Measuring the Properties of the Higgs with the ATLAS Detector

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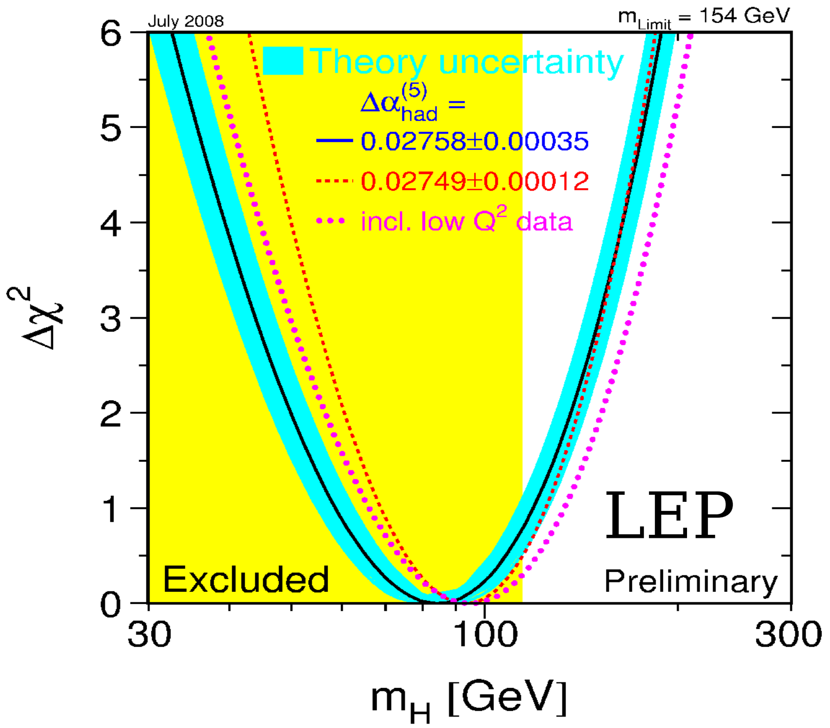
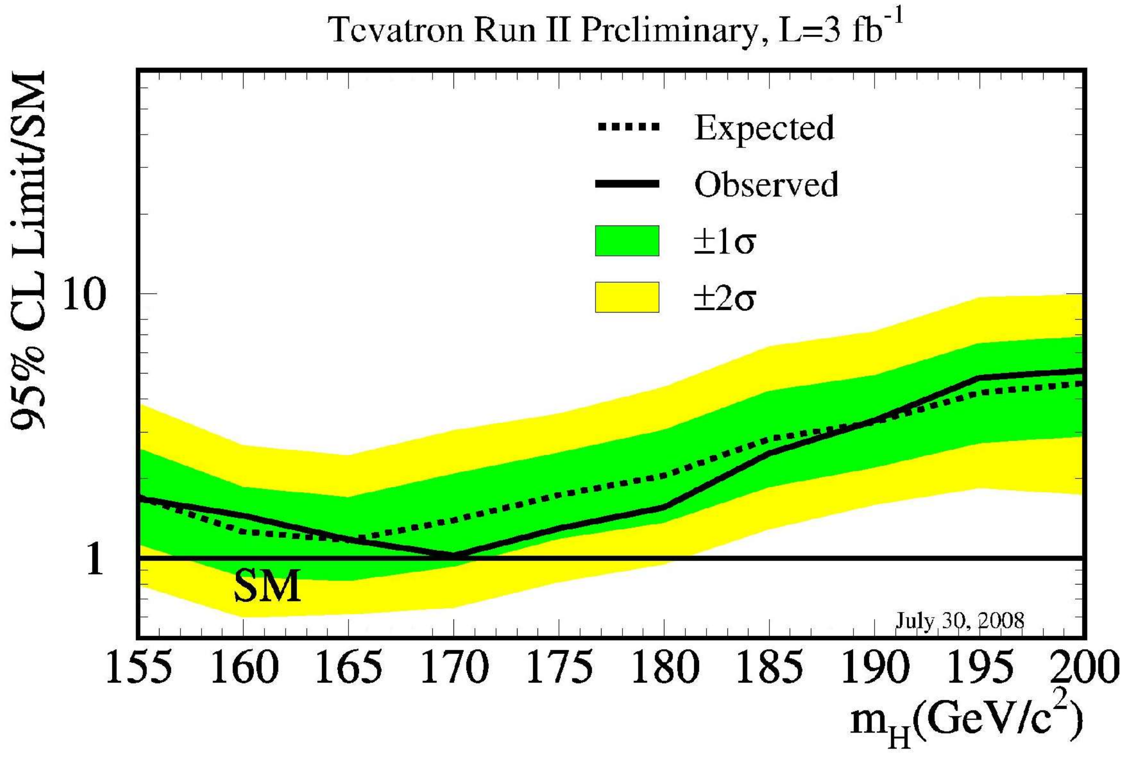
Introduction

- One of the major goals of the LHC is to understand the mechanism of Electroweak symmetry breaking.

- If evidence of a Higgs-like particle is discovered, its properties must be measured to establish that the excess is caused by a Higgs boson and not something else
  - Mass and natural width
  - Couplings to gauge bosons and fermions
  - Spin and CP properties

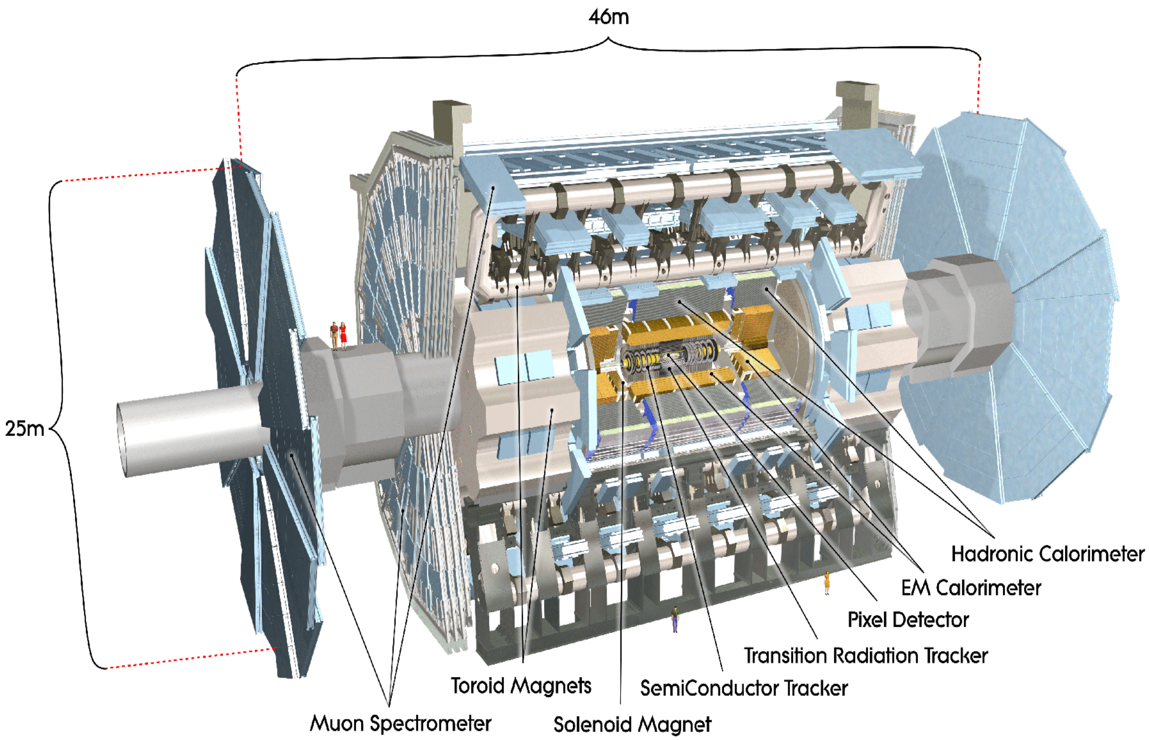
Current Limits





- From direct searches at LEP, lower bound on Standard Model Higgs is M_H>114.4 GeV
- From direct searches at Tevatron, M_H=170 GeV is excluded at 95% CL
- Fits to precision EW data favor a light Higgs

The LHC and the ATLAS Detector



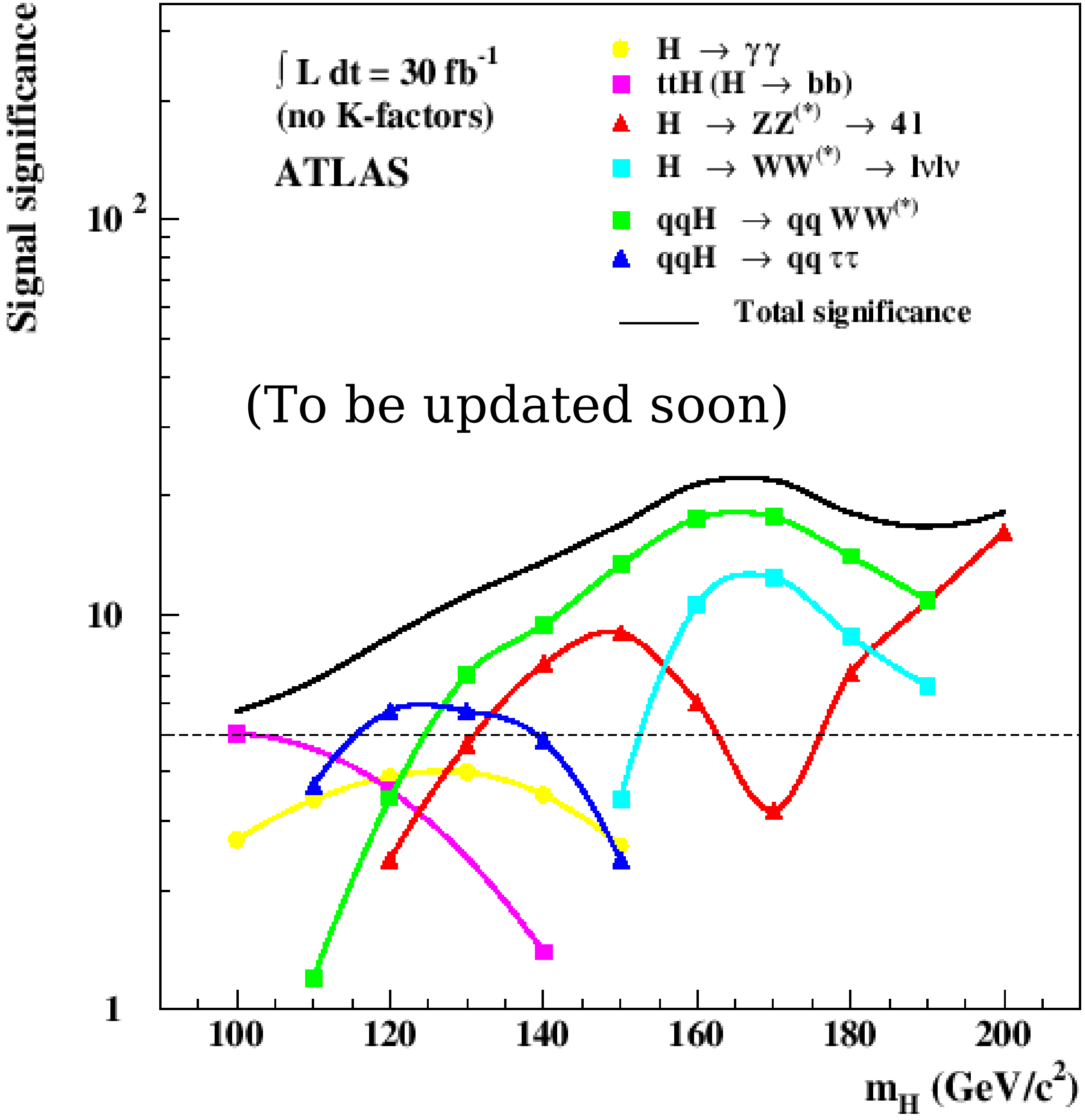
- LHC: 14 TeV pp collider, lumi up to 10^{34} $cm^{-2}s^{-1}$
- ATLAS: general-purpose detector with precision tracking in $|\eta|<2.5$, calorimeters in $|\eta|<4.9$, and muon spectrometer coverage in $|\eta|<2.7$

- Inner Tracker: B=2T, $\sigma/P_T \sim 5x10^{-4} P_T \oplus 0.01$
- EM Calo: Pb-liquid Ar, $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.007$
- Hadronic Calo: Fe-scint+Cu-liquid Ar (10λ), $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$
- Muon spectrometer: $\sigma/P_T \sim 2\%$@50 GeV, 10%@1TeV

Higgs Search Sensitivity

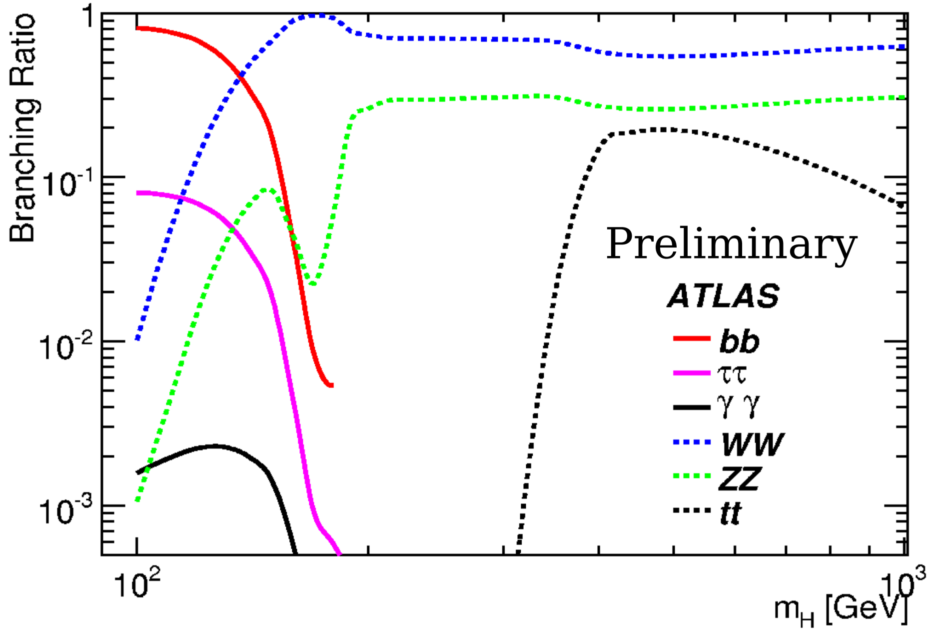
- ATLAS can observe a Standard Model Higgs boson with a mass above the LEP limit

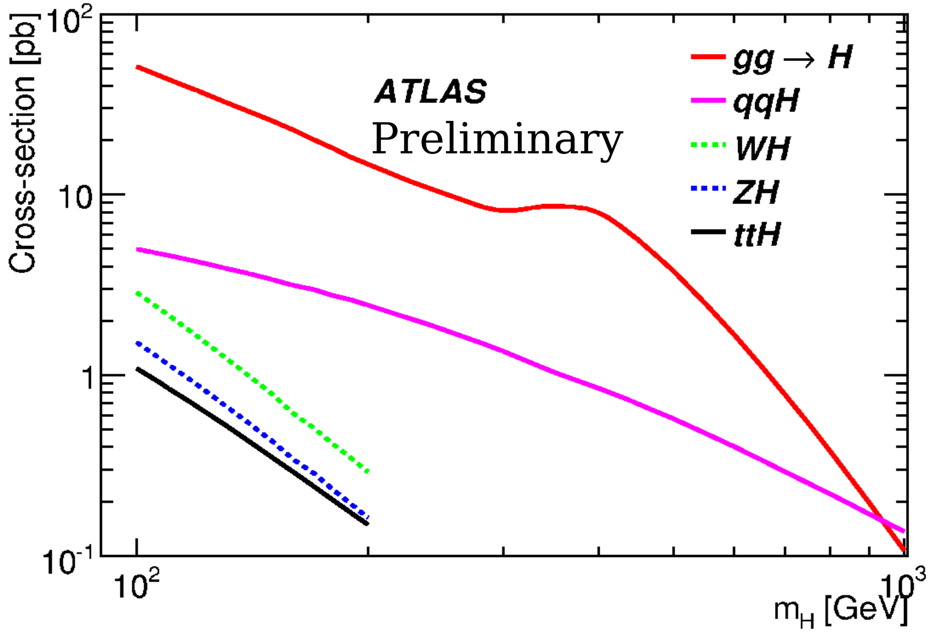
- Most powerful discovery modes are H→WW and H→ZZ, but a variety of handles exist, especially at low mass



(To be updated soon)

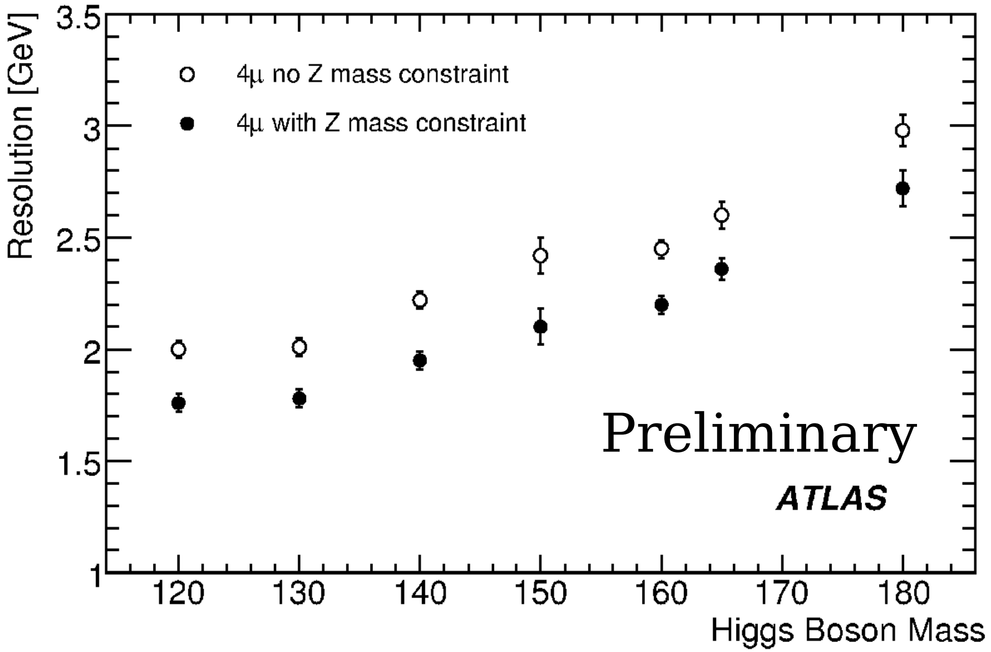
Higgs Mass Measurements (1)

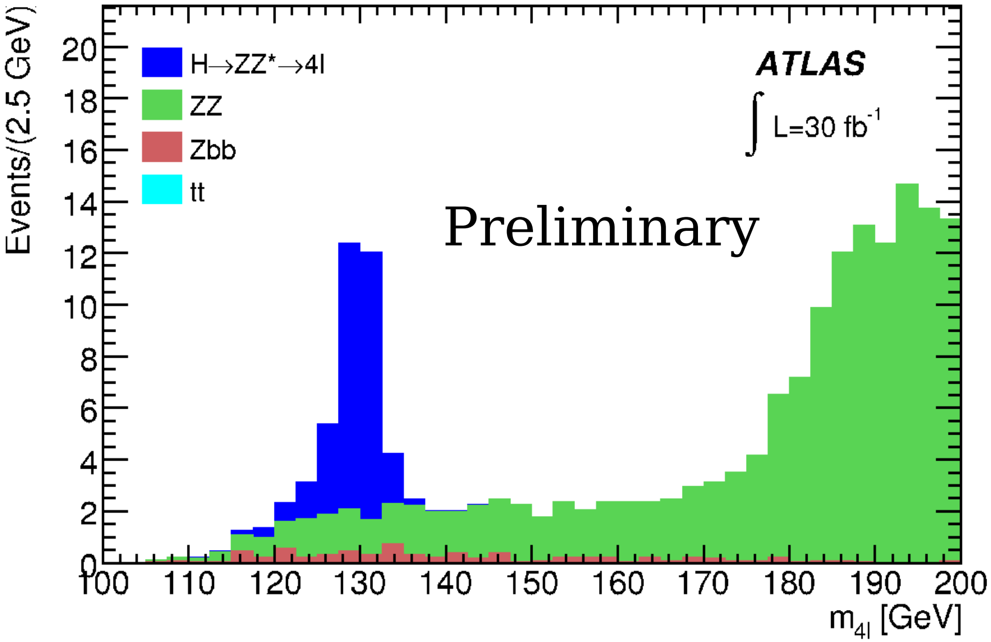




- Important observables like cross-sections and branching ratios depend sensitively on the Higgs mass
- In order to interpret measured properties in terms of model parameters, need to know the mass

Higgs Mass Measurements (2)



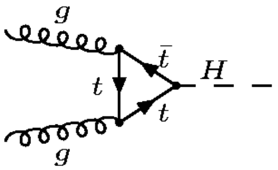
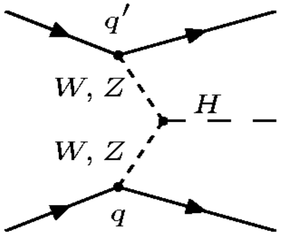
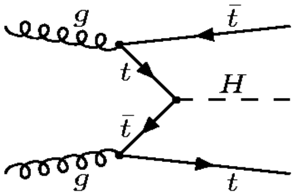
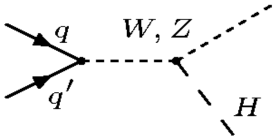


- Mass determination is dominated by H→ZZ→4l and H→$\gamma\gamma$ for most values of M_H
  - H→ZZ→4l (above): resolution is better than ~2-3 GeV for M_H below ZZ threshold (degrades slightly at higher masses)
  - H→$\gamma\gamma$: resolution is ~1.36 GeV

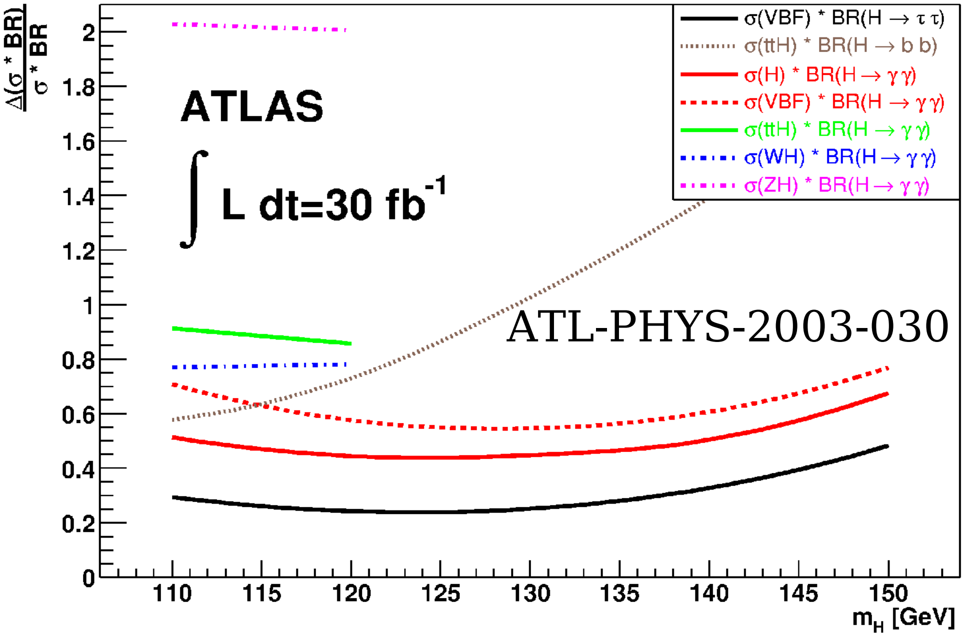
Coupling Measurements

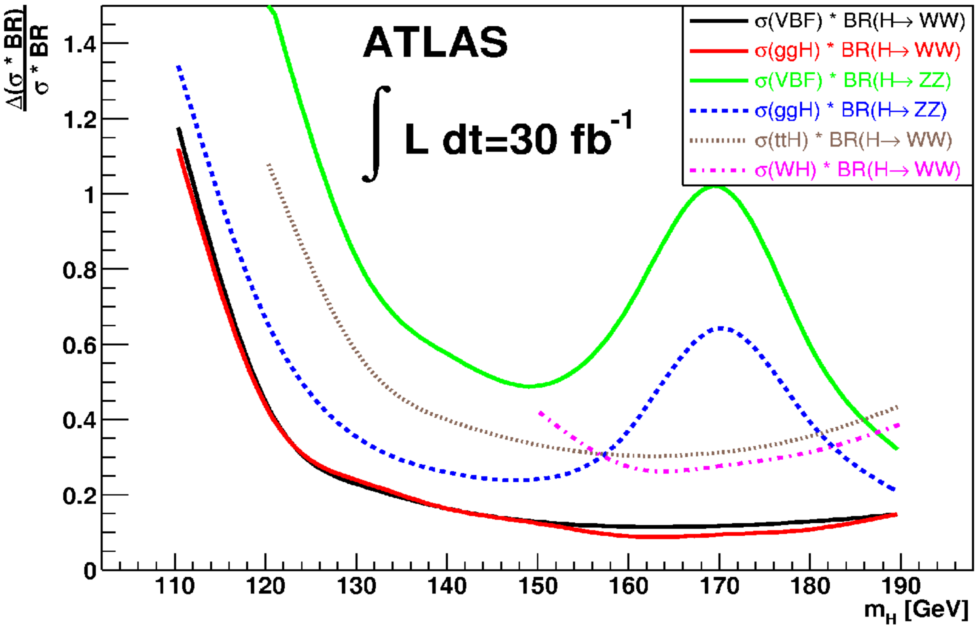
- Depending on assumptions, different quantities can be measured
  - CP-even, spin 0 (implicit in H→WW event selection): measure only σ•BR
  - Also assume only one Higgs boson, i.e. no degenerate Higgs pairs: extract relative branching ratios (equivalent to Γ_X/Γ_W)
  - Also assume only Standard Model couplings, no extra particles or strong couplings to light fermions: extract ratios of Higgs couplings
  - Also assume that the sum of all visible Branching Ratios is the same as in Standard Model: extract absolute couplings

Channels Used in Coupling Fit

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
		$H \to \tau\tau \to l\nu\nu\, \mathrm{had}\nu$	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

Rate Measurements

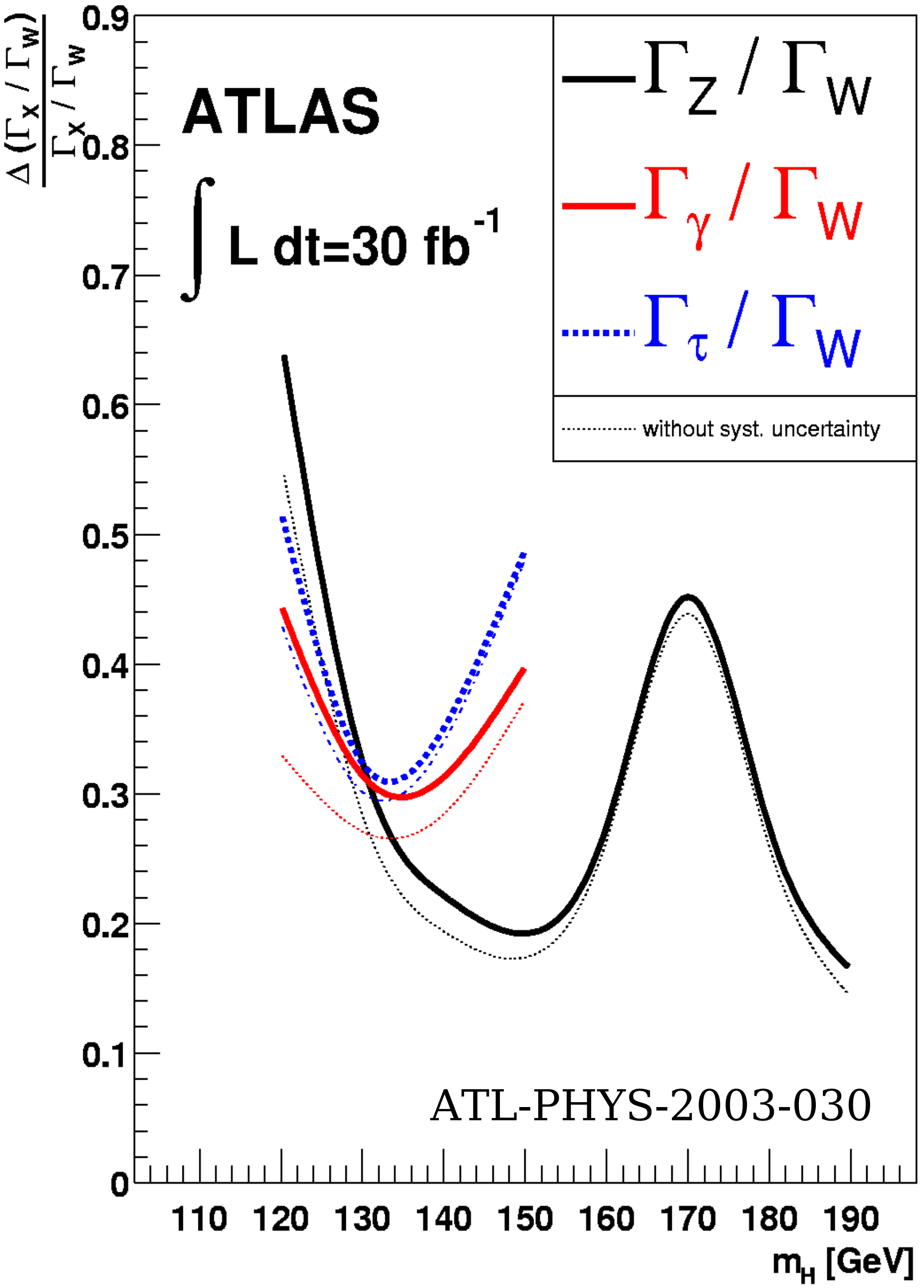




- Left: for M_H<150 GeV, rates can be measured with an accuracy typically between 30-100% with 30 fb^{-1} of integrated luminosity
  - This assumes a 5% uncertainty on the luminosity measurement.
- Right: for channels that can be seen in the mass range 110<M_H<190 GeV, error is smaller

Ratios of Partial Decay Widths

- Assume only one Higgs
- Total width cannot be measured due to detector resolution.
- H→WW used as normalization since it is measured with the smallest error
- Right: with 30 fb^{-1} of integrated luminosity, ratios of partial widths can be measured with an accuracy better than 60%



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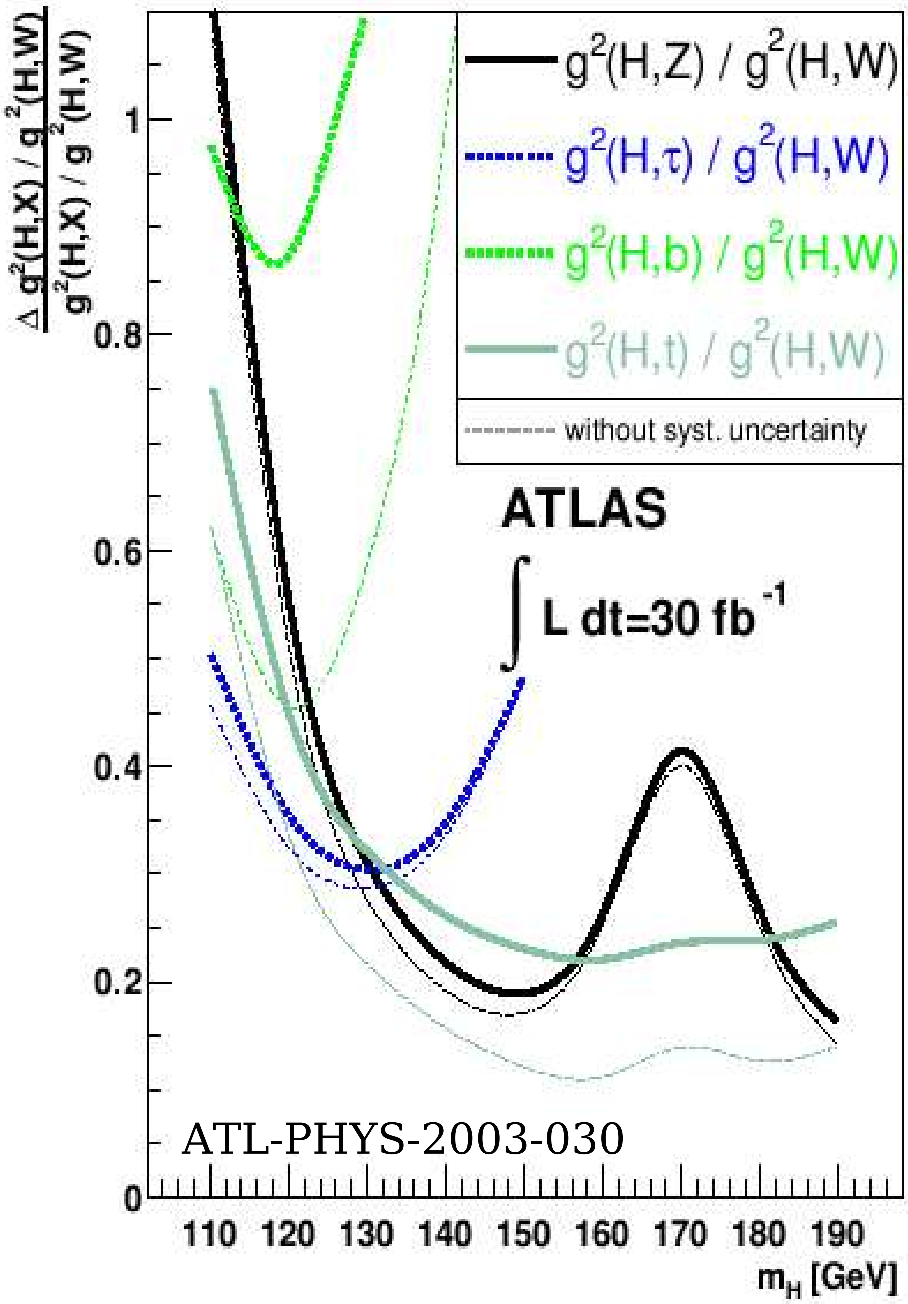
Ratios of Higgs Couplings

- Assume no unobservable decay modes, etc.
- Cross-sections and branching ratios are proportional to the squares of couplings
- Proportionality constants, along with systematic errors, are computed from theory
- With 30 fb^{-1} of integrated luminosity, Ratios of Higgs couplings can be measured with an accuracy ranging from ~20% to ~100%



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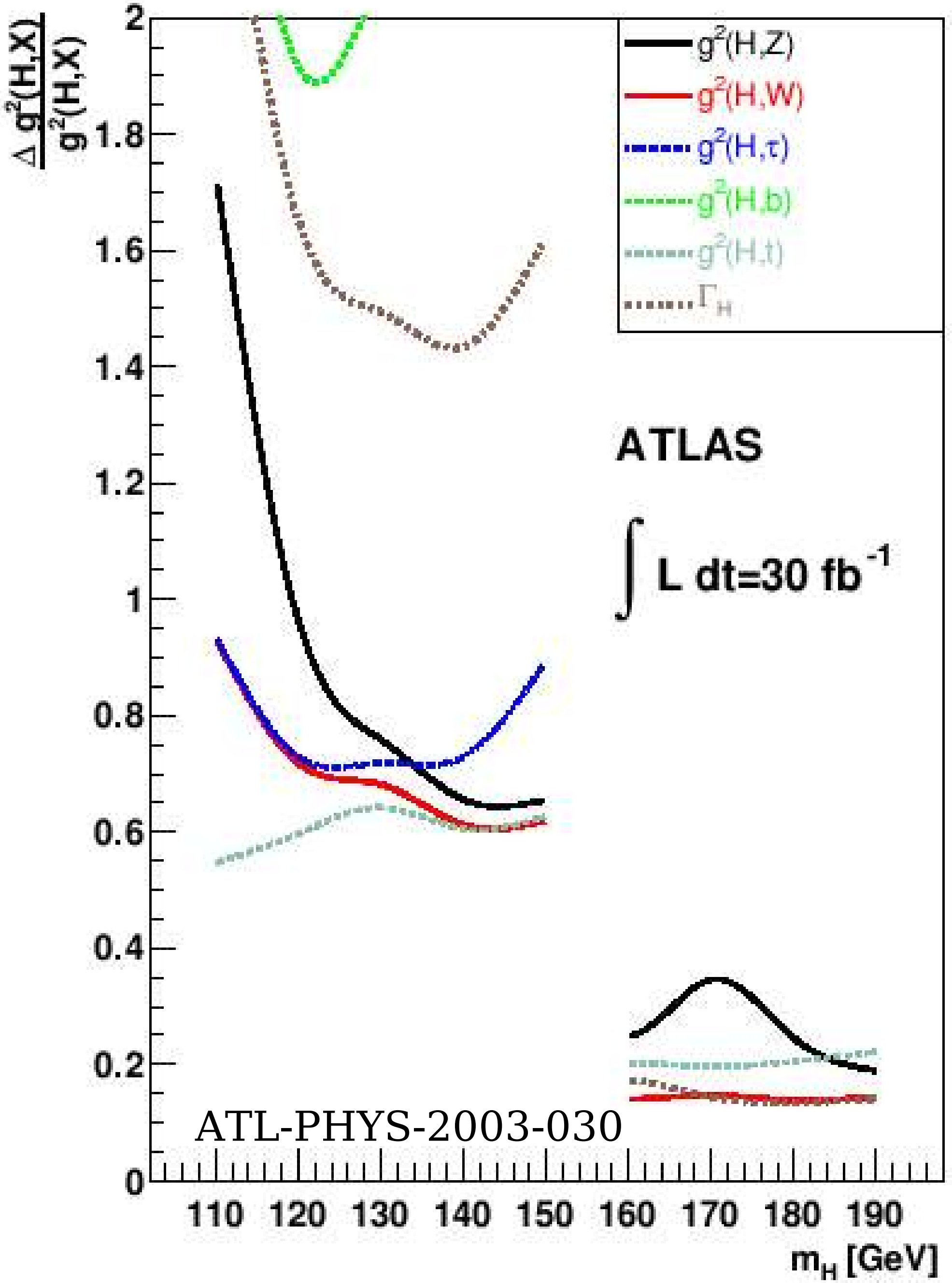
Absolute Couplings

- Additional assumption: sum of visible branching ratios (H→WW, ZZ, plus $\gamma\gamma$, $\tau\tau$, and bb, depending on mass) is the same as in Standard Model, with an error corresponding to the sum of undetected branching ratios

- Couplings to Z, W, and τ can be measured with a precision better than 100%



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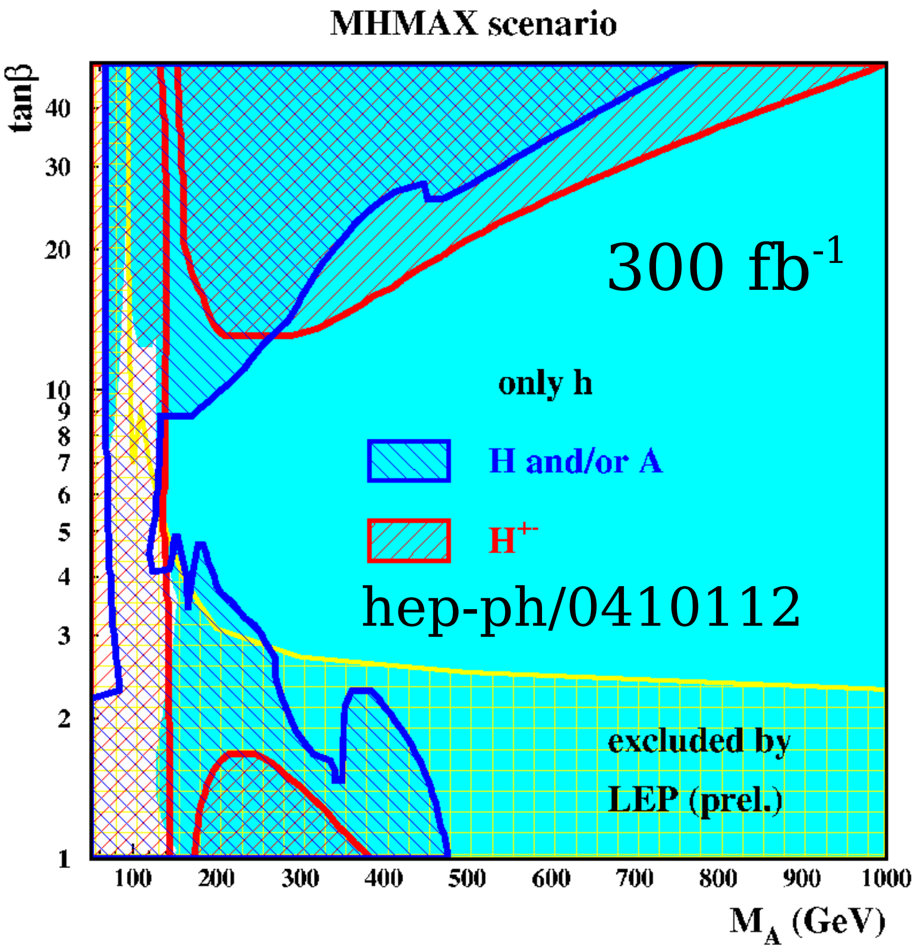
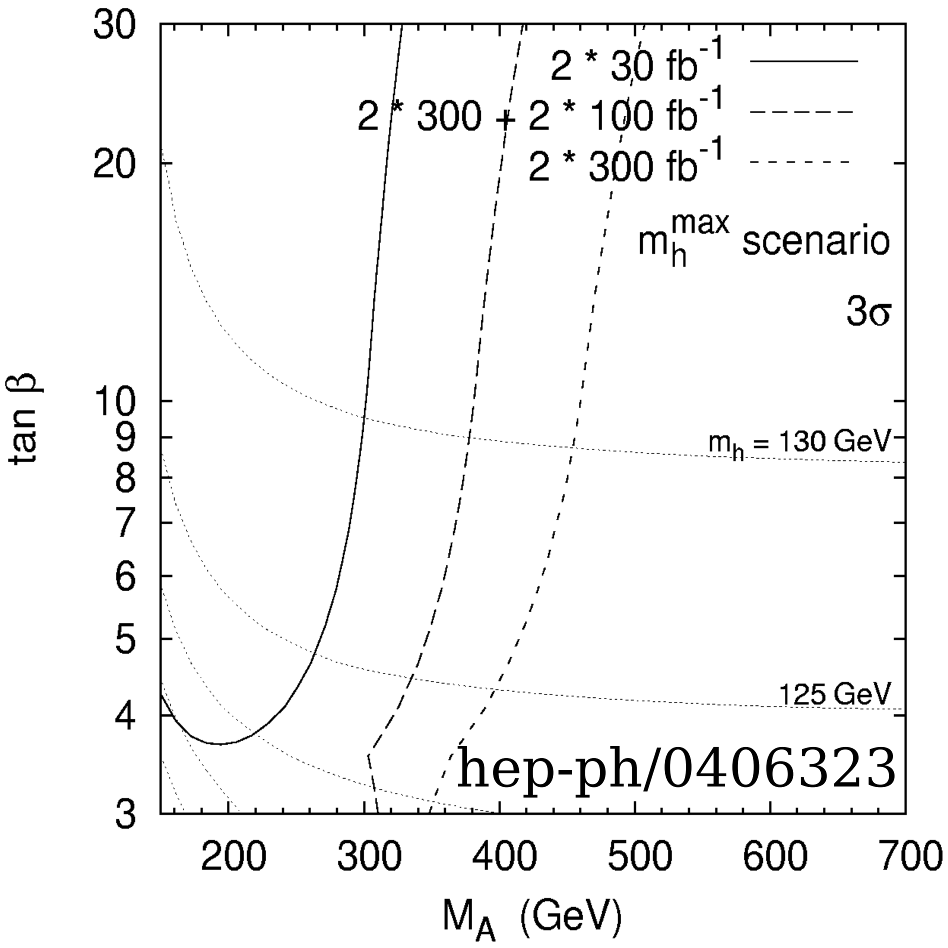
Excluding Non-SM Higgs





- In some regions of the MSSM parameter space, only one light Higgs is visible (left)
- Try to exclude MSSM using a χ^2 analysis of coupling fits (right)

Spin/CP Measurements (1)

- Spin:
  - Spin 1: no decays H→$\gamma\gamma$ and no production of gg→H
  - Angular correlations of decay products in H→ZZ→4l

- CP:
  - Angular correlations of decay products in H→ZZ→4l
  - Angular correlations of tagging jets in WBF Higgs

- It is possible to study the structure of the VV→Φ tensor at LHC (non-SM contributions could come from heavy particle loops)

$$\begin{aligned} T^{\mu\nu}(q_1,q_2) &= \boxed{a_1(q_1,q_2)g^{\mu\nu}} \leftarrow \text{Standard Model} \\ &\boxed{+a_2(q_1,q_2)[q_1\bullet q_2 g^{\mu\nu}-q_2{}^{\mu}q_1{}^{\nu}]} \leftarrow \text{CP-even} \\ &\boxed{+a_3(q_1,q_2)\epsilon^{\mu\nu\rho\sigma}q_{1\rho}q_{2\sigma}} \end{aligned}$$

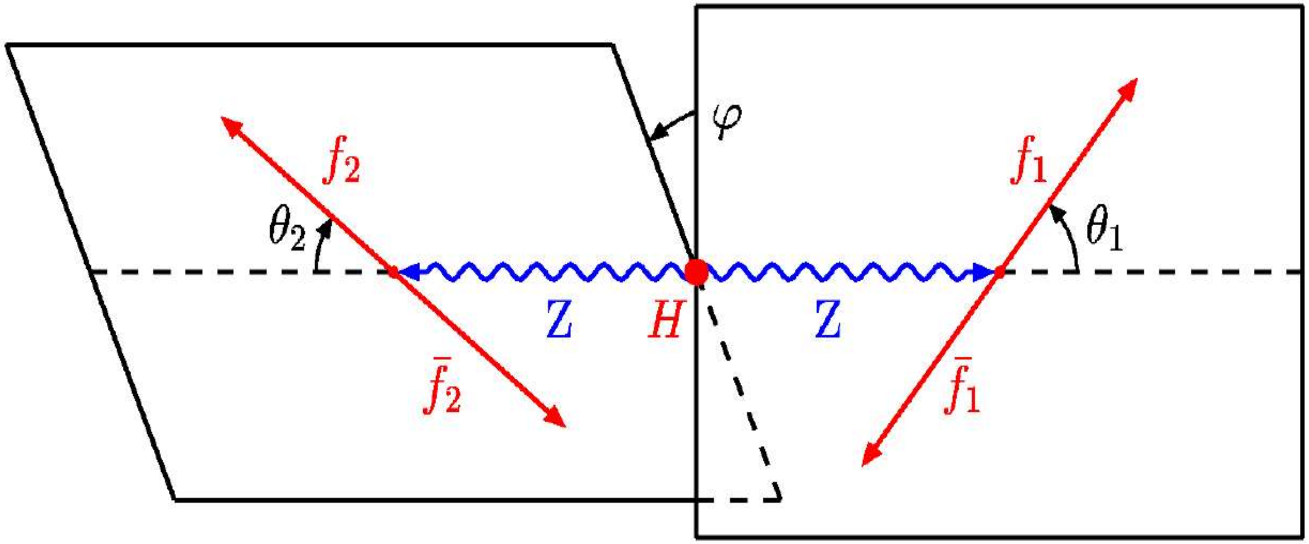
CP-odd

Spin/CP Measurements (2)

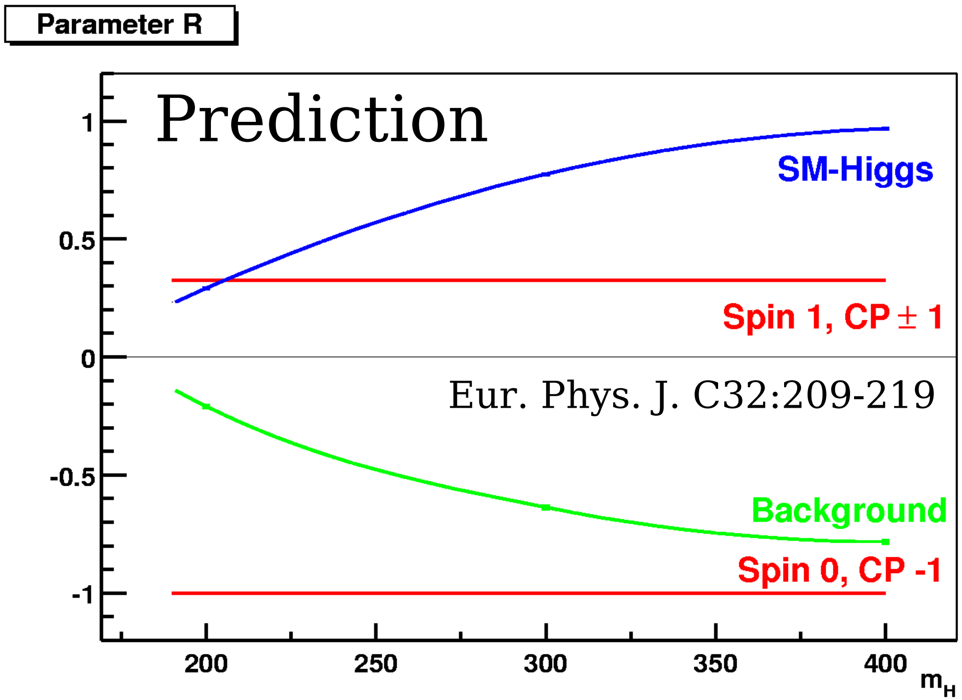
- In $H \to ZZ \to 4l$, extract spin information by measuring decay angles in Higgs rest frame
  - Focus on $M_H > 200$ GeV
- Three discriminating variables (α, β, and R), obtained by fitting to angular distributions:
  - Decay plane angle ϕ: $F(\phi) = 1 + \alpha \cos(\phi) + \beta \cos(2\phi)$
  - Polar angle θ: $G(\theta) = T\,(1+\cos^2\theta) + L \sin^2\theta$

    : $R = (L-T)/(L+T)$

- Test for:
  - Spin 1, CP +1
  - Spin 1, CP -1
  - Spin 0, CP -1



Spin/CP Measurements (3)



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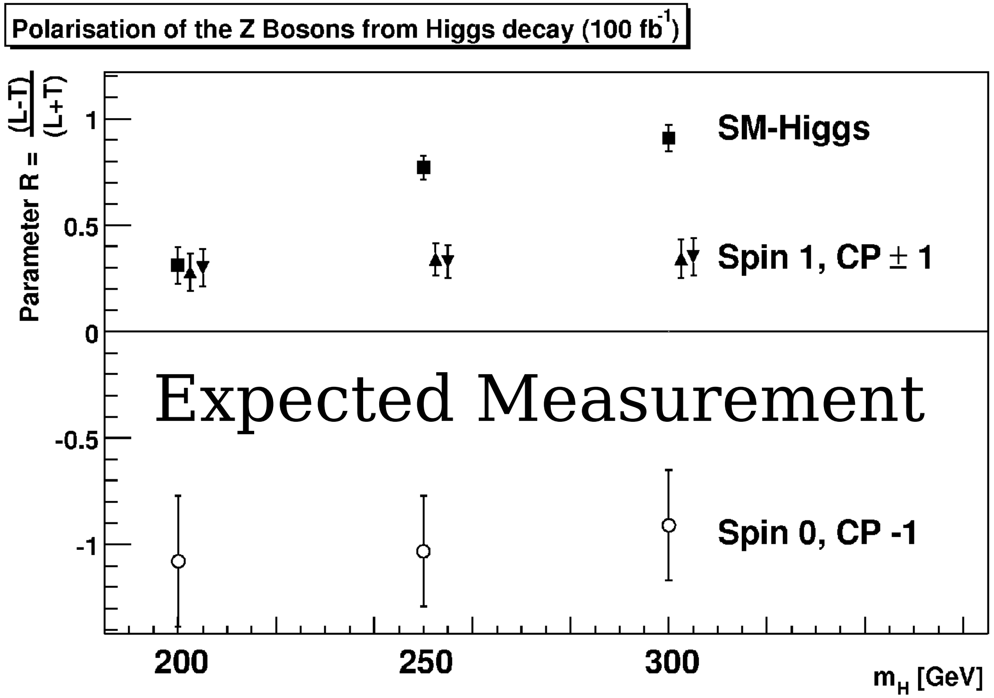
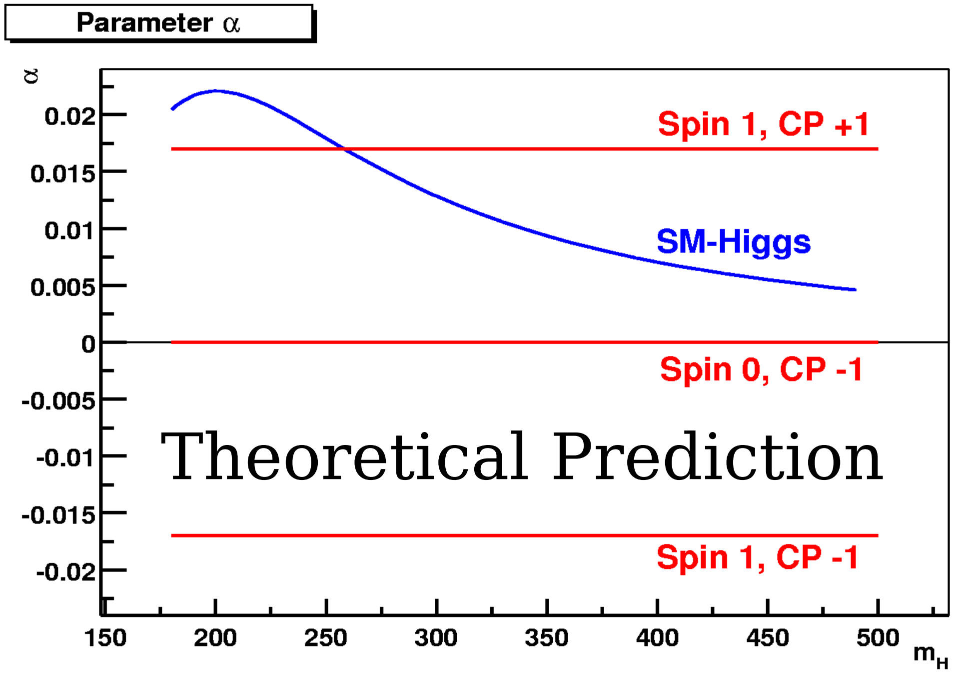
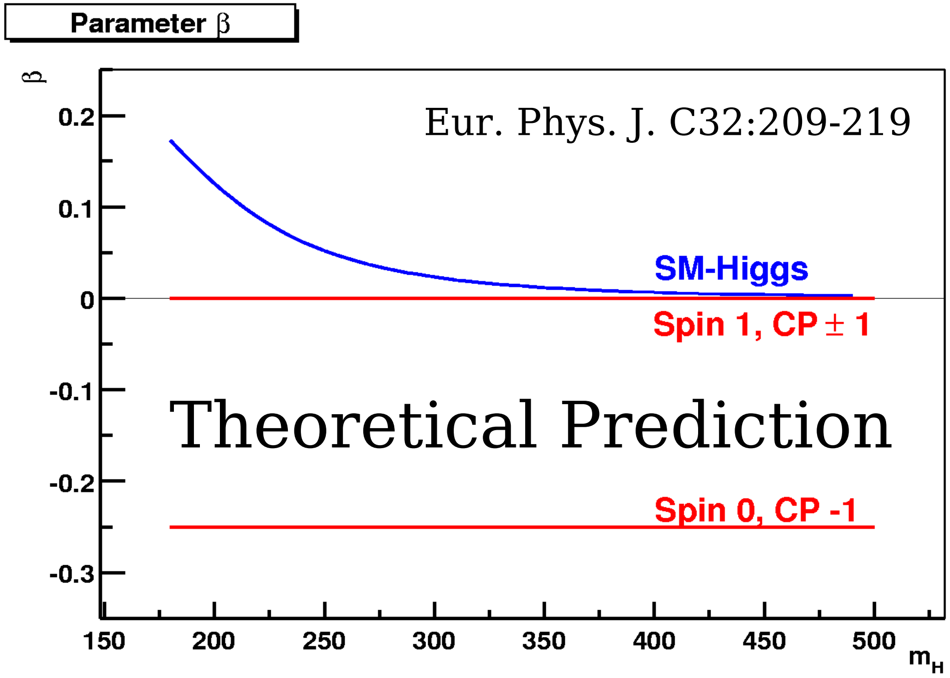


- Left: the predicted value of R as a function of M_H for the Standard Model case, and several alternatives. Right: the expected error on the measurement of R.
- The parameter R offers good separation between the Standard Model Higgs and both the spin 1 and pseudoscalar alternatives for $M_H \geq 250$ GeV
- For $M_H=200$ GeV, it is only able to rule out the pseudoscalar alternative

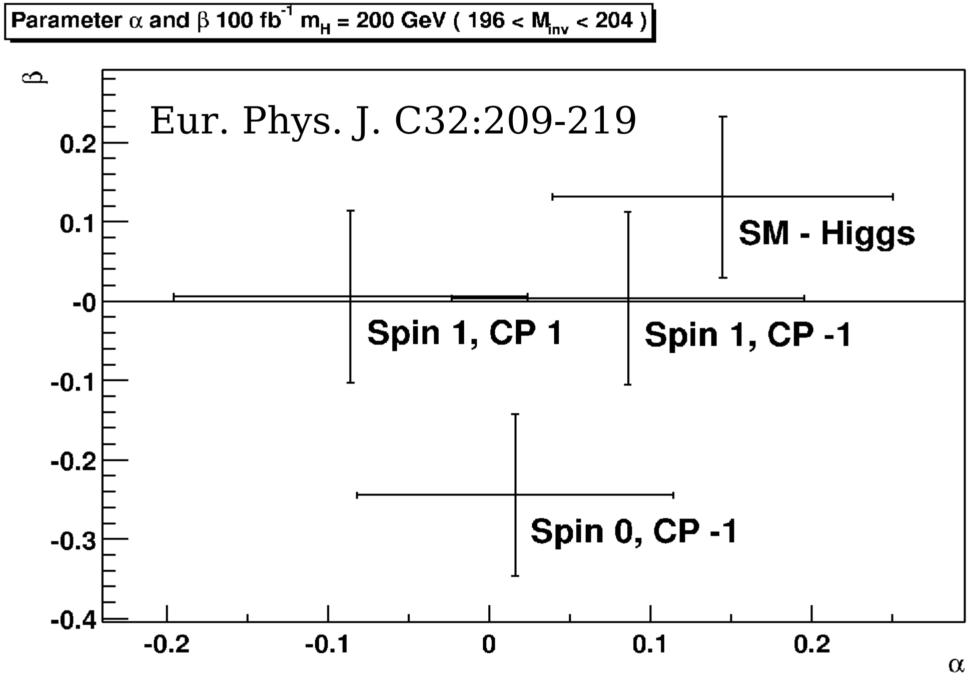
Spin/CP Measurements (4)





- Both the parameters α (left) and β (right) can provide additional discrimination between the Standard Model case and the alternative case.

Spin/CP Measurements (5)



Parameter α and β 100 fb^{-1} m_H = 200 GeV (196 < M_{inv} < 204)

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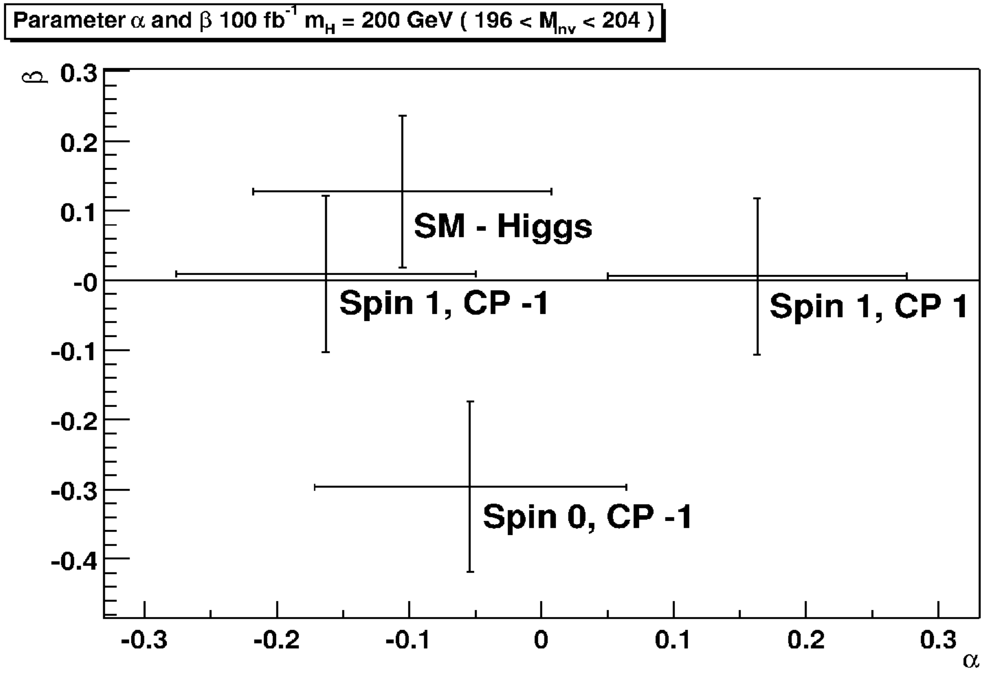
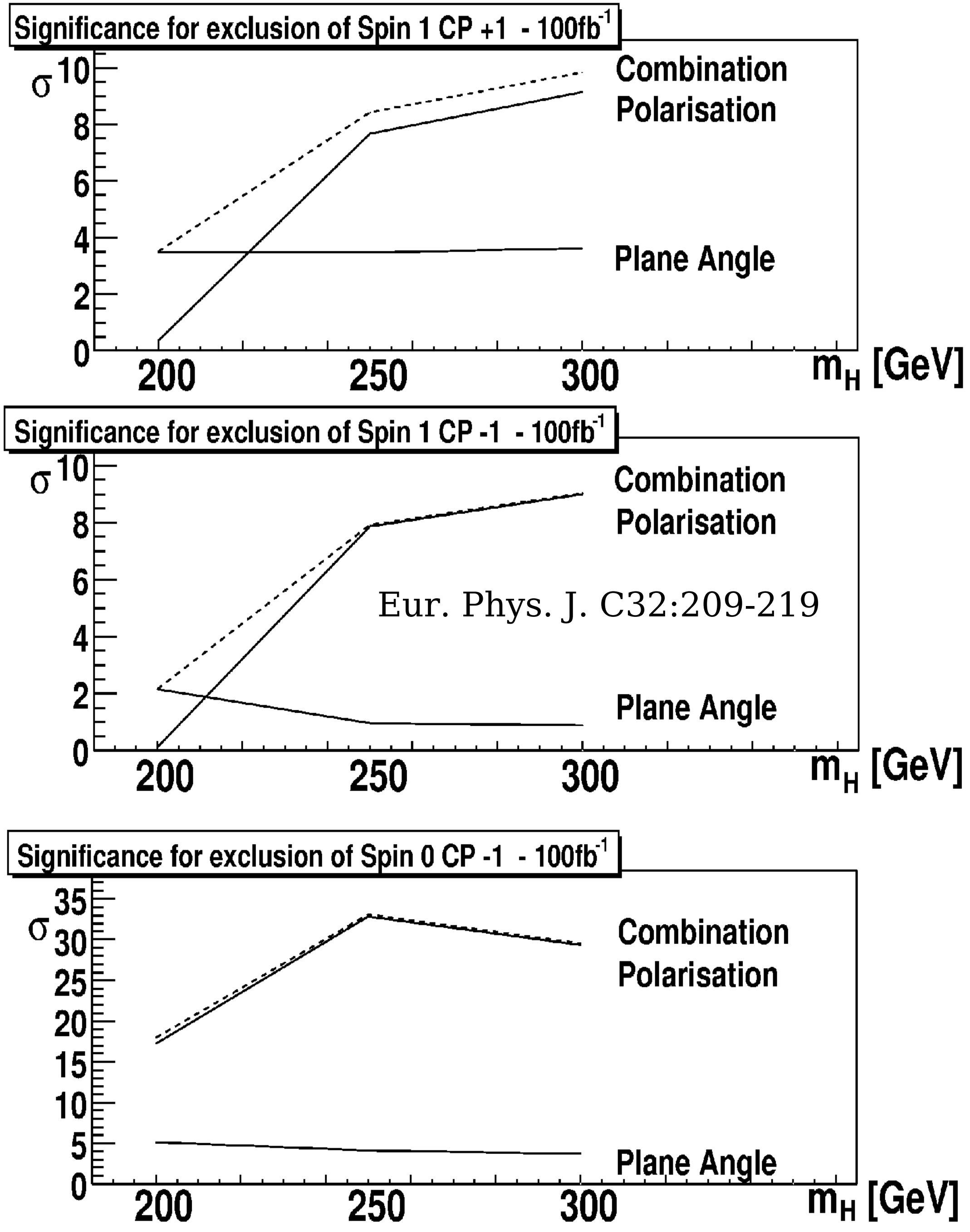


Parameter α and β 100 fb^{-1} m_H = 200 GeV (196 < M_{inv} < 204)

- Sensitivity to α and β can be enhanced if information about the correlation between the signs of the Z boson spins is used.
- Above Left: cos(θ) has the same sign for both Z bosons. Above Right: cos(θ) has the opposite sign for the two Z bosons.

Spin/CP Measurements (6)

- Analysis of H and Z decay angles can exclude possible Higgs-like particles that have unusual spin/CP properties.


Significance for exclusion of Spin 1 CP +1 - $100fb^{-1}$

Significance for exclusion of Spin 1 CP -1 - $100fb^{-1}$

Significance for exclusion of Spin 0 CP -1 - $100fb^{-1}$

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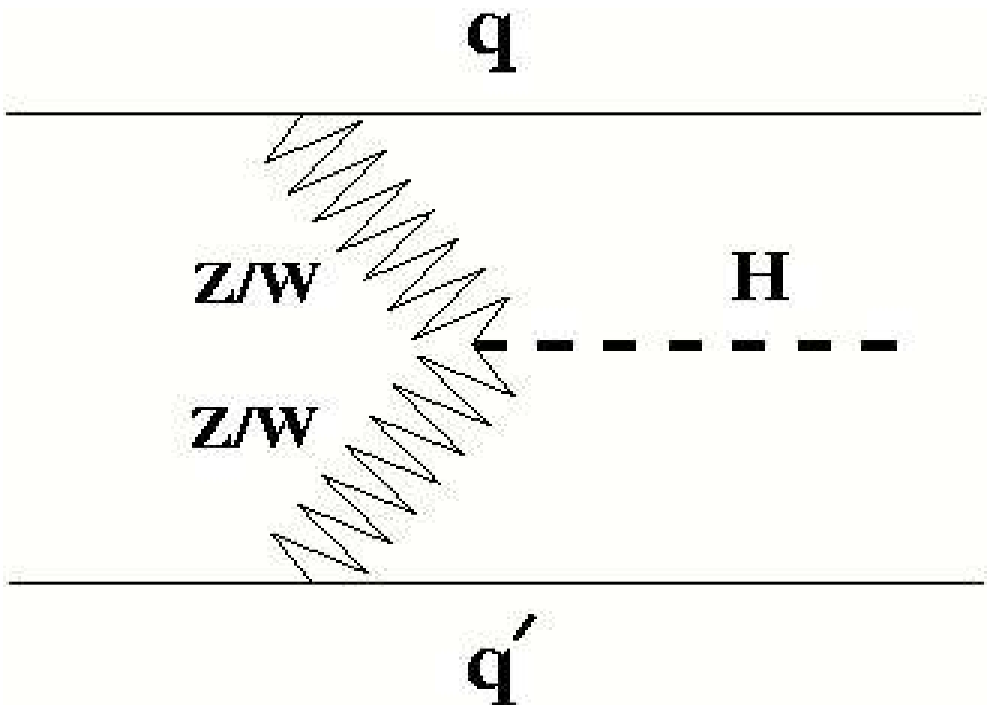
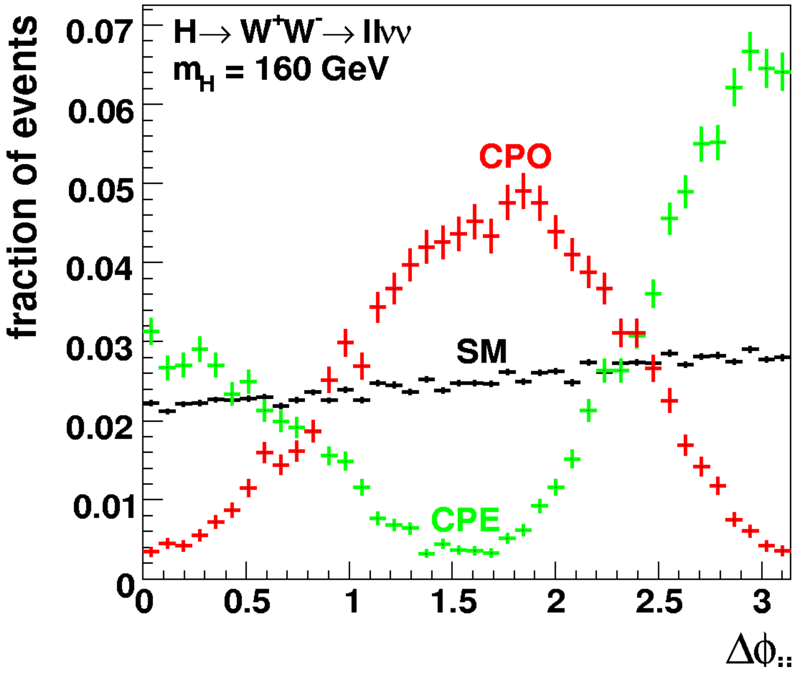
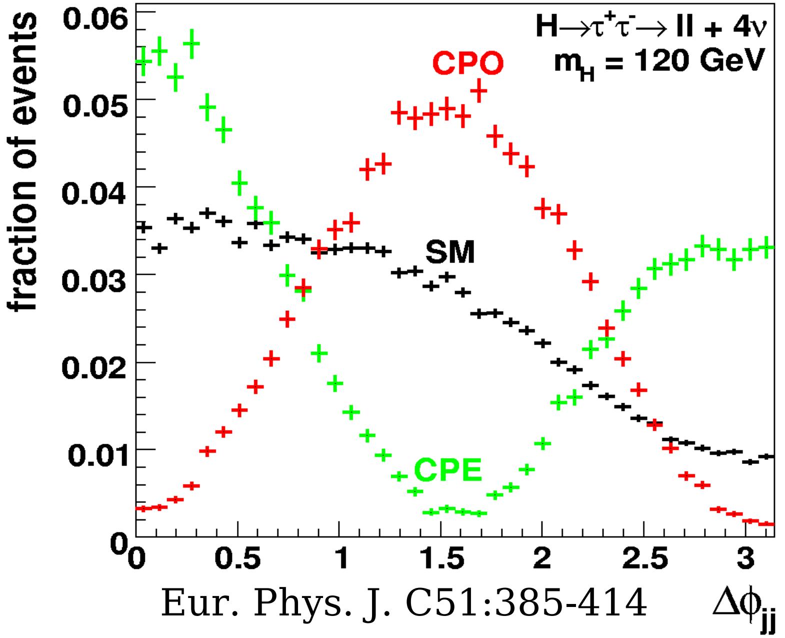
Spin/CP Measurements (7)







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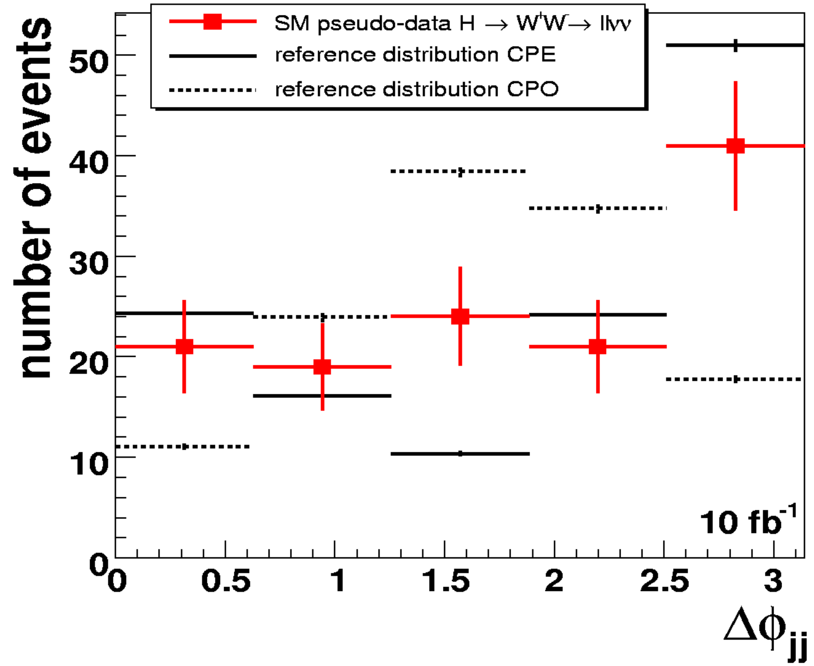
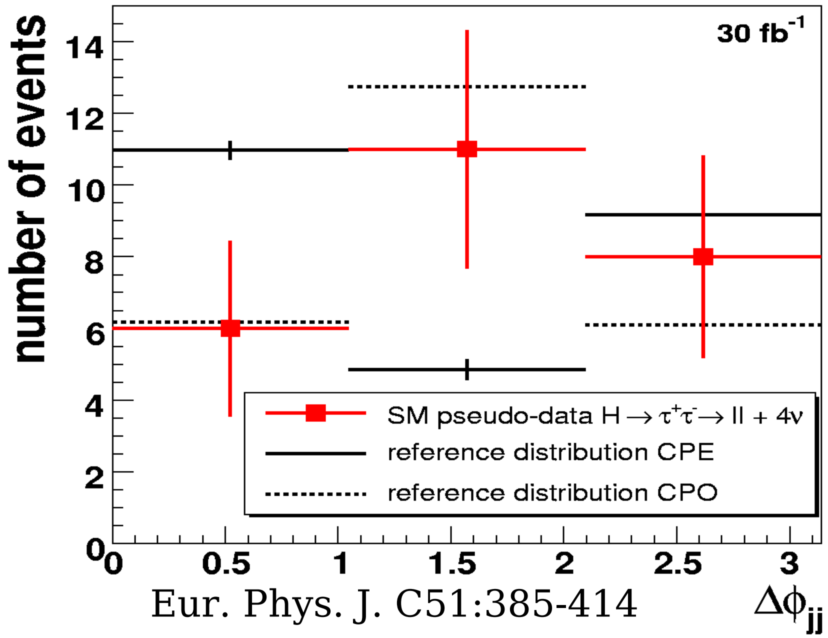
- Angle between struck quarks in VBF events are sensitive to tensor structure of HVV vertex
  - Typically: $P_T(j_{1,2})$>20-40 GeV, $\Delta\eta_{jj}$>3-4.5; M_{jj}>500-1000 GeV
- H→ττ for M_H~120 GeV, H→WW for M_H~160 GeV

Spin/CP Measurements (8)

- Use a χ^2 hypothesis test to determine dominant couplings

- Right: toy Monte Carlo outcomes corresponding to the plots on the previous page.





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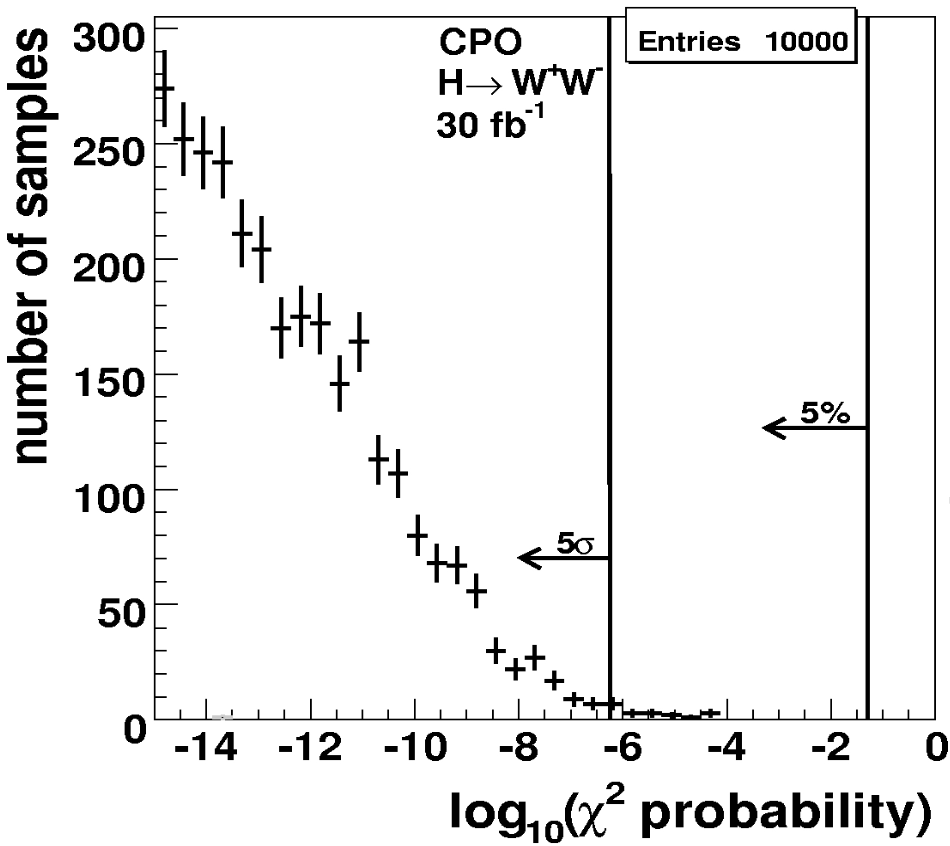
Spin/CP Measurements (9)



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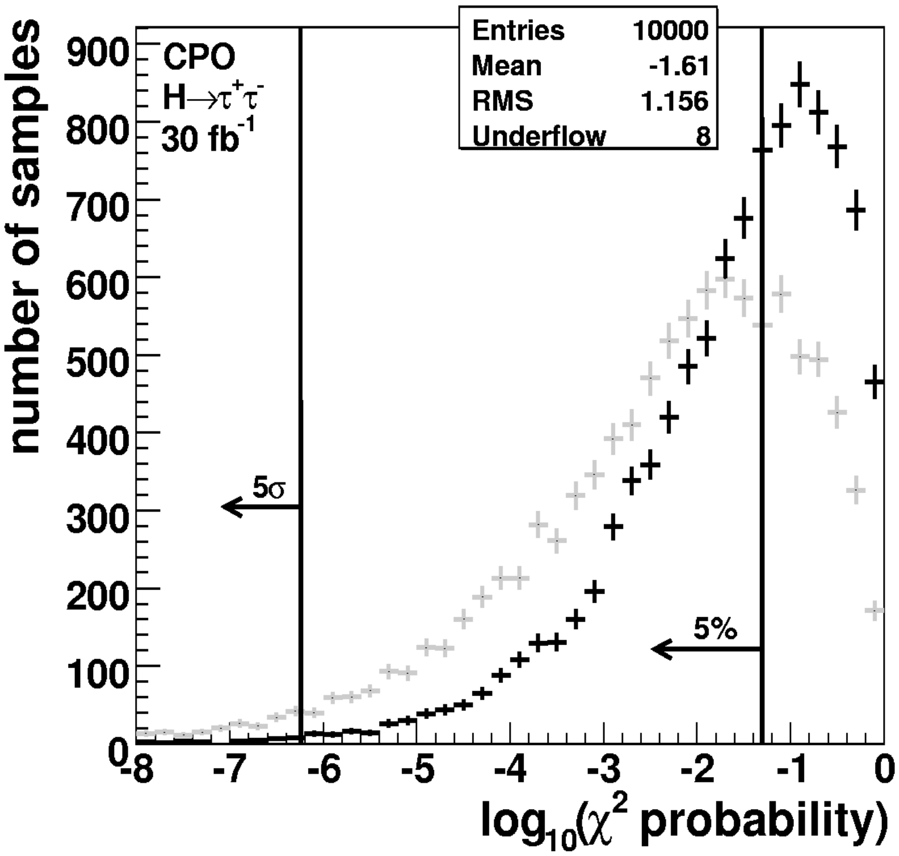
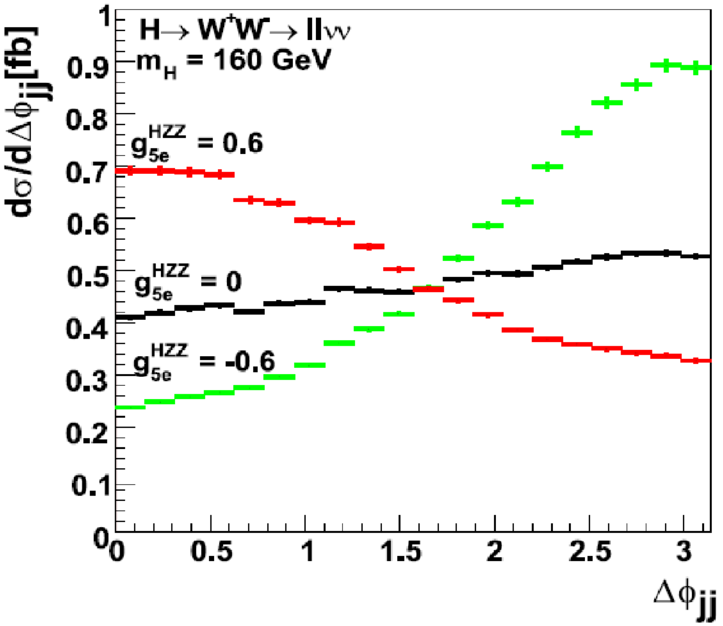
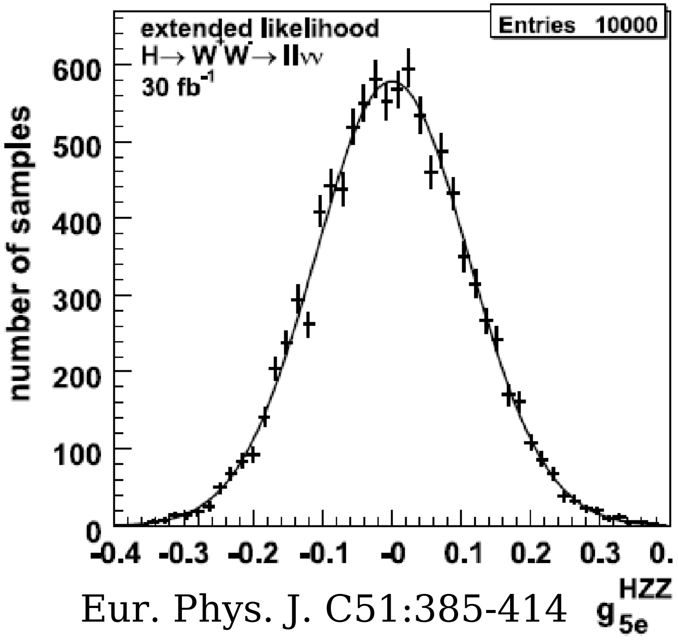


- Repeat test for 10000 SM pseudo-data samples
- Above: example plots of the χ^2 probability distribution for outcomes with a CP-odd signal
- Median deviation of SM from CP-Even(CP-Odd):
  - 5.4σ (4.6σ) for H→WW at 10 fb^{-1}
  - 2.5σ (2.0σ) for H→$\tau\tau$ at 30 fb^{-1}

Spin/CP Measurements (10)



Signal, high statistics:



Fit results effective coupling:

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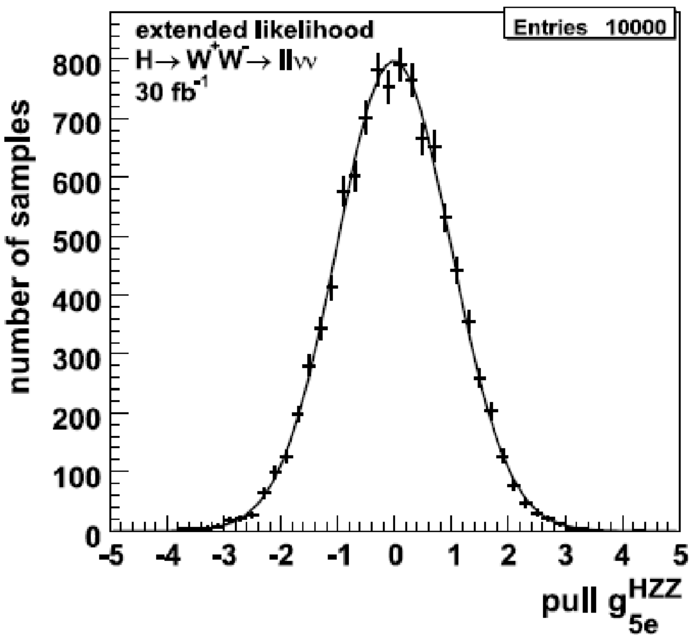

Pulls of fit results:

- After establishing that the dominant coupling is Standard Model-like, one can still test for the presence of a small CP-even anomalous coupling
  - Interference terms modify the $\Delta\phi_{jj}$ distribution
- Expected sensitivity
  - H→WW (30 fb^{-1}): $\sigma(g_{5e}^{HZZ})=0.11$
  - H→$\tau\tau$ (30 fb^{-1}): $\sigma(g_{5e}^{HZZ})=0.24$
  - 10% BG uncertainty adds additional error of ~0.02

Summary

- ATLAS can measure properties of Higgs boson
  - Mass resolution as good as 1.36 GeV for some M_H
  - Determination of relative widths through fit to results from different channels
    - Measurements of absolute couplings possible with additional assumptions
    - Typical precision ~a few 10%
  - Spin/CP in $H \rightarrow ZZ \rightarrow 4l$ for masses above 200 GeV
    - Distinguish clearly between SM and non-SM cases for $M_H > 230$ GeV
  - Structure of HVV couplings and CP properties studied in Vector Boson Fusion
    - Strong exclusion of non-SM cases at 160 GeV; weaker exclusion possible at 120 GeV
    - Sensitive to interference between SM and CP-even effective coupling