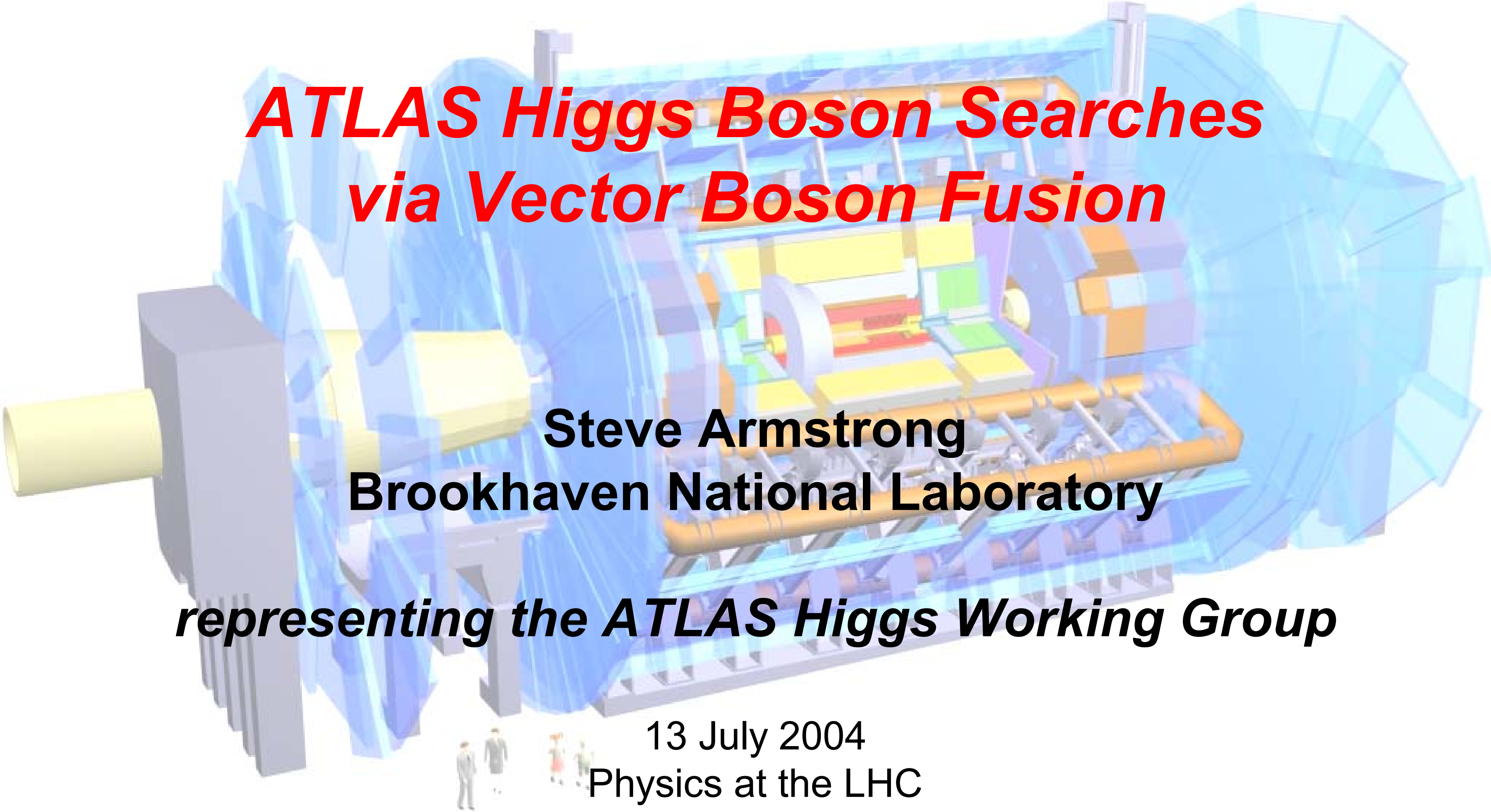


ATLAS Higgs Boson Searches via Vector Boson Fusion

Steve Armstrong
Brookhaven National Laboratory

representing the ATLAS Higgs Working Group

13 July 2004
Physics at the LHC
Vienna, Austria
13 – 17 July 2004

OUTLINE

- **INTRODUCTION AND EXPERIMENTAL CONSIDERATIONS**
- **LOW MASS RANGE DISCOVERY CHANNELS**
- **RECENT PROGRESS IN INTERMEDIATE MASS RANGE**
- **FURTHER ISSUES**
- **SUMMARY**

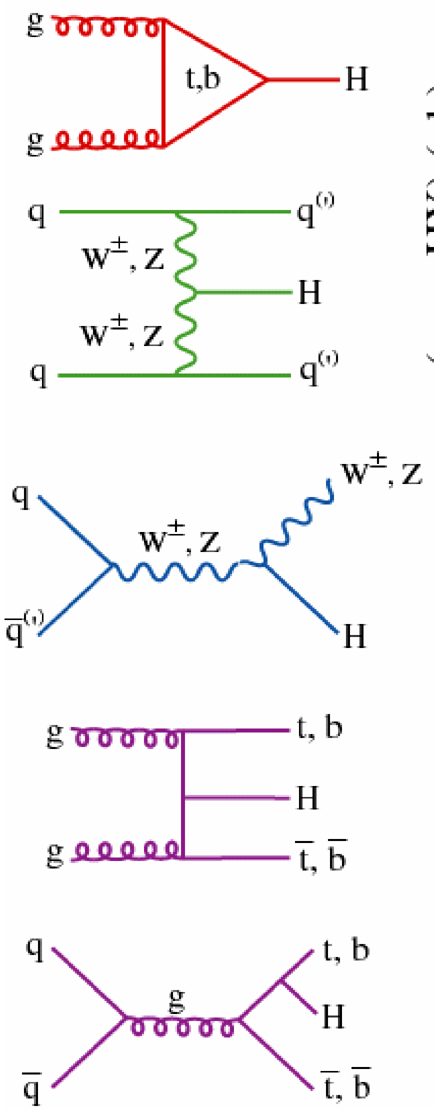
STANDARD MODEL HIGGS PRODUCTION AT LHC

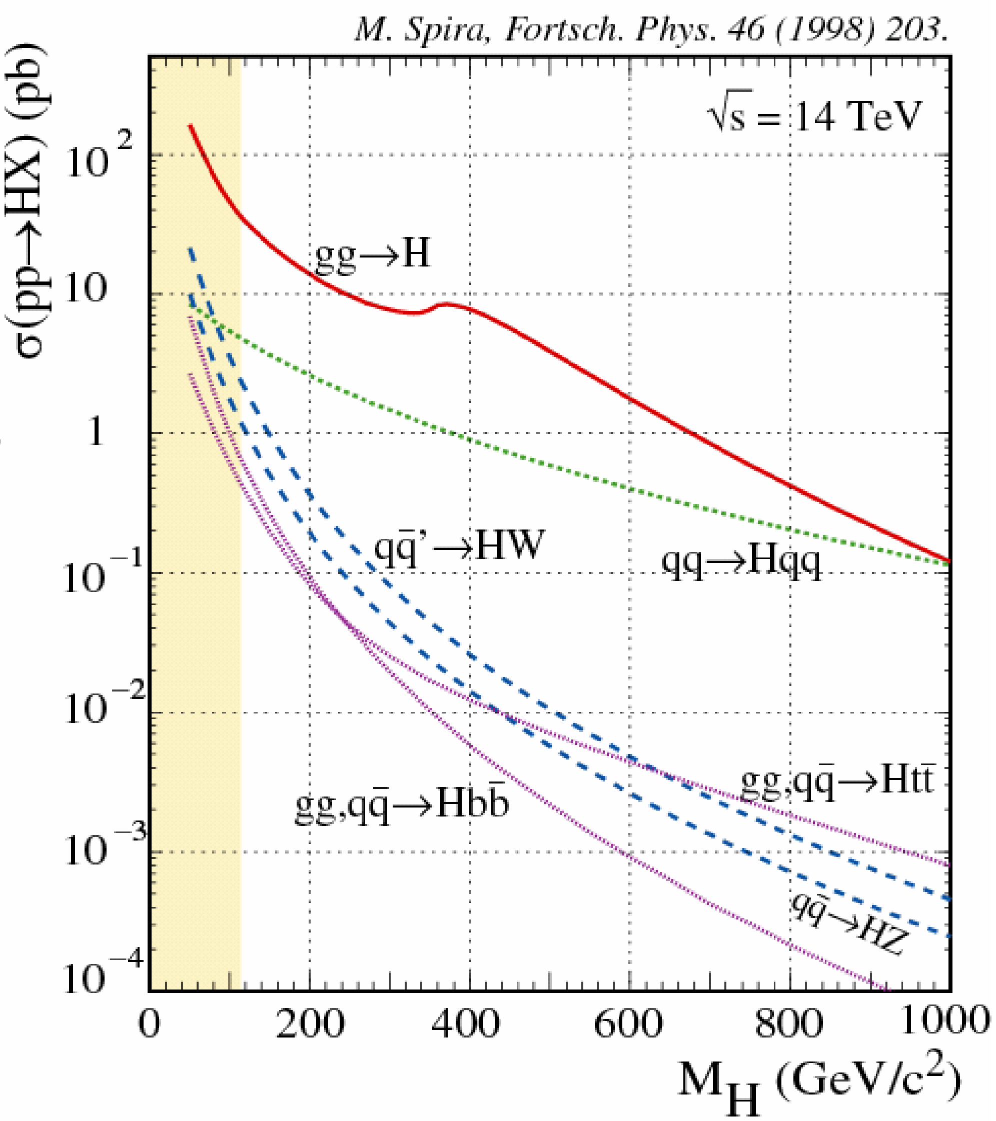
Direct:
Gluon Fusion
large bkg. close to LEP limit

Vector Boson Fusion (VBF):
Distinct Final State

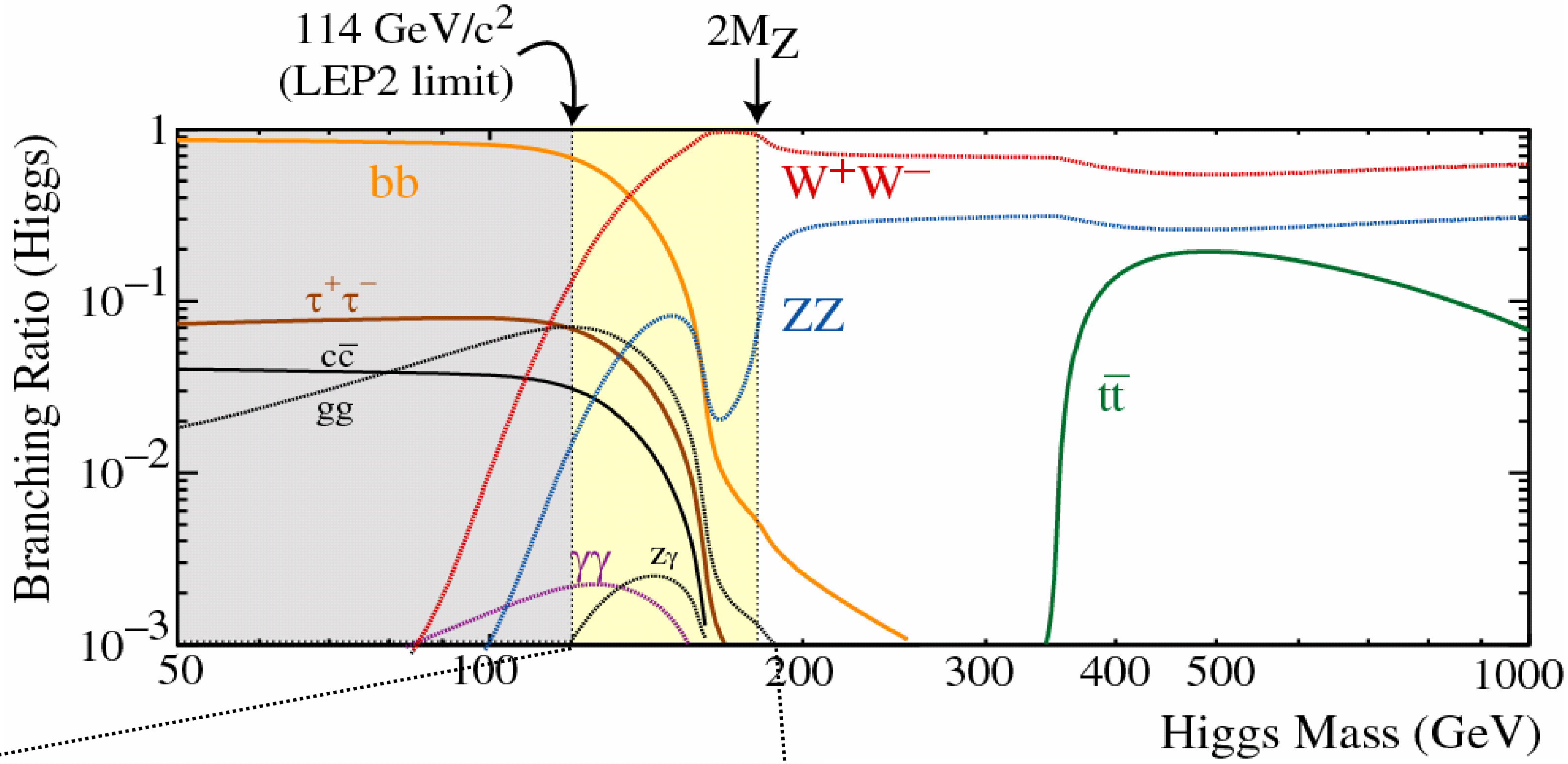
Associated Production (W or Z):
Small σ

Associated Production (tt or bb):
Small σ





STANDARD MODEL HIGGS DECAY



"Low" Mass Range
(i.e., LEP2 limit to ~2 M_Z)

$H\rightarrow\gamma\gamma$: smallest BR but best resolution

$H\rightarrow b\bar{b}$: good BR but poor resolution

$H\rightarrow\tau\tau$: via VBF

$H\rightarrow WW^*\rightarrow\ell^+\nu\ell^-\nu$ or $\ell^\pm\nu qq$: via VBF

$H\rightarrow ZZ^*\rightarrow 4\ell^\pm$

VBF production mode enhances low mass Higgs sensitivity

- **Rainwater & Zeppenfeld (1997)**
- **Beyond SM:Invisible Higgs decays (Eboli and Zeppenfeld, 2000)**
- **Improves Higgs parameters measurements (couplings)**

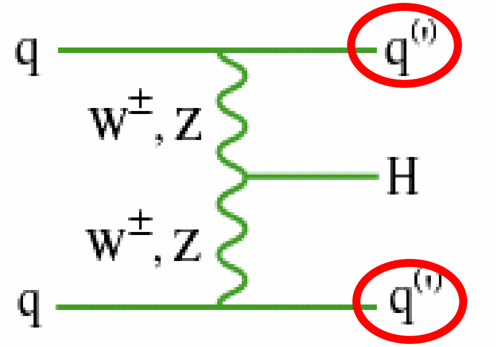
DISTINCT VBF EXPERIMENTAL SIGNATURES

VBF Production Mode yields a distinct final state:

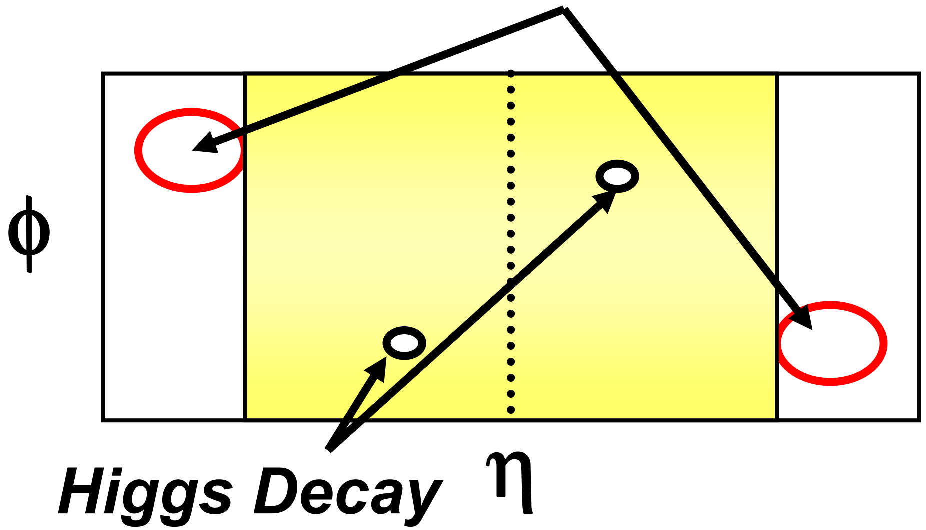
two initial quark jets have small scattering angle → high η signatures

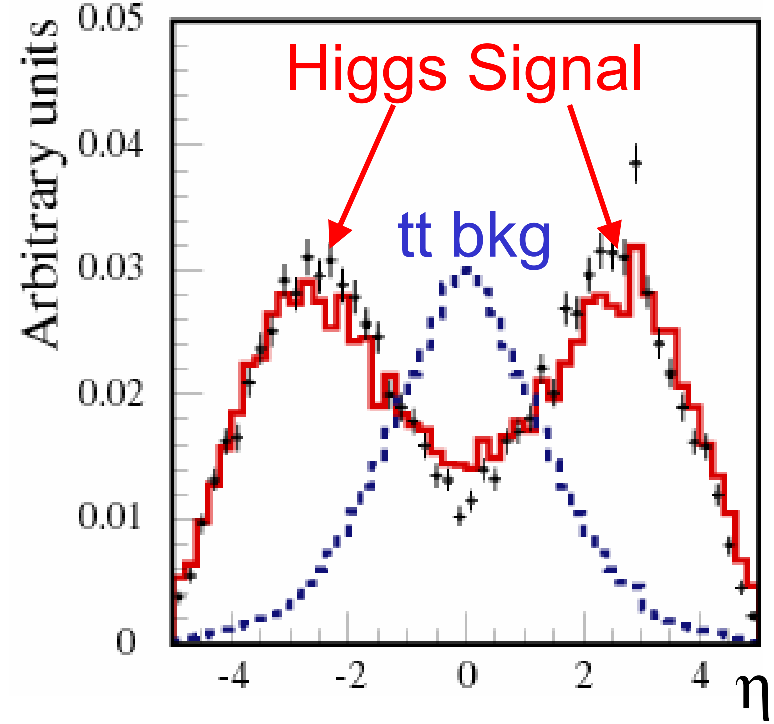
AND

suppression of central jet activity due to lack of color exchange



Forward Tagging Jets





Feasibility studies:

CMS Note 2003/033

ATLAS SN-ATLAS-2003-024

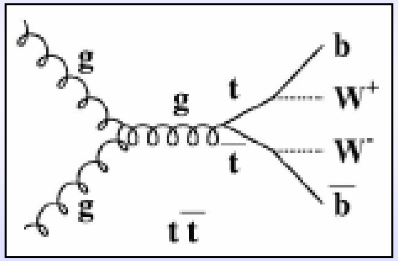
Updates and new studies in progress

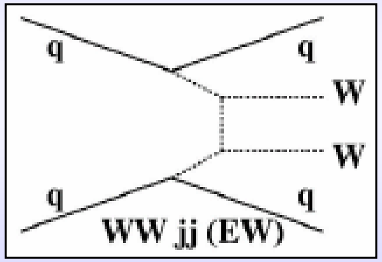
LOW MASS VBF FINAL STATES

H → WW* → ℓνℓν or ℓνqq'

- **Strongest channel: 125 < M_H < 190 GeV/c^2**
- **Higgs mass from transverse mass (M_T)**

Main Background

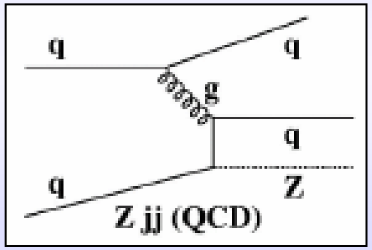


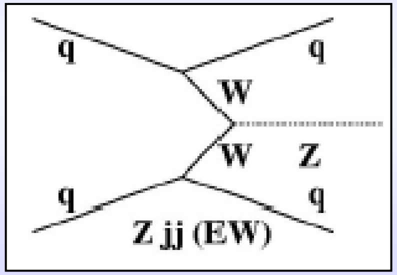


H → $\tau^+\tau^-$ → ℓννℓν or ℓνν had.ν

- **Strong near LEP limit M_H ~ 115 GeV/c^2**
- **Higgs mass from collinear approximation $M_{\tau\tau}$ with $\Delta M_H/M_H$ ~ 10%**

Main Background



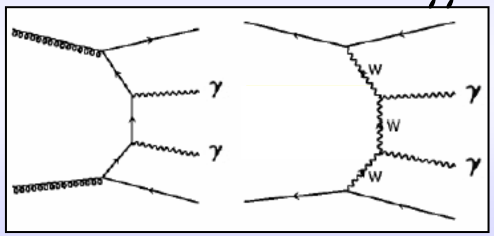


H → γγ *(2 jets VBF-style)*

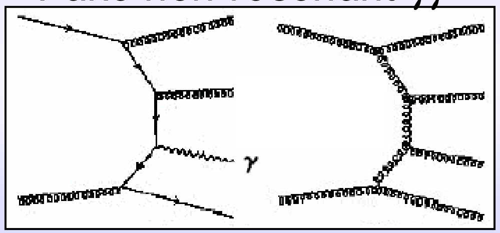
- **Sensitive:115 < M_H < 150 GeV/c^2**
- **Excellent Higgs mass from $M_{\gamma\gamma}$ with $\Delta M_H/M_H$ ~ 1.4%**

Main Background

Real non-resonant γγ



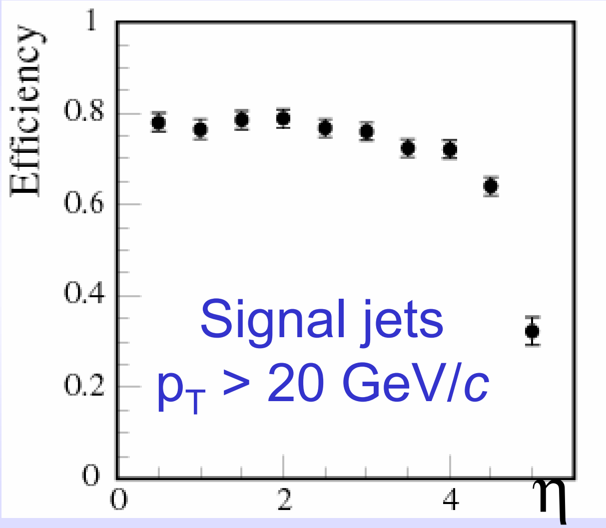
Fake non-resonant γγ



JETS: TAGGING AND VETO

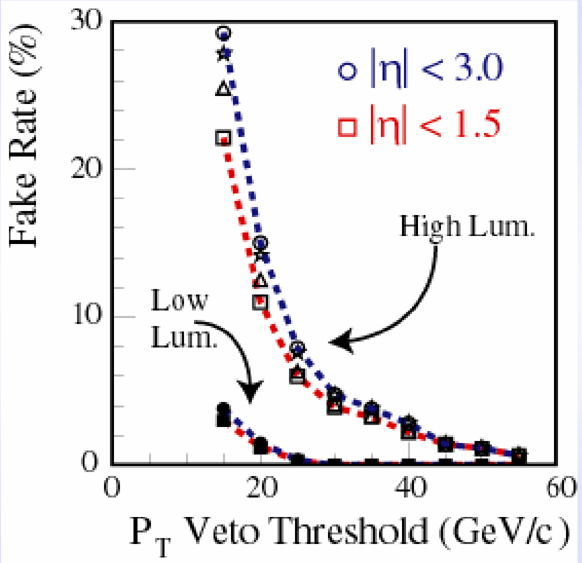
FORWARD JET TAG

- Forward jet tag reconstruction studies with full simulation
- Tag jets searched for within full calorimeter coverage ($|\eta|<4.9$)
- Jets with highest p_T in + and – rapidity regions taken as tag jets



FAKE JET VETO

- Jets from pile-up in central and forward regions could degrade
- Studies in full simulation as function of LHC luminosity
- Low luminosity: jet veto threshold of 20 GeV/*c*
- High luminosity: steep rise – veto must be raised to ~30 GeV/*c*



OUTLINE

¶ **INTRODUCTION AND EXPERIMENTAL CONSIDERATIONS**

¶ **LOW MASS RANGE VBF DISCOVERY CHANNELS**

- **H $\rightarrow$ WW$^{(*)}$ $\rightarrow$ $\ell\nu\ell\nu$ and $\ell\nu qq'$**
- **H $\rightarrow$ $\tau^+\tau^-$**
- **H $\rightarrow$ $\gamma\gamma$**
- **COMBINED STANDARD MODEL HIGGS SENSITIVITY**
- **INVISIBLE HIGGS DECAYS**

¶ **RECENT PROGRESS IN INTERMEDIATE MASS RANGE**

¶ **FURTHER ISSUES**

¶ **SUMMARY**

$H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$

HIGGS MASS RECONSTRUCTION

- **For $M_H < 2M_W$: W's at rest in Higgs center-of-mass: $M_{\ell\ell} \approx M_{\nu\nu}$**

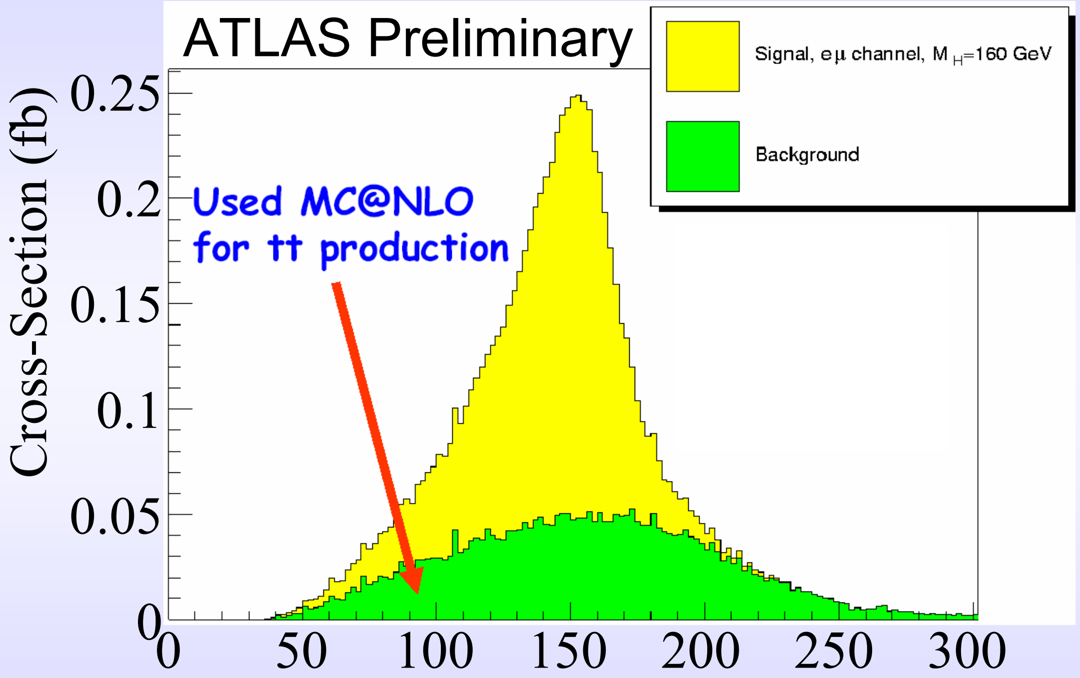
$$E_T^{\ell\ell} = \sqrt{(P_T^{\ell\ell})^2 + m_{\ell\ell}^2},$$

$$E_T^{\nu\nu} = \sqrt{(P_T^{miss})^2 + m_{\ell\ell}^2}.$$

$$M_T = \sqrt{(E_T^{\ell\ell} + E_T^{\nu\nu})^2 - (\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{miss})^2}.$$

ANALYSIS STRATEGY

- **Leption identification**
- **p_T cuts on leptons**
- **Two energetic and well rapidity-separation for tag jets**
- **Leptons between tag jets**
- **Lepton criteria (angular, invariant mass, p_T)**
- **Tau veto**
- **Invariant mass of two tag jets**
- **Transverse momentum balance**
- **Jet veto**

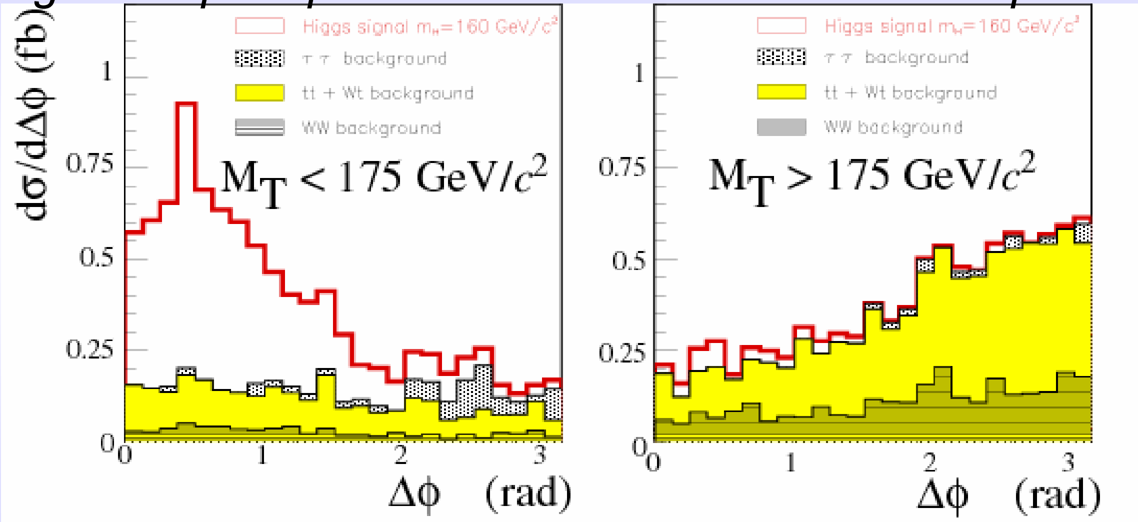


Multivariate (NN) analyses are also being developed with promising ~45% improvement

SELECTED $H \to WW^{(*)} \to \ell\nu\ell\nu$ ANALYSIS DETAILS

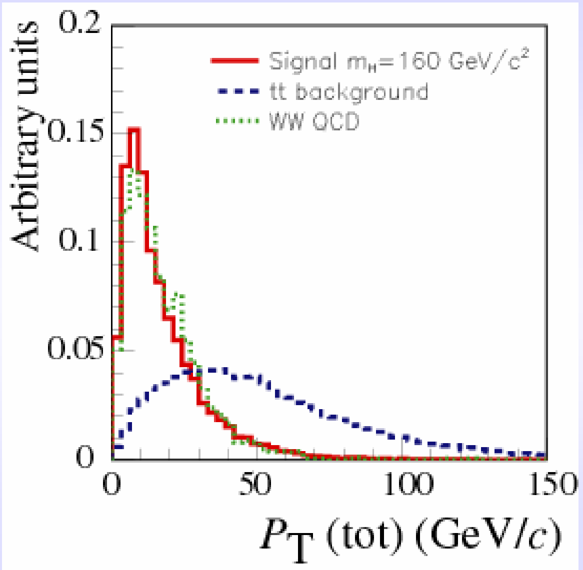
Azimuthal opening angle of lepton pair sensitive to kinematics and spin of Higgs boson

LEPTON KINEMATIC/SPIN-0 CONSISTENCY



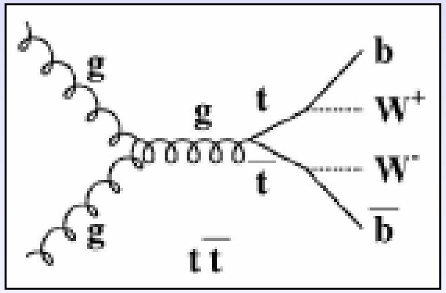
TRANSVERSE MOMENTUM BALANCE

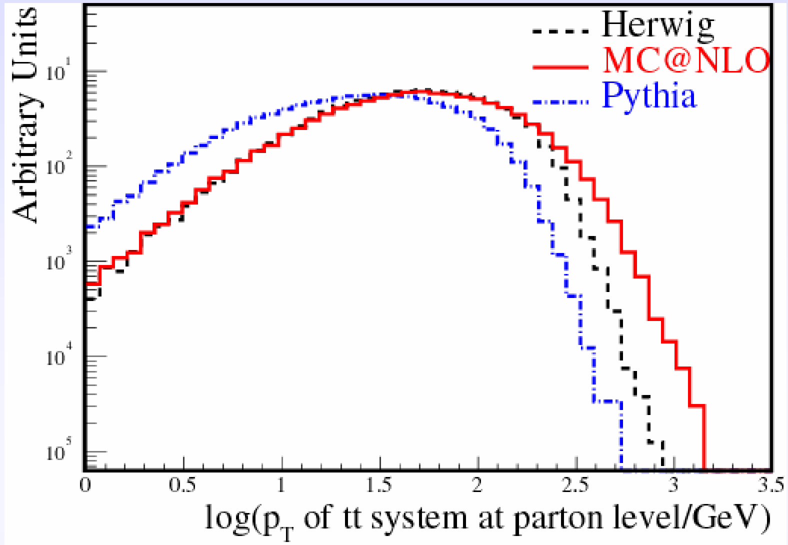
- If no hard initial- or final-state gluons, p_T of Higgs balanced by p_T of tag jets
- $P_T^{tot} = P_T^{\ell,1} + P_T^{\ell,2} + P_T^{miss} + P_T^{j,1} + P_T^{j,2}$
- At high luminosity, only broadening of p_T distribution; largely insensitive to jets from pile-up

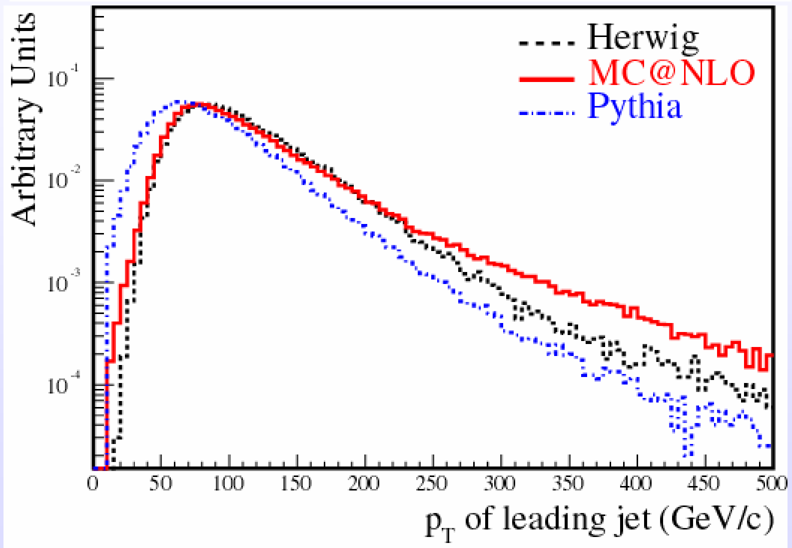


$H \rightarrow WW^{(*)}$ STUDIES OF tt BACKGROUND

Differences between PYTHIA, HERWIG, and MC@NLO studied for tt+jets processes which comprise the main background for $H \rightarrow WW^{(*)}$



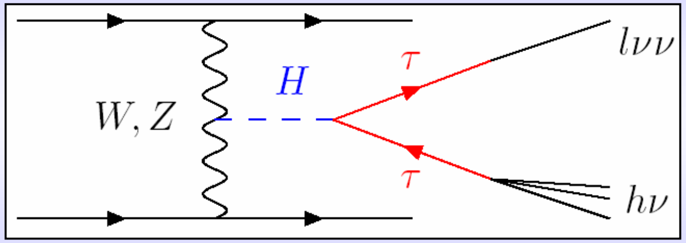




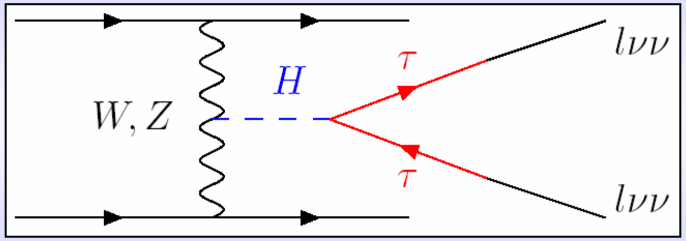
- **PYTHIA and HERWIG use Leading Order (LO) calculation of tt process combined with leading log. treatment of higher orders described by Parton Shower (PS) approximation**
- **MC@NLO combines PS and NLO calculations**
- **Strong difference in p_T distributions observed**
- **Fortunately, overall analysis level discovery potential does not suffer significantly (~10%) → robustness**

$H \to \tau^+\tau^-$

FULLY OR SEMI LEPTONIC FINAL STATES

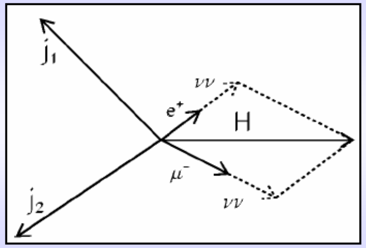


or



HIGGS MASS RECONSTRUCTION

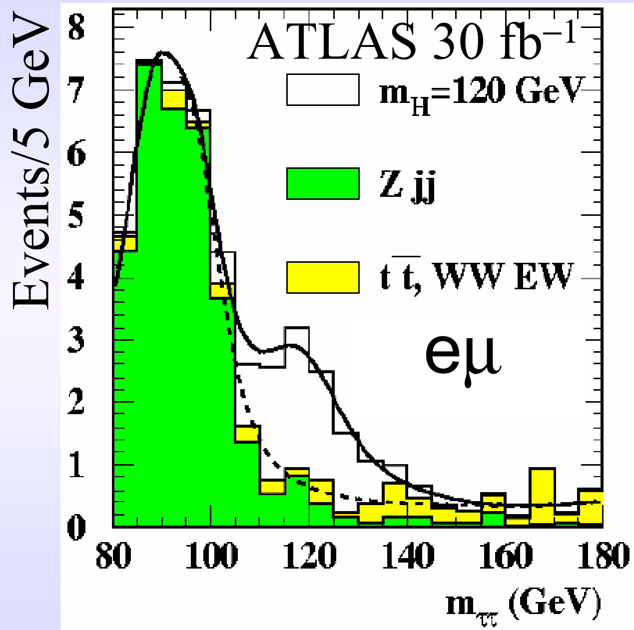
- Visible lept. or had. decay products = τ direction
- Use $\not{p}_T$ to solve for fraction of visible τ energy
- $m_{\tau\tau} = m_{\ell\ell}/\sqrt{x_{\tau1}x_{\tau2}}$ yields 10% resolution



ANALYSIS STRATEGY

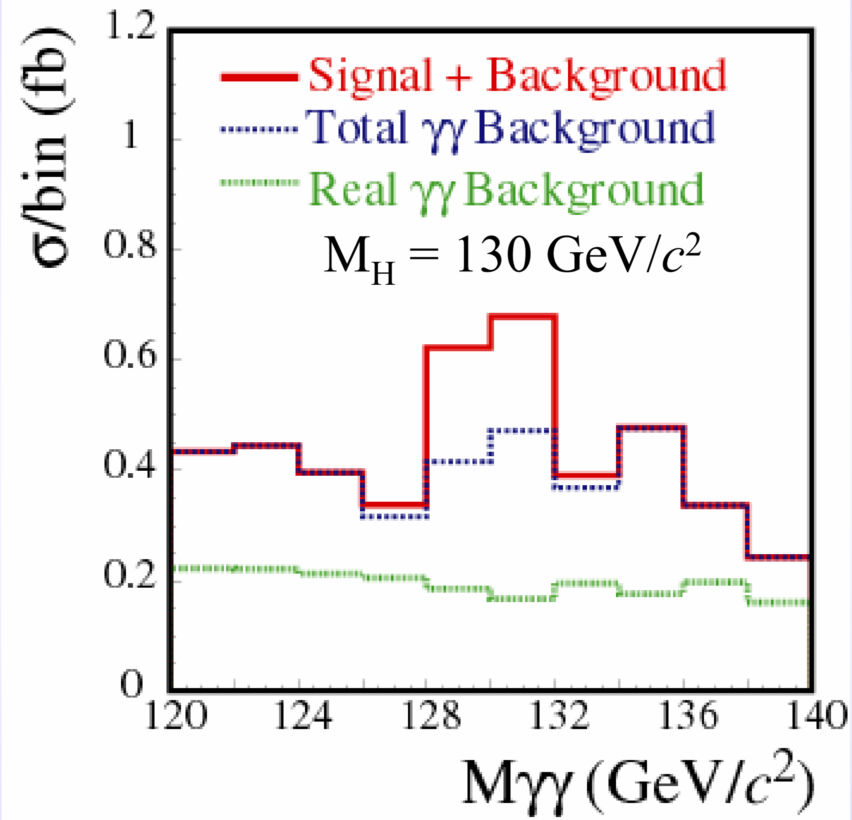
- Leption identification and isolation
- b-jet veto
- Two energetic and well rapidity-separation for tag jets
- Missing transverse momentum
- High invariant mass of two tag jets
- Central jet veto
- Limited aximuthal separation of tag jets
- Valid tau reconstruction
- Mass window around Higgs mass

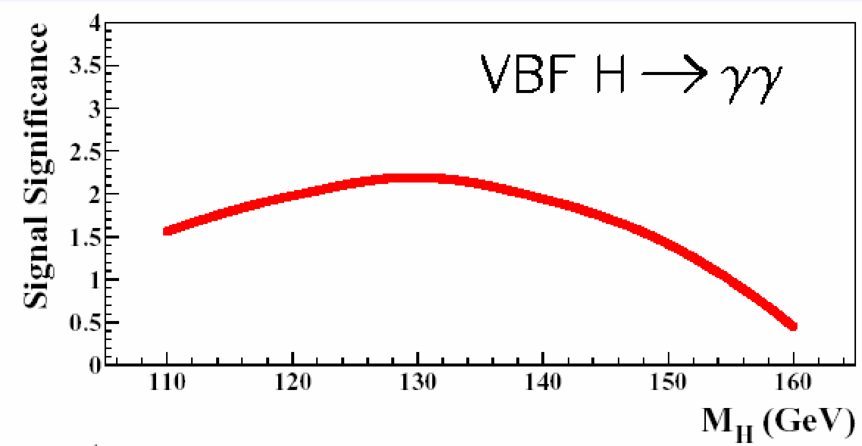
Multivariate (NN) analyses are also being developed with promising ~45% improvement



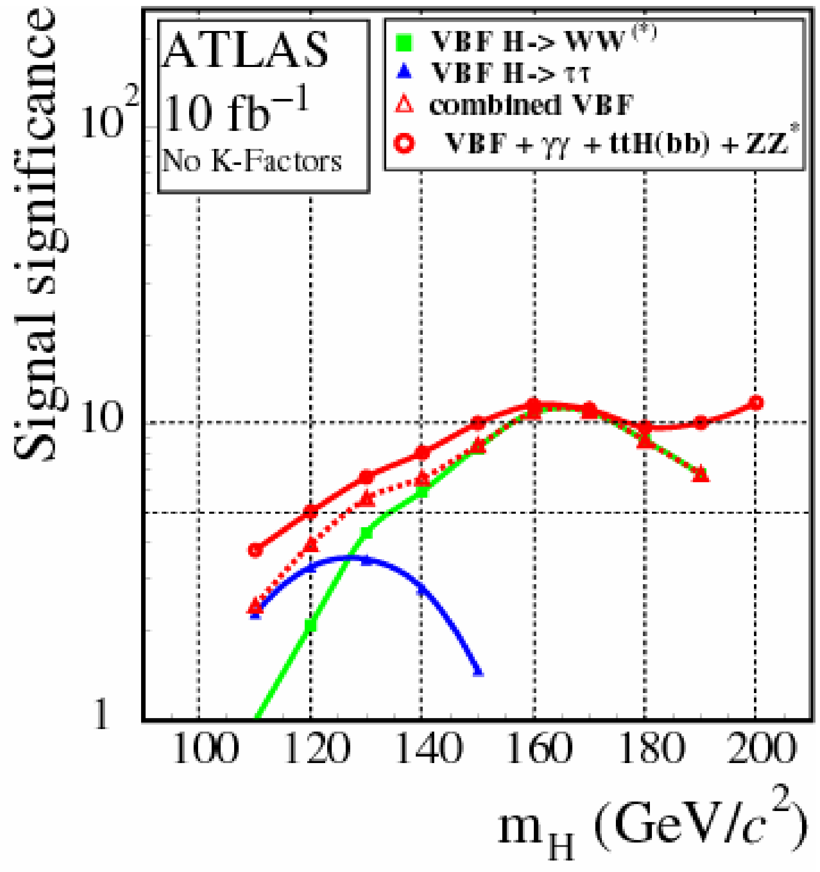
H → γγ WITH VBF

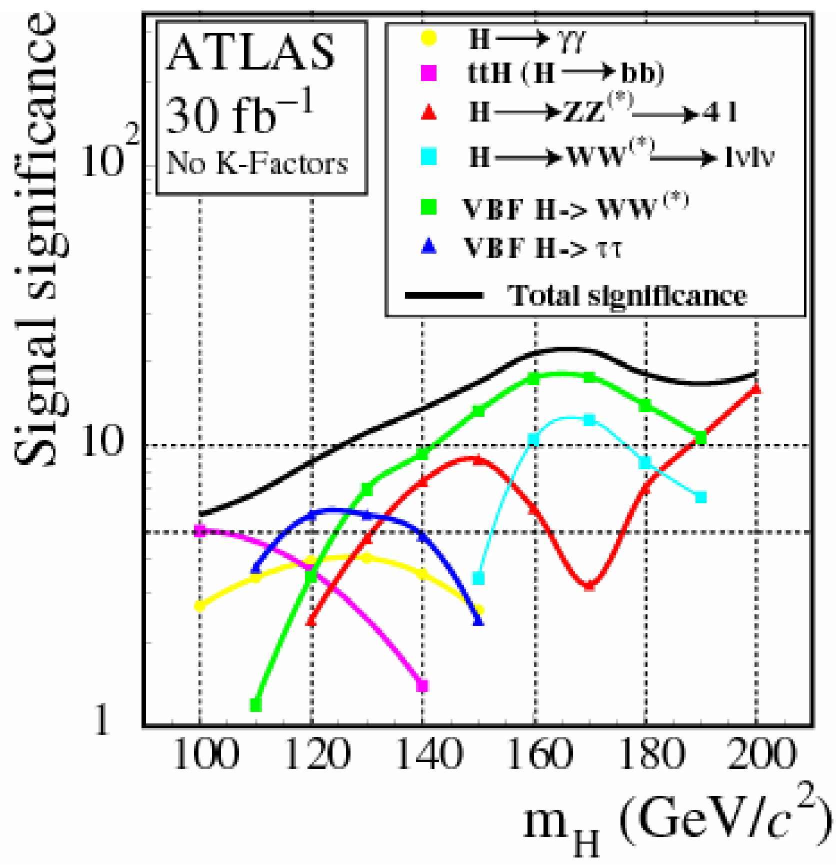
- **Complements inclusive H→γγ analyses**
- **Excellent calorimeter performance allows $M_{\gamma\gamma}$ to resolve Higgs mass to ~1.4%**
- **Analysis Strategy to reject real and fake di-photon background:**
  - **Photon p_T cuts**
  - **Two tagging jets with large rapidity separation**
  - **Photons between tagging jets**
- **~2σ sensitivity for 30 fb^{-1}**





STANDARD MODEL HIGGS SENSITIVITY





***N.B.* Updated and revised sensitivities incorporating most recent VBF developments and improvements are in progress**

INVISIBLE HIGGS DECAYS VIA VBF

In a variety of models and scenarios beyond the SM, Higgs could decay to new weakly interacting particles (i.e., invisible decay products)

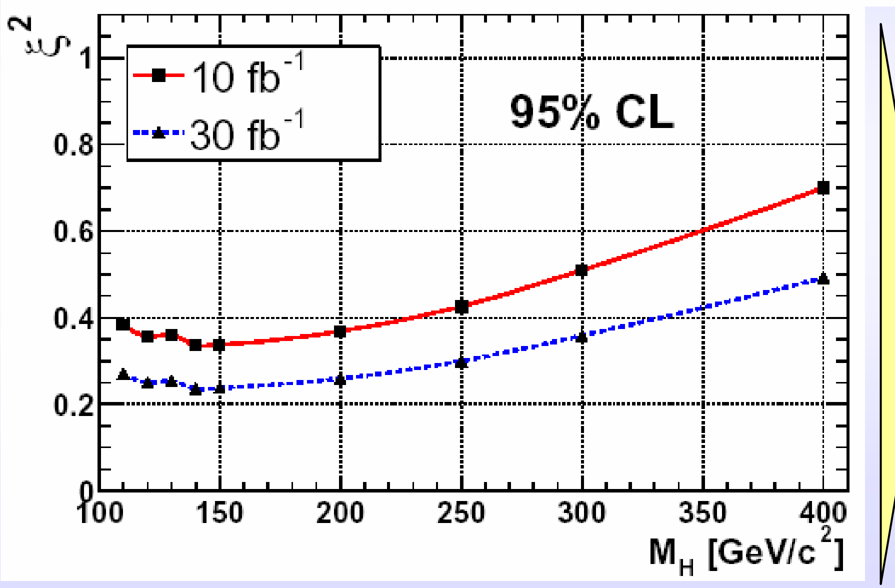
SIGNAL

- **Two high |η| tagging jets**
- **considerable $\not{p}_T$ in central region**
- **need to augment LVL1 $\not{E}_T$ trigger with 2 jets, if not x2.5 less sensitive**

BACKGROUND

- **Zjj with Z→νν**
- **Wjj with W→ℓν, ℓ undetected**
- **QCD multi-jet with semileptonic decays and/or undetected particles**

	m_H (GeV/c^2)	110	120	130	140	150	200	250	300	400
L (fb^{-1})	$\sigma(\phi_{jj} < 1)$ (fb)	55.4	60.0	59.1	63.5	63.1	57.8	50.1	41.8	30.5
10	ξ^2(%)(stat)	19.4	18.0	18.3	17.0	17.1	18.7	21.5	25.8	35.4
	ξ^2(%) (stat+ sys)	38.5	35.6	36.1	33.6	33.8	36.9	42.6	51.0	70.0
30	ξ^2(%)(stat)	11.2	10.4	10.5	9.8	9.9	10.8	12.4	14.9	20.4
	ξ^2(%) (stat+ sys)	27.1	25.0	25.4	23.6	23.8	26.0	30.0	35.9	49.2



Model-dependent parameter

$$\xi^2 = BR(H \to Inv.) \times \frac{\sigma(qq \to qqH)}{\sigma(qq \to qqH)_{SM}}$$

Via VBF, possible to probe ξ^2 values down to 35% for m_H = 140 GeV/c^2 and down to 70% for 400 GeV/c^2

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¶ **LOW MASS RANGE VBF DISCOVERY CHANNELS**

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¶ **FURTHER ISSUES**

¶ **SUMMARY**

INTERMEDIATE MASS VBF MODES

For $2M_Z < M_H < 600$ GeV/c² possible to complement/confirm powerful $H \to ZZ \to 4\ell$ with VBF modes $H \to ZZ \to \ell\ell\, qq$ and $H \to WW \to \ell\nu\, qq'$

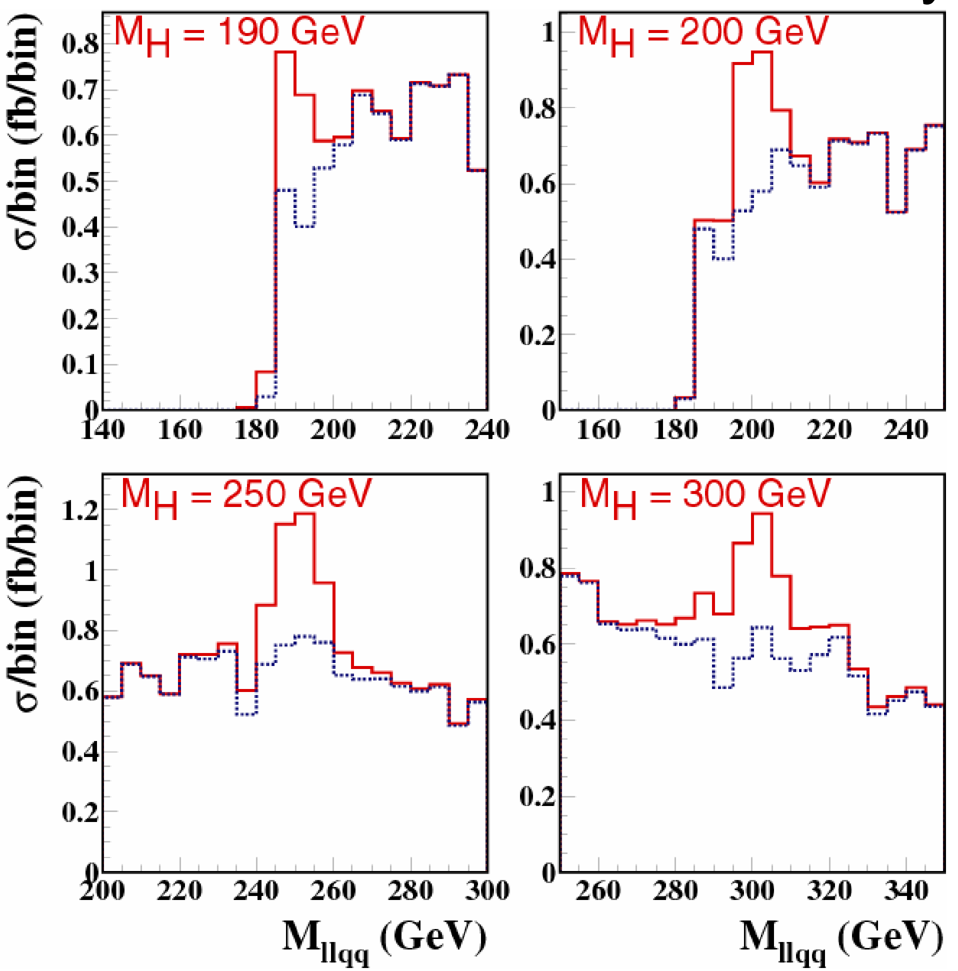
- **Re-use almost all features of low mass VBF analyses**
- **For *$H \to ZZ \to \ell\ell\, qq$*:**
  - **jet ambiguity issue resolved with use of Z mass**
  - **two oppositely charged leptons of same flavour**
  - **no b-tag since $Z \to bb$**
  - **Kinematic fit improves reconstructed Higgs mass resolution to ~2.5%**

$H \to ZZ \to \ell\ell\, qq$

ATLAS 30 fb^{-1} Preliminary

M_H(GeV)	S	B	S/B	σ_L
190	18.9	31.2	0.61	3.47
200	27.3	52.8	0.52	3.76
300	39.3	116.1	0.34	3.75
500	20.1	124.2	0.16	1.98

Preliminary



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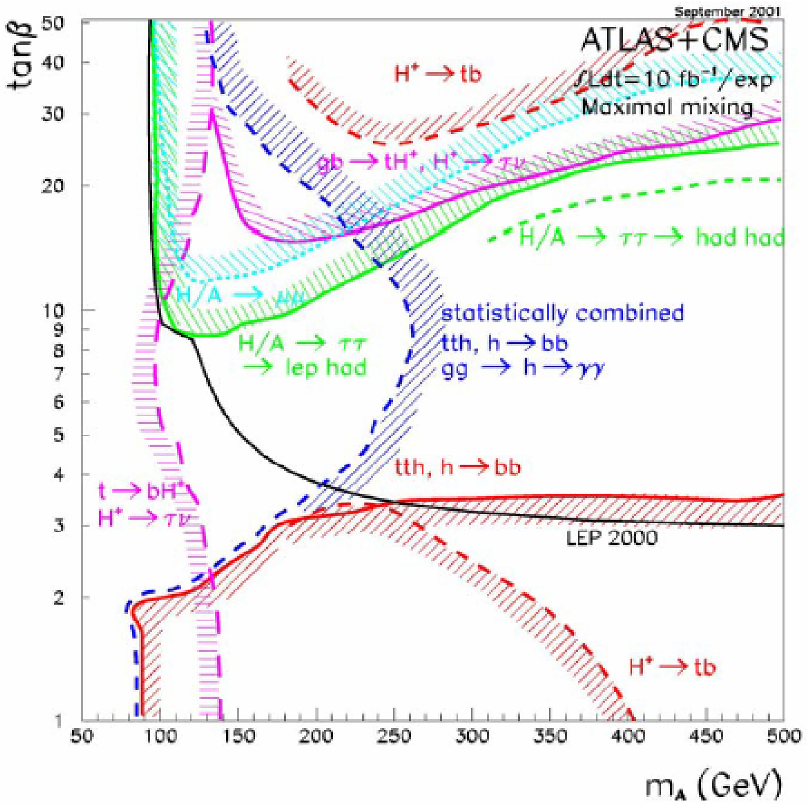
¶ **FURTHER ISSUES**
- **MSSM HIGGS WITH VBF**
- **MEASUREMENT OF HIGGS PARAMETERS**

¶ **SUMMARY**

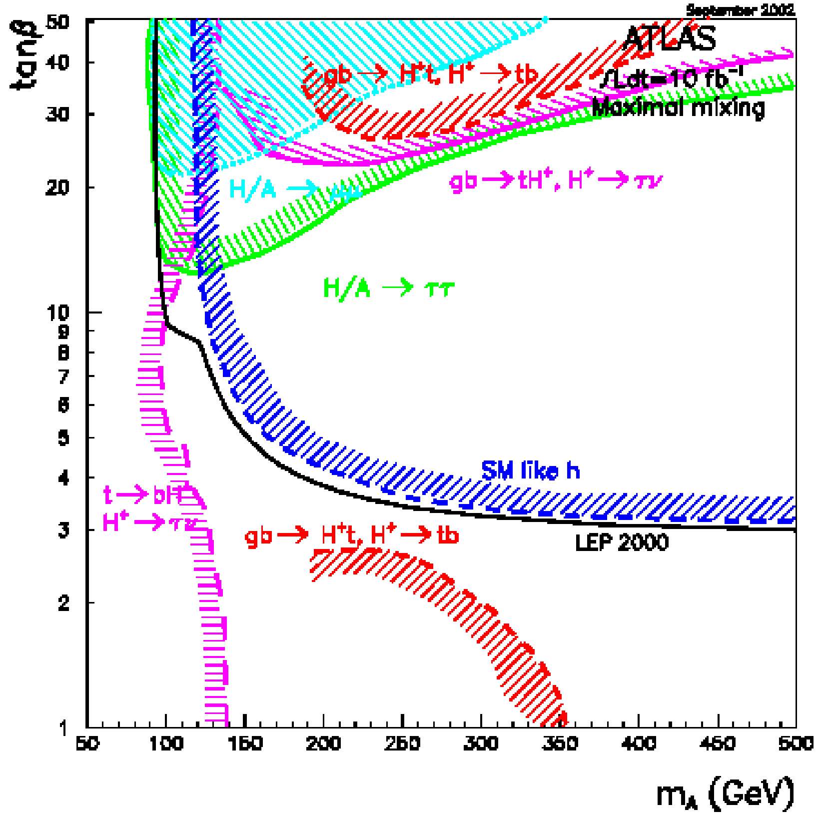
VBF ENHANCEMENT OF MSSM HIGGS SENSITIVITY

Use of VBF channels in SM-like Higgs Seaches allows single experiment to cover tanβ/m$_A$ plane (including LEP200 limit) with 10 fb^{-1}

2 experiments, no VBF

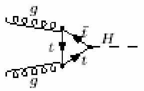
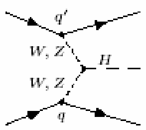
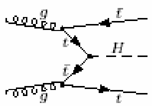
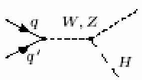


1 experiment, with VBF

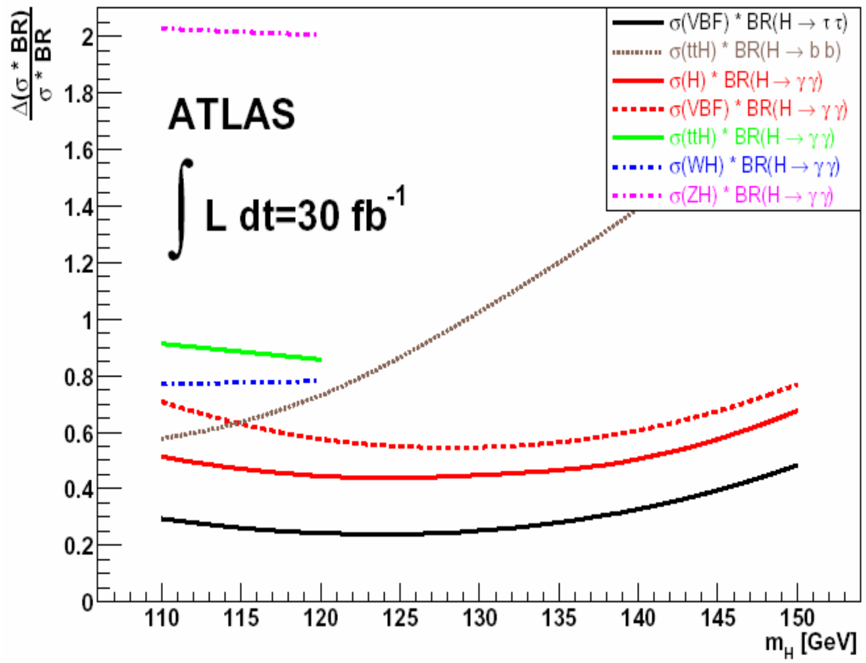


MEASUREMENT OF HIGGS PARAMETERS

To verify existence of Higgs boson, it is necessary to determine it parameters (e.g., couplings); VBF channels offer significant aid to do this.

Production		Decay	Mass range
	GF: Gluon Fusion $(gg \to H)$	$H \to ZZ^{(*)} \to 4l$	110 GeV - 200 GeV
		$H \to WW^{(*)} \to l\nu\, l\nu$	110 GeV - 200 GeV
		$H \to \gamma\gamma$	110 GeV - 150 GeV
	WBF: Weak Boson Fusion $(qq\,H)$	$H \to ZZ^{(*)} \to 4l$	110 GeV - 200 GeV
		$H \to WW^{(*)} \to l\nu\, l\nu$	110 GeV - 190 GeV
		$H \to \tau\tau \to l\nu\nu\, l\nu\nu$	110 GeV - 150 GeV
		$H \to \tau\tau \to l\nu\nu$ hadν	110 GeV - 150 GeV
		$H \to \gamma\gamma$	110 GeV - 150 GeV
	$t\bar{t}H$	$H \to WW^{(*)} \to l\nu\, l\nu\, (l\nu)$	120 GeV - 200 GeV
		$H \to b\bar{b}$	110 GeV - 140 GeV
		$H \to \tau\tau$ (not included)	110 GeV - 150 GeV
		$H \to \gamma\gamma$	110 GeV - 120 GeV
	WH	$H \to WW^{(*)} \to l\nu\, l\nu\, (l\nu)$	150 GeV - 190 GeV
		$H \to \gamma\gamma$	110 GeV - 120 GeV
	ZH	$H \to \gamma\gamma$	110 GeV - 120 GeV

Source: M. Dührssen, ATLAS Physics Note 2003-030



Intermediate Mass VBF analyses allow direct measurement of coupling ratio:

$$\frac{\sigma \times BR(H \to WW)_{VBF}}{\sigma \times BR(H \to ZZ)_{VBF}} = \frac{\Gamma_{HWW}}{\Gamma_{HZZ}}$$

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SUMMARY

- **Standard Model Higgs boson searches in VBF modes significantly enhances low mass sensitivity from roughly 120 GeV/c^2 to $2M_Z$**
  - **Distinct final state features: forward jet tagging and central jet veto**
  - **Studies of main backgrounds with different generator techniques indicate analyses are robust**
- **ATLAS has encouraging preliminary results with extending VBF to intermediate mass ranges from $2M_Z$ to 500 GeV/c^2 as confirmation mode**
- **VBF modes are promising for Invisible Higgs searches**
- **Large portion/all of relevant MSSM Higgs parameter space can be covered with a single experiment using VBF modes**
- **VBF allows measurement of Standard Model Higgs parameters**