Search for the Higgs Boson at Hadron Colliders

- **Introduction**

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

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

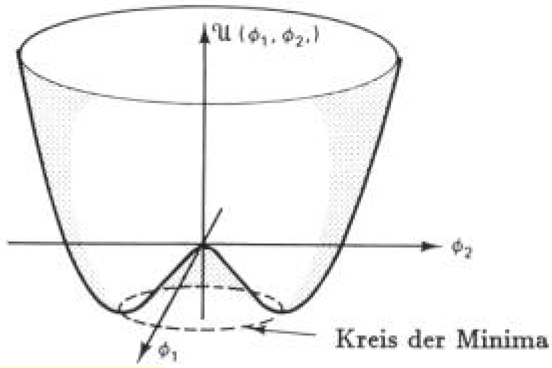
- **Present status at Fermilab**

Karl Jakobs
Institut für Physik
Universität Mainz
55099 Mainz

The Higgs Mechanism

• Essential ingredient of the Standard Model**:**

complex scalar field with potential $\mathcal{U}(\phi) = \mu^2(\phi^*\phi) + \lambda(\phi^*\phi)^2$



• Used to break the el.weak symmetry......

$M_{W^\pm} = \frac{1}{2} v g$ $\quad$ $M_Z = \frac{1}{2} v g / \cos\theta_W = M_W / \cos\theta_W$

..... and to generate fermion masses:

$$m_f = g_f v / \sqrt{2} \qquad \Rightarrow g_f = m_f \sqrt{2} v$$

• Search for the associated Higgs Boson is a key issue for experiments at future colliders

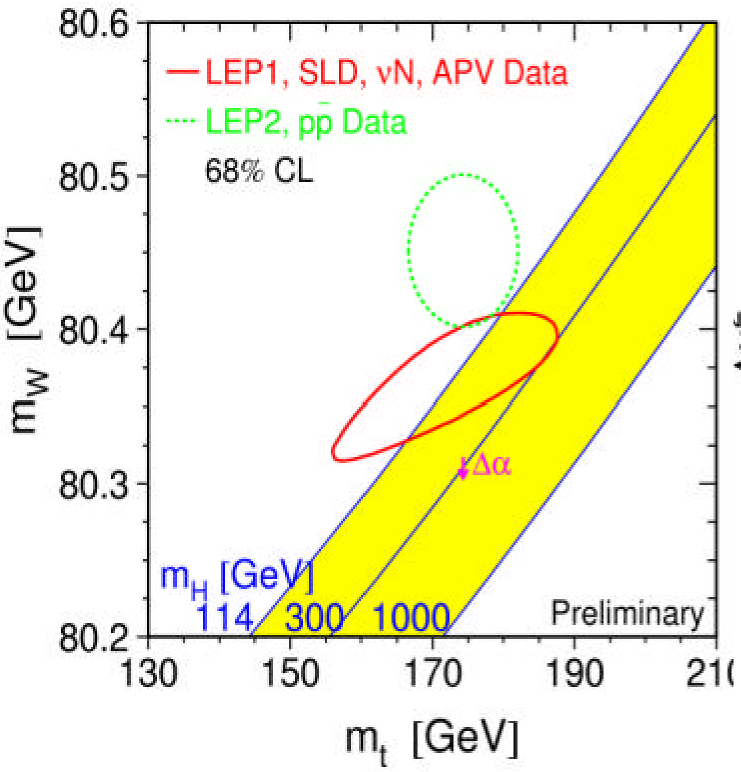
Experimental steps:

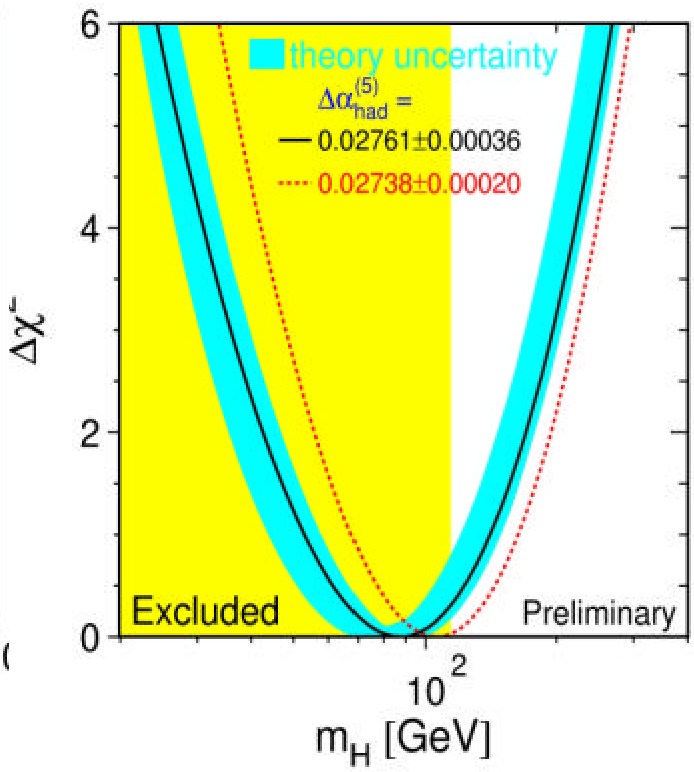
1. Higgs boson discovery
2. Measurement of Higgs boson parameters (couplings to bosons and fermions)
3. Measurment of the Higgs self coupling
   $\Rightarrow$ Higgs potential

Constraints on the Higgs boson mass:

1. Direct searches at LEP: **M_H > 114.4 GeV/c²**

2. Indirect mass limits from el.weak precision data (LEP + Tevatron):





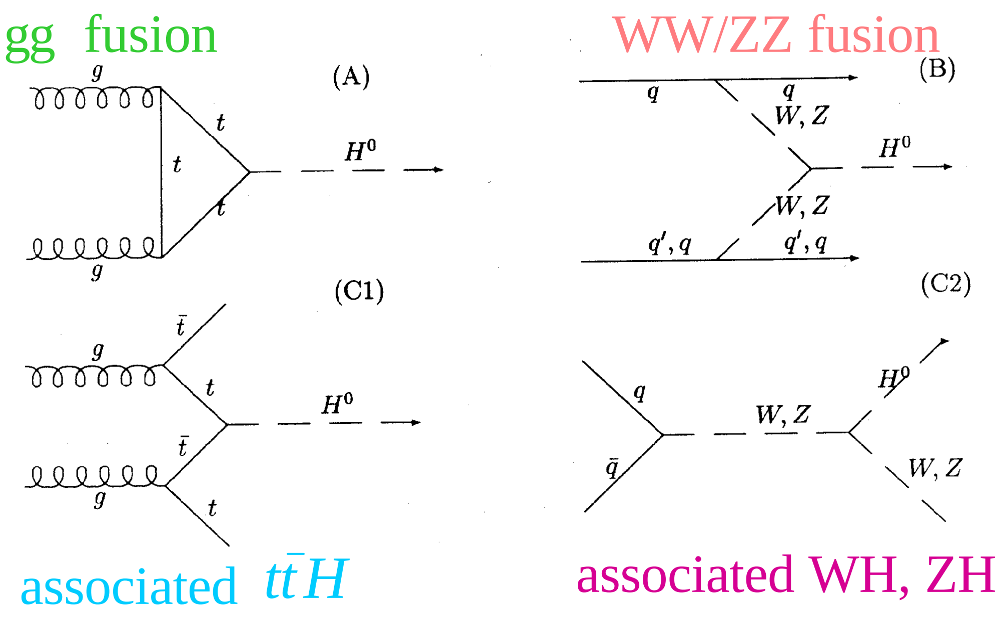
M_H = 81 (+52) (-33) GeV/c²

M_H < 193 GeV/c² (95 % CL)

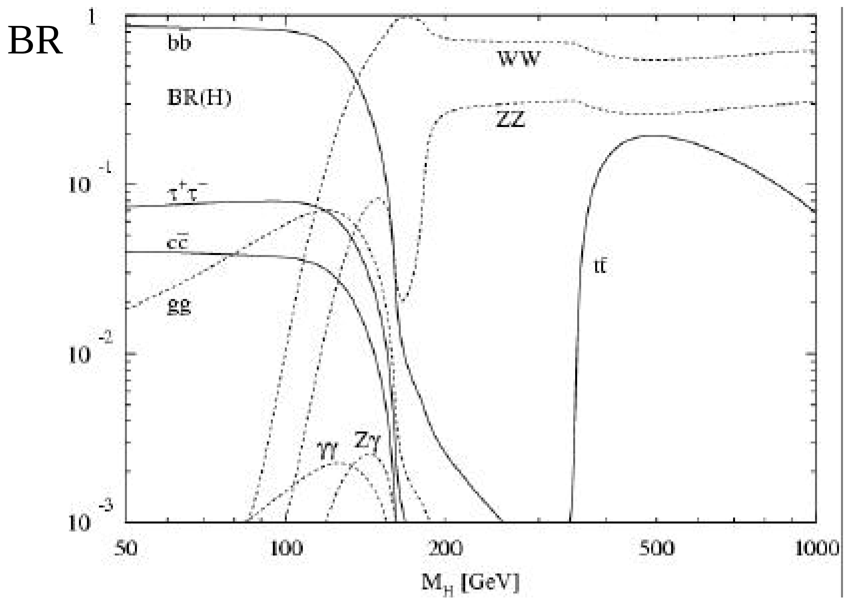
3. Upper mass limit form unitarity bound in WW scattering:

M_H < ~ 1 TeV/c²

Higgs production in Hadron Colliders



Higgs decay branching ratios:

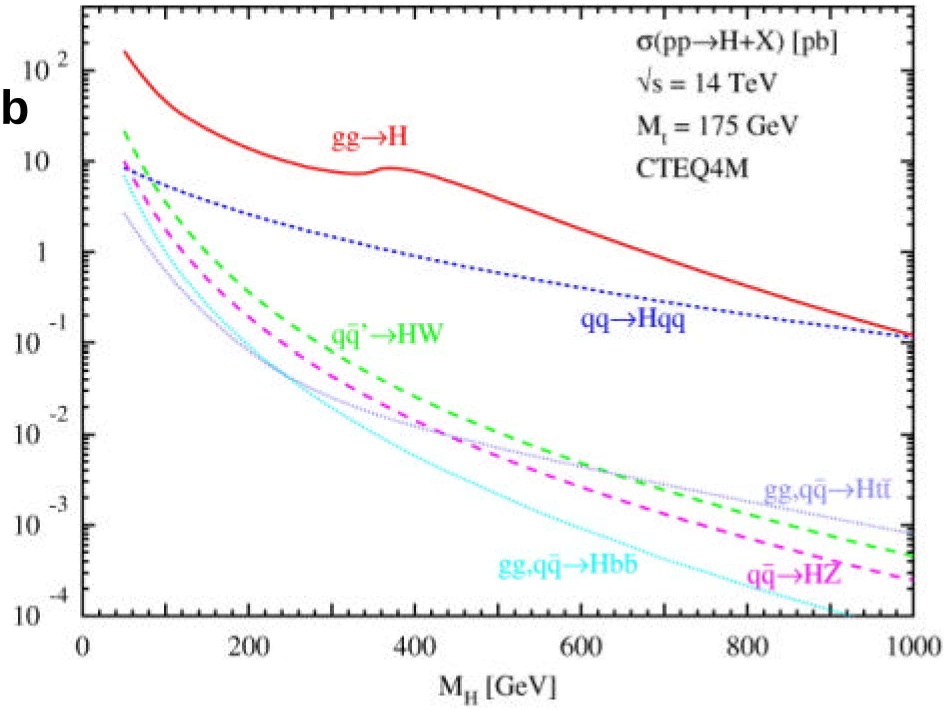


- Lepton or photon decay modes are essential,
  due to large hadronic background from QCD jet production

- bb decay mode only accessible in associated production

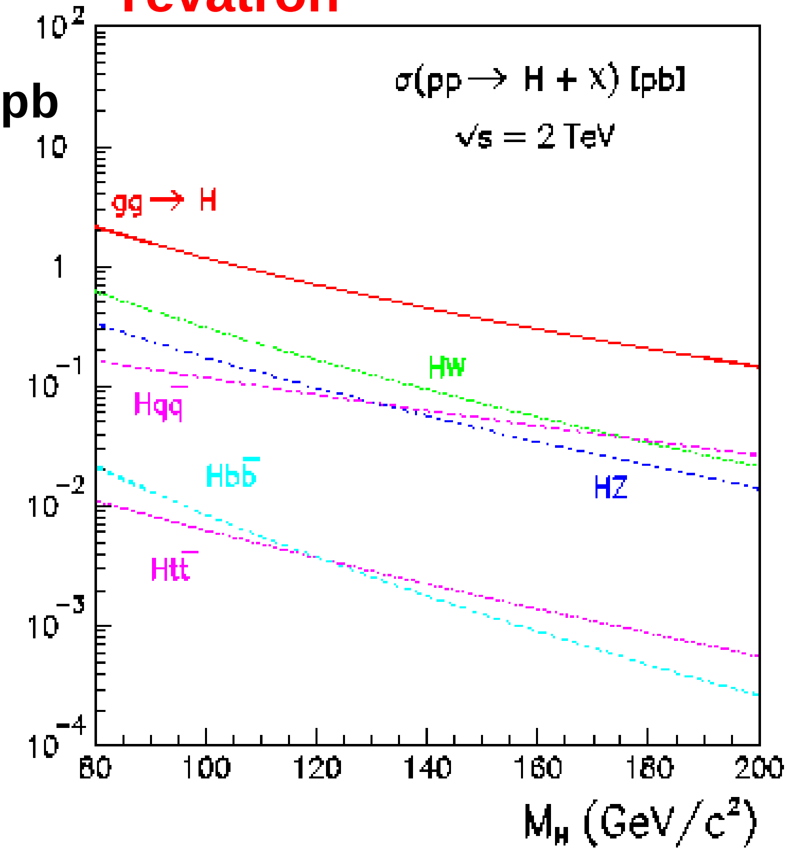
Leading order production cross sections

LHC



M.Spira et al.

Tevatron



M.Spira et al.

qq → W/Z + H cross sections ~10x larger at LHC

gg → H ~70-80x larger at LHC

Status of higher order corrections:

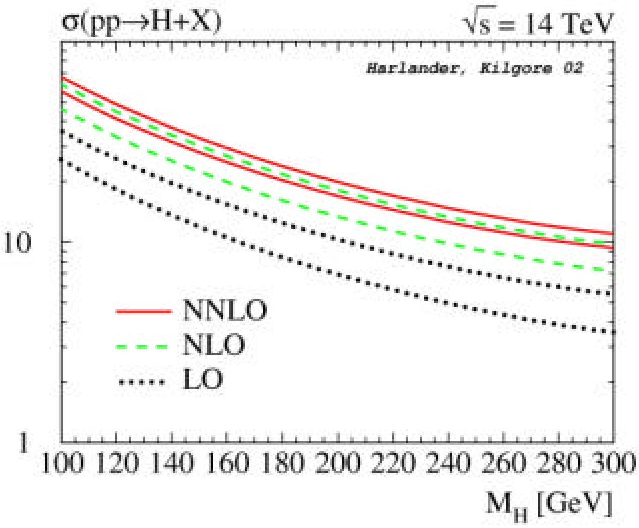
NLO corrections (K-factors) have meanwhile been calculated for all Higgs production processes
(huge theoretical effort !)

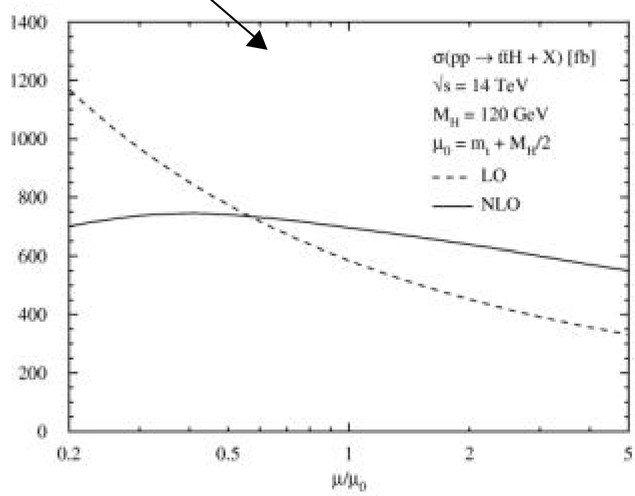
1. gg fusion:

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

2. ttH associated production:

- full NLO calculation LHC: K ~ 1.2
  Tevatron: K ~ 0.8
- scale uncertainty drastically reduced
  [Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas (01)] [Dawson, Reina (01)]





3. Weak boson fusion: K ~1.1

[Han, Valencia, Willenbrock (92)] [Spira (98)]

4.WH associated production: K ~ 1.3

(QCD corrections from Drell-Yan process)

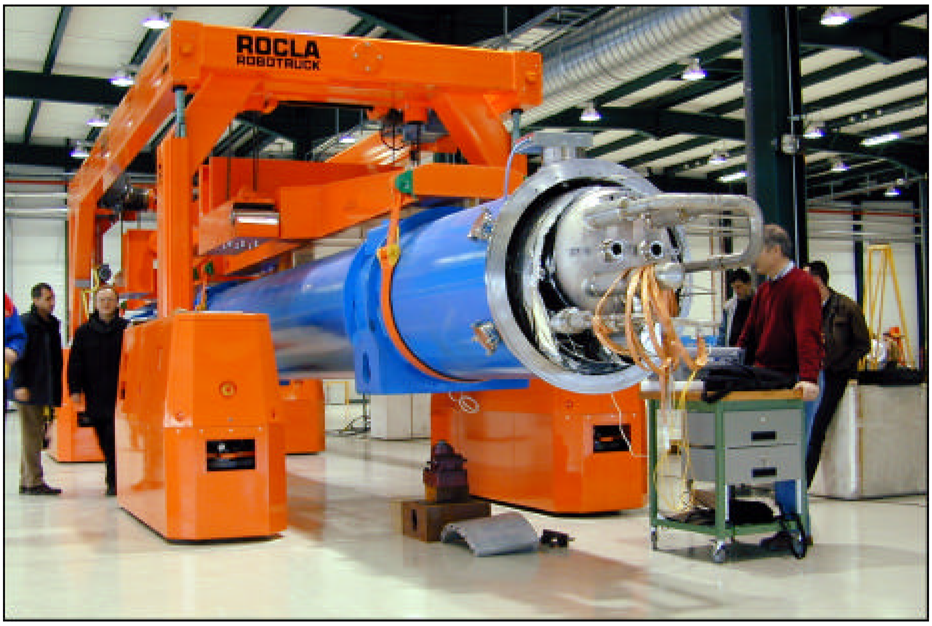
The Large Hadron Collider (LHC)

- Superconducting proton proton accelerator in the LEP tunnel

p Þ Ü p

7000 GeV 7000 GeV

- planned experiments: ATLAS, CMS (pp-physics)
  LHC-B, ALICE (b-physics, heavy ions)



- <u>Revised Time Schedule:</u>

Dec. 2006 — Ring closed and cold

Jan. - Mar. 2007 — Machine commissioning

Spring 2007 — First collisions , pilot run
$L=5\times10^{32}$ to 2×10^{33} cm^{-2} sec^{-1}, ≤ 1 fb^{-1}
Start detector commissioning
~ 10^5 $Z \rightarrow \ell\ell$, $W \rightarrow \ell\nu$, tt events

June - Dec. 2007 — Complete detector commissioning,
Physics run

$\rightarrow$ 2009 — $L=1\text{-}2\times10^{34}$, 100 fb^{-1} per year
(high luminosity LHC)

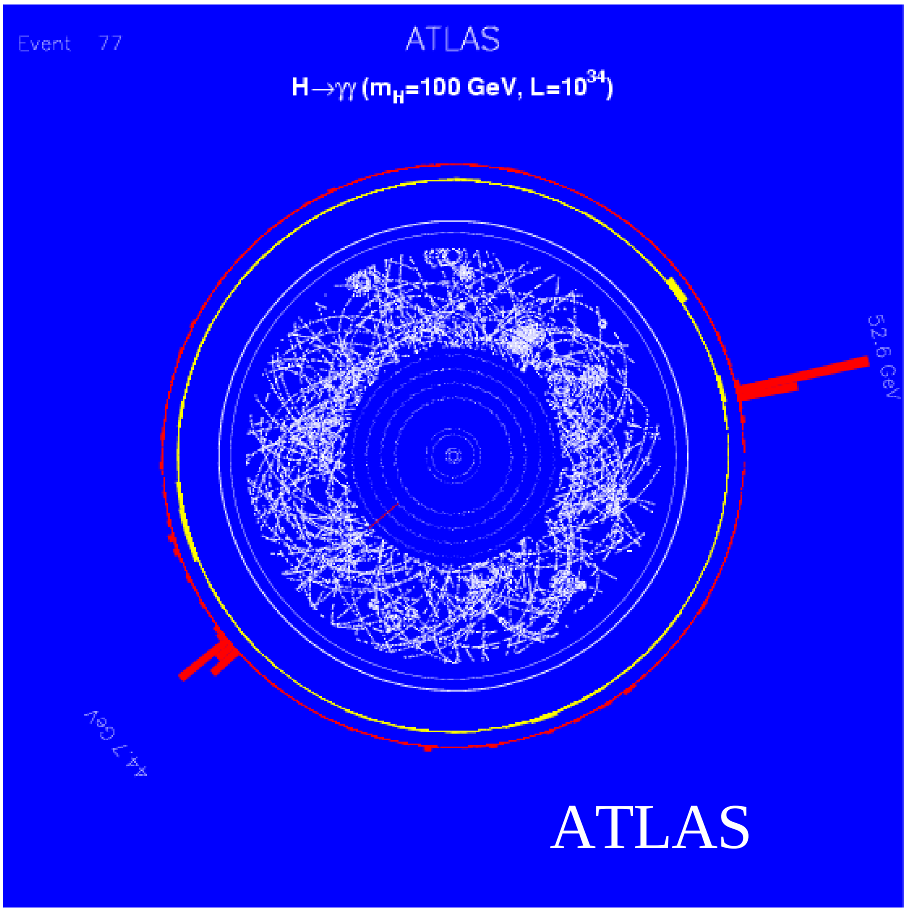
Experimental conditions

L = 1.0 10^{34} cm^{-2} sec^{-1}

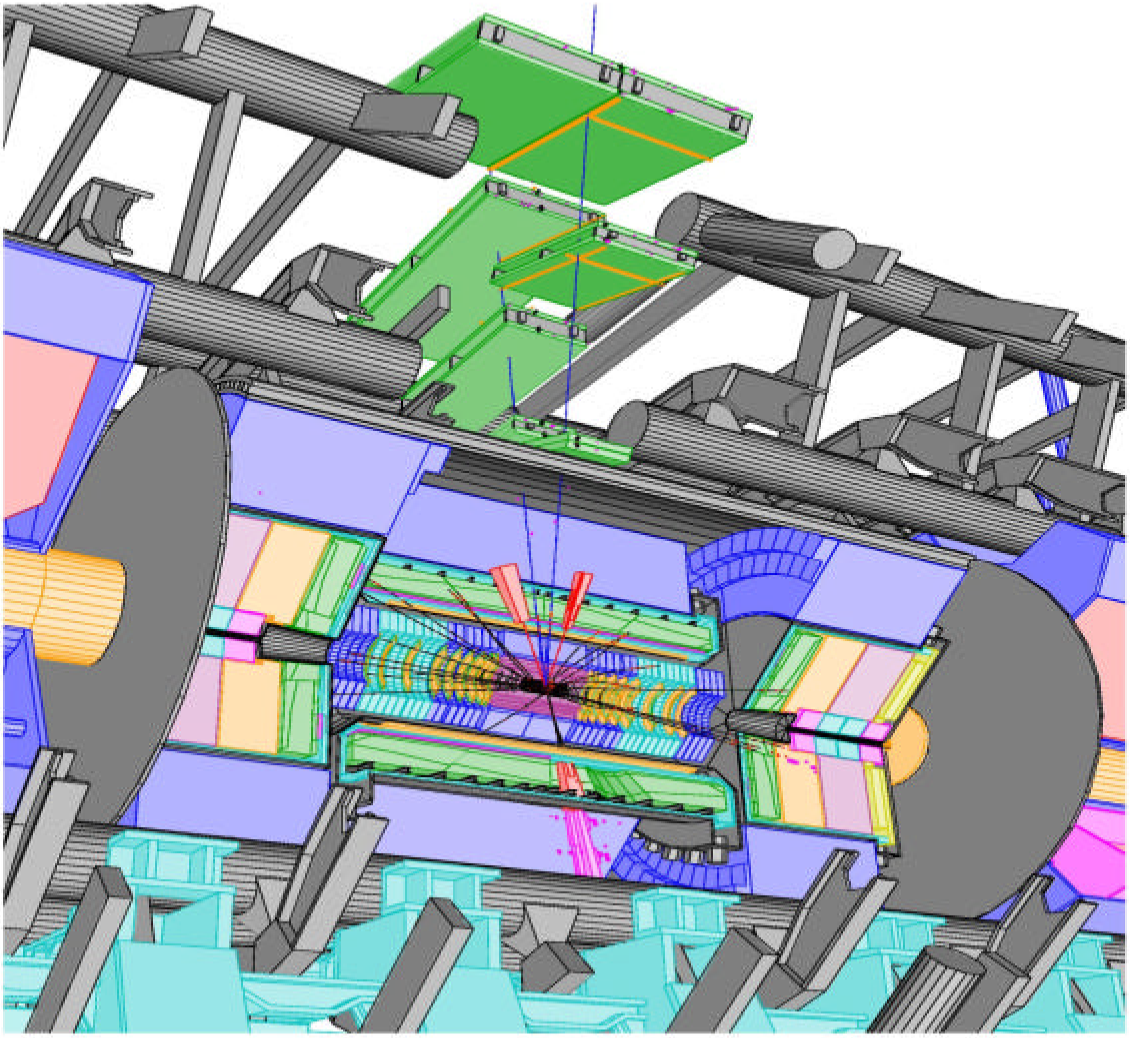
- interaction rate of 40 MHz
  (separation between bunch crossings of 25 ns)

- 23 inelastic pp-collisions per bunch crossing
  Þ ~500 charged particles in the
  interval $| \eta | < 2.0$ $(15^0 < \theta < 165^0)$

- superposition of several collisions during the sensitive time of the detectors
  $\Rightarrow$ fast detectors, rad. hard detectors and electronics
  $\Rightarrow$ on-line signal processing, filtering



Detector Requirements



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

and

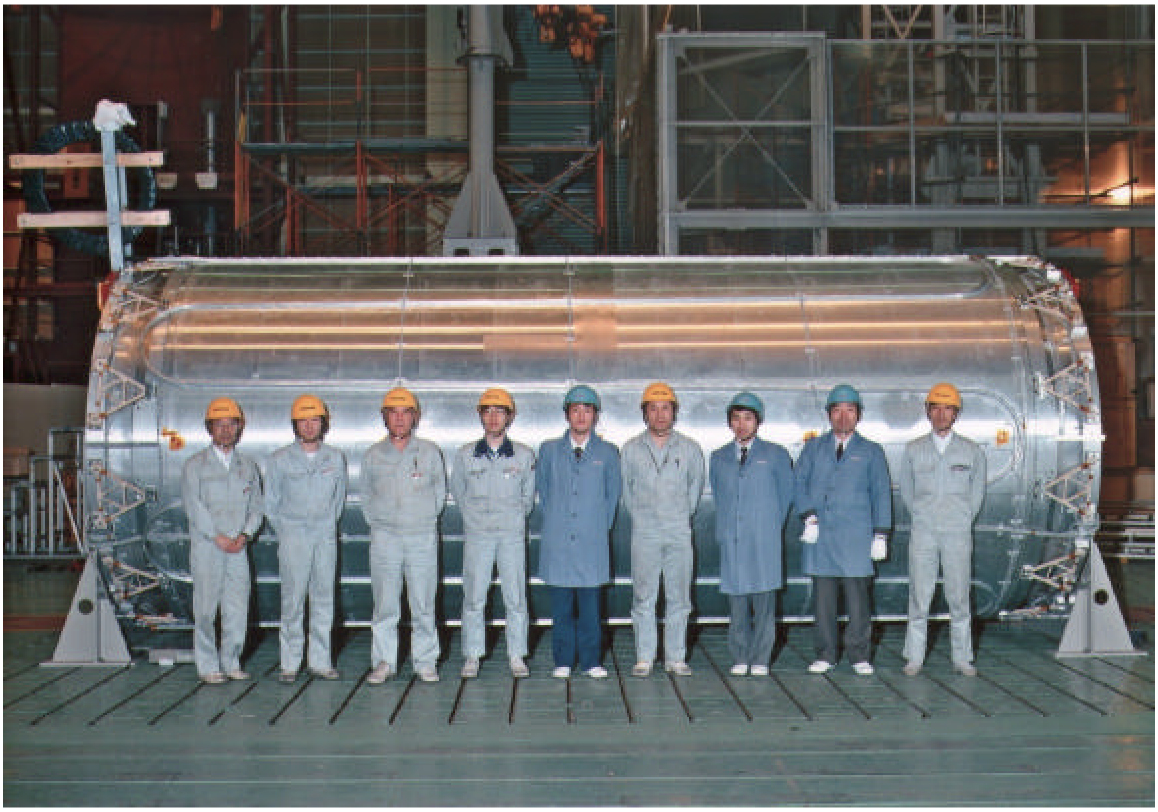
Jet energy measurements and jet-tagging in forward region
$\Rightarrow$ calorimeter coverage down to $\eta \sim 5$

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

Detector construction

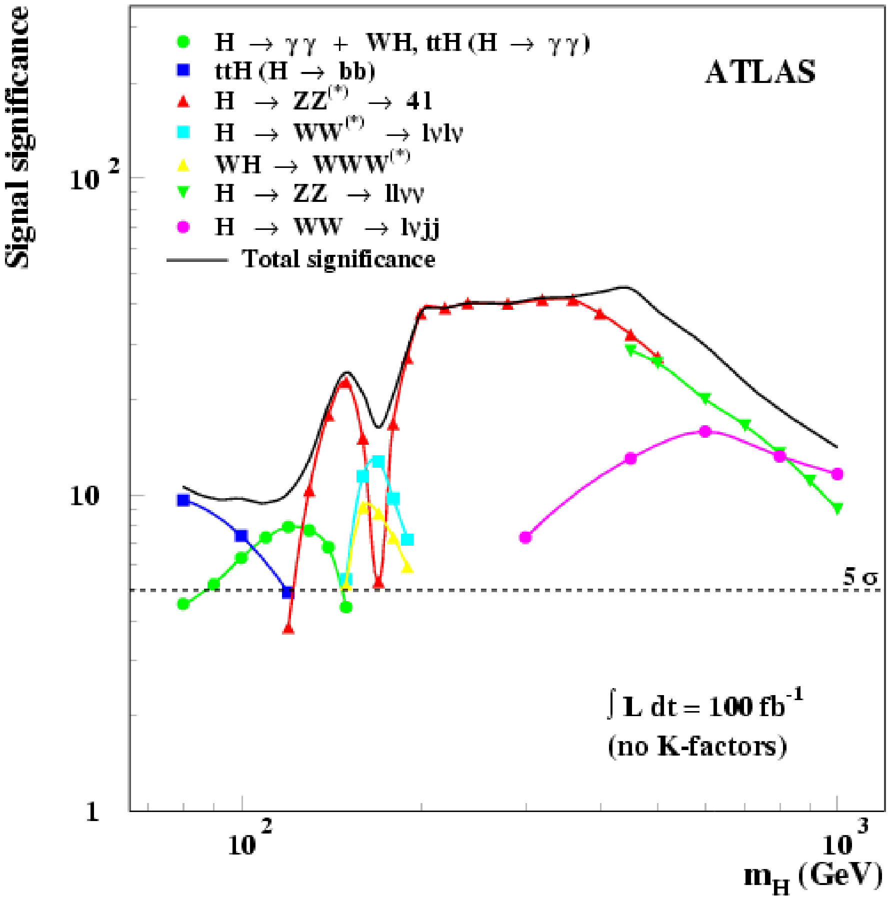
CMS HCAL assembly

ATLAS superconducting solenoid



Main search channels at the LHC

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



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

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

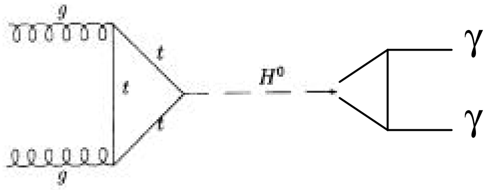
$m_H > 2\, m_Z$: $\quad H \rightarrow ZZ \rightarrow 4\ell$

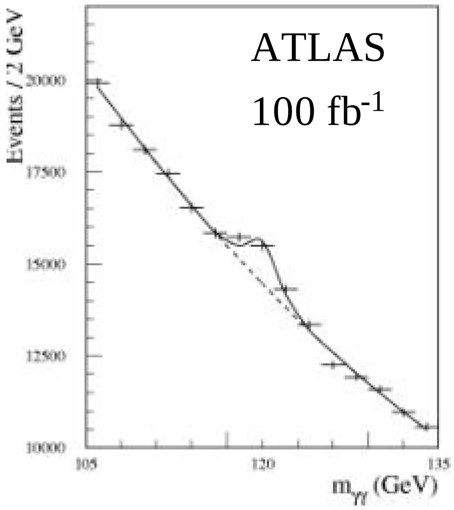
$$\left.\begin{array}{l} qqH \rightarrow ZZ \rightarrow \ell\ell\,\nu\nu \\ qqH \rightarrow ZZ \rightarrow \ell\ell\,jj \\ qqH \rightarrow WW \rightarrow \ell\nu jj \end{array}\right\} \quad \begin{array}{l} m_H > 300\text{ GeV} \\ \text{forward jet tag} \end{array}$$

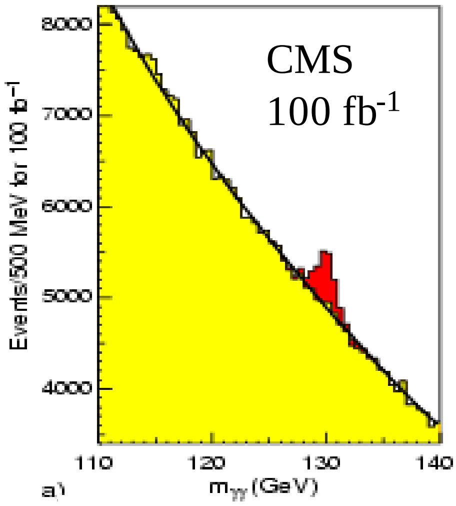
10 fb^{-1}: Discovery possible over the full mass range, however, needs combination of ATLAS + CMS

M_H = 115 GeV: **S/ ÖB = 4.7**

Gluon-fusion: H$\rightarrow \gamma\gamma$





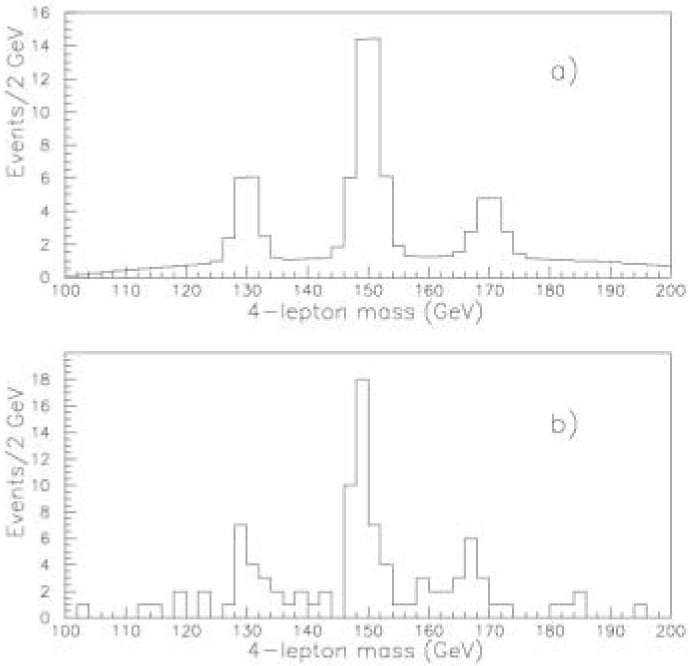


Signal / background ~ 4%

background (dominated by $\gamma\gamma$ events) can be determined from side bands

important: $\gamma\gamma$-mass resolution in the calorimeters, γ / jet separation

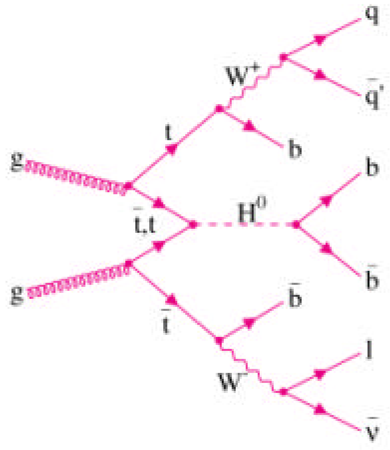
Gluon fusion: H $\rightarrow$ ZZ $\rightarrow l^+l^- l^+l^-$



ATLAS, 30 fb^{-1}

important: b-jet rejection (b$\rightarrow$l), $\Rightarrow$ Zbb and tt-background

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



σ x BR ≈ 300 fb

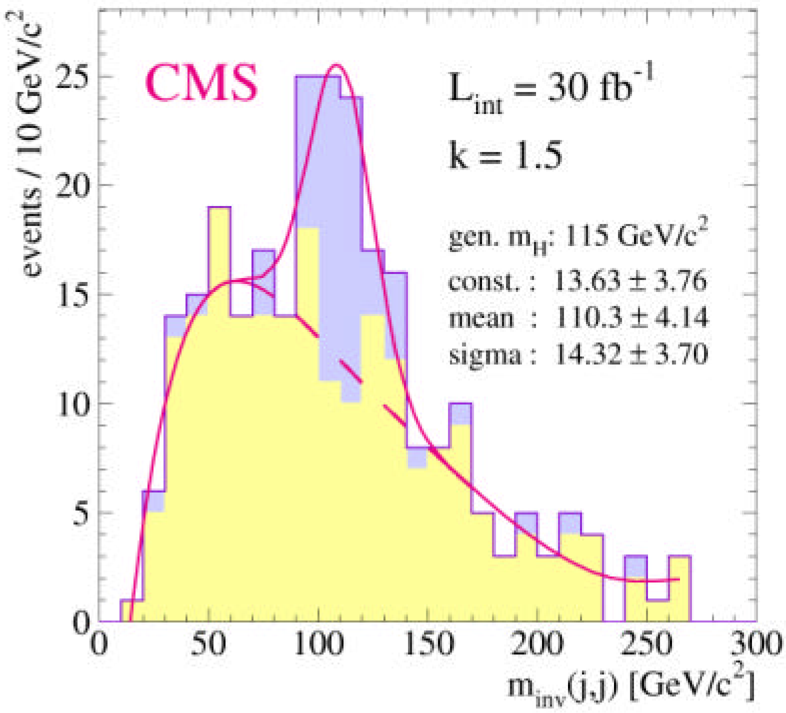
Complex final state: H→bb , t → bjj, t → b$\ell\nu$

•Main backgrounds:

-- combinatorial from signal (4b in final state)

-- Wjjjjjj, WWbbjj, etc.

-- ttjj (dominant, non-resonant)



S = 38 events

B = 52 events

S/B ~ 0.73

S/ √B = 3.5

for K = 1.0

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

- 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)

Higgs production via Vector Boson Fusion

Motivation:

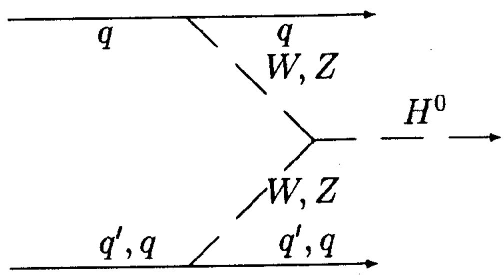
• Increase discovery potential at low mass

• Improve measurement of Higgs boson parameters
(couplings to bosons, fermions (taus))

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

Destinctive Signature of:

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



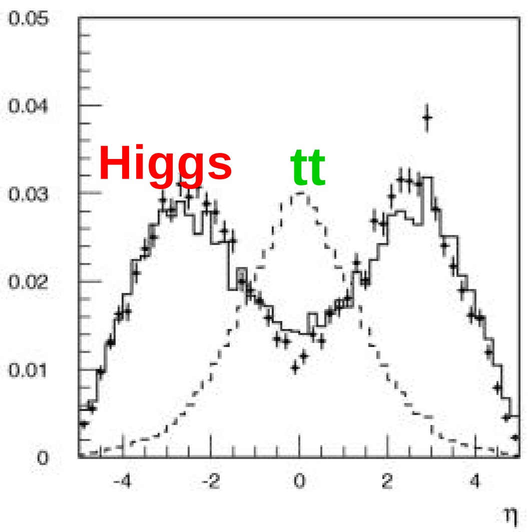
Þ **Experimental Issues:**
- Forward jet reconstruction
- Jets from pile-up in the central/forward region

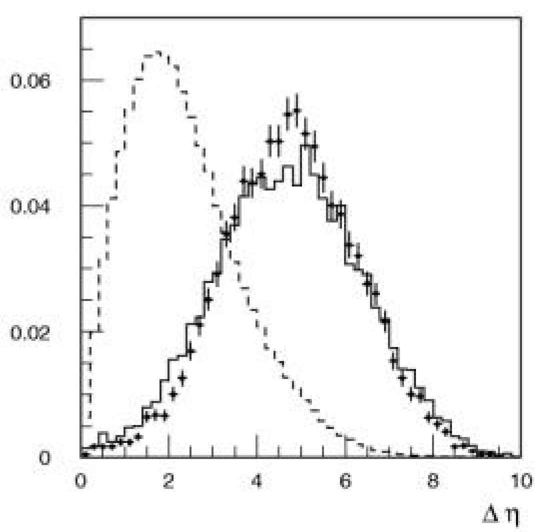
Channels studied: **qqH ® qqWW* ® qq** ℓ n ℓ n
qqH ® qq t t ® **qq** ℓ n n ℓ n n
® **qq** ℓ n n **had** n

Forward tag Jets

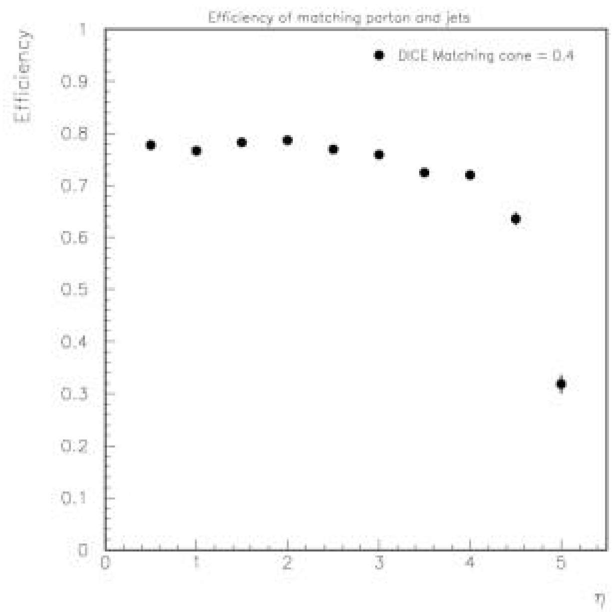
Rapidity distribution of tag jets
VBF Higgs events vs. tt-background

Rapidity separation





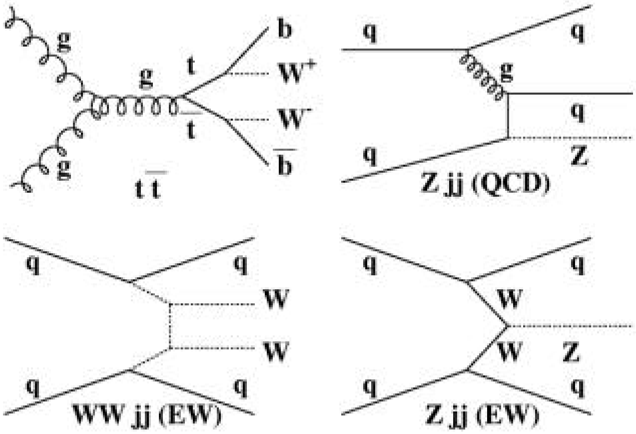
Forward tag jet reconstruction has been studied in full simulation in ATLAS



kin. eff. for tag jets = 51.9%
(P_T > 40/20 GeV, , Δ η > 3.6)

tag eff. per jet: around 75%

Background:



QCD backgrounds:
tt production
Z + 2 jets
(PYTHIA MC)

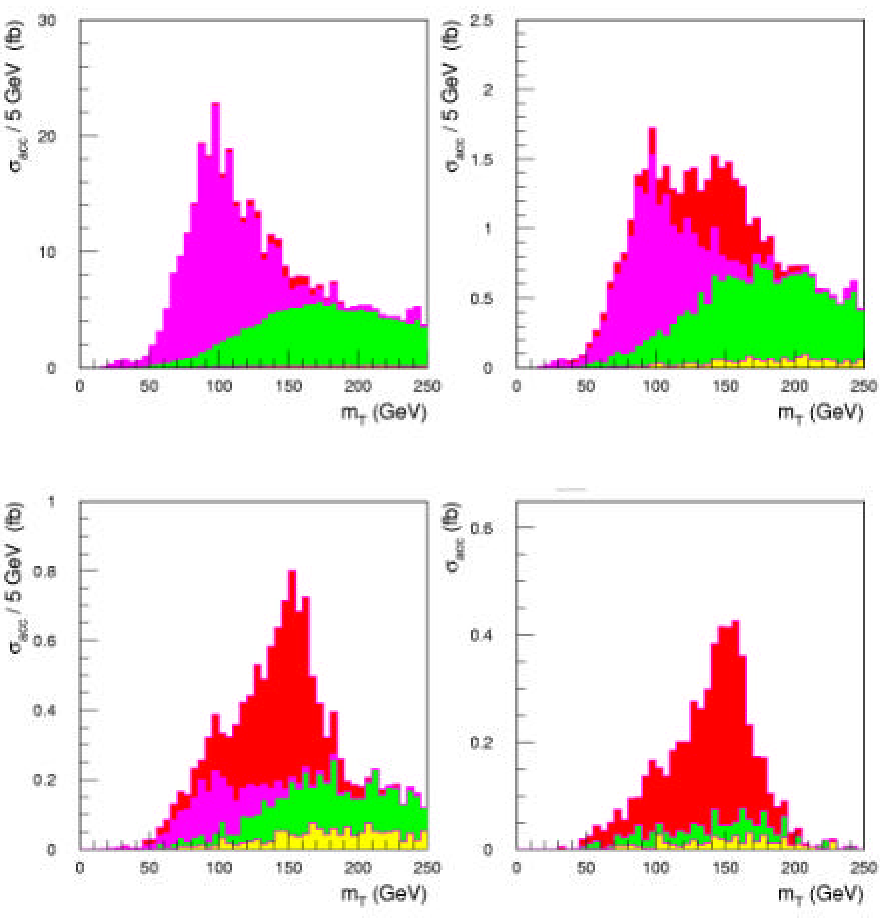
el.weak background:
WW jj production
Z + 2 jets
(matrix elements interfaced to PYTHIA)

Background rejection: qqH ® qqWW* ® qq l n l n

- Lepton P_T cuts and tag jet requirements (Δ η, P_T)
- Require large mass of tag jet system, tau rejection
- Jet veto
- Lepton angular and mass cuts

$$M_T = \sqrt{(E_T^{ll} + E_T^{\nu\nu})^2 - (\vec{p}_T^{\,e\mu} + \vec{p}_T^{\,miss})^2}$$

qqH ® WW* ® l n l n



tt background

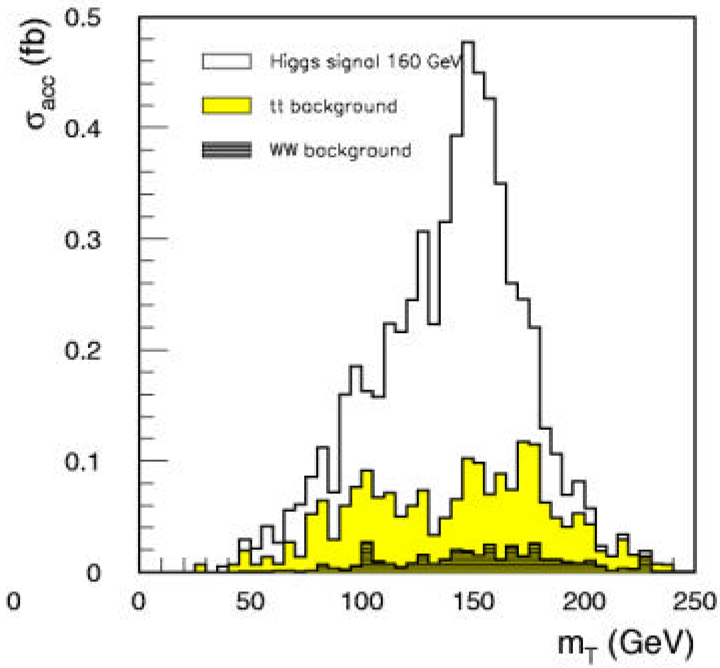
g* / Z + jets

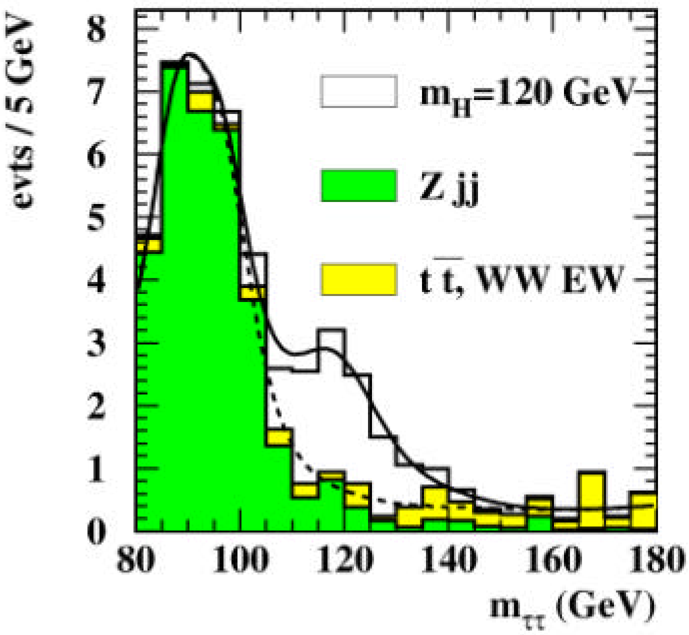
el.weak WW jj

Higgs boson
m_H = 160 GeV

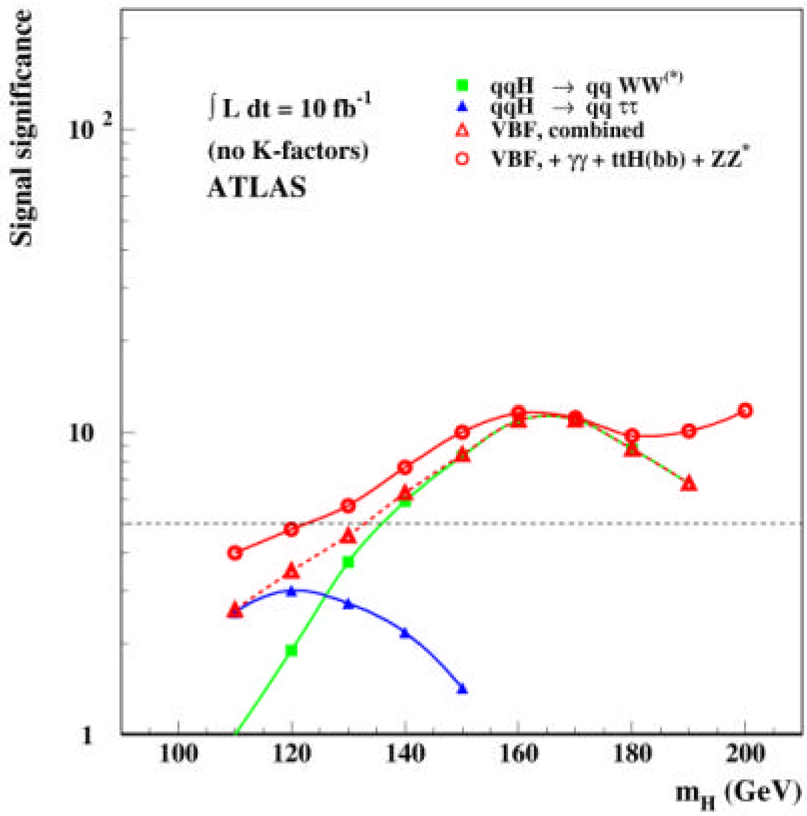
qq H ® qq WW*
® qq l n l n

qq H ® qq t t
® qq l n n l n n
® qq l n n h n





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

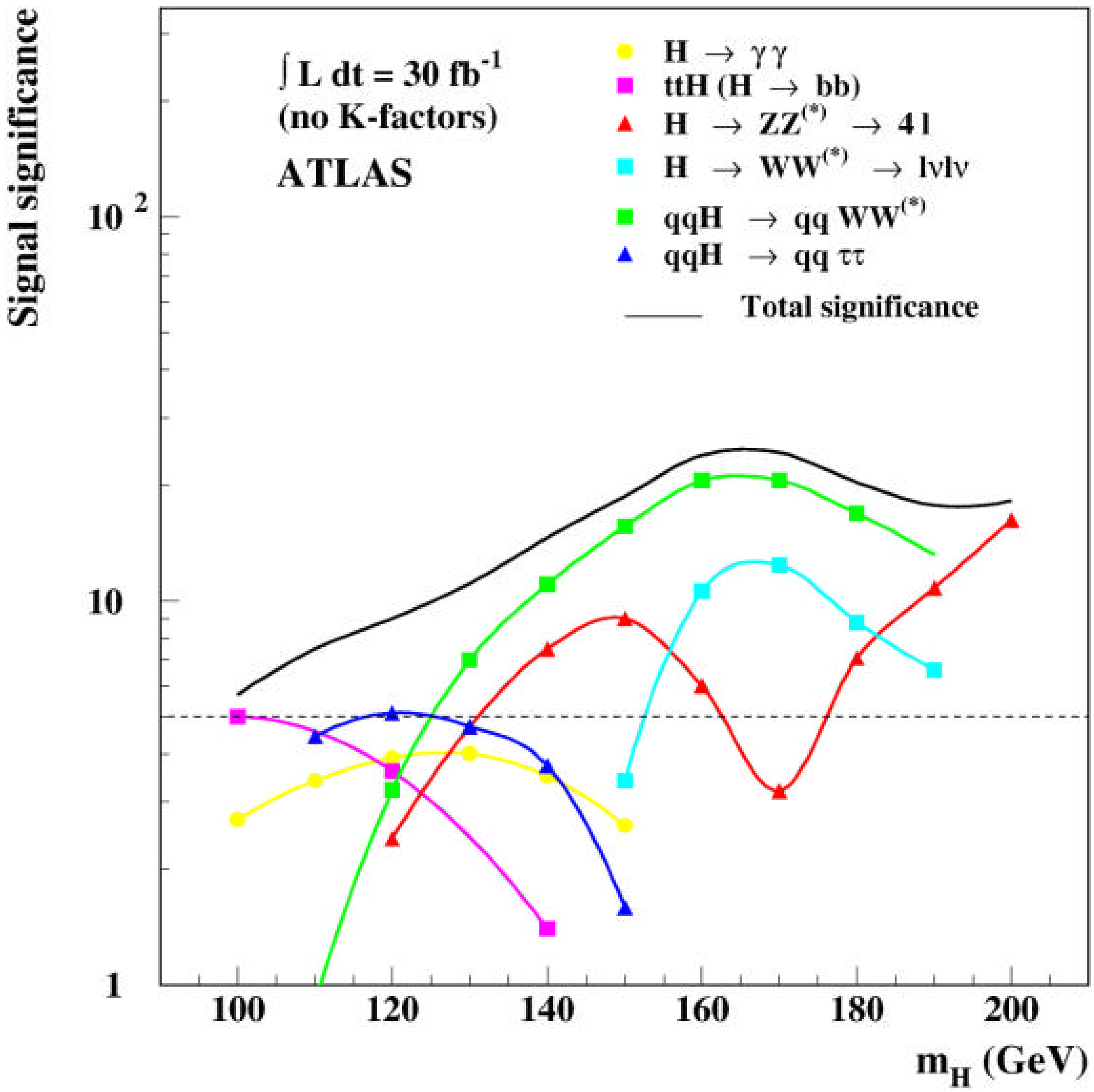


- VBF channels
  (in particular WW*)
  are discovery channels
  at low luminosity

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

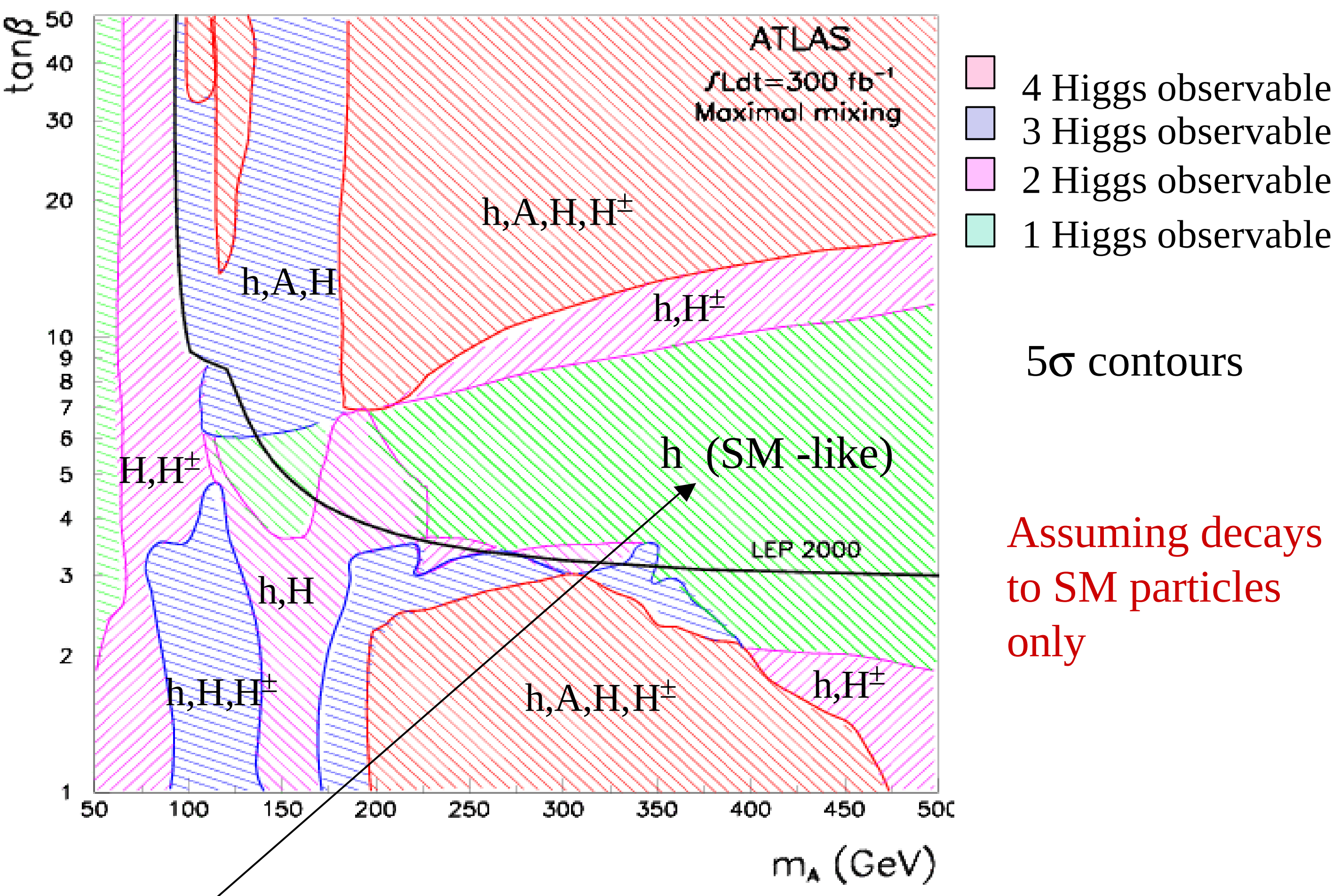
  5 s significance for
  120 £ m_H £ 190 GeV

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

LHC discovery potential for MSSM Higgs bosons



5σ contours

Assuming decays to SM particles only

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

- Plane fully covered (no holes) at low L (30 fb^{-1})
- Main channels : $h \rightarrow gg$, $b\bar{b}$, A/H $\rightarrow mm$, tt , $H^{\pm} \rightarrow tn$

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

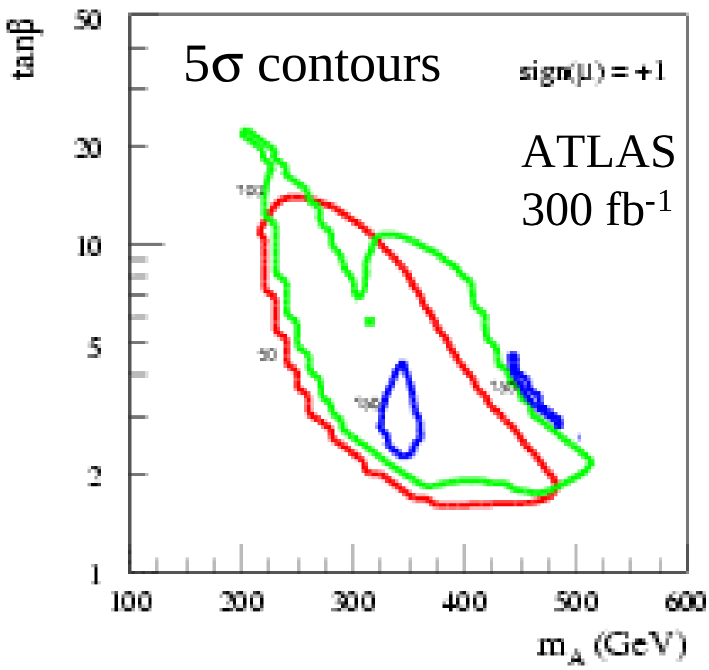
Possible coverage :* via SUSY decays (model dependent, under study)

* luminosity (only moderate improvement)

Higgs decays via SUSY particles

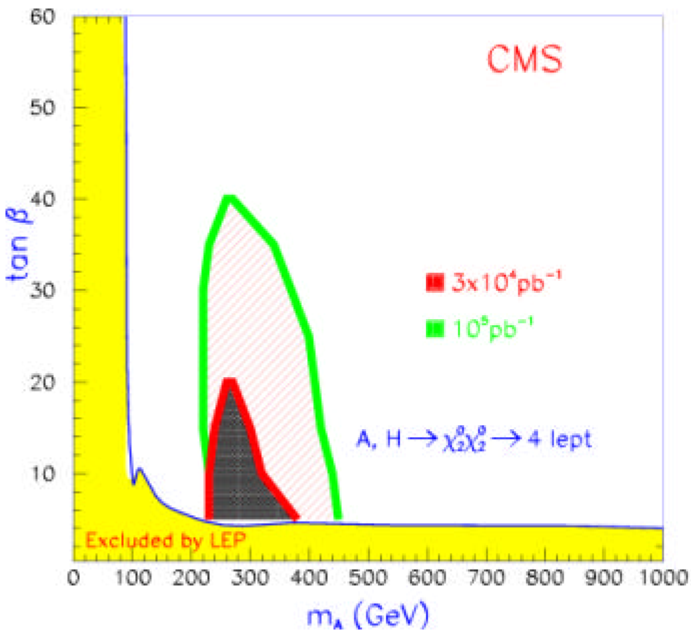
If SUSY exists : search for

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



ATLAS:
SUGRA scan

m_0 = 50 - 250 GeV
$m_{1/2}$ = 100 - 300 GeV
$\tan\beta$ = 1.5 - 50
A_0 = 0

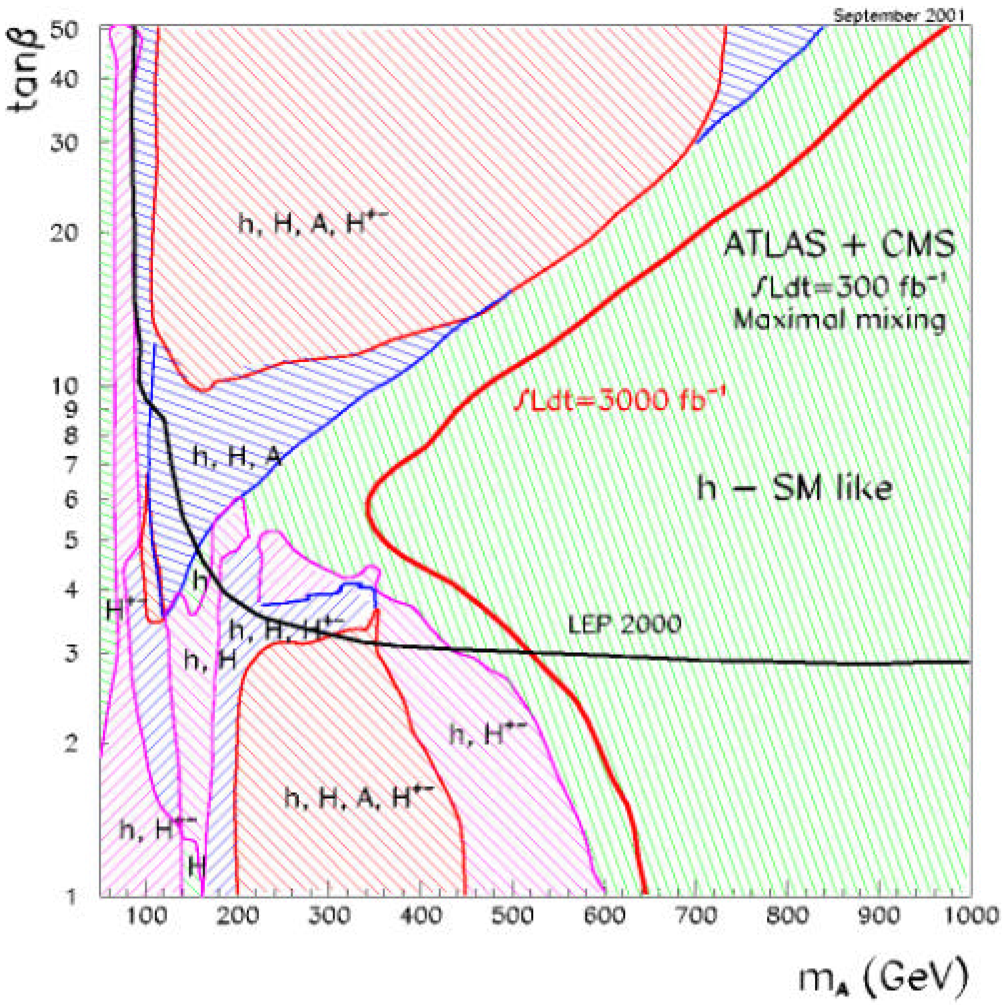


CMS:
special choice in MSSM
(no scan)
M_1 = 60 GeV
M_2 = 110 GeV
μ = -500 GeV

Exclusions depend on MSSM parameters (slepton masses, μ)

MSSM discovery potential for Super-LHC

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



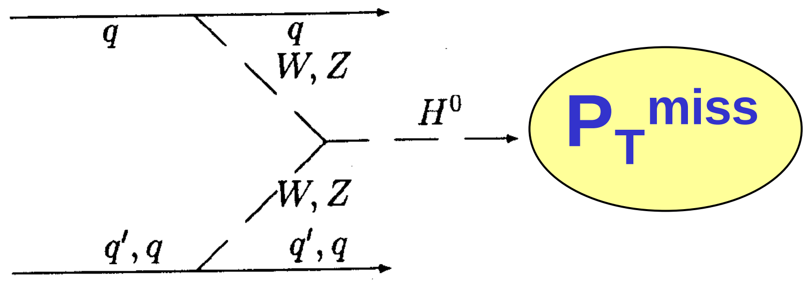
- Situation can be improved, in particular for m_A < ~400 GeV

- 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}



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))

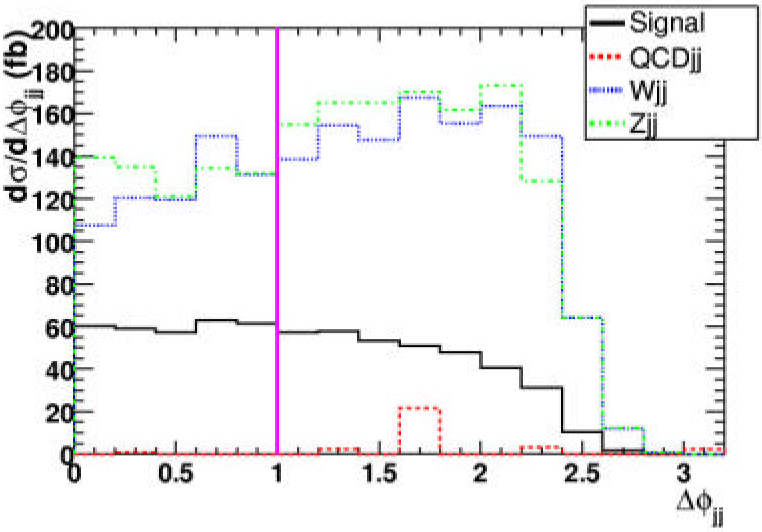
Event selection: 2 tag jets, (P_T, $\Delta\eta$, M_{jj}>1200 GeV)
P_T^{miss} > 100 GeV
Lepton and Jet veto
(no jets with P_T> 20 GeV)

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:

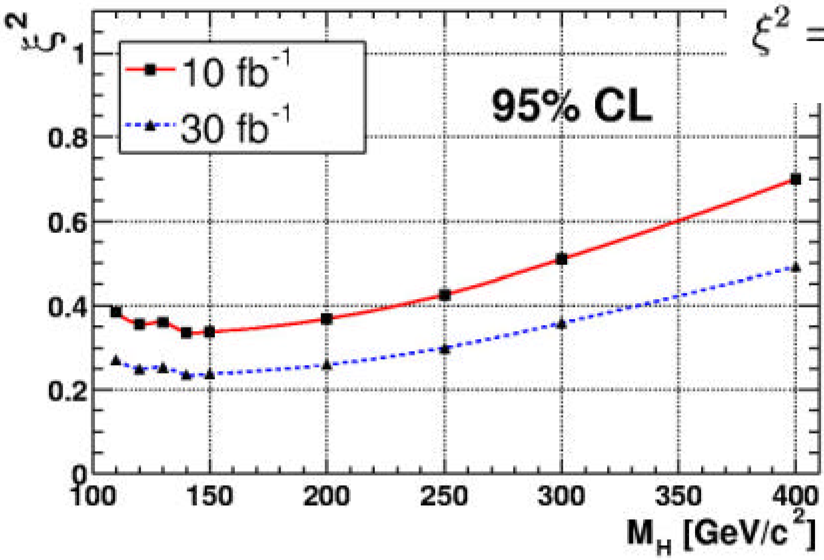


Expected rates
for 10 fb^{-1}:

Signal: 590 events
W-backgr: 1215 events
Z -backgr: 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

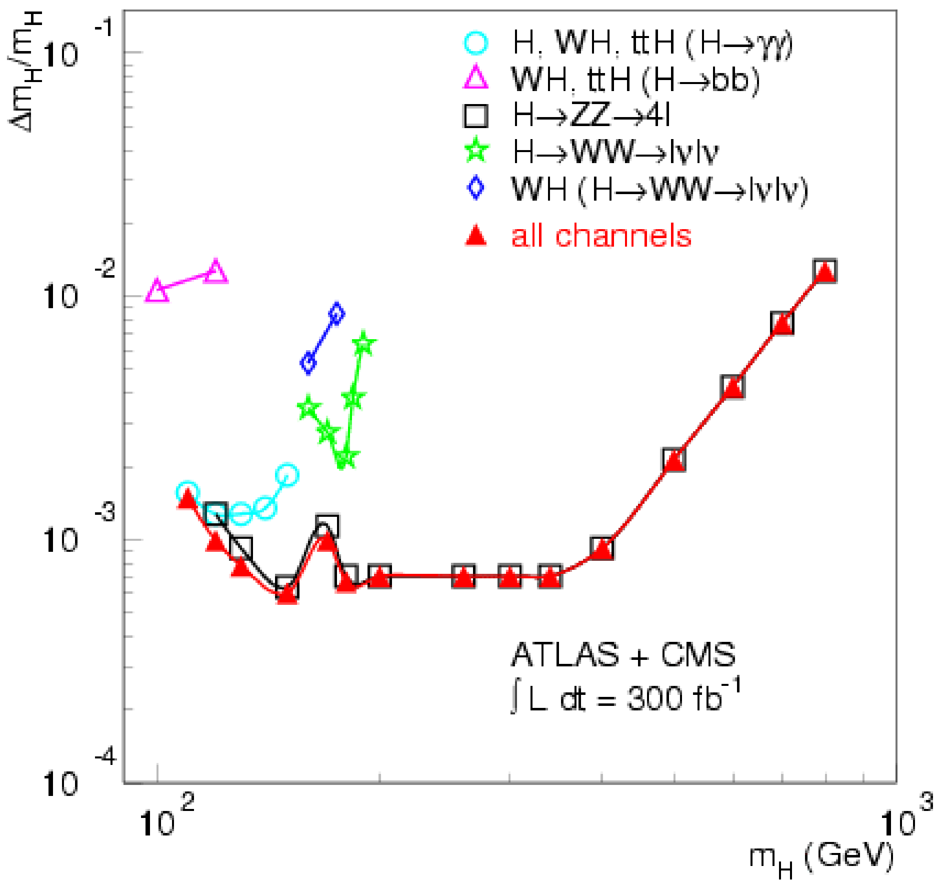
1. Mass

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)

MSSM Higgs	$\Delta m/m$ (%)
h, A, H $\rightarrow \gamma\gamma$	0.1–0.4
H $\rightarrow$ 4 ℓ	0.1–0.4
H/A $\rightarrow \mu\mu$	0.1-1.5
h $\rightarrow$ bb	1–2
H $\rightarrow$ hh $\rightarrow$ bb $\gamma\gamma$	1-2
A $\rightarrow$ Zh $\rightarrow$ bb $\ell\ell$	1–2
H/A $\rightarrow \tau\tau$	1-10

300 fb^{-1}

Note: present theoretical error Δm_h ~ 3 GeV

Measurements of Higgs boson couplings

i) Ratio between W and Z partial widths

- **Direct measurements**

$$- \frac{\sigma \times BR(H \to WW^*)}{\sigma \times BR(H \to ZZ^*)} = \frac{\Gamma_g \Gamma_W}{\Gamma_g \Gamma_Z} = \frac{\Gamma_W}{\Gamma_Z}$$

VBF: measurement can be extended to low masses

- **Indirect measurements (via H ® gg)**

ii) Ratio of boson to fermion couplings

- Direct measurement

VBF:

$$- \frac{\sigma \times BR(qq \to qqH(H \to WW))}{\sigma \times BR(qq \to qqH(H \to \tau\tau))} = \frac{\Gamma_W \Gamma_W}{\Gamma_W \Gamma_\tau} = \frac{\Gamma_W}{\Gamma_\tau}$$

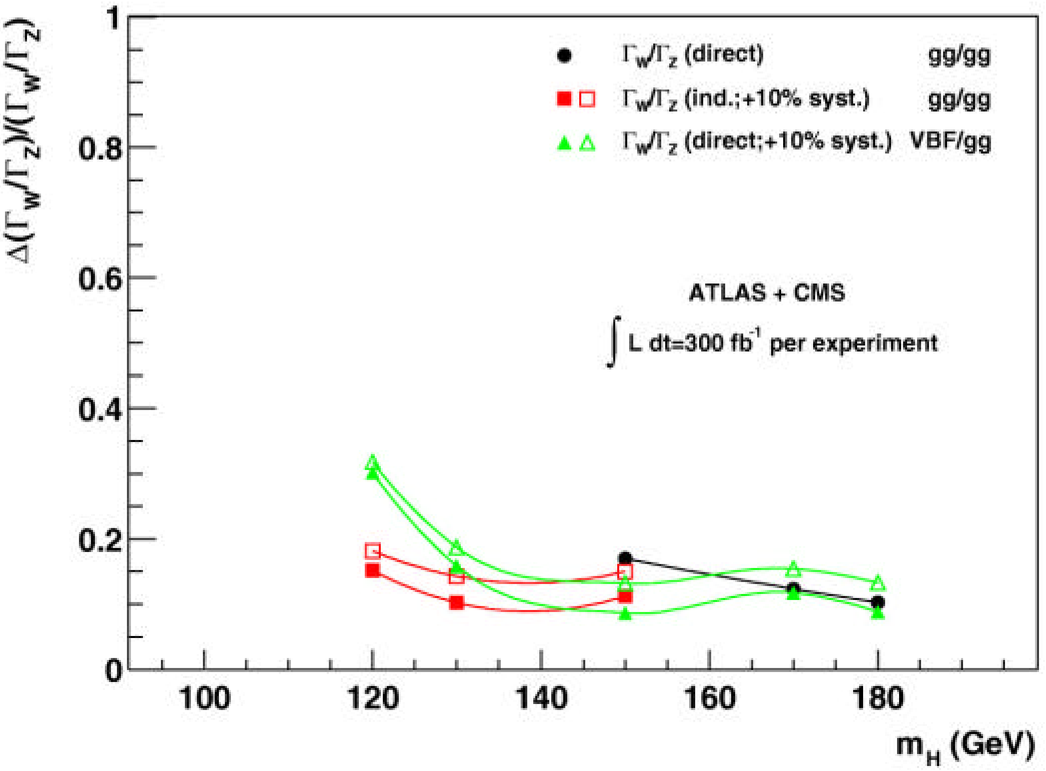
- Indirect measurement

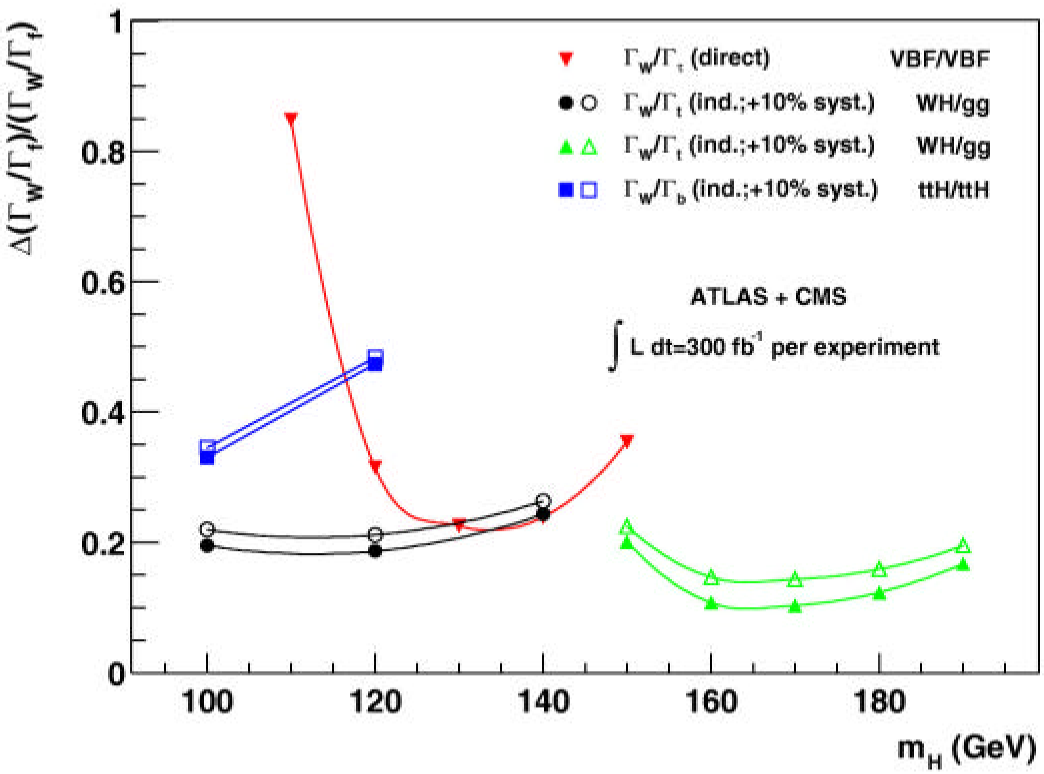
$$- \frac{\sigma \times BR(WH(H \to \gamma\gamma))}{\sigma \times BR(H \to \gamma\gamma)} = \frac{\Gamma_W \Gamma_\gamma}{\Gamma_g \Gamma_\gamma} \sim \frac{\Gamma_W}{\Gamma_t} * C_{QCD}$$

$$- \frac{\sigma \times BR(WH(H \to WW))}{\sigma \times BR(H \to WW^*)} = \frac{\Gamma_W \Gamma_W}{\Gamma_g \Gamma_W} \sim \frac{\Gamma_W}{\Gamma_t} * C_{QCD}$$

$$- \frac{\sigma \times BR(ttH(H \to bb))}{\sigma \times BR(ttH(H \to \gamma\gamma))} = \frac{\Gamma_t \Gamma_b}{\Gamma_t \Gamma_\gamma} \sim \frac{\Gamma_b}{\Gamma_W}$$

* Uncertainties on the ratio arising through different production processes are not included





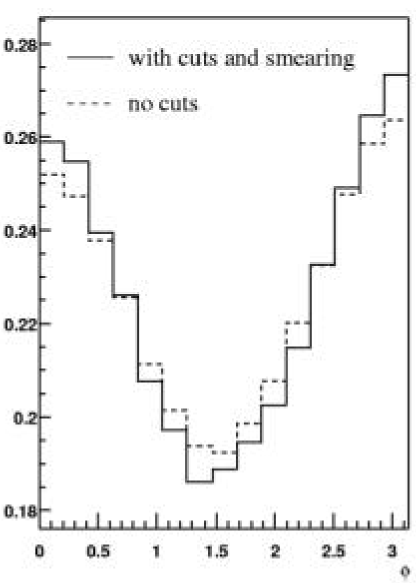
additional channels: tt H , $H \to WW^*$
(under study) qqH, $H \to$ bb (??)

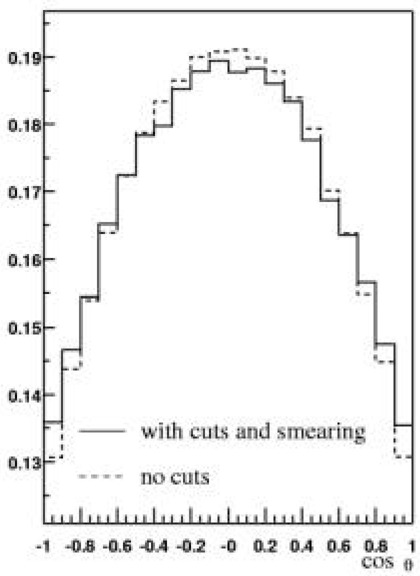
both would add to the measurement of Γ_b / Γ_W

Higgs boson spin?

Angular distributions in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4\,\ell$ are sensitive to spin and CP eigenvalue

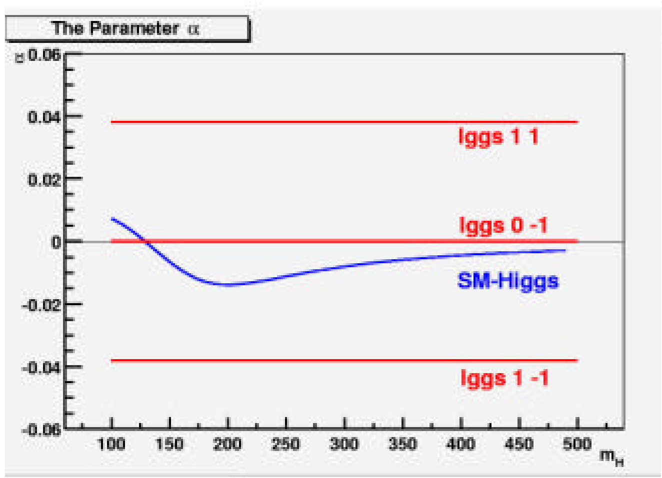
- azimuthal angle ϕ, defined as angle between the decay planes of the two Z-bosons in the restframe of the Higgs
- polar angle θ, defined as angle of neg. charged lepton in the restframe of the Z to the direction of motion of the Z in the restframe of the Higgs

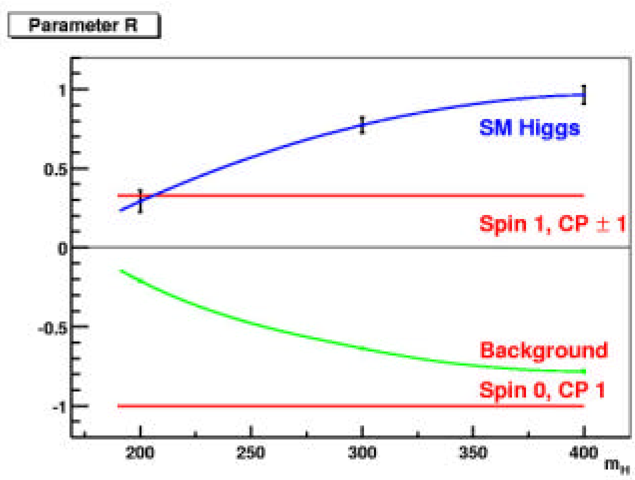




Fit to $F(\phi) = \alpha \cos(\phi) + \beta \cos(2\phi)$

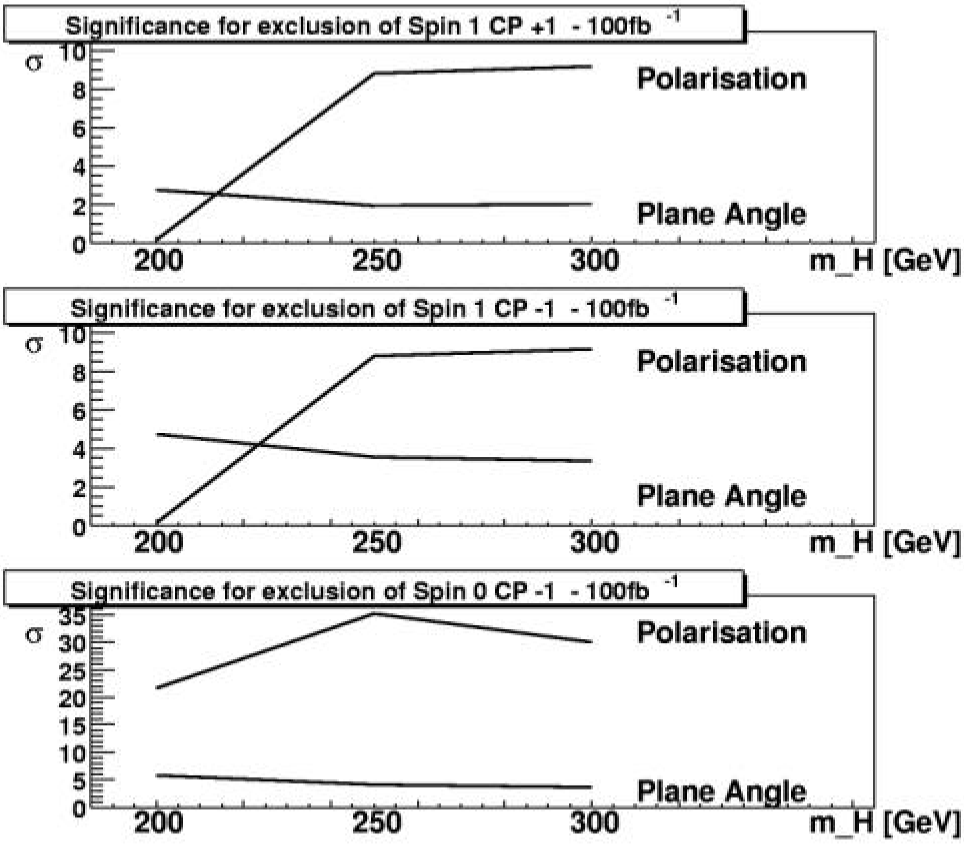
$F(\theta) = T\,(1+\cos^2\theta) + L\,\sin^2\theta \qquad R = (L-T)\,/\,(L+T)$





(J.R. Dell´Aquila, C.A. Nelson)

expected results:



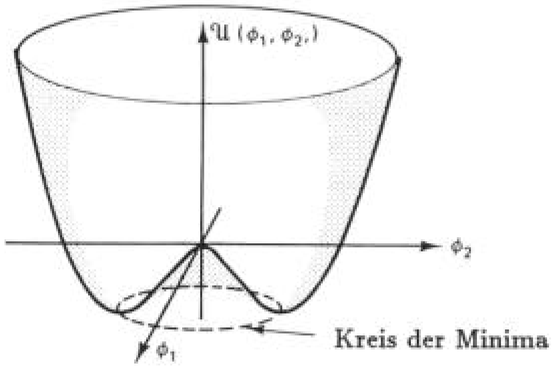
- Method will be applied in low mass region (ZZ*)
  (C.P. Buscello, J.v.d. Bij)

- Additional channles will be studied

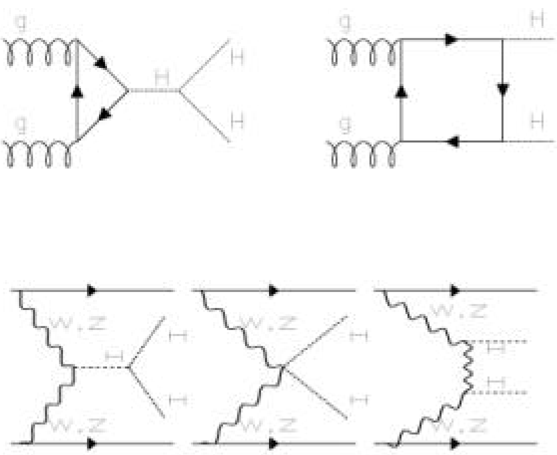
Higgs boson self coupling ?

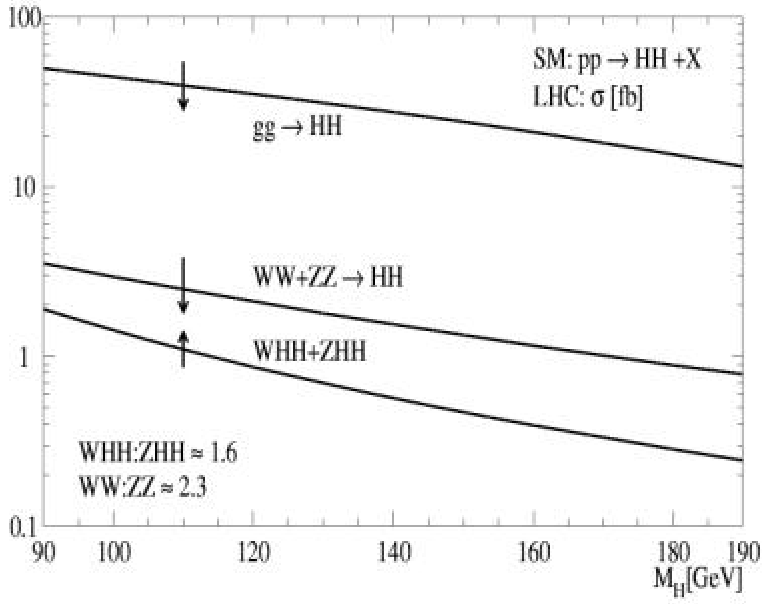
to establish the Higgs mechanism the
Higgs boson self-coupling has to be measured:

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



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:

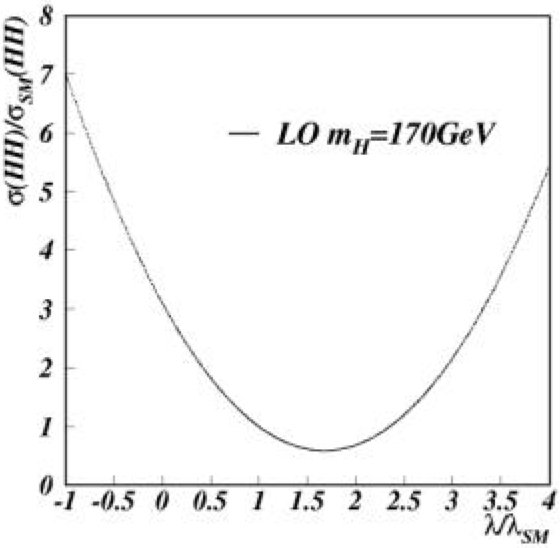
gg ® HH ® WW WW ® ℓn jj ℓn jj

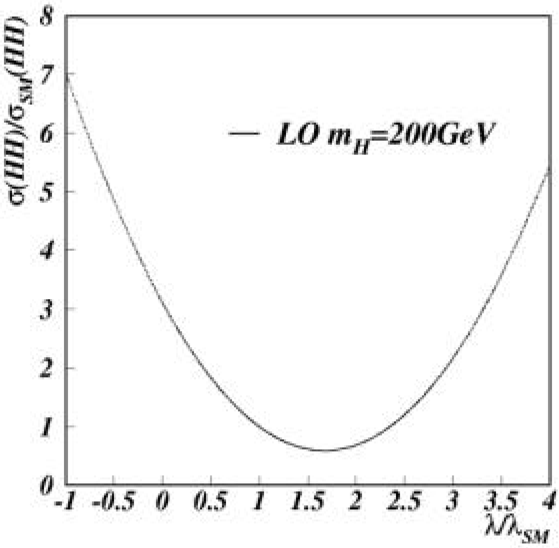
- accessible in mass range 160 GeV - 200 GeV
- bb-decay mode at lower masses is hopeless

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)

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)

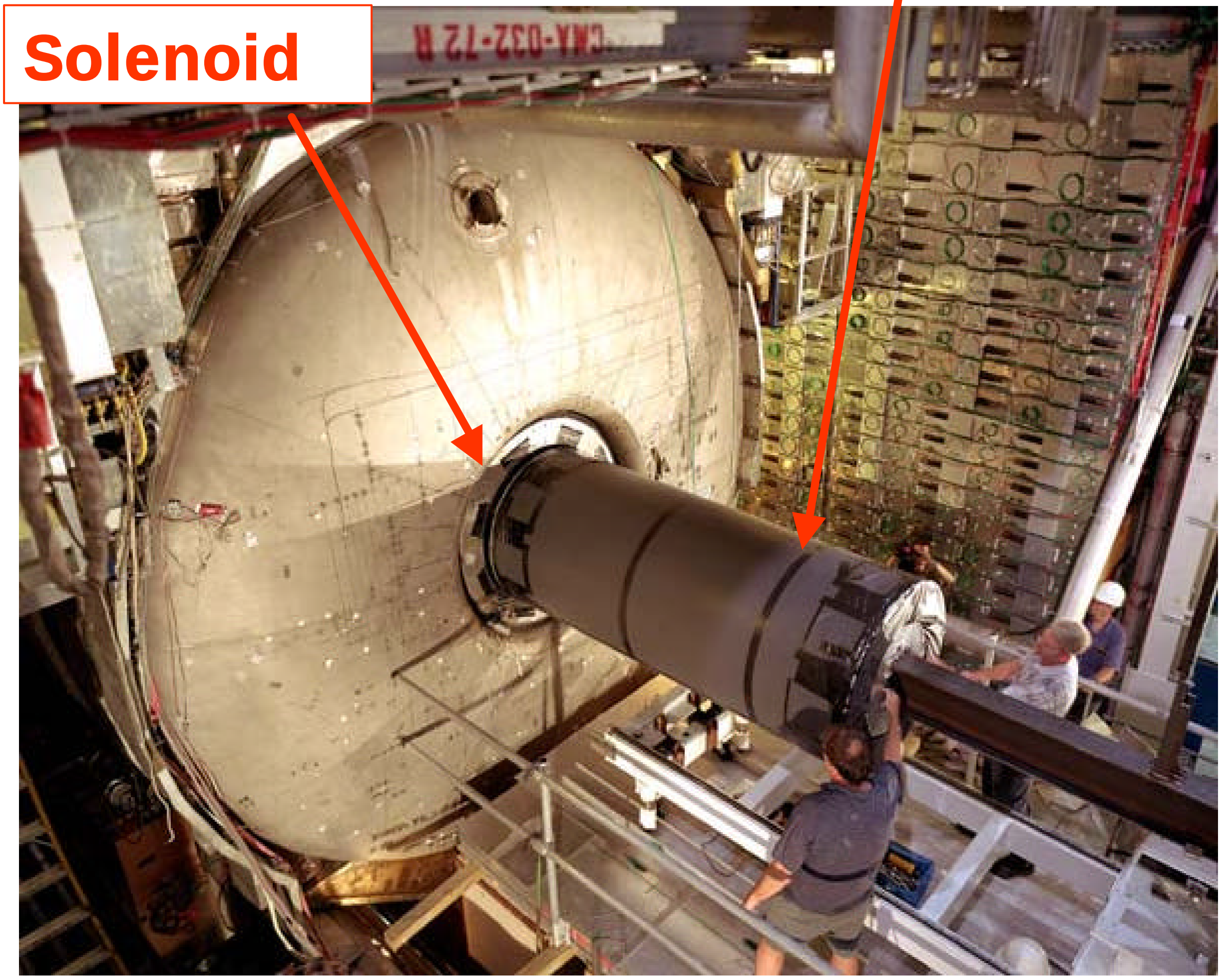
- **since March 2001: Run II a,** $\sqrt{s}$ **= 1960 GeV, 2 fb^{-1}**
- **2005 - LHC : Run II b,** $\sqrt{s}$ **= 1960 GeV, 10-20 fb^{-1}**

  0.8 $\rightarrow$ 5.0 10^{32} cm^{-2} s^{-1}

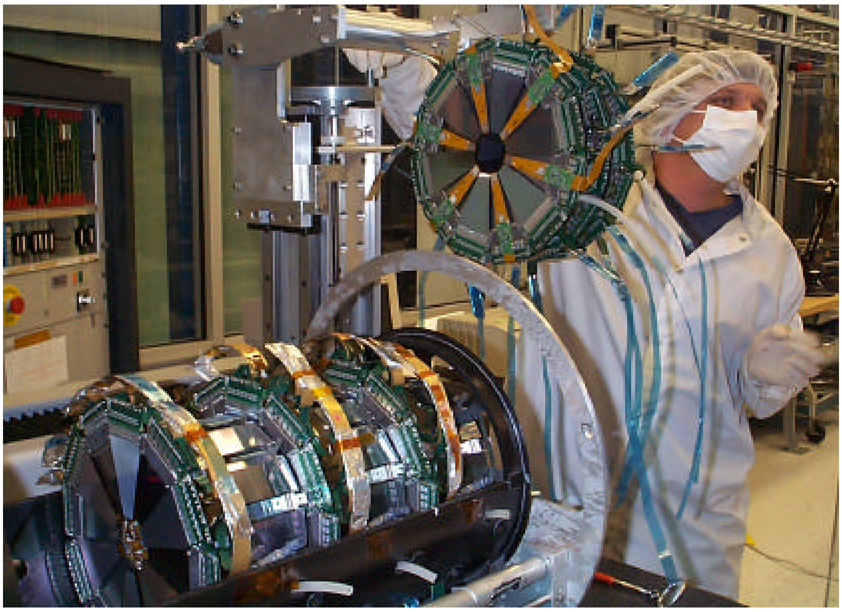
DØ Detector

Fiber Tracker

Solenoid



Silicon Detector



The work of many people.....

German participation:

Aachen, Bonn, Mainz, LMU München, Wuppertal

Search channels at the Tevatron

-- important decays: WH, ZH, WW(*)
-- hopeless: $H \rightarrow \gamma\gamma$, 4 ℓ (rate limited)

$$\sigma \text{ BR } (H \rightarrow ZZ \rightarrow 4l) = 0.07 \text{ fb} \quad (MH{=}150 \text{ GeV})$$

Mass range 110 - 130 GeV:	**LHC**
* **WH** ® ln **bb**	(✓) **weak**
* **ZH** ® l^+l^- **bb**	**weak**
* **ZH** ® nn **bb**	Æ **(trigger)**
* **ZH** ® **bb bb**	Æ **(trigger)**
* **ttH** ® ln **b jjb bb**	✓

Mass range 150 - 180 GeV:	**LHC**
* **H** ® $WW^{(*)}$ ® ln ln	✓
* **WH** ® $WWW^{(*)}$ ® ln ln ln	✓
* **WH** ® $WWW^{(*)}$ ® l^+n l^+n **jj**	✓

Triggering is easier at the Tevatron:
- better P_T^{miss}-resolution
- track trigger at level-1 (big challenge)

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)

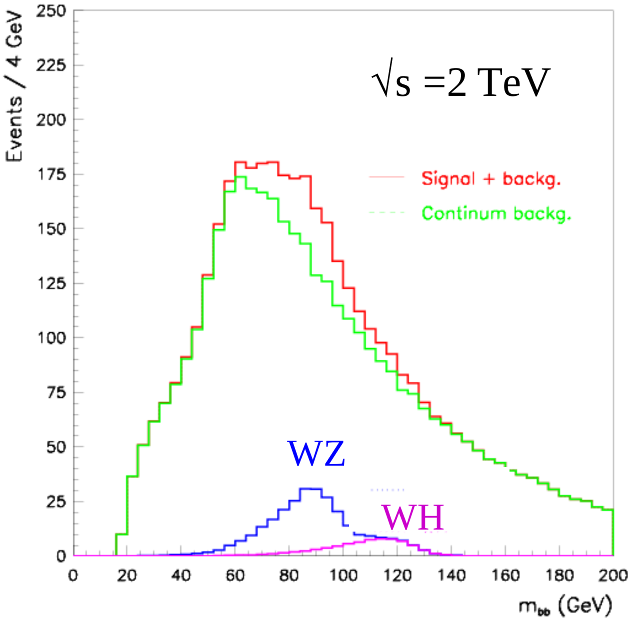
Signal and background ratios after detector acceptance:

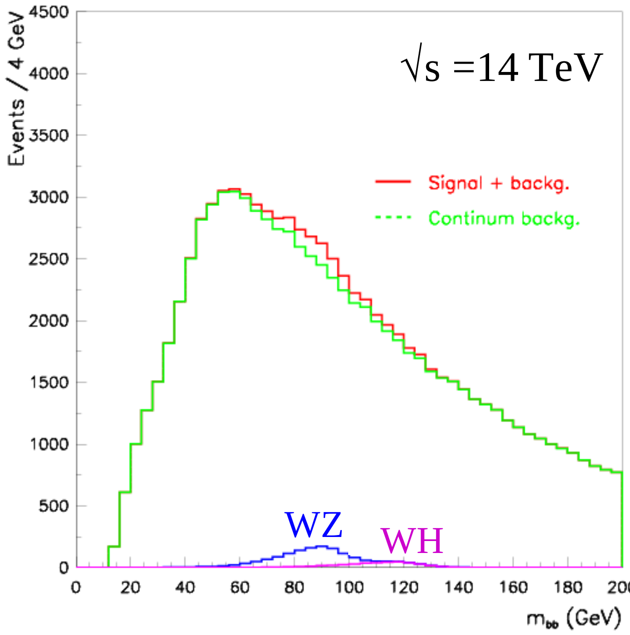
	$WH \to \ell\nu\ b\bar{b}$ $ZH \to \ell\ell\ b\bar{b}$	$H \to WW^{(*)} \to \ell\nu\ell\nu$ (M_H = 160 GeV)
S (14 TeV) / S (2 TeV)	≈ 5	≈ 30
B (14 TeV) / B (2 TeV)	≈ 25	≈ 6
S/B (14 TeV) / S/B (2 TeV)	≈ 0.2	≈ 5
S/√B (14 TeV) / S/√B (2 TeV)	≈ 1	≈ 10

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

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

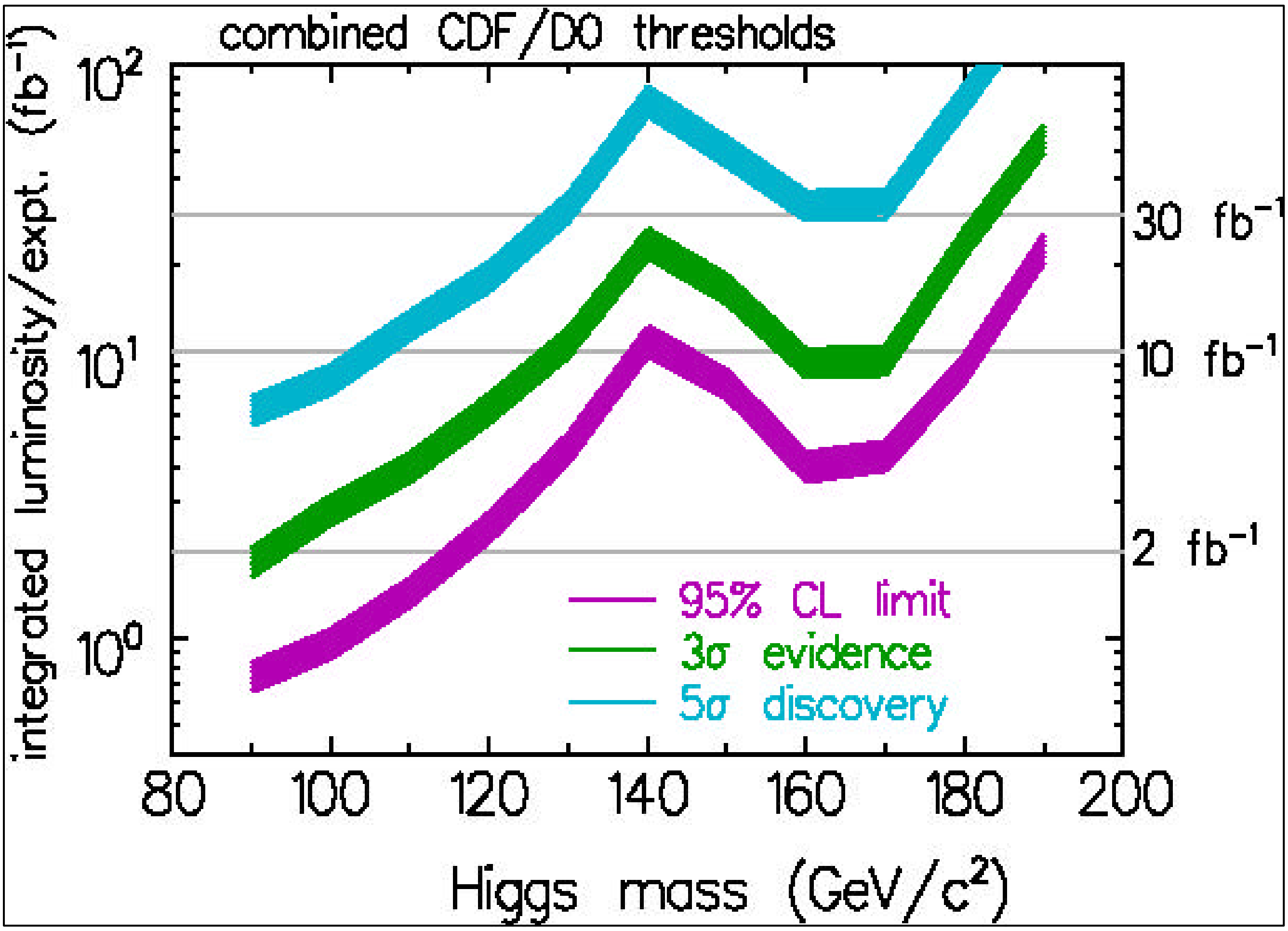




Tevatron discovery potential for a light Higgs

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)**

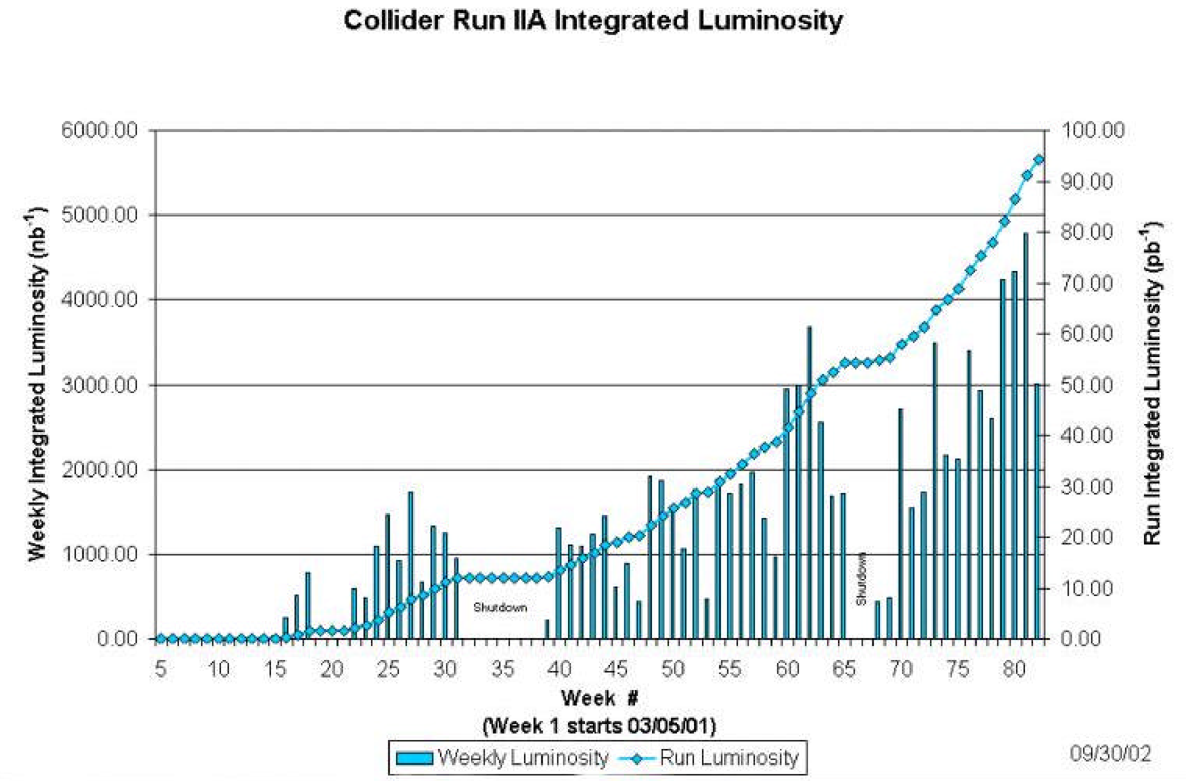
(ii) **3-s evidence for M_H < 130 GeV and**
155 GeV < M_H < 175 GeV

For 30 fb^{-1} (optimistic) :

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

Status of the CDF/D0 data taking

- Detector commissioning essentially completed
- Luminosity much lower than expected, but steadily improving
- present luminosity: 3.6 10^{31} cm^{-2} sec^{-1}
- int. luminosity until 1. October: ~ 35 pb^{-1} per exp. for physics analysis

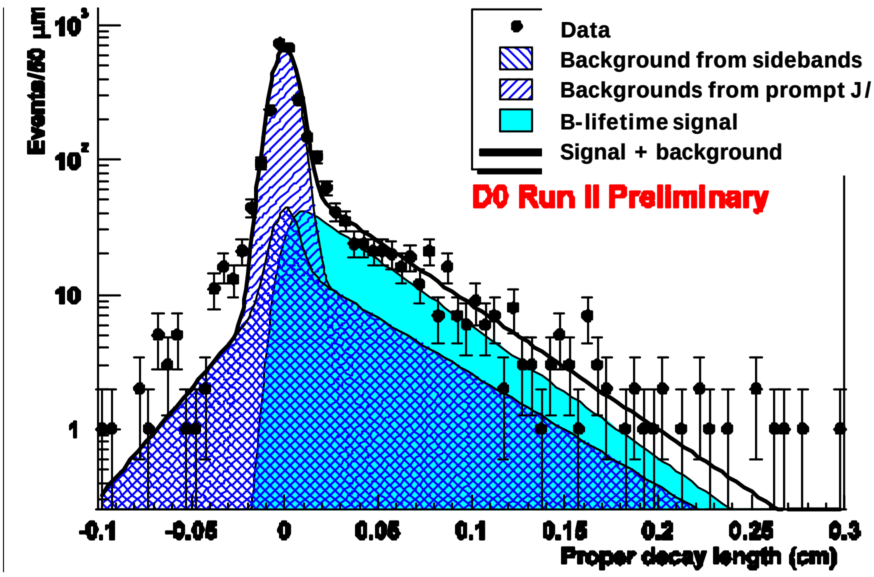


First Signals from B-physics in D0

B lifetime measurement from inclusive J/ψ

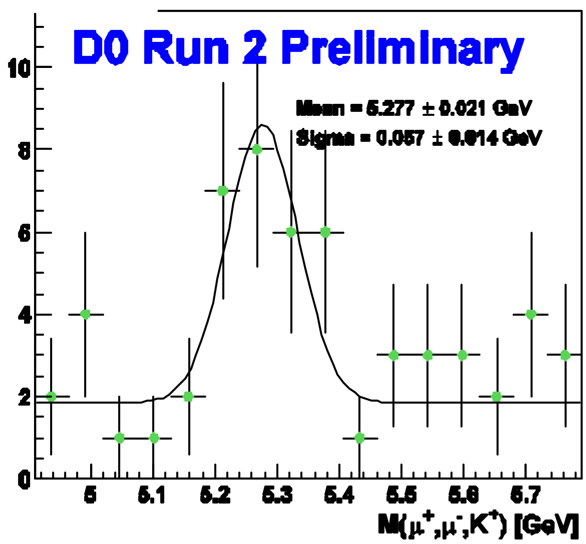
- Measured lifetime consistent with the world average

Proper B decay length (B J/y +X)



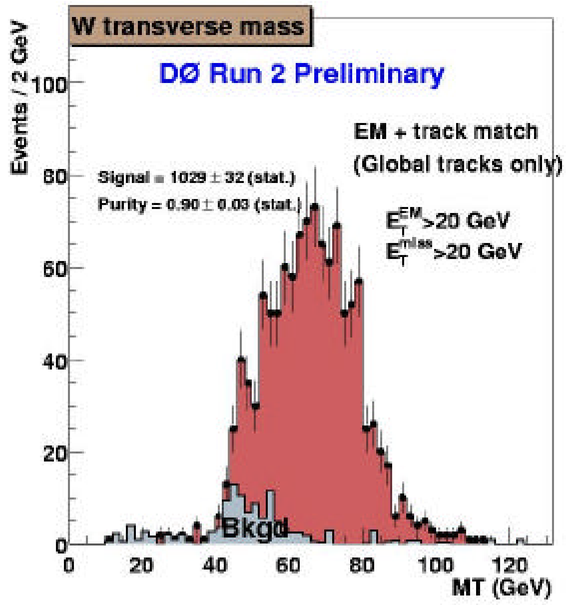
Exclusive
B reconstruction

- **$B^{\pm}$ ® J/y $K^{\pm}$**
- First time in DØ
- Expect more soon!

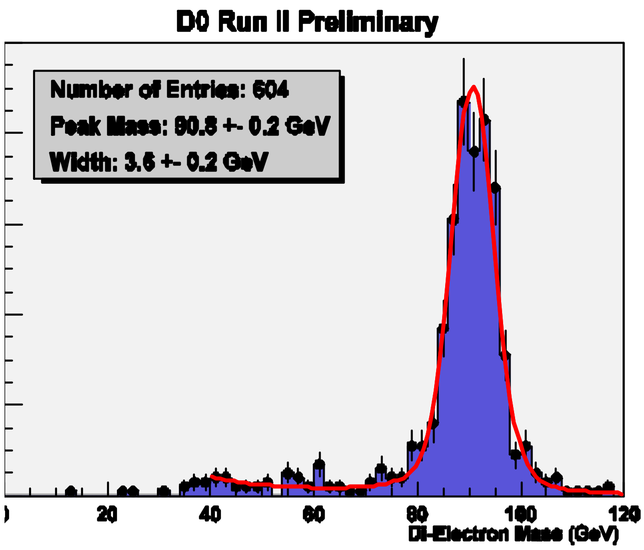


First W and Z signals in Run II

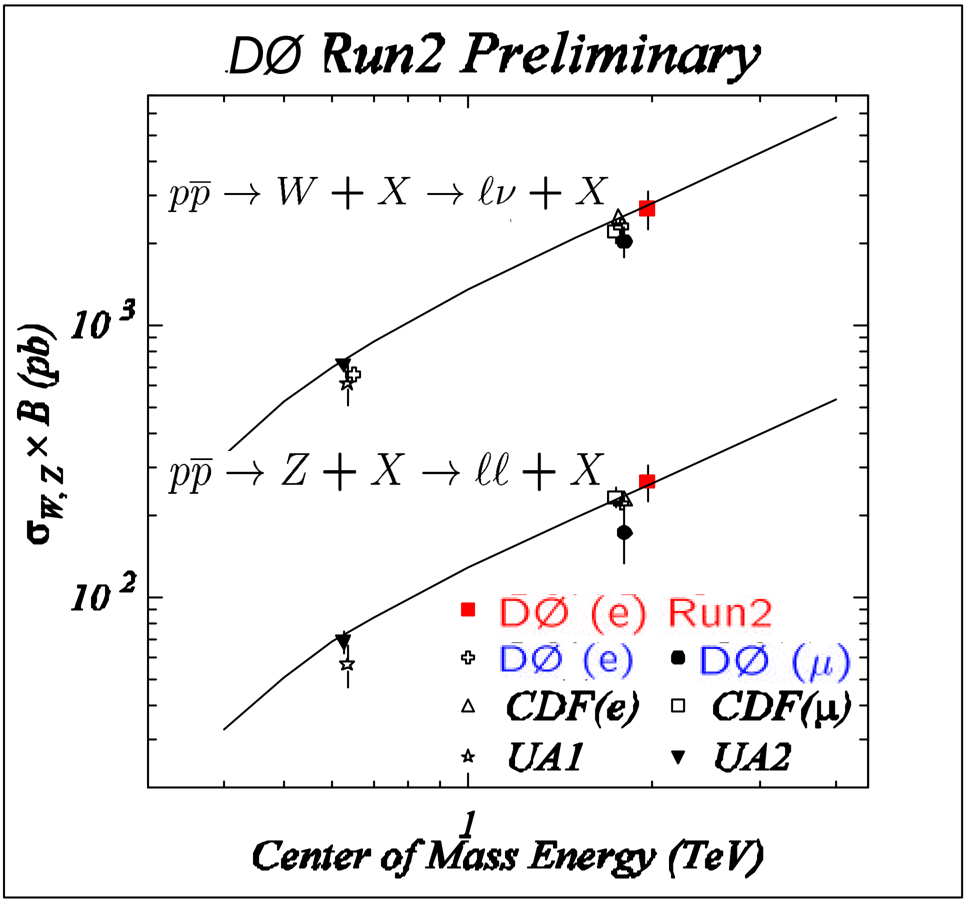
Luminosity ~ 7.5 pb^{-1}



$Z \to e^+e^-$ signal



No. of $W \to e\nu$: 3493±75±296 No. of $Z \to ee$: 186±14±1



Background for H ® WW ® e n e n

- **No sensitivity yet for SH Higgs**

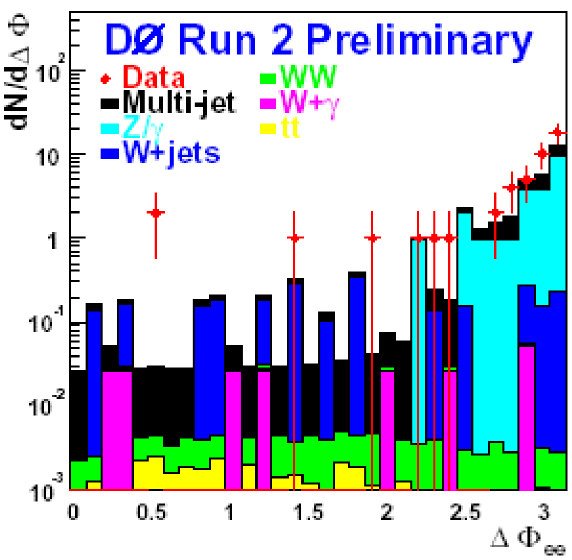
  Þ **first look at backgrounds**

- **However, enhanced rates in Exotic Higgs Models:**
  - 4^{th} SM family enhance Higgs cross sections by a factor of ~8.5 for Higgs mass between 100-200 GeV
  - Fermiophobic/Topcolor Higgs: BR (H ® VV) >98% for $m_H \geq 100$ GeV

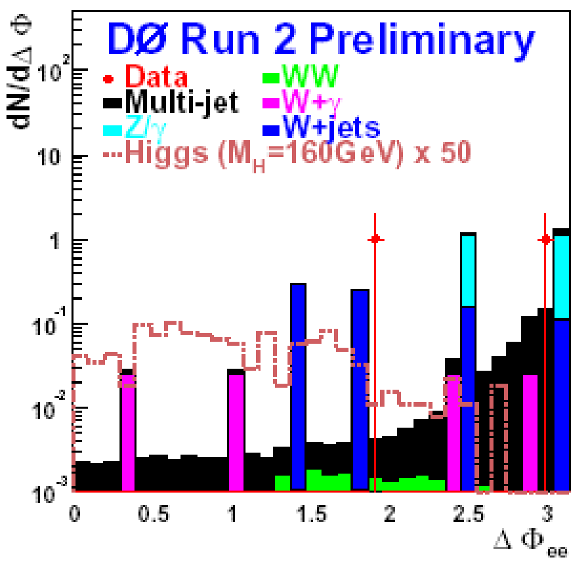
- **Search for ee + P_T^{miss} events**

luminosity 8.8 pb^{-1}

Azimuthal opening angle between the leptons



Require good e^+e^-



Require good e^+e^-, missing ET, no jets

Data are consistent with background expectations

Summary

The question of the existence of the Higgs boson can be answered at the LHC

- Discovery over the full mass range possible (SM, MSSM)
- First parameter measurements can be performed
  (for precise measurements: $\rightarrow$ Tesla)

Also the Tevatron experiments have a discovery potential in the intermediate mass range

- 95% CL exclusion over mass range $m_H < 185$ GeV possible with 10 fb^{-1} per experiment
- badly needed: luminosity

Hadron colliders offer interesting physics potential over the next ~ 10 years....

- also beyond the Higgs sector -