Higgs physics at LHC

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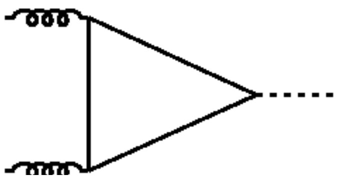
(CERN)

Beijing 14/12/2006

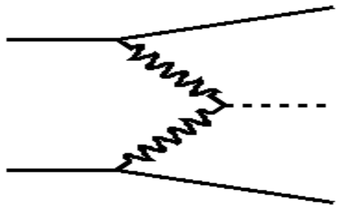
- Higgs production and decay
- SM Higgs boson search
  - Emphasis on $M_H < 200$ GeV
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow 4$ leptons
  - $H \rightarrow WW^*$ ("counting" experiment)
  - VBF Higgs production
- Higgs properties measurement
- Higgs sector in Supersymmetry

Higgs production @ LHC

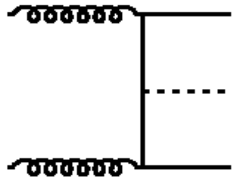
gg → H
via top loop



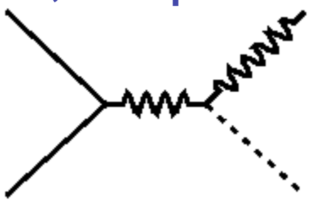
Vector Boson
Fusion



Associated
production with top



WH,ZH production



All processes are computed at NLO or NLLO for the total rate.
Higgs production distribution ($d\sigma/dp_t$) also available at NLO/NNLL

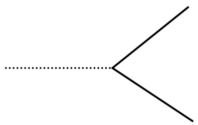
Many progresses in the recent years in QCD computations

see review hep-ph/0503172 by A.Djouadi

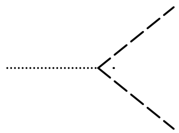
Typical uncertainties on cross-section
- gg 10-20 % (NNLO)
- VBF ~ 5% (NLO)
- WH,ZH ~< 5% (NNLO)
- ttH 10-20 % (NLO)

Higgs decay

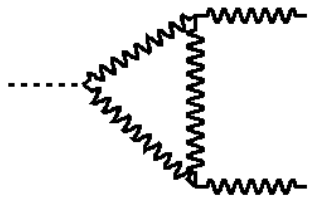
Higgs → f-fbar (~mf**2)



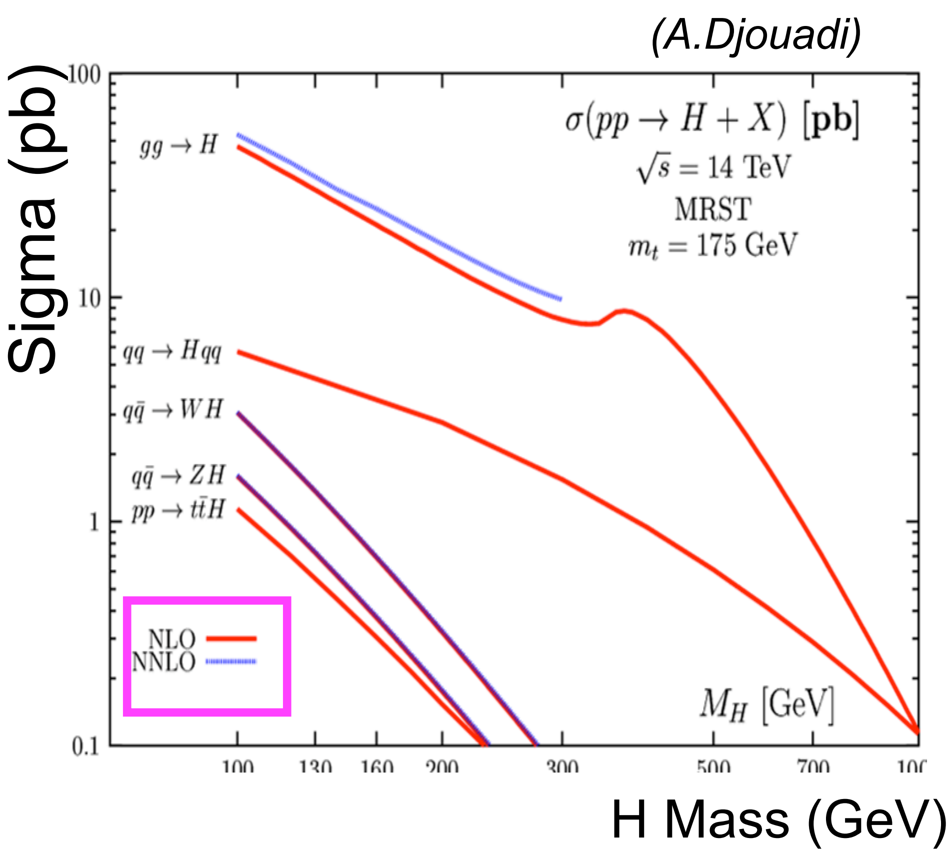
Higgs → WW(*),ZZ(*)

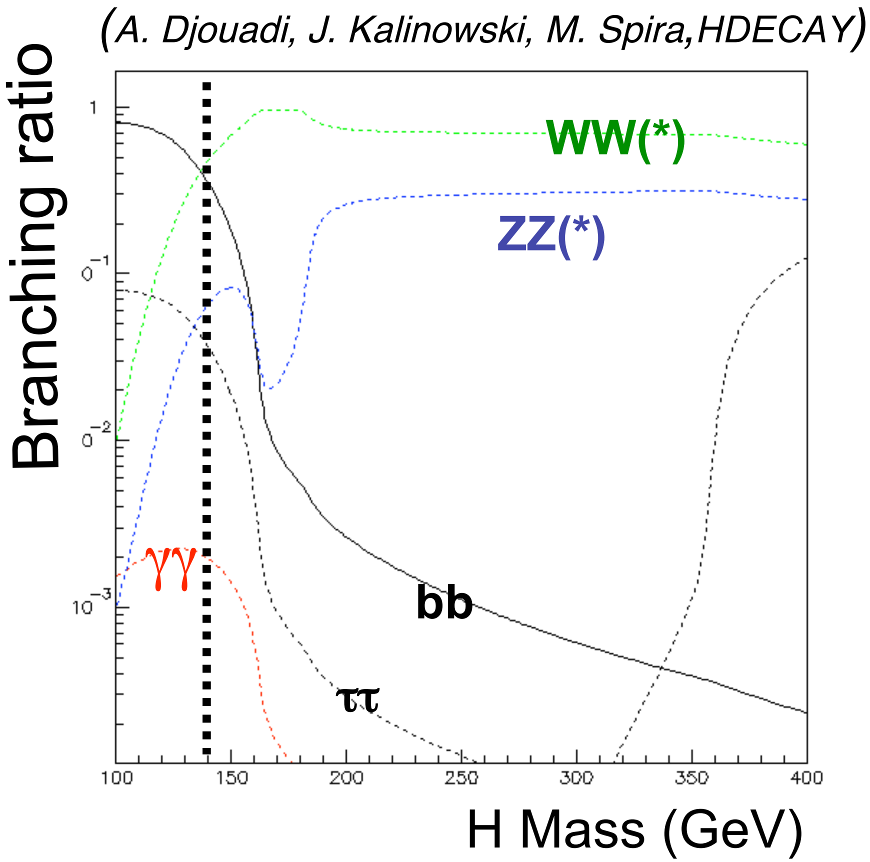


H → γγ



All the relevant BR known with few % accuracy (NLO computations)





•gg→H : dominant production, large QCD corrections, H “often” produced associated with a “hard” jet (ZZ*,WW*, γγ decays)

•qq→Hqq (WW,ZZ fusion “VBF”). Specific signature allowing better background rejection (ττ,WW*, γγ decays, also bb ??)

•ttH production Lepton from top allows to trigger (bb decay, also ττ,WW* for coupling measurements, γγ at high lumi.)

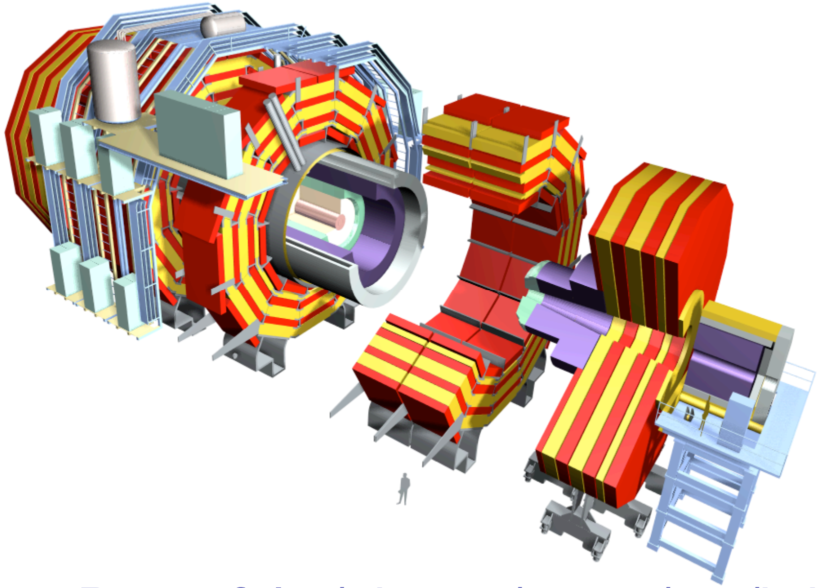
•WH,ZH production: γγ, WW* at high lumi.

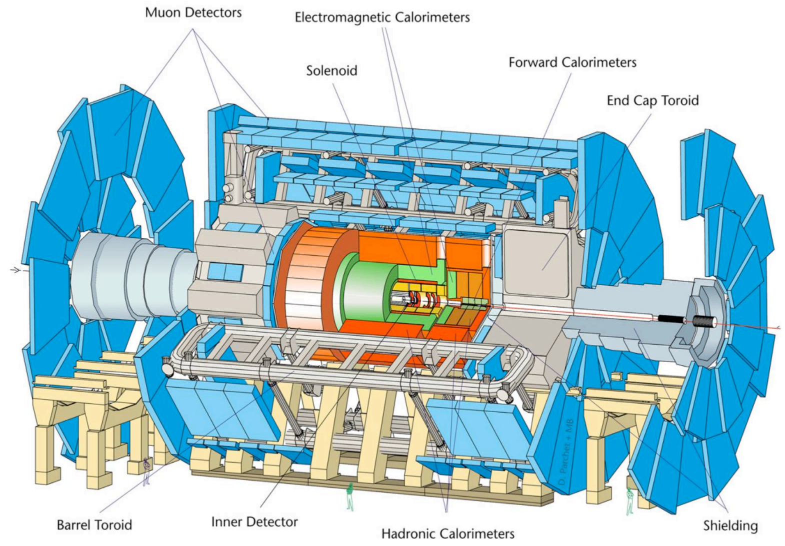
Chinese-French collaboration on ttH,WH with H→WW

Diffractive Higgs production

- pp→ppH
- Higgs mass from measurement of outgoing proton (Roman pots) => ~1% resolution
  - Could allow to access bb final state at low mass
- Significant uncertainty on production rate
- Not obvious to trigger
- Not discussed further here

CMS and ATLAS





- Powerful e/photon/muon/tau/b-jet identification
  Rjet ~few 10^3 for eff(photon) ~ 80%
  - Rjet ~10^5 for eff(elec) ~80%
  - R(light flavor jets) ~100 for eff(b-jet) ~60%
  - R(jet) ~few 10^2 for eff(tau→hadrons) ~50 %
- Very good energy measurement of e/photon and muons
  - ~1 - 2 % for elec pt~25-50 GeV
- Jets and Transverse missing momentum

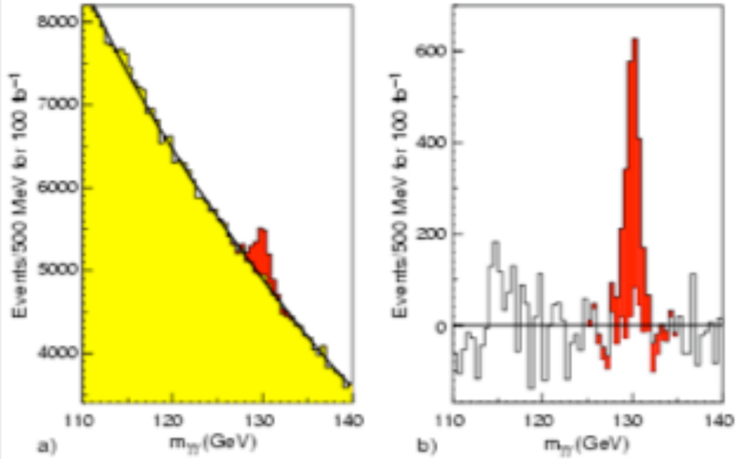
SM Higgs Searches

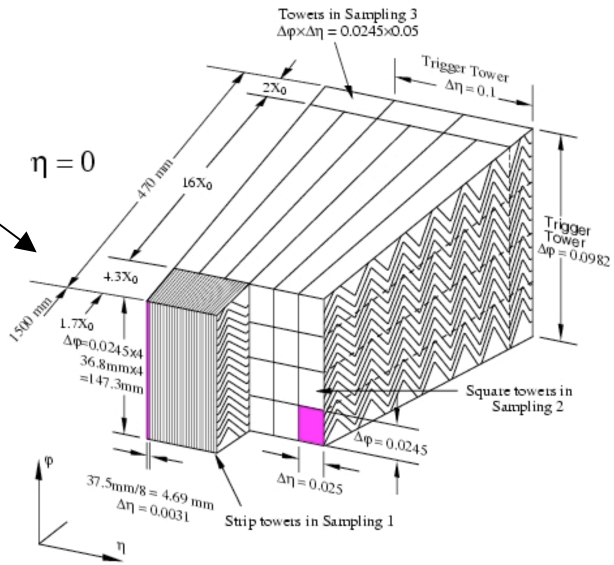
- Benchmark channels for detector performances
  - $H \rightarrow \gamma\gamma$ *(old channel, new variations)*
  - $H \rightarrow 4l$
- "counting experiment" channels
  - $H \rightarrow WW^{(*)}$
- Vector Boson fusion production channels
  - $H \rightarrow \tau\tau$, $WW^{(*)}$

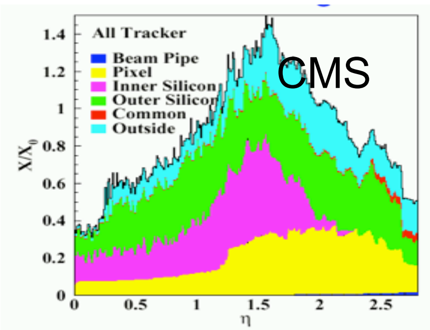
$H \rightarrow \gamma\gamma$

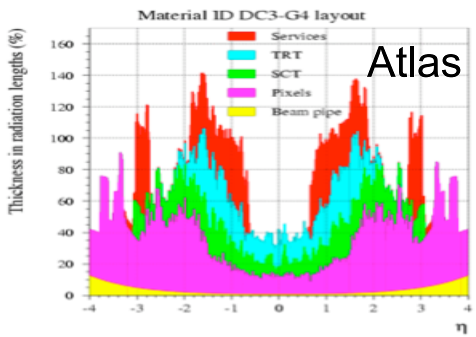
- Narrow peak over “smooth” background
- Key points:
  - Good mass resolution (Intrinsic width is negligible) => Energy resolution of e.m. calorimeter + primary vertex determination
  - Good photon identification: To reduce jet background below true photon background
    - Very fine segmentation (*ATLAS*) to allow photon/π^0 separation event by event
    - Isolation cuts
    - Recovery of conversions:
      - ~30% of photons convert in tracker

(CMS ECAL TDR)







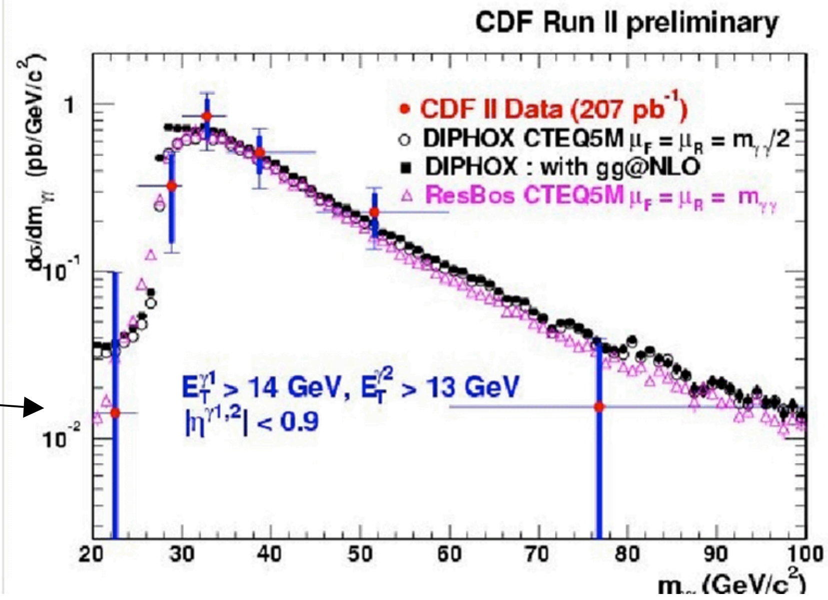


Diphoton background is now computed at NLO (Binoth et al, *Eur.Phys.J.C16(2000)311,* Bern,Dixon,Schmidt hep-ph/0206194, C.Balasz et al, *Phys.Lett.B489(2000)157*

✓Computation agrees with Tevatron data

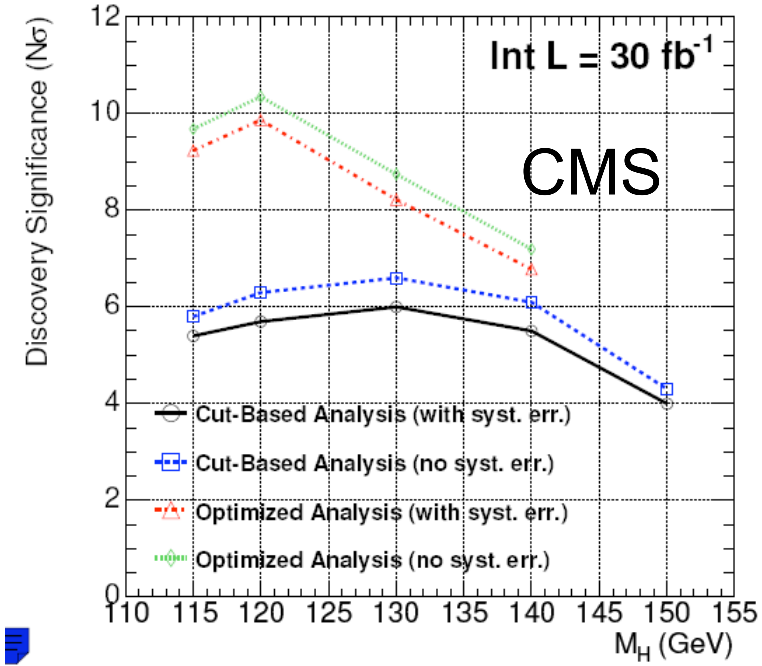
✓Allows to use also NLO for signal

✓Resbos program for NLO normalization of S and B + resummation effects



- Different strong points for CMS (Energy resolution) and ATLAS (fine segmentation, photon angle measurement). Overall, sensitivity is similar if using same input cross-sections.
- Inclusive channel is still one of the most powerful at low mass (~6-8 sigmas for 30 fb^{-1})
- Several possibilities to divide events according to production mode (H+0J vs H+1Jet, VBF production, associated production, etc..) Can further increase the discovery potential

- Simple cut based analysis: count events in mass window after kinematical cuts
- "Optimized" analysis:
  - CMS: Add kinematic information and photon isolation (help to distinguish reducible background from direct photons)
  - ATLAS: Add Pt(photon pair), angular distribution in likelihood
  - Typically ~30-40% improvement in significance
  - Systematic error from fitting background rate ~ 10-15 % effect *(ATLAS study)*



Significance (m=130GeV)for 30fb^{-1}

CMS *(all using NLO rates)*

TDR	new "cut"	new "optimized"
7.5	6.0	**8.2**

ECAL TDR→new: better NLO bkg computation, fake estimation, more conversions.

ATLAS *(stat. errors only)*

TDR(LO)	new NLO "cut"	+likelihood
3.9	6.3	**8.7**

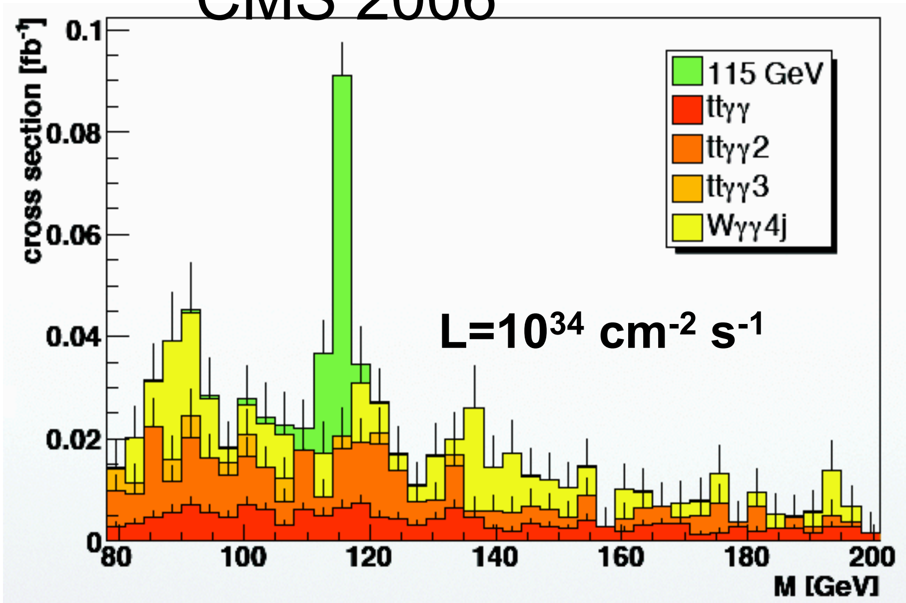
Exact level of background will only be known from data…

H→γγ in associated production

ttH final state:
for 100fb^{-1}:
~7 signal events,3.5 sigmas

Background: t-tbar events
with radiated photons,
W+4j+photons.

CMS 2006



Can also consider WH,ZH (lepton-gamma-gamma) final states,
and H produced with VBF process (H+2 jets final state)

=> Combining all channels should increase discovery potential

H→4leptons

Rely on good e/muon identification and energy resolution

(mass resolution ~1.5-2 GeV)

Irreducible background: ZZ(*) -> 4l

q qbar annihilation known at NLO

add ~20% to account for gg->ZZ

Reducible backgrounds:

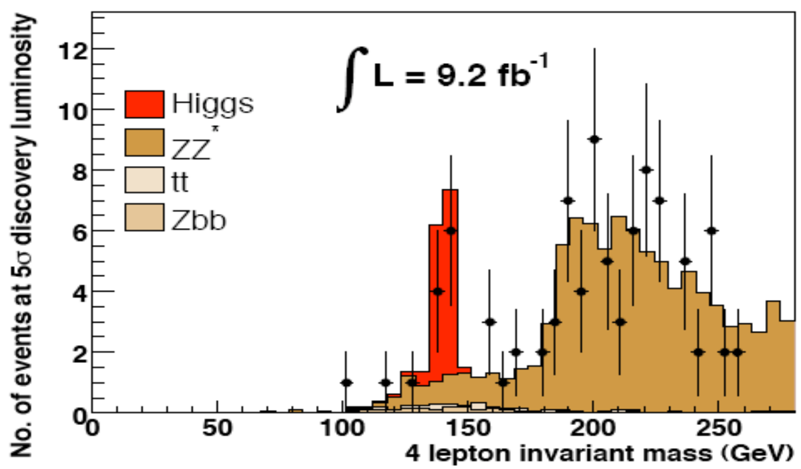
Zbb -> 4 leptons

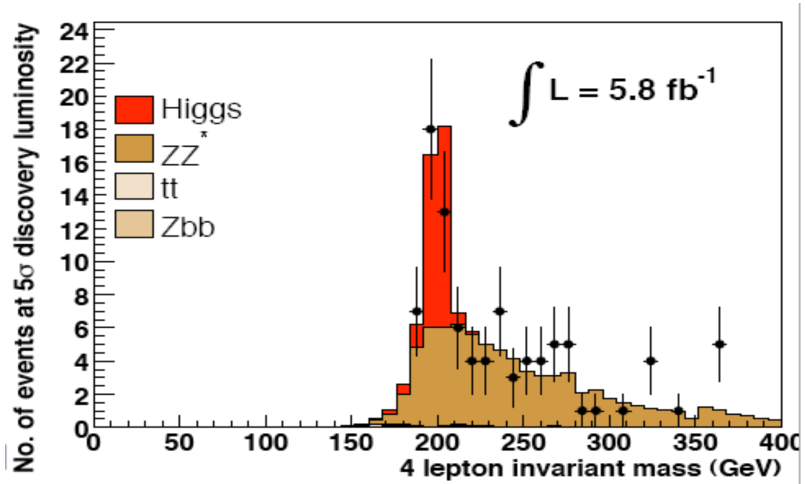
$t\,\bar{t}$ -> 4 leptons (also non resonant)

Reduced by isolation cuts + anti impact parameters

Typical rejection ~ 100 for Zbb => rejected one order of magnitude below ZZ

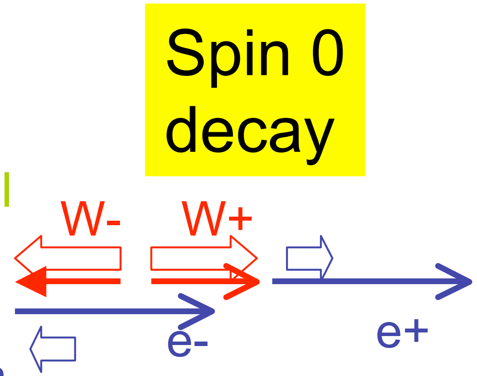
Clean but low statistics (especially < 130 GeV and ~170 GeV)





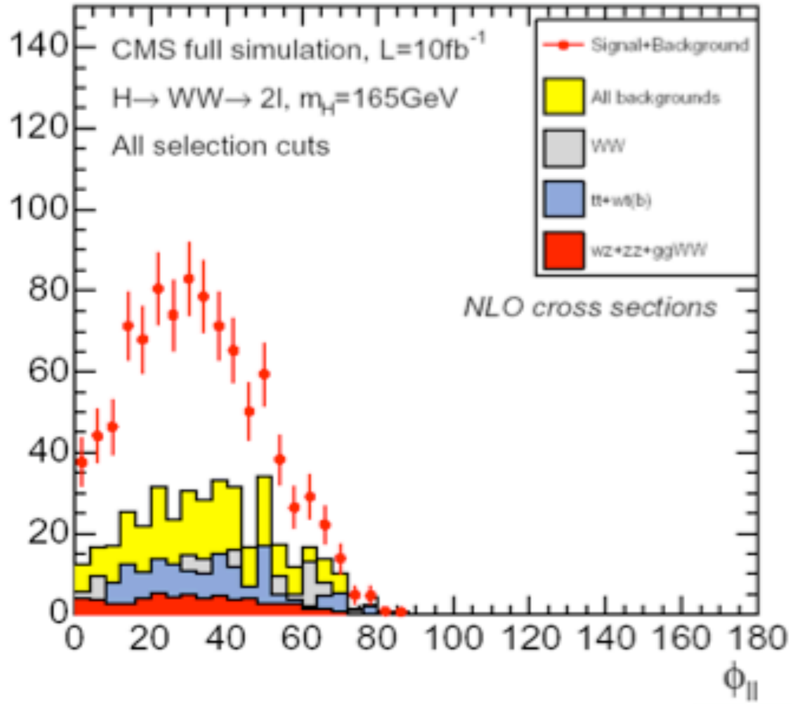
$H \rightarrow WW^*$

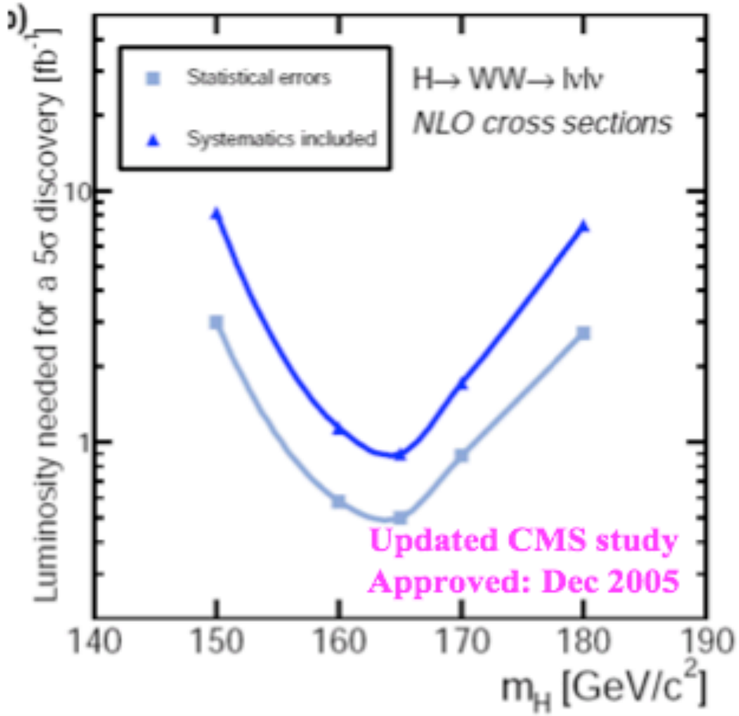
- In gluon fusion production
- Main interest is near M_H ~160 GeV:
  - BR($H \rightarrow WW$) >95%, other decay modes are suppressed
- Look at dilepton final state (ee,$\mu\mu$ and eμ)
- Backgrounds:
  - t-tbar production: rejected by jet-veto
  - WW continuum: Use spin correlation to distinguish signal from background
- Difficulty:
  - Counting experiment, essentially no mass reconstruction and no mass peak
  - Rely on accurate estimate of background rate
  - Strategy: Use control region(s) to estimate background(s) and extrapolate to signal region
- New developments:
  - Include $gg \rightarrow WW$ continuum contribution: Small increase in background but shape more similar to signal
  - Include both t-tbar and single top backgrounds @ NLO *(Les Houches 2005)*



Selection (CMS note 2006-047):

2 leptons η<2, 30<p_t^{max}<55 GeV, p_t^{min}>25 GeV
Etmiss>50 GeV
No jet Et(raw)>15 GeV
$\Delta\varphi$ <45°, 12<M_{ll}<40 GeV



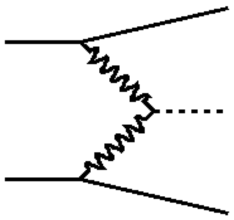


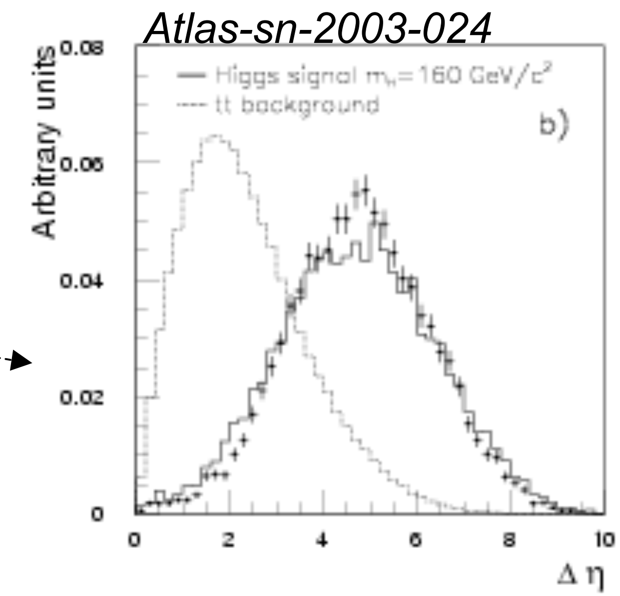
Systematic uncertainty on total bkg ~13%(normalized in control samples for t $\bar{t}$ and qq →WW, relies on MC for single top and gg →WW)

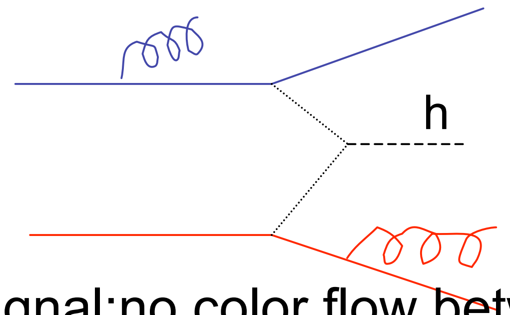
Will need detailed studies with data

VBF Higgs production

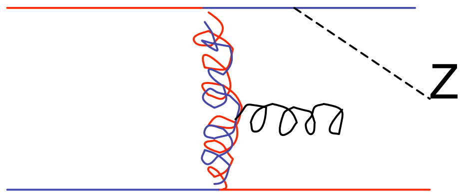
- Forward tagging jets
  - Pt ~$M_W/2$
  - Large separation in η
- No jet radiation in central region







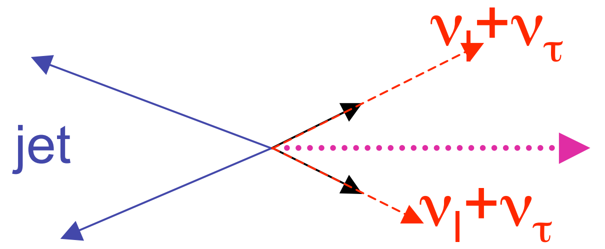
Signal:no color flow between tagging jets



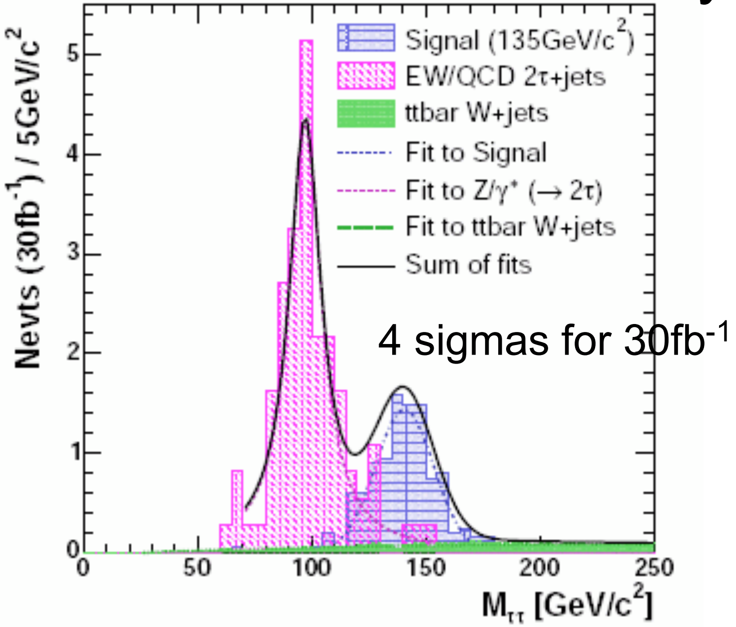
Most backgrounds: strong "acceleration" of color charge between tagging jets => radiation

VBF $H \rightarrow \tau\tau$

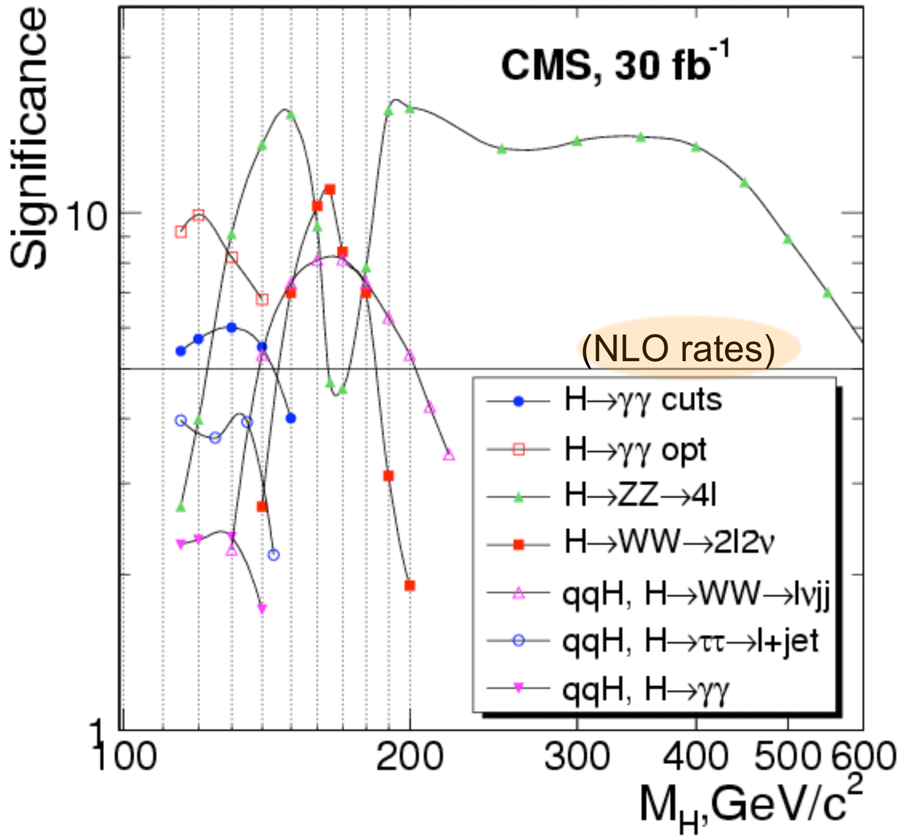
- Typical selection:
  - 2 tagging jets
  - Higgs decay products in central region between tagging jets
  - Jet veto
  - Lepton-lepton or lepton-hadron final state for tau decays
  - Use missing transverse momentum + collinear approximation of tau decays to reconstruct invariant mass of tau pair
  - Resolution limited by missing pt resolution: ~10 GeV-13 GeV
- Main background:
  - $Z \rightarrow \tau\tau$ + 2 jets. Dangerous for low M_H



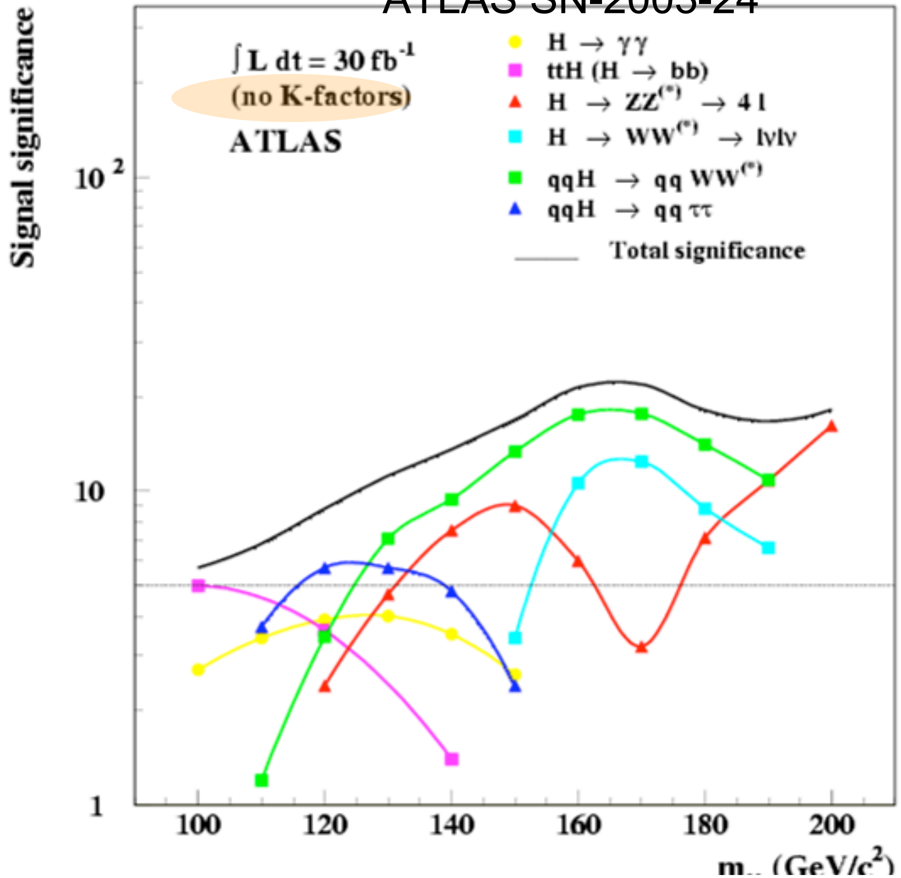
CMS full simulation study



SM Higgs Discovery potential



ATLAS SN-2003-24



-note difference between LO and NLO cross-sections

-For M_H ~115 GeV, several channels can be combined

-In principle, already good discovery potential with $10fb^{-1}$

Provided detector performances and background systematics are under control

Background systematics and how to normalize bkg from data

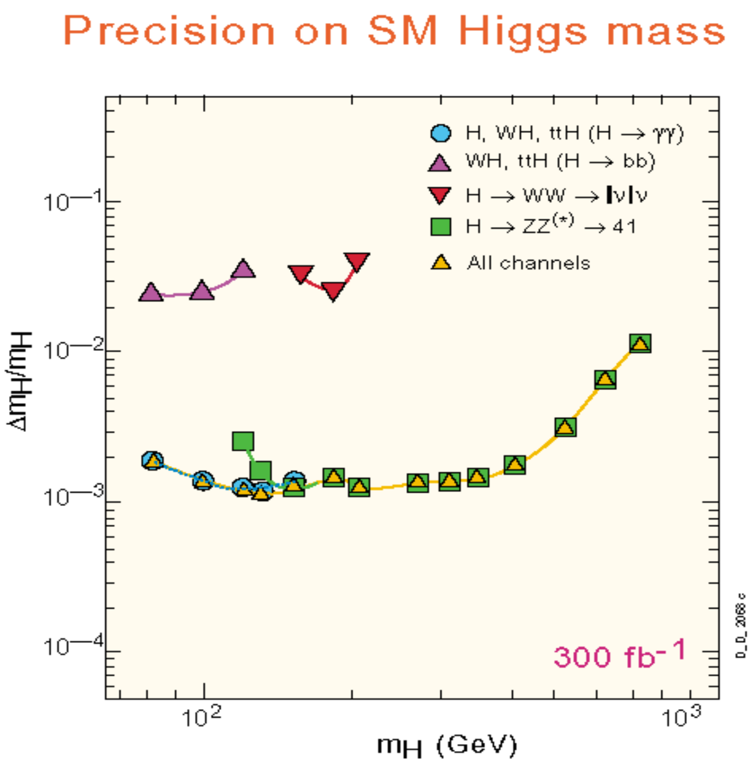
Channel	Main background	S/B	Bkg. sys for 5s	Proposed technique/comments
H->γγ	Irreduc. γγ Reducible qγ	3-5%	0.8%	Side-bands (bkg shape not known a priori)
ttH H->bb	ttbb	30%	6%	Mass side-bands Anti b-tagged ttjj ev.
H->ZZ*-> 4 lep	ZZ->4l Reducible tt, Zbb	300-600%	60%	Mass side-bands Stat Err <30% 30fb^{-1}
H->WW*->llνν	WW*, tW	30-150%	6-30%	No mass peak Bkg control region and extrapolation
VBF channels In general	Rejection QCD/EW	Study forward jet tag and central jet veto		Use EW ZZ and WW QCD Z/W + jets
VFB H->WW	tt, WW, Wt	50-200%	10%	Study Z,W,WW and tt plus jets
VBF H->ττ	Zjj, tt	50-200%	10-40%	Mass side-bands Beware of resolution tails

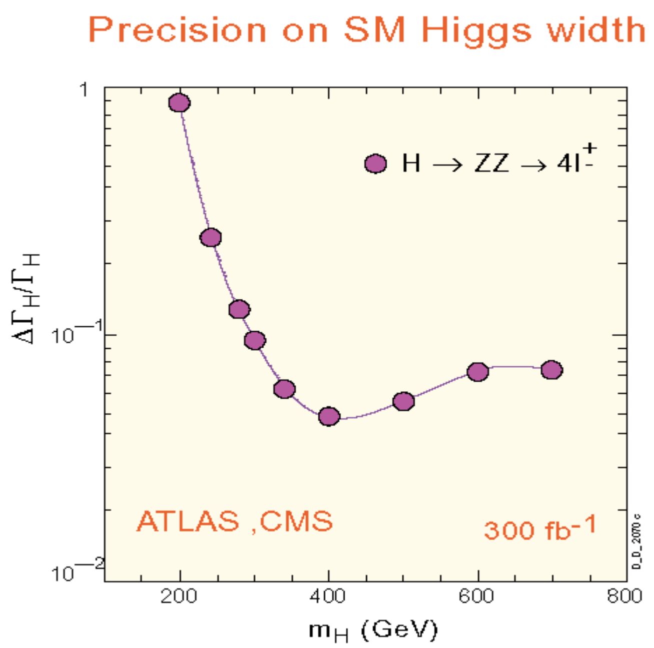
Higgs boson properties

- Mass,Width
- Spin,CP (SM 0^{++})
- Couplings to other bosons and to fermions
- Higgs auto-coupling

Higgs mass measurement

- Relatively easy from H→γγ or 4leptons. The channel H→ττ can also contribute at low luminosity



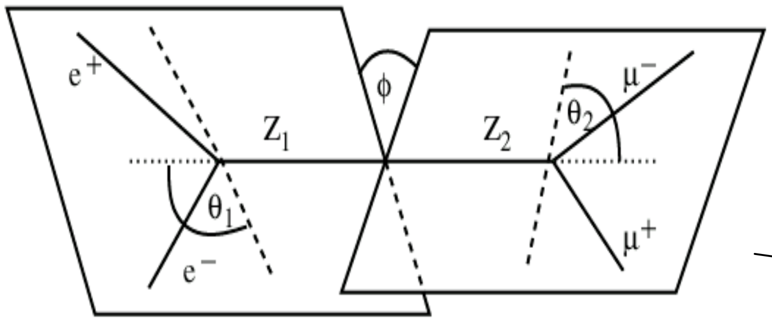


Γ(H) only directly accessible for m>200 GeV

Spin,CP

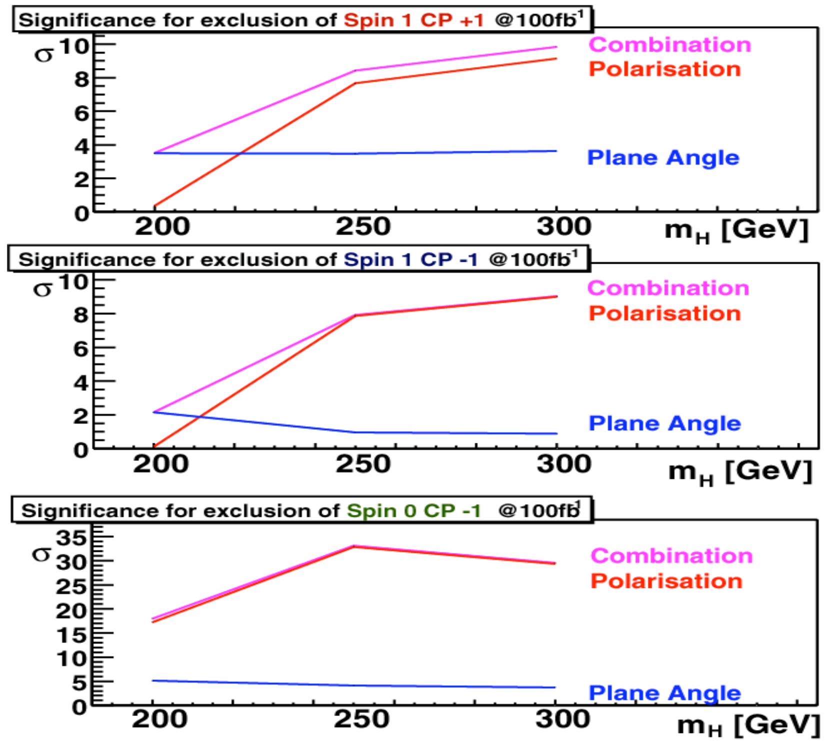
Observation of gg→H or H→γγ excludes spin 1

For M_H>200 GeV, study spin/CP from H→ZZ→4l



Θ→Z polariation
φ→plane angle

Atlas-sn-2003-025

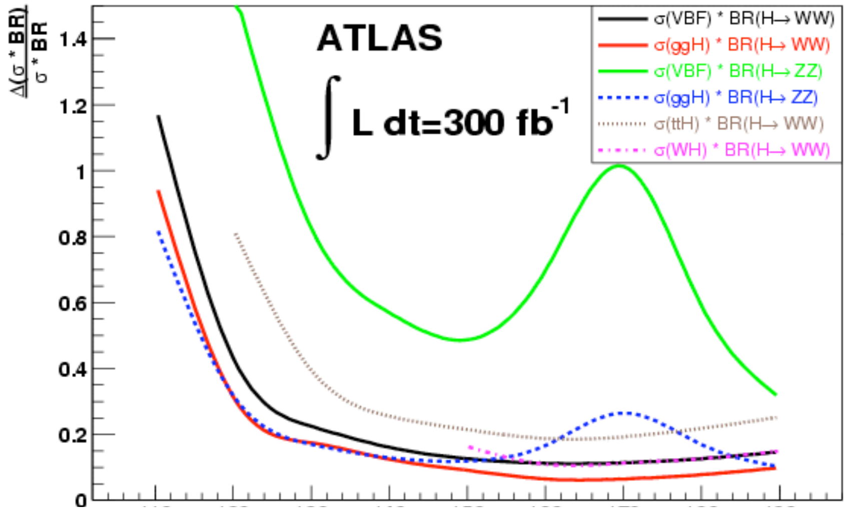


CP Properties of HWW coupling can be studied from VBF processes

Couplings

Concentrate on “low” M_H

Atlas note phys-2003-030



First step:

Assume spin 0

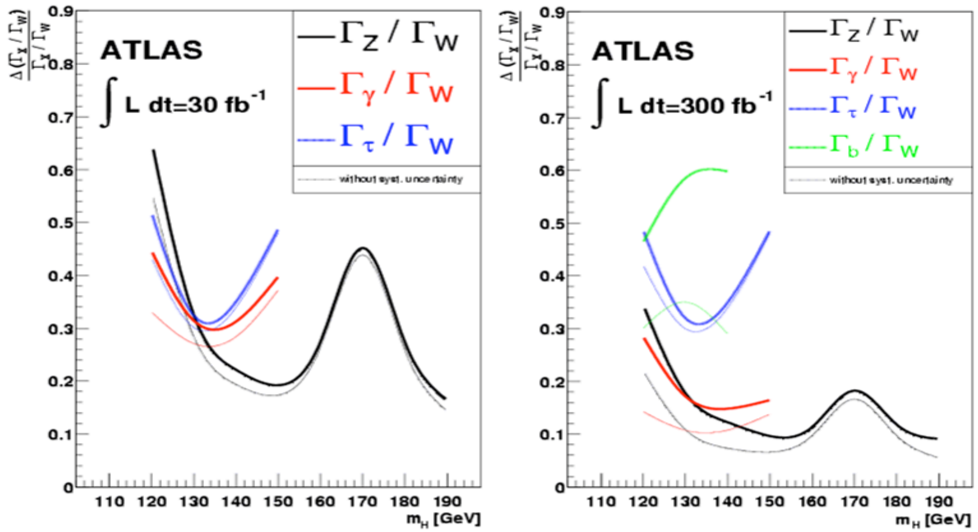
⇒Measure σ.BR in different channels

Uncertainties:

Selection efficiencies

Background subtraction

(Luminosity for absolute cross-sections)



Second step:

Assume only H

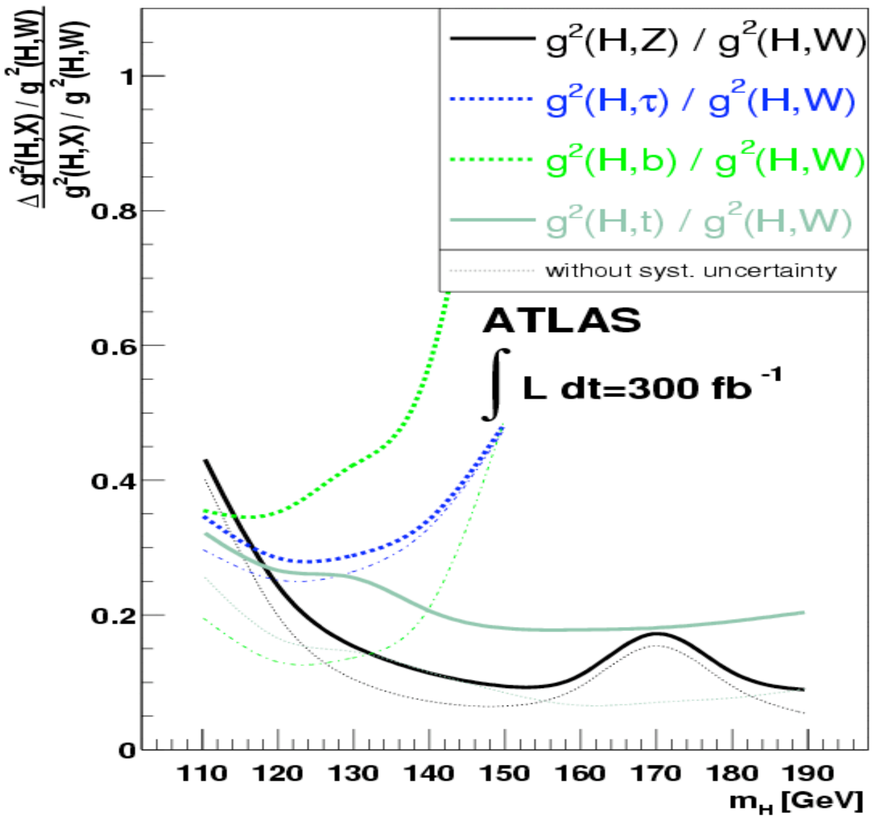
⇒Ratio of BR

Third step:
-No new particles in loop,
-No strong coupling to light fermions
⇒Express all rates and BR as a function of 5 couplings $g_W, g_Z, g_{top}, g_b, g_\tau$

Example:
σVBF: $a_{WF} \cdot g_W^2 + a_{ZF} \cdot g_Z^2$
BR(γγ): $(b_1 \cdot g_W^2 - b_2 \cdot g_{top}^2)/\Gamma_H$

« Abolute » scale not measurable:
Measure $g_Z/g_W, g_{top}/g_W, g_\tau/g_W$ and $g_W/\sqrt{\Gamma_H}$

Syst uncertainties from exp+theory



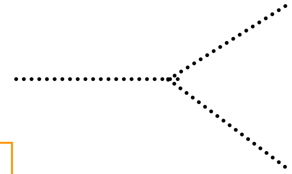
Most difficult: b Yukawa coupling
VBF HW->l bb feasibility ?

If more assumptions (like $g_W < g_W SM$), can get abolute couplings

Auto-coupling

At SLHC ?

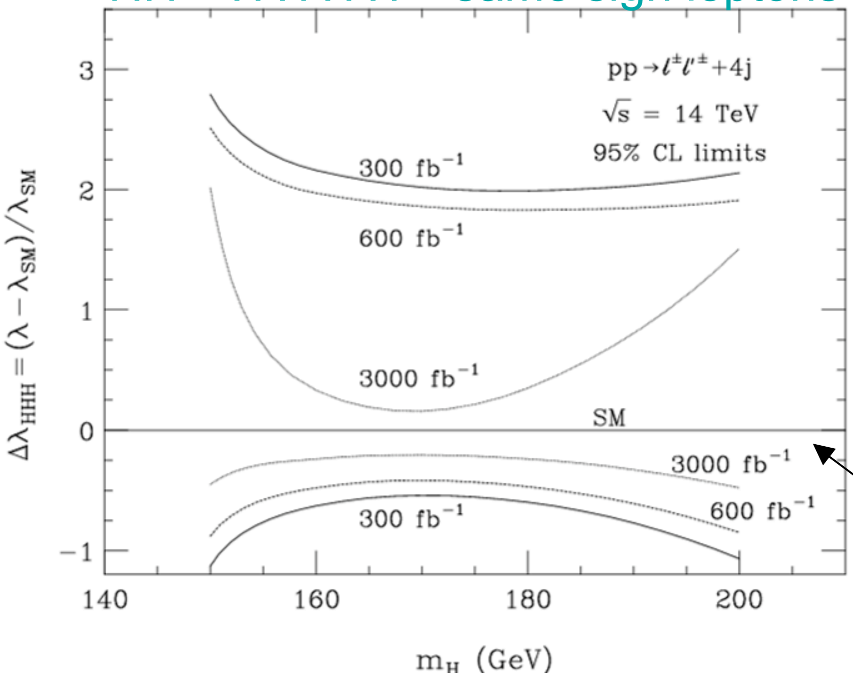
From Higgs potential:
trilinear coupling



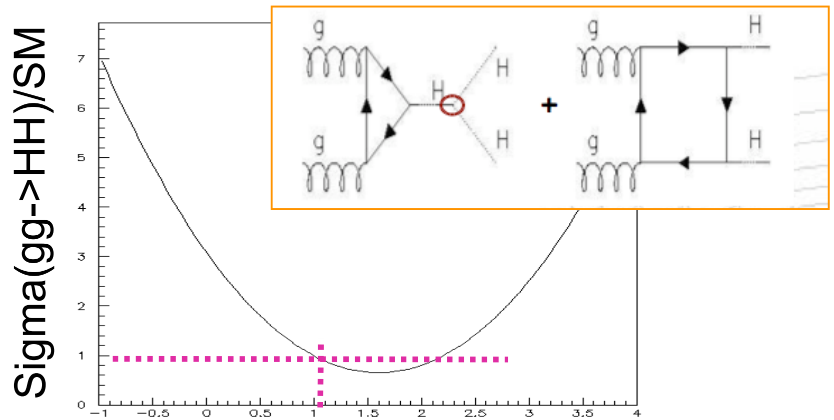
$$\frac{-3\,i\,g\,m_H^2}{2m_w}$$

Look at Higgs pair production
Small x-sec, ~ 20fb (before BR!)

HH→WWWW→same sign leptons



m_H=170 GeV



λ/λSM

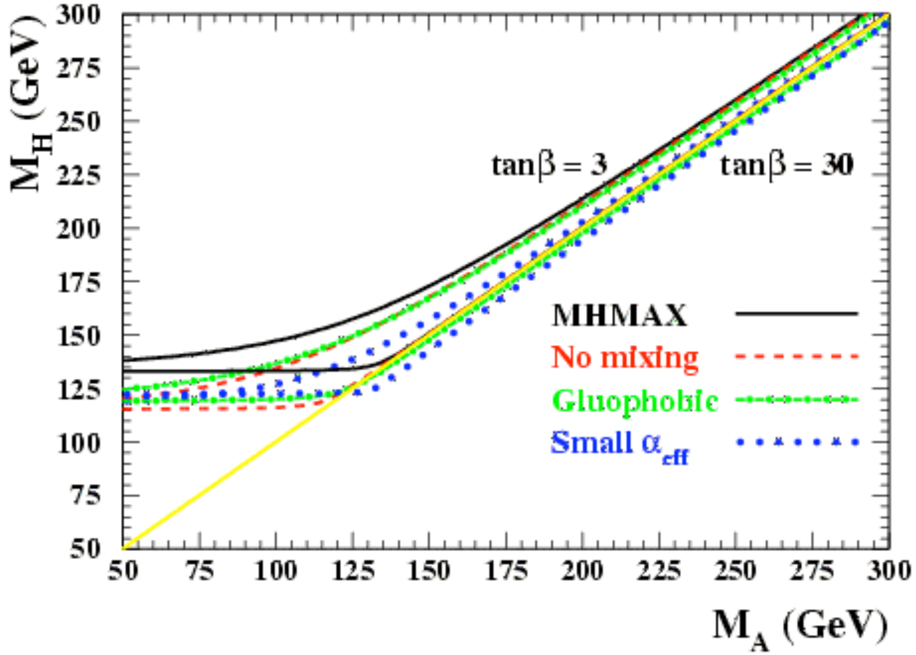
Parton level study
Baur,Plehn,Rainwater hep-ph/0211224
Still to be confirmed by more detailed exp.
Studies including bkg systematics

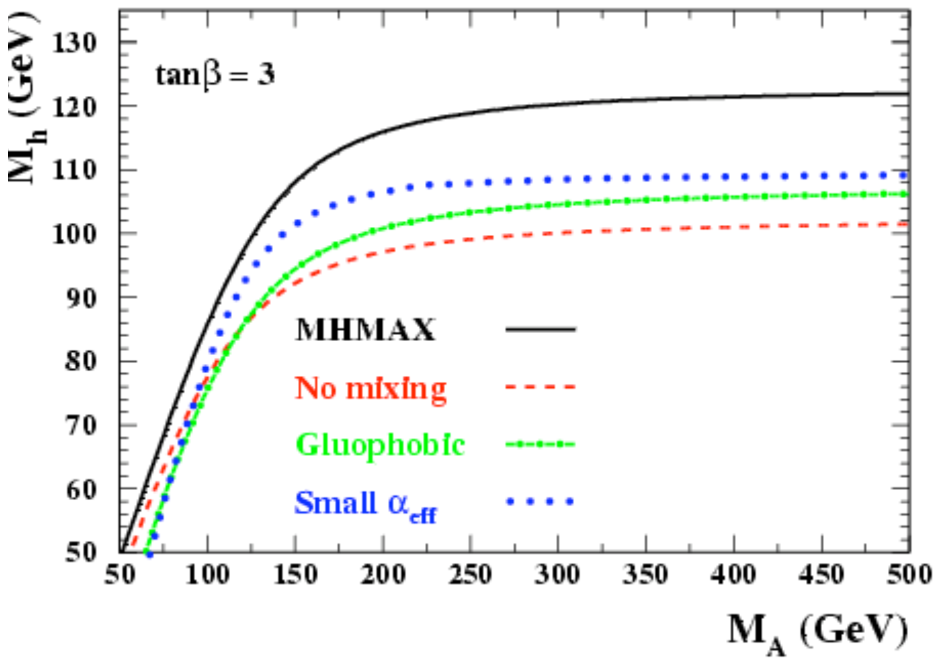
MSSM Higgs searches

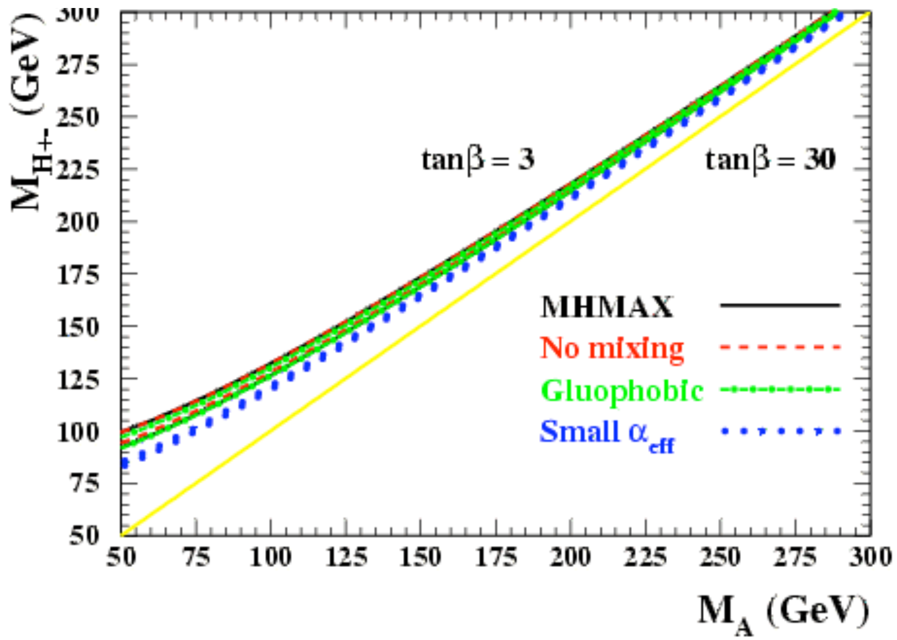
- 2 Higgs doublets
- 5 physical states after EW symmetry breaking
  h,H,A,$H^{\pm}$ (h,H CP=+1, A CP=-1)
- 2 parameters at tree level
  - Usually use M_A and tan(β)
  - $M_h < M_Z$ at tree level
- Large radiative corrections
  - Introduce dependence on other Susy parameters
  - Increase upper bound on M_h ~ 135 GeV
- Define few scenario *(Carena et al, hep-ph/0202167)*
  - "M_h^{max}",gluophobic (minimizes effective ggh vertex), no-mixing,small α_{eff} (reduces hbb)
- CP violating scenario are also investigated (not discussed here)

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$	$g_{\Phi AZ}$	$g_{\Phi H^{\pm}W^{\mp}}$
H_{SM}	1	1	1	0	0
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\mp\cos(\beta-\alpha)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$	$-\sin(\beta-\alpha)$	$\pm\sin(\beta-\alpha)$
A	$\cot\beta$	$\tan\beta$	0	0	1

$\cos 2\alpha = -\cos 2\beta \, ((M_A^2-M_Z^2)/(M_H^2-M_h^2))$


tanβ = 3
tanβ = 30
MHMAX
No mixing
Gluophobic
Small α_{eff}
M_H (GeV)
M_A (GeV)

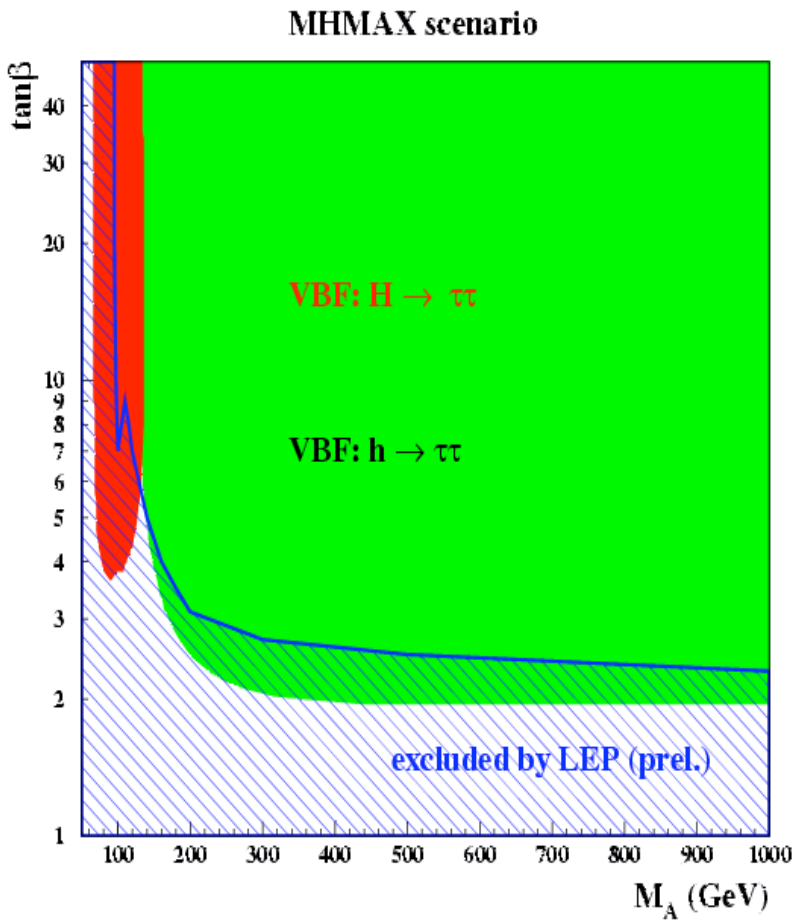

tanβ = 3
MHMAX
No mixing
Gluophobic
Small α_{eff}
M_h (GeV)
M_A (GeV)


tanβ = 3
tanβ = 30
MHMAX
No mixing
Gluophobic
Small α_{eff}
M_{H+-} (GeV)
M_A (GeV)

MSSM Higgs Searches

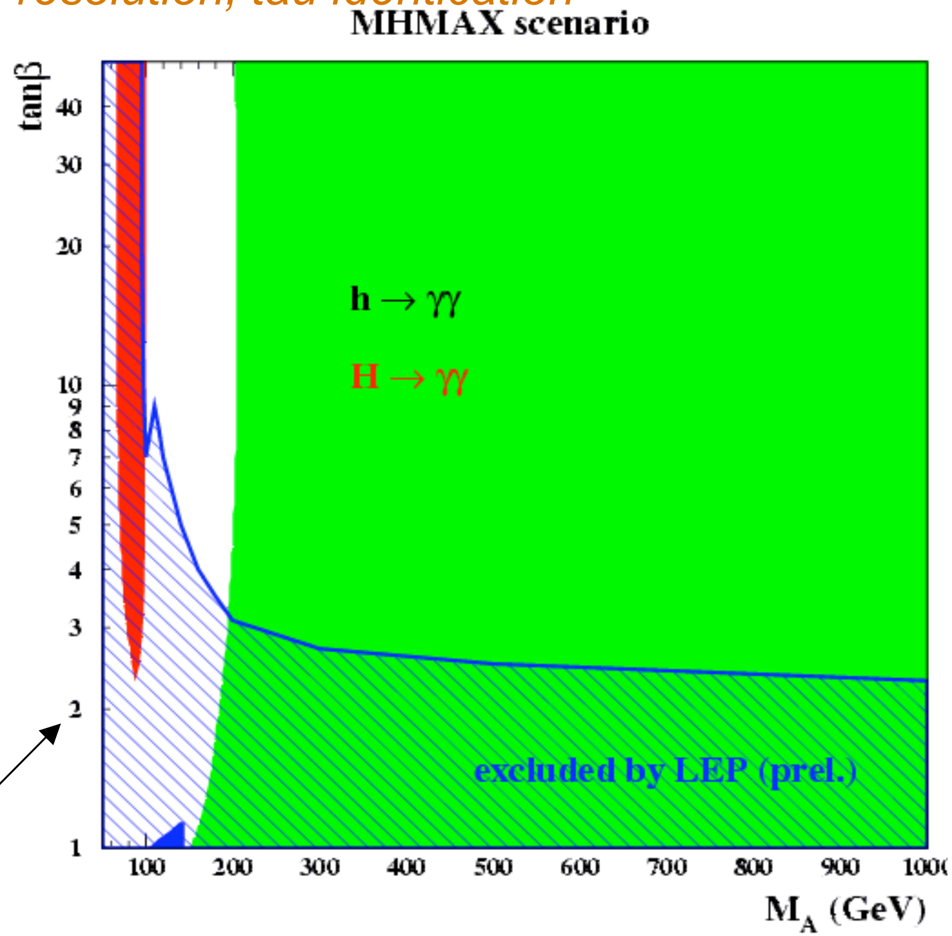
- Apply SM searches
  - Rescale cross-section and BR
    - $\sigma(gg \to h) = \sigma_{SM}\, \Gamma(h \to gg)_{MSSM} / \Gamma(h \to gg)_{SM}$
    - $\sigma(VBF \to h) = \sigma_{SM} \sin^2(\alpha - \beta)$
  - Mostly relevant for h searches when it is SM like (also for H at low M_A)
- Direct searches of $H/A \to$ SM particules
  - Degenerate in mass in most of parameter space
  - Cross-section $gg \to bb\ H/A \sim \tan^2(\beta)$ => explore large $\tan(\beta)$
    - Final state $H/A \to \tau\tau$ (BR ~10%) or $\mu\mu$ (BR ~ 3.10^{-4})
    - Can tag or not the “soft” b produced in association with Higgs
    - $H/A \to bb$ challenging (trigger)
- Direct searches of $H^{\pm}$
  - $gg \to t\ b\ H^{\pm}$ production followed by $H^{\pm} \to \tau\nu$ or tb
  - Produced in top decays if mass < top mass
- Searches of Susy→h (not discussed here) or Higgs→Susy (→4leptons+Etmiss, →invisible, …)

Application of SM Higgs searches



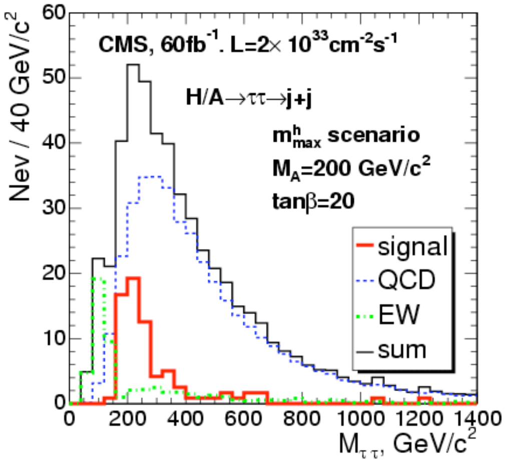
VBF H,h -> ττ
with 30 fb^{-1} (ATLAS)

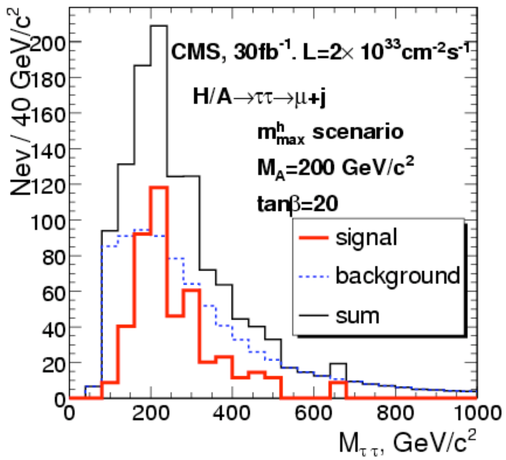
Difficult channel: tagging jet, Etmiss resolution, tau identication



H,h ->γγ
with 300 fb^{-1} (ATLAS)

H,A →ττ searches (CMS example)





Lepton-Lepton, Lepton-hadron and hadron-hadron final states

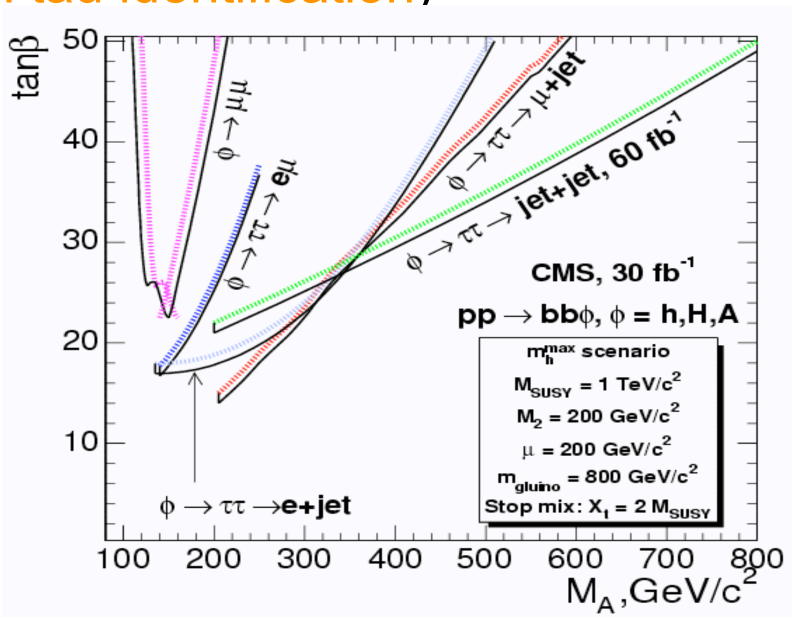
Mass reconstruction with collinear approximation (Etmiss resolution)

Can tag or not soft-b's

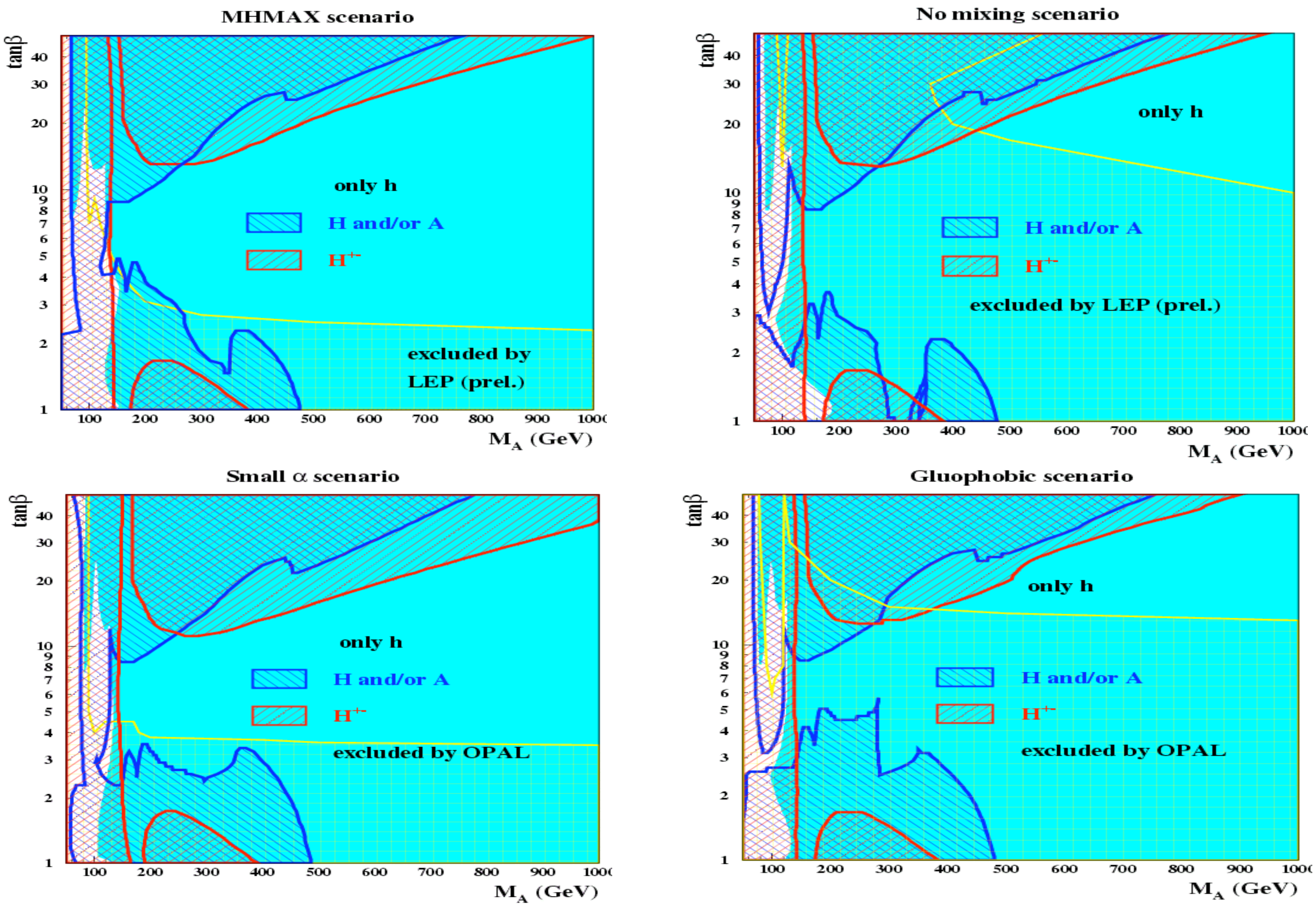
Main backgrounds:

Z/Drell-Yan, ttbar, W+jets

QCD (for hadron-hadron final state, need powerful tau identification)

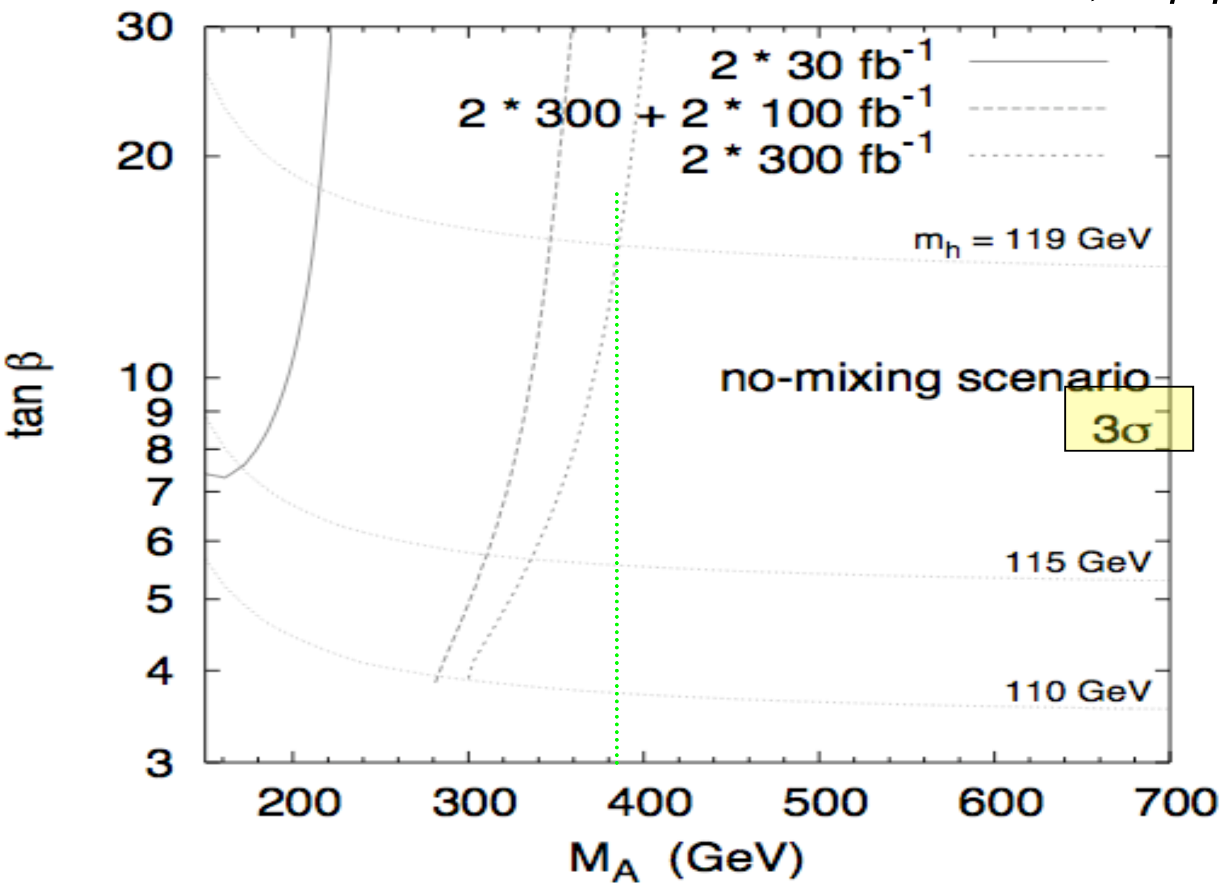


MSSM Summary for 300 fb^{-1} (ATLAS) no H->Susy



If tan(β) ~10, M_A>200 GeV, only h is seen
Can we observe deviation in coupling measurements ?

M.Duehrssen et al, hep-ph/0407190



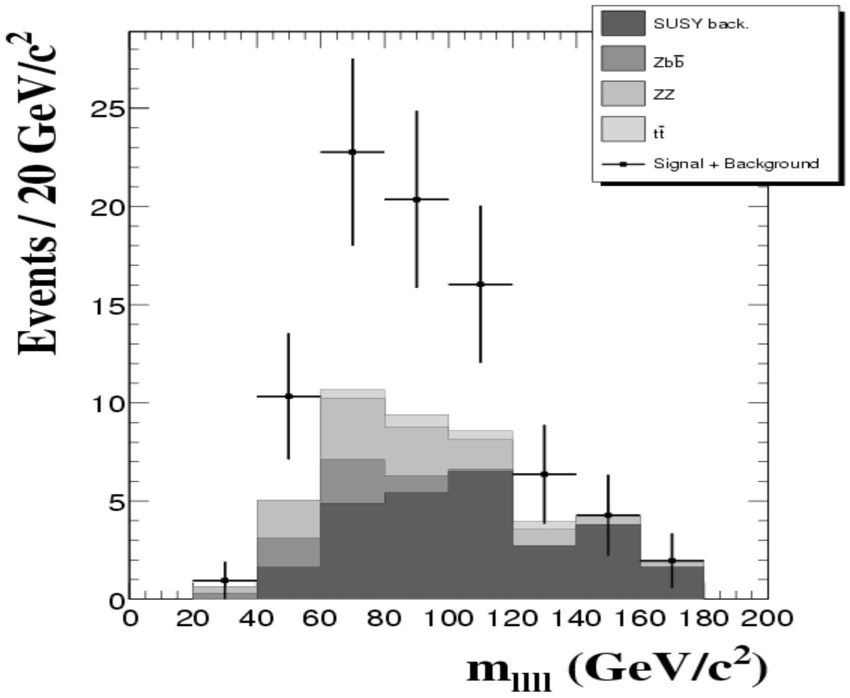
(5 sigmas effect up to 300 GeV)

Example of H->SUSY

$H \to \chi\chi \to 4$ lepton + Etmiss
Nice experimental signature
Can cover intermediate tan(β), M_A
SUSY parameters dependent

Example for mSUGRA
$m_0=50$,$_{m1/2}$=150,$A_0=0$,
tan(β) =5, μ>0

Visible mass



$H \to$ invisible also considered (in some non-minimal SUYS models or more exotics models)

Conclusions

- Many SM Higgs channels have been studied in details
  - Already good sensitivity to SM Higgs with ~10 fb^{-1}
  - Provided detector performances and backgrounds are under control. *Only data will tell*
- Detailed Higgs studies will require more statistics (as well as WW scattering at high energy)
- MSSM Higgs sector covered
  - But could observe only h “SM like”
- Stay open to more complicated scenario