

Associated SM Higgs boson searches with ATLAS



$ttH, H \rightarrow bb$

$ttH, H \rightarrow WW$

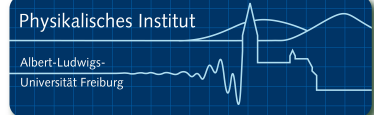
$WH, H \rightarrow WW$

Physics at LHC

Split, 29th September 2008

Inga Ludwig

on behalf of the ATLAS collaboration





Associated SM Higgs boson production

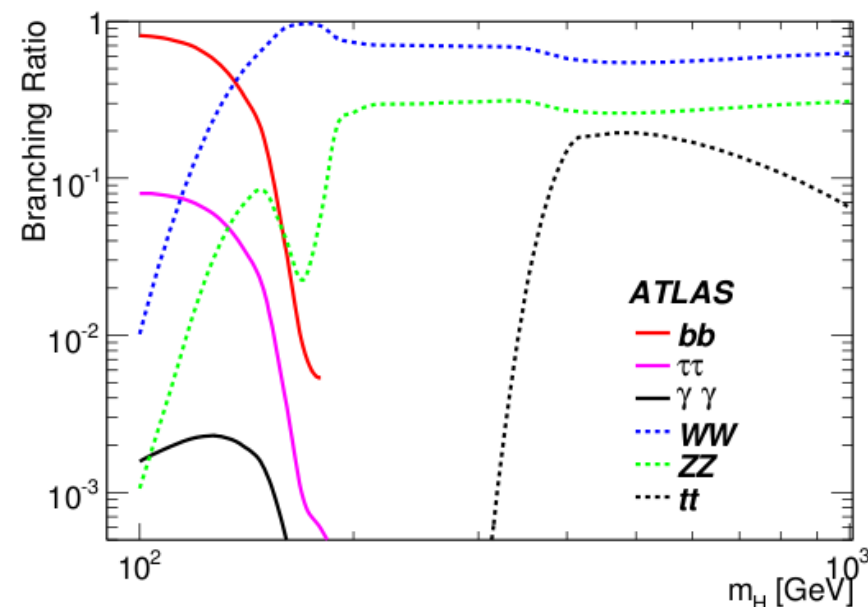
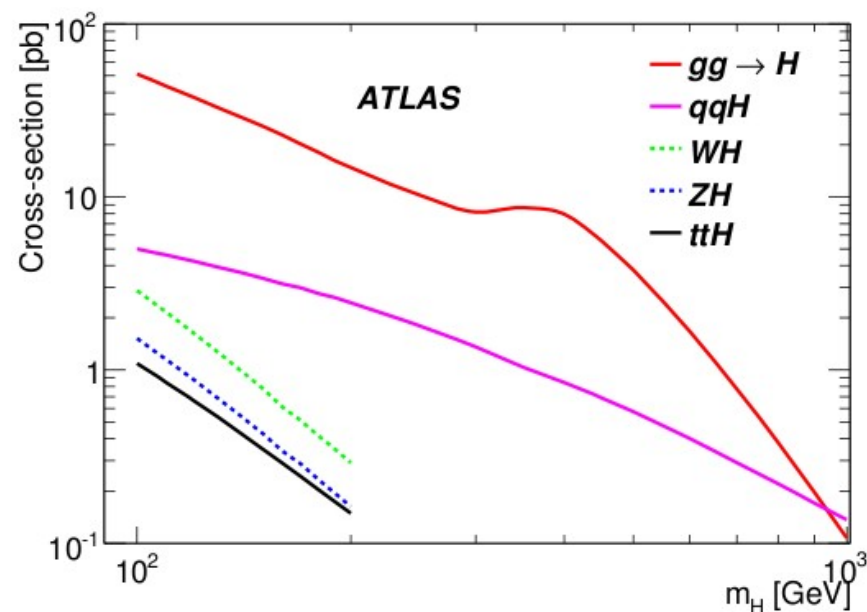
- **$ttH, H \rightarrow bb$**

- $\sigma \times BR \sim 0.4 - 0.2$ pb for $m_H \sim 115 - 130$ GeV
- expected to **contribute to discovery** potential of a low mass SM Higgs boson
- access to t - and b -Yukawa **couplings**

- **$ttH, H \rightarrow WW$ and $WH, H \rightarrow WW$**

- relevant in the mass range around **160 GeV** (probably after several years of LHC running)
- $\sigma \times BR (ttH, H \rightarrow WW, m_H = 160 \text{ GeV}) \sim 0.26$ pb
- $\sigma \times BR (WH, H \rightarrow WW, m_H = 170 \text{ GeV}) \sim 0.49$ pb
- provides access to t -Yukawa and W - H couplings \rightarrow no discovery but **relevant for testing the Standard Model**

- All three channels under study in ATLAS with **full detector simulation** and for an integrated luminosity of **30 fb^{-1}**



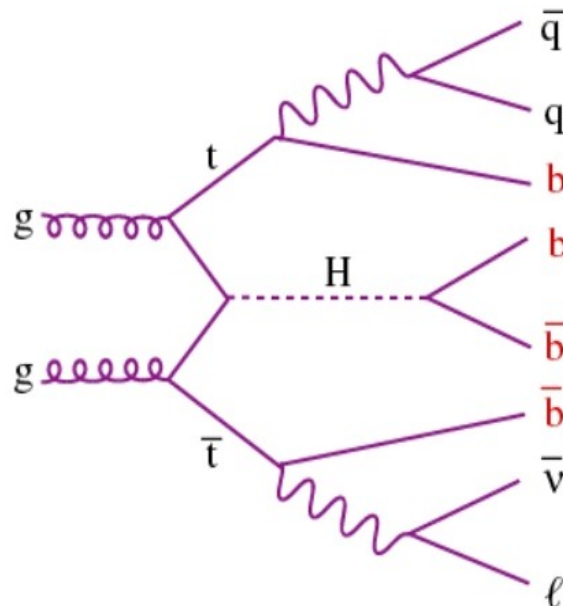


- $t\bar{t}H \rightarrow l\nu b q\bar{q}b b\bar{b}$

- **signature:** 1 isolated lepton (trigger!), high jet multiplicity with 4 b -jets
- challenge: **Higgs mass reconstruction**

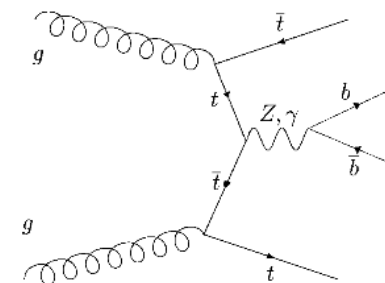
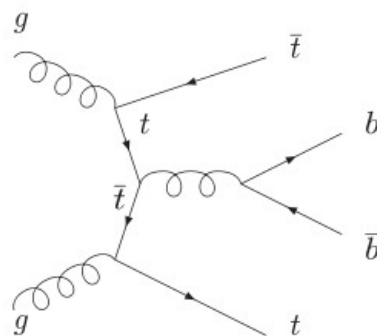
- **Other final states:** full hadronic hard to trigger on (study underway), 2L with low branching fraction (no ATLAS study so far)

$m_H = 120 \text{ GeV}$ studied



- **Main backgrounds:**

- irreducible: $t\bar{t}b\bar{b}$ QCD+EW
- reducible: $t\bar{t}$ +jets



- **Other backgrounds:** W +jets, tW , $b\bar{b}b\bar{b}$, jet production from QCD processes (QCD background) not considered here



- **Trigger requirements:** single lepton triggers
- **Offline:**
 - **one isolated lepton** ($p_T > 25 / 20$ GeV for e / μ , $|\eta| < 2.5$)
 - at least **six jets** (cone algorithm $\Delta R = 0.4$) within $|\eta| < 5.0$ and $p_T > 20$ GeV
 - at least **four jets passing the b -tag requirements:**
combined impact-parameter and secondary vertex tagger (\rightarrow talk by L. Vacavant on Thursday)
tight b -tag: $\epsilon \sim 65\%$, light / charm jet rejection = 60 / 6
loose b -tag: $\epsilon \sim 85\%$, light / charm jet rejection = 8.6 / 2.4
 - soft muon assignment to b -jets; flavour-dependent jet recalibration

preliminary

| Preselection cut | $t\bar{t}H$ (fb) | $t\bar{t}b\bar{b}$ (EW) (fb) | $t\bar{t}b\bar{b}$ (QCD) (fb) | $t\bar{t}X$ (fb) |
|----------------------------|------------------|------------------------------|-------------------------------|------------------|
| lepton cuts (ID + p_T) | $57. \pm 0.2$ | 141 ± 1.0 | 1356 ± 6 | 63710 ± 99 |
| + ≥ 6 jets | 36 ± 0.2 | 77 ± 0.9 | 665 ± 4 | 26214 ± 64 |
| + ≥ 4 loose b -tags | 16.2 ± 0.2 | 23 ± 0.7 | 198 ± 3 | 2589 ± 25 |
| + ≥ 4 tight b -tags | 3.8 ± 0.06 | 4.2 ± 0.2 | 30 ± 0.8 | 51 ± 2 |

LO LO LO NLO



Cut-based reconstruction

- **Hadronic W candidates** from all pairs of light jets
- **Leptonic W** : neutrino p_z from lepton and missing E_T , assuming the W mass

- **Mass window cuts**: hadronic W and top quark candidates within ± 25 GeV of their nominal masses

- Select combination with **minimal χ^2**

$$\chi^2 = \left(\frac{m_{jjb} - m_{top}}{\sigma_{m_{jjb}}}\right)^2 + \left(\frac{m_{lvb} - m_{top}}{\sigma_{m_{lvb}}}\right)^2$$

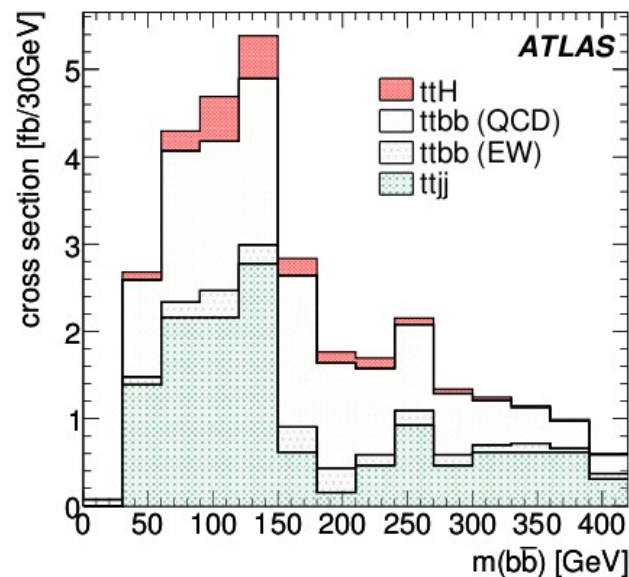
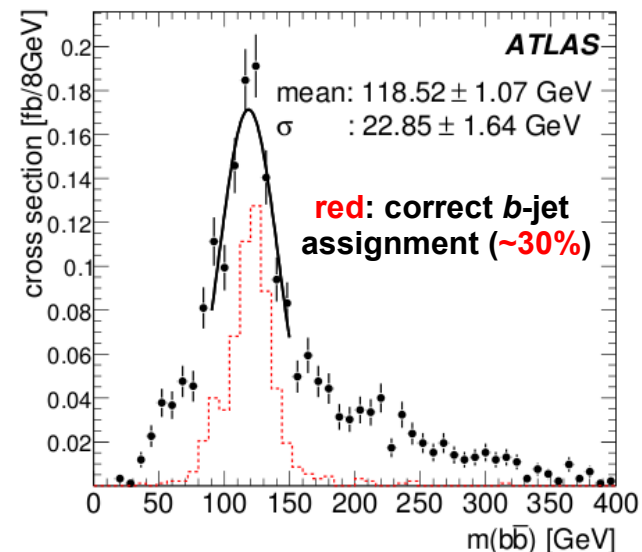
$$\sigma_{m(jjb)} = 13 \text{ GeV}, \sigma_{m(lvb)} = 19 \text{ GeV}$$

- Remaining b -jets assigned to the Higgs-decay
- **Mass cut** of ± 30 GeV around the nominal Higgs boson mass

→ **accepted $\sigma(\text{signal}) = (1.00 \pm 0.03) \text{ fb}$,**
 $S:B = 0.11$,
irreducible background ($ttbb$) contribution = 46%

preliminary

Reconstructed H boson mass $m_H = 120 \text{ GeV}$





- **“Pairing likelihood”:**

- **Topological distributions of t -quark system** as input for a likelihood:

$$m_{qq}, m_{qqb}, m_{lvb}, \Delta R(qq,b), \Delta R(l,b), \text{angle}(q,q)$$

- rejection of combinatorial background

→ **accepted $\sigma(\text{signal}) = (1.2 \pm 0.04) \text{ fb}$**

$$\mathbf{S:B = 0.10}$$

irreducible background contribution = 45%

- **“Constrained fit”:**

- fit to adjust jet momenta and missing E_T to give W and top quark masses

- **two-step likelihood:** χ^2 output of fit, event kinematics, jet charge and b -tag weights (only “loose” requirements for candidates!) as input

- rejection of combinatorial **and** physics background

→ **accepted $\sigma(\text{signal}) = (1.3 \pm 0.05) \text{ fb}$**

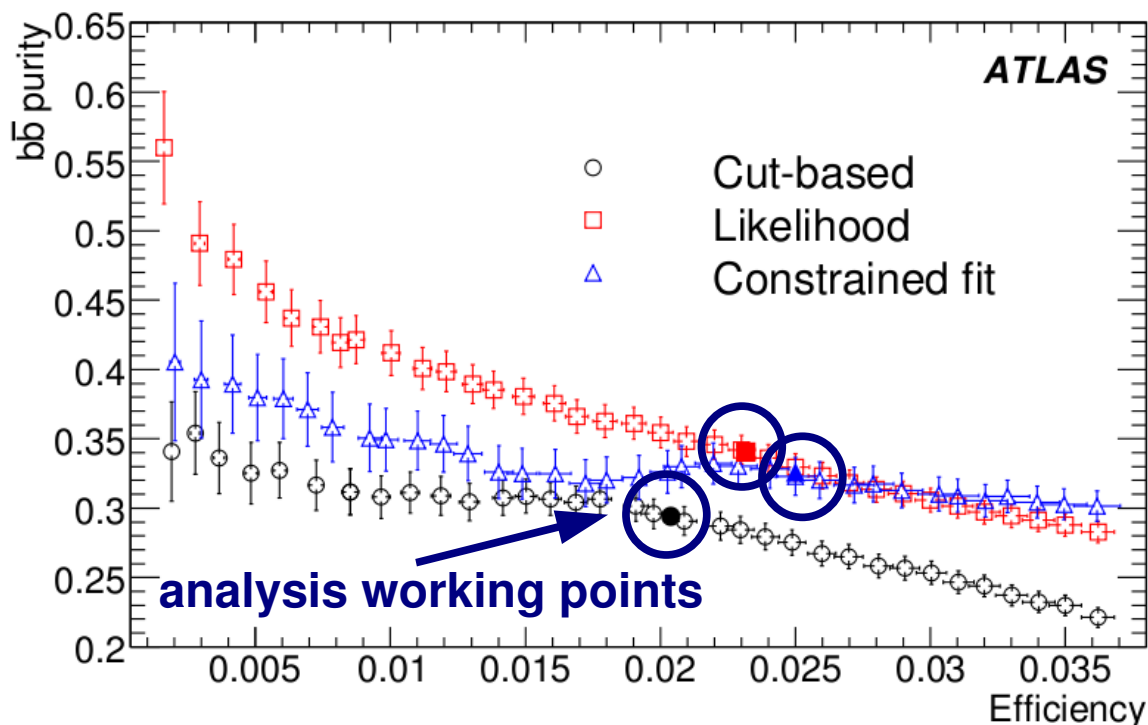
$$\mathbf{S:B = 0.12}$$

irreducible background contribution = 50%



Comparison of the performance

Signal selection efficiency vs. bb purity



Analysis working points

| | cuts | likelihood | fit |
|---------------------|------|------------|------|
| σ_{acc} [fb] | 1.0 | 1.2 | 1.3 |
| S:B | 0.11 | 0.10 | 0.12 |
| irred. BG | 46% | 45% | 50% |

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| | Cut Based | Pairing likelihood | Constrained fit |
|---------------------------------------|-------------------|--------------------|-------------------|
| b jet from Hadronic top correct | $44.4 \pm 1.1\%$ | $49.2 \pm 1.1\%$ | $51.0 \pm 1.5\%$ |
| b jet from Leptonic top correct | $50.5 \pm 1.2\%$ | $57.4 \pm 1.1\%$ | $56.2 \pm 1.5\%$ |
| Higgs boson jets correctly chosen | $29.4 \pm 1.0\%$ | $34.0 \pm 1.0\%$ | $32.0 \pm 1.4\%$ |
| Four b quarks correct | $23.3 \pm 1.0\%$ | $27.5 \pm 1.0\%$ | $27.1 \pm 1.3\%$ |
| Higgs boson mass peak resolution, GeV | 22.8 ± 1.6 | 20.1 ± 1.1 | 22.3 ± 2.1 |
| Signal Efficiency | $2.04 \pm 0.05\%$ | $2.32 \pm 0.05\%$ | $2.49 \pm 0.07\%$ |
| Signal to background | 0.110 ± 0.014 | 0.103 ± 0.014 | 0.123 ± 0.019 |
| s/\sqrt{b} , 30fb^{-1} | 1.82 | 1.95 | 2.18 |



Systematic uncertainties

- **Theory uncertainty:** large for all contributions
- Overall **detector performance** (signal / background):
 - 18% / 22% (cuts)
 - 20% / 25% (likelihood)
 - 19% / 28% (constrained fit)
- MC statistical uncertainty on the $t\bar{t}$ background $\sim 20\%$

→ **background contribution needs to be determined from data**

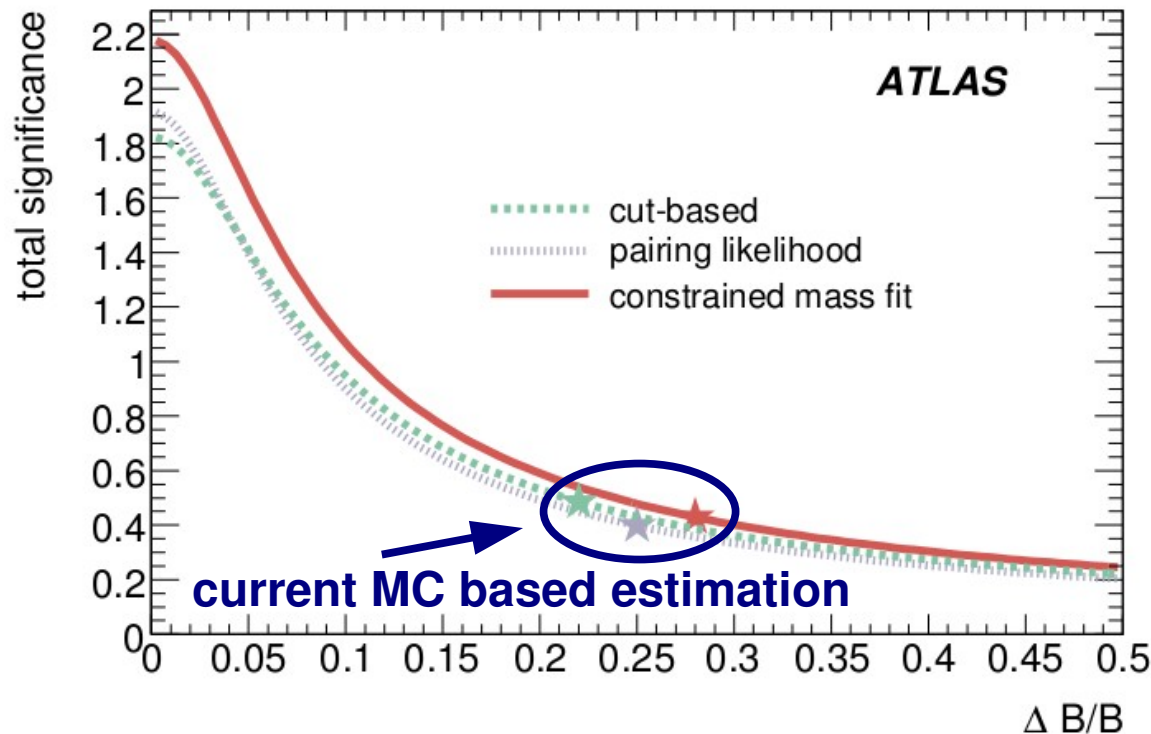
- Background uncertainty $\sim 5\%$ necessary to achieve reasonable significance

Main sources of detector performance uncertainties (maximum values, dep. on analysis)

| | signal | background |
|-------------------------|-------------|-------------|
| jet energy scale | $\leq 9\%$ | $\leq 14\%$ |
| jet resolution | $\leq 5\%$ | $\leq 14\%$ |
| b -tagging efficiency | $\leq 18\%$ | $\leq 20\%$ |
| light jet mistag | $\leq 3\%$ | $\leq 10\%$ |

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Signal significance vs. syst. BG uncertainty





WW final states: feasibility study

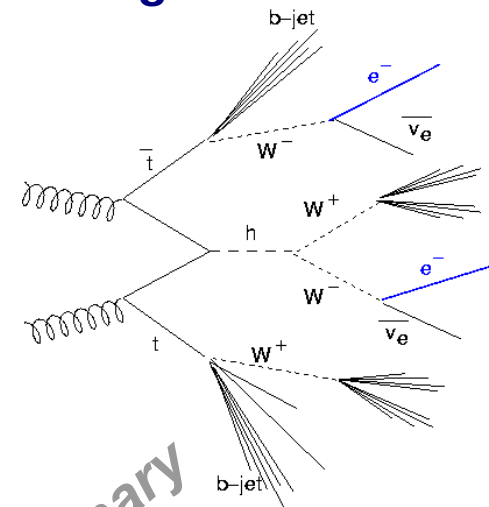
• $ttH, H \rightarrow WW$

- Cut-based studies for 2 like-sign lepton + 6 jets and 3 lepton + 4 jets final states, $m_H = 120 - 200$ GeV
- Main backgrounds: $tt (+X)$ production
- QCD background, Wt, WZ, Wbb not considered
- $S:B = 0.19$ (2L) / 0.24 (3L)

| $m_H = 160$ GeV | signal | tt | $ttbb$ | $tttt$ | ttW | ttZ | total BG |
|---|-------------|--------|--------|--------|-------|-------|-------------|
| $\sigma_{total} \times BR$ [fb] (2L) | 11.1 | 833000 | 2619 | 2.68 | 188.5 | 110 | |
| accepted σ [fb] (2L) | 1.85 | 7.4 | 0.6 | 0.06 | 1.7 | 1.14 | 10.3 |
| $\sigma_{total} \times BR$ [fb] (3L) | 7.1 | 833000 | n.a.* | n.a.* | 188.5 | 110 | |
| accepted σ [fb] (3L) | 0.82 | 2.1 | n.a.* | n.a.* | 0.47 | 0.86 | 3.4 |

* not analysed

$ttH, H \rightarrow WW$
like-sign leptons
signal final state

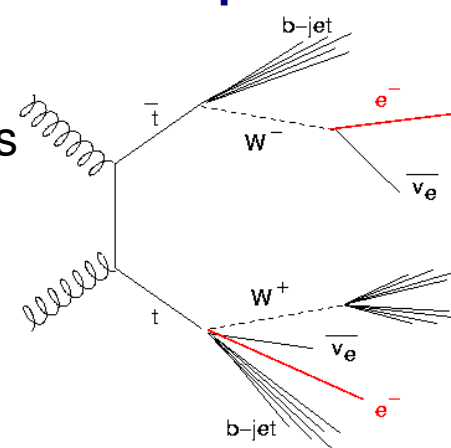


• $WH, H \rightarrow WW$

- Cut based study of the 3L final state, $m_H = 170$ GeV
- Signature: 3 isolated leptons, low jet activity, missing E_T
- Main BG: tt, WZ, ZZ, ttW ; not considered: $ttZ, Wbb, WWW, W+$ jets
- $S:B = 0.75$

| $m_H = 170$ GeV | signal | tt | WZ | ZZ | ttW | total BG |
|--|-------------|--------|------|-------|-------|-------------|
| $\sigma_{total} \times BR$ [fb] | 5.04 | 833000 | 750 | 73 | 188.5 | |
| accepted σ [fb] | 0.31 | 0.34 | 0.1 | 0.005 | 0.003 | 0.45 |

Main background:
semi-leptonic tt



preliminary



ttH, H → bb

- Accepted signal cross sections of **roughly 1 fb** can be achieved with $S/B \sim 0.10$, leading to **statistical significances ~ 2**
- **Higgs mass reconstruction**: broad (non-distinct) mass peak (limited jet resolution, wrong assignments) on top of large background
- Large systematic uncertainties (background normalisation!)
- **Background normalisation from data necessary** (needs more studies)
- Possible improvements in *b*-tagging and mass resolutions to suppress real and combinatorial background

ttH / WH, H → WW

- Small signals (~ 1 fb), no mass peaks → signal can only be claimed as excess above backgrounds (not all backgrounds considered yet)
- To reduce background uncertainties, normalisation **from data required** (no detailed study so far)
- **Analyses very challenging!**
- If backgrounds can be controlled → **valuable input for measurements of SM Higgs couplings**



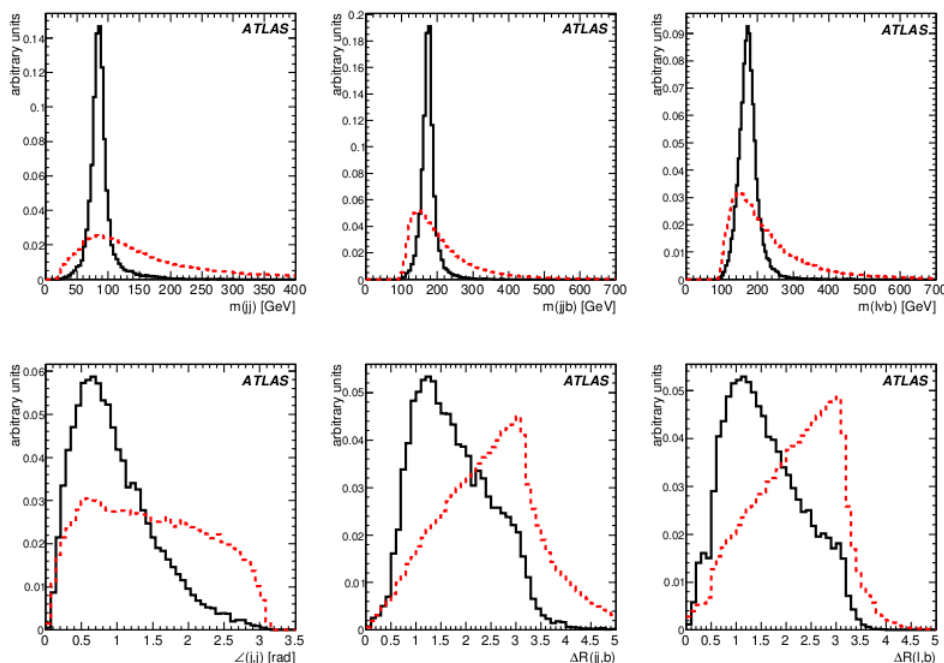
Backup: pairing likelihood

- W - and t -candidates as in case of the cut based approach
- **Topological distributions of t -quark system** as input for a pairing likelihood:

$$m_{qq}, m_{qqb}, m_{lvb}, \Delta R(qq,b), \Delta R(l,b), \text{angle}(q,q)$$

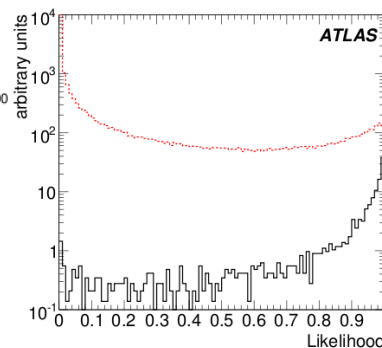
- Select combination with **maximum likelihood value** (event is discarded, if $<$ minimum value of 0.9)
- Remaining b -jets assigned to the Higgs boson decay
- **H -mass window cut:** $m_H \pm 30$ GeV

Pairing likelihood: PDF templates

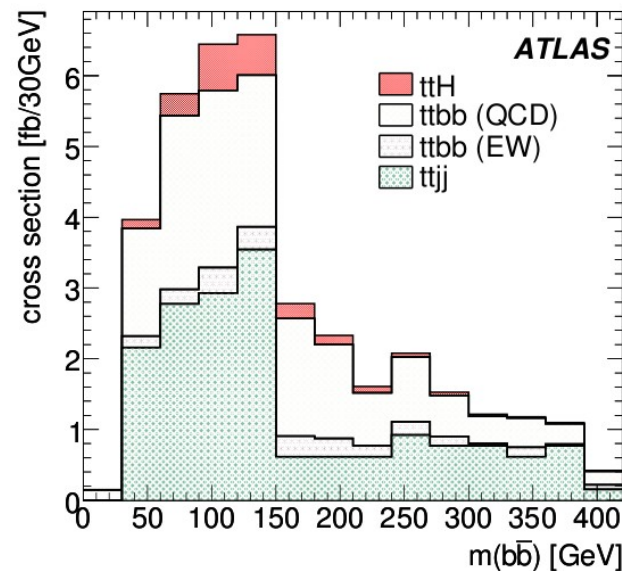
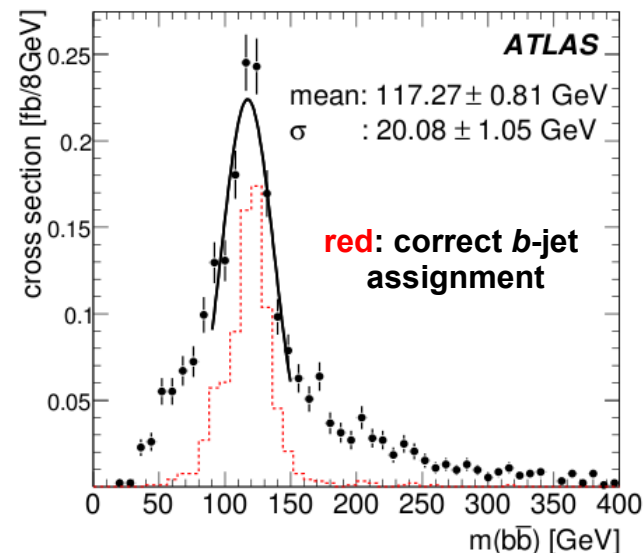


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Output distributions



Reconstructed H boson mass $m_H = 120$ GeV





Backup: constrained fit analysis

- **Fit to optimise jet momenta and missing E_T** according to jet p_T -resolutions

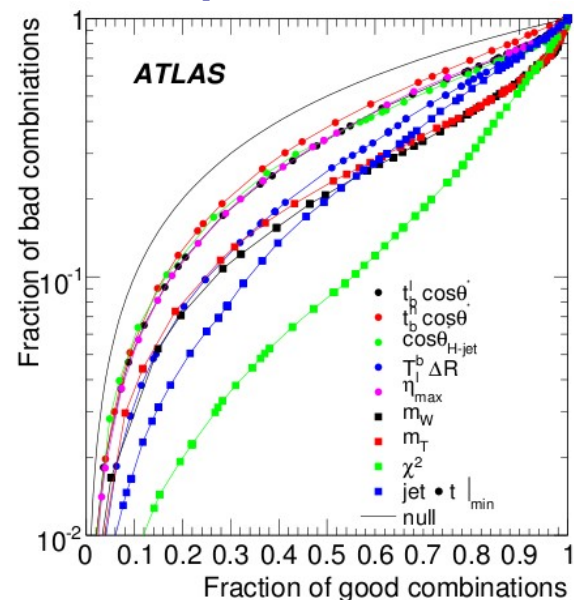
- Fit χ^2 defined by:
$$\chi^2 = \sum_{i=1}^6 \left(\frac{f_{jet}^i - 1}{\sigma_{jet}^i / P_{jet}^{i,initial}} \right)^2 + \frac{(m_W^{lep} - 80.425)^2}{\sigma_W^2} + \frac{(m_t^{lep} - 175)^2}{\sigma_t^2}$$

with $f_{jet}^i = P_{jet}^i / P_{jet}^{i,initial}$, $\sigma_W = 2.1 \text{ GeV}$, $\sigma_t = 1.5 \text{ GeV}$, $\sigma_{P_{light}} / P_{light} = 0.988 / \sqrt{p_T} \oplus 0.035$
 $\sigma_{P_b} / P_b = 0.888 / \sqrt{p_T} \oplus 0.125$

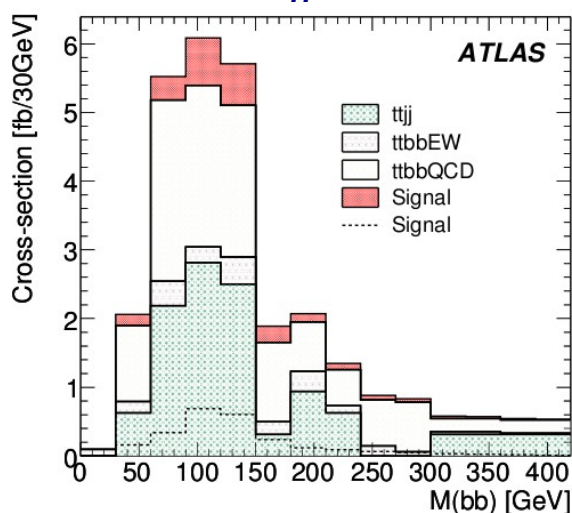
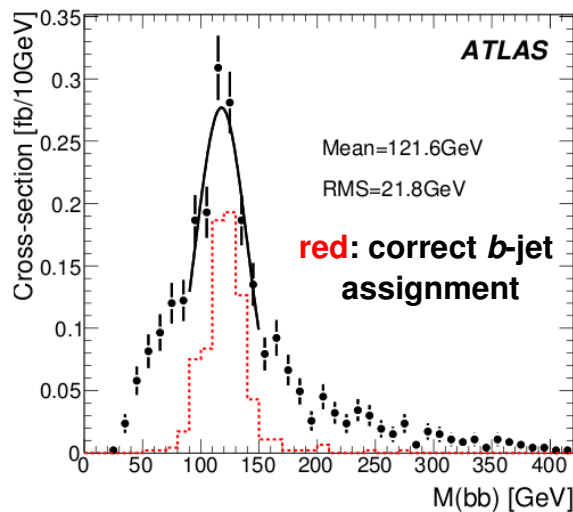
preliminary

- **Pairing likelihood: χ^2 of fit** as one out of several input variables, together with kinematic properties of the Higgs boson, **b -tag info** and **jet charge**
- **Second likelihood to reject physics background:** output of first likelihood as input + b -tag information and event kinematics
- **H -mass window** cut of $\pm 30 \text{ GeV}$

Performance of input variables



Reconstructed Higgs boson mass, $m_H = 120 \text{ GeV}$





Backup: $t\bar{t}H, H \rightarrow b\bar{b}$ results

preliminary

Cut analysis: accepted signal and background σ

| cut | $t\bar{t}H$ (fb) | $t\bar{t}b\bar{b}$ (EW) (fb) | $t\bar{t}b\bar{b}$ (QCD) (fb) | $t\bar{t}X$ (fb) |
|-----------------------------------|------------------|------------------------------|-------------------------------|------------------|
| $W_{\text{had}} + W_{\text{lep}}$ | 2.49 ± 0.05 | 2.9 ± 0.2 | 18.2 ± 0.7 | 22.5 ± 1.9 |
| + $t\bar{t}$ +Higgs | 2.04 ± 0.05 | 2.2 ± 0.2 | 14.7 ± 0.6 | 14.3 ± 1.5 |
| + Higgs boson mass window | 1.00 ± 0.03 | 0.52 ± 0.07 | 3.6 ± 0.3 | 4.9 ± 0.9 |

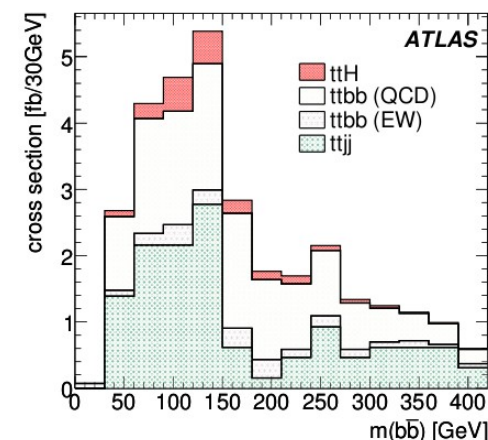
Pairing likelihood: accepted signal and background σ

| applied cuts | $t\bar{t}H$ (fb) | $t\bar{t}b\bar{b}$ (EW) (fb) | $t\bar{t}b\bar{b}$ (QCD) (fb) | $t\bar{t}X$ (fb) |
|---------------------------|------------------|------------------------------|-------------------------------|------------------|
| Leptonic W | 3.6 ± 0.06 | 4.1 ± 0.2 | 29 ± 0.8 | 48 ± 2.7 |
| + Best likelihood > 0.9 | 2.3 ± 0.05 | 2.5 ± 0.2 | 16 ± 0.6 | 19 ± 1.7 |
| + Higgs boson mass window | 1.2 ± 0.04 | 0.68 ± 0.08 | 4.6 ± 0.3 | 6.5 ± 1.0 |

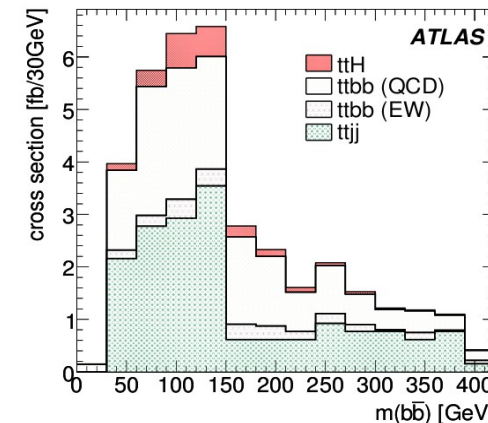
Constrained fit: accepted signal and background σ

| Selection | $t\bar{t}H$ (fb) | $t\bar{t}b\bar{b}$ (EW) (fb) | $t\bar{t}b\bar{b}$ (QCD) (fb) | $t\bar{t}X$ (fb) |
|-----------------------------|------------------|------------------------------|-------------------------------|------------------|
| Initial Sample | 100 | 255 | 2371 | 109487 |
| Pass preselection | 16 | 23 | 198 | 2589 |
| Fit quality requirements | 14 | 20 | 165 | 1584 |
| $\mathcal{L}_{s/b} > -4.40$ | 4.9 | 5.1 | 35 | 58 |
| $\mathcal{L}_{s/b} > -4.20$ | 2.5 | 2.3 | 13.9 | 11.9 |
| $\mathcal{L}_{s/b} > -4.10$ | 1.4 | 0.96 | 7.11 | 4.5 |
| Mass window 90 to 150 GeV. | | | | |
| $\mathcal{L}_{s/b} > -4.40$ | 2.3 ± 0.07 | 1.4 ± 0.17 | 10.8 ± 0.7 | 22 ± 3.1 |
| $\mathcal{L}_{s/b} > -4.20$ | 1.3 ± 0.05 | 0.62 ± 0.12 | 4.6 ± 0.5 | 5.3 ± 1.5 |
| $\mathcal{L}_{s/b} > -4.10$ | 0.71 ± 0.04 | 0.23 ± 0.07 | 2.5 ± 0.35 | 2.2 ± 1.0 |

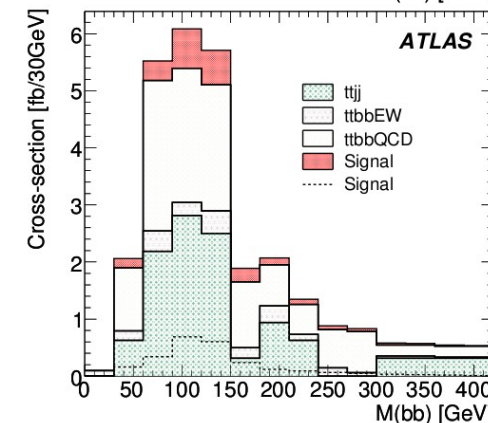
cut analysis



likelihood



constrained fit





Maximum effects on the ttH , $H \rightarrow bb$ selection efficiencies (sig/back):

- **Muons:** efficiency: 0.8%/0.1%; energy scale: 0.7%/4%; resolution: 1%/3%
- **Electrons:** efficiency: 0.5%/2%; energy scale: 1%/3%; resolution: 0.5%/4%
- **Jets:** energy scale: 9%/14%; resolution: 5%/14%
- **b-tagging:** efficiency: 18%/20%; light jet fakes: 3%/10%
- **Overall:** 18%/22% (cuts); 20%/25% (likelihood); 19%/28% (constrained fit)