ATLAS Sensitivity to the SM Higgs boson in the HW/HZ channels at High Transverse Momenta

(most of the material contained in **ATL-PHYS-PUB-2009-088**)

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Outline

- Why a “low” mass Higgs Boson?
- Higgs searches based on H → bb
- WH with H → bb at high pT
  - Identification of higly boosted H → bb candidates
  - The analysis
- Combination with the ZH channels
- Likelihood fit based approach to reduce impact of systematic uncertainties
- Residual uncertainties (experimental and theoretical issues)

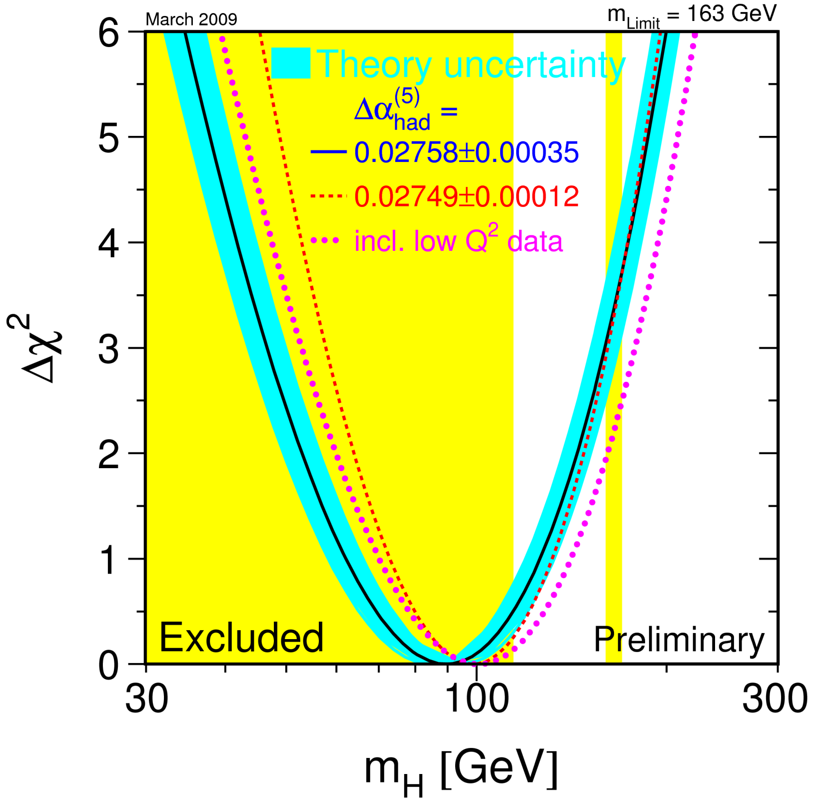
Where does the Higgs Boson sit?

Assume the Standard Model is valid: ➡ Higgs mass predicted by EW precision measurements is:

- 63 – 126 GeV (at 69 % C.L.)
- < 163 GeV (at 95 % C.L.)

Excluded regions at 95 % C.L.:

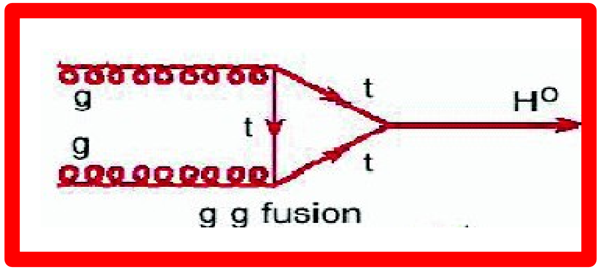
- m_H<114.4 GeV (LEP-II)
- (160 < m_H < 170) GeV (Tevatron)

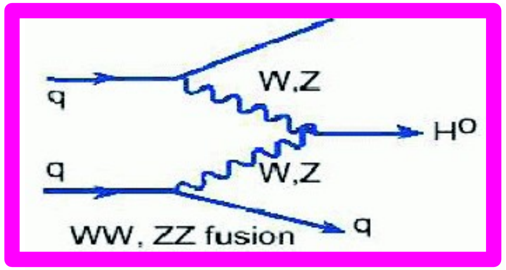


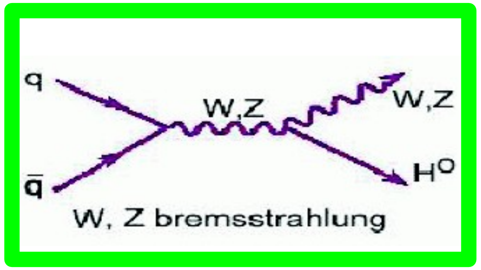
[LEP EW Working Group, March '09]

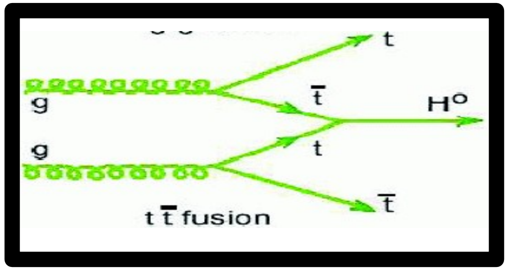
➡ Important to ensure LHC can discover a light Higgs boson as fast as possible!

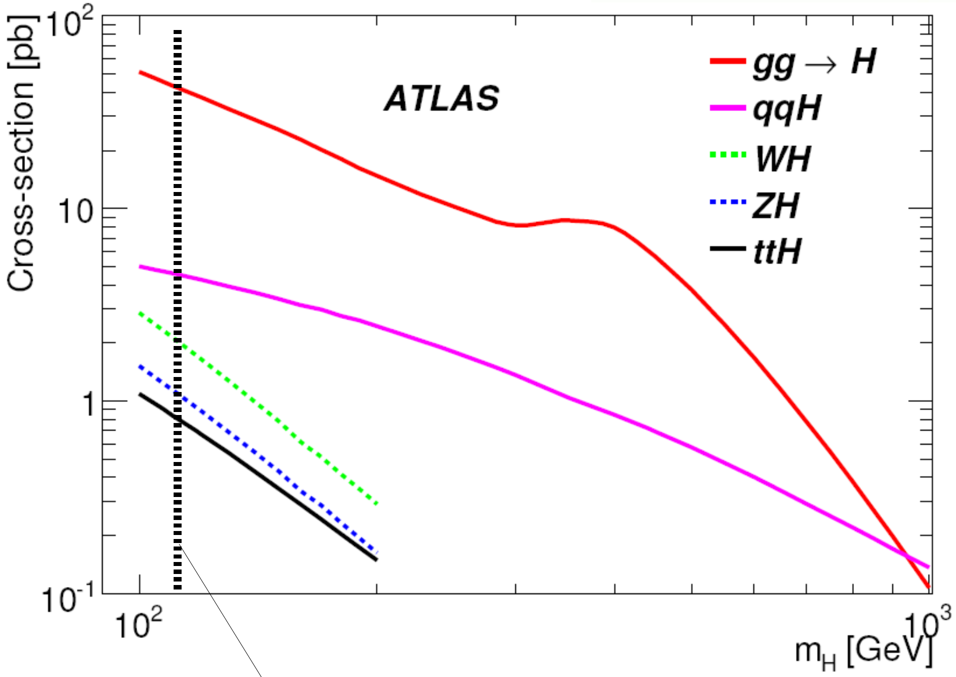
Higgs production and decay modes

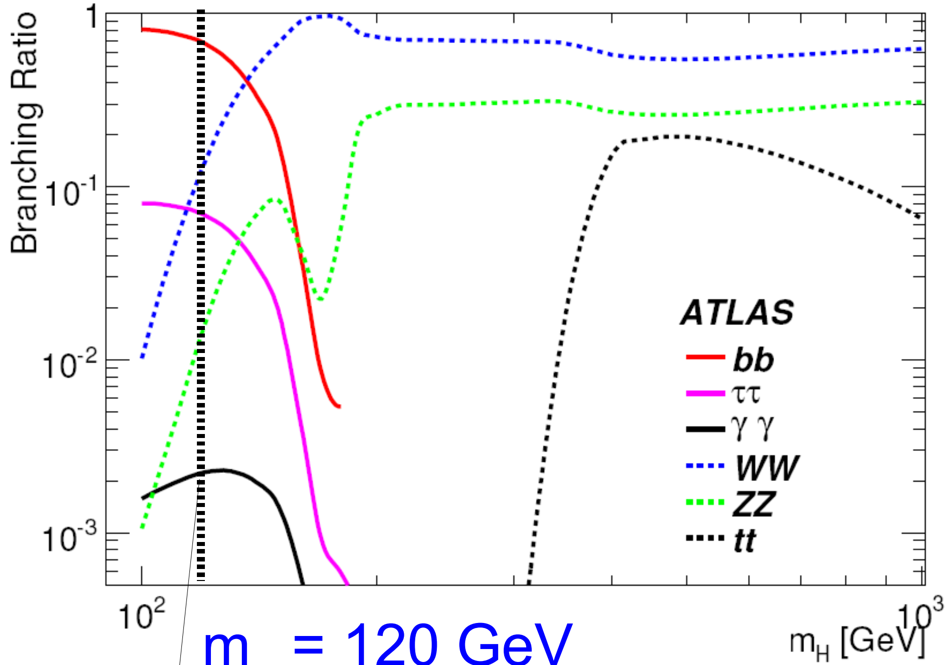












m_H = 120 GeV

m_H = 120 GeV

σ

(NLO)

gg → H: ~38 pb
qq → qqH: ~4 pb
qq → W/ZH: 1.6/0.9 pb
qq → ttH: ~0.7 pb

X

BR

H → bb: 67 %
H → WW(*): 13.3 %
H → ττ: 6.9 %
H → ZZ(*): 1.5 %
H → γγ: 0.2 %

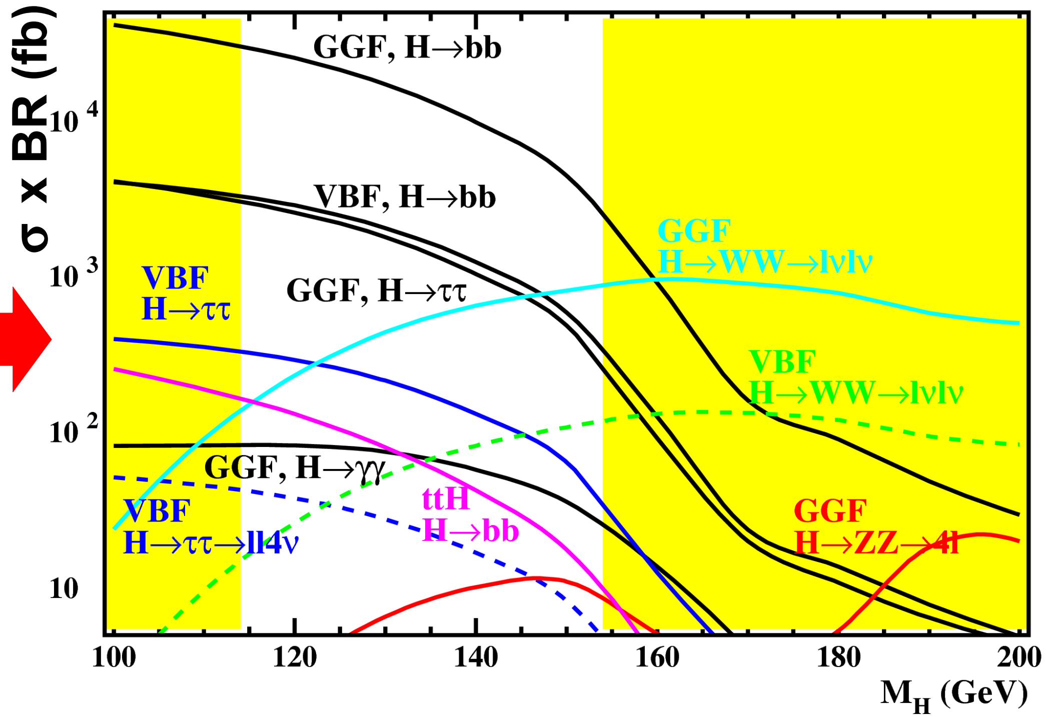
=

Best signatures for a low mass Higgs...

- σ x *BR* is not everything, e.g.:

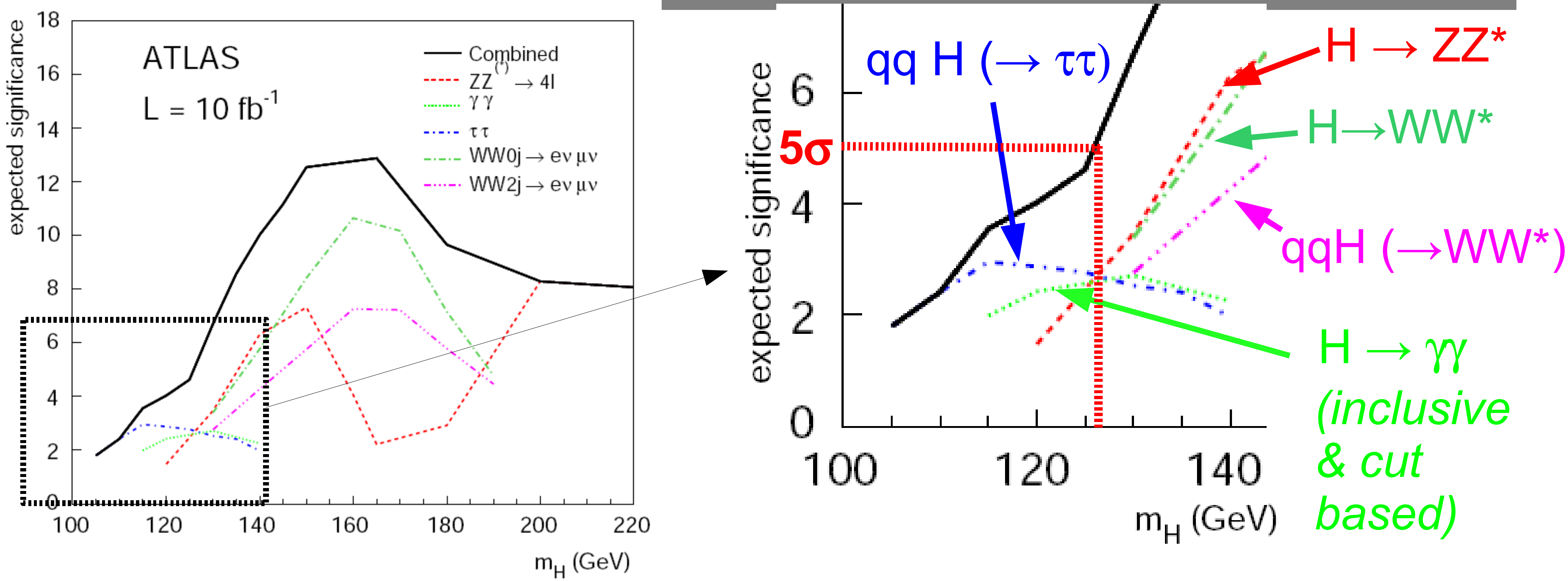
gg → H qq → qqH	H → bb	*Very hard due to bb background from QCD*

σ x BR



- Most promising signatures:
  - **gg → H → γγ, ZZ, WW**
  - **VBF qqH → qqττ, qqWW**
- Signatures with b-quarks experimentally difficult to access, but it may be possible in:
  - **ttH → ttH → ttbb**
  - **qq → W/Z H → W/Z bb**

Discovery potential of a SM Higgs boson (ATLAS)



- With 10 fb^{-1} integrated luminosity and a center of mass energy of 14 TeV:
  - a 5σ discovery is possible for Higgs masses above ~127 GeV
  - at lower masses (m_H~115-120 GeV), the situation is the most challenging, and requires a combination of several channels, in particular H→ττ and H→γγ
- What about **H → bb** ? It didn't make it into the combination yet...

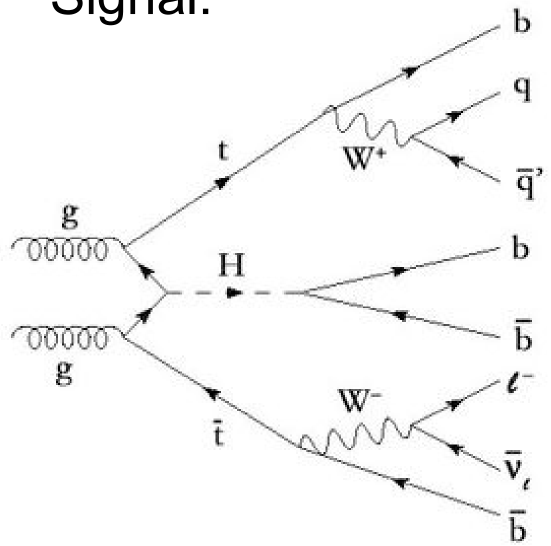
What about H → bb ?

- Largest BR, in particular at low masses.
- This decay mode is not only important for discovery
  - Absolutely crucial to **constraint the Higgs coupling to b-quarks**!
- But experimentally challenging:
  - 1. b-jet identification not available during online event selection (Level 1 Trigger)

    → need to rely on associated Higgs production
    (**1. ttH** or **2. W/ZH**: e.g. trigger on lepton from W/Z)
  - 2. excellent b-tagging performance (up,down,strange-quark backgrounds up to >10^2-10^4 times larger than signal)
    → need ε_{mistag} < 1 %, trying to keep most of the signal
  - 3. events with b-jets copiously produced at LHC
    → large irreducible backgrounds in **ttH** from ttbb
    in **W/ZH** from W/Z + bb

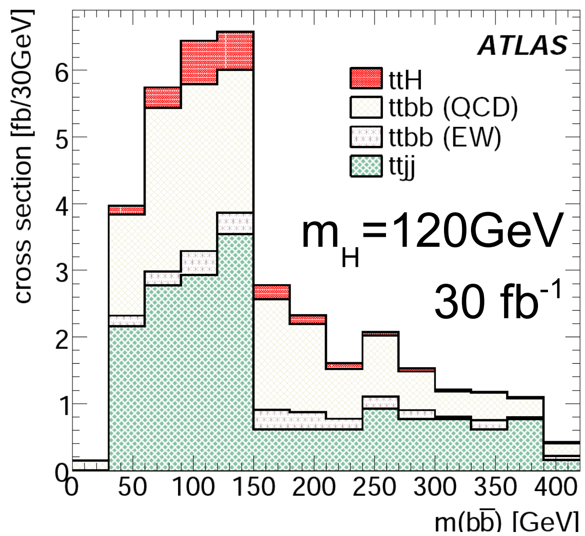
ttH (H→bb): why it looks very difficult...

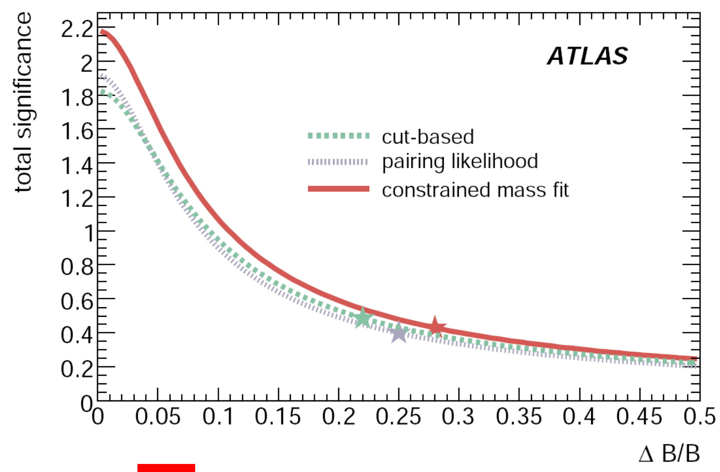
- Signal:



- Complex final state:
  - 4 b-jets in final state: e.g. ε_B ~ 65 % → **ε_B^4~ 18%** !
  - Combinatorics: difficult to associate correct b-jets to Higgs → $\sigma(m_H)$ ~ 20 GeV

- Main backgrounds: **ttjj** and **ttbb**
  - higher rate predicted by more realistic matched LO Matrix Element (e.g. ALPGEN) or NLO codes (e.g. MC@NLO) w.r.t. previous studies





Precise background normalization from data is needed, to recover significance !

WH (H→bb) – the inclusive analysis

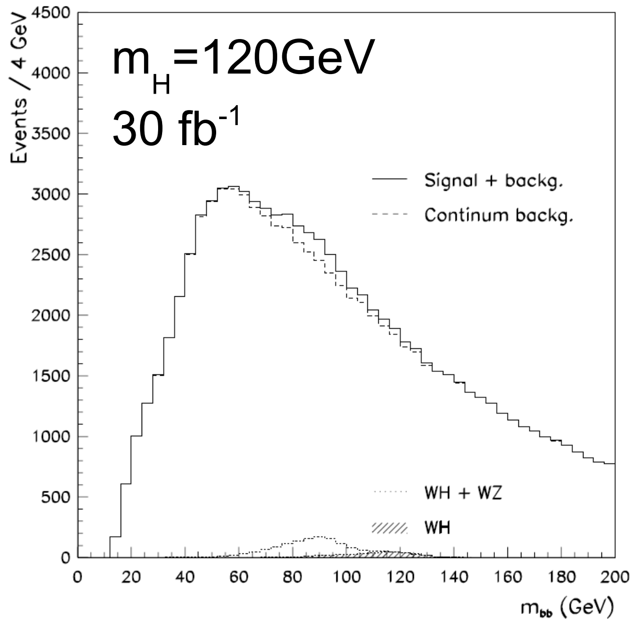
30 fb^{-1}

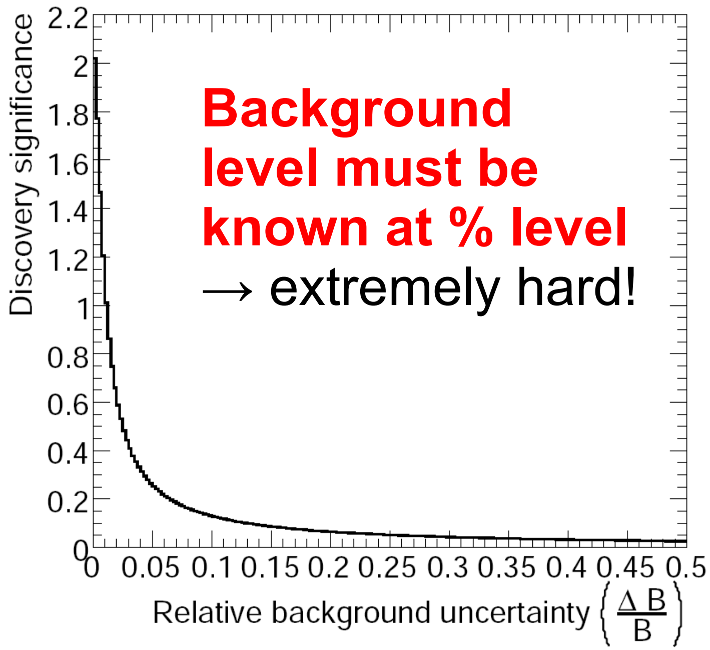
Process	Jet veto 30 GeV
WH	325
WZ	325
Wjj ($b\bar{b}$)	7800
Wjj (other)	5300
tt	10500
$W^* \to tb$	640
tb, tc	330
Total bgd	24900
$S/\sqrt{B}$	2.1
S/B	1.3%
B_{other}/B_{total}	21%

[E. Richter-Was, ATL-PHYS-2000-018]

(based on old fast simulation of the ATLAS detector)

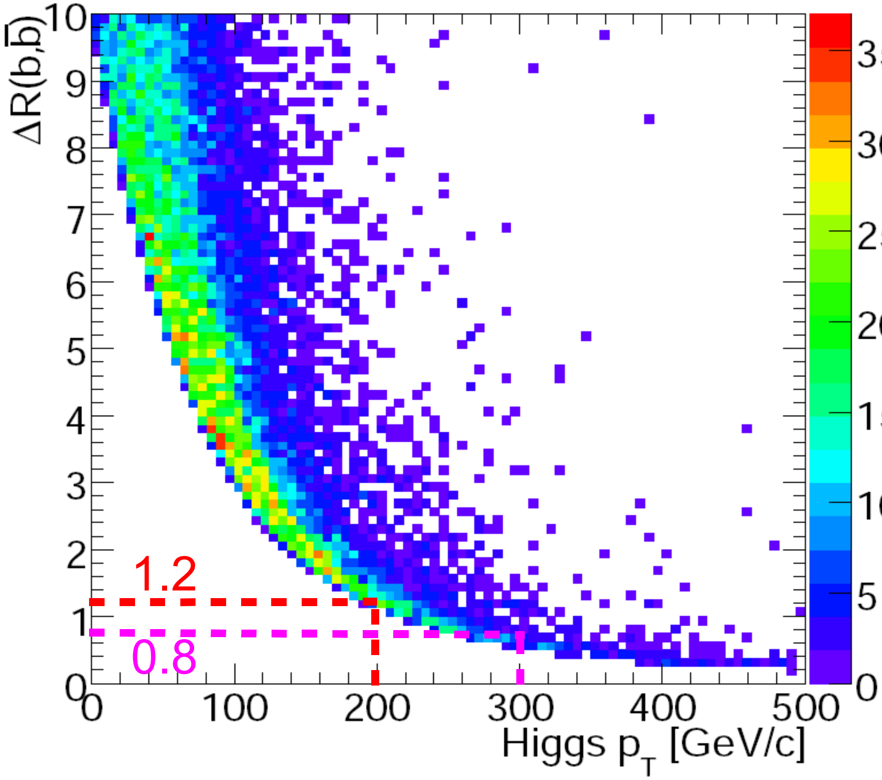
- The WH (lvbb) channel was considered during ATLAS TDR study and in an updated study of 2000 (shown here).
- Selection:
  - One triggered lepton (pT(e)>20 GeV, pT(μ)>20GeV,|η|<2.5)
  - Two b-tagged jets (ϵ_B~60%)
  - No other lepton pT>6 GeV
  - Jet veto (p_T>30 GeV,|η|<5) (against ttbar background)
  - Mass cut ±25GeV (σ ~10%)

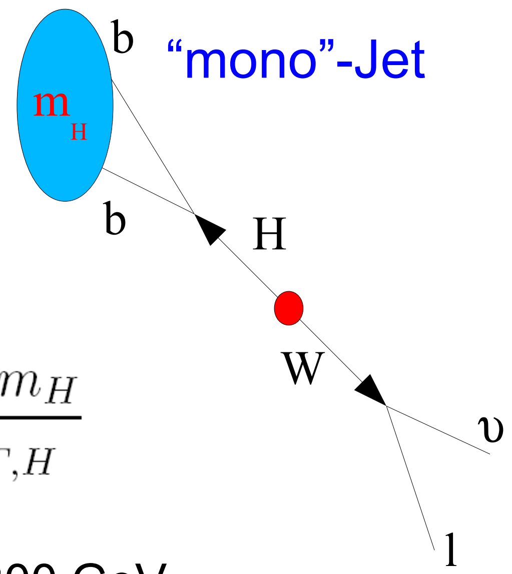




New hope: WH (W→lν, H→bb) at high p_T

- Proposed in [J. Butterworth et al, PRL 100:242001,2008]
- Require the W and Higgs bosons to have high transverse momenta (e.g. p_T>200 GeV) (only ~5 % of overall cross section!)
- → the bb-quark pair is very collimated





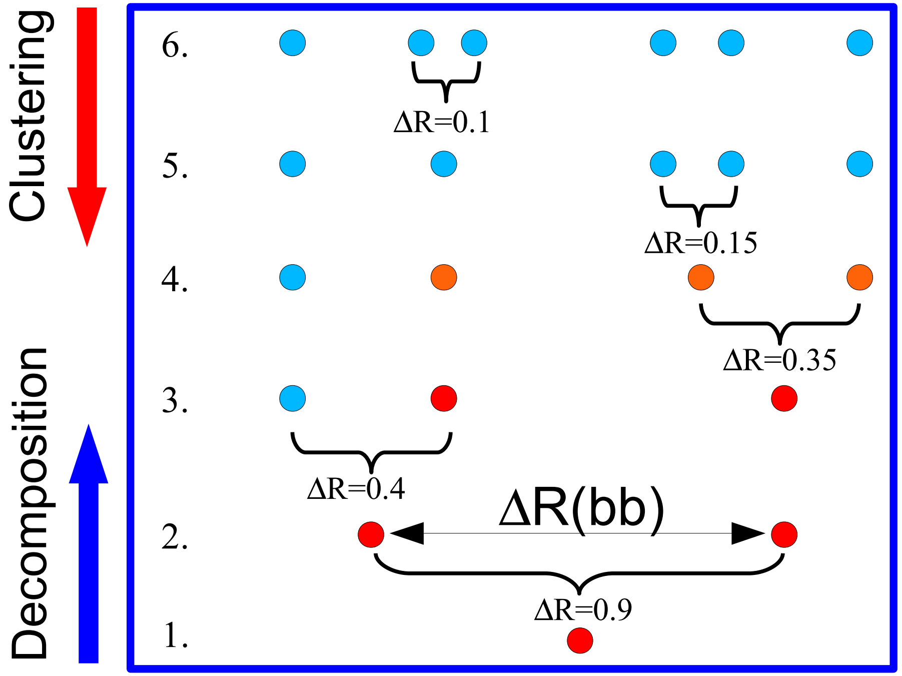
$$\Delta R(b,\bar{b}) \approx \frac{2 \cdot m_H}{p_{T,H}}$$

- For p_T(Higgs)>300 GeV, DeltaR(bb) < 0.8
- Starts to get difficult for a conventional jet finding algorithm (1 big fat jet with two b-subjets!)
- → new dedicated jet finding algorithm (proposed in the same paper)

New jet clustering algorithm (step 1)

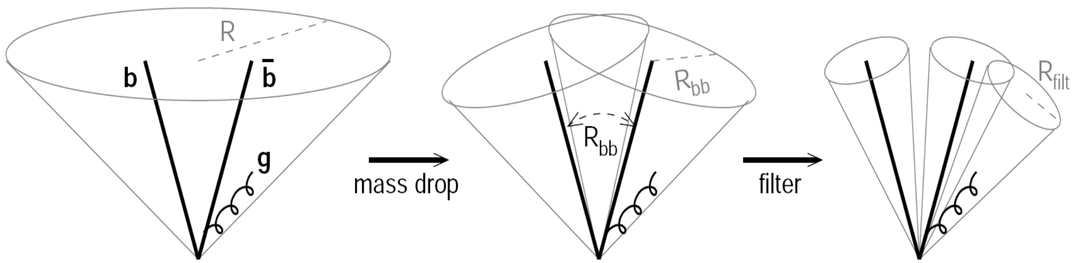
- First all Cambdrige-Aachen jets with size R=1.2 in the event are found (the boosted H $\rightarrow$ bb decay is expected to be contained in one of these)
- The C/A jet algorithm is analogous to the k_T algorithm, but the distance between jets is simply the distance $\Delta R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$, where ϕ is the azimutal angle and y the pseudorapidity of the two jets.
- Iterative procedure:
  - 1. Consider all input objects to jet finding (final state stable particles for the hadron level study)
  - 2. Compute the distance ΔR between all particles i and j
  - 3. Merge the closest pair
  - 4. Start again from 2., until no pair is closer than DR=1.2
- The procedure results in a set of “fat” R=1.2 jets.
- The jet clustering history (merging steps) is stored to be used for the decomposition.

New jet clustering algorithm (step 2)



(a) $$y = \frac{\min(p_{tj_1}^2, p_{tj_2}^2)}{m_j^2} \Delta R_{j_1,j_2}^2$$

(b) $$m_{j_1} < \mu m_j$$

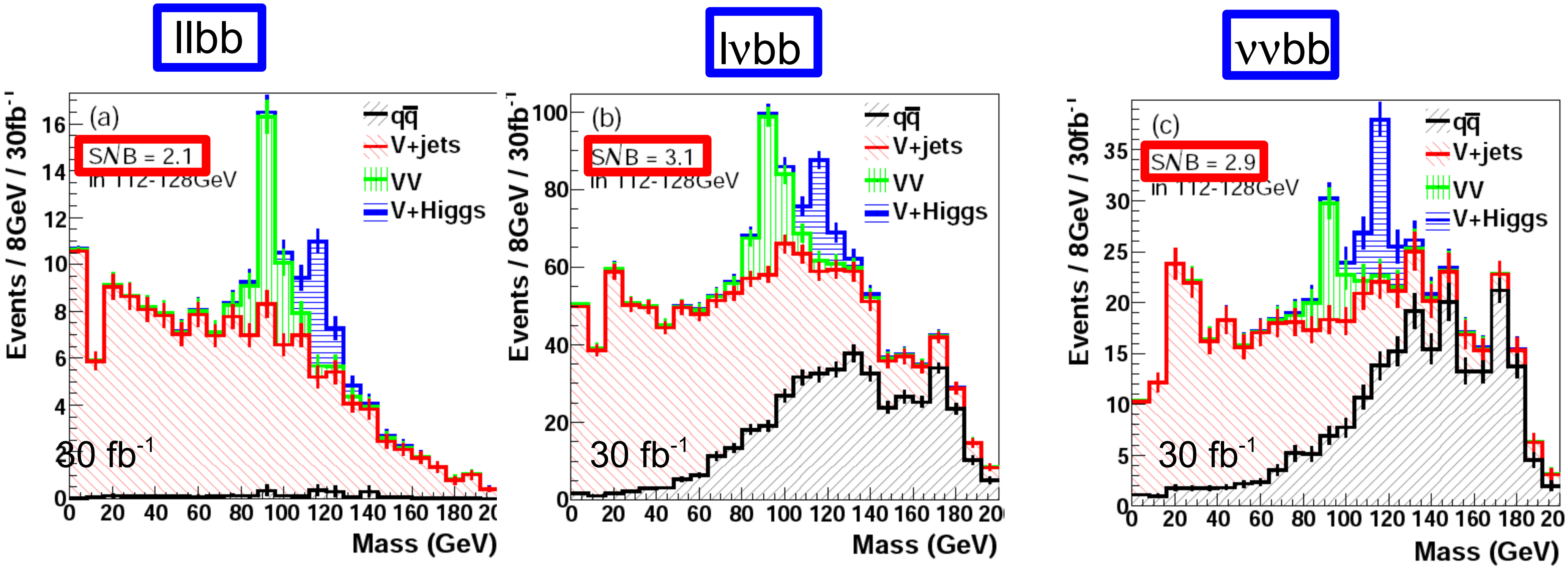


- Using the jet clustering history, the R=1.2 jets are decomposed, going back in the history step by step:
  - 1. Break jet j into 2 subjets (j_1 and j_2), label j_1 so that mass(j_1)>mass(j_2)
  - 2. If the splitting is sufficiently symmetric **(a)** and the mass of j_1 drops with respect to j **(b)**:
    - <u>Then</u> accept (j_1,j_2) as the subjets of the Higgs candidate
    - <u>Otherwise</u> continue again from 1 with the jet j_1.
  - 3. Filter the found jet j up to ΔR_{filt}=min(ΔR_{bb},0.3)
    - consider the subjets j_1 and j_2
    - go back in the history until all splittings down to a distance of ΔR_{filt} are included
    - Take only the 3 subjets with highest p_T

Result of hadron level study

[J. Butterworth, A. Davison, G. Salam, M. Rubin, PRL 100:242001,2008]

- Performed for three final states (also the ZH channels were considered):

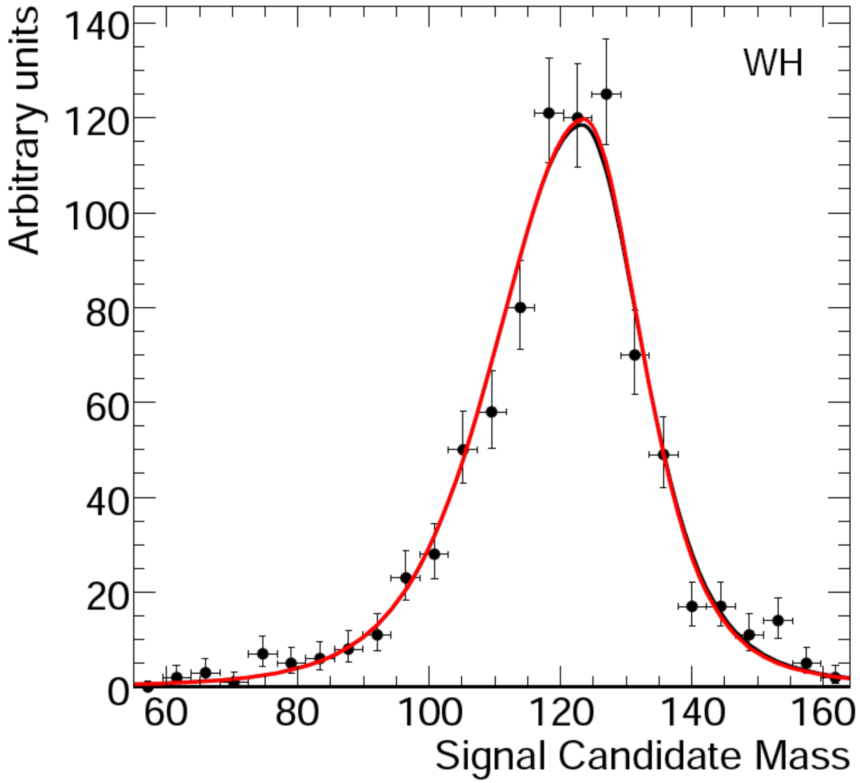


- Hadron level result:
  → combining the three channels, with 30 fb^{-1} a significance above 4 should be feasible.

- Most crucial experimental issues:
  - (1) realistic estimation of di-b quark invariant mass resolution
  - (2) it is assumed b-tagging works well on subjets. Does it really work?

di-subjet invariant mass resolution

- After detector level calibration, the resolution on the Higgs signal (m_H=120 GeV) is analysed by fitting the filtered mass distribution with a modified bifurcated Gauss function.
- The core resolution is found to be around **10 %**.
  - Resolution is worse than in the hadron level study (as expected)
    - However a mass window cut of ± 7 % was used in the hadron level study to take this partially into account (based on previous single-jet mass studies)
- The mass peak (overall energy scale) is not calibrated here

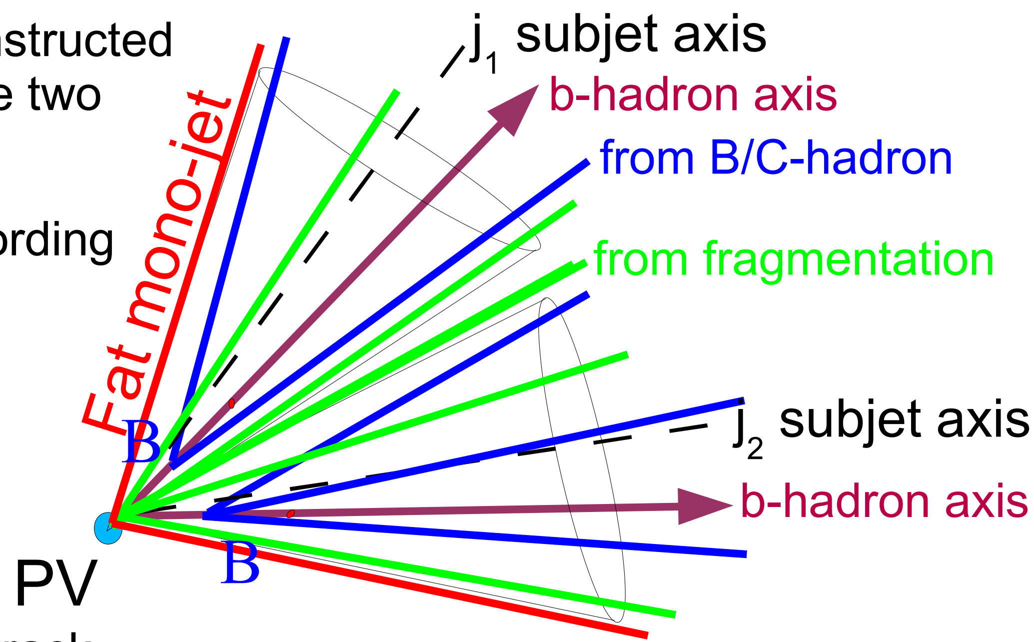


$$f(x; m, \sigma_\pm, \alpha_\pm) = exp\left[-\frac{(x-m)^2}{2\sigma_\pm^2 + \alpha_\pm (x-m)^2}\right]$$

Parameter	ESD-based
$mean$	123 ± 1 GeV
σ_+	9 ± 1 GeV
σ_-	13 ± 1 GeV
α_+	0.12 ± 0.02
α_-	0.15 ± 0.02

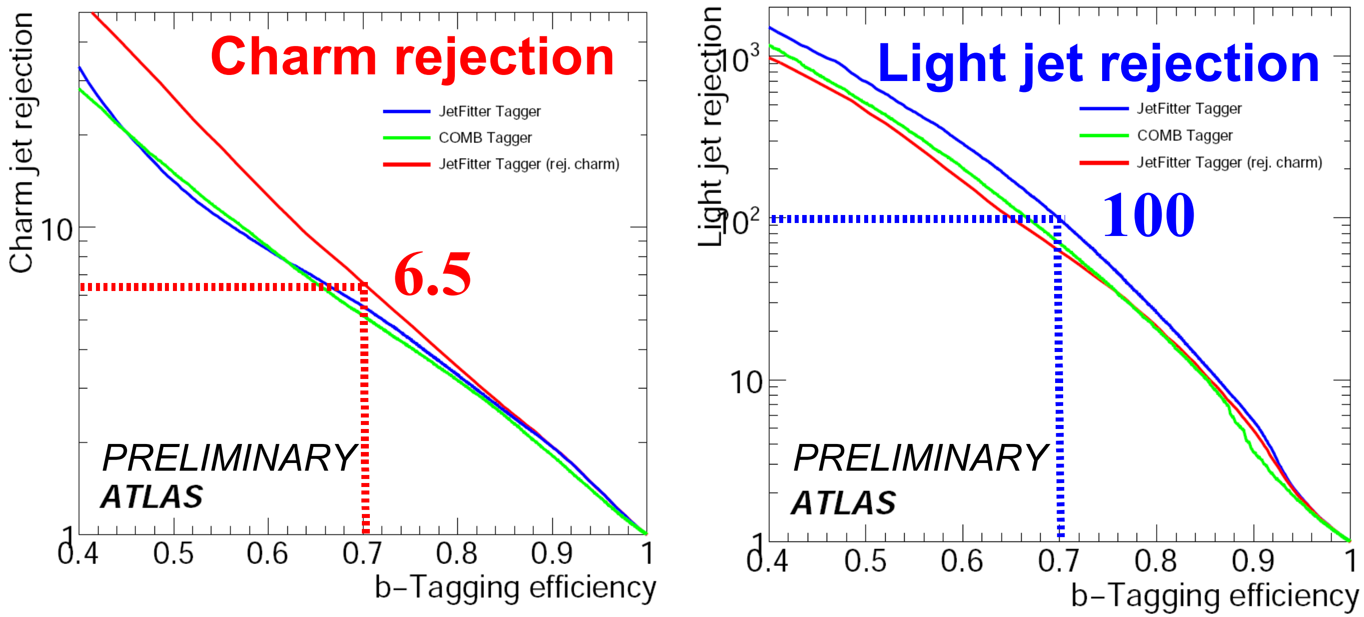
b-tagging on subjets

- In order to apply b-tagging, the tracks as reconstructed in the inner detector need to be assigned to the two subjets from the Higgs candidate.
- The direction of the two subjets is defined according to the direction of the two highest p_T filtered subjets.
- A track is assigned to the subjet if:
  - $\Delta R(p_{trk}, p_{subjet\ i}) < 0.3$
- In case of shared tracks between subjets, the track is assigned to the nearest subjet.
- *Alternative approaches were considered*
  - the use of the filtered subjets momenta ensures that the momentum of the subjet is closer to the b-hadron direction: this in fact reduces the impact of additional final state radiation (i.e. additional uninteresting tracks with no lifetime)



b-tagging performance on subjets

- Once the tracks in a subjet are selected, b-tagging can be applied:



Rej. = $1/\varepsilon_{misid}$

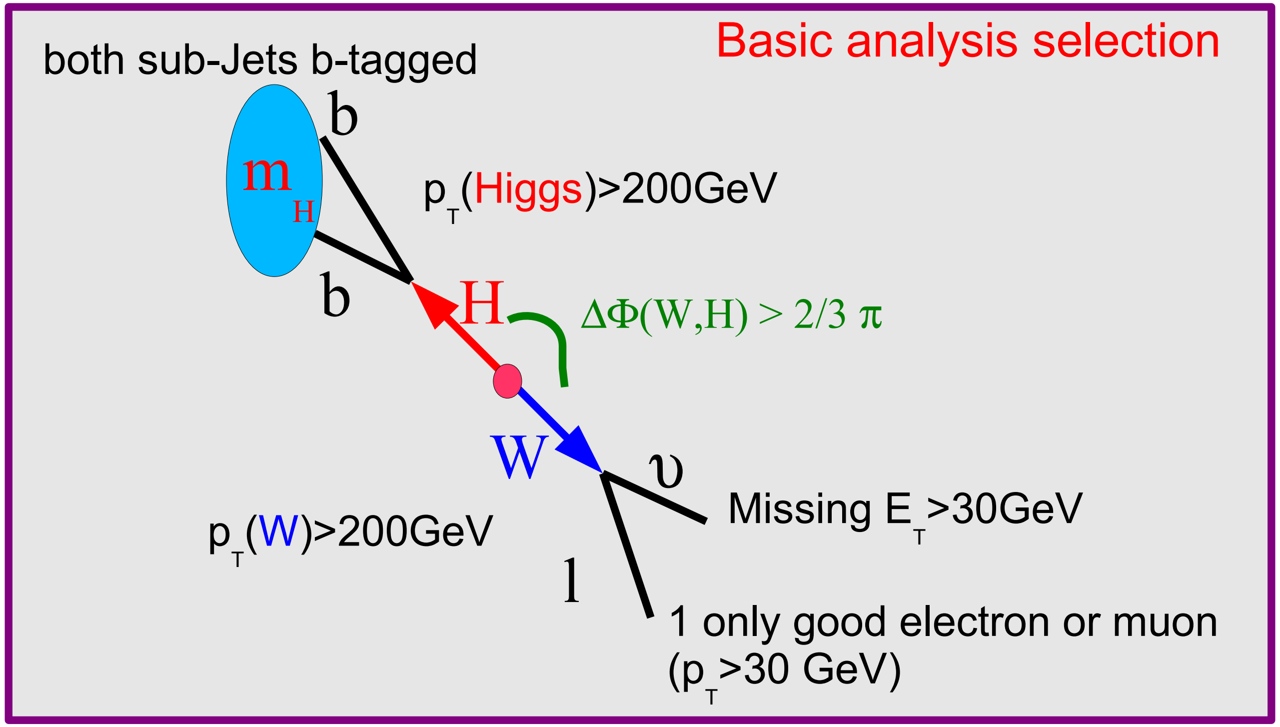
Charm rejection at ε_b = 60%:
hadron level study: 50
detector simulation: 8-12

Light rejection at ε_b = 60%:
hadron level study: 50
detector simul.: 160-290

- Only the kinematic region relevant for this analysis is considered here...
- At 70 % b-tagging efficiency (~50 % H → bb signal efficiency):
  - Charm rejection: up to **6.5** using JetFitter optimized against charm
  - Light rejection: up to **100** (!) using JetFitter optimized against light
  - Both results cannot be obtained simultaneously, but a rejection curve intermediate between the **blue** and **red** one will be obtained according to the chosen value of c(light) → specifically optimized later to c(light)=20 %
- Result: **b-tagging works very well on subjets!** (+ favorable kinematic region)

The WH ($W \rightarrow l\nu, H \rightarrow bb$) analysis selection

- The Higgs candidate identification (both jet finding + b-tagging steps) is now properly defined.
- The analysis selection relies on the following selection criteria:



- To suppress top pair production:
  - Veto on any additional b-jets in the event
  - Veto on any additional jets in the event with p_T>20 GeV/c

The WH ($W\to l\nu, H\to bb$) analysis:signal and background samples

	Process	Generator cut	σ(pb)	Filter	Filter efficiency
Signal	$WH(115)$	none	1.157pb	$p_{\mathrm{T}}(H) > 150\mathrm{GeV}$, $p_{\mathrm{T}}(W) > 100\mathrm{GeV}$, $p_{\mathrm{T}}(e,\mu) > 15\mathrm{GeV}$	$4.04 \pm 0.03\%$
	$WH(120)$	none	0.953pb	$p_{\mathrm{T}}(H) > 150\mathrm{GeV}$, $p_{\mathrm{T}}(W) > 100\mathrm{GeV}$, $p_{\mathrm{T}}(e,\mu) > 15\mathrm{GeV}$	$4.38 \pm 0.04\%$
	$WH(130)$	none	0.602pb	$p_{\mathrm{T}}(H) > 150\mathrm{GeV}$, $p_{\mathrm{T}}(W) > 100\mathrm{GeV}$, $p_{\mathrm{T}}(e,\mu) > 15\mathrm{GeV}$	$5.19 \pm 0.03\%$
	$WH(120)$	none	0.953pb	$p_{\mathrm{T}}(H) > 150\mathrm{GeV}$, $E_{\mathrm{T}}^{\mathrm{miss}} > 100\mathrm{GeV}$	$4.39 \pm 0.04\%$
	$ZH(115)$	none	0.660pb	$p_{\mathrm{T}}(H) > 150\mathrm{GeV}$, $p_{\mathrm{T}}(Z) > 100\mathrm{GeV}$, $p_{\mathrm{T}}(e,\mu) > 15\mathrm{GeV}$	$3.21 \pm 0.02\%$
	$ZH(120)$	none	0.545pb	$p_{\mathrm{T}}(H) > 150\mathrm{GeV}$, $p_{\mathrm{T}}(Z) > 100\mathrm{GeV}$, $p_{\mathrm{T}}(e,\mu) > 15\mathrm{GeV}$	$3.51 \pm 0.02\%$
	$ZH(130)$	none	0.347pb	$p_{\mathrm{T}}(H) > 150\mathrm{GeV}$, $p_{\mathrm{T}}(Z) > 100\mathrm{GeV}$, $p_{\mathrm{T}}(e,\mu) > 15\mathrm{GeV}$	$4.18 \pm 0.03\%$
Backgrounds	WW	$\hat{p}_T^{\mathrm{min}} = 150\mathrm{GeV}$	2.059pb	$p_{\mathrm{T}}(e,\mu) > 15\mathrm{GeV}$	$40.7 \pm 0.4\%$
	ZZ	$\hat{p}_T^{\mathrm{min}} = 150\mathrm{GeV}$	0.440pb	$p_{\mathrm{T}}(e,\mu) > 15\mathrm{GeV}$	$61.2 \pm 0.2\%$
	WZ	$\hat{p}_T^{\mathrm{min}} = 150\mathrm{GeV}$	0.96pb	$p_{\mathrm{T}}(e,\mu) > 15\mathrm{GeV}$	$33.6 \pm 0.2\%$
	$t\bar{t}$	$\hat{p}_T^{\mathrm{min}} = 150\mathrm{GeV}$	112.7pb	$p_{\mathrm{T}}(e,\mu) > 20\mathrm{GeV}$	$47.5 \pm 0.2\%$
	$t\bar{t}$	$\hat{p}_T^{\mathrm{max}} = 150\mathrm{GeV}$	298.7pb	$p_{\mathrm{T}}(e,\mu) > 20\mathrm{GeV}$	$39.8 \pm 0.5\%$
	$Z + jet$	$\hat{p}_T^{\mathrm{min}} = 150\mathrm{GeV}$	160.3pb	$p_{\mathrm{T}}(e,\mu) > 15\mathrm{GeV}$	$13.2 \pm 0.2\%$
	$W + jet$	$\hat{p}_T^{\mathrm{min}} = 150\mathrm{GeV}$	384.5pb	$p_{\mathrm{T}}(e,\mu) > 15\mathrm{GeV}$	$21.1 \pm 0.1\%$
	Wbb	none	89.96pb	$p_{\mathrm{T}}(W) > 150\mathrm{GeV}$, $p_{\mathrm{T}}(e,\mu) > 15\mathrm{GeV}$	$0.51 \pm 0.01\%$
	Wt	none	57.896pb	$p_{\mathrm{T}}(W) > 150\mathrm{GeV}$, $p_{\mathrm{T}}(top) > 100\mathrm{GeV}$, $p_{\mathrm{T}}(e,\mu) > 15\mathrm{GeV}$	$9.76 \pm 0.09\%$

- All samples were generated using HERWIG, as input to the ATLAS simulation + reconstruction
  - except for Wt, which relies on AcerMC (which was not considered in the hadron level study)
- Only LO generators were used (since no NLO Monte Carlo is available for W+jets)
- In the case of W+jets (dominated by Wg → Wbb with g→bb produced by the parton shower) a hadron level study was done, to ensure the parton shower approximation doesn't break down

The WH (W→lν,H→bb) analysis: cut flow (main signal and backgrounds samples)

L=30 fb^{-1}

Loose jet veto and loose b-tagging (to be used as input to likelihood fit):

	WH(120)	WZ	$t\bar{t}(p_T^{min})$	Wt	W+jets
After filter cuts	1252.8 ± 7.8	9331	1609356	169519	2433885
1 Higgs candidate	569.7 ± 3.0	3509.7 ± 8.0	806175	69375	562030
filtered p_T > 200 GeV	512.7 ± 3.2	3108 ± 10	709271	60241	413406
Missing E_T > 30 GeV	362.4 ± 3.2	2183 ± 13	552284	46779	318400
p_T(W) > 200 GeV	171.0 ± 2.6	1216 ± 12	137946	18524	206331
p_T(e/μ)>30 GeV	145.6 ± 2.4	996 ± 11	115053	15724	178004
p_T(additional μ)<10 GeV	144.6 ± 2.4	942 ± 11	106836	14992	177542
p_T(additional e)<10 GeV	142.9 ± 2.4	885 ± 11	97305	13881	174941
$\Delta\phi$(W,H)> $\frac{2}{3}\pi$	142.2 ± 2.4	841 ± 11	84773	12999	167704
no additional b-jets p_T >15 GeV	130.6 ± 2.3	790 ± 10	30605	7805	160608
add. jets on W side p_T <60 GeV	115.7 ± 2.2	637.2 ± 9.5	19422	5870	121437
add. jets on H side p_T <60 GeV	102.7 ± 2.1	525.6 ± 8.8	13841	4370	94055
one subjet b-tagged	91.4 ± 2.0	126.1 ± 4.5	8638	2421	6964
both subjets b-tagged	45.6 ± 1.4	43.7 ± 2.7	576	161.4 ± 7.0	266
loose fit cuts	45.4 ± 1.4	43.0 ± 2.7	565	156.3 ± 6.9	257

Tight jet veto and tight b-tagging at ε_b~63 % and c(l)=0.2 (for counting based analysis)

	WH(120)	WZ	$t\bar{t}(p_T^{min})$	Wt	W+jets
add. jets on W side p_T <20 GeV	83.2 ± 1.9	461.3 ± 8.3	7227	3343	86087
add. jets on H side p_T <20 GeV	55.8 ± 1.6	275.6 ± 6.6	1895	1142	48229
one subjet b-tagged	46.4 ± 1.5	49.8 ± 2.9	986	498 ± 12	1825
both subjets b-tagged	19.51 ± 0.96	16.5 ± 1.7	38.9 ± 4.9	18.2 ± 2.4	87.3 ± 9.0
112 GeV < mass(H) < 136 GeV	13.25 ± 0.79	1.18 ± 0.45	5.6 ± 1.9	4.2 ± 1.1	8.3 ± 2.8

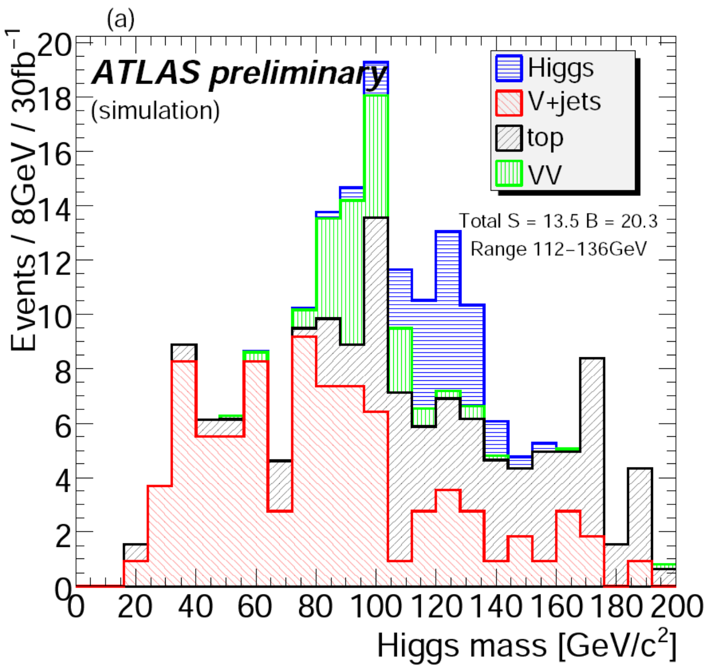
Signal events (m_H~120 GeV): ~13.5

Background events: ~20.3

$$\frac{S}{\sqrt{B}} = 3.0 \pm 0.3$$

Final mass distribution

L=30 fb^{-1}



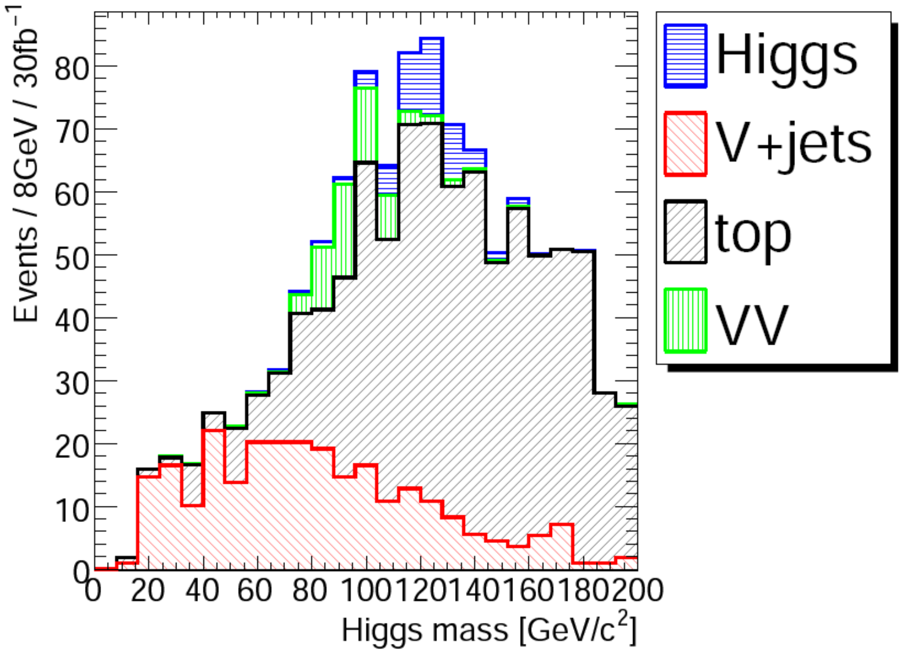
Mass distribution after tight selection

→ Mass resolution is good enough that H→ bb peak can be distinguished Z→ bb peak (from WZ events)

→ W+jets background is dominated by W+bb, which provides a continuum decreasing bb mass distribution (from g→bb splitting)

Mass distribution after loose selection

→ ttbar has a double peak structure, with a first ~continuum peak between the W and top mass (2/3 jets from the top correctly reconstructed) and a second peak at the top mass (all three jets from the top reconstructed in a single Higgs candidate)

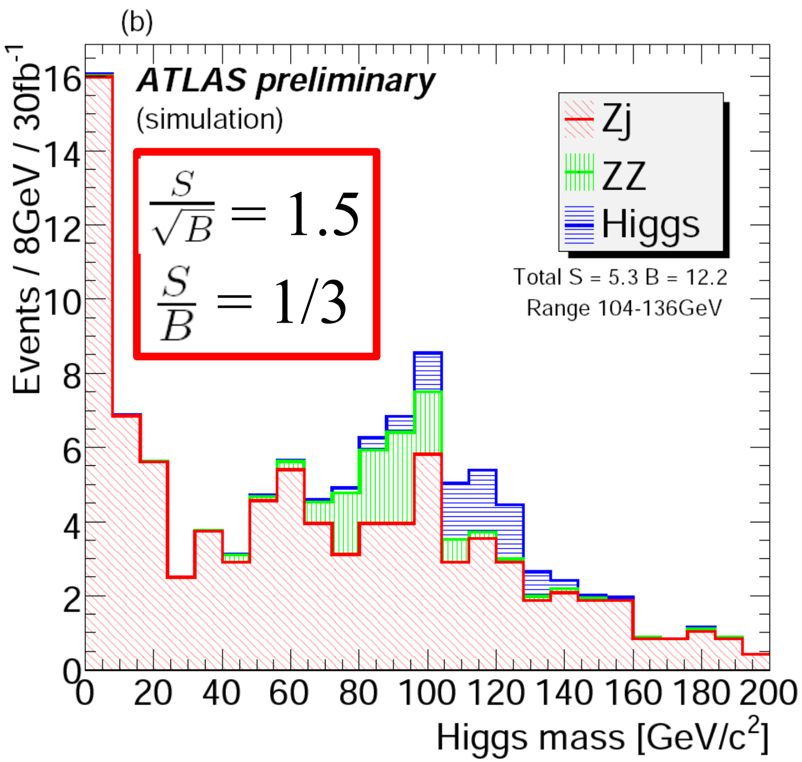


The ZH → ll/νν bb channels

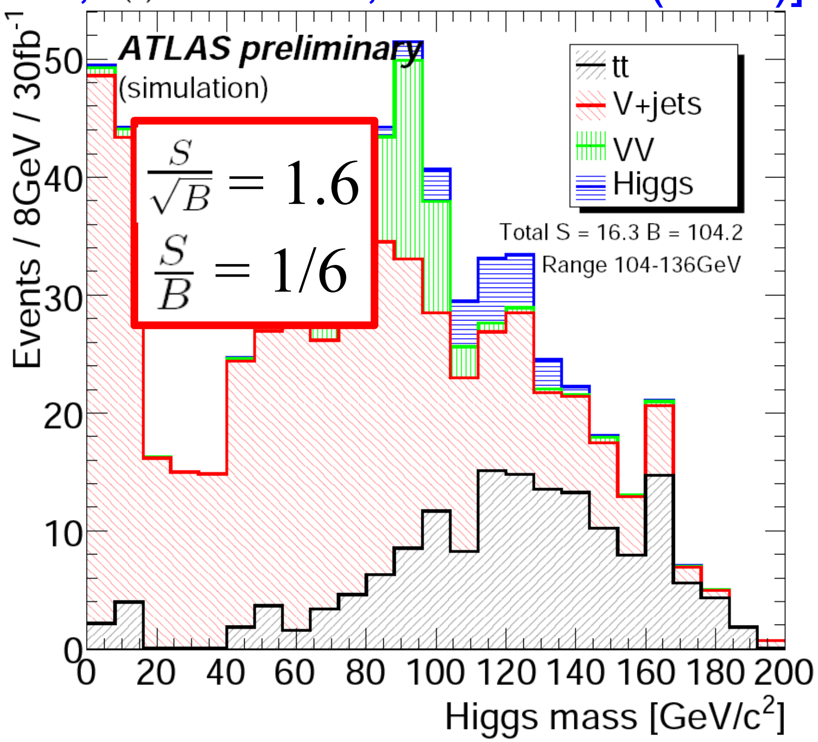
- The WH channel is finally combined with the ZH channels
- Advantage of going to high p_T: the Z → νν signature gets accessible to the MET Trigger
- Selection is similar to the WH channel (but Z is selected). Final mass distributions:

[J. Butterworth, A. Davison, E. Orkcan (UCL)]

llbb



ννbb



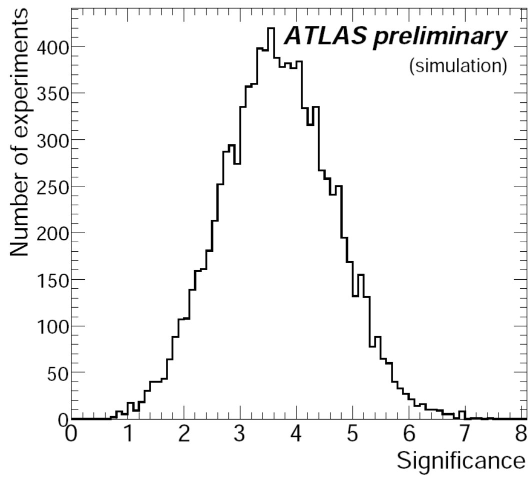
- ZH → ll bb is cleaner (because of |m(ll)-m(Z)| requirement), but suffers from the low BR of the leptonic decay of the Z.

Counting based combination

- Combined sensitivity of the lvbb, llbb and ννbb channels with L=30 fb^{-1}:
  - $3.7^{+0.3}_{-0.2}\sigma$
- This requires a perfect knowledge of the background expectation values (cross section, luminosity, acceptance)
- The impact of the background uncertainty is analyzed by subdividing the backgrounds into three categories and assuming they are fully correlated between the three different channels.

Channel	signal	t_i	w_i	z_i	$S/\sqrt{B}$
$llb\bar{b}$	5.34	0.98	0.0	11.2	1.5
$l\nu b\bar{b}$	13.5	7.02	12.5	0.78	3.0
$\nu\nu b\bar{b}$	16.3	45.2	27.4	31.6	1.6
Combined					3.7

[J. Butterworth, A. Davison, E. Orkcan (UCL)]



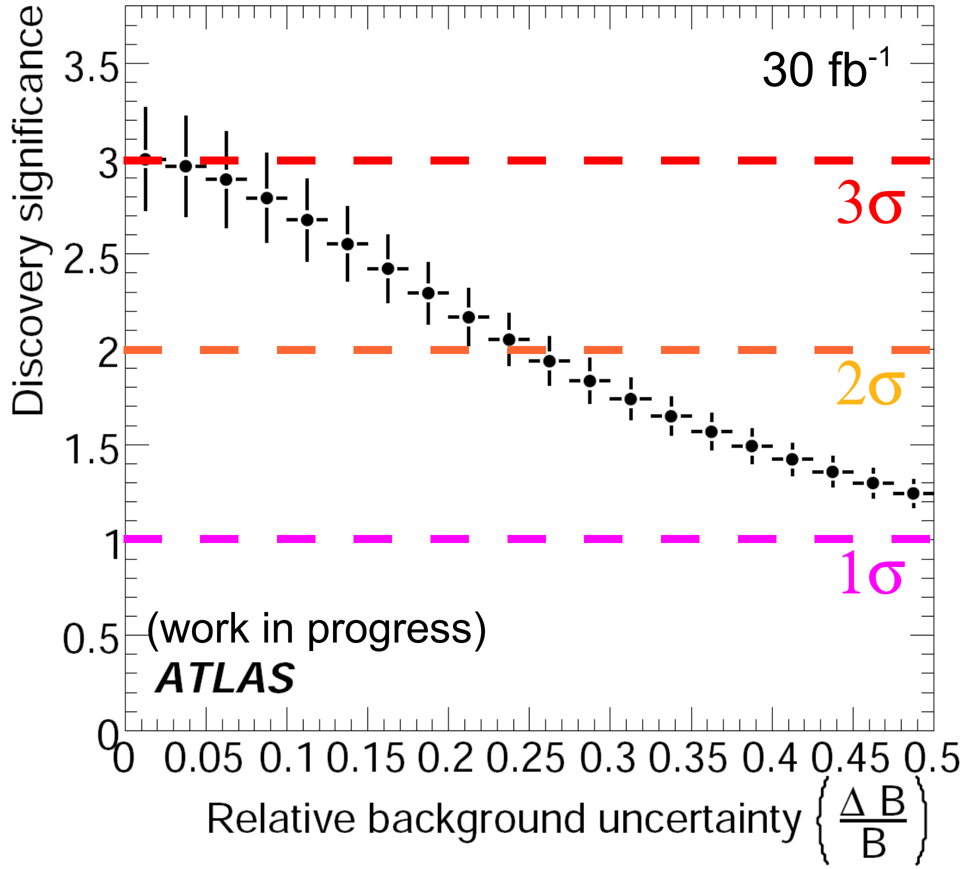
- Result:

σ_t	σ_w	σ_z	Significance
Perfect	Perfect	Perfect	3.7
5%	5%	5%	3.5
10%	10%	10%	3.2
15%	15%	15%	3.0
20%	20%	20%	2.8
30%	30%	30%	2.5
50%	50%	50%	2.2

- **10/15 %** uncertainty considered as realistic:
  - Median discovery significance: **3.0-3.2**
- **Needs justification !**

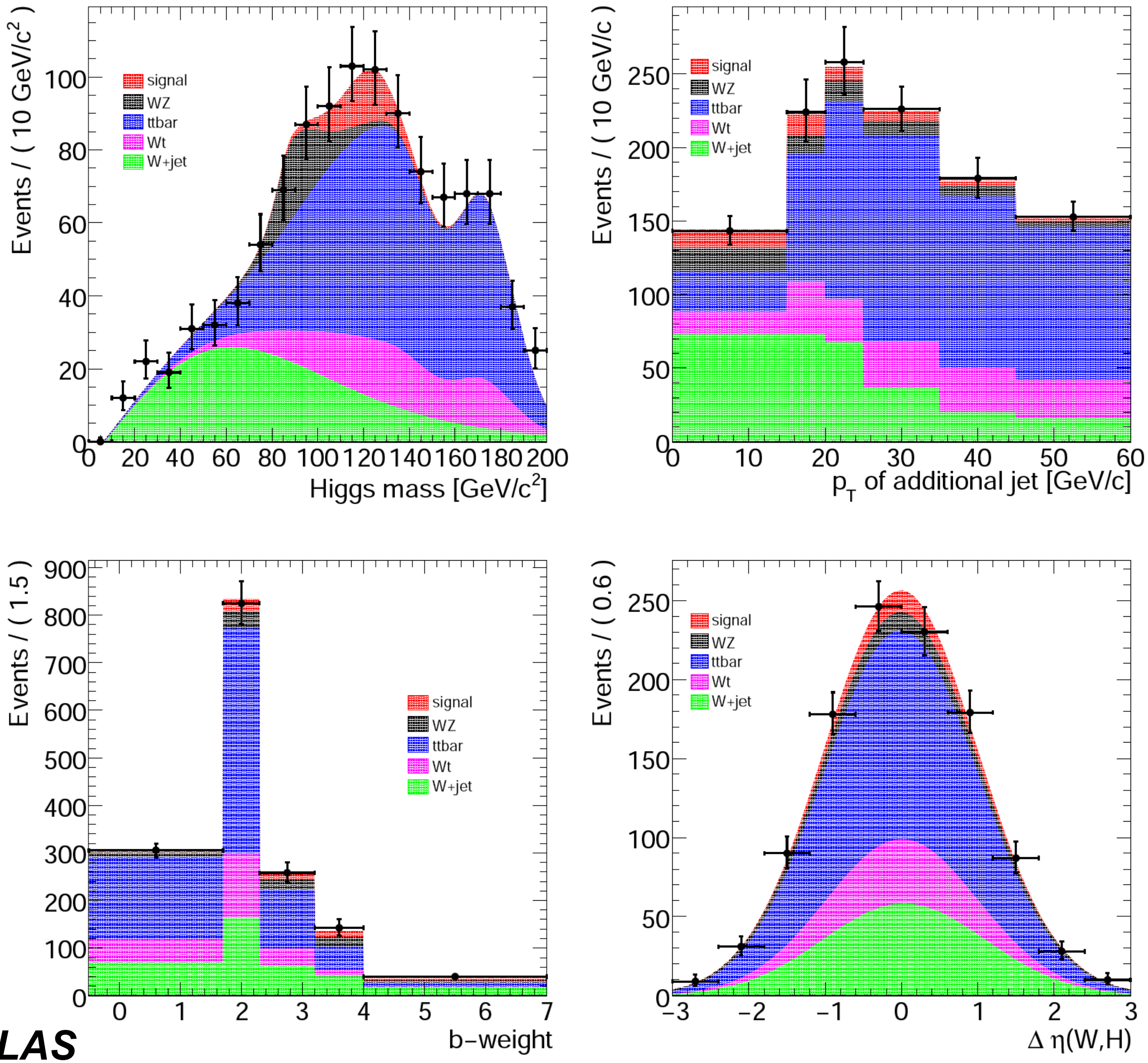
What level of background uncertainty?

- Discovery significance of the WH channel as a function of the relative background uncertainty
- If the expectation values for the backgrounds are taken from:
  - Theoretical cross section in very specific region of signal acceptance
  - Measured integrated luminosity
  - Acceptance as predicted from Monte Carlo
- this uncertainty can be as high as >25% !
- More promising:
  - Extraction of amount of signal events and different background contributions from data using a likelihood fit, based on the knowledge of the shapes of few discriminating variables
  - The WH channel is used as a study case (to be extended later to the ZH channels)



Maximum likelihood fit

- Based on four discriminating variables:

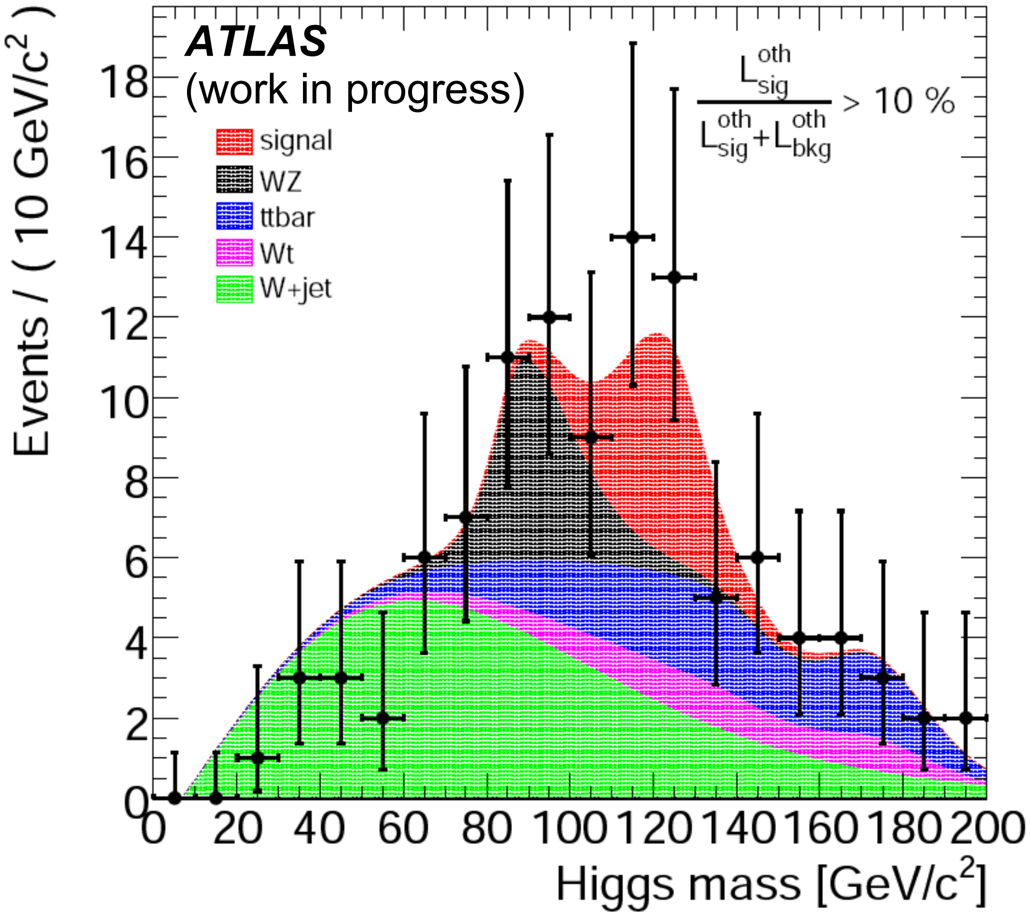


ATLAS
(work in progress)

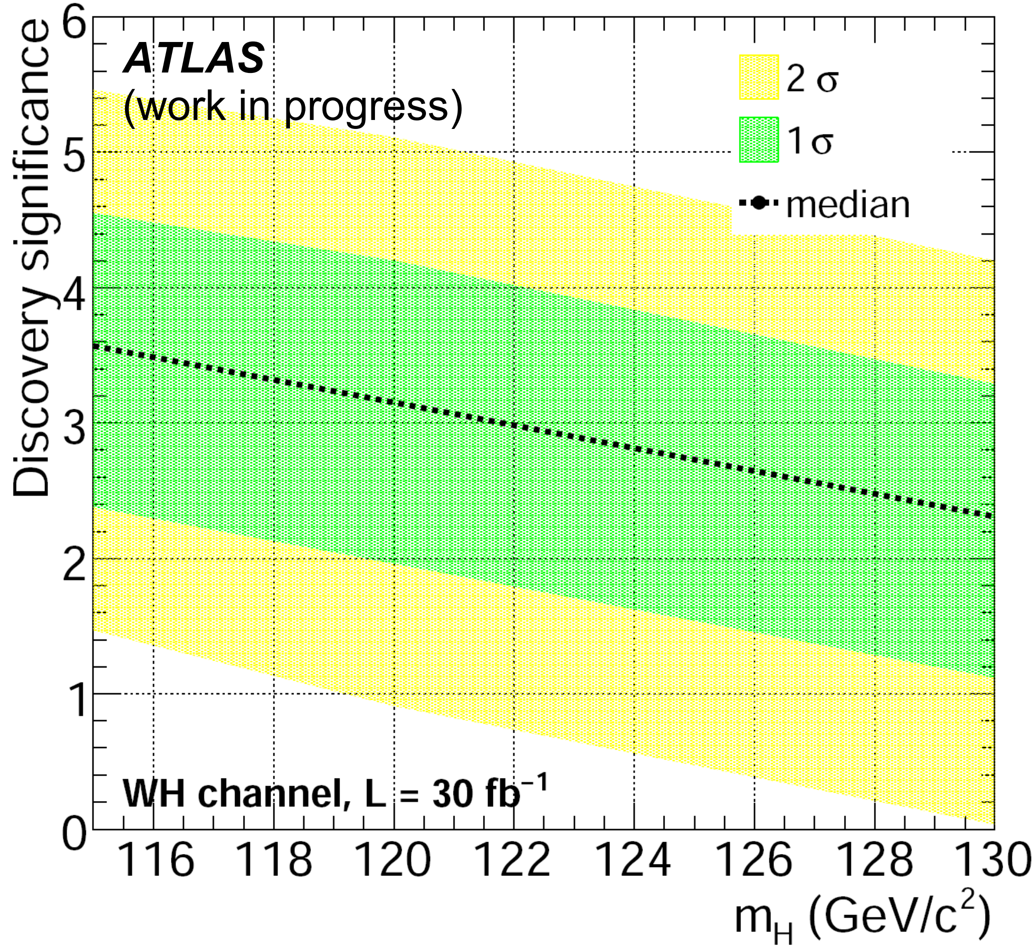
- The normalization of the single signal and background contributions is determined directly on data
- This relies on a very good knowledge of the PDFs (shapes)!
- The discovery significance is estimated through a large set of Monte Carlo pseudoexperiments

Sensitivity with likelihood fit

- Possible outcome of fit (m_H=120 GeV):

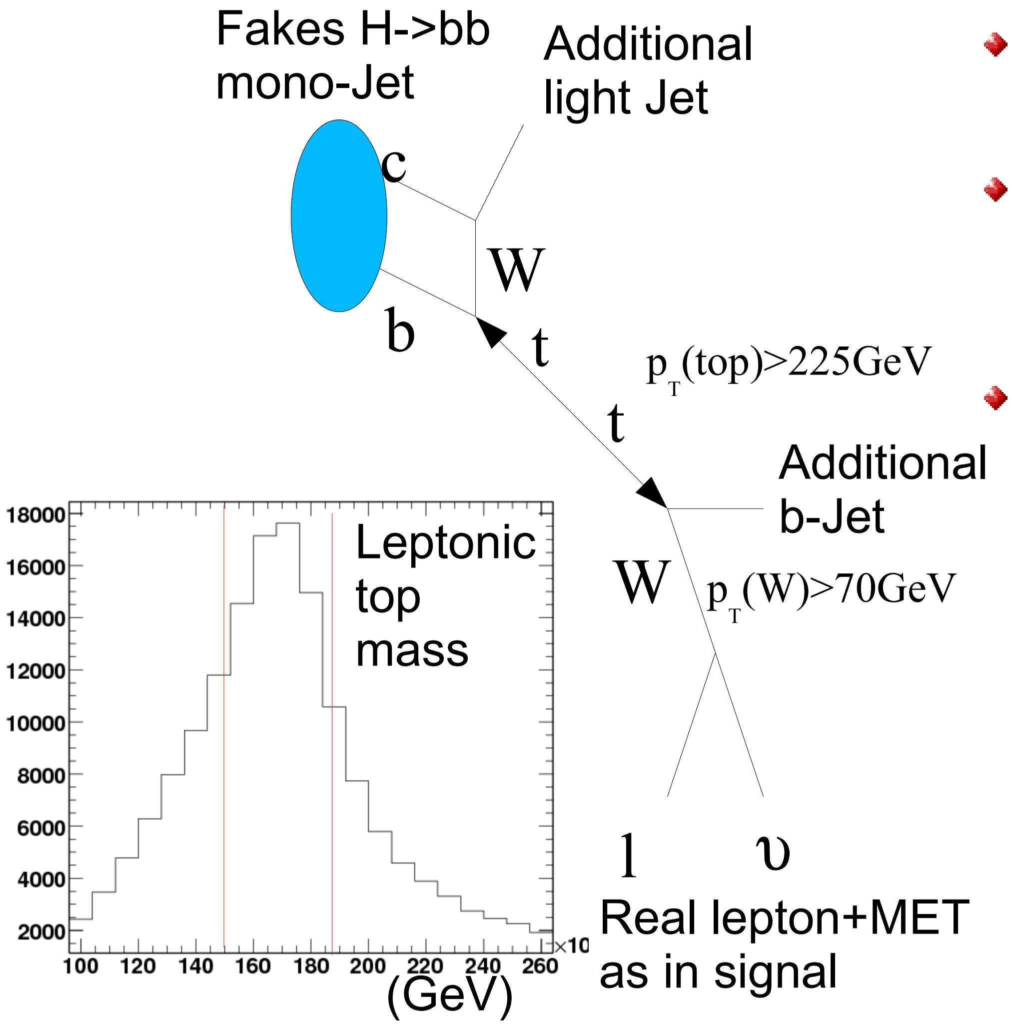


- Discovery potential as a function of the Higgs mass (using profile likelihood ratio method):

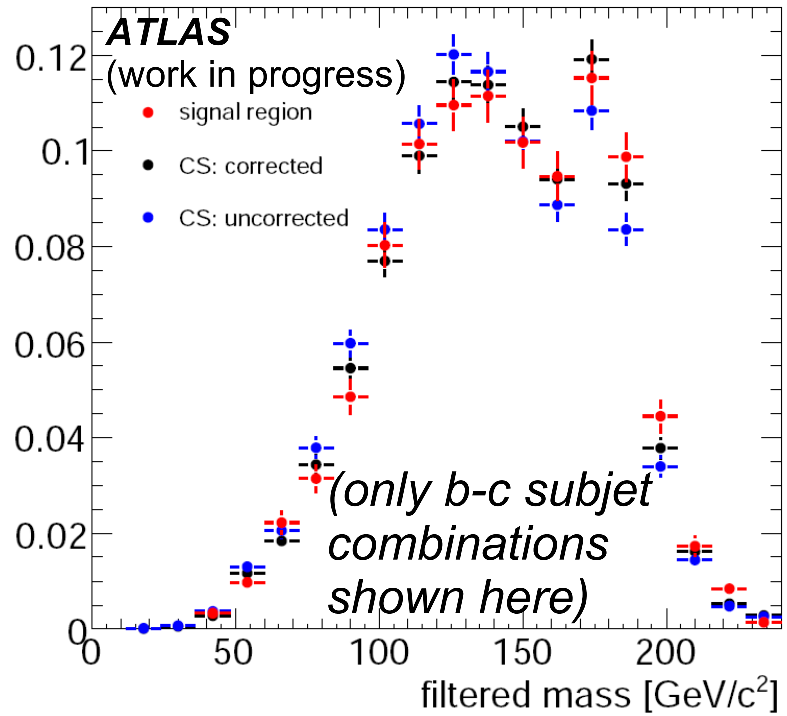


- But what about the impact of systematic uncertainties ?
  - Need to determine background shapes on control sample, when possible (ttbar)
  - Need to include effect of remaining systematic deformations of shapes into the fit

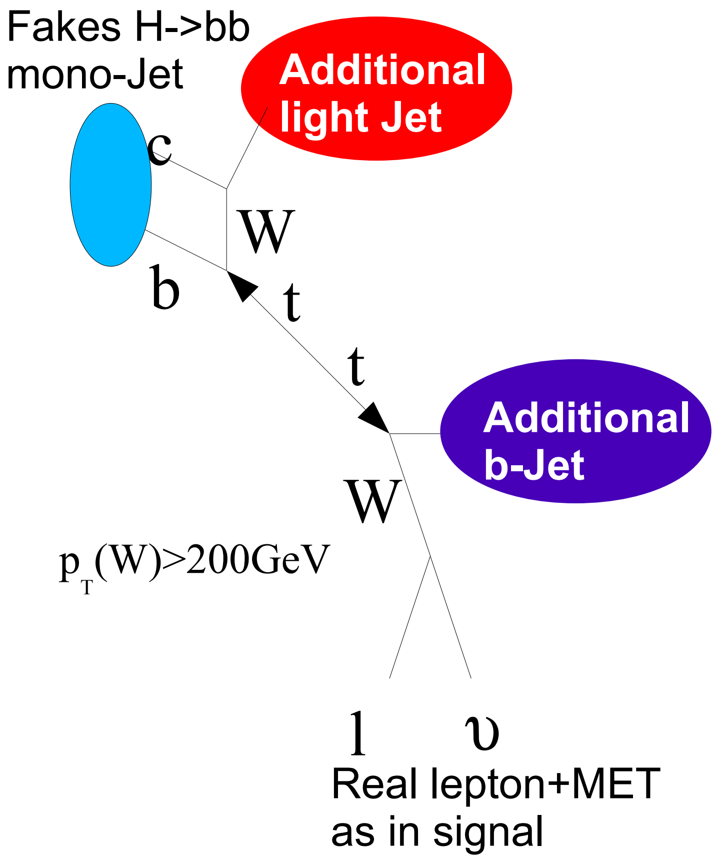
PDFs for the ttbar background (I)



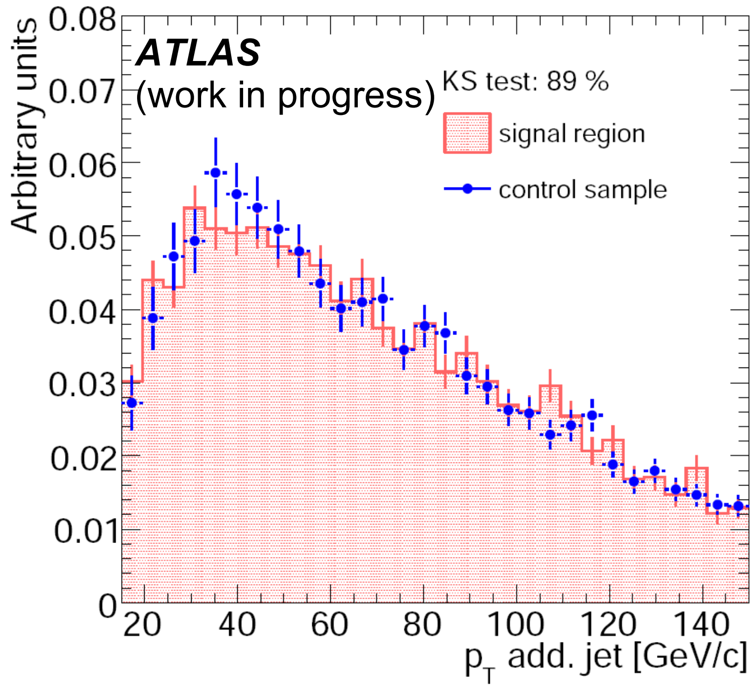
- Select a pure top sample, requiring a leptonic decaying top quark
- → Get the mass and the b-weight PDFs from data (since these depend only on the top quark faking the H → bb system)
- Comparison of mass PDF in signal region and in control sample (CS):



PDFs for the ttbar background (II)



- p_T of additional jet PDF more difficult to get from control sample
- Can be obtained by unfolding the effect of b-tagging efficiency (however errors are not small!)
- Comparison of p_T of additional jet PDF between signal region and control sample:

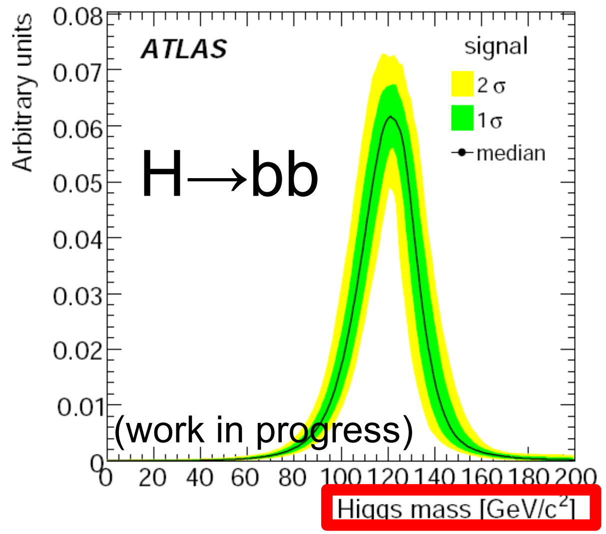


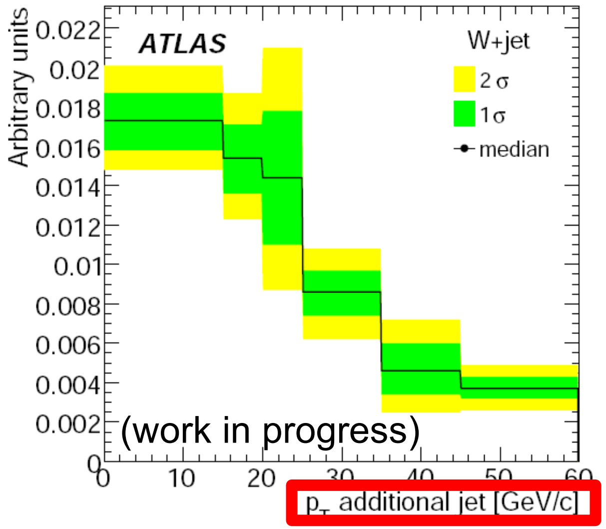
PDFs for the ttbar background can be obtained from data.

Including experimental uncertainties

Scenarios considered

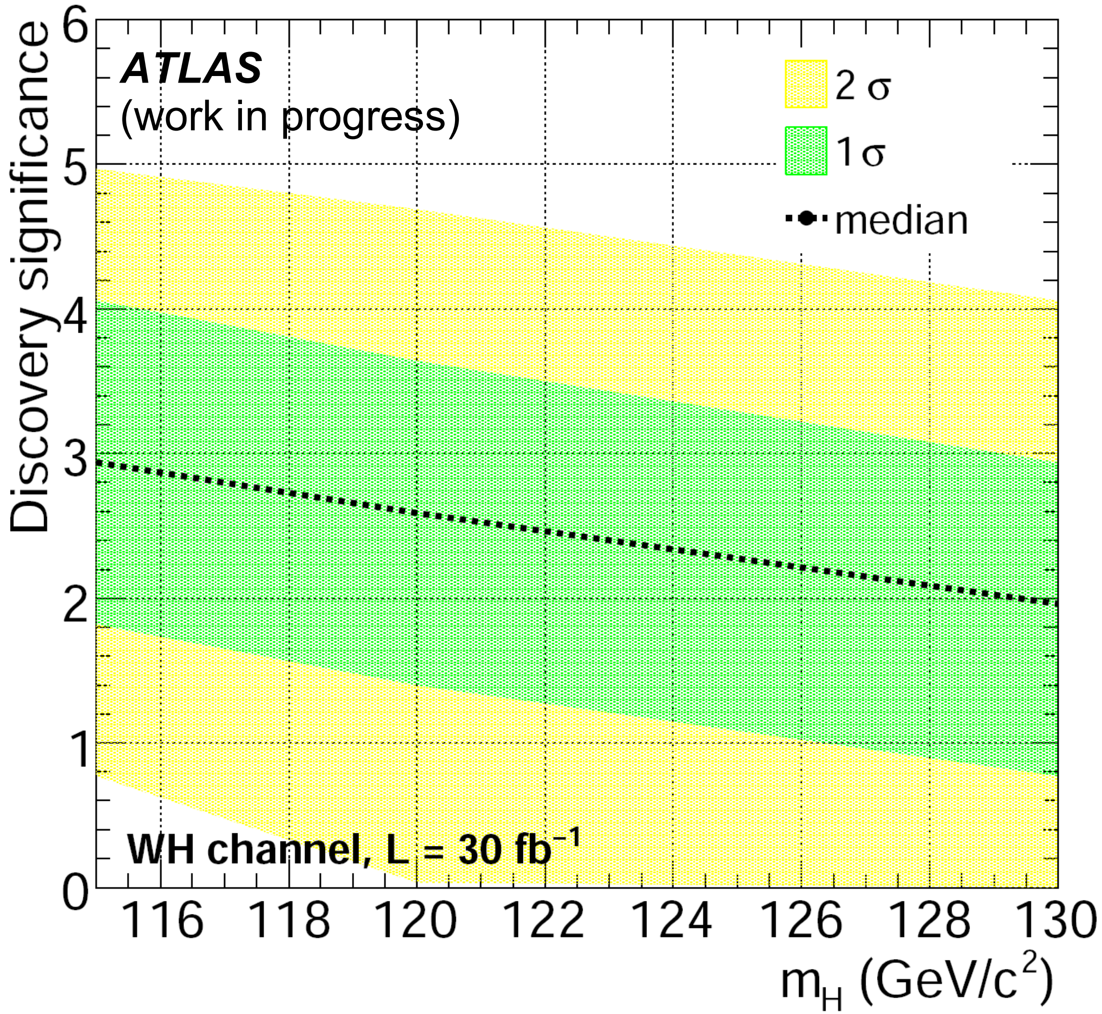
Systematic Uncertainty
Jet energy scale up
Jet energy scale down
Jet energy smearing
Muon efficiency
Muon energy smearing
Muon energy scale up
Muon energy scale down
Electron energy smearing
Electron energy scale up
Electron energy scale down
Electron efficiency up
Electron efficiency down
b-tagging eff. down
b-tagging rej. up
b-tagging rej. down





- B-tagging performance is decreased according to CSC (resid. misalig., ...)
  - → +15 % ttbar
  - → +25 % W+jet
- AtlFast-II to fullsim corrections + trigger acceptance considered
- Systematic deformations of PDFs due to experimental uncertainties included directly into the fit

Final sensitivity including systematics



- Median significance:
  - ~3 σ at m_H=115 GeV
  - ~2.6 σ at m_H=120 GeV
  - ~2 σ at m_H=130 GeV
- Roughly equivalent to assuming **10-15 % uncertainty** on the background level in the counting based analysis
- Assuming a similar fit can be applied to the ZH channels, a combined significance of **3.0-3.2** should be realistic

- Some systematic effects not included in this study:
  - Impact of pile-up
  - Theoretical uncertainty on shapes of signal, WZ and **W+jet** background

Residual (not considered) uncertainties

- Experimental uncertainties
  - Impact of pile-up
    - Impact on mass resolution and b-tagging expected to be small
    - However: jet veto expected to be significantly affected
- Theoretical uncertainties on PDFs used in the fit:
  - For the ttbar background all PDFs are obtained from data
  - For the signal (WH) and WZ background, the Monte Carlo generators (e.g. MC@NLO) should be sufficiently accurate (uncertainties will be estimated, e.g. considering renorm./factoriz scale variations and PDF uncertainties)
  - For the W+jet background (dominated by W+bbbar) an accurate prediction of m(bb) or pT(bb) or pT(add. jet) is theoretically more challenging:
    - will be absolutely crucial for this analysis
    - Predictions will be compared with data in complementary phase space regions.
- In addition the discovery potential is based on LO cross sections only !

Conclusion

- Looking at highly boosted Higgs bosons and exploiting jet substructure, the W/ZH channels can be recovered as promising Higgs search channels at the LHC
- Based on LO estimates, a combined discovery significance of 3.0-3.2 σ should be achievable with 30 fb^{-1} of integrated luminosity (all experimental systematic uncertainties except for pile-up included)
- This will:
  - increase the overall discovery sensitivity for a low mass Higgs boson
  - provide a way to measure the Higgs coupling to b-quarks (+ significantly constraints the other couplings in a global fit analysis, see next talk by **Michael Rauch**)
- However, a long way still to go:
  - Impact of pile-up
  - Impact of theoretical uncertainties
  - Complete NLO estimate of significance (no available Monte Carlo for W+jj @NLO)

Quite some work also for theorists !

BACKUP

Why not: $qq \rightarrow qq(H \rightarrow bb)$?

Difficult!

Even if triggering on the forward jets could be possible, large background from qqbb! Low sensitivity...

[M. Mangano et al. (2003), arXiv:hep-ph/0210261v2]

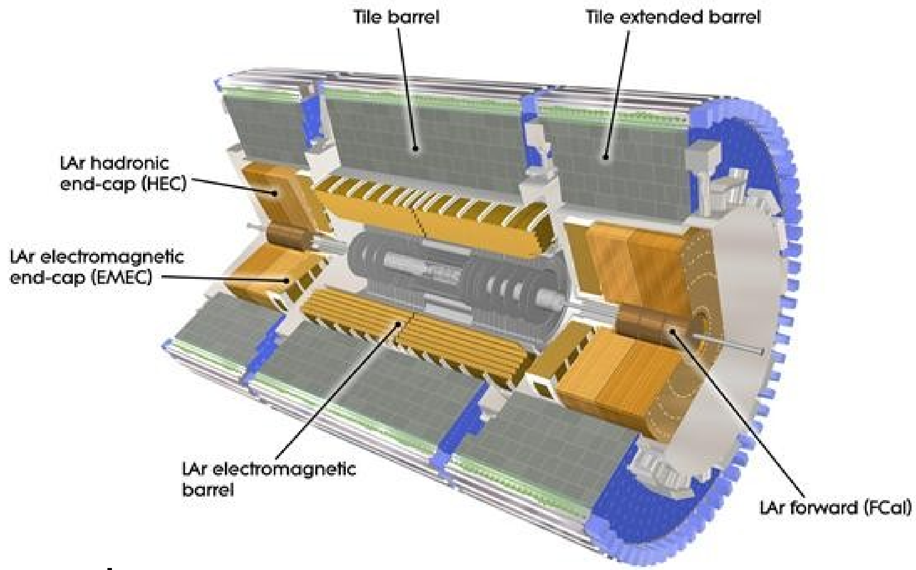
Why not: $gg \rightarrow H \rightarrow bb$?

Impossible!

QCD background from di b-jet events (~7 order of magnitudes higher than signal)

Jet energy calibration

- In the case of a real detector, instead of particles, three-dimensional clusters of energy reconstructed in the calorimeter (***Topoclusters***) are used as input.
- Their energy needs to be corrected (according to the fraction of electromagnetic and hadronic shower, since ATLAS has a non-compensating calorimeter) and calibrated
- The default calibration in ATLAS relies on the calibration procedure used by the H1 Collaboration:
  - The jets are corrected reweighting the energy contribution cell-by-cell according to the respective energy density (more density means more EM like shower, less more hadronic like)
  - Then an overall jet p_T and y dependent jet scale factor is used, to correct for residual non linearities (including out-of-cone corrections)

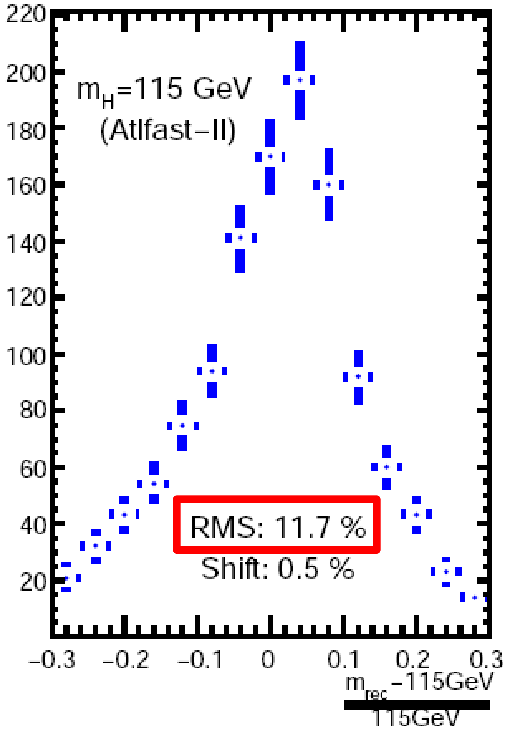


- Since non specific calibration for C/A jets is available, only the first part of this calibration procedure is applied.

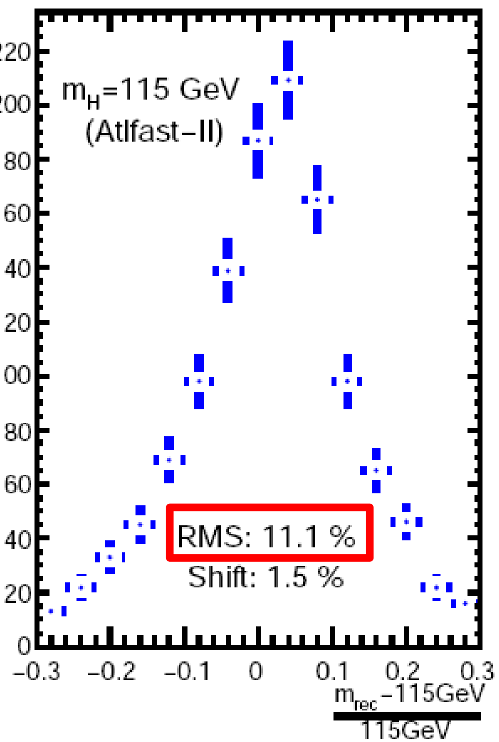
b-jet based energy scale correction

- In the case of a b-jet, a b-quark is produced. This hadronizes into a b-hadron and then ($|V_{cb}|^2 >> |V_{ub}|^2$) it decays most of the times into a c-hadron.
- In 20 % of all cases either the b- or the c-hadron decays semileptonically in a (e,ν_e) or a (μ,ν_μ) pair. As a consequence:
  - The neutrino escapes detection (but no correction considered in this study)
  - The muon releases only a minor part of its energy in the calorimeter (~3 GeV)

Jet calibration



Adding muon (if present)



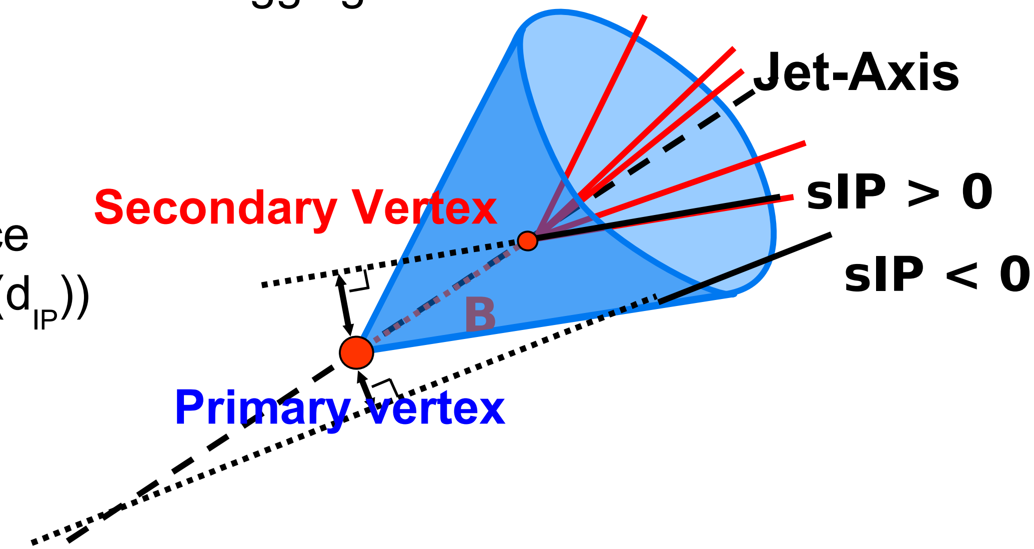
- The muon is corrected for by just adding it to the Higgs subjets 4-mom, if a muon is reconstructed in the surrounding $[\Delta R(\mu,j_i) < 0.4]$
- The resolution is slightly improved

b-tagging: from hadron to detector level

- The successful application of b-tagging is a crucial ingredient to this analysis. In fact, without it, it would impossible to reject the large W/Z+jet and ttbar backgrounds.
- How b-tagging was applied in the hadron level study:
  - The b-quarks were not decayed during generation. If a b-quark is present as a constituent of a subjet, then the subjet is considered as a b-jet, otherwise it is considered as a non-b jet.
  - If a subjet is labeled as a b-subjet, then a fixed b-tagging efficiency of 60 % is applied, for non b-subjet a fixed mistagging efficiency of ε_{udsc}= 2 % (Rejection = 1/ε_{udsc} = 50)
  - No distinction is made between light- (uds) and charm-jets (for which a much lower rejection is achievable)
- The detector level study should answer the following questions:
  - Can the two subjets be tagged separately?
  - What is the impact of the dependence of the b-tagging rejection on jet p_T and pseudorapidity?
  - What is the impact of the presence of charm-jets in the background ? Can the b-tagging performance be improved further to reject specifically such backgrounds?

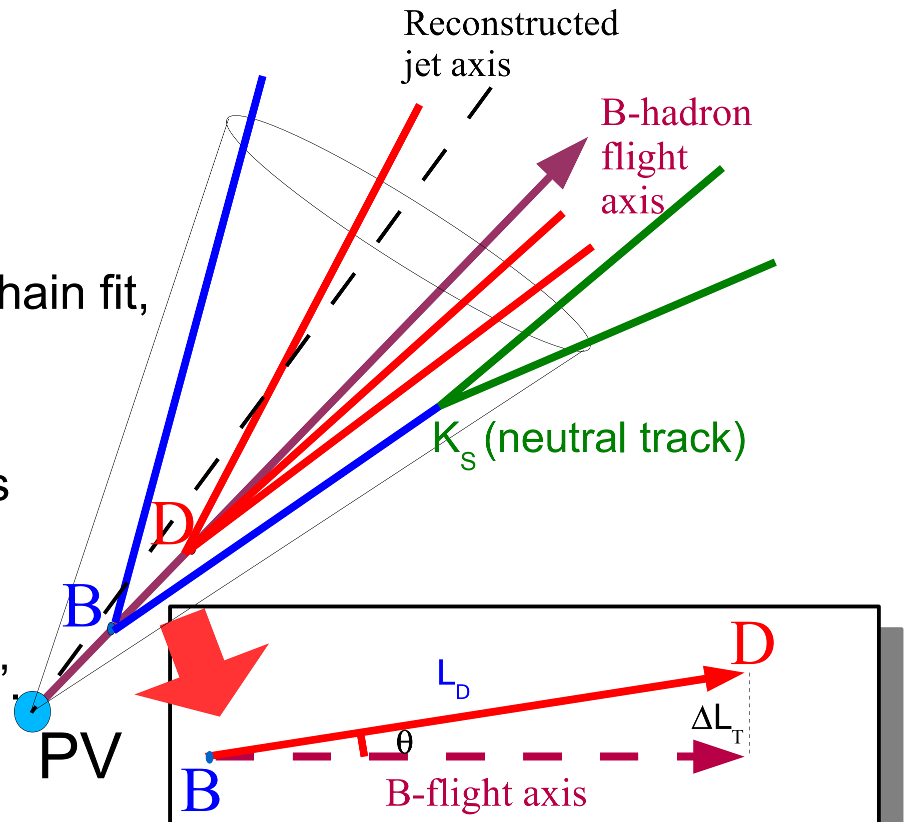
B-tagging in ATLAS (short introduction - I)

- B-tagging should tell us if the origin of a jet was a b-quark. Main discriminating properties:
  - presence of a displaced vertex (for a B^0 of 30GeV $L \sim \beta\gamma c\tau \sim 3$ mm)
    - used for the "lifetime based" identification algorithms ("Taggers")
  - presence of non-isolated leptons (e,μ) NOT CONSIDERED HERE
    - limited by the BR($b \rightarrow l\ X$)~20%, but precious for b-tagging calibration
- Main "*lifetime based*" algorithms in ATLAS:
  - **Impact Parameter based** "Taggers"
    - Exploit the Impact Parameter significance of the tracks in z ($z_{IP}/\sigma(z_{IP})$) and $r\phi$ ($d_{IP}/\sigma(d_{IP})$) with respect to the Primary Vertex, after assigning a lifetime sign to them (sIP)
  - **Secondary vertex based** "Tagger"
    - Find and "fit" displaced tracks into a single inclusive vertex
    - Exploit the mass of charged particles at vertex, vertex energy fraction and vertex track multiplicity



B-tagging in ATLAS (short introduction - II)

- The combination of the previous mentioned algorithms provides the default combined b-tagging algorithm in ATLAS
  - "**COMB**" later in the plots
- An additional "secondary vertex based" b-tagging algorithm is also available:
  - accomodates the displaced tracks in a decay chain fit, trying to find multiple vertices (PV → b → c-hadron vertices).
- The assumption is that the c-hadron momentum is nearly aligned with the b-hadron flight axis.
- This is again combined with the impact parameter based algorithm and will be denoted as "**JetFitter**".
- This algorithm can be specifically optimized to reject charm-jets (at the cost of a reduced light-jet rejection), by **tuning the prior background light/charm jet content** (c(light) = [0 – 1]).



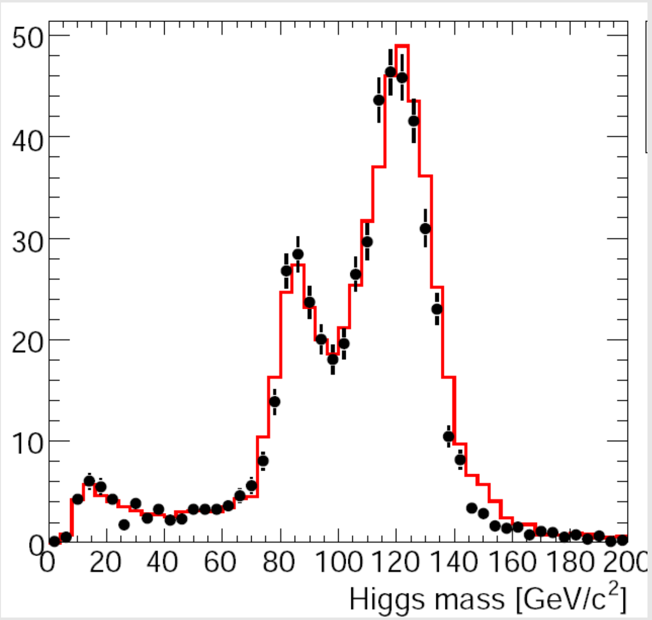
- Deviation $\Delta L_T \approx 40\ \mu m$.
- Best resolution of tracks from D $\approx 60\ \mu m$

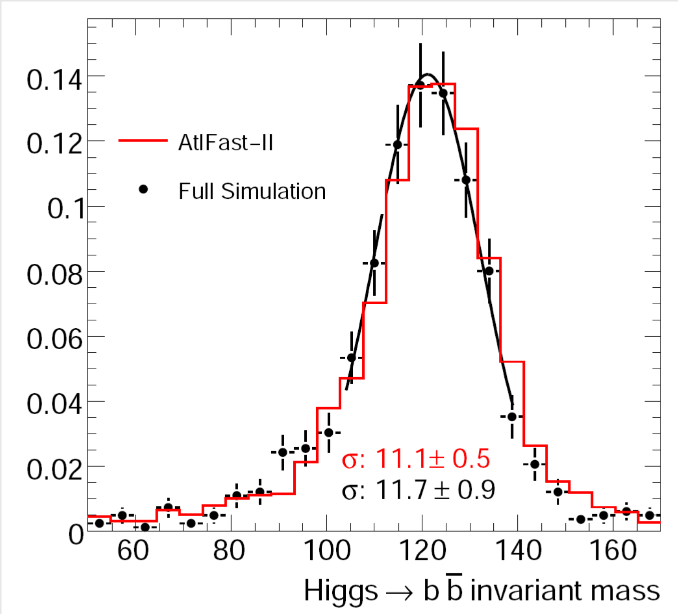
-->approximation is not too bad (small bias on vertex χ^2)

Detector simulation

- The ATLAS detector simulation is based on:
  - A new fast simulation of the calorimeter response in its full granularity
  - The Geant4 full simulation of the inner detector and of the muon system

A part a small shift in the energy scale, the fast simulation of the calorimeter reproduces the subjet structure correctly...

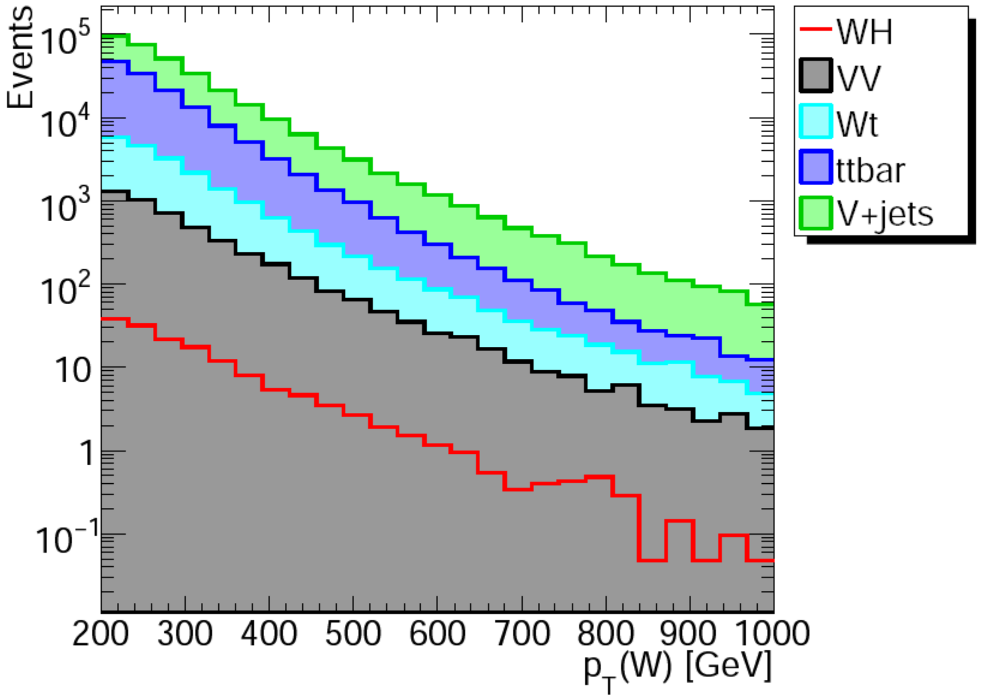




- The fast simulation of the calorimeter was compared with the full Geant4 simulation.
- Small differences found:
  - considered as additional systematic uncertainties in the likelihood fit based analysis

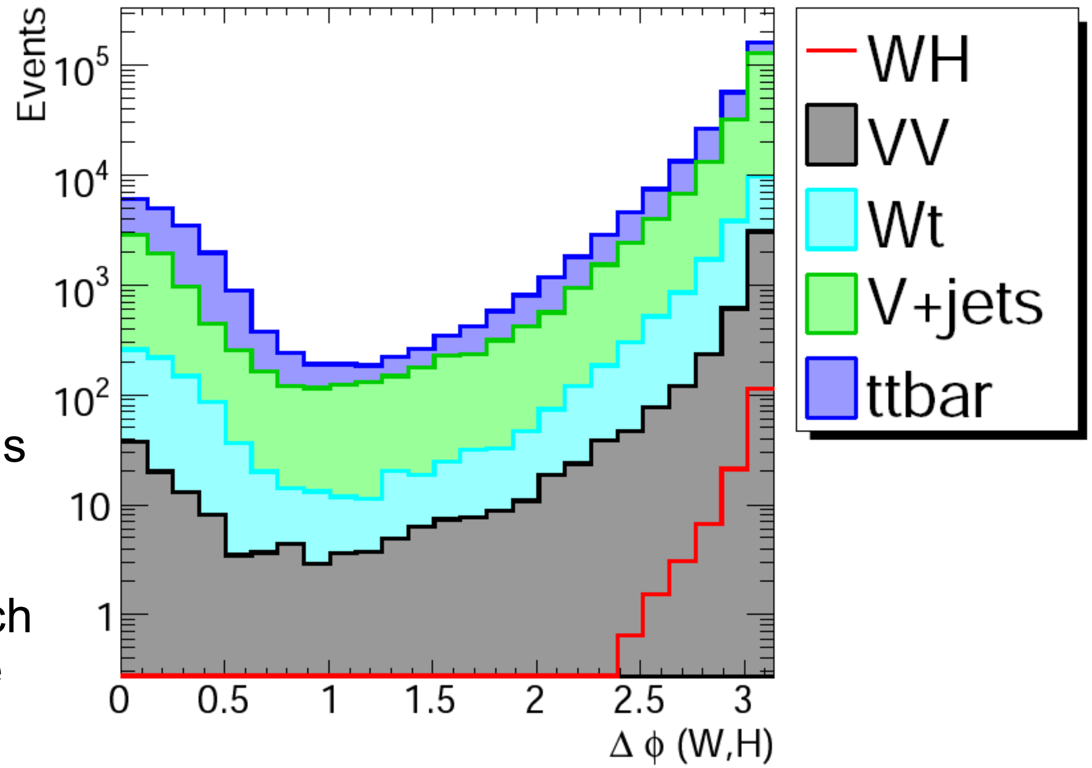
Some distributions

L=30 fb^{-1}



pT(W) after first 4 selection cuts

→ distributions not too different
(dominated in all cases by real W bosons)



Δφ(W,H) after add. lepton veto

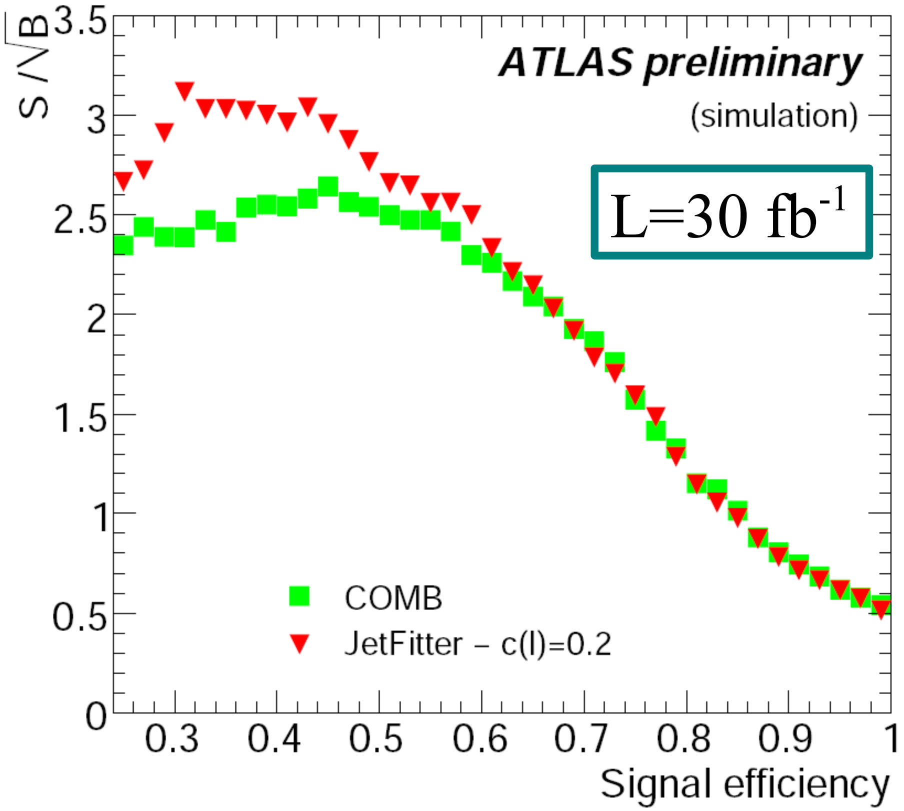
→ signal peaks at back-to-back configurations

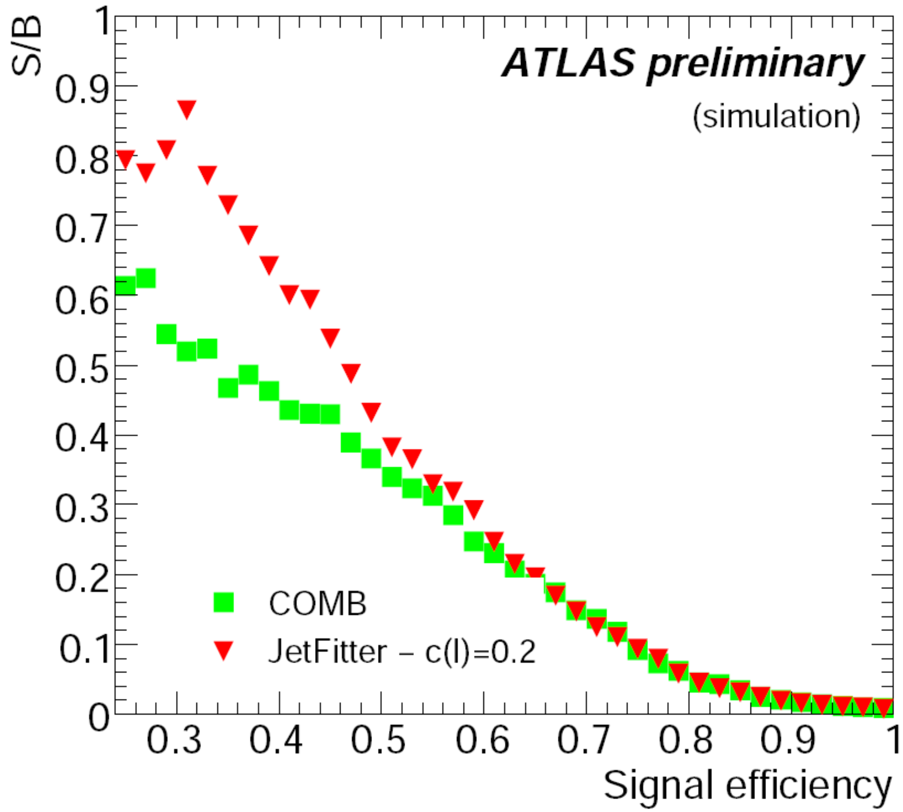
Loose cut at Δφ(W,H)>2.1

First NLO signal MC studies show that a much tighter cut can be applied! Will be done in the future !

Optimization of b-tagging performance

- Two b-tagging algorithms considered here (**COMB** and **JetFitter** with c(light)=0.2).
- The analysis is rerun with different values of the b-tagging discriminator cut and the significance (and signal-to-background ratio) is analyzed as a function of the bb-pair tagging efficiency.

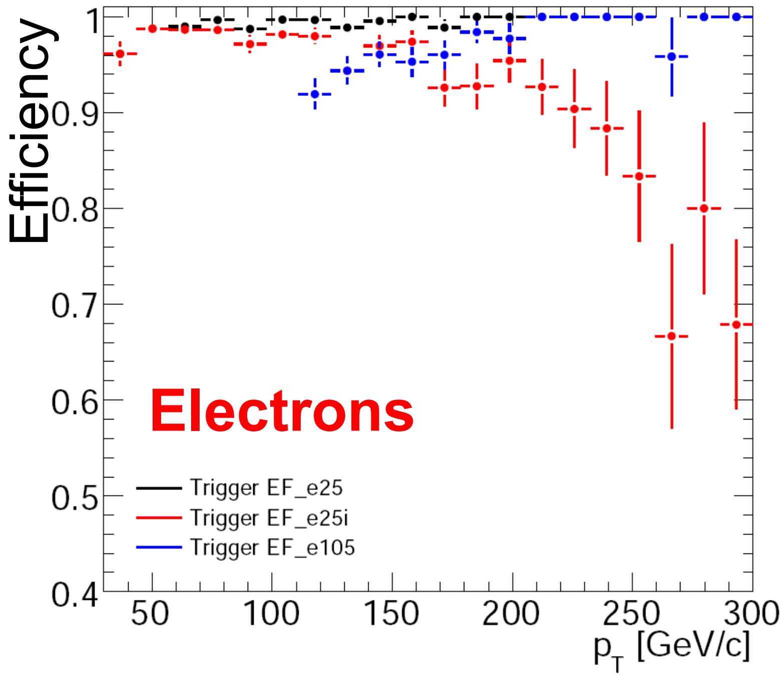


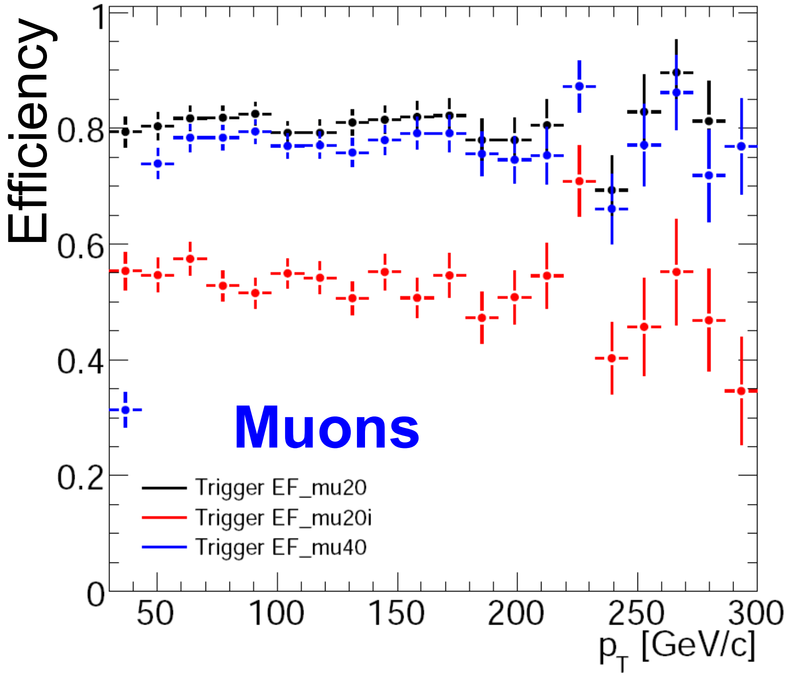


- → The JetFitter algorithm with a signal efficiency of ~40 % is used in the nominal analysis.

Impact of trigger selection (I)

- In order to record the events of interest on tape, they need to pass the trigger selection.
- Impact on signal efficiency estimated through trigger simulation on signal events.
- Main signature: **high p_T lepton from W boson**

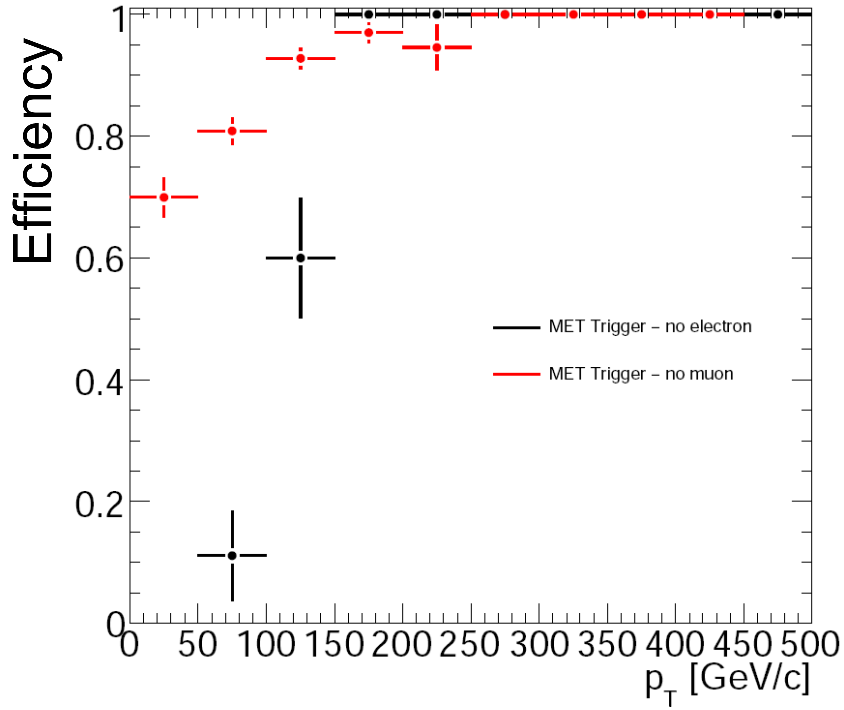




- Combining the lepton triggers, a signal efficiency of ~90 % can be obtained.
- Residual inefficiency of ~10% is essentially due to the limited geometrical acceptance of muon chambers used by the L1 trigger.

Impact of trigger selection (II)

- Residual inefficiency can be recovered by combining the lepton triggers with the "Missing transverse energy + jet" based trigger
- Effect on the events where the lepton trigger fails:



→ Muons not recognized in the muon chambers give rise to a high amount of MET and can be therefore recovered by the MET+jet trigger !

- Impact of trigger selection on signal efficiency:
  - (99.4 ± 0.2) %
- Almost no effect on analysis!

- Effect of trigger selection on signal events <u>after offline selection cuts</u>:

(loose selection)	No trigger	Lepton triggers	Lepton triggers w/o isolation	Lepton + MET·jet triggers
$112 < m_H < 136$ GeV	29.5 ± 1.4	26.1 ± 1.3	26.5 ± 1.3	29.2 ± 1.4
trigger efficiency	-	$(88.1 \pm 0.6)\%$	$(89.5 \pm 0.6)\%$	$(99.4 \pm 0.2)\%$

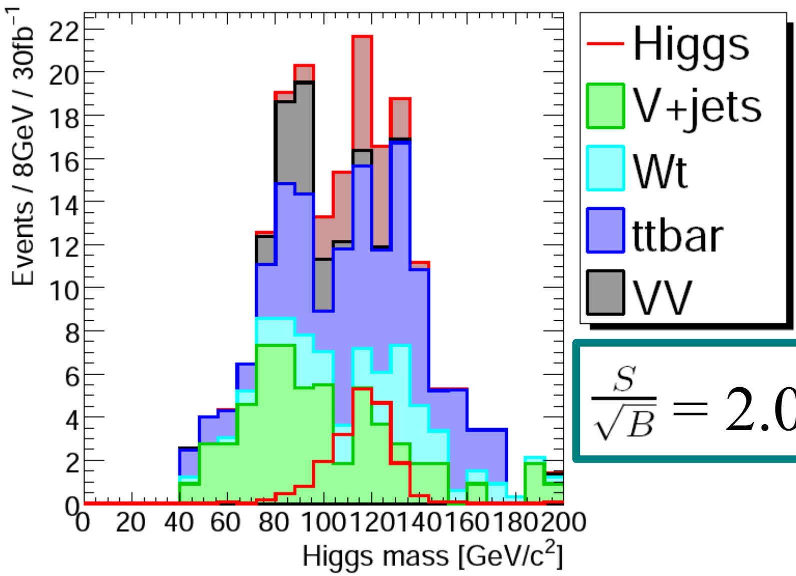
Comparison with a conventional jet finding algorithm (I)

- The WH analysis was repeated by using a more conventional kT (R=0.4) jet finding algorithm
- In order to make the subjet- and conventional jet-based analyses comparable:
  - No specific charm-jet rejection was used (in neither of the two analyses)
  - In the conventional jets based analysis few additional cuts were made:

- Di-jet symmetry $\left(\frac{min(p_T(j_1),p_T(j_2))\Delta R(j_1,j_2)}{mass(j_1j_2)}\right)^2 > 0.1$
- Mass drop $\frac{\max(mass(j_1),mass(j_2))}{mass(j_1j_2)} < \frac{1}{\sqrt{3}}$
- $\Delta R(j_1, j_2) < 1.2.$

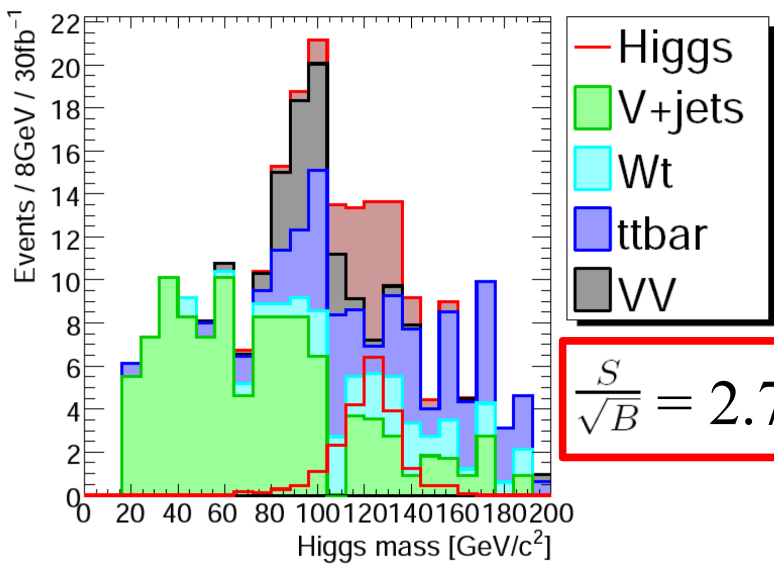
$L = 30\ fb^{-1}$

Jet based



$\frac{S}{\sqrt{B}} = 2.0$

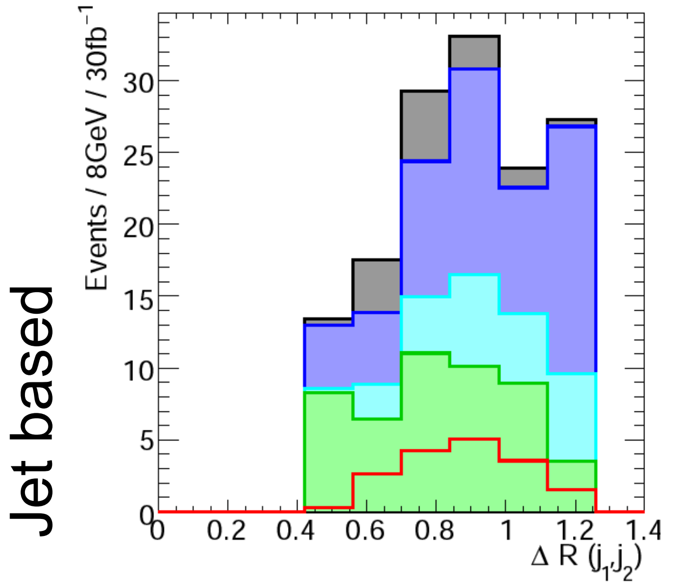
Subjet based (no c-jet rejec.)

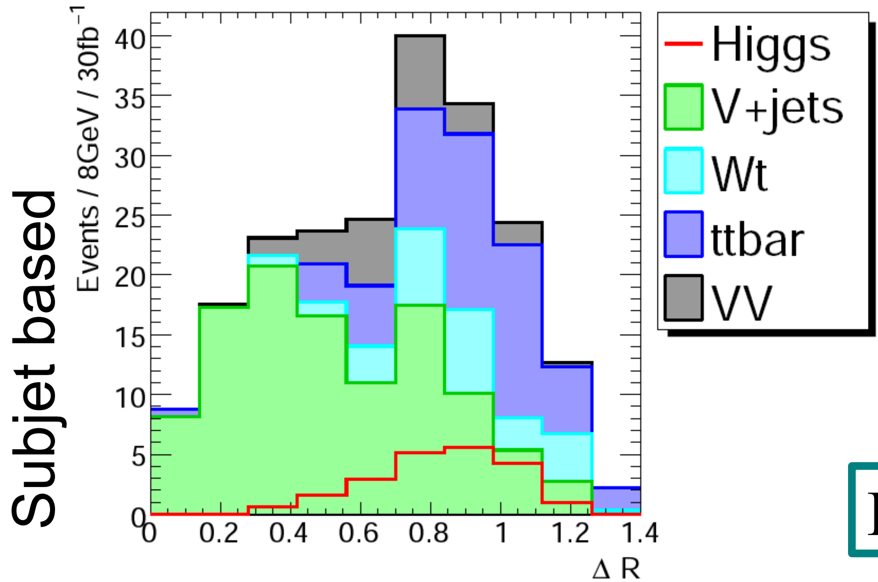


$\frac{S}{\sqrt{B}} = 2.7$

Comparison with a conventional jet finding algorithm (II)

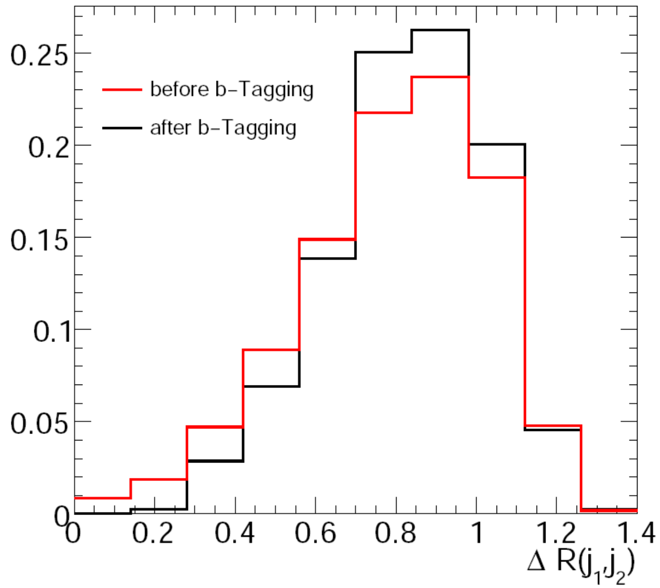
- The signal efficiency is not very different: this can be studied by looking at $\Delta R(b,b)$ for the two different jet finding methods





L=30 fb^{-1}

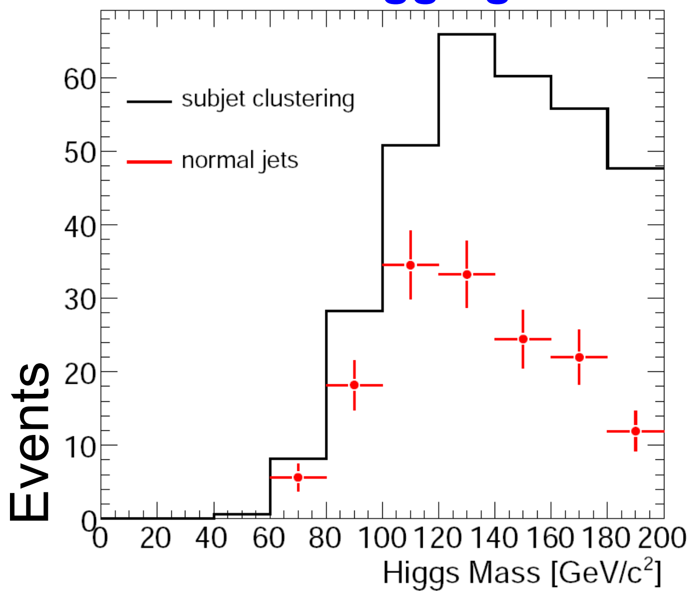
- Nearly no signal with $\Delta R(b,b)<0.4$?
- Not really:
  - b-tagging provides an effective turn on curve in $\Delta R(b,b)$
  - The effect seems small, but events with small DR have the highest significance !



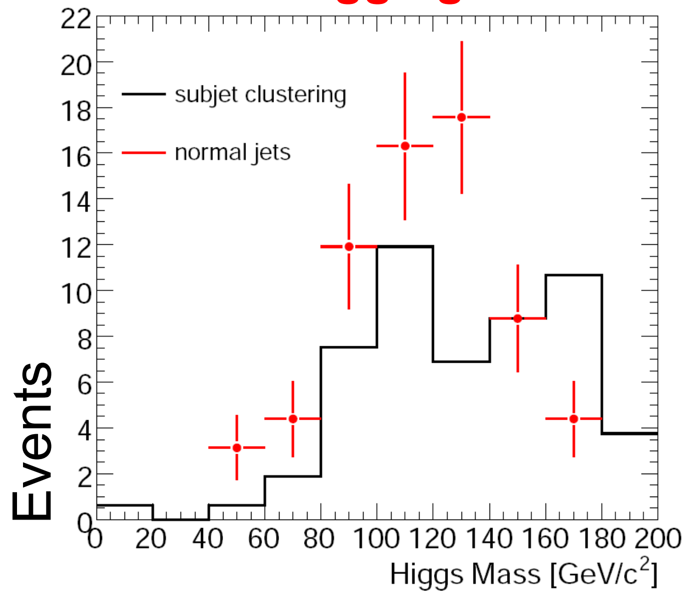
Comparison with a conventional jet finding algorithm (III)

- The most significant difference between the analyses based on subjets and based on kT jets is in the rejection of the ttbar background. The ttbar background is shown here:

...before b-tagging



...after b-tagging



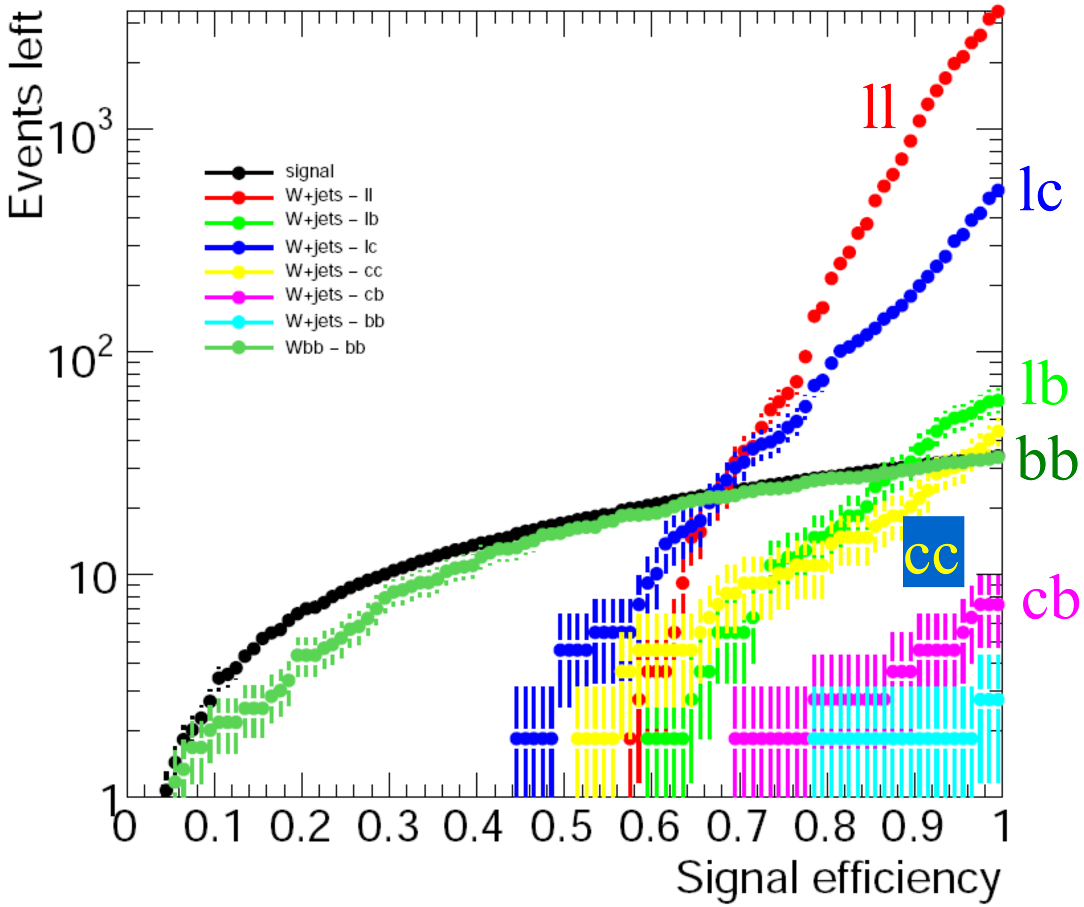
$L = 30\ fb^{-1}$

- After b-tagging is applied, both methods end up with a similar amount of ttbar events
- However, with the subjet based method, more of them are peaking towards the top mass and therefore do not enter the final signal mass window cut.
- This explains most of the higher significance of the subjet based analysis
- In addition, the inclusion of Higgs candidates with low DR(b,b) provides potentially a very useful sideband region to extract the W+jet background from data...

W+bb background

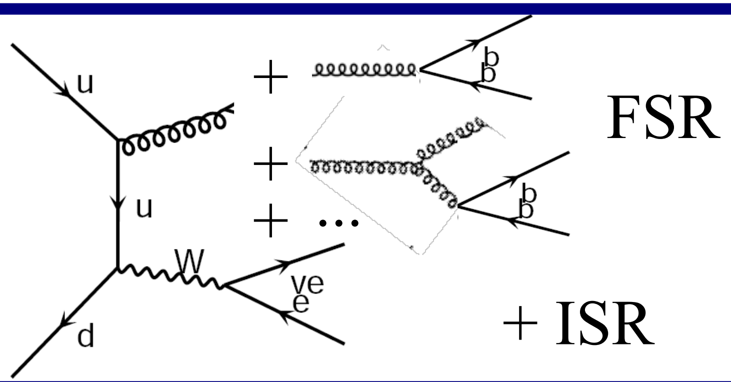
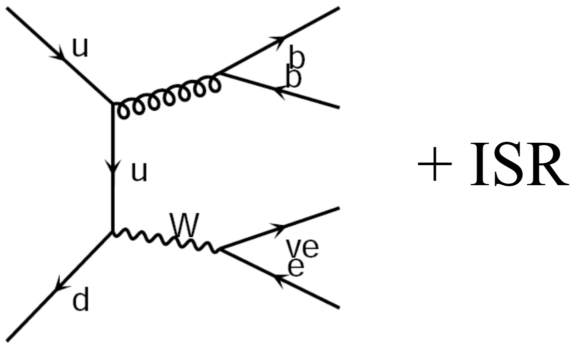
- The W+jet background is dominated by bb-quark combinations
- Apart bad surprises, the **W+c** and **W+b** backgrounds should not be too dangerous (if not dramatically underestimated by parton shower approach)
- For all other signal + important background, NLO complete Monte Carlo generators are available (MC@NLO, now also POWHEG)
  - Not for W+bb !
- Two parton level NLO calculations are available:
  - [Ellis, Veseli] (available in MCFM)
  - [Cordero, Reina, Wackeroth]
- The second includes b-quark mass effects.

W+jet flavour composition as a function of bb-tagging efficiency



Wbb background @ LO (I)

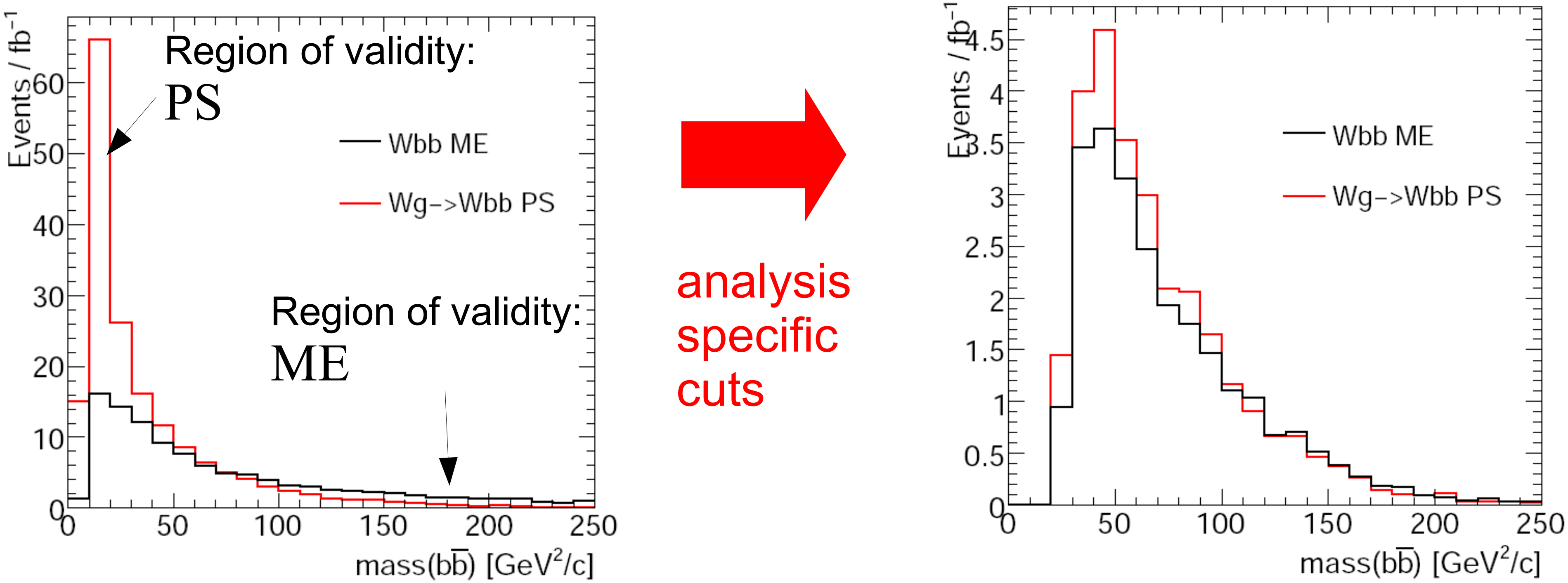
- Approaches available at LO:

HERWIG (or PYTHIA)		ME: qq → Wg (LO) PS: g → bb[gg...] • Full Final State Radiation (up to "all" orders in LL accuracy) • No complete ME
AcerMC		ME: qq → Wbb (LO) • Full gluon propagator implemented • 3 body phase space • Missing complete FS radiation

- First comparison between LO Parton Shower and Matrix Element based approaches done.
  - Parton Shower should be more reliable in this region of phase space.

Wbb background @ LO (II)

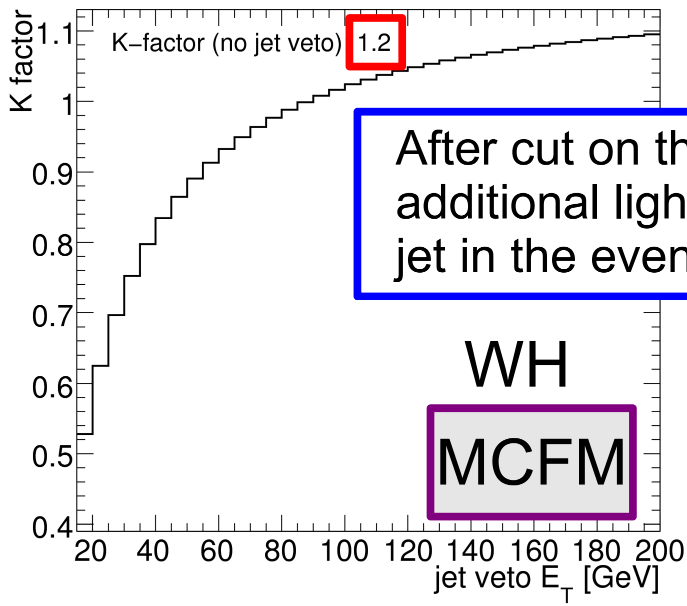
- At parton level:

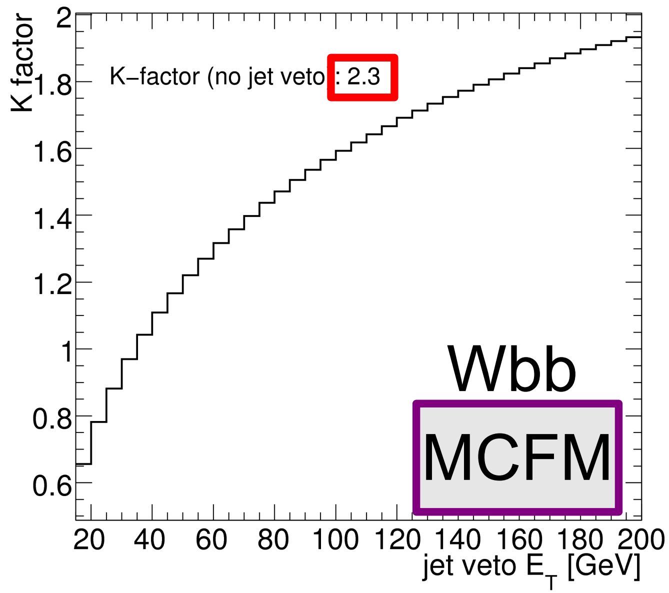


- Mass(bb) distribution not too different in the specific kinematic region of this analysis (parton shower approximation doesn't seem to break down)
- But: how accurate are the final distributions for the discriminating variables?
- Need to go beyond LO ...

W+bb background @ NLO

- (1) K factor very large (~2.3) also at high $p_T(bb)$
  - This is due to the additional contribution to $qq \rightarrow Wbb$ of the gluon initiated $gq \rightarrow Wbbq$
  - The K factor is dramatically reduced by the jet veto.
  - Needs to be estimated more precisely...





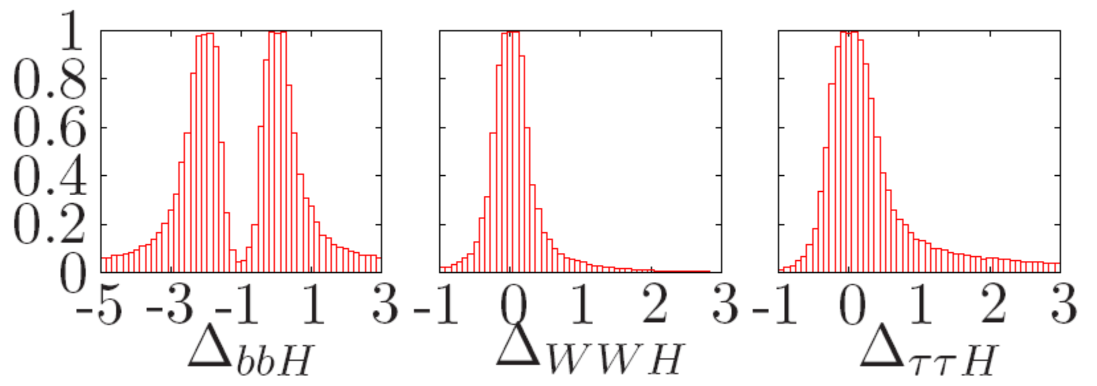
- (2) Kinematic of the bb-quark system
  - Since b-jets are selected at high p_T and at small ΔR, large logarithms in $m(bb)/p_T(bb)$ or $\Delta p_T(bb)/p_T(bb)$ are very likely to appear. Jet shapes also depend on these large logs.
  - At NLO diagrams where the two b-jets are not produced directly by a single gluon are also present. They shoulnd't pass the mono-jet selection. However, if they do, their invariant mass would peak at significantly higher values.
- Les Houch project started on these topics (with L. Reina, S. Dawson, J. Butterworth,...).

Impact on measurement of Higgs couplings

- Studied in ["Measuring the Higgs sector", Lafaye, Plehn, Rauch, Zerwas, Dührssen] (for m_H~120 GeV)
- The W/ZH channels with H → bb will be extremely important to constraint the Higgs coupling to b-quarks
- In addition they are crucial to constraint the other couplings, as well.
- Results in the paper are based on the hadron level study

$$g_{jjH} \longrightarrow g_{jjH}^{\mathrm{SM}} \; (1 + \Delta_{jjH})$$

- With W/ZH channels (hadron level study)



- Without W/ZH channels (only ttH)