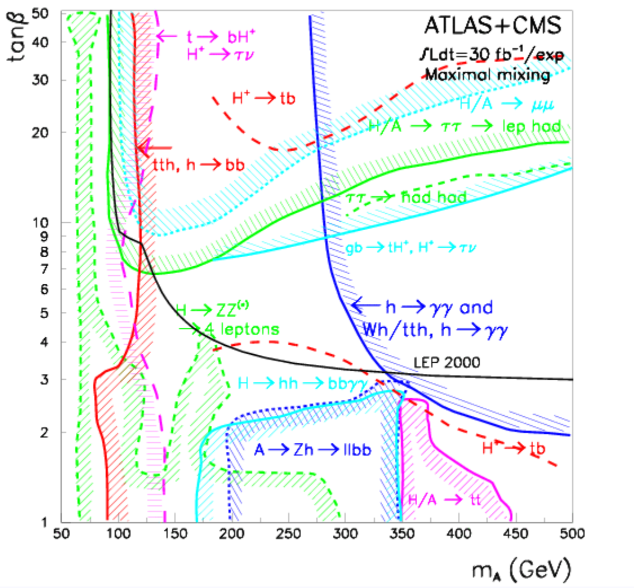
   evaluation of performance is based on SM results

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

3. Other interesting channels:
   - H/A → tt
   - H/A → Zh → ℓℓ γγ
     → ℓℓ bb
   - H → hh

LHC can also discover MSSM Higgs bosons

5σ discovery in m_A – tan β plane

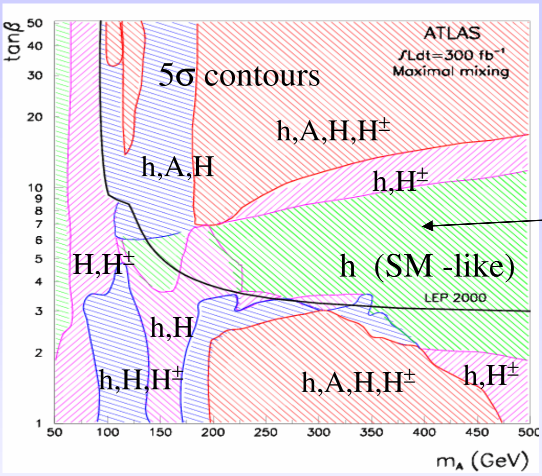


m_{SUSY} = 1 TeV, m_{top} = 175 GeV/c^2

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

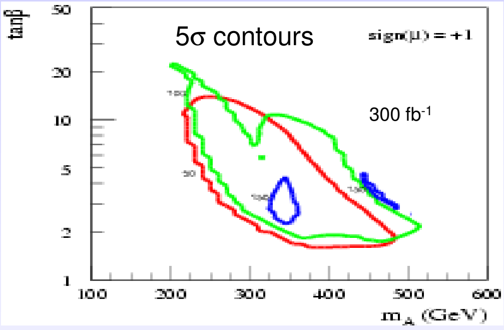
Possible coverage: * via SUSY decays (model dependent, under study)
* luminosity (only moderate improvement)

K. Jakobs CTEQ school, Sant Feliu de Guixols, Spain, May 2003

Higgs decays via SUSY particles

If SUSY exists : search for

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



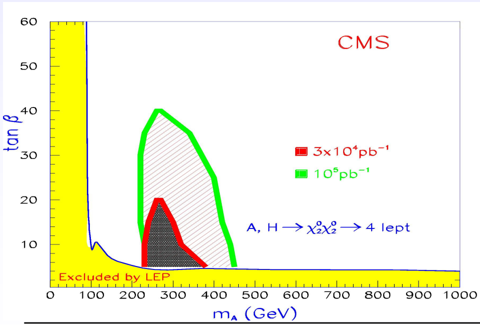
ATLAS: SUGRA scan

m_0 = 50 - 250 GeV

$m_{1/2}$ = 100 - 300 GeV

tan β = 1.5 - 50

A_0 = 0



CMS: special choice in MSSM (no scan)

M_1 = 60 GeV

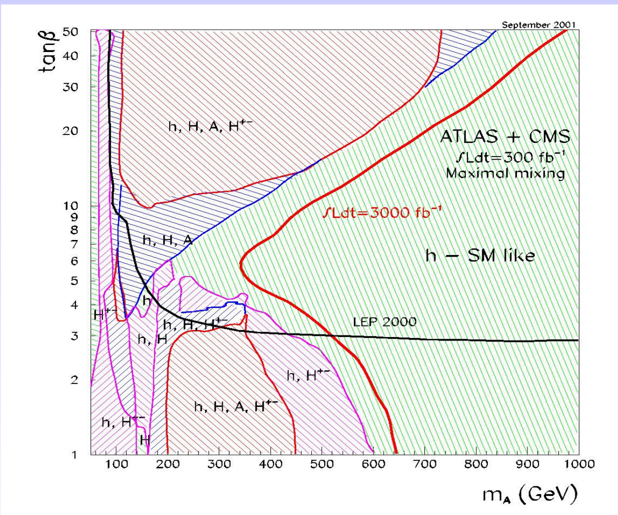
M_2 = 110 GeV

μ = -500 GeV

Exclusions depend on MSSM parameters (slepton masses, μ)

MSSM discovery potential for Super-LHC

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

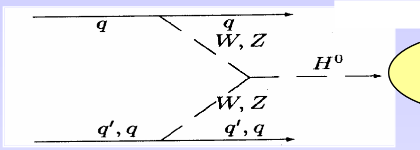


- Situation can be improved, in particular for m_A < ~400 GeV
- But: (S)LHC can not promise a complete observation of the heavy part of the MSSM Higgs spectrum ....

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

Invisible Higgs decays ?

Possible searches: tt H $\rightarrow$ $\ell\nu$b qqb + P_T^{miss}
W/Z H $\rightarrow$ $\ell\nu$ ($\ell\ell$) + P_T^{miss}
qq H $\rightarrow$ qq + P_T^{miss}



P_T^{miss}

Preliminary ATLAS study:

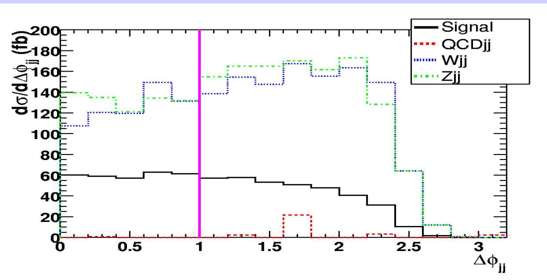
search for invisibly decaying Higgs boson in VBF mode
(based on study by O.Eboli and D.Zeppenfeld, Phys.Lett.B495 (2000))

Event selection: 2 tag jets, (P_T, $\Delta\eta$, 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 $\rightarrow$ $\ell\nu$)
Z jj production (Z $\rightarrow$ $\nu\nu$)
QCD jet production, fake P_T^{miss}

Requires special forward jet + P_T^{miss} trigger (preliminary studies $\Rightarrow$ seems feasible)

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

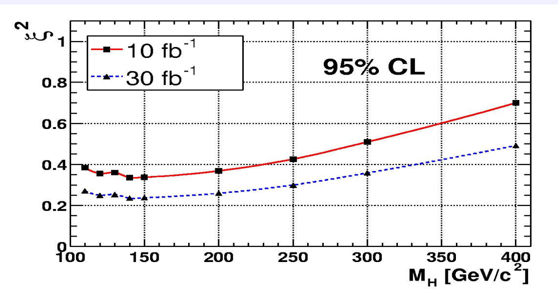


Expected rates for 10 fb^{-1}:

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

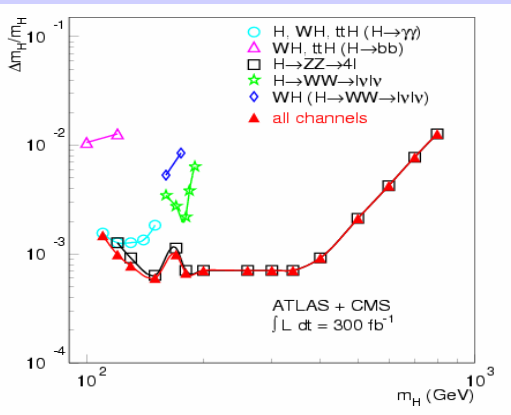


- Needs confirmation from more detailed simulation (trigger)
- Non-Standard Model background ??
- Needs confirmation in ttH and/or WH channel to demonstrate presence of a Higgs boson

Determination of Higgs Boson Parameters

1. Mass
2. Couplings to bosons and fermions
   (impact of vector boson fusion channels)
3. Spin
4. Higgs self coupling

Measurement of the Higgs boson mass



No theoretical error, e.g. mass shift for large Γ_H
(interference resonant/non-resonant production)

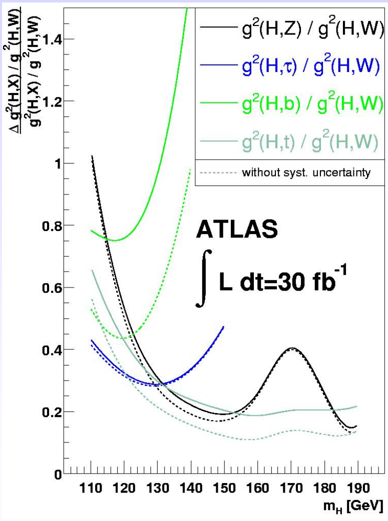
Dominant systematic uncertainty: γ / ℓ E scale.
Assumed 1‰
Goal 0.2‰
Scale from $Z \rightarrow \ell\ell$ (close to light Higgs)

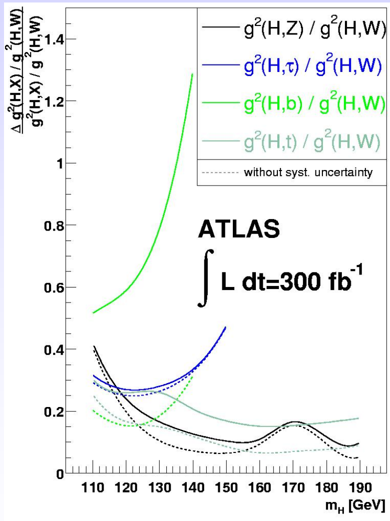
Higgs boson mass can be measured with a precision of 0.1%
over a large mass range (130 - ~450 GeV / c^2)

Measurement of Higgs Boson Couplings

Global likelihood-fit   (at each possible Higgs boson mass)
Input: measured rates, separated for the various production modes

Output: Higgs boson couplings, normalized to the WW-coupling

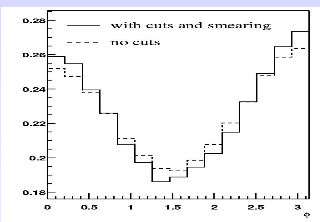


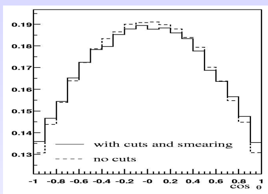


Relative couplings can be measured with a precision of 10-20% (for 300 fb^{-1})

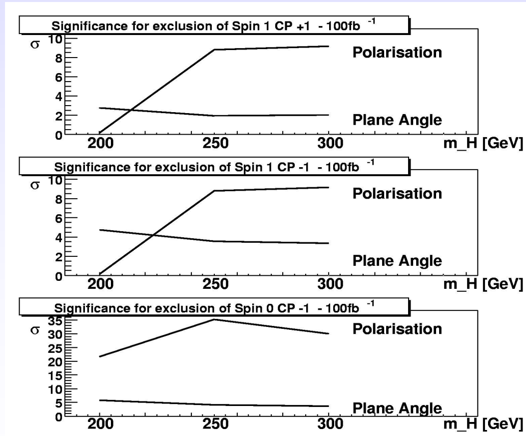
Higgs Boson spin ?

- 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

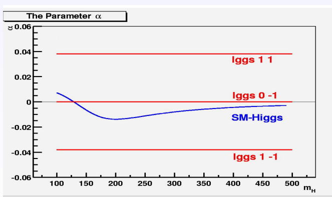


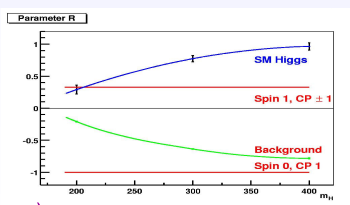


Expected results:



Fit to $F(\phi) = \alpha \cos(\phi) + \beta \cos(2\phi)$
$F(\theta) = T\,(1+\cos^2\theta) + L \sin^2\theta$ $R = (L-T) / (L+T)$

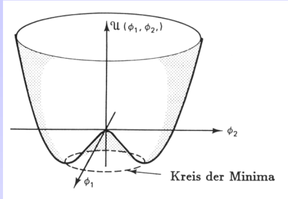




(J.R. Dell´Aquila, C.A. Nelson)

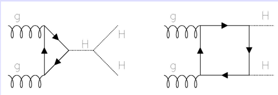
Higgs Bosons Self-coupling ?

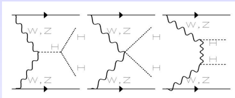
to establish the Higgs mechanism the Higgs boson self-coupling has to be measured:

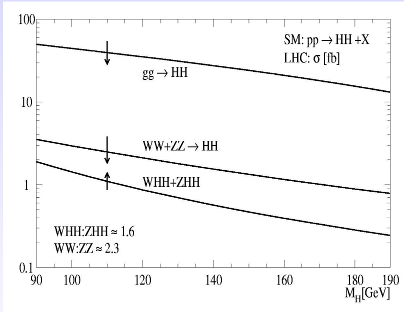


$$\lambda_{HHH}^{SM} = 3\,\frac{m_H^2}{v}\,, \quad \lambda_{HHHH}^{SM} = 3\,\frac{m_H^2}{v^2}$$

Cross sections for HH production:







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

⇒ no significant measurement possible at the LHC

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

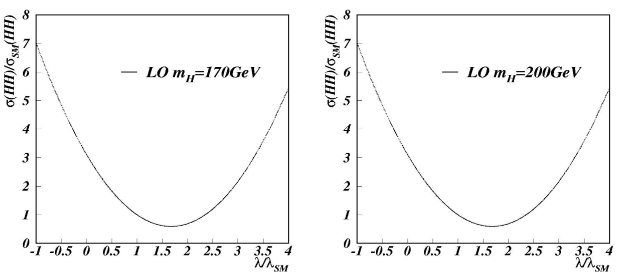
Most sensitive channel: **gg → HH → WW WW → ℓν jj ℓν jj**

- 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} ⇒ $\Delta\lambda_{HHH}/\lambda_{HHH}$ = 19 % (stat.) (for m_H = 170 GeV)
$\Delta\lambda_{HHH}/\lambda_{HHH}$ = 25 % (stat.) (for m_H = 200 GeV)

The Search for the

Higgs Boson

at Fermilab

The Tevatron collider at Fermilab

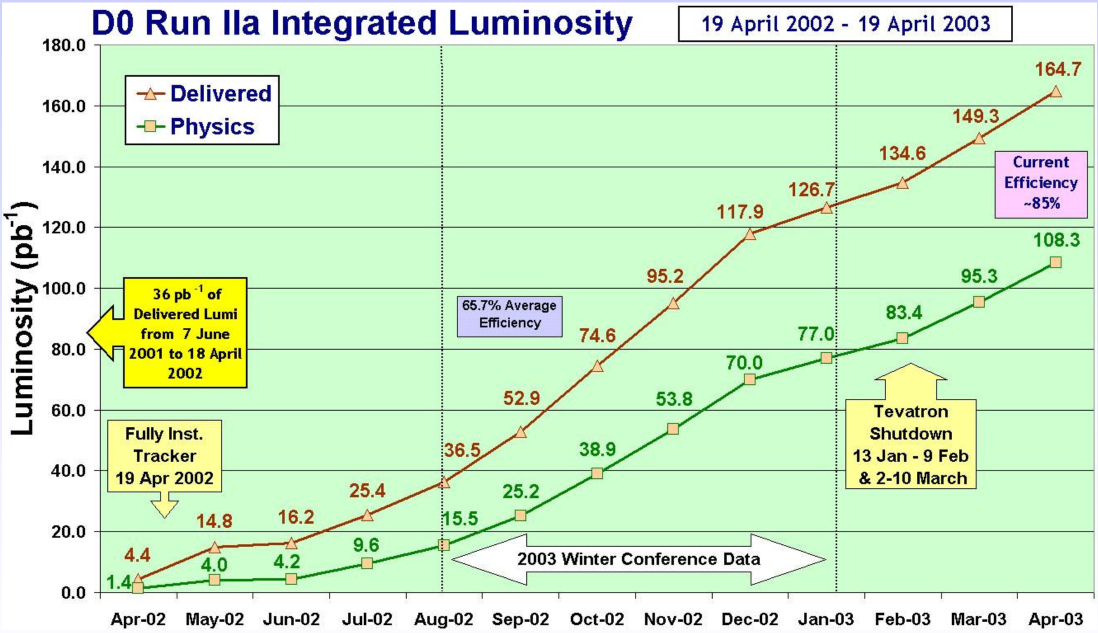
Proton-antiproton collider

- **1992 - 1996: Run I, 2 experiments**
  CDF und D0, $\sqrt{s}$ = 1800 GeV
  $\int L\,dt$ = 125 pb $^{-1}$

- **1996 - 2001: Upgrade programme**
  (maschine und detectors)

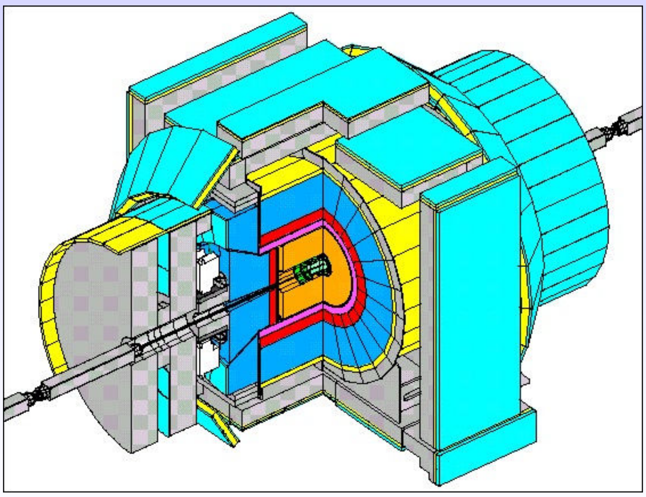
- **since March 2001: Run II a,**
  $\sqrt{s}$ = 1960 GeV, 2 fb^{-1}
- **2005 - LHC : Run II b,**
  $\sqrt{s}$ = 1960 GeV, 10-20 fb^{-1}
  0.8 → 5.0 10^{32} cm^{-2} s^{-1}

The Tevatron Run-IIa performance



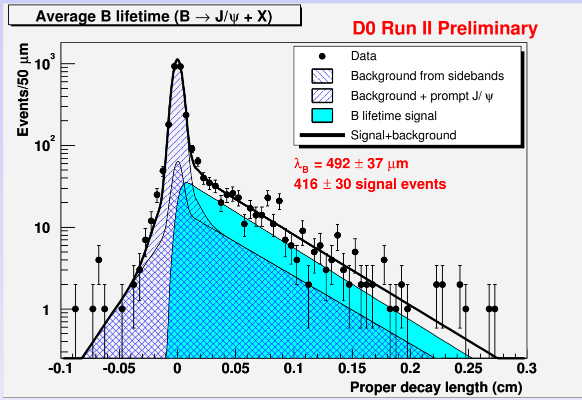
The Upgraded CDF Detector

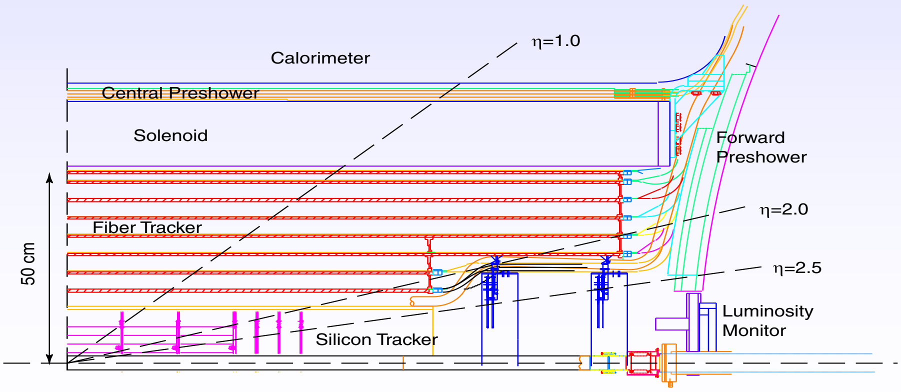
- New central drift chamber and silicon tracker
- New forward calorimeters ("plug") $(1<|\eta|<3)$
- New TOF, extended muon coverage, improved triggers, ...



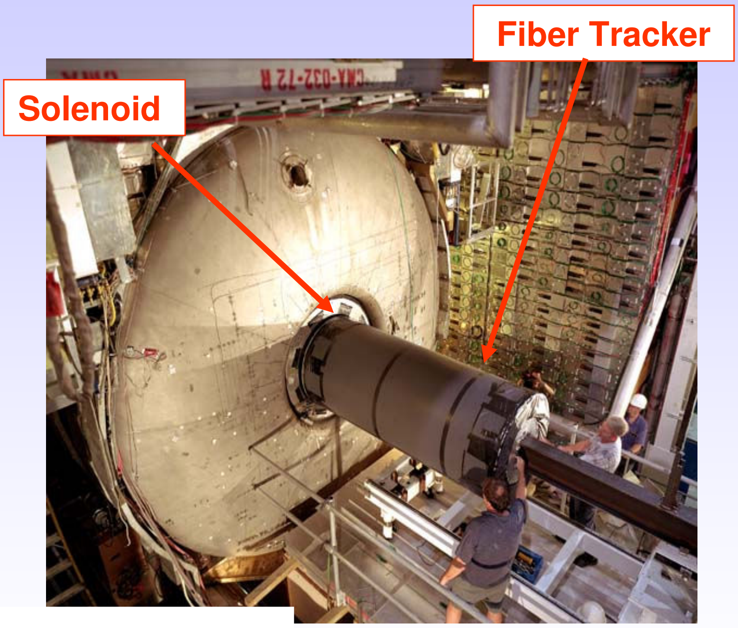
The Upgraded DØ Detector

- First time charged particle tracking added to a major "non-magnetic" detector!
  - 2T solenoid
  - >100K scintillating fibers
  - >700K silicon strips
- Major improvements to muon spectrometer, trigger/DAQ, ...

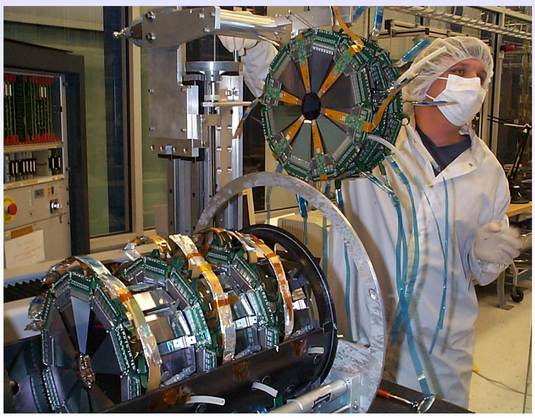




DØ Detector



Silicon Detector



Search channels at the Tevatron

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

Mass range 110 - 130 GeV: **LHC**

- **WH → lν bb** **(✔) weak**
- **ZH → l^+l^- bb** **weak**
- **ZH → νν bb** **∅ (trigger)**
- **ZH → bb bb** **∅ (trigger)**
- **ttH → lν b jjb bb** ✔

Triggering:

is easier at the Tevatron:

- better P_T^{miss}-resolution
- track trigger at level-1 (big challenge)

Mass range 150 - 180 GeV: **LHC**

- **H → $WW^{(*)}$ → lν lν** ✔
- **WH → $WWW^{(*)}$ → lν lν lν** ✔
- **WH → $WWW^{(*)}$ → $l^+\nu$ $l^+\nu$ 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:

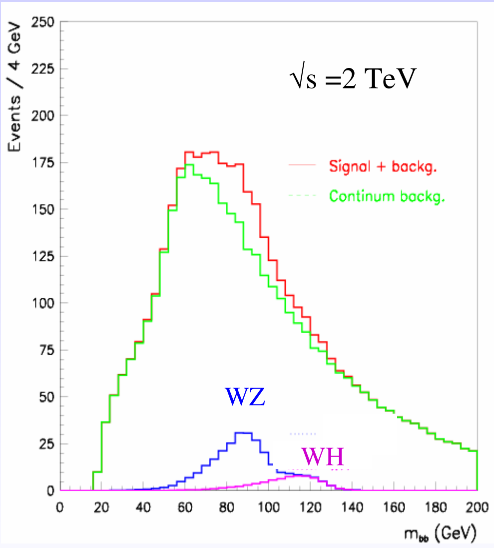
	low mass	high mass
	$WH \to \ell\nu\ b\bar{b}$ $ZH \to \ell\ell\ \ b\bar{b}$	$H \to WW^{(*)} \to \ell\nu\ell\nu$ (M_H = 160 GeV)
S (14 TeV) / S (2 TeV)	≈ 5	≈ 30
B (14 TeV) / B (2 TeV)	≈ 25	≈ 6
S/B (14 TeV) / S/B (2 TeV)	≈ 0.2	≈ 5
S/√B (14 TeV) / S/√B (2 TeV)	≈ 1	≈ 10

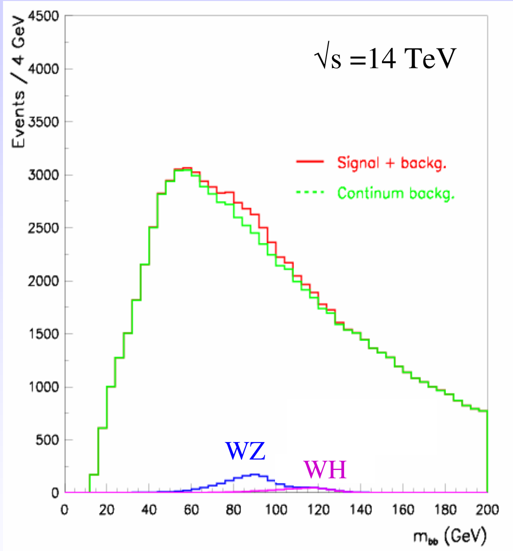
➡ -- comparable discovery potential for WH and ZH:
- larger signal at the LHC
- better S/B-ratio at theTevatron
- difficult at both colliders

-- 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

Expected Tevatron significance in ind. channels

Signal and background rates and S/√B for 1 fb^{-1}

Channel	Rate	Higgs Mass (GeV/c^2) 90	100	110	120	130
$\ell\nu b\bar{b}$ (CDF)	S	8.4	6.6	5.0	3.7	2.2
	B	48	52	48	49	42
	$S/\sqrt{B}$	1.2	0.9	0.7	0.5	0.3
$\ell\nu b\bar{b}$ (SHW)	S	10	8	5	4	3
	B	75	68	57	58	52
	$S/\sqrt{B}$	1.1	1.0	0.7	0.5	0.4
$\ell\nu b\bar{b}$ (NN)	S	8.7	9.0	4.8	4.4	3.7
	B	28	39	19	26	46
	$S/\sqrt{B}$	1.6	1.4	1.1	0.9	0.5
$\nu\bar{\nu}b\bar{b}$ (CDF)	S	2.5	2.2	1.9	1.2	0.6
	B	20.0	18.6	16.0	13.0	9.6
	$S/\sqrt{B}$	0.6	0.5	0.5	0.3	0.2
$\nu\bar{\nu}b\bar{b}$ (SHW)	S	8.9	6.7	4.6	3.2	2.1
	B	77	69	56	39	30
	$S/\sqrt{B}$	1.0	0.8	0.6	0.5	0.4
$\nu\bar{\nu}b\bar{b}$ (NN)	S	12	8	6.3	4.7	3.9
	B	123	70	55	45	47
	$S/\sqrt{B}$	1.1	1.0	0.8	0.7	0.6
$\ell^+\ell^-b\bar{b}$ (CDF)	S	1.0	0.9	0.8	0.5	0.3
	B	3.6	3.1	2.5	1.8	1.1
	$S/\sqrt{B}$	0.5	0.5	0.5	0.4	0.3
$\ell^+\ell^-b\bar{b}$ (SHW)	S	1.5	1.2	0.9	0.6	0.4
	B	4.9	4.3	3.2	2.3	1.9
	$S/\sqrt{B}$	0.7	0.6	0.5	0.4	0.3
$\ell^+\ell^-b\bar{b}$ (NN)	S	1.2	0.9	0.8	0.8	0.6
	B	2.9	1.9	2.3	2.8	1.9
	$S/\sqrt{B}$	0.7	0.7	0.5	0.5	0.4
$q\bar{q}b\bar{b}$ (SHW)	S	8.1	5.6	3.5	2.5	1.3
	B	6800	3600	2800	2300	2000
	$S/\sqrt{B}$	0.10	0.09	0.07	0.05	0.03

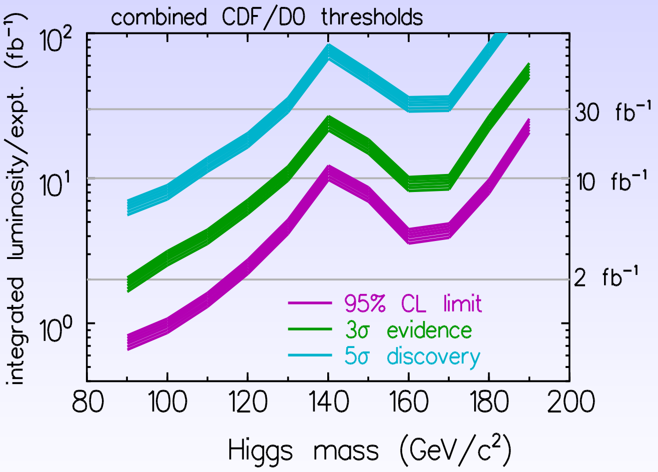
Channel	Rate	Higgs Mass (GeV/c^2) 120	130	140	150	160	170	180
$\ell^+\ell^-\nu\bar{\nu}$	S	-	-	2.6	2.8	1.5	1.1	1.0
	B	-	-	44	30	4.4	2.4	3.8
	$S/\sqrt{B}$	-	-	0.39	0.51	0.71	0.71	0.51
$\ell^\pm\ell^\pm jj$	S	0.08	0.15	0.29	0.36	0.41	0.38	0.26
	B	0.58	0.58	0.58	0.58	0.58	0.58	0.58
	$S/\sqrt{B}$	0.11	0.20	0.38	0.47	0.54	0.50	0.34

Main conclusions:

- Discovery can not be made in a single channel alone; data from all channels must be combined
- Must also combine the data from two experiments
- Must improve the understanding of the background
- and signal processes

Tevatron discovery potential for a light Higgs Boson

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



For 10 fb^{-1} :

(i) 95% CL exclusion of a SM Higgs boson is possible over the full mass range (M_H < 185 GeV)

(ii) 3-σ evidence for M_H < 130 GeV and 155 GeV < M_H < 175 GeV

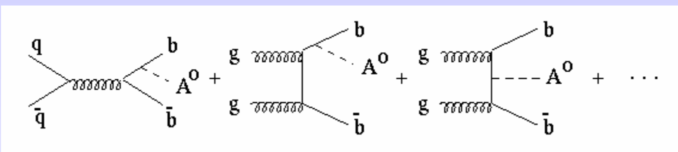
Für 30 fb^{-1} (optimistic) :

(i) 3-σ evidence for the SM Higgs boson is possible over the full mass range (M_H < 185 GeV)

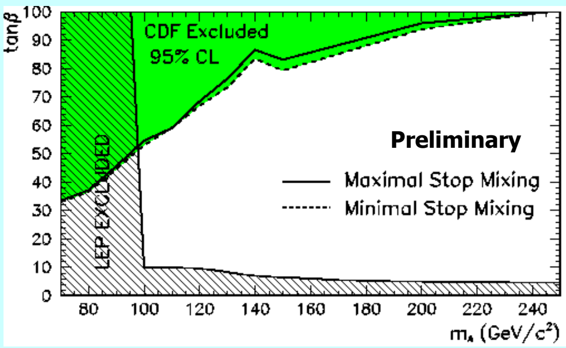
Results of studies with more detailed detector simulations are consistent with previous simulations.

SUSY Higgs Production at the Tevatron

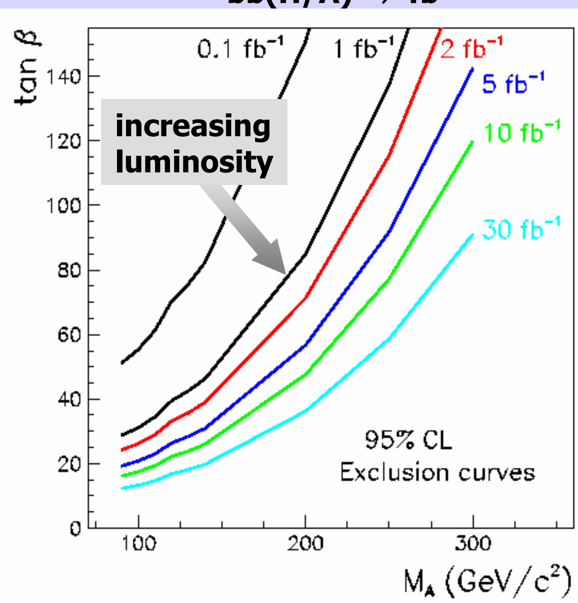
- bb(h/H/A) couplings are enhanced at large tan β
  - σ ~ 1 pb for tan β = 30 and m_h = 130 GeV



CDF Run 1 analysis (4 jets, 3 b tags) sensitive to tan β > 60



bb(H/A) → 4b



First steps towards the Higgs search at the Tevatron

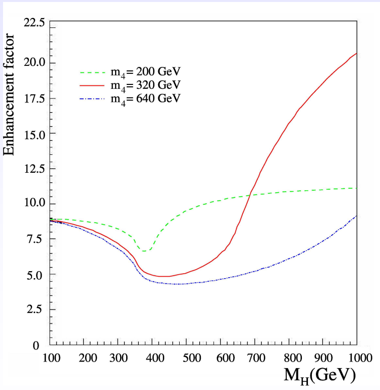
With present integrated luminosity, no sensitivity yet for a SM Higgs boson:

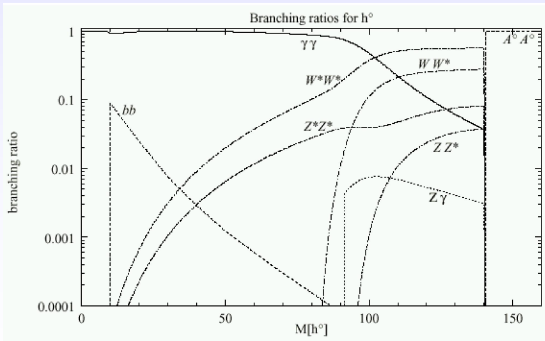
⇒ study the backgrounds

⇒ search for **exotic Higgs bosons**

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





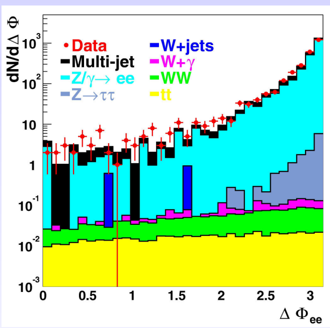
D0´s first look at: $H \rightarrow WW \rightarrow e \nu e \nu$

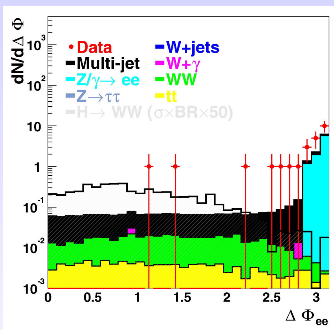
Search for ee + P_T^{miss} events,

Study of $\Delta\phi$ (ℓℓ) distribution at various level of the cuts:

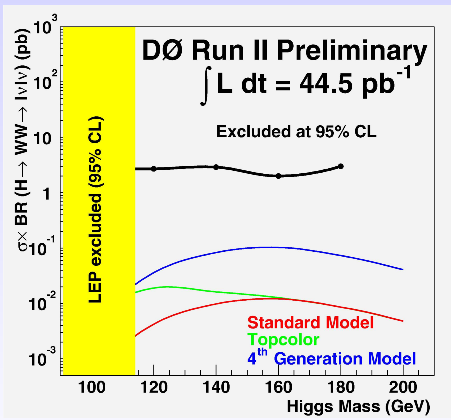
luminosity

44.5 pb^{-1}





Require good e^+e^- , missing E_T



Data are consistent with background expectations

Conclusions

- Electroweak precision data from LEP/SLC suggest a light Higgs boson
- Significance for a 115 GeV Higgs boson at LEP is only at the 1.7 σ level (after final analysis)

- Should a SM Higgs boson or MSSM Higgs bosons exist, they can not escape detection at the LHC

- Tevatron might have a 3-σ discovery windows, however, much depends on the detector and accelerator performance.

Updated set of transparencies under: http://www.uni-mainz.de/~jakobs/atlas/cteq-2003.ppt
http://www.uni-mainz.de/~jakobs/atlas/cteq-2003.pdf