

STRONG DOUBLE HIGGS PRODUCTION AT THE LHC IN COMPOSITE HIGGS MODELS

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Work in progress

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any comment or suggestion Welcome !

THE FRAMEWORK

👉 Models where the Higgs is a **composite** Pseudo-Goldstone Boson (PGB) of a new **strongly**-interacting sector

👉 New fundamental parameter:

$$\xi = \left(\frac{v}{f} \right)^2$$

$f = \sigma$ -model scale

Other composites expected at :

$$m_* \sim \frac{4\pi}{\sqrt{N}} f = \frac{4\pi}{\sqrt{N}} \frac{v}{\sqrt{\xi}}$$

- $\xi \rightarrow 0$ SM (decoupling) limit

All resonances become heavy

- $\xi \rightarrow 1$ Technicolor limit

No separation of scales

For a composite Higgs one expects modifications in its couplings at $\mathcal{O}(\xi)$

- Couplings to vectors depend only on the symmetry-breaking pattern
- Couplings to fermions are more model-dependent

Different shifts for fermions and vectors imply a different pattern of BR's for the Higgs decay:

SO(5)/SO(4) predicts:

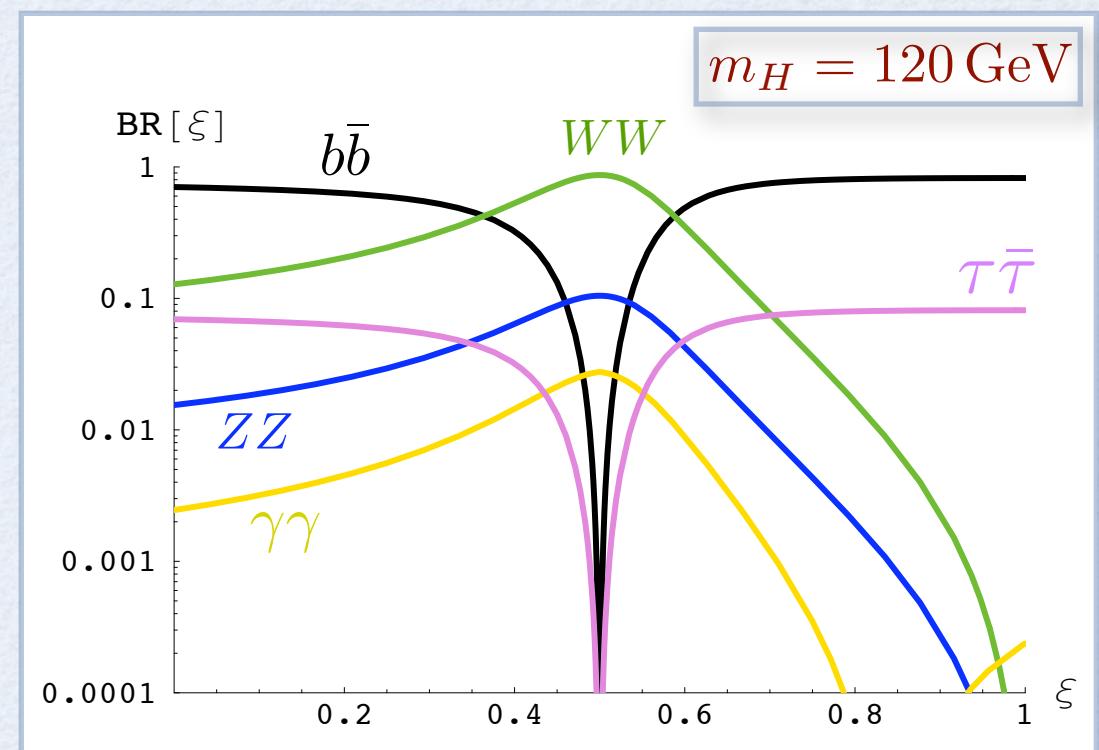
$$g_{hVV} = g_{hVV}^{SM} \sqrt{1 - \xi}$$

$$g_{hhVV} = g_{hhVV}^{SM} (1 - 2\xi)$$

$$(V = W, Z)$$

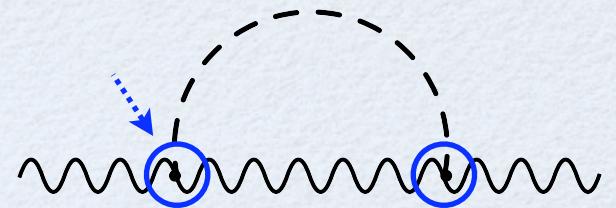
In the SO(5)/SO(4) of
PRD 75 (2007) 055014 :
[R.C., DaRold, Pomarol]

$$g_{h\bar{f}\bar{f}} = g_{h\bar{f}\bar{f}}^{SM} \frac{1 - 2\xi}{\sqrt{1 - \xi}}$$



👉 as stressed in: Barbieri et al. PRD 76 (2007) 115008

the shifts in the Higgs couplings induce an IR correction to the precision parameters $\epsilon_{1,3}$



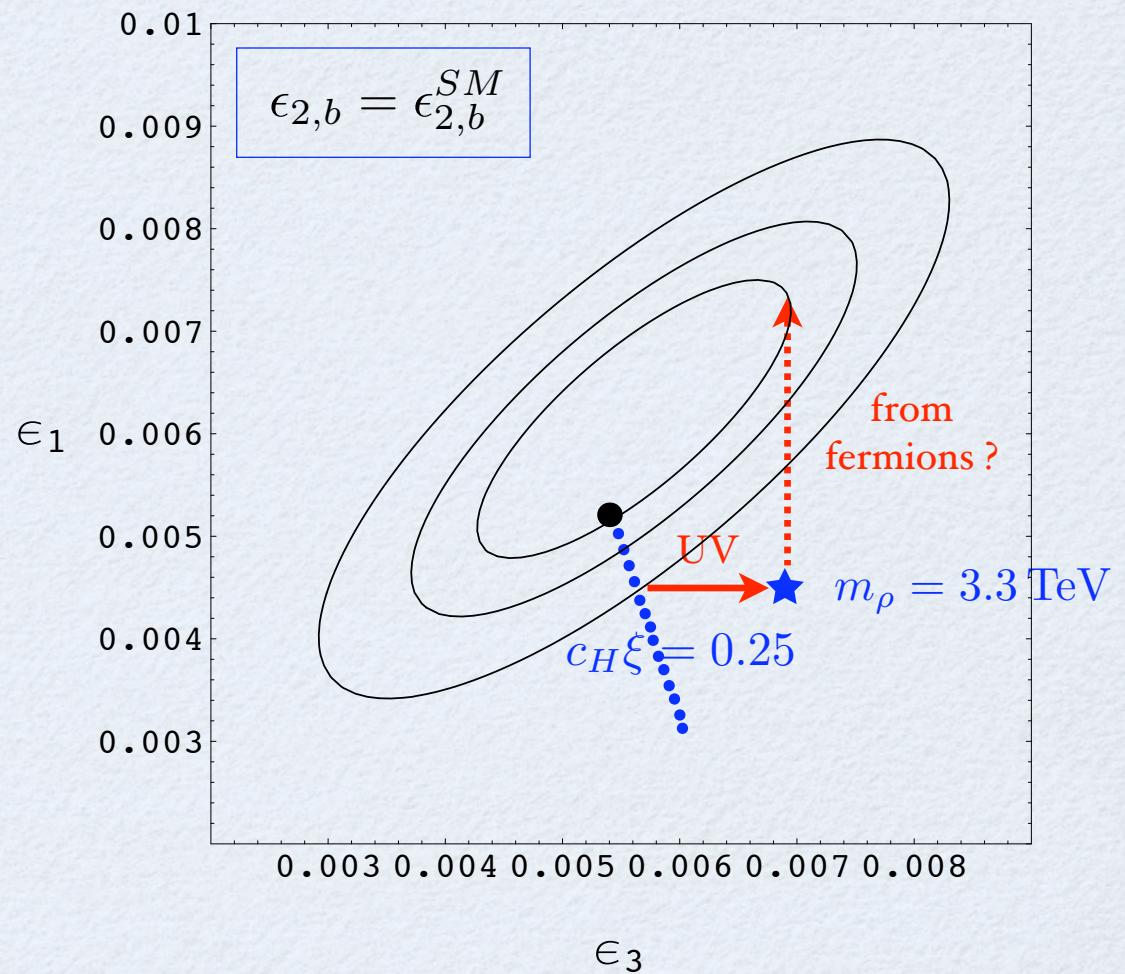
$$\epsilon_{1,3} = a_{1,3} \log \left(\frac{M_Z^2}{\mu^2} \right) - a_{1,3} (1 - c_H \xi) \log \left(\frac{m_h^2}{\mu^2} \right) - a_{1,3} (c_H \xi) \log \left(\frac{m_\rho^2}{\mu^2} \right) + \text{finite terms}$$

$$a_1 = + \frac{3}{16\pi} \frac{\alpha(M_Z)}{\cos^2 \theta_W}$$

$$a_3 = - \frac{1}{12\pi} \frac{\alpha(M_Z)}{4 \sin^2 \theta_W}$$

$$\Delta \epsilon_1 = a_1 (c_H \xi) \log \left(\frac{m_h^2}{m_\rho^2} \right)$$

$$\Delta \epsilon_3 = a_3 (c_H \xi) \log \left(\frac{m_h^2}{m_\rho^2} \right)$$



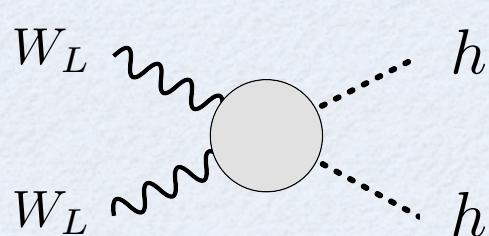
The $WW \rightarrow hh$ scattering is a probe
of the Higgs strong interaction

Giudice, Grojean, Pomarol, Rattazzi
JHEP 0706:045 (2007)

$$H = \begin{pmatrix} \pi^+ \\ h + i\pi^0 \end{pmatrix}$$

$$\mathcal{L} = \frac{1}{2} \partial_\mu H^\dagger \partial^\mu H + \frac{1}{2f^2} [\partial_\mu (H^\dagger H)]^2 + \dots$$

$$(\pi^2 + h^2) \square (\pi^2 + h^2)$$



$$= \begin{array}{c} \pi^+ \quad h \\ \diagdown \quad \diagup \\ \pi^- \quad h \end{array} + \mathcal{O}\left(\frac{M_W^2}{E^2}\right)$$

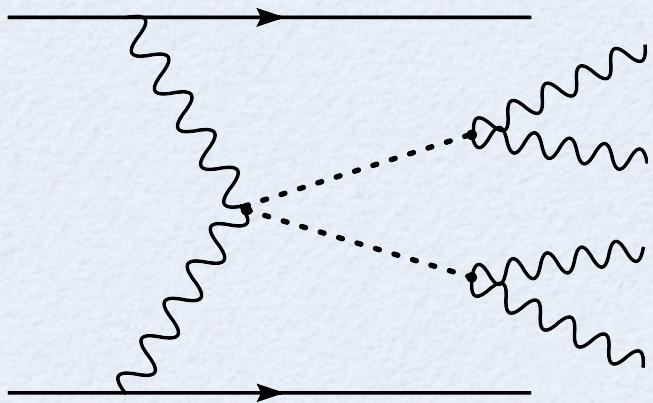
$$\boxed{\mathcal{A} = \frac{s}{v^2} \xi}$$



Let us put our **Pheno Cap** on and determine the sensitivity of the LHC on ξ (without worrying about the LEP constraint)

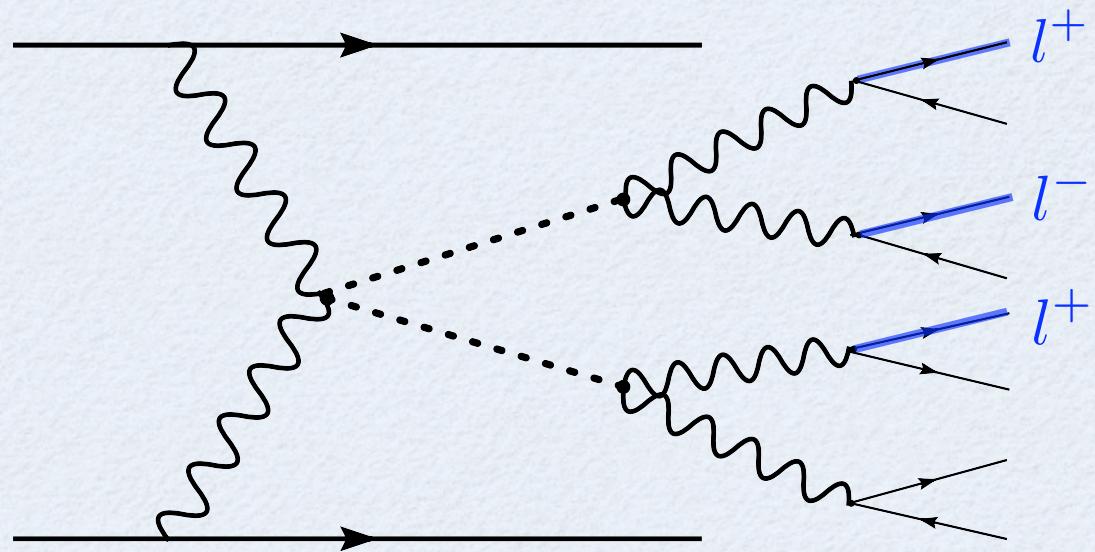
ANALYSIS OF $WW \rightarrow HH$ SCATTERING

We considered the Higgs decay mode $H \rightarrow WW$ and set $m_H = 180$ GeV



- ◆ For $H \rightarrow bb$ QCD background huge, even with 4 b-tags
- ◆ $\text{BR}(H \rightarrow WW)$ can be sizable even for light Higgs ($m_H < 140$ GeV)
if fermion couplings are suppressed (model dependent)

We studied final states with 2 same-sign leptons
and 3 leptons



- ◆ 4 leptons final state: still work in progress

Signal and Background Simulation

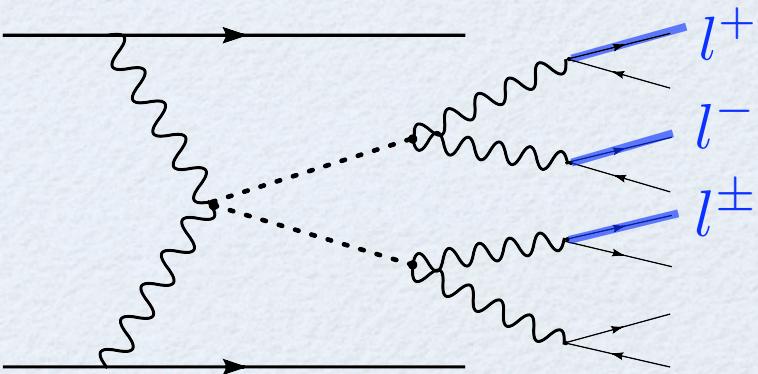
- ❖ Analysis at the Partonic Level (quarks, gluons = jets)
- ❖ Matrix Element computed with: MadGraph-MadEvent + ALPGEN
- ❖ Jet energy and momentum smeared by $100\%/\sqrt{E}$ to simulate the detector resolution
- ❖ Acceptance cuts:

$$p_{Tj} > 30 \text{ GeV} \quad |\eta_j| < 5 \quad \Delta R_{jj'} > 0.7$$

$$p_{Tl} > 20 \text{ GeV} \quad |\eta_l| < 2.4 \quad \Delta R_{jl} > 0.4 \quad \Delta R_{ll'} > 0.2$$

Strategy for 3 lepton case

- We require at least 4 jets



$$\mathcal{S}_3 : pp \rightarrow hhjj \rightarrow 4Wjj \rightarrow l^+l^-l^\pm + E_T + 4jets$$

Cross sections (in units 10^{-3} fb)
after acceptance cuts:

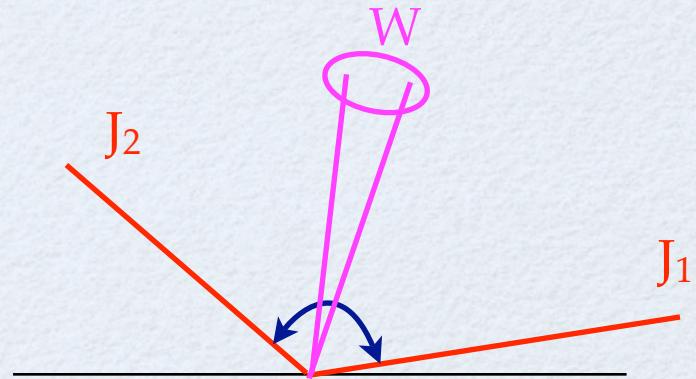


Background dominates over signal

Channel	σ_1
$\mathcal{S}_3 (\xi = 1)$	48.3
$\mathcal{S}_3 (\xi = 0.8)$	32.8
$\mathcal{S}_3 (\xi = 0.5)$	14.6
$\mathcal{S}_3 (\xi = 0)$	1.73
Wl^+l^-jjjj	11.94×10^3
$WWWWjjjj$	86.2
$t\bar{t}Wjj$	408
$t\bar{t}Wjjj$	287
$t\bar{t}WW$	315
$t\bar{t}WWj$	817
$t\bar{t}hjj \rightarrow t\bar{t}WWjj$	610
$t\bar{t}hjjj \rightarrow t\bar{t}WWjjj$	329
$W\tau^+\tau^-jjjj$	206
Total background	15.00×10^3

STEP 1. Identifying the “reference” jets

- i) pick the most forward jet
- ii) choose other jet with largest $M(jj)$
- iii) all other jets form W candidate



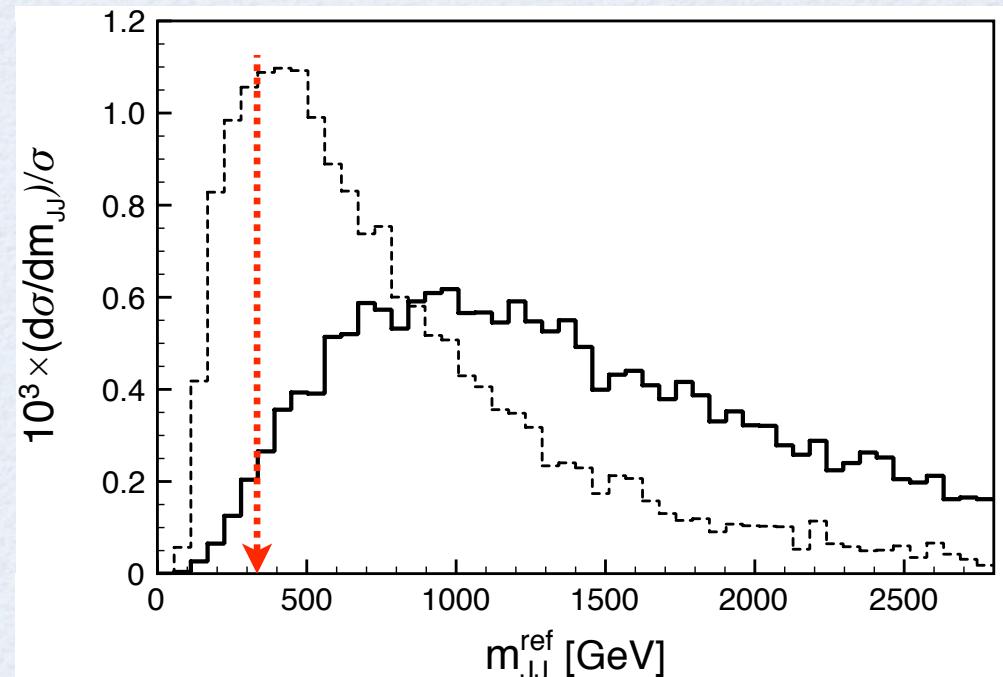
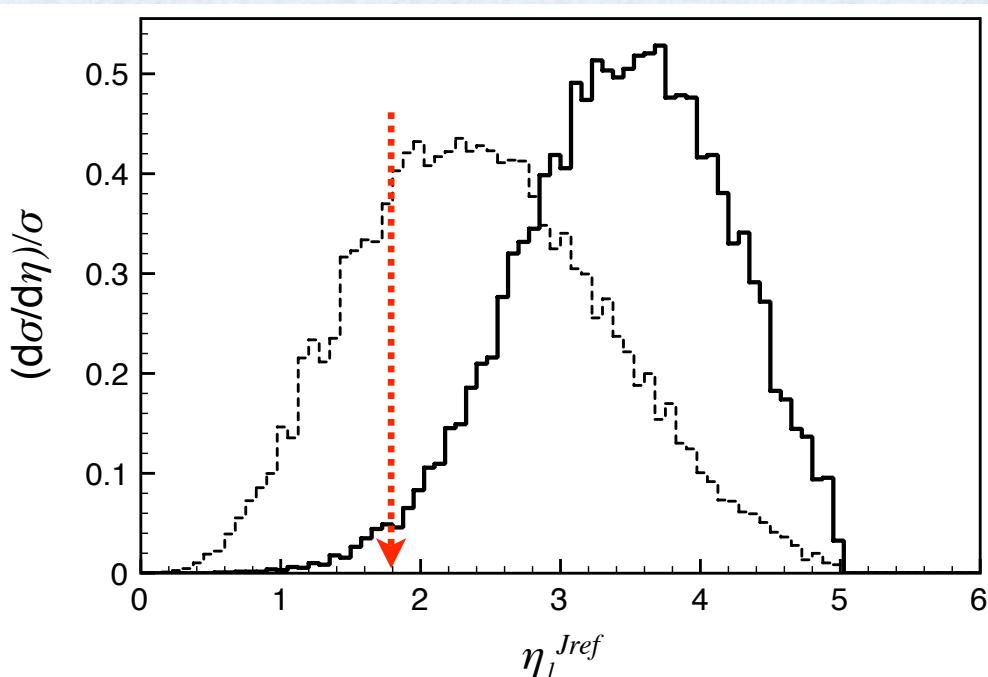
Preliminary cuts:

$$|\eta_1^{J_{ref}}| \geq 1.8$$

$$m_{JJ}^{ref} \geq 320 \text{ GeV}$$

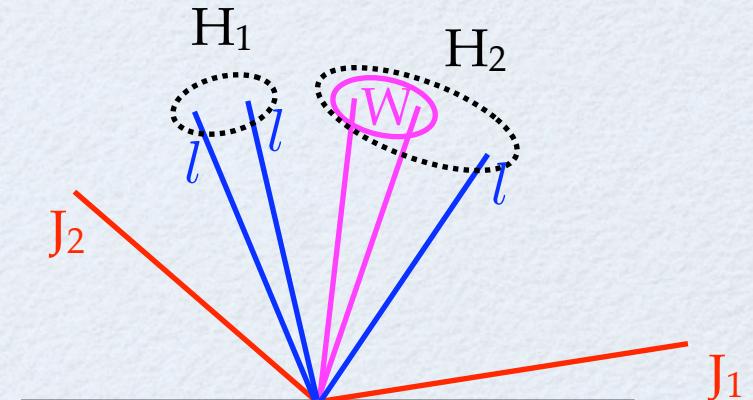
$$|\eta_1^{J_{ref}} - \eta_2^{J_{ref}}| \geq 2.9$$

$$|m_{JJ}^W - M_W| \leq 40 \text{ GeV}$$



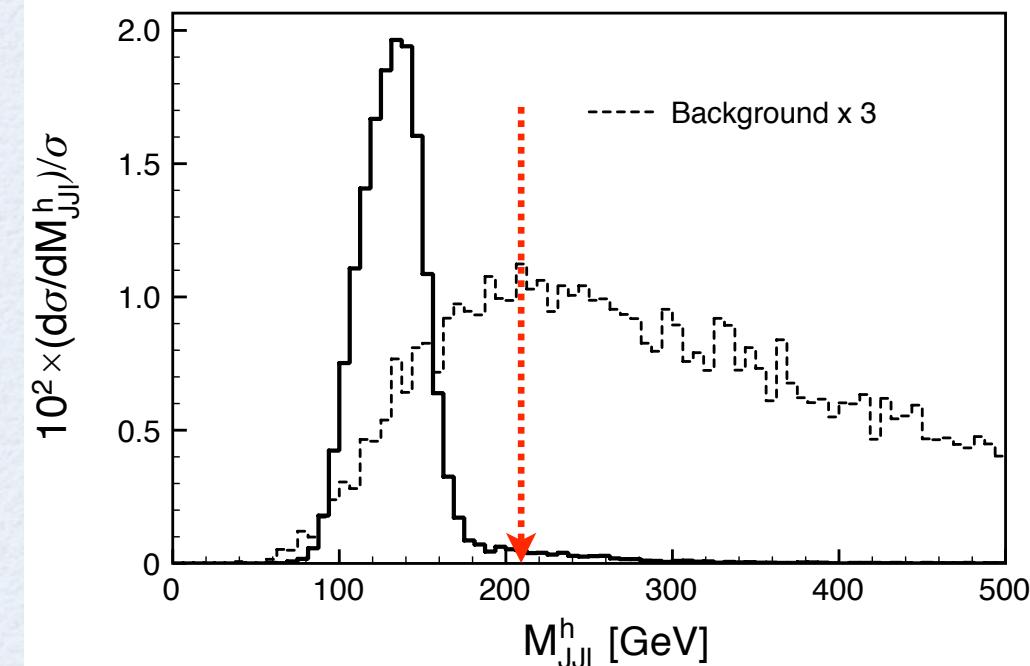
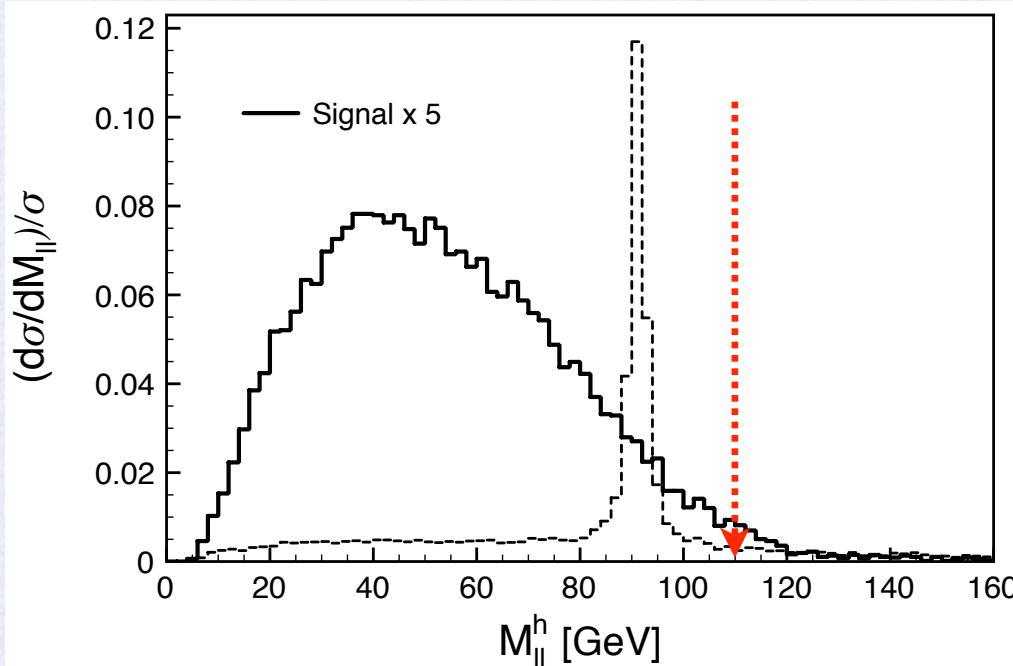
STEP 2. Reconstructing the two Higgses

- i) First Higgs system made of $(l^+ l^-)$ pair with smallest relative angle
- ii) Second Higgs system made of other lepton plus hadronic W



Preliminary cuts:

$$m_{ll}^h \leq 110 \text{ GeV} \quad m_{J_Jl}^h \leq 210 \text{ GeV}$$



Cross sections (in units 10^{-3} fb) after:

★ Preliminary cuts (σ_2)



★ Optimal cuts (σ_3)

Channel	σ_1	σ_2	σ_3
\mathcal{S}_3 ($\xi = 1$)	48.3	43.8	24.8
\mathcal{S}_3 ($\xi = 0.8$)	32.8	29.7	16.8
\mathcal{S}_3 ($\xi = 0.5$)	14.6	13.4	7.60
\mathcal{S}_3 ($\xi = 0$)	1.73	1.34	0.73
$Wl^+l^- jjjj$	11.94×10^3	654	2.31
$WWW jjjj$	86.2	3.47	0.23
$t\bar{t}W jj$	408	11.3	0.37
$t\bar{t}W jjj$	287	2.40	0.09
$t\bar{t}WW$	315	4.48	0.02
$t\bar{t}WWj$	817	28.1	0.89
$t\bar{t}hjj \rightarrow t\bar{t}WW jj$	610	8.9	0.38
$t\bar{t}hjjj \rightarrow t\bar{t}WW jjj$	329	0.8	0.03
$W\tau^+\tau^- jjjj$	206	11.5	0.68
Total background	15.00×10^3	725	5.00

STEP 3. Optimizing cuts through iterative procedure:

$$M_{e^+e^-, \mu^+\mu^-} \geq 20 \text{ GeV} \quad |M_{e^+e^-, \mu^+\mu^-} - M_Z| \geq 7 \Gamma_Z$$

$$|\eta_1^{Jref} - \eta_2^{Jref}| \geq 4.5 \quad m_{JJ}^{ref} \geq 700 \text{ GeV} \quad m_{JJl}^h \leq 160 \text{ GeV}$$

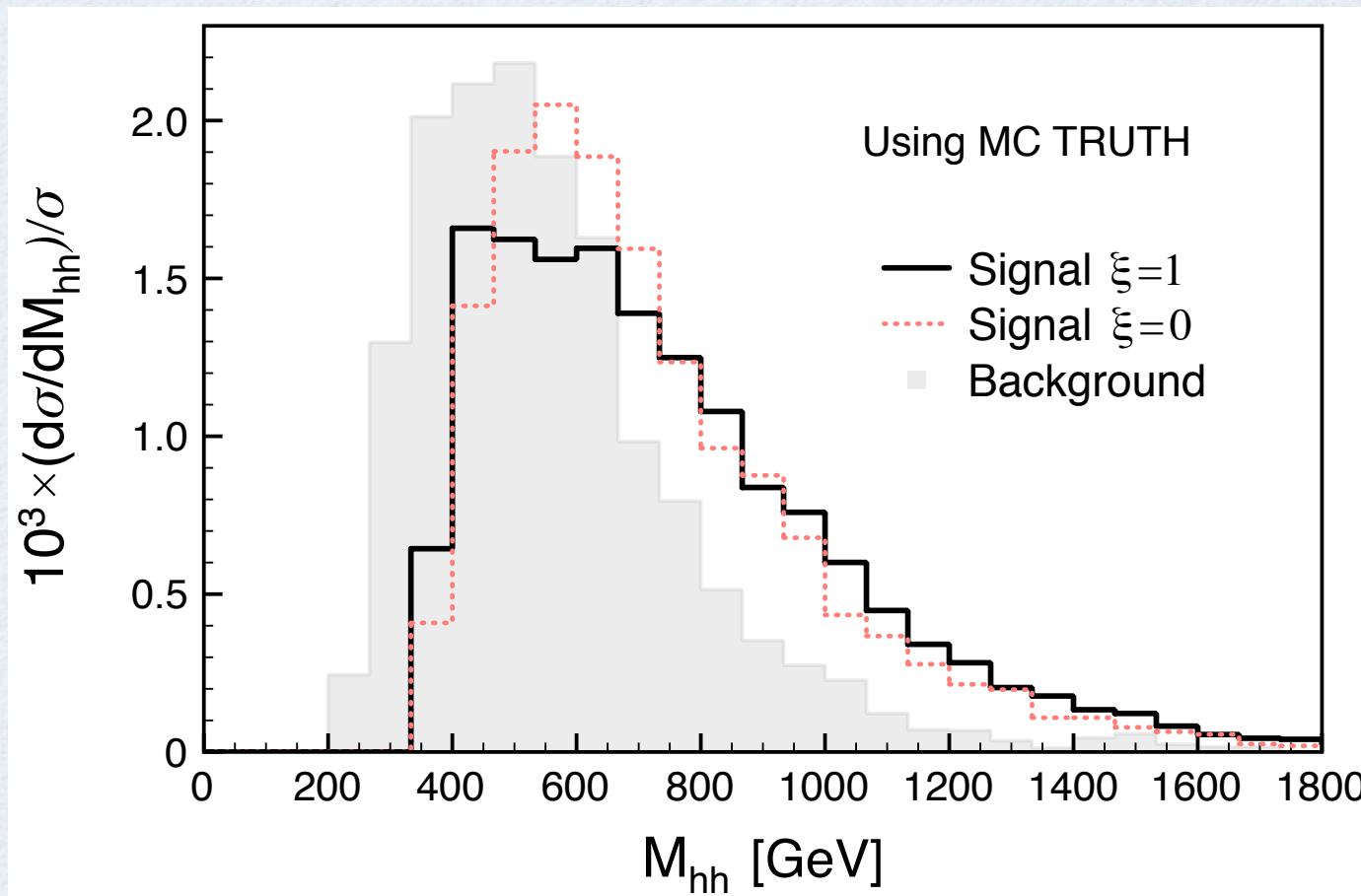
$$|m_{JJ}^W - M_W| \leq 20 \text{ GeV}$$

(twice ATLAS M(jj) resolution)

NOTICE: Cutting on the invariant mass of the two Higgs systems is **not** convenient



Not enough energy at the LHC !



Final Results

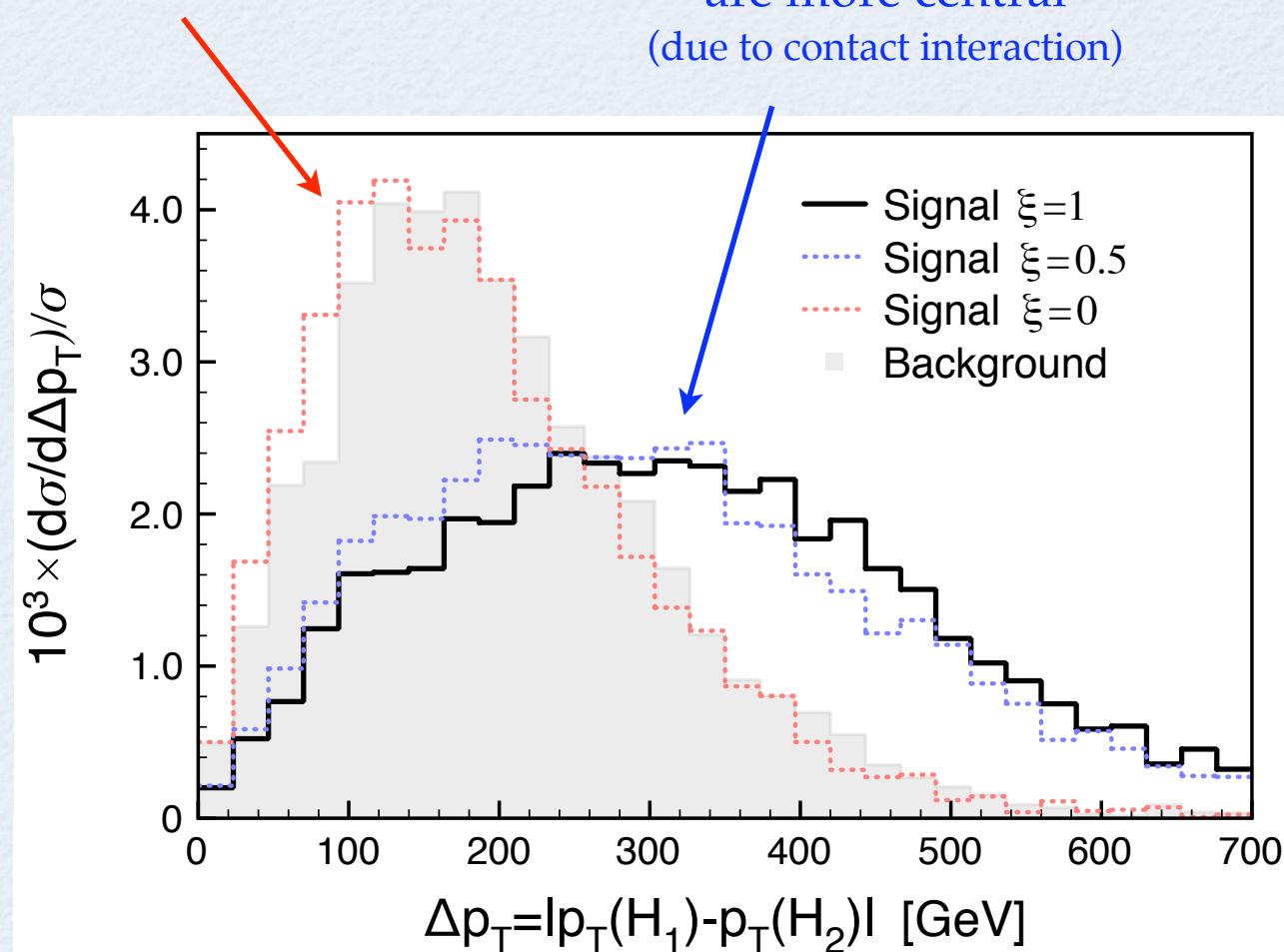
		N_{ev} (300 fb $^{-1}$)	σ (300 fb $^{-1}$)	σ (3000 fb $^{-1}$)
3 leptons	$\xi = 1.0$	7.4	3.7	12
	$\xi = 0.8$	5.0	2.6	8.7
	$\xi = 0.5$	2.3	1.2	4.4
	Background	1.5	—	—
2 same-sign leptons	$\xi = 1.0$	23.6	4.0	11
	$\xi = 0.8$	16.0	2.8	7.6
	$\xi = 0.5$	7.6	1.3	3.7
	Background	26.2	—	—

[Significance computed using Poisson statistics]

Strong vs SM behavior

SM Higgses are more forward
(due to t-channel singularity)

Strongly-interacting Higgses
are more central
(due to contact interaction)



CONCLUSIONS

- Double Higgs production via VBF challenging due to complex final state (and small cross section)
- Yet competitive with $WW \rightarrow WW$ because much less polluted by transverse scattering
- Strong-interaction regime barely reached at the LHC (luminosity upgrade welcome but energy upgrade better)
- Future investigation: other decay channels (ex: $h \rightarrow \tau\bar{\tau}$) plus full analysis with showering + detector simulation

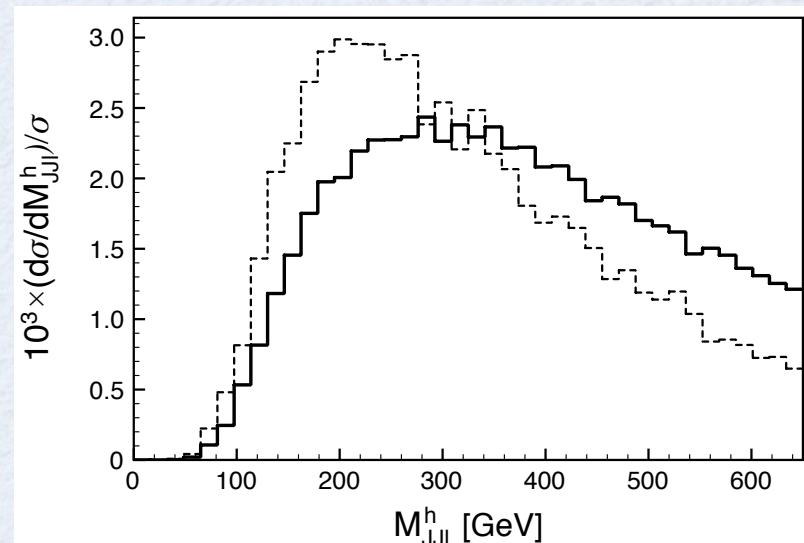
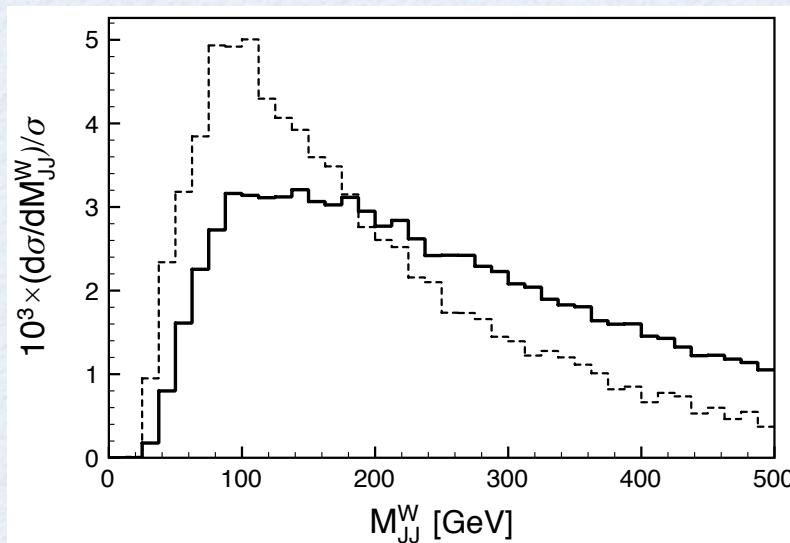
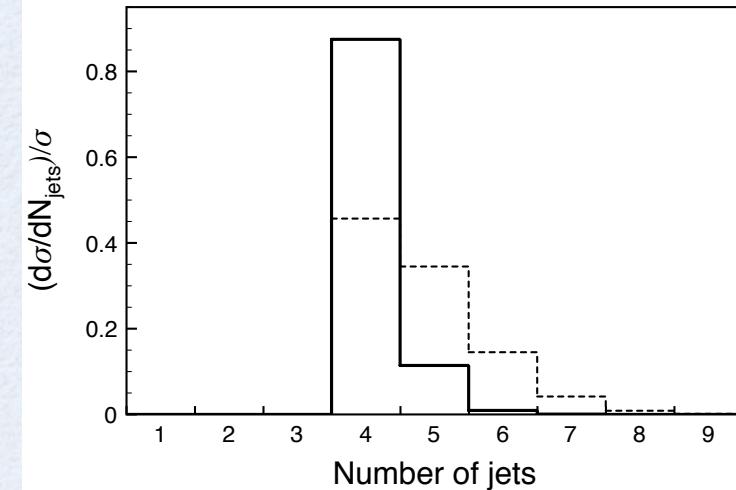
EXTRA SLIDES

Effect of showering (crude estimate)

- Little hadronic activity expected for the signal in the central region

- Larger ISR for the background implies:

- more jets
- m_{JJ}^W , m_{JJI}^h shifted towards larger values

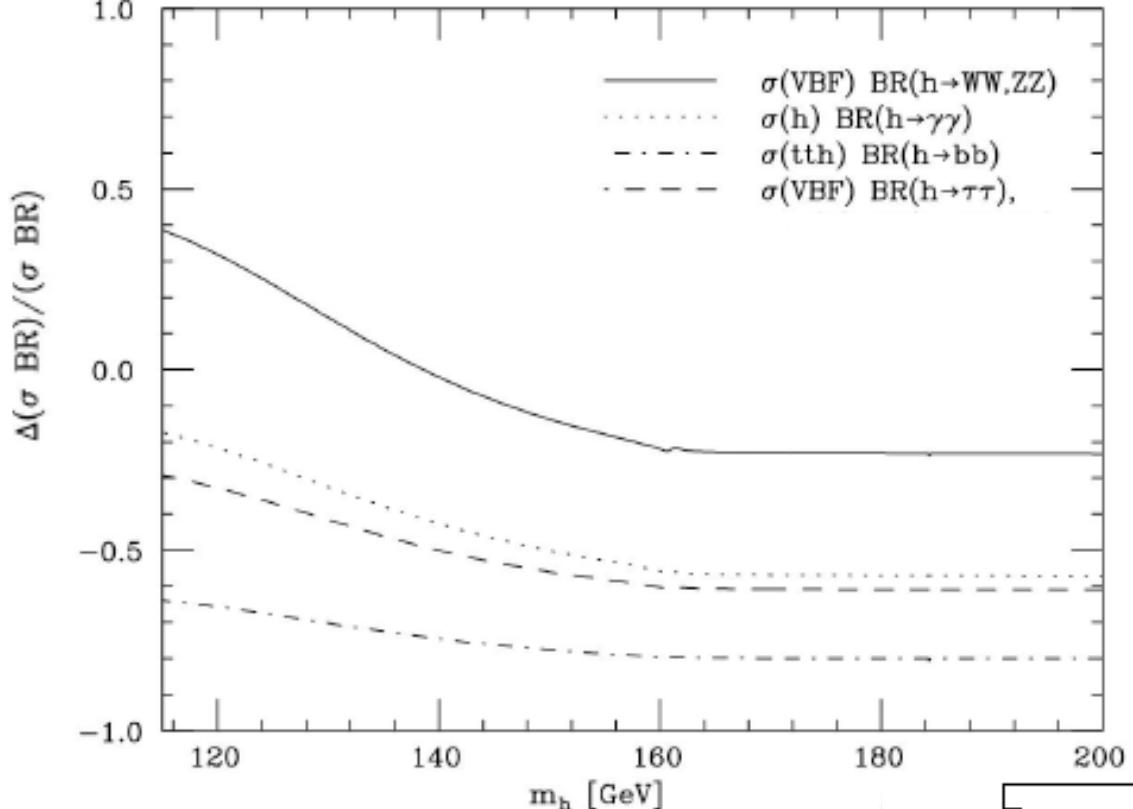


Crude Estimate of the (relative) effect of
the showering on the m_{JJ}^W , $m_{J\bar{J}l}^h$ cuts:

	\mathcal{S}_3 ($\xi = 1, 0.8, 0.5$)	Wl^+l^-jjjj
$\epsilon_{shower}/\epsilon_{parton}$	0.80	0.59



After cuts on m_{JJ}^W , $m_{J\bar{J}l}^h$ veto on additional jets is useless

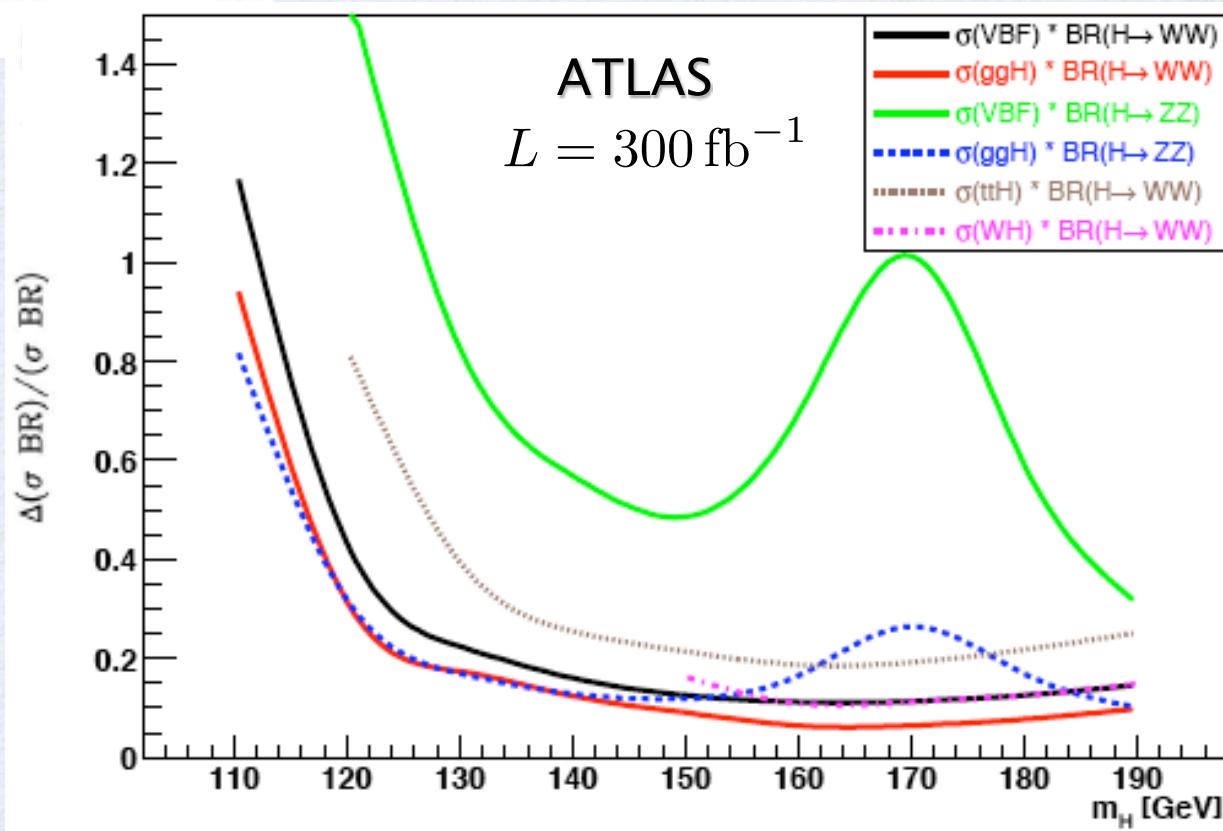


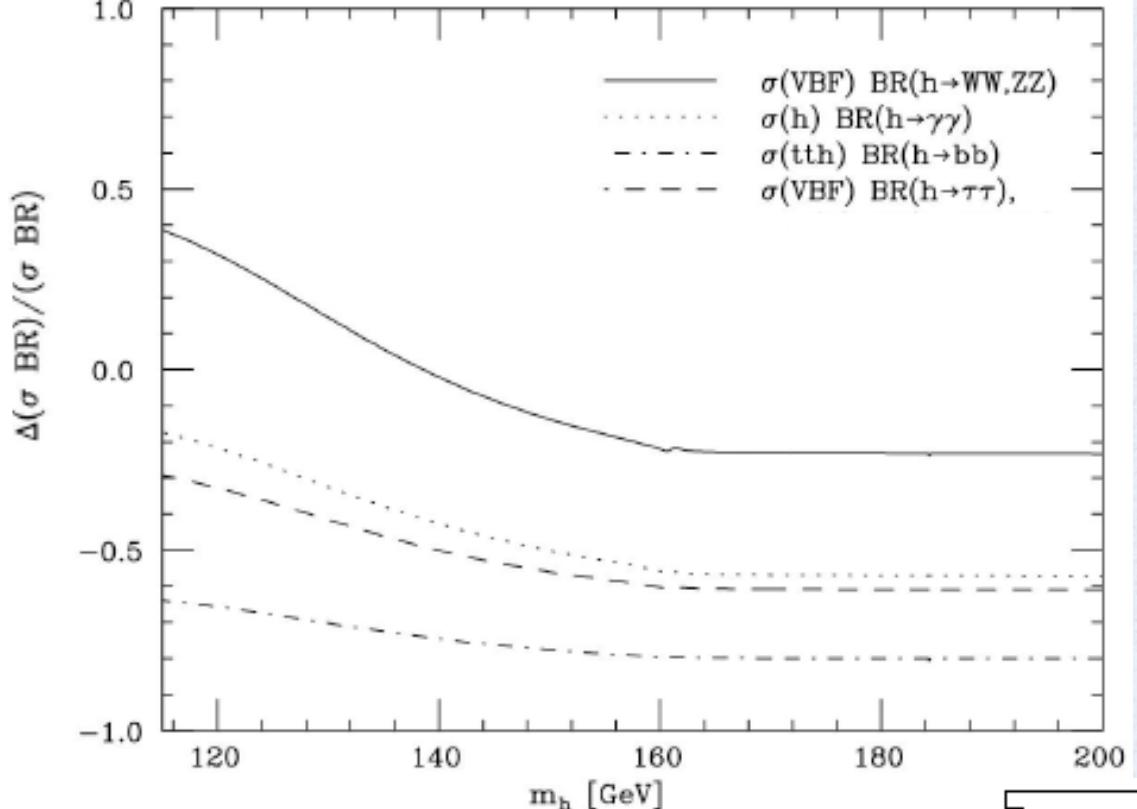
LHC sensitive up to $c_H\xi = 0.2 - 0.4$

[Duhrssen ATL-PHYS-2003-030]

prediction of the SO(5)/SO(4) model [$c_y/c_H = 1$] for $c_H\xi = 0.25$

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