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on behalf of the ATLAS and CMS Collaboration

Discovery potential for the SM Higgs boson in exclusive final states

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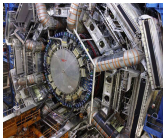
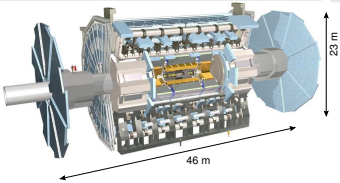
Outline

- Higgs boson production and decays at the LHC.
- Searches in exclusive channels (related to Higgs production mode).
- Discovery potential for low luminosity running ($\mathcal{L}$=2×10^{33} cm^{-2}s^{-1}).

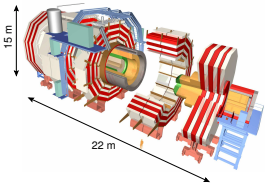
ATLAS

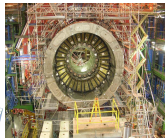


July 2007



CMS





May 2007

Detector design optimized for the Higgs search in a wide mass range:

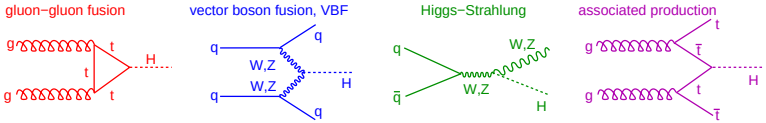
Good, hermetic calorimetry → missing E_T measurement, jet reconstruction up to $|\eta|$ =4.9

Powerful particle identification:

- ∼90% muon efficiency, cleanest identification (combining tracker and muon spectrometer).
- ∼80% electron efficiency for jet rejection of $\sim 10^5$.
- ∼80% photon efficiency for jet rejection of $\sim 10^3$.
- ∼60% b-tagging efficiency for light-flavour jet rejection of $\sim 10^2$ (good vertexing).
- ∼50% τ-hadron efficiency for jet rejection of $\sim 10^2$.

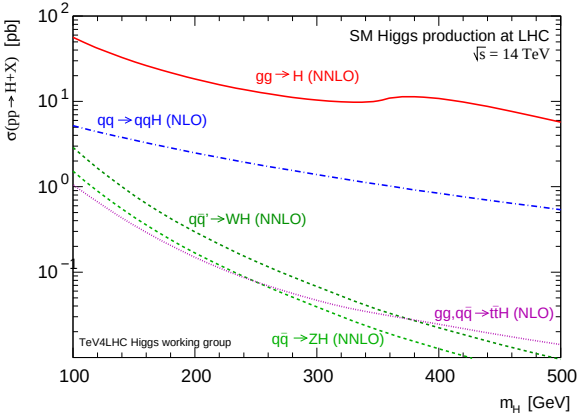
Electron, photon and muon energy- and p_T-resolution: 2-3%.

Higgs production at the LHC



	gluon−gluon fusion	vector boson fusion, VBF	Higgs−Strahlung	associated production
K−factor (N)NLO/LO:	~2	~1.1	~1.4	~1.2
Scale uncertainty:	~15%	~4%	~7%	~15%

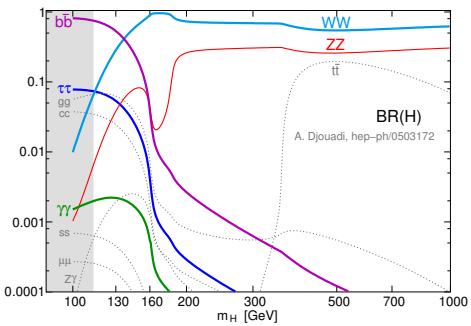
PDF uncertainties: 5-15% for all production modes.

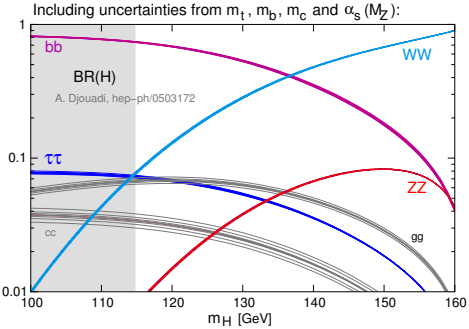


σ(Backgrounds) [pb]:

- $t\bar{t}$: $\sim 0.8 \cdot 10^3$
- $Z \to \ell^+\ell^-$: $\sim 1.6 \cdot 10^3$
- $W^\pm \to \ell^\pm\nu$: $\sim 1.2 \cdot 10^4$
- $b\bar{b}$: $\sim 0.6 \cdot 10^9$
- *inelastic*: $\sim 0.7 \cdot 10^{11}$

Higgs decay modes





m_H <130 GeV

- $H \to b\bar{b}$: Dominant decay; large QCD-background supressed only in $t\bar{t}H$ mode.
- $H \to \tau\tau$: Accessible only via vector boson fusion mode.
- $H \to \gamma\gamma$: Very low BR (decay via top- and W-loops),

  but still significant due to an excellent γ-resolution and γ/jet-separation.

m_H >130 GeV

- $H \to WW^{(*)}$
- $H \to ZZ^{(*)}$; Gold-plated channel above $m_H = 2M_Z$: $H \to ZZ \to 4\ell$.

Searches in exclusive final states

(i.e. given production and decay products - and nothing else - in the final state.)

Complementary to inclusive searches.
Essential for the measurement of the Higgs boson properties.

Vector Boson Fusion ($qq \to V^* V^* \to qqH$):

- $H \to \tau^+\tau^-$ (110 - 150 GeV)
- $H \to W^+W^-$ (120 - 300 GeV)
- $H \to \gamma\gamma$ (110 - 150 GeV)

Associated production with $t\bar{t}$ ($gg, q\bar{q} \to t\bar{t}H$):

- $H \to b\bar{b}$ (110 - 130 GeV)
- $H \to \gamma\gamma$ (110 - 130 GeV)

Associated production with W/Z ($q\bar{q} \to VH$):

- $H \to \gamma\gamma$ (110 - 140 GeV)
- $H \to W^+W^-$ (150 - 190 GeV)

Gluon fusion ($gg \to H$) is usually considered for inclusive searches.

- Exclusive search needed for measurement of the Higgs couplings $\Rightarrow$ veto on additional jets to supress the VBF-contribution. ($H \to \gamma\gamma,\ H \to WW,\ H \to ZZ \to 4\ell$).

Strategy of ATLAS and CMS analyses

ATLAS:

- Using LO cross-sections for signal and background for consistency, since not all background processes are known to NLO.
- All shown results were taken from the most recent publications; mostly based on parametrized, fast detector simulation.
  (Parametrization obtained from the detailed detector simulation - realistic performance for the key objects: μ, e, jets, b-tag, τ-jet, E_T^{miss}, jet veto...)
- Ongoing `Computing System Commissioning (CSC)` effort:
  - ⋆ Detailed G4 detector simulation with an up-to-date detector layout, including trigger simulation and pile-up effects.
  - ⋆ New preliminary results do not show big discrepancies w.r.t. the present ones.

$\Rightarrow$ Final, updated results expected in December 2007.

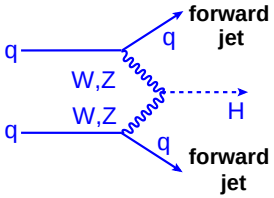
CMS:

- NLO cross-sections used for the Higgs boson production and for the backgrounds when available.
  HIGLU, HDECAY, HQQ, VV2H, V2HV, MCFM
- Generators at LO, advanced generators for multi-jet events:
  Alpgen, MADGRAPH, CompHEP, TopRex
- Almost all analyses done using detailed G4 detector simulation.
- All results published in PTDR `Vol.2`, `CERN/LHCC 2000-21 (June 2006)`.

Vector Boson Fusion (VBF) Channels

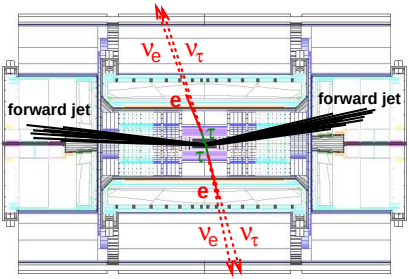
First particle-level analyses at LHC by D.Zeppenfeld, D.Rainwater et al. (1997).

Production rates are large enough (10-50% w.r.t gluon fusion).



Very characteristic topology:

- Two forward jets.
- Large rapidity gap (no additional jets in central region).
- Higgs decay products are central, can be used for triggering.



Decay modes:

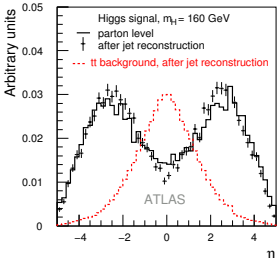
$$H \to \tau^+\tau^- \to (\ell^+\nu\nu)(\ell^-\nu\nu)$$
$$H \to \tau^+\tau^- \to (\ell\nu\nu)(\tau_{jet}\nu)$$

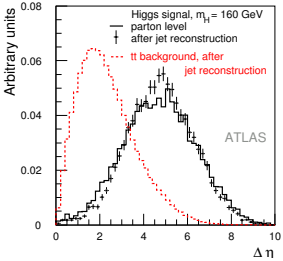
$$H \to W^+W^- \to (\ell^+\nu)(\ell^-\nu)$$
$$H \to W^+W^- \to (\ell^\pm\nu)(jj)$$

$$H \to \gamma\gamma$$

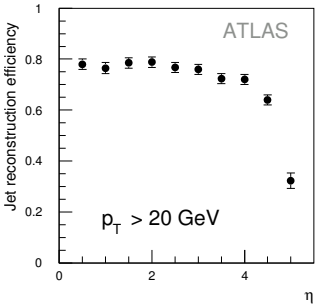
VBF channels: Forward jets

Forward jet separation: discrimination from QCD-backgrounds.





- $\eta_{j1} \cdot \eta_{j2} < 0$
- $|\Delta\eta_{jj}| > 3.5$ - 4
- $m_{jj} > 500$ - 700 GeV



Jet reconstruction performance:

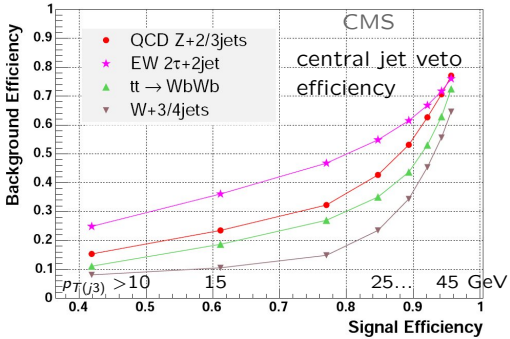
- Evaluated with full G4 simulation, including pile-up.
- Reliable forward-jet tagging.

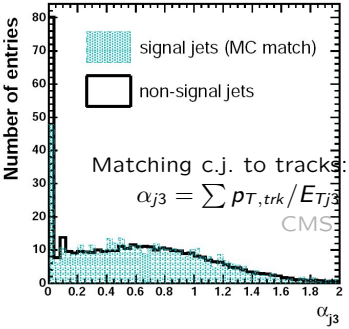
VBF channels: Central jet veto

Rapidity gap between the tagging jets (no colour exchange b. quarks).

First discussed by Yu.Dokshitzer, V.Khoze, S.Troyan, Sov.J.Nucl.Phys.46(1987)712;
Yu.Dokshitzer, V.Khoze, T.Sjostrand, Phys.Lett.B274(1992)116;

- Veto on additional jets in the central region:





Experimental challenge: Fake central jets from the pile-up.
→ matching central jets to the signal vertex (by means of tracks).

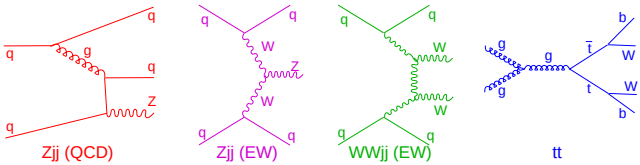
Theoretical questions: Jet distributions at NLO. Underlying event.

VBF $H \to \tau\tau \to (\ell\nu\nu\ \ell\nu\nu,\ \ell\nu\nu\ \tau_{jet}\nu)$

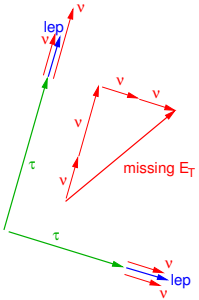
Hadron-hadron mode difficult to trigger, under investigation.

Backgrounds:

- $Z + jets,\ W + jets,\ WW + jets,\ t\bar{t}$



Higgs mass reconstruction possible despite of neutrinos.



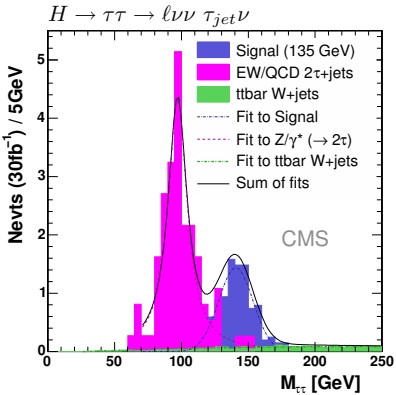
Collinearity approximation:

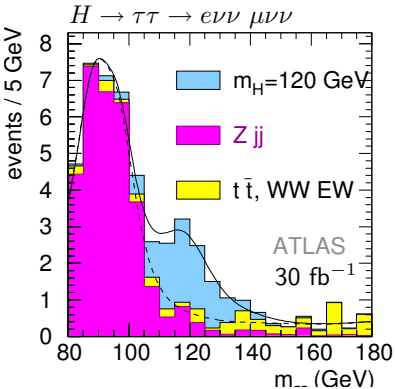
Decay products of highly boosted τ-s all fly in the τ-direction. Neutrino momenta can be extracted.

(Method is not valid when τ-s are back-to-back, since the missing E_T vanishes in that case.)

- Mass resolution $\sim 10\%$, mostly limited by the measurement of the missing E_T.

VBF $H \to \tau\tau$: Analysis results





EW/QCD $Z \to \tau\tau + jets$: dominant contribution after all cuts.

Expected uncertainty on the background rate: 5-10%.

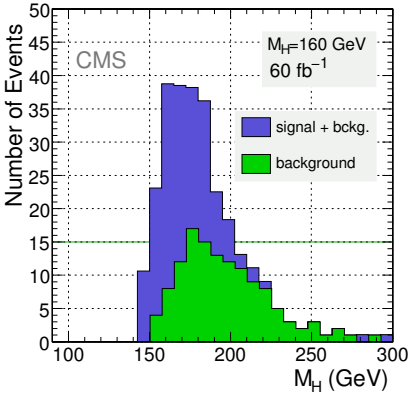
- Above m_H >125 GeV: Determination from the flat sidebands.
- For m_H <125 GeV: Normalize to the Z-peak, but understand shape?
  - ⋆ Relaxing particular cuts (central jet veto).
  - ⋆ Estimating $Z \to \tau\tau$ contribution from the $Z \to \mu\mu$ data.

VBF $H \to WW \to \ell\nu jj$

Already established as a discovery channel for the high Higgs mass region.

Extending to low masses: complemetary to $H \to ZZ^* \to 4\ell$ when $160 < m_H < 180$ GeV.

- Similar backgrounds as for $H \to \tau\tau$.
- Event selection:
  forward jet tagging, isolated lepton, 4 jets, $E_T^{miss} > 30$.
  Dominant contribution after cuts: $t\bar{t} + jets$, $W + jets$.
- Mass reconstruction possible:



Detector systematic uncertainties - impact on signal and background rates:

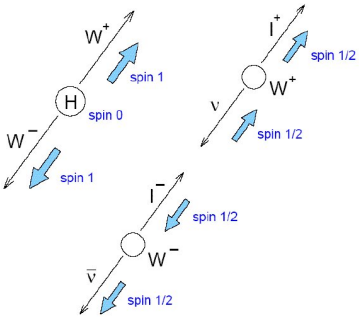
- Jet energy scale: $\sim 12\%$.
- Jet energy resolution: $\sim 1\%$.
- E_T^{miss}: $\sim 2\%$.
- Lepton isolation: $\sim 1\%$.

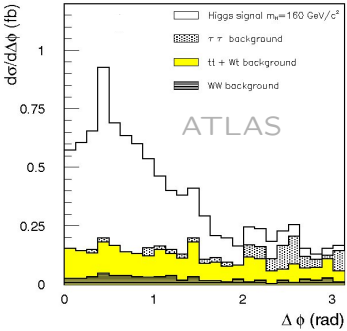
Largest uncertainty comes from the selection efficiency w.r.t. jet-p_T cut.
$\Rightarrow$ reduced by data-driven estimates.

Lower rate than in the semi-leptonic case, but $W + jet$ suppressed.
Backgrounds: Drell-Yan, $EW/QCD\ Z + jets$, $t\bar{t}$, $EW/QCD\ WW + jets$

Event selection:

- high E_T^{miss}, $Z \rightarrow \tau\tau$ veto, τ-jet veto
- forward jet tagging, central jet veto (b-jet veto for $|\eta| < 2.5$)
- spin corelations
  (leptons tend to be emitted in the same direction, $\Delta\Phi_{\ell\ell} < 1.5$):





Dominant background after cuts: $t\bar{t}$, $EW\ WW + jets$.

VBF $H \to WW \to \ell\nu\ell\nu$ (cont'd)

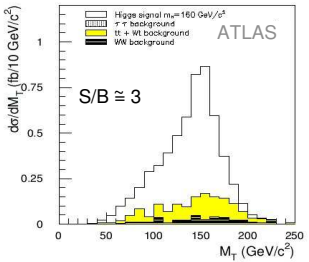
No Higgs mass reconstruction possible:

Counting excess of signal events over the background in a given region of transverse mass $m_T = \sqrt{2 \cdot p_T^{\ell\ell} \cdot E_T^{miss}(1 - \cos\Theta)}$.

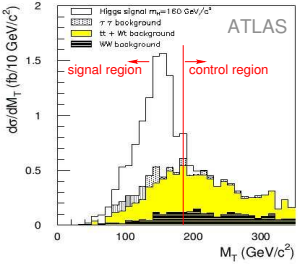
$\Rightarrow$ need good knowledge of background distributions ($\pm 10\%$ uncert.):

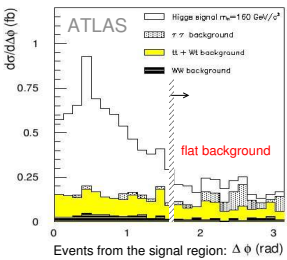
- $t\bar{t}$ from the semi-leptonic decay mode (after forward jet tagging)
- relaxing selection cuts (on lepton pairs) and then using m_T side bands (if the shape is taken from Monte Carlo) + $\Delta\Phi_{\ell\ell}$-region >1.5 for events from the signal region (i.e. $m_T < m_H$).

After all cuts



Without lepton cuts





VBF $H \rightarrow \gamma\gamma$

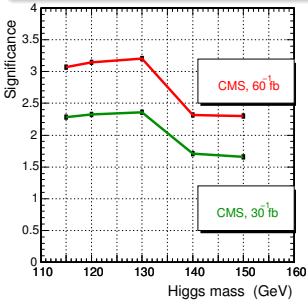
Background process	Cross section (pb)
QCD hadronic jets	$2.8*10^7$
Gluon fusion	83
Drell Yan	4.1×10^3
$\gamma\gamma$ + 2jets, QCD	47.24
$\gamma\gamma$ + 2jets, EW	0.33
γ + 3 jets, QCD	5970
γ + 3 jets, EW	5.15

Event selection:

- Photon isolation. (Track- and calorimeter-based).
- Higgs vertex reconstruction.
- Forward jet tagging efficiently reduces the background.

  $\Rightarrow$ Remaining bckg. comparable to the expected Higgs signal.

Signal significance:



60fb^{-1}	$m_H = 115$ GeV/c^2	$m_H = 120$ GeV/c^2	$m_H = 130$ GeV/c^2	$m_H = 140$ GeV/c^2	$m_H = 150$ GeV/c^2
N_s	20.2	21.1	19.1	15.7	11.2
γ+3jets (QCD)	2.7	4.7	3.5	2.0	5.8
γ+3jets (EW)	2.5	2.5	2.5	2.5	2.5
$\gamma\gamma$ + 2jets (QCD)	11.2	13.2	9.85	8.9	4.6
$\gamma\gamma$ + 2jets (EW)	10	7.0	7.0	11.0	2.0
Drell Yan	0	0	0	0	0
N_b	26.0	26.2	21.4	28.2	14.9
ΔN_b	2.8	3.2	2.4	3.0	1.8
S	3.07	3.15	3.21	2.32	2.30

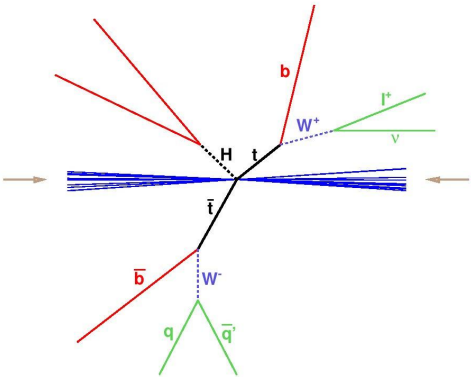
ΔN_b - bck. uncertainty estimated from the side bands.

$t\bar{t}H$ Channels

$t\bar{t}H$ production rate is ~ 50 times lower compared to gluon fusion.

However, this signature can provide:

- Additional handle for the suppression of a large QCD-background. (In particular for $H \to b\bar{b}$.)
- In the (semi-)leptonic mode: high-p_T lepton for triggering.

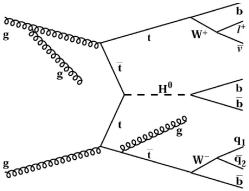


Decay modes:

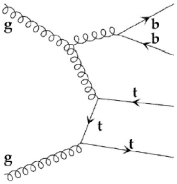
- $t\bar{t}H \to (\ell\nu b)(\ell\nu b)b\bar{b}$
  $t\bar{t}H \to (\ell\nu b)(jjb)b\bar{b}$
  $t\bar{t}H \to (jjb)(jjb)b\bar{b}$
- $t\bar{t}H \to (\ell\nu b)(jjb)\gamma\gamma$

⋆ $H \to WW$:
Ongoing studies in ATLAS.

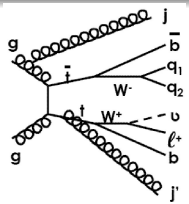
$t\bar{t}H \rightarrow (\ell\nu b)(jjb)b\bar{b}$



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



$t\bar{t}b\bar{b}$ background



$t\bar{t}jj$ background

Complex final state:

- 6 jets: 4 b-jets and 2 light jets,
- 1 high-p_T lepton,
- missing energy from neutrino,
- additional jets from ISR/FSR.

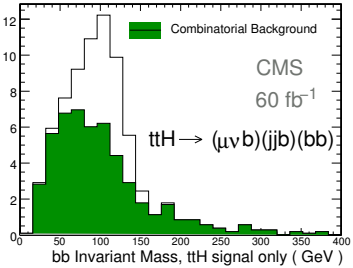
Large backgrounds:

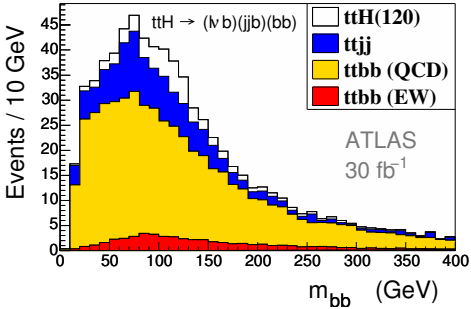
- combinatorial from mis-pairing of jets,
- irreducible from $t\bar{t}b\bar{b}$ events,
- reducible from $t\bar{t} + jets$ events.

Full event reconstruction is required,
good jet reconstruction and good b-tagging are essential.

$t\bar{t}H \to (\ell\nu b)(jjb)b\bar{b}$: Results

Using likelihood methods to improve the selection of jet-pairings.





Channel (m_H=120 GeV)	Luminosity [fb^{-1}]	S	B	$S/\sqrt{B}$
CMS $t\bar{t}H \to (\ell\nu b)(jjb)(b\bar{b})$	60	40	427	1.9
CMS $t\bar{t}H \to (\ell\nu b)(\ell\nu b)(b\bar{b})$	60	132	9090	1.4
CMS $t\bar{t}H \to (jjb)(jjb)(b\bar{b})$	60	45	505	2.0
ATLAS $t\bar{t}H \to (\ell\nu b)(jjb)(b\bar{b})$	30	41	218	2.8

- Only ∼30% of b-pairings are correct.
- Signal and background mass distributions have a similar shape.
  ⇒ strong sensitivity to the background uncertainties.

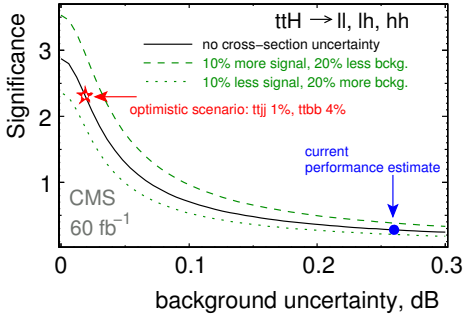
$t\bar{t}H \to (\ell\nu b)(jjb)b\bar{b}$: Systematic uncertainties

$t\bar{t} + jets$ cross-section highly depends on the scale choice (LO).
$\Rightarrow$ Background should be determined from the data.

- Shape (depends on the mistagging of the jets):
  select ($\ell\nu b$ jjb jjb)-sample, randomly tag two jets as b-jets, extract $m_{b\bar{b}}$ as usual $\Rightarrow$ estimated stat. uncertainty $\sim$1% (ATLAS).
- Absolute normalization: from the side-bands.
  Statistical uncertainty $\sim$6%, systematic uncertainty $\sim$4% (ATLAS).

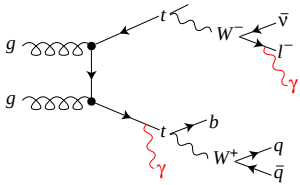
Systematic uncertainties from the detector performance (CMS):

- Jet energy scale: 3-10%.
- Jet resolution: 10%.
- b,c-tagging: 4%.
- u,d,s-tagging: 10%.
- Luminosity: 3%.



$t\bar{t}H \rightarrow (\ell\nu b)(jjb)(\gamma\gamma)$

Dominant background: tt$\gamma\gamma$

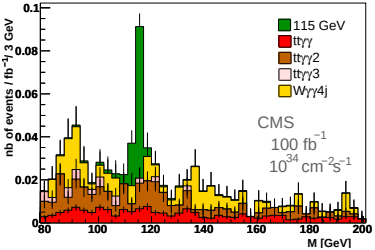


Lepton from the top-decay allows for

- discrimination of the QCD bckg.,
- and for the primary vertex reconstruction
  $\Rightarrow$ lower sensitivity to the photon resolution.

Analysis results for 100 fb^{-1} at $L = 10^{34}$ cm^{-2}s^{-1}:

- Systematic uncertainties taken into account.

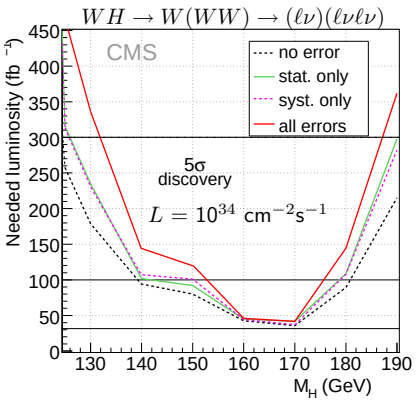


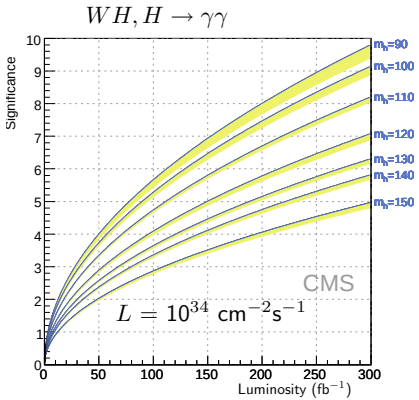
Higgs Boson Mass (GeV)	115	120	130	140
Sig. Selection Eff. (%)	10.7	11.2	11.3	11.3
Number Signal	7.42 ±0.33	7.33 ± 0.33	5.96±0.27	4.21±0.19
Total Number Bcgkd	1.61 ±0.53	2.79 ±0.62	1.98±0.66	1.10± 0.51
Total Number Bcgkd from fit w. syst.	2.23±0.34	1.94±0.32	1.60±0.22	1.39±0.22
Signal Significance (ScP)	3.541	3.662	3.257	2.510
Signal Significance (ScP) w. syst.	3.414	3.523	3.184	2.453

$(W/Z)H$ Channels

Similarly as for the $t\bar{t}H$ production, additional lepton(s) from W(Z)-decay allow for a stronger background discrimination.

- Due to the low production rate, these signatures become significant only at integrated luminosities above 100 fb^{-1}.





Discovery potential at 30 fb^{-1}