Higgs boson searches at LHC

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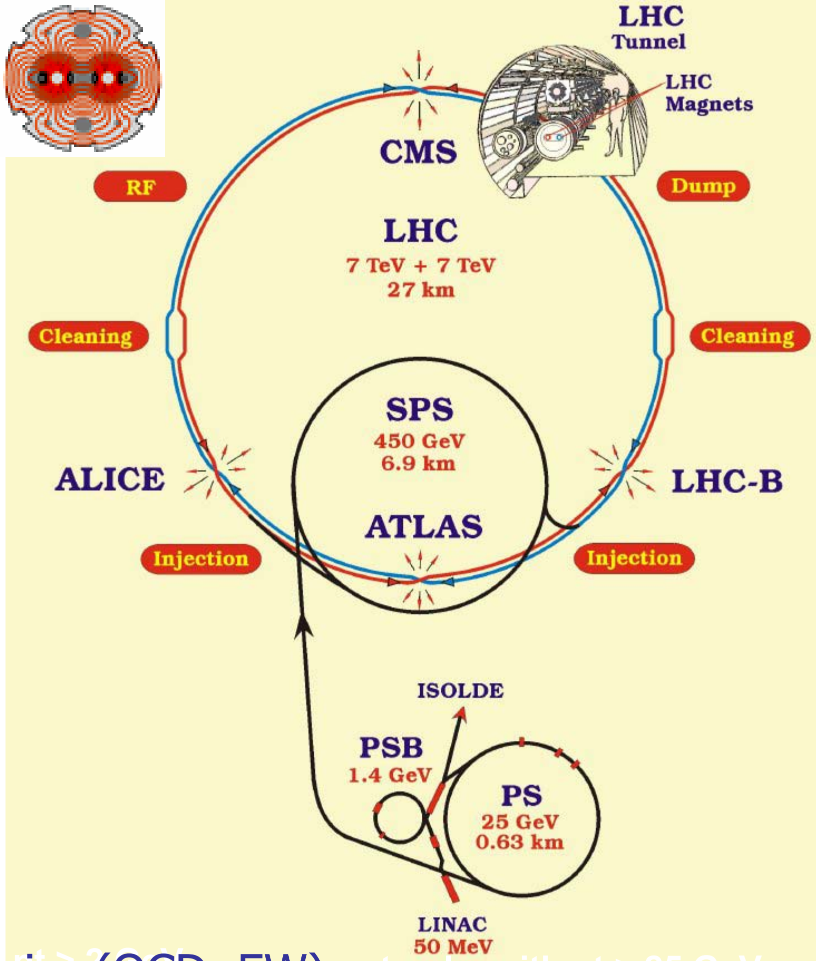
Catania, 30/3 – 01/04/2005

The Large Hadron Collider

p-p collider

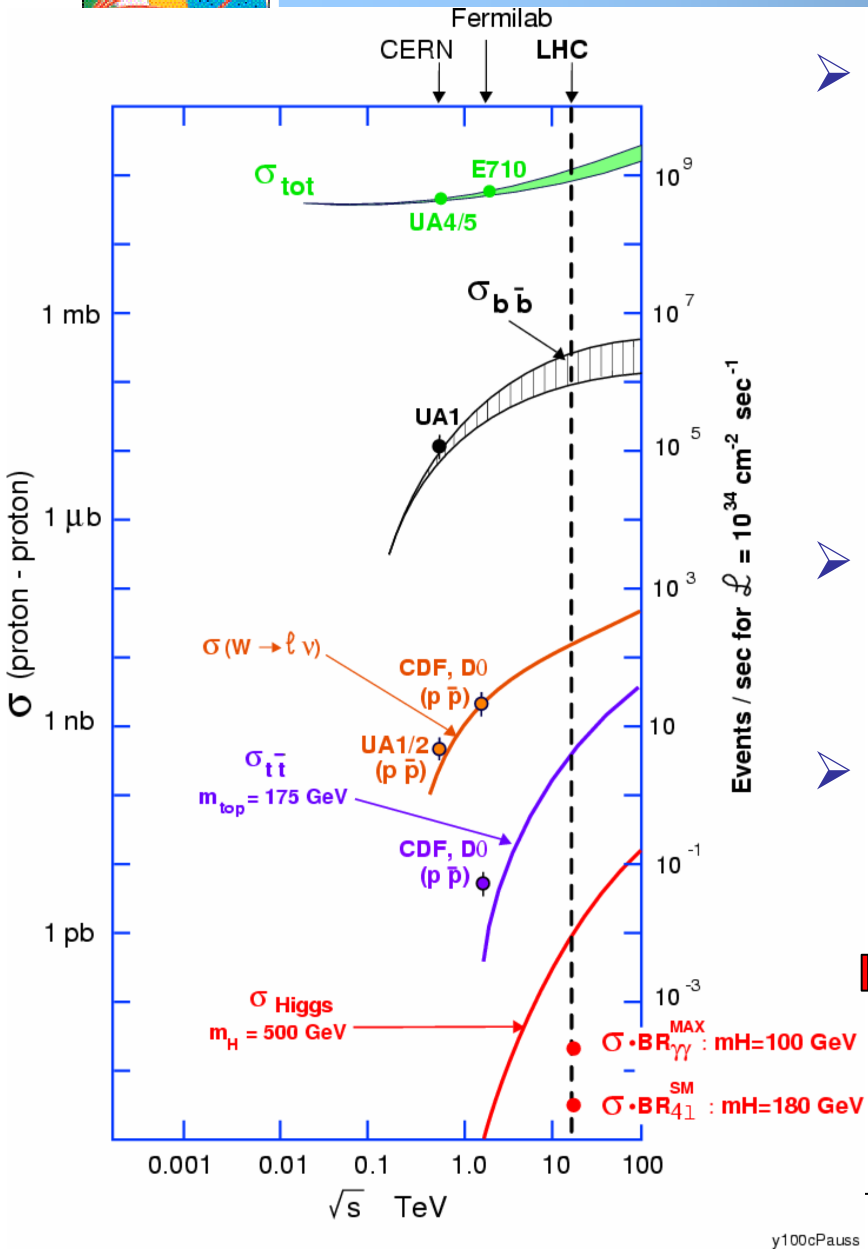
Beam Energy 7 TeV
Bunch Crossing Rate 40 MHz
Luminosity
Low 2×10^{33} $cm^{-2}s^{-1}$ = 2×10^{6} $mb^{-1}Hz$
High 10^{34} $cm^{-2}s^{-1}$ = 10^{7} $mb^{-1}Hz$
Interaction Rate ~1 GHz
Interactions/Crossing ~23 (@ High Lumi.)
basically minimum bias events



Physics goals:

- SM Higgs boson discovery
- Supersimmetry discovery
- B-physics, Top quark physics, Standard physics (QCD, EW)
- Heavy Ion physics

LHC Physics



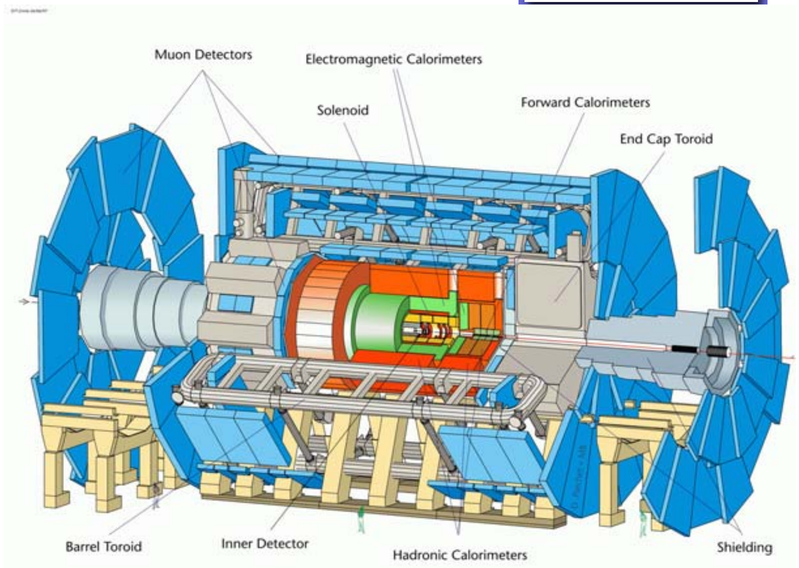
- Cross-sections of physics processes vary over many orders of magnitude
  - Inelastic σ(pp) = 55 mb;
  - heavy-flavor factory:
    σ(bb)= 500 μb; σ(tt)= 1 nb;
  - vector-bosons factory;
  - $\sigma(H) = O(10\ pb)$ (m_H=200 GeV)
- Low cross sections for discovery physics (Higgs production)
  - → Rejection power $O(10^{13})$ (H->γγ 120 GeV)
- Huge event rate
  - → Highly Selective Trigger System

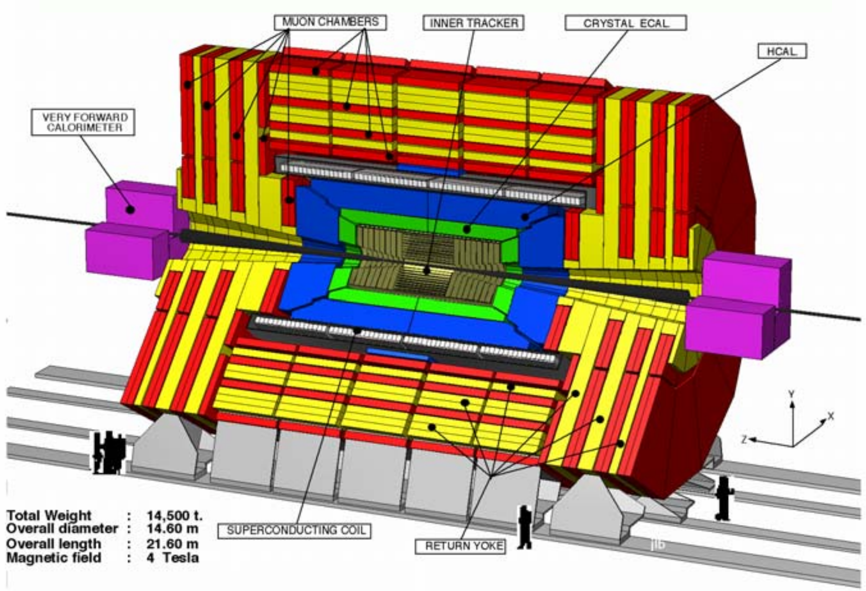
Extreme demands on detectors:
- high granularity
- high radiation environment
- high data-taking rate

ATLAS & CMS

General pourpose detectors optimized for Higgs boson and New Physics search

- Variety of signatures
  - γ, $e/\mu/\tau$, E_T^{miss}, b, t, jets
- Experimental requirements
  - Large acceptance in η coverage
  - Precise muon detection system (trigger & p_T meas. - e.g. $H \rightarrow ZZ \rightarrow 4\mu$)
  - Very good em calorimetry (excellent e/γ identif., good E resol. - e.g. $H \rightarrow \gamma\gamma$)
  - Good hermetic jet and E_T^{miss} calorimetry (e.g. $H \rightarrow \tau\tau$)
  - Efficient tracking, vertex reconst. (good IP resol. - e.g. $H \rightarrow bb$)

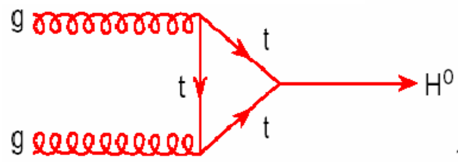




SM Higgs production @ LHC

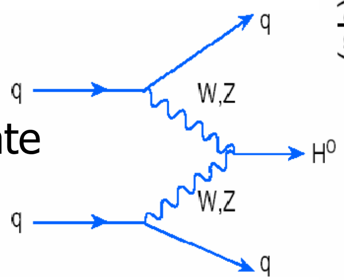
Four main production mechanisms

g g fusion

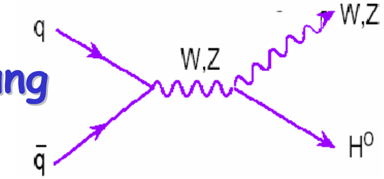


- Largest rate
- k = 1.5÷1.8

WW, ZZ fusion

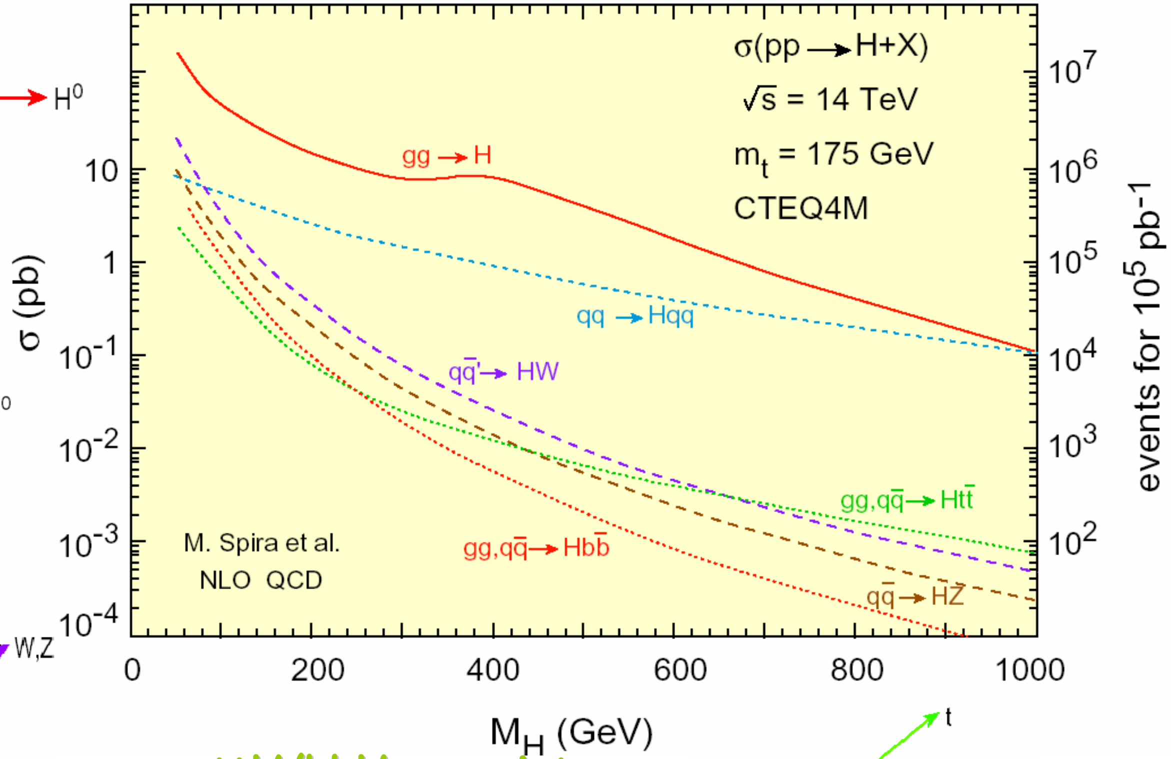


- Second largest rate
- k ~1.1
- two forward jets with high inv. mass

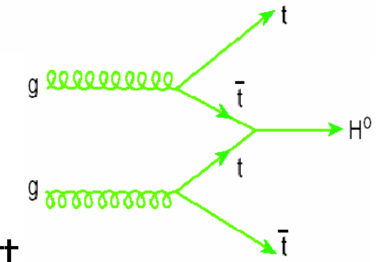


W, Z bremsstrahlung

- k ~1.3
- Same coupling as in WW, ZZ fusion, different partonic luminosity
- Trigger on 1 or 2 leptons @ high p_T



ttH/bbH associate production



- k ~1.2
- Reconstruction of tt pair allows bkg discrimination

SM Higgs decays

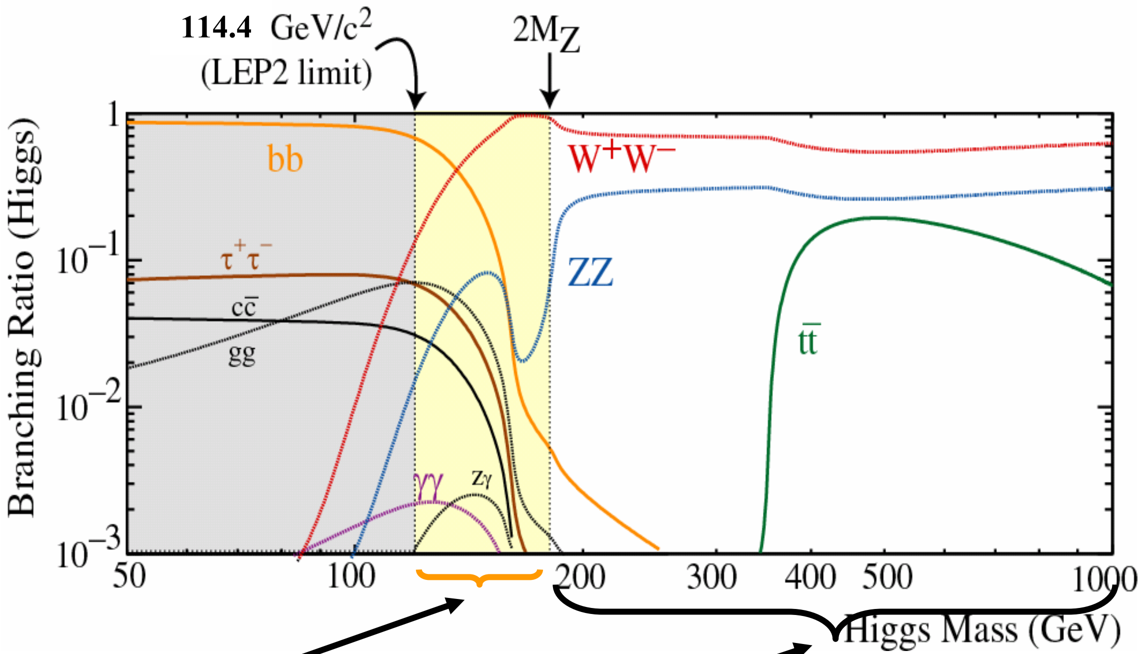
Higgs couples to the heaviest possible particles:

H ⟶ bb dominates ...
... until WW, ZZ thresholds open

Large QCD backgrounds:
σ (H → bb) ≈ 20 pb;
σ (bb) ≈ 500 μb

⟹ no hope to trigger/extract fully had. final states

⟹ look for final states with e(μ), γ



Low mass region: $m_H < 2\ m_Z$:

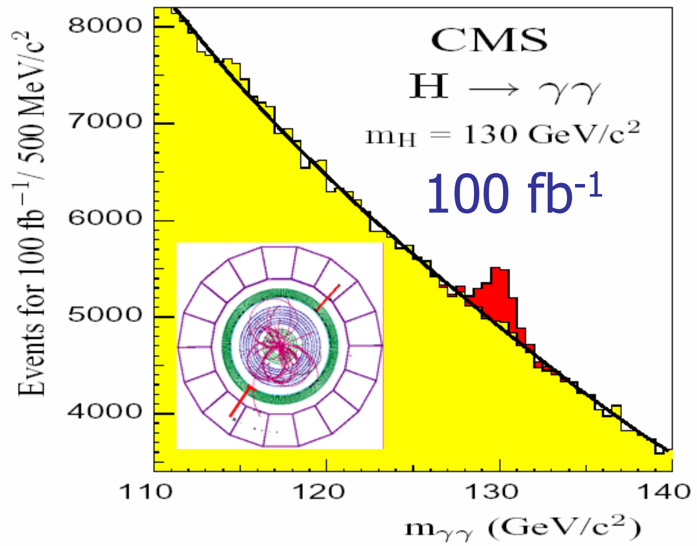
H → bb : good BR, poor resolution ➔ ttH, WH
H → γγ : small BR, but best resolution
H → ττ : via VBF
H → ZZ* → 4l
H → WW* → lνlν or lνjj : via VBF

$m_H > 2\ m_Z$:

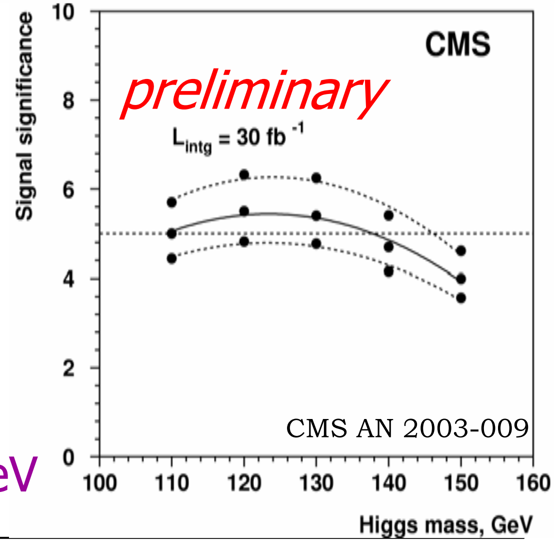
H → ZZ → 4l "golden channel"
qqH → ZZ → ll νν *
qqH → ZZ → ll jj *
qqH → WW → lνjj *
* forward jet tagging

Low mass Higgs: $H \to \gamma\gamma$

- Rare decay mode ($BR \sim 10^{-3}$) accessible for $m_H < 150$ GeV
- Look for mass peak
  - achieve ≈1% resolution on m_H
  - severe requirements on ECAL:
    - acceptance, energy and angle resolution, γ/jet and γ/π^0 separation
    - motivation for LAr/$PbWO_4$ calorimeters



- Inclusive production mode $pp \to H \to \gamma\gamma X$:
  - σ_{NLO}*BR= 91.1 fb (m_H = 120 GeV)
- Large background (S/B ≈ 1:20):
  - smooth continuum of $\gamma\gamma$ pairs
    - Dominant, irreducible
    - can be estimated from sidebands
  - γj and QCD jets with mis-identified γ's



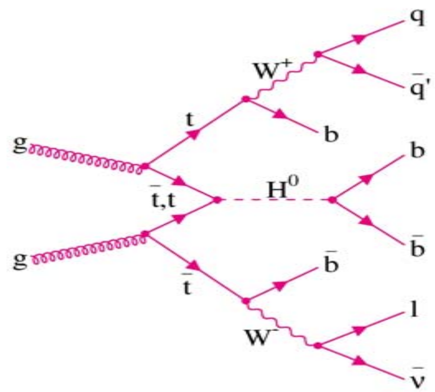
ATLAS study: $S/\sqrt{B}$ ~6 for 30 fb^{-1}, m_H= 120 GeV

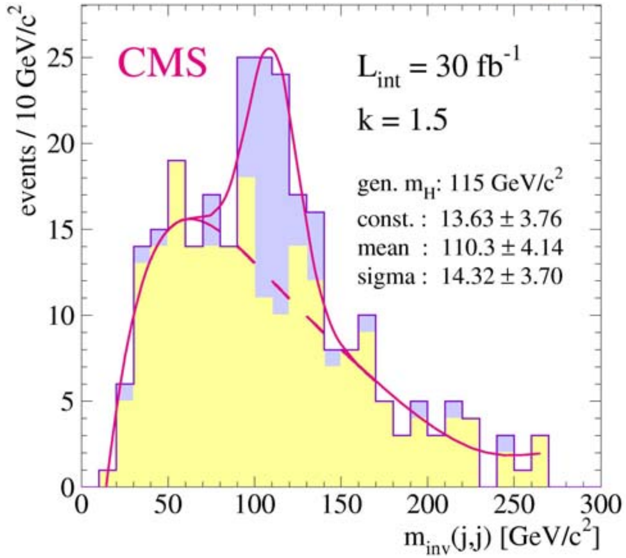
Low mass Higgs: ttH → ttbb

- Complementary to $H \rightarrow \gamma\gamma$ for $m_H \leq 130$ GeV
  - $\sigma_{LO}(ttH)*BR(H \rightarrow bb) = 1.09 - 0.32$ pb
- Complex final state topology:
  - 1 high p_T isolated lepton (trigger) and E_T^{miss}
  - ≥ 6 jets out of which ≥ 4 b-tagged jets
- b-tagging and jet energy performance crucial !
- Backgrounds
  - ttbb, Ztt, tt+jets, W+jets
  - Systematic uncertainties: mainly from ttjj bkg

    Significant discrepancy between ATLAS and CMS

    σ_{LO} sensitive to factoriz. scale, PDF and parton level cuts
- Likelihood based study
  - b-tagging of 4 jets, anti-b-tagging of 2 jets
  - mass reconstruction of $W^{\pm}$ and 2 top quarks





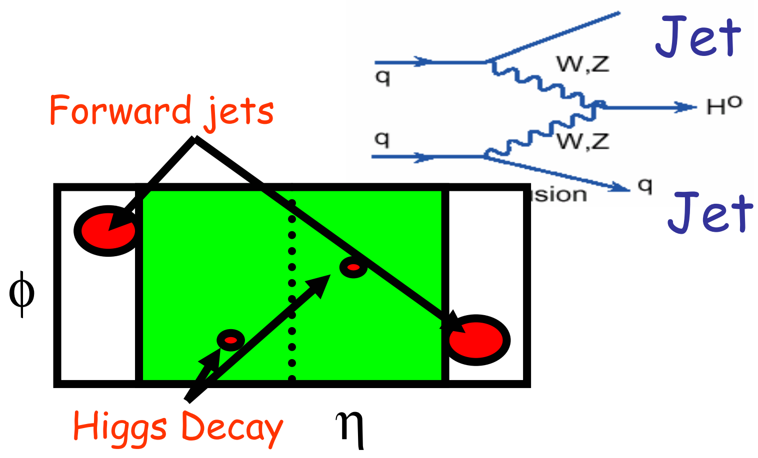
ATLAS(CMS)	L=30 fb^{-1}, no K-factors		
m_h (GeV) =	120	130	140
$S/\sqrt{B}$	2.8(3.5)	1.9(2.8)	1.0

ATLAS: results of a new analysis respect to TDR
ttbb from AcerMC, new PDF, new QCD-scale

Higgs searches via VBF

Motivation

- Strong discovery potential for m_H< 150 GeV
- Determine Higgs coupling to W/Z
- Useful for Invisible Higgs



Production

σ = 4 pb @ 120 GeV = 20% of σ_{total}

Signature

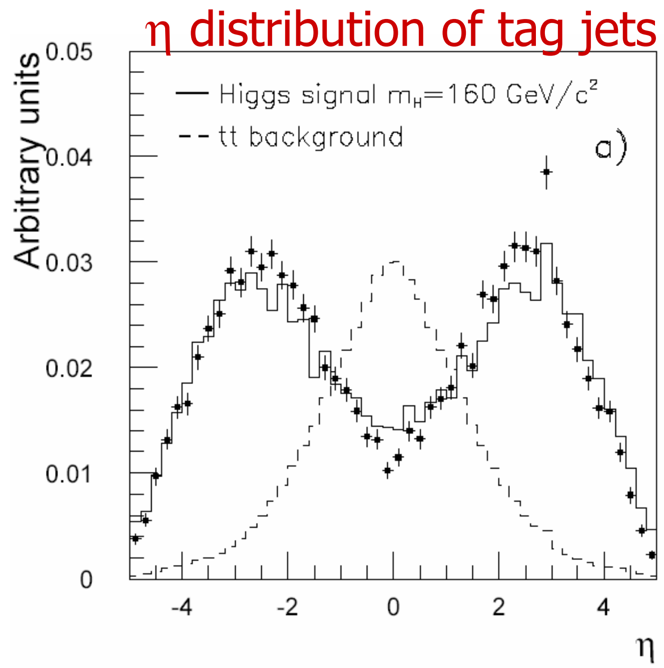
- Two high p_T jets at large η and large $\Delta\eta$

  Tag jets = highest p_T jet in each η-hemisphere
- Lack of colour exchange in initial state

  small jet activity in central region

  ➔ central jet veto (p_T>20 GeV LowLumi)

  (ATLAS Full simulation: fake jet rate <2%)



Decays **(all by ATLAS, red by CMS)**

- $H\to WW\to ll\nu\nu$ and $l\nu jj$
- $H\to\tau\tau\to l\nu\nu l\nu\nu$ $l\nu\nu j$
- $H\to\gamma\gamma$

VBF: $H \rightarrow WW^*$

σ = 500 to 2000 fb for M_H = 120 to 190 GeV

Background

- tt, WWjj, W+4jets

Selection

- VBF cuts, m_{jj},
- 2 isolated high p_T leptons,
- $m_T(ll\nu)$ (against DY)
- τ–jet veto (against $\tau\tau jj$)
- lepton angular correlation (against tt, WW)

(anti-correlation of W spins from H decay)

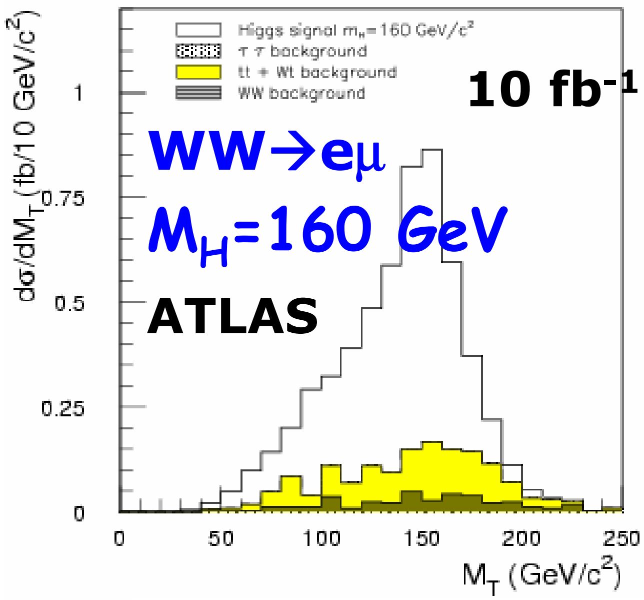
Bkg estimation

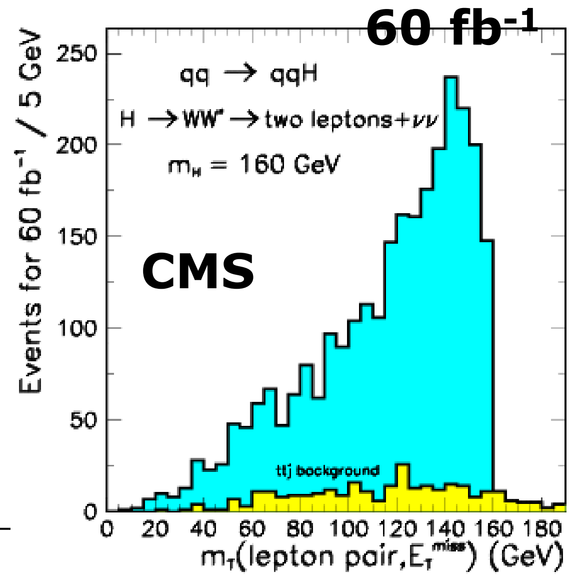
at level of 10% from data + MC shape relaxing lepton cuts

Significance

- >5 @ 10 fb^{-1} (m_H=140 ÷190 GeV)

(combined WW→ll $\nu\nu$ and lνjj, ΔBG = 10%)





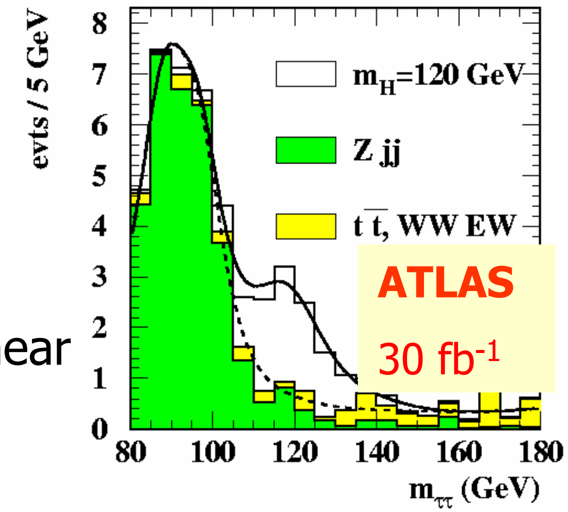
VBS: $H\rightarrow\tau\tau$, $H\rightarrow\gamma\gamma$

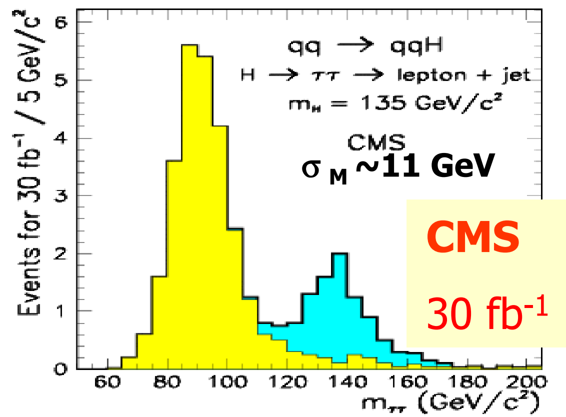
$H\rightarrow\tau\tau$ σ = 300(64) fb @ m_H= 120(150) GeV

- Main Backgrounds
  - $\tau\tau\rightarrow l\nu\nu l\nu\nu$: tt, QCD Zjj
  - $\tau\tau\rightarrow l\nu\nu$ hν : EW & QCD Z($\tau\tau$)jj
- Selection:

  VBF cuts, τ and $M_{\tau\tau}$ reconstruction using collinear approximation (resolution ~10%)
- Background estimate:
  - From sidebands (m_H > 125 GeV)
  - From Z($\tau\tau$) peak (m_H < 125 GeV)

H→ττ→eμ

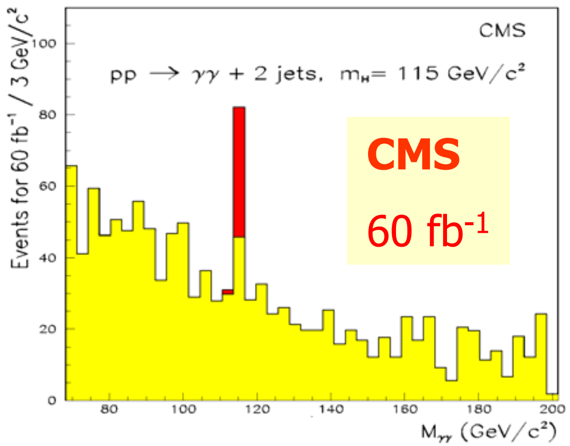




$H\rightarrow\gamma\gamma$

- Main Background: $\gamma\gamma$jj
- Clear improvement respect to inclusive production

  (S/B ~ 1 m_H = 115-140 GeV)



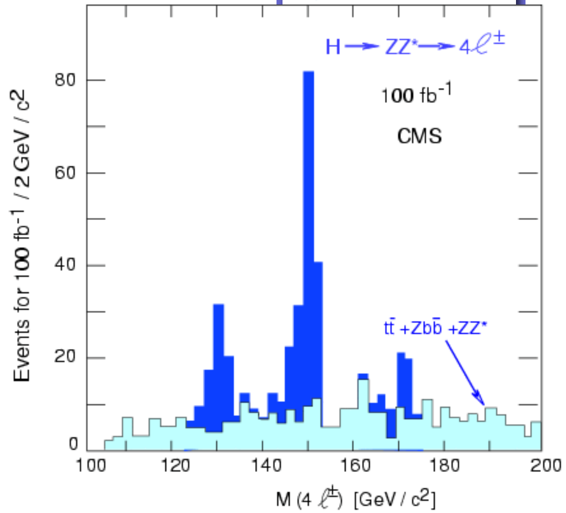
The "golden channel": $H \to ZZ^{(*)} \to 4l$

Very clean signature $H \to ZZ^{(*)} \to l^+l^-l'^+l'^-$ ($l=e,\mu$)

Four isolated high p_T leptons

Three topologies 4μ, $2e2\mu$, $4e$

Valid for the mass range $120 < m_H < 600$ GeV

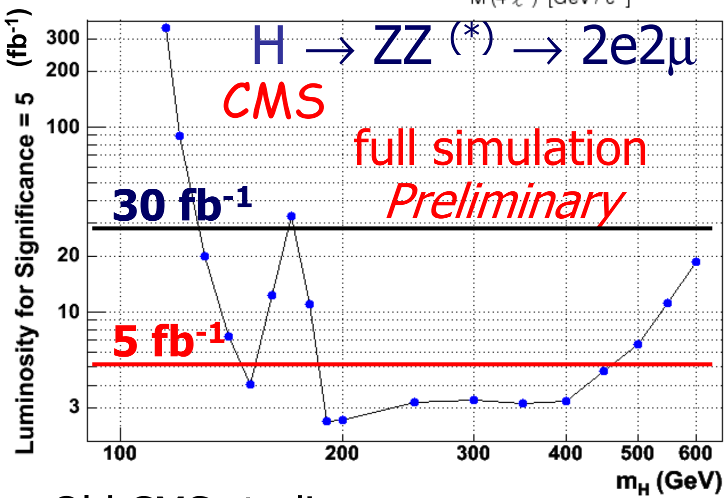


Background

- Irreducible: ZZ   Reducible: Zbb, tt

Selection

- Cut on p_T of four leptons
- Isolation of four leptons (Zbb, tt)
- Impact parameter, vertex (Zbb, tt)
- Mass of two lepton pairs and 4 lepton state



Significance > 5

- With <30 fb^{-1}: $m_H \in [120; 600]$ GeV
- Already at 5 fb^{-1}: $m_H \in [190; 450]$ GeV

Higgs properties

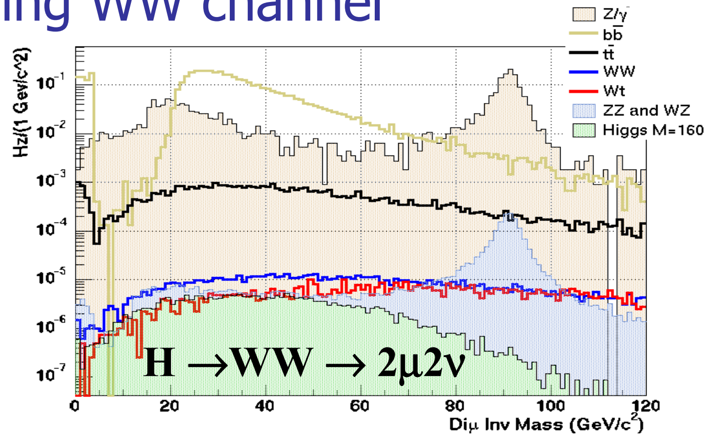
Mass, spin CP quantum numbers

Old CMS studies

Higgs Mass, GeV	120	130	140
4e; L for 5 σ discovery, fb^{-1}	351	106	31
4μ; L for 5 σ discovery, fb^{-1}	152	35	15

Interm. Mass Higgs: $H \to WW^{(*)} \to 2l2\nu$

This channel can contribute in the mass region 160÷180 GeV where the BR ($H \to ZZ$ (*)) is smallest due to opening WW channel

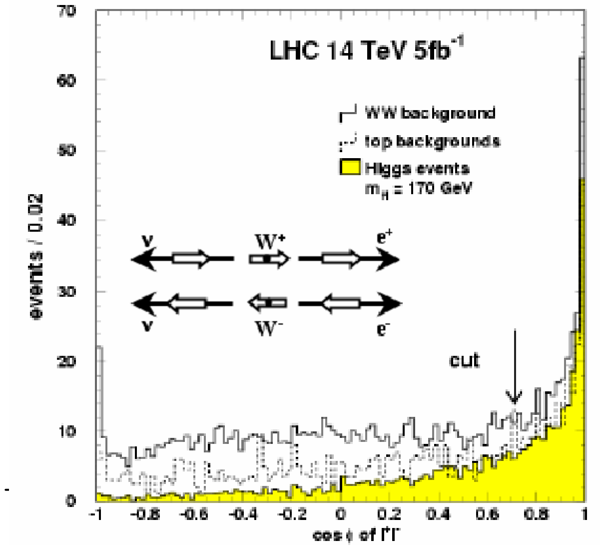


Backgrounds:

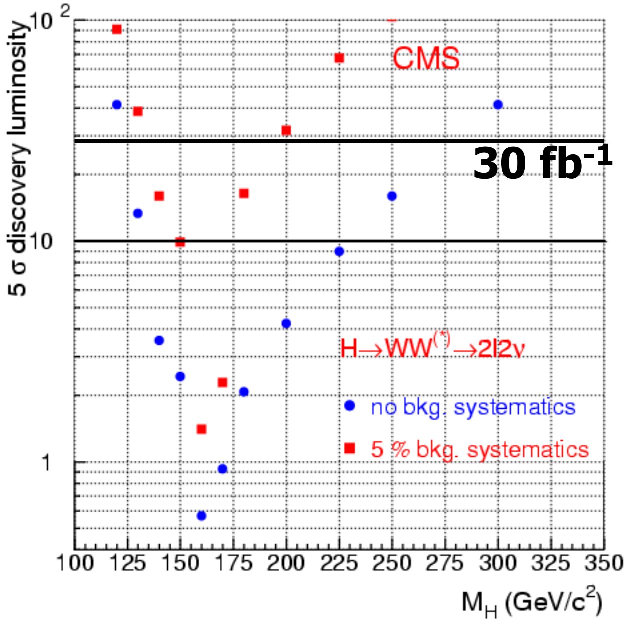
WW, WZ, tt, Wt

Signature:

- 2 isolated high p_T leptons, and 2 neutrinos
- M_T(ll) (No narrow mass peak)
- central jet veto, b-jet veto
- strong lepton angular correlations

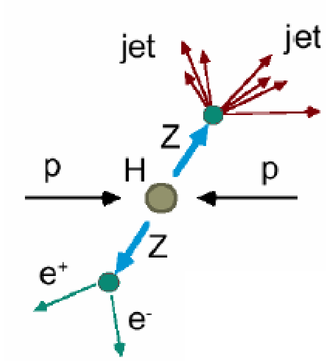


bkg. Systematic (ATLAS/CMS) need more justification;
learn systematic from Tevatron analysis

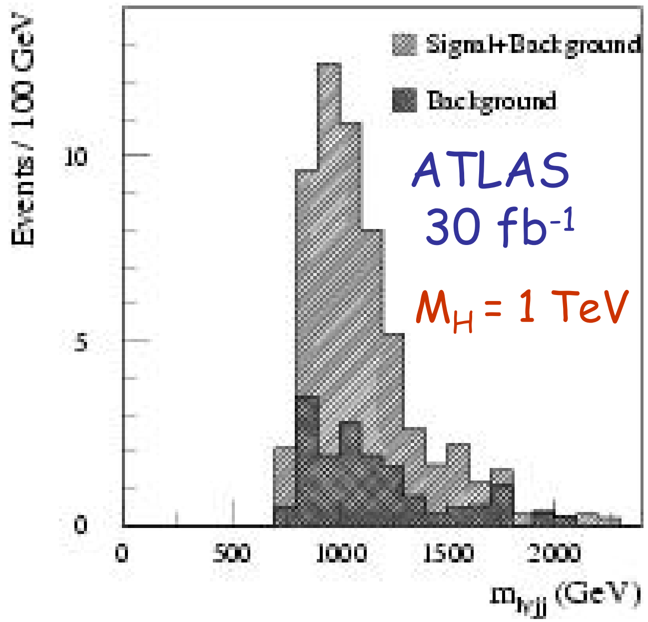


Very High Mass Higgs

- Cross-section O(pb) for m_H>600 GeV
- Higgs width increases dramatically with M_H ($\Gamma_H \propto M_H{}^3$)



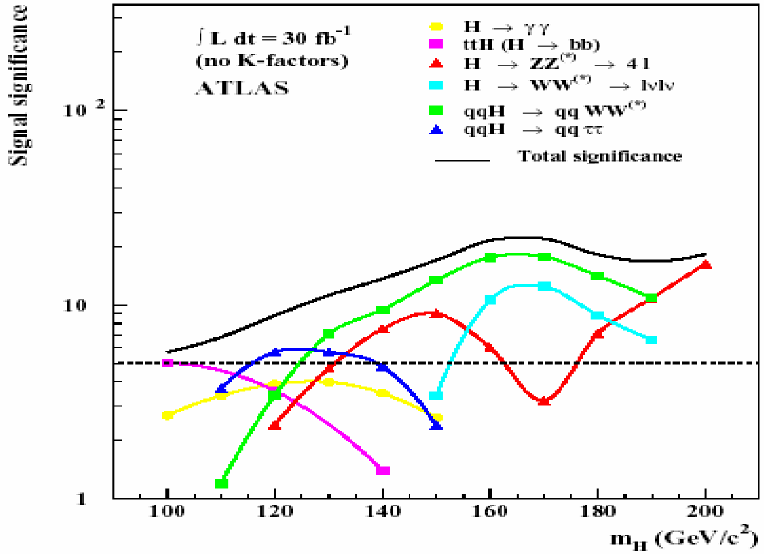
- Need more abundant channels
  - final states: $ll\nu\nu$, $lljj$, $l\nu jj$
- VBF distinctive signature of two very forward jets:
  - qqH → qqZZ → qq$ll\nu\nu$
  - qqH → qqWW → qq$l\nu jj$
  - qqH → qqZZ → qq$lljj$

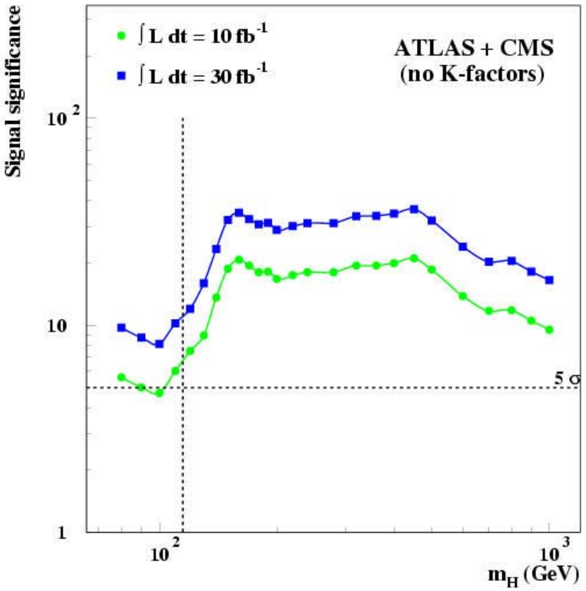


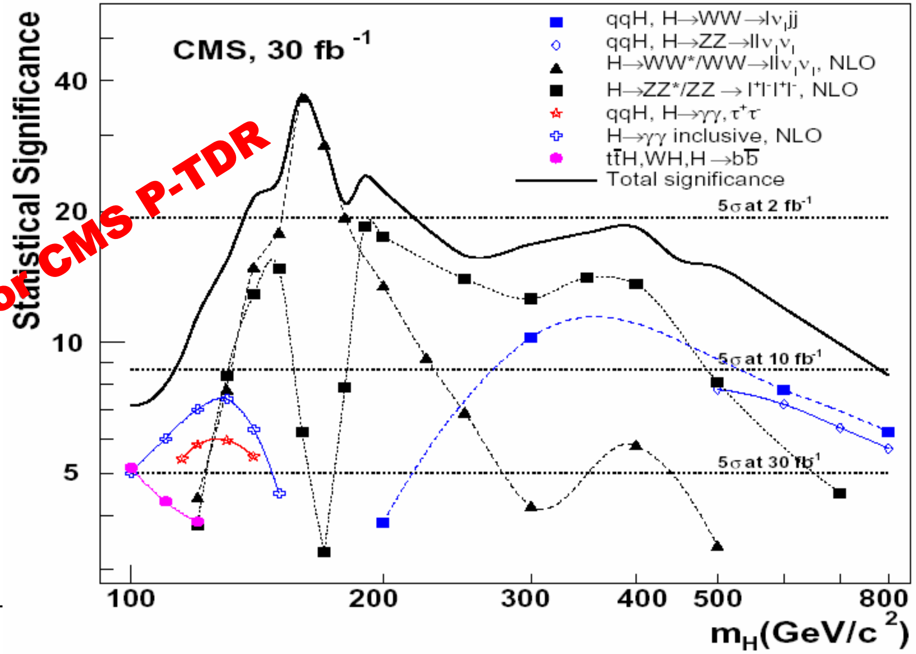
SM Higgs discovery potential

LHC can probe entire set of "allowed" Higgs mass values (100 GeV – 1 TeV)

- ✓ Several channels available over the full mass range
- ✓ Good coverage also at low mass after inclusion of VBF channels
- ✓ Discovery over full mass range possible already at 10 fb^{-1} (< one year at 10^{33} cm^{-2} s^{-1})
  - – However, it will take time to operate, understand and calibrate detectors ...



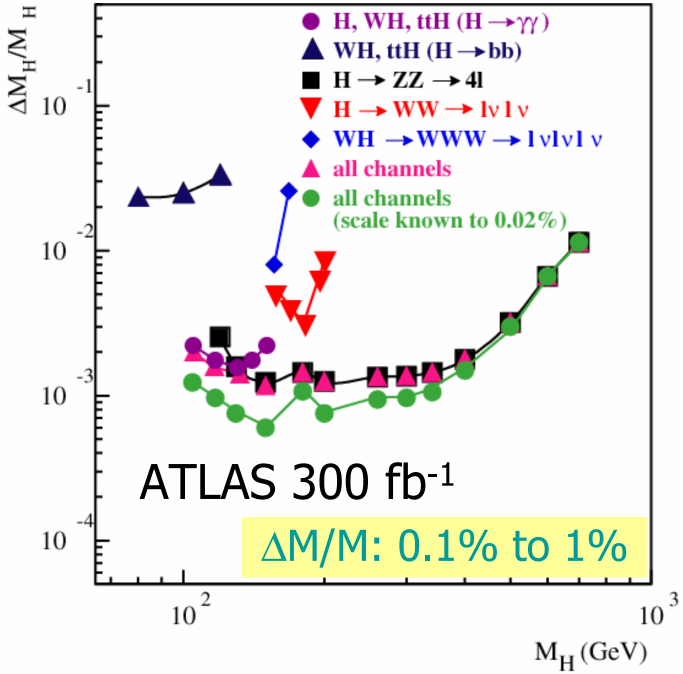




Under update for CMS P-TDR (end 2005)

Higgs Mass & Width Measurements

- Direct where Higgs mass can be reconstructed:
  $H \rightarrow \gamma\gamma$, $H \rightarrow bb$, $H \rightarrow ZZ \rightarrow 4l$
- "Indirect" from Likelihood fit to transverse mass spectrum:
  $H \rightarrow WW \rightarrow l\nu l\nu$,$WH \rightarrow WWW \rightarrow l\nu l\nu\ l\nu l\nu$



Uncertainties

- statistical
- absolute energy scale (0.1% for l/γ, 1% for jets)
- 5% on BG and signal rates for $H \rightarrow WW$ channels

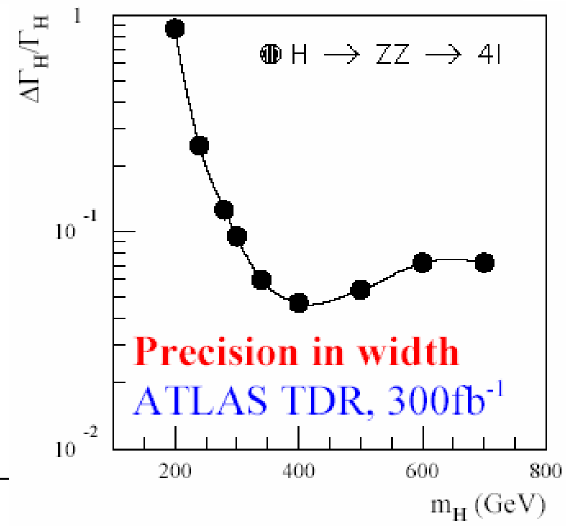
Resolution:

- For $\gamma\gamma$ & 4l ≈ 1.5 GeV/c^2
- For bb ≈ 15 GeV/c^2
- At large masses **decreasing precision** due to large Γ_H

Direct width measurement:

Mass peak width of $H \rightarrow ZZ \rightarrow 4l$ channel for $M_H > 200$ GeV

($\Gamma_H > \Gamma_{exp}$)



The Higgs sector of MSSM

Minimal Higgs sector structure:

- 2 Higgs doublets
  - ❖anomaly-free theory
  - ❖generate mass for "up" and "down" type quarks (and charged leptons)
- 5 Higgs bosons: h, H, A, $H^{\pm}$;
- 2 free parameters defining Higgs sector (tree-level): m_A, $\tan\beta = v_u/v_d$

  Mass limits: $m_h < m_Z \cos\beta$, $m_A < m_H$, $m_W < m_{H^+}$
- Large radiative corrections to masses & couplings:
  - depends on SUSY parameters
  - top mass, stop mixing
  - m_h < 135 GeV

MSSM: benchmark scenarios

i. SUSY particles are heavy: no contribution to Higgs production/decay

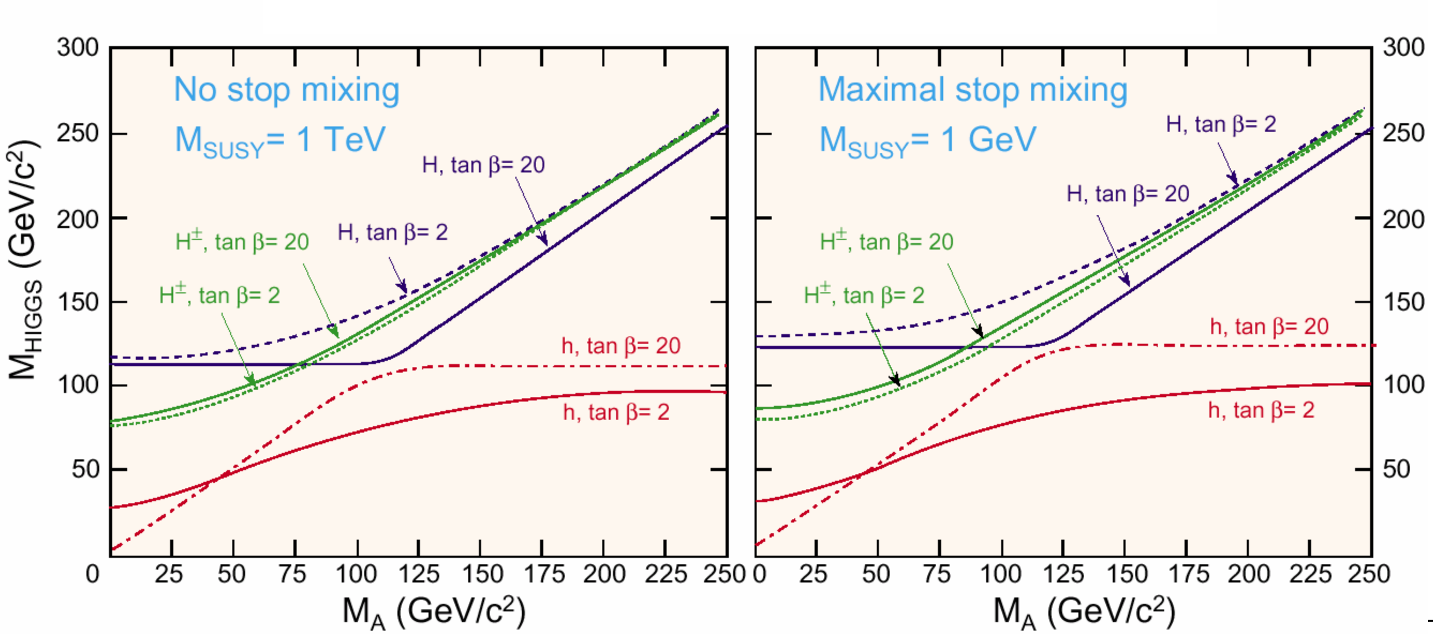
ii. SUSY particles contribute in production/decays

- $H/A \rightarrow \chi^2_0 \chi^2_0 \rightarrow 4l + E^{miss}$; h prod. in cascade decays ($\chi^2_0 \rightarrow h\, \chi^1_0$)
- Impact on Higgs decay to SM particles generally small

$h \rightarrow \gamma\gamma$ 10% smaller, A/H $\rightarrow$ SM at most 40% smaller

Other branches

- stop mixing: Maximal – No mixing
- tan β value: low – high



MSSM Higgses

Couplings MSSM/SM

	t	b/τ	W/Z
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\alpha-\beta)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\alpha-\beta)$
A	$\cot\beta$	$\tan\beta$	-----

α = mixing bw h/H

- High $\tan\beta$ → Large BR(h,A,H →bb,$\tau\tau$)
- Small α → small BR(h→bb,$\tau\tau$)
- A does not couple to W/Z → No VBF prod.
- HVV suppressed for large $\tan\beta$

➢ h/H and A

Production:

- direct gg->h/H/A and ass. prod. gg→bb h/H/A

M_A>300 GeV, $\tan\beta$>10: >90% from ass. prod

h is SM-like for $m_A > m_h^{max}$

Decay modes:

- h →bb (90%) →$\tau\tau$ (8%)
- H/A→$\mu\mu$ and H/A→$\tau\tau$ enhanced with tan β

➢ H^{+-}

Production:

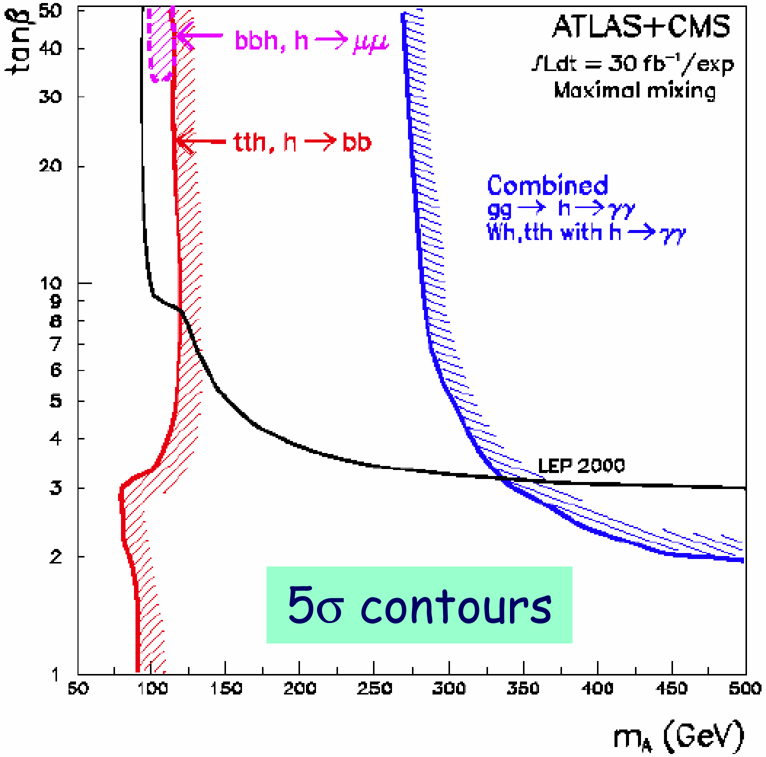
- $M_H^{+-} < M_t$: tt events with decay t→b H^{+-}
- gb→t H^{+-}; gg(qq)→tb H^{+-} ; qq→H^{+-}

Decay modes:

- H^{+-}→$\tau\nu$
- H^{+-}→tb ($M_H^{+-} > M_t$)

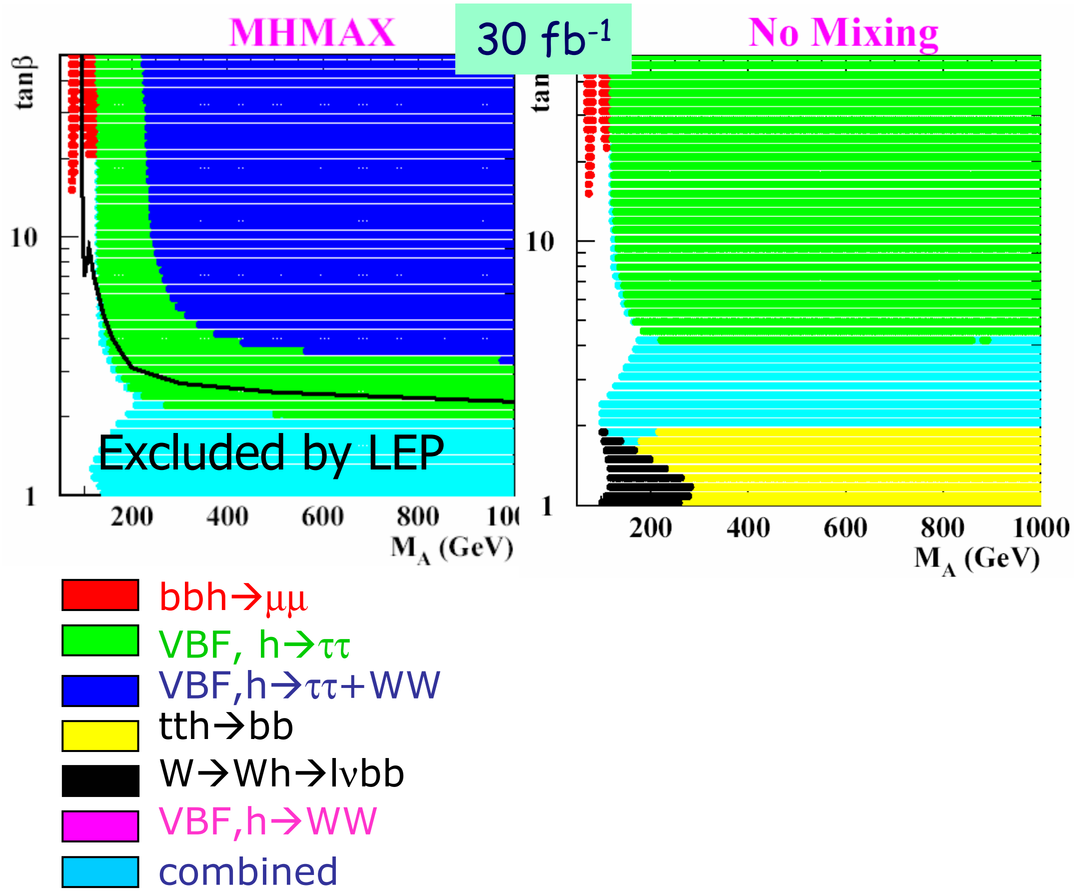
Light Higgs boson h

Search for SM-like channels



VBF channels very useful:
"cover large part of MSSM plane"

ATLAS new, updated analysis



pp → bbH/A

➤ H/A → μμ

Clean signature and good mass resolution (1-2%)

BR(H/A→2μ) 4×10^{-3} but x-sec enhanced by tanβ

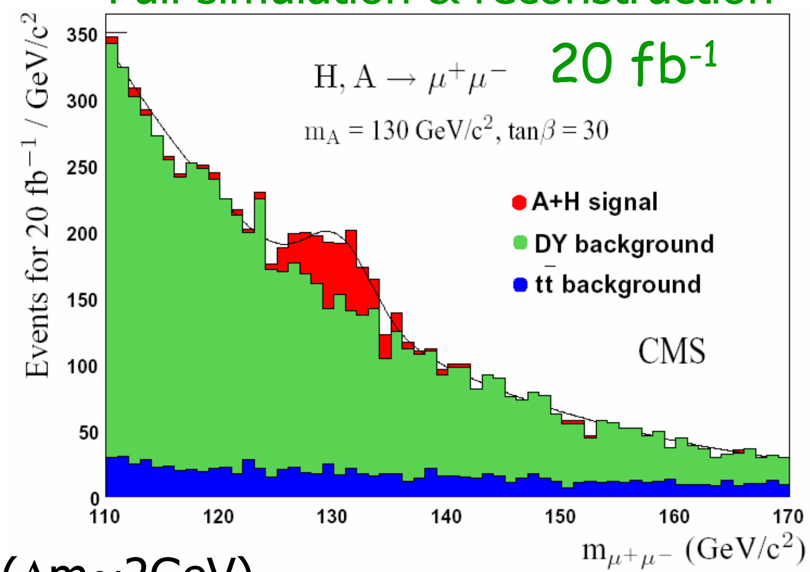
Background

- Z/γ*→ 2μ (dominant) rejected using b-tagging (vertex + i.p. ε~40%)
- tt (W→ μν) rejected using central jet veto

Signal

- in this param space is superposition of H and A (Δm~2GeV)
- Two-muon mass resol. not enough to resolve 2 GeV

Full simulation & reconstruction



➤ H/A → ττ

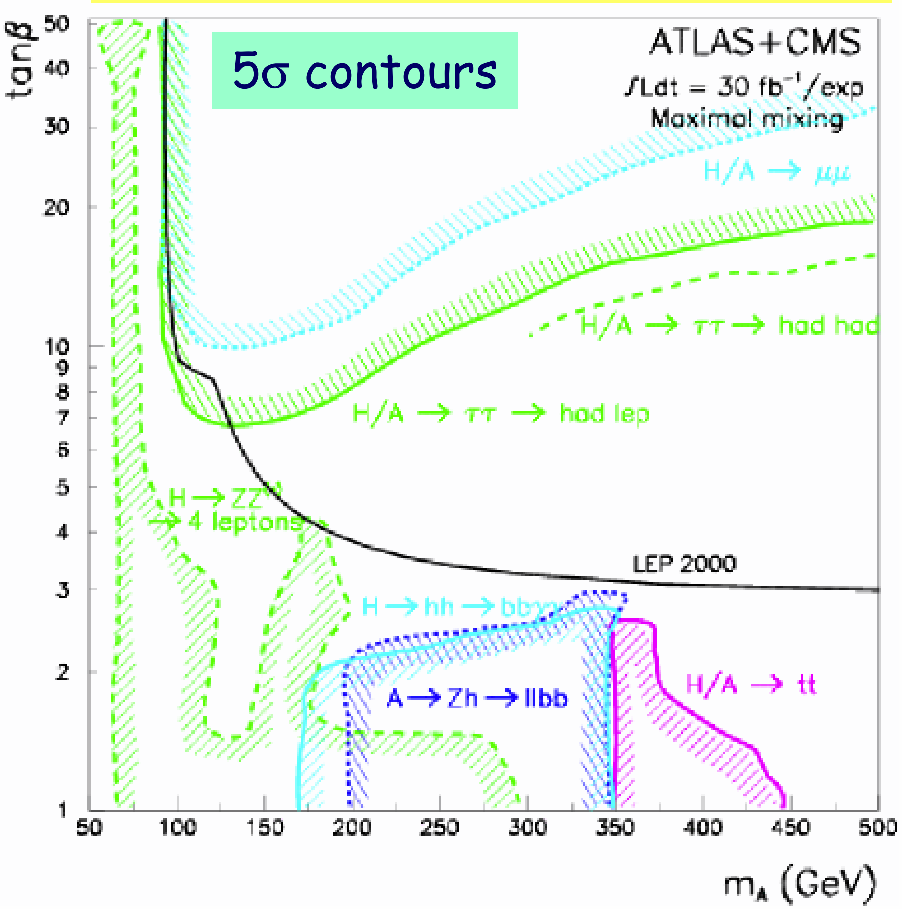
- Channels: ll, l+jet, jet+jet
- Measure tanβ from event rate with uncertainty from 17.2% (jet+jet) to 10.8% (l+jet)

Background

- Z/γ*, QCD rejected using b-tagging
- tt rejected using central jet veto
- W+jet, QCD rejected using τ-tagging

Discovery potential for H,A

(SUSY particles heavy)



Discovery potential for $H^\pm$

- $m_{H^\pm} < m_t$

  $pp \to tt \to H^\pm(\tau\nu)$ b Wb , $\tau \to$ hadr.

  - Leptonic channel

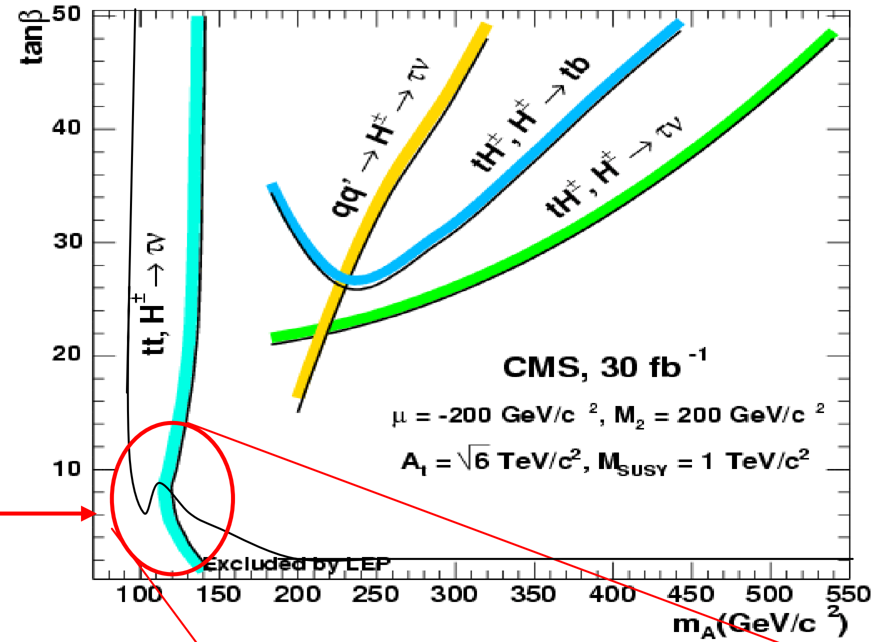
    $H^\pm(\tau\nu)$b W($l\nu$) b

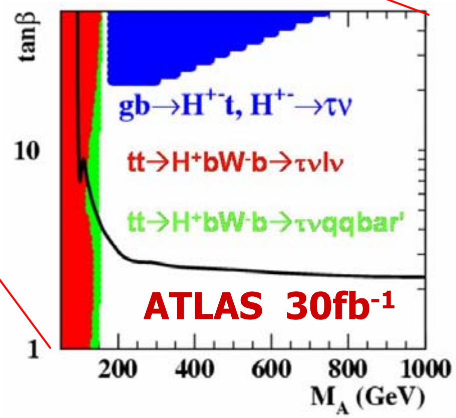
    Excess of τ's in tt event

  - Hadronic channel

    $H^\pm(\tau\nu)$b W(qq) b (ATLAS)

    Closes "hole" at tanβ~7





- $m_{H^\pm} > m_t$

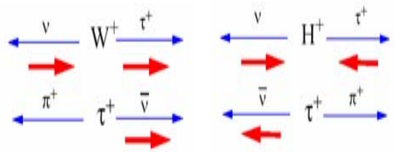
  - assoc. prod. with t: $gb \to tH^\pm$ ($\tau\nu$, tb)

    bkg: tt, Wt

  - direct prod. $qq \to H^\pm(\tau\nu)$

    bkg: W($\tau\nu$)

  - In $H^\pm(\tau\nu)$: ($\tau \to \pi\nu$) use helicity correlations to suppress bkg.



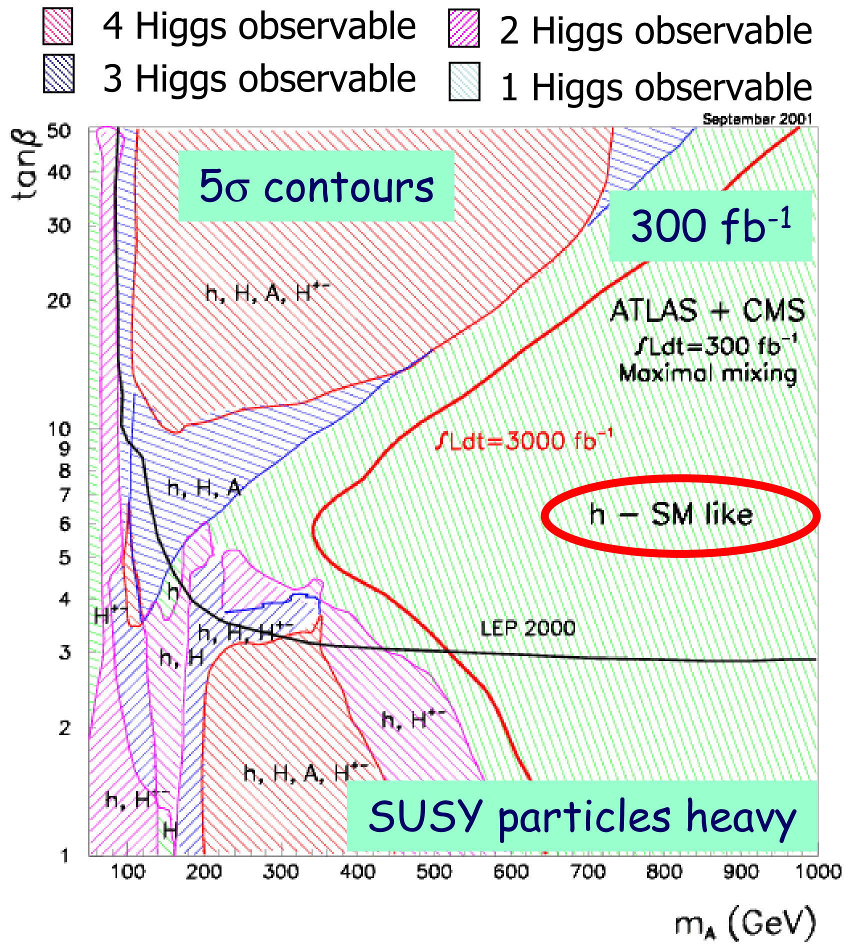
Overall discovery potential

- Plane fully **covered** with 30 fb^{-1}
- 2 or more Higgses observable in large fraction of plane

  ⇒ **disentangle SM / MSSM**

But…

- significant area where only lightest Higgs boson h is observable
- can SM be discriminated from extended Higgs sector by parameter determination?



Conclusions

- SM Higgs boson can be discovered (5σ) at LHC over the full mass range with <30 fb^{-1}
  - Vector Boson Fusion significantly enhances sensitivity for low and medium M_H
    - Forward jet tagging crucial
- MSSM M_A-tanβ space will be almost completely accessible with 30 fb^{-1}
  - for M_A < 500 GeV, several Higgs bosons observable
  - "weak region" for M_A > 500 GeV:

    ~ only h observable unless $A/H/H^{\pm} \rightarrow$ SUSY particles

BUT…

- The discovery is only the first step:

  need to determine Higgs properties in order to distinguish bw different models (and make sure that it is really a Higgs boson)

  - mass, spin, CP properties, couplings to different particles, ….
- Still a lot of work to be done
  - Detector understanding (calibration, alignment, …)
  - Improvement, validation and tuning of MC tools (use of Tevatron data)
  - Full simulation analyses (CMS P-TDR, end 2005)

Backup slides

Trigger requirements

- Cover all SM topologies and those expected from new physics
- Inclusive selection (to discover unexpected new physics)
- Keep safety margin against uncertainties
  - Knowledge of (background) cross-sections
  - Real detector behavior, beam-related (and other) backgrounds
  - Performance of the selection software (Efficiency must be measurable from data)

HLT @ 2×10^{33} cm^{-2} s^{-1}

ATLAS

Object		Rates (Hz)
Electrons	e25i, 2e15i	~40
Photons	γ60, 2γ20i	~40
Muons	μ20i, 2μ10	~40
Rare b-decays ($B\to J\Psi(\Psi')X$)	2μ6 + $\mu^+ \mu^-$ + mass cut	~25
Jets	j400, 3j165, 4j110	~20
Jet+missing E_T	j70 + xE70	~5
Tau+missing E_T	τ35i + xE45	~10
Calibration/Others		~20
Total HLT Output Rate		~200

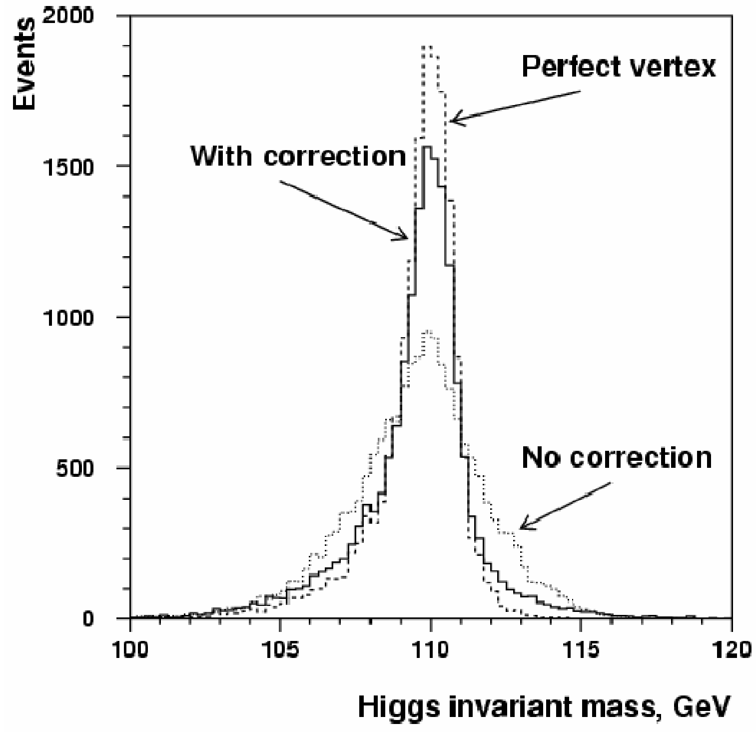
CMS

Trigger	Threshold (ε=90-95%) (GeV)	Indiv. Rate (Hz)
1e, 2e	29, 17	34
1γ, 2γ	80, (40*25)	9
1μ, 2μ	19, 7	29
1τ, 2τ	86, 59	4
Jet * Miss-E_T	180 * 123	5
1-jet, 3-jet, 4-jet	657, 247, 113	9
e * jet	19 * 52	1
Inclusive b-jets	237	5
Calibration/other		10
Total HLT Output Rate		105

$H \rightarrow \gamma\gamma$: Vtx reco

The vertex of the Higgs boson can be found with the help of additional tracks in the same event:

- Higgs boson p_T is balanced by the rest of the particles in the event
- Vertex can be identified by the hardest tracks of the bunch crossing.



Vertex correction significantly improves the m_H resolution:

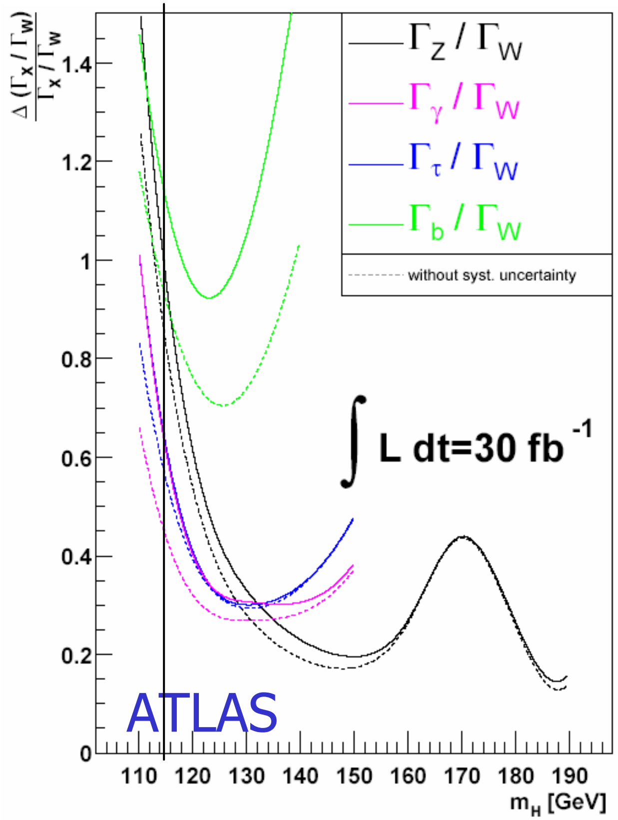
- σ_H/m_H 0.7% (m_H = 110-150 GeV)
- efficiency in 2.5 GeV mass window is improved by 31%.

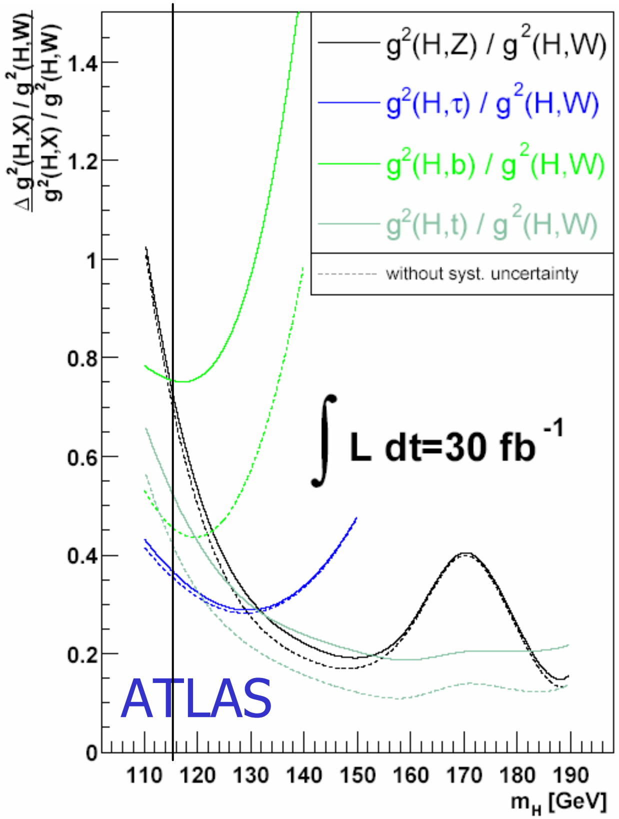
Higgs partial widths and coupling ratios

With 30 fb^{-1} of data

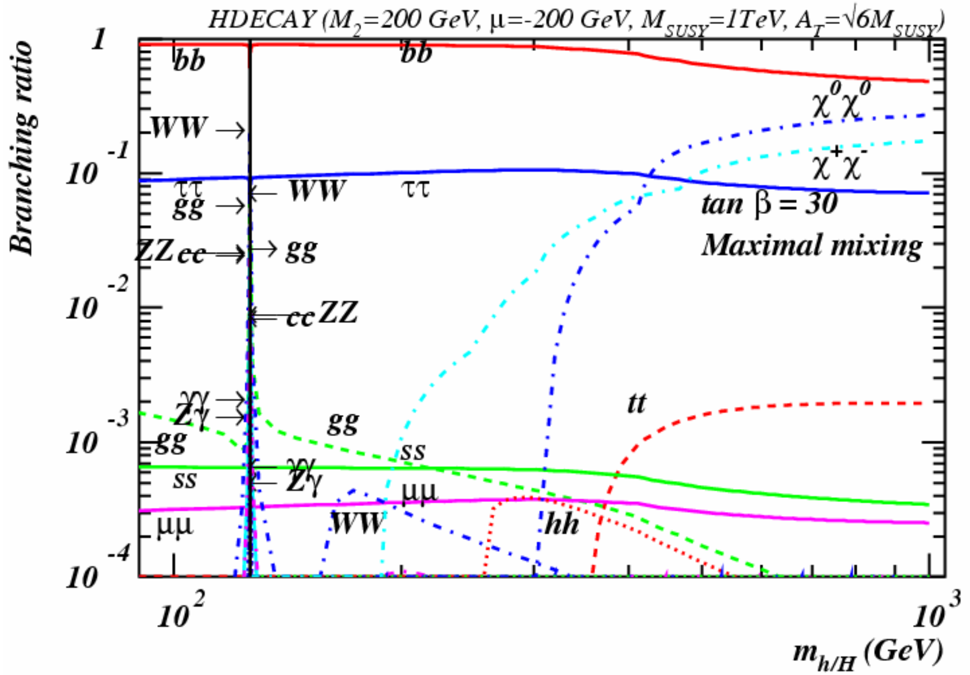
- Accuracy of relative branching ratios and relative couplings vary from 20% to 60% depending on coupling and mass
- Worst channel: $H \rightarrow bb$

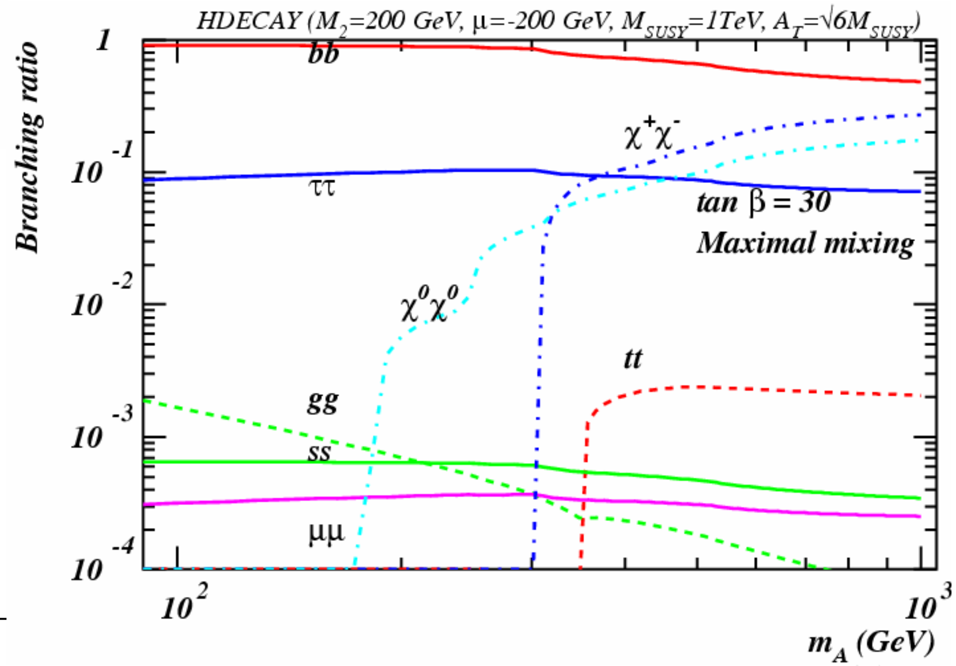
$H \rightarrow WW$ chosen as reference as best measured for M_H>120 GeV





MSSM Higgses decay



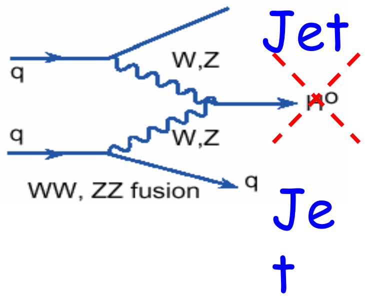


Invisible Higgs

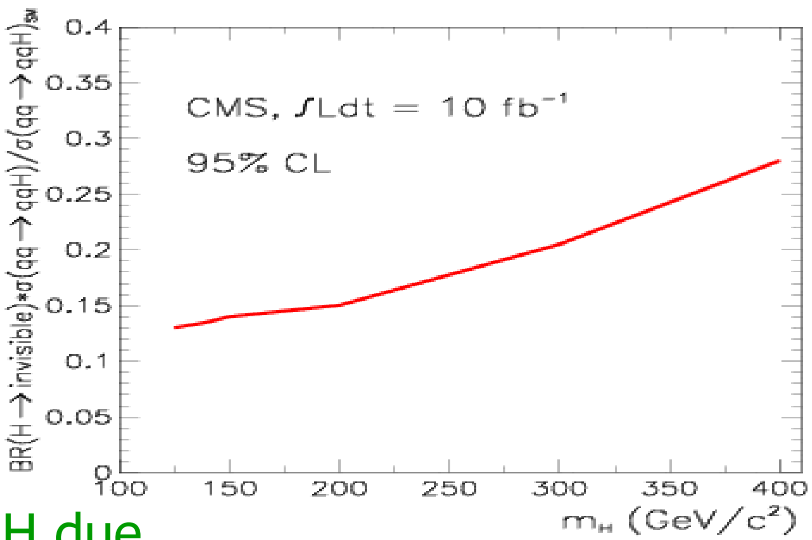
h → LSP

VBF most promising channel

- Trigger on forward jets + E_T^{miss}
- Backgrounds:
  - Events that originate E_T^{miss}: Wjj, Zjj, QCD multi-jets
  - Bkg estimate from data ($Z \to ll$, $W \to l\nu$) to level of 3%
- Selection
  - VBF cuts (forward jets, central jet veto)
  - Lepton veto
  - $\Delta\phi_{jj}$



Model independent, 95% CL upper limit of h →invisible x-sec

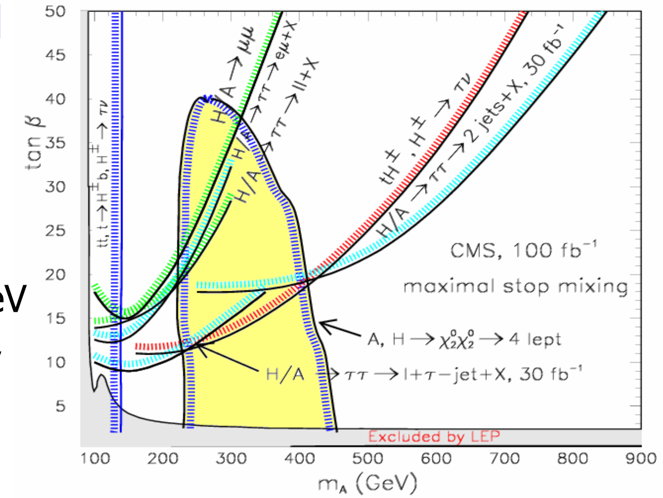


No sensitivity is expected for heavy scalar H due to suppression of the VBF x-sec

Higgs decays to SUSY particles

If SUSY particles kinematically accessibles

- ✓ Higgses can decay directly to or come from decays of SUSY particles
- ✓ possible complementary coverage respect to SM



- $A/H \to \chi_2^0\, \chi_2^0 \to 4l + E_T^{miss}$ $(\chi_2^0 \to \chi_1^0 ll)$

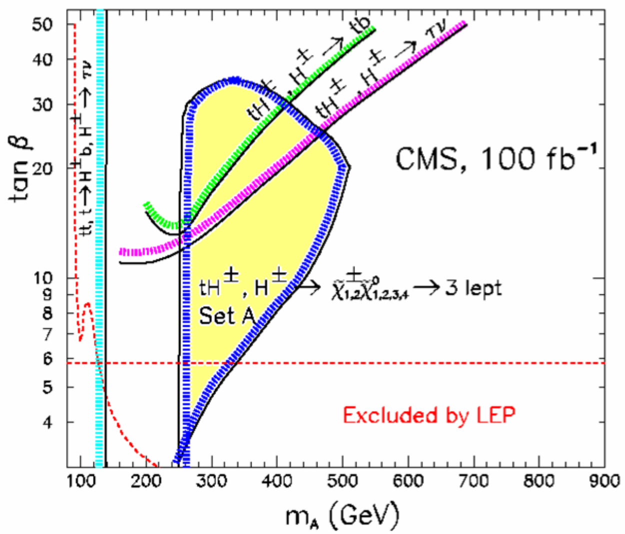
Selection:

Lepton isolation, E_T^{miss},
jet veto

M1=60 GeV, M2=120/180 GeV
μ=-500GeV, $M_{sleptons}$=250 GeV
$M_{squark,gluino}$=1TeV

- $gb \to tH^+$, $H^\pm \to \chi_{2,3}^0\, \chi_{1,2}^\pm \to 3l + E_T^{miss}$

Accesses only a limited fraction
of parameter space



M_2 = 210 GeV,
μ = 135 GeV,
$M_{sleptons}$ = 110 GeV,
$M_{squark,\ gluino}$ = 1TeV

Light Higgs boson h: 30 fb $^{-1}$