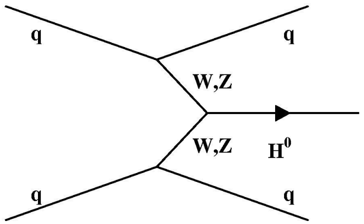
HIGGS Boson Searches at the LHC using Vector Boson Fusion



- **Summary of the LHC Higgs boson discovery potential (standard channels)**
- **Vector boson fusion channels**
  qqH → WW* → l ν l ν
  qqH → τ τ
- **Measurement of Higgs boson parameters**

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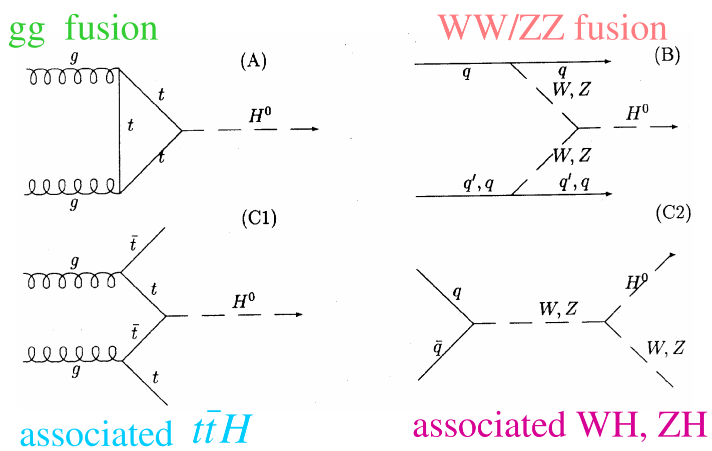
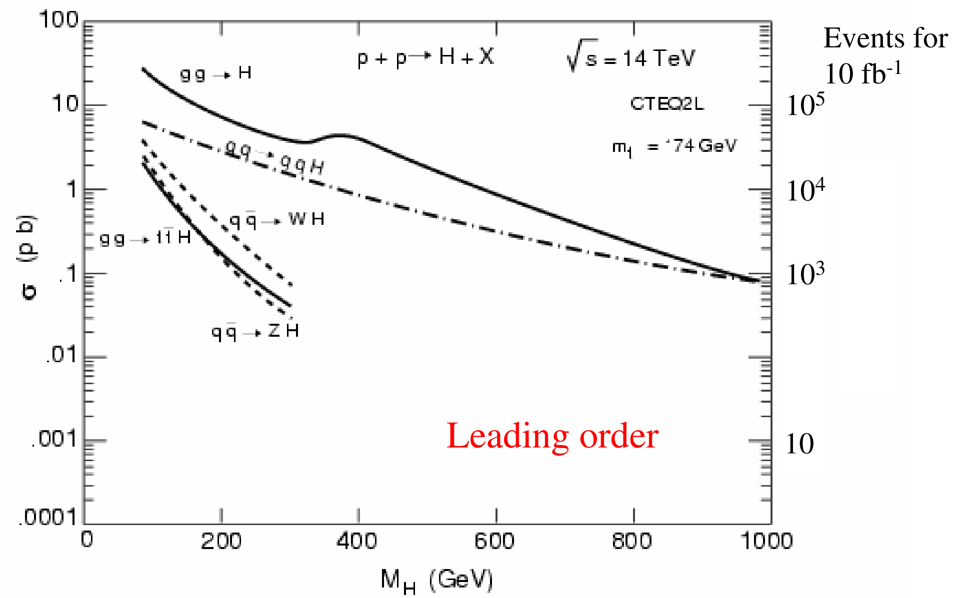
SM Higgs production at the LHC





- K-factors (≡ higher-order corrections) = 1.6 – 1.9 gg → H
- Residual uncertainties on NLO cross-sections (PDF, NNLO, etc.) ≤ 20%

Main search channels at the LHC

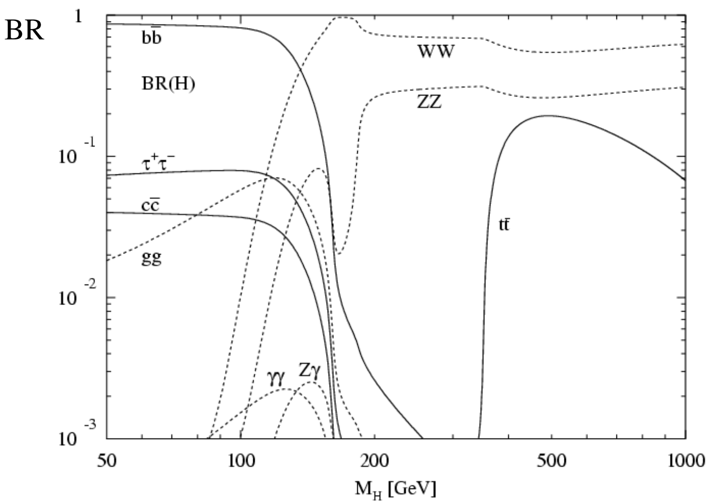
Large QCD backgrounds:

σ ($H \to b\bar{b}$) ≈ 20 pb   direct production, m_H =120 GeV

σ ($b\bar{b}$)   ≈ 500 μb

→ no hope to trigger / extract fully hadronic final states

→ look for final states with ℓ, γ (ℓ = e,μ)



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

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

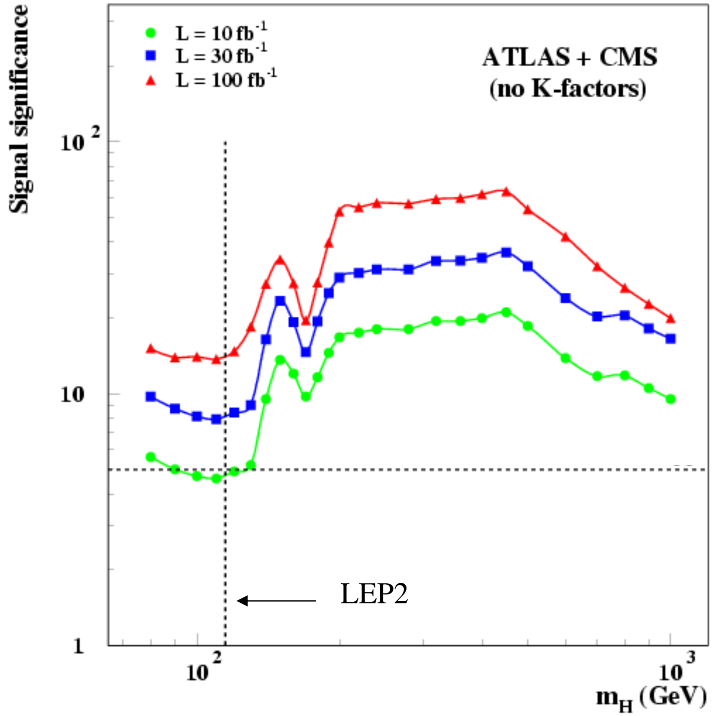
$m_H > 2\, m_Z$: $H \to ZZ \to 4\ell$

$qqH \to ZZ \to \ell\ell\, \nu\nu$

$qqH \to ZZ \to \ell\ell\, jj$ $m_H > 300$ GeV

$qqH \to WW \to \ell\nu jj$ forward jet tag

Detector performance is crucial: b-tag, ℓ/γ E-resolution, γ/j separation, E_T^{miss} resolution, forward jet tagging, ...



L per experiment

M_H = 115 GeV
10 fb^{-1}
S/ $\sqrt{B}$ = 4.7

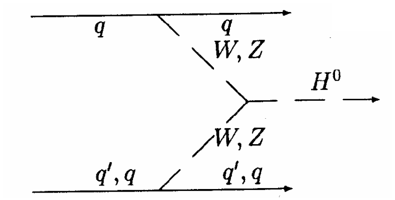
5σ

- The Higgs boson discovery is possible over the full mass range already with ~10 fb^{-1}

However:

- It requires the combination of both experiments and two channels ($H \to \gamma\gamma$ and ttH, $H \to$ bb) in the low mass region
- It will take time to operate, understand and calibrate the detectors

Higgs production via Weak Boson Fusion



Motivation:

•Additional potential for Higgs boson discovery
•Important for the measurement of Higgs boson parameters (couplings to bosons, fermions (taus), total width)
•Detection of an invisible Higgs

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

σ = 4 pb (20% of the total cross section for m_H = 130 GeV)
however: distinctive signature of

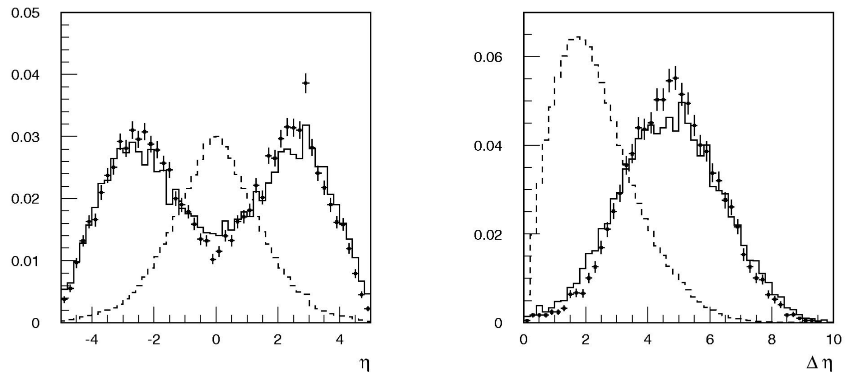
- **two high P_T forward jets**
- **little jet activity in the central region**

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

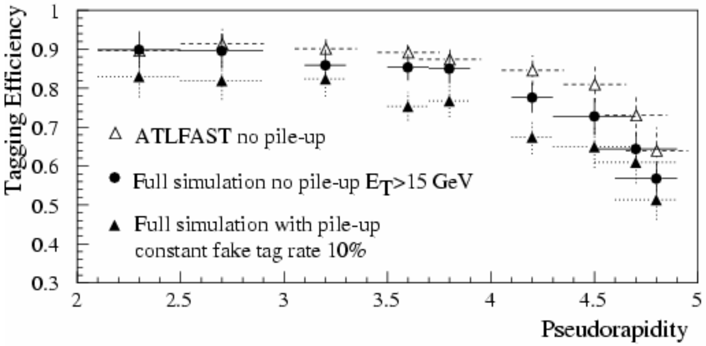
Forward tag Jets

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

Rapidity separation



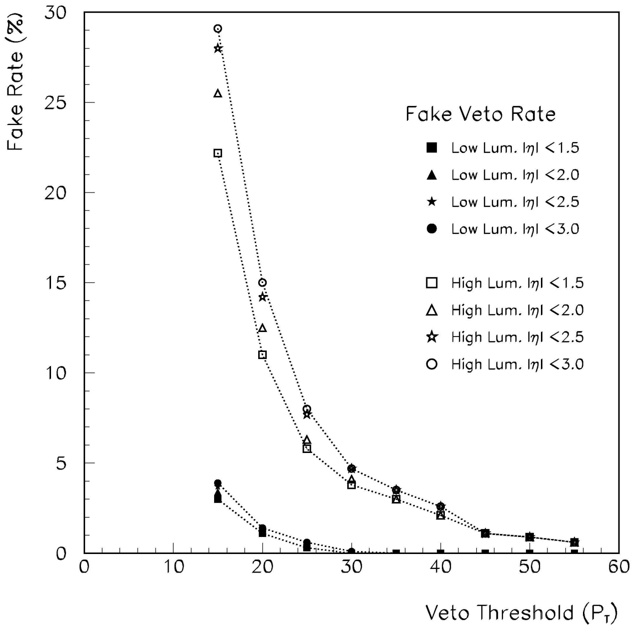
Forward tag jet reconstruction has been studied in full simulation in ATLAS



Physics studies based on a fast simulation have been corrected for efficiency losses

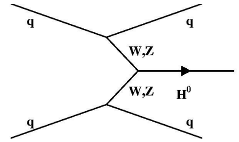
Jets from pile-up events

Fake Jet rate in the central detector region has been studied in full simulation as a function of the LHC luminosity for the vector boson fusion process



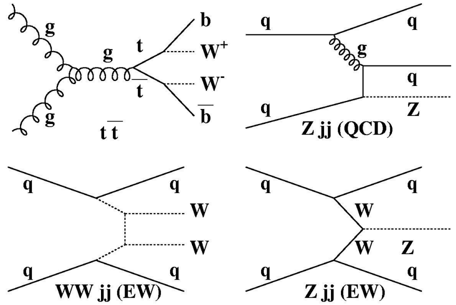
- **At low luminosity: a jet veto thresholds of 20 GeV looks feasible (consistent with TDR result)**
- **It has to be raised at high luminosity**

Signal cross sections:



m_H (GeV)	120	140	160	170	180
$\sigma(qqH)$ (pb)	4.36	3.72	3.22	3.06	2.82
$\sigma \cdot BR(H \to WW^{(*)})$ (fb)	531	1785	2955	2959	2620
$\sigma \cdot BR(H \to \tau\tau)$ (fb)	304	135	11.9	2.8	1.6

Background cross sections:



- QCD processes computed with PYTHIA Monte Carlo
- El.weak processes from matrix element calculation interfaced to PYTHIA

process	p_T-cutoff	cross-section
$t\bar{t}$	> 10 GeV	55.0 pb
QCD $WW + jets$		16.7 pb
$Z/\gamma^* + jets,\ Z/\gamma^* \to \tau\tau$		1742.0 pb
EW $WW + jets$		81.6 fb
EW $\tau\tau + jets$		170.8 fb
$Z/\gamma^* + jets,\ Z/\gamma^* \to ee/\mu\mu$	> 10 GeV	3485.0 pb
ZZ		37.8 pb
$H \to ZZ$		0.26 - 2.5 pb

incl. $W \to l\,\nu$, $Z \to ll$ branching ratios

$H \to WW^{(*)} \to l\nu l\nu$ selection criteria

1. Two isolated leptons:

   $P_T^1 > 20$ GeV, $P_T^2 > 15$ GeV and $|\eta| < 2.5$;

2. Two tag jets:

   $P_T^1 > 40$ GeV, $P_T^2 > 20$ GeV and $\Delta\eta_{tags} = |\eta^1_{tag} - \eta^2_{tag}| > 3.8$;

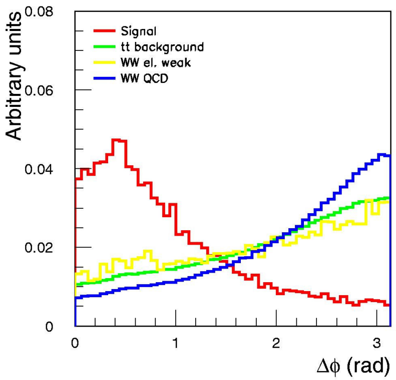
   $\eta^{min}_{tag} < \eta_{l_{1,2}} < \eta^{max}_{tag}$;

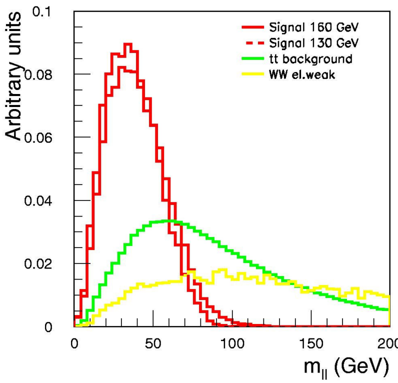
   Tag jets should not be b-jets
   $\Rightarrow$ b-jet veto ($\epsilon_b = 0.70$) for tag jets within $|\eta| < 2.5$

3. Lepton Angular and Di-lepton mass cuts:

   (exploit angular correlations (Spin-0 Higgs $\to$ Spin-1 W's)
   $\Rightarrow$ leptons are expected to have a small angular separation)

   $\Delta\phi_{ll} \leq 1.05$, $\Delta R_{ll} \leq 1.8$, $\cos\theta_{ll} \geq 0.2$
   $M_{ll} < 85$ GeV, $P_T(l_{1,2}) < 120$ GeV

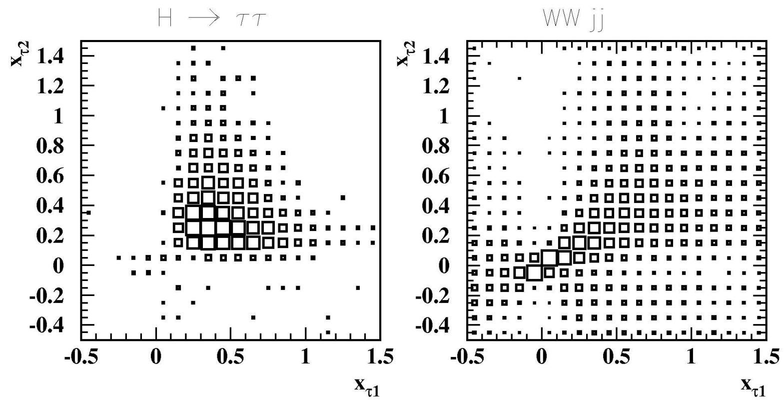




4. Real tau reconstruction:

   Reconstruct τ momenta in the approximation that the τ direction is given by the direction of the charged leptons

   x_τ : fraction of the τ momentum carried by the lepton



expect: $0 \leq x_\tau \leq 1$ for real τs

$\tau - \tau$-mass reconstruction possible: $m_{\tau\tau} = m_{ll}/\sqrt{x_{\tau_1} x_{\tau_2}}$

$Z \to \tau\tau$ rejection (in WW^*-analysis):
require: $x_{\tau_1}, x_{\tau_2} > 0.0$ and
$M_Z - 25$ GeV $< M_{\tau\tau} < M_Z + 25$ GeV;

5. Invariant mass of the two tag jets: $M_{jj} > 550$ GeV;

6. Transverse momentum balance: $|\vec{P}_T^{tot}| < 30$ GeV.

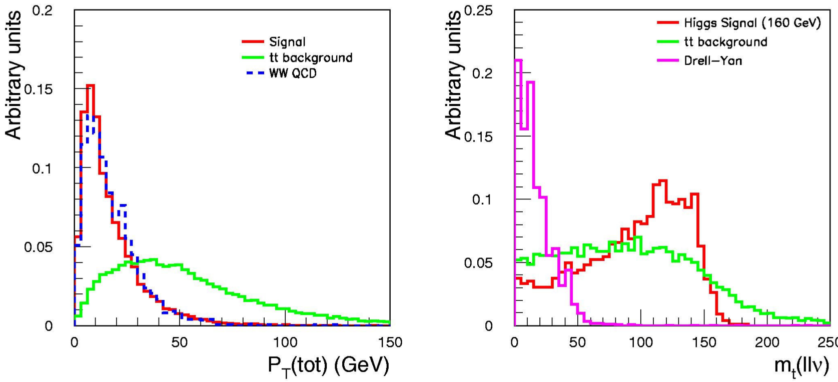
$$\vec{P}_T^{tot} = \vec{P}_T^{l,1} + \vec{P}_T^{l,2} + \vec{P}_T^{miss} + \vec{P}_T^{j,1} + \vec{P}_T^{j,2}$$

(less sensitive to pile-up than jet veto)

7. Jet veto:

   no jets with $P_T > 20$ GeV in the pseudorapidity range $|\eta| < 3.2$;

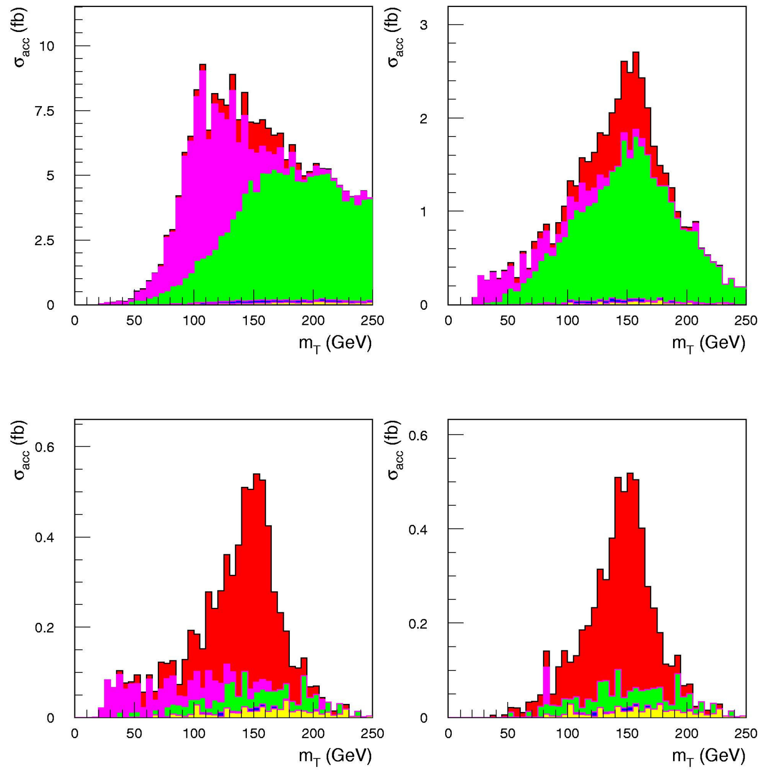
8. $Z/\gamma^* \to \tau\tau$ rejection: $m_T(ll\nu) > 30$ GeV.



Accepted signal and background cross sections:

- Lepton P_T cuts and Tag jet requirements
- Lepton angular and mass cuts
- Tau rejection, momentum balance and jet veto cuts
- Drell-Yan rejection

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



m_H = 160 GeV

Accepted signal and background cross sections:

	signal (fb)		background (fb)			
	VV	gg	$t\bar{t}$	$WW + jets$ EW	$WW + jets$ QCD	γ^*/Z QCD
Lepton acceptance	29.6	121.9	5493	14.2	590.5	25222
+ Forward Tagging						
+ Lepton angular cuts						
+ Real τ rejection	6.64	1.34	15.3	0.50	0.17	5.93
+ Jet mass						
+ P_T^{tot}	4.52	0.50	1.80	0.38	0.04	2.70
+ Jet veto	3.87	0.34	0.42	0.34	0.03	1.70
+ M_T-cut	3.76	0.31	0.41	0.32	0.02	0.03
$H \to WW^{(*)} \to e\mu + X$ incl. $\tau \to e, \mu$ contr.	4.32	0.33	0.50	0.35	0.03	0.03
$H \to WW^{(*)} \to ee/\mu\mu + X$ incl. $\tau \to e, \mu$ contr.	3.92	0.30	0.48	0.36	0.04	0.12

Systematic uncertainties ?

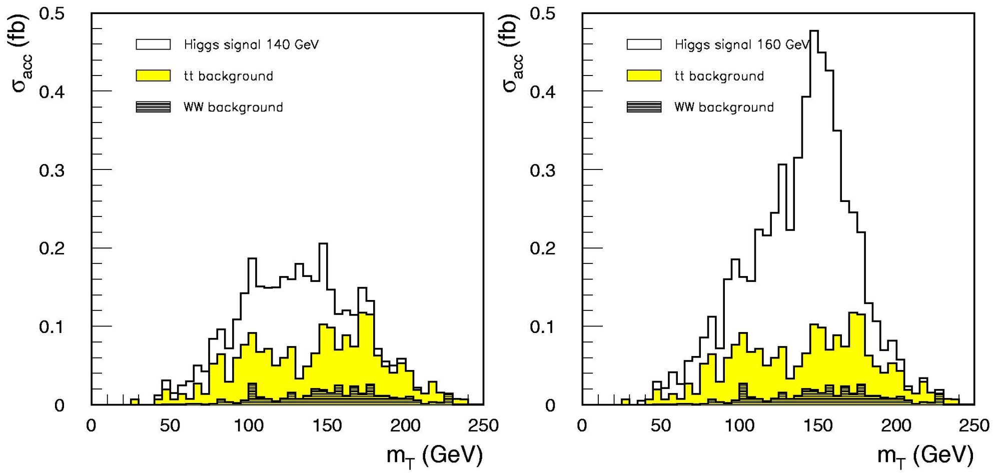
- QCD backgrounds (incl. tt) have been computed in the PYTHIA parton shower approach
- tt+0,1, and 2 jet explicit matrix element calculation predicts a larger background
  conservative estimate: σ (tt) = 1.08 fb (factor 2.1 larger)

For the evaluation of the signal significnce:

- use tt + 0, 1, and 2 jet matrix element prediction
- assign a systematic uncertainty of ±10% on the background

(can be measured in the experiment, using tt-events, normalization can be done outside the signal region)

Final signal significance



m_H (GeV)	130	140	150	160	170	180
Upper M_T bound for mass window (GeV)	140	150	160	175	190	220
$H \to WW^{(*)} \to e\mu + X$						
Signal (5 fb^{-1})	4.7	8.3	13.3	21.6	21.7	18.1
Background (5 fb^{-1})	3.1	3.8	4.3	5.5	6.2	6.9
Stat. significance (5 fb^{-1})	2.1	3.3	4.7	6.5	6.3	5.2
$H \to WW^{(*)} \to ee/\mu\mu + X$						
Signal (5 fb^{-1})	4.4	8.3	14.1	20.4	22.8	18.3
Background (5 fb^{-1})	4.2	4.7	5.5	6.4	7.3	7.9
Stat. significance (5 fb^{-1})	1.8	3.0	4.6	6.0	6.2	5.1
$H \to WW^{(*)} \to l\nu\ jj + X$						
Signal (30 fb^{-1})	4.5	7.5	10.5	24.0	24.0	18.0
Background (30 fb^{-1})	6.0	6.0	6.0	18.0	18.0	18.0
Stat. significance (30 fb^{-1})	1.5	2.4	3.3	4.6	4.6	3.5

$H \rightarrow \tau\tau$ decay channels

Two decay modes considered: $H \rightarrow \tau\tau \rightarrow l^+ l^- P_T^{miss}$
$H \rightarrow \tau\tau \rightarrow l^{\pm}\nu\nu\ had\ \nu$

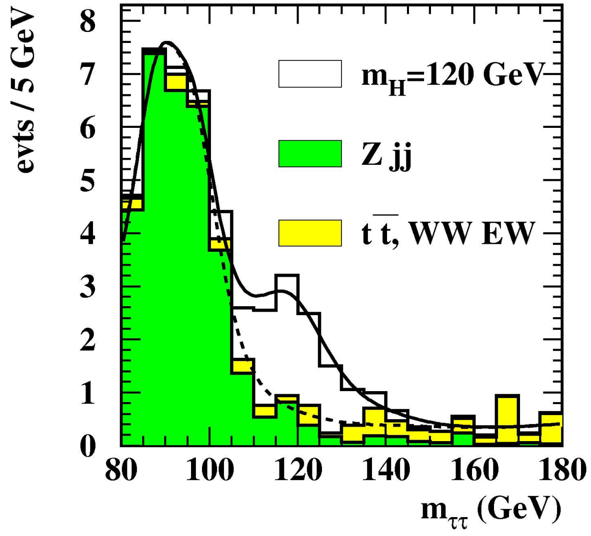
Similar selection as for the WW^* decay mode;

example: l-had decay mode:

- One isolated lepton (e or μ)
  $P_T(e) > 25$ GeV and $|\eta_e| \leq 2.5$ or
  $P_T(\mu) > 20$ GeV and $|\eta_\mu| \leq 2.5$
- One identified hadronic τ
  $P_T > 40$ GeV (hadr. τ reconstruction eff. of 50%)
- Two tag jets:
  $P_T^1 > 40$ GeV, $P_T^2 > 20$ GeV and $\Delta\eta_{tags} = |\eta_{tag}^1 - \eta_{tag}^2| \geq 4.4$
- Real Tau reconstruction:
  $0 < x_{\tau_l} < 0.75$ and $0 < x_{\tau_h} < 1$
- (l-P_T^{miss})-transverse mass cut:
  $m_T(l\nu) = \sqrt{2P_T(l)P_T^{miss} \cdot (1 - cos\Delta\phi)} < 30$ GeV
- $M_{jj} > 700$ GeV and central jet veto
- Mass window cut of ± 10 GeV

Results for the three final states considered: $m_H = 120$ GeV

	signal (fb)		background (fb)			
	VV	gg	$t\bar{t} + jets$	$\tau\tau + jets$ QCD	$\tau\tau + jets$ EW	Total
$H \rightarrow \tau\tau \rightarrow e\mu$	0.23	0.01	0.02	0.02	0.04	0.09
$H \rightarrow \tau\tau \rightarrow ee/\mu\mu$	0.24	0.02	0.05	0.04	0.08	0.17
$H \rightarrow \tau\tau \rightarrow l\ hadP_T^{miss}$	0.50	0.02	0.06	0.05	0.14	0.25

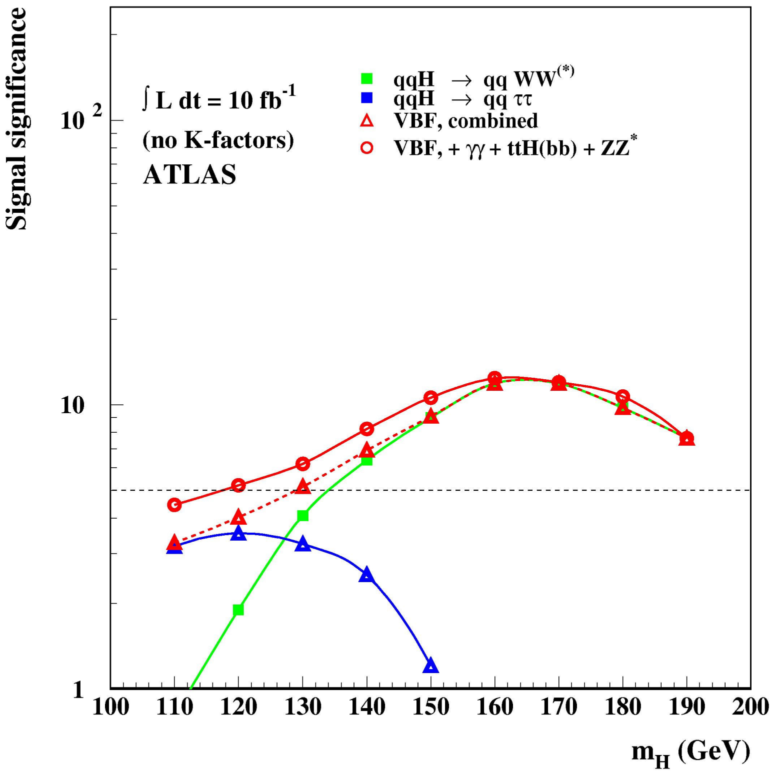


m_H (GeV)	110	120	130	140	150
$H \rightarrow \tau\tau \rightarrow e\mu P_T^{miss}$					
Signal (30 fb^{-1})	7.7	7.0	5.1	3.3	1.5
Background (30 fb^{-1})	7.0	2.6	2.3	1.9	1.5
Stat. significance (30 fb^{-1})	2.4	3.2	2.5	1.8	-
$H \rightarrow \tau\tau \rightarrow ee/\mu\mu P_T^{miss}$					
Signal (30 fb^{-1})	9.2	7.2	5.7	3.1	1.5
Background (30 fb^{-1})	10.5	5.2	3.8	3.1	2.3
Stat. significance (30 fb^{-1})	2.4	2.6	2.3	1.4	-
$H \rightarrow WW^{(*)} \rightarrow l\ had\ P_T^{miss}$					
Signal (30 fb^{-1})	19	15	13	10	5
Background (30 fb^{-1})	15.0	6.5	5.9	4.1	3.7
Stat. significance (30 fb^{-1})	4.1	4.6	4.2	3.7	2.1
combined Stat. significance (30 fb^{-1})	5.1	6.1	5.5	4.5	2.6

Combined significance exceeds 5 σ for 110 GeV $< m_H <$ 135 GeV

mass resolution: 11 GeV for m_H =120 GeV

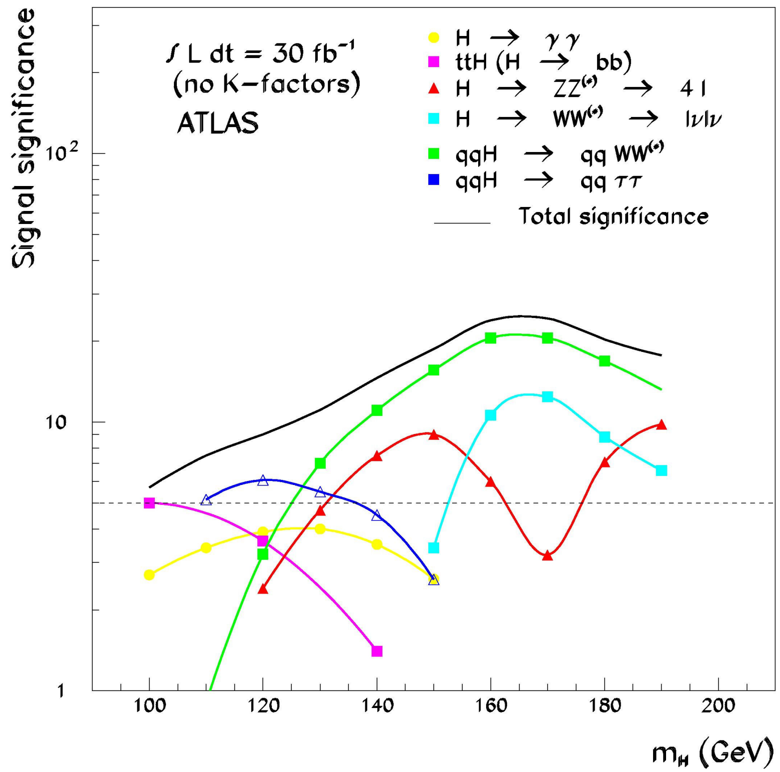
Combined significance of VBF channels for 10 fb^{-1}



- Vector boson fusion channels (in particular WW*) are discovery channels at low luminosity

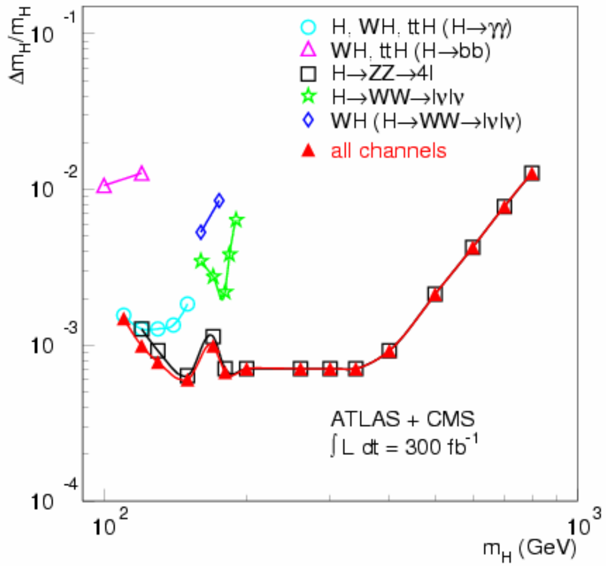
- For 10 fb^{-1} in ATLAS: **5 σ significance for $120 \leq m_H \leq 190$ GeV**
  (after combination with the standard channels)

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
  (important for Higgs boson parameter determination)

Mass of Standard Model Higgs boson



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)

VBF channels do not add much, dominated by standard ZZ and γγ channels

Mass of MSSM Higgs bosons

MSSM Higgs	Δm/m (%)
h, A, H → γγ	0.1–0.4
H → 4 ℓ	0.1–0.4
H/A → μμ	0.1-1.5
h → bb	1–2
H → hh → bb γγ	1-2
A → Zh → bb ℓℓ	1–2
H/A → ττ	1-10

300 fb^{-1}

Measurements of Higgs couplings

i) Ratio between W and Z partial widths

- **Direct measurements**

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

- QCD corrections cancel

VBF: σ x BR (qqH → qq WW*) / σ x BR (H → ZZ*)

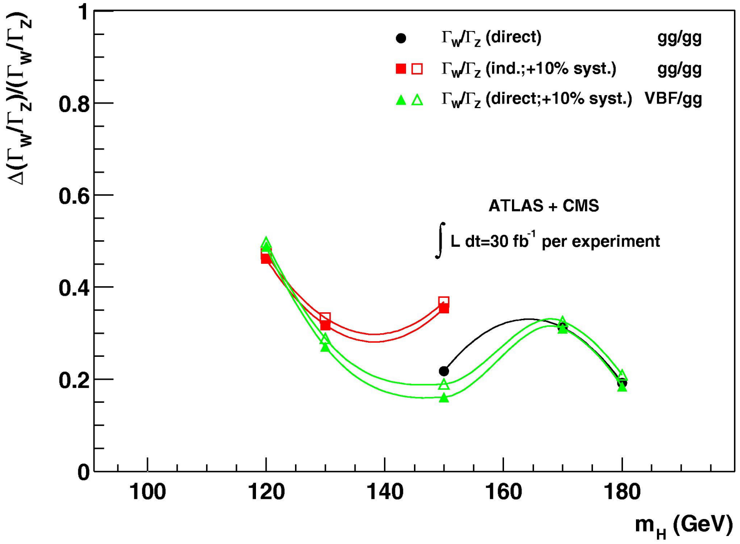
- different processes, QCD corrections do not cancel, i.e. add. uncertainty

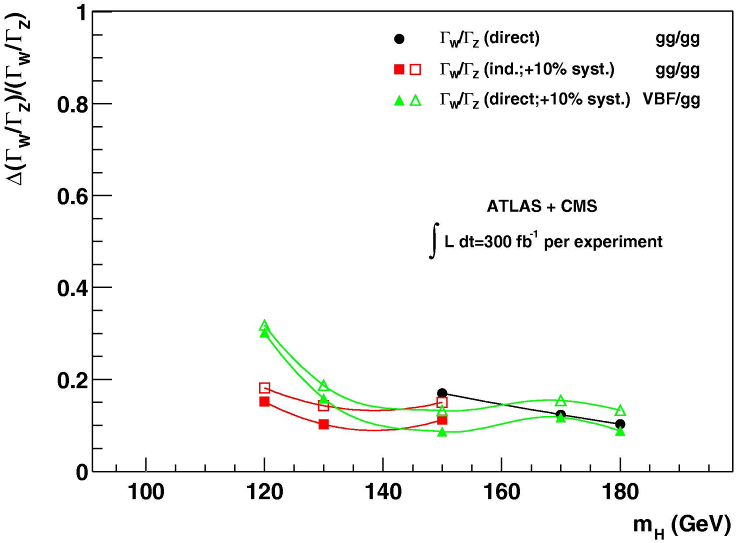
- working on qqH → qq ZZ*)

- **Indirect measurement**

$$- \frac{\sigma \times BR(H \rightarrow \gamma\gamma)}{\sigma \times BR(H \rightarrow ZZ^*)} = \frac{\Gamma_g \Gamma_\gamma}{\Gamma_g \Gamma_Z} \sim \frac{\Gamma_W}{\Gamma_Z}$$

(Use proportionality between Γ_W and Γ_γ, needs theoretical input, 10% uncertainty assumed)





Ratios of boson/fermion couplings

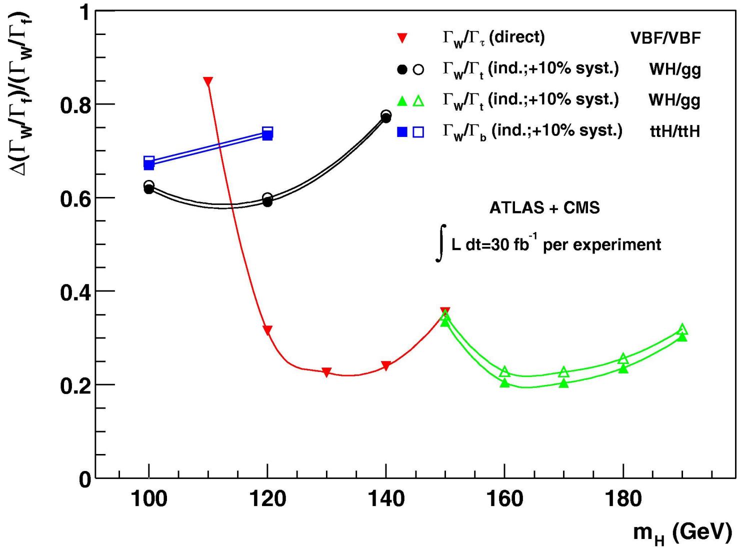
VBF: **allows a direct measurement of Γ_W / Γ_τ in the mass range 120 - 150 GeV**

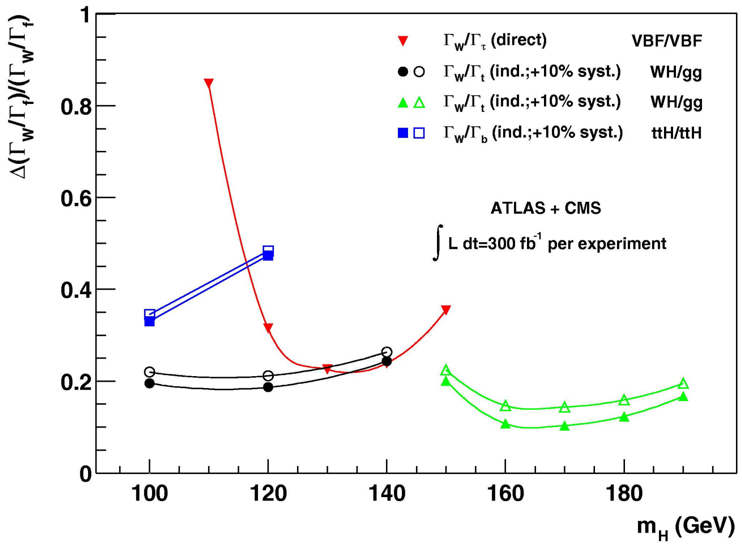
- Direct measurement
  - $\frac{\sigma\times BR(qq\to qqH(H\to WW))}{\sigma\times BR(qq\to qqH(H\to\tau\tau))} = \frac{\Gamma_W\Gamma_W}{\Gamma_W\Gamma_\tau} = \frac{\Gamma_W}{\Gamma_\tau}$
- Indirect measurement
  - $\frac{\sigma\times BR(WH(H\to\gamma\gamma))}{\sigma\times BR(H\to\gamma\gamma)} = \frac{\Gamma_W\Gamma_\gamma}{\Gamma_g\Gamma_\gamma} \sim \frac{\Gamma_W}{\Gamma_t} * C_{QCD}$
  - $\frac{\sigma\times BR(WH(H\to WW))}{\sigma\times BR(H\to WW^*)} = \frac{\Gamma_W\Gamma_W}{\Gamma_g\Gamma_W} \sim \frac{\Gamma_W}{\Gamma_t} * C_{QCD}$
  - $\frac{\sigma\times BR(ttH(H\to bb))}{\sigma\times BR(ttH(H\to\gamma\gamma))} = \frac{\Gamma_t\Gamma_b}{\Gamma_t\Gamma_\gamma} \sim \frac{\Gamma_b}{\Gamma_W}$

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

under study: qqH →qq bb

Karl Jakobs ECFA/DESY workshop, St.Malo,April 2002





Conclusions

1. **The large LHC Higgs boson discovery potential can be significantly enlarged by the Vector Boson Fusion channels**

2. **They are important for both a fast Higgs boson discovery in the WW* channel (130-190 GeV)**

and

for the measurement of Higgs boson parameters