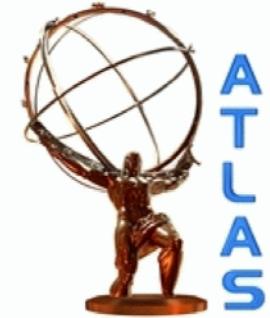


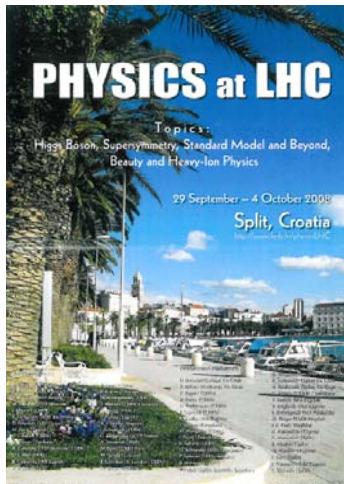
# Higgs at LHC

*Introduction*  
*Updated results on SM*  
*Measurement of Higgs Boson parameters*  
*MSSM*  
*Higgs Boson, Supersymmetry, Standard Model and Beyond,*  
*Beauty and Heavy-Ion Physics*  
*Other exotica*

29 September – 4 October 2008  
Split, Croatia



*A non exhaustive review*



Physics at LHC 2008

*see specific talks on Higgs at LHC here by*

D Trocino

Y Fang

F Stoeckli

S Xella

M Vazquez Acosta

I Ludwig

*and posters*

B Murray

F.Ferri

A D'Orazio

*for more details*

L.Fayard 29-9-2008

## Disclaimer

We will not answer all what interest theorists

C.Quigg Rept.Prog.Phys.70:1019-1054,2007

- (i) Is it there? Is there only one?
- (ii) What are its quantum numbers?
- (iii) Does the Higgs boson generate mass both for the electroweak gauge bosons and for the quarks and leptons?
- (iv) How does the Higgs boson interact with itself



## no Higgs boson

Quand la théorie en prévoit un ! Car en 2003, cinq chercheurs dont Christophe Grojean, du Cern, ont carrément proposé une théorie avec dimension supplémentaire permettant purement et simplement de se passer du boson de Higgs ! “*Car tout élégant qu'il soit, le mécanisme de Higgs est une invention qui pose autant de questions qu'il en résout*”, avoue Christophe Grojean. “*La seule certitude, résume*

### “Le concept de boson de Higgs pose autant de questions qu'il en résout”

CHRISTOPHE GROJEAN,  
DIVISION DE LA PHYSIQUE THÉORIQUE, CERN



*rité... que rien n'étaye par ailleurs*”, précise Fabienne Ledroit, spécialiste de la traque des Higgs “exotiques” au Laboratoire de physique subatomique et de cosmologie, à Grenoble.

#### DES DIMENSIONS CACHÉES ?

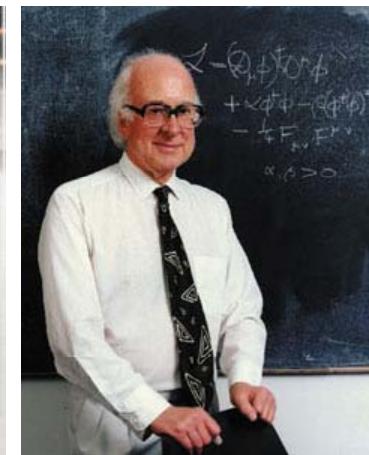
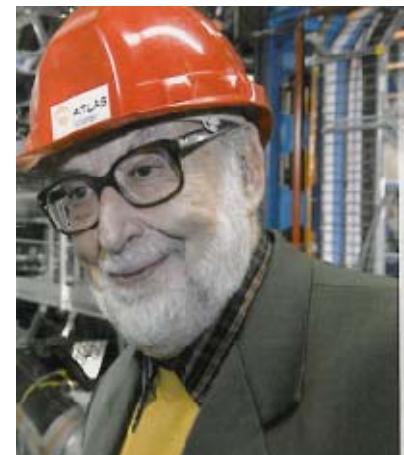
Parmi tous ces modèles, les plus exotiques, mais aussi les plus excitants, restent cependant ceux qui impliquent des dimensions supplémentaires. En l'occurrence, de minuscules dimensions qui seraient passées inaperçues parce que repliées sur elles-mêmes. Comme un fil tendu entre deux poteaux: pour le funambule qui ne peut qu'avancer ou reculer dessus, c'est un espace à une seule dimension; mais pour la fourmi qui peut en faire le tour, le long de son périmètre, cet espace a une petite dimension supplémentaire enroulée sur elle-

même. De là, l'idée proposée par Lisa Randall, à Harvard, et Raman Sundrum, à l'université John-Hopkins, à la fin des années 1990: alors que dans la plupart des approches théoriques, on admet que la gravitation est trop peu intense pour jouer un rôle dans la physique des accélérateurs, les deux physiciens ont imaginé qu'à l'échelle du TeV, celle-ci se manifeste à travers les dimensions supplémentaires. Si l'idée paraît surprenante, elle prédit, selon le détail des modèles envisagés, de nouvelles particules, des fuites d'énergie dans les dimensions supplémentaires, voire la création au LHC de minitrous noirs qui, sur le papier, préservent la validité de la théorie électrofaible et stabilisent la masse du boson de Higgs.

Quand la théorie en prévoit un ! Car en 2003, cinq chercheurs dont Christophe Grojean, du Cern, ont carrément proposé une théorie avec dimension supplémentaire permettant purement et simplement de se passer du boson de Higgs ! “*Car tout élégant qu'il soit, le mécanisme de Higgs est une invention qui pose autant de questions qu'il en résout*”, avoue Christophe Grojean. “*La seule certitude, résume* Marcela Carena, c'est qu'il va se passer quelque chose autour de 1 TeV !” Le monde de la physique théorique attend donc avec impatience que le LHC fasse le tri entre ces propositions, et indique la voie que la nature a choisie pour faire jaillir la matière de l'énergie. ■

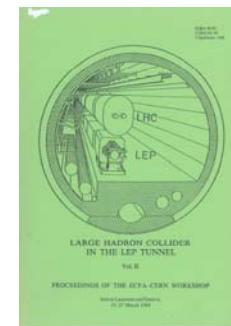
1964

Brout  
Englert  
Higgs



1984

Lausanne



1992 ← LHC experiments LOI

1994 ← ATLAS and CMS TP

1999 ← ATLAS Physics TDR CERN/LHCC/99-14 CERN/LHCC/99-15

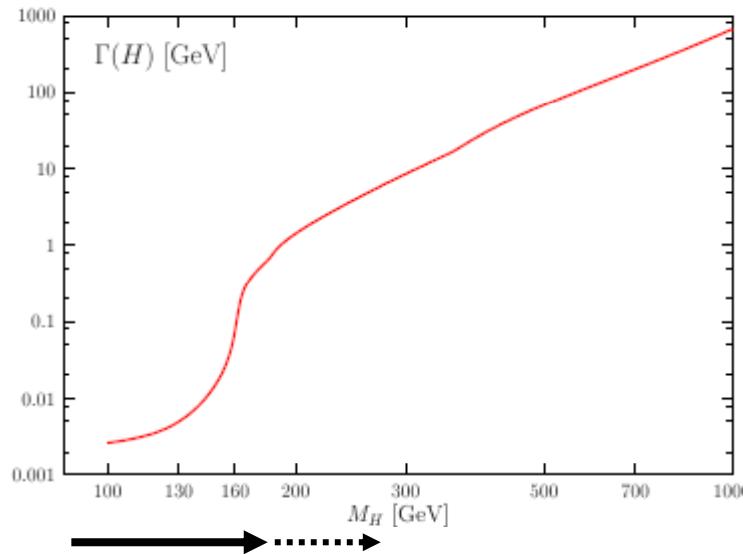
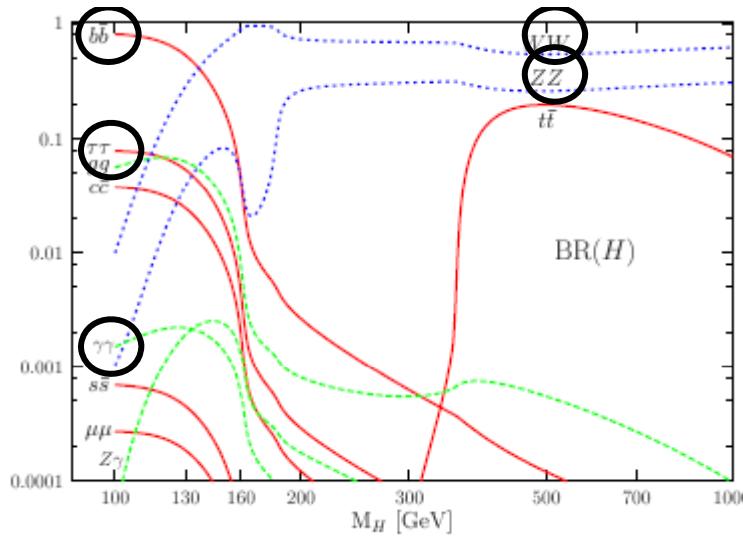
2006 ← CMS Physics TDR CERN/LHCC 2006-001 CERN/LHCC 2006-021  
J. Phys. G: Nucl. Part. Phys. 34 (2007) 995–1579

2008 ← new ATLAS notes to be released soon + additional CMS notes

*A lot of things  
(even important  
like trigger and  
description of  
data driven  
background  
estimation)  
are missing in  
this talk !*

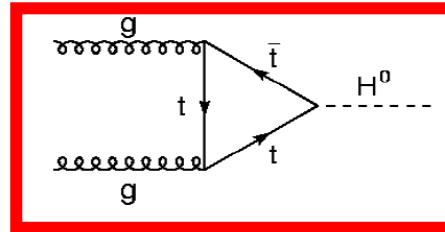
**Increasing complexity of the analysis  
( that should be more realistic )**

# SM Higgs

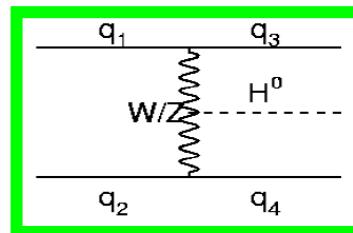


## Width smaller than ‘leptonic/ $\gamma$ resolution’

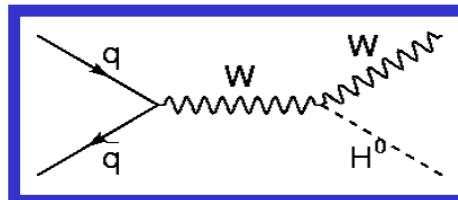
**Favored by LEP**  $\rightarrow m_H = 84^{+35}_{-26} \text{ GeV}$   $m_H < 154 \text{ GeV}, \underbrace{185 \text{ GeV}}_{\text{including direct LEP limit}} 95\% \text{ CL}$



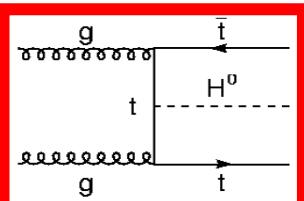
**GF**  $H \rightarrow WW, ZZ, \gamma\gamma$



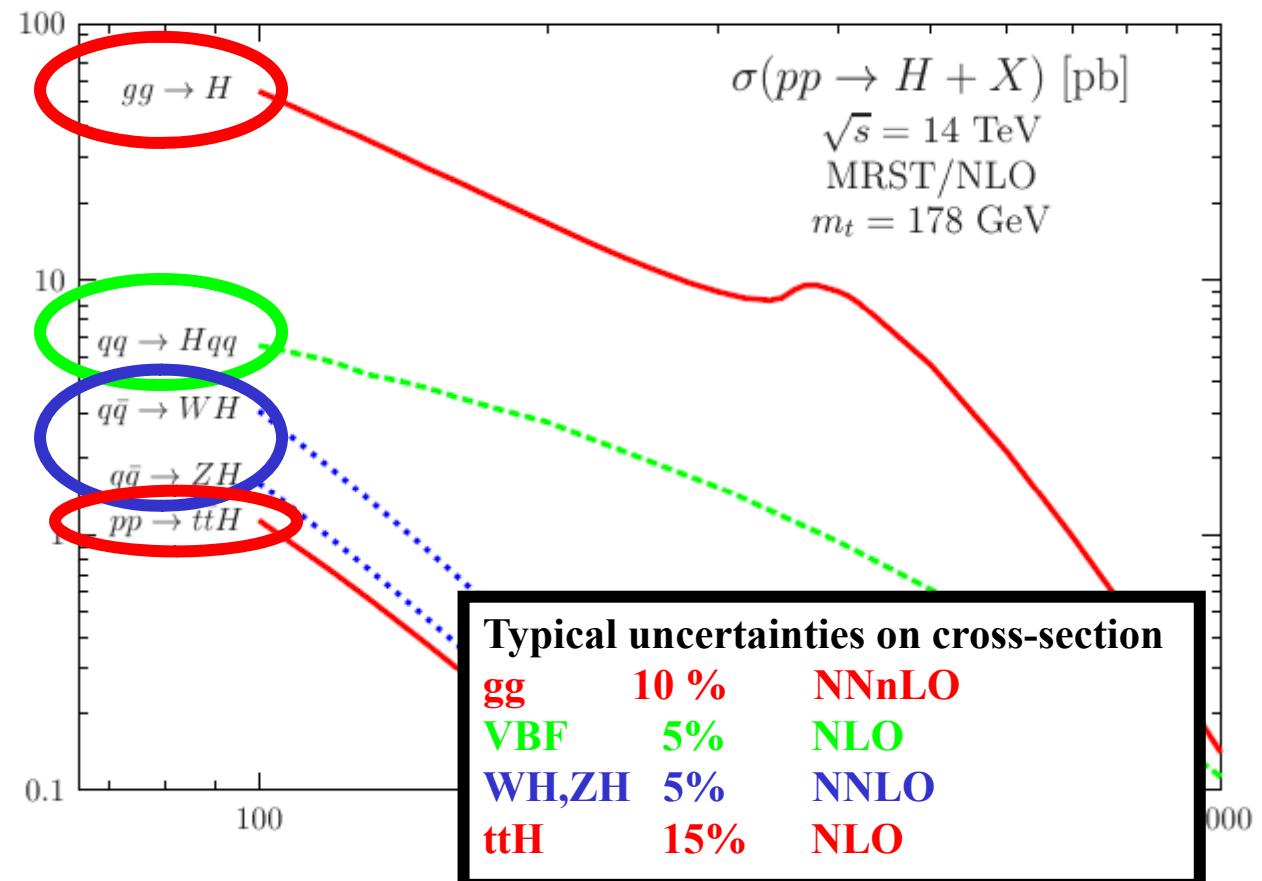
**VBF**  $H \rightarrow WW, \gamma\gamma, \tau\tau$



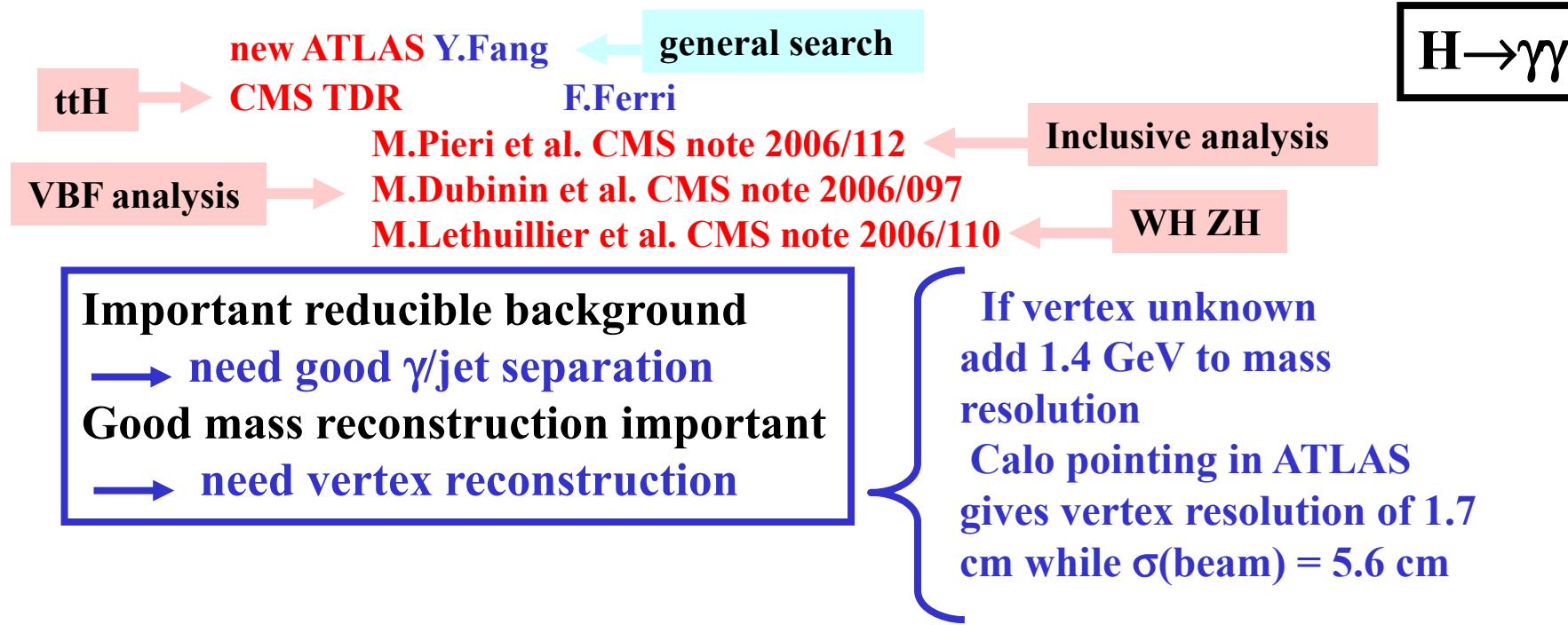
$H \rightarrow WW, \gamma\gamma$



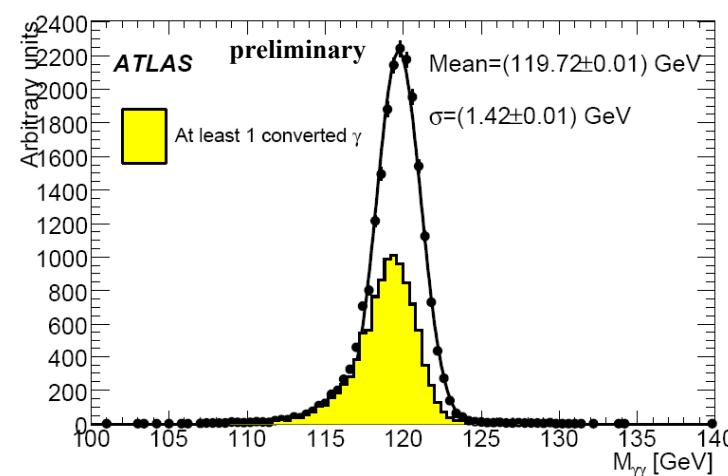
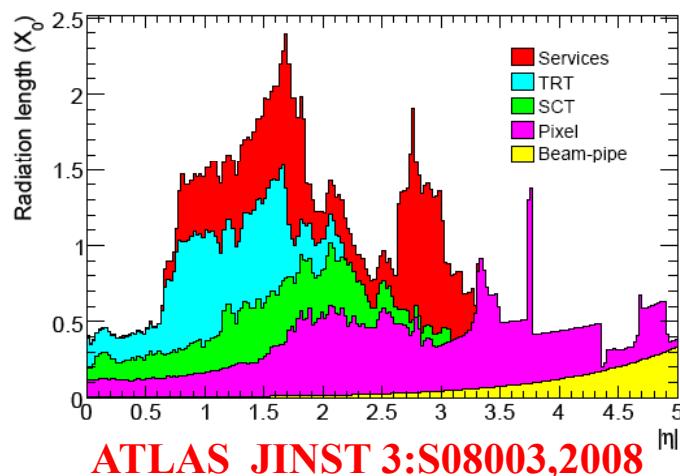
$H \rightarrow WW, \gamma\gamma, bb$

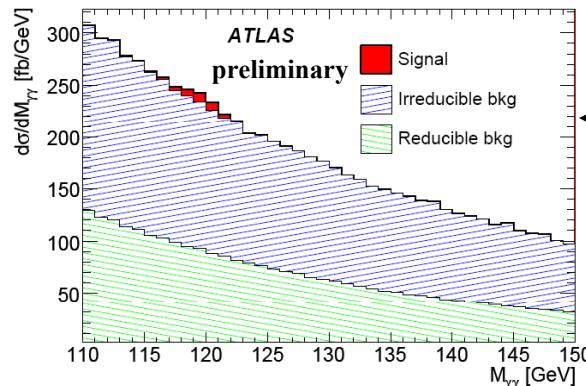


*These production cross sections have to be used with the decays  $bb, \tau\tau, WW, ZZ, \gamma\gamma$*

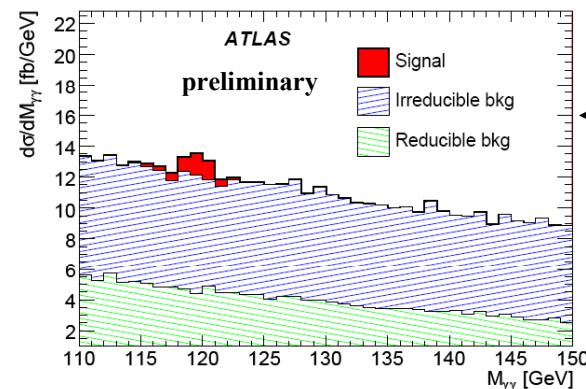


*A large amount of material in the Inner Detector in front of the em calorimeter  $\Rightarrow$  importance of conversions*

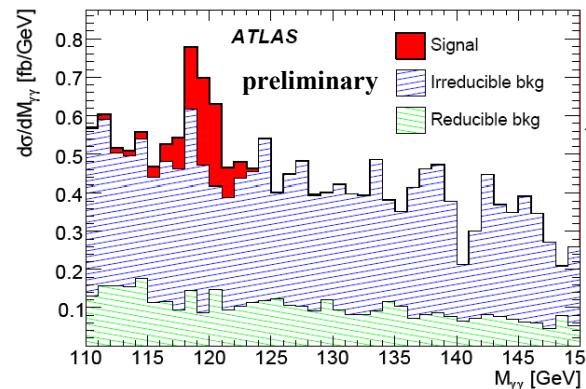




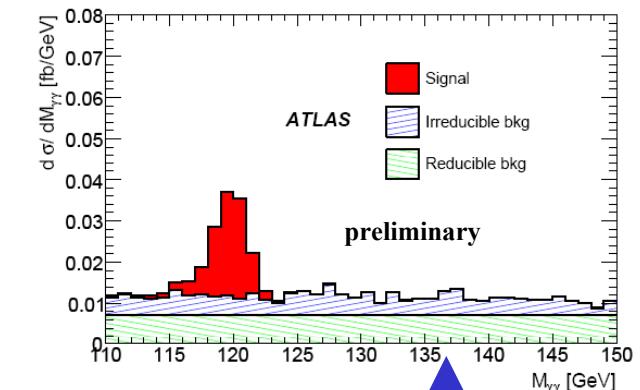
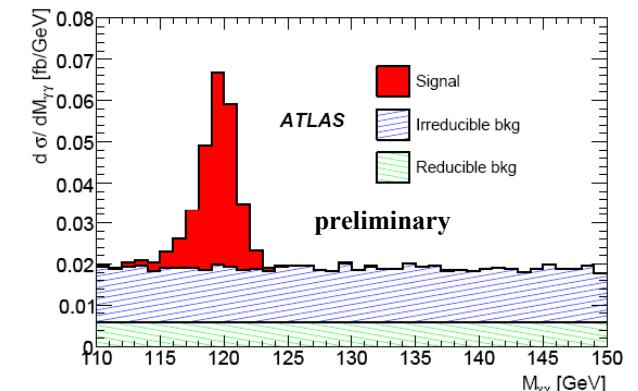
inclusive  
S/B ~ .03



H+1j  
S/B ~ .08  
VBF + more  
jets with gg → H



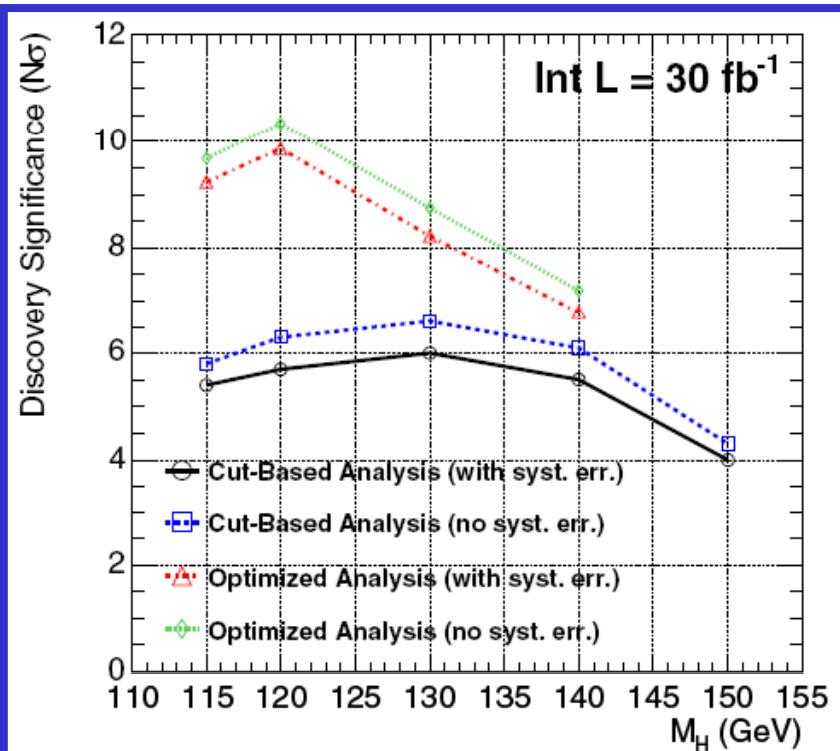
H+2j  
S/B ~ .4  
VBF mainly



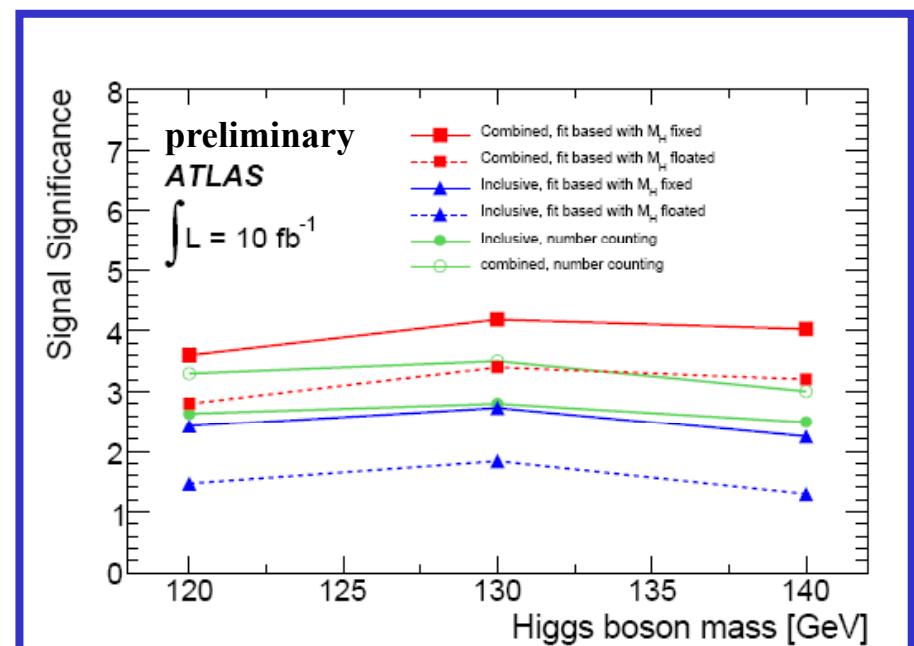
H+E<sub>T</sub><sup>miss</sup>  
S/B ~ 2  
ZH WH

For different final states different S/B

29-9-2008



**CMS optimized : NN with kinematics as input , using categories (  $\eta$  , cluster size  $\equiv$  conversion info )**



**ATLAS : combined fit using variables (  $p_T$  ,# jets ,  $\cos\theta^*$  ) and categories (  $\eta$  , conversions )**

*small differences ~ understood*

**H $\rightarrow$  4l**

4 $\mu$

new ATLAS ee $\mu\mu$  4 $\mu$  4e

CMS TDR D.Futyan,D.Fortin and D.Giordano CMS note 2006/136

M.Aldaya et al. CMS note 2006/106 S.Abdullin et al. Acta Phys.Pol.B38(2007) 731-738

S.Baffioni et al. CMS note 2006/115

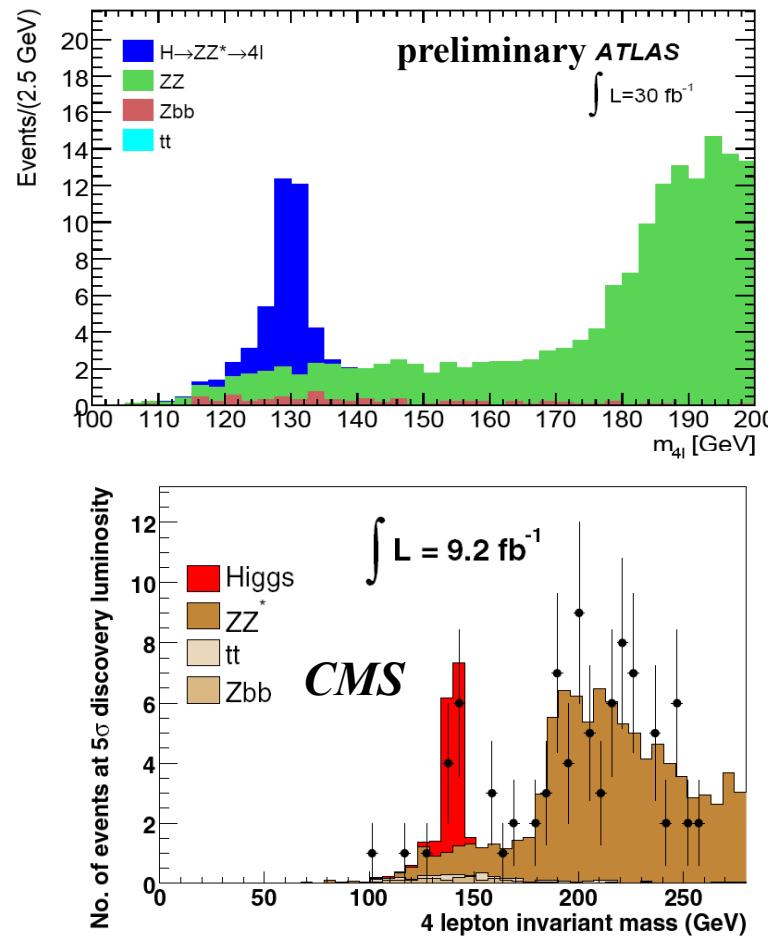
D.Trocino A.D'Orazio

4e

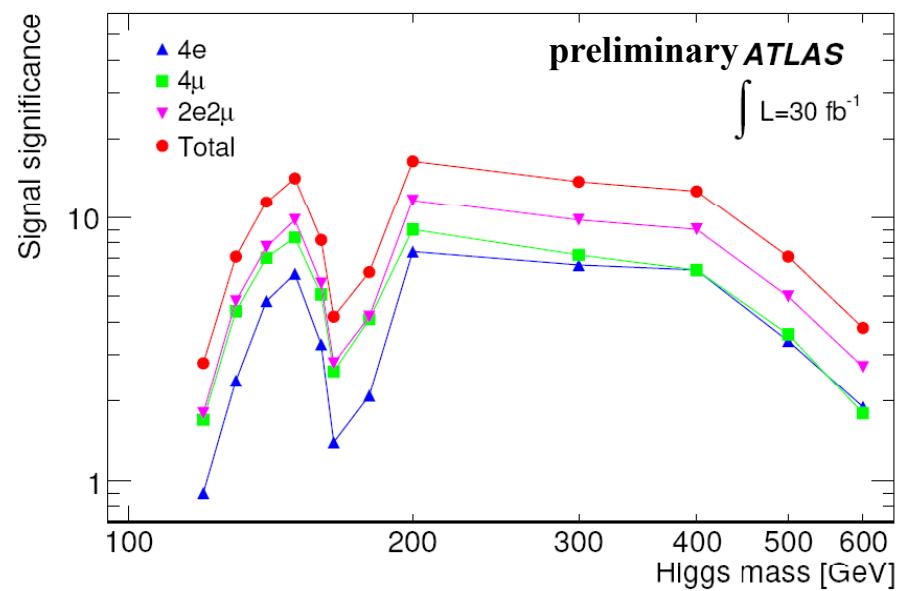
ee $\mu\mu$

Main backgrounds : ZZ (irreducible) , tt and Zbb (reducible)

Tools for background suppression : lepton isolation and impact parameter



*there are 4 leptons* ! *be careful about efficiency*



L.Fayard 29-9-2008

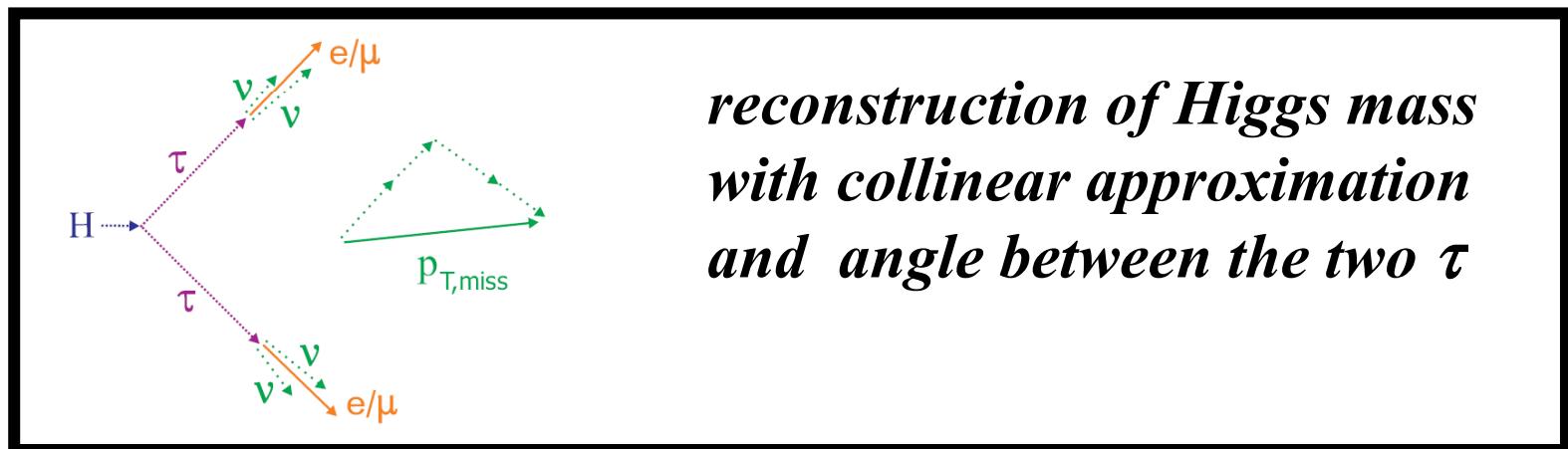
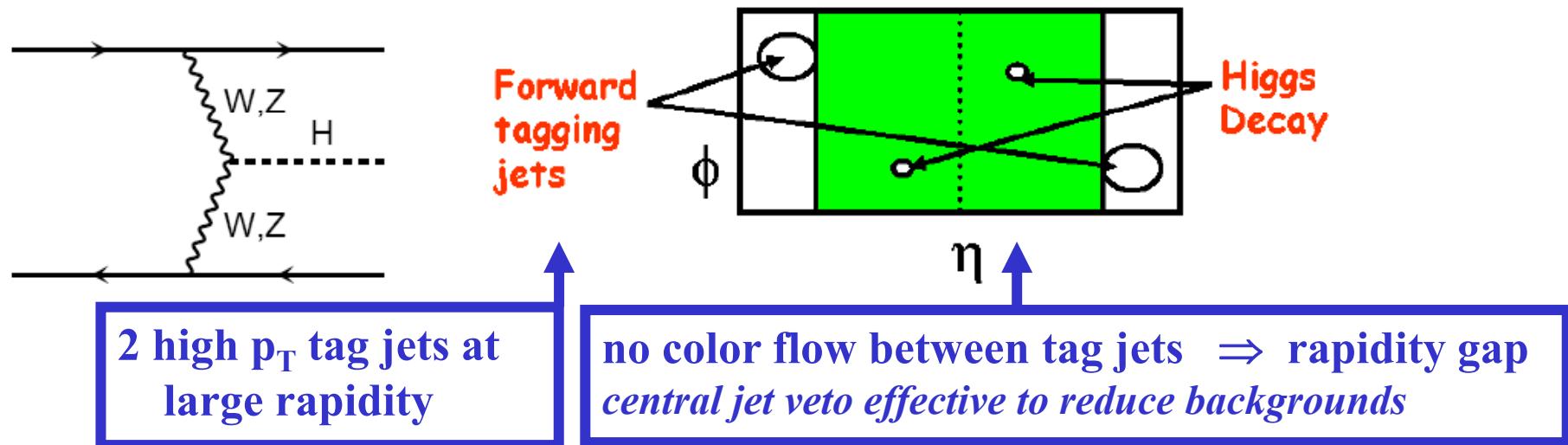
10

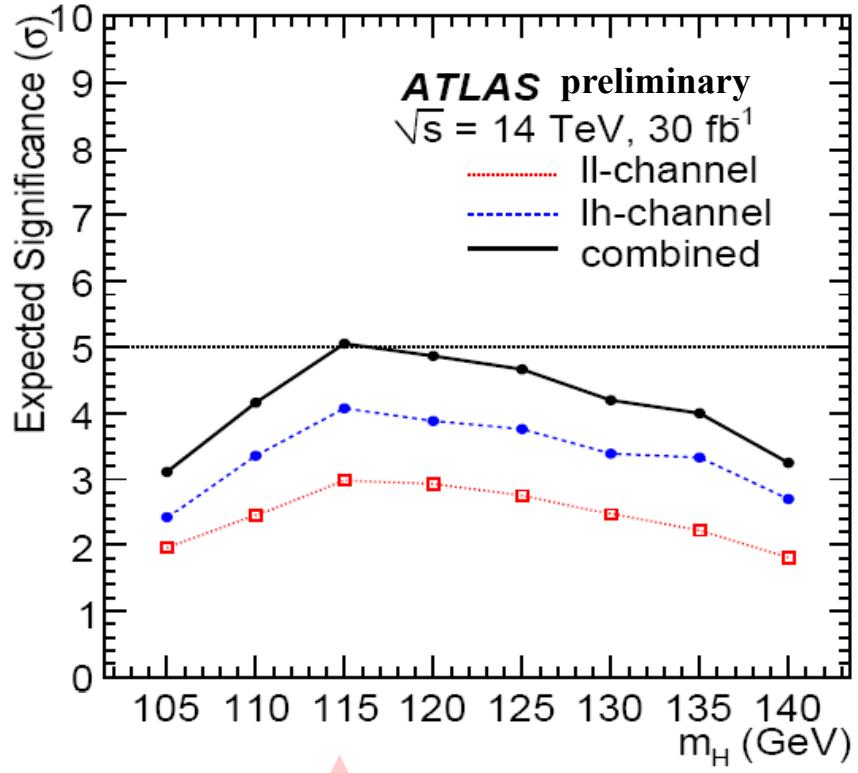
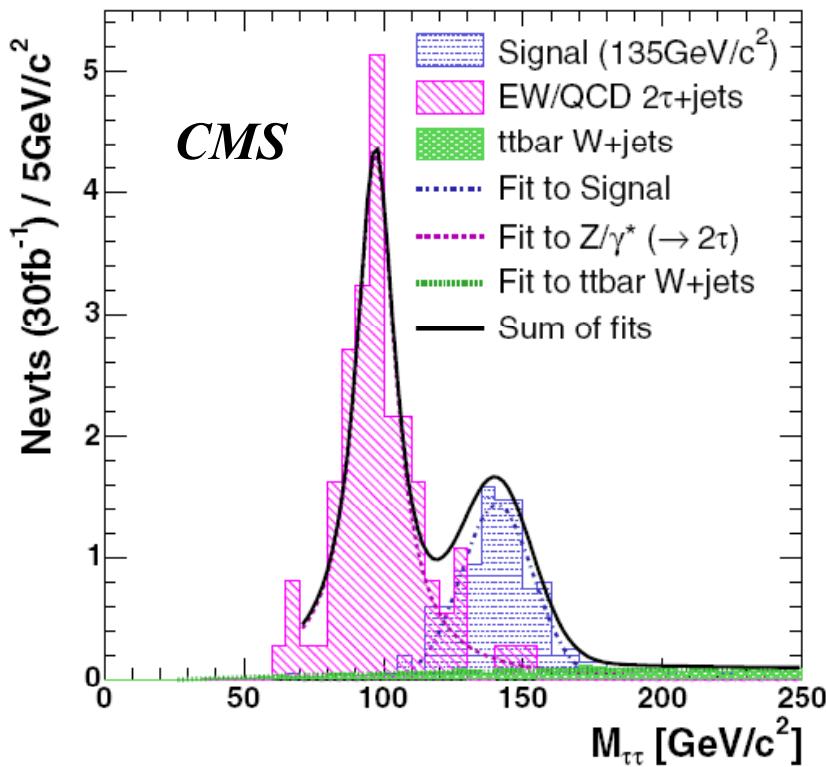
## VBF H $\rightarrow$ $\tau\tau$

new ATLAS  $\leftarrow \tau\tau \rightarrow ll, lh, hh$

S.Xella M.Vasquez Acosta

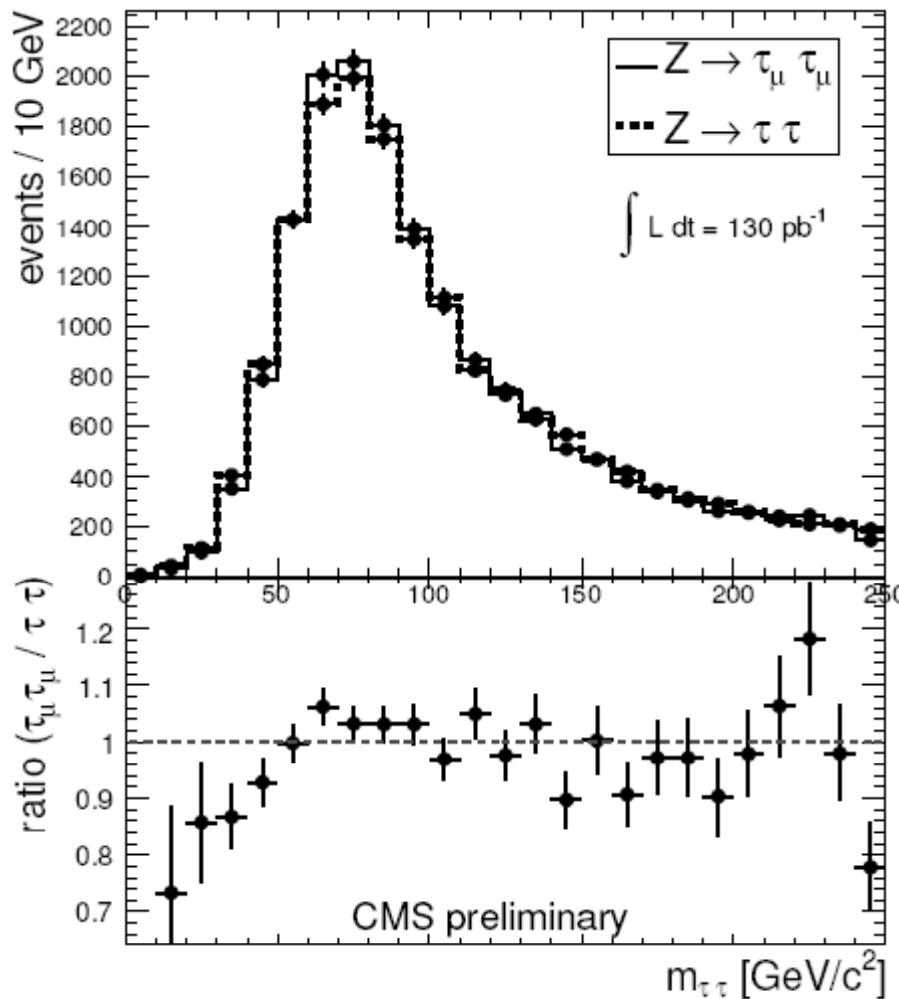
CMS TDR C.Foudas,A.Nikitenko and M.Takahashi CMS note 2006/088





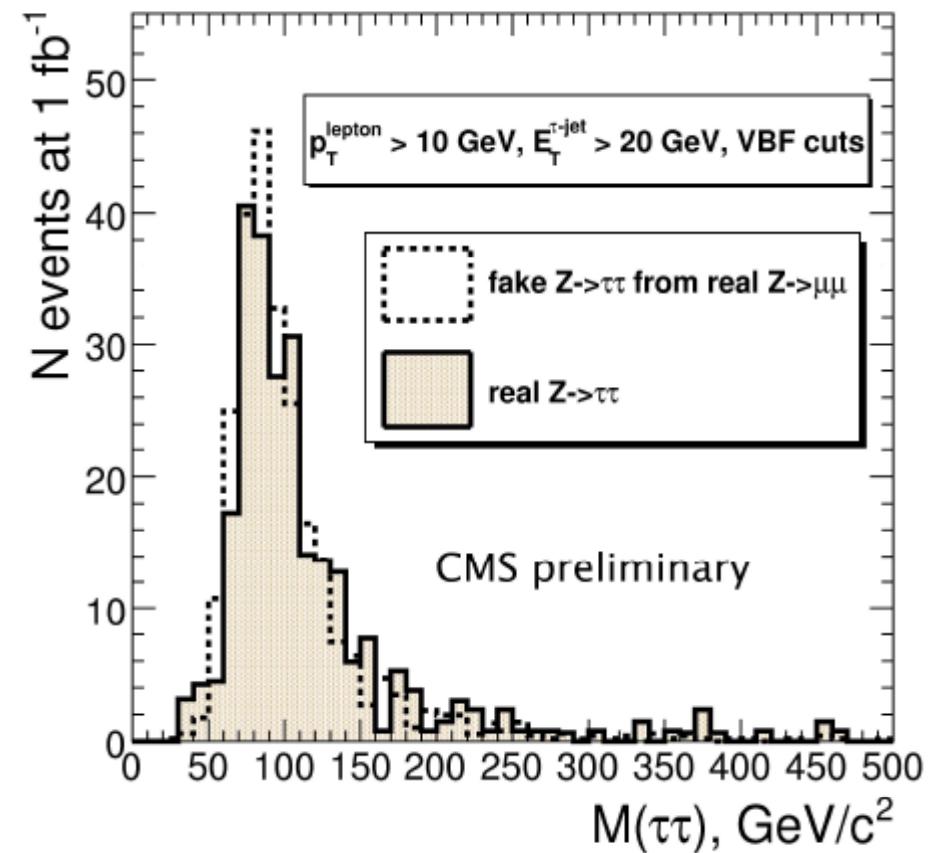
similar in CMS , slightly  
tighter cuts (pile-up included)  
 $L = 2 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  )

*example of data driven analysis . estimate  
 $Z \rightarrow \tau\tau$  from  $Z \rightarrow \mu\mu$  and replacement of  $\mu$  by  $\tau$*



Physics at LHC 2008

L.Fayard 29-9-2008



13

**H $\rightarrow$  WW**

new ATLAS I.Ludwig  
CMS TDR F.Stoeckli

H $\rightarrow$  WW  $\rightarrow$  l $l$ lv

WH (3l)

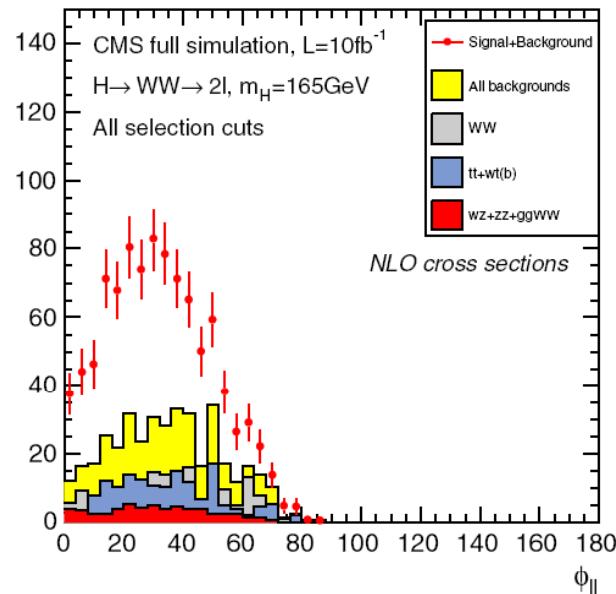
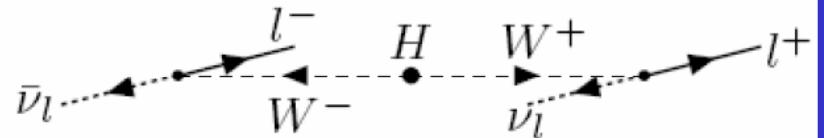
V.Drollinger et al. CMS note 2006/055  
G.Davatz,M.Dittmar and A.Giolo-Nicollerat CMS note 2006/047 J.Phys.G33:N85,2007  
C.Delaere CMS note 2006/053

VBF WW $\rightarrow$  l $l$ lv

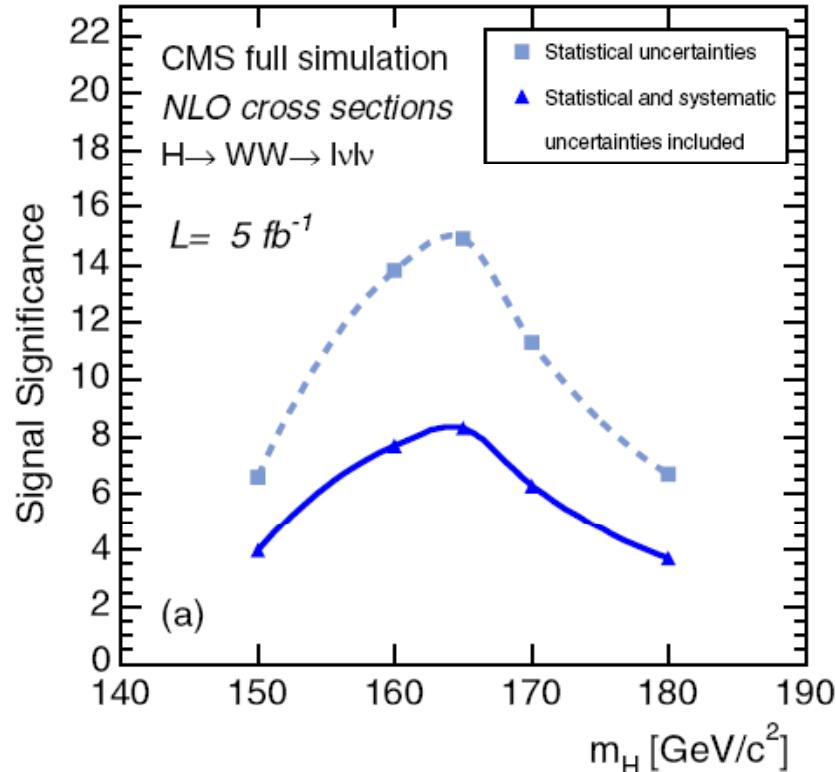
H.Pi et al. CMS note 2006/092  
E.Yazgan et al. CMS note 2007/011

VBF WW $\rightarrow$  l $l$ jj

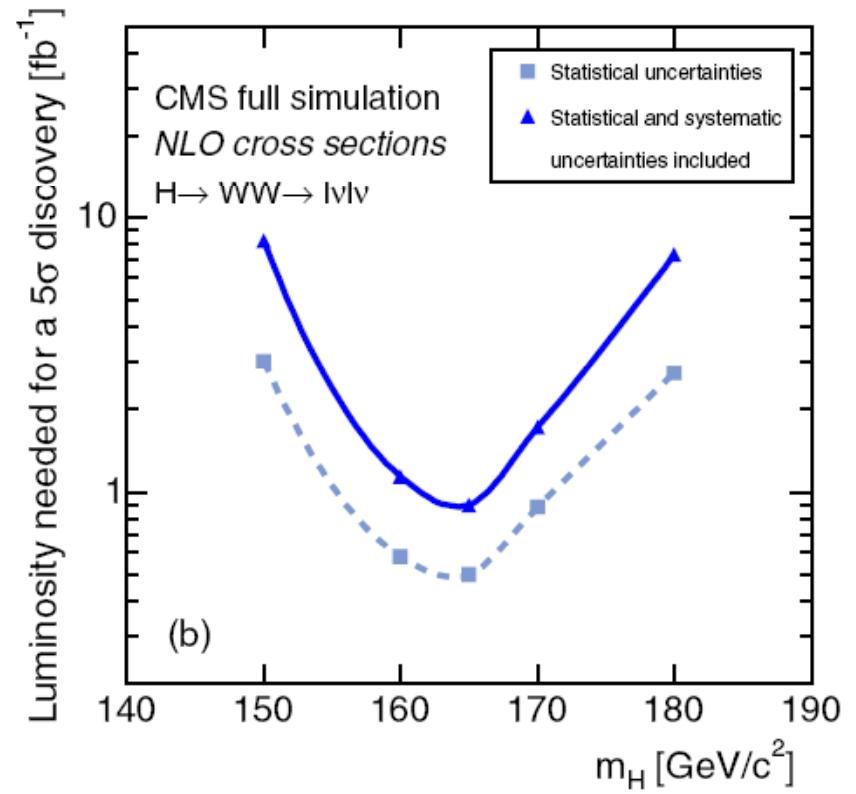
correlation in  $\phi$   
between 2 leptons



*no mass peak*  
*⇒ need precise*  
*knowledge of*  
*background*  
*⇒ develop data driven*  
*methods*



could be a discovery channel at modest L



systematic effects important (especially at high L)

**ttH, H $\rightarrow$  bb**

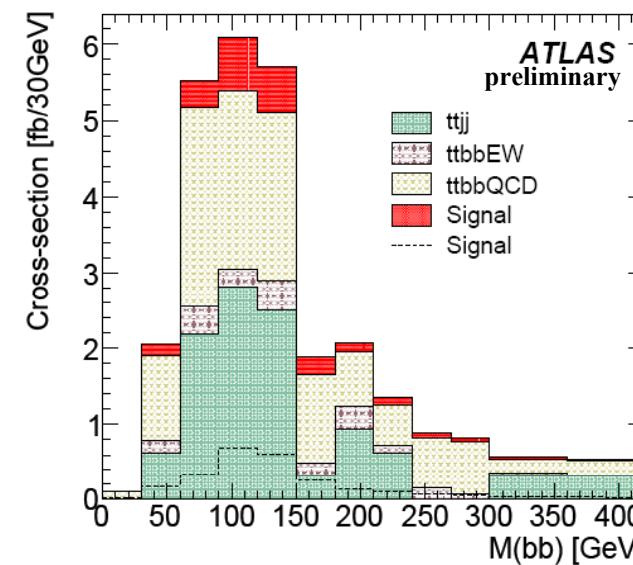
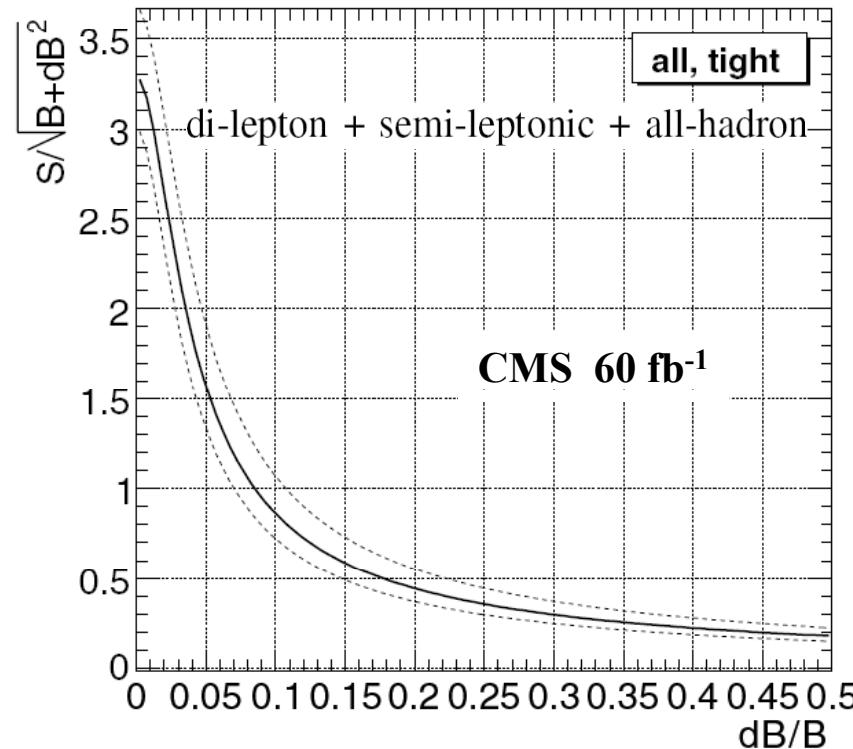
new ATLAS I.Ludwig

semileptonic top decay

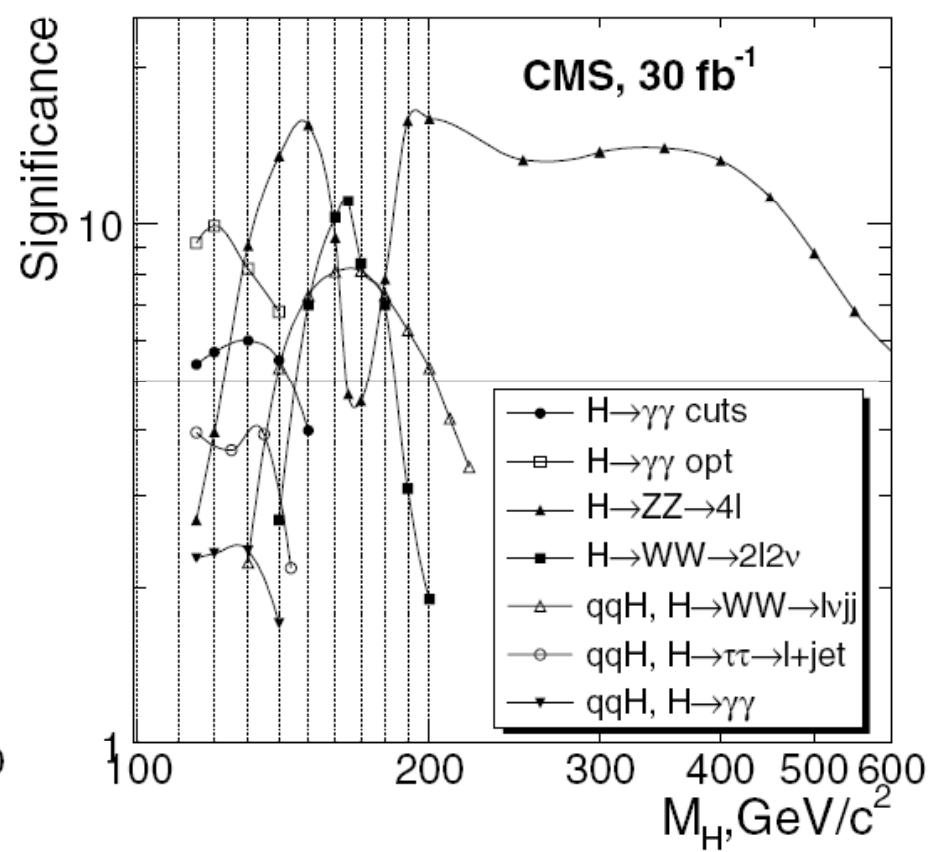
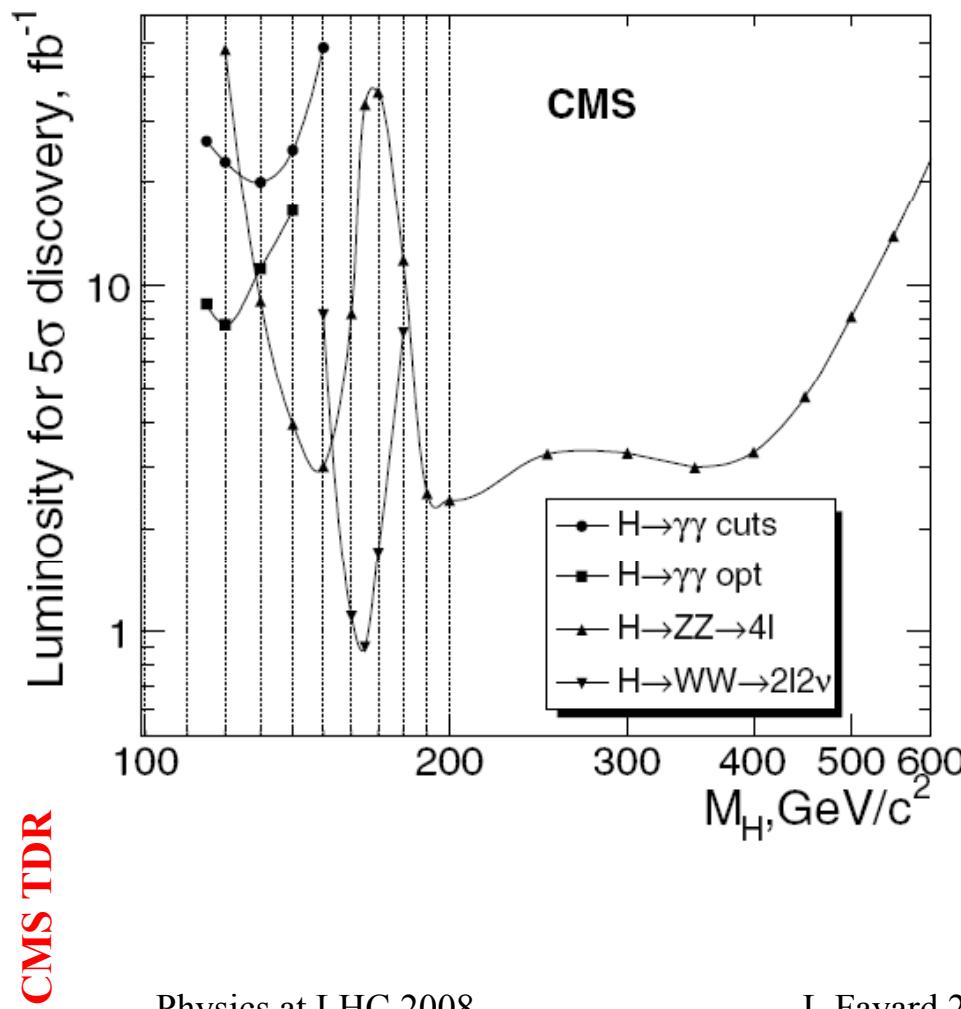
CMS TDR S.Cucciarelli,A.Schmidt,C.Weiser,  
C.Riccardi,P.Torre, D.Benedetti,A.Santocchia,C.Hill,  
J.Incandela and S.Koay CMS note 2006/119  
J.Phys.G:Nucl.Part.Phys. 34 (2007) N221-N250

semileptonic ,  
dileptonic and  
all hadronic  
channels

**Very difficult**  
*large background , similar to signal*



# General Higgs significances



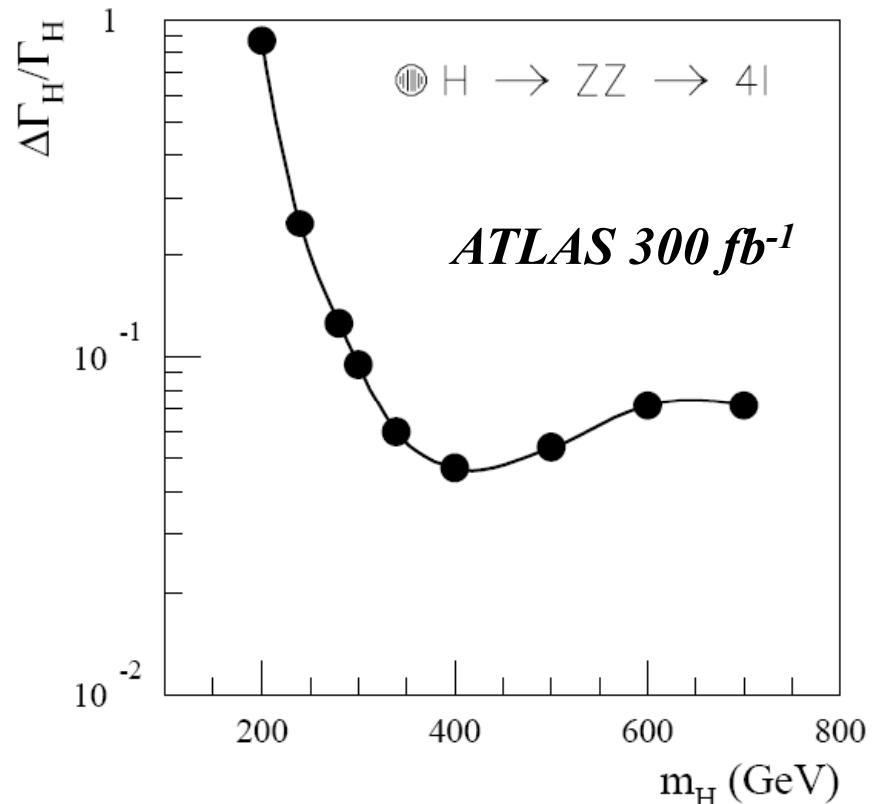
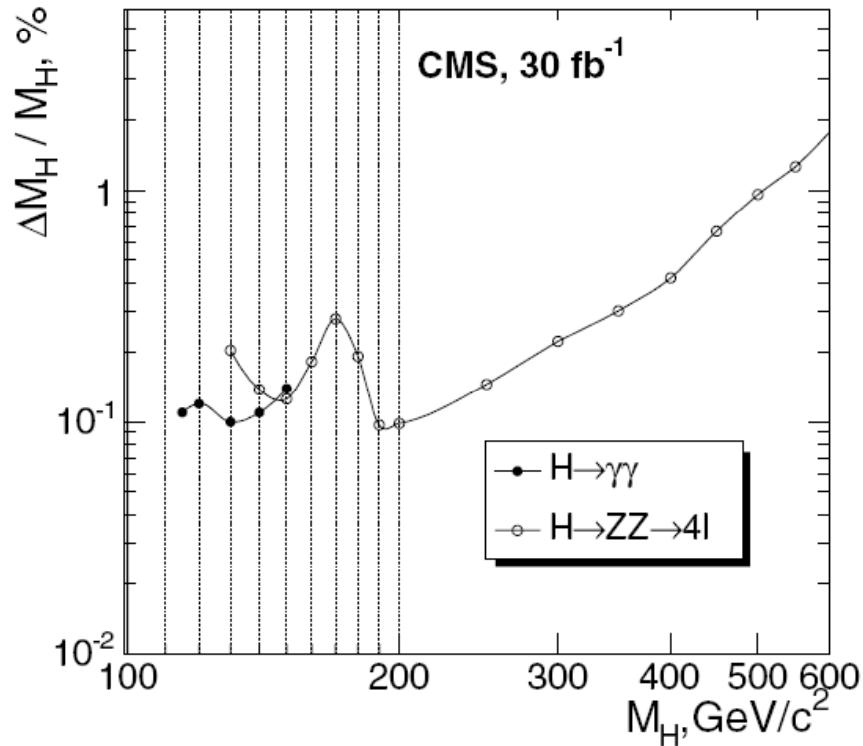
# Is it a Standard Model Higgs ?

- electric charge [neutral]
- color charge [neutral]
- mass [free parameter]
- spin [0]
- CP [even]
- gauge coupling ( $g_{WWH}$ ) [ $SU(2)_L$  with tensor structure  $g^{\mu\nu}$ ]
- Yukawa couplings [ $m_f/v$ ]
- spontaneous symmetry breaking potential (self-couplings) [fixed by the mass]

D.Rainwater hep-ph/0702124  
B.Murray

Very (!) difficult  
 $pp \rightarrow HH \rightarrow WWWW$   
*limited H mass range*  
*sLHC luminosities needed*

## Direct mass and width measurement



statistical precision on Higgs mass  
measurement (~ not limited by  
systematic uncertainties)

ATLAS and CMS TDR  
B Murray

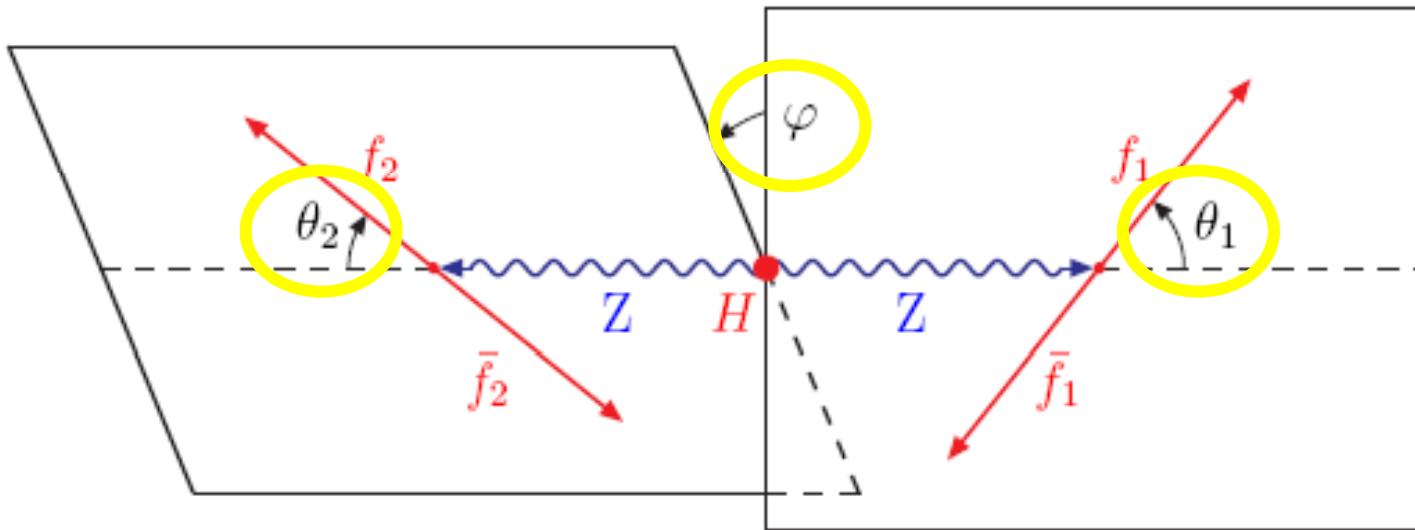
## Spin and CP measurement

- ▶ angular distributions in  $H \rightarrow ZZ \rightarrow 4l^\pm$
- ▶ jet distributions in vector boson fusion

*Not for early data ... needs to find Higgs first !*

*Remember that if  $H \rightarrow \gamma\gamma$  cannot be spin 1 (Yang's theorem)*

# angular distributions in $H \rightarrow ZZ \rightarrow 4l^\pm$



**3 Observables**

J.R. Dell'Aquila and C.A. Nelson Phys.Rev.D33:101,1986

S.Chi,D.Miller,M.Muhlleitner and P.Zerwas Phys.Lett.B553:61-71,2003

C.P.Buszello,I.Fleck,P.Marquard and J.J. van der Bij Eur Phys J C32,209,2004

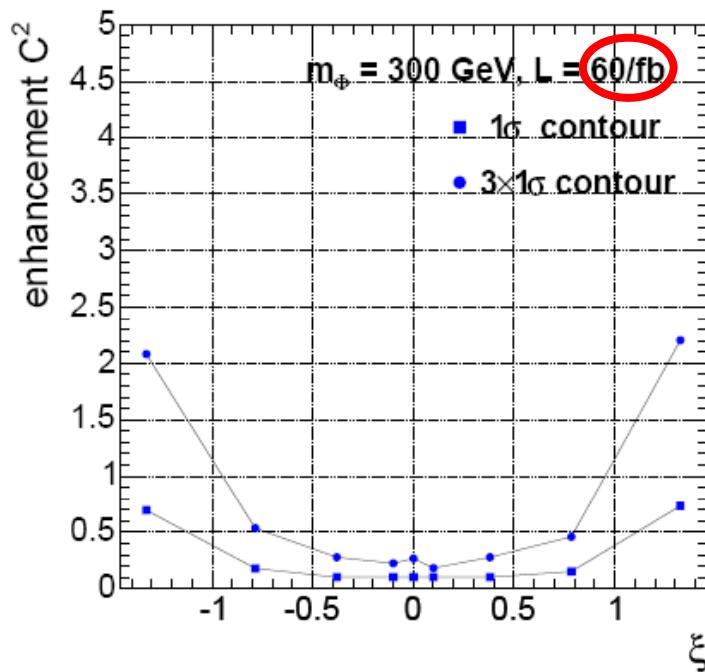
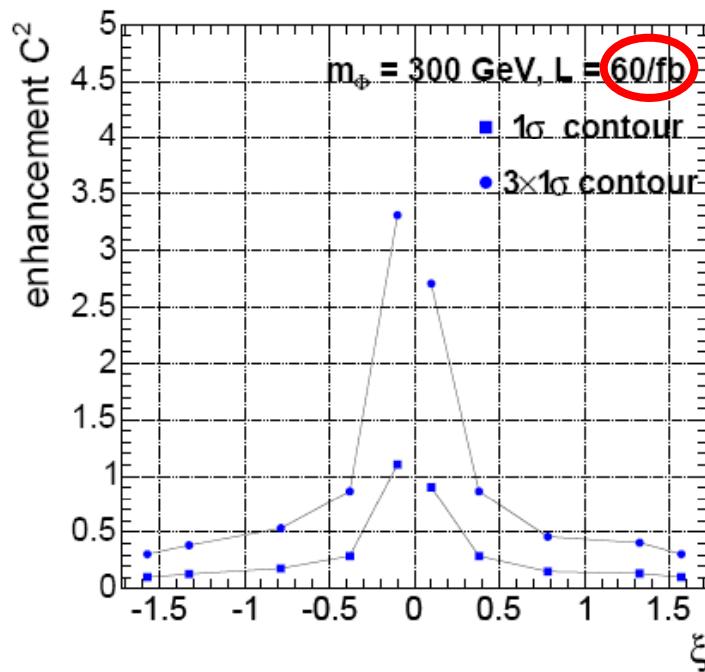
CMS TDR - M.Bluj CMS NOTE 2006/094

R.Godbole,D.Miller and M.Muhlleitner JHEP 0712:031,2007

## Spin 0 CP couplings

$$\mathcal{C}_{\Phi VV}^{J=0} = \underbrace{\kappa \cdot g^{\mu\nu} + \frac{\zeta}{m_V^2} \cdot p^\mu p^\nu}_{\text{scalar}} + \underbrace{\frac{\eta}{m_V^2} \cdot \epsilon^{\mu\nu\rho\sigma} k_{1\rho} k_{2\sigma}}_{\text{pseudoscalar}}$$

$\kappa = 1$   
 $\zeta = 0$   
 $\tan \xi \equiv \eta$

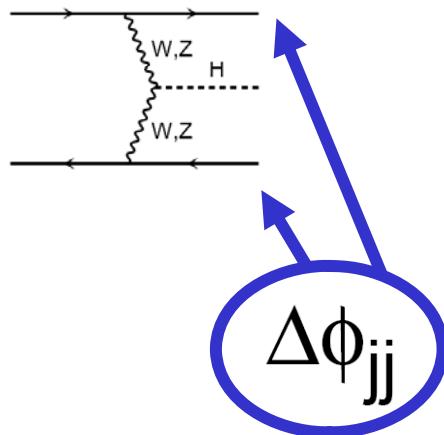


The minimal value of the factor  $C^2$  needed to exclude the scalar (left) and the pseudoscalar (right) Higgs boson at “N sigmas” level ( $N=1, 3$ ) as a function of the parameter  $\xi$  (pseudoscalar = CP odd part)

$$C^2 = (\sigma \times Br) / (\sigma_{SM} \times Br_{SM})$$

CMS TDR - M.Bluj CMS NOTE 2006/094

# Anomalous Higgs Couplings in VBF fusion



T.Plehn,D.Rainwater and D.Zeppenfeld Phys Rev Lett 88,051801,2002

T.Figy and D.Zeppenfeld Physics Letters B 591 (2004) 297-303

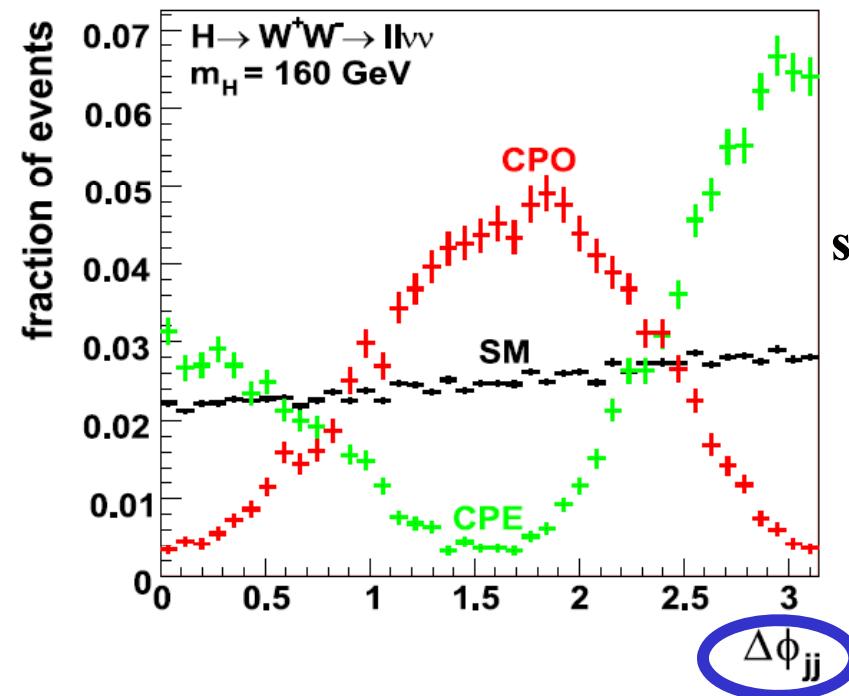
V.Hankele,G.Klamke,D.Zeppenfeld and T.Figy Phys.Rev.D74:095001,2006

C.Ruwiedel,M.Schumacher and N.Wermes Eur.Phys.J.C51:385-414,2007

$$T^{\mu\nu}(q_1, q_2) = a_1(q_1, q_2)g^{\mu\nu} \text{ SM}$$

$$\text{CPE} + a_2(q_1, q_2)[q_1 \cdot q_2 g^{\mu\nu} - q_2^\mu q_1^\nu]$$

$$\text{CPO} + a_3(q_1, q_2)\epsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}.$$



statistics  
in this  
plot is  
infinite

With **10 fb<sup>-1</sup>** can exclude CPE and CPO anomalous couplings at **5 sigmas** in  $WW \rightarrow llvv$  for  $m_H=160$  GeV and with **30 fb<sup>-1</sup>** at **2 sigmas** in  $\tau\tau$  for  $m_H=120$  GeV

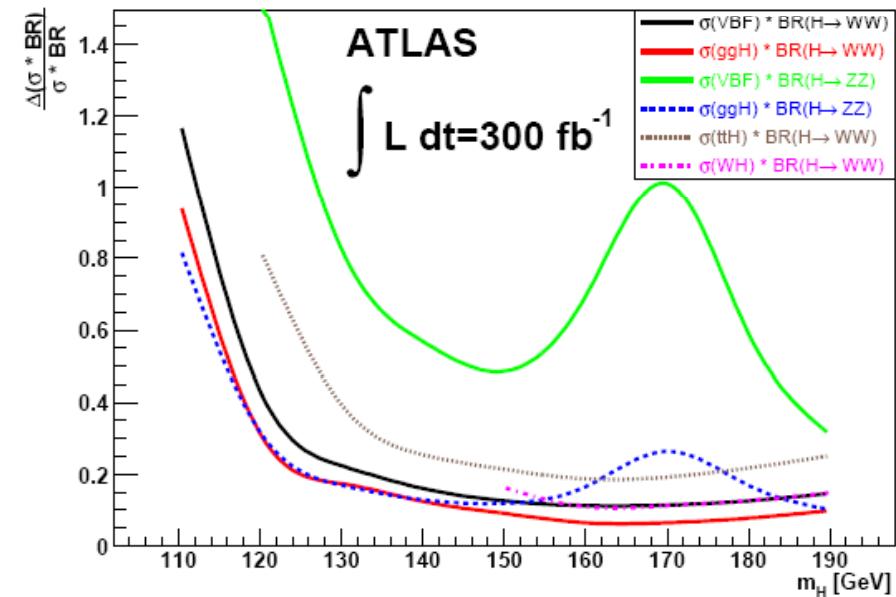
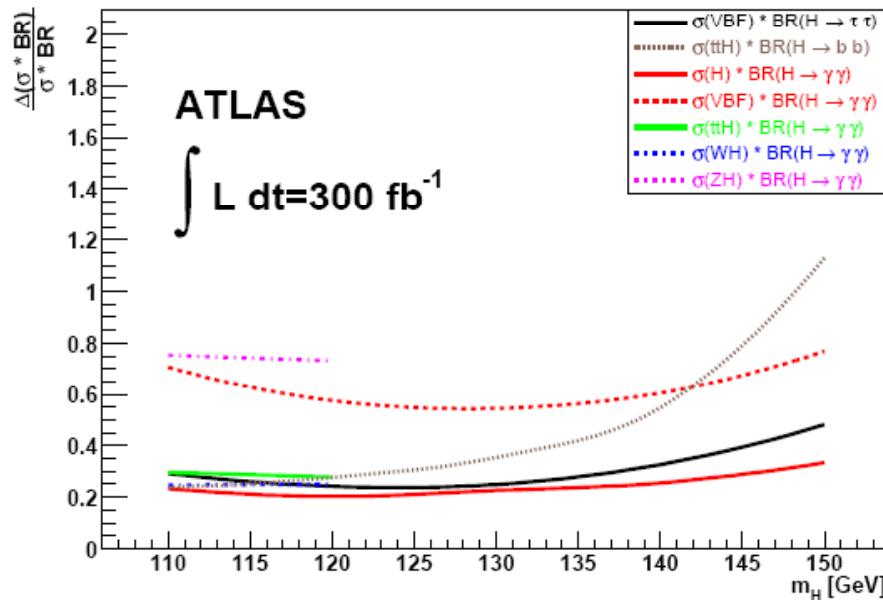
Additional results for SM + CPE

# Higgs couplings

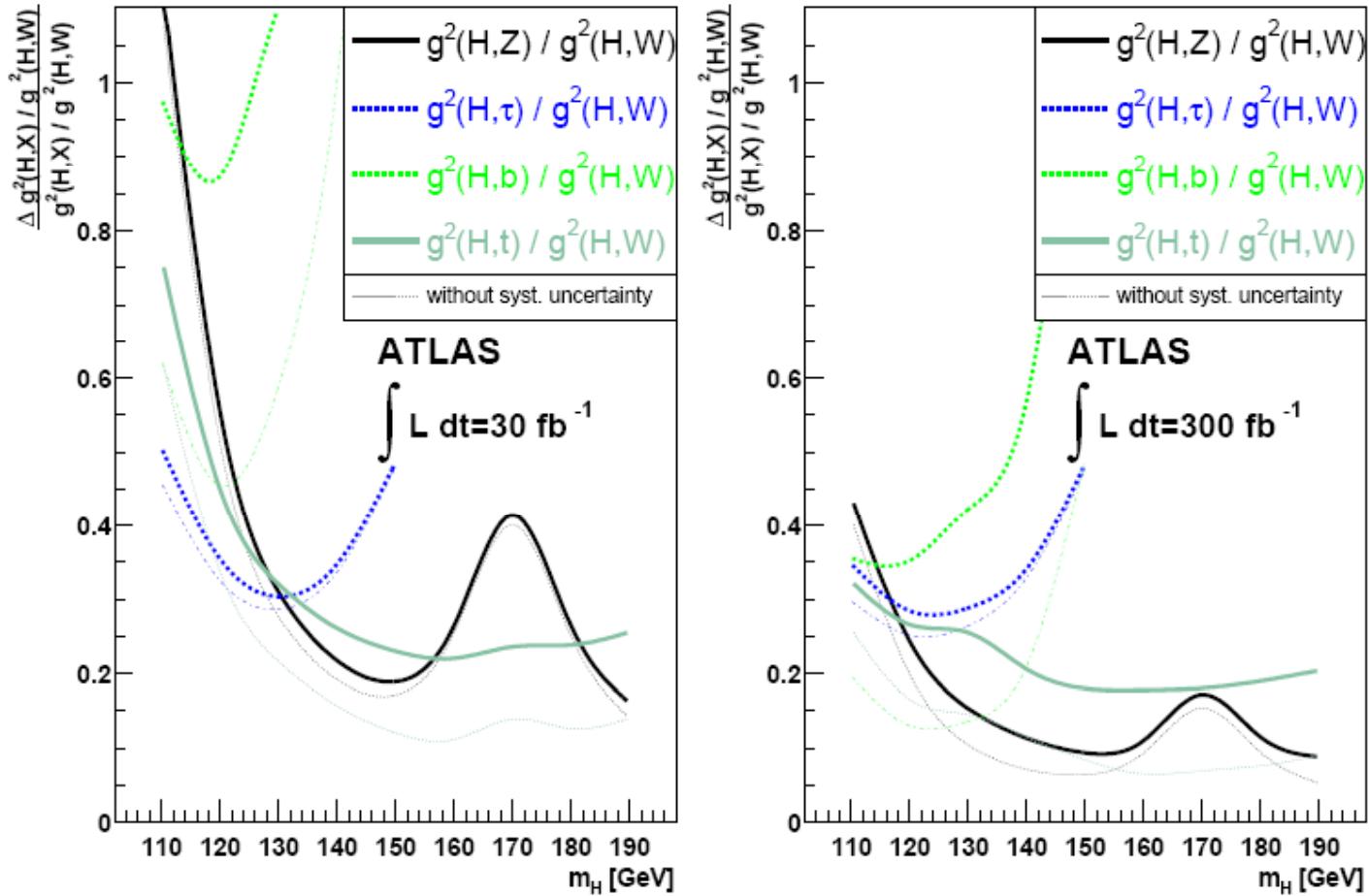
M.Duhrssen ATL-PHYS-2003-030

*based on ‘old’ expectations*

M.Duhrssen,S.Heinemeyer,H.Logan,D.Rainwater,G.Weiglein  
and D.Zeppenfeld Phys Rev D70,113009,2004



Measure  $\sigma \cdot \text{BR}$  in different channels with  
*almost no assumptions (uncertainties = selection  
efficiencies , background)*



*assuming mainly no new particles in loop ... one can express rates  
and BR as a function of 5 couplings  $g_W, g_Z, g_t, g_b, g_\tau$*

*One can also do other analysis with stricter assumptions*

# MSSM

5 Higgs bosons  
( 3 neutrals and 2 charged )

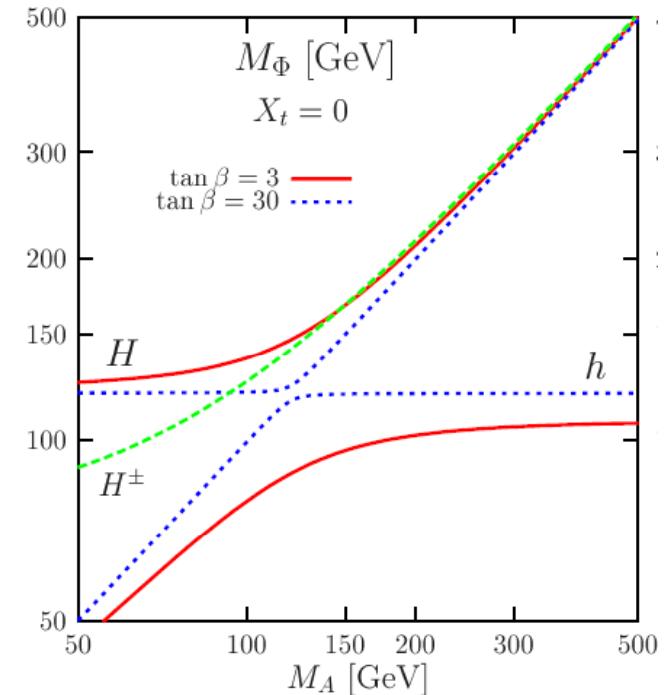
D.Rainwater hep-ph/0702124

MSSM {

$\Phi$	$\frac{g_{\Phi u \bar{u}}}{g_f}$	$\frac{g_{\Phi d \bar{d}}}{g_f}$	$\frac{g_{\Phi VV}}{g_V}$	$\frac{g_{\Phi ZA}}{g_V}$
$h$	$-\frac{\cos \alpha}{\sin \beta}$	$-\frac{\cos \alpha}{\sin \beta}$	$\sin(\beta - \alpha)$	$-\frac{1}{2}i \cos(\beta - \alpha)$
$H$	$-\frac{\sin \alpha}{\sin \beta}$	$-\frac{\sin \alpha}{\sin \beta}$	$\cos(\beta - \alpha)$	$\frac{1}{2}i \sin(\beta - \alpha)$
$A$	$-i\gamma_5 \cot \beta$	$i\gamma_5 \cot \beta$	0	0
$h$	$-\frac{\cos \alpha}{\sin \beta}$	$\frac{\sin \alpha}{\cos \beta}$	$\sin(\beta - \alpha)$	$-\frac{1}{2}i \cos(\beta - \alpha)$
$H$	$-\frac{\sin \alpha}{\sin \beta}$	$-\frac{\cos \alpha}{\cos \beta}$	$\cos(\beta - \alpha)$	$\frac{1}{2}i \sin(\beta - \alpha)$
$A$	$-i\gamma_5 \cot \beta$	$-i\gamma_5 \tan \beta$	0	0

Type I (upper) and II (lower) 2HDMs

couplings to down part of doublets  
(  $b, \tau, \mu$  ) enhanced at high  $\tan(\beta)$



at LO MSSM Higgs sector depends of 2 parameters  $M_A$   $\tan(\beta)$

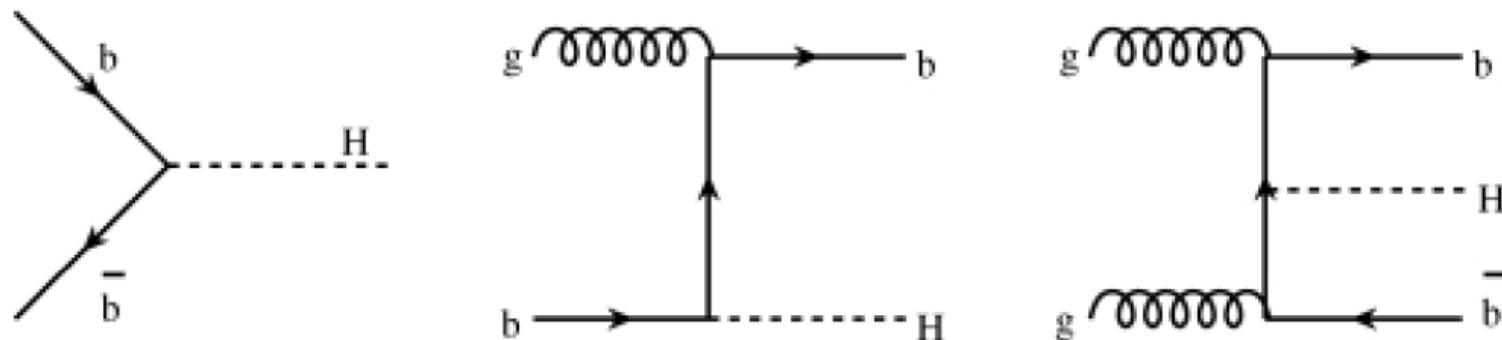
at NLO more SUSY parameters

⇒ choose a benchmark scenario  $m_h^{\max}$

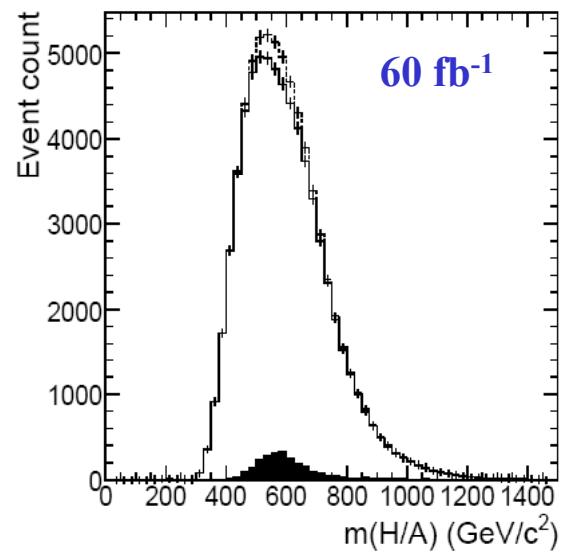
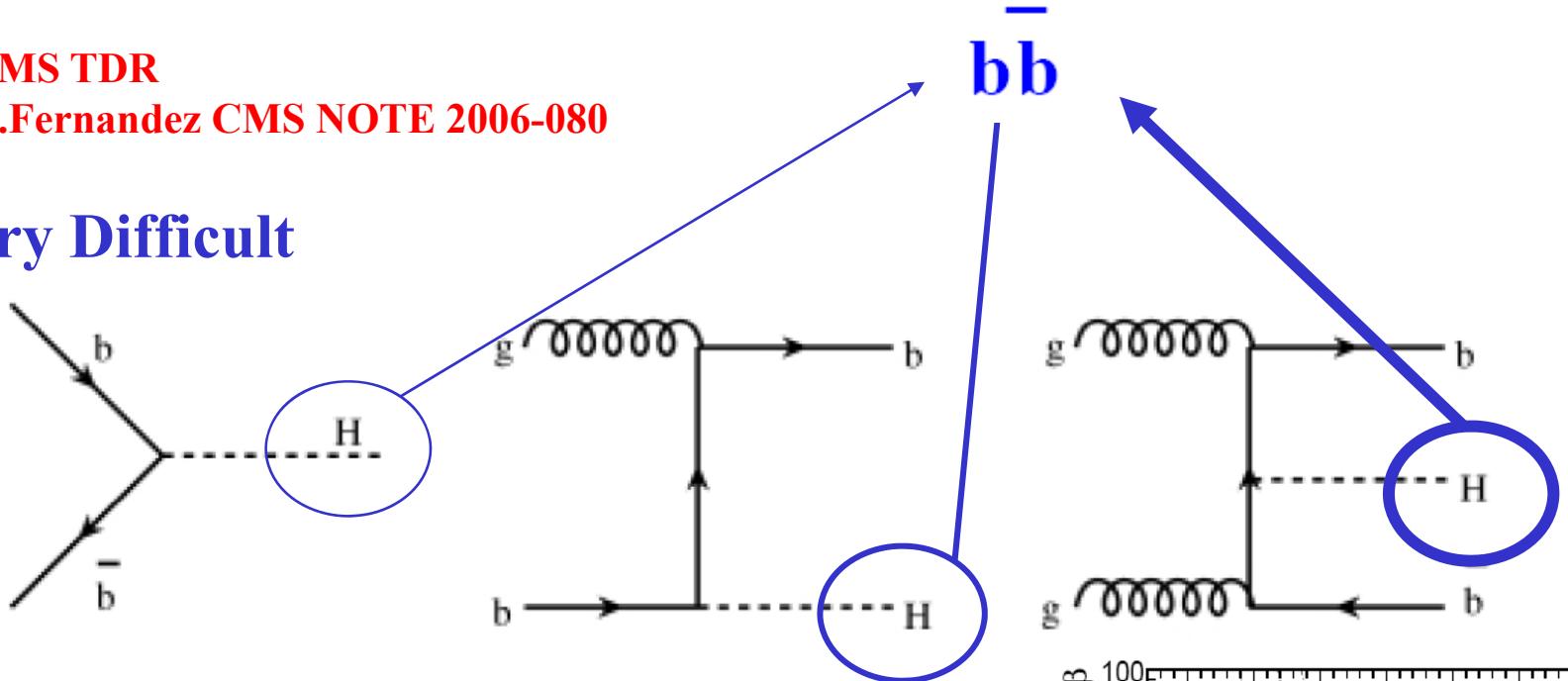
corresponds to maximal theoretically allowed region for  $m_h$

## Search for neutral MSSM Higgs

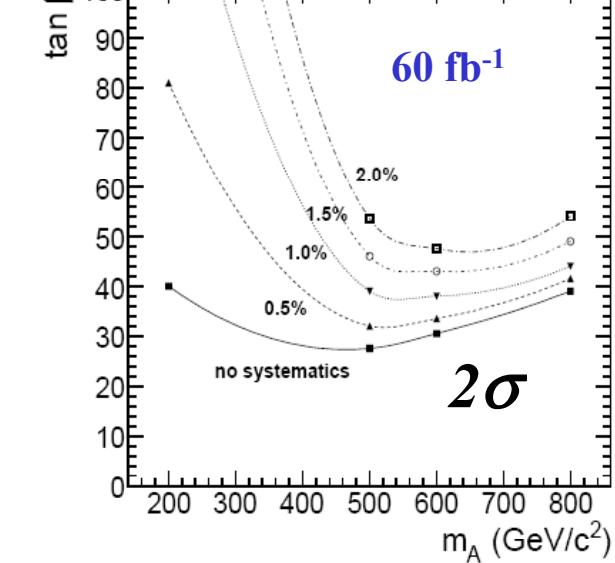
### Associated production with b

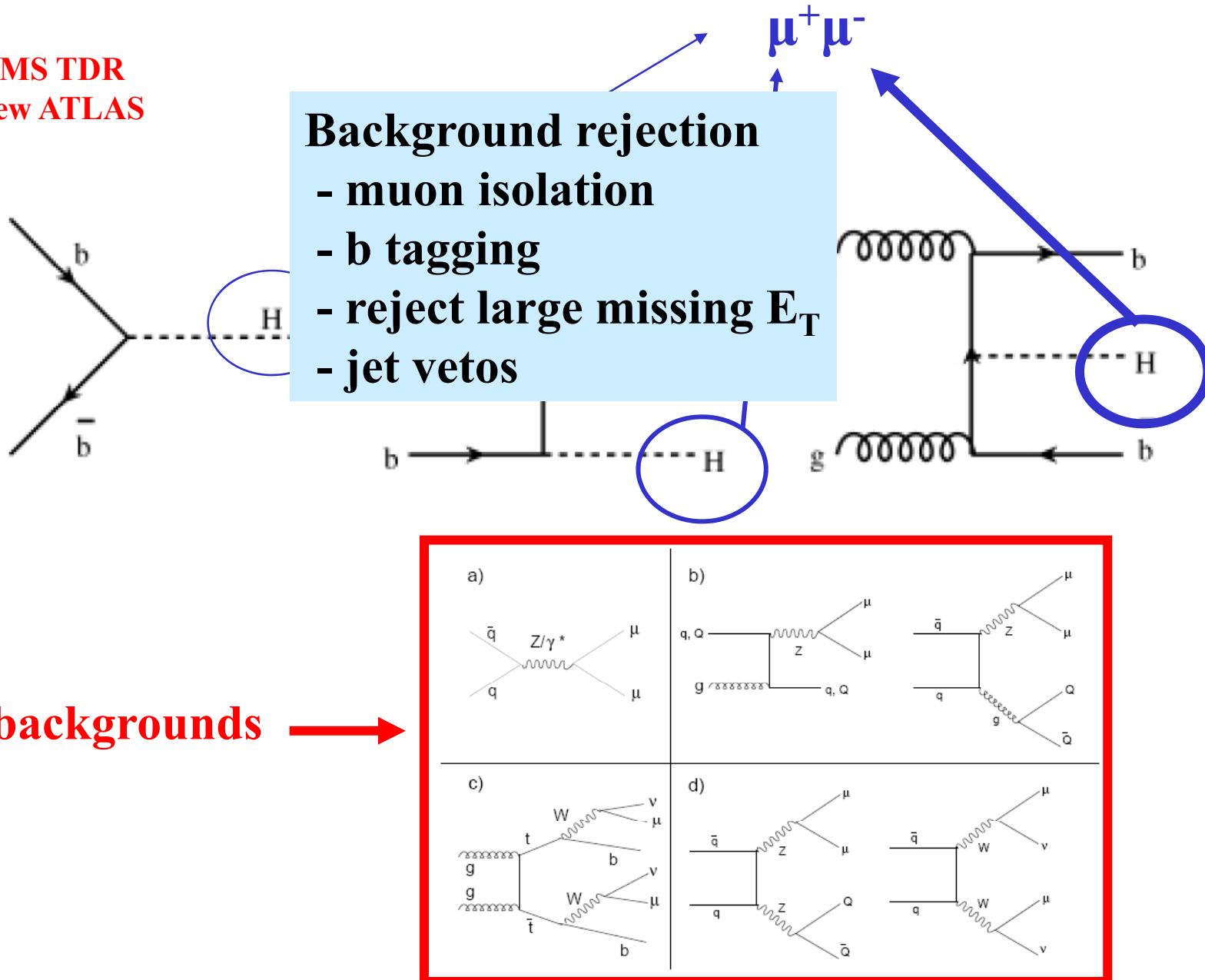


Very Difficult



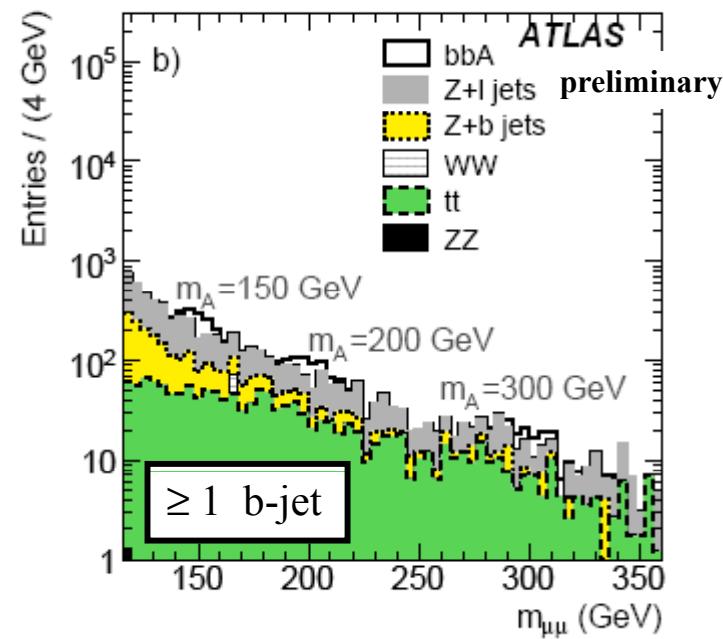
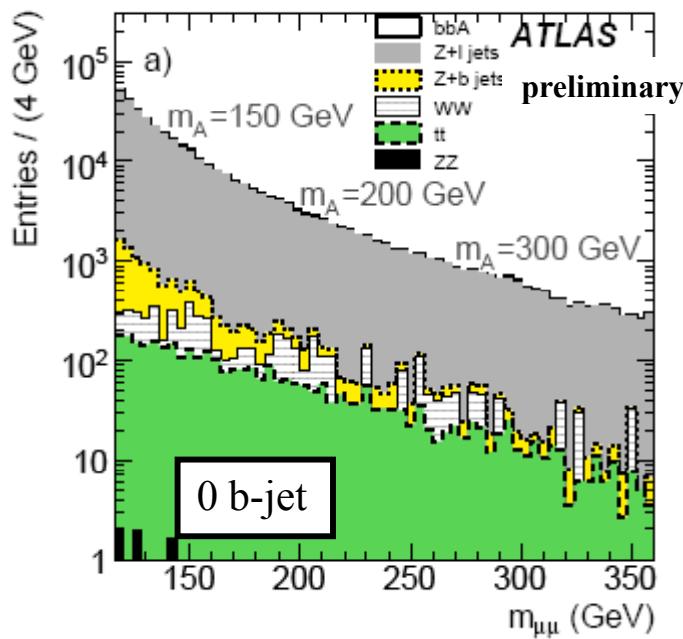
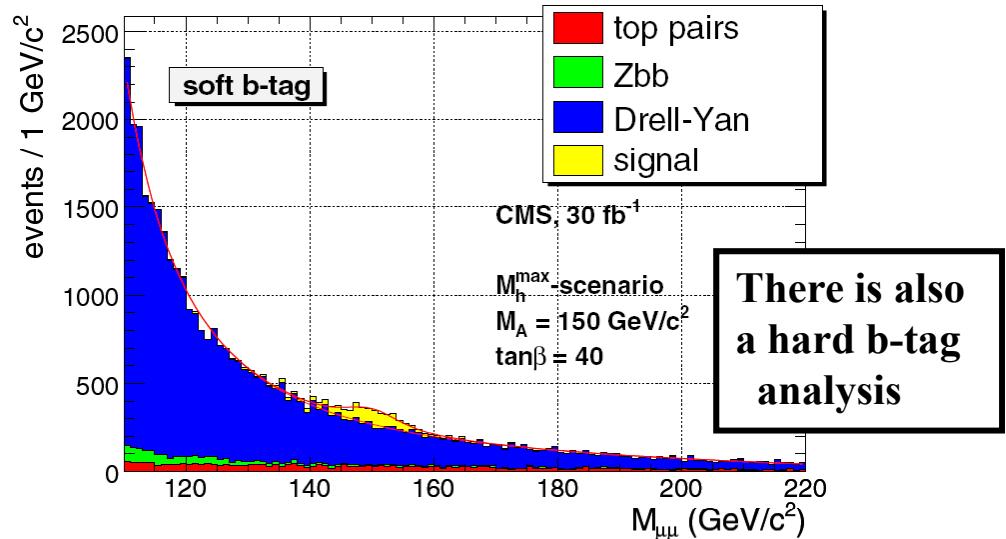
Ask for  $\geq 3$  b jets



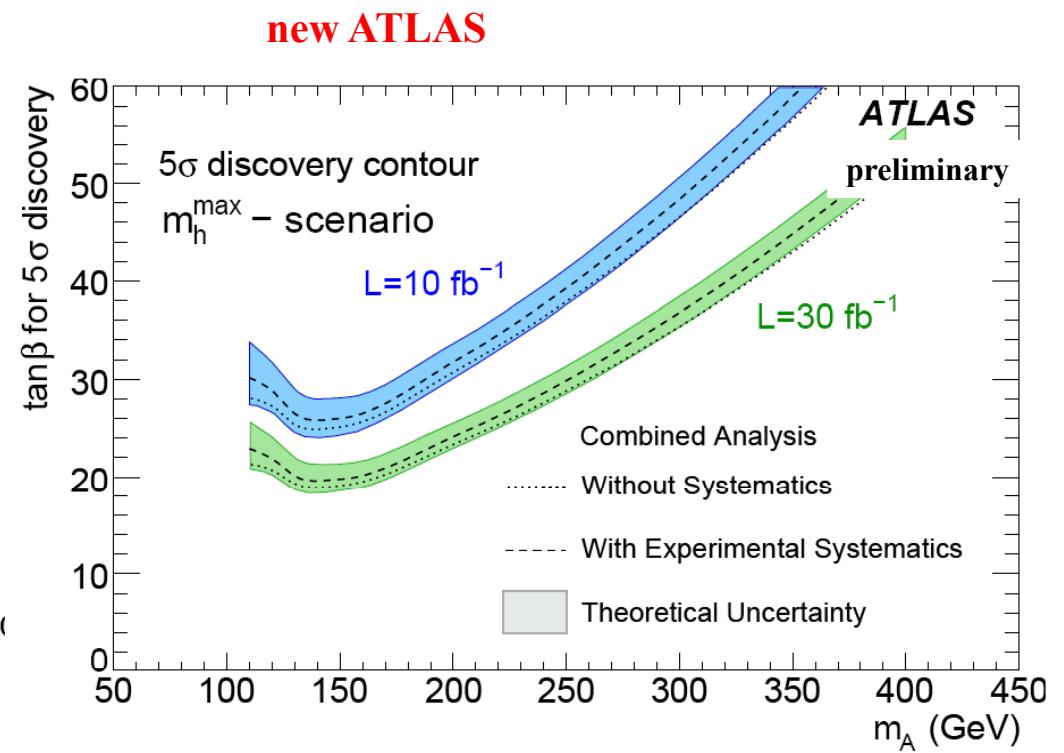
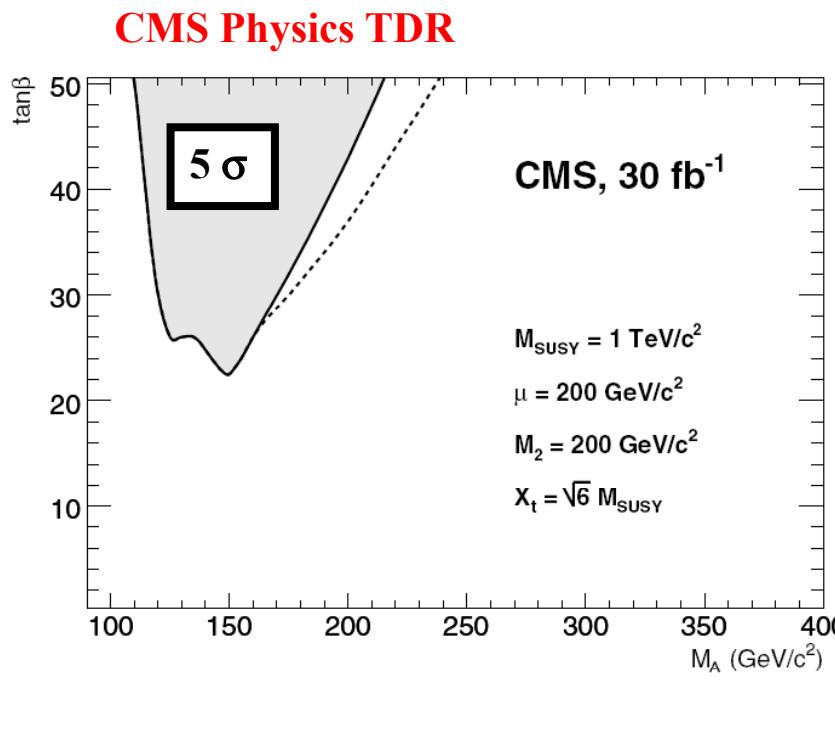


# MSSM Higgs $\rightarrow \mu\mu$

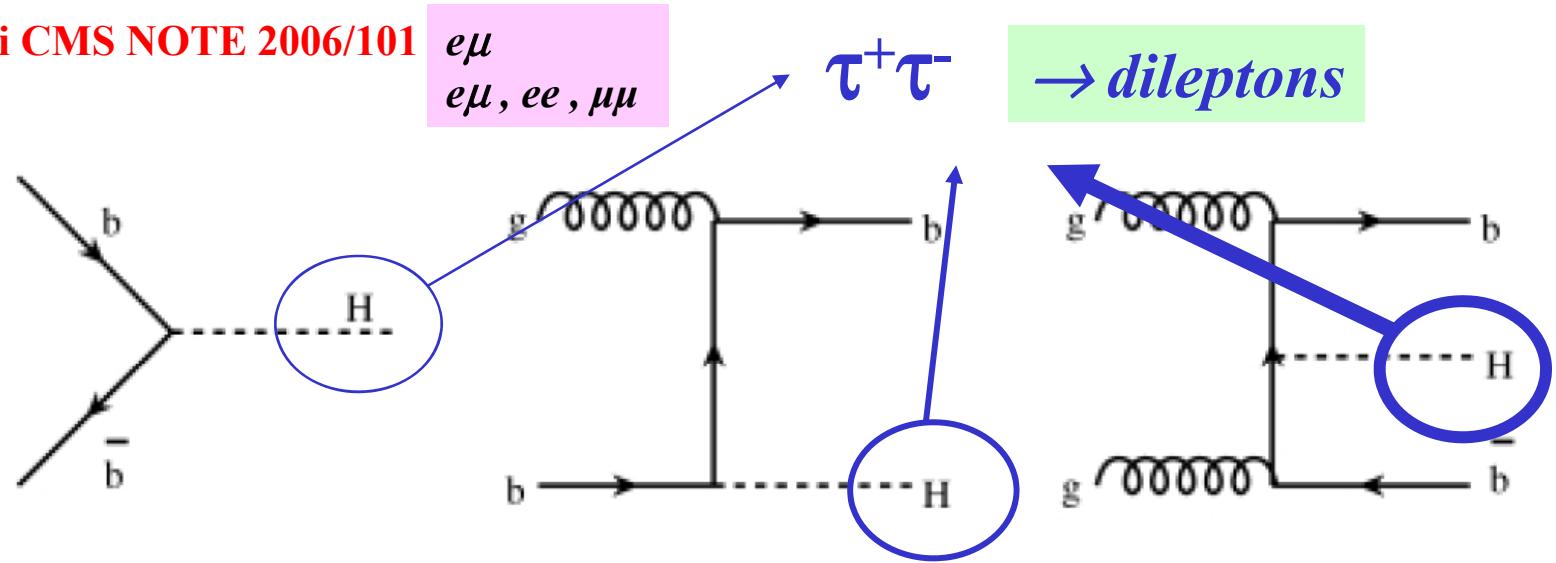
*excellent dimuon mass  
resolution of ATLAS and  
CMS is a key point in this  
analysis*



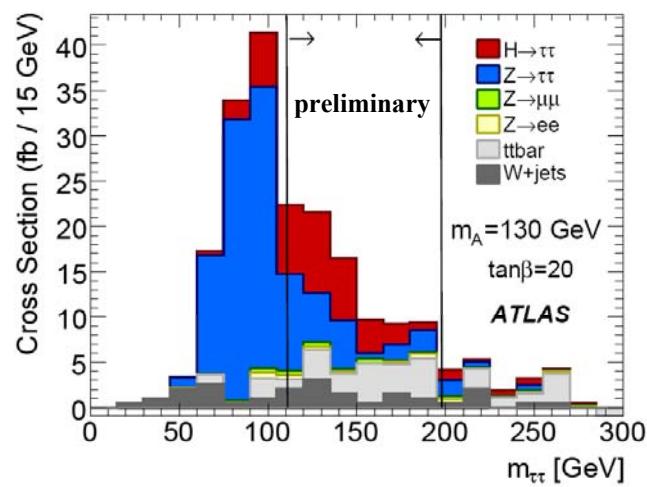
# MSSM Higgs $\rightarrow \mu\mu$



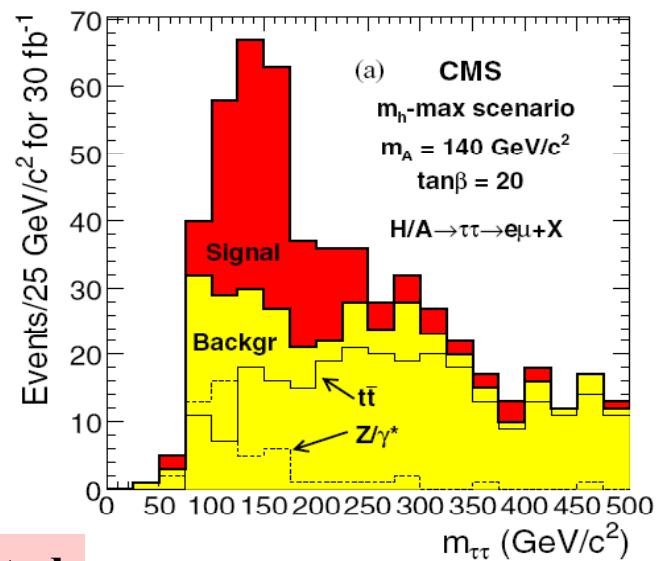
***One can measure the width and then « measure »  $\tan(\beta)$***

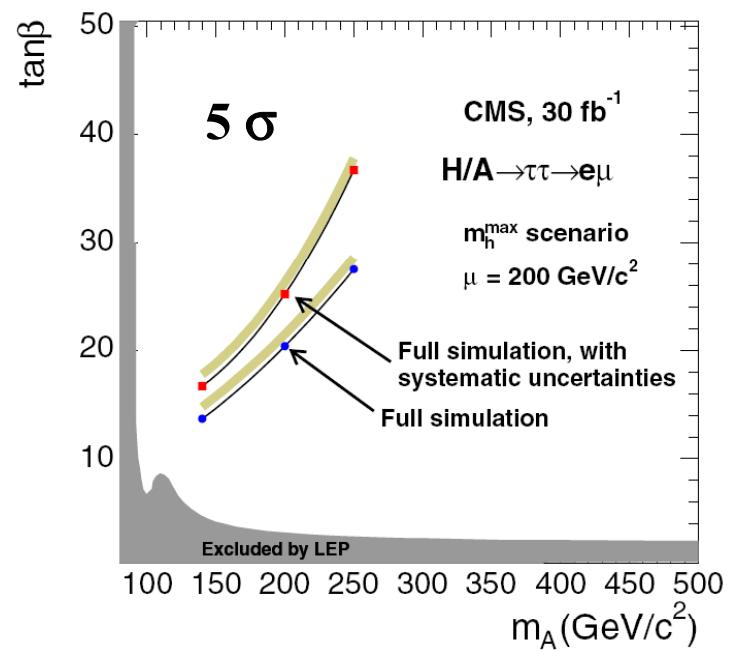
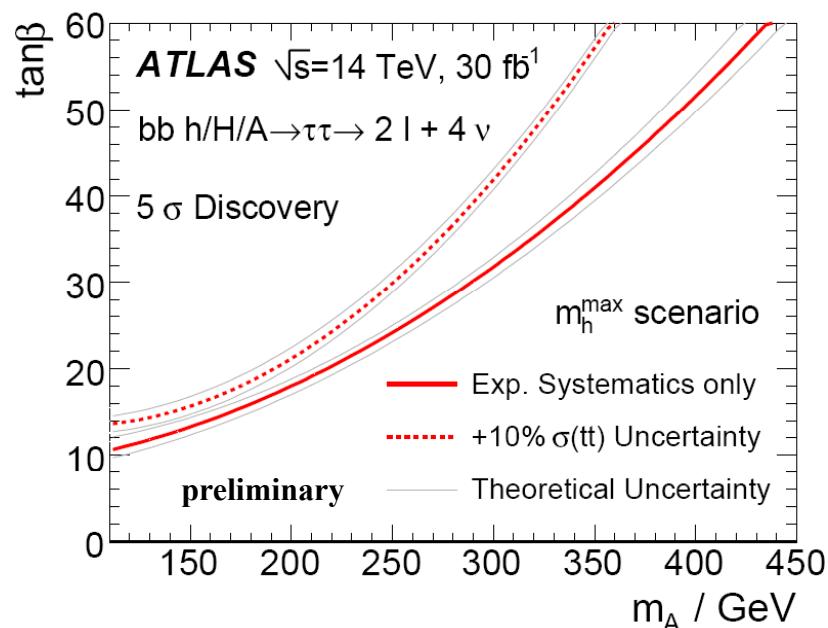
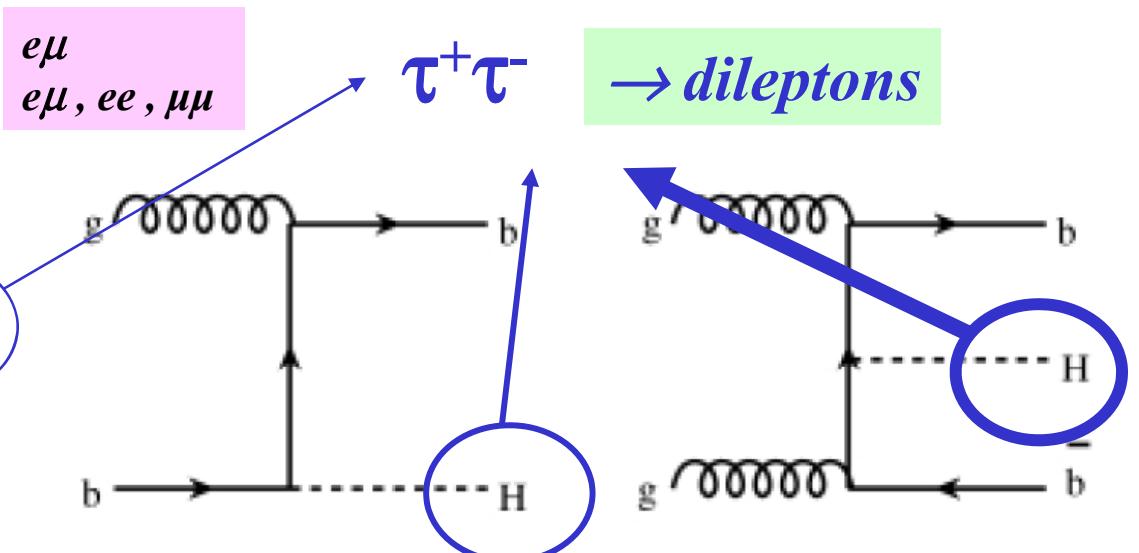


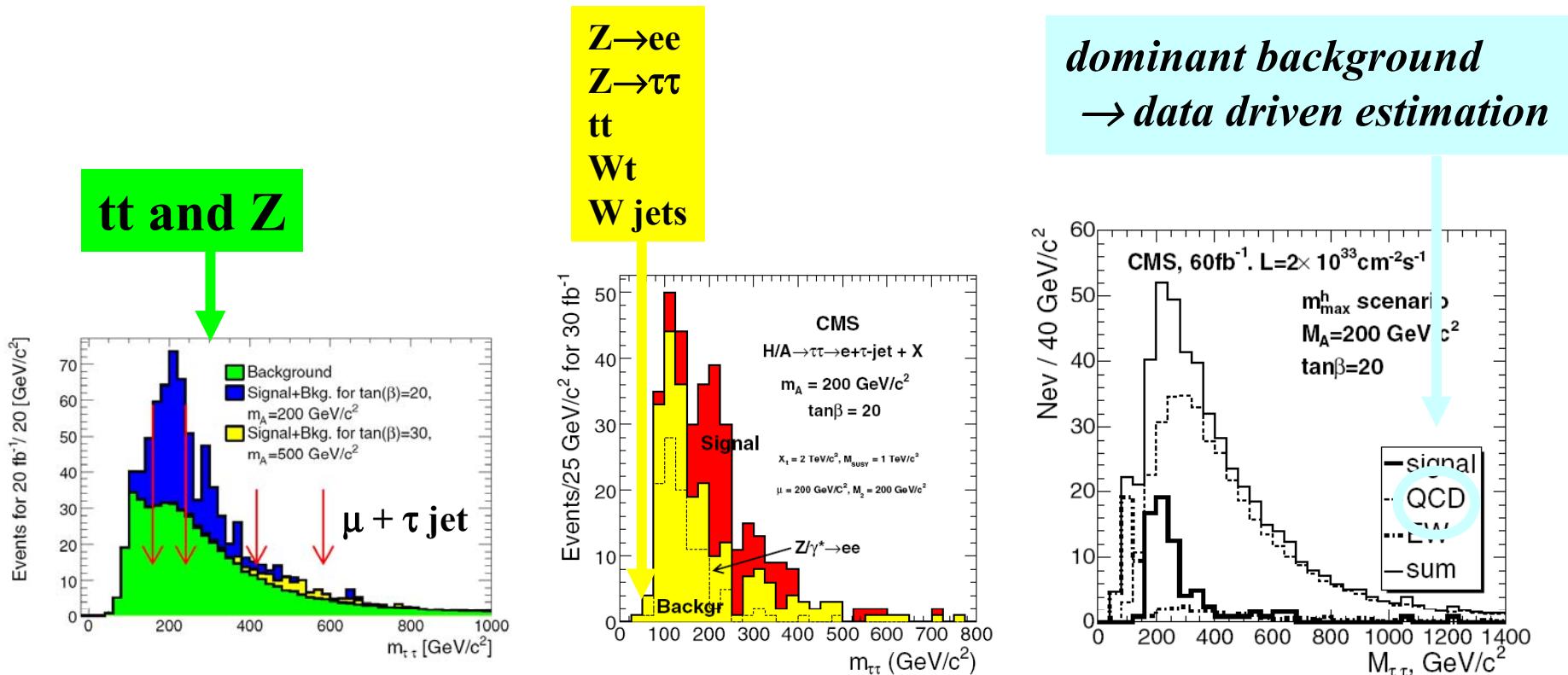
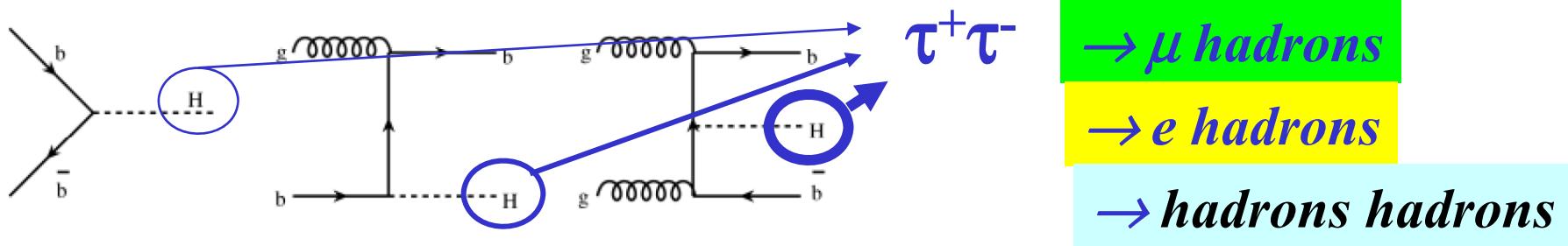
**Cuts on missing  $E_T$  (ATLAS),  $b$  momentum , lepton momentum  
number of jets (=1 for CMS) to reject Z and tt backgrounds**



*tighter  
cuts for  
CMS*







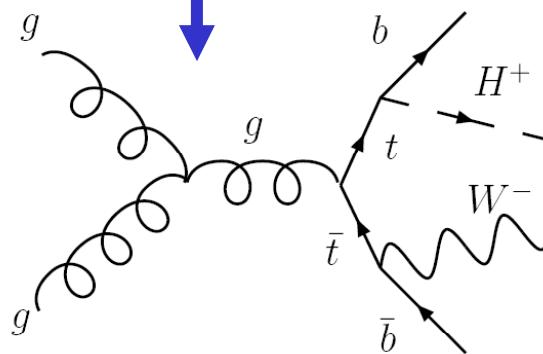
CMS TDR A.Kalinowski,M.Konecki and D.Kotlinski CMS NOTE 2006/105

R.Kinnunen and S.Lehti CMS note 2006/075

S.Gennai,A.Nikitenko and L.Wendland CMS NOTE 2006/126

## Search for charged MSSM Higgs

**Low mass charged Higgs**  
 $m(H^+) < m(\text{top})$

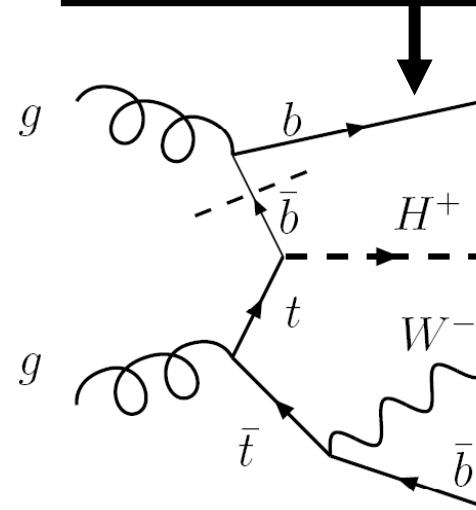


**AC**  $t\bar{t} \rightarrow bH^+bW \rightarrow b\tau(\text{had})\nu b\ell\nu$

**A**  $t\bar{t} \rightarrow bH^+bW \rightarrow b\tau(\text{lep})\nu bqq$

**A**  $t\bar{t} \rightarrow bH^+bW \rightarrow b\tau(\text{had})\nu bqq$

**High mass charged Higgs**  
 $m(H^+) > m(\text{top})$



$gg/gb \rightarrow t[b]H^+ \rightarrow t[b]tb \rightarrow bW[b]bWb \rightarrow b\ell\nu[b]bqqb$  **AC**

$gg/gb \rightarrow t[b]H^+ \rightarrow bqq[b]\tau(\text{had})\nu$  **AC**

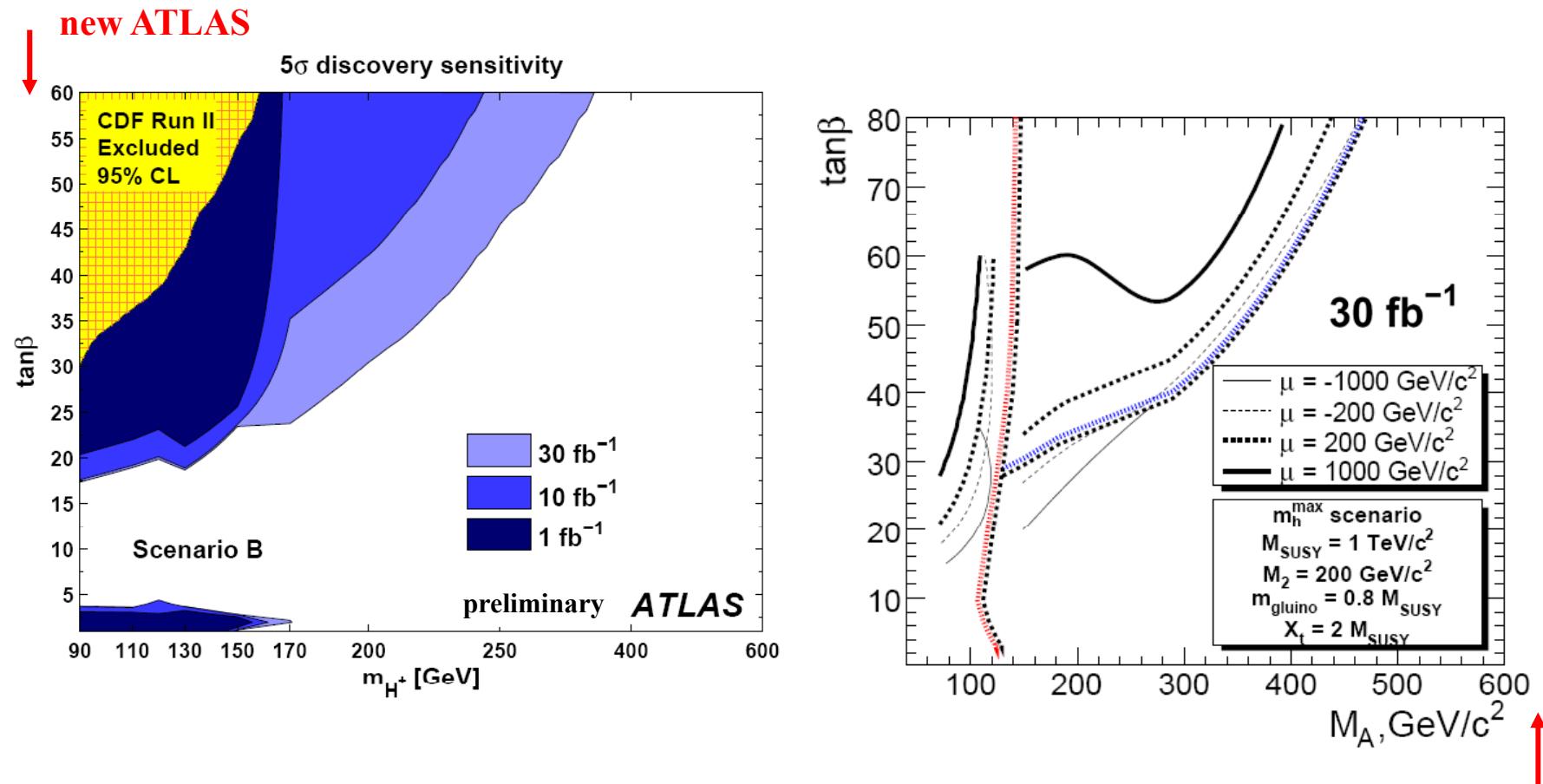
new ATLAS CMS TDR

M.Baarmann,M.Hashemi and A.Nikitenko J. Phys. G32 (2006) N21-N40

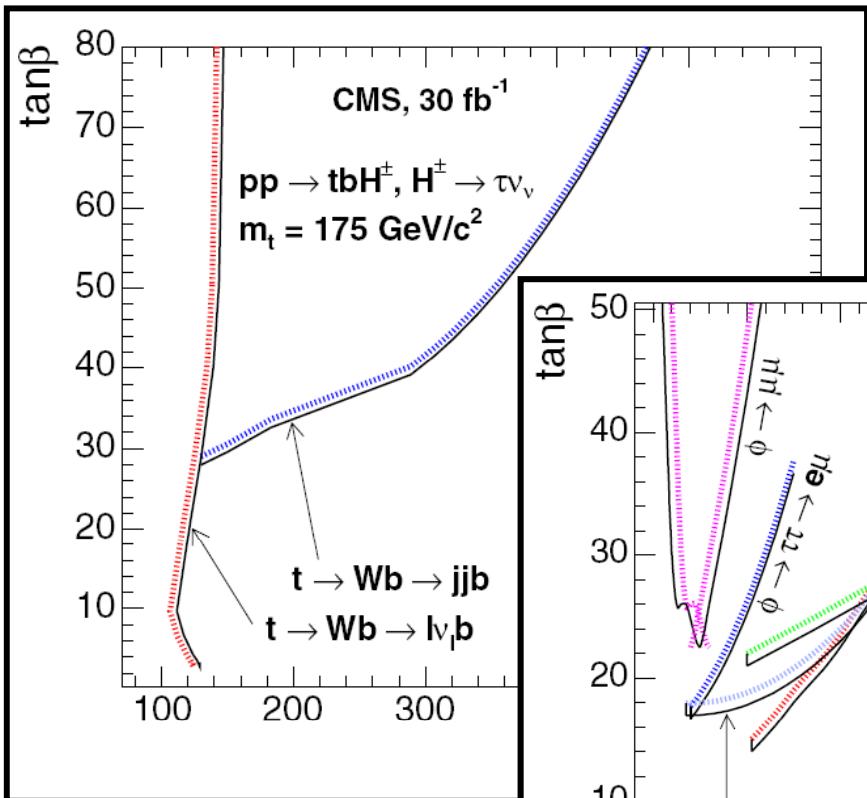
S.Lowette,J.D'Hondt,P.Vanlaer CMS-NOTE-2006-109

R.Kinnunen CMS-NOTE-2006-100

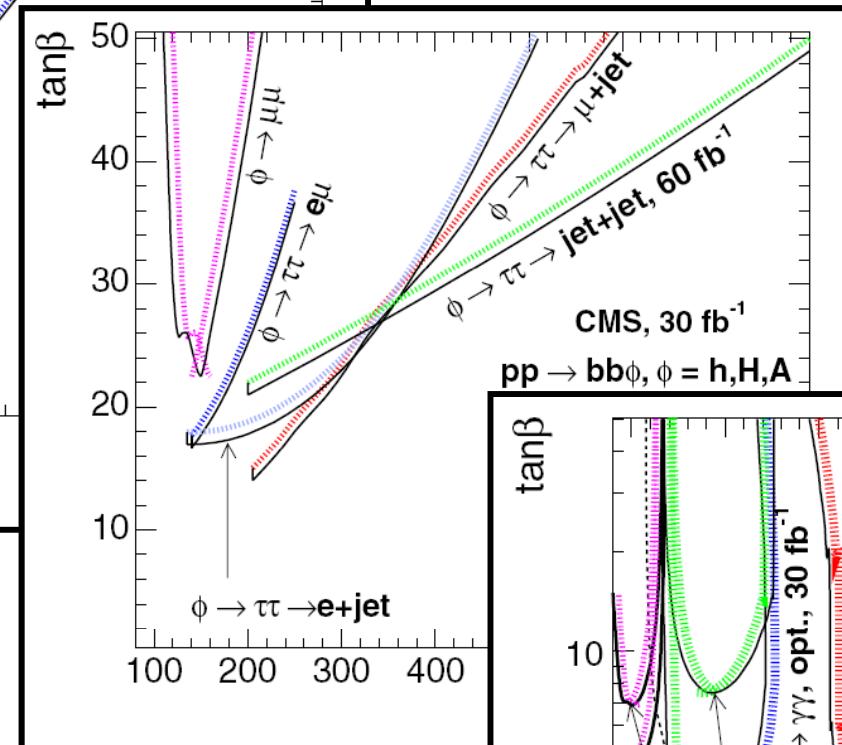
# General discovery sensitivity on H<sup>+</sup>



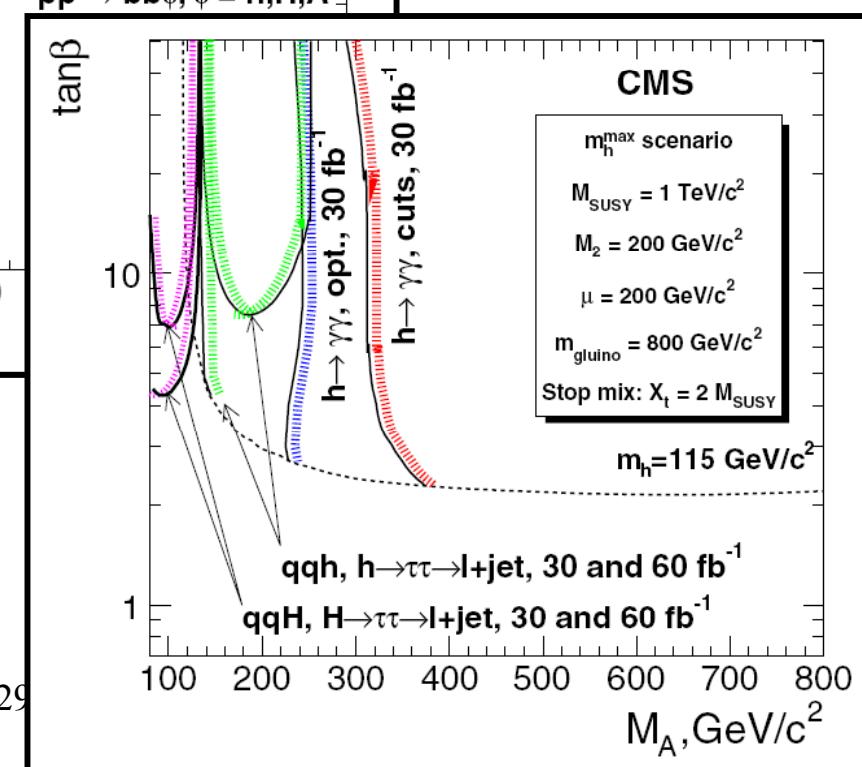
M.Hashemi,S.Heinemeyer,R.Kinnunen,A.Nikitenko and G.Weiglein arXiv:0804.1228 [hep-ph]



## General $5\sigma$ discovery regions in MSSM ( $m_h^{\max}$ scenario)



CMS TDR



*everything is covered*

MSSM charged Higgs decays  $g b \rightarrow t H+ (\rightarrow \chi_i^0 \chi_j^+) \rightarrow 3 l^\pm$

M.Bisset,F.Moortgat and S.Moretti Eur.Phys.J.C30:419-434,2003

C.Hansen,N.Gollub,K.Assamagan and T.Ekelof Eur.Phys.J. C44, s2.1-s2.9 (2005)

MSSM Higgs decays  $H,A \rightarrow \chi_i^0 \chi_j^0, \chi_i^+ \chi_j^- \rightarrow 4 l^\pm + \text{MET}$

M.Bisset,J.Li,N.Kersting,F.Moortgat and S.Moretti arXiv:0709.1029

CMS Physics TDR

C.Charlot,R.Salerno and Y.Sirois CMS-NOTE-2006-125

ATLAS presented at Charged-Higgs-08

Search for  $A \rightarrow Z (\rightarrow l^+ l^-) h (\rightarrow bb)$

CMS Physics TDR

G.Anagnostou and G.Daskalakis CMS-NOTE-2006-063

NMSSM Higgs

I.Rottlaender and M.Schumacher ATL-PHYS-CONF-2008-009

Updated MSSM scan for different benchmark scenarios

M.Schumacher hep-ph/0410112

CMS Physics TDR

CPX scenario

M.Schumacher et al hep-ph/0608079

Non SUSY models and little Higgs

G.Azuelos et al. Eur.Phys.J.direct C4:16,2002

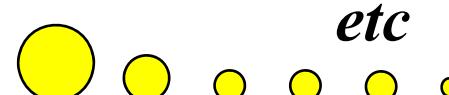
CMS Physics TDR

D.Dominici,G.Dewhirst,A.Nikitenko,S.Gennai and L.Fano CMS-NOTE-2005-007

G.Azuelos et al Eur.Phys.J.C39S2:13-24,2005

Invisible Higgs

new ATLAS



## *Conclusions*



*MSSM Higgs sector covered*

*Detailed Higgs studies will require a lot of statistics*

*Be open to more exotic scenarios*

# Backup

# We will not answer all what interest theorists

## Disclaimer

C.Quigg Rept.Prog.Phys.70:1019-1054,2007

Here are some of the questions that will shape the explorations to come:

- (i) What is the agent that hides the electroweak symmetry?
- (ii) Is there a Higgs boson? Might there be several?
- (iii) Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons?
- (iv) How does the Higgs boson interact with itself? What shapes the Higgs potential?
  - (v) Could we be living in a false (metastable) vacuum?
  - (vi) Is the Higgs boson elementary or composite?
- (i) (vii) Does the pattern of Higgs-boson decays imply new physics? Will unexpected or rare decays of the Higgs boson reveal new kinds of matter?
- (ii) (viii) What stabilizes the Higgs-boson mass on the Fermi scale? Is Nature supersymmetric? Is electroweak symmetry breaking an emergent phenomenon? sons and for connected with strong dynamics? Is electroweak symmetry breaking related to gravity through extra spacetime dimensions?
- (iii) (ix) How can a light Higgs boson coexist with the absence of signals for new phenomena?
- (iv) (x) What resolves the vacuum energy problem?
- (xi) What lessons does electroweak symmetry breaking hold for unified theories of the strong, weak, and electromagnetic interactions? for the inflationary Universe? for dark energy?

It is an inspiring list. Within a decade, we can expect to have many answers—and even better questions!



introduction to collider physics at Lausanne and is thus singled out as Chapter XII. These theoretical contributions altogether review in great detail the topical questions and expectations concerning collider physics in the multi-TeV range, which were summarized by Ch. Llewellyn Smith in his report at CERN (Chapter I). Two of the reports presented at Lausanne were already included in Volume I. These are in Chapter IX, which reviews Composite Models. (Logically, Chapter IX should be combined with Chapter XIII.)

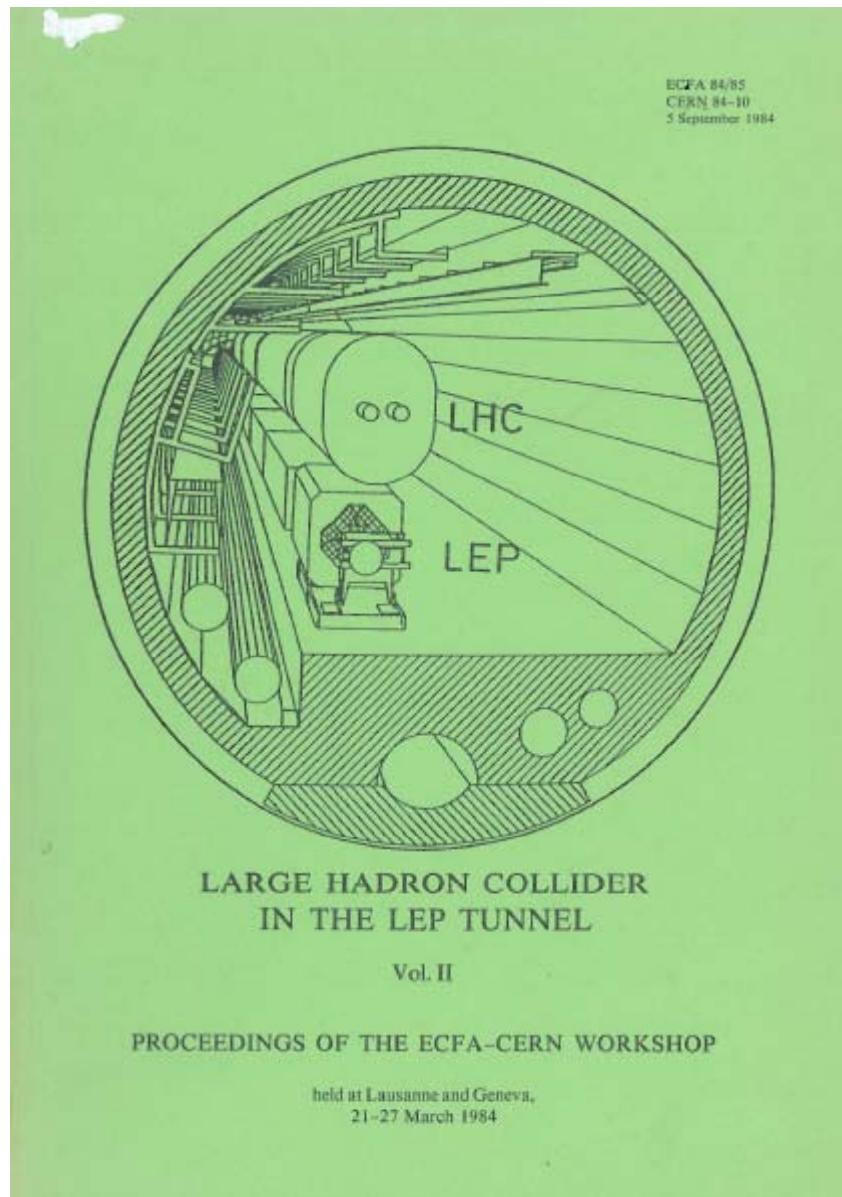
We then move to physics issues which are potentially very interesting but which take us away from hadron-hadron interactions in the collider mode. The potential of ep collisions, as in principle accessible with LEP and a hadron collider in the same tunnel, is reviewed by G. Altarelli, B. Mele, and R. Rückl. The rather intense, very high energy neutrino beams, which one could obtain (for free) from the abundant production of charmed particles, open up very interesting possibilities, as discussed by A. De Rújula and R. Rückl.

With the material thus put together, one finds a thorough discussion of collider physics in the multi-TeV range, as it is foreseen today.

We conclude these proceedings with the brilliant address of G. 't Hooft, 'Prospects of theoretical particle physics', which concluded the CERN meeting.

The Organizing Committee would like to express its thanks to those people in various sections of the CERN Documentation Department, whose conscientious work brought these Proceedings to their present form.

M. Jacob, CERN  
Editor



#### FOREWORD

The first part of the Workshop on the Feasibility of Hadron Colliders in the LEP Tunnel took place at the Dorigny Campus of the University of Lausanne. It lasted four days and brought together close to 150 participants. The second part was a one-and-a-half day meeting held at CERN, immediately following upon the Lausanne meeting, and during which the conclusions were presented to and debated by a very large audience of physicists and engineers.

The installation of a hadron collider in the LEP tunnel, using superconducting magnets, has always been foreseen as the natural long-range extension of the CERN facilities beyond LEP. The recent successes of the CERN p $\bar{p}$  Collider now give us confidence that such a large hadron collider would be an ideal machine for exploring physics in the few TeV range at the constituent (quarks and gluons) level -- an energy domain which the very success of the Standard Model, based on the SU(2)  $\times$  U(1)  $\times$  SU(3) gauge symmetry of the electroweak and strong interactions, leads us to consider as being crucial for a deeper understanding.

Whilst the installation of a large hadron collider in the LEP tunnel may at present be considered as a rather remote possibility, the design of the high-performance magnets which we would like to use for such a machine still demands a great amount of research and development; this indeed appears as a prerequisite for the definition of the parameters of such a project. A Workshop bringing together theorists, experimentalists, accelerator physicists, and also experts in superconducting magnets was thus deemed timely.

Although the Workshop proper was rather short, it was actively prepared by different Working Groups dealing with various facets of the whole scheme. A large amount of work was thus invested in the Workshop, and its outcome can be seen in these Proceedings, which are presented in two volumes.

This two-volume structure was adopted in order to make at least part of the material available at the earliest possible date -- rather than, as initially planned, to put into the first volume the texts of the talks presented during the open meeting at CERN, which in fact concluded the Workshop. The table of contents now covers both Volume I and Volume II. At the beginning of Volume II we find the part of the proceedings of the CERN meeting which were not available for inclusion in Volume I and, in particular, the reports of the Working Groups on Electron-Photon Identification and on Data Acquisition. However, in order to strike the right key note, we actually start Volume II with the concluding remarks presented by C. Rubbia at the end of the CERN meeting.

Next to the two reports from experimental working groups, which logically should have followed Chapter IV and Chapter VI, respectively, we find a series of theoretical contributions which were presented at Lausanne. This starts with the report of J. Ellis, G. Gelmini and H. Kowalski, 'New particles and their experimental signatures', which served as a general

(\*) large mtop approximation

S.Moch and A.Vogt Phys Lett B631,48,2005

T.Han,G.Valencia and S.Willenbrock Phys Rev Lett 69,3274,1992

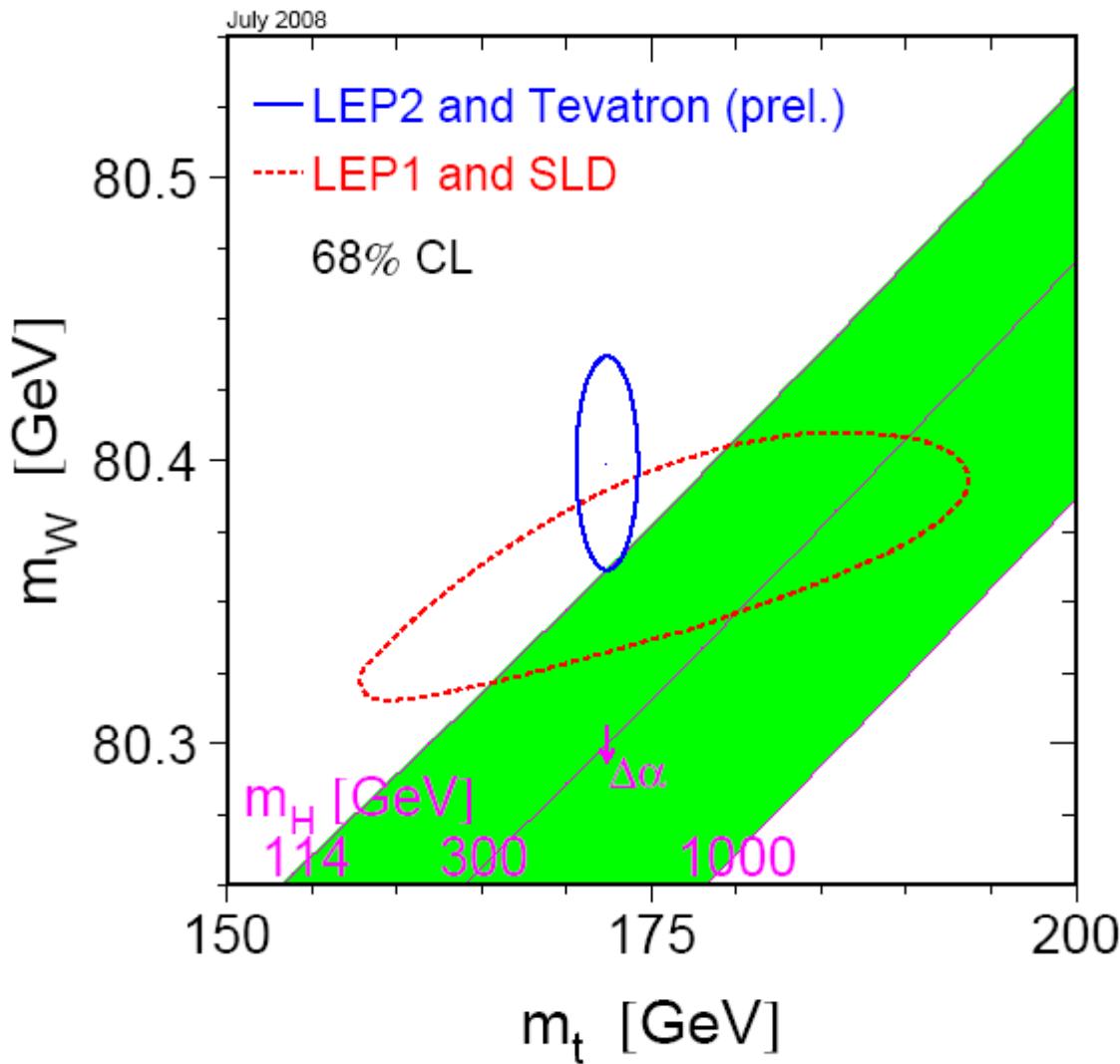
Typical uncertainties on cross-section

gg	10 %	NNnLO (*)
VBF	5%	NLO
WH,ZH	5%	NNLO
ttH	15%	NLO

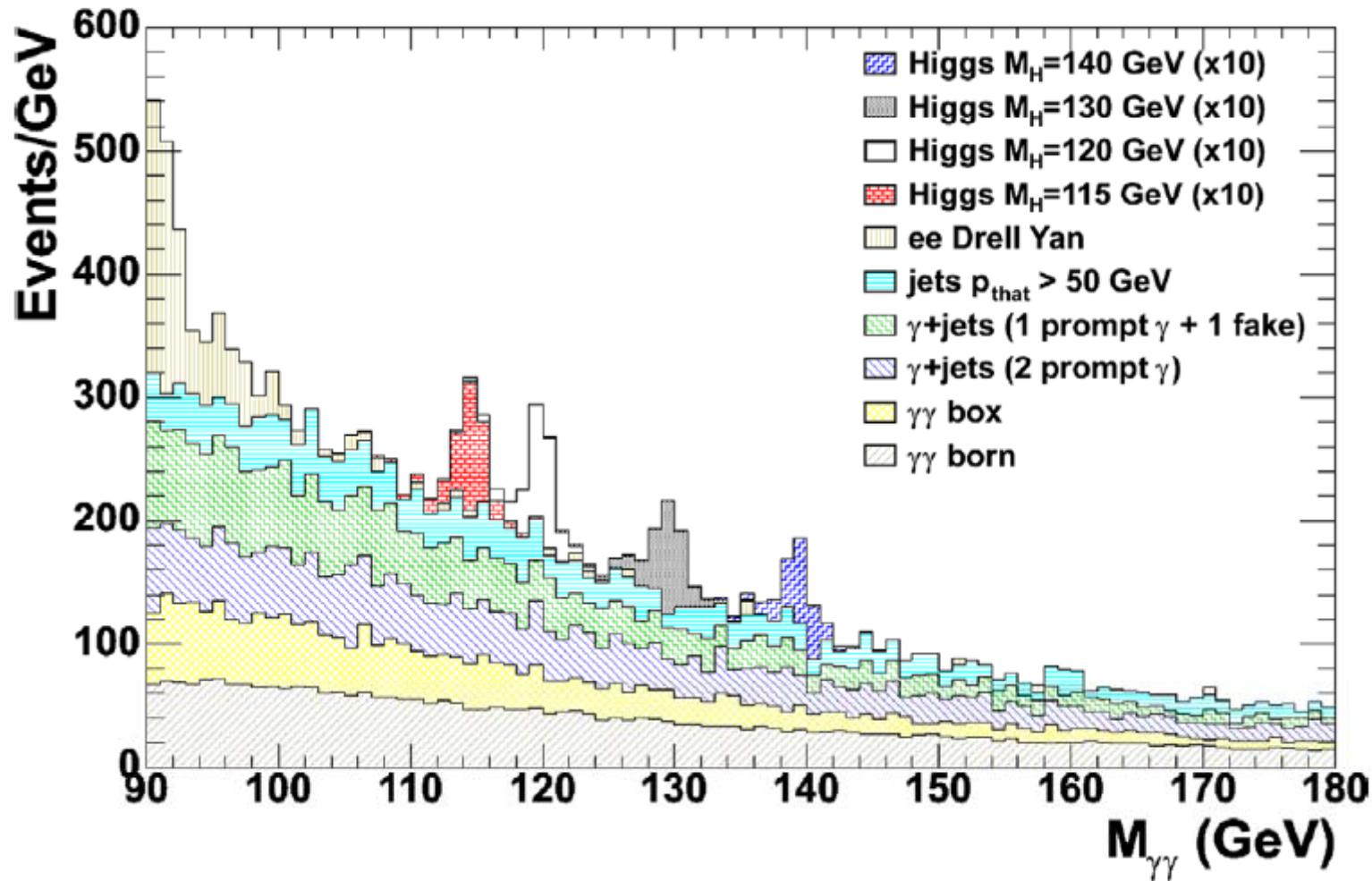
O.Brein,A.Djouadi and R.Harlander Phys.Lett.B579:149-156,2004

W.Beenaker,S.Dittmaier,M.Kramer,B.Plumper,  
M.Spira and P.Zerwas Phys Rev Lett 87,201805,2001  
S.Dawson,C.Jackson,L.Orr,L.Reina and D.Wackerloeh Phys.Rev.D68:034022,200

<http://lepewwwg.web.cern.ch/LEPEWWG/>



## CMS TDR



**Figure 2.2.** Diphoton invariant mass spectrum after the selection for the cut-based analysis. Events are normalised to an integrated luminosity of  $1 \text{ fb}^{-1}$  and the Higgs signal, shown for different masses, is scaled by a factor 10.

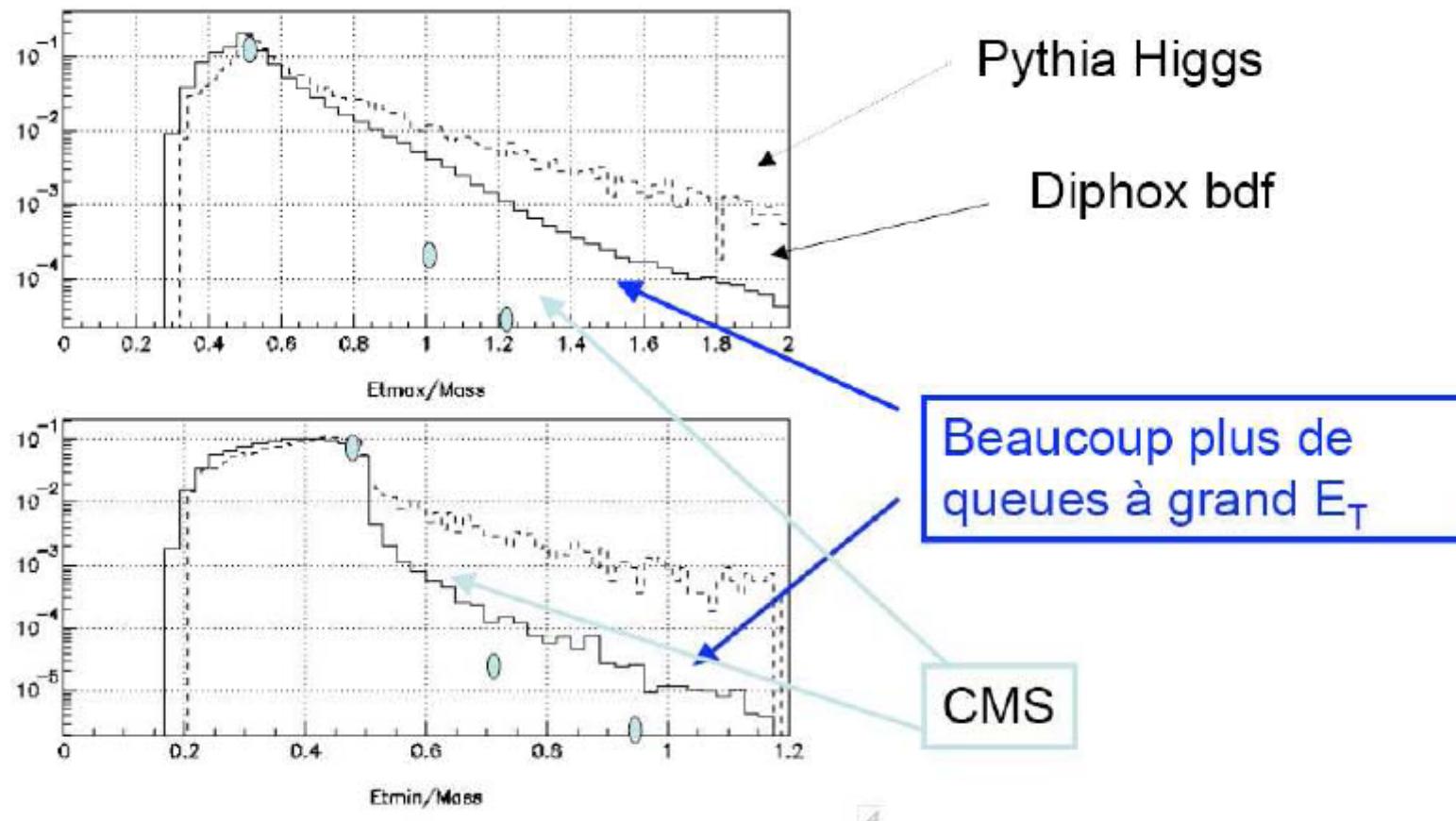
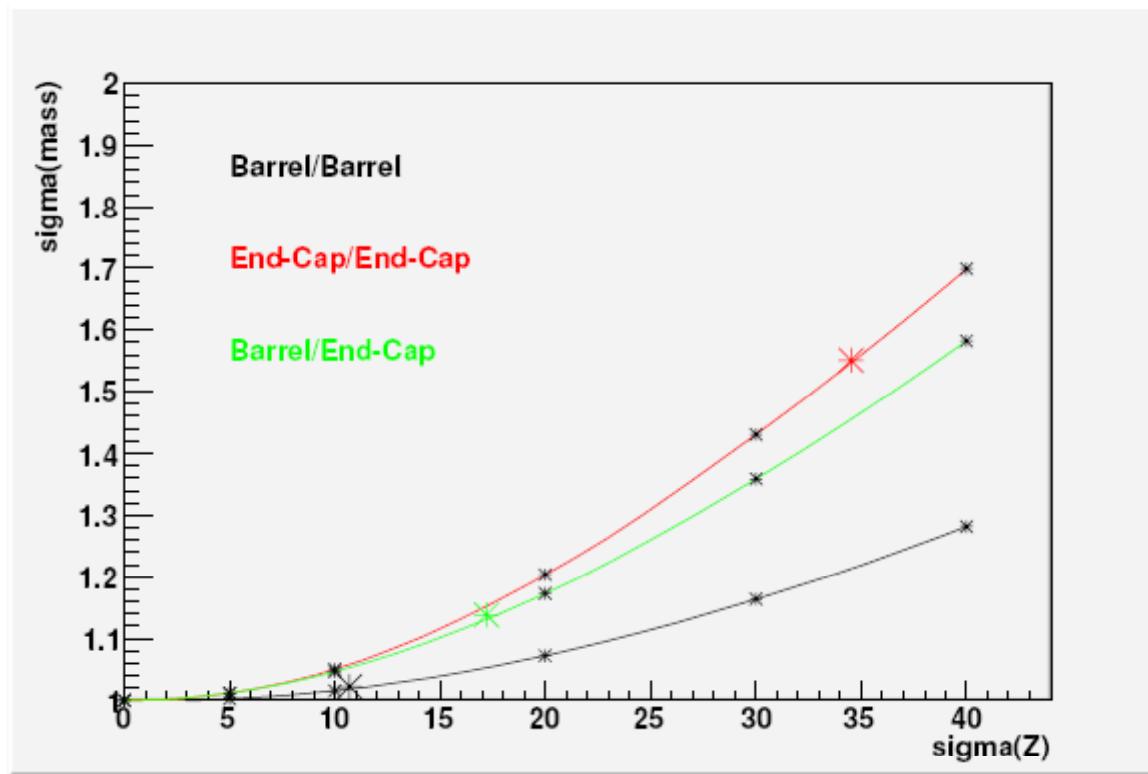
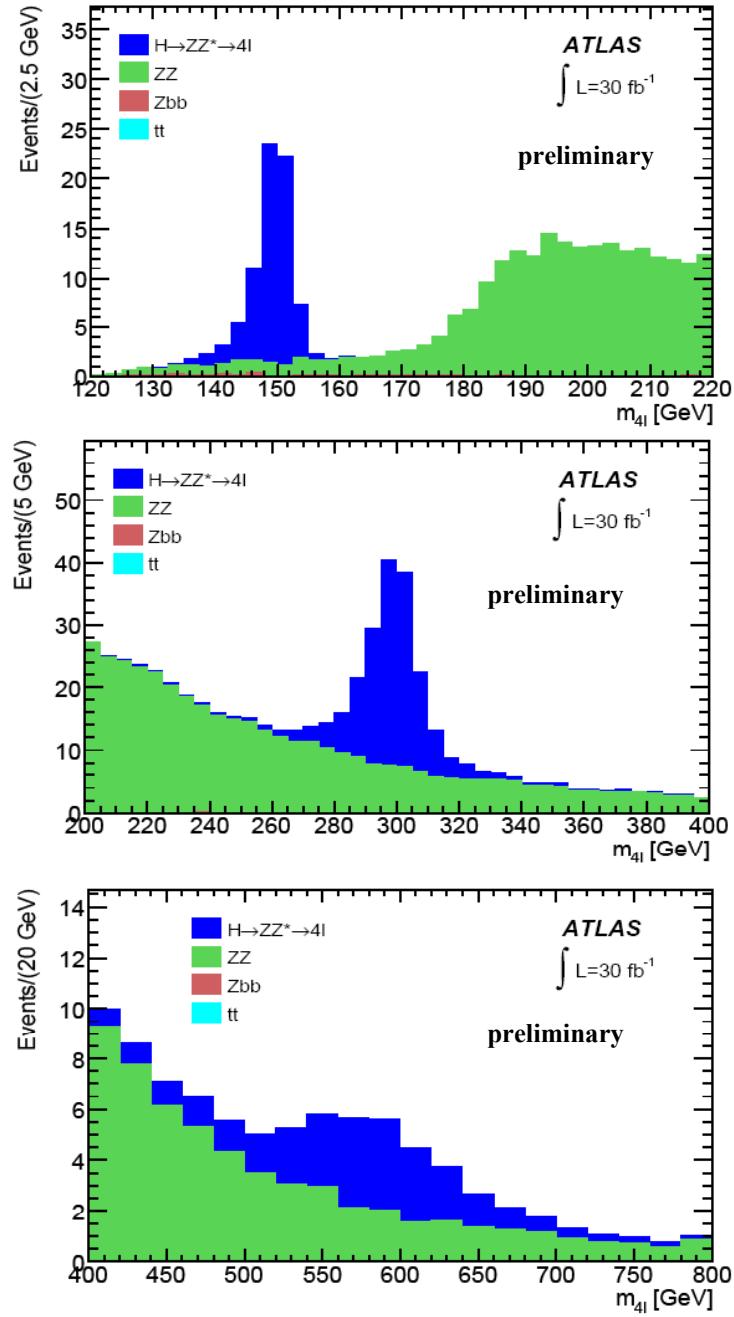
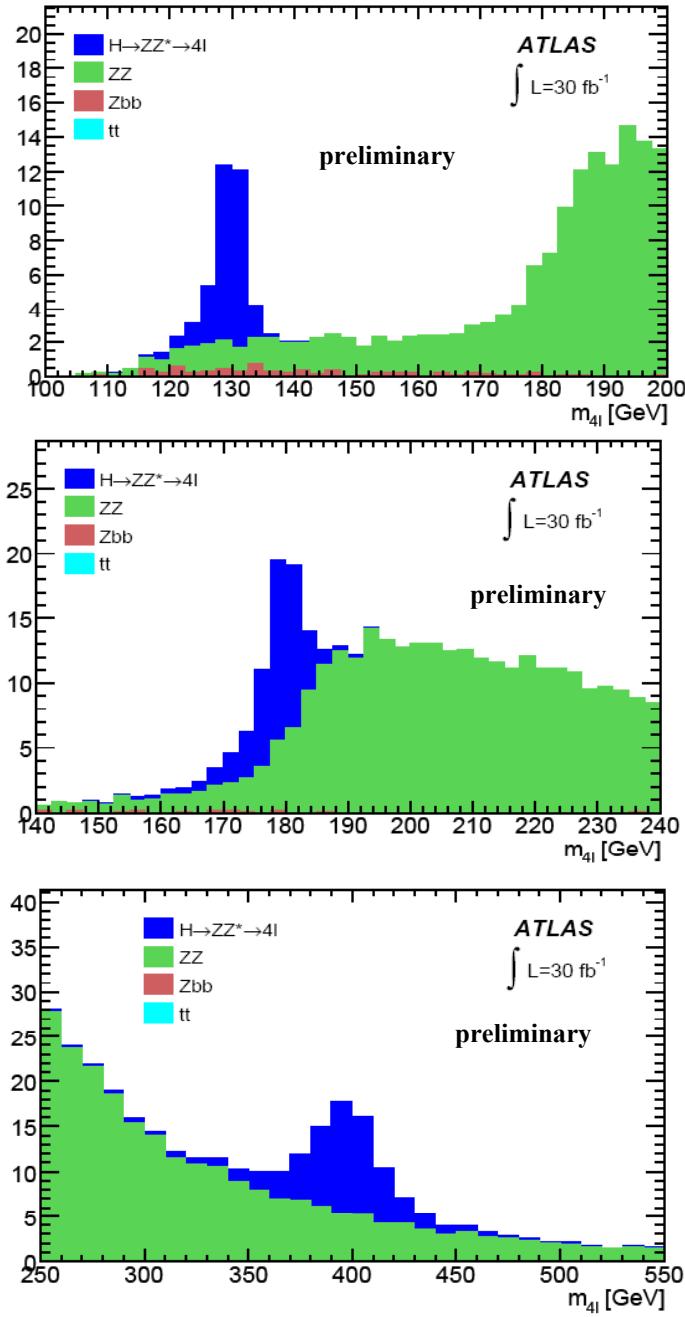


FIG. 4.4 – Distribution de  $P_T$  des photons (divisé par  $m_{\gamma\gamma}$ ) calculée par ATLAS et CMS.





VBF H $\rightarrow$   $\tau\tau$

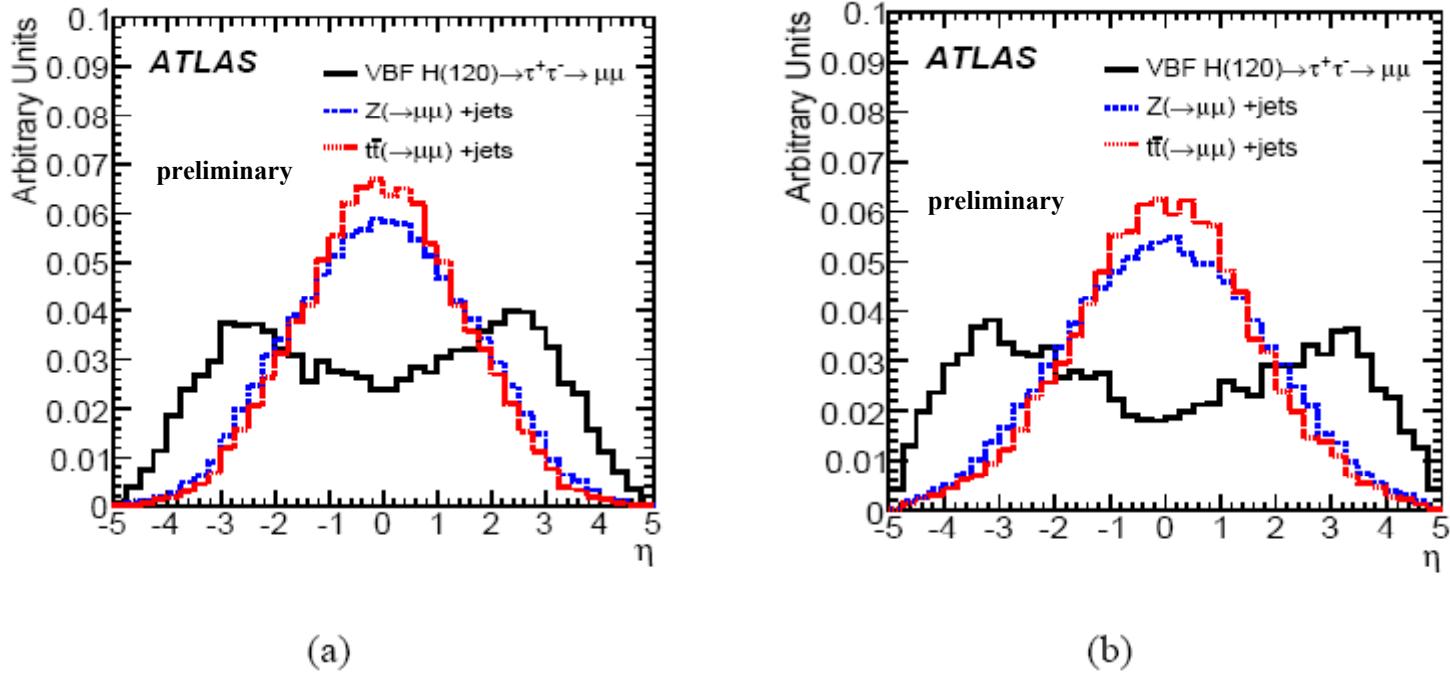


Figure 2: Pseudorapidity of the highest  $p_T$  (a) and the second highest  $p_T$  (b) jets for the Cone jet algorithm based on TopoClusters with  $R = 0.4$  in VBF  $H \rightarrow \tau\tau \rightarrow \mu\mu$  ( $m_H=120$  GeV) and background events. Only  $p_T$  cuts were applied to jets. Solid (black) histogram is for signal, dashed (red) histogram is for  $t\bar{t} \rightarrow WW \rightarrow (\mu\mu)$ , and dotted (blue) histogram is for  $Z \rightarrow \mu\mu + n$  jets.

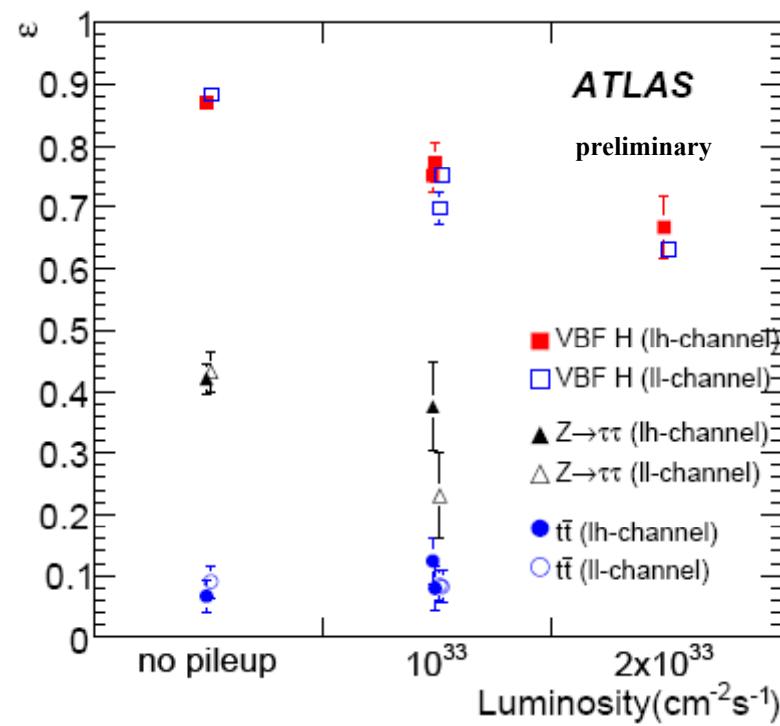


Figure 7: Central jet veto performance in the presence of varying levels of pileup for signal and background samples.

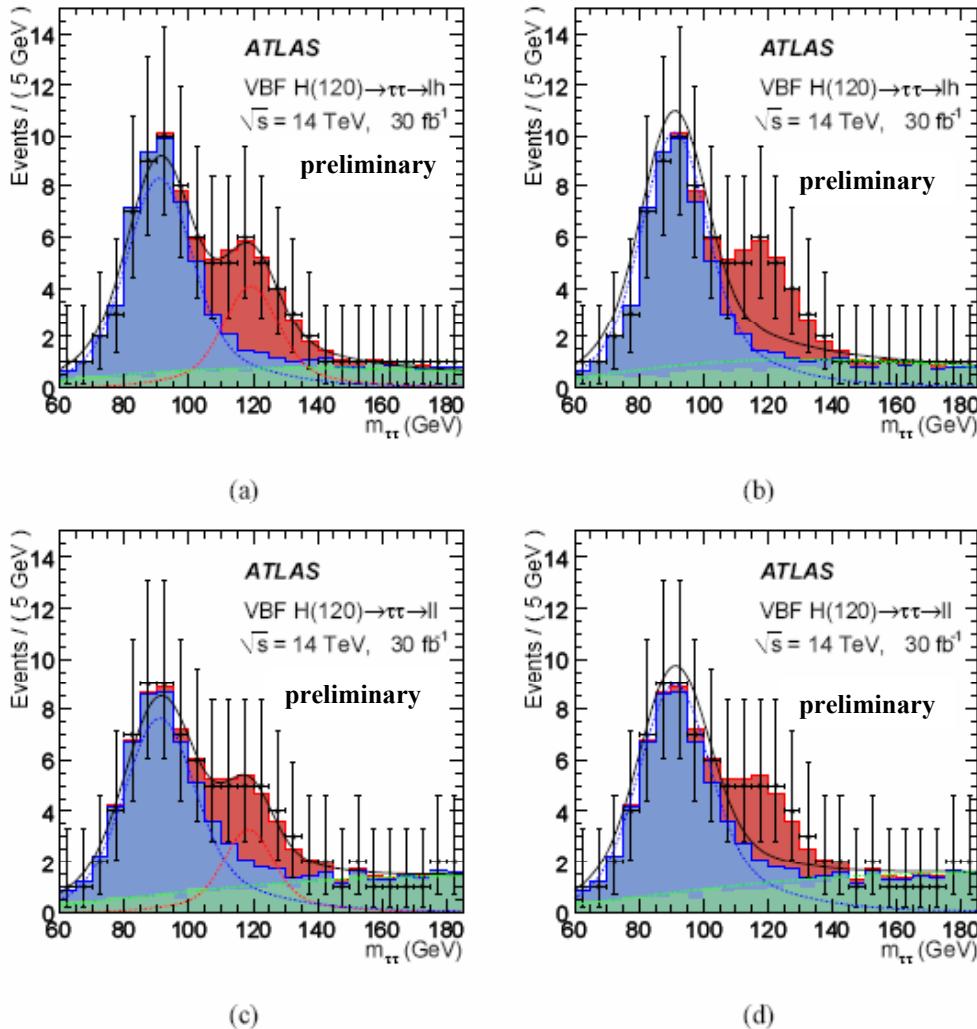
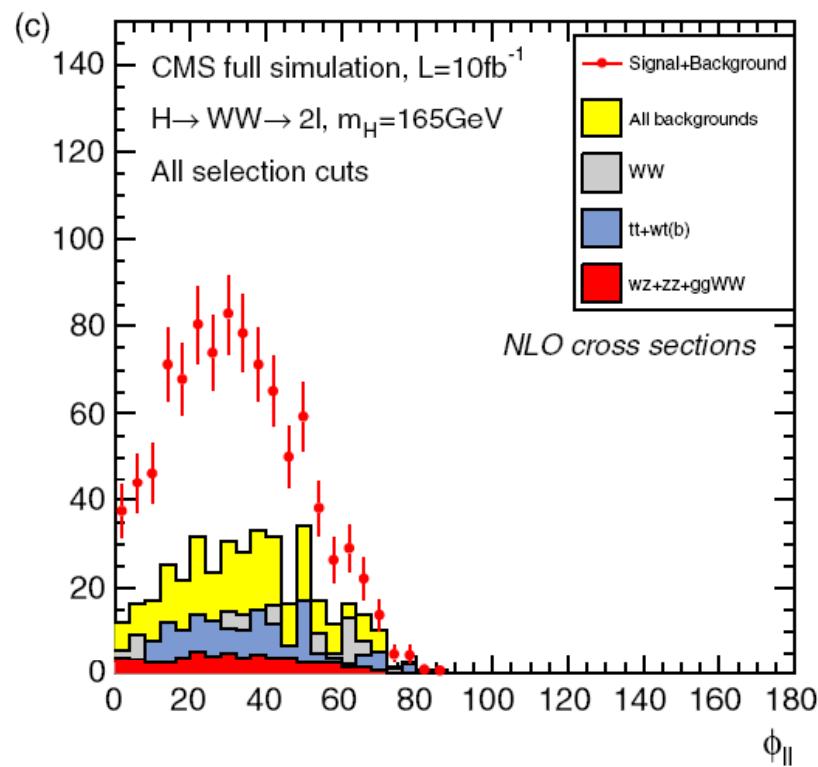


Figure 15: Example fits to a data sample with the signal-plus-background (a,c) and background only (b,d) models for the  $lh$ - and  $ll$ -channels at  $m_H = 120$  GeV with  $30 \text{ fb}^{-1}$  of data. Not shown are the control samples that were fit simultaneously to constrain the background shape. The fits are performed to the signal and background expectation (histograms), while the overlaid data with error bars are only indicative of a possible data set. These samples do not include pileup.

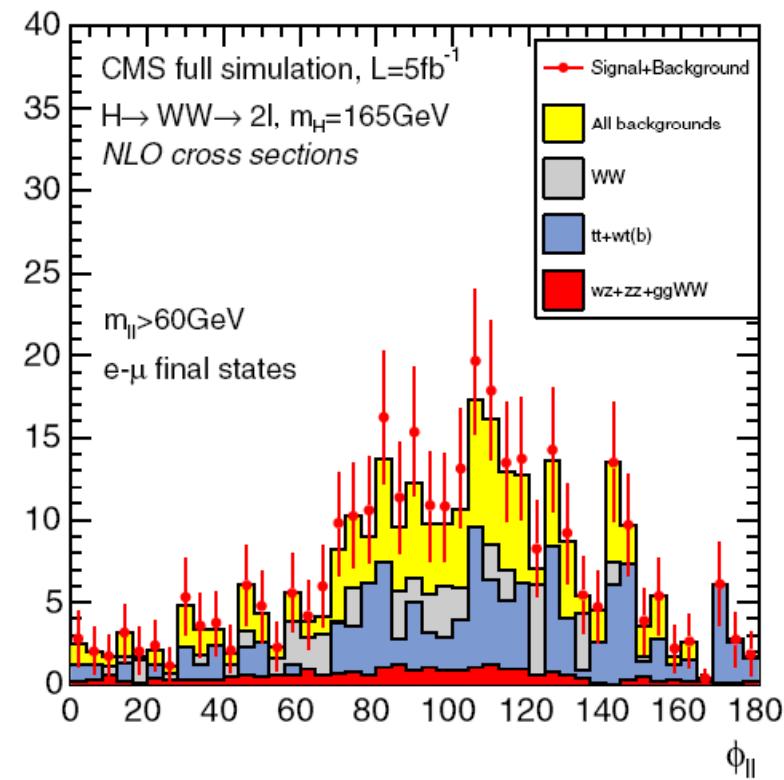
# $H \rightarrow WW \rightarrow llvv$

G.Davatz,M.Dittmar and A.Giolo-Nicollerat CMS note 2006/047 J.Phys.G33:N85,2007

## *Signal zone*

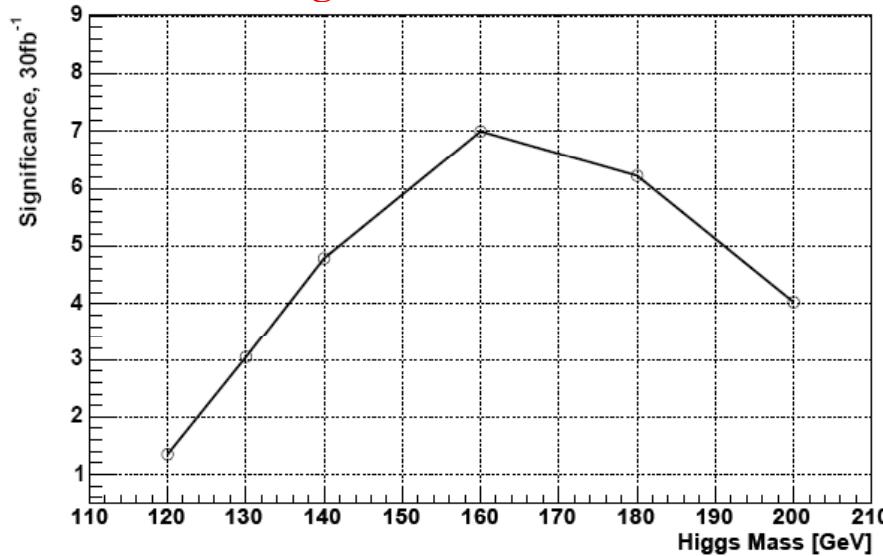


## *Background zone*



# VBF H $\rightarrow$ WW $\rightarrow$ llvv

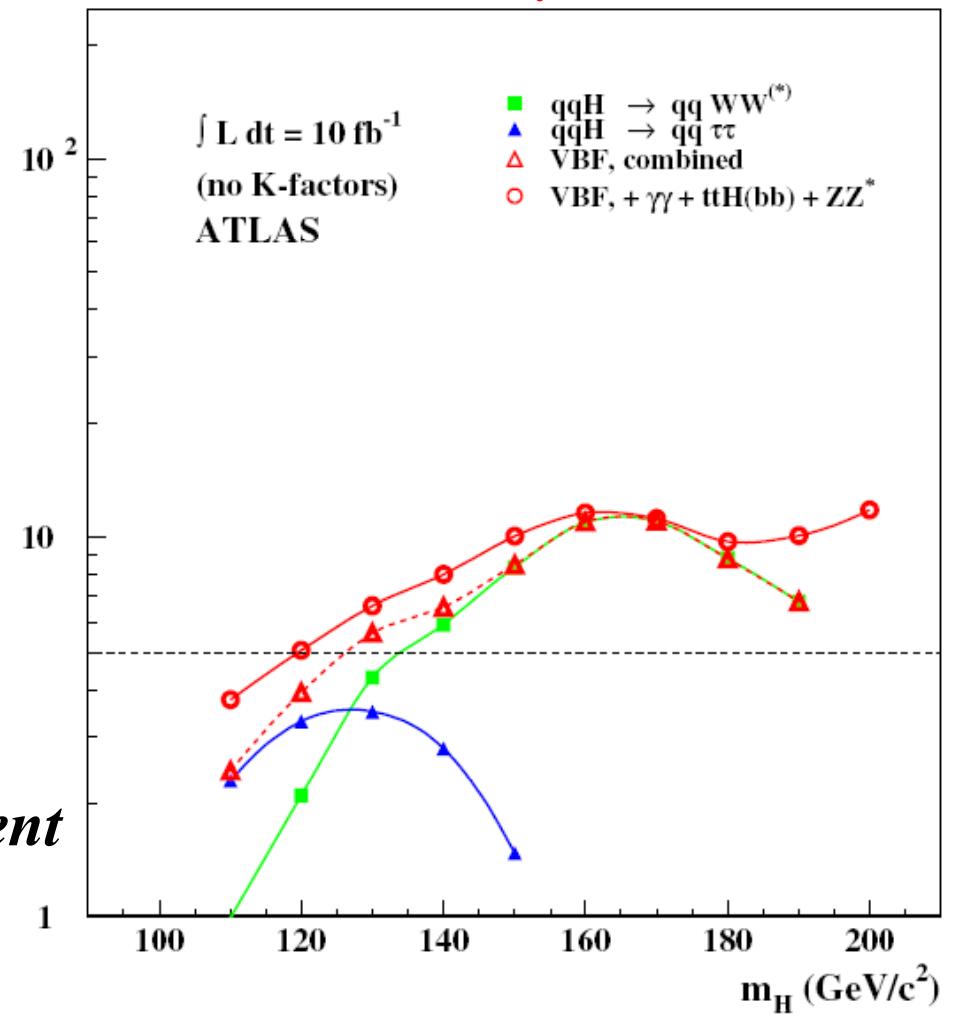
E.Yazgan et al. CMS note 2007/011



*ttH ALPGEN*

*tt 0,1,2 j matrix element*

S.Asai et al. Eur Phys J C32,2004,19



# **ttH, H $\rightarrow$ bb**

new ATLAS I.Ludwig

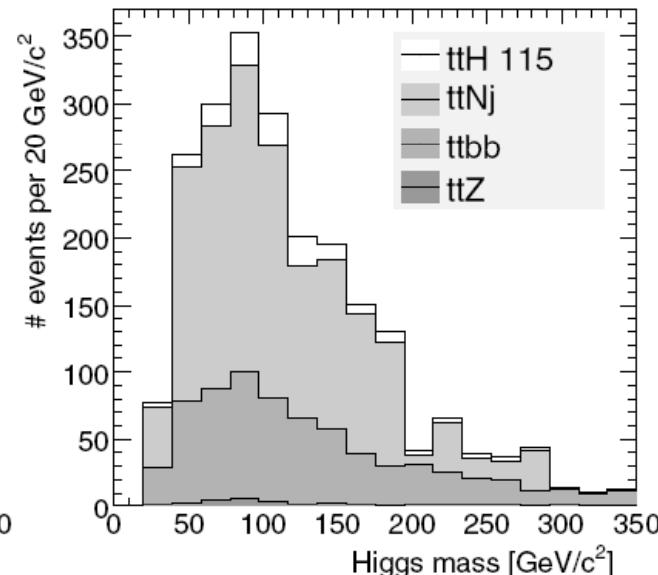
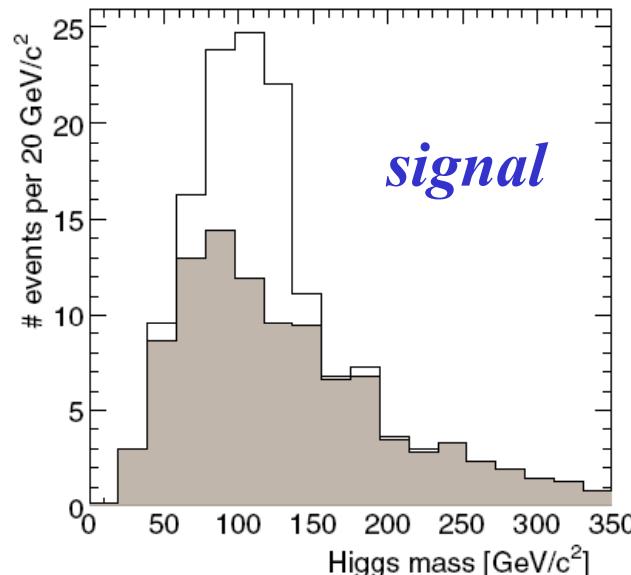
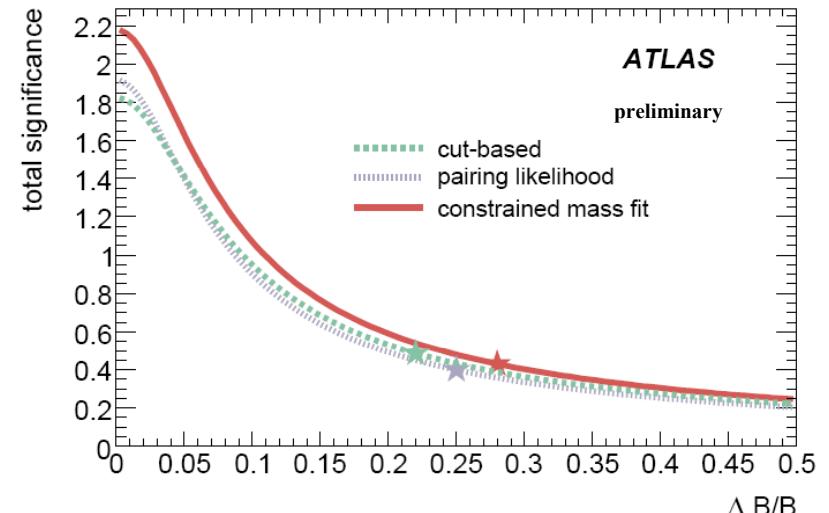
CMS TDR S.Cucciarelli,A.Schmidt,

C.Weiser, C.Riccardi,P.Torre,

D.Benedetti, A.Santocchia,C.Hill,

J.Incandela and S.Koay CMS note 2006/119

J.Phys.G:Nucl.Part.Phys. 34 (2007) N221-N250



**CMS 60 fb $^{-1}$  W $\rightarrow$  qq W $\rightarrow$  lepton ν**

**H $\rightarrow$  WW**

new ATLAS I.Ludwig  
CMS TDR F.Stoeckli

H $\rightarrow$  WW

WH (3l)

V.Drollinger et al. CMS note 2006/055  
G.Davatz,M.Dittmar and A.Giolo-Nicollerat CMS note 2006/047 J.Phys.G33:N85,2007  
C.Delaere CMS note 2006/053

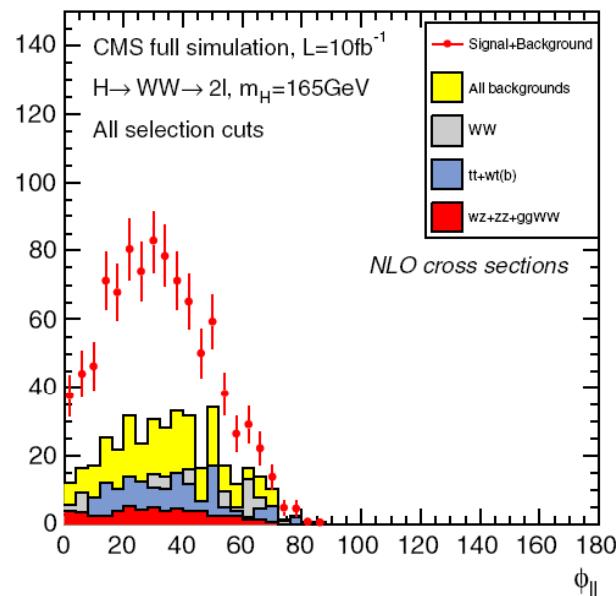
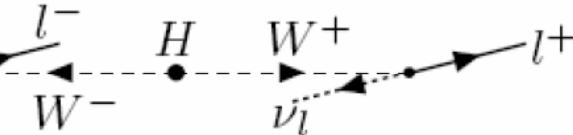
VBF WW $\rightarrow$  l l jj

⚠ difference with 'old' ATLAS results to be understood

VBF WW $\rightarrow$  l l jj

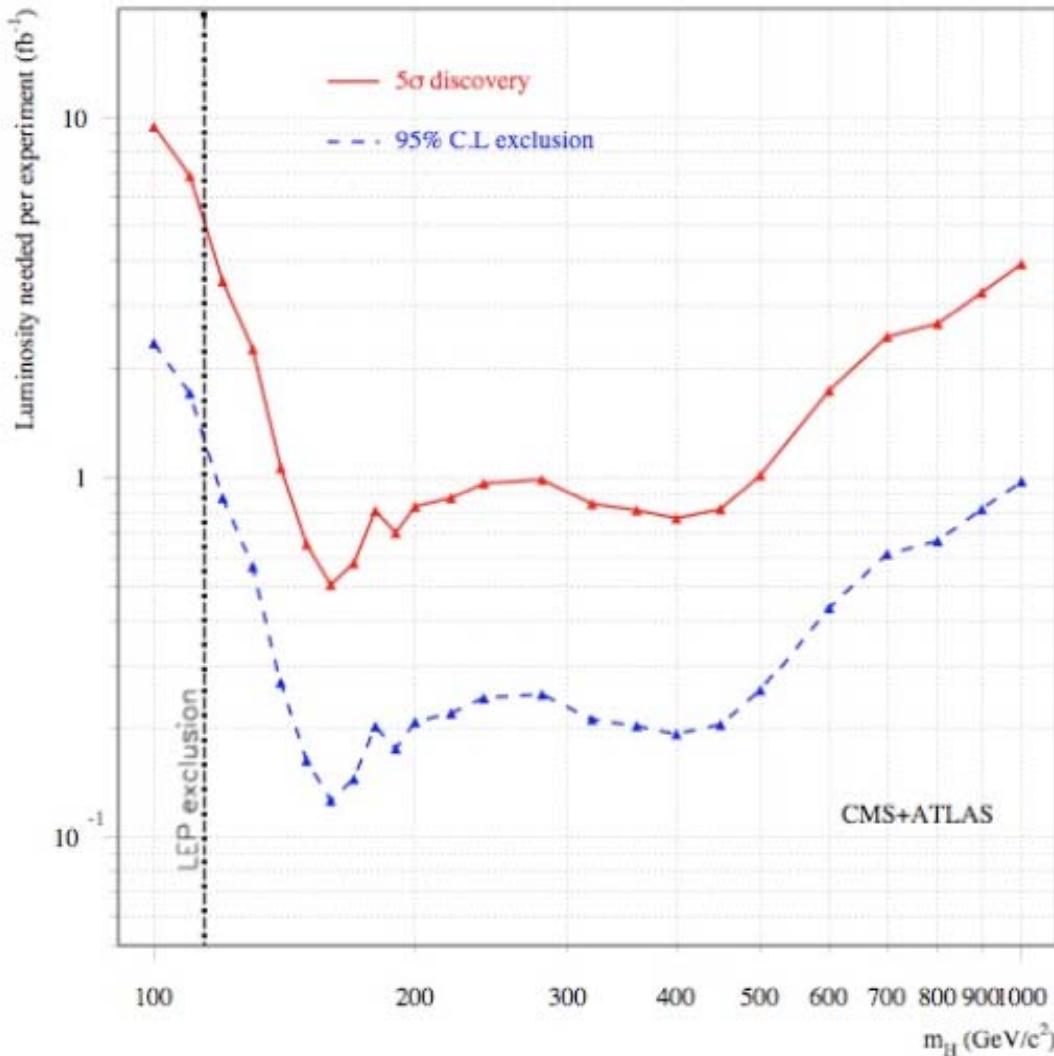
H.Pi et al. CMS note 2006/092  
E.Yazgan et al. CMS note 2007/011

correlation in  $\phi$  between 2 leptons



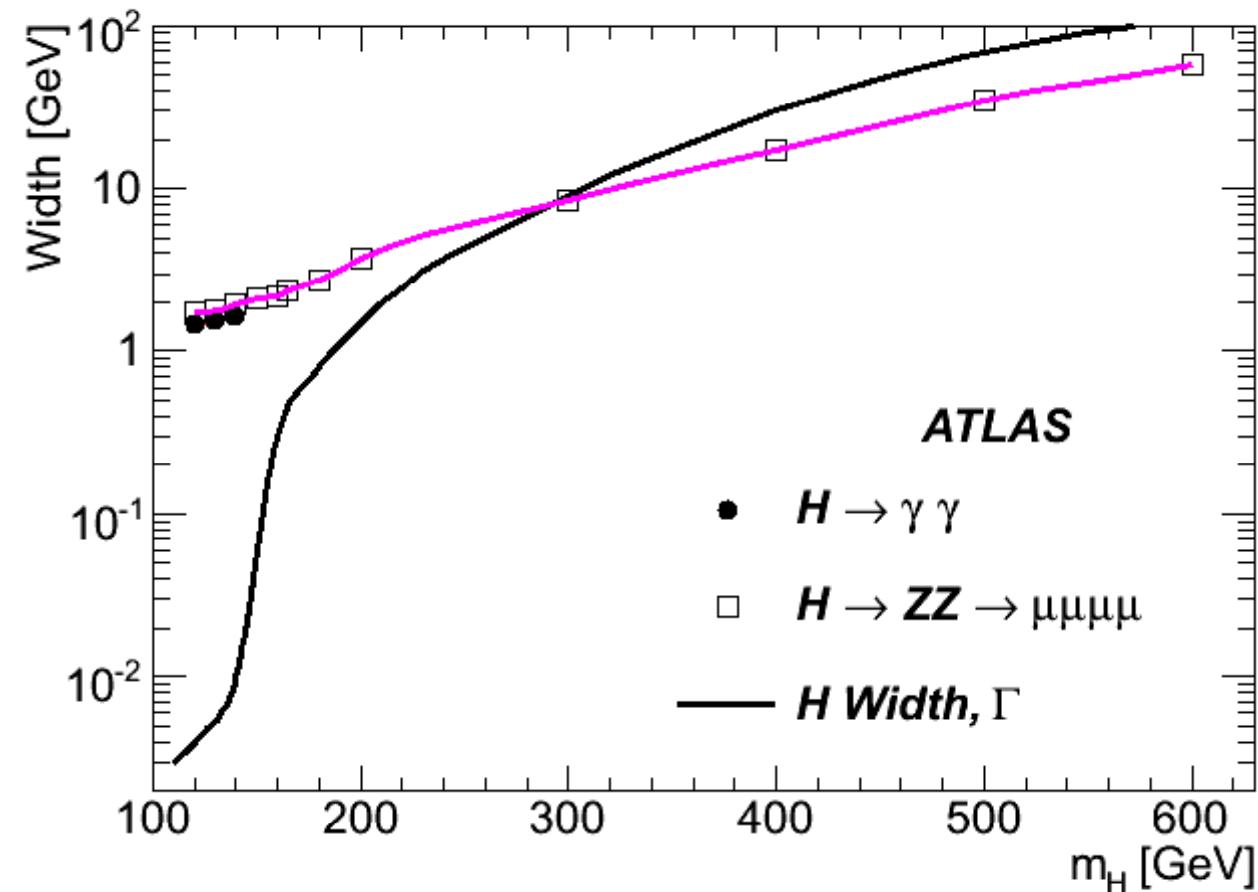
*no mass peak*  
*⇒ need precise knowledge of background*  
*⇒ develop data driven methods*

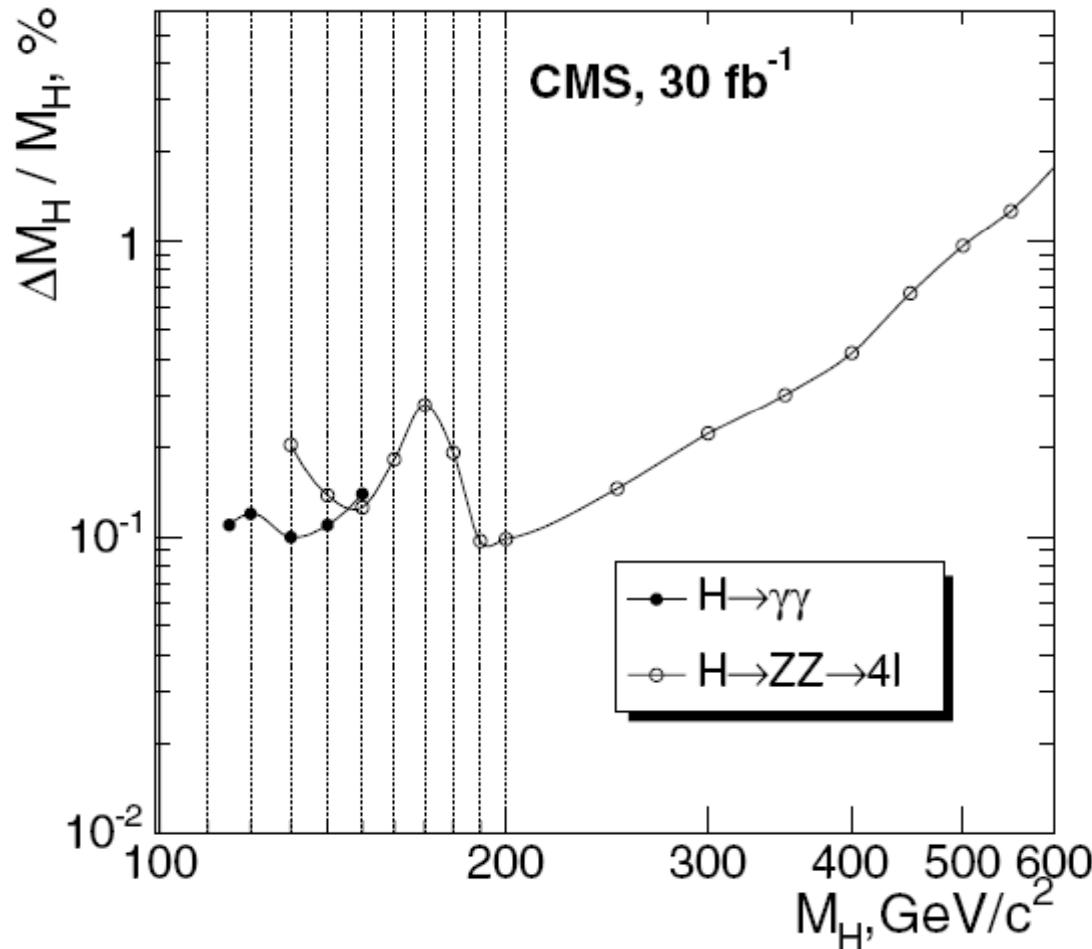
## General limits/discovery plots



## **Mass and width measurement**

## Bill Murray

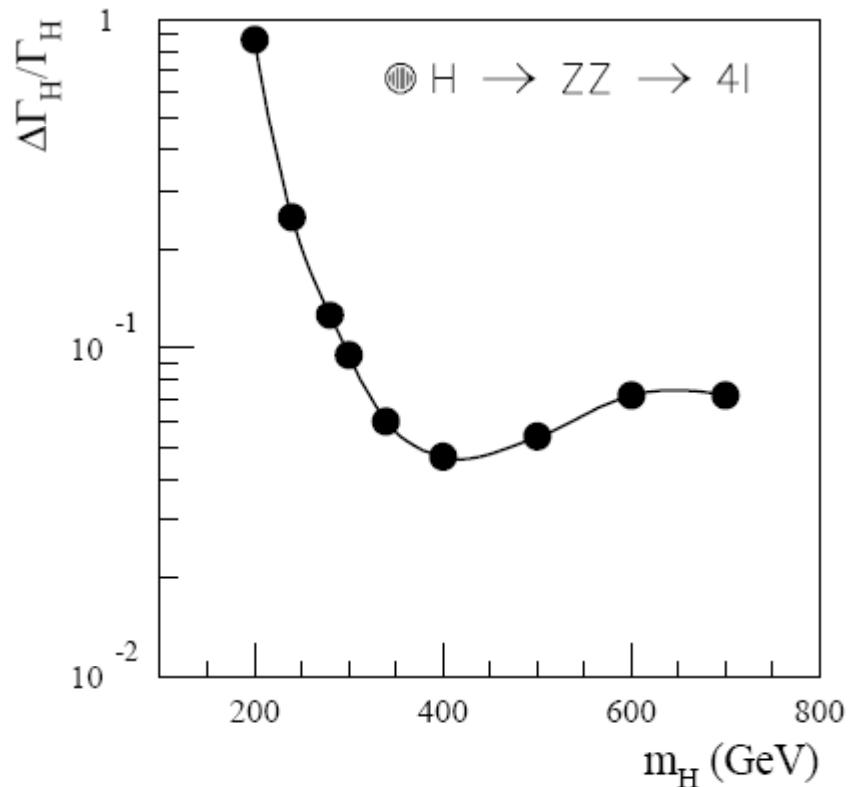




Useful for futur  
tests of consistency  
of SM

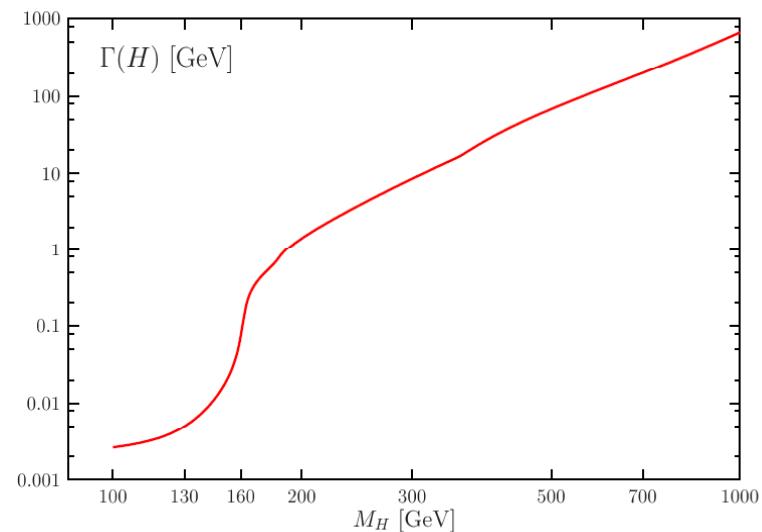
not limited by  
systematic uncertainties

**Figure 10.37.** The **statistical precision** of the Higgs boson mass measurement for the  $30 \text{ fb}^{-1}$  using inclusive Higgs boson production  $\text{pp} \rightarrow H + X$  and the  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ \rightarrow 4l$  decay modes.



**Figure 19-46** Relative precision  $\Delta\Gamma_H/\Gamma_H$  on the measured Higgs-boson width as a function of  $m_H$ , assuming an integrated luminosity of  $300 \text{ fb}^{-1}$ .

**ATLAS TDR**  
see also Bill Murray



*Figure 2.26: The SM Higgs boson total decay width as a function of  $M_H$ .*

**A.Djouadi Phys.Rept.457:1-216**

## **Spin and CP measurement**



**angular distributions in  $H \rightarrow ZZ \rightarrow 4l^\pm$**

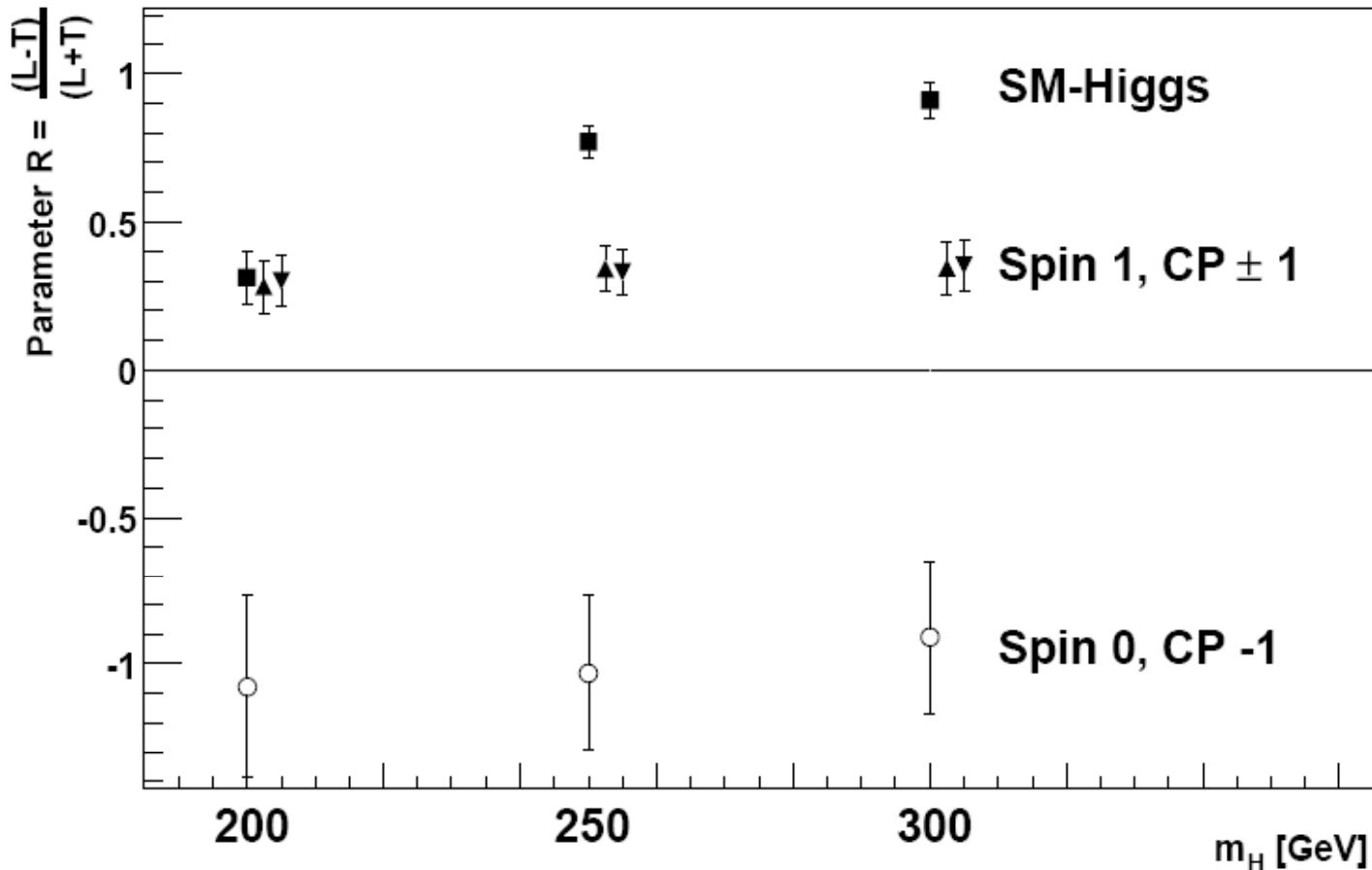
$$V_{\text{HZZ}}^{\mu\nu} = \frac{igm_Z}{\cos \theta_W} \left[ a g_{\mu\nu} + b \frac{p_\mu p_\nu}{m_Z^2} + c \epsilon_{\mu\nu\alpha\beta} \frac{p^\alpha k^\beta}{m_Z^2} \right]$$

**CP even**      **CP odd**

**R.Godbole,D.Miller and M.Muhlleitner JHEP 0712:031,2007**

**$\tan(\xi)=c$      $b=0$    dans l'analyse CMS**

Polarisation of the Z Bosons from Higgs decay ( $100 \text{ fb}^{-1}$ )



$$G(\theta) = T \cdot (1 + \cos^2(\theta)) + L \cdot \sin^2(\theta)$$

C.P.Buszello,I.Fleck,P.Marquard and J.J. van der Bij Eur Phys J C32,209,2004

## **Spin and CP measurement**

- **jet distributions in vector boson fusion**

$$\begin{aligned}
 T^{\mu\nu}(q_1, q_2) = & a_1(q_1, q_2) g^{\mu\nu} && \text{SM} \\
 & + a_2(q_1, q_2) [q_1 \cdot q_2 g^{\mu\nu} - q_2^\mu q_1^\nu] && \text{CP-even} \\
 & + a_3(q_1, q_2) \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}. && \text{CP-odd}
 \end{aligned}$$

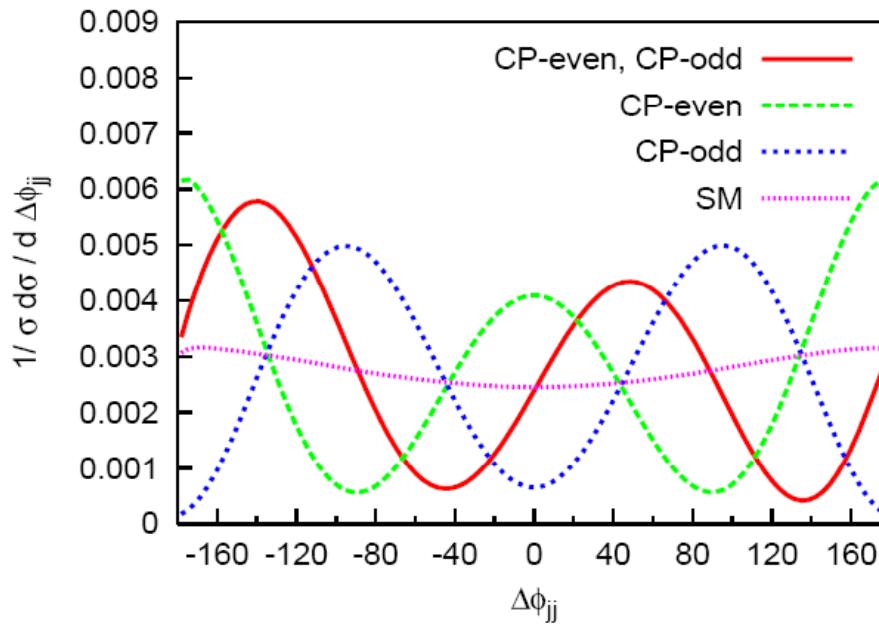


Figure 4: Normalized distribution of the azimuthal angle  $\Delta\phi_{jj}$  defined in Eq. (4.2) for a Higgs mass of 120 GeV and a mixed CP scenario ( $d = \tilde{d} = 0.18$ , red solid curve), a CP-even anomalous coupling ( $d = 0.18$ ,  $\tilde{d} = 0$ , green dashed curve), a CP-odd coupling ( $d = 0$ ,  $\tilde{d} = 0.18$ , blue dotted curve) and the SM case (purple narrow dotted line).

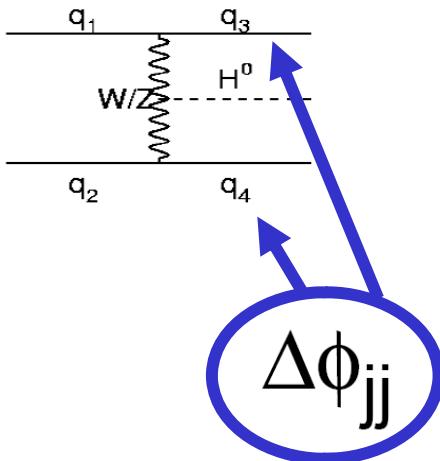
V.Hankele,G.Klamke,D.Zeppenfeld and T.Figy Phys.Rev.D74:095001,2006

**C.Ruwiedel,M.Schumacher and N.Wermes Eur.Phys.J.C51:385-414,2007**

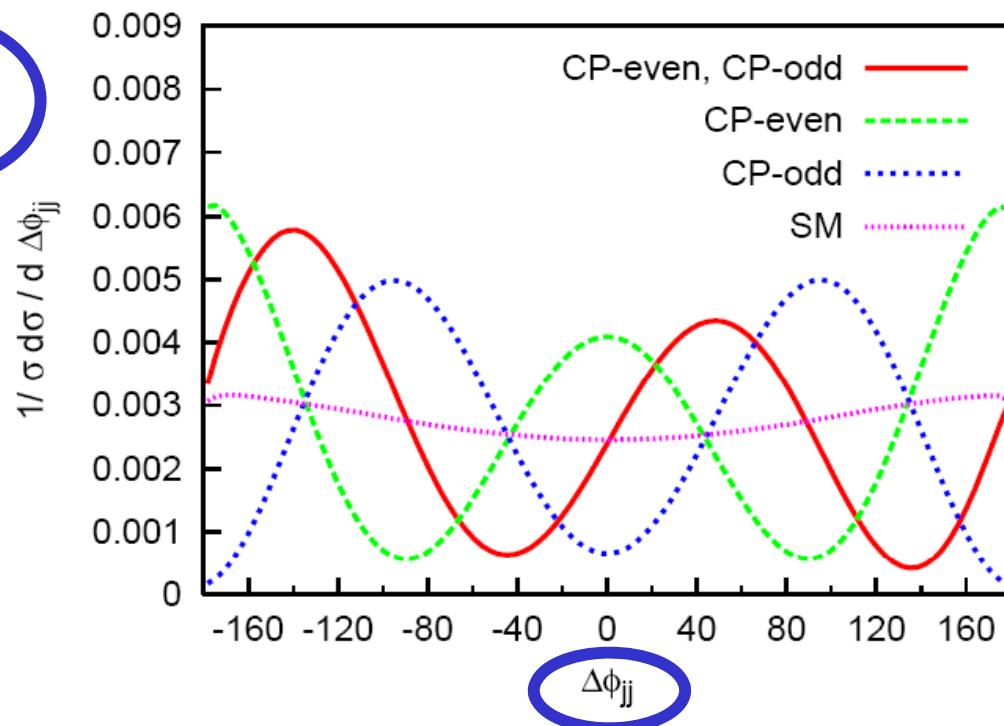
**Table 10.** The first two columns show the probabilities for a standard model pseudo-data sample in tests of the hypotheses of purely CP even (CPE) and CP odd (CPO) anomalous couplings to have a  $\chi^2$  probability below 5% or  $5.7 \times 10^{-7} \hat{=} 5\sigma$ . The third and fourth columns show the median  $\chi^2$  probabilities and the corresponding deviations from the mean of a Gaussian distribution in standard deviations

integrated luminosity, hypothesis tested		probability for		median	
		> $5\sigma$	< 5%	$\chi^2$ -prob.	dev. in $\sigma$
<i>H → W<sup>+</sup>W<sup>-</sup> → llνν</i>					
10 fb <sup>-1</sup>	CPE	59%	100%	$1.3 \times 10^{-7}$	$5.3\sigma$
	CPO	35%	98%	$6.0 \times 10^{-6}$	$4.5\sigma$
30 fb <sup>-1</sup>	CPE	100%	100%	—	—
	CPO	100%	100%	—	—
<i>H → τ<sup>+</sup>τ<sup>-</sup> combined</i>					
30 fb <sup>-1</sup>	CPE	2%	68%	$1.2 \times 10^{-2}$	$2.5\sigma$
	CPO	0%	52%	$4.3 \times 10^{-2}$	$2.0\sigma$

# Anomalous Higgs Couplings in VBF fusion



T.Plehn,D.Rainwater and D.Zeppenfeld Phys Rev Lett 88,051801,2002  
T.Figy and D.Zeppenfeld Physics Letters B 591 (2004) 297-303  
V.Hankele,G.Klamke,D.Zeppenfeld and T.Figy Phys.Rev.D74:095001,2006  
**C.Ruwiedel,M.Schumacher and N.Wermes Eur.Phys.J.C51:385-414,2007**



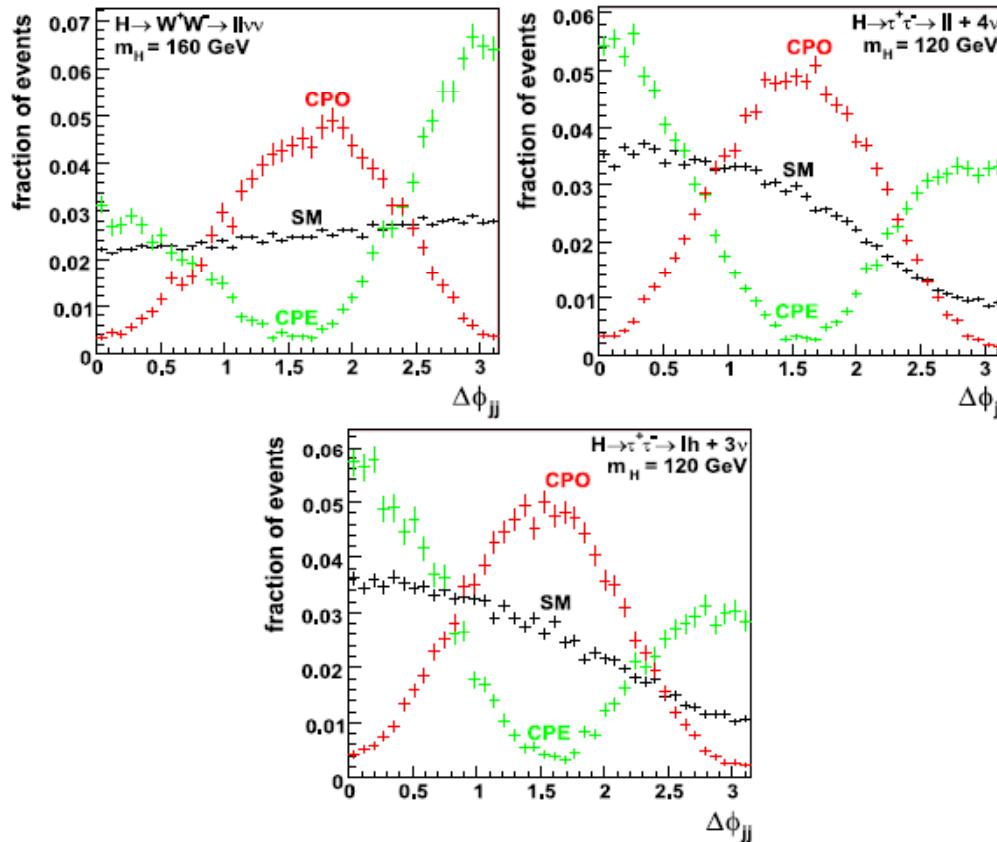
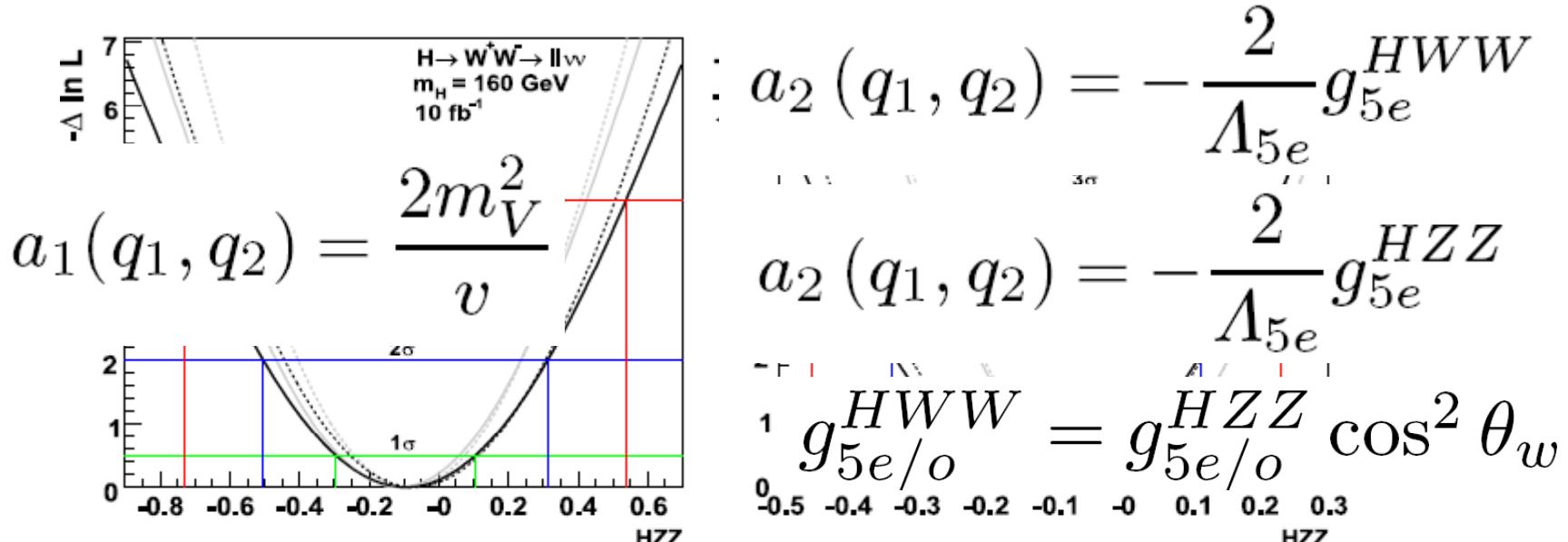


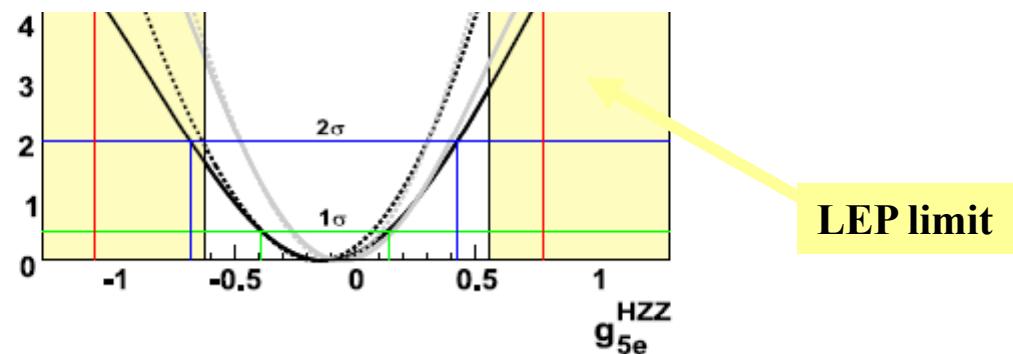
Fig. 9. Distributions of the variable  $\Delta\phi_{jj}$  with high statistics for signal events after all cuts have been applied. Distributions are shown for each of the three different couplings and each of the channels studied

**With  $10 \text{ fb}^{-1}$  can exclude CPE and CPO at 5 sigmas in  $WW \rightarrow ll\nu\nu$  for  $m_H=160 \text{ GeV}$  and with  $30 \text{ fb}^{-1}$  at 2 sigmas in  $\tau\tau$  for  $m_H=120 \text{ GeV}$**

### Additional results for SM + CPE



**Fig. 17.** The logarithm of the likelihood as a function of the anomalous coupling constant  $g_{HZZ}$  for one pseudo-data sample per channel and integrated luminosity studied. The curves that were calculated taking into account are shown in black. For comparison, curves that were calculated without  $\Lambda_5 = 480 \text{ GeV}$  are shown in grey. The continuous lines were calculated using the non-extended likelihood. The white lines were calculated using the extended likelihood. The areas marked in light yellow (light grey) are excluded according to the approximate limits at 95% confidence level given in Table 3. 1-, 2-, and 3 $\sigma$  intervals are shown for the case of a non-extended likelihood with background contributions taken into account



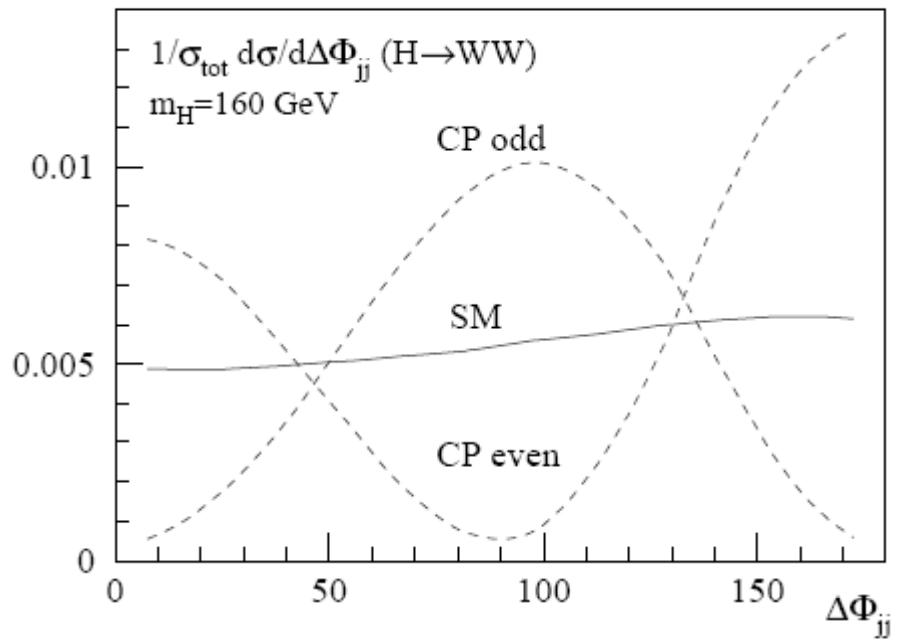
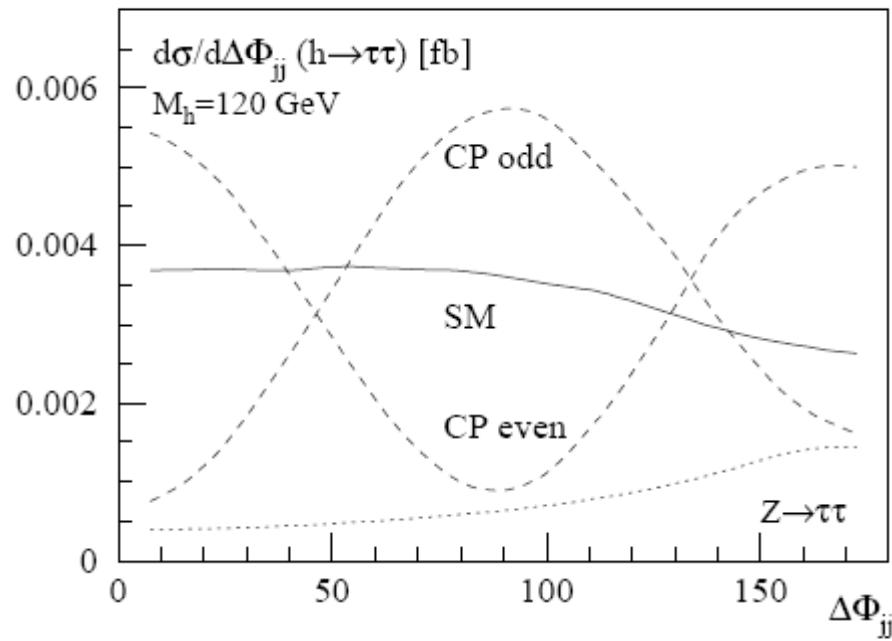


FIG. 36: Azimuthal angular distributions of the tagging jets in WBF production of a SM Higgs v. scalar field coupled to weak bosons via CP-even/odd D6 operators. The dotted line in the left panel is the SM background, which is added to the signal curves. Figures from Ref. [85].

**T.Plehn,D.Rainwater and D.Zeppenfeld Phys Rev Lett 88,051801,2002  
D.Rainwater hep-ph/0702124**

## **ILC results on spin**

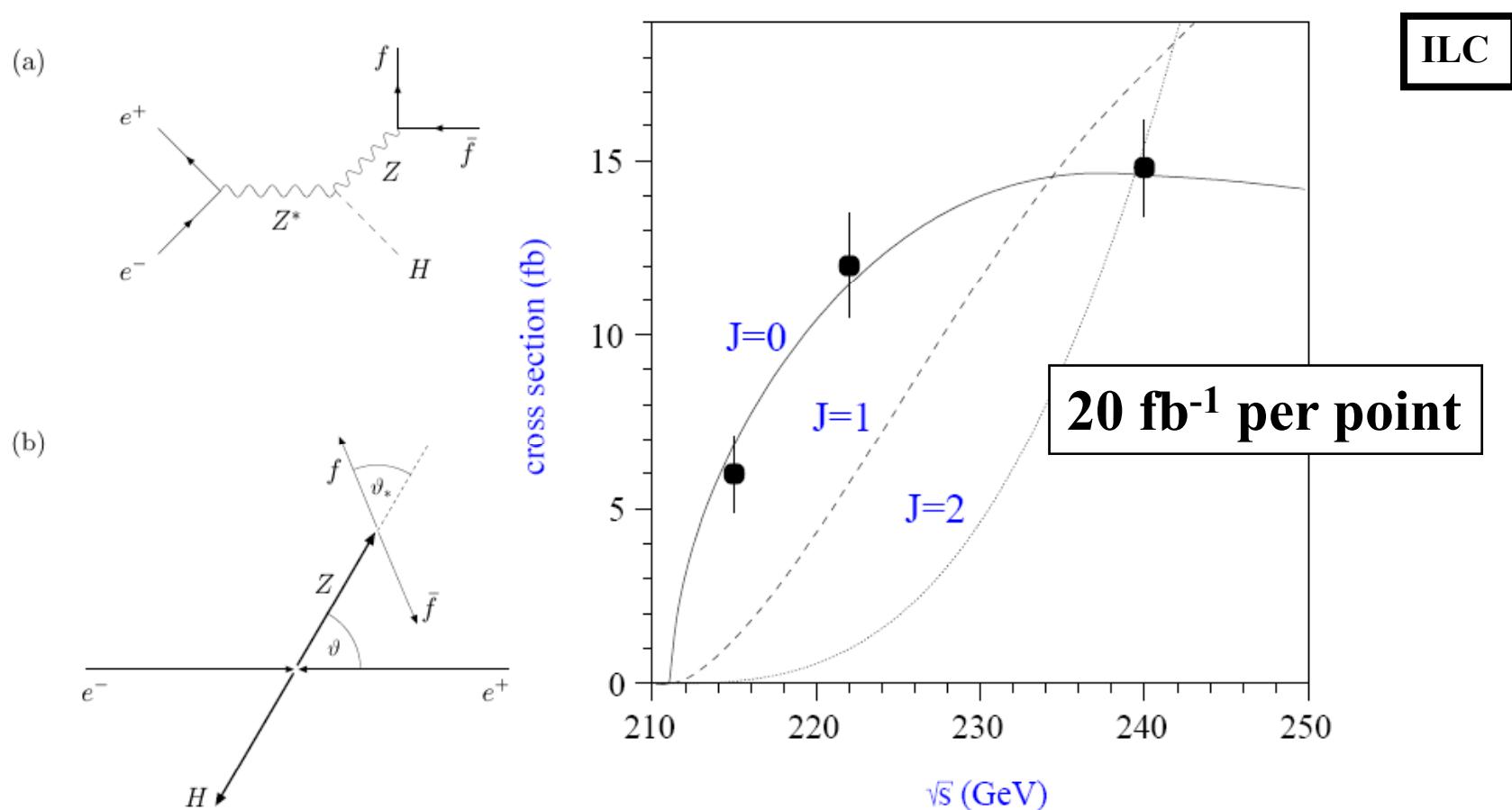


FIG. 38: Left: Feynman diagram for  $e^+e^- \rightarrow ZH$  and schematic [88] showing the analyzing angles. Right: curves showing the threshold rate dependence for  $J = 0, 1, 2$  states in this channel [71].

**J.A.Aguilar-Saavedra et al. arXiv:hep-ph/0106315**

**D.Miller,S.Chi,B.Eberle,M.Muhlleitner and P.Zerwas Phys.Lett.B505:149-154,2001**

**D.Rainwater hep-ph/0702124**

## **Measurement of couplings with different channels**

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

Table 1: List of all ATLAS studies used for the Maximum Likelihood fit. The mass range is the range of Higgs boson mass considered in the studies (not the discovery region).

$$\begin{aligned}
 \text{BR}(H \rightarrow WW) &= \beta_W \frac{g_W^2}{\Gamma_H} \\
 \text{BR}(H \rightarrow ZZ) &= \beta_Z \frac{g_Z^2}{\Gamma_H} \\
 \text{BR}(H \rightarrow \gamma\gamma) &= \frac{(\beta_{\gamma(W)} \cdot g_W - \beta_{\gamma(t)} \cdot g_t)^2}{\Gamma_H} \\
 \text{BR}(H \rightarrow \tau\tau) &= \beta_\tau \frac{g_\tau^2}{\Gamma_H} \\
 \text{BR}(H \rightarrow b\bar{b}) &= \beta_b \frac{g_b^2}{\Gamma_H} .
 \end{aligned}$$

$$\begin{aligned}
 \sigma_{ggH} &= \alpha_{ggH} \cdot g_t^2 \\
 \sigma_{\text{WBF}} &= \alpha_{\text{WF}} \cdot g_W^2 + \alpha_{\text{ZF}} \cdot g_Z^2 \\
 \sigma_{t\bar{t}H} &= \alpha_{t\bar{t}H} \cdot g_t^2 \\
 \sigma_{WH} &= \alpha_{WH} \cdot g_W^2 \\
 \sigma_{ZH} &= \alpha_{ZH} \cdot g_Z^2 .
 \end{aligned}$$

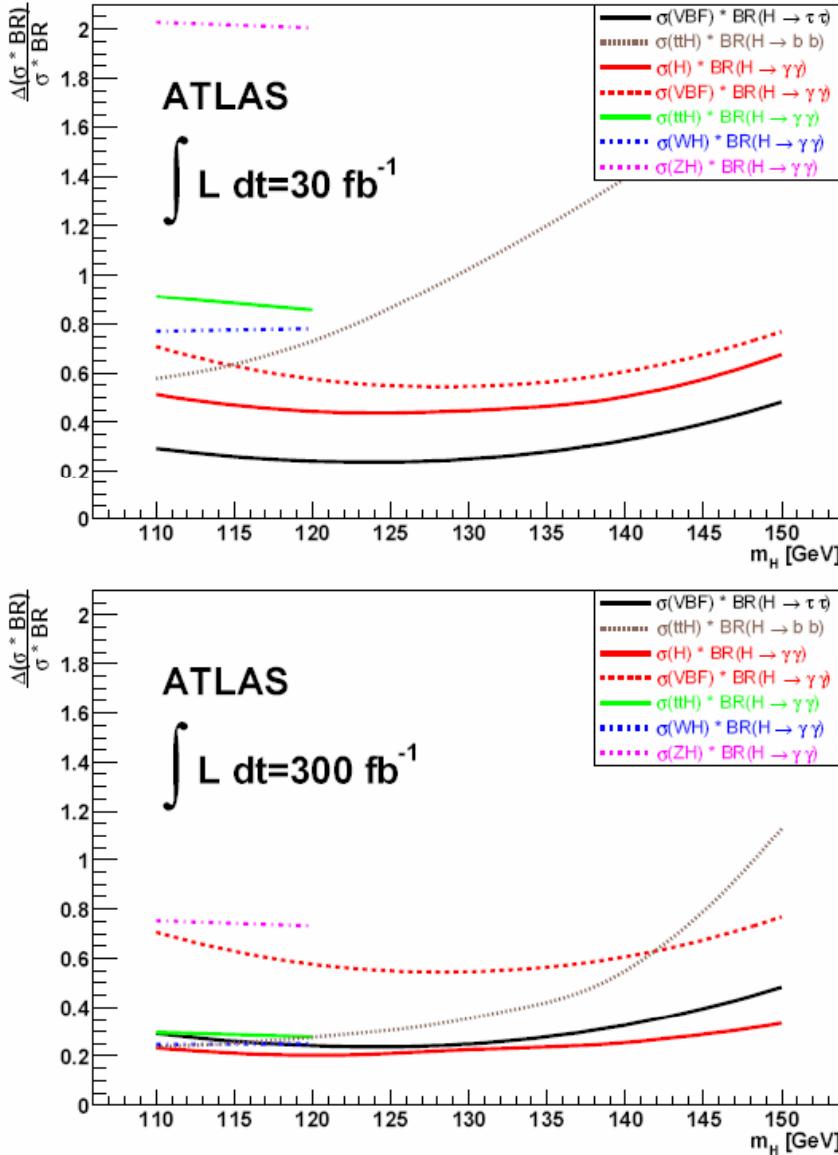


Figure 1: Relative error for the measurement of rates  $\sigma \cdot \text{BR}$  for those channels that can be seen only for Higgs boson masses below 150 GeV.

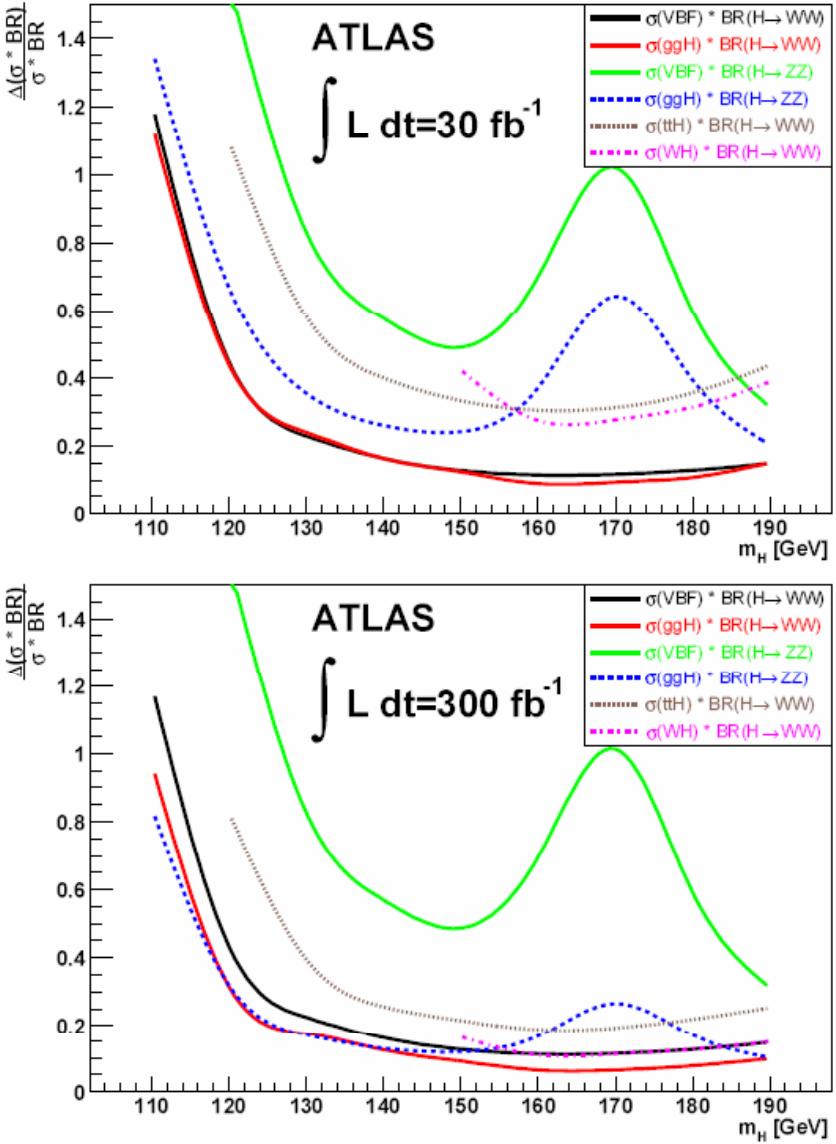


Figure 2: Relative error for the measurement of rates  $\sigma \cdot \text{BR}$  for those channels that can be seen in the complete considered mass range 110 GeV - 190 GeV.

## **MSSM general information**

# Parameter Count in the Standard Model and MSSM Extensions

model	real	phases	TOTAL
SM	17	2	19
MSSM	79	45	124
(MSSM) <sub>B</sub>	157	122	279
(MSSM) <sub>RPV</sub>	175	140	315

**H.Haber Nucl.Phys.Proc.Suppl.101:217-236,2001**

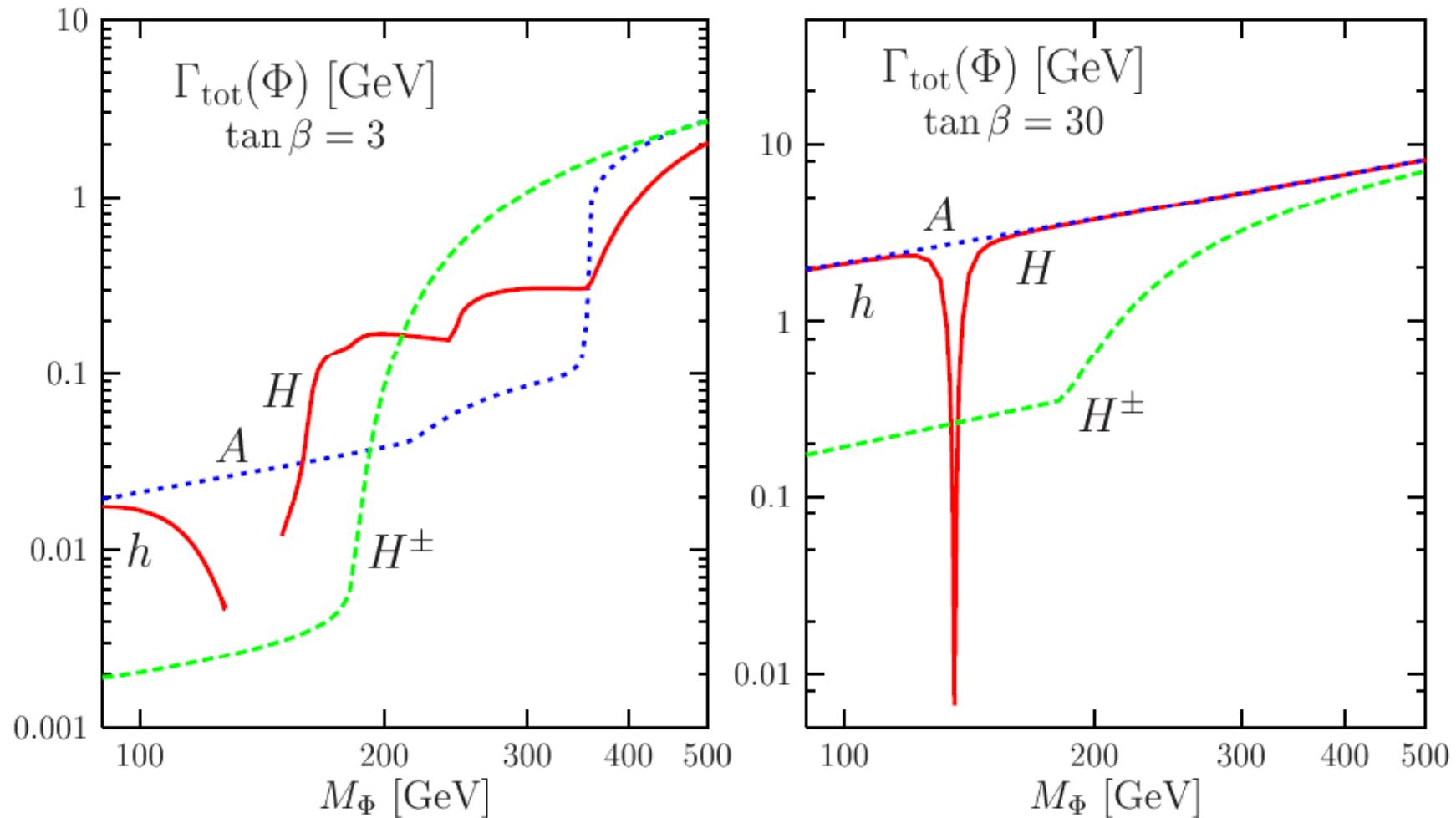


Figure 2.21: The total decay widths in GeV of the four MSSM Higgs particles  $h$ ,  $H$ ,  $A$  and  $H^\pm$  as a function of their masses for the two values  $\tan \beta = 3$  (left) and  $\tan \beta = 30$  (right).

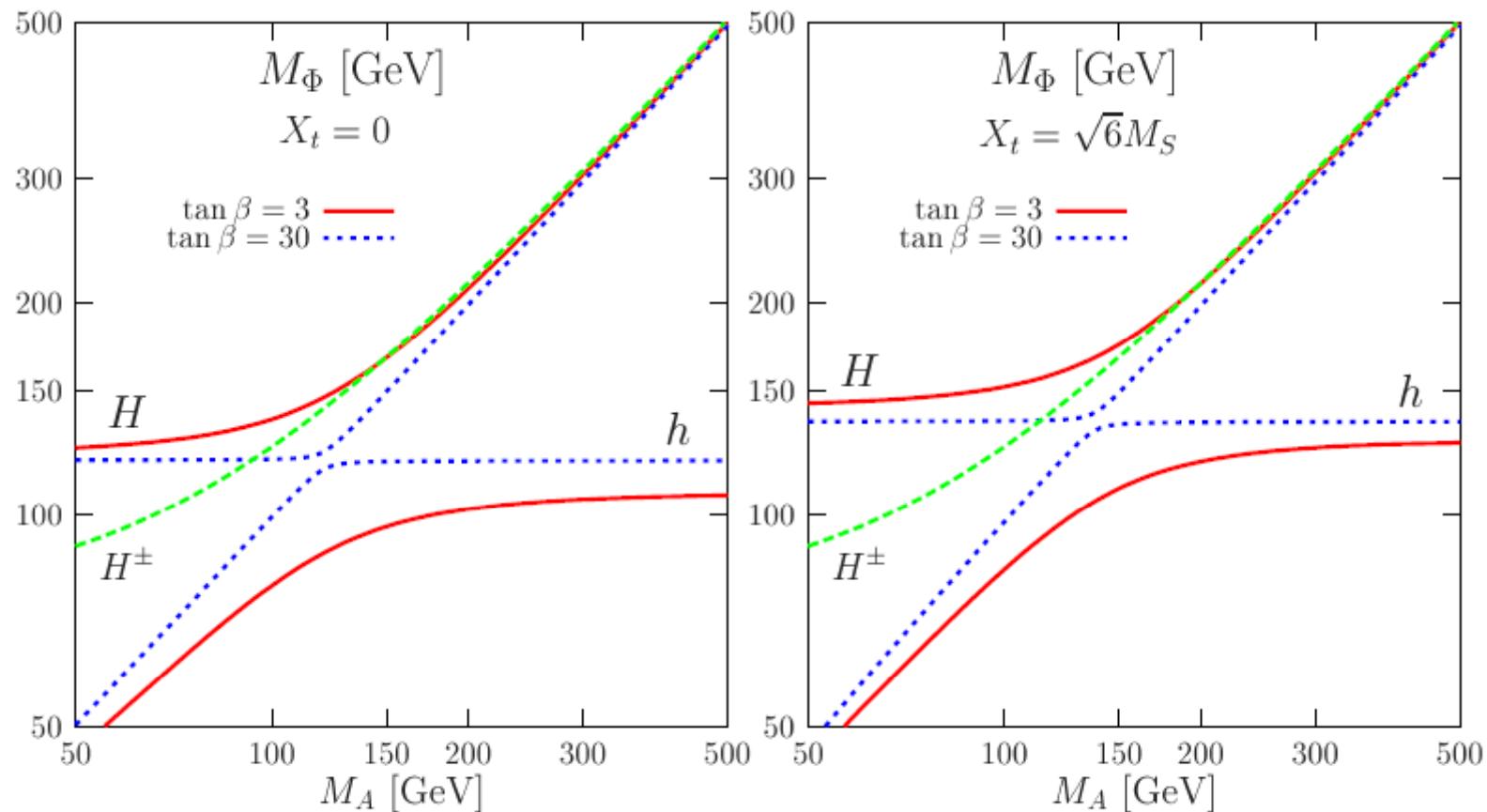
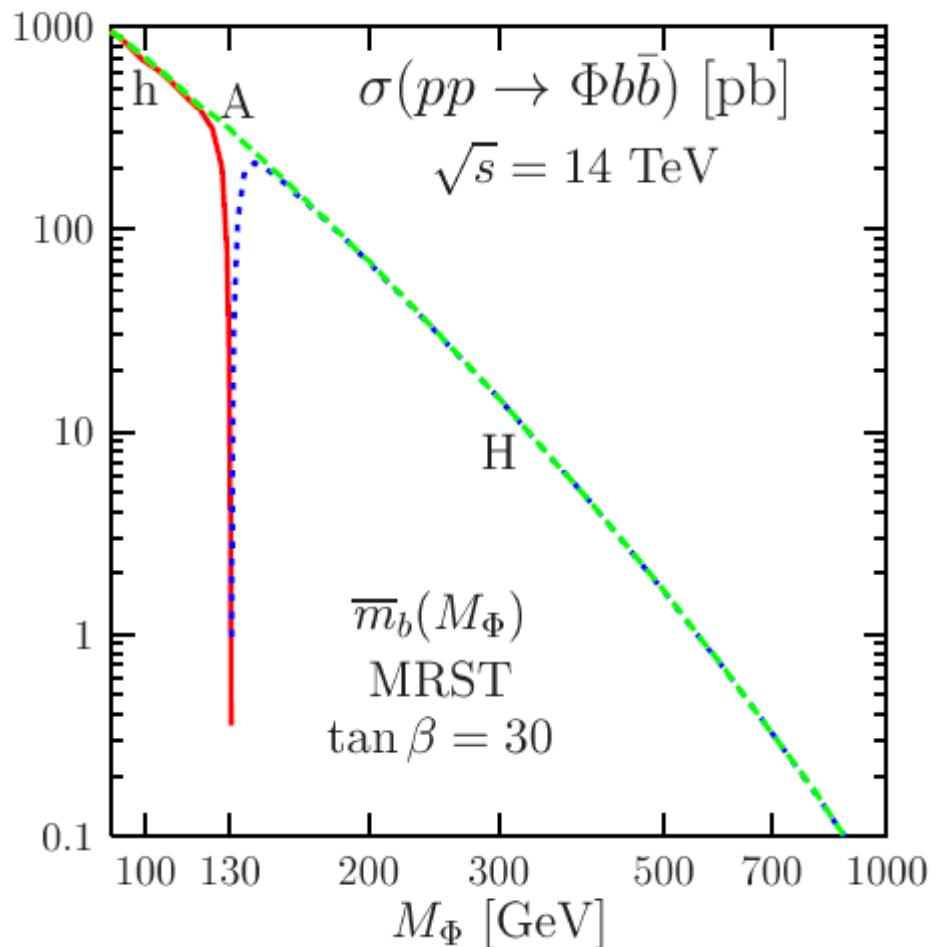
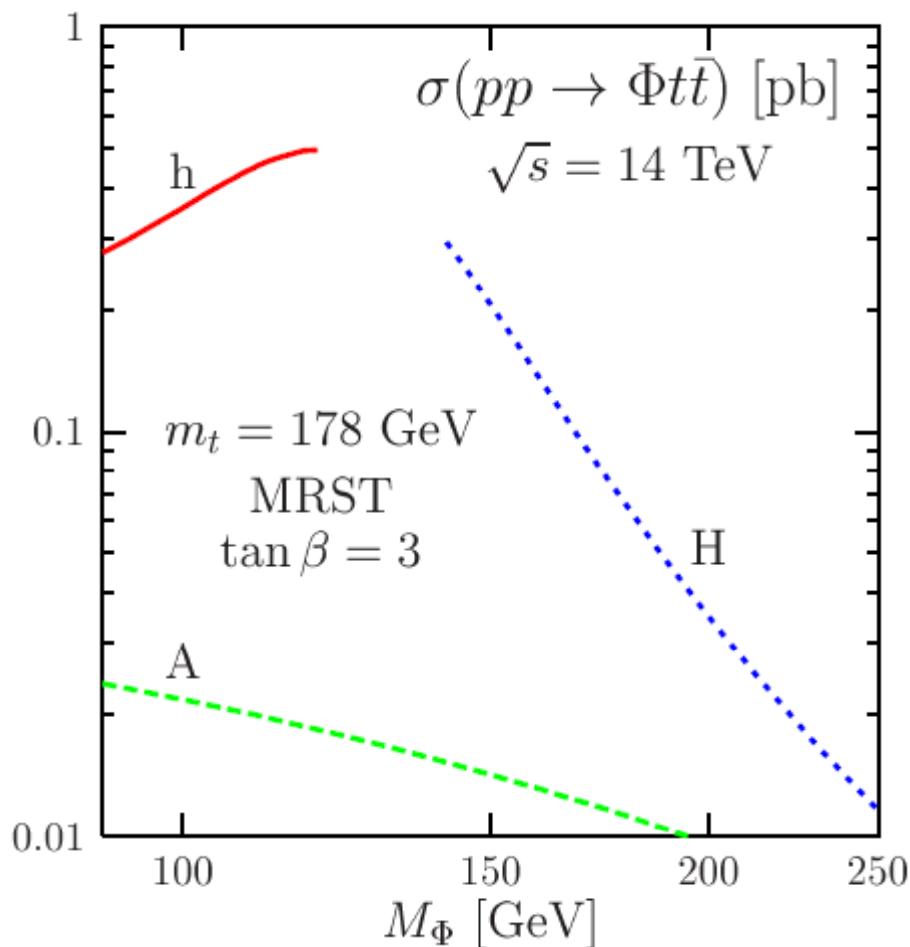
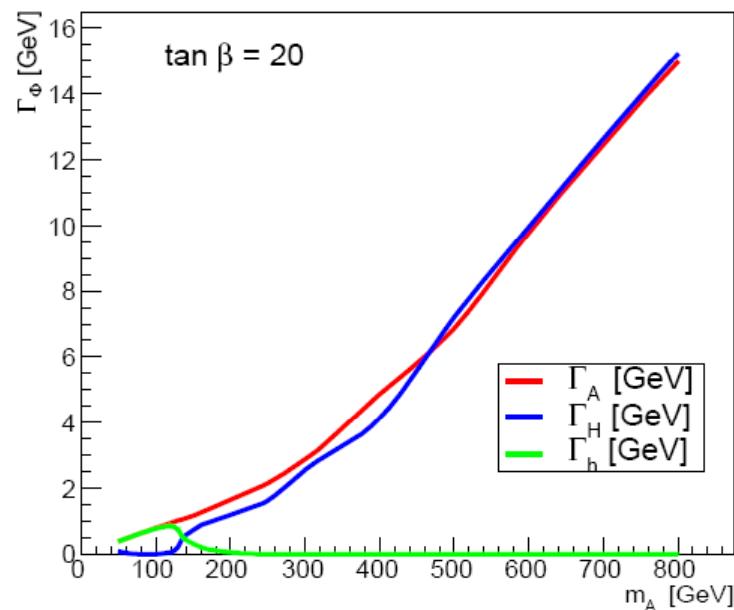
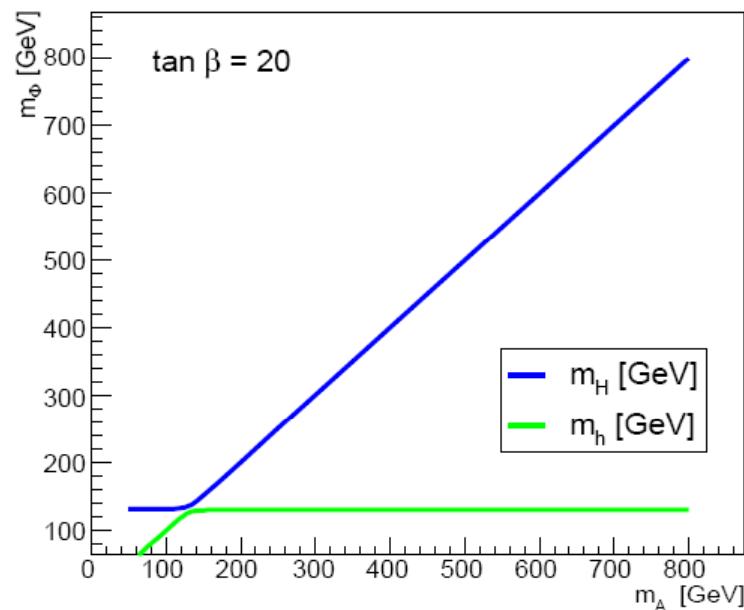


Figure 1.7: The masses of the MSSM Higgs bosons as a function of  $M_A$  for two values  $\tan \beta = 3$  and 30, in the no mixing (left) and maximal mixing (right) scenarios with  $M_S = 2$  TeV and all the other SUSY parameters set to 1 TeV. The full set of radiative corrections is included with  $m_t = 178$  GeV,  $m_b = 4.88$  GeV and  $\alpha_s(M_Z) = 0.1172$ .

A.Djouadi Phys.Rept.459:1-241,2008





**Figure 4.1:** Feynhiggs predictions for Higgs masses (left) and total decay widths (right) as function of  $m_A$ .

In NLO the following five parameters (in addition to  $m_A$  and  $\tan\beta$ ) describe the Higgs sector of the MSSM:

$M_{SUSY}$  Energy scale of SUSY breaking (mass scale of sfermions at EW scale)

$M_2$  Gaugino mass at EW scale

$\mu$  Strength of the supersymmetric Higgs mixing

$m_{\tilde{g}}$  Gluino mass

$X_t$  Stop mixing parameter

Parameters [GeV]	$m_h^{\max}$	nomixing	gluophobic	small $\alpha_{eff}$
$M_{SUSY}$	1000	2000	350	800
$M_2$	200	200	300	500
$\mu$	200	200	300	2000
$M_{\tilde{g}}$	800	8000	500	500
$X_t$	2000	0	-750	-1100
<i>max. <math>m_h</math></i>	133	116	119	123

**Table 2.5:** Parameters of the benchmark scenarios.

**M.Carena,S.Heinemeyer,C.Wagner and G.Weiglein Eur.Phys.J.C26:601-607,2003  
J.Schaarschmidt , thesis , Dresden 2007**

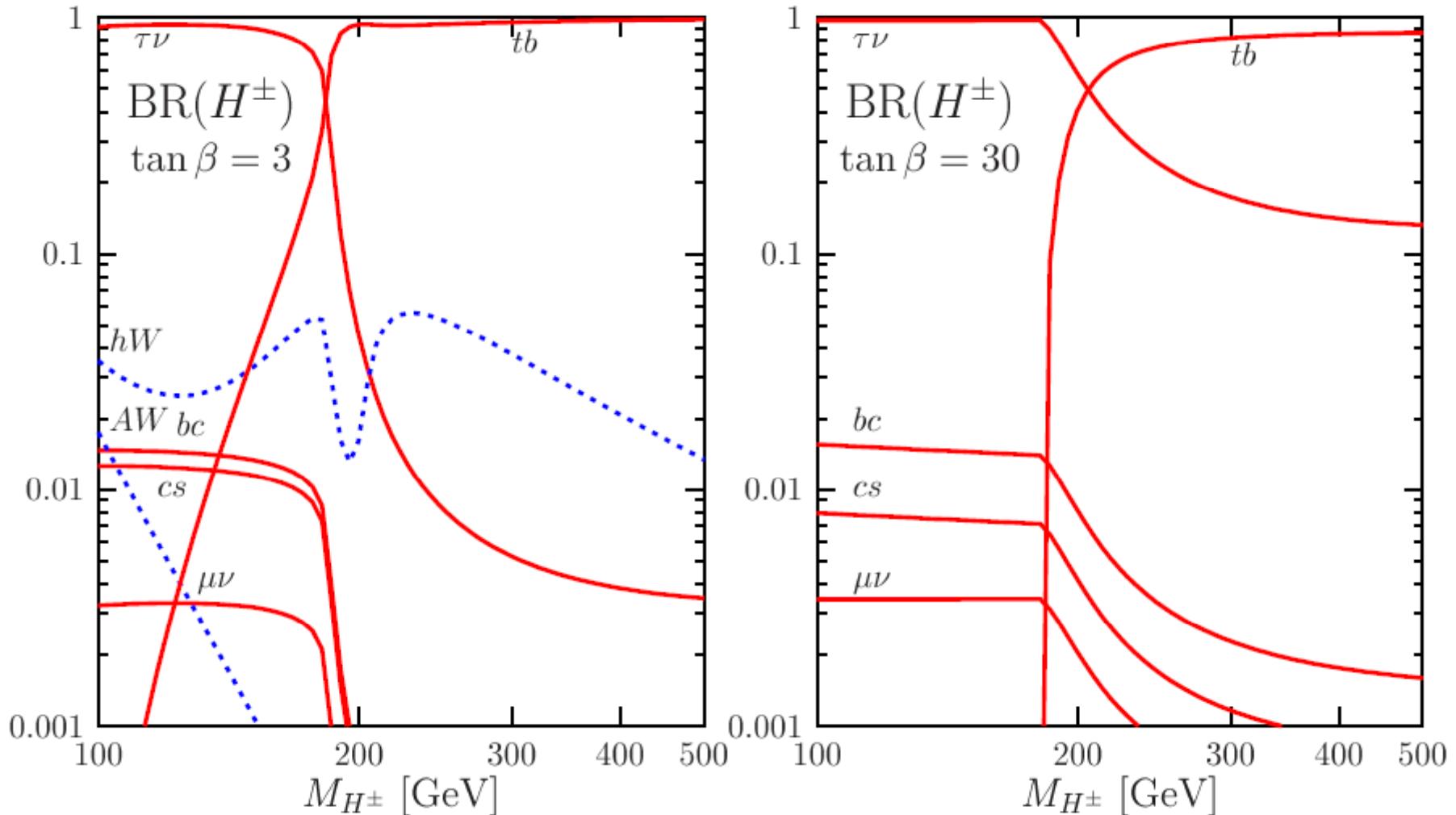


Figure 2.20: The decay branching ratios of the charged MSSM Higgs particles as a function of their mass for the two values  $\tan\beta = 3$  (left) and  $\tan\beta = 30$  (right).

**MSSM Higgs  $\rightarrow \mu\mu$**

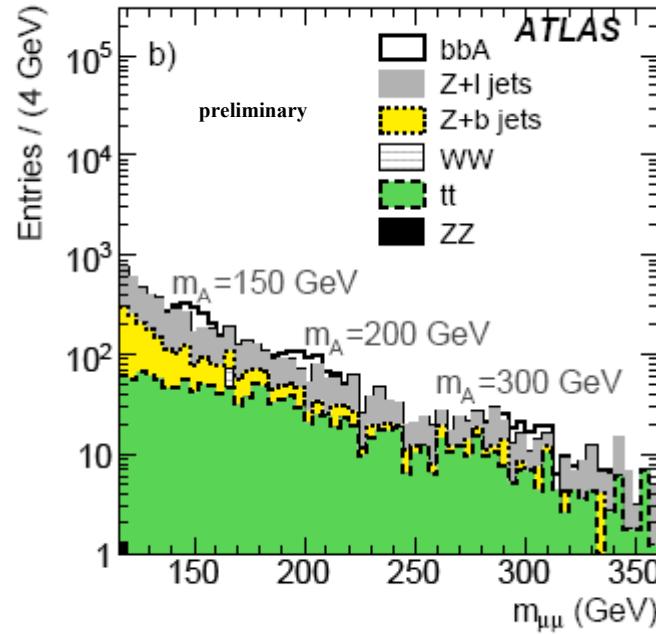
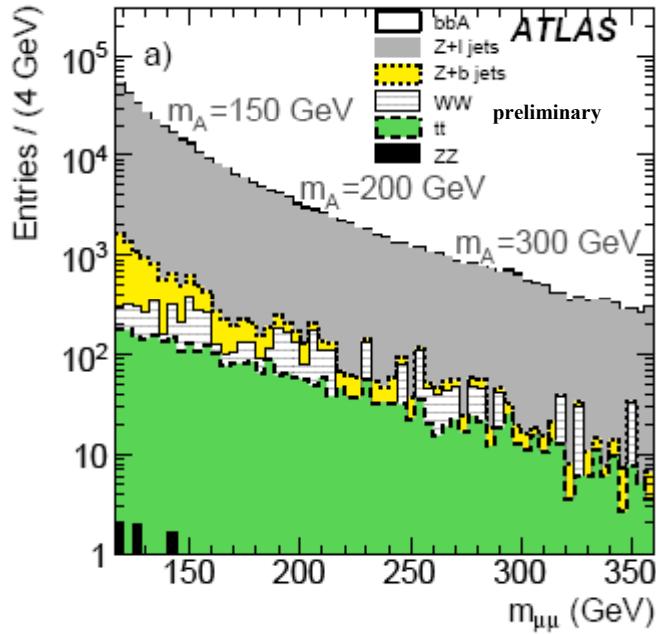
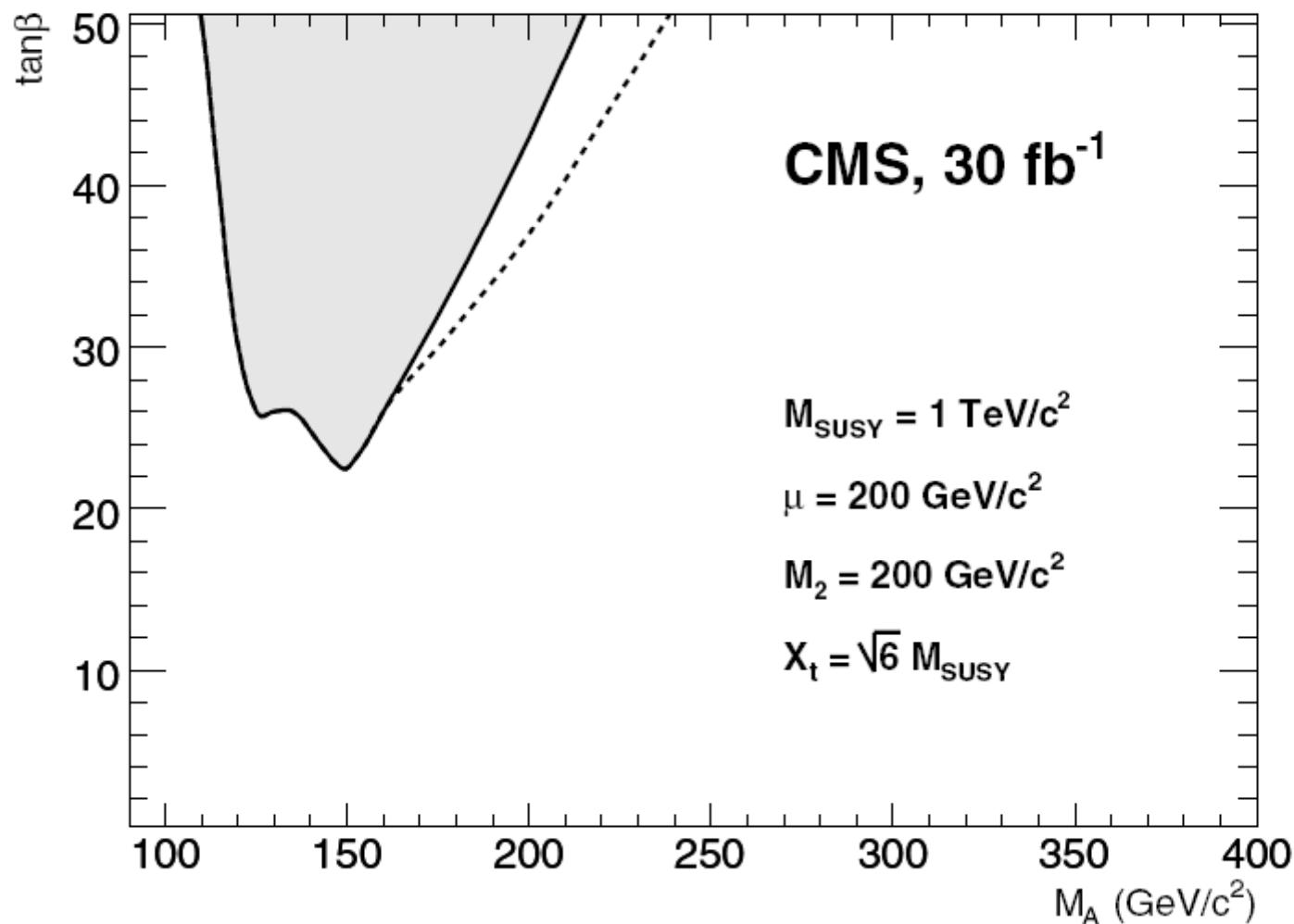


Figure 13: Invariant dimuon mass distributions of the main backgrounds and the  $A$  boson signal at masses  $m_A=150, 200$  and  $300$  GeV and  $\tan\beta = 30$ , obtained for the integrated luminosity of  $30 \text{ fb}^{-1}$ . B-tagging has been applied for the event selection. The production rates of  $H$  and  $A$  bosons have been added together. a) for the 0 b-jet final state and b) for the final state with at least 1 b-jet.

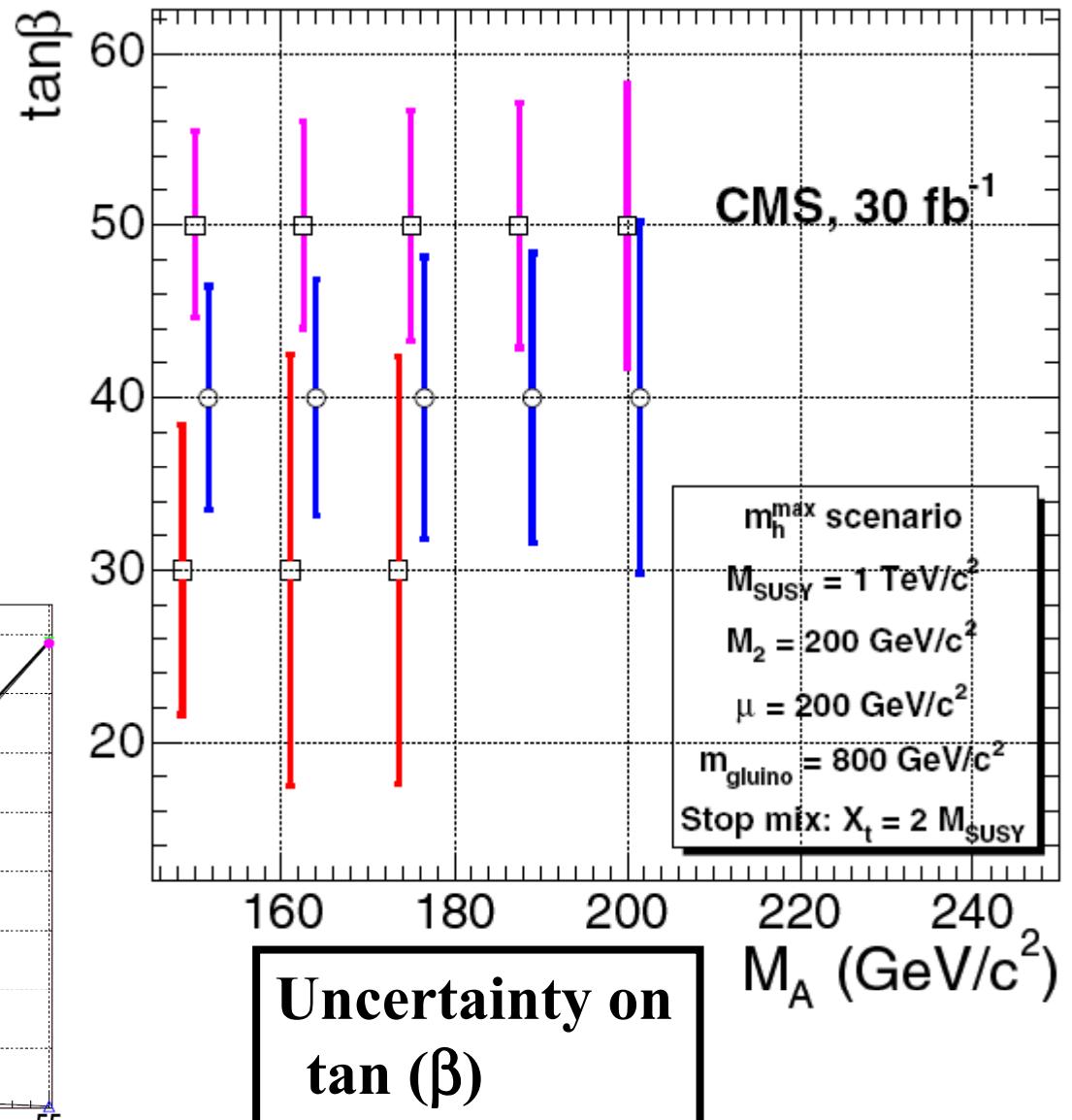
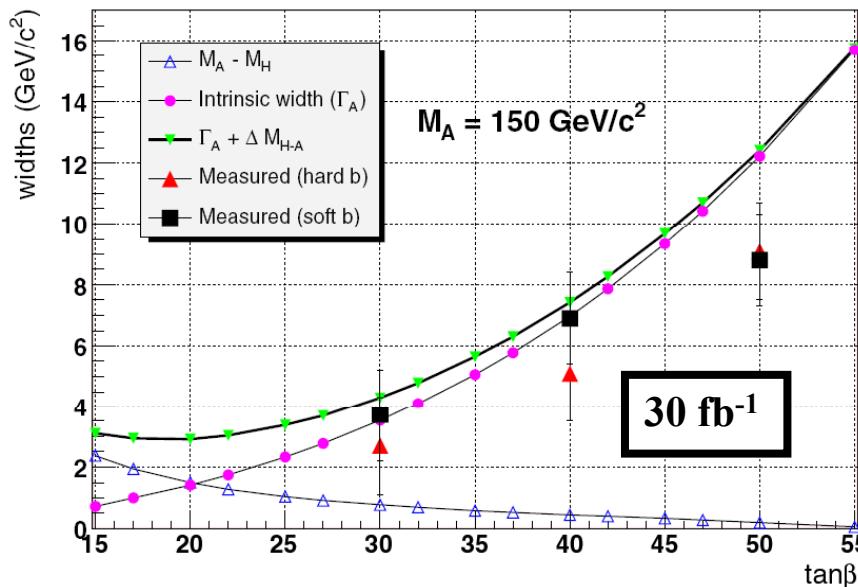


**Figure 11.9.** Discovery contour plot for the MSSM neutral Higgs in dimuon analysis. The signal significance inside the grey area is  $> 5$  with an integrated luminosity of  $30 \text{ fb}^{-1}$ .

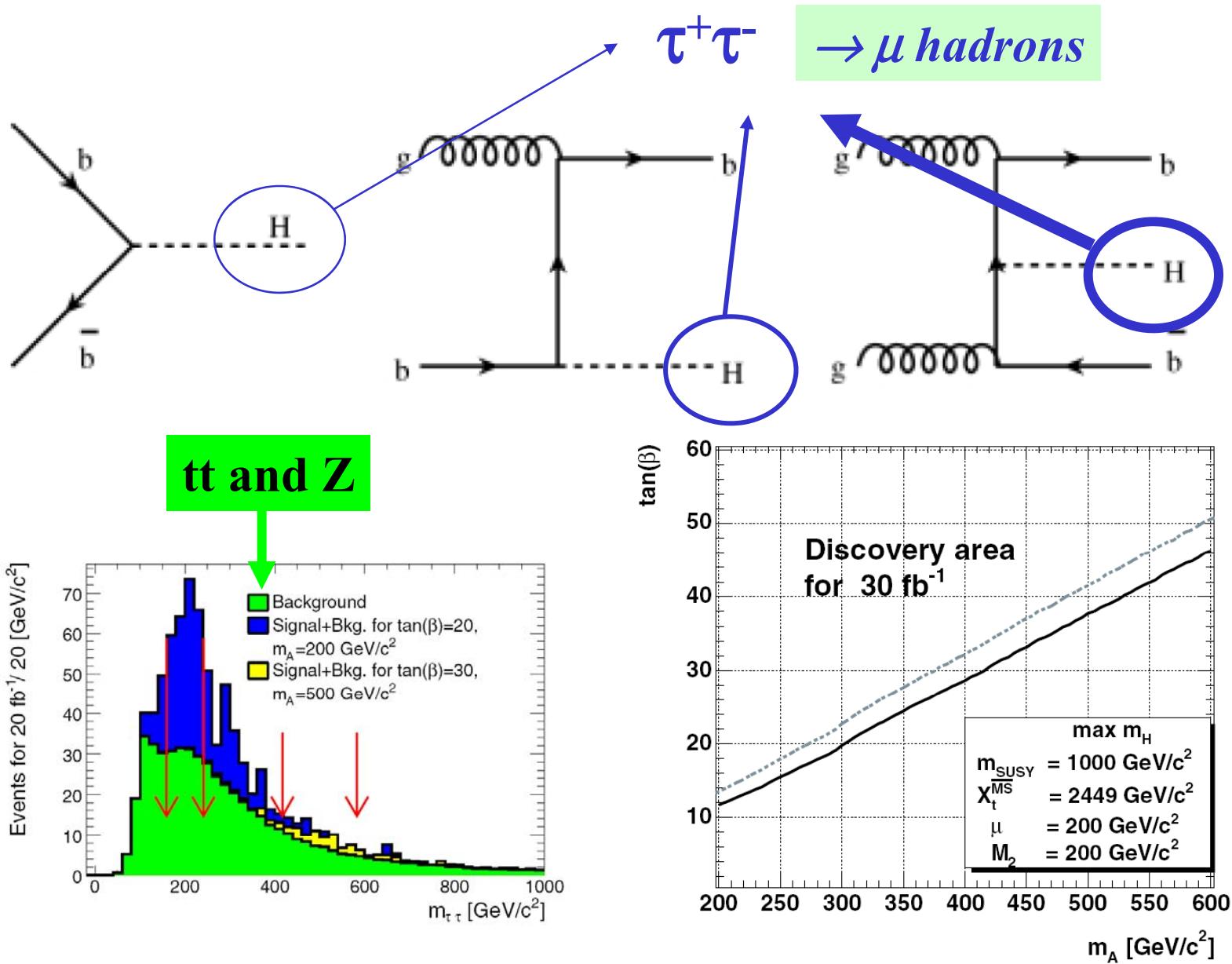
# MSSM Higgs $\rightarrow \mu\mu$

CMS TDR

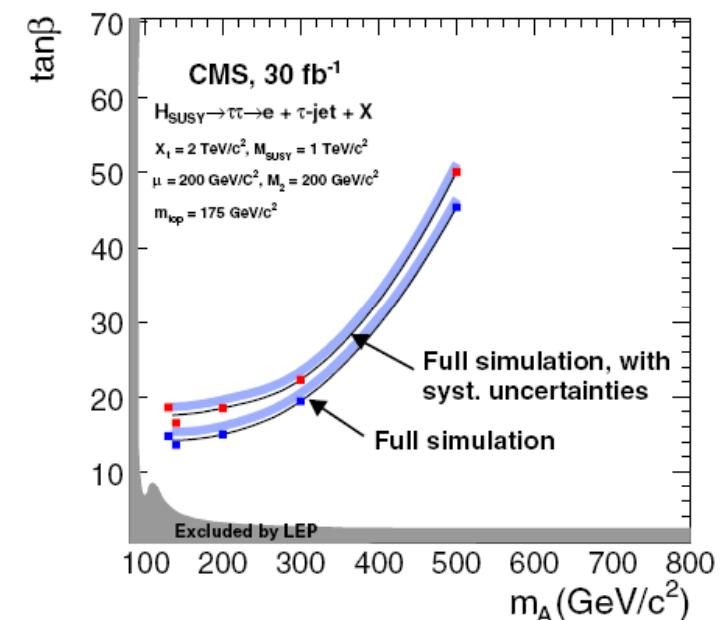
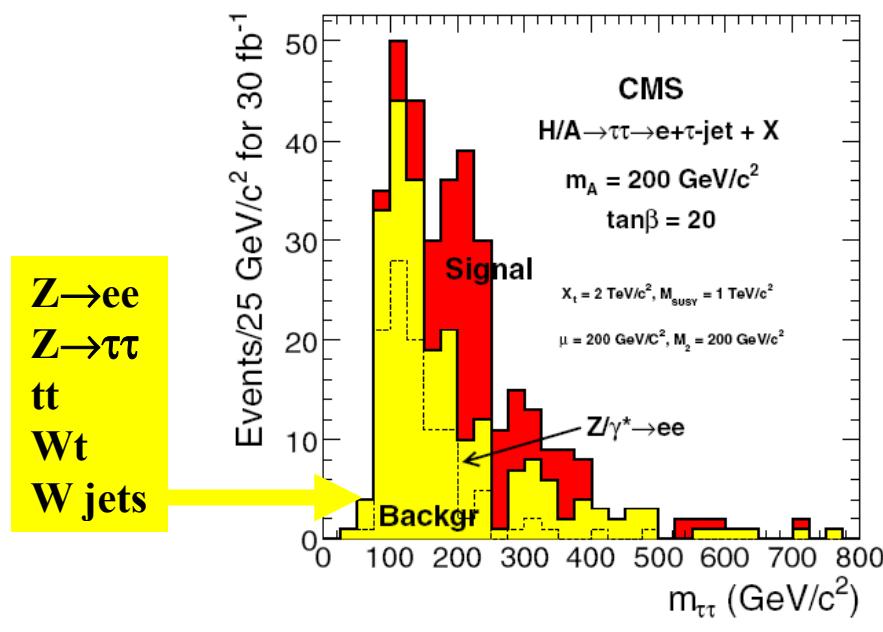
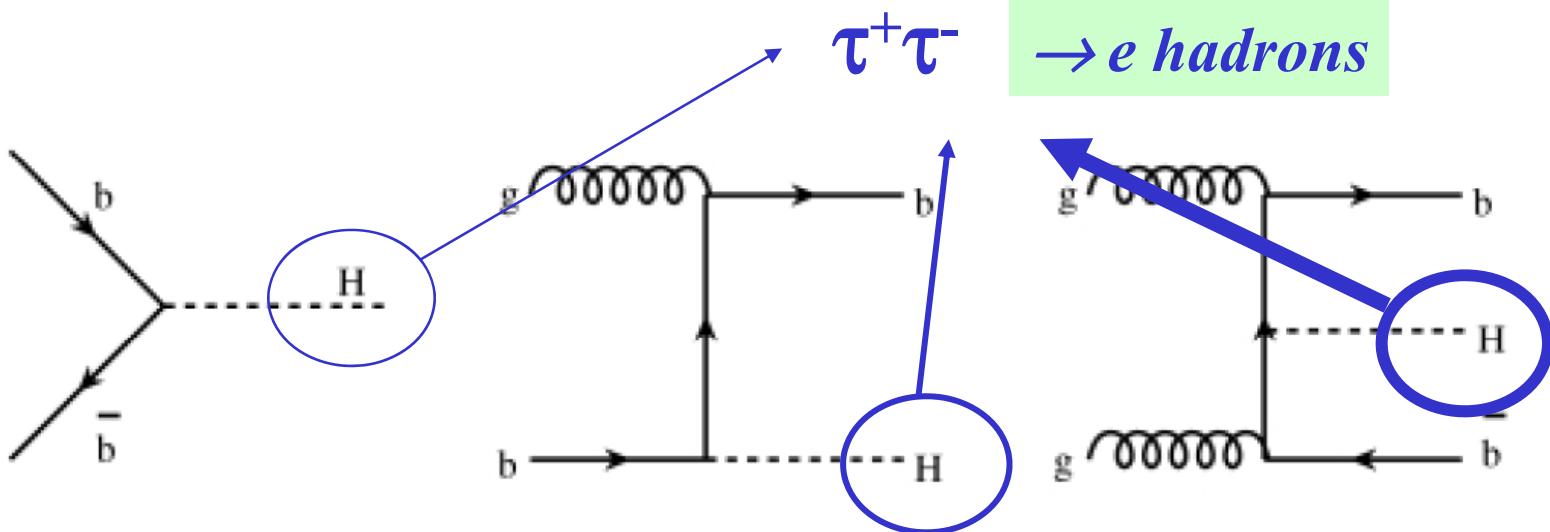
Comparing expected  
and measured width



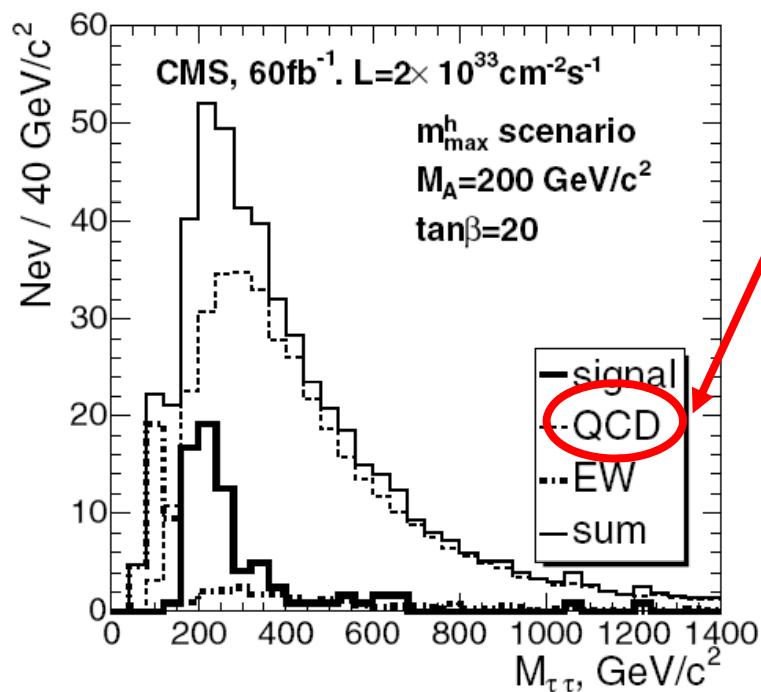
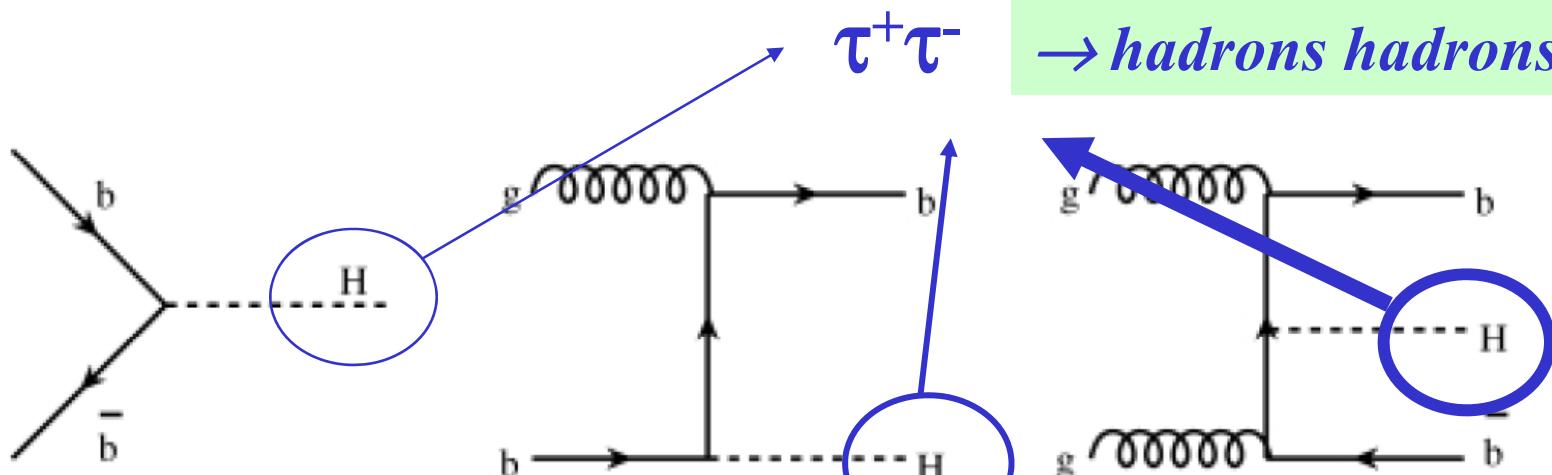
**MSSM Higgs  $\rightarrow \tau\tau$**



CMS TDR A.Kalinowski,M.Konecki and D.Kotlinski CMS NOTE 2006/105



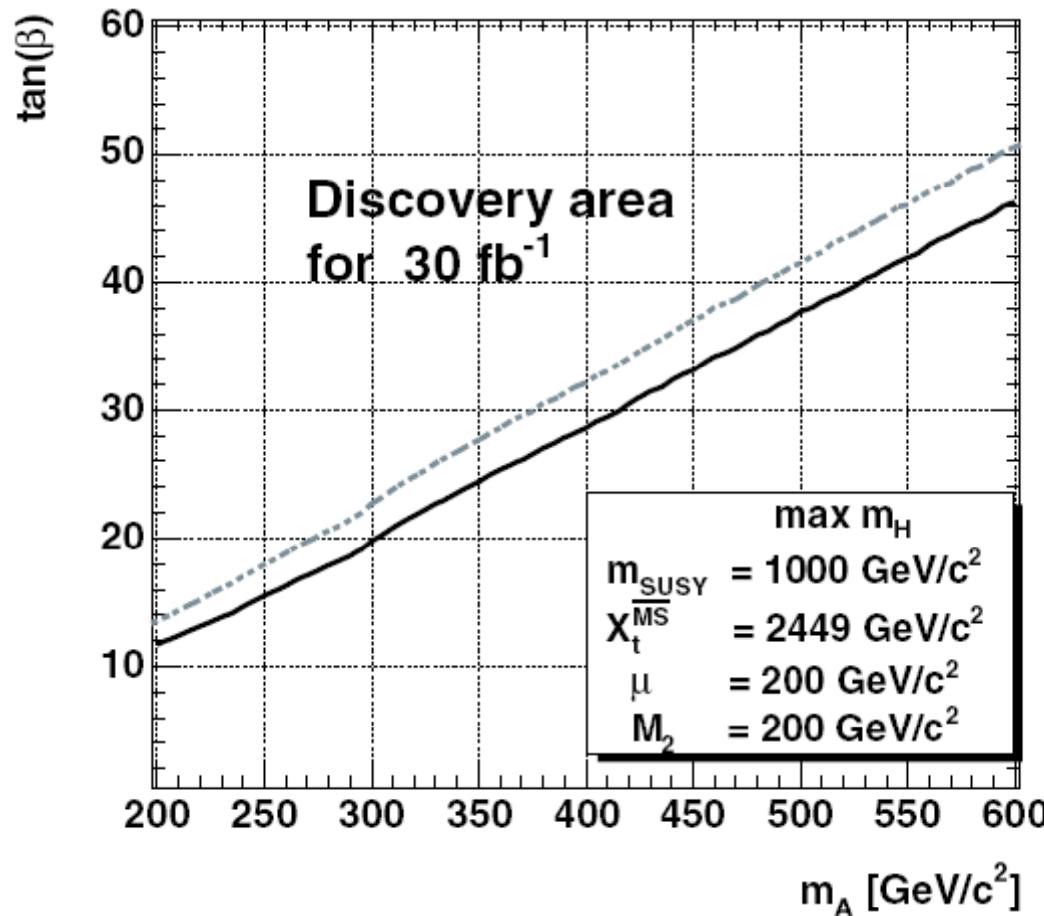
**CMS TDR R.Kinnunen and S.Lehti CMS note 2006/075**



*dominant background  
→ data driven estimation*

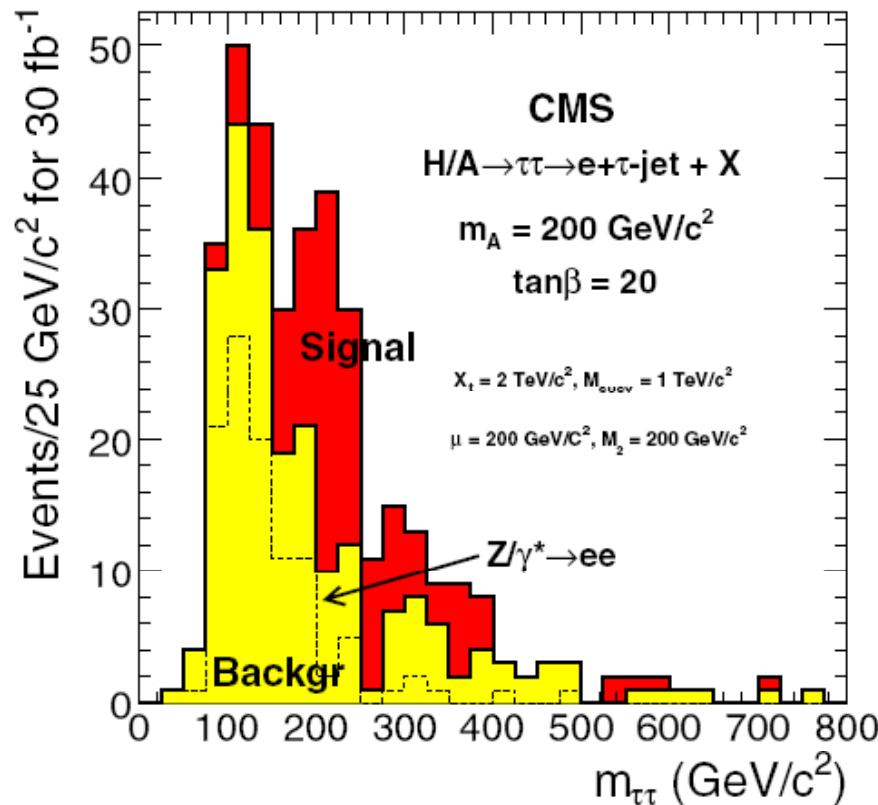
Table 5.14. The lower limit of  $\tan\beta$  where a  $5\sigma$  discovery is possible with  $60\text{fb}^{-1}$

Low $\tan\beta$ limit for $5\sigma$ discovery	$m_A = 200 \text{ GeV}/c^2$	$m_A = 500 \text{ GeV}/c^2$	$m_A = 800 \text{ GeV}/c^2$
no systematics	20	32	46
with systematics	21	34	49

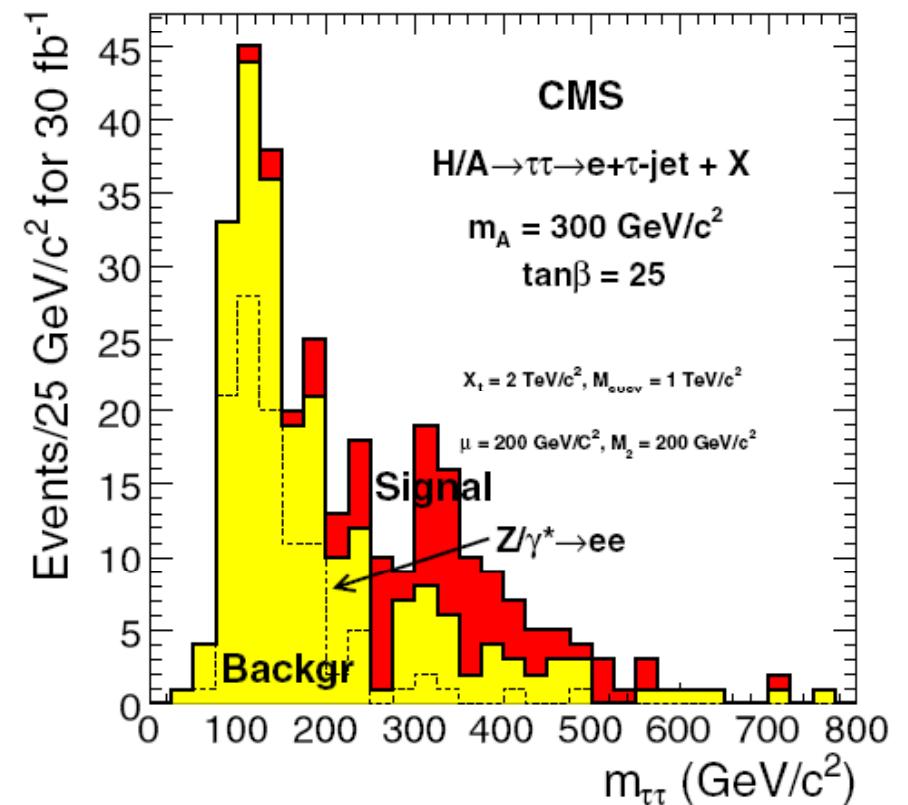


**MSSM**  
 $H \rightarrow \tau\tau \rightarrow \mu jet$

**Figure 5.6.** The  $5\sigma$  discovery region in the  $M_A - \tan \beta$  plane with  $30 \text{ fb}^{-1}$  of the integrated luminosity for the  $m_H^{\max}$  MSSM scenario. The regions are shown without (lower curve) and with (upper curve) the uncertainty on the background taken into account.

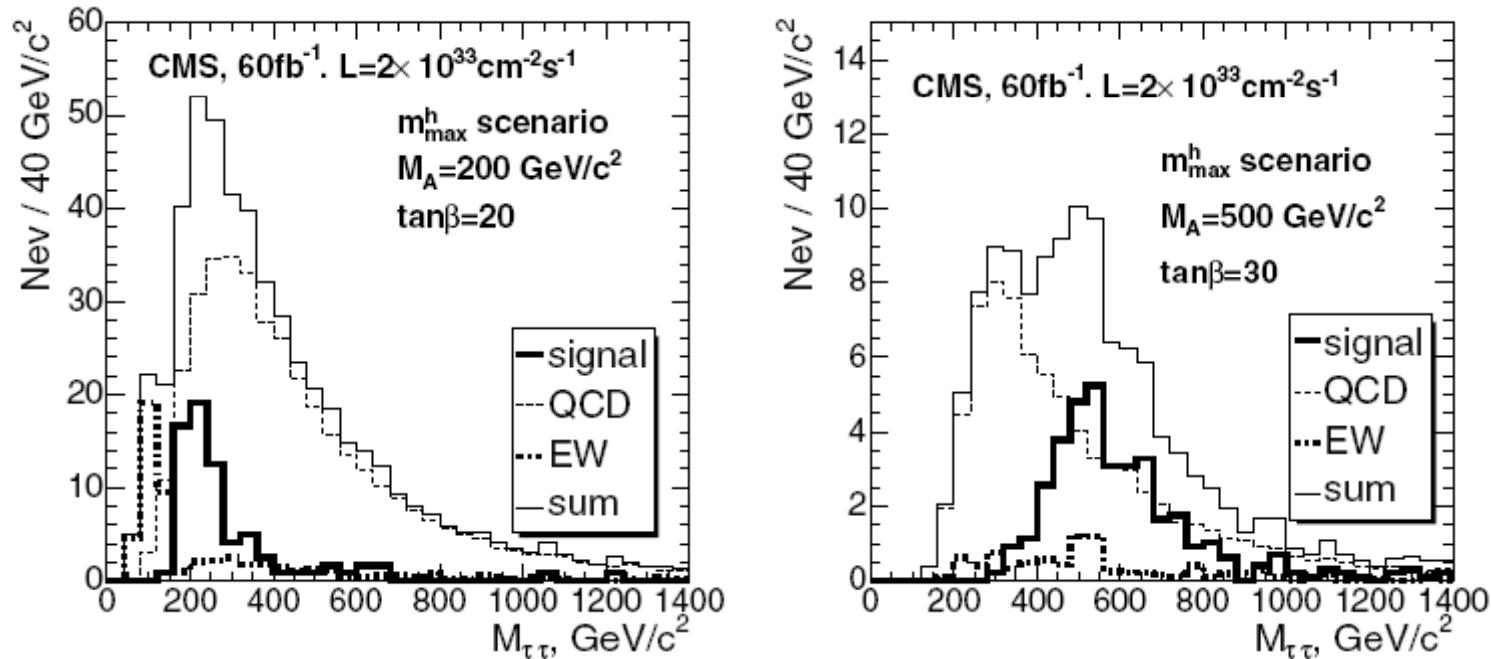


**Figure 5.9.** Reconstructed Higgs boson mass for the signal of  $M_A = 200 \text{ GeV}/c^2$ ,  $\tan\beta = 20$  and for the total background for an integrated luminosity of  $30 \text{ fb}^{-1}$ . The dashed line shows the sum of the  $Z/\gamma^* \rightarrow e^+e^-$  and  $b\bar{b}Z/\gamma^* e^+e^-$  backgrounds.



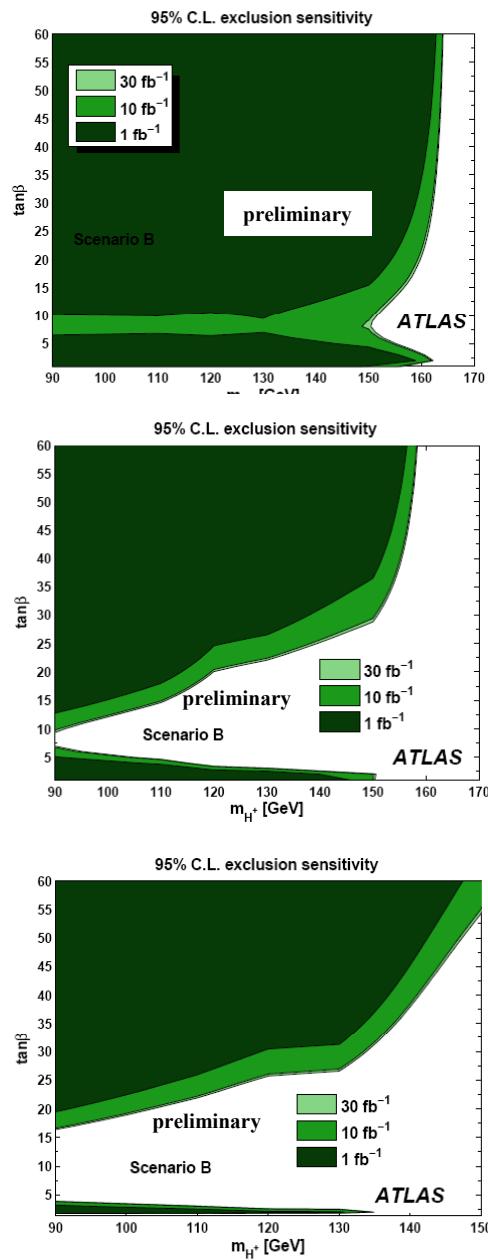
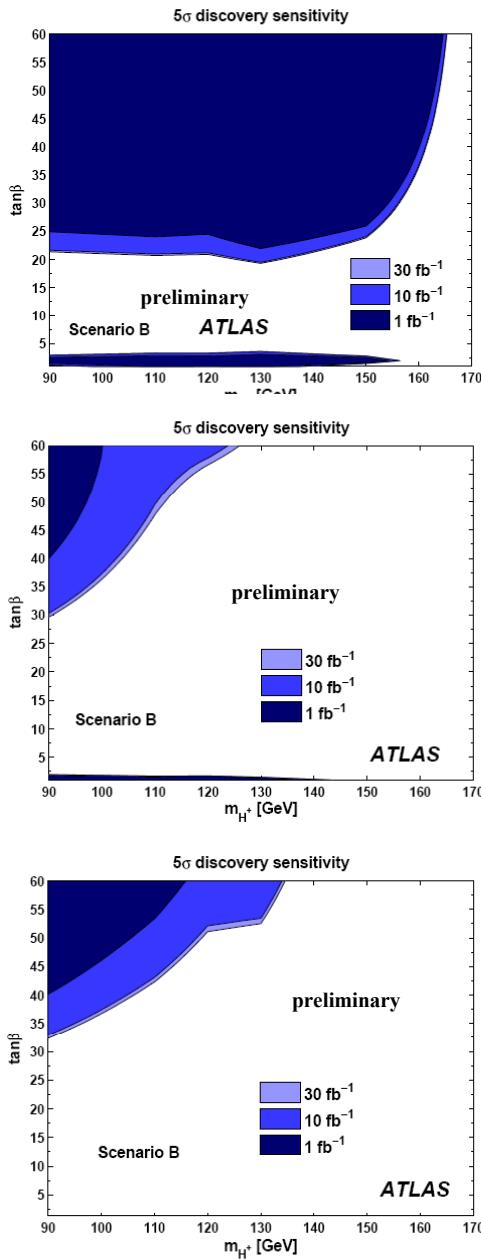
**Figure 5.10.** Reconstructed Higgs boson mass for the signal with  $M_A = 300 \text{ GeV}/c^2$ ,  $\tan\beta = 25$  and for the total background for an integrated luminosity of  $30 \text{ fb}^{-1}$ . The dashed line shows the sum of the  $Z/\gamma^* \rightarrow e^+e^-$  and  $b\bar{b}Z/\gamma^* e^+e^-$  backgrounds.

**MSSM**  
 $H \rightarrow \tau\tau \rightarrow jet jet$



**Figure 5.3.** The expected  $M_{\tau\tau}$  distributions for the signal of  $M_A = 200 \text{ GeV}/c^2$ ,  $\tan\beta = 20$  (left plot) and  $M_A = 500 \text{ GeV}/c^2$ ,  $\tan\beta = 30$  (right plot) and the background with  $60 \text{ fb}^{-1}$ . Thick solid histogram – signal in the  $m_h^{\max}$  scenario; dashed histogram – the QCD multi-jet background; thick dashed-dotted histogram – the irreducible background; normal solid histogram – signal plus background.

CMS TDR S.Gennai,A.Nikitenko and L.Wendland CMS NOTE 2006/126



**new ATLAS**

$$t\bar{t} \rightarrow bH^+ bW \rightarrow b\tau(had)v bqq$$

$$t\bar{t} \rightarrow bH^+ bW \rightarrow b\tau(lep)v bqq$$

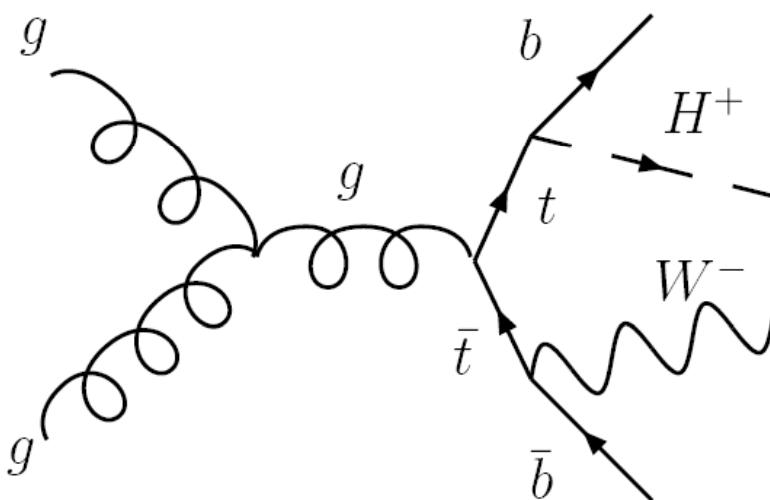
$$t\bar{t} \rightarrow bH^+ bW \rightarrow b\tau(had)v blv$$

**Light H+**

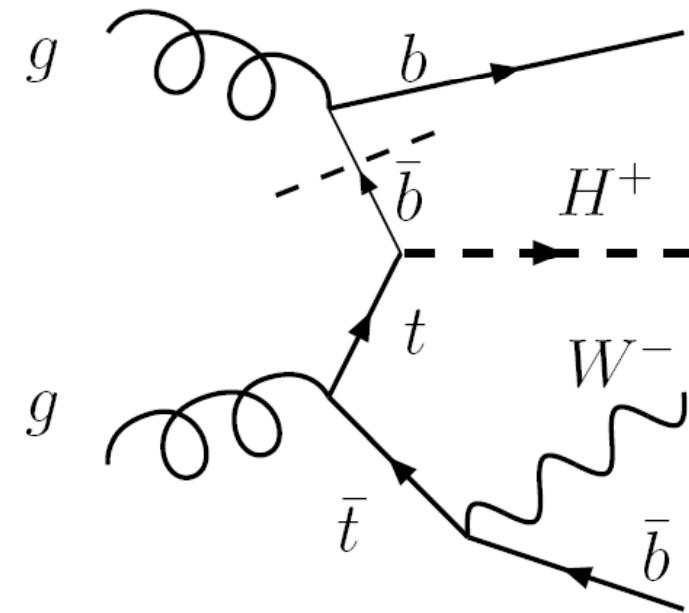
# **MSSM Charged Higgs**

## Search for charged MSSM Higgs

**Low mass charged Higgs**  
 $m(H^+) < m(\text{top})$

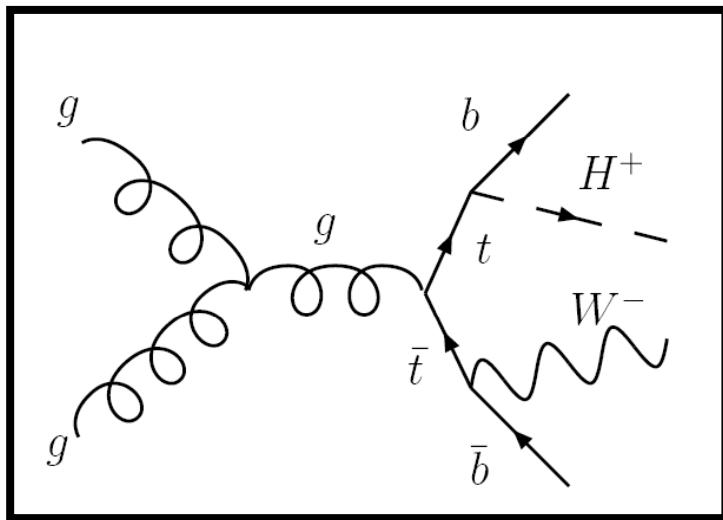


**High mass charged Higgs**  
 $m(H^+) > m(\text{top})$



## Low mass charged Higgs

$m(H^+) < m(\text{top})$



$$t\bar{t} \rightarrow bH^+bW \rightarrow b\tau(\text{had})\nu b\ell\nu$$

$$t\bar{t} \rightarrow bH^+bW \rightarrow b\tau(\text{lep})\nu bqq$$

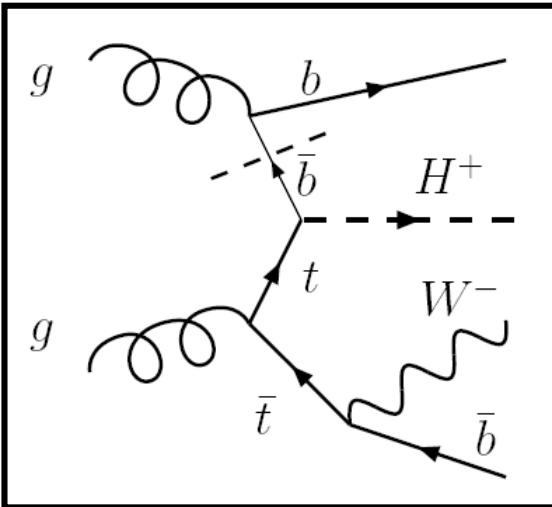
$$t\bar{t} \rightarrow bH^+bW \rightarrow b\tau(\text{had})\nu bqq$$

main background :  $t\bar{t}$

This assumes  $H^+ \rightarrow \tau\nu$  but there can be some studies of  $H^+ \rightarrow cs$   
at low  $\tan(\beta)$  K.Assamagan Acta Phys Pol B31,863,2000

new ATLAS CMS TDR

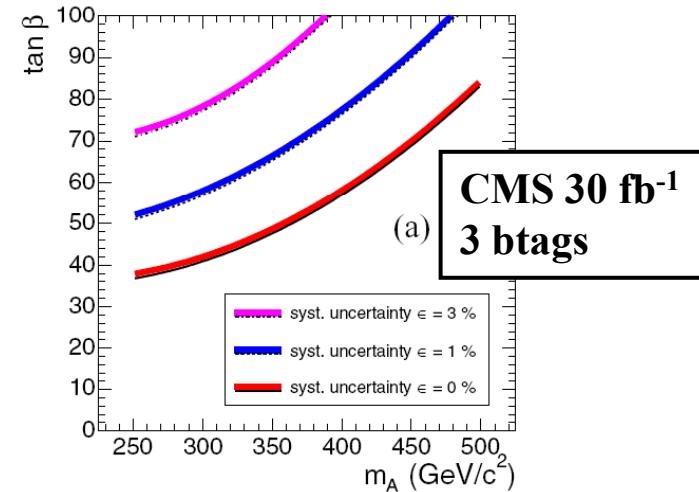
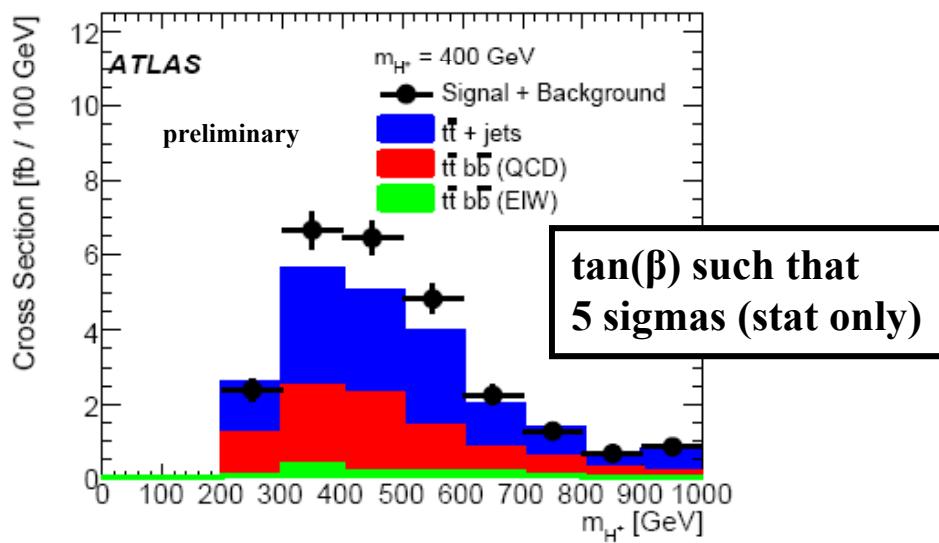
M.Baarmand,M.Hashemi and A.Nikitenko J. Phys. G32 (2006) N21-N40



## High mass charged Higgs $m(H^+) > m(\text{top})$

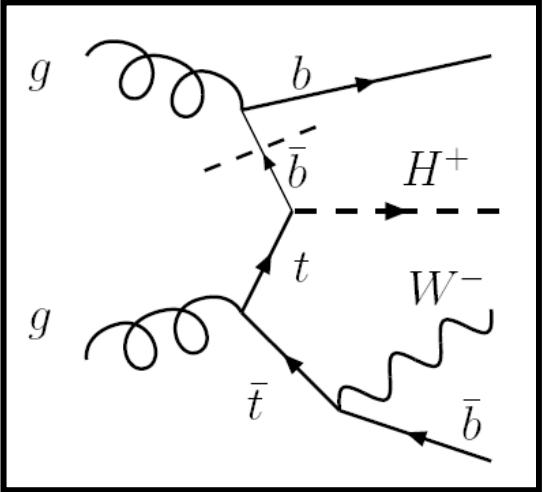
$$gg/gb \rightarrow t[b]H^+ \rightarrow t[b]tb \rightarrow bW[b]bWb \rightarrow b\ell\nu[b]bqqb$$

**complicated final state, analysis similar to  
SM  $t\bar{t} H(\rightarrow bb)$  can try to reconstruct  
 $H^+$  mass but large systematic uncertainties**



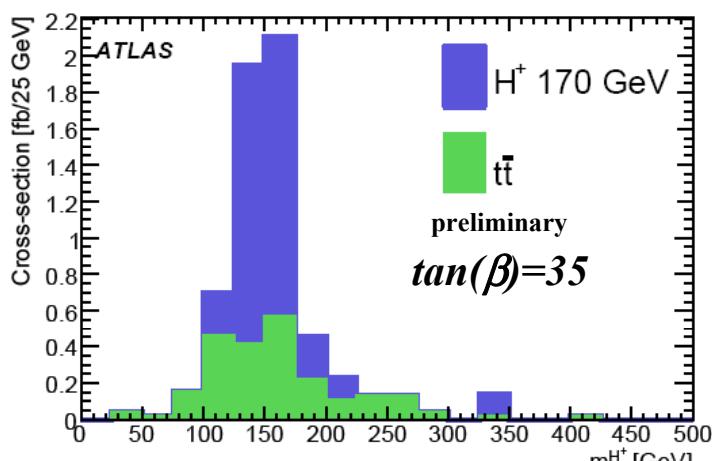
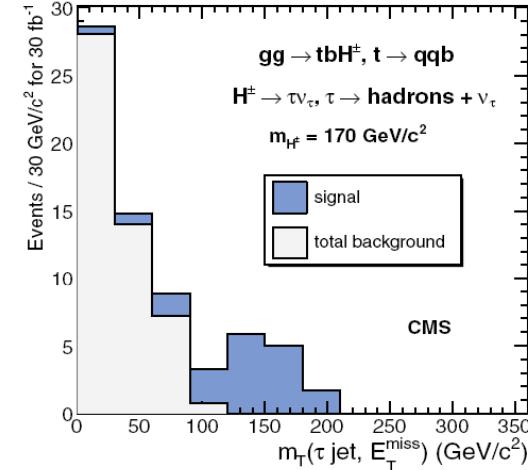
**new ATLAS**

**CMS TDR S.Lowette,J.D'Hondt,P.Vanlaer CMS-NOTE-2006-109**

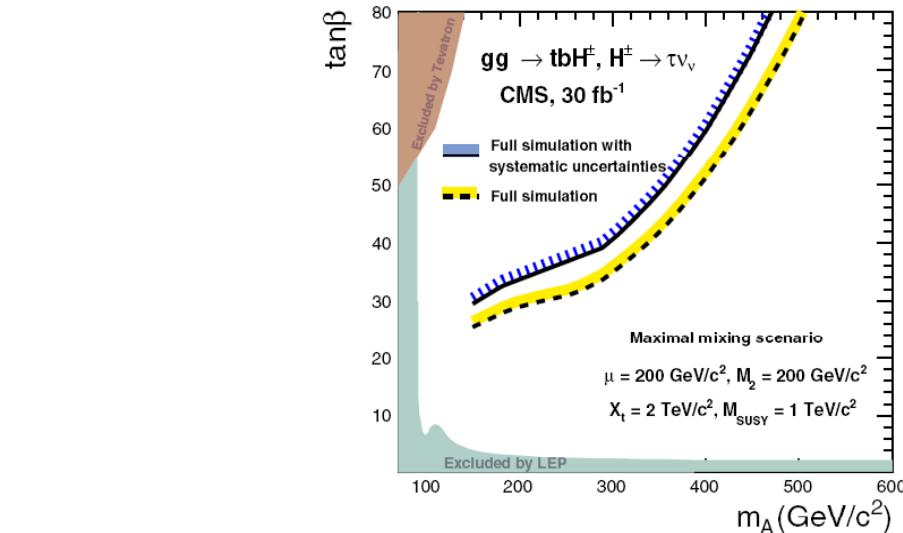


## High mass charged Higgs $m(H^+) > m(\text{top})$

$$gg/gb \rightarrow t[b]H^+ \rightarrow bqq[b]\tau(had)\nu$$



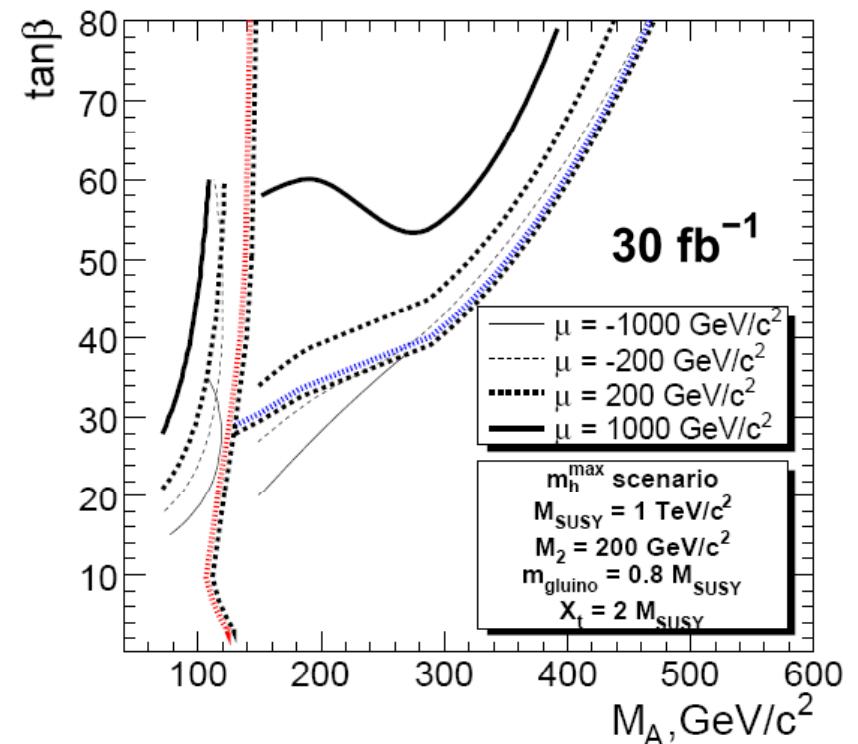
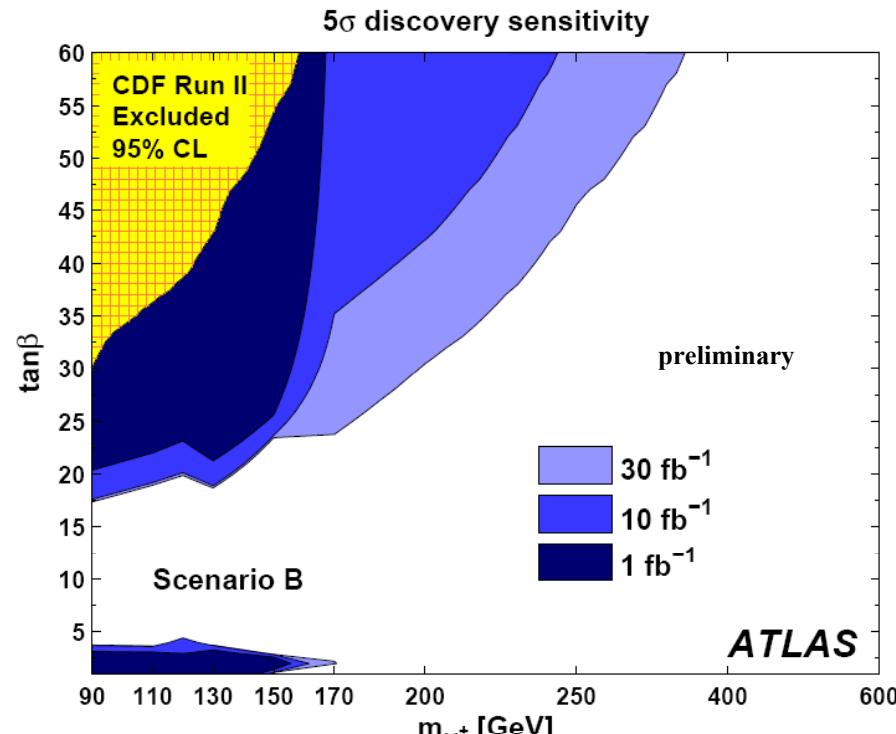
new ATLAS



CMS TDR R.Kinnunen CMS-NOTE-2006-100

## General discovery sensitivity on H+

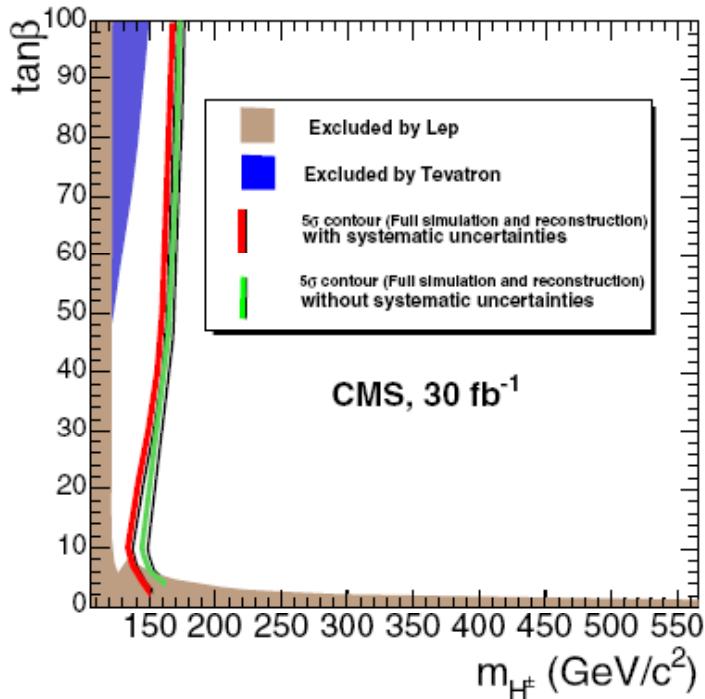
ATLAS CSC



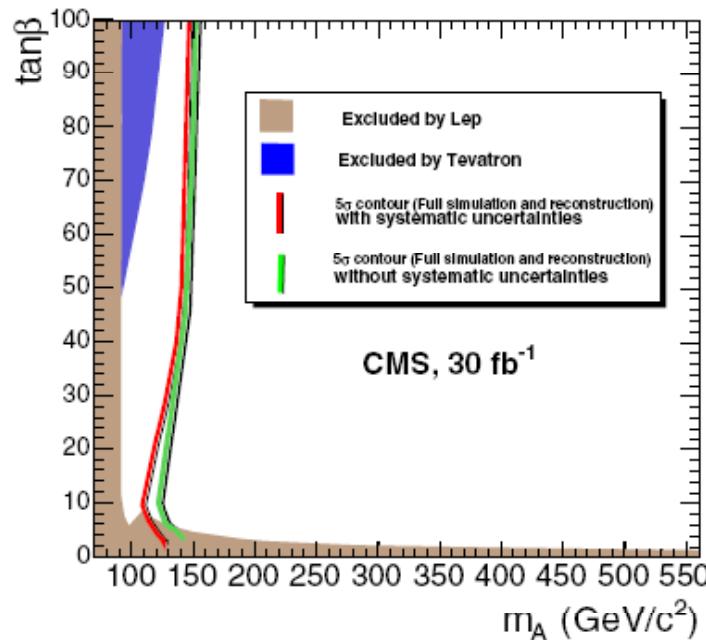
M.Hashemi,S.Heinemeyer,R.Kinnunen,A.Nikitenko and G.Weiglein arXiv:0804.1228 [hep-ph]

## CMS TDR

M.Baarmand,M.Hashemi and A.Nikitenko J. Phys. G32 (2006) N21-N40



**Figure 11.15.** The  $5\sigma$  contour in the  $(M_{H^\pm}, \tan \beta)$  plane for light charged Higgs boson discovery at  $30 \text{ fb}^{-1}$  including the effect of systematic uncertainties.



**Figure 11.16.** The  $5\sigma$  contour in the  $(M_A, \tan \beta)$  plane for light charged Higgs boson discovery at  $30 \text{ fb}^{-1}$  including the effect of systematic uncertainties.

$$t\bar{t} \rightarrow bH^+bW \rightarrow b\tau(had)vblv$$

**Light H<sup>+</sup>**

**new ATLAS**

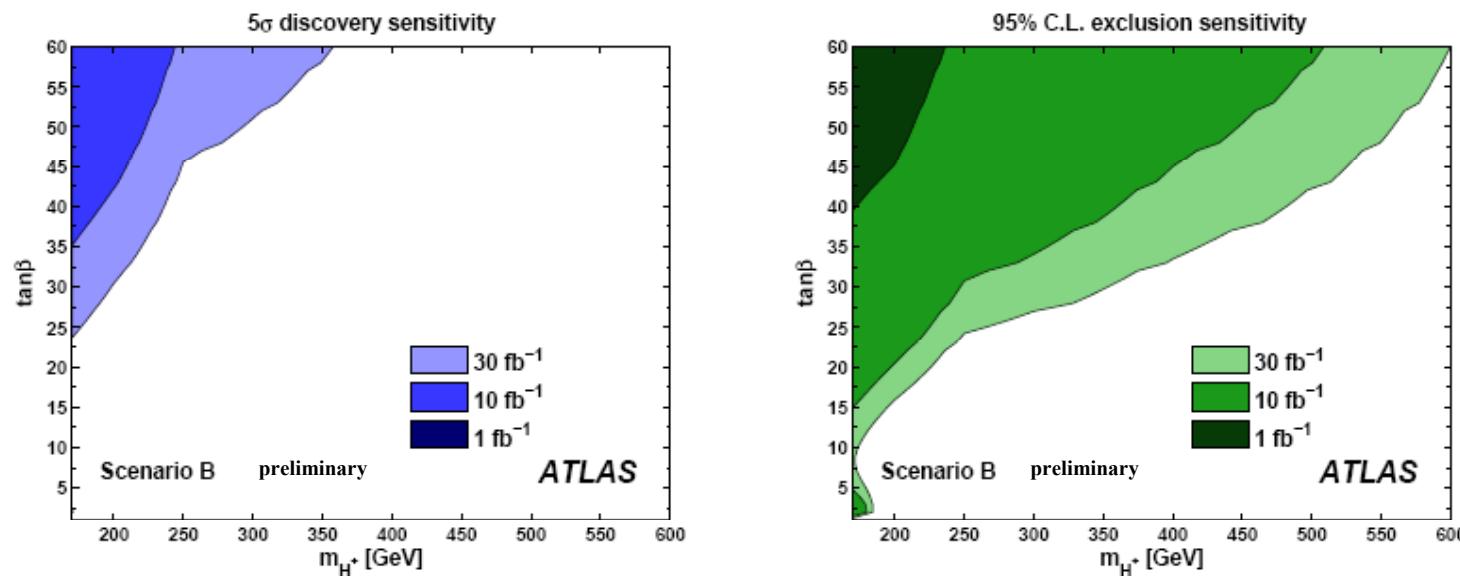


Figure 13:  $gg/gb \rightarrow t[b]H^+ \rightarrow bqq[b]\tau(had)v$ : Discovery (left) and exclusion contour (right) for Scenario B ( $m_h$ -max) [1]. Systematic and statistical uncertainties are included. The systematic uncertainty is assumed to be 10% for the background, and 44% for the signal (see Sections 5.2 and 5.1). The lines indicate a  $5\sigma$  significance for the discovery and a 95% CL for the exclusion contour.

$$gg/gb \rightarrow t[b]H^+ \rightarrow bqq[b]\tau(had)v$$

**Heavy H<sup>+</sup>**

**new ATLAS**

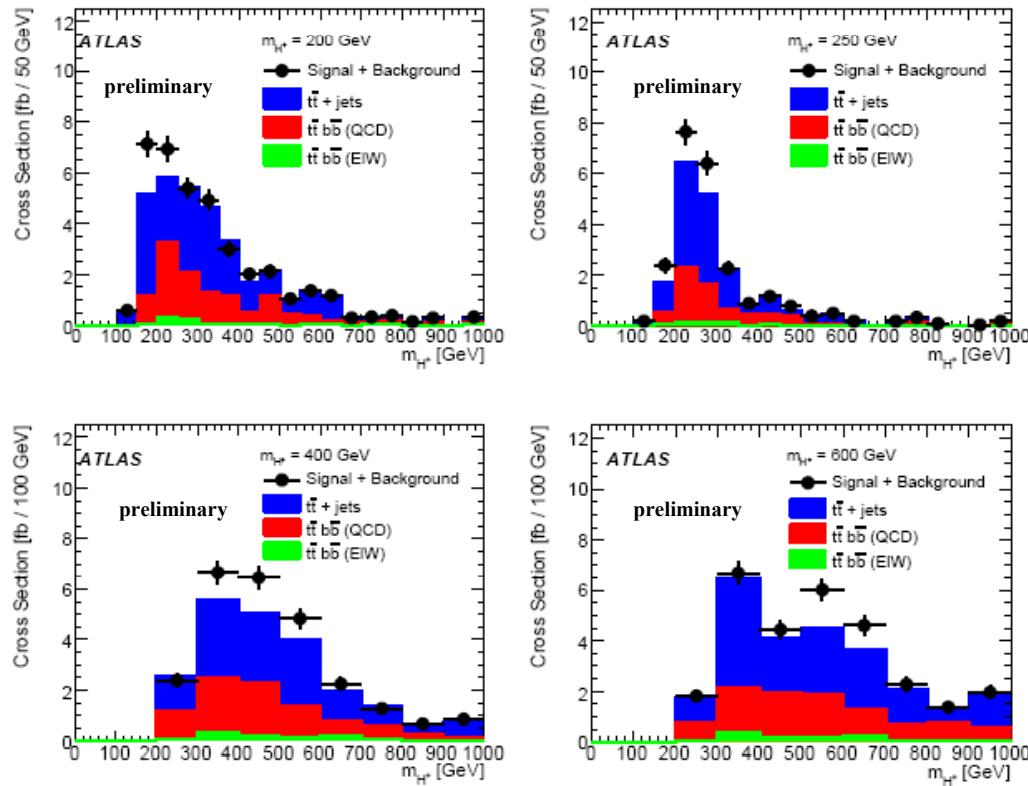
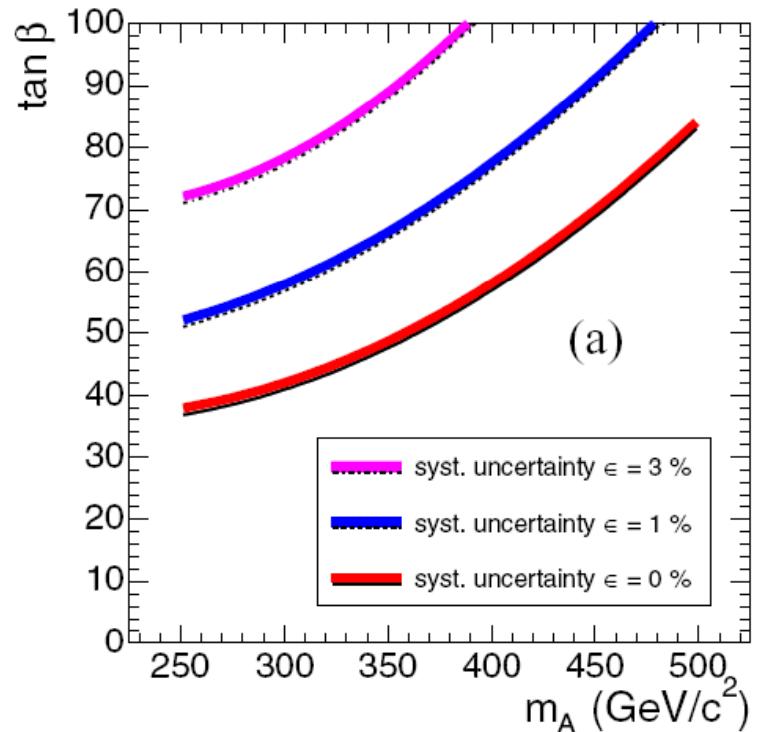
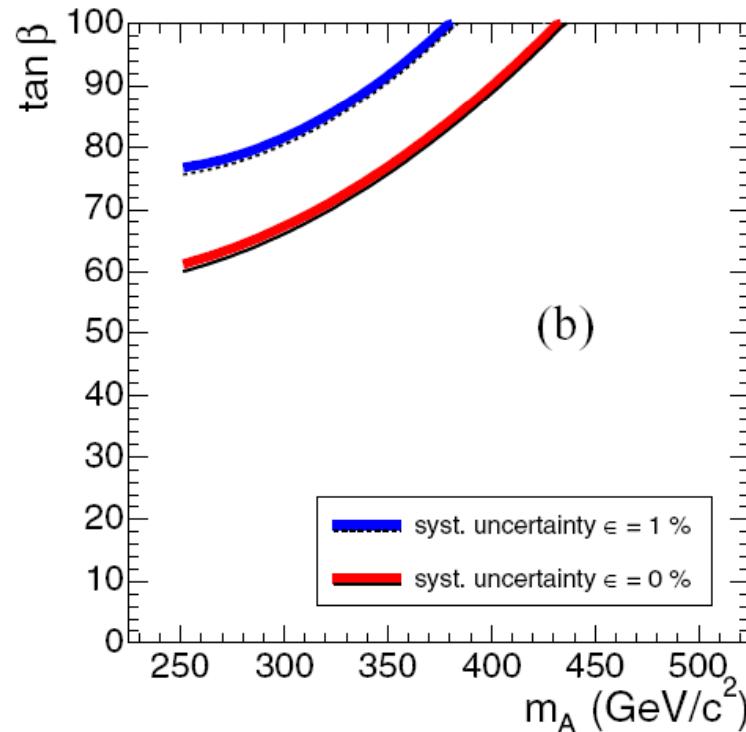


Figure 14:  $gg/gb \rightarrow t[b]H^+ \rightarrow t[b]tb \rightarrow bW[b]bWb \rightarrow b\ell\nu[b]bqqb$ : Reconstructed  $H^+$  mass. The value of  $\tan\beta$  has been chosen such that the pure statistical significance results in a value of 5.

**Heavy  $H^+$**

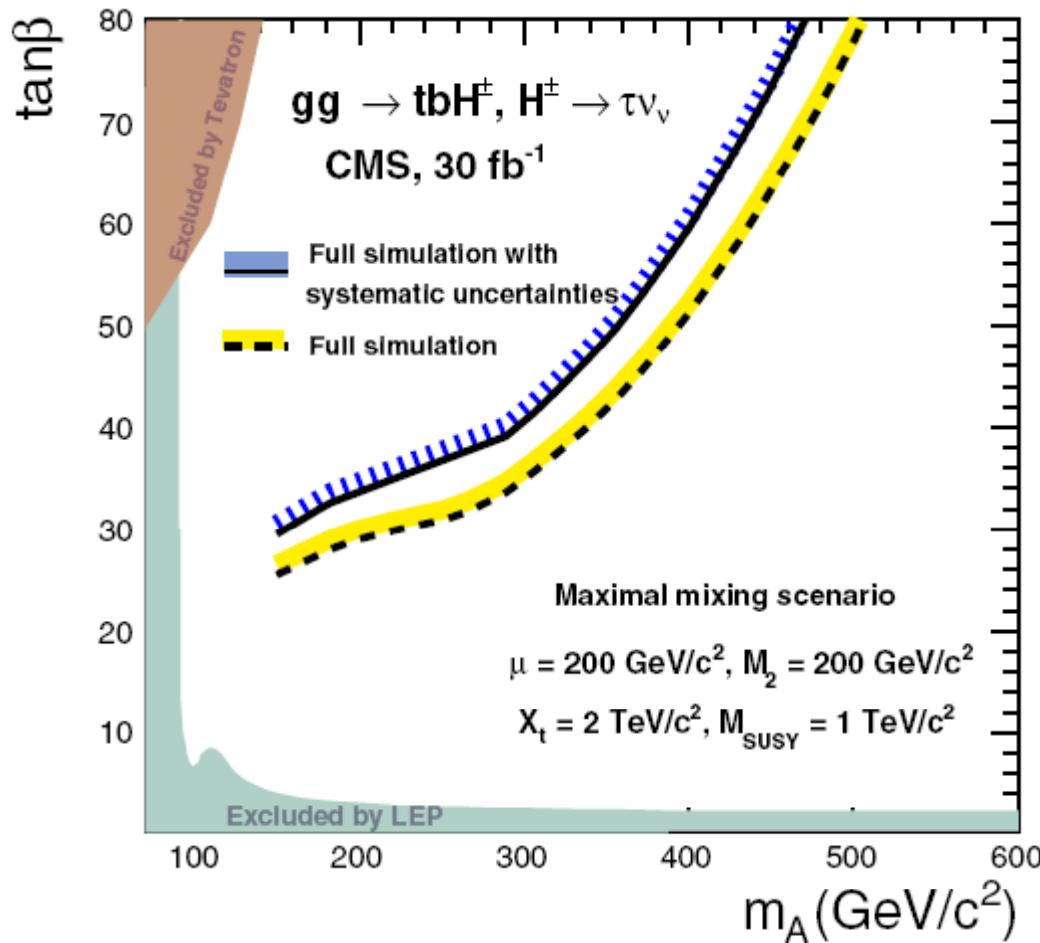


(a)



(b)

**Figure 11.24.** Discovery contour for the charged Higgs boson in the  $H^\pm \rightarrow tb$  decay for  $30 \text{ fb}^{-1}$ , (a) applying 3 b tags, (b) applying 4 b tags; systematic uncertainties on the background of  $\varepsilon = 0\%$ ,  $\varepsilon = 1\%$  and  $\varepsilon = 3\%$  are taken into account.



**Figure 11.19.** The  $5\sigma$ -discovery region in the  $m_A$ - $\tan \beta$  plane for  $gg \rightarrow tbH^\pm, H^\pm \rightarrow \tau \nu_\tau$  with an integrated luminosity of  $30 \text{ fb}^{-1}$  in the maximal mixing scenario with  $\mu = 200 \text{ GeV}/c^2$ . The discovery regions with and without systematic uncertainties are shown. The regions excluded by the LEP and Tevatron searches are also shown in the figure.

CMS TDR R.Kinnunen CMS-NOTE-2006-100

Heavy H $^+$

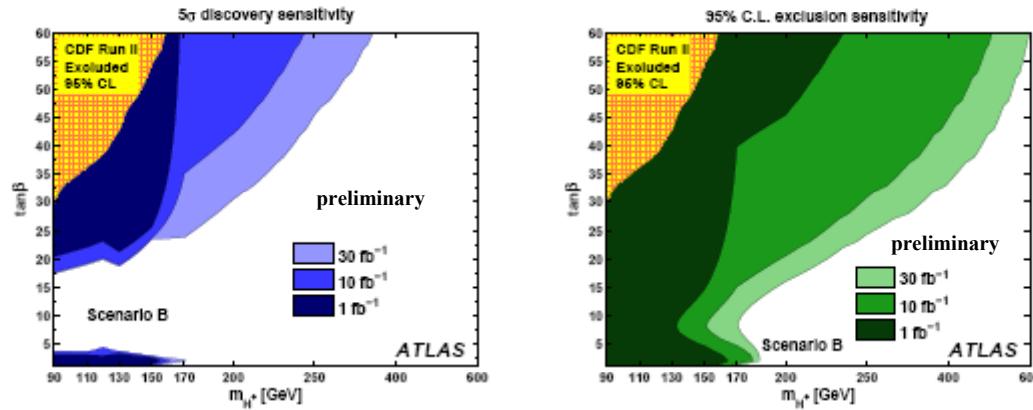


Figure 18: Scenario B ( $m_h$ -max): Combined Results. Left: Discovery contour, Right: Exclusion contour. Systematic and statistical uncertainties are included.

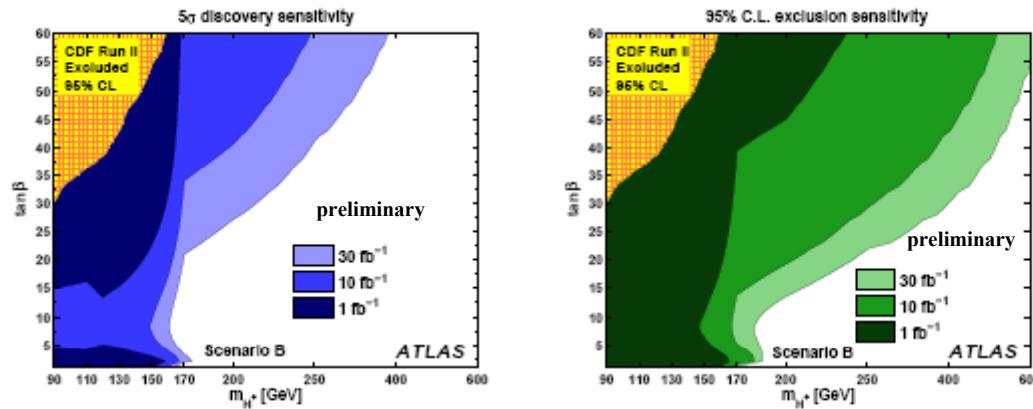


Figure 19: Scenario B ( $m_h$ -max): Combined Results. Left: Discovery contour, Right: Exclusion contour. Statistical errors arising from simulation statistics are neglected.

## new ATLAS

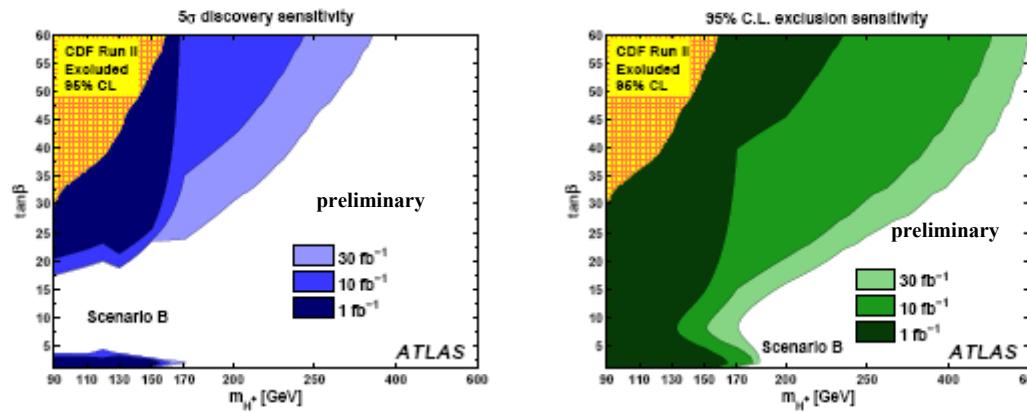


Figure 18: Scenario B ( $m_h$ -max): Combined Results. Left: Discovery contour, Right: Exclusion contour. Systematic and statistical uncertainties are included.

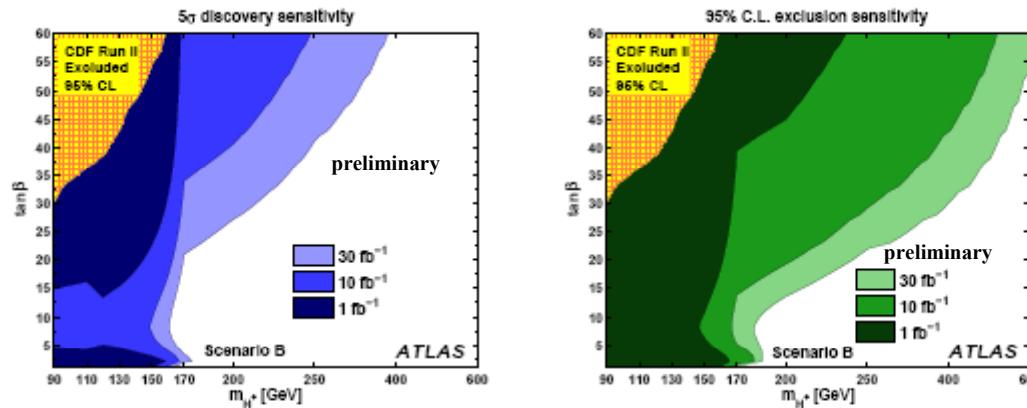


Figure 19: Scenario B ( $m_h$ -max): Combined Results. Left: Discovery contour, Right: Exclusion contour. Statistical errors arising from simulation statistics are neglected.

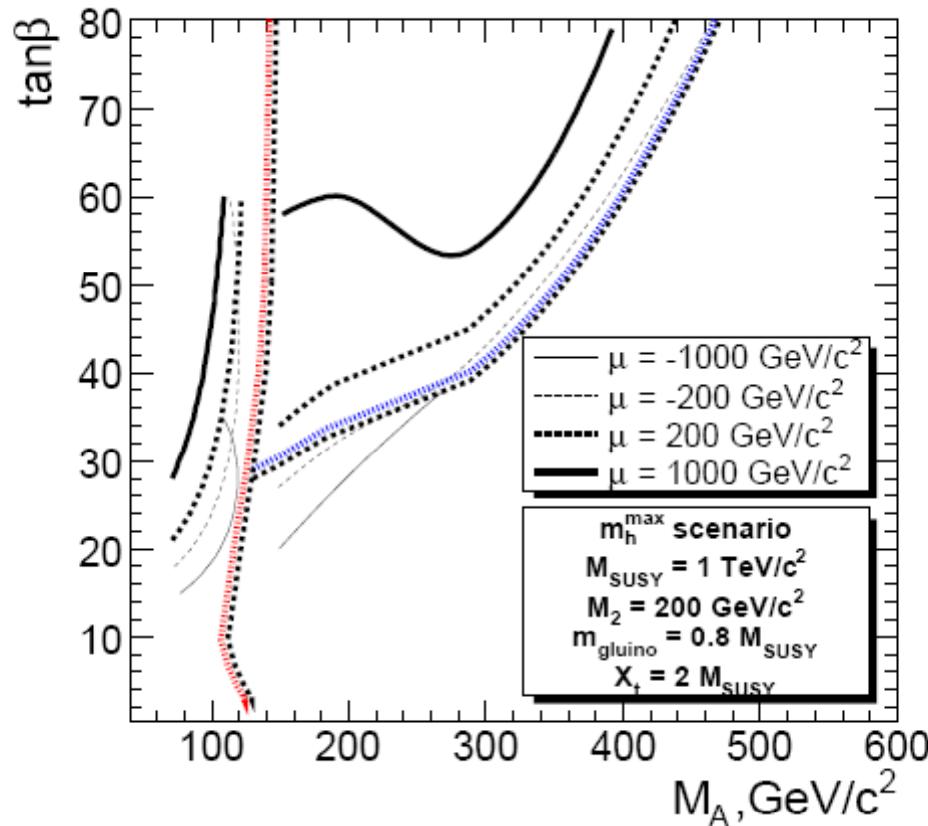


Figure 3: Discovery reach for the charged Higgs boson of CMS with  $30 \text{ fb}^{-1}$  in the  $M_A - \tan\beta$  plane for the  $m_h^{\max}$  scenario for  $\mu = \pm 200, \pm 1000 \text{ GeV}$  in comparison with the results from the CMS PTDR (thickened dotted (red and blue) lines), obtained for  $\mu = +200 \text{ GeV}$  and neglecting the  $\Delta_b$  effects.

**M.Hashemi,S.Heinemeyer,R.Kinnunen,A.Nikitenko and G.Weiglein arXiv:0804.1228 [hep-ph]**

# MSSM charged Higgs decays $g b \rightarrow t H^+ (\rightarrow \chi i 0 \chi j+) \rightarrow 3 l^\pm$

M.Bisset,F.Moortgat and S.Moretti Eur.Phys.J.C30:419-434,2003

C.Hansen,N.Gollub,K.Assamagan and T.Ekelof Eur.Phys.J. C44, s2.1-s2.9 (2005)

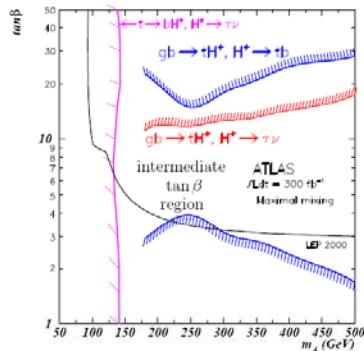


Figure 1: The ATLAS 5- $\sigma$  discovery contour of the charged Higgs [4]. Both the processes  $t \rightarrow bH^\pm$ ,  $H^\pm \rightarrow \tau\nu$  provides coverage for most  $\tan\beta$ . At the  $gb \rightarrow bH^\pm$ ,  $H^\pm \rightarrow \tau\nu$  covers the high  $\tan\beta$  region ( $\tan\beta \gtrsim 10$ ) while the channel covers the  $\tan\beta \lesssim 4$  region. In the intermediate  $\tan\beta$  region the decays to SM particles are undetectable at the LHC.

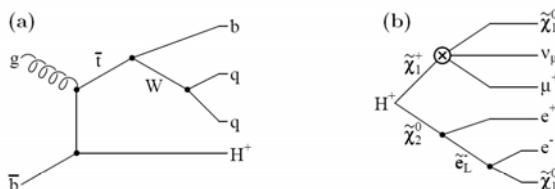


Figure 11: The parameter set corresponding to the cross section shown in figure 10.

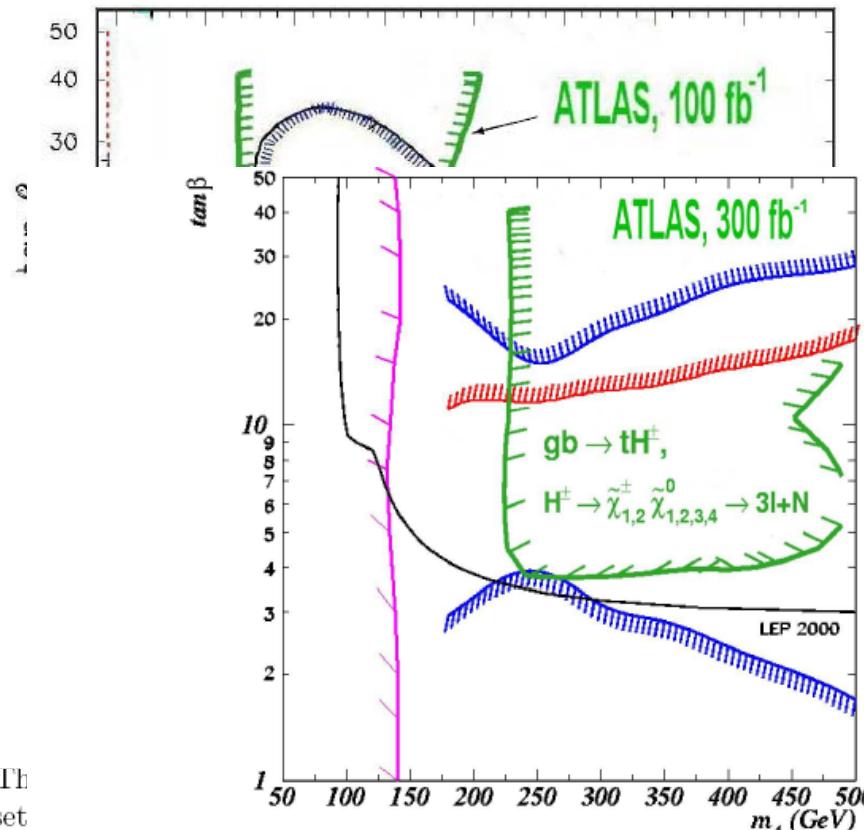


Figure 10: The 5- $\sigma$  discovery contour for the  $H^\pm \rightarrow \tilde{\chi}_{1,2}^\pm \tilde{\chi}_{1,2,3,4}^0 \rightarrow 3\ell + N$  channel for the parameter set defined in section 2 is shown in the  $\tan\beta$  vs.  $m_A$  plane. The integrated luminosity is  $300 \text{ fb}^{-1}$ .

## **Other MSSM , NMSSM**

## MSSM Higgs decays

$$H, A \rightarrow \chi_i^0 \chi_j^0, \chi_i^+ \chi_j^- \rightarrow 4 l^\pm + MET$$

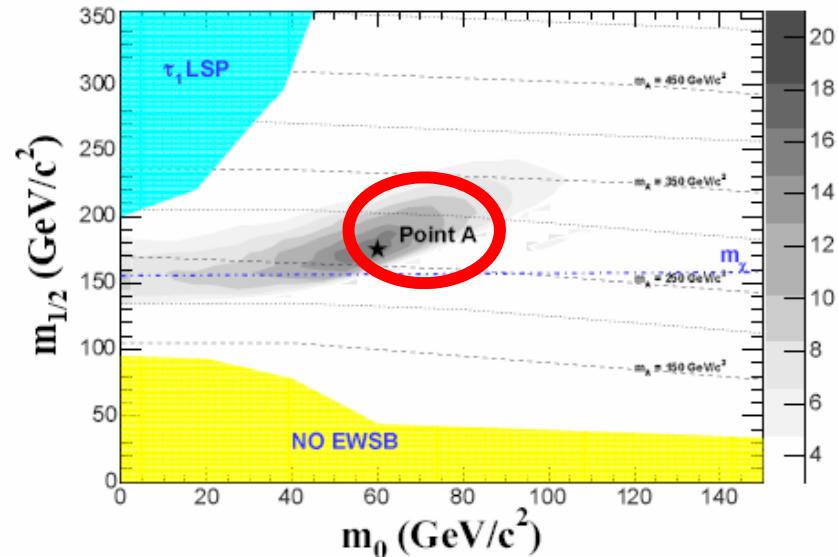
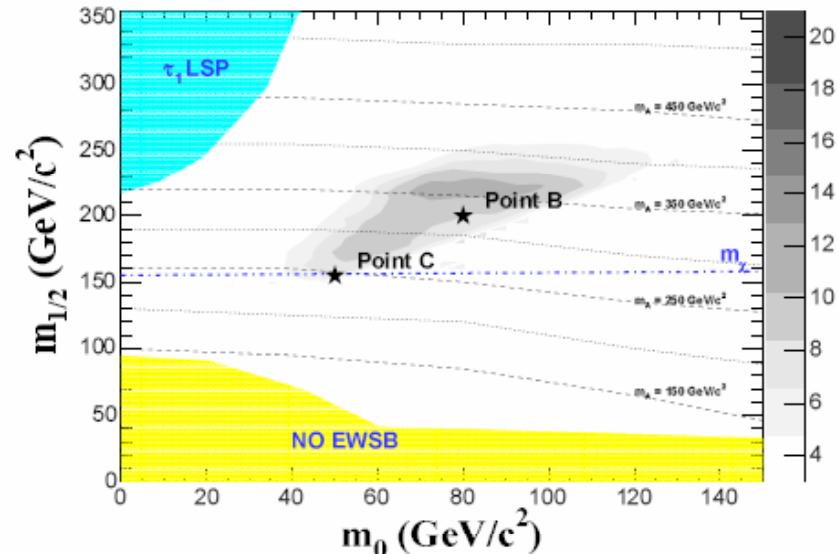
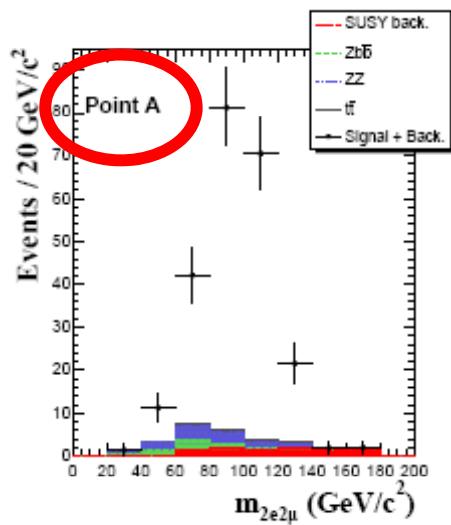


Figure 16:  $5\sigma$ -discovery contours for  $A^0/H^0 \rightarrow \chi_2^0 \chi_2^0 \rightarrow 4l + \cancel{E}_T$  in the  $(m_0, m_{1/2})$  plane for fixed  $A_0 = 0$ ,  $\text{sign}(\mu) = +$  and for (top)  $\tan\beta = 5$  and (bottom)  $\tan\beta = 10$ . Iso-mass curves for the CP-even Higgs boson are indicated (dashed and dotted lines). The results are shown for an integrated luminosity of  $30 \text{ fb}^{-1}$ .

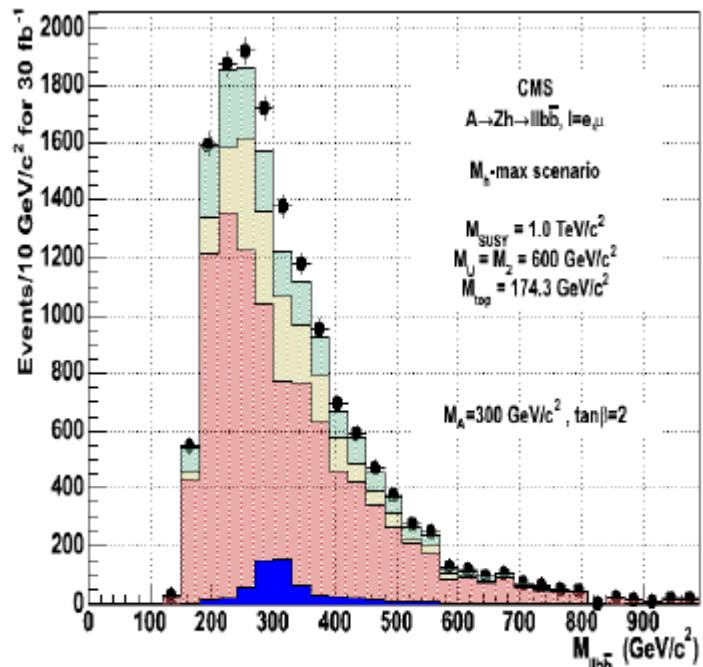


Figure 20: Distribution of  $M_{\ell^{+/-} \ell^{-} b\bar{b}}$  for signal and background after event selection for  $30 \text{ fb}^{-1}$  of integrated luminosity. Red (dark gray), yellow (light gray) and green (medium gray) distributions represent the  $Zb\bar{b}$ ,  $t\bar{t}$  and  $Z+\text{jets}$  backgrounds. Blue (black) distribution is the signal ( $M_A=300, \tan\beta=2$ ) and black dots the data (sum of signal and background).

## Search for $A \rightarrow Z (\rightarrow l^+ l^-) h (\rightarrow b\bar{b})$

**G.Anagnostou and G.Daskalakis CMS-NOTE-2006-063**  
**CMS Physics TDR**

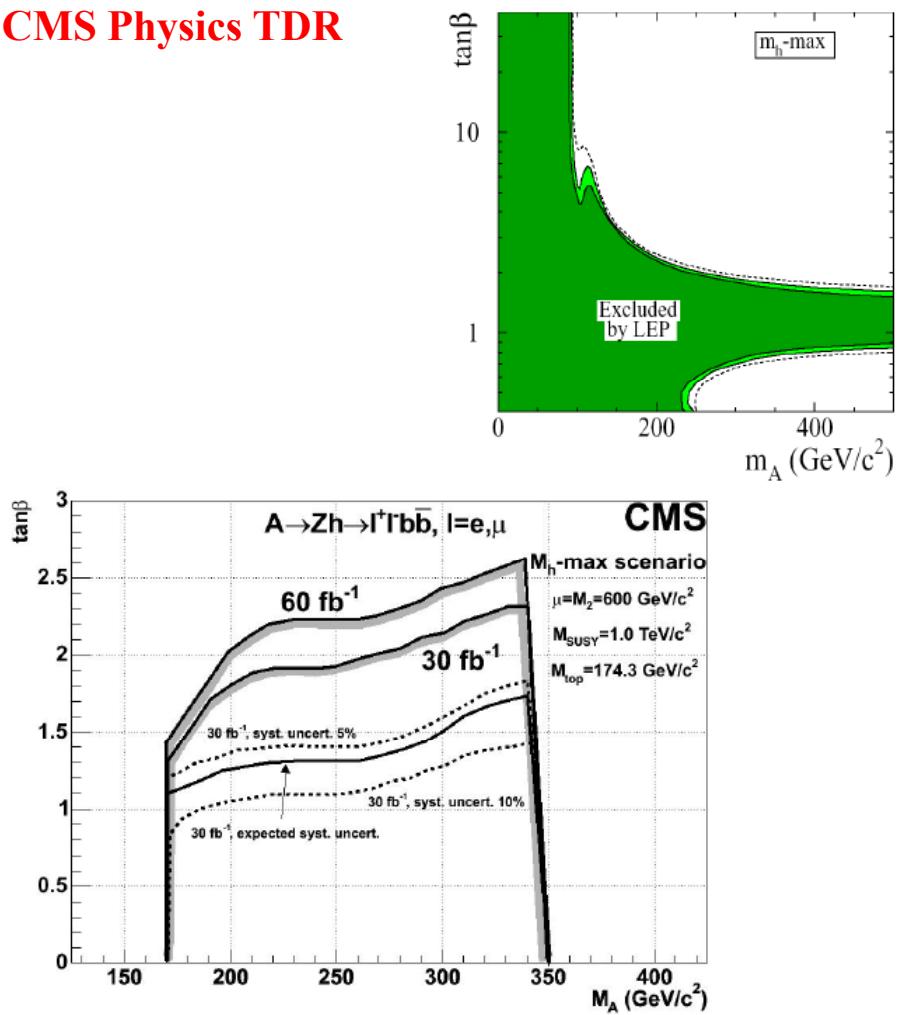


Figure 23: The  $5\sigma$  contours for  $30$  and  $60 \text{ fb}^{-1}$  integrated luminosity with/without systematic uncertainties. The effect of underestimation or overestimation of the background systematic uncertainty can be seen in the curve of  $30 \text{ fb}^{-1}$ .

**NMSSM**  
**5 neutral Higgs bosons**  
**3 CP-even**  $H_1 H_2 H_3$   
**2 CP-odd**  $A_1 A_2$

An evaluation of the ATLAS discovery potential for NMSSM Higgs bosons within two benchmark scenarios was performed. At least one Higgs boson was found to be observable in regions without a light  $A_1$  or where the branching ratio of  $H_{1/2} \rightarrow A_1 A_1$  is smaller than about 60%. In the other cases, searches for the decay chains  $H_{1/2} \rightarrow A_1 A_1 \rightarrow \tau \tau b\bar{b}$  or  $H_{1/2} \rightarrow A_1 A_1 \rightarrow 4\tau$  could be considered.

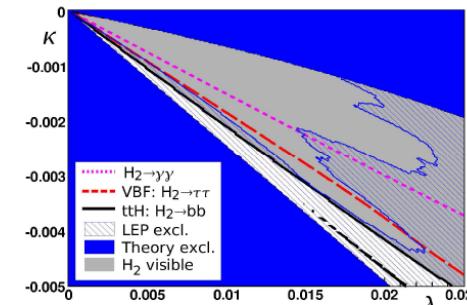


Fig. 1:  $5\sigma$  discovery contours of the  $H_2$  in the  $\lambda$ - $\kappa$  plane for the *Reduced Couplings Scenario*

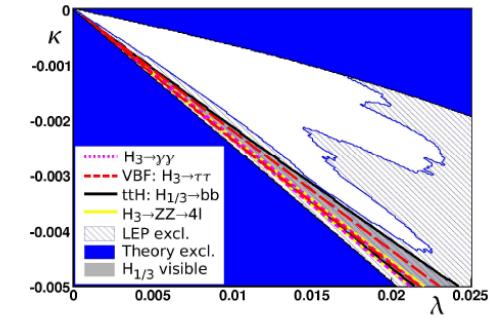
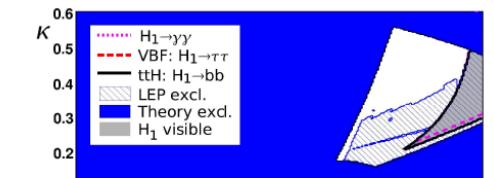
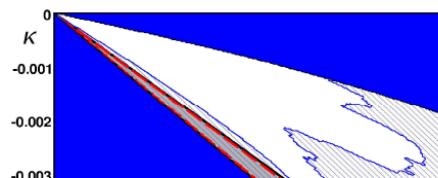


Fig. 2:  $5\sigma$  discovery contours of the  $H_1$  and  $H_3$  in the  $\lambda$ - $\kappa$  plane for the *Reduced Couplings Scenario*



or the

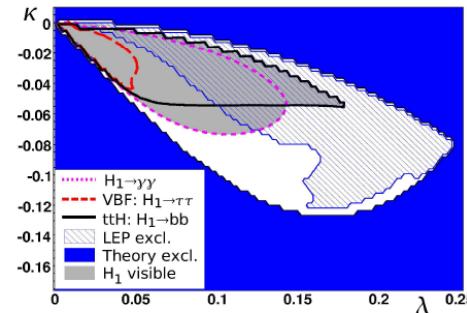


Fig. 5:  $5\sigma$  discovery contours of the  $H_1$  in the  $\lambda$ - $\kappa$  plane for the *Light  $A_1$  Scenario*, restricted to low  $\lambda$  and  $\kappa$  values.

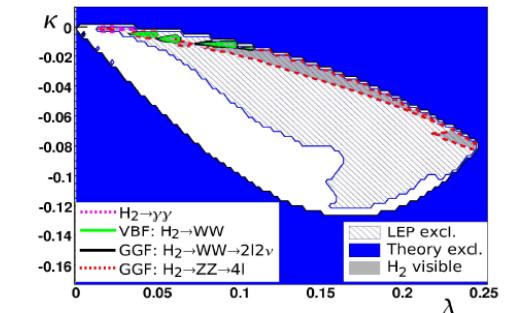
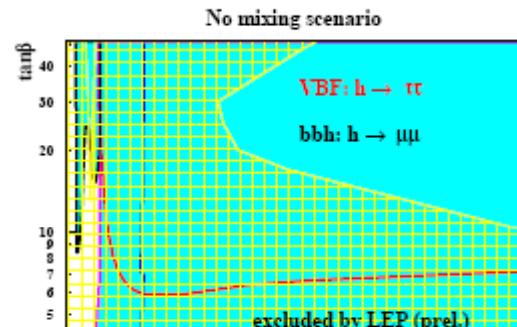
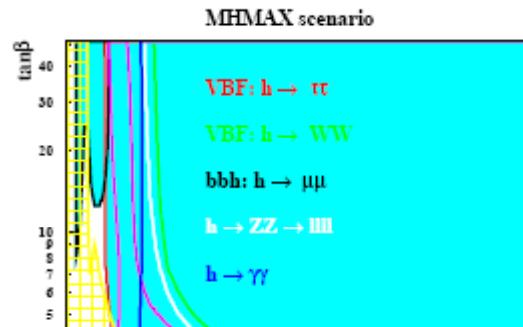


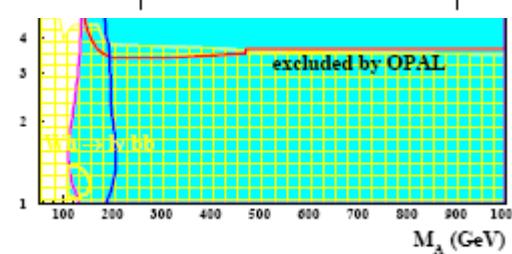
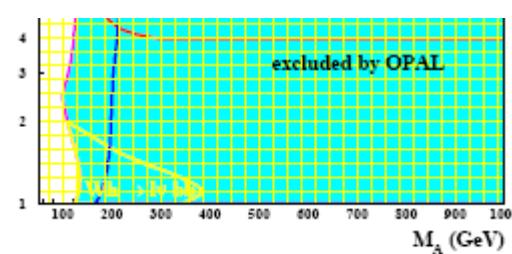
Fig. 6:  $5\sigma$  discovery contours of  $H_2$  in the  $\lambda$ - $\kappa$  plane for the *Light  $A_1$  Scenario*, restricted to low  $\lambda$  and  $\kappa$  values.



$m_h^{\max}$   
 maximal  
 theoretically  
 allowed  
 region  
 for  $m_h$

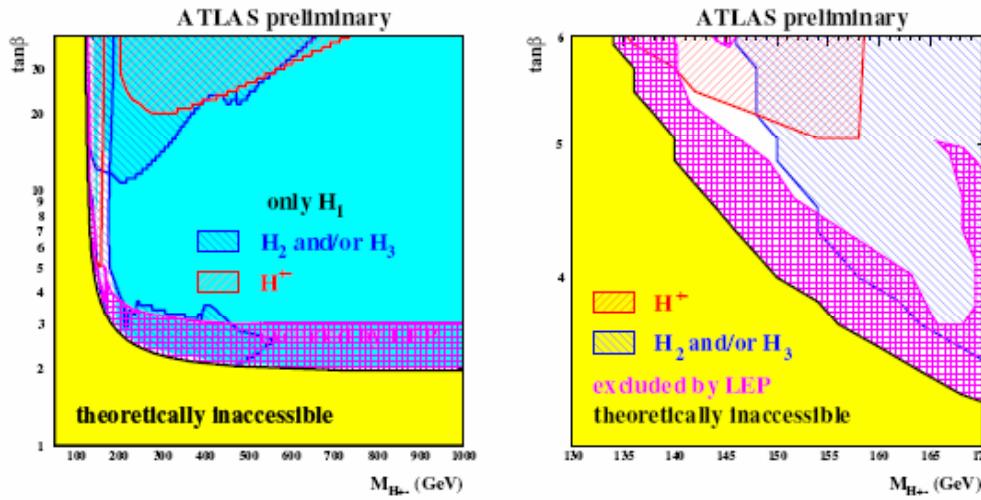
*small  $\alpha$*   
 coupling to b  
 and  $\tau$   
 suppressed  
 (cancellation  
 of sbottom  
 gluino loops)

Parameters [GeV]	$m_h^{\max}$	nomixing	gluophobic	small $\alpha_{eff}$
$M_{SUSY}$	1000	2000	350	800
$M_2$	200	200	300	500
$\mu$	200	200	300	2000
$M_{\tilde{g}}$	800	8000	500	500
$X_t$	2000	0	-750	-1100



unseen  
 for LHC

suppressed  
 Cancellation  
 of top stop  
 loops



**M.Carena,J.Ellis,A.Pilaftsis and C.Wagner**

**Phys.Lett.B495:155-163,2000**

**Nucl.Phys.B625:345-371,2002**

**M.Schumacher et al hep-ph/0608079**

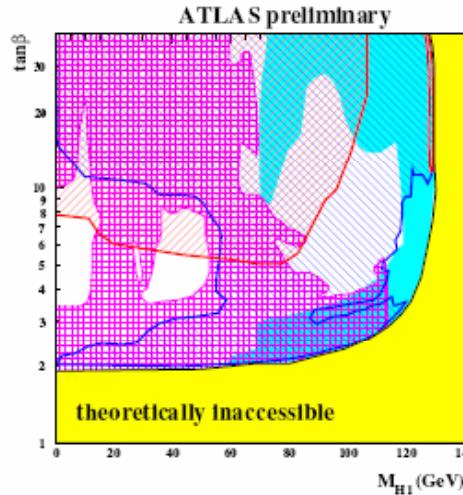
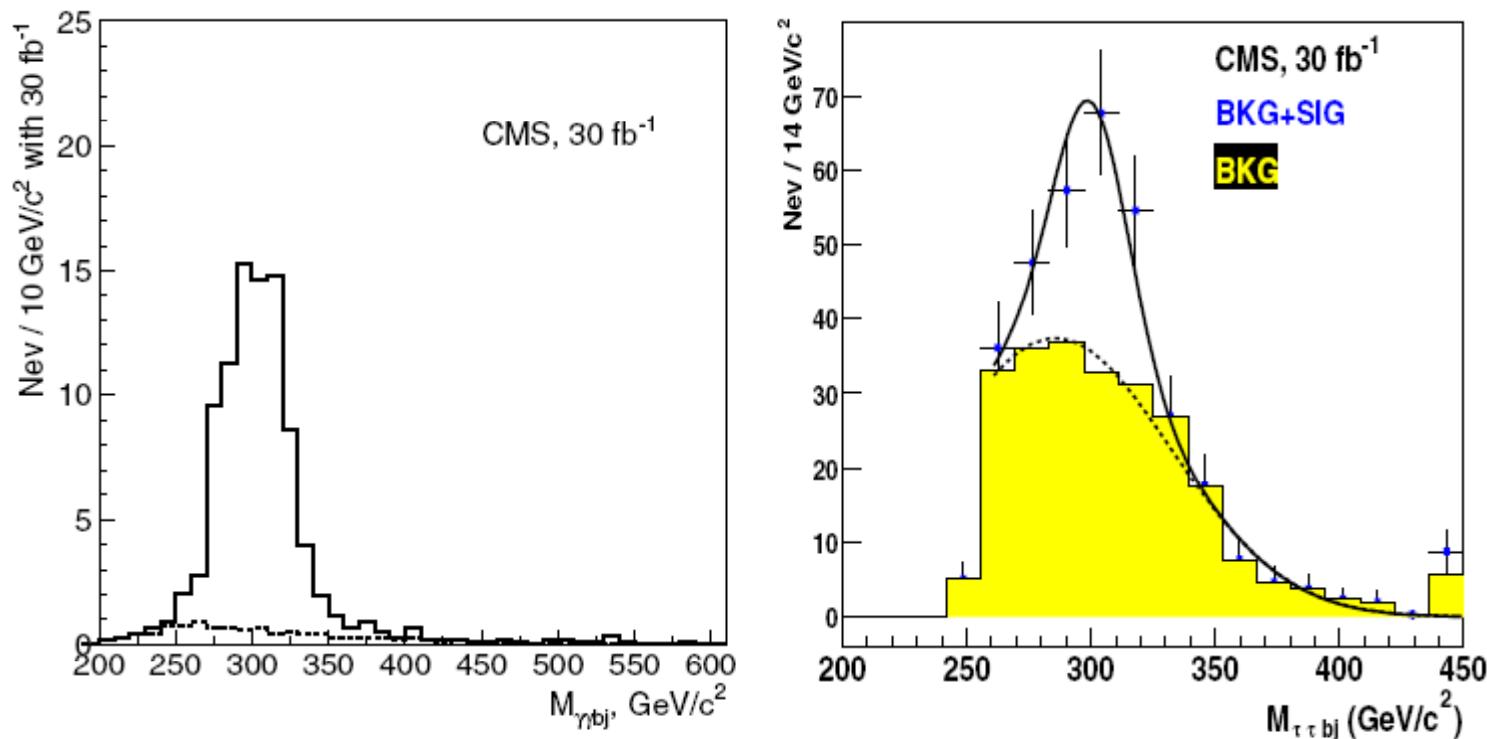


Fig. 3.12: Overall ATLAS discovery potential for Higgs bosons after collecting  $300 \text{ fb}^{-1}$ . The lightest neutral Higgs boson  $H_1$  is expected to be seen in the solid medium gray (cyan) area. One or both of the heavier neutral Higgs bosons  $H_2$  and  $H_3$  are expected to be observed in the right top to left bottom hatched (blue) area. The charged Higgs bosons  $H^\pm$  are expected to be observed in the right bottom to left top hatched (red) area. The cross hatched (magenta) area is excluded by the LEP experiments [206]. The light gray (yellow) area is theoretically inaccessible.

## **Radion decays , Little Higgs**

## CMS Physics TDR

D.Dominici,G.Dewhirst,A.Nikitenko,S.Gennai and L.Fano CMS-NOTE-2005-007



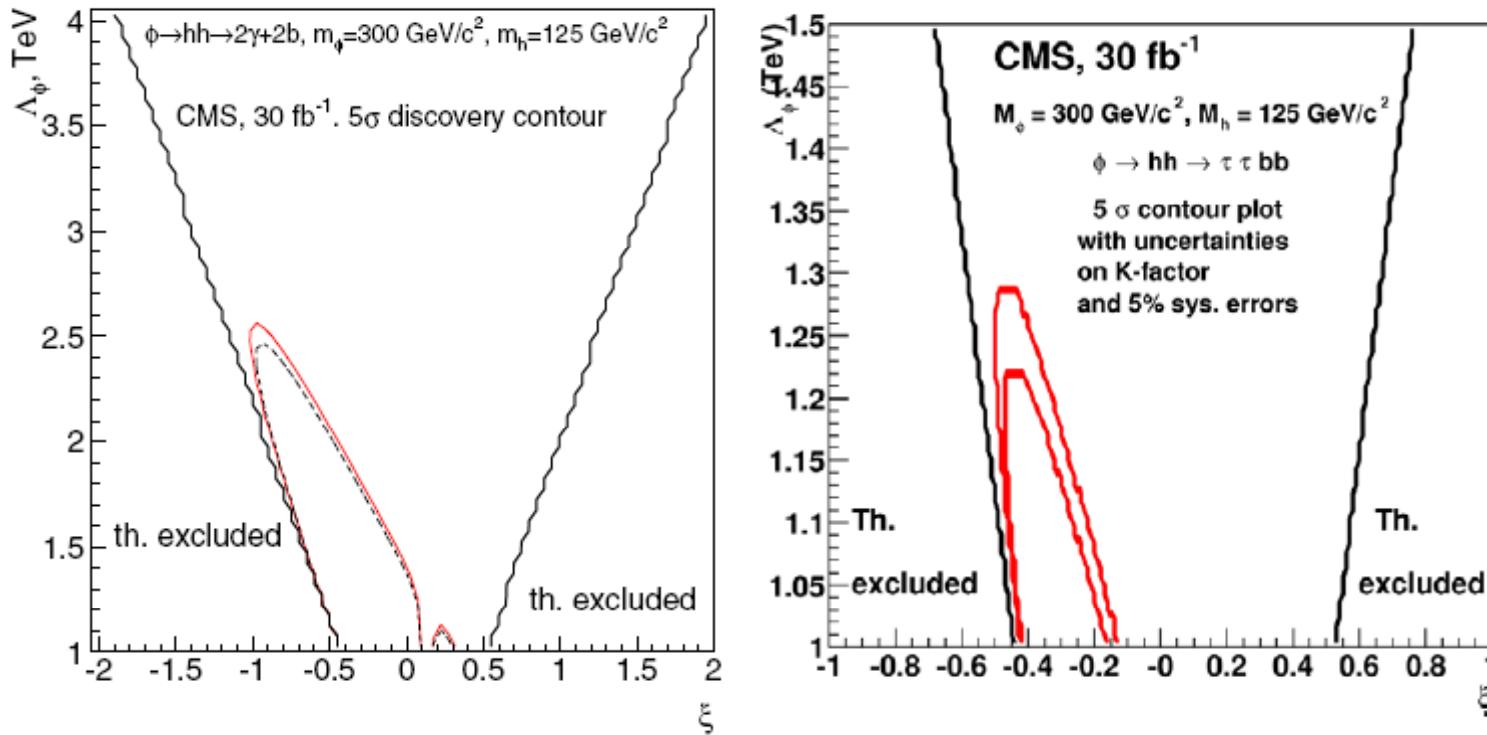
**Figure 12.2.** Left plot: the  $M_{\gamma\gamma\text{bj}}$  distribution for the background (dashed histogram) and for the signal of  $\phi \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$  plus background (solid histogram) after all selections for  $30 \text{ fb}^{-1}$ . Right plot: the  $M_{\tau\tau\text{bj}}$  distribution for the background (full grey (yellow) histogram) and for the signal of  $\phi \rightarrow hh \rightarrow \tau\tau b\bar{b}$  plus background (black points with the error bars) after all selections for  $30 \text{ fb}^{-1}$ . The fitted curves for the background and signal plus background are superimposed. On both plots the signal is shown for the maximal cross section times branching ratios point in  $(\xi - \Lambda_\phi)$ .

# Radion decays in Higgs pair

G. Azuelos,D. Cavalli, H. Przysiezniak and L. Vacavant Eur.Phys.J.direct C4:16,2002

CMS Physics TDR

D.Dominici,G.Dewhirst,A.Nikitenko,S.Gennai and L.Fano CMS-NOTE-2005-007



**Figure 12.3.** Left plot: the  $5\sigma$  discovery contours for the  $\phi \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$  channel for  $30 \text{ fb}^{-1}$ . The solid (dashed) contour shows the discovery region without (with) the effects of the systematic uncertainties (find more explanations in the text). Right plot: the  $5\sigma$  discovery contours for the  $\phi \rightarrow hh \rightarrow \tau\tau b\bar{b}$  channel for  $30 \text{ fb}^{-1}$ . The two contours corresponds to the variation of the background NLO cross sections due to the scale uncertainty. The 5% experimental systematics on the background is taken into account (see text).

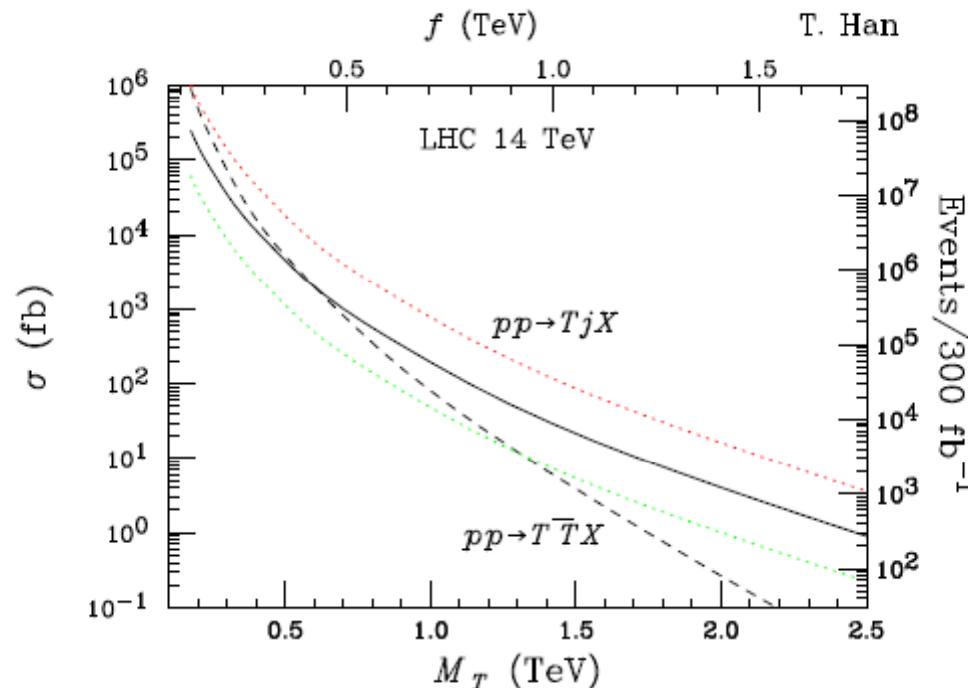


Figure 1: Figure showing the production rate of the T quark at the LHC as a function of its mass [15]. The heavy dashed line shows the pair production and the solid and two dotted lines the single production rate for three value of  $\lambda_2/\lambda_1$ ; from highest to lowest  $\lambda_2/\lambda_1 = 2, 1, 0, 5$ . (We are grateful to T. Han for providing this figure.)

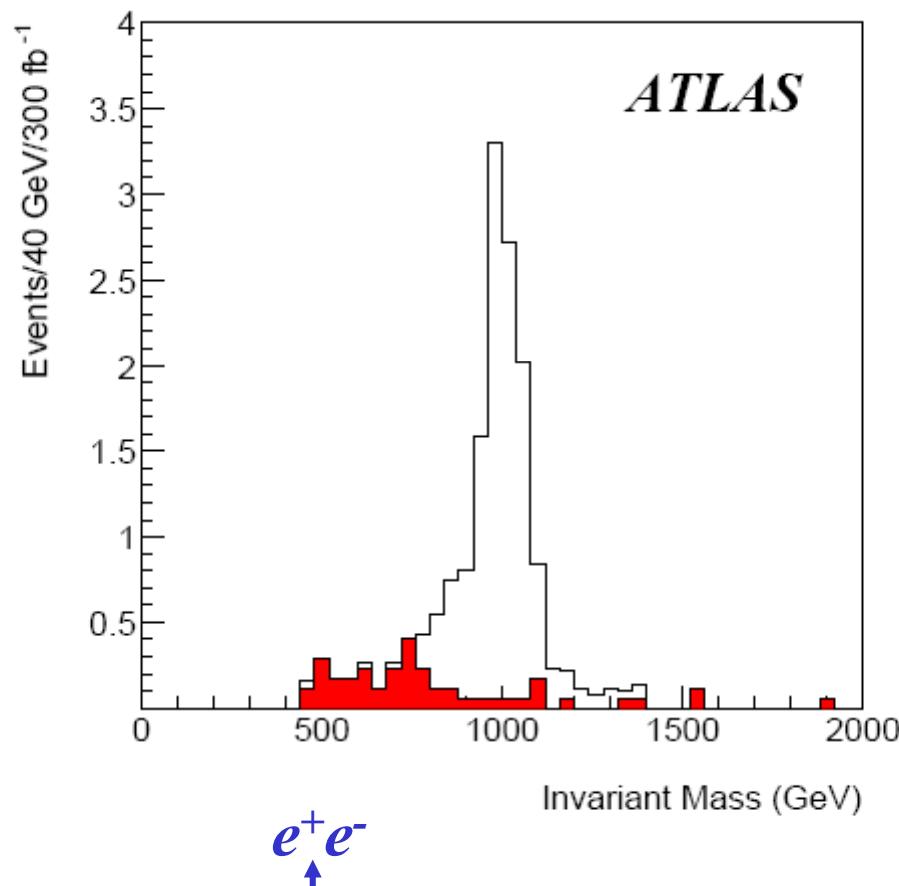


Figure 2: Reconstructed mass of the  $Z$  and  $t$  (inferred from the measured lepton,  $\not{E}_T$ , and tagged  $b$ -jet). The signal  $T \rightarrow Zt$  is shown for a mass of 1000 GeV. The background, shown as the filled histogram, is dominated by  $WZ$  and  $tbZ$  (the latter is larger) production. The signal event rates correspond to  $\lambda_1/\lambda_2 = 1$  and a  $BR(T \rightarrow ht)$  of 25%. More details can be found in Ref [17].

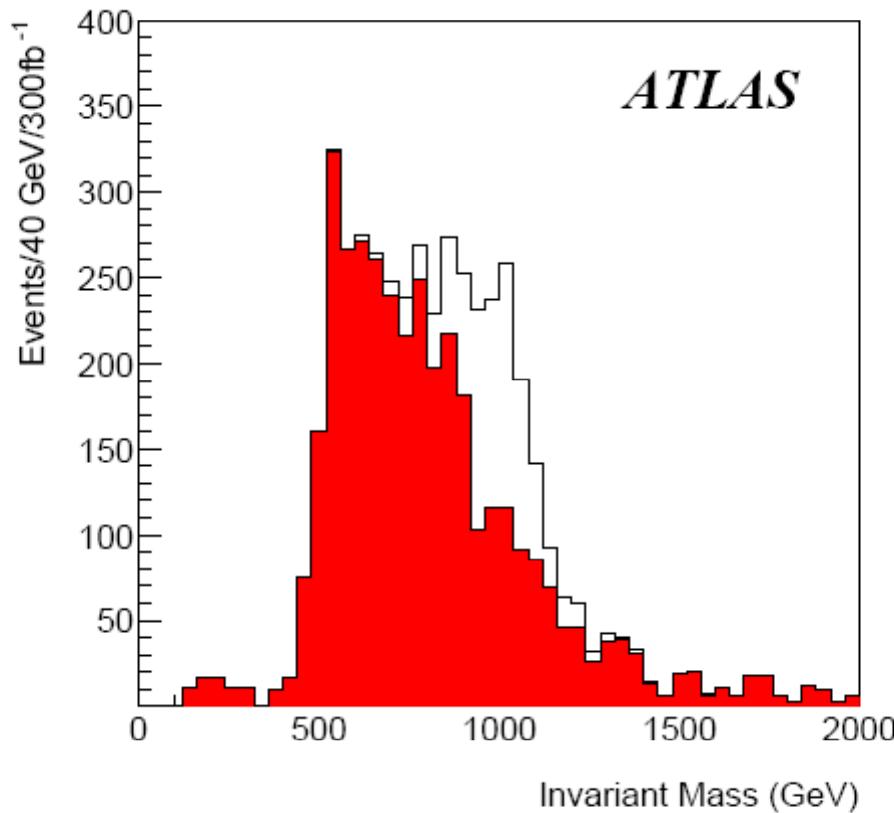


Figure 3: Reconstructed mass of the  $W$  (inferred from the measured lepton and  $E_T$ ) and tagged  $b$ -jet. The signal arises from the decay  $T \rightarrow Wb$  and is shown for mass of 1000 GeV. The background, shown separately as the filled histogram, is dominated by  $t\bar{t}$  and single top production (the former is larger). The signal event rates correspond to  $\lambda_1/\lambda_2 = 1$  and a  $BR(T \rightarrow Wb)$  of 50%. More details can be found in Ref [17].

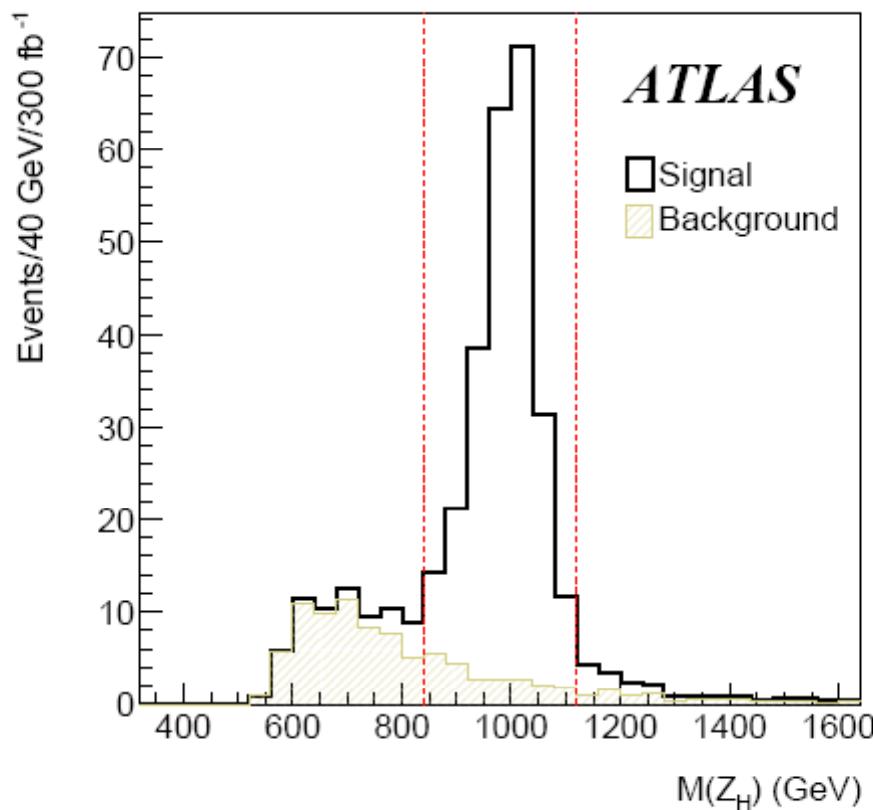
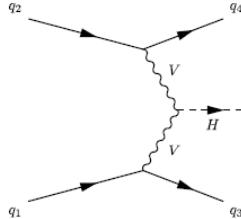


Figure 14: Invariant mass of the  $Zh$  system reconstructed from the  $\ell^+ \ell^- b\bar{b}$  final state showing the signal from a  $Z_H$  of mass 1000 GeV with  $\cot \theta = 0.5$  above the Standard Model background. The vertical lines define the signal region.

# Invisible Higgs

## Invisible Higgs

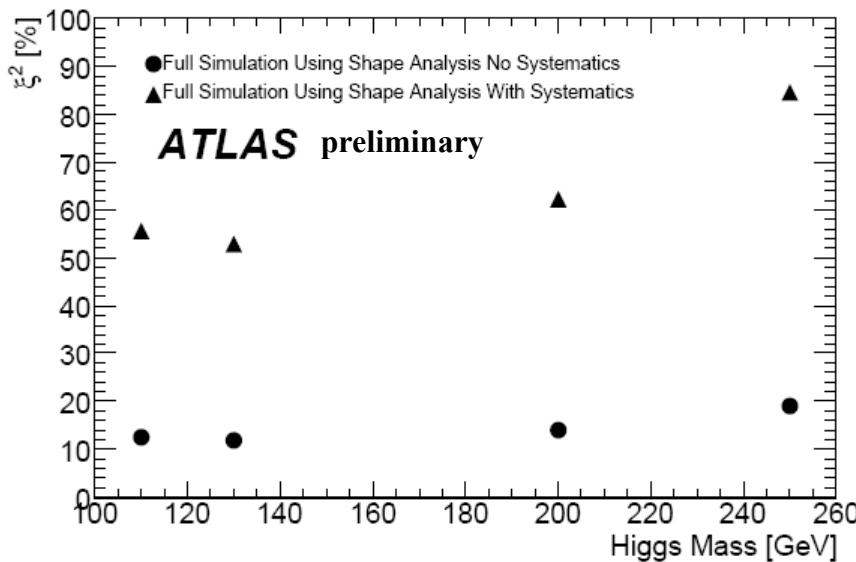
$$\xi^2 = BR(H \rightarrow \text{inv.}) \frac{\sigma_{BSM}}{\sigma_{SM}}$$



$$\begin{aligned} ttH &\rightarrow tt P_T^{\text{miss}} \\ ZH &\rightarrow ll P_T^{\text{miss}} \\ qqH &\rightarrow qq P_T^{\text{miss}} \end{aligned}$$

Background  
ZZ Z+jet tt

**Backgrounds Z + jet W + jet difficult to trigger**



new ATLAS

Figure 6: Sensitivity for an invisible Higgs boson at 95% C.L. via the VBF channel using shape analysis for an integrated luminosity of  $30\text{fb}^{-1}$  with and without systematic uncertainties. The black triangles (circles) are the results from this analysis with (without) systematic uncertainties.

# Invisible Higgs

new ATLAS

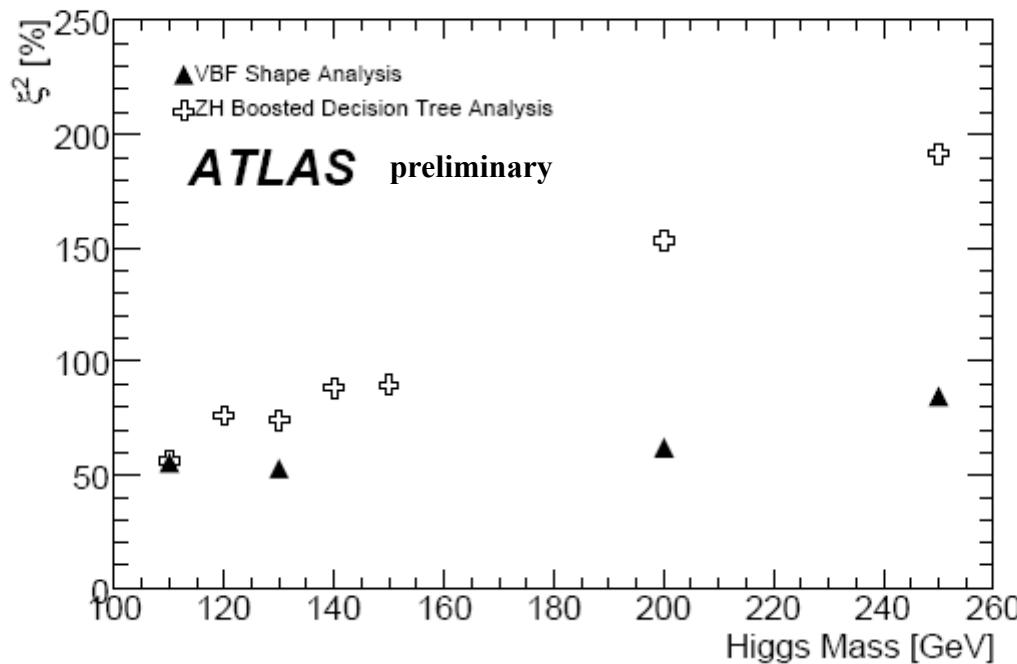


Figure 13: Sensitivity to an invisible Higgs boson with ATLAS for both the VBF and  $ZH$  channels with  $30 \text{ fb}^{-1}$  of data assuming only Standard Model backgrounds. The open crosses show the sensitivity for the  $ZH$  analysis and the solid triangles show the sensitivity for the VBF shape analysis for 95 % CL. Both these results include systematic uncertainties.

