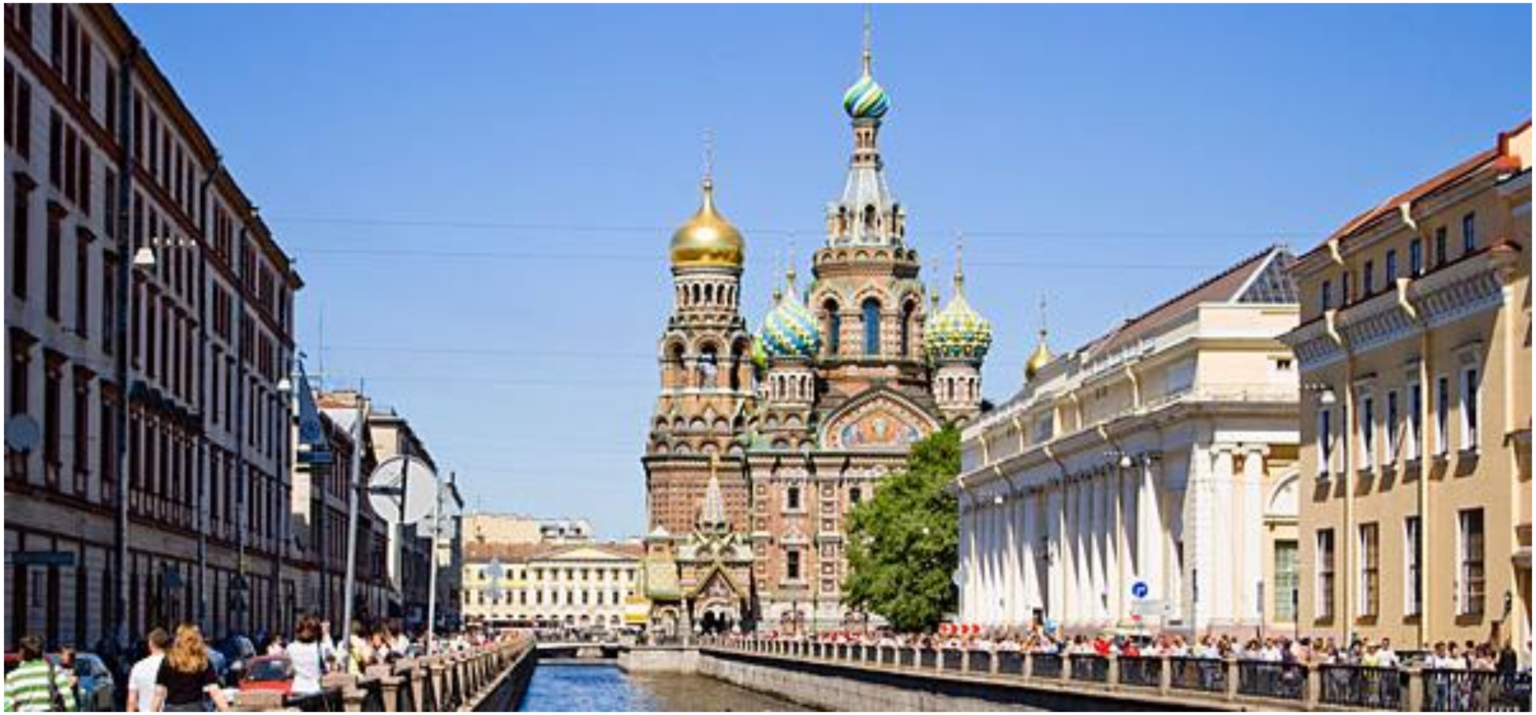


Review of ATLAS Higgs → WW Results with 25 fb^{-1} of Data

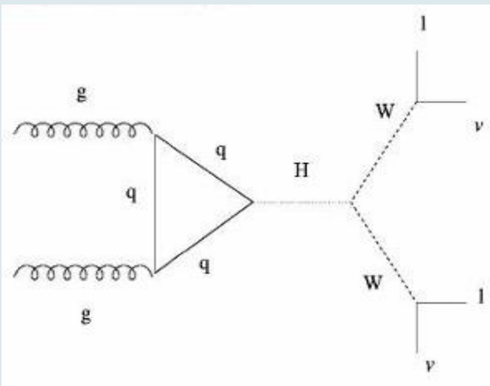
Nikolina Ilic, University of Toronto
QFTHEP 2013, St. Petersburg, Russia

Outline

- Introduction
- Backgrounds
  - W+jets and Wγ, Wγ*, WZ, ZZ
  - Z/γ* +jets
  - Top
  - WW
- Signal Extraction
  - Gluon Gluon Fusion (ggf)
  - Vector Boson Fusion (VBF)
- Results
  - 7TeV+8TeV Combined
  - VBF and couplings
- Spin
- Conclusions

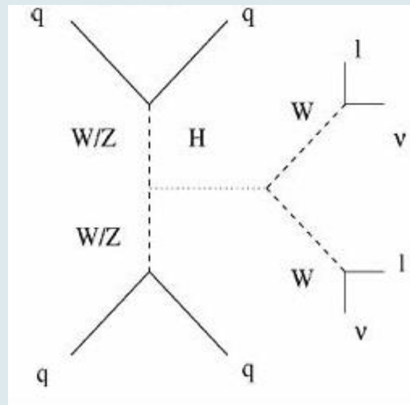
Introduction

Gluon Gluon Fusion (ggf)



Search for in 0/1 jet channel

Vector Boson Fusion (VBF)



Search for in 2 ≥ jet channel

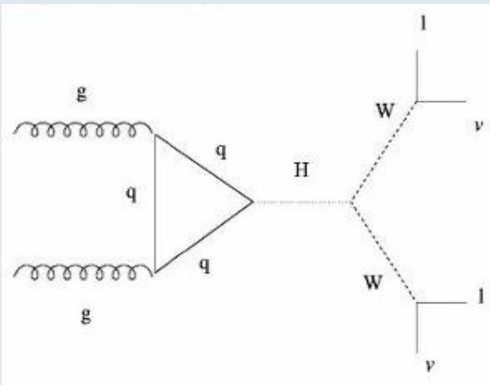
Search in 4 channels

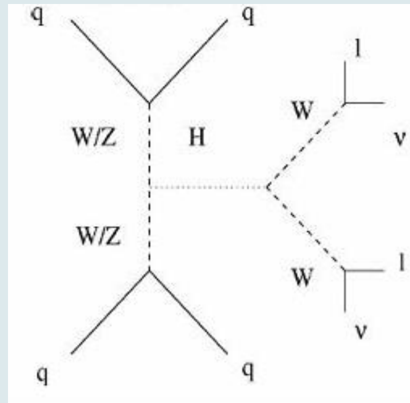
- Different Flavour (DF): $e\mu/\mu e$ + E_T^{miss}
- Same Flavour (SF) : $ee/\mu\mu$ + E_T^{miss}

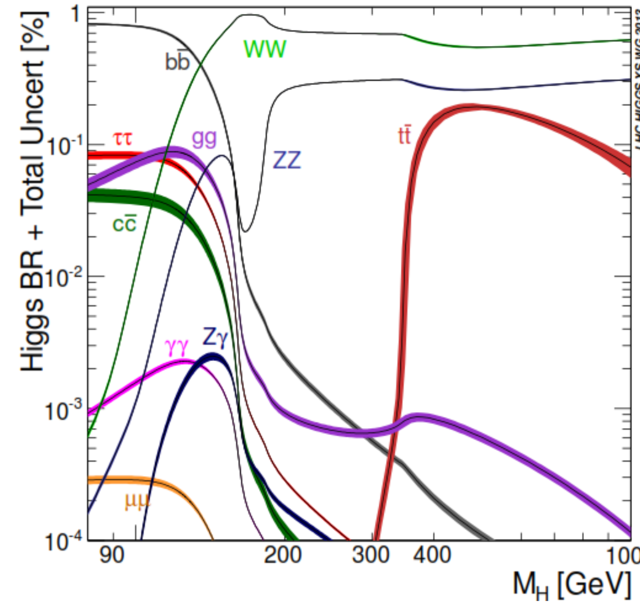
Split by jet multiplicity: 0, 1, ≥ 2jet

Introduction

Gluon Gluon Fusion (ggf)	Vector Boson Fusion (VBF)
Search for in 0/1 jet channel	Search for in 2 ≥ jet channel







Search in 4 channels

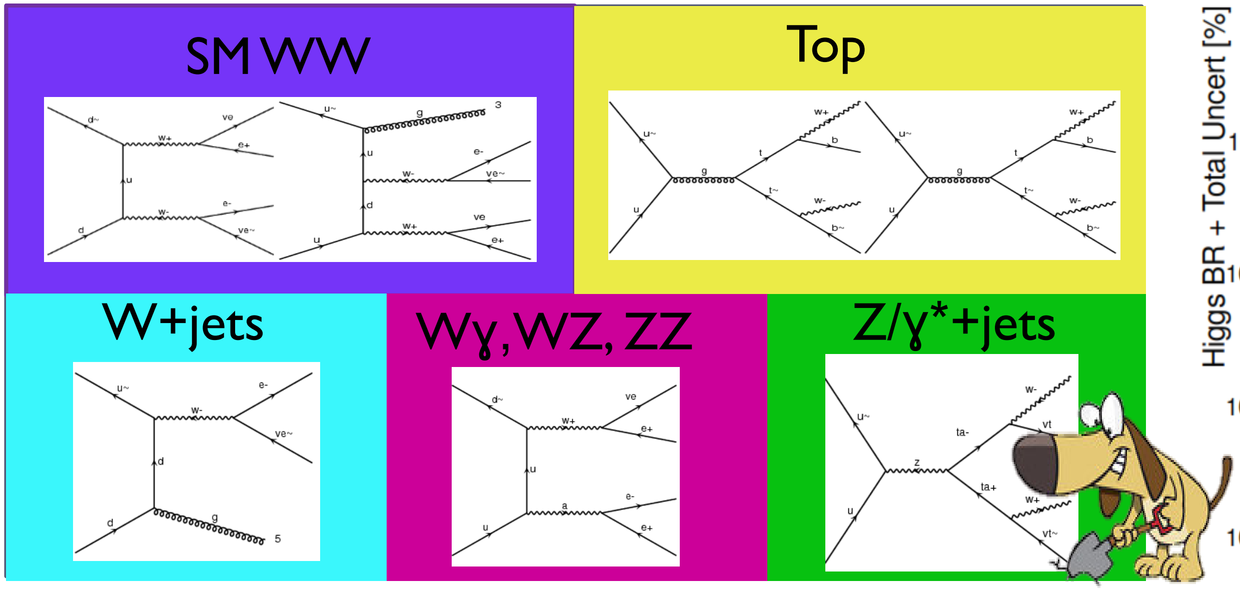
- Different Flavour (DF): $e\mu/\mu e$ + E_T^{miss}
- Same Flavour (SF) : $ee/\mu\mu$ + E_T^{miss}

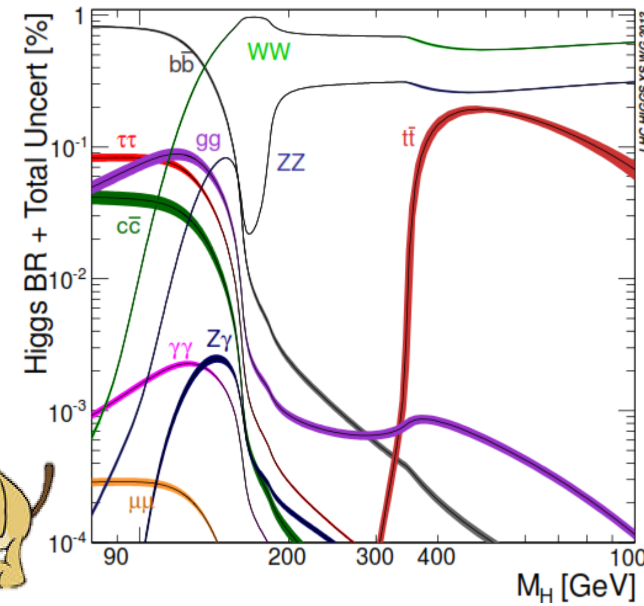
Large BR over wide range of M_H

→ Poor mass resolution

Split by jet multiplicity: 0, 1, ≥ 2jet

Introduction





Search in 4 channels

- Different Flavour (DF): $e\mu/\mu e + E_T^{miss}$
- Same Flavour (SF) : $ee/\mu\mu + E_T^{miss}$

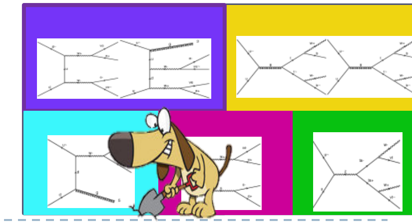
Split by jet multiplicity: 0, 1, ≥ 2jet

Large BR over wide range of M_H

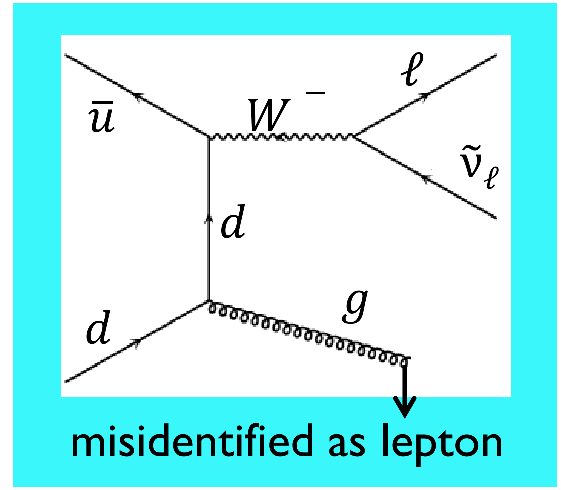
→ Poor mass resolution

Lots of background to dig through!

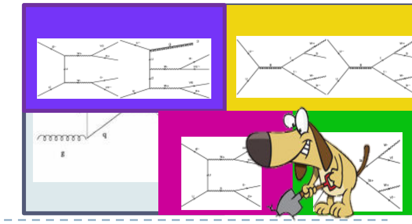
Backgrounds: W+jet/ Wγ, WZ, ZZ



- W+jets
  - Small but kinematic distributions are similar to signal
  - Hard to model in MC so estimated from data



Backgrounds: W+jet/ Wγ, WZ, ZZ



- W+jets
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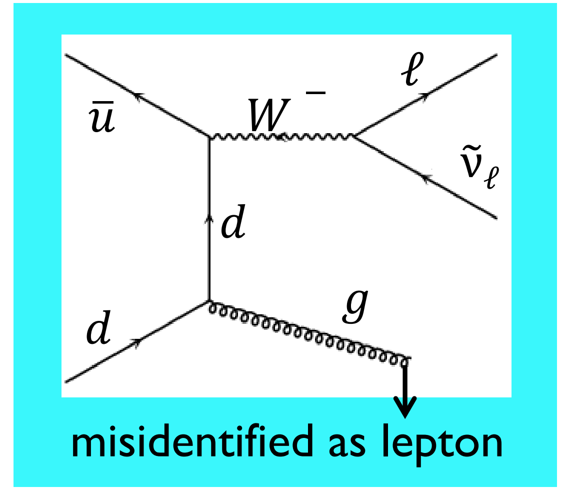
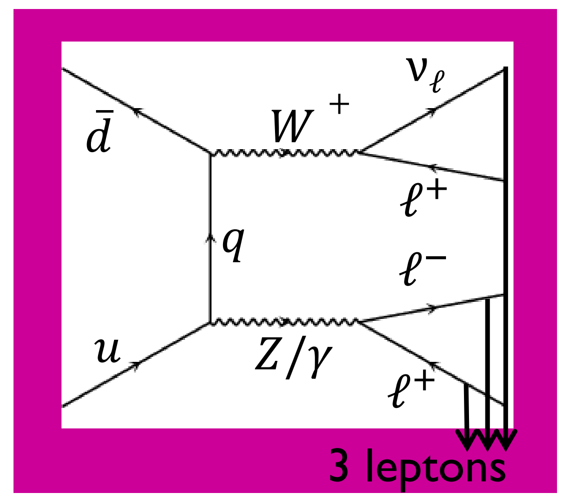
  - Hard to model in MC so estimated from data

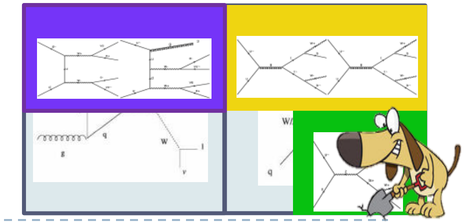


- Wγ, Wγ* WZ, ZZ
  - Small and estimated from MC
  - Reduced with 2 lepton selection

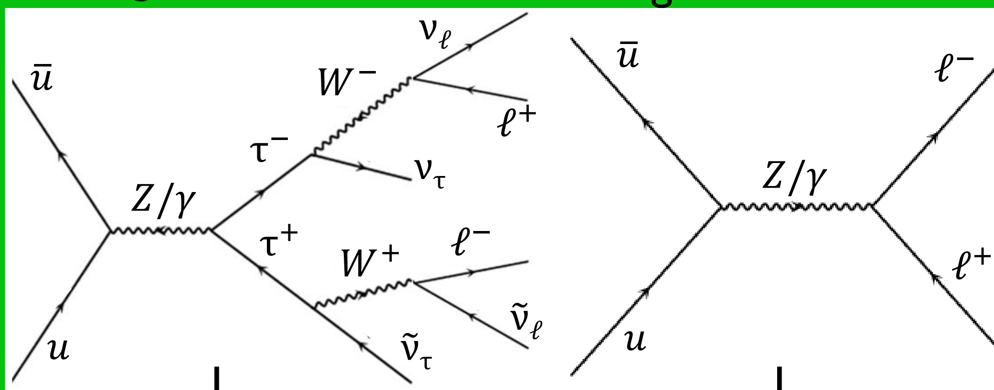
- Background estimations checked in same sign validation region



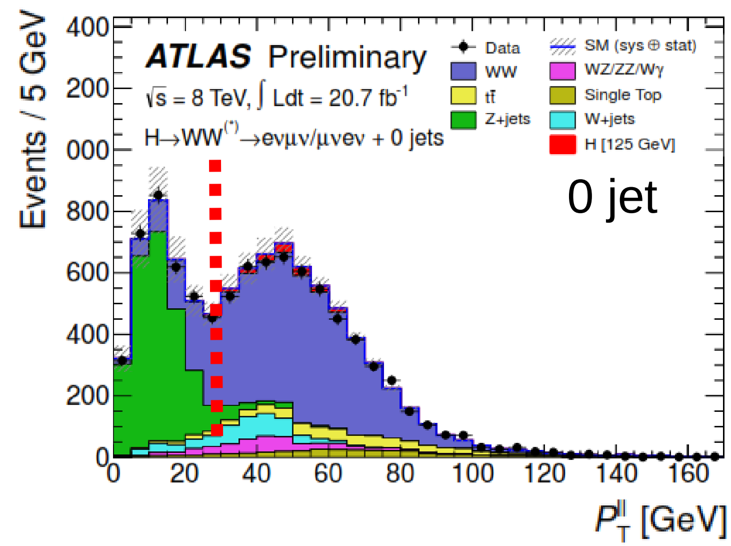
Backgrounds: Z/γ* +jets



ττ Big for DF $\ell\ell$ Big for SF

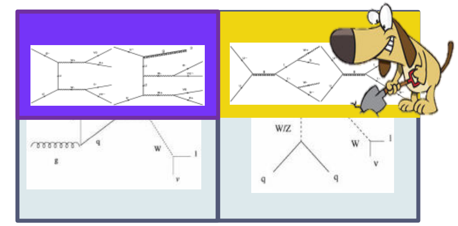


Estimated from CR Estimated from Data (SF), MC (DF)

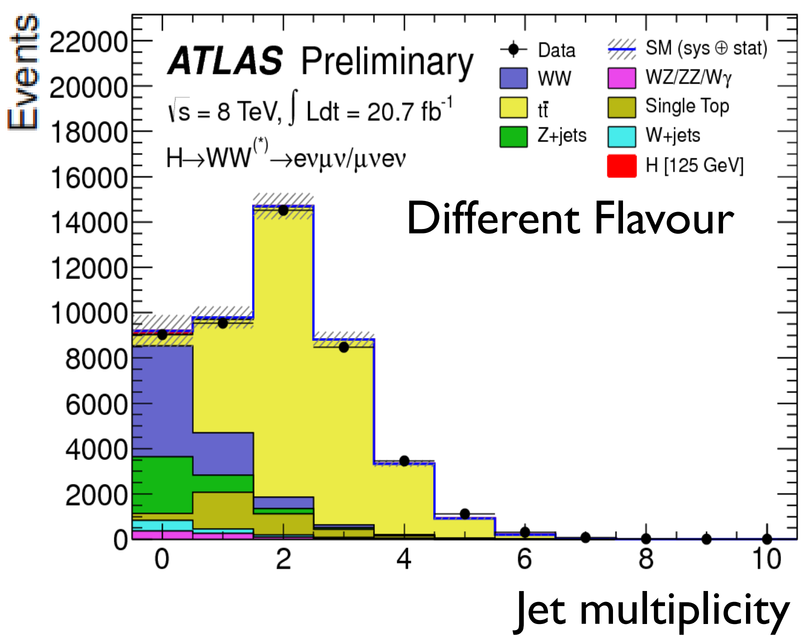


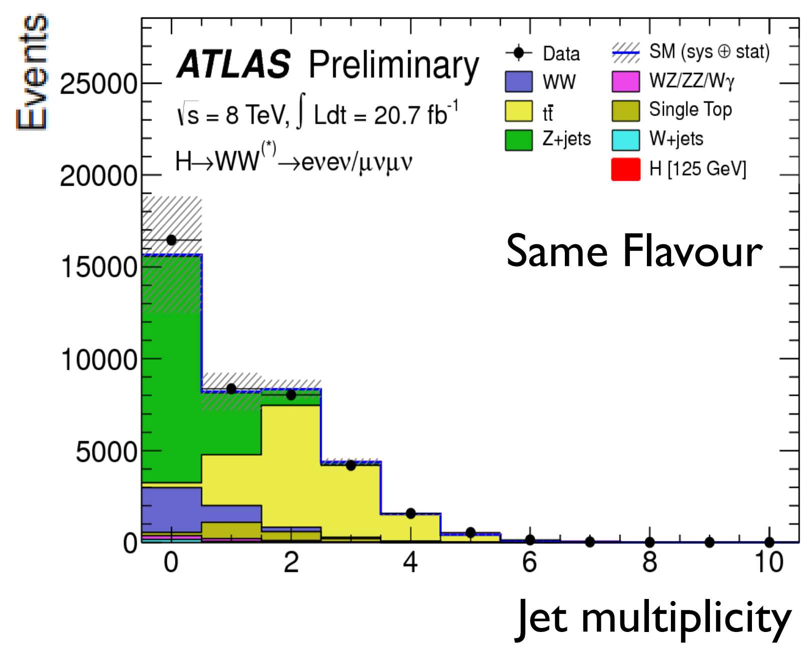
- Background reduction depends on flavour channel and jet multiplicity
  - Reduce γ*: $m_{\ell\ell}$ >10 (12) GeV for DF (SF)
  - Reduce Z: remove events around the Z mass peak
  - Reduce Z/γ*: E_T^{miss} variables > 20- 45 GeV. In Z/γ* → ττ events, the leptons emerge back to back and E_T^{miss} from neutrinos cancel
  - Reduce Z/γ*: $p_T^{\ell\ell}$ >30 for 0jet

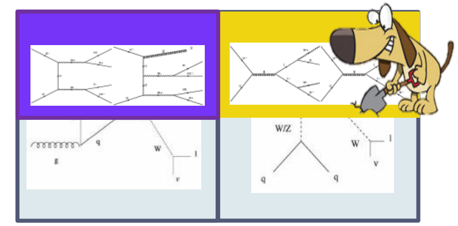
Backgrounds: What is left?



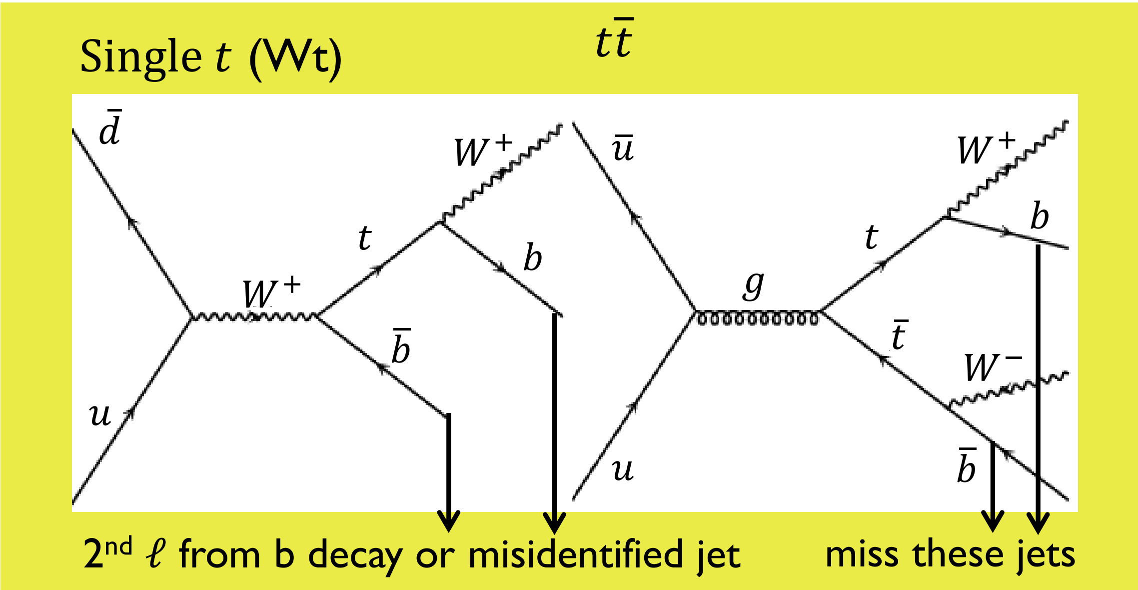
- After W+jets, Wγ , WZ, ZZ and Z/γ* + jets background is reduced, what is left?
- Z/γ*+jets in SF is reduced with cuts on hadronic recoil, and the less pileup sensitive ${p_T}^{miss}$
- Must reduce top and SM WW backgrounds



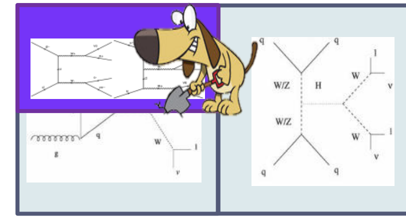




Backgrounds: Top

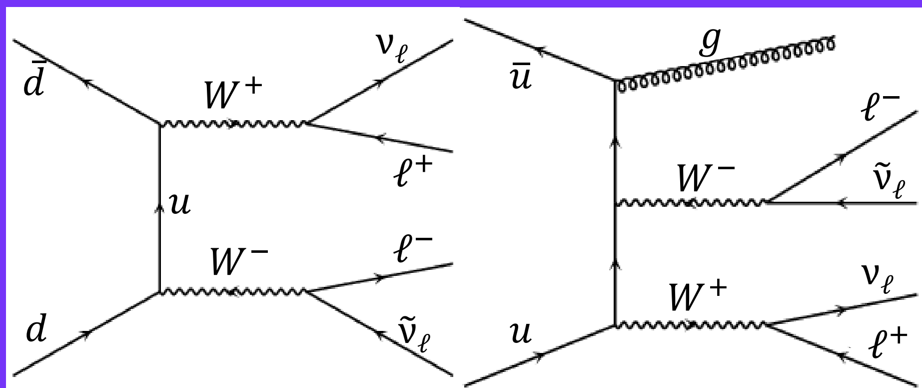


- Modelled by MC, corrected to data from a control region which contain b tagged jets
- To reduce top background
  - $N_{b\text{-jet}} = 0$ in ≥ 1 jet, p_T (all objects) < 45 GeV in ≥ 2 jet



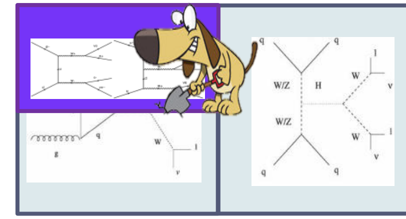
Backgrounds: WW

Biggest bkg for 0 jet | 2^{nd} Biggest bkg for 1 jet

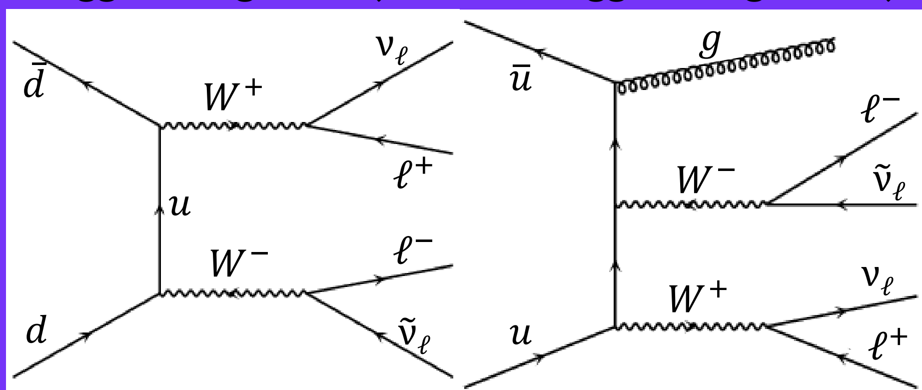


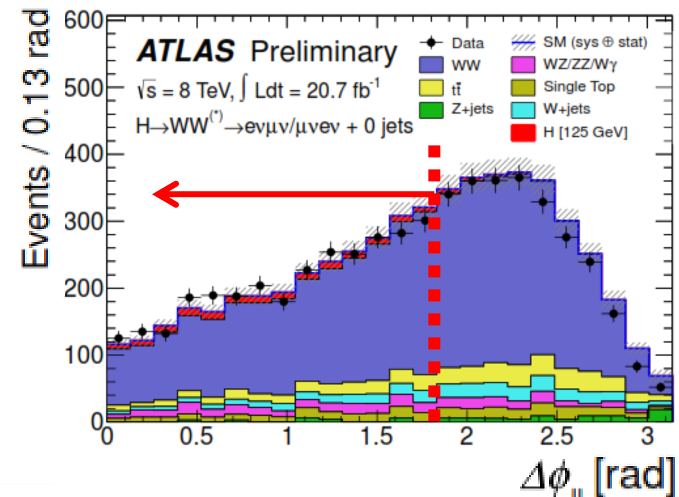
- Modelled by MC and corrected to data from CR for 0/1j, taken from MC (Sherpa+MC@NLO) for ≥ 2j

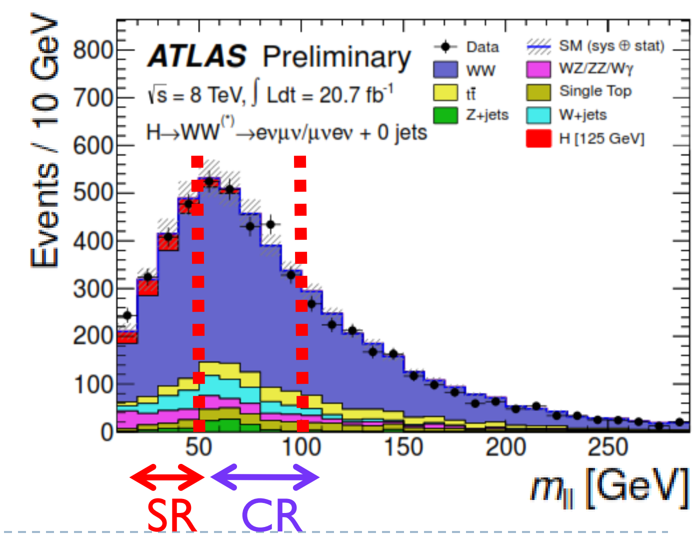
Backgrounds: WW



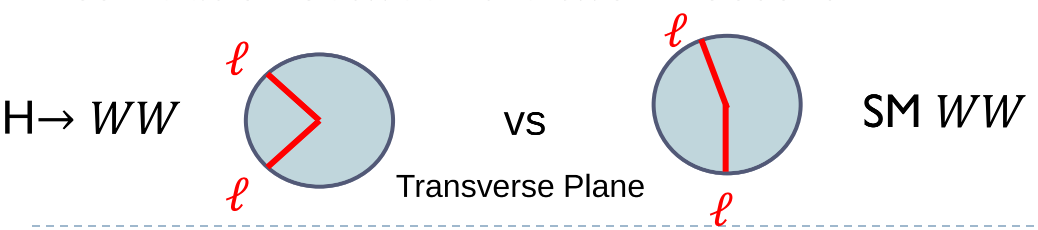
Biggest bkg for 0 jet 2nd Biggest bkg for 1 jet



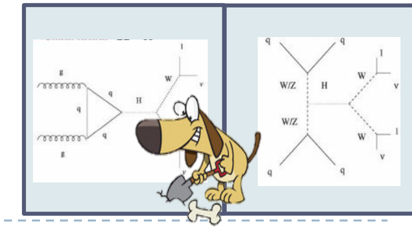




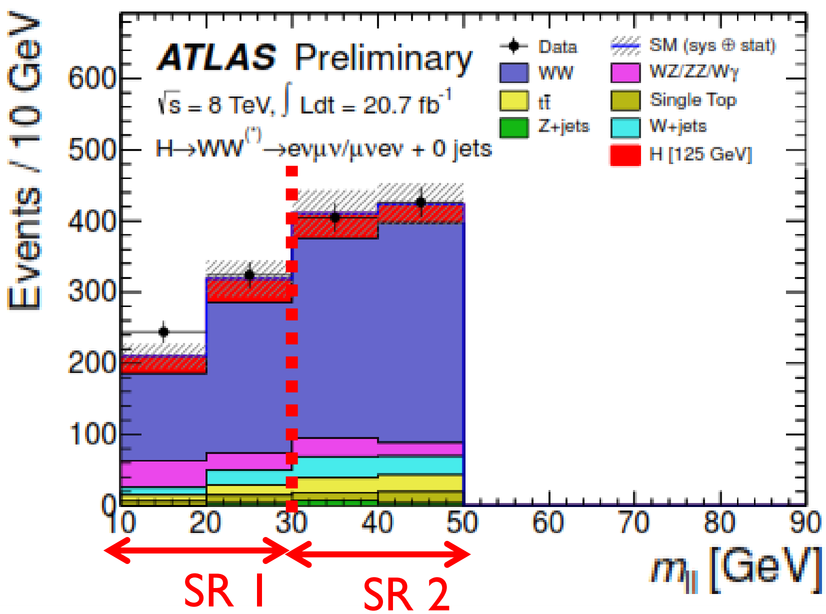
- Modelled by MC and corrected to data from CR for 0/1j, taken from MC (Sherpa+MC@NLO) for ≥ 2j
- Opening angle between the two leptons ($\Delta\phi_{\ell\ell}$) is small for signal since Higgs is spin 0 and there is spin correlation between the two W bosons



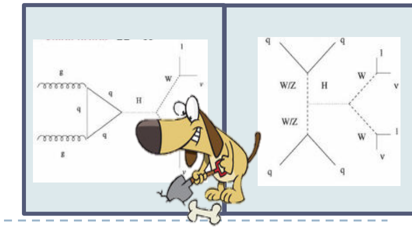
Signal Extraction: ggF



- After selections to reduce backgrounds, signal extracted
- Split SR to improve sensitivity (different Signal/Bkg ratio)

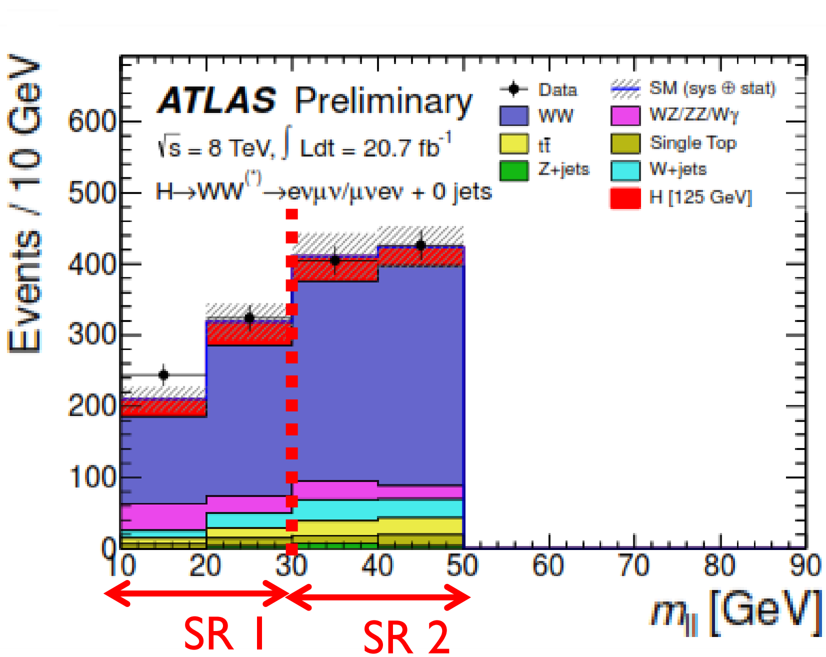


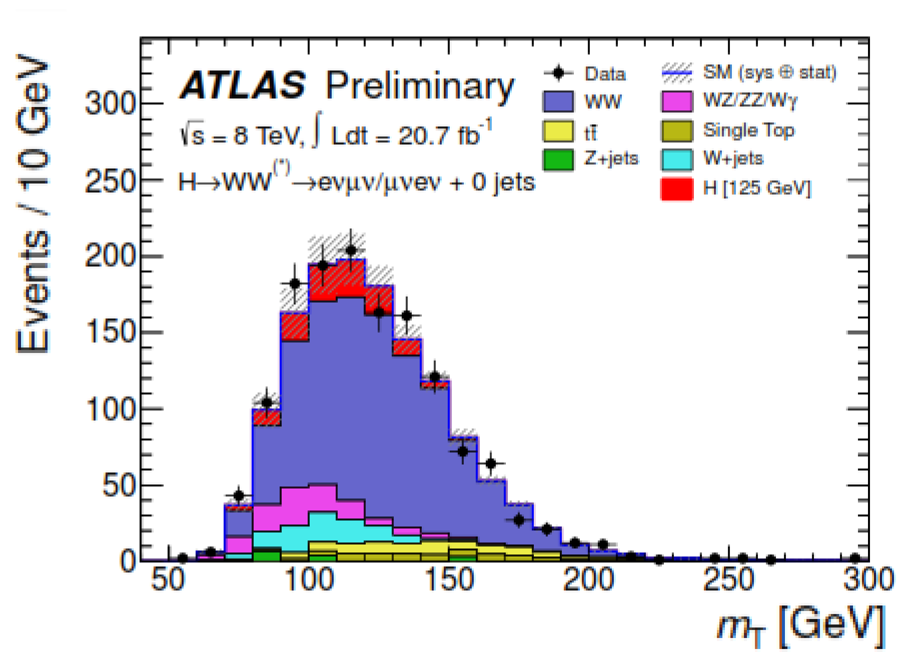
Signal Extraction: ggF



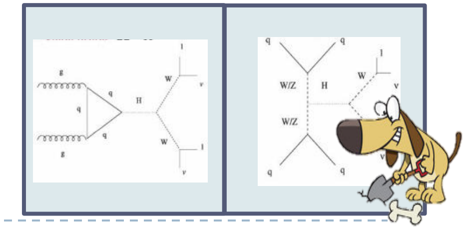
- After selections to reduce backgrounds, signal extracted
- Split SR to improve sensitivity (different Signal/Bkg ratio)
- Final likelihood fit is to m_T

$$m_T^2 = \left(\sqrt{m_{ll}^2 + |\vec{p}_{T ll}|^2} + E_T^{\text{miss}}\right)^2 - \left(\vec{p}_{T ll} + \vec{E}_T^{\text{miss}}\right)^2$$

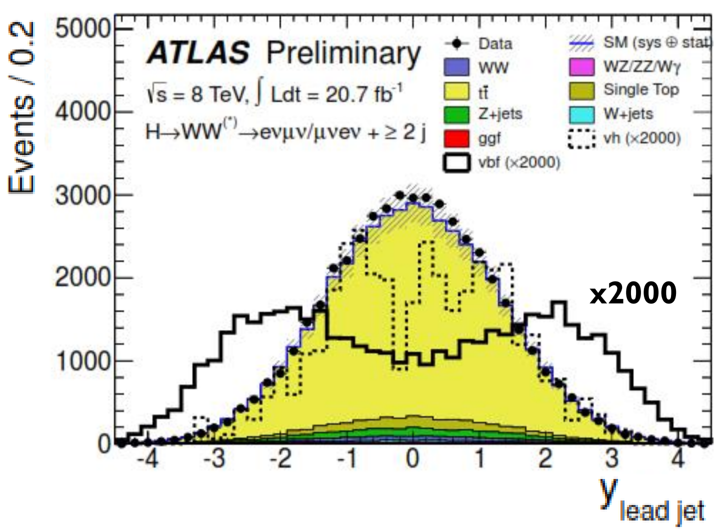


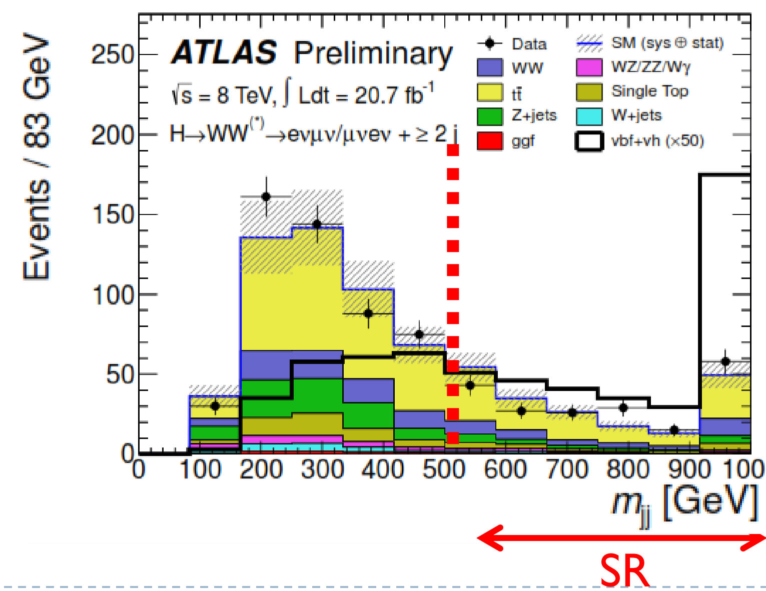


Signal Extraction: VBF

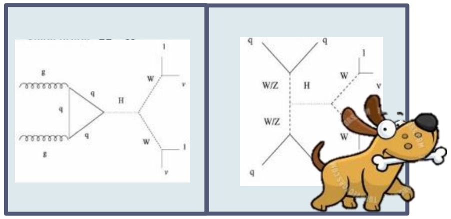


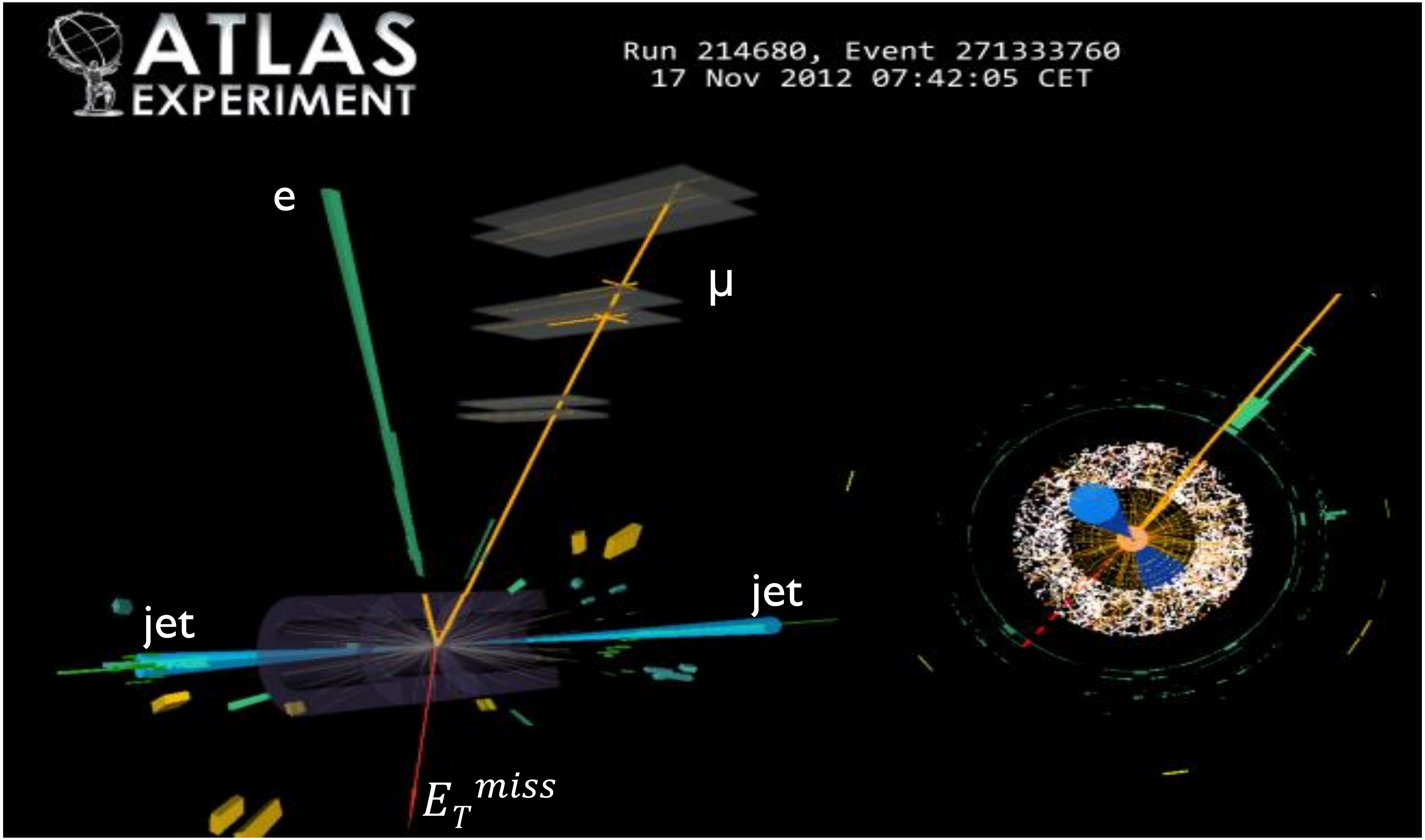
- VBF signal is WW+2 forward jets with a large rapidity gap
  - p_T (all objects) < 45 GeV to reduce dominant $t\bar{t}$ background
  - m_{jj} > 500 GeV, rapidity($\Delta Y_{\text{lead jet, sublead jet}}$) > 2.8
  - No additional jets between the two forward ones to reduce $t\bar{t}$ and ggF
  - Require leptons to be between forward jets
  - Define signal region: $m_{\ell\ell}$ < 60, $|\Delta\phi_{\ell\ell}|$ <1.8 and fit m_T in 4 bins



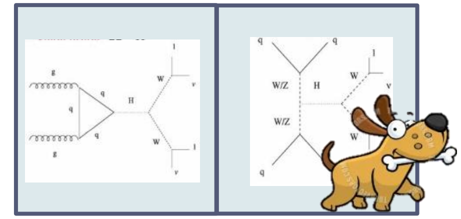


Results

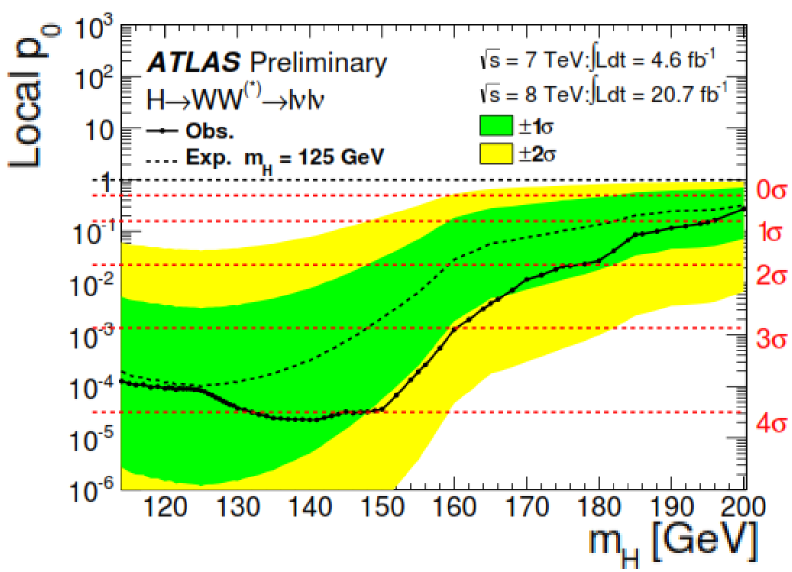


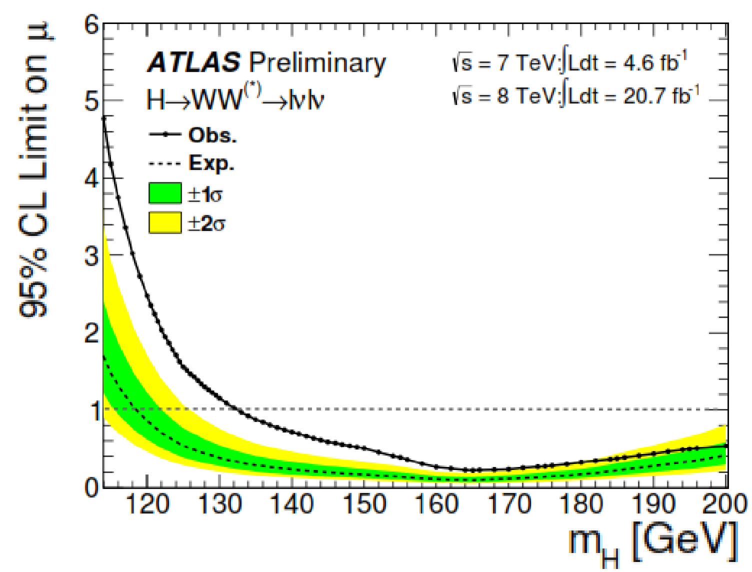

ATLAS
EXPERIMENT
Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET
e
μ
jet
jet
$E_T{}^{miss}$

Results: 7TeV+8TeV Combined

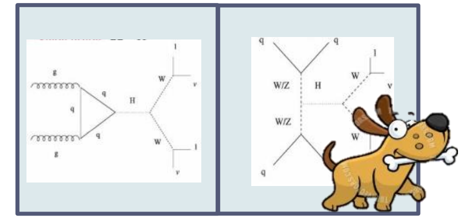


- At m_H =140 GeV
  - Observed significance of 4.1σ
- Study excess of events at m_H = 125 GeV that was observed by H→γγ/ZZ
  - Expected Significance : 3.7σ
  - Observed Significance : 3.8σ





Results: 7TeV+8TeV Combined

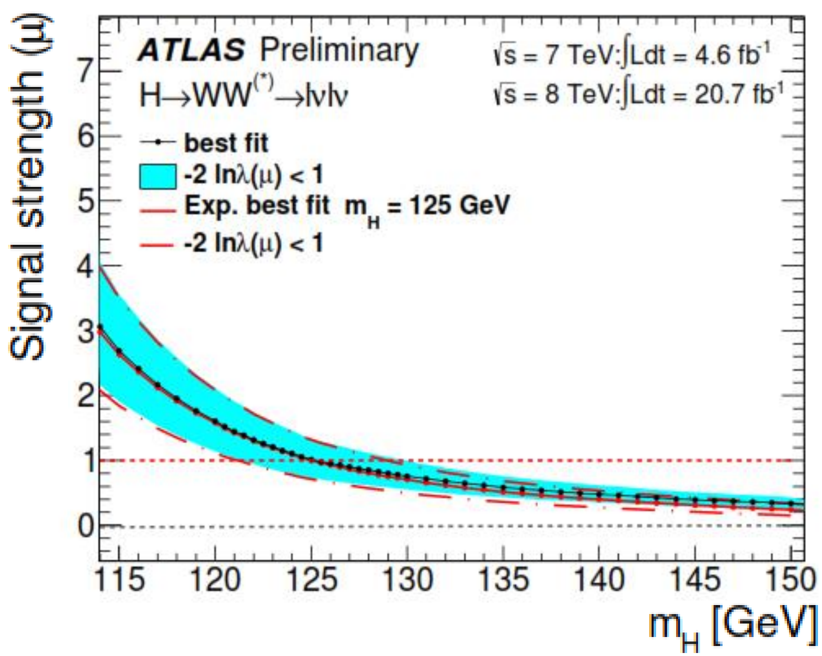


- Study signal strength, $\mu = \frac{\sigma_{obs}}{\sigma_{SM}}$, at m_H = 125 GeV

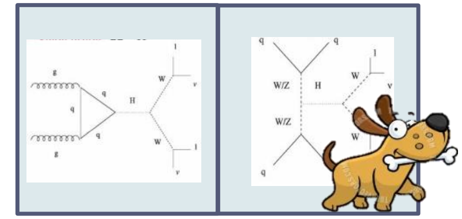
$$\boldsymbol{\mu_{obs} = 1.01 \pm 0.21\,(stat.) \pm 0.19\,(theo.\,syst.) \pm 0.12\,(expt.\,syst.) \pm 0.04\,(lumi.)}$$
$$\boldsymbol{= 1.01 \pm 0.31}$$

theo. syst.:
Signal Yield ($\sigma \cdot BR$)
WW bkg normalisation

expt. syst.:
B-tagging efficiency
Jet energy scale/resolution

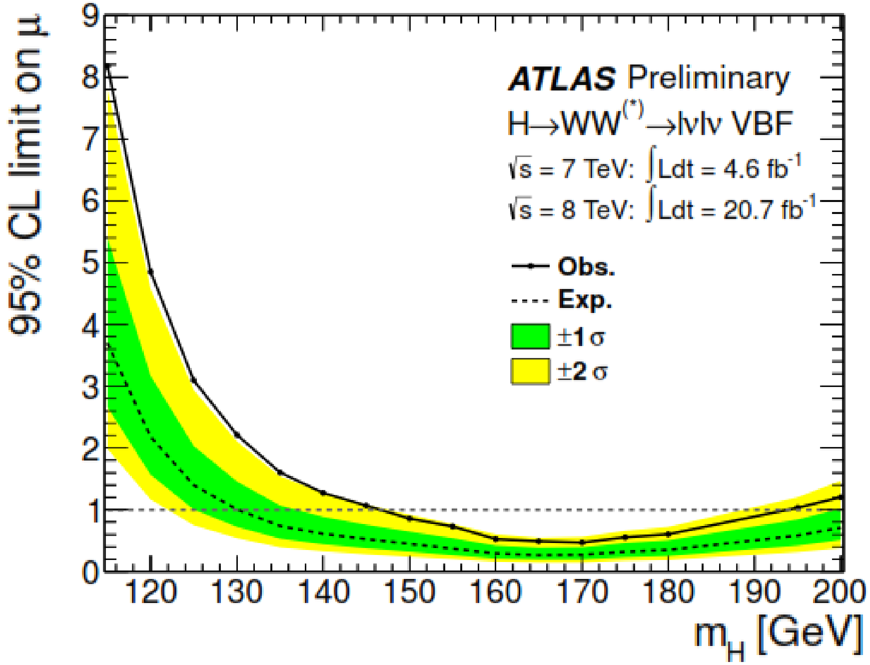


Results: VBF and Couplings

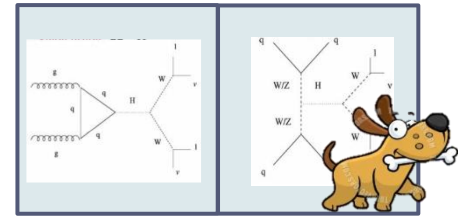


- At m_H =125 GeV (ggF is background)
  - Expected Significance : 1.6σ
  - Observed Significance : 2.5σ

$$\mu_{obs,VBF} = 1.66 \pm 0.79$$



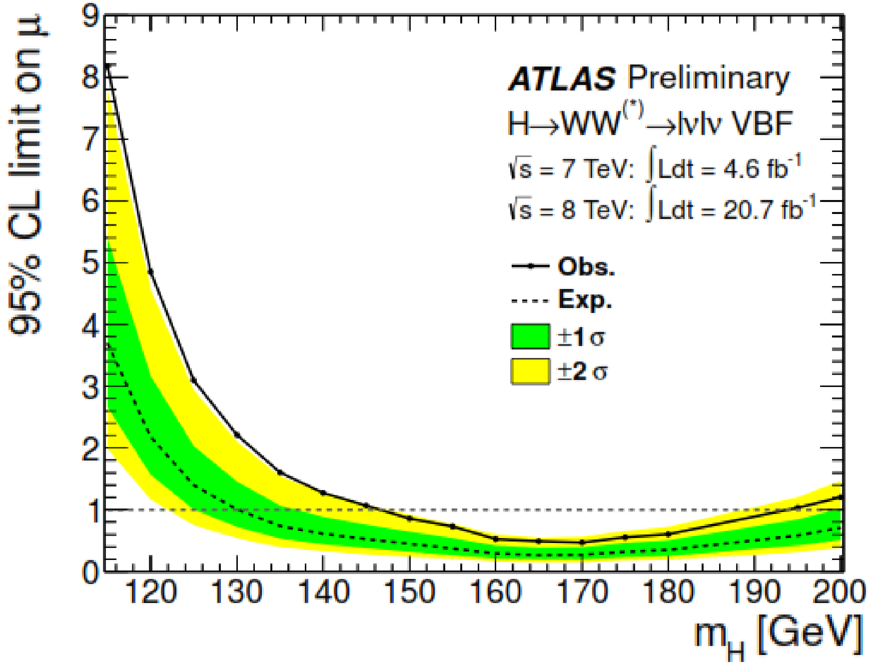
Results: VBF and Couplings

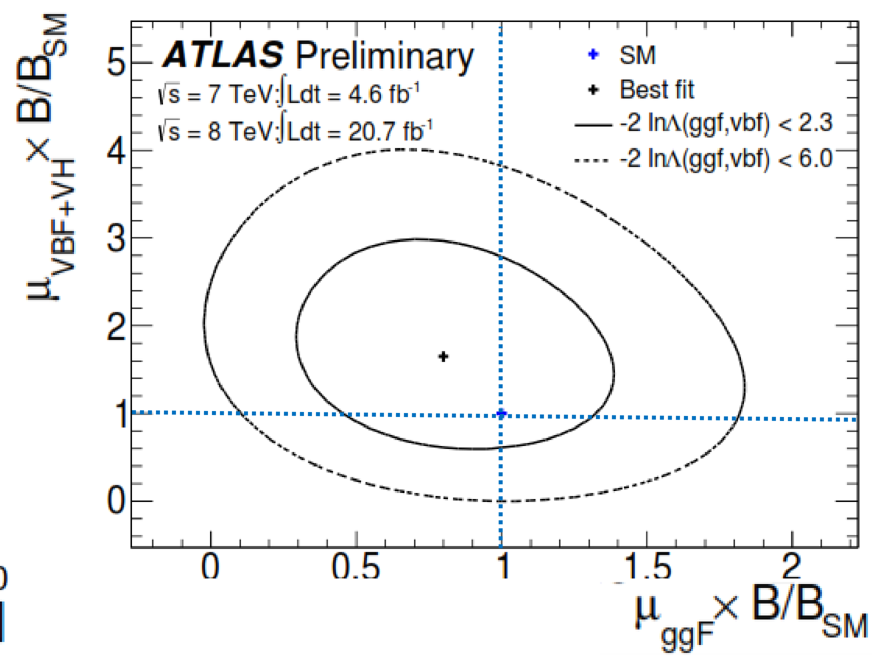


- At m_H =125 GeV (ggF is background)
  - Expected Significance : 1.6σ
  - Observed Significance : 2.5σ

$$\mu_{obs,VBF} = 1.66 \pm 0.79$$

- Consistent with SM value of 1

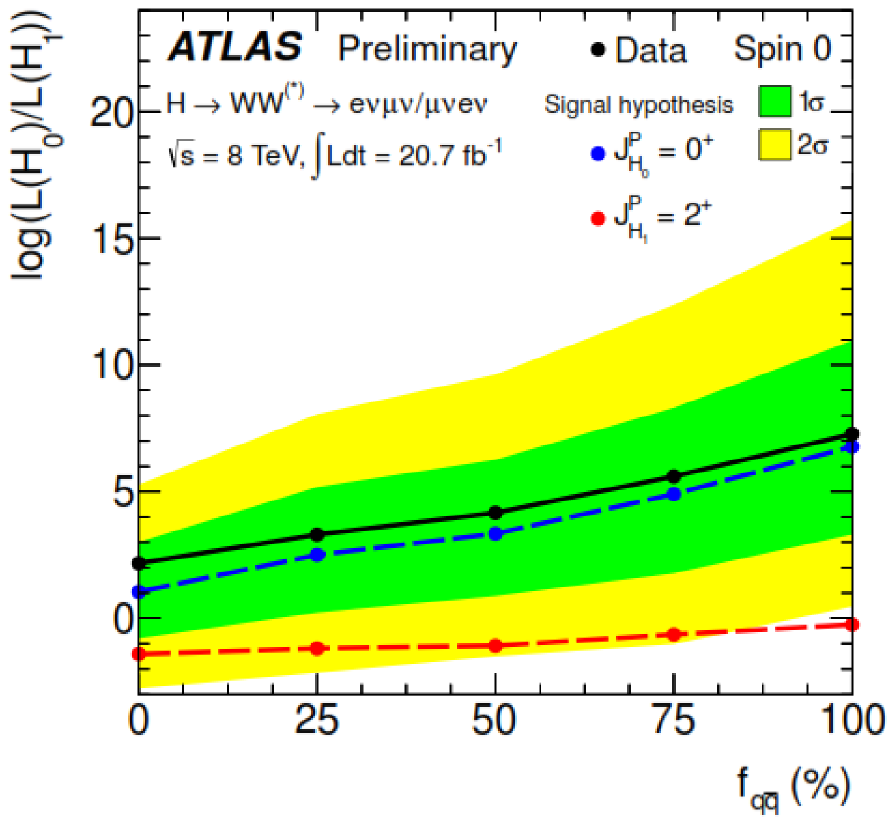




Spin

- Try to differentiate between Higgs with spin 0^+ and graviton-like spin 2^+ particle
- Focus on Different Flavour, 0 jet channel and 2012 data
- Use a Boosted Decision Tree (BDT) analysis, train 4 variables: m_T , $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, $p_T^{\ell\ell}$
- For spin 2^+ the fraction of gg vs $\bar{q}q$ production is unknown so scan is performed over 5 different fractions ($f_{q\bar{q}}$)
- Data are compatible with spin 0^+
- 2^+ $\bar{q}q$ excluded at 99% CL, gg excluded at 95% CL

$$q = \log\frac{\mathcal{L}(H_{0^+})}{\mathcal{L}(H_{2^+_m})} = \log\frac{\mathcal{L}(\epsilon=1,\hat{\hat{\mu}}_{\epsilon=1},\hat{\hat{\theta}}_{\epsilon=1})}{\mathcal{L}(\epsilon=0,\hat{\hat{\mu}}_{\epsilon=0},\hat{\hat{\theta}}_{\epsilon=0})}$$



Conclusions

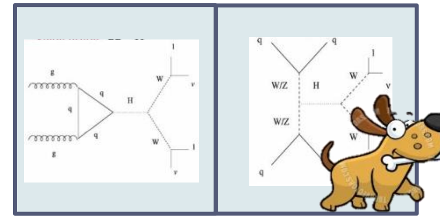
- The $H \to WW \to \ell\nu\ell\nu$ channel is presented in the mass range of 115 GeV - 200GeV with the full 25fb $^{-1}$ 7TeV+8 TeV dataset in 4 flavour channels split by 3 jet multiplicities
- The largest significance of 4.1σ occurs at m_H =140 GeV
- For m_H = 125 GeV:
  - $\mu_{obs} = 1.01 \pm 0.31$, $\mu_{obs,VBF} = 1.66 \pm 0.79$
- Spin analysis favours spin 0^+ Higgs, and rejects spin 2^+ with > 95% CL

References

- The Atlas Collaboration, Study of spin properties of the Higgs-like boson in the $H \to WW$ channel with 21fb^{-1} of $\sqrt{s}$= 8 TeV data collected with the ATLAS detector, ATLAS-CONF-2013-31, CERN, Geneva, 2013
- The Atlas Collaboration, Measurement of the properties of the Higgs-like boson in the $WW \to \ell\nu\ell\nu$ decay channel with the ATLAS detector using 25 fb^{-1} of proton-proton collision data, ATLAS-CONF-2013-030, CERN, Geneva, 2013
- J. Jovicevic, Probing the Standard Model Higgs boson in the WW decay mode with the ATLAS detector at the LHC, Licentiate Thesis, KTH Engineering Sciences, Stockholm, Sweden, 2013

BACKUP

Results: 7TeV+8TeV Combined



- Previous 7 TeV analysis improved with 2012 updates, better WW Modelling (MC@NLO → Powheg), improved lepton definition for W+jets reduction
- Event Yields for 0.75 $m_H < m_T < m_H$ ($m_T < 1.2\ m_H$ for ≥2j)

7 TeV improved	**Signal m_H = 125**	**Bkg**	**Data**
0 jet	24±5	161±11	154
1 jet	7±2	47±6	62
≥2 jet	1.4±0.2	4.6±0.8	2

8 TeV	**Signal m_H = 125**	**Bkg**	**Data**
0 jet	97±20	739±39	831
1 jet	40±13	261±28	309
≥2 jet	10.6±1.4	36±4	55

- Leading systematics are theoretical systematics on signal yields, jet energy scale/resolution and b-tagging efficiency

W+jets Estimation

- Estimated using data driven method since hard to model in MC
- Control Region: select 1 good lepton and 1 lepton does not satisfy strict selection requirements (Denominator Lepton)

$$\mathrm{N}_{\mathrm{W+j}}^{\mathrm{Bkg}} = f \times \mathrm{N}_{\mathrm{W+j}}^{\mathrm{CR}} \qquad f = \frac{N_{Good\ Lepton}}{N_{Denomiator}} \longrightarrow$$

Calculated from dijet events. ~45% uncertainty due to differences between di-jet and wjets, pileup and real lepton contamination from W/Z

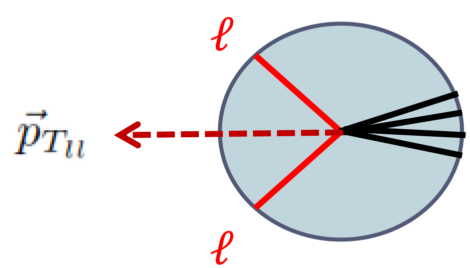
- Includes QCD background estimation, when both leptons are misidentified as jets
- A validation region with same sign leptons containing mostly W+jets is used to validate this method

Z/γ* Estimation

- Z/γ* $\rightarrow \tau\tau$
  - Background normalised to data using a different flavour CR defined by $m_{\ell\ell}$ < 80GeV and |Δφ|>2.8
  - The ≥ 2 jet CR in addition to above requires $N_{b\text{-jet}}$= 0 and p_T^{tot} <45 GeV
- Z/γ* $\rightarrow \ell\ell$
  - Small in different flavour, so taken from MC
  - In same flavour, N_{jet}≤1, f_{recoil} is used to define CR. For N_{jet} ≥2 E_t^{miss} - $m_{\ell\ell}$ in the Z peak is used to estimate DY since the statistics are to low and there are too many jets to use f_{recoil} method

quadrant opp. $\vec{p}_{T_{ll}}$; pileup weight

$$f_{\rm recoil} = \frac{\sum\limits_{\rm soft\ jets} w_i \times \vec{p}_{T_i}}{\vec{p}_{T_{ll}}}$$



Top Estimation

- MC Top normalised to data yields in CR after subtracting non-top backgrounds in 1j and 2 j
- 0j : $N^{est}_{top} = N^{data}_{top} + P^{est}_{0j}$, $P^{est}_{0j} = P^{mc}_{0j} \times \frac{\left(P^{Btag.Data}_{veto}\right)^2}{\left(P^{BtagMC}_{veto}\right)^2}$

$$\downarrow$$

$$= \frac{N^{Btag}_{No\ probing\ jets}}{N^{Btag}}$$

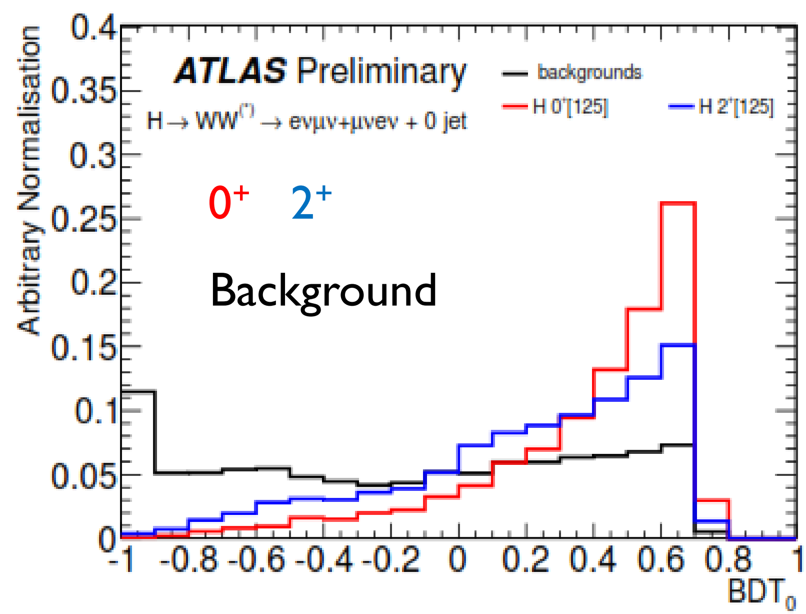
From btagged CR

- ≥1j: $N^{SR} = N^{CR}\alpha$, $\alpha = \frac{N_{SR}}{N_{CR}}$ is from simulation
  - CR region is defined using same selection but with N_{bjet}=1 and requirements on $\Delta\phi_{\ell\ell}$ and $m_{\ell\ell}$ removed
  - α = 1.04± .02(stat) for 1j, α = 0.59 ± .07(stat) for 2jet

Spin

- Do 2 BDT trainings for 0^+ and 2^+ and perform 2D fit on BDT_0 and BDT_2

Variable	Spin analysis	Rate analysis [5]
	common $e\mu/\mu e$ lepton selection	
$E_{T,rel}^{miss}$	> 20 GeV	> 25 GeV
N_{jets}	0 jets	$0, 1, \geq 2$ jet selections
$p_T^{\ell\ell}$	> 20 GeV	> 30 GeV
$m_{\ell\ell}$	< 80 GeV	< 50 GeV
$\Delta\phi_{\ell\ell}$	< 2.8	< 1.8



Systematics

Source	Signal processes (%)			Background processes (%)		
	$N_{jet} = 0$	$N_{jet} = 1$	$N_{jet} \geq 2$	$N_{jet} = 0$	$N_{jet} = 1$	$N_{jet} \geq 2$
Theoretical uncertainties						
QCD scale for ggF signal for $N_{jet} \geq 0$	13	-	-	-	-	-
QCD scale for ggF signal for $N_{jet} \geq 1$	10	27	-	-	-	-
QCD scale for ggF signal for $N_{jet} \geq 2$	-	15	4	-	-	-
QCD scale for ggF signal for $N_{jet} \geq 3$	-	-	4	-	-	-
Parton shower and UE model (signal only)	3	10	5	-	-	-
PDF model	8	7	3	1	1	1
$H \rightarrow WW$ branching ratio	4	4	4	-	-	-
QCD scale (acceptance)	4	4	3	-	-	-
WW normalisation	-	-	-	1	2	4
Experimental uncertainties						
Jet energy scale and resolution	5	2	6	2	3	7
b-tagging efficiency	-	-	-	-	7	2
f_{recoil} efficiency	1	1	-	4	2	-

Full Selection

Category	$N_{\text{jet}} = 0$	$N_{\text{jet}} = 1$	$N_{\text{jet}} \geq 2$
Pre-selection	Two isolated leptons ($\ell = e, \mu$) with opposite charge Leptons with $p_{\text{T}}^{\text{lead}} > 25$ and $p_{\text{T}}^{\text{sublead}} > 15$ $e\mu + \mu e$: $m_{\ell\ell} > 10$ $ee + \mu\mu$: $m_{\ell\ell} > 12$, $\|m_{\ell\ell} - m_Z\| > 15$		
Missing transverse momentum and hadronic recoil	$e\mu + \mu e$: $E_{\text{T,rel}}^{\text{miss}} > 25$ $ee + \mu\mu$: $E_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $p_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $f_{\text{recoil}} < 0.05$	$e\mu + \mu e$: $E_{\text{T,rel}}^{\text{miss}} > 25$ $ee + \mu\mu$: $E_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $p_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $f_{\text{recoil}} < 0.2$	$e\mu + \mu e$: $E_{\text{T}}^{\text{miss}} > 20$ $ee + \mu\mu$: $E_{\text{T}}^{\text{miss}} > 45$ $ee + \mu\mu$: $E_{\text{T,STVF}}^{\text{miss}} > 35$ -
General selection	- $\|\Delta\phi_{\ell\ell,MET}\| > \pi/2$ $p_{\text{T}}^{\ell\ell} > 30$	$N_{b\text{-jet}} = 0$ - $e\mu + \mu e$: $Z/\gamma^* \rightarrow \tau\tau$ veto	$N_{b\text{-jet}} = 0$ $p_{\text{T}}^{\text{tot}} < 45$ $e\mu + \mu e$: $Z/\gamma^* \rightarrow \tau\tau$ veto
VBF topology	- - - -	- - - -	$m_{jj} > 500$ $\|\Delta y_{jj}\| > 2.8$ No jets ($p_{\text{T}} > 20$) in rapidity gap Require both ℓ in rapidity gap
$H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$ topology	$m_{\ell\ell} < 50$ $\|\Delta\phi_{\ell\ell}\| < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_{T}	$m_{\ell\ell} < 50$ $\|\Delta\phi_{\ell\ell}\| < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_{T}	$m_{\ell\ell} < 60$ $\|\Delta\phi_{\ell\ell}\| < 1.8$ - Fit m_{T}

Monte Carlo

Signal	MC generator	$\sigma \cdot \mathcal{B}$ (pb)
ggF	POWHEG [30]+PYTHIA8 [31]	0.44
VBF	POWHEG+PYTHIA8	0.035
VH	PYTHIA8	0.13

Background	MC generator	$\sigma \cdot \mathcal{B}$ (pb)
$q\bar{q}, gq \to WW$	POWHEG+PYTHIA6 [32]	5.7
$q\bar{q}, gq \to WW{+}2j$	Sherpa [33] with no $O(\alpha_s)$ terms	0.039
$gg \to WW$	GG2WW 3.1.2 [34, 35]+HERWIG [36]	0.16
$t\bar{t}$	MC@NLO [37]+HERWIG	240
Single top: tW, tb	MC@NLO+HERWIG	28
Single top: tqb	AcerMC [38]+PYTHIA6	88
Z/γ^*, inclusive	ALPGEN+HERWIG	16000
$Z^{(*)} \to \ell\ell + 2j$	Sherpa processes up to $O(\alpha_s)$	1.2
$Z^{(*)}Z^{(*)} \to 4\ell$	POWHEG+PYTHIA8	0.73
$WZ/W\gamma^*, m_{Z/\gamma^*}{>}7$	POWHEG+PYTHIA8	0.83
$W\gamma^*, m_{\gamma^*} \leq 7$	MadGraph [39–41]+PYTHIA6	11
$W\gamma$	ALPGEN+HERWIG	370