Higgs Boson Production via Vector Boson Fusion in ATLAS

Experimental Challenges and Prospects

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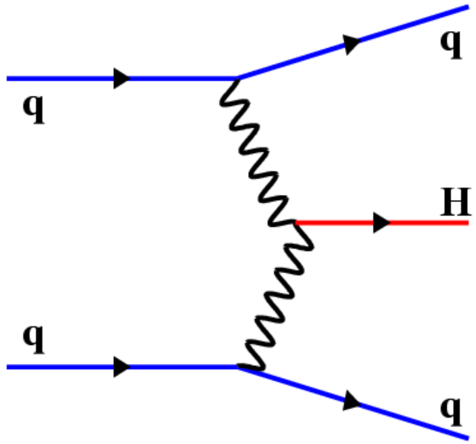
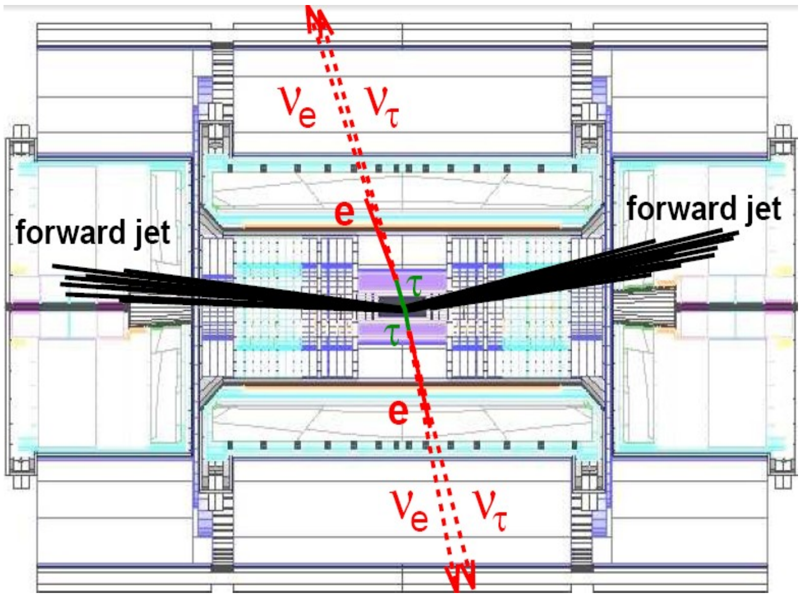
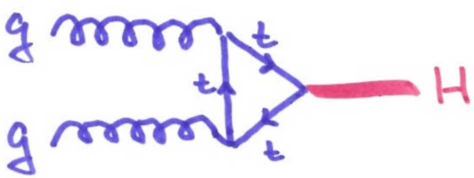
IOP Workshop on VBF, 23 February 2011, Oxford



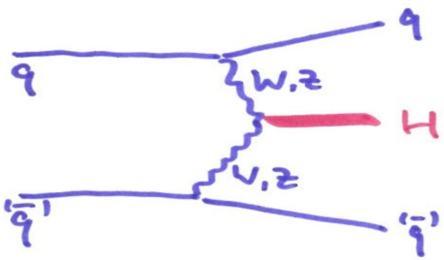


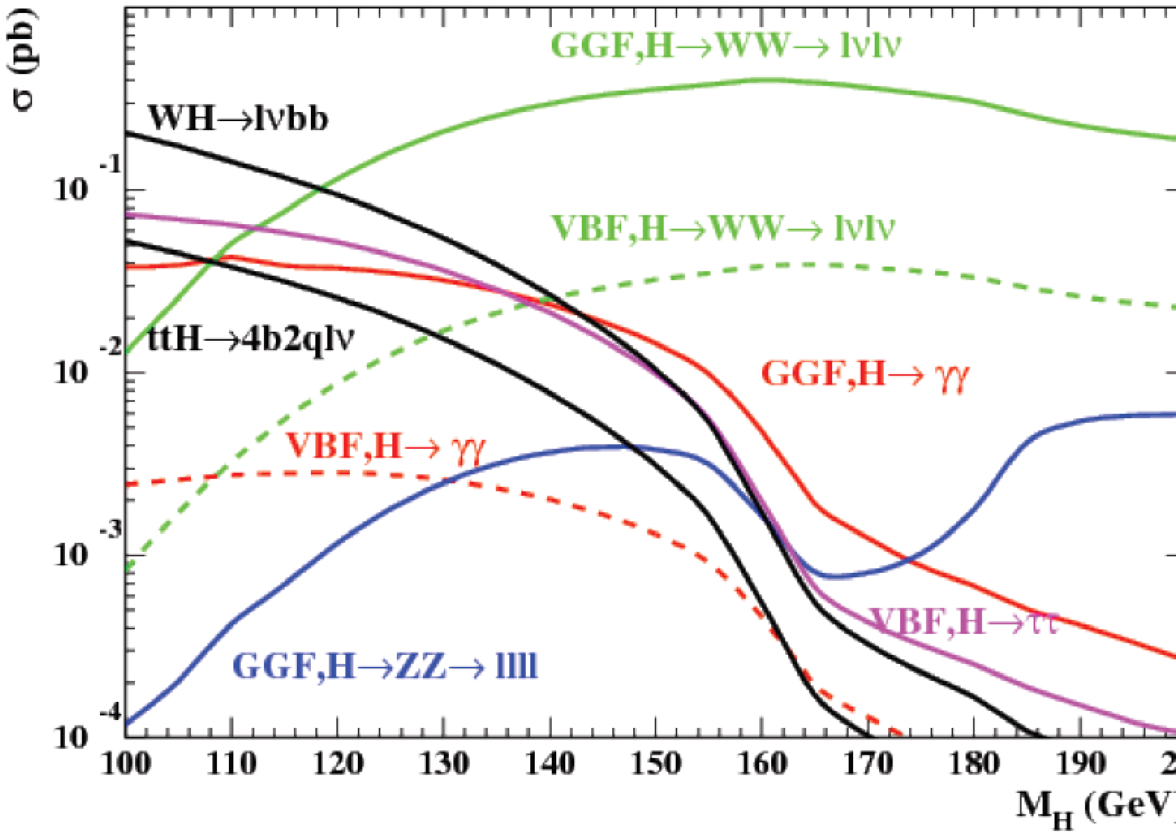
Signal rates for Higgs Boson Production

Gluon gluon fusion (GGF)



Vektor boson fusion (VBF)

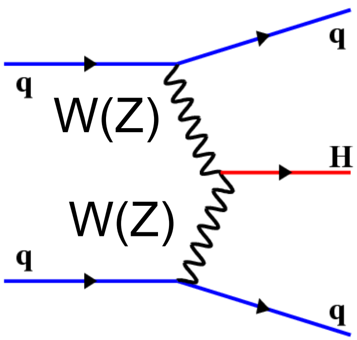


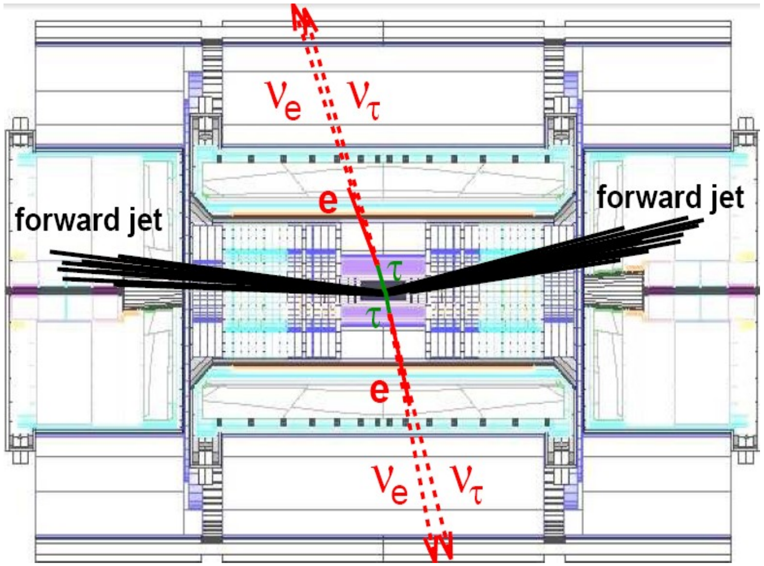


Based on LHC H XSEC Group

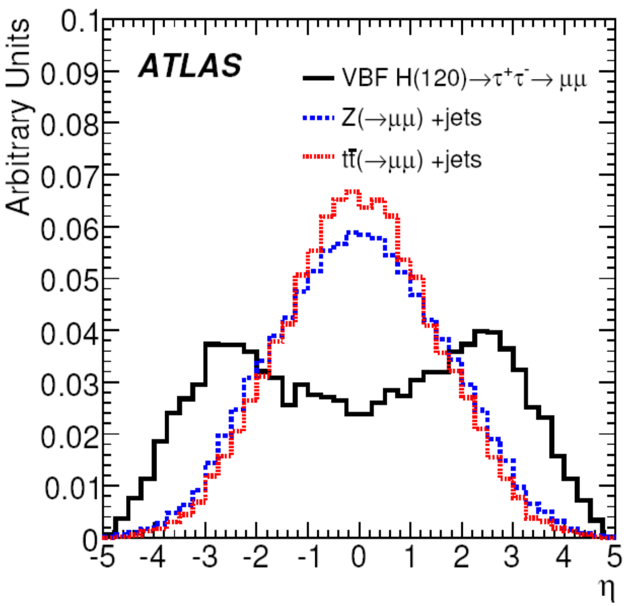
- VBF searches: H→2 photons, H→ 2 τ, H→WW→ 2(l+ν)
- VBF important contribution to the discovery potential
- VBF key ingredient for investigation of Higgs profile (couplings, CP, ...)

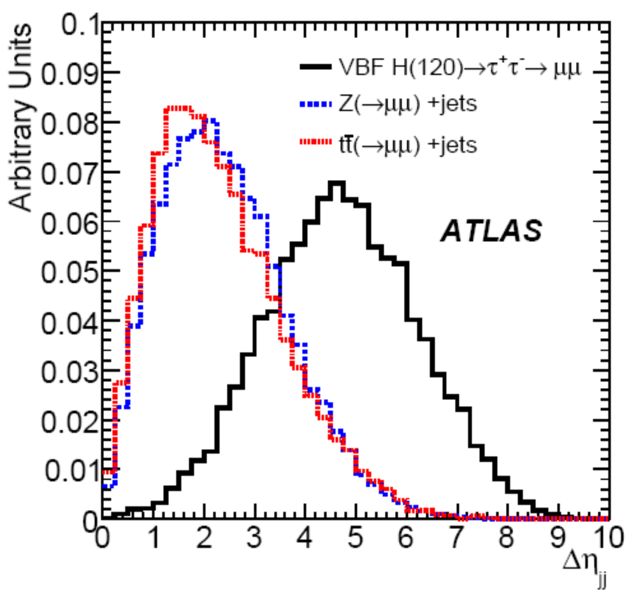
Signature of Vector Boson Fusion

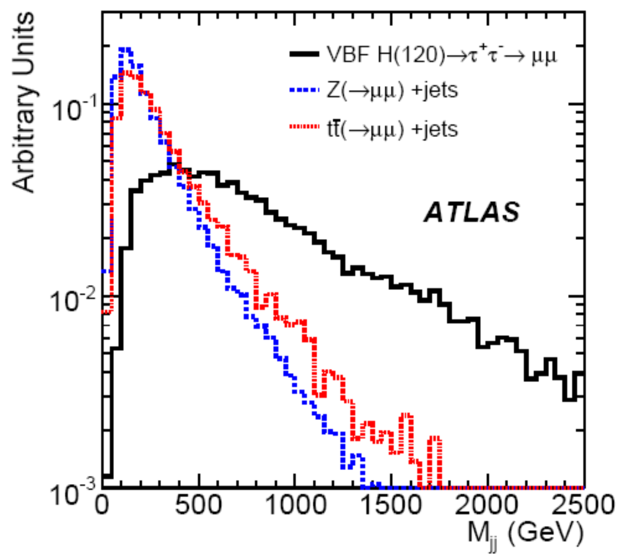




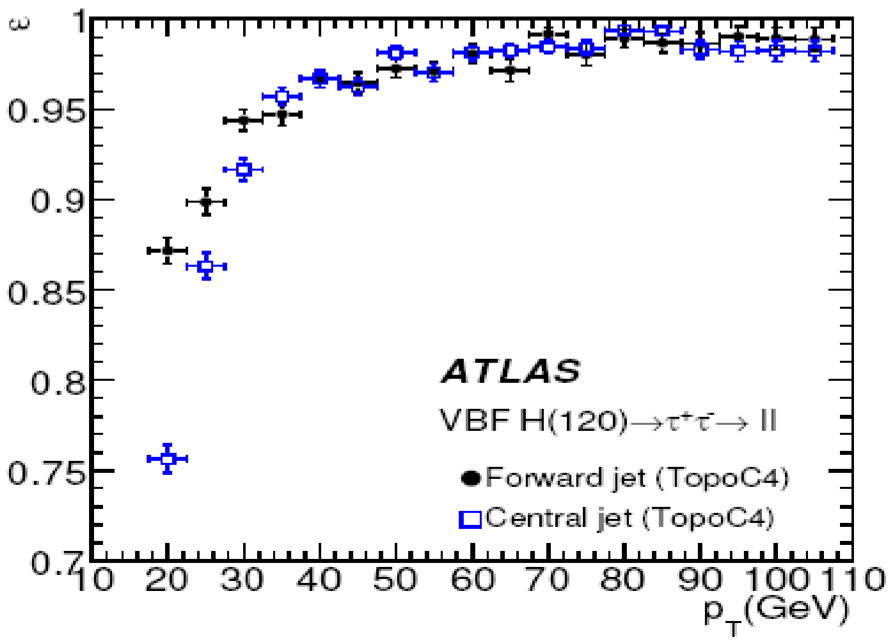
- signature:
- 2 forward tag jets in opposite hemishperes with rapidity gap
- Higgs decay products in central detector between tag jets
- no additional jets due to no colour flow in t channel
- WW, ττ: missing transverse energy due to neutrinos

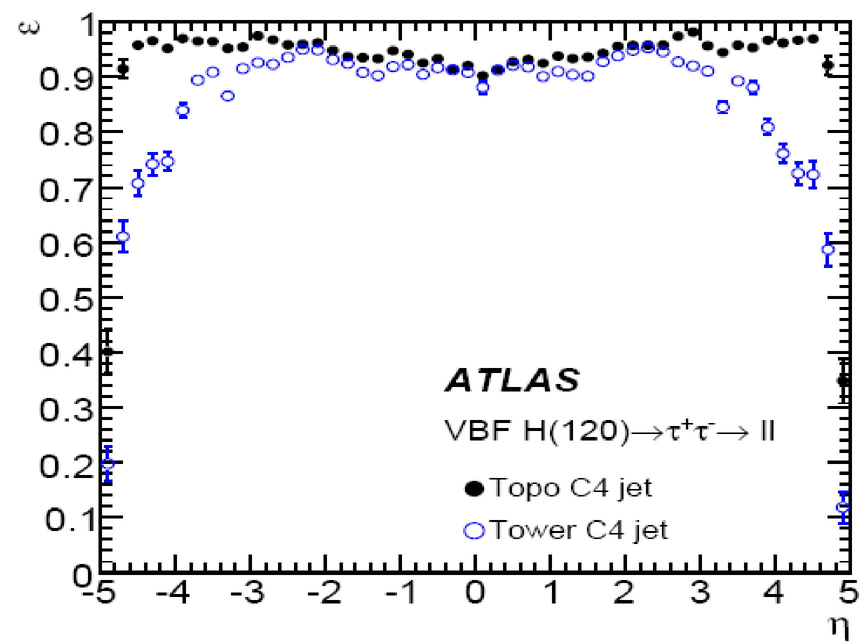






Tagging of Forward Jets in VBF (H→ττ 14 TeV study)





jet reconstruction: (at CSC times cone R=0.4 now anti-kt R=0.4)

- high efficiency for tagging jets up to pseudorapidty of 4.8 (1 degree)

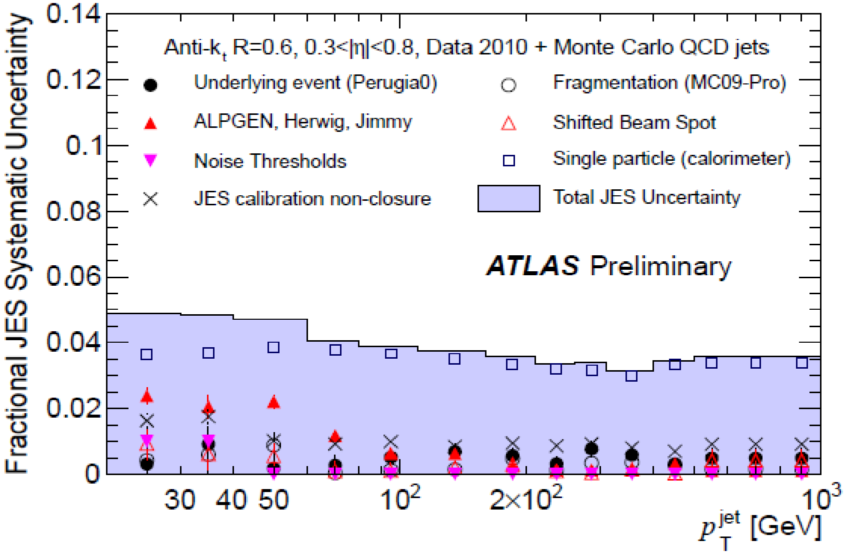
- fake rate only few %

- currently moderate sensitivity to pileup observed

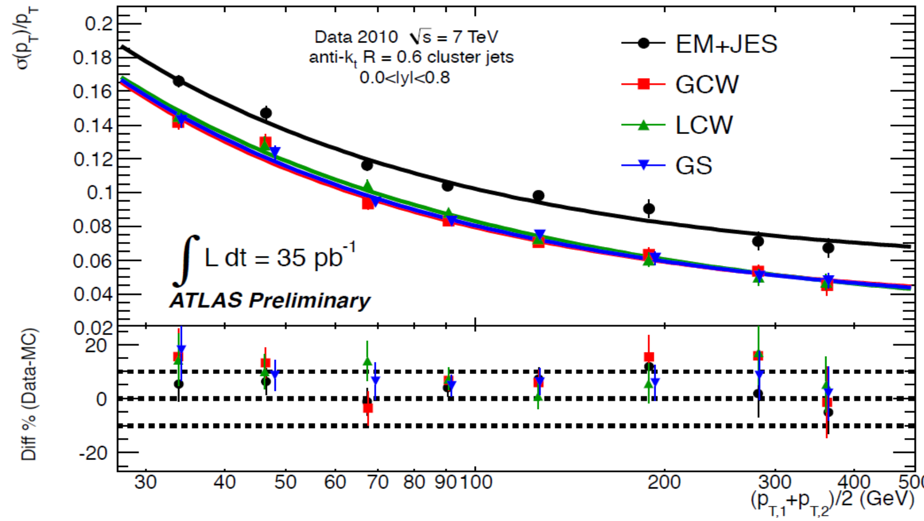
  (depending on noise suppression tool, cluster and jet algo used)

Detector Performance from Collision Data 2010

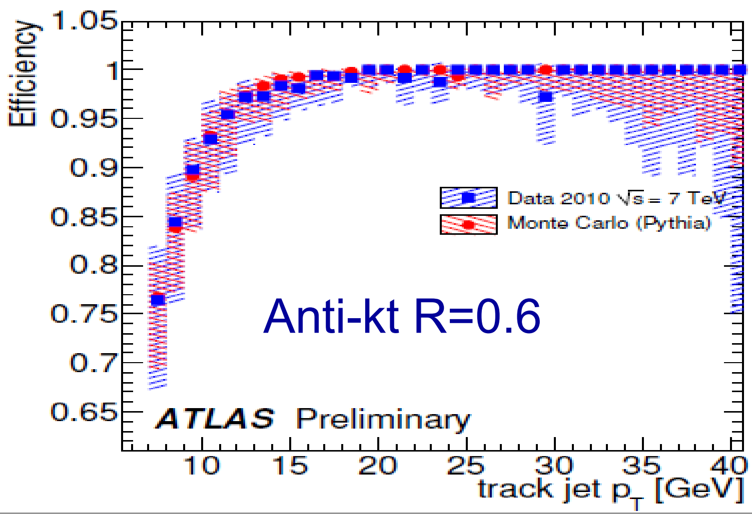
- jet energy scale



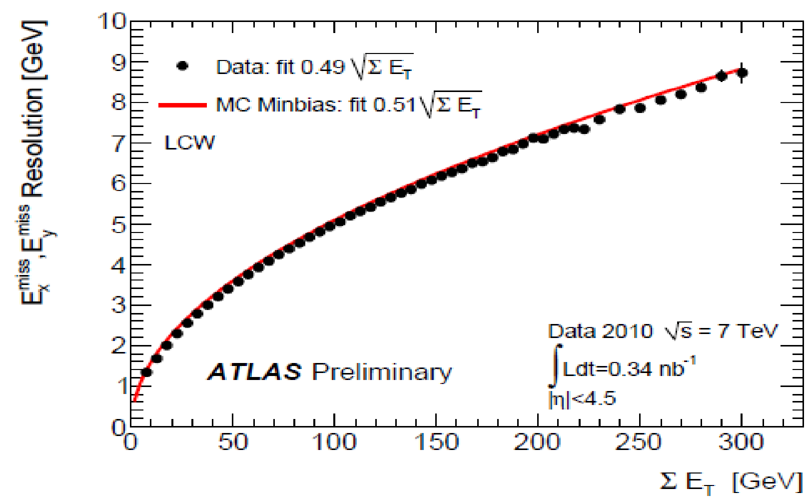
- jet energy resolutuoin



- jet reconstruction efficiency



- MET resolution

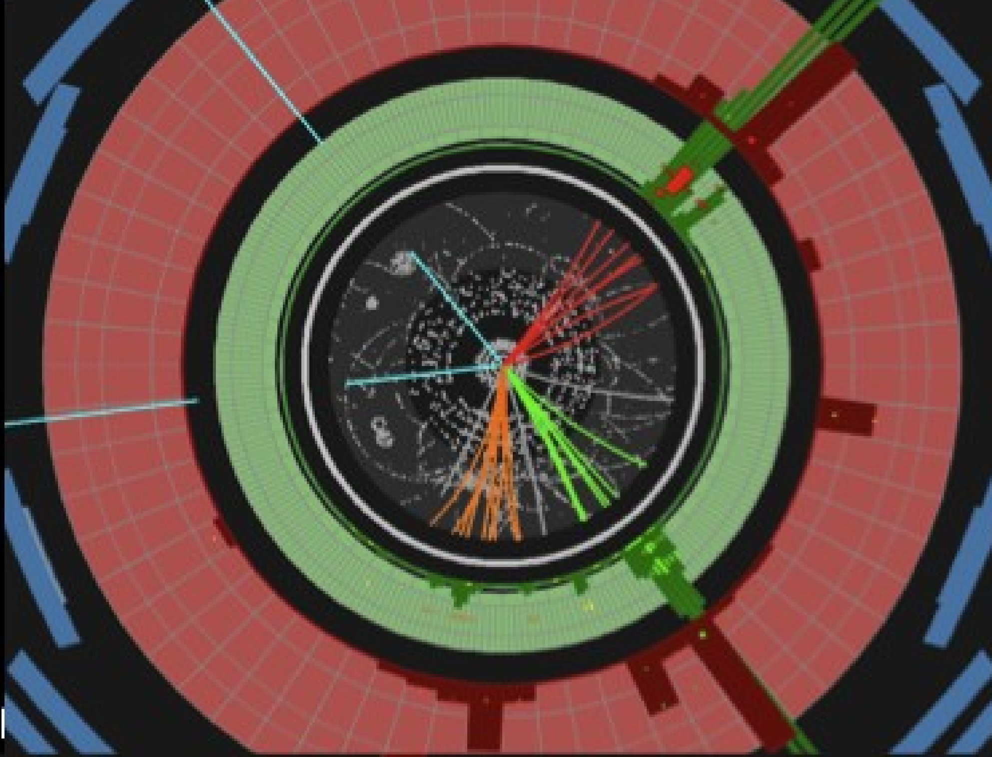


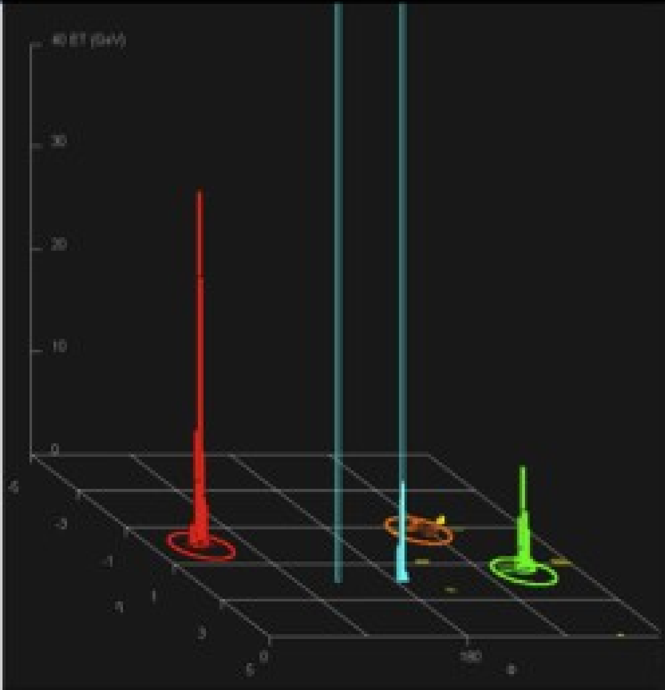
ATLAS EXPERIMENT

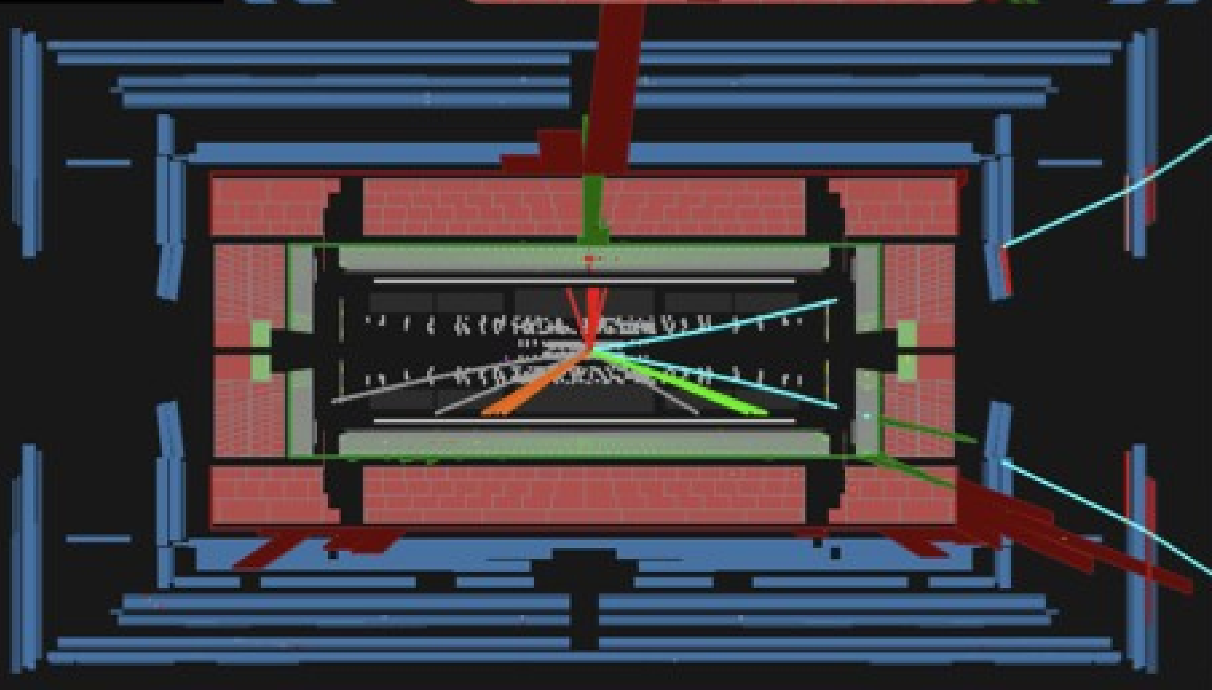
$$Z \rightarrow \mu^- \mu^+ + 3 \text{ jets}$$

Run Number 158466, Event Number 4174272

Date: 2010-07-02 17:49:13 CEST

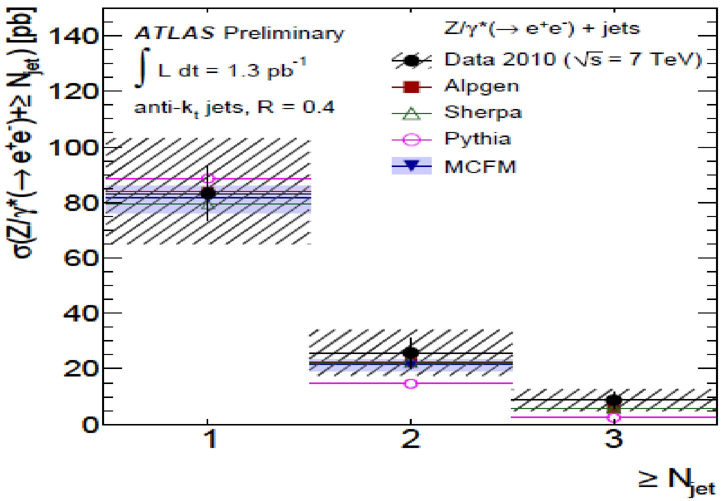


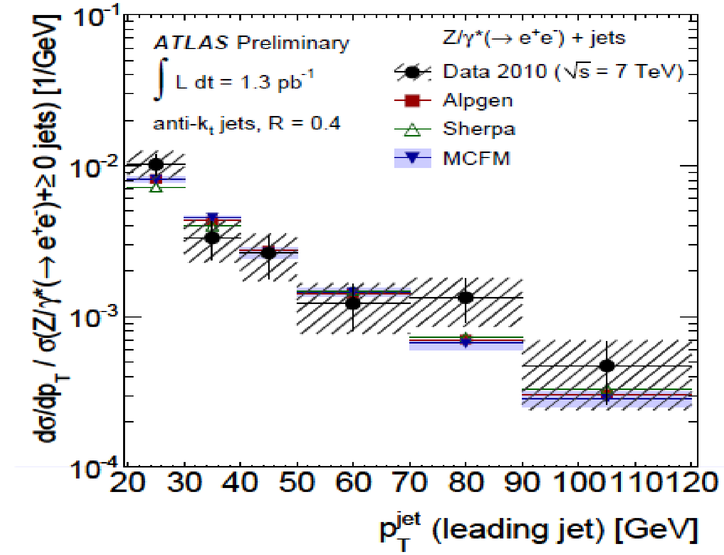


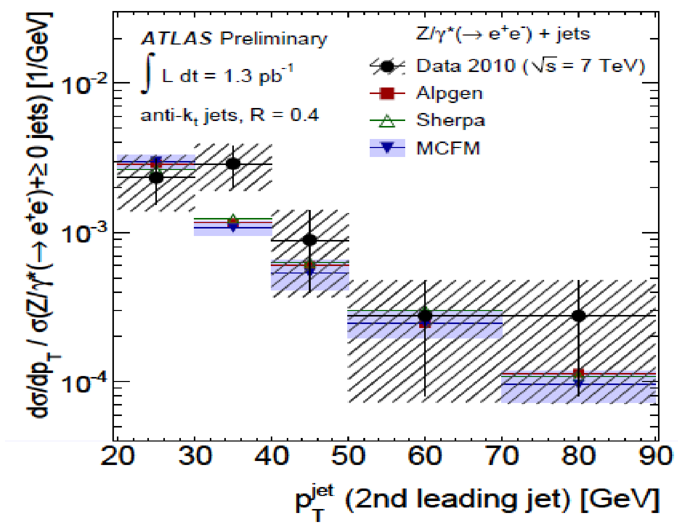


Z + Jets Production (shown Z→ee)

- after background subtraction and unfolding (jet pt>20GeV)







good description by MC generators

with matching of matrix element and parton shower at leading order

higher precision needed to

discrimniate quality of description

similar results for W+jets

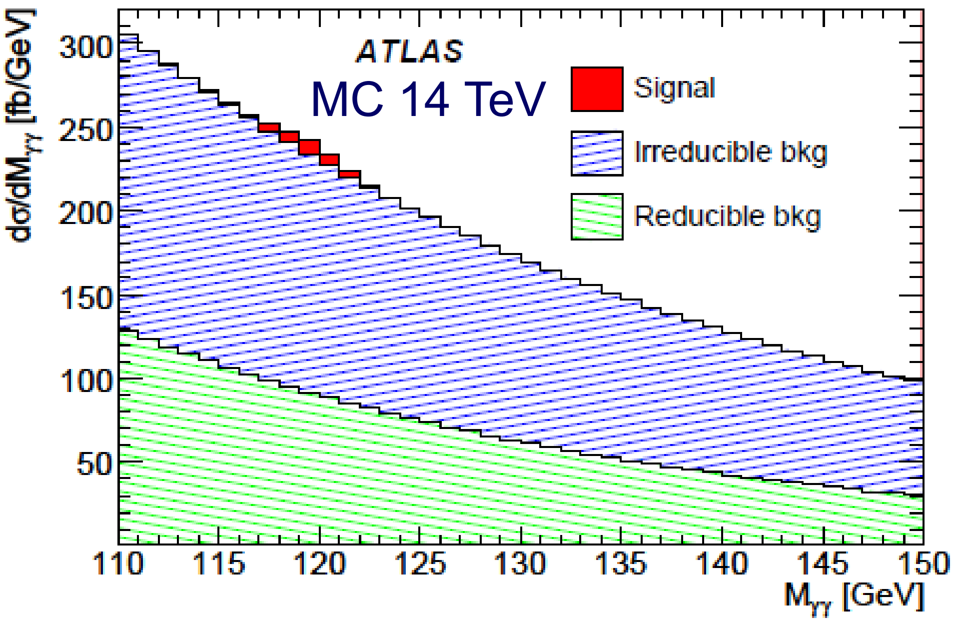
H→γγ: 14 TeV MC Study (CSC Book)

- inclusive analysis:
  2 photons, pt >40 and 25 GeV
  mass window: M_H+-1,4 s_M

- backgrounds:
  irreducible: γj, jj, Z→ee
  reducible: γγ

Signal Process	Cross-section (fb)	Background Process	Cross-section (fb)
$gg \to H$	21	$\gamma\gamma$	562
VBF H	2.7	Reducible γj	318
ttH	0.35	Reducible jj	49
VH	1.3	$Z \to e^+e^-$	18

- signal to background ratio: 1 to 38
  significance with 10fb^{-1}: 2.4



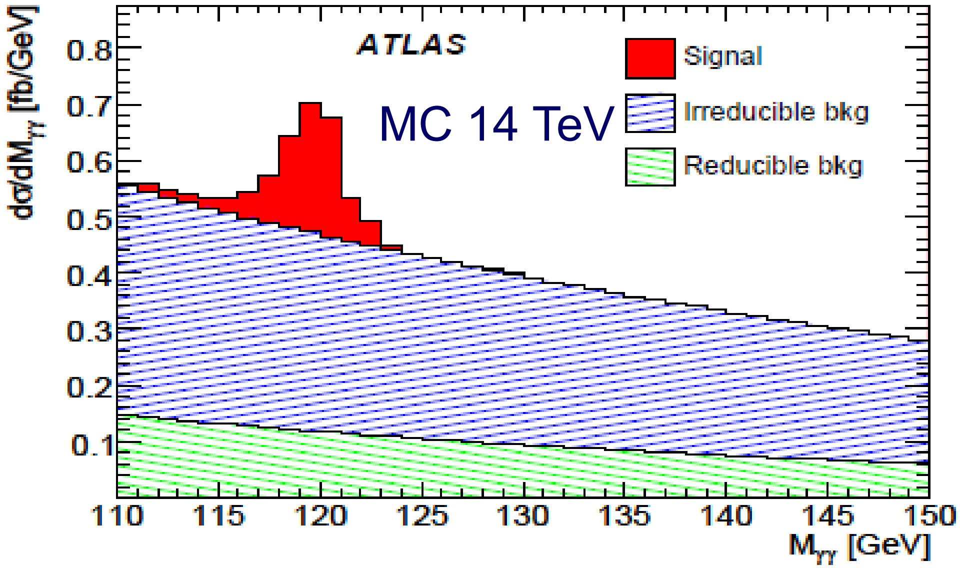
- background from sidebands
  fit exponential with nuisance
  parameters: slope and norm.

- signal: crystal ball + gaussian

- using more information pt(Higgs)
  etc. increase significance by 50%

H→γγ: 14 TeV MC Study (CSC Book)

- VBF analysis:
  - 2 photons, pt >50 (25) GeV
  - 2 jets,pt>40 (20) GeV with $\eta_1 * \eta_2 < 0$, $\Delta\eta > 3.6$
  - photons btw. tagging jets
  - m_{jj} >500 GeV
  - veto on additional jet with pt>20GeV and $|\eta|<3.2$
  - mass window: M_H+- 2GeV

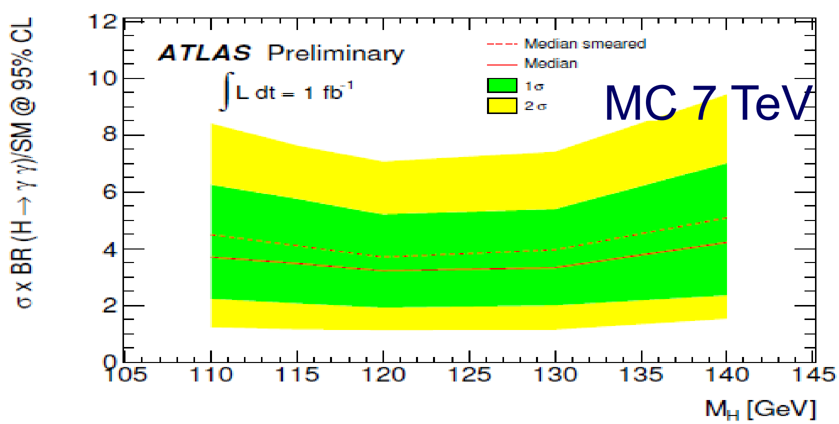


- accepted signal: GGF: 0.18 fb VBF: 0.79fb

  accepted background: 1.95 fb (γγ: 0.86fb, γj:0.42fb, jj:0.06fb, γγjj(EW): 0.59fb)

- background from sidebands
- good signal to background ratio: 1 to 2

  observation significance with $10 fb^{-1}$: 2.0
- first data: only inclusive analysis considered so far

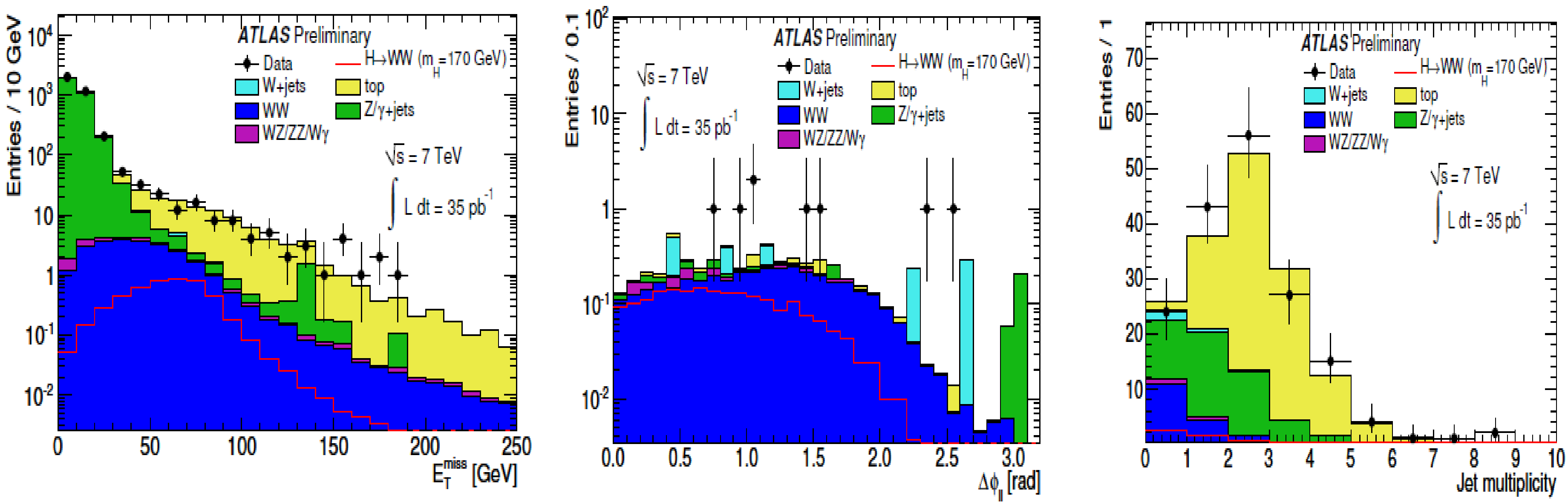


H→ WW→lνlν with 35 pb^{-1} at 7 TeV

- signal production via gluon fusion (MC@NLO) and VBF (SHERPA) considered
- backgrounds: diboson qqbar,gg→WW,ZZ,WZ, W+jets, Z+jets, ttbar, single top

- preselection:
  - 2 pleptons (e,μ), pt >20(15) GeV
  - MET>30 GeV: eμ (ee,μμ)
  - M_{ll} >15, $|M_Z$-Mll$|$>10GeV (ee,μμ)
  - $\Delta\phi_{ll}$ <1.3 (1.8) M_H<170 (>=170GeV)

- final cut on transverse mass 0.75 M_H< $m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$ <M_H

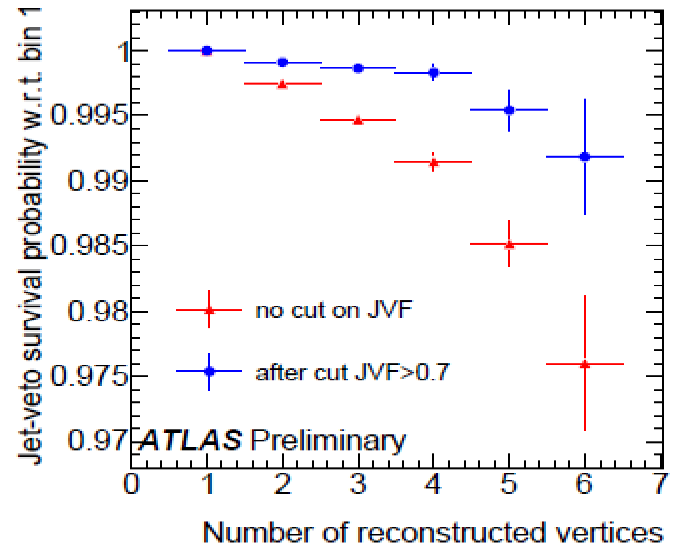


H→WW→lνlν: Branching in Jet Multiplicites

- branch analysis in 0, 1 and 2 jets
  - jets reconstructed with anti-kt R=0.4 algorithm, pt>25 GeV, |η|<4.5
  - associated to primary vertex PV by requiring fraction of momentum from tracks from PV to total jet track momentum> 0.75 (for jets |η|<2.1)

dijet events in data:

no 2 add. jets with pt>20 GeV



- uncertainty on fraction of signal events
  0 jet: 10% 1 jet: 6% 2 jet:35%
  evaluated by variation of renorm., factor. scales, PDFs, α_s in HNNLO

- ac $|\mathbf{P}_T^{\ell\ell}|$ nal cuts fo $m_{\ell\ell} < 50$ GeV ltiplicity branch:

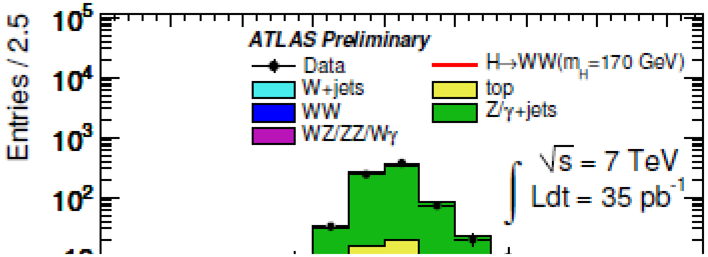
0jet: <30 GeV

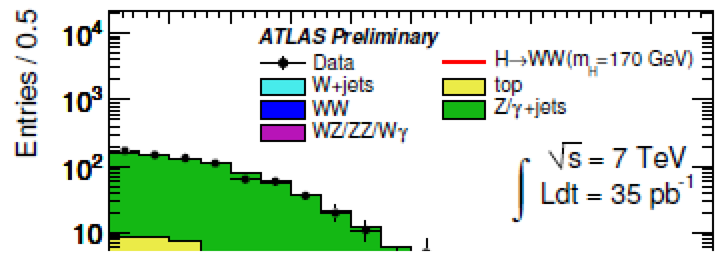
1jet: veto on b-jet , $\mathbf{P}_T^{tot} = \mathbf{P}_T^{l1} + \mathbf{P}_T^{l2} + \mathbf{P}_T^{j} + \mathbf{P}_T^{miss}$ <30GeV, Z→ττ veto, $m_{\ell\ell} < 50$ GeV

2 jet: veto on b-jet, $\mathbf{P}_T^{tot}(2j) = \mathbf{P}_T^{l1} + \mathbf{P}_T^{l2} + \mathbf{P}_T^{j1} + \mathbf{P}_T^{j2} + \mathbf{P}_T^{miss}$ <30 GeV, Z→ττ veto, $m_{\ell\ell}$ <80GeV

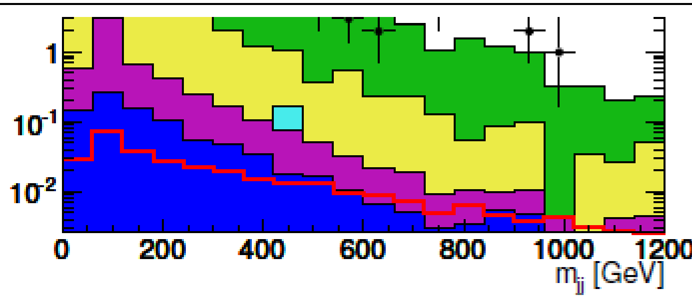
plus VBF cuts: m_{jj}>500GeV, $\Delta\eta_{jj}$>3.8, no 3rd central jet pt>25 GeV |η|<3.2

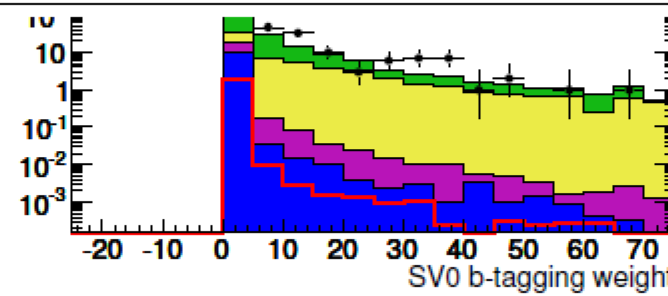
Distributions and cut flow in 2 jet analyis





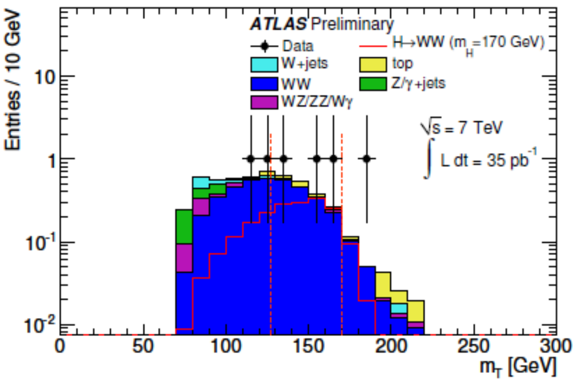
Selection	Signal	WW	W+jets	Z+jets	top	$WZ/ZZ/W\gamma$	Total Background	Observed
$\geq$ 2 jets	0.81 ± 0.01	1.86	17.1	0.35	78.3	0.33	97.9 ± 1.89	106
$\eta_{j1} * \eta_{j2} < 0$	0.52 ± 0.01	0.89	7.87	0.00	35.7	0.14	44.6 ± 1.27	46
$\Delta\eta_{jj} > 3.8$	0.25 ± 0.01	0.16	0.51	0.00	2.68	0.02	3.37 ± 0.33	5
$m_{jj} > 500$ GeV	0.17 ± 0.01	0.08	0.14	0.00	1.58	0.01	1.81 ± 0.23	3
Extra jet veto	0.15 ± 0.01	0.05	0.12	0.00	0.42	0.00	0.61 ± 0.15	1
b-jet veto	0.14 ± 0.01	0.05	0.12	0.00	0.24	0.00	0.42 ± 0.15	1
$\lvert \mathbf{P}_T^{tot} \rvert < 30$ GeV	0.13 ± 0.01	0.04	0.11	0.00	0.14	0.00	0.31 ± 0.12	1
$Z \to \tau\tau$ veto	0.12 ± 0.01	0.04	0.11	0.00	0.08	0.00	0.24 ± 0.11	1
$m_{\ell\ell} < 80$ GeV	0.12 ± 0.01	0.02	0.11	0.00	0.01	0.00	0.15 ± 0.10	1
$\Delta\phi_{\ell\ell} < 1.8$	0.10 ± 0.01	0.01	0.11	0.00	0.01	0.00	0.14 ± 0.10	0
$0.75 \times m_H < m_T < m_H$	0.06 ± 0.01	0.01	0.00	0.00	0.01	0.00	0.02 ± 0.01	0



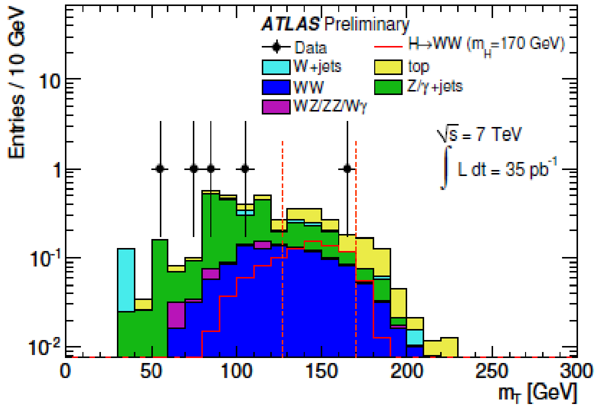


H→WW→lνlν : Selection Results

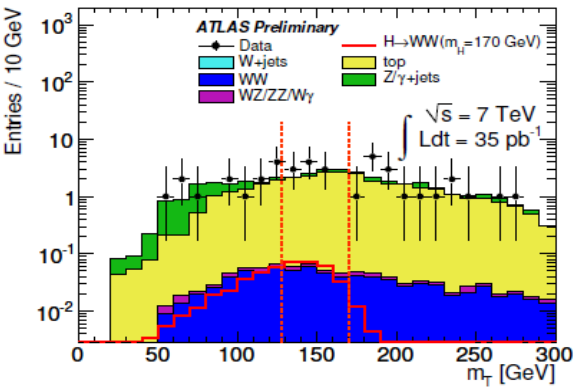
H+0 jets:



H+1jet:



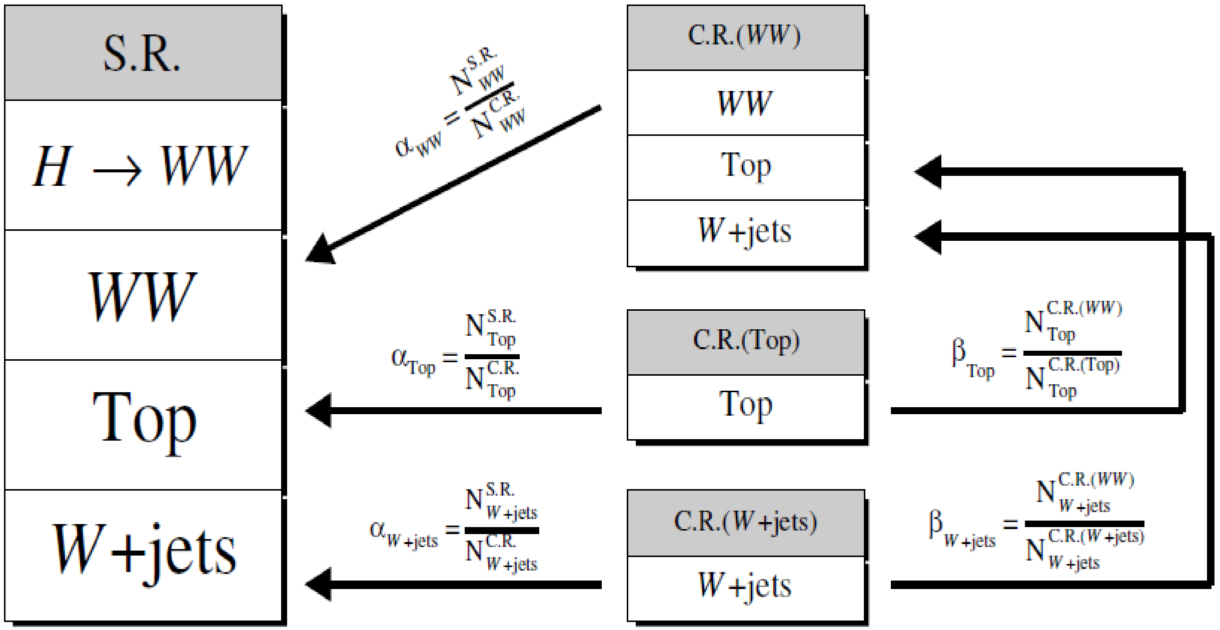
H+2 jets:



Channel	Signal	top	WW	$WZ/ZZ/W\gamma$	Z+jets	W+jets	Total Bkg.	Observed
				$H+0j$				
$e\mu$	$0.62 \pm 0.01 \pm 0.18$	0.09	0.71	0.02	0.00	0.01	$0.83 \pm 0.07 \pm 0.13$	1
ee	$0.20 \pm 0.01 \pm 0.07$	0.03	0.20	0.00	0.00	0.02	$0.25 \pm 0.08 \pm 0.04$	1
$\mu\mu$	$0.44 \pm 0.01 \pm 0.12$	0.08	0.53	0.01	0.00	0.00	$0.62 \pm 0.05 \pm 0.10$	1
				$H+1j$				
$e\mu$	$0.31 \pm 0.01 \pm 0.09$	0.26	0.18	0.01	0.00	0.02	$0.47 \pm 0.08 \pm 0.16$	0
ee	$0.08 \pm 0.01 \pm 0.03$	0.10	0.05	0.00	0.05	0.03	$0.23 \pm 0.04 \pm 0.06$	0
$\mu\mu$	$0.21 \pm 0.01 \pm 0.06$	0.15	0.16	0.00	0.25	0.00	$0.56 \pm 0.09 \pm 0.14$	1
				$H+2j$				
$e\mu$	$0.03 \pm 0.01 \pm 0.01$	0.01	0.00	0.00	0.00	0.00	$0.01 \pm 0.01 \pm 0.01$	0
ee	$0.01 \pm 0.01 \pm 0.01$	0.00	0.00	0.00	0.00	0.00	0.00	0
$\mu\mu$	$0.02 \pm 0.01 \pm 0.01$	0.00	0.01	0.00	0.00	0.00	$0.01 \pm 0.01 \pm 0.01$	0

Background Estimate from Data

- create control region CR for each individual background contribution
- extrapolate BG from CR to signal region SR with α factor obtained from MC
- pollution in control region constrained from other control regions via β factor from MC

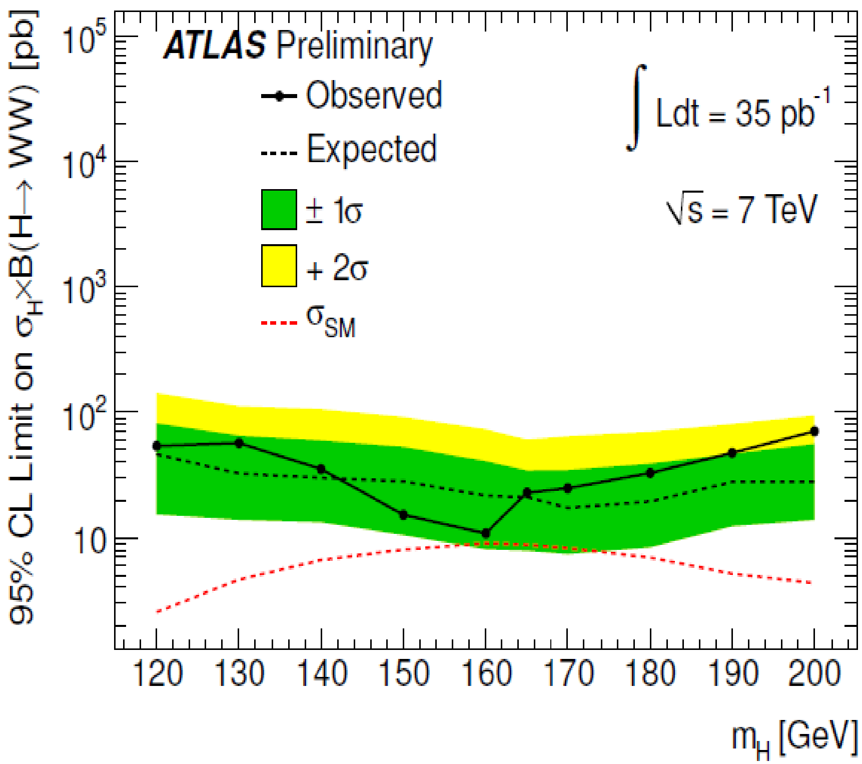


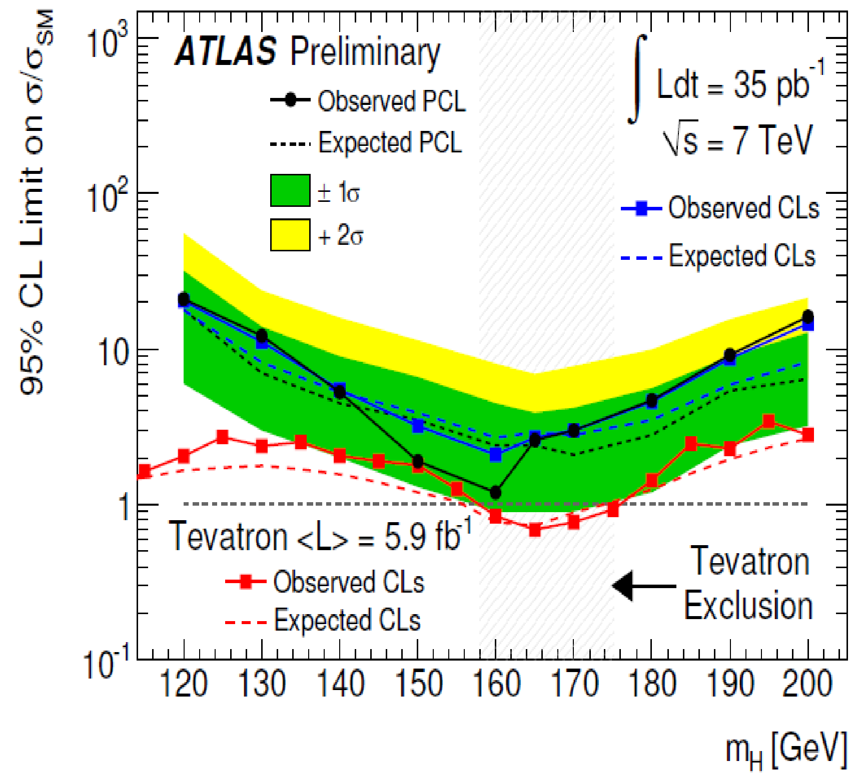
- consider exp. uncertainties (E scale and resolution, tagging efficiencies, ...) and theo. uncertainties (variation of renormalisation scales, ...) as systematic uncertainty on α and β factors

First ATLAS Result in Higgs Boson Searches

Limit calculation based on profile likelihood with 16% power constraint

Power contraint: if observed < expected -1 σ then quote expected – 1 σ





Cross section limits:

54 (11,71) pb at M_H=120 (160,200) GeV

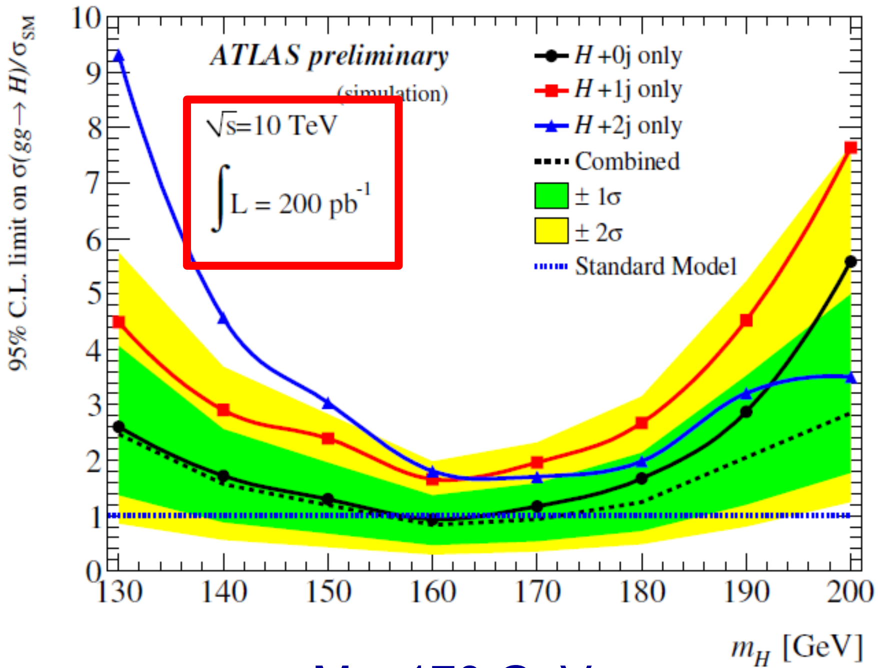
Contribution from VBF marginal

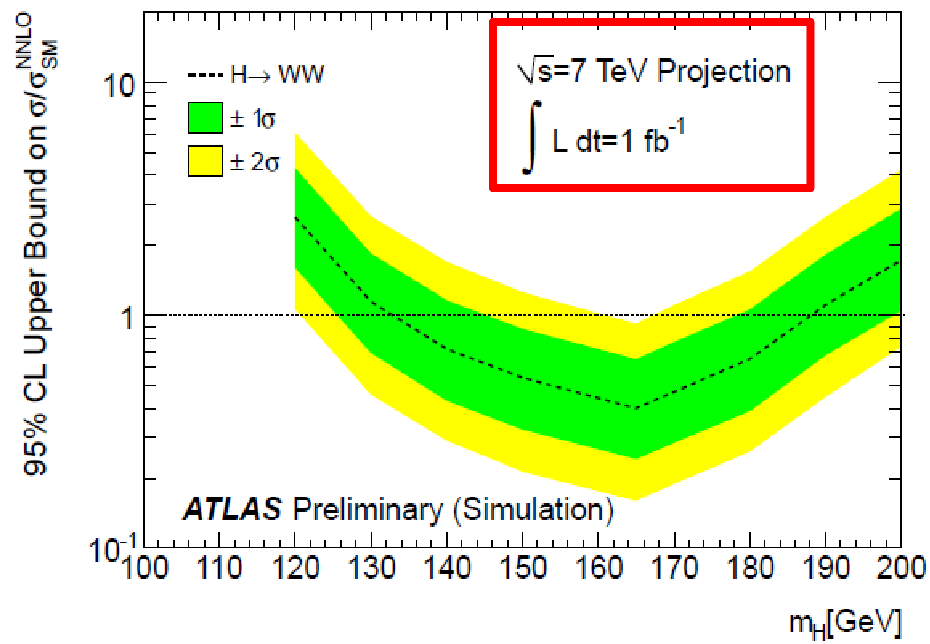
1.2 x SM cross section

excluded at M_H = 160 GeV

H→WW MC: Sensitivity at 10 and 7 TeV

Limit calculation based on CL_S method as used at LEP and TEVATRON





M_H=170 GeV

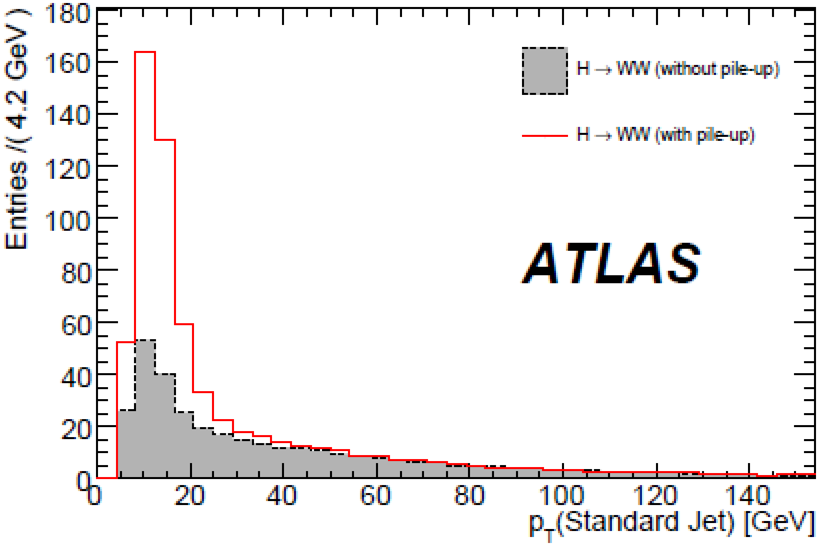
Channel	N_S	N_B	$\sigma^{95\%C.L.}/\sigma_{SM}$
	$H+0j$ analysis		
ee	1.4	2.4±0.2	
$\mu\mu$	2.9	6.5±0.6	1.2
$e\mu$	4.4	8.5±0.5	
	$H+1j$ analysis		
ee	0.79	2.2 ±0.5	
$\mu\mu$	1.7	3.9±0.3	2.0
$e\mu$	2.3	5.4±0.4	
	$H+2j$ analysis		
ee	0.16	0.05±0.03	
$\mu\mu$	0.24	0.03±0.04	1.7
$e\mu$	0.44	0.17±0.07	
Combined	-	-	0.9

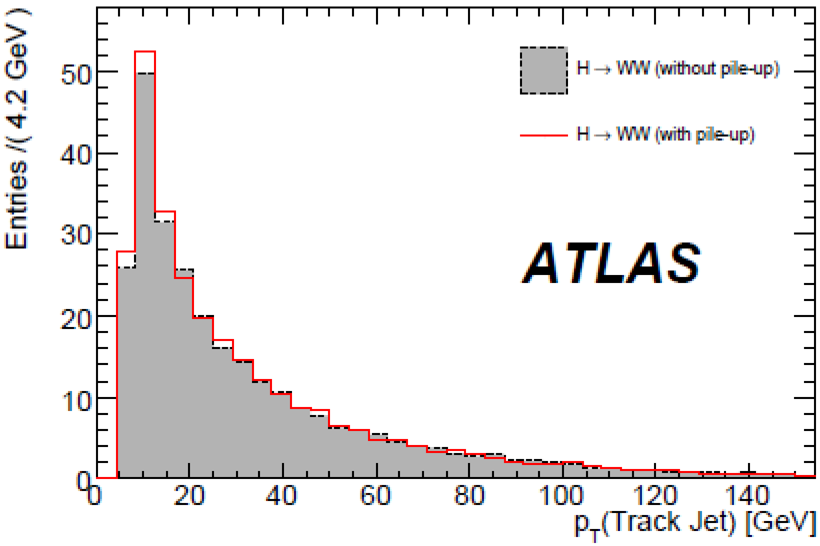
Importance of contribution from VBF depends on luminosity.

Understanding of scaling with lumi needs further studies.

H→WW→eνμν: jet veto using track jets (14 TeV MC Study)

- minimise influence of pile-up by using track jets associated to primary vertex



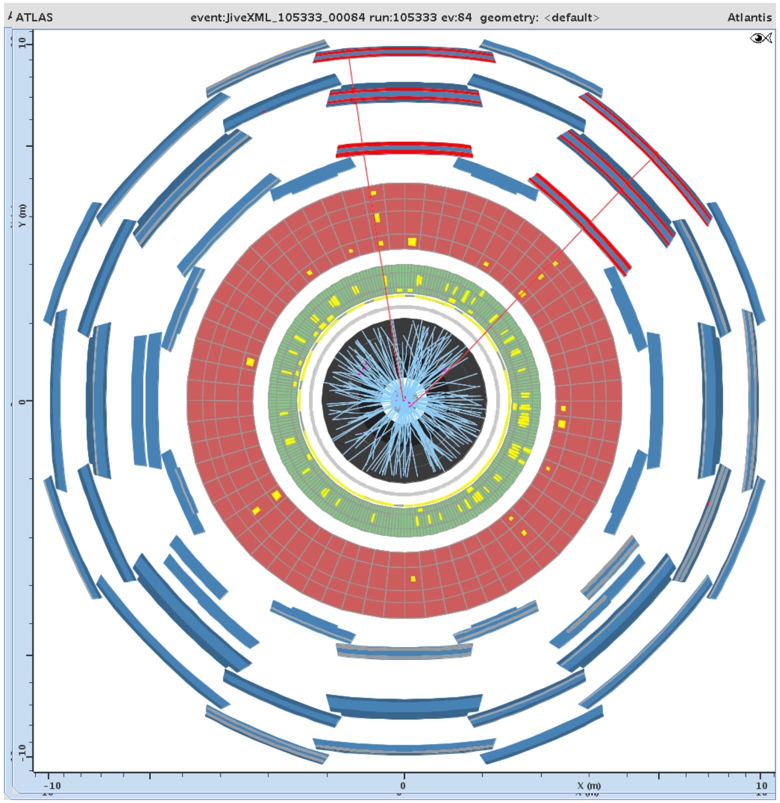


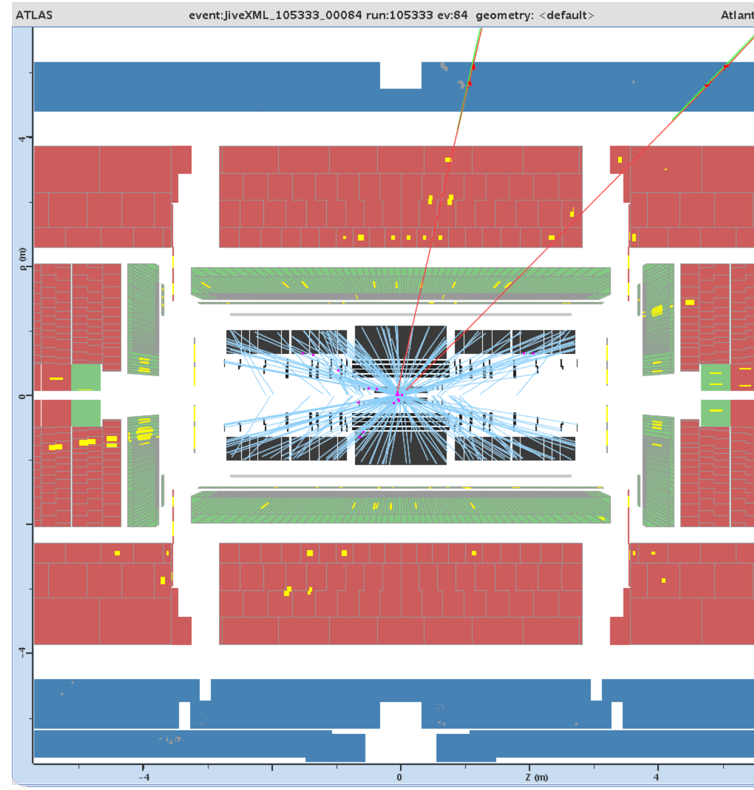
- survival probability for jet veto ($\Delta R=0.5$, cone): calo jets pt>20GeV $|\eta|<4.8$,

  track jets >12.3 GeV $|\eta|<2.5$

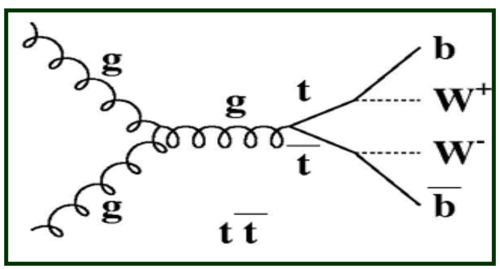
	$H \to WW$		$t\bar{t}$	
	no pile-up	with pile-up	no pile-up	with pile-up
std jets ($\|\eta\| < 2.5$)	72.0 ± 1.0	63.0 ± 1.2	28.6 ± 3.4	19.7 ± 3.3
track jets	72.0 ± 1.0	73.5 ± 1.1	28.6 ± 3.4	25.9 ± 3.6
std jets ($\|\eta\| < 3.2$)	65.4 ± 1.0	57.0 ± 1.2	24.0 ± 3.2	16.3 ± 3.0
combination	65.8 ± 1.0	65.9 ± 1.1	24.0 ± 3.2	23.1 ± 3.5

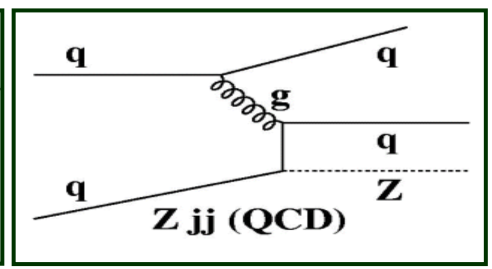
Weak vector boson fusion H→ττ (14 teV MC Study)

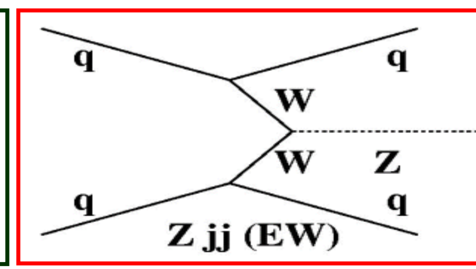




- background: reducible --→ irreducible





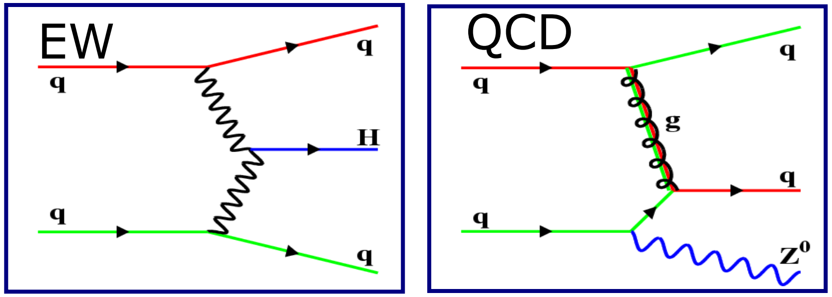


kinematics, colour flow, …

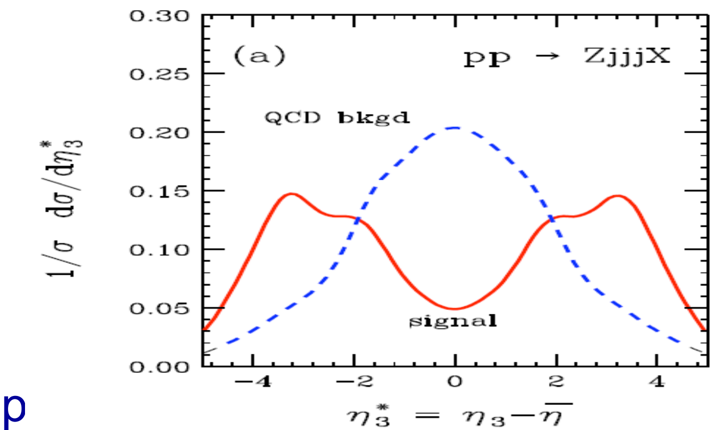
mass reconstruction

Central Jet Veto

- different color flow in EW and QCD processes



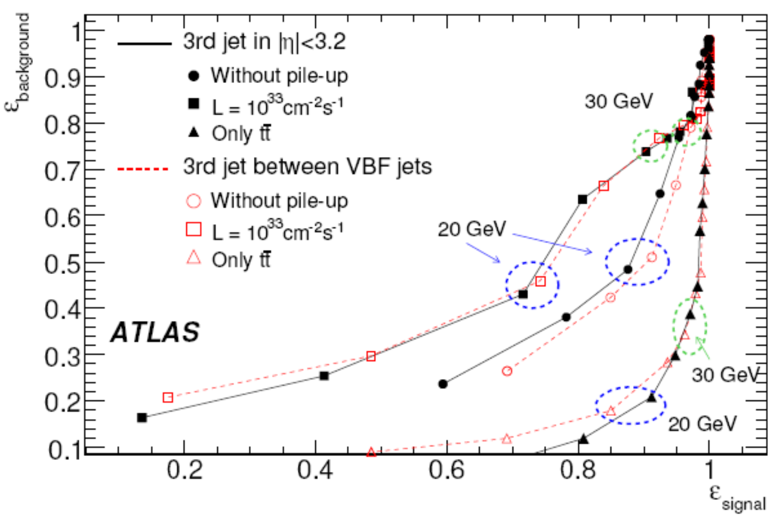
D. Zeppenfeld et al., Phys.Rev.D54 (1996)6680

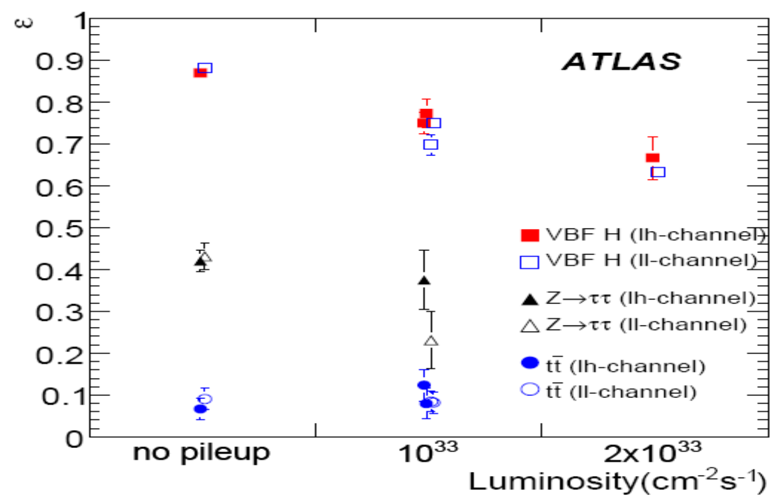


- radiation in signal close to tagging jets → rapidity gap

QCD background (Z+jets,tt): additional central jets likely

→ veto on additional jet with P_t>20 GeV and |η| <3.2 (ATLAS)



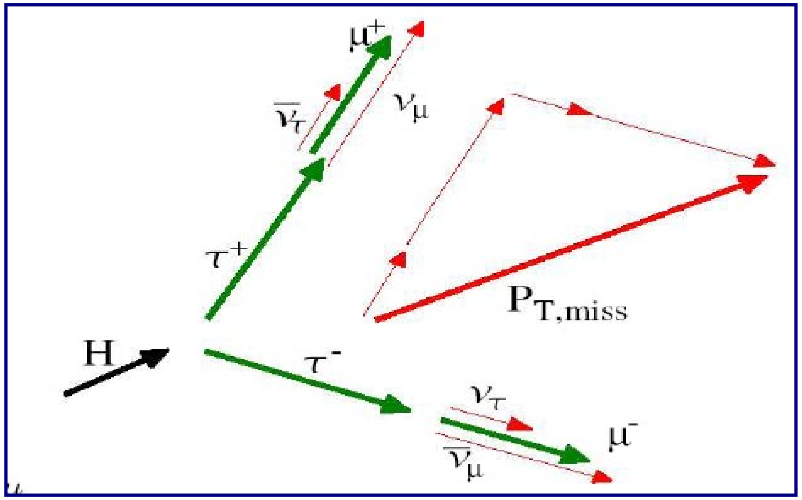


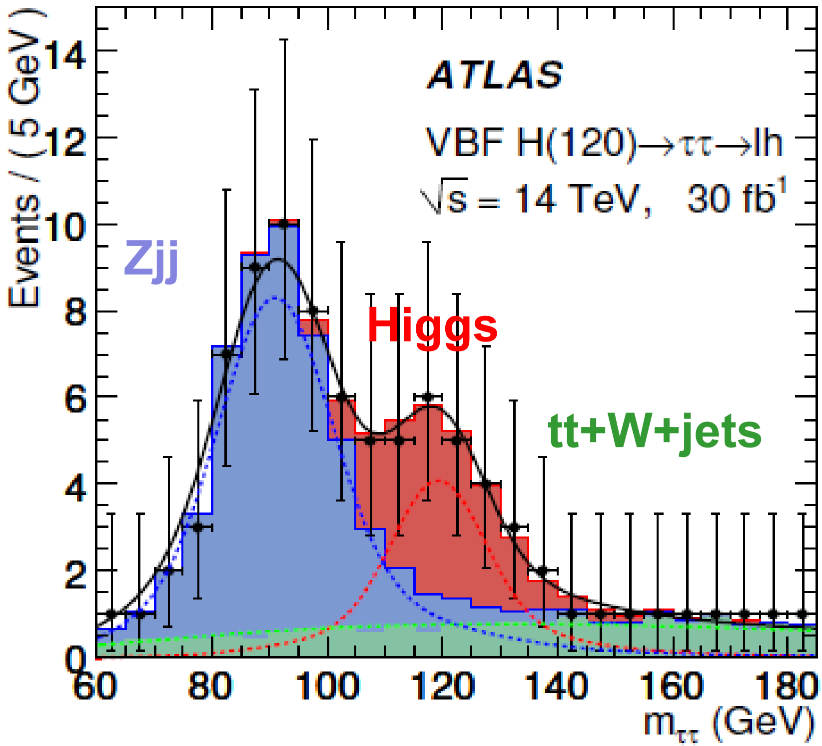
influence of pile up significant →use of tracking information under investigation

Mass Reconstruction: 14 TeV MC Study

- in collinear approximation

  despite four neutrinos



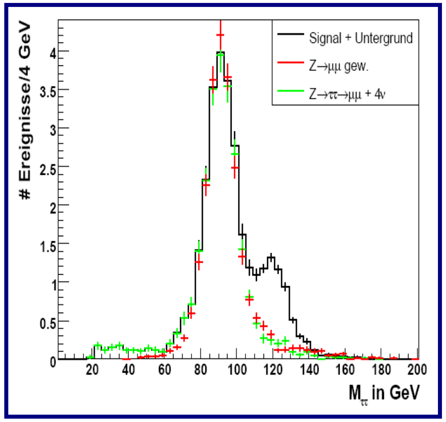


- mass resolution $\sigma_M/M \sim 9$ % dominated by missing transverse energy
  - 40% contrinbution of it from approximation
  - w/ pile up: 30% worse in 14 TeV MC study

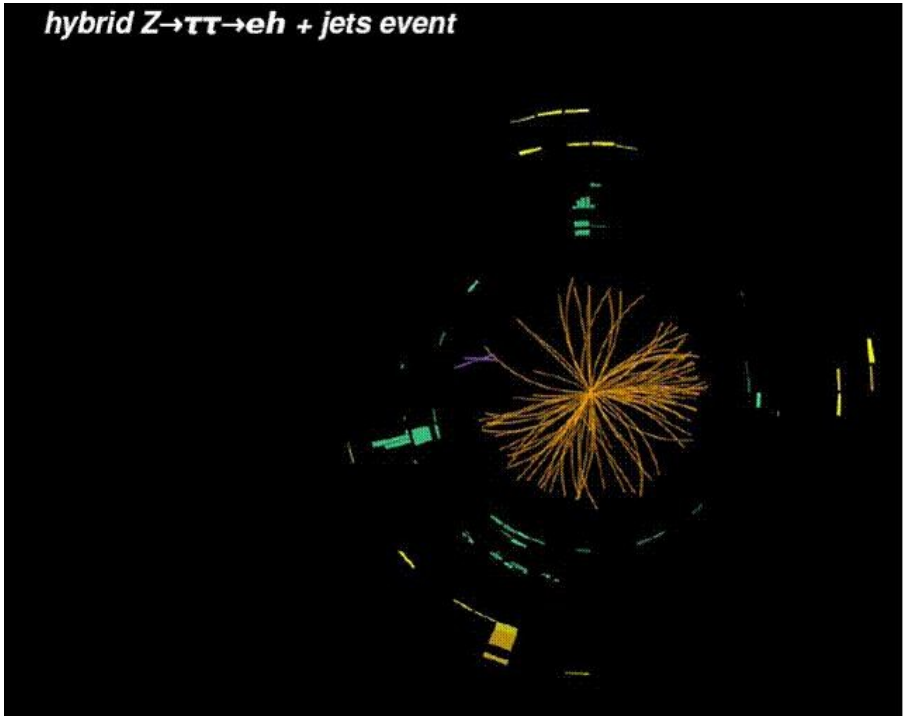
- Higgs boson on tail of Z peak mass resolution
  → no easy sideband method
  → more sophisticated method for background estimation needed

Z→ττ background from data via „embedding“

- use jjZ→μμ to model jjZ→ττ→X as they have same topology
- Z→μμ: signal free and high purity control sample selectable
- apart from μ and τ→X energy deposits same detector response (including pileup, underlying event, noise, …)

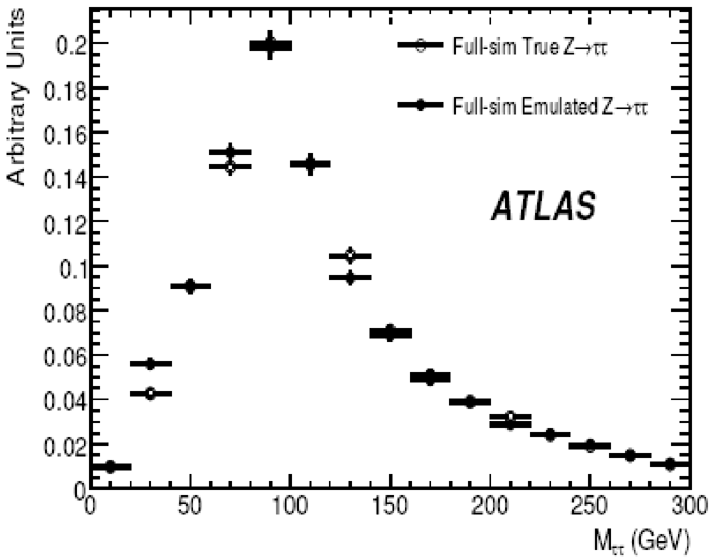


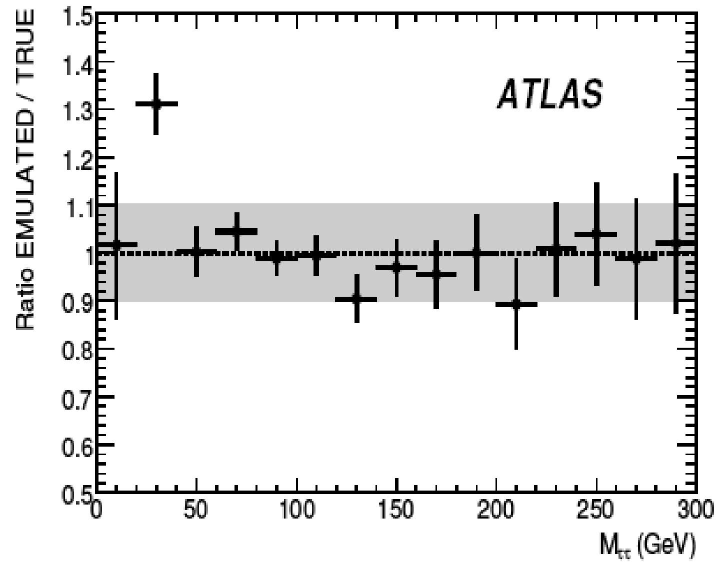
- Methodology:
  1) select Z→μμ event in collision data
  2) use 4-momenta of μ as input for τ decays
  3) simulate Z→ττ→XY decay
  4) replace cones around μ in data event by cones in simulated Z→ττ decay on calorimeter cell level → „embedding“
  5) re-reconstruct merged hybrid event
  6) apply standard selection



Background Estimation from Data: Z→ττ (MC study)

- mass distributions after embedding





- works for all tau lepton decay modes
- shape: prediction with better than 10% accuracy
- normalisation: i) from sideband

  ii) nuisance parameter in statistics machinery

  ii) theory prediction or measured Z→ll cross section

Daten Driven Estimate for H→ττ → l had (Data)

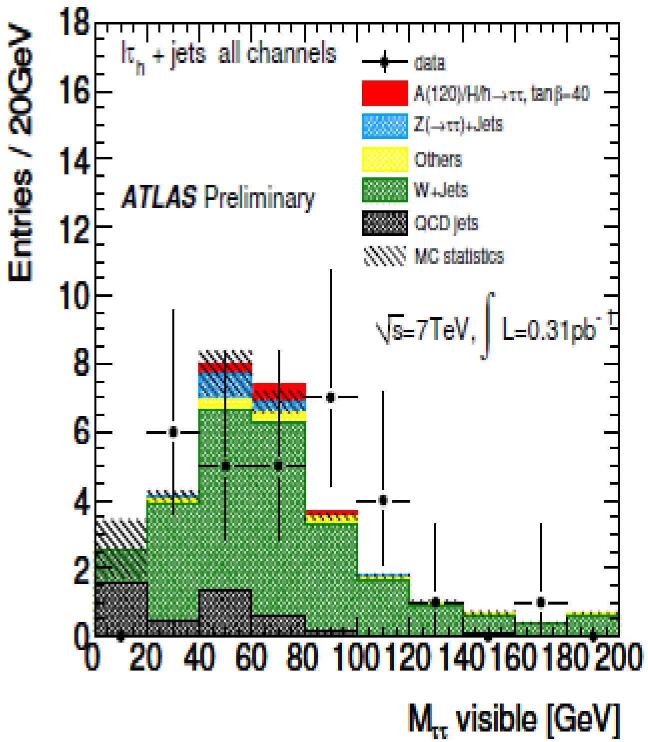
- selection: 1 electron or muon pt>15 GeV 1 tau candidate pt>20 GeV
  MET>20 GeV $m_T = \sqrt{2p_T^{lep} E_T^{miss}(1 - \cos\Delta\phi)}$ <30GeV

- comparison of MC expectation and observed event yield

	Electron channel		Muon channel	
	Missing E_T	Transverse mass	Missing E_T	Transverse mass
QCD jets	2.0±1.0	0.75±0.57	2.1±0.4	1.6±0.3
W+jets	10.34±0.12	0.45±0.02	12.0±0.1	0.48±0.02
$Z \to \tau\tau$+jets	0.58±0.02	0.48±0.02	0.67±0.02	0.56±0.02
Others	0.56±0.01	0.061±0.004	0.81±0.02	0.11±0.01
Total	13.5±1.0	1.7±0.6	15.6±0.4	2.8±0.3
Observed	12	3	17	7

QCD jet expectation normalised to

MET<15 GeV control region



- agreement between MC prediction and data
  → nevertheles aim for data driven BG estimate
  (OS versus SS tau + lepton candidates)

Daten Driven Estimate for H→ττ → l had.

- assumptions:

  shape of visible mass distribution is the same for OS and SS events

  ratio r between OS and SS events is the same in signal and control region

- number of events in signal region (OS) can be expressed like:

$$n_{\mathrm{OS}}(m_{\mathrm{vis}}) = r_{\mathrm{QCD}} \cdot n_{\mathrm{SS}}^{\mathrm{QCD}}(m_{\mathrm{vis}}) + r_{W\text{+jets}} \cdot n_{\mathrm{SS}}^{W\text{+jets}}(m_{\mathrm{vis}}) + r_{\mathrm{other}} \cdot n_{\mathrm{SS}}^{\mathrm{other}}(m_{\mathrm{vis}})$$

- define k as the deviation from r = 1 yields:

$$r_{W\text{+jets}} = \frac{n_{\mathrm{OS}}^{W\text{+jets}}}{n_{\mathrm{SS}}^{W\text{+jets}}} = 1 + k_{W\text{+jets}} \qquad r_{\mathrm{other}} = \frac{n_{\mathrm{OS}}^{\mathrm{other}}}{n_{\mathrm{SS}}^{\mathrm{other}}} = 1 + k_{\mathrm{other}}$$

$$n_{\mathrm{OS}}(m_{\mathrm{vis}}) = r_{\mathrm{QCD}} \cdot n_{\mathrm{SS}}^{\mathrm{QCD}}(m_{\mathrm{vis}}) + n_{\mathrm{SS}}^{W\text{+jets}}(m_{\mathrm{vis}}) + n_{\mathrm{SS}}^{\mathrm{other}}(m_{\mathrm{vis}}) + k_{W\text{+jets}} \cdot n_{\mathrm{SS}}^{W\text{+jets}}(m_{\mathrm{vis}}) + k_{\mathrm{other}} \cdot n_{\mathrm{SS}}^{\mathrm{other}}(m_{\mathrm{vis}})$$

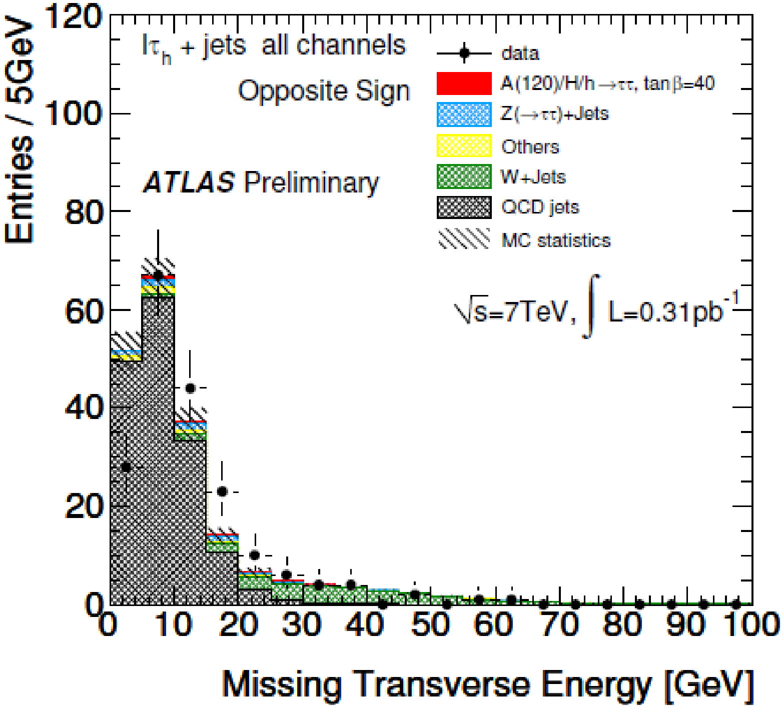
- finally one gets:

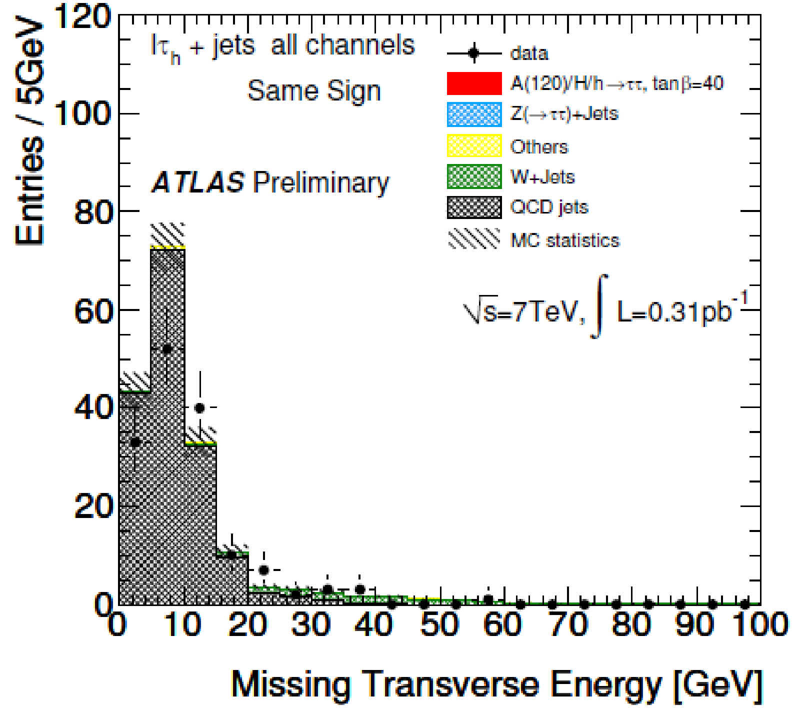
$$n_{\mathrm{OS}}(m_{\mathrm{vis}}) = n_{\mathrm{SS}}^{\mathrm{all}}(m_{\mathrm{vis}}) + k_{W\text{+jets}} \cdot n_{\mathrm{SS}}^{W\text{+jets}}(m_{\mathrm{vis}}) + k_{\mathrm{other}} \cdot n_{\mathrm{SS}}^{\mathrm{other}}(m_{\mathrm{vis}}) \qquad \text{Assuming } r_{\mathrm{QCD}} = 1$$

obtained from data data MC MC

Determination of r_{QCD}

- missing transverse energy MET for OS and SS events after had. tau cut :





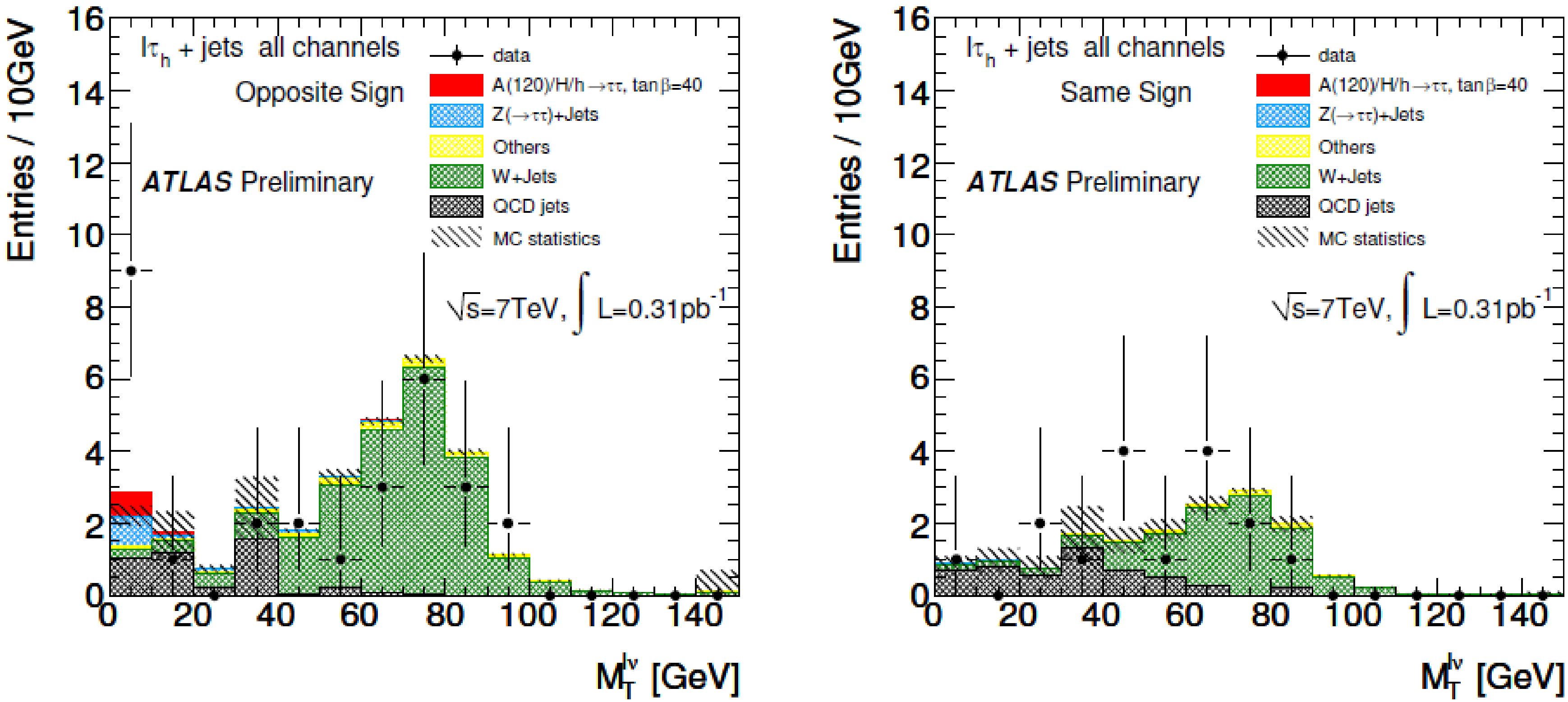
- QCD control region missing transverse energy MET < 15 GeV (signal >20 GeV)

  data: OS 139 SS 125 → r_{qcd}= 1.11+-0.14

  → use r_{QCD}=1.00+-0.11+-0.14

Determination of r_{WW} (k_{WW})

- transverse mass for OS and SS events after MET cut :



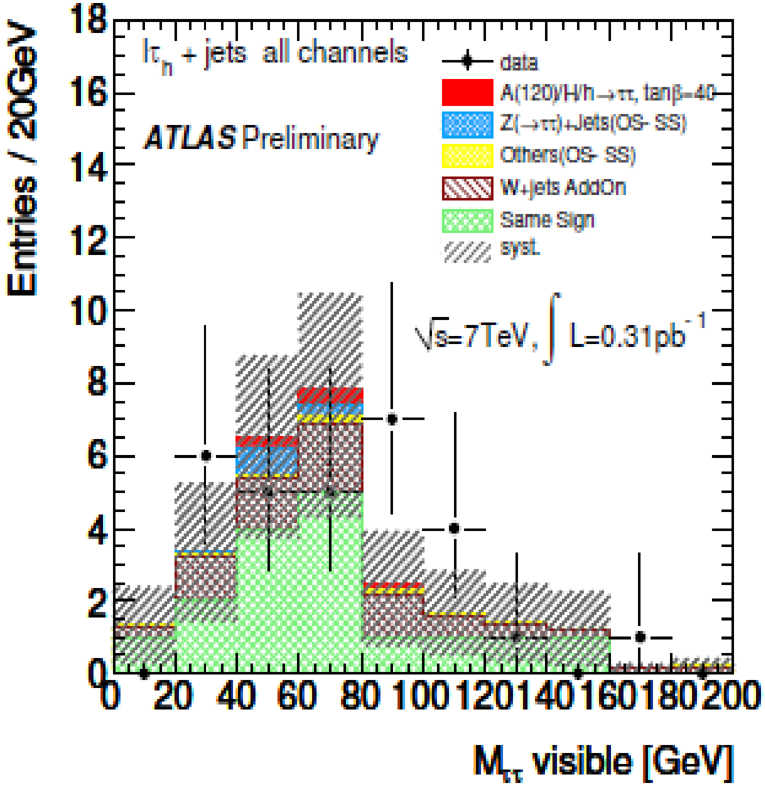
- W control region M_T>50GeV (signal region<30GeV)

  data: OS 15 (1.1 non WW BG from MC) 8 (0.5 non WW BG from MC)

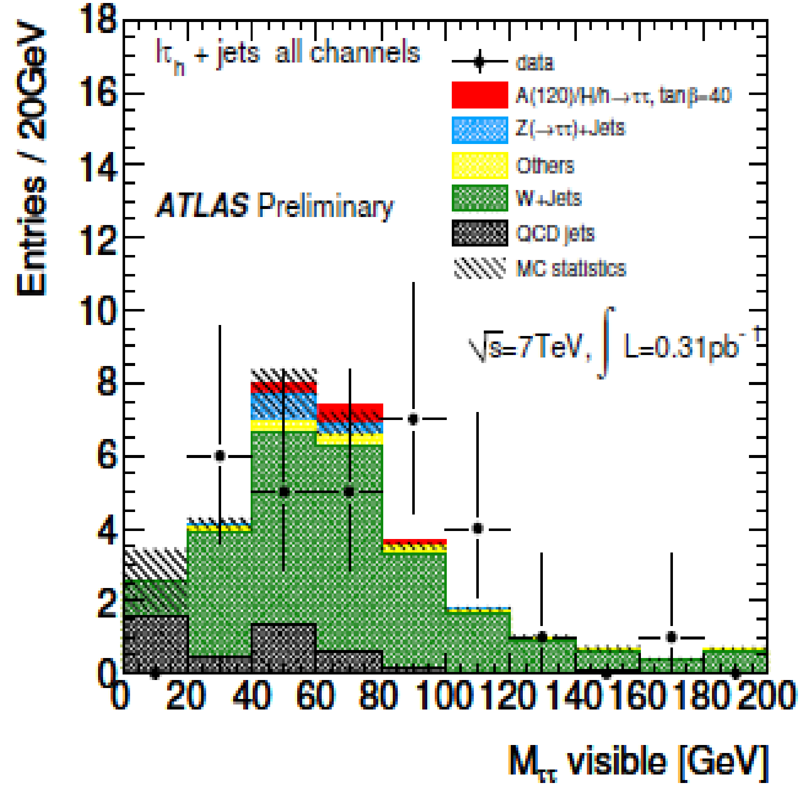
$$k_{W+\text{jets}} = r_{W+\text{jets}} - 1 = \frac{n^{m_T \text{ req.}}_{\text{OS,data}} - n^{\text{other},m_T \text{ req.}}_{\text{OS,MC}}}{n^{m_T \text{ req.}}_{\text{SS,data}} - n^{\text{other},m_T \text{ req.}}_{\text{SS,MC}}} - 1 = 0.85 \pm 0.87 \text{ (stat.)}$$

Result of BG Estimation

Data driven



MC prediction



n^{SS}_{all}: 16 +- 5

$k_{wjet}\, n^{ss}_{w+jet}$ = 7.6+- 7.8

$k_{other}\, n_{other}$ = 1.9 +- 0.5

sum: = 25 +- 9

observation: 29

Uncertainty on Signal Efficiency (14 TeV MC study)

- dominant experimental systematic uncertainty: jet energy scale

jet energy scale†	$\pm 7\%$ ($\|\eta\| \leq 3.2$) $\pm 15\%$ ($\|\eta\| \geq 3.2$)	$^{+16\%}/_{-20\%}$

seems ATLAS can do better than that

- parton level uncertainties and parton-shower and underlying event model

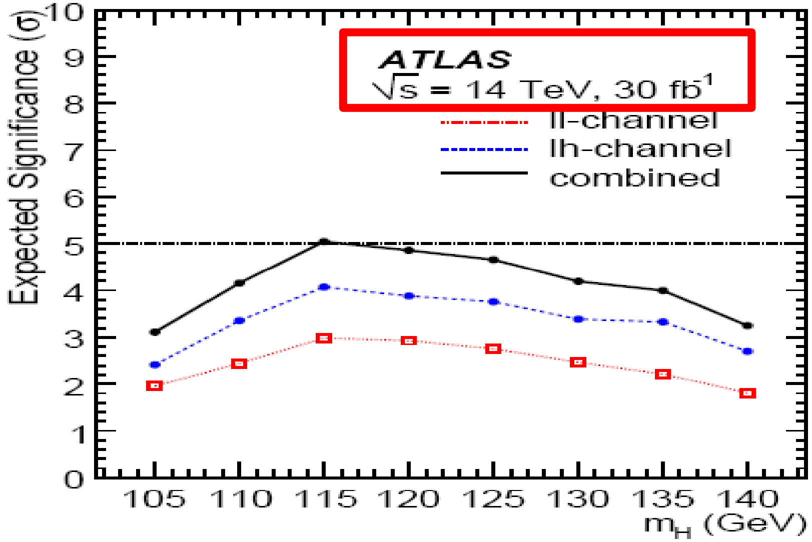
Source	Relative uncertainty	Effect on signal efficiency
PDF uncertanties	$\pm 3.5\%$	$\pm 3.5\%$
scale dependence on cross-section	$\pm 3\%$	$\pm 3\%$
scale dependence CJV efficiency	$\pm 1\%$	$\pm 1\%$
parton-shower and underlying event	$\pm \leq 10\%$	$\pm < 10\%$
total summed in quadrature		$\pm < 10\%$

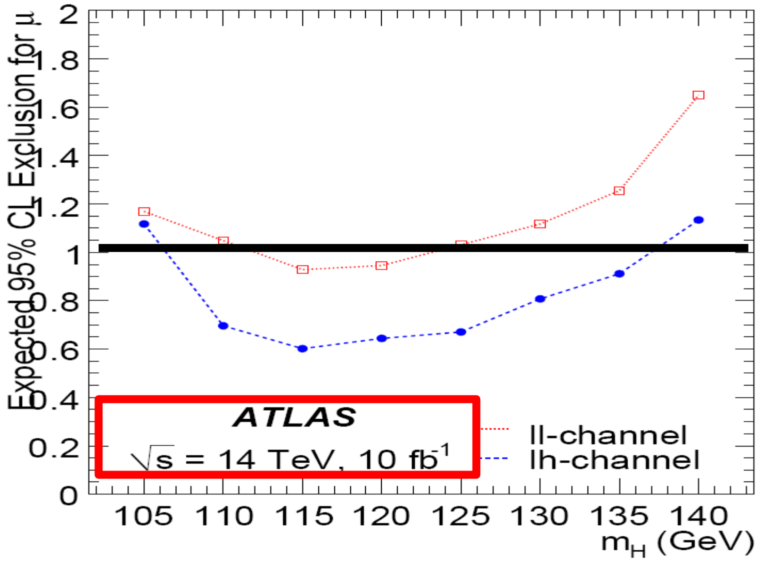
10% indicate our belive that we will achieve this precision after tuning and using better simulation tools for signal

(in 2008 comparsion of HERWIG, PYTHIA, SHERPA indicate 40% uncertainty)

→ determination of CJV survival probabilty from data appreciated

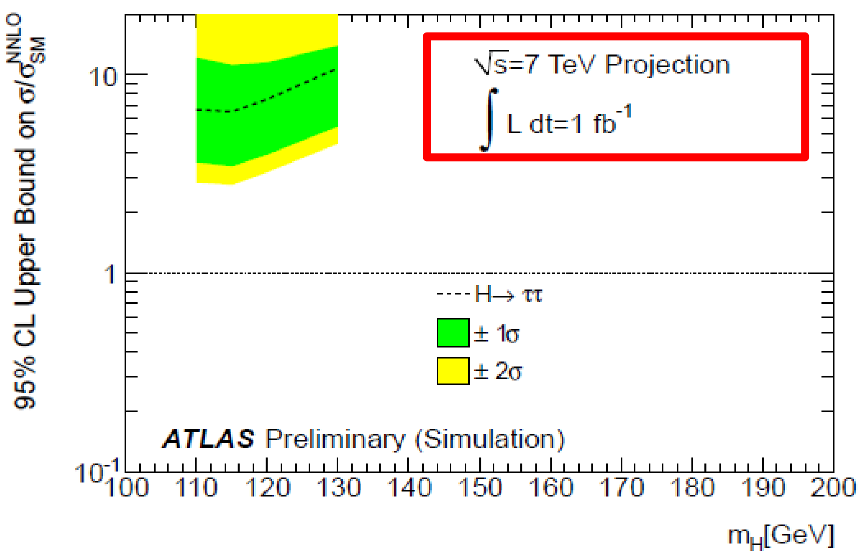
VBF H→ττ Sensitivity at 14 and 7 TeV



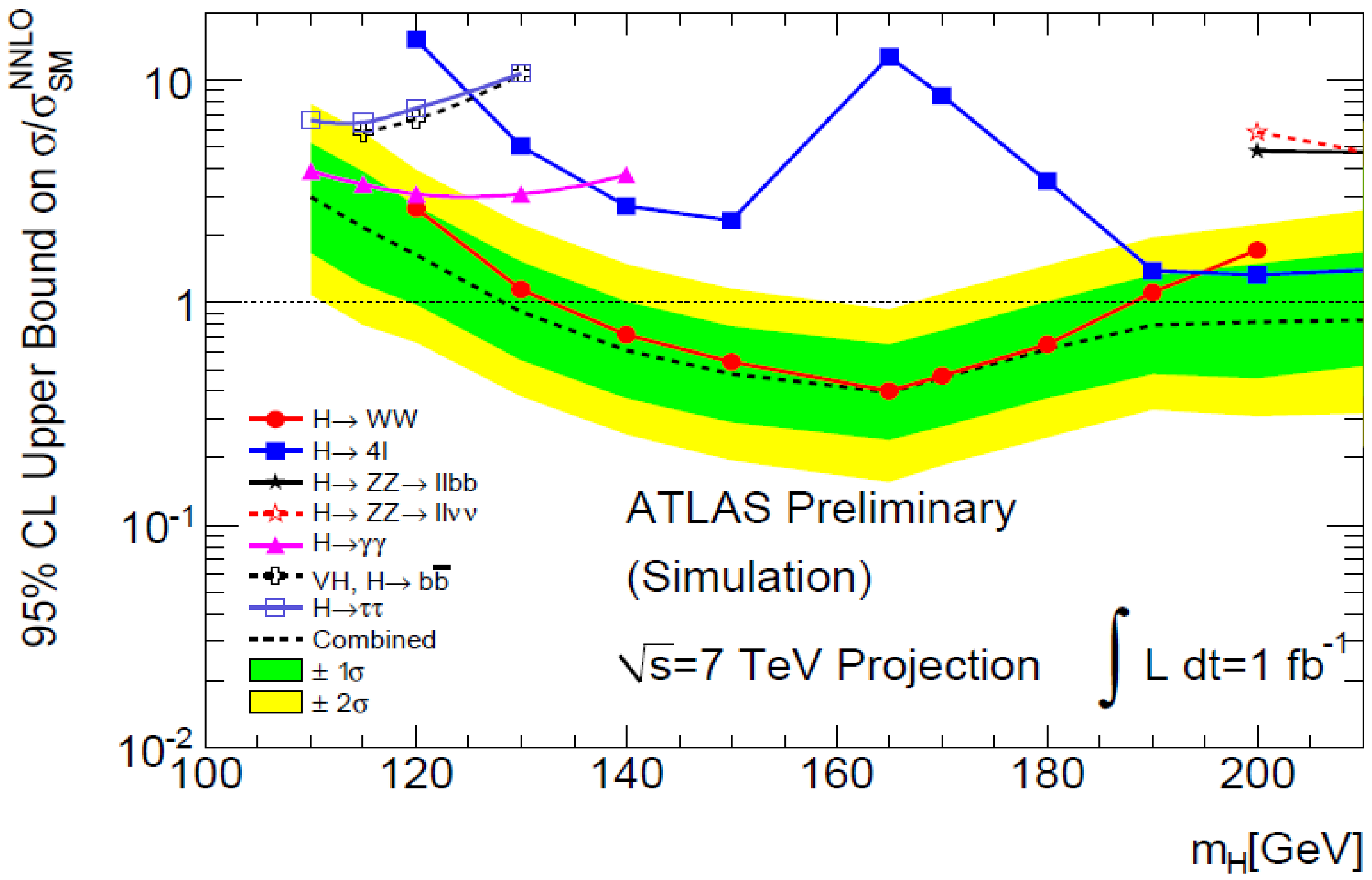


rescaled from 14 TeV MC study for 1fb^{-1} at 7 TeV

assuming 20% uncertainty on signal and Z→tt background and 50% on W+jets, tt, ...



Combined Projected Sensitivity at 7 TeV



- expected 95% CL exclusion with $1 fb^{-1}$ at 7 TeV from ~130 to ~ 450 GeV
- low mass most difficult: dominated by $H \rightarrow \gamma\gamma$

  important contribution from $H \rightarrow \tau\tau$ and $H \rightarrow bb$

Conclusions

- ATLAS detector performs very well, sometimes better than expected
- VBF still a very promising channel for discovery and exclusion
- exp. uncertainties are mostly under control:

  - jet energy scale better than expected
  - use of tracking information stababilises CJV aganist effects from pile-up
  - missing energy reconstruction with pile up still improvable

- need better understanding and modelling in MC event generators

  (use SHERPA (w/ MENLOOPS) and POWHEG)

  - jet multiplicities for braching of analysis and CJV
  - determination of CJV survival probabilites for EW processes

  also to be studied in the LHC Higgs cross section WG

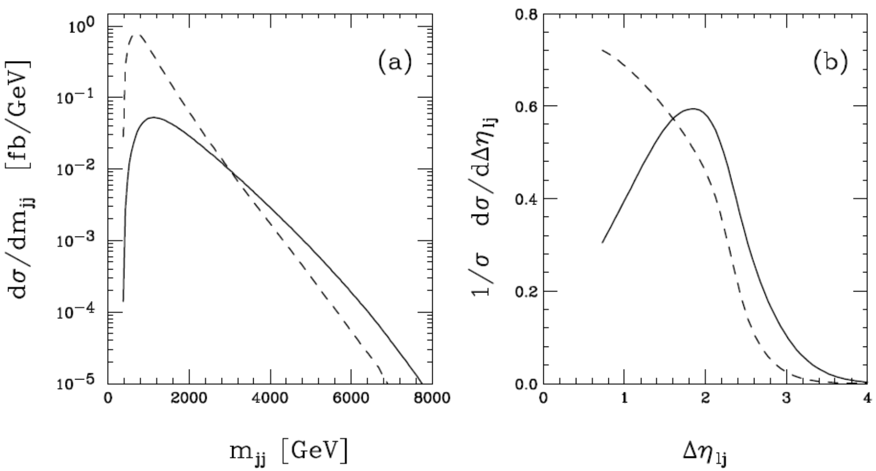
  (Sinead is the contact person for VBF production in ATLAS)

Estimating the CJV Efficiency from Data

- knowledge of central jet veto efficiency needed for investigation of properties and optimisation of selection strategy
- find and select samples with similar topology as VBF signal with reasonable rate and signal-to-background ratio
- determine radiation pattern and transfer to Higgs signal process directly or via tuning of MC generators

the obvious candidate: jjZ→ee+$\mu\mu$

after basic VBf cuts



competing QCD and EW contribution

loose cuts:

EW/QCD = 1:7.2 σ_{EW} = 87 fb

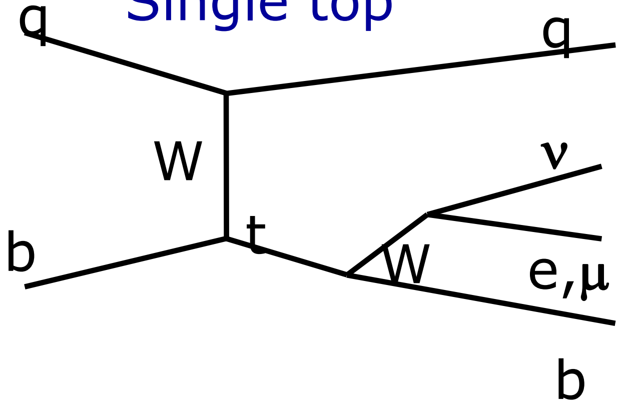
tight cuts:

EW/QCD= 1.6 (2.9) σ_{EW} = 11(5) fb

D. Zeppenfeld et al., Phys.Rev.D54:6680-6689,1996

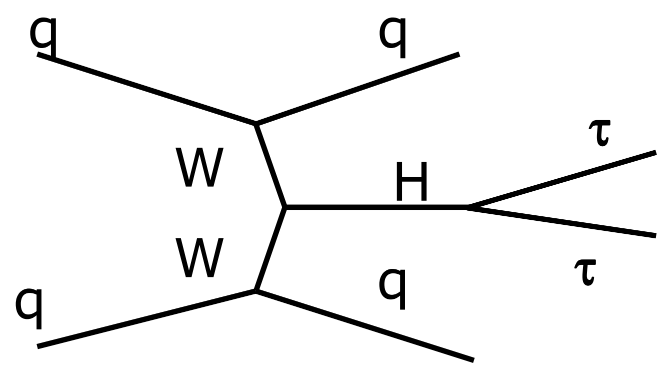
CJV Efficiency from Data via a single top? (LH07)

Single top

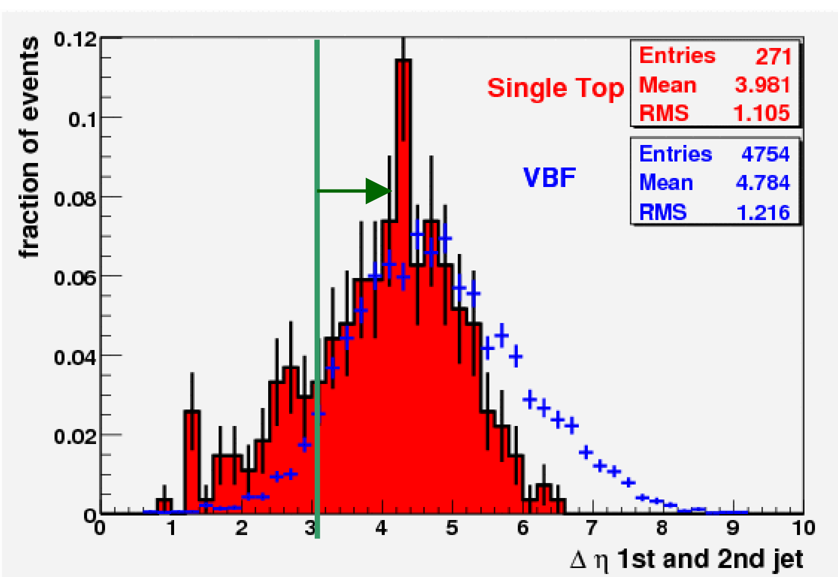


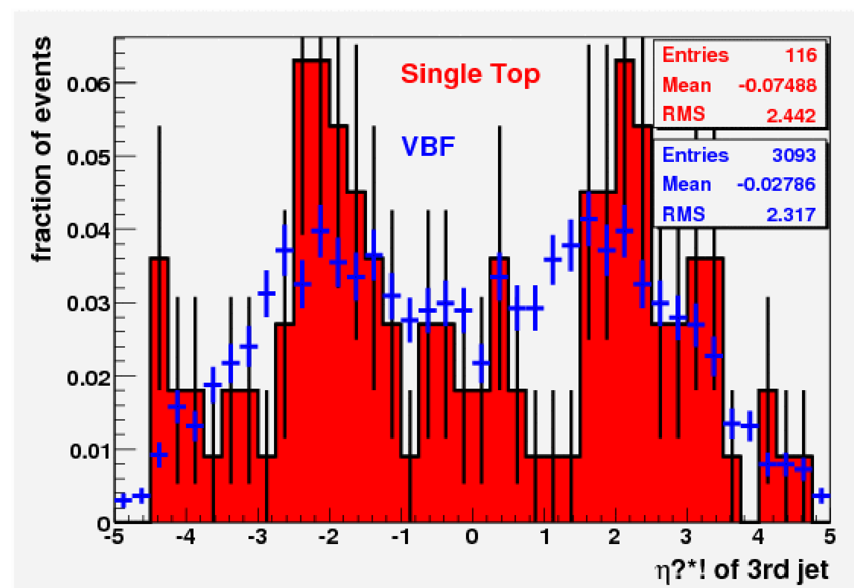
signal: BG (mainly tt)~ 2 :1?

VBF H→ττ



- similar radiation pattern ?
- similar topology selectable?
- what is influence of differences?





Uncertainty on signal efficiency (14 TeV MC study)

5.3 Theoretical uncertainty

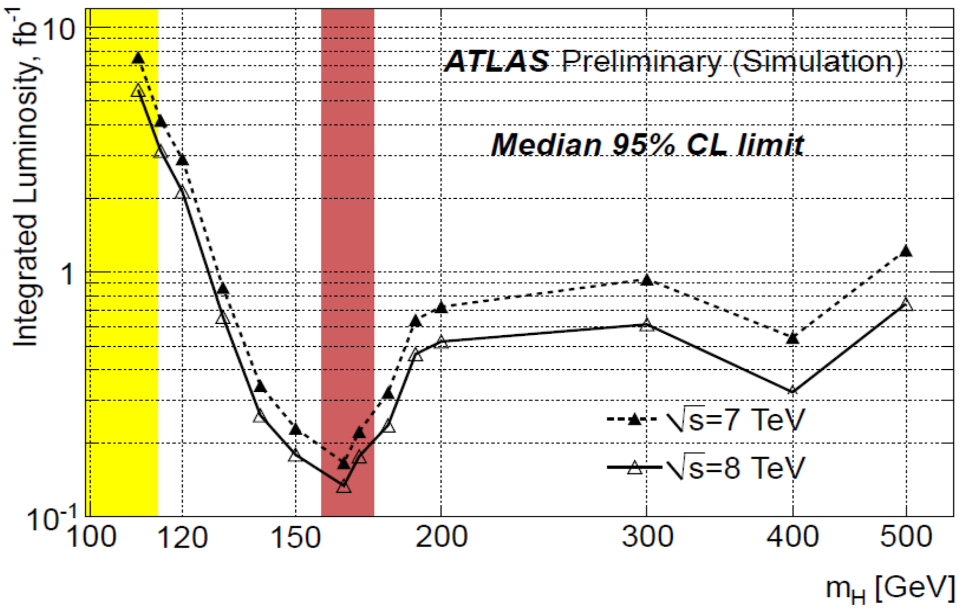
In addition to the effect of systematic mis-measurement on the signal efficiency, theoretical uncertainties also limit our ability to estimate the signal efficiency. Next-to-leading order QCD calculations are now available for the vector boson fusion process. A dedicated study [39] investigated the overall renormalization and factorization scale dependence (2%) as well as the parton distribution function (PDF) uncertainties (3.5%). Next-to-leading order electroweak corrections are also quite large for the vector boson fusion process, giving a 3% uncertainty for the full next-to-leading order calculation [40]. Recently, the dominant next-to-leading order QCD corrections to the Higgs boson plus three jets have been calculated for vector boson fusion, providing a scale uncertainty on the parton-level central jet veto survival probability of 1% [41].

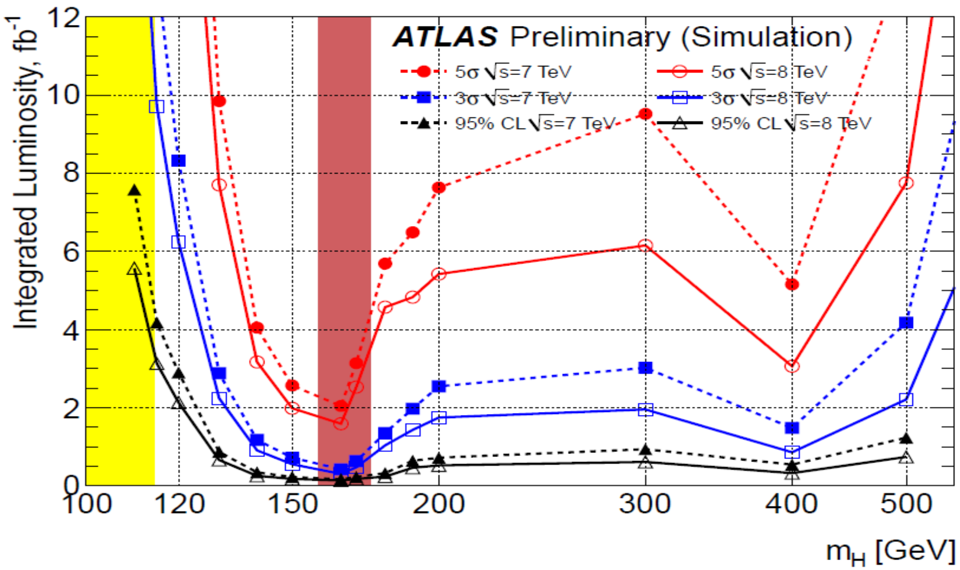
While the parton-level theoretical uncertainties are under very good control and below the level of both the statistical error and measurement-related systematics, the same is not true for the theoretical uncertainty related to the parton-shower and underlying-event. We rely on Monte Carlo simulations that model the parton-shower, hadronization, and underlying event to simulate the detector response. The uncertainty in these calculations is not comparable to the accuracy of the parton-level predictions. The central jet veto efficiency was studied with the signal process generated with PYTHIA (with various tunings), HERWIG and SHERPA and the fast detector simulation. After the analysis cuts, the different generators differ by 41%. Studies focusing specifically on the matrix element–parton shower matching indicate a substantially smaller uncertainty [33, 42]. We will measure the underlying event [43, 44] and tune the parton shower and hadronization with data, but it is likely that this contribution of the uncertainty will remain significant. Currently there is no estimate of the expected uncertainty related to the parton-shower, hadronization, and underlying event tuning. Clearly, this is an area that deserves attention as such a large uncertainty will hinder exclusions if a Higgs boson does not exist in this mass range and cross-section and coupling measurements if one does. After discussions with the authors of PYTHIA, HERWIG and SHERPA we feel that the residual uncertainty in the parton shower after tuning to the data will be less than the 18% uncertainty quoted for the jet energy scale. Thus, the uncertainty in the signal efficiency will be dominated by the jet energy / E_T^{miss} scale uncertainty and the precise uncertainty in the parton shower is not relevant. Table 15 summarizes the theoretical uncertainties for the signal production.

Table 15: Theoretical uncertainties which affect the estimation of the signal efficiency.

Source	Relative uncertainty	Effect on signal efficiency
PDF uncertanties	$\pm 3.5\%$	$\pm 3.5\%$
scale dependence on cross-section	$\pm 3\%$	$\pm 3\%$
scale dependence CJV efficiency	$\pm 1\%$	$\pm 1\%$
parton-shower and underlying event	$\pm \leq 10\%$	$\pm < 10\%$
total summed in quadrature		$\pm < 10\%$

Combined Projected Sensitivity at 7 TeV (CL_S method)





- expected luminosity required for 95% CL exclusion

- channels considered:
  inclusive $H \rightarrow \gamma\gamma$
  VBF $H \rightarrow \tau\tau \rightarrow$ ll, l had.
  W(Z)H, $H \rightarrow bb$ (boosted)
  $H \rightarrow WW \rightarrow l\nu l\nu$ (=0,1,2, jets)
  $H \rightarrow ZZ \rightarrow 4l$
  $H \rightarrow ZZ \rightarrow ll\nu\nu$ and $\rightarrow llbb$

- expected luminosity required for
  95% CL exclusion
  3 and 5 σ observation

One example: ttbar and WW BG in H+1 jet analysis

- ttbar control region: replace b-veto by b-tag and drop cuts on m_{ll}, M_T, $\Delta\phi_{ll}$

Lepton Flavors	signal	top	WW	$WZ/ZZ/W\gamma$	Z+jets	W+jets	Total Bkg.	Observed
$e\mu$	0.01 ± 0.01	2.19	0.03	0.00	0.00	0.00	2.2 ± 0.1	2
ee	0.00	0.71	0.01	0.00	0.08	0.09	0.9 ± 0.1	0
$\mu\mu$	0.00	1.54	0.02	0.00	0.01	0.00	1.6 ± 0.1	1

→ α_{tt} + systematic uncertainty

- WW control region: m_{ll} >100 GeV and drop cuts on M_T, $\Delta\phi_{ll}$

Lepton Flavors	signal	top	WW	$WZ/ZZ/W\gamma$	Z+jets	W+jets	Total Bkg.	Observed
$e\mu$	0.02 ± 0.00	1.49	1.01	0.07	0.08	0.00	2.65 ± 0.18	3
ee	0.00 ± 0.00	0.39	0.25	0.03	0.12	0.14	0.93 ± 0.29	1
$\mu\mu$	0.00 ± 0.00	0.87	0.56	0.02	1.78	0.00	3.23 ± 0.43	4

→ α_{ww} + systematic uncertainty

combining both tables → β_{tt} (pollution in WW control region)

- similar methids for all background in all jet mutiplicity bins

Summery of sytematic uncertainties

Background extraction

	α_{WW}	α_{top}	α_{W+jets}	β_{top}	α_{Z+jets}
			$H + 0j$ analysis		
WW MC Q^2 Scale	5%	–	–	–	–
Jet E Scale + Resolution	1.5%		–		4.6/5.0%
Algorithmic Uncertainty	–	69%	52/46%	–	-
MC Statistics	4.3%		–		47/21%
Total Uncertainty	7%	69%	52/46%		47/22%
			$H + 1j$ analysis		
WW MC Q^2 Scale	11%	–	–	–	–
Top MC Q^2 Scale	–	23%	–	7%	–
Jet E Scale + Resolution	9%	27%	–	11%	5.0/7.6%
b-tagging efficiency	–	22%	–	15%	
Algorithmic Uncertainty	–	–	52/46%	–	
MC Statistics	12.9%	–		6%	30/20%
Total Uncertainty	19%	42%	52/46%	20%	30/21%
			$H + 2j$ analysis		
WW MC Q^2 Scale		–	–	–	–
Top MC Q^2 Scale	–	38%	–	8%	–
Jet E Scale + Resolution		8%	–	2.5%	
b-tagging efficiency		20%	–	16%	
Algorithmic Uncertainty	–	–	–	–	11.2/12.6%
MC Statistics		–	–	1.4%	40/26%
Total Uncertainty		44%	–	18%	42/29%

Experimental uncertainties

Source of Uncertainty	Treatment in analysis
Jet Energy Resolution (JER)	~ 14%, see Ref. [56]
Jet Energy Scale (JES)	$< 10\%$ for $p_T > 15$ GeV and $\|\eta\| < 4.5$, see Ref. [53].
Electron Selection Efficiency	6 – 16% as a function of p_T
Electron Energy Scale	1% for $\|\eta\| < 1.4$, 3% for $1.4 < \|\eta\| < 2.5$
Electron Energy Resolution	Sampling term 20%, a small constant term has a large variation with η
Muon Selection Efficiency	1.2% for $p_T < 20$ GeV and 0.4% for $p_T > 20$ GeV
Muon Momentum Scale	η dependent scale offset in p_T, up to ~ 3.5%
Muon Momentum Resolution	p_T and η dependent resolution smearing functions, $\leq 10\%$
b-tagging Efficiency	p_T dependent scale factor uncertainties, 10-12%, see Ref. [54]
b-tagging Mis-tag Rate	up to 26%
Missing Transverse Energy	Add/subtract object uncertainties into the E_T^{miss}, up to 20%
Luminosity	11%

Result of BG estimation

n^{SS}_{all}: 16 +- 5

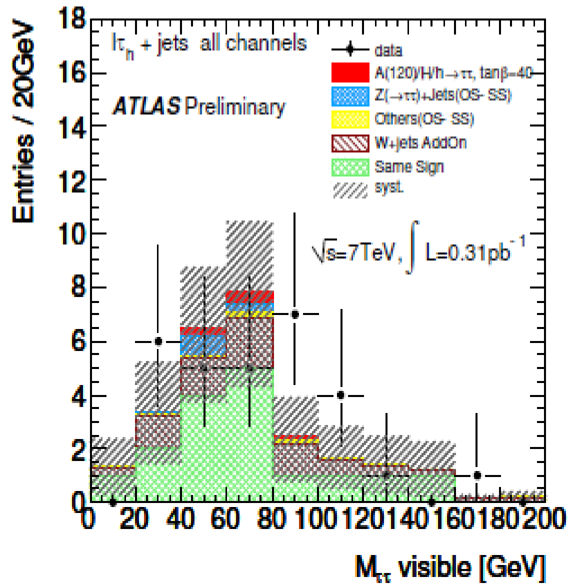
$k_{wjet}\, n^{ss}_{w+jet}$ = 7.6+- 7.8

$k_{other}\, n_{other}$ = 1.9 +- 0.5

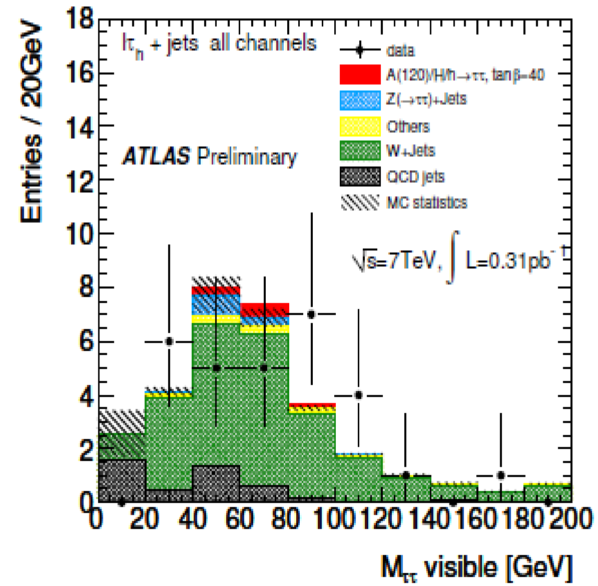
sum: = 25 +- 9

observation: 29

Data driven



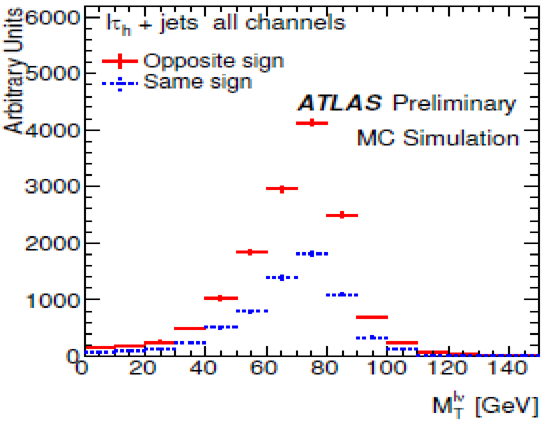
MC prediction

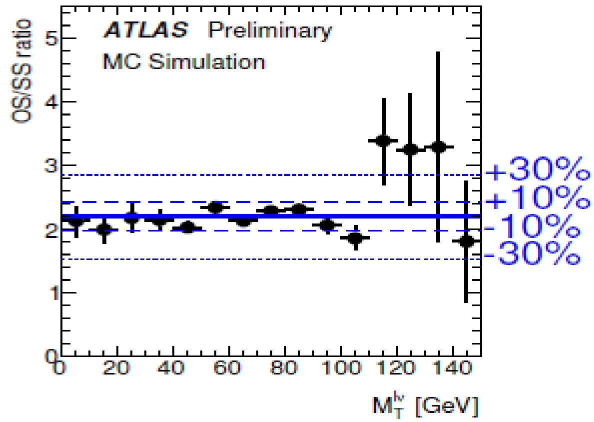


overview of systematic uncertainties

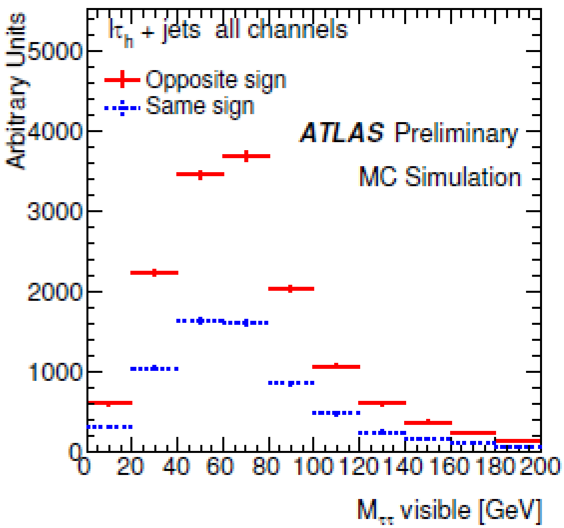
Sources	Uncertainty
Same-sign component (n_{SS}^{all})	
Same-sign statistics	25%
QCD OS/SS ratio $r_{QCD} = 1$	17%
Add-on component ($k_{W+jets} \cdot n_{SS}^{W+jets}$)	
Add-on statistics n_{SS}^{W+jets}	2.1%
OS/SS-1 statistics k_{W+jets}	102%
Dependence of k_{W+jets} between signal and control regions	10%
Acceptance due to MC modelling	
MC statistics	Table 4
Scales for $t\bar{t}$	5%
Scales, PDF and MLM matching scheme for Z+jets	13%
Electron, muon and tau	8%, 7%, 10%
Jet energy scale	1-21%
Theoretical uncertainties on the cross-sections of Z and $t\bar{t}$	4% and 6%
Luminosity	11%

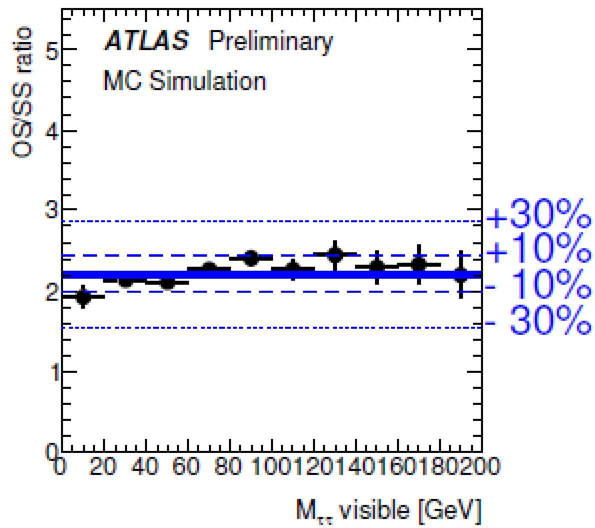
Determination of WW background





- transverse mass and visible mass shapes agree within 10% for OS and SS events





- correction factor for M_T requiremnt

$$k_{W+\text{jets}} \cdot n_{\text{SS}}^{W+\text{jets}} = k_{W+\text{jets}} \times \left(n_{\text{SS,data}}^{m_T \text{ req.}} - n_{\text{SS,MC}}^{\text{other},m_T \text{ req.}} \right) \times \frac{n_{\text{SS,MC}}^{W+\text{jets},E_T^{\text{miss}} \text{ req.}}}{n_{\text{SS,MC}}^{W+\text{jets},m_T \text{ req.}}} = 7.6 \pm 7.8,$$