The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1970-6

Signaling the Arrival of the LHC Era

8 - 13 December 2008

Searches for Higgs Bosons at the LHC

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Searches for Higgs Bosons at the LHC

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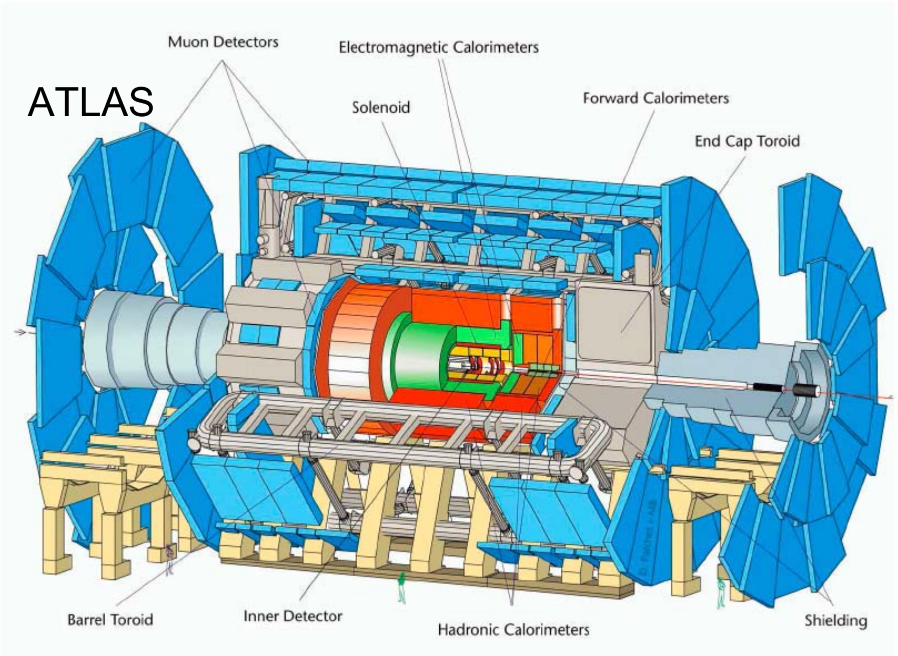
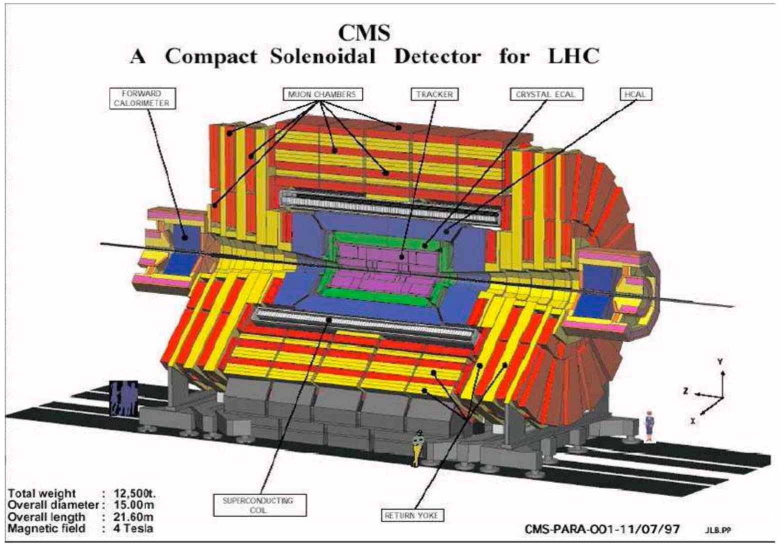
Outline

- **Searching for Higgs Bosons at ATLAS & CMS - I**
  - Strategy to new physics
  - Before collisions
    - Test beams
    - Commissioning with cosmic rays
    - Alignment strategies and pre-alignments
    - Full simulations of realistic “as-built” and “as-installed” detector
    - Triggers for initial luminosities
  - In the early going …
    - Luminosity measurements
    - Sanity checks - $J/\Psi(Y) \to \mu\mu$ and $Z \to \mu\mu/ee$ ...
    - Minimum bias and underlying events
    - Constraining PDF with early data
    - Inclusive jet cross section
    - Commissioning with top events
    - Jet energy scale and b-tagging efficiency
    - First discoveries
- **Searching for Higgs Bosons at ATLAS & CMS - II**
  - Standard Model Higgs
  - Higgs in Extended Models
  - Higgs property measurements

~ already introduced by previous speakers

ATLAS and CMS …





Parameter	ATLAS	CMS
Total weight (tons)	7,000	12,500
Overall diameter (m)	22	15
Overall length (m)	46	20
Magnetic field for tracking (T)	2	4
Solid angle for lepton ID or tracking $(\Delta\phi \times \Delta\eta)$	$2\pi \times 5.0$	$2\pi \times 5.0$
Solid angle for energy measurements $(\Delta\phi \times \Delta\eta)$	$2\pi \times 9.6$	$2\pi \times 9.6$
Total cost (MCHF)	550	550

A historical moment:
Closure of the LHC beam pipe ring on 16th June (the last piece was the one shown here in ATLAS side A)

Strategy to new physics discovery …

- Before data taking:
  - Quality controls of detector construction to meet physics requirements
  - Test beam: several years of activities culminating in the combined test beam of 2004/2007 to understand and calibrate sub-detectors, and to validate/tune software tools, e.g., Geant4 simulation
  - Full simulations of realistic "as-built" and "as-installed" detector (misalignments, material non-uniformity, dead channels): test and validate calibration and alignment strategies
  - Some aspects of commissioning with cosmics are being addressed now or have already been addressed:
    - Pre-alignment and calibration
    - Initial detector shake-down
    - Data processing at the Tier 0 (CERN), distributed to Tier 1's and some Tier 2's. Analysis at the Tier 2's.

now we are almost here

- With first data
  - Commission and calibrate detector and trigger in situ with minimum bias, $Z \rightarrow ll$, etc
  - Rediscover SM at $\sqrt{s}$ = 10 TeV (minimum bias, W, Z, tt, QCD jets, etc)
  - Validate and tune tools (MC generators)
  - Measure main backgrounds to new physics: W+jets, Z+jets, tt+jets, QCD multijets, …

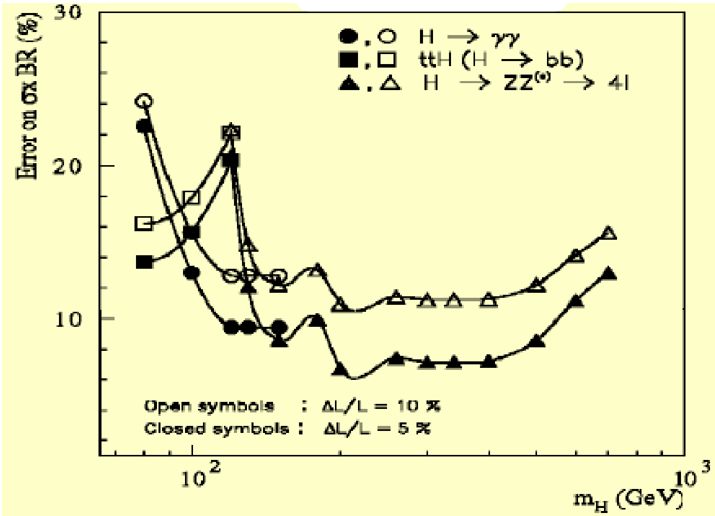
Luminosity - why measure it?

- Measure the cross sections for "Standard " processes
  - Top pair production
  - Jet production
  - ……

Theoretically known to ~ 10 %

- New physics manifesting in deviation of $\sigma \times$ BR relative to the Standard Model predictions. Precision measurement becomes more important if new physics not directly seen. (characteristic scale too high!)

- Important precision measurements
  - Higgs production $\sigma \times$ BR
  - tanβ measurement for MSSM Higgs
  - …….



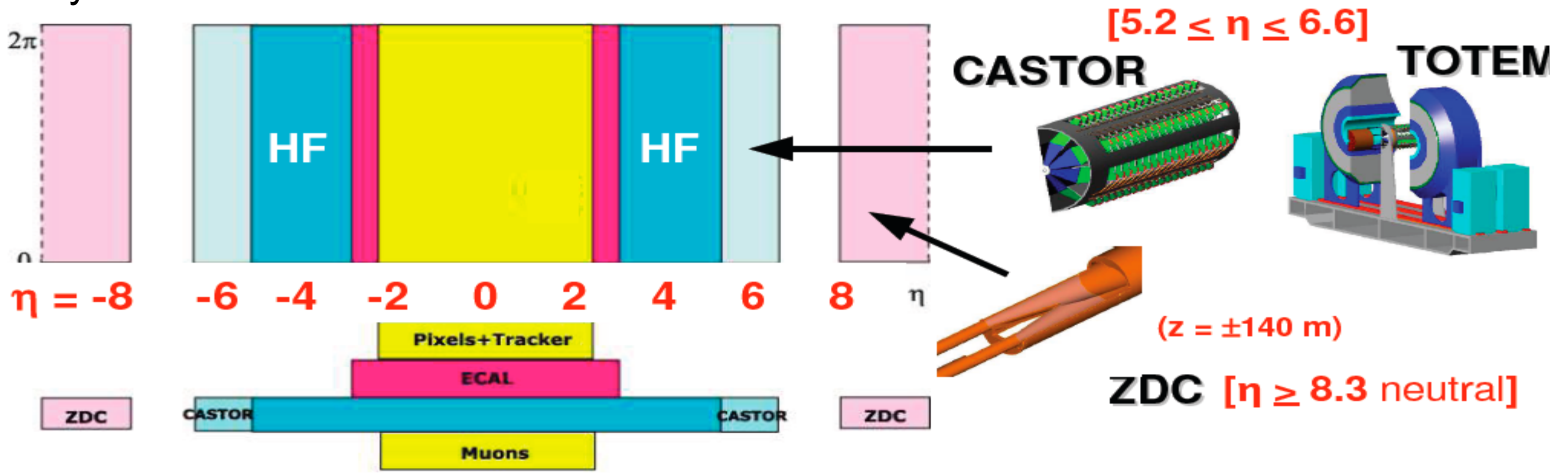
Relative precision on the measurement of $\sigma_H \times$BR for various channels, as function of m_H, at $\int Ldt$ = 300 fb^{-1}. The dominant uncertainty is from Luminosity: 10% (open symbols), 5% (solid symbols).

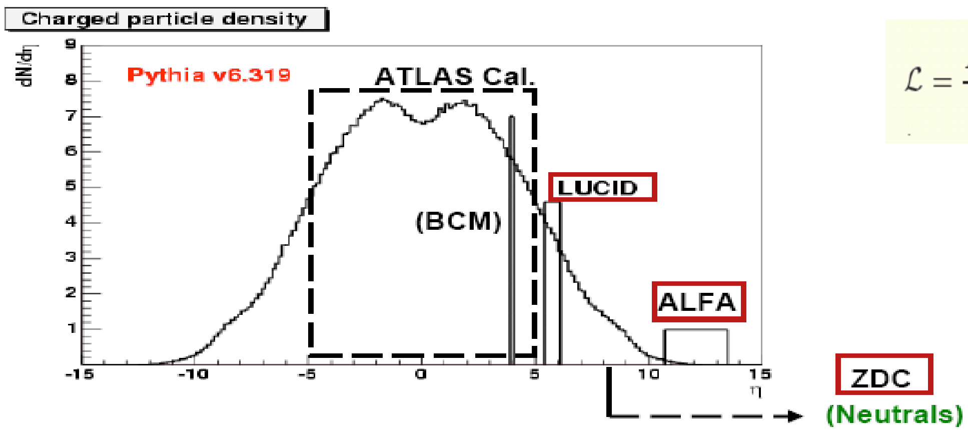
(ATLAS Physics TDR , May 1999)

Significant uncertainty from luminosity unless measuring ratio of observables where luminosity cancels out in the ratio

Luminosity measurements …

CMS/TOTEM and ATLAS forward detectors for forward physics, heavy ion, … and luminosity measurements





- Initially from machine parameters
  - Precision ~10-15%

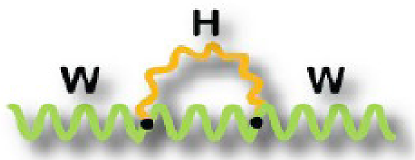
$$\mathcal{L} = \frac{N^2 f_{rev} n_b}{4\pi\sigma^{*2}}$$

Depends on f_{rev} revolution frequency
n_b number of bunches
N number of particles/bunch
σ^* beam size or rather overlap integral at IP

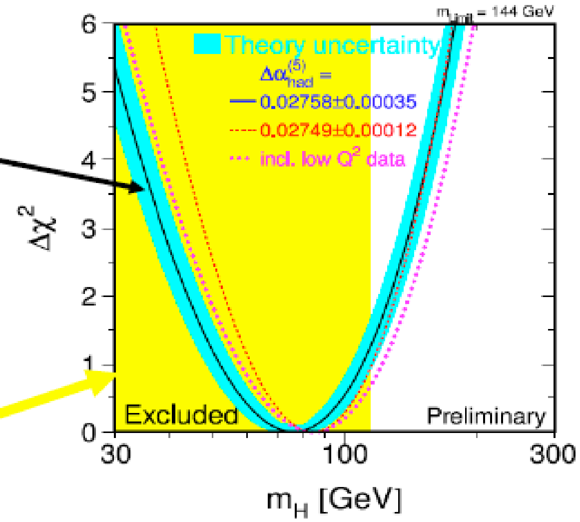
- Medium term from physics processes: W/Z & μμ/ee
  - Precision ~5-10%
- 2010 from Roman Pot detectors
  - Precision ~2-3%

Higgs Searches: present limits

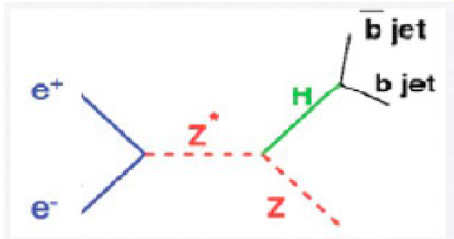
- **The electroweak measurements are sensitive to m_H through radiative corrections:**



$$\log \frac{m_H}{m_Z}$$



- **Direct search at LEP2:**

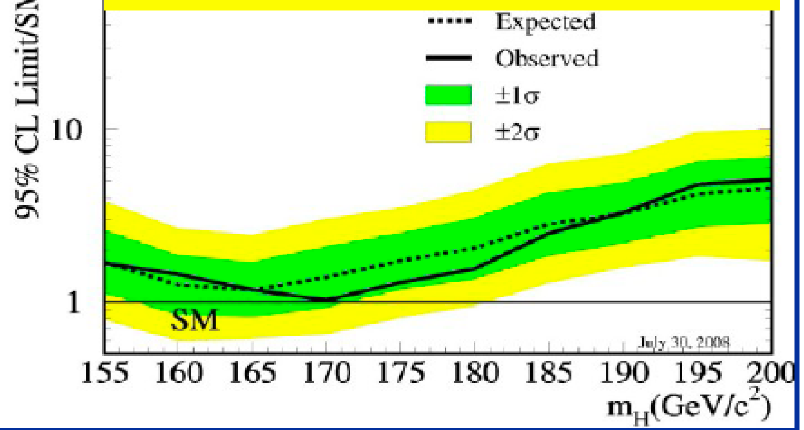


LEP limits:

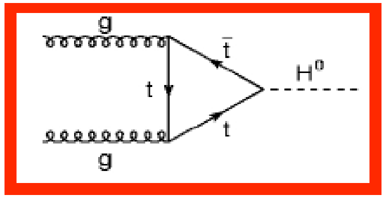
$114.4 < m_H \lesssim 182$ GeV/c²

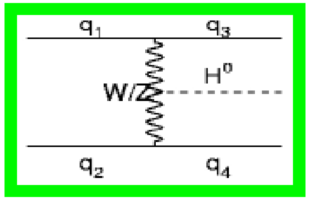
Directe | *Indirecte*

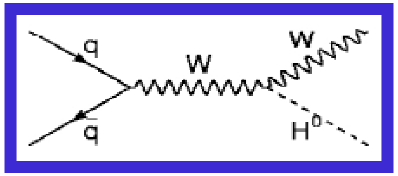
ICHEP08: Tevatron excludes m_H=170 GeV with 3fb^{-1}

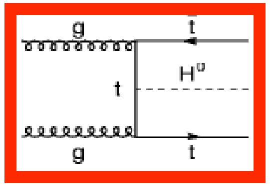


Higgs Production at the LHC

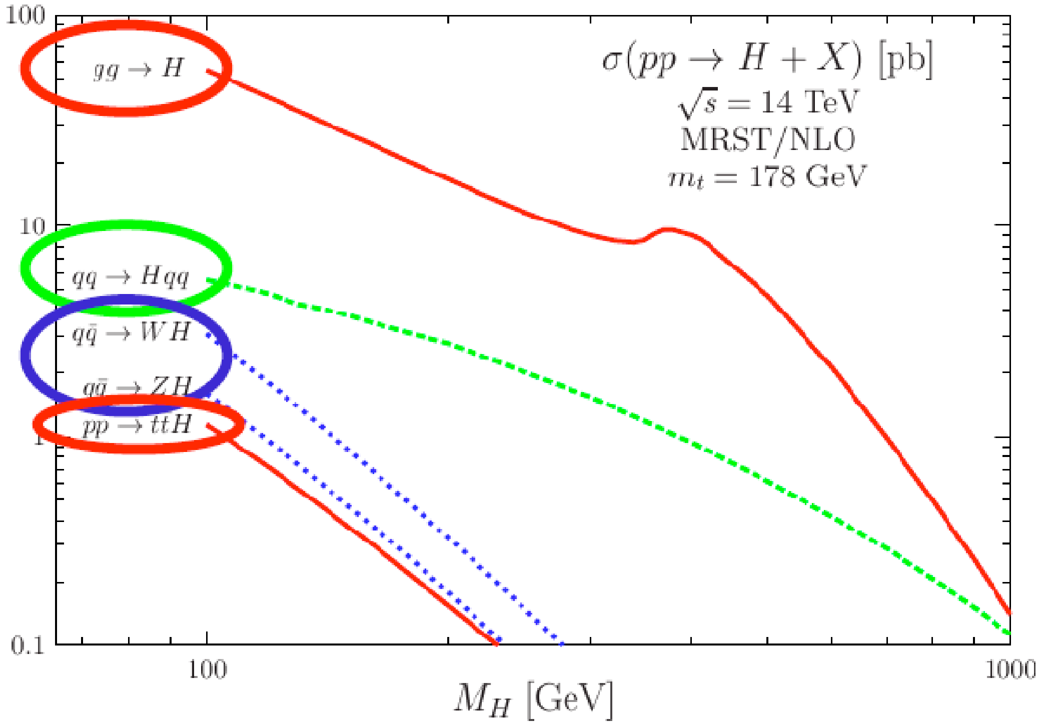








A.Djouadi Phys.Rept.457:1-216

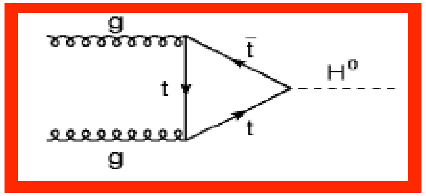


***gg fusion* process is the more abundant, followed by the *Vector Boson Fusion* process.**

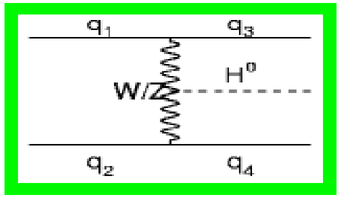
Typical uncertainties on cross-section

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

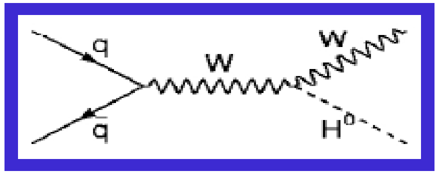
SM Higgs Decays at the LHC



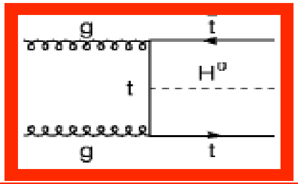
GF **H → WW, ZZ , γγ**



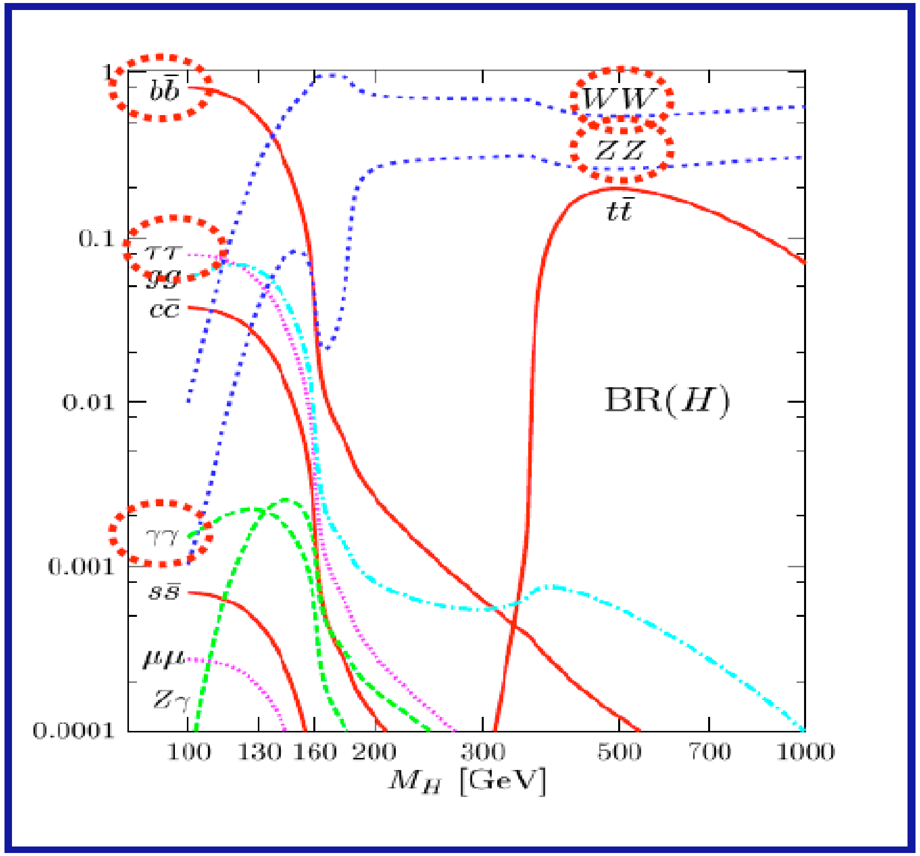
VBF **H → WW , γγ , ττ**



H → WW, γγ

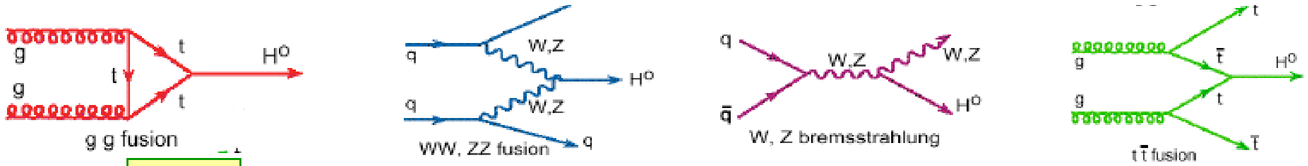


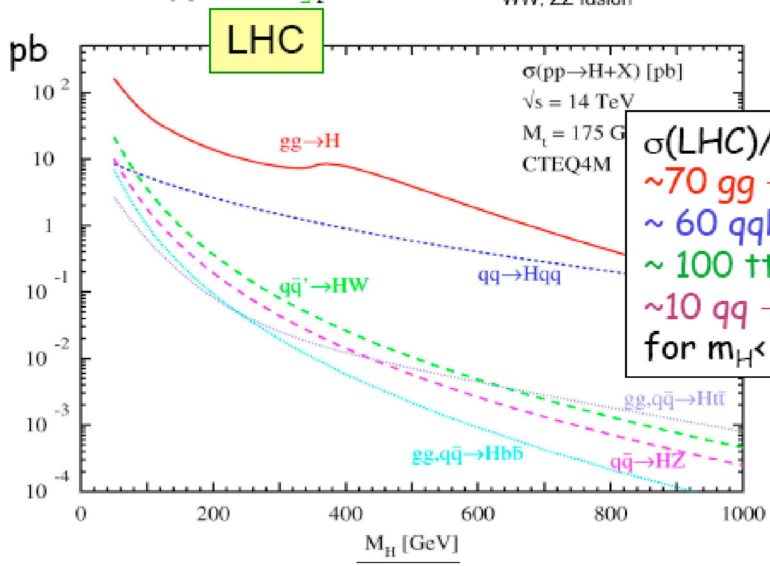
H → WW, γγ, bb



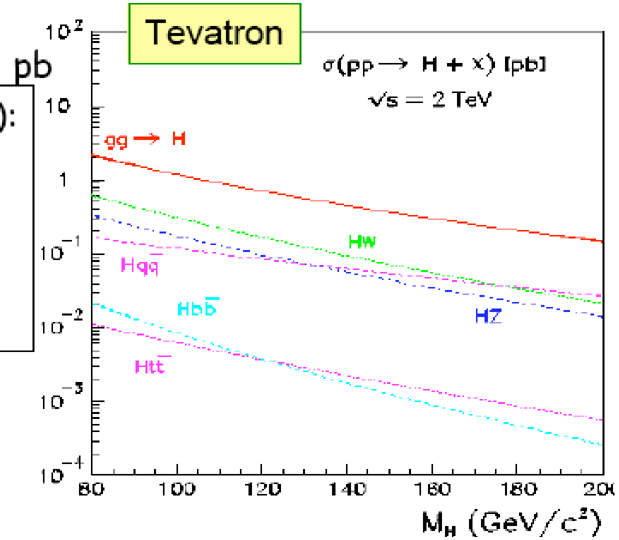
Many channels explored!
All the mass range is covered!

Light Higgs Boson …





σ(LHC)/σ(Tevatron):
~70 gg → H
~ 60 qqH → qqH
~ 100 ttH
~10 qq →WH/ZH
for m_H<200 GeV



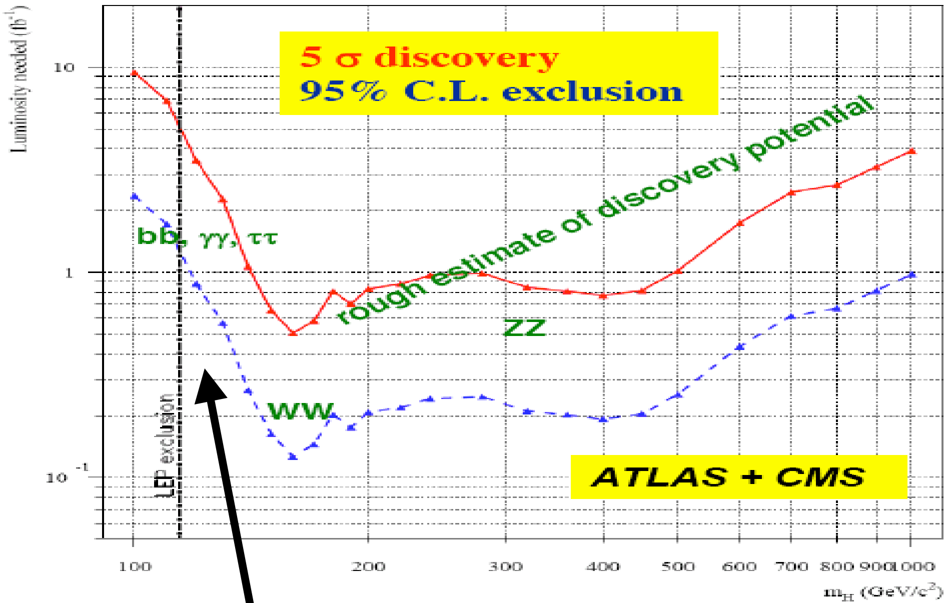
	Tevatron Main Search Channels	LHC Main Search Channels
m_H ~115 GeV	WH→ lνbb ZH → ννbb, llbb	H → γγ, qqH → qqττ ttH→ lνbbX
m_H ~ 160 GeV	H →WW → lνlν	H → WW→ lνlν,H→ZZ*→4l, qqH→ qqWW→ qqlνlν

Large backgrounds at the LHC

Cross-sections too small at the Tevatron

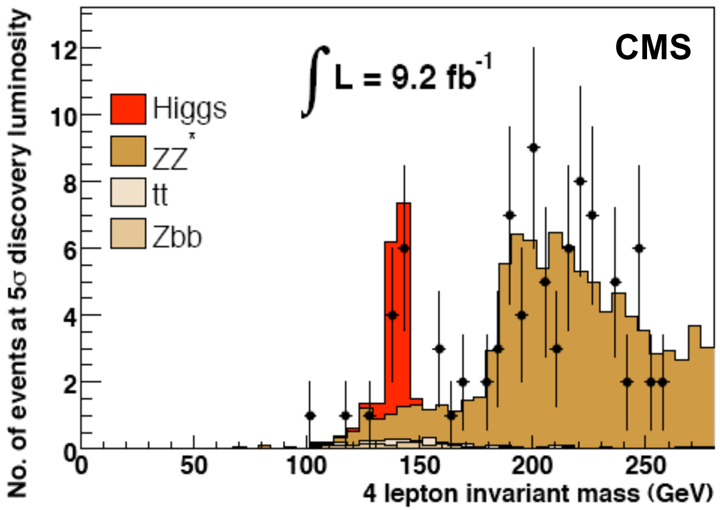
Light Higgs Boson …

Need ~ fb^{-1} of well-understood data per experiment



J.J. Blaising, A. De Roeck, J. Ellis, F. Gianotti, P. Janot, G. Rolandi and D. Schlatter, **Eur. Strategy workshop (2006)**

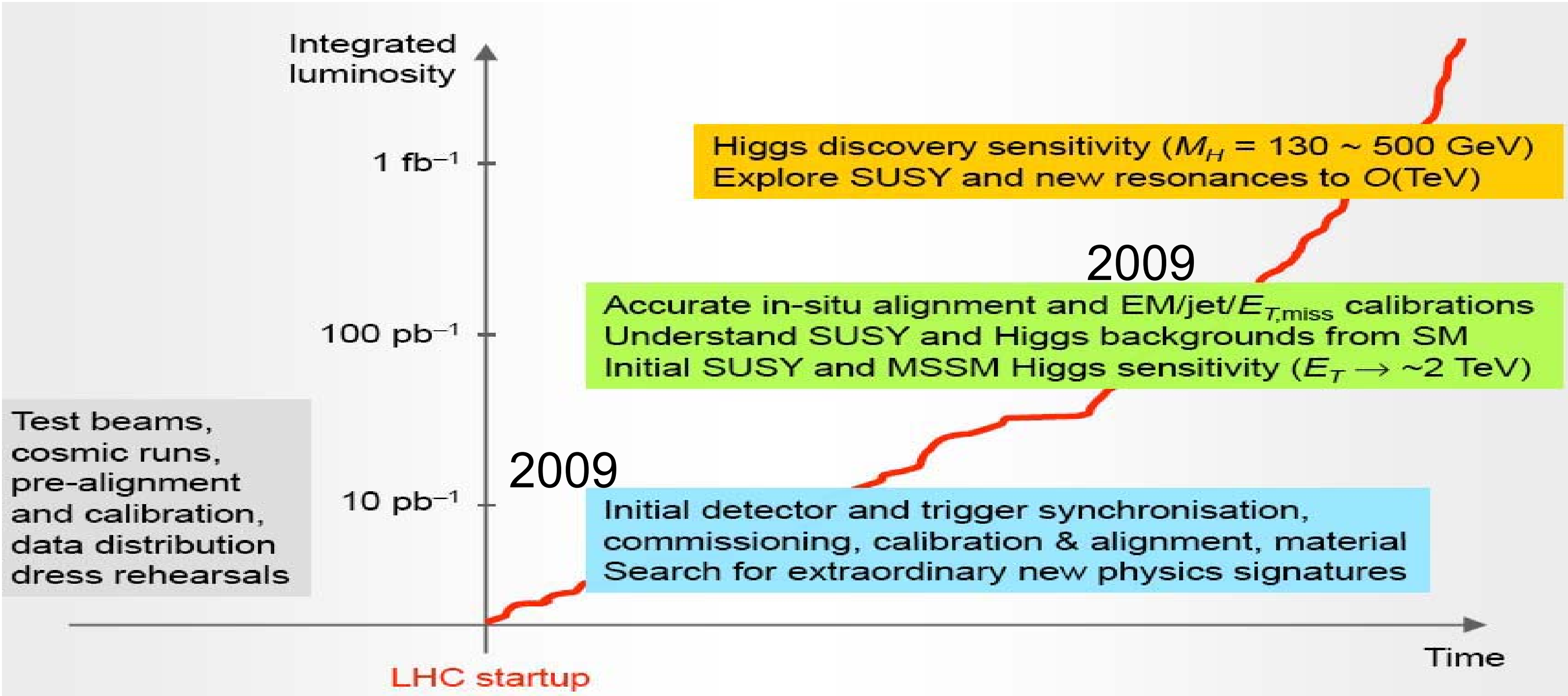
$\leq$ 1 fb^{-1}: 95% CL exclusion
$\leq$ 5 fb^{-1}: 5σ discovery
2010 for definitive word on Higgs?



Most difficult region: combine many channels with small S/B

m_H > 140 GeV, easier discovery with $H \to ZZ^* \to 4l$
$H \to WW \to l\nu l\nu$ dominates at 160 but no mass peak (counting experiment)

In the early going …



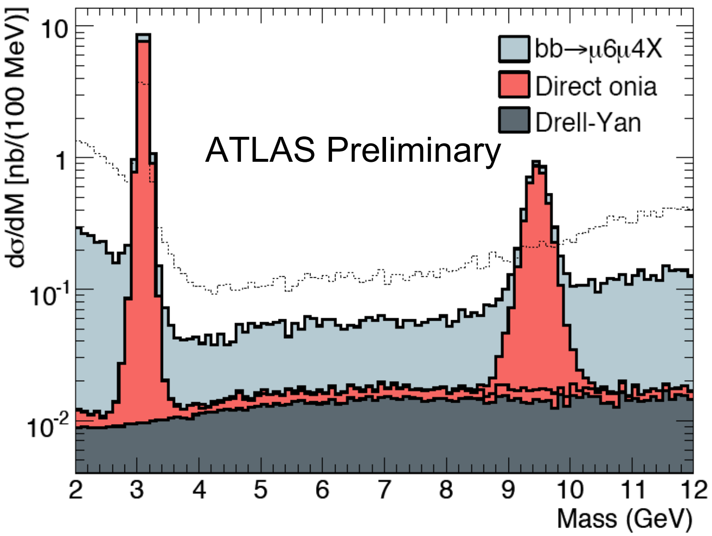
Expected data samples with only 100 pb^{-1} ~ 38.5 days at 10^{32} cm^{-2} s^{-1} with 30% eff.

Channels (examples ...)	Events to tape for 100 pb^{-1} (ATLAS)	Total statistics from LEP and Tevatron
$W \to \mu \nu$	~ 10^6	~ 10^4 LEP, ~ 10^{6-7} Tevatron
$Z \to \mu \mu$	~ 10^5	~ 10^6 LEP, ~ 10^{5-6} Tevatron
$tt \to W b W b \to \mu \nu + X$	~ 10^4	~ 10^{3-4} Tevatron
QCD jets p_T > 1 TeV	> 10^3	---
$\tilde{g}\tilde{g}$ m = 1 TeV	~ 50	---

$J/\Psi(\Upsilon) \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$ ...

$1\ pb^{-1}$ = 3.85 days at 10^{31} with 30% efficiency

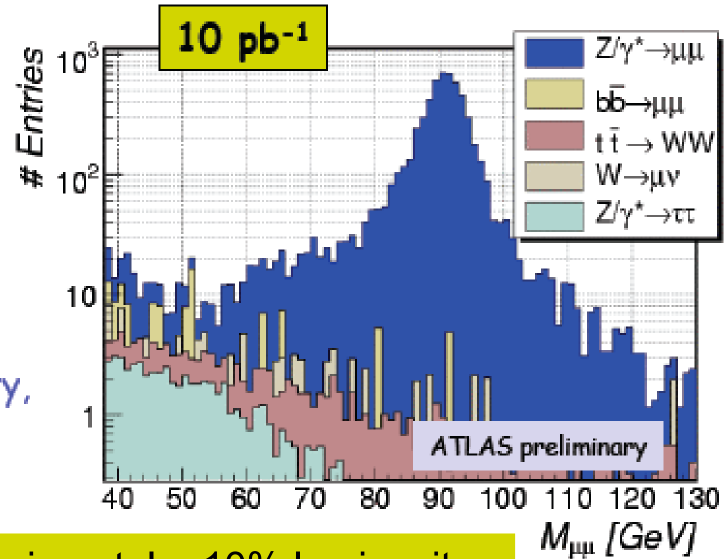
During the initial run of the LHC, mu4mu4 trigger will be used



After all cuts:
~ 4200 (800) J/ψ (Υ) → $\mu\mu$ evts per day at L = 10^{31}
(for 30% machine x detector data taking efficiency)
~16000 (3100) events per pb^{-1}

→ tracker momentum scale, trigger performance, detector efficiency, sanity checks, ...

After all cuts:
~ 160 $Z \rightarrow \mu\mu$ evts per day at L = 10^{31}
~ 600 events per pb^{-1}



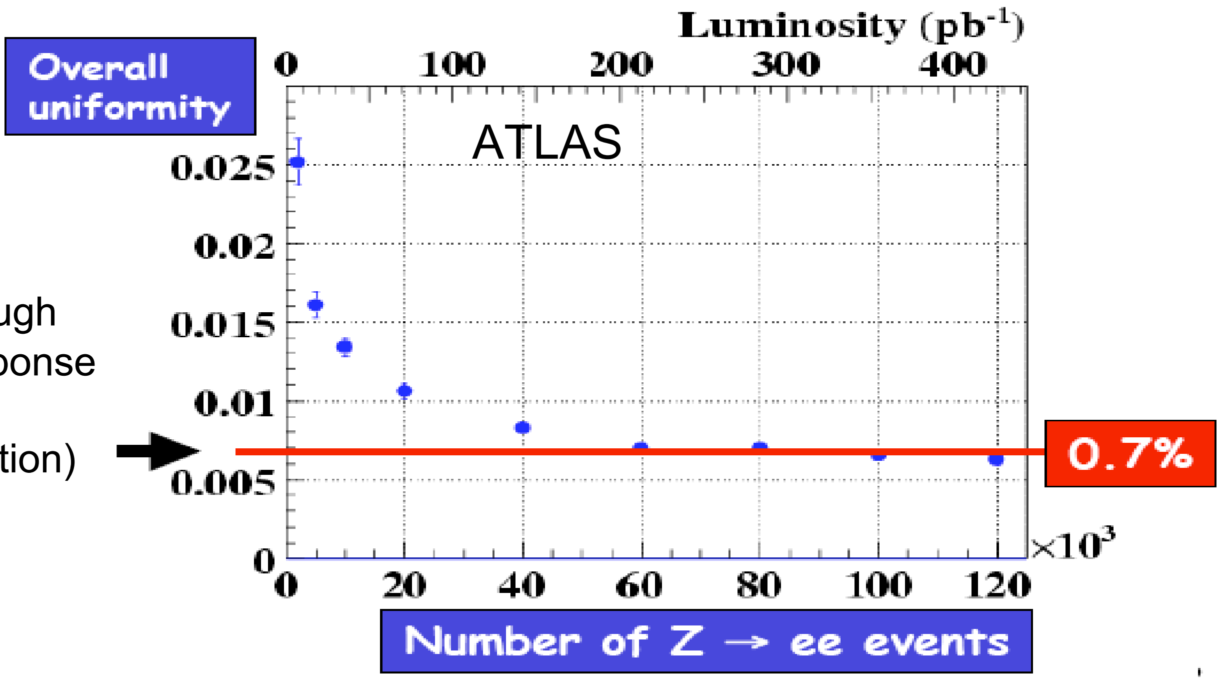
→ Muon Spectrometer alignment, ECAL uniformity, energy/momentum scale of full detector, lepton trigger and reconstruction efficiency, ...

Expected precision on σ ($Z \rightarrow \mu\mu$): < 2% experimental, ~10% luminosity

EM Calorimeter uniformity…

- Use Z→ee to correct for residual long range non-uniformity due to
  - Module-to-module variation
  - Temperature effects

10^5 Z→ee would be enough to achieve a uniform response at the level of ~0.7% (from full detector simulation)



Minimum bias/Underlying Event …

Minimum bias events

- Inelastic hadron-hadron events selected with an experiment's "minimum bias trigger".
- Usually associated with inelastic non-single-diffractive events (NSD) (e.g. UA5, E735, CDF … ATLAS/CMS?)

$$\sigma_{tot} = \sigma_{elas} + \sigma_{s.dif} + \sigma_{d.dif} + \sigma_{n.dif}$$

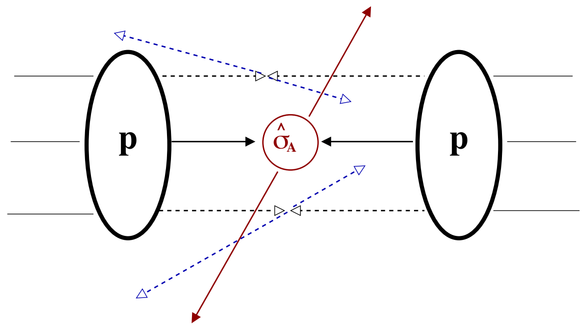
$\sigma_{tot} \sim$ 102 - 118 mb (PYTHIA) (PHOJET)

$\sigma_{NSD} \sim$ 65 - 73mb (PYTHIA) (PHOJET)

- Need minimum bias data to:
  - Study general characteristics of proton-proton interactions
  - Investigate multi-parton interactions and the structure of the proton etc.
  - Understand the underlying event: impact on physics analyses?

The underlying event (UE)

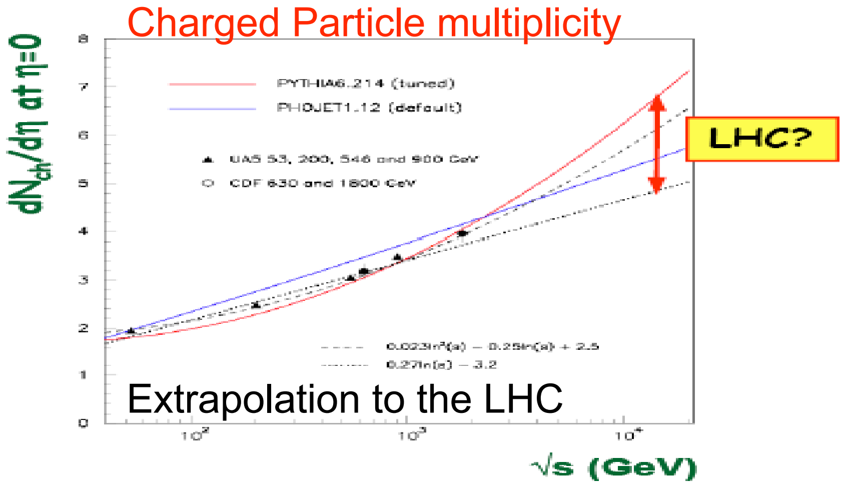
- The "soft part" associated with hard scatters



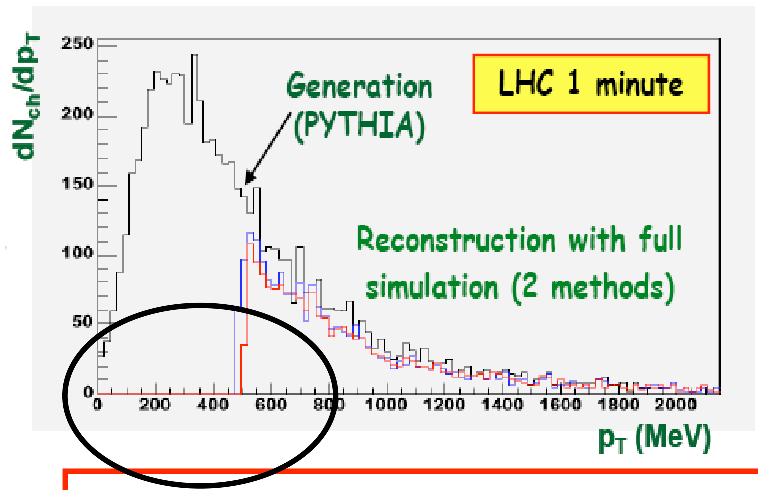
- In parton-parton scattering, the UE is usually defined to be everything except the two outgoing hard scattered jets:
  - Beam-beam remnants.
  - Additional parton-parton interactions.
  - ISR + FSR

- Can we use "minimum bias" data to model the "underlying event"?
  - At least for the beam-beam remnant and multiple interactions?

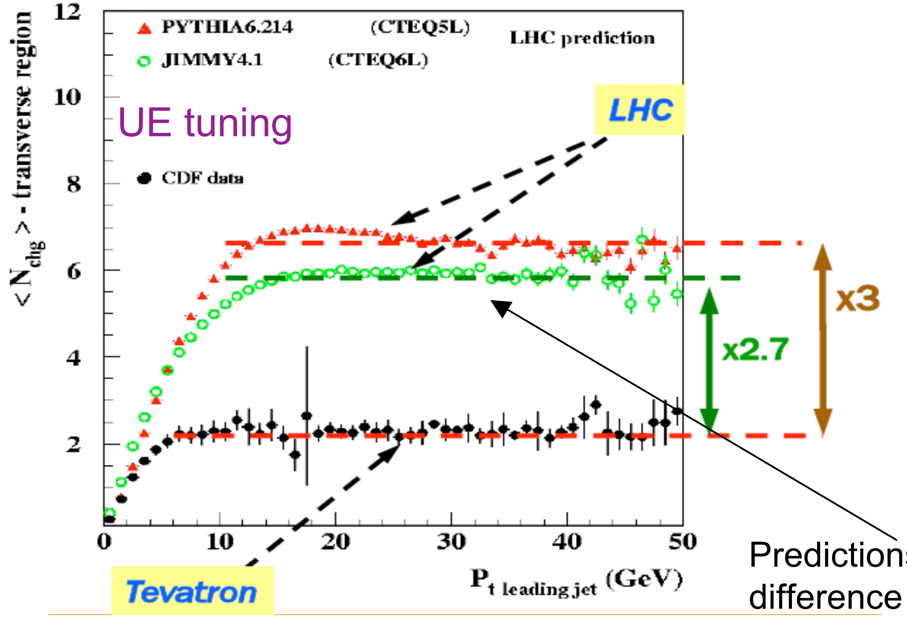
Minimum bias/Underlying Event …



Minimum bias tuning on data



Take special run with low B field to reach p_T ~ 200 MeV.

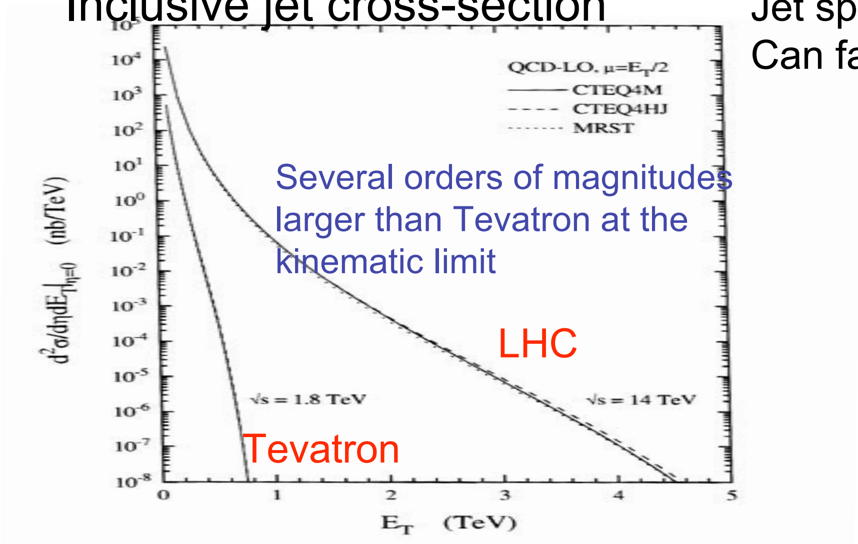


Predictions similar:
difference used to be a factor 2

- Measurements from different LHC experiments should be complementary:
  - LHC-b tracks charged particles to higher rapidities than ATLAS or CMS
  - ALICE tracks charged particles down to lower momenta than ATLAS or CMS

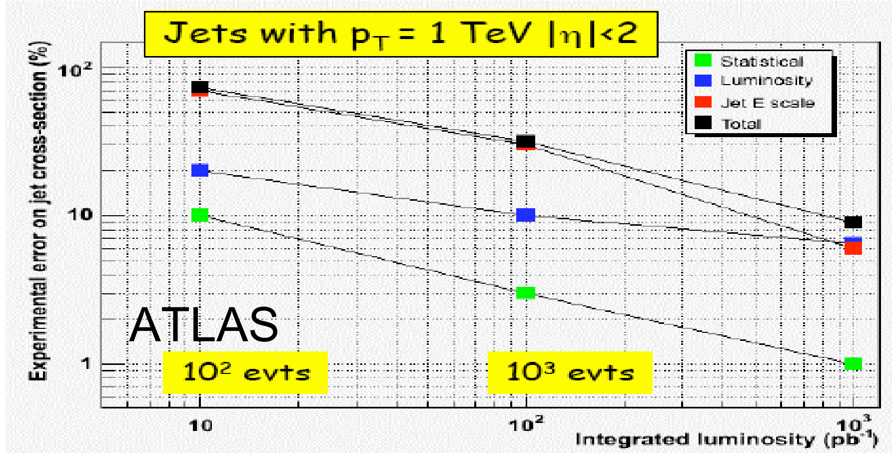
Inclusive jet cross-section …

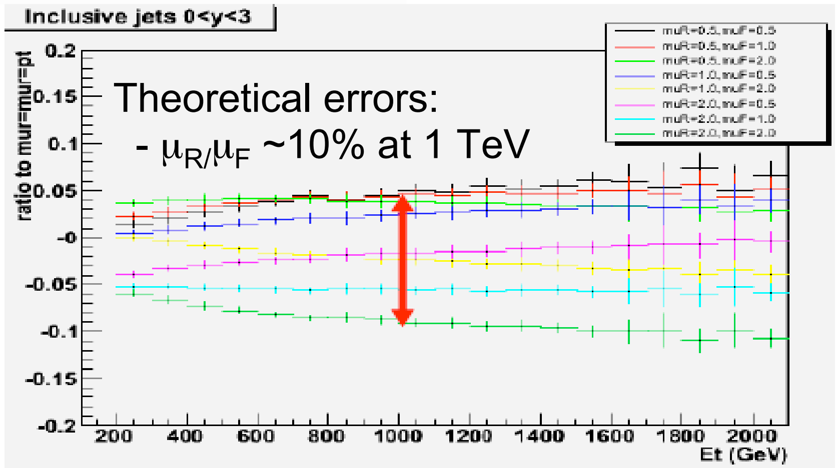
Inclusive jet cross-section



Jet spectrum at high p_T sensitive to new physics

Can fake/mask signal if not well understood …





Addition theoretical errors from PDF uncertainties ~15% at 1 TeV

Constraining PDF with early data …

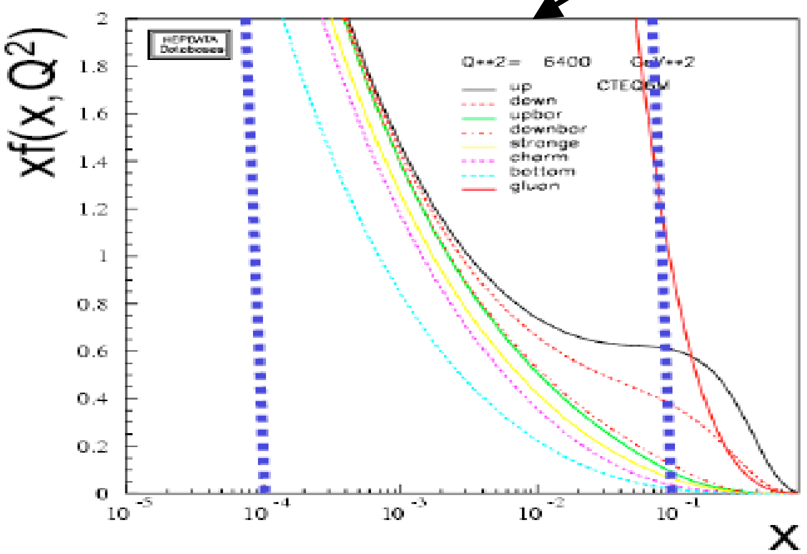
Using W→lν angular distribution

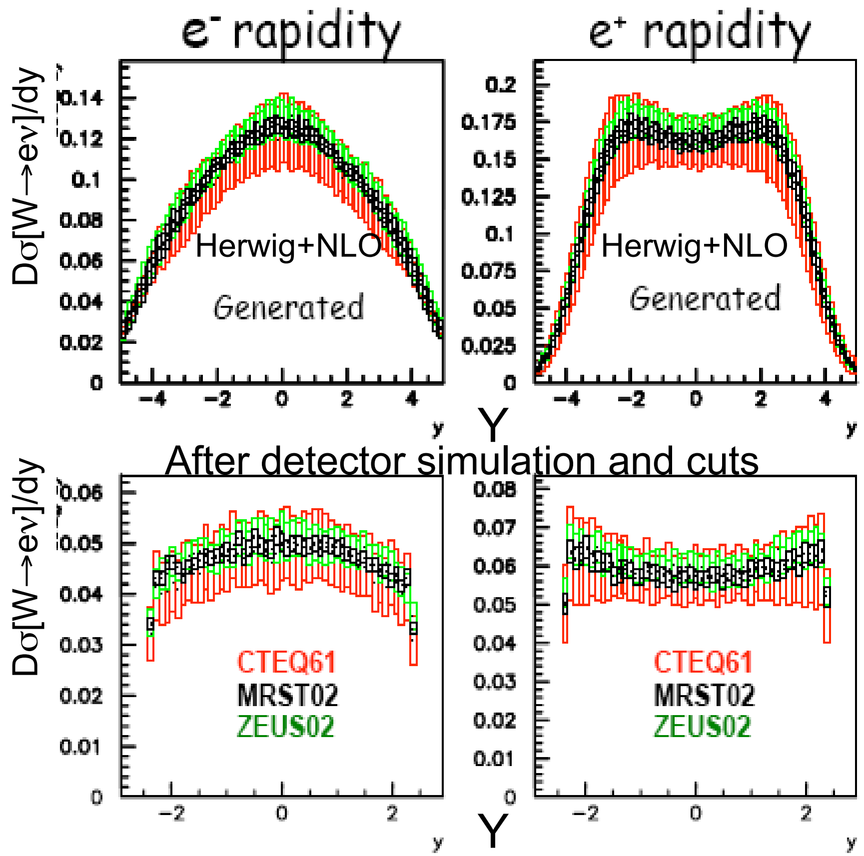
$$u\bar{d} \rightarrow W^{+} \rightarrow e^{+}\nu$$
$$d\bar{u} \rightarrow W^{-} \rightarrow e^{-}\bar{\nu}$$

A particle of mass M, at a rapidity y, produced by a pair of partons (1,2) carrying a fraction $x_{1,2}$ of the proton momentum:

$$x_{1,2} = \frac{M}{\sqrt{s}}\exp(\pm y)$$

W production at LHC over |y|<2.5 implies $10^{-4} < x_{1,2} < 0.1$: region dominated by g→qq

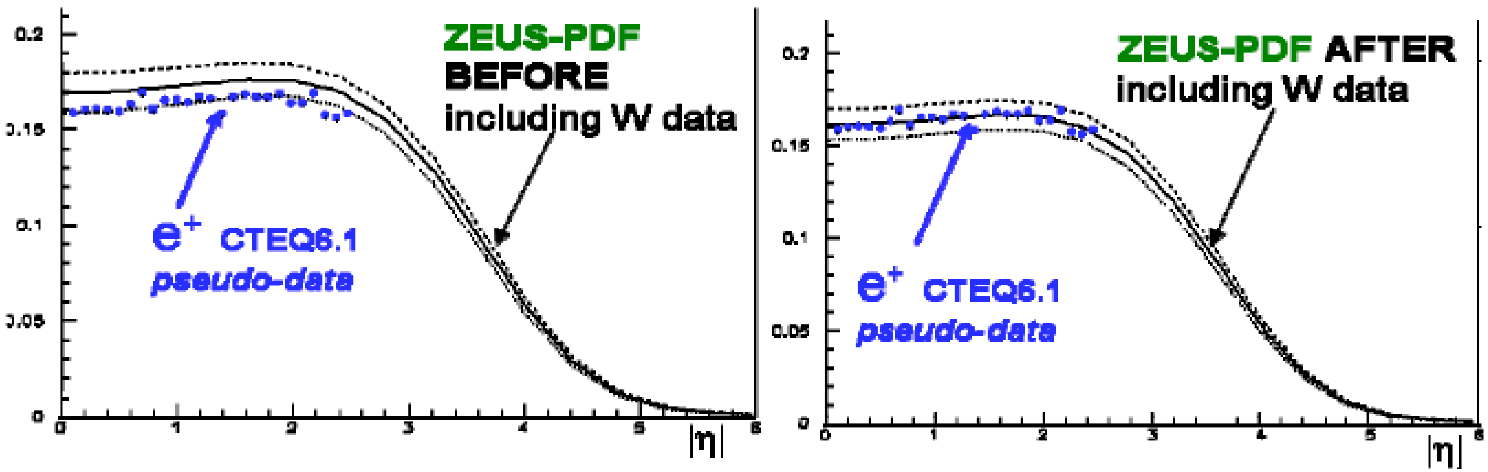




- The goal is experimental uncertainty < 5%:
  - Possibility to discriminate between PDFs

Constraining PDF with early data …

- What will be the effect of including LHC data in global PDF Fits?
  - How much can we reduce the error?
- Take 10^6 $W \to e\nu$ events generated with CTEQ6.1 PDF and ATLFAST detector simulation to probe the low-x gluon PDF at $Q^2=m_W^2$: $W^+ \to e^+\nu$ rapidity spectrum sensitive to gluon shape parameter λ
  - The statistics corresponds to 150 pb^{-1}
  - Introduce 4% systematic errors by hand
- This "data" included in the global fit

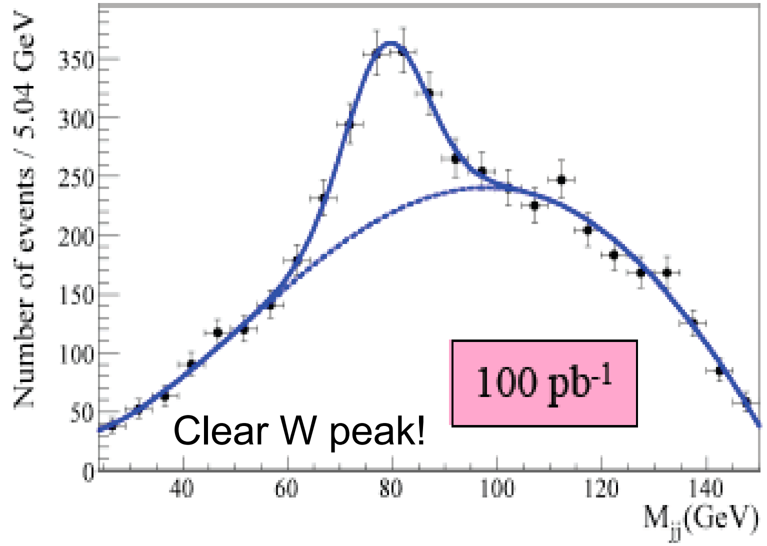


The central value of the ZEUS-PDF prediction shifts and uncertainty is reduced;
Error on low-x gluon shape parameter λ [$xg(x) \sim x^{-\lambda}$] reduced by 35%

The systematics on electron acceptance versus η, will be controlled to a few percent using $Z \to ee$ (~3 10^4 events at 100 pb^{-1})

Jet Energy Scale / b-tagging Efficiency…

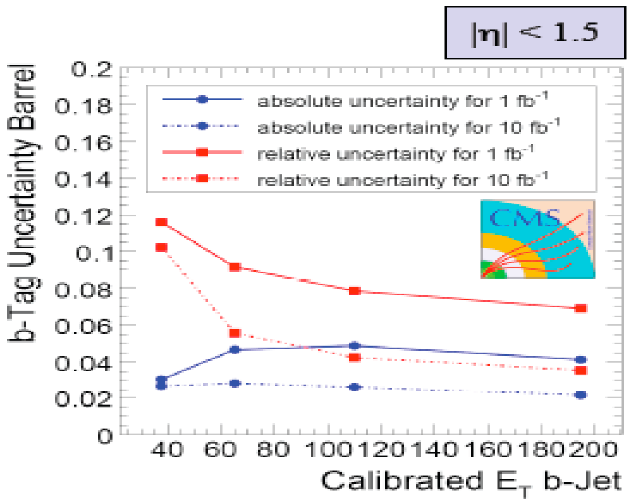
- Calibration of light jet energy scale, to complement γ+jets sample
  - Remove $|m_{jj}-m_W|<10GeV/c^2$ (bias requirement) and look at m_{jj} for all the 3jet combinations in m_t mass window

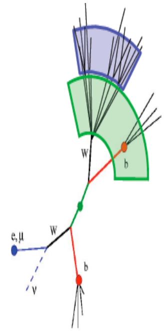


Jet E-scale:

- initially to ~ 10% from test beam + simulation (Geant4 reproduces test-beam pion response of hadronic end-cap calorimeter to ~2%)
- Then eventually from data (γ/Z+jets, W→jj in tt events) + simulation →1%

- Calibration of b-tagging efficiency
  - Select 3jets from the hadronic top
  - Perform a fit using resolution, m_t, and m_W as constraints
  - Measure the b-tag efficiency for the 4th jets a function of E_T and eta

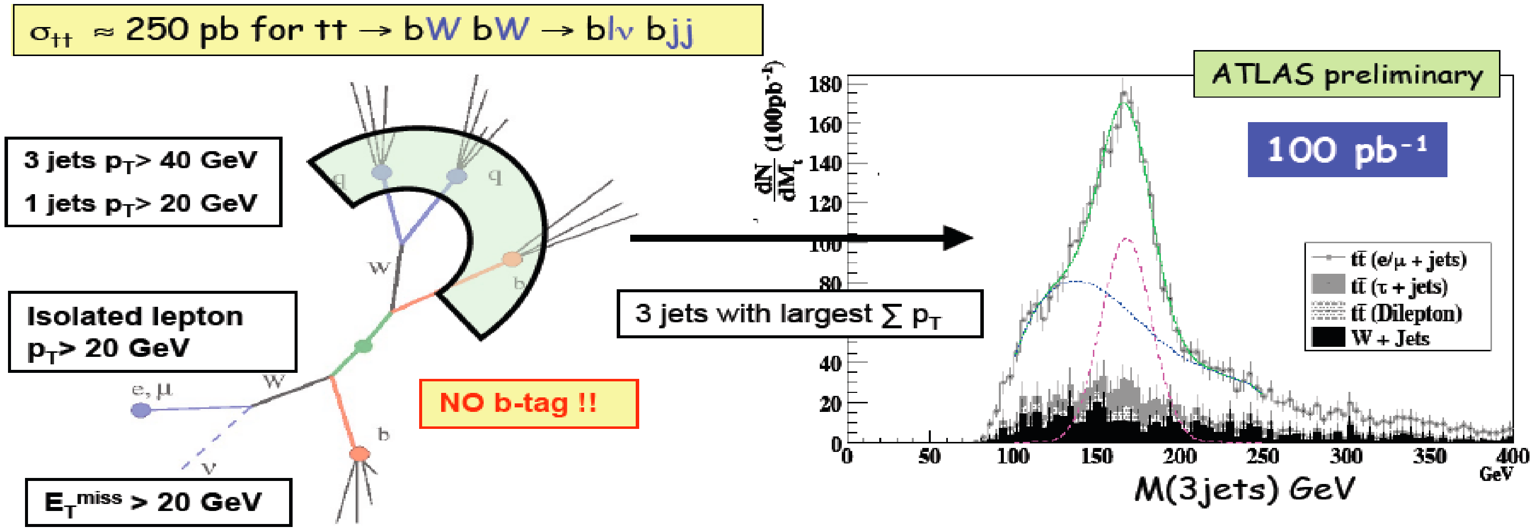




Calibration can also use dilepton events

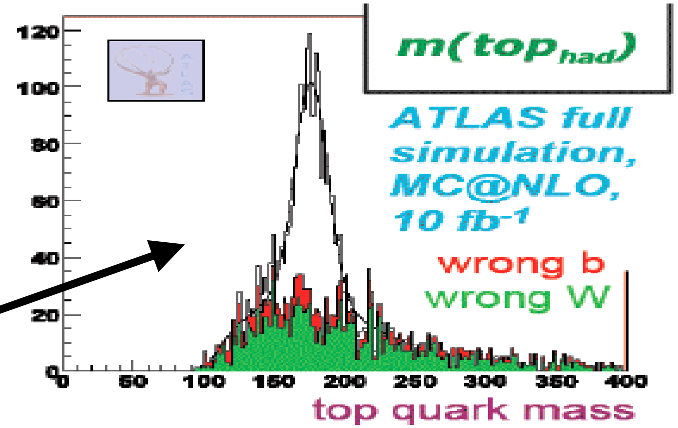
top reconstruction & mass measurement …

- Several methods for early top mass measurement - for example, kinematic fit to reconstruct hadronic top in lepton+jet sample. Implications for Higgs:
  - ttH (H→bb); $H^+ \to tb$; $t \to bH^+$



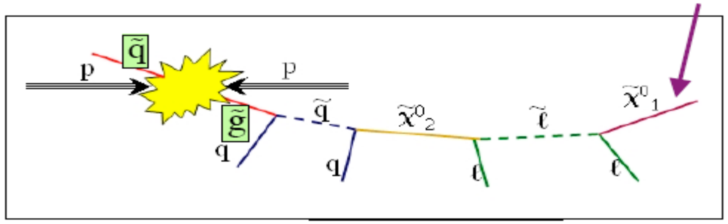
Even without b-tagging, simple analysis, expect to measure m_t to within 10 GeV with 100 pb^{-1}

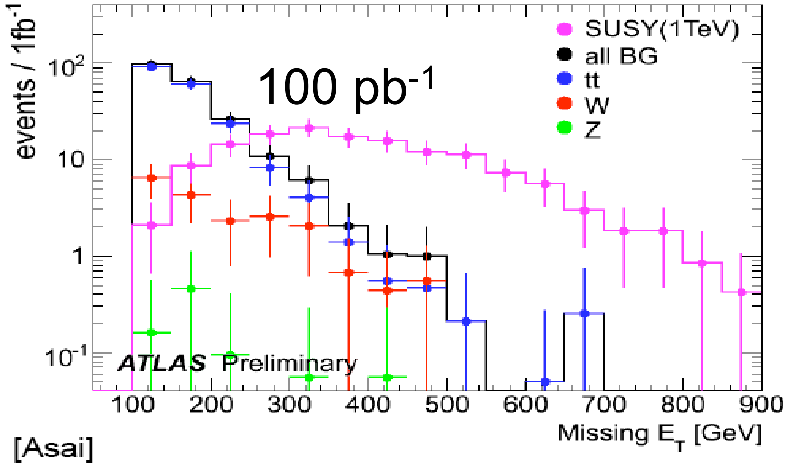
Statistical errors @10fb^{-1}: 0.05-0.2 GeV
Systematics uncertainties: 0.9-1.6 GeV



Excess number of events in tails…

Lepton(e or μ) +multijets+MET analysis



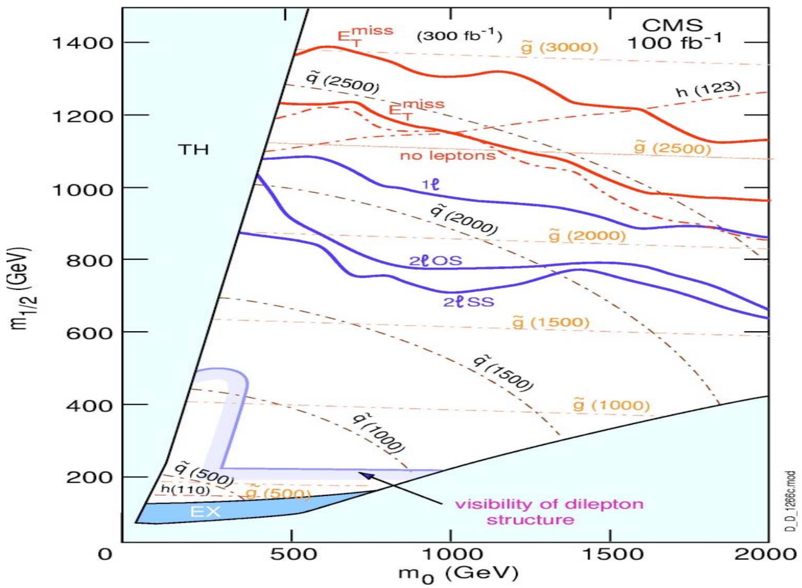


[Asai]

LHC reach for Squark- and Gluino masses:

0.1 fb^{-1}	⇒	M ~ 750 GeV
1 fb^{-1}	⇒	M ~ 1350 GeV
10 fb^{-1}	⇒	M ~ 1800 GeV

Deviation from the SM could be seen quickly: but need time to demonstrate that it is SUSY

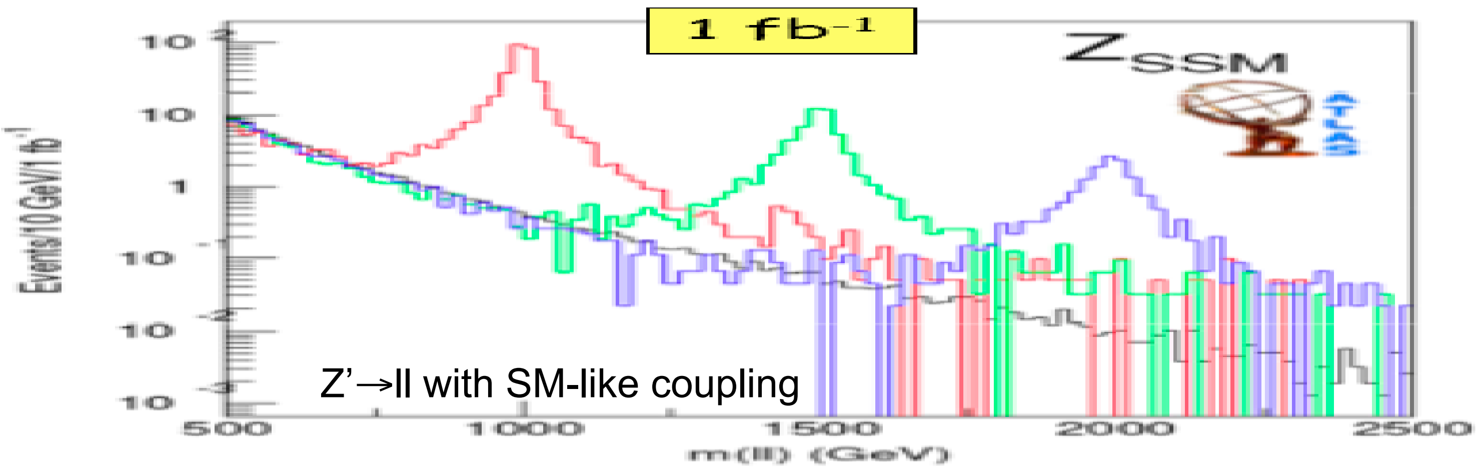


With only 100 pb^{-1},
deviation from the SM up to ~ 1 TeV.
But understanding backgrounds
would require 1 fb^{-1}:

Implications for Higgs

- Higgs production from SUSY cascade decays
- Higgs decays to SUSY particles (and invisibles)

Narrow Resonance→ll at ~ 1TeV…



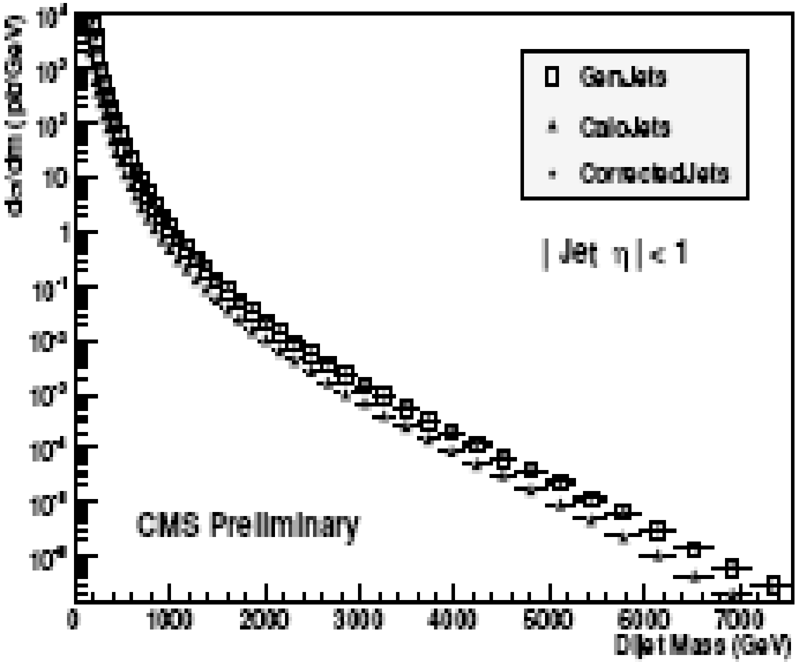
Mass (TeV)	Expected Events for 1fb^{-1} after cuts	Luminosity needed for discovery (corresponds 10 observed events)
1.0	~ 160	~ 70 pb^{-1}
1.5	~ 30	~ 300 pb^{-1}
2.0	~ 7	~ 1.5 fb^{-1}

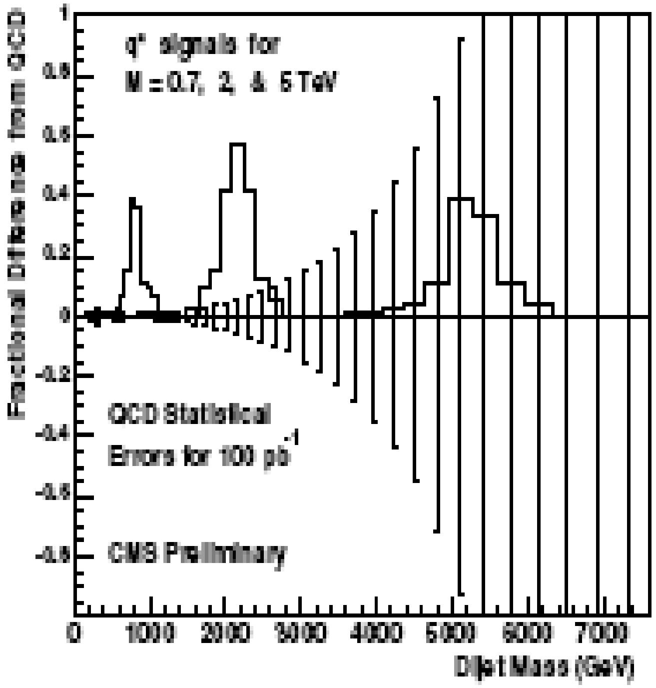
- With 100 pb^{-1}, signal large enough for discovery up to m>1 TeV
- Signal is a narrow resonance on top of a small Drell-Yan background
- Ultimate calorimeter performance not needed

Discovery likely in the e+e- channel but μ+μ- channel needed for couplings, asymmetry, etc

Di-jet Resonances …

- Physics interest is in the high mass tail:
  - Sensitivity to excited quarks, W', Z', etc.
  - Limits from **CDF** and **D0** are in the range **< 0.78 TeV**
  - With **few pb^{-1}** at **14 TeV** we can extend the range
  - **Crucial** experimental parameter is the **energy resolution** in measuring jet energy (**They are narrow resonances**)





Convincing signal for a 2 TeV excited quark with 100 pb^{-1}

Summary

- With first data, up to 100 pb^{-1} (2009)
  - Detector and Trigger commissioning and calibration in situ
  - Simulation/reconstruction software tuning
  - "Re-discover" the SM: W, Z, top, jets
  - Help constrain PDF uncertainties
  - Could discovery some new physics
    - ~ TeV scale resonance $X \rightarrow ll$
    - Narrow resonance in di-jet mass tail
    - Hint for SUSY
    - Hint for a light neutral scalar
- With more data ($\geq$ 1 fb^{-1}: 2010 -)
  - Discover a TeV scale SUSY
  - Discover at least one Higgs boson
  - Understand deviation, excess as signal for new physics

➔Searches for Higgs Bosons at the LHC - ||

Outline

- Introduction
- Standard Model Higgs
- MSSM Higgs
- Higgs Property measurements

Some of the questions …

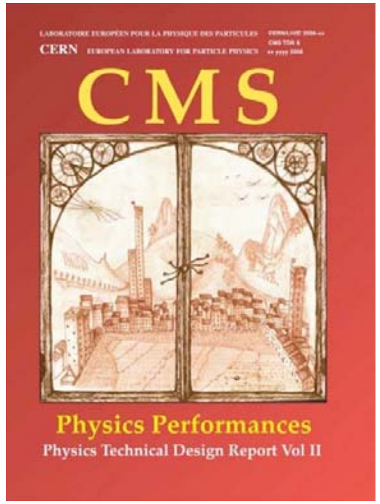
- What is the origin of mass?
  - How is the Electroweak symmetry broken?
  - Do Higgs bosons exist?
- What is the underlying theory of unification?
  - Are the interactions unified at some larger energy scale?
  - How is gravity incorporated?
  - Is there supersymmetry?
- Flavor
  - Why are there 3 flavor families?
  - Neutrino masses and mixing?
  - The origin of CP violation

Answers to some of these questions are expected at the TeV mass scale, i.e. at the LHC

Improvement in Higgs Studies at the LHC

•Many studies have meanwhile been performed using detailed GEANT simulations of the detectors

- Physics Performance Technical Design Report from the CMS collaboration
- ATLAS CSC (Computing System Challenge) notes in preparation, to be released towards the end of 2008



CMS: CERN / LHCC 2006-021

ATLAS: CERN-OPEN 2008-020
(to appear soon)

• New (N)NLO Monte Carlos (also for backgrounds)

- MCFM Monte Carlo, J. Campbell and K. Ellis, http://mcfm.fnal.gov
- MC@NLO Monte Carlo, S.Frixione and B. Webber, wwwweb.phy.cam.ar.uk/theory/
- T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. D68, 073005 (2003)
- E.L.Berger and J. Campbell, Phys. Rev. D70, 073011 (2004)
- C. Anastasiou, K. Melnikov and F. Petriello, hep-ph/0409088 and hep-ph/0501130
- …..

• New approaches to match parton showers and matrix elements

- ALPGEN Monte Carlo + MLM matching, M. Mangano et al.
- SHERPA Monte Carlo, F. Krauss et al.
- …

Tevatron data are extremely valuable for validation, work has started

• More detailed, better understood reconstruction methods
(partially based on test beam results,…)

• Further studies of new Higgs boson scenarios
(Various MSSM benchmark scenarios, CP-violating scenarios, Invisible Higgs boson decays,…..)

Standard Model Higgs

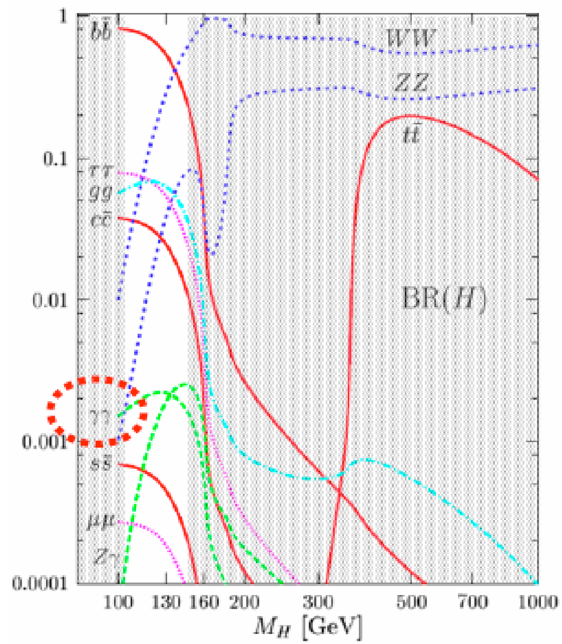
Higgs → gamma gamma

- ***Important channel in the low mass region.***
- ***It gives the best mass resolution thanks to excellent electromagnetic energy resolution***

SELECTION

- **Trigger**: at least 2 isolated photons, with $p_T > 20\ GeV/c$ each
  → ε *(respect to offline)* $= (93.6 \pm 0.4)\%$
- **Identification cut** exploiting the shower shape.
- **Fiducial cut**: $0 < |\eta| < 1.37$ & $1.52 < |\eta| < 2.37$.
- **Isolation cut**: $\Sigma p_T < 4\ GeV/c$, considering all tracks with $p_T > 1 GeV/c$ in a $\Delta R = 0.3$ cone around the electromagnetic cluster.
- **Momentum cut**: $p_T > 25 GeV/c$ and $p_T > 40 GeV/c$ for the two most energetic photons.

Selection efficiency:
$\varepsilon = 36.0\ \%$ *(32.2% with pileup $10^{33} cm^{-2} s^{-1}$)*



In a mass window M_H +/- 1.4σ GeV:

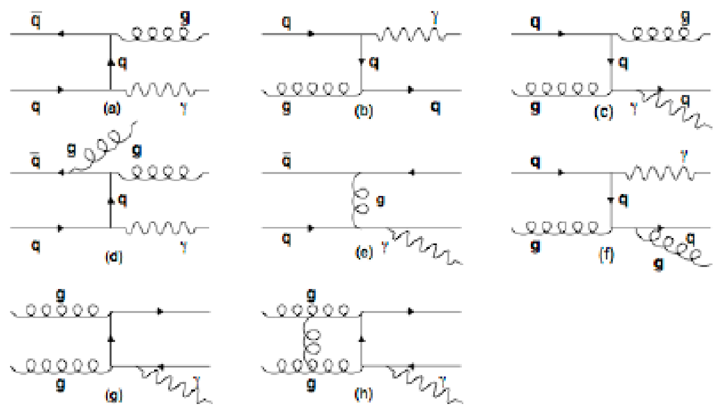
Signal Process	Cross-section (fb)
$gg \to H$	21
VBF H	2.7
ttH	0.35
VH	1.3

Higgs → gamma gamma backgrounds

Within a mass window *M_H +/- 1.4σ GeV*:

Background Process	Cross-section (fb)
$\gamma\gamma$	562
Reducible γj	318
Reducible jj	49
Drell Yan	18

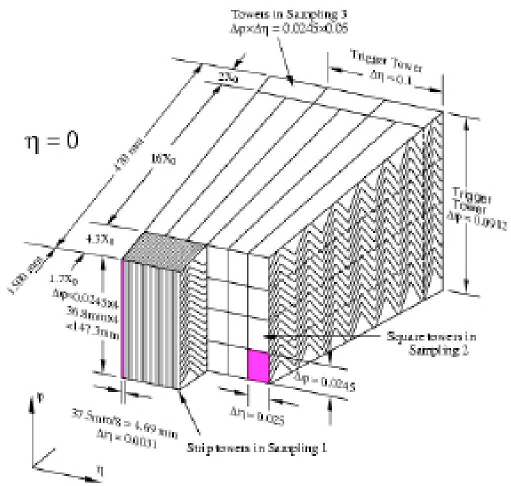
Example: γ-jet processes



- Background is evaluated with ***NLO*** simulations.
- ***It will be measured from data sidebands.***

Strategy for jet rejection:

- *Longitudinal segmentation* of the calorimeter.
- Fine segmentation of the first layer (*η-strips*) => good π^0 rejection.
- *Isolation* of the *electromagnetic* cluster.
- *Isolation based on tracks* reconstructed by the inner detector.

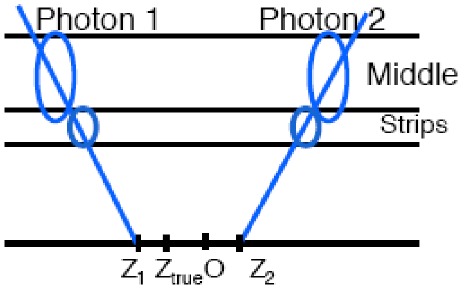


Higgs → gamma gamma reconstruction

PRIMARY VERTEX

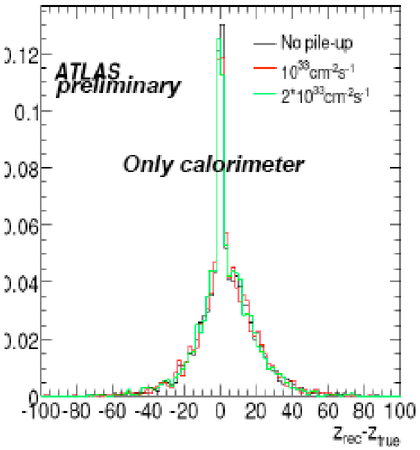
If the vertex is unknown, add 1.4 GeV to the mass resolution.

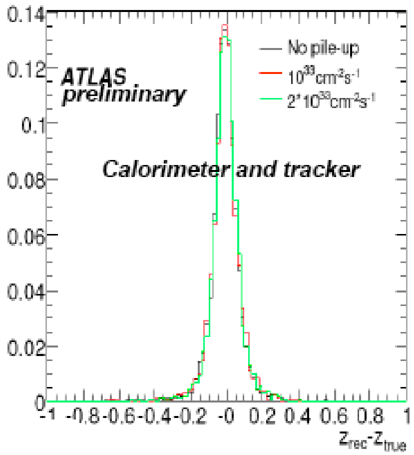
Combine calorimeter and tracker informations!



- Calorimeter → vertex position accuracy of ***19 mm***
- Combining with the tracker information → ***~0.1 mm***

Calorimeter information is useful in case of pile-up or events with low tracks multiplicity.

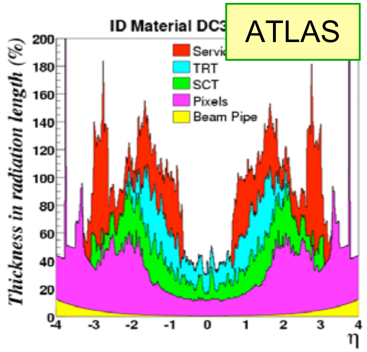


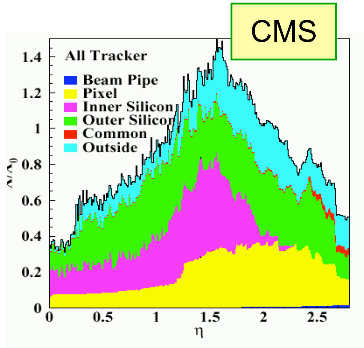


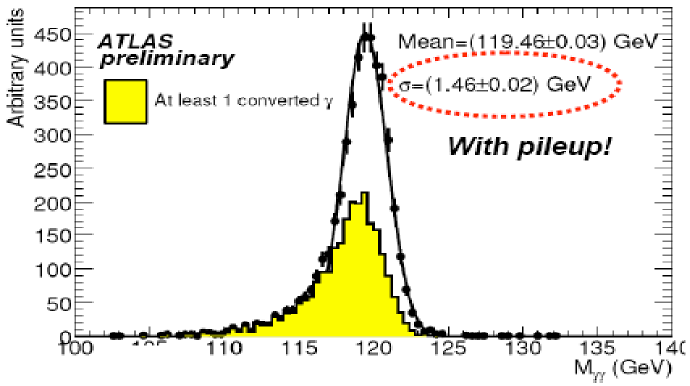
CONVERSIONS

~50% of the events with at least one converted γ !

- ad hoc energy calibration required in late conversions;
- conversion vertex used in computation of the direction;
- used for gamma-jet background estimation.



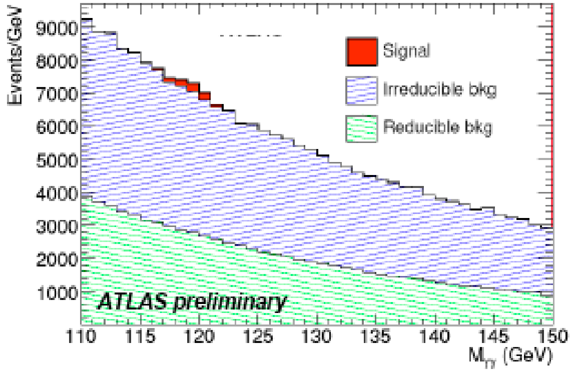




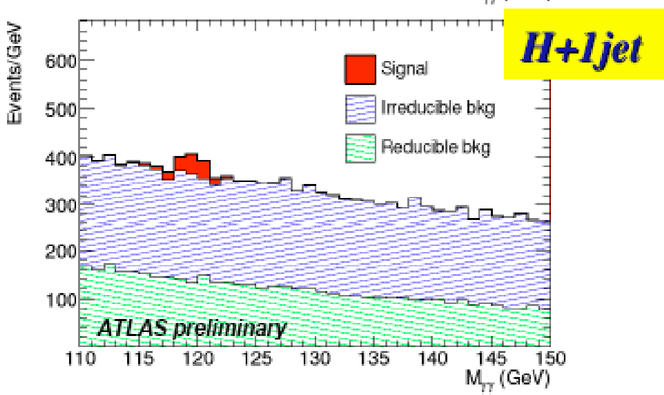
CMS: fraction of converted γs

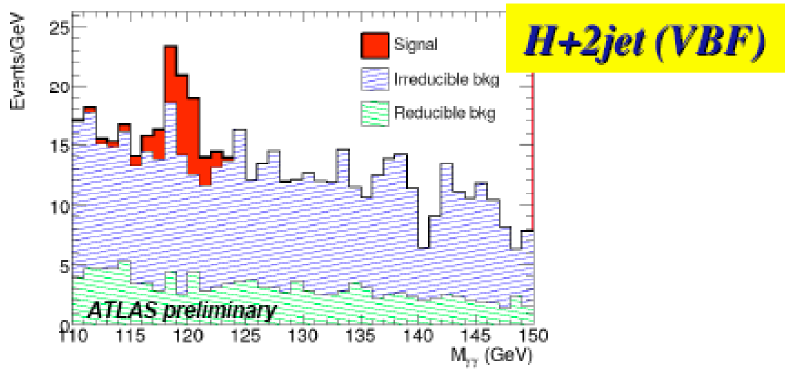
Barrel region:	42.0 %
Endcap region:	59.5 %

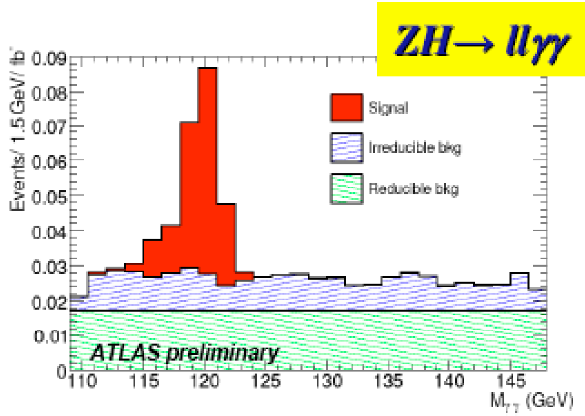
Higgs → gamma gamma reconstruction

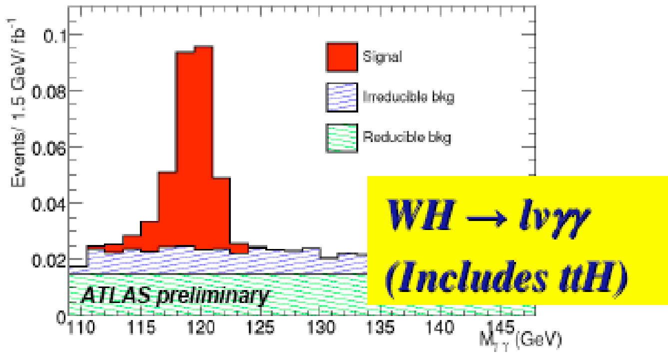


From associated production, high levels of purity for signal achieved thanks to additional requirements (but less events….)





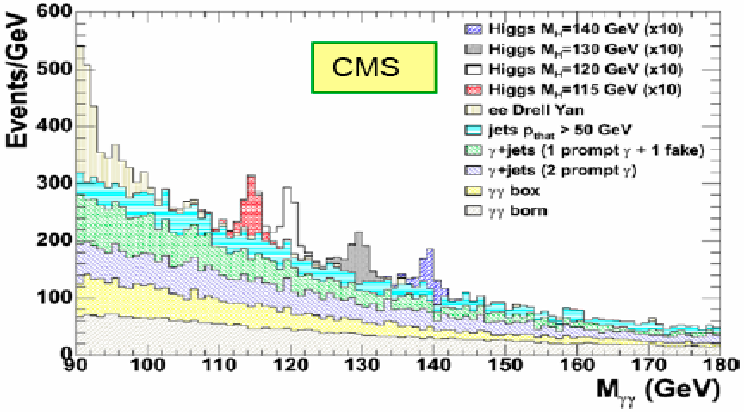


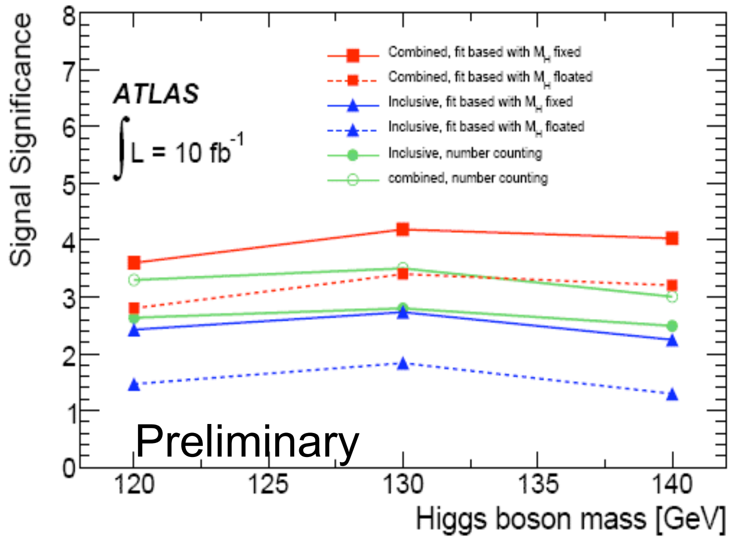


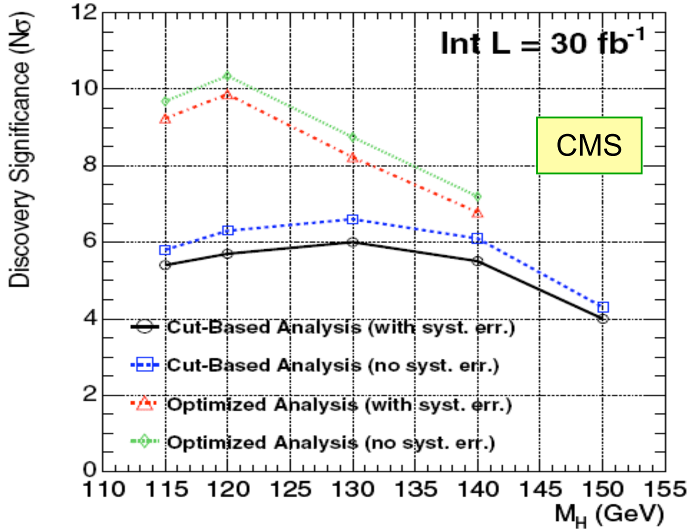
Higgs → gamma gamma significance

New elements of the analyses:

- NLO calculations available
  (Binoth et al., DIPHOX, RESBOS)
- Realistic detector material
- More realistic K factors (for signal and background)
- Split signal sample acc. to resolution functions

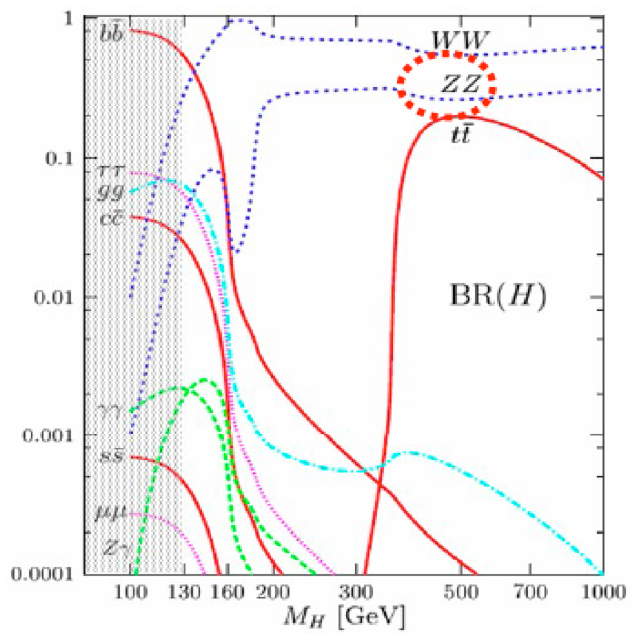






- Comparable results for ATLAS and CMS
- Improvements possible by using more exclusive γγ + jet topologies

Higgs → ZZ* → 4l



SELECTION

- **Trigger**: - single isolated μ (e) with p_T>20 (25) GeV/c;
  - two μ (e) with p_T>10 (15) GeV/c.
- **Kinematic**: - 2 pairs of same flavor opposite charge lept.
  - p_T>7GeV (at least two with p_T>20GeV)
  - calorimeter identification
  - $|M_{ll1}-M_Z|<\Delta M_{12}$ and $M_{ll2}>M_{34}$
- **Fiducial cut**: $|\eta| < 2.5$
- **Isolation cut**: - Calorimeter: $\Sigma E_T/p_T < 0.23$
  - tracker: $\Sigma p_T/p_T < 0.15$
- **Vertexing cut** on maximum lepton ***impact parameter***:

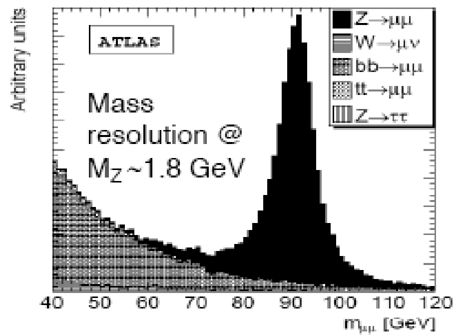
  $d_0/\sigma_{d0}<3.5$ (6.0) for μ (e)

It is the "golden channel"!

- ***Observation of a clear peak on top of a smooth background!***
- ***Wide range of masses explored***

Background will be estimated in sidebands
→ low systematic uncertainties

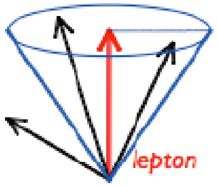
•Look to the Z with first data to understand lepton reconstruction and detectors response.
•$Z \rightarrow ee$ mass peak is affected by electron bremsstrahlung.

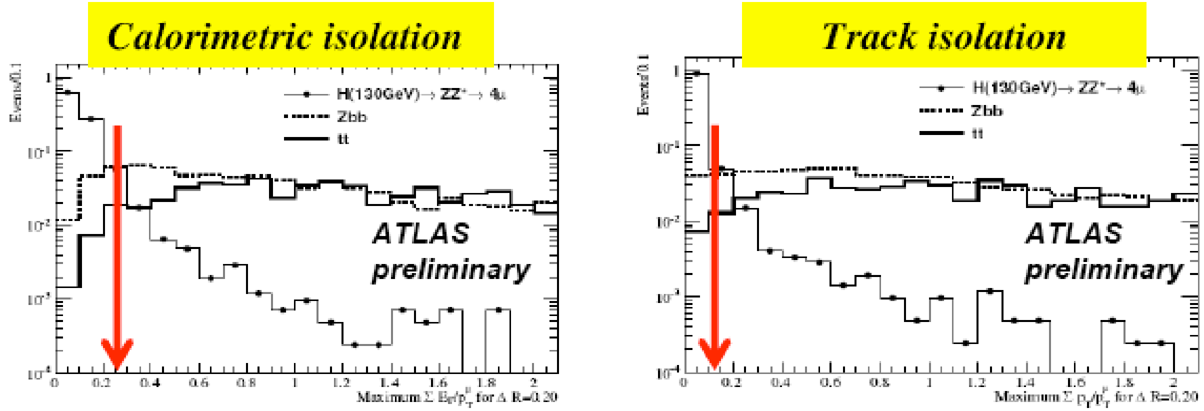


Higgs → ZZ* → 4l

Reducible backgrounds have activity around leptons from b-decay

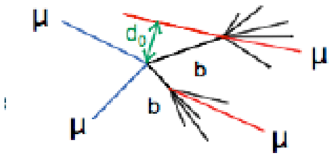
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

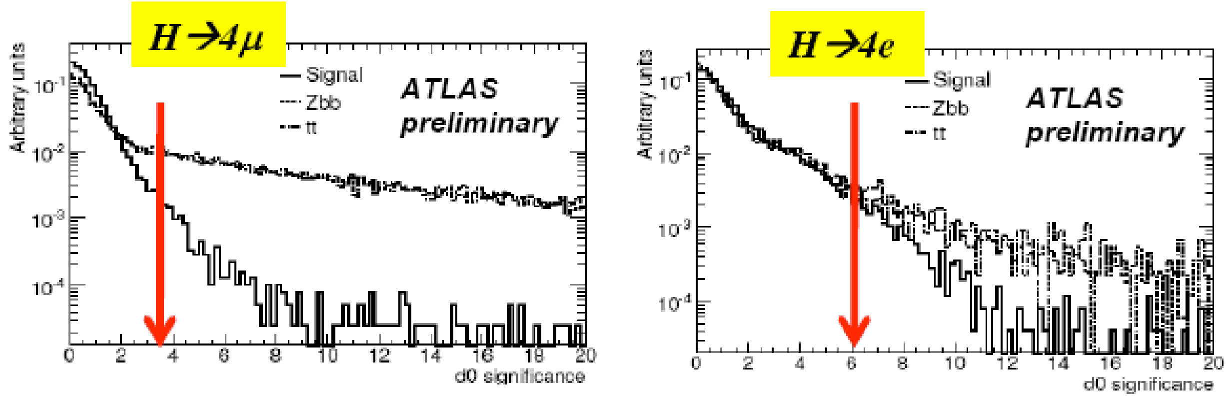




Normalized calorimetric and track isolation (ΔR=0.2) for the signal (m_H = 130) and the *Zbb* and tt backgrounds in the 4μ channel.

Lepton from b-quark decay do not point towards primary vertex

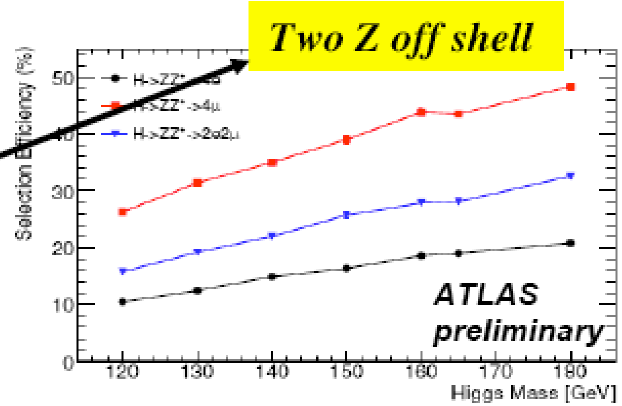


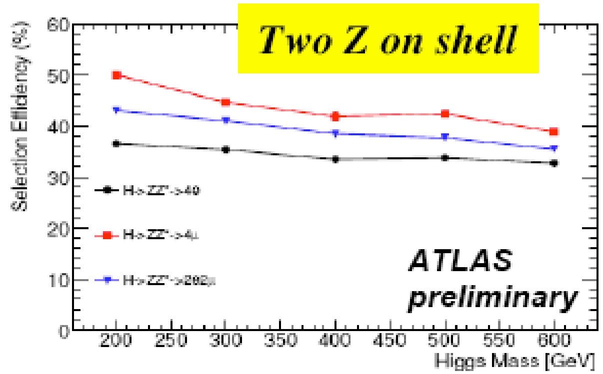


Transverse impact parameter significance in signal and reducible background events.

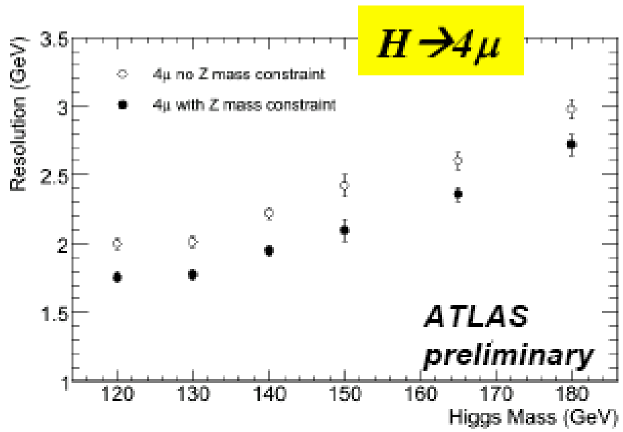
Higgs → ZZ* → 4l

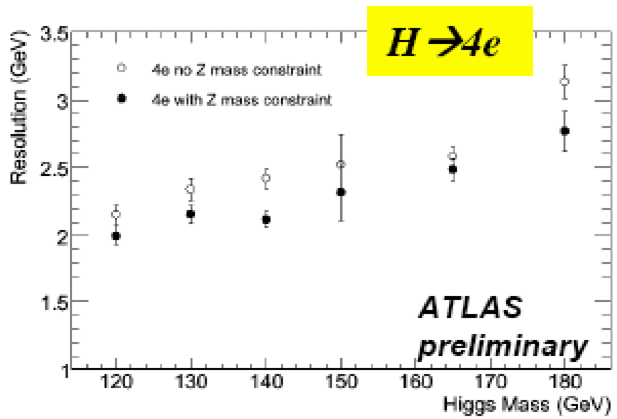
Higher background requires a stronger selection





Selection efficiency as a function of the Higgs mass, for each of the three decay channels.

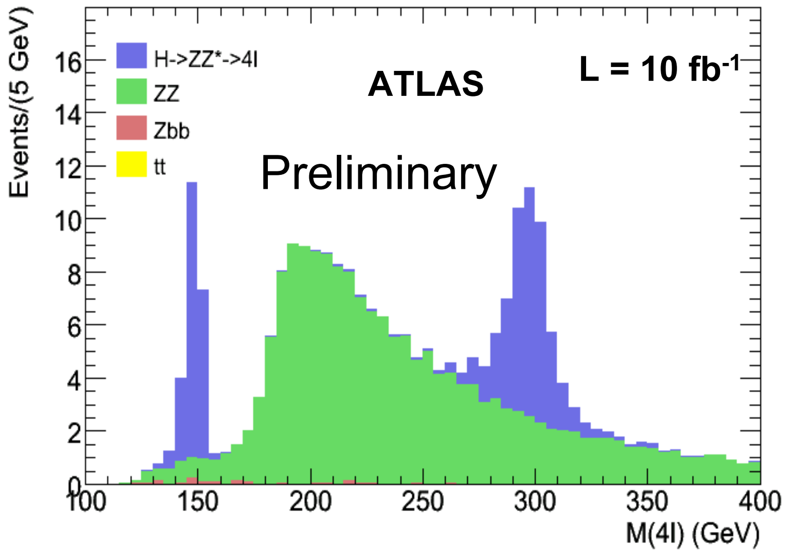




Mass resolution as a function of the Higgs mass. Open circles denote the resolution Z mass constraint improves resolution.

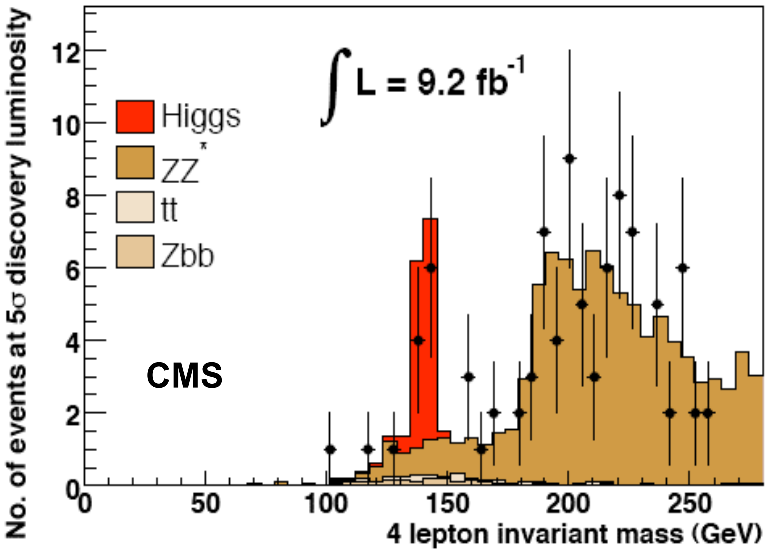
Higgs → ZZ* → 4l

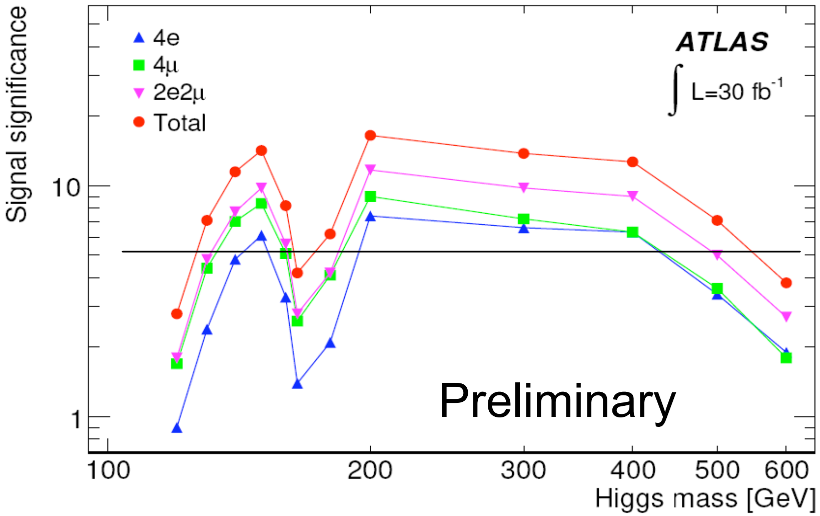
- Main backgrounds: ZZ (irreducible), tt, Zbb (reducible)
- Main experimental tools for background suppression:
  - lepton isolation in the tracker and in the calorimeter
  - impact parameter



Updated ATLAS and CMS studies:

- ZZ background: NLO K factor used
- background from side bands

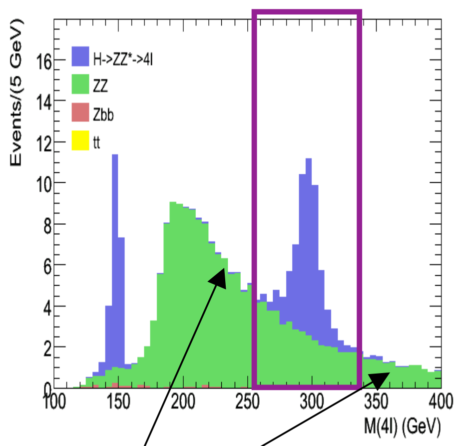




ZZ background estimation

What is the expected number of ZZ background events under the signal region?

- *direct simulation ZZ→4l process :*
  - large uncertainties theoretical knowledge, MC modelling detector acceptance
  - statistical precision "only" limited by Monte Carlo statistics
- *control samples :*
  - full cancellation pp luminosity uncertainty
  - reduced sensitivity to theoretical and experimental uncertainties



normalization to single Z data

$$R = \frac{(\sigma_{ZZ\to 4l}\epsilon_{4l}\int Ldt)}{(\sigma_{Z\to 2l}\epsilon_{2l}\int Ldt)}$$

theoretical uncertainty : 2– 8%

statistical precision : high thanks to large statistics of Z →l+l- data

normalization to sidebands

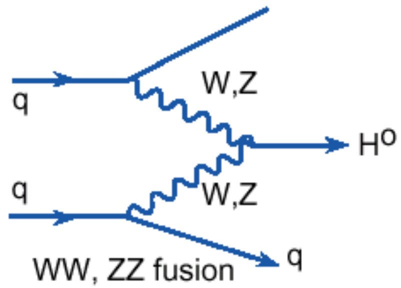
$$N^{signal\ region}_{estimated\ bkg} = \alpha_{MC} N^{sidebands}_{observed\ bkg}$$

$$\alpha_{MC} = \frac{N^{signal\ region}_{expected\ bkg}}{N^{sidebands}_{expected\ bkg}}$$

theoretical uncertainty: 0.5- 4%

statistical precision : available statistics in sidebands limiting factor?

Vector Boson Fusion qq H

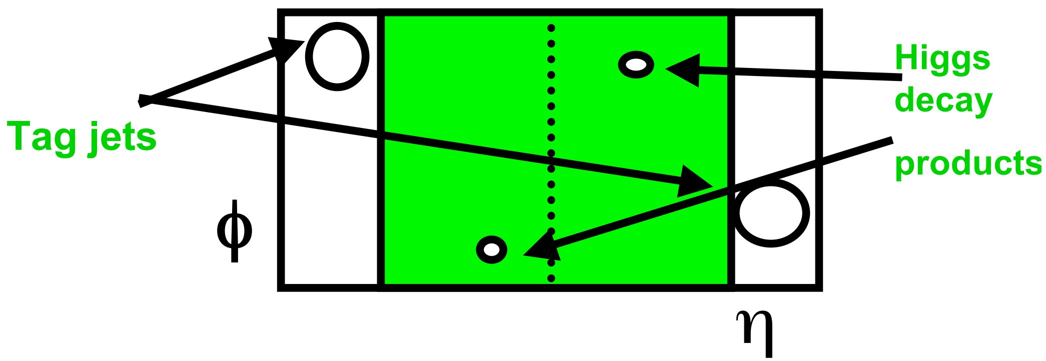


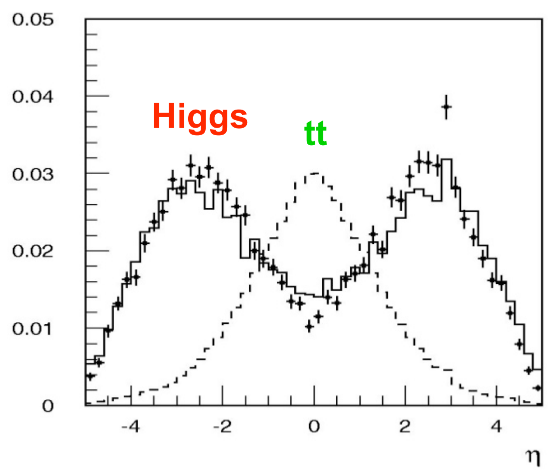
Motivation: Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters
(couplings to bosons, fermions)

Established (low mass region) by D. Zeppenfeld et al. (1997/98)
Earlier studies: R.Kleiss W.J.Stirling, Phys. Lett. 200 (1988) 193;
Dokshitzer, Khoze, Troyan, Sov.J. Nucl. Phys. 46 (1987) 712;
Dokshitzer, Khoze, Sjöstrand, Phys.Lett., B274 (1992) 116.

Distinctive Signature of:
- two high P_T forward tag jets
- little jet activity in the central region
  ⇒ central jet Veto

Rapidity distribution of jets in tt and Higgs signal events:





$H \rightarrow WW(*)$

Interesting for $2M_W<M_H<2M_Z$ where all other decay modes are suppressed.

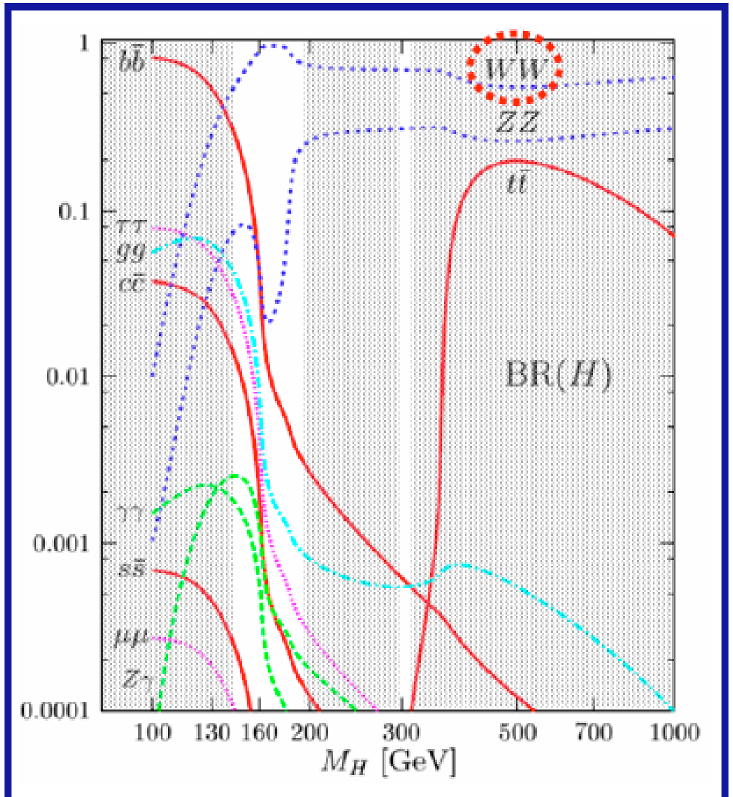
Signature is $e\mu$ (or lqq) $+ E_T^{miss}$.

Three channels:

- *- $H \rightarrow WW \rightarrow e\ \nu\ \mu\ \nu$ (H+0jet)*
- *- $H \rightarrow WW \rightarrow e\ \nu\ \mu\ \nu$*
- *- $H \rightarrow WW \rightarrow l\ \nu\ q\ q$*
- *(only for M_H=300 GeV)*

VBF (H+2jet)

Measure of spin and CP properties possible for heavy $H \rightarrow WW \rightarrow lvqq$



Comments:
- No mass peak ➔ use transverse mass. $M_T = \sqrt{(E_T^{ll} + E_T^{\nu\nu})^2 - (\vec{p}_T^{e\mu} + \vec{p}_T^{miss})^2}$
- **High backgrounds**: *WW, Wt, ttbar, Z→2l, bb,cc,QCD multijet*

Evaluation of the sensitivity expected very soon.

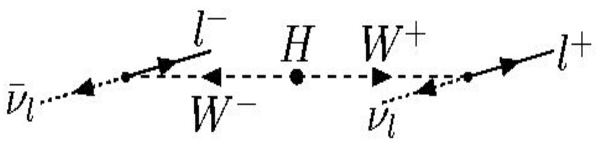
H → WW → ℓν ℓν

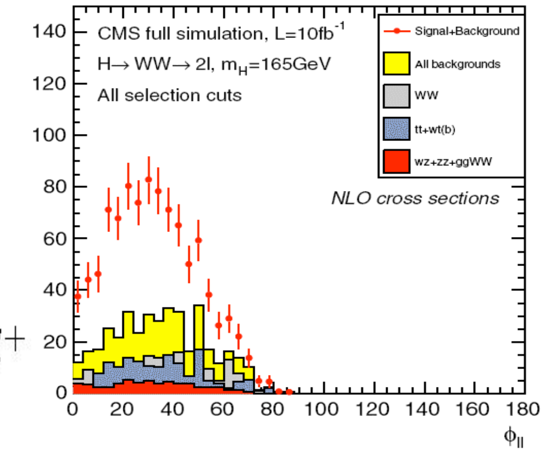
gg → H → W W*
→ ℓν ℓν

qq H → qq W W*
→ qq ℓν ℓν

- Large H → WW BR for m_H ~ 160 GeV/c²
- Neutrinos → no mass peak,
- Large backgrounds: WW, Wt, tt
- <u>Two main discriminants</u>:

(i) Lepton angular correlation





(ii) Jet veto: no jet activity in central detector region

<u>Difficulties:</u>

(i) need precise knowledge of the backgrounds
Strategy: use control region(s) in data, extrapolation in signal region

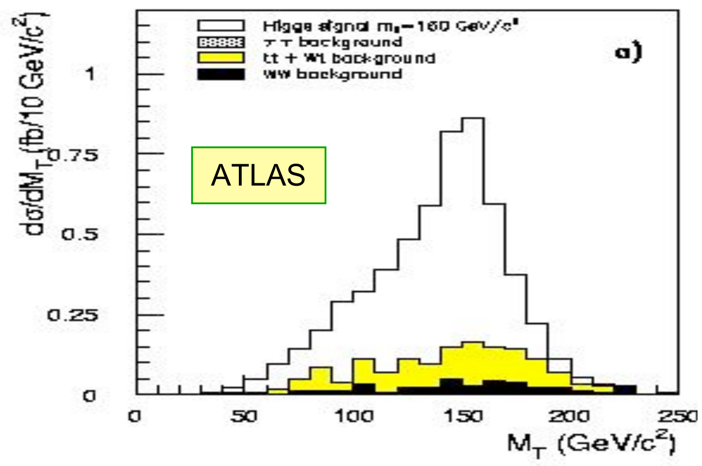
(ii) jet veto efficiencies need to be understood for signal and background events

→ reliable Monte Carlo generators, data driven-background normalizations

<u>Selection criteria:</u>

- Lepton P_T cuts and tag jet requirements ($\Delta\eta$, P_T)
- Require large mass of tag jet system
- Jet veto (important)
- Lepton angular and mass cuts

$$M_T = \sqrt{(E_T^{ll} + E_T^{\nu\nu})^2 - (\vec{p}_T^{\,e\mu} + \vec{p}_T^{\,miss})^2}$$



Vector Boson Fusion qq H(→ ττ)

• ***High BR in the low mass region.***

• ***3 channels: ll, lh, hh (65% of τ gives hadrons)***

SELECTION

• **Trigger**: isolated electrons (μ) with p_T>22 (20)GeV/c (ε~10%)

$\tau + E_T^{miss}$ (ε~3.7%) for the *hh* channel

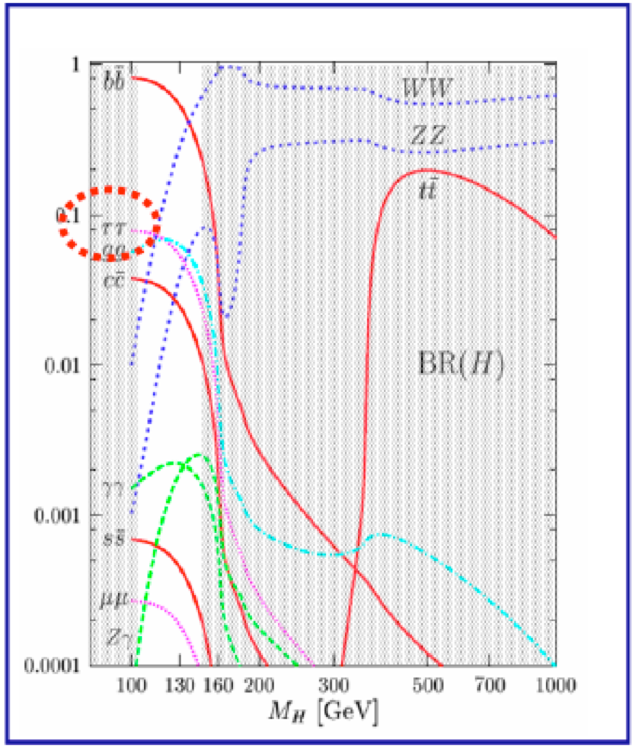
• **Isolation cut**

• **Likelihood** exploiting the shower shape and the track quality to separate τ and jet.

• **b-jet veto** to kill *tt(+jets)→lνb lνb (+jets)* (background for the ll channel)

• select highest E_T jets in opposite hemispheres

• **Central jet veto**



BACKGROUNDS

• $Z \to \tau\tau + jets$
• $W \to \tau\nu + jets$
• *tt+jets*
• *QCD* multi-jets for the *hh* channel

MAIN ISSUES:

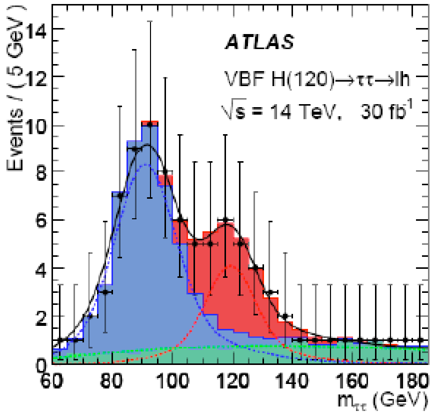
- Discrepancies in Monte Carlo generator → impact on veto efficiency
- Pileup → impact on E_T^{miss} and jet veto
- Estimation of QCD multi-jet → no sensitivity yet on *hh* channel

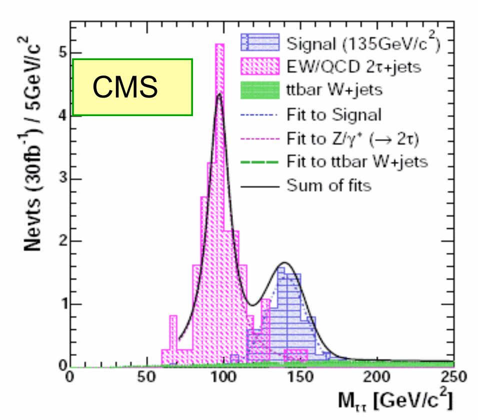
Vector Boson Fusion qq H(→ ττ)

qq H → qq τ τ
→ qq ℓνν ℓνν
→ qq ℓνν hν

Experimental challenges:

- In-time pileup, out-of-time pileup, underlying event.
  - test simulations & use vertexing for the jet
  - calorimeter timing
  - early data underlying event measurement
- Identification of hadronic τ
- Good E_T^{miss} resolution (since there are neutrinos…)
- Knowledge of the $Z \to \tau\tau$ background shape in the high mass region: use data $Z \to \mu\mu$ to emulate it!

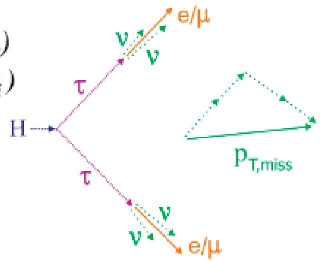


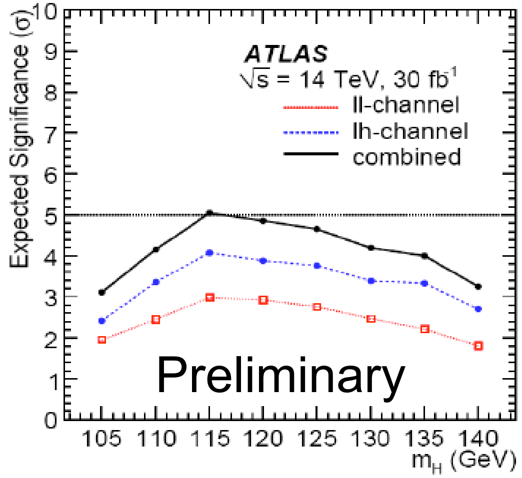


Higgs mass reconstructed using the angle between the two τ and the **collinear approximation:**

$m_{\tau\tau} = m_{ll} / sqrt(X_1 X_2)$

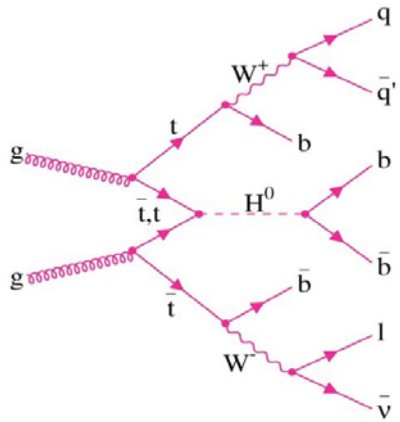
with $X_i = P_T(l_i)/P_T(\tau_i)$





ttH → ttbb

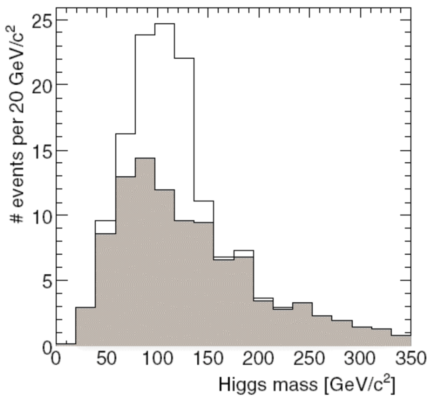
Complex final states: H→ bb, t → bjj, t → b$\ell\nu$
t → b$\ell\nu$, t → b$\ell\nu$
t → bjj, t → bjj



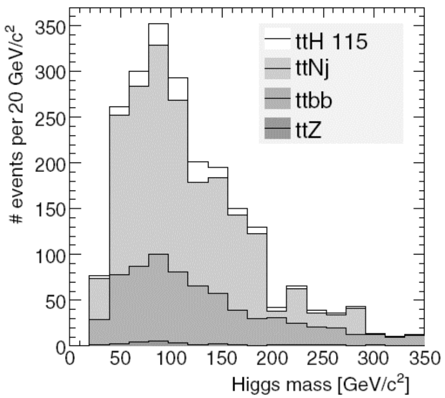
Main backgrounds:
- combinatorial background from signal (4b in final state)
- ttjj, ttbb, ttZ,…
- Wjjjjjj, WWbbjj, etc. (excellent b-tag performance required)

• Updated CMS study (2006): ALPGEN matrix element calculations for backgrounds → larger backgrounds (ttjj dominant), experimental + theoretical uncertainties, e.g. ttbb, exp. norm. difficult…..

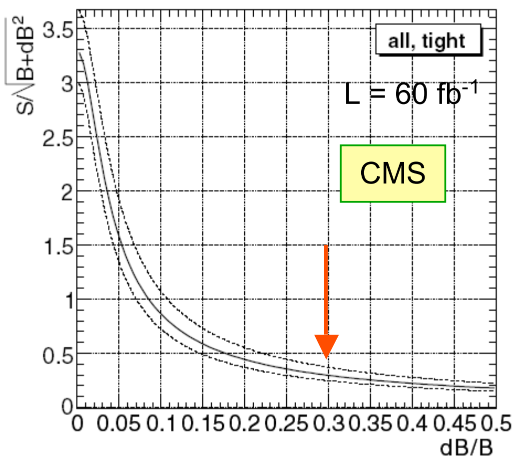
M (bb) after final cuts, 60 fb^{-1}



Signal events only

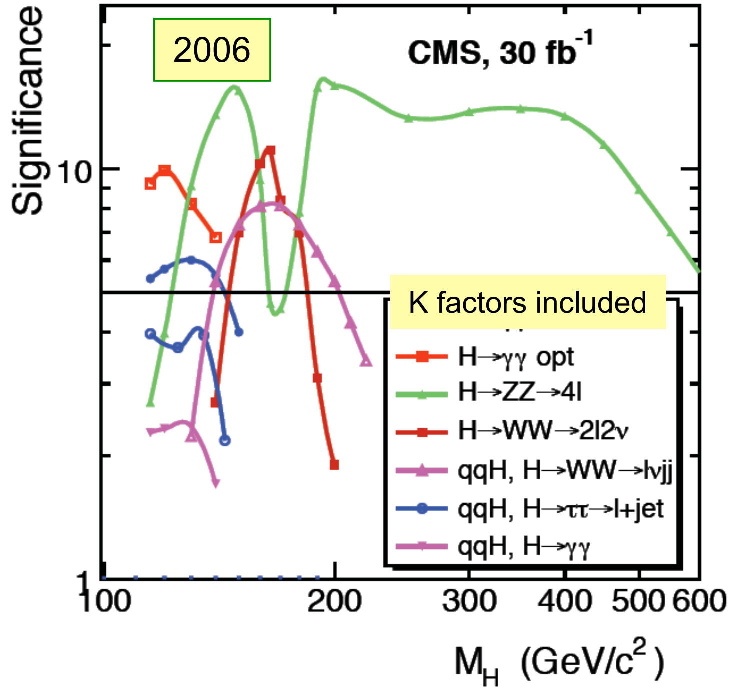


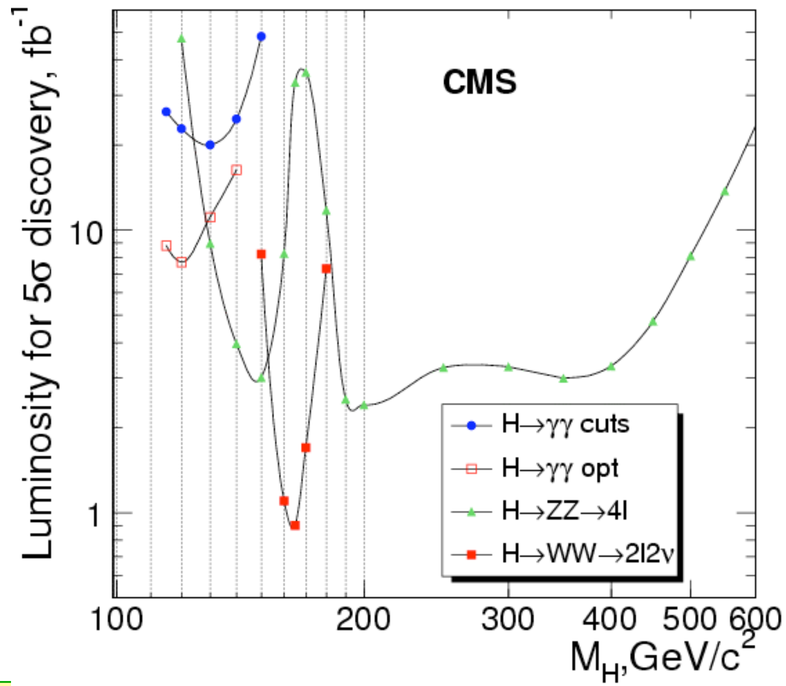
…. backgrounds added



Signal significance as function of background uncertainty

LHC discovery potential for 30 fb^{-1}





- Full mass range can already be covered after a few years at low luminosity
- Similar performance in ATLAS
- Several channels available over a large range of masses

Vector boson fusion channels play an important role at low mass !

Important changes w.r.t. previous studies:

- **H → γγ** sensitivity of ATLAS and CMS comparable
- **ttH → tt bb** disappeared in both ATLAS and CMS studies

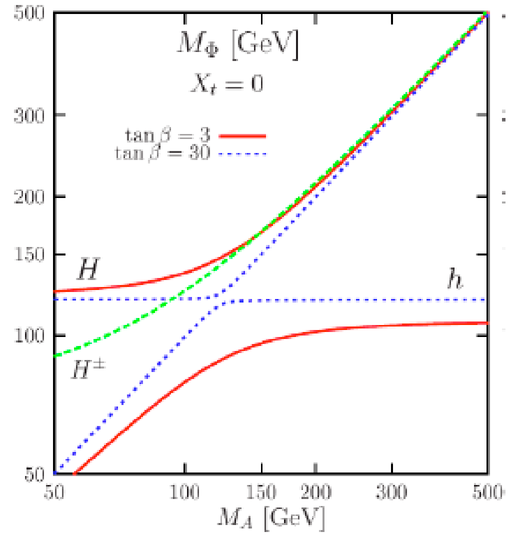
The Extended Higgs Sector

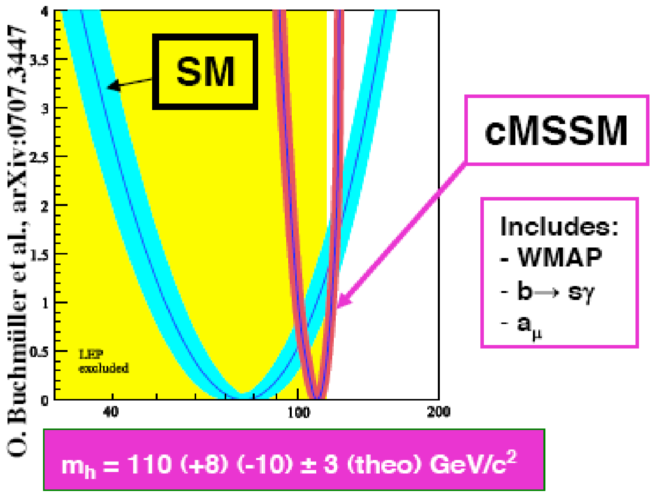
MSSM Higgs

- One doublet of Higgs pseudo-scalar fields is replaced with two:
  - One couples to up-fermions and has $vev=v_u$
  - One couples to down fermions and has $vev=v_d$

- 2X4-3=5 physical scalar fields/particles: $h, H, A, H^\pm$

- Properties at tree level:
  - fully defined by 2 free parameters: m_A, $tan\beta=v_u/v_d$
  - CP-odd A:
    never couples to Z or W;
    decays to bb, $\tau\tau$ (and additionally tt for small $tan\beta$).
  - CP-even h and H:
    SM-like near their mass limits vs m_A;
    at large $tan\beta$ enhanced coupling with down fermions, suppressed couplings to W and Z.
  - $H^\pm$ "strongly" couples to tb and $\tau\nu$
  - All Higgs bosons are narrow (Γ<10GeV)

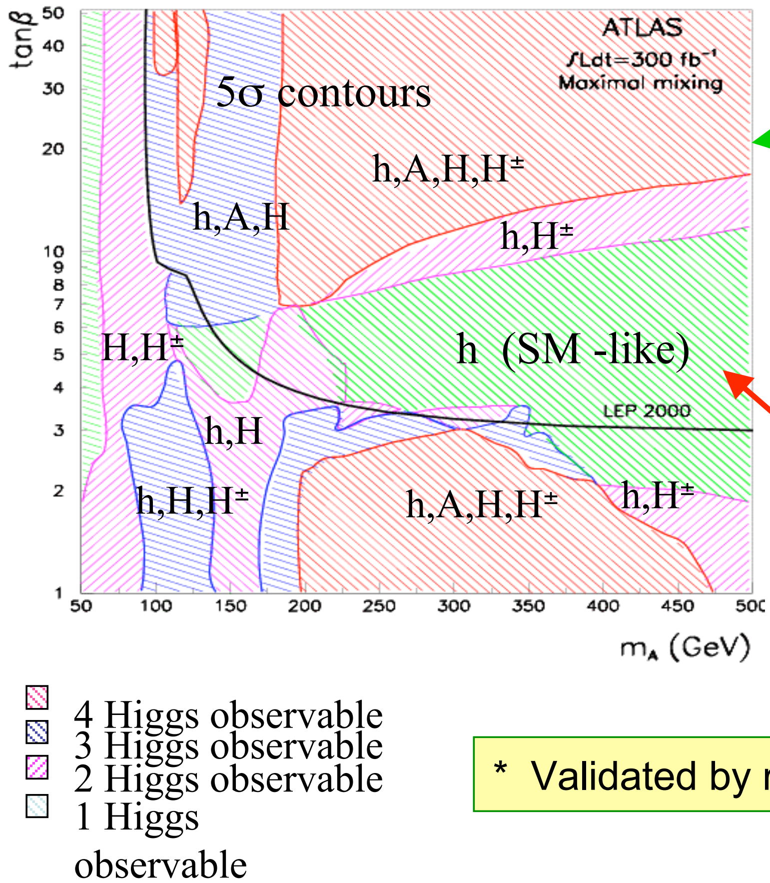




….watch the low mass region !

We choose the benchmark scenario m_h^{max} corresponding to maximal theoretically allowed region for m_h.

Discovery potential for SUSY Higgs bosons



A, H, H± cross-sections ~ $\tan^2\beta$

- best sensitivity from A/H → ττ, H± → τν
  (not easy the first year ....)

- A/H → μμ experimentally easier
  (esp. at the beginning)

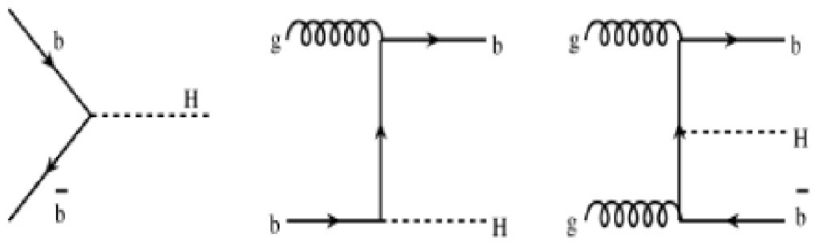
Here only SM-like h observable if SUSY particles neglected.

* Validated by recent ATLAS and CMS full simulation studies *

Coverage in the large m_A wedge region can be improved (slightly) by:
- Higher luminosity: sLHC
- Additional SUSY decay modes (is however model dependent)

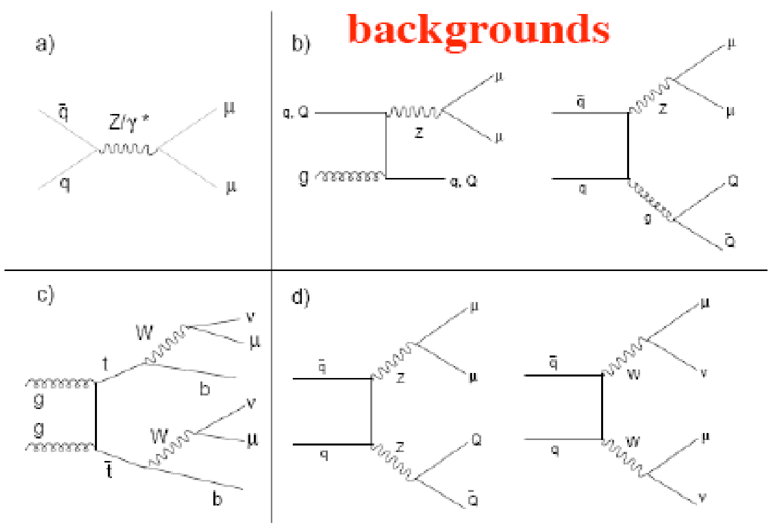
A/H → μμ

At high tanβ the associated production with a *b* quark is enhanced respect to gluon gluon fusion



- Decay prohibited in *SM*
- Enhanced in *MSSM*
- Clear signature!
- Direct mass measurement (no E_T^{miss})!

backgrounds

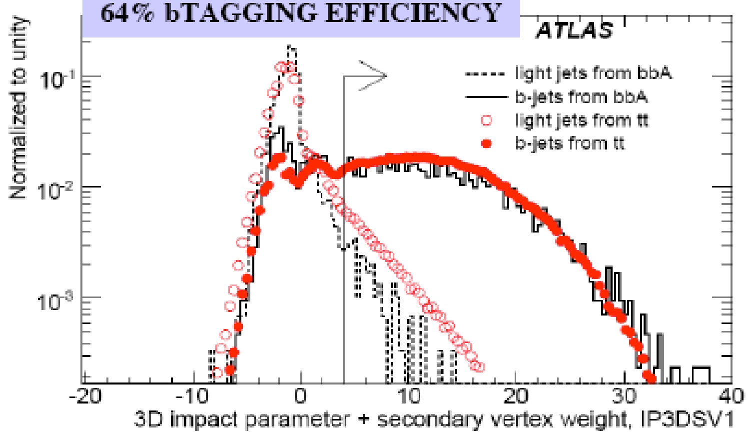


WW and ZZ backgrounds are expected small.

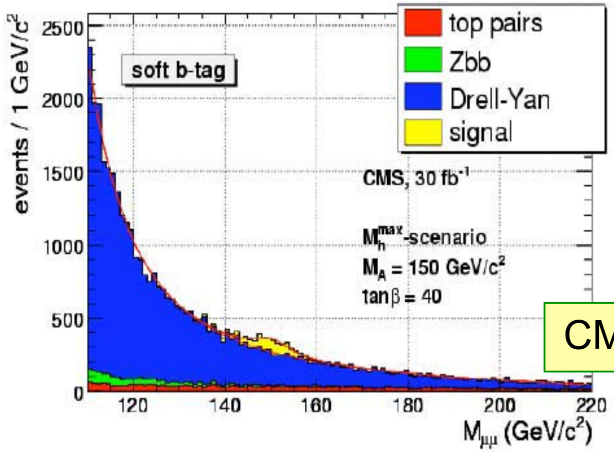
Background rejection:

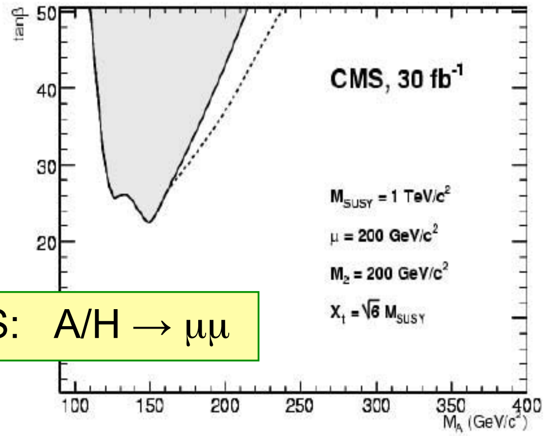
- Additional jet required => kill Drell-Yan
- muon isolation
- b tagging (based on longitudinal impact parameter and secondary vertex)
- reject large E_T^{miss} (against ttbar)
- jet vetos

64% bTAGGING EFFICIENCY



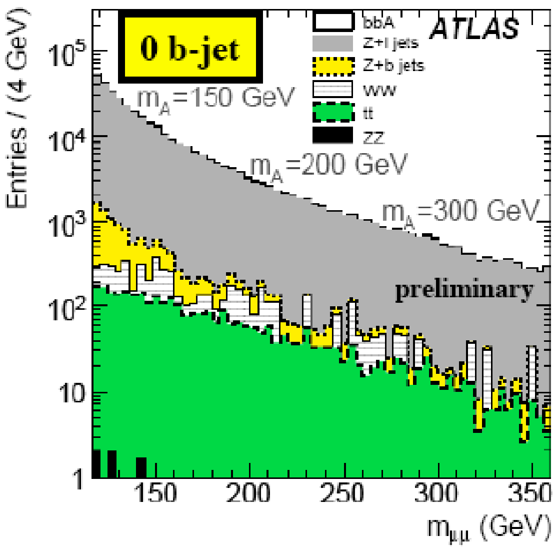
A/H → μμ

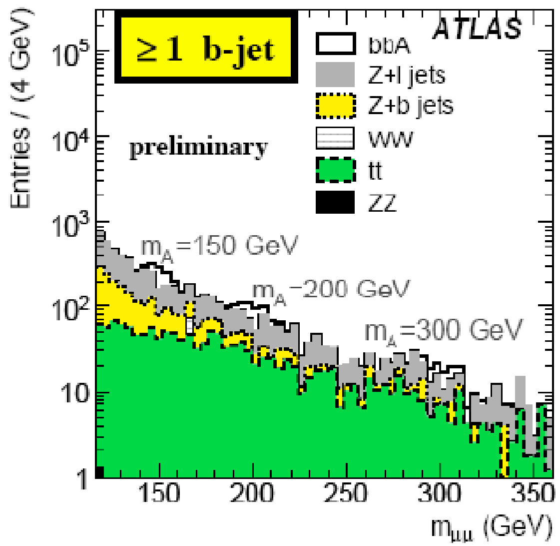


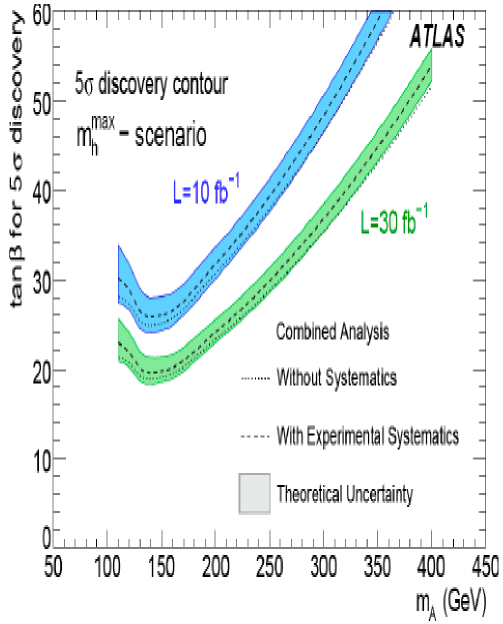


CMS: A/H → μμ

Excellent dimuon
Mass resolution
Essential. Measure
Width and tan(beta)







$H \rightarrow \tau\tau$ ($\rightarrow$ ll)

SELECTION.

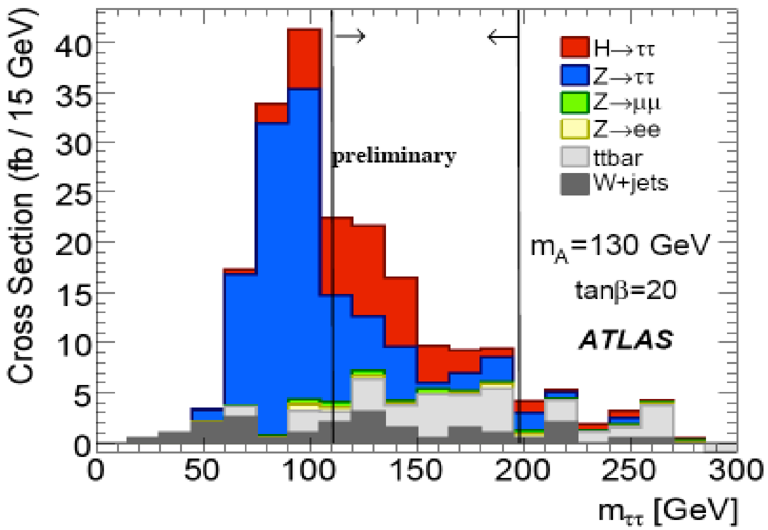
- **Trigger: isolated $\mu(e)$ with p_T>20 (25)GeV || two isolated e || or one e & one μ**
- **b-tagging on at least one jet to suppress light jets**
- **Cuts on *missing E_T , b momentum , lepton momentum, number of jets* (<3) to reject *Z* and *tt* backgrounds**
- **Collinear approximation**

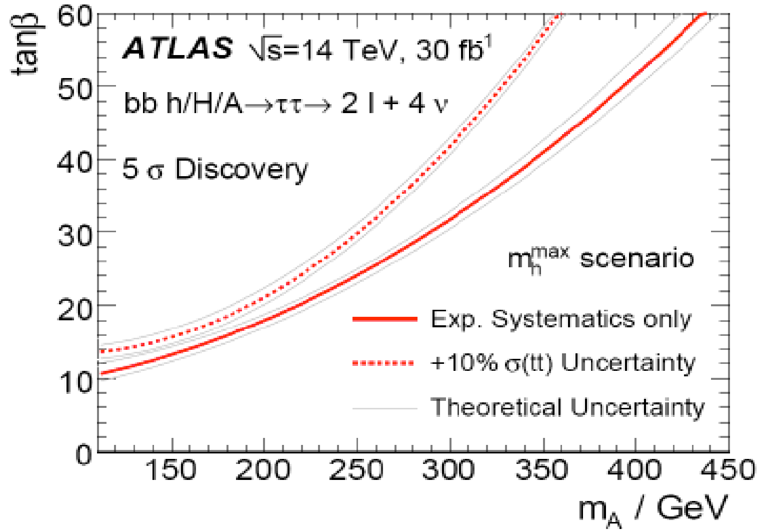
BACKGROUNDS:

- ***Drell-Yan***
- ***$Z \rightarrow ee$***
- ***$Z \rightarrow \tau\tau$***
- ***tt***
- ***W jets***

Z estimated from data!

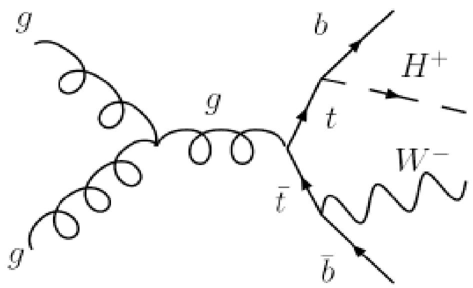
- **Studies ongoing on hadronic τ decay mode**
- **Mass reconstruction as for *SM VBF $H \rightarrow \tau\tau$***





Charged Higgs

m(H+) < m(top)



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

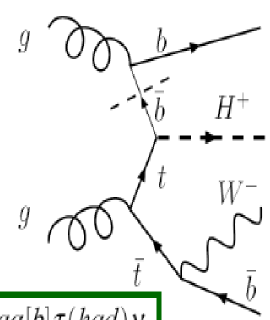
$t\bar{t} \rightarrow bH^{+}bW \rightarrow b\tau(lep)\nu bqq$

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

DECAY MODES:
$H^{+} \rightarrow \tau\nu$
$H^{+} \rightarrow tb$

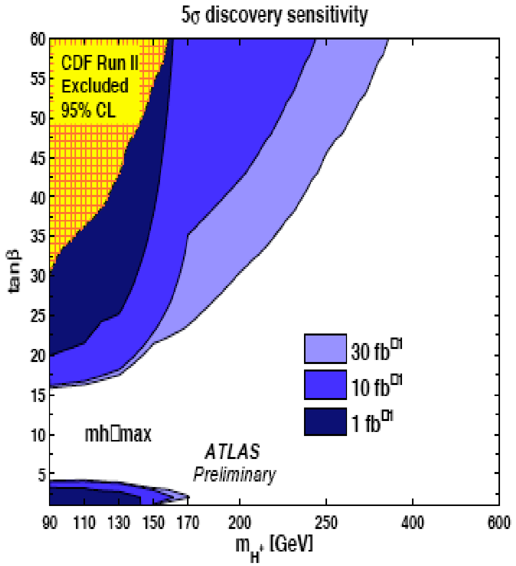
- High tanβ well covered already with 10 fb^{-1}
- Intermediate region hard to reach (only exclusion)

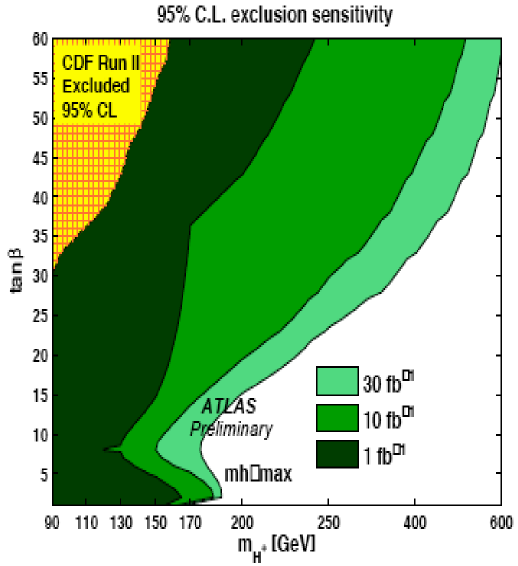
m(H+) > m(top)



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

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

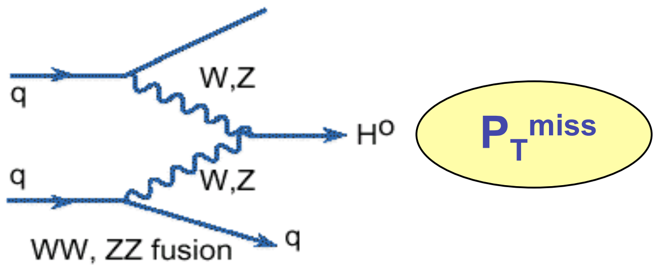




Invisible Higgs decays ?

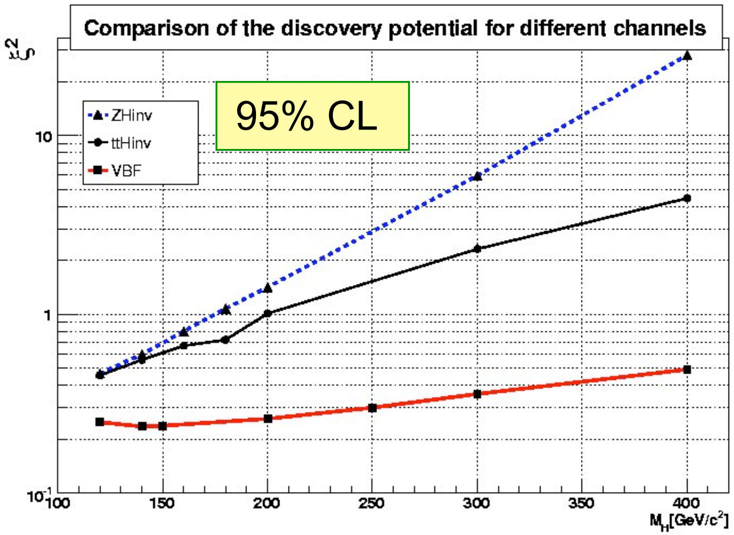
Possible searches: $t\bar{t}H \rightarrow \ell\nu b\, qqb + P_T^{miss}$
$ZH \rightarrow \ell\ell + P_T^{miss}$
$qqH \rightarrow qq + P_T^{miss}$

- J.F. Gunion, Phys. Rev. Lett. 72 (1994)
- D. Choudhury and D.P. Roy, Phys. Lett. B322 (1994)
- O. Eboli and D. Zeppenfeld, Phys. Lett. B495 (2000)



All three channels have been studied:
key signature: excess of events above SM backgrounds with large P_T^{miss} (> 100 GeV/c)

Sensitivity: $\xi^2 = Br(H \rightarrow Inv.)\frac{\sigma_{qq\rightarrow qqH}}{\sigma_{qq\rightarrow qqH}|_{SM}}$



ATLAS preliminary

Problems / ongoing work:

- ttH and ZH channels have low rates
- More difficult trigger situation for qqH
- backgrounds need to be precisely known (partially normalization using ref. channels possible)
- non SM scenarios are being studied at present
  first example: SUSY scenario

Invisible Higgs decays ?

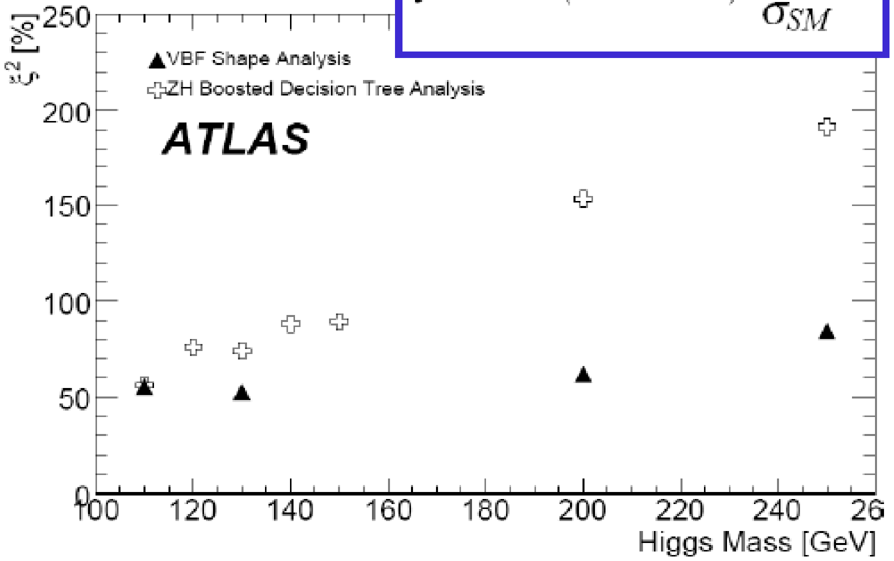
$$\xi^2 = BR(H \to inv.)\frac{\sigma_{BSM}}{\sigma_{SM}}$$

Higgs→Lightest Susy Particle

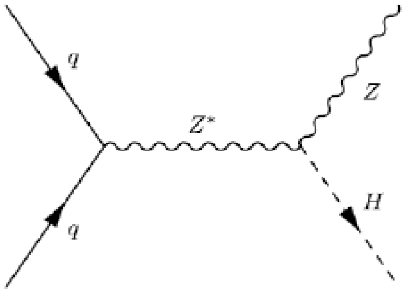
Two production modes analyzed:

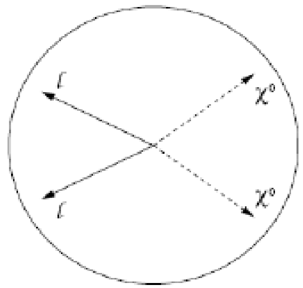
- **Associated production** *ZH*.
  - Background from *ZZ→llvv*.
  - Too much background to analyze *WH*.
- **VBF**.
  - Backgrounds from *QCD-dijets*, *W+jets* and *Z+jets*, when leptons are outside the detector acceptance or $Z \to \nu\nu$.

Caution: there could be nonSM backgrounds…
Missing energy is crucial



Associated production:
$H \to \chi^0\chi^0$ recoiling against $Z \to ll$



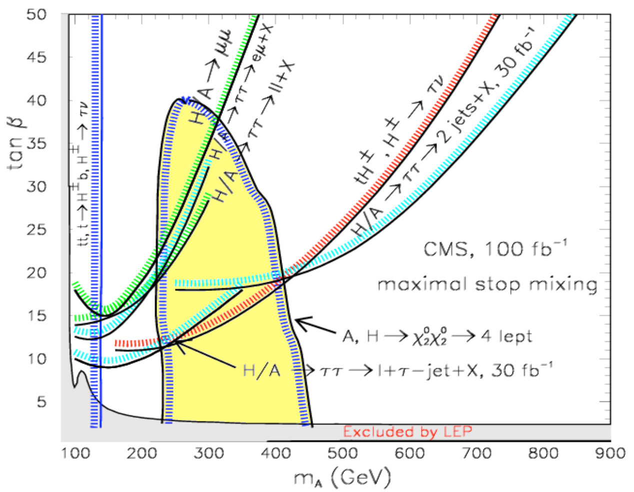


Higgs decays via SUSY particles

If SUSY exists : search for

$H/A \rightarrow \chi^0{}_2\chi^0{}_2 \rightarrow \ell\ell\chi^0{}_1\ \ell\ell\chi^0{}_1$

$gb \rightarrow tH^+,\ H^\pm \rightarrow \chi_{2,3}{}^0\ \chi_{1,2}{}^\pm \rightarrow 3\ell + E_T{}^{miss}$

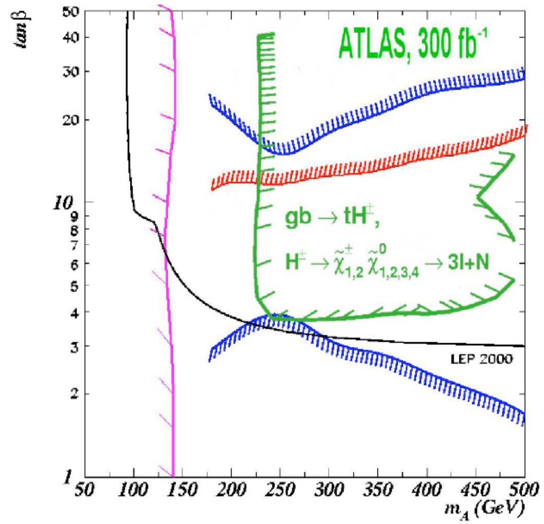


CMS: special choice in MSSM (no scan)

M_1 = 60 GeV/c^2

M_2 = 110 GeV/c^2

μ = -500 GeV/c^2



ATLAS: special choice in MSSM (no scan)

M_1 = 60 GeV/c^2

M_2 = 210 GeV/c^2

μ = 135 GeV/c^2

m(s-ℓ_R) = 110 GeV/c^2

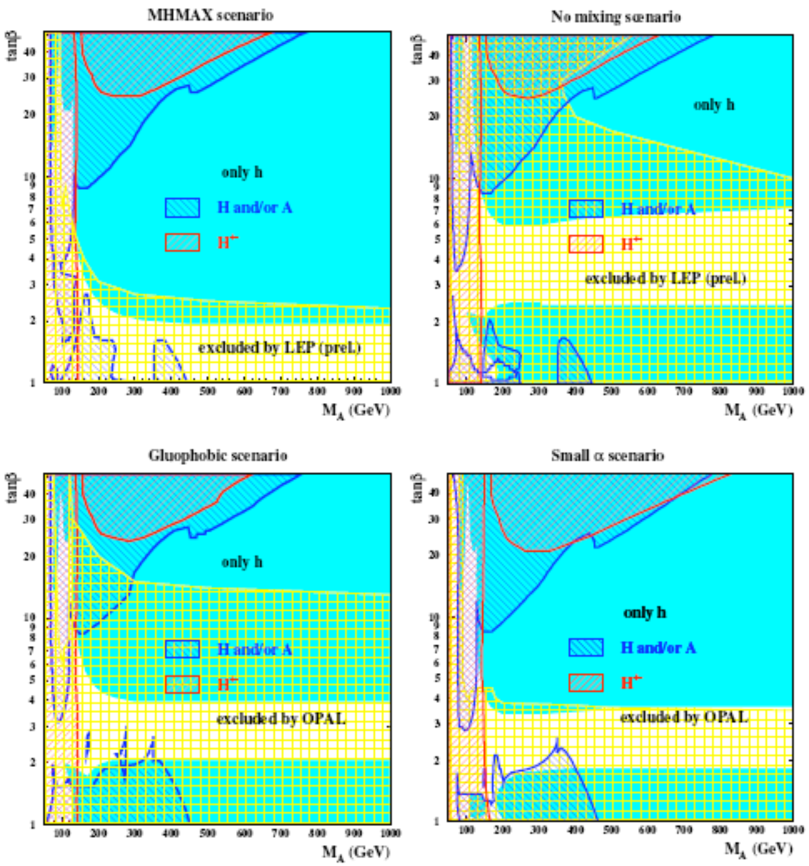
m(s-τ_R) = 210 GeV/c^2

- Exclusions depend on MSSM parameters (slepton masses, m)
- More systematic studies are needed (initiated by A. Djouadi et al., also started in ATLAS)

Updated MSSM scan for different benchmark scenarios

Benchmark scenarios as defined by M.Carena et al. (h mainly affected)

ATLAS preliminary,   30 fb^{-1},   5σ discovery



MHMAX scenario (M_{SUSY} = 1 TeV/c^2)
maximal theoretically allowed region for m_h

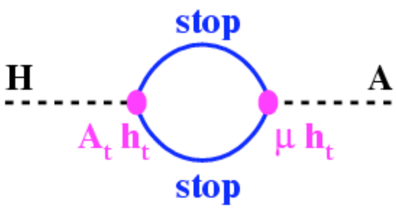
Nomixing scenario (M_{SUSY} = 2 TeV/c^2)
(1TeV almost excl. by LEP)
small m_h → difficult for LHC

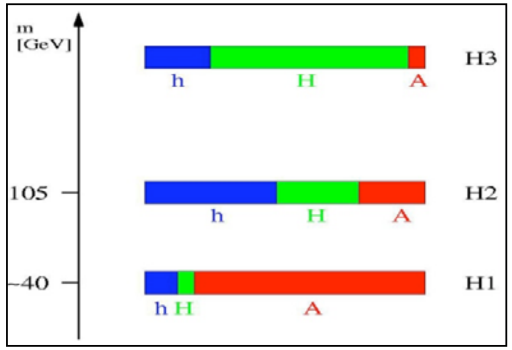
Gluophobic scenario (M_{SUSY} = 350 GeV/c^2)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for g g → H, H→ γγ and Z→4 ℓ

Small α scenario (M_{SUSY} = 800 GeV/c^2)
coupling to b (and **t**) suppressed
(cancellation of sbottom, gluino loops) for large tan β and M_A 100 to 500 GeV/c^2

Higgs search at the LHC in CP-violating scenarios

- Tree level CP of Higgs Potential in MSSM may be violated sizably at higher orders by loop effects involving CP-violating interactions of Higgs to stop and sbottom





- CP eigenstates h, A, H mix to mass eigenstates H_1, H_2, H_3

- Effect maximized in a defined benchmark scenario (CPX)

(M. Carena et al., Phys.Lett. B 495 155 (2000))

$\arg(A_t) = \arg(A_b) = \arg(M_{gluino}) = 90°$

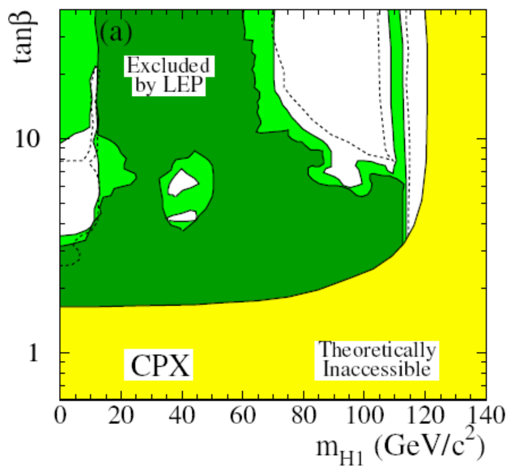
- No lower mass limit for H_1 from LEP !

(decoupling from the Z)

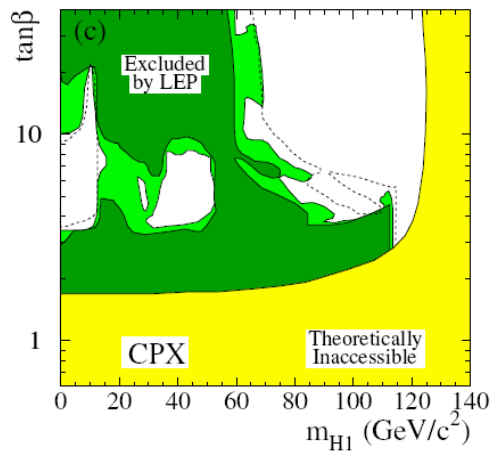
details depend on m_{top} and on theory model

(FeynHiggs vs. CPsuperH)

m_{top} = 169.3 GeV/c^2

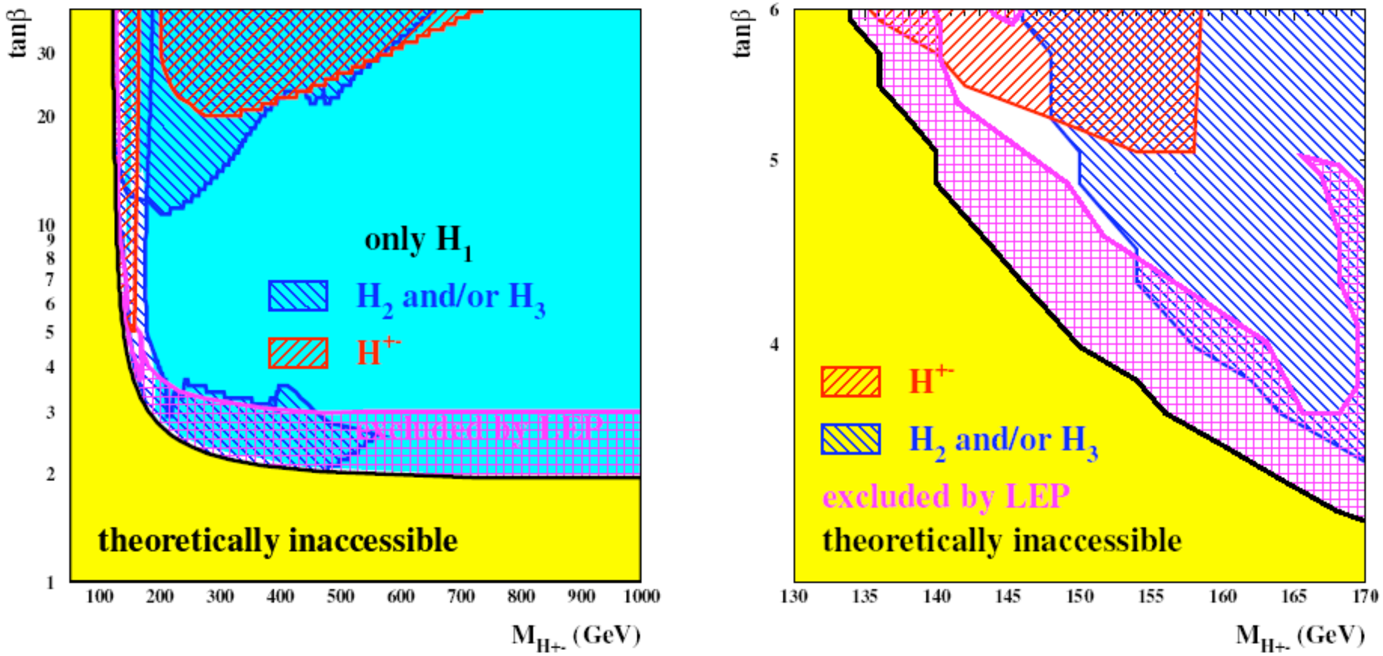


m_{top} = 174.3 GeV/c^2



MSSM discovery potential for the CPX scenario

ATLAS preliminary (M. Schumacher)



- Large fraction of the parameter range can be covered, however, small hole at (intermediate tanβ , low m_{H+}) corresponding to low m_{H_1}

- More studies needed, e.g. investigate lower H_1 masses, additional decay channels: $tt \rightarrow Wb\ H^+b \rightarrow \ell\nu b\ WH_1b,\ \ H_1 \rightarrow bb$

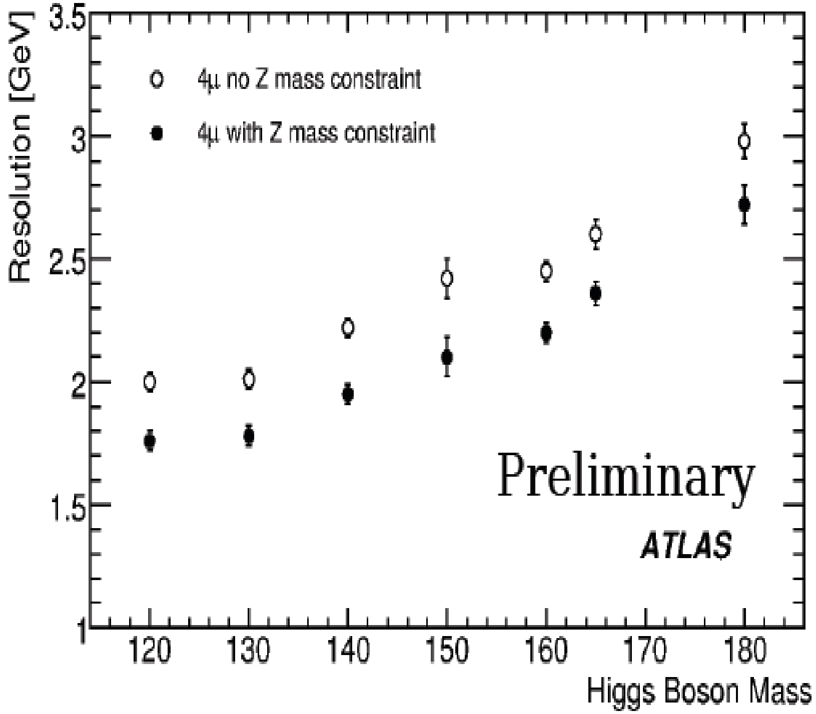
Higgs Property Measurements

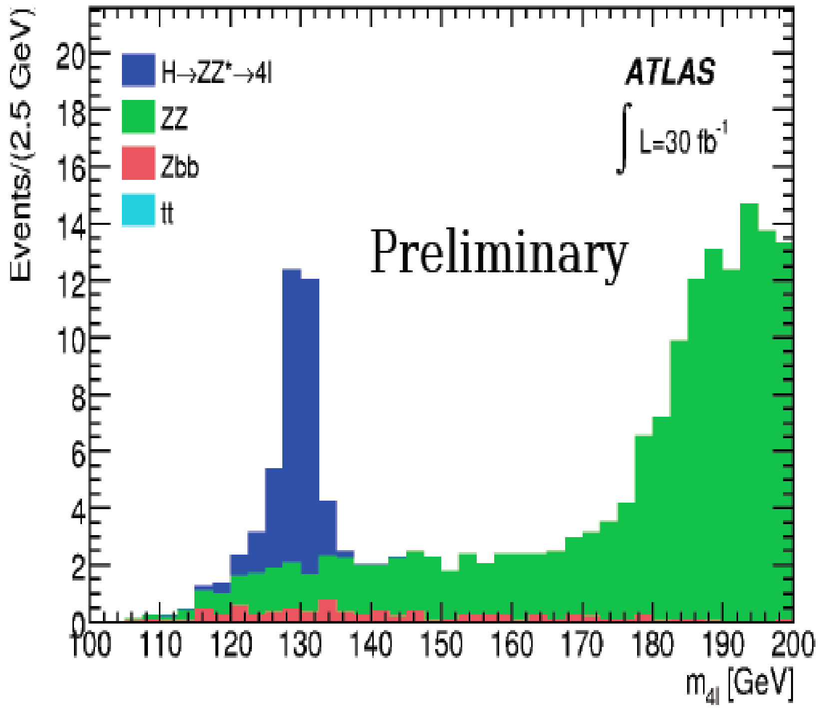
Higgs Property Measurements

- If a Higgs-like particle is discovered, its properties must be measured to establish its nature:
  - Mass
  - Couplings to fermions and bosons
  - Spin and CP
  - Higgs self coupling

Higgs mass measurements

- Higgs boson mass can be measured with a precision of 0.1% over a large mass range (130 - ~450 GeV/c^2) ($\gamma\gamma$ and ZZ$\rightarrow$ 4ℓ resonances, el.magn. calo. scale uncertainty assumed to be ± 0.1%)





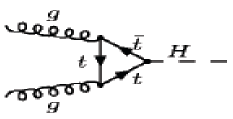
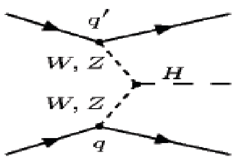
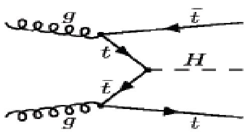
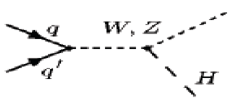
Higgs couplings measurements

- Different quantities can be measured depending on assumptions:
  - CP-even, Spin 0 implicit in H -> WW event selection. Measure only the rate: σ*BR
  - Assuming only one Higgs boson, no degenerate Higgs pair, extract relative branching ratios
  - Assuming Standard Model couplings, no extra particles, or strong couplings to light fermions: extract ratios of Higgs couplings
  - Assuming that the sum of the visible branching ratios is the same as in the SM: extract absolute couplings

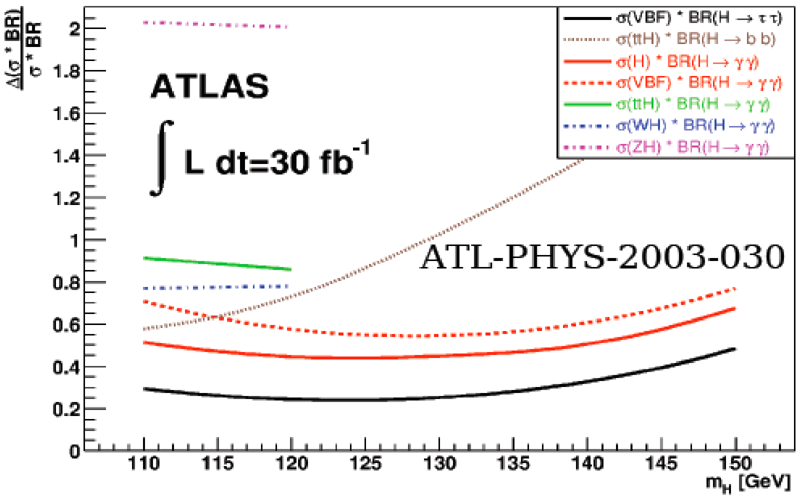
Higgs couplings measurements

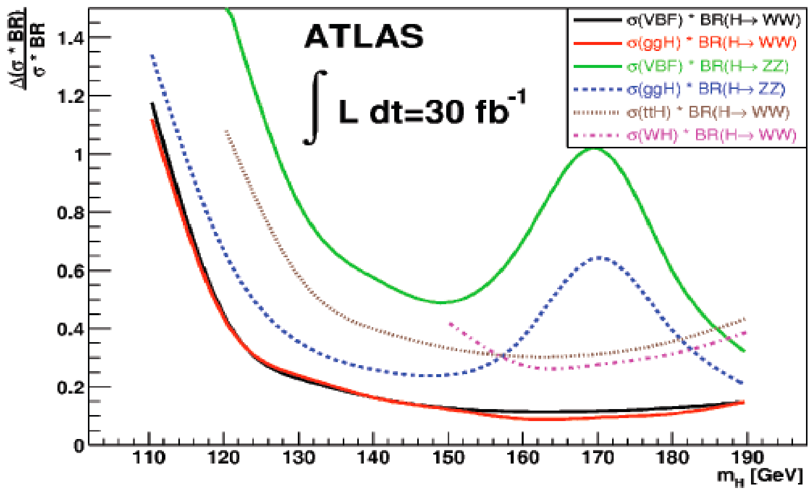
Global likelihood-fit (at each possible Higgs boson mass)
Input: measured rates, separated for the various production modes
Output: Higgs boson couplings, normalized to the WW-coupling.

Channels used in coupling fit:

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

Rate Measurements

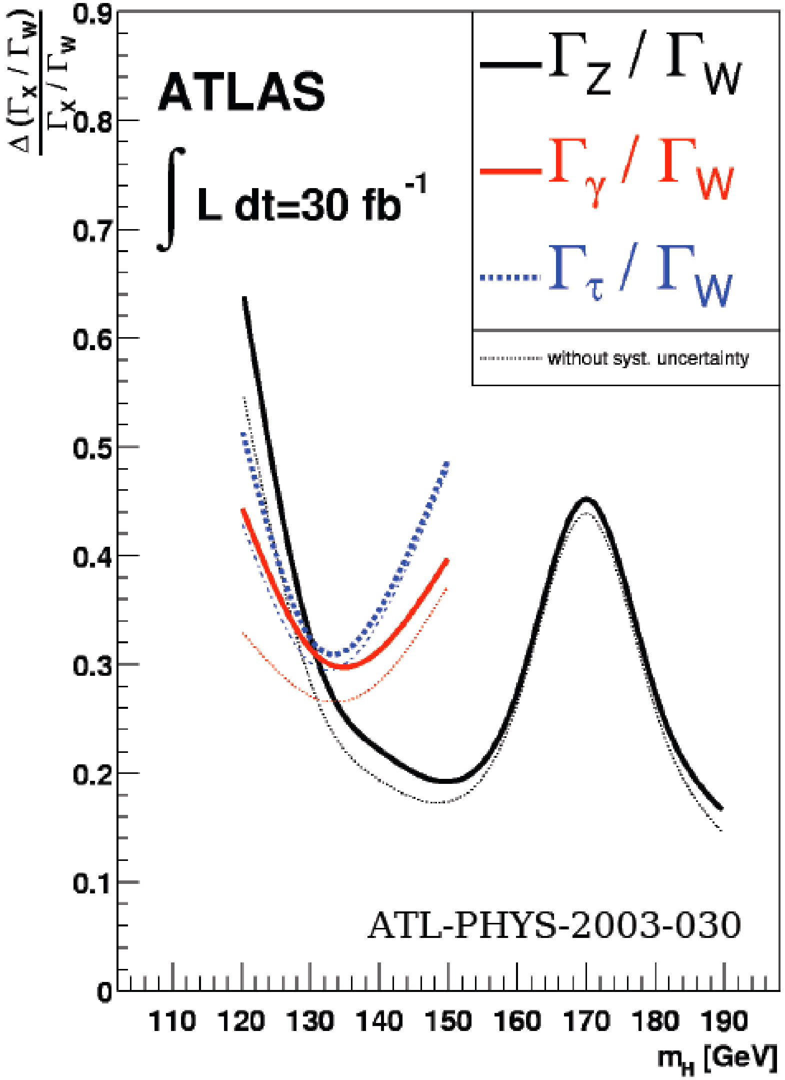




- Left: for M_H<150 GeV, rates can be measured with an accuracy typically between 30-100% with 30 fb^{-1} of integrated luminosity
  - This assumes a 5% uncertainty on the luminosity measurement.
- Right: for channels that can be seen in the mass range 110<M_H<190 GeV, error is smaller

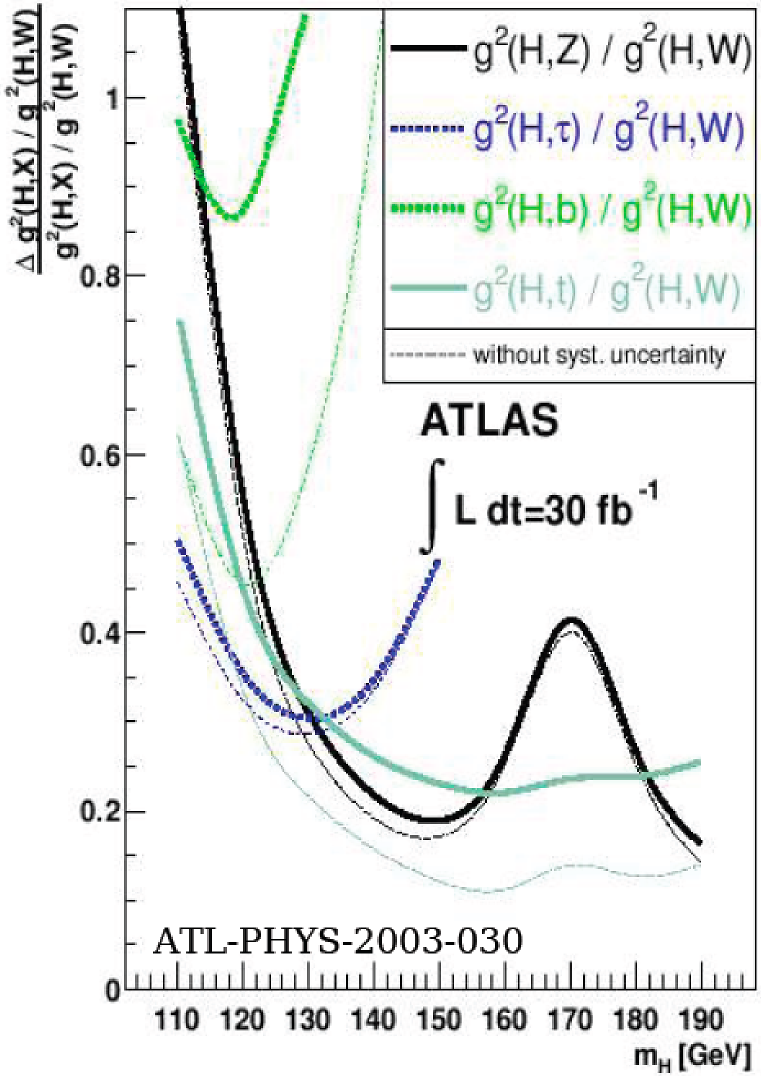
Ratios of partial widths

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



Ratios of Couplings

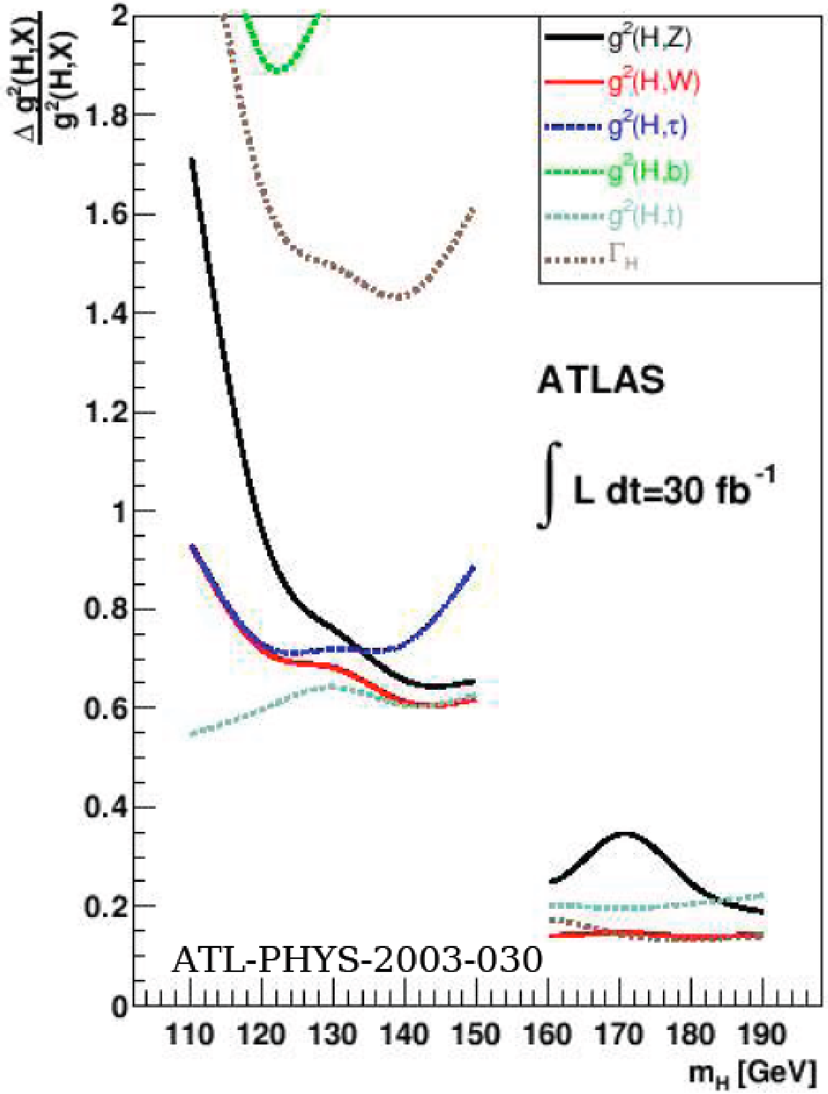
- Assume no unobservable decay modes, etc.
- Cross-sections and branching ratios are proportional to the squares of couplings
- Proportionality constants, along with systematic errors, are computed from theory
- With 30 fb^{-1} of integrated luminosity, Ratios of Higgs couplings can be measured with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



Absolute couplings

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

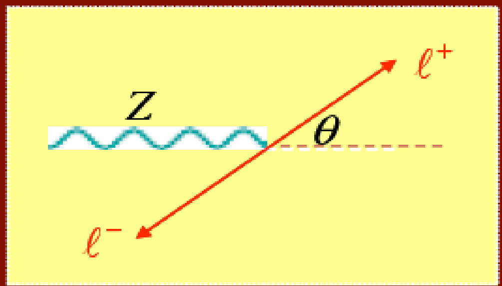
- Couplings to Z, W, and τ can be measured with a precision better than 100%



Spin/CP measurements

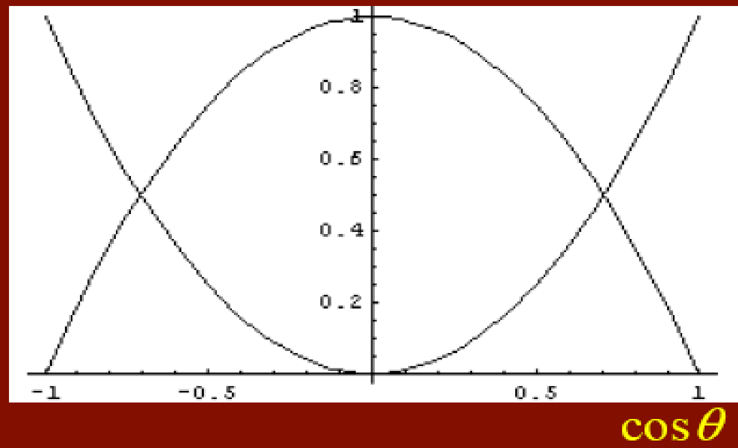
The SM Higgs is CP even scalar (spin 0). Spin information in its decay products. The Z bosons from Higgs decay are polarized. Polarizations depend on Higgs mass. For m_H>300 GeV, the Z's mostly longitudinally polarized

In the center-of-mass frame of the Z, longitudinal and transverse polarized Z bosons lead to different angular distributions of the decaying leptons:



$$\frac{d\Gamma}{d\cos\theta}(Z_L \to \ell\ell) \propto \sin^2\theta$$

$$\frac{d\Gamma}{d\cos\theta}(Z_T \to \ell\ell) \propto 1+\cos^2\theta$$



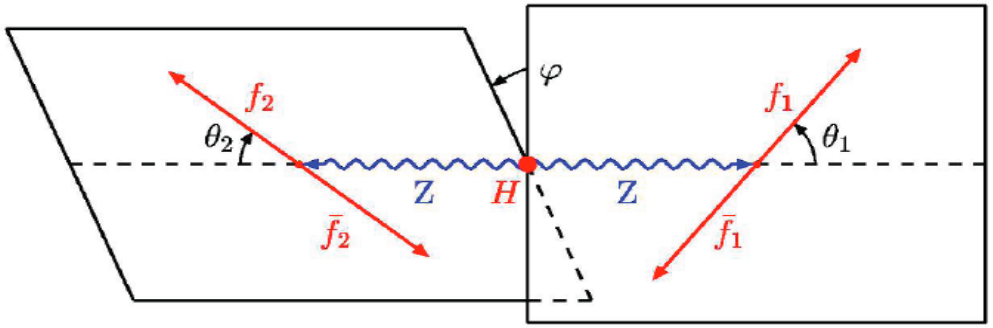
Z bosons from other processes are mostly transversely polarized

See the talk by Biswal in the contributed session yesterday

Spin/CP measurements

The decay planes of the 2 Z's are expected to be correlated, due largely to the transversely polarized Z's. For m_H>300 GeV, correlation would "disappears" as the Z's becomes longitudinally polarized

- In $H \rightarrow ZZ \rightarrow 4l$, extract spin information by measuring decay angles in Higgs rest frame
  - Focus on M_H>200 GeV
- Three discriminating variables (α, β, and R), obtained by fitting to angular distributions:
  - Decay plane angle ϕ: $F(\phi)=1+\alpha\cos(\phi)+\beta\cos(2\phi)$
  - Polar angle θ: $G(\theta)=T\,(1+\cos^2\theta)+L\,\sin^2\theta$
    : $R=(L-T)/(L+T)$
- Test for:
  - Spin 1, CP +1
  - Spin 1, CP -1
  - Spin 0, CP -1



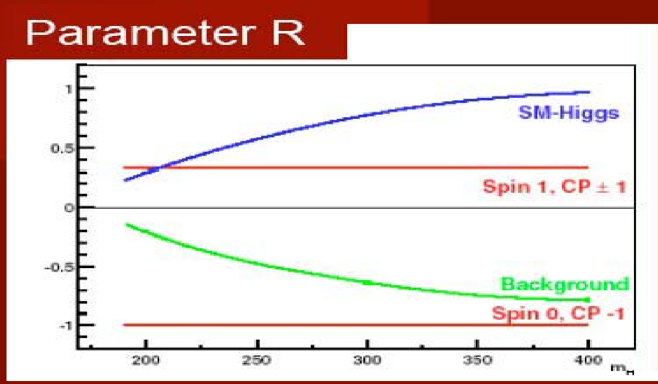
Aspects of CP-violation in HZZ coupling, R. Godbole, et al, hep-ph/07080458

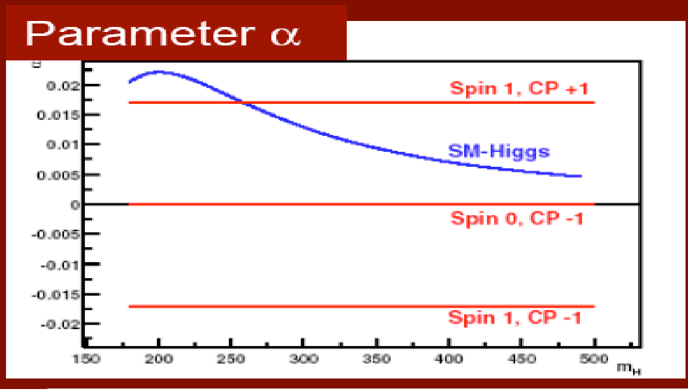
Spin/CP measurements

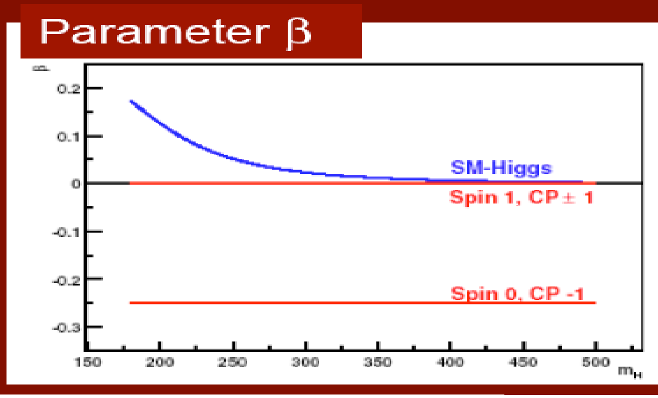
Variation of α, β, and R parameters with the mass of the Higgs

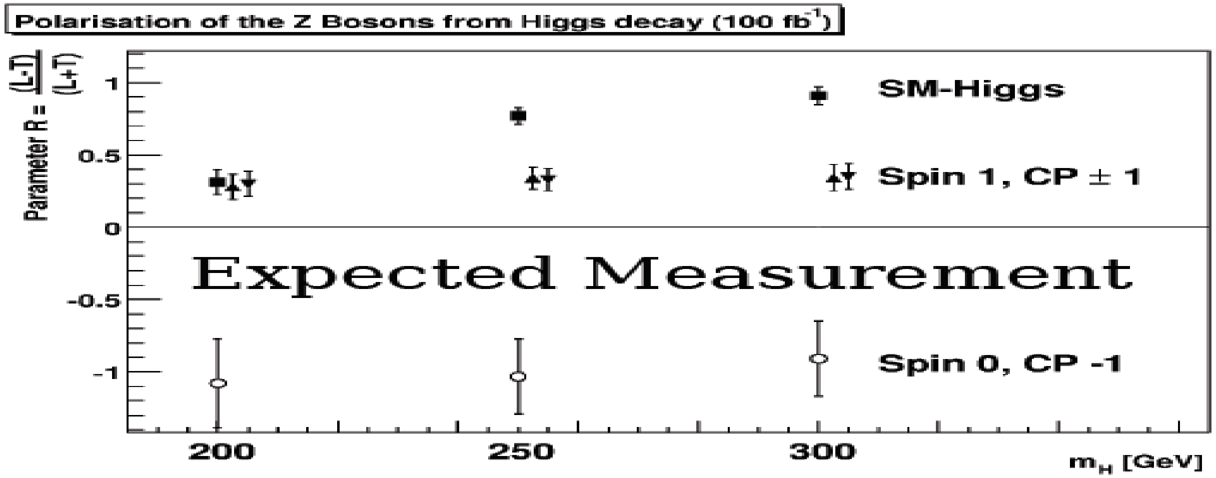
[C.P. Buszello et al., Eur. Phys. J. C 32, 209 (2004)]

α, β and R are simply parameters that characterize the correlation between the final state products







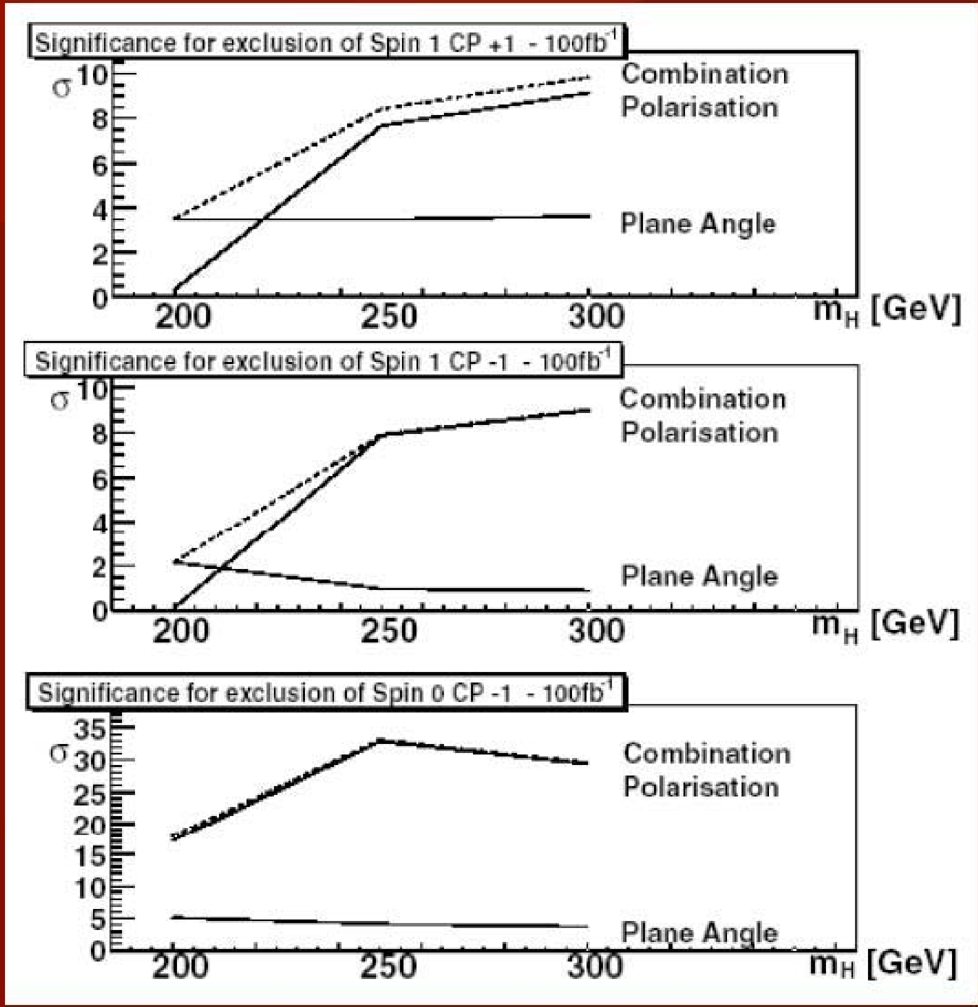


Spin/CP measurements

Results:

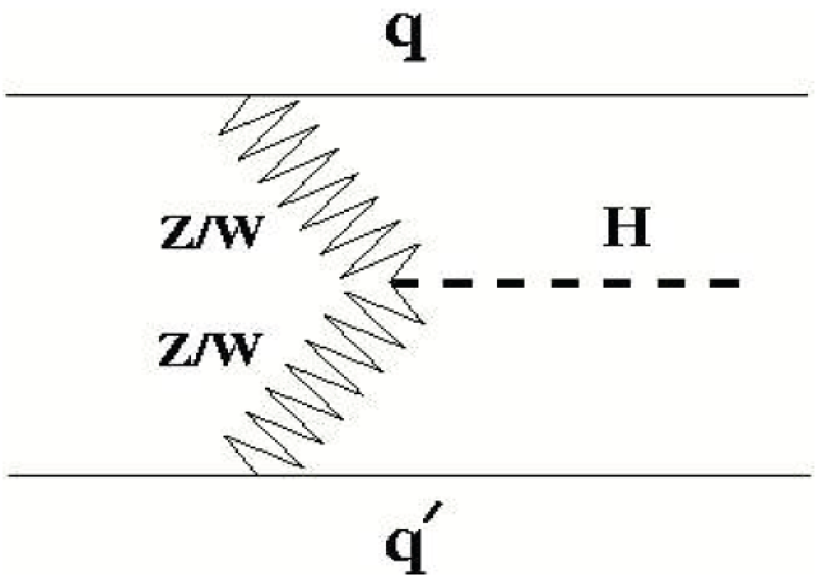
[*C.P. Buszello et al., Eur. Phys. J. C 32, 209 (2004)*]

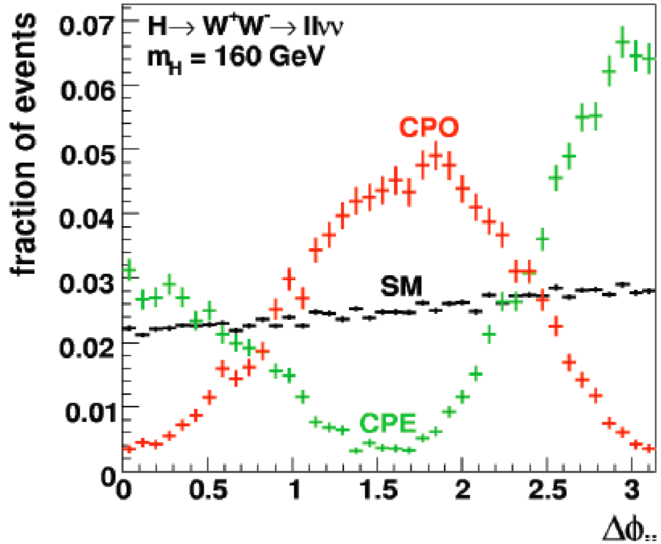
- For Higgs masses larger than about 230 GeV/c^2, a spin 1 hypothesis can be ruled out with 100 fb^{-1}.
- A spin-CP hypothesis of 0^- can be ruled out with less than 100 fb-1.

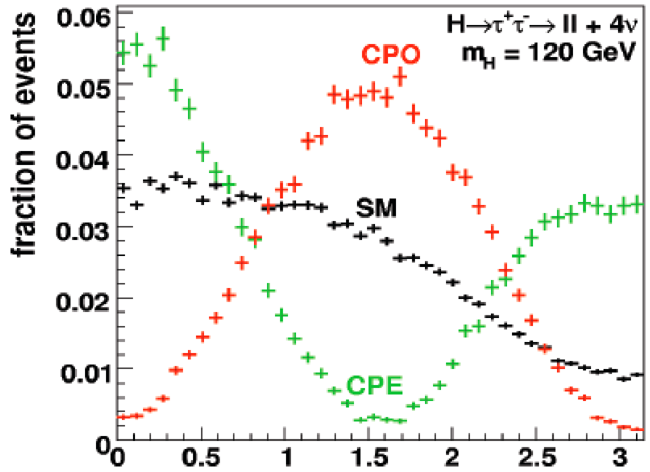


Analysis of H and Z may exclude Higgs-like particles with unusual spin/CP properties. Not for early data However.

Spin/CP measurements



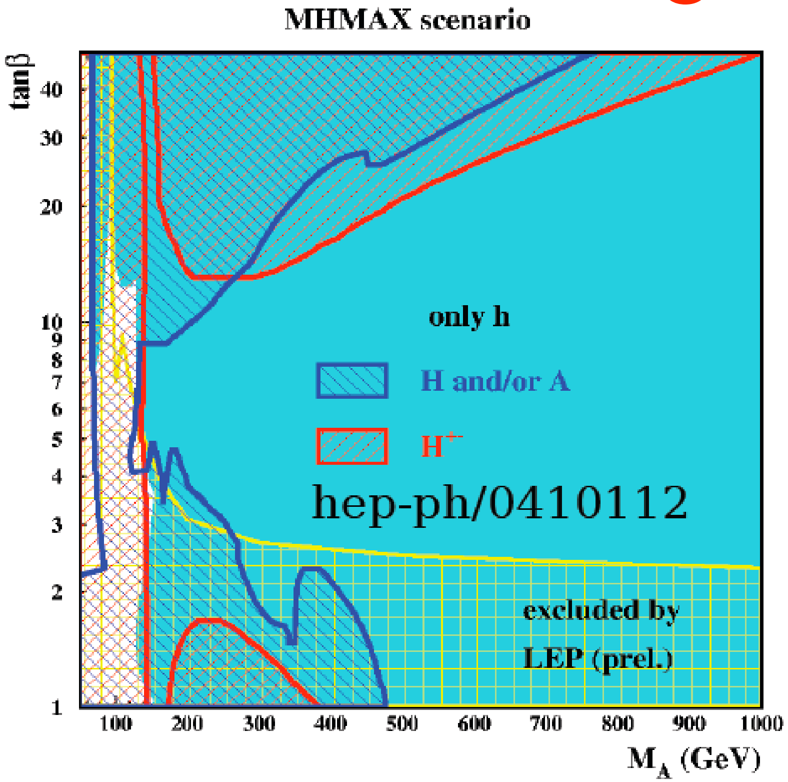


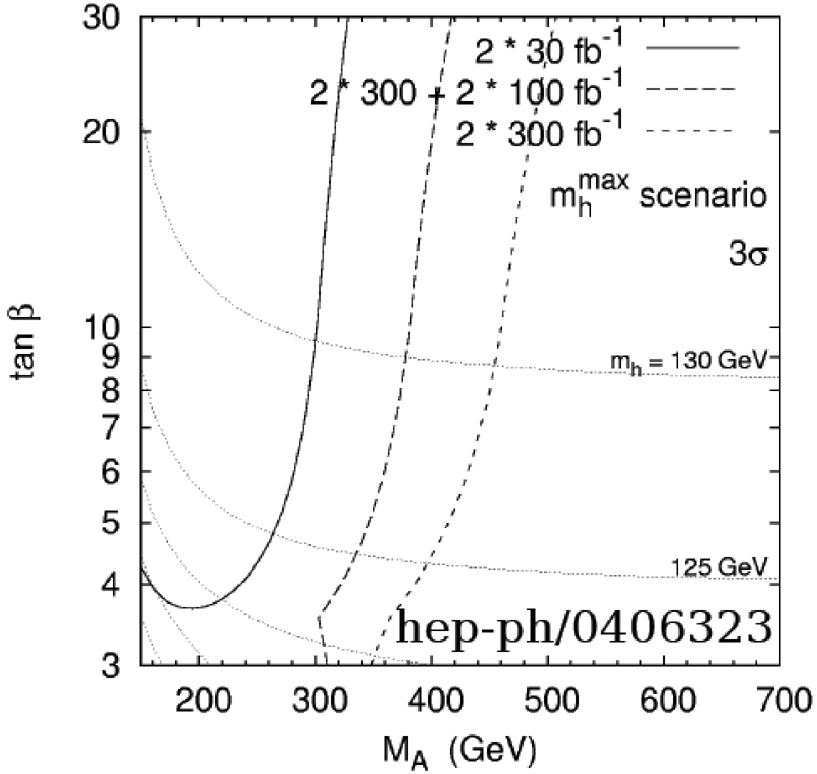


Eur. Phys. J. C51:385-414

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

Excluding non-SM Higgs

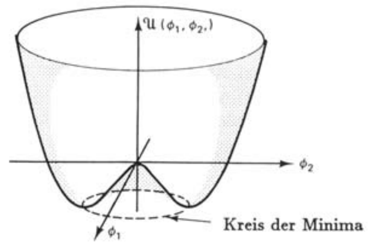




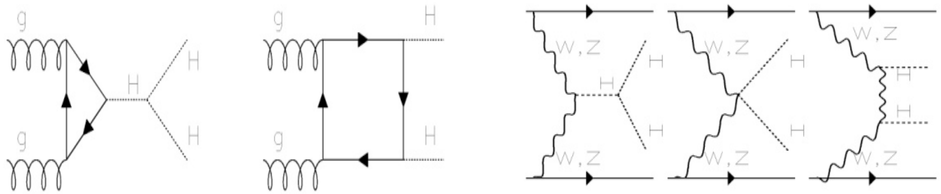
- In some regions of the MSSM parameter space, only one light Higgs is visible (left)
- Try to exclude MSSM using a 2 analysis of coupling fits (right)

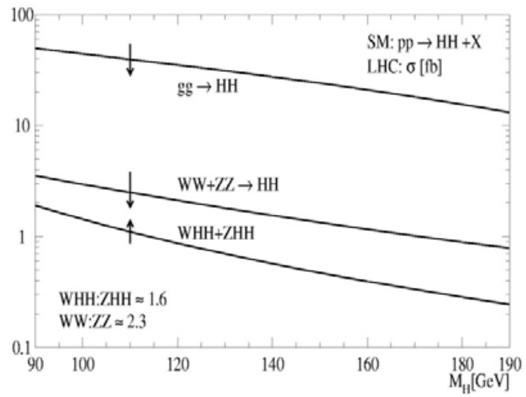
Higgs Self coupling

To establish the Higgs mechanism the Higgs boson self-coupling has to be measured:



<u>Cross sections for HH production:</u>





small signal cross sections,
large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

⇒ no significant measurement possible at the LHC
need Super LHC L = 10^{35} cm^{-2} sec^{-1}, 6000 fb^{-1}

Most sensitive channel: **gg → HH → WW WW → ℓν jj ℓν jj**

6000 fb^{-1} ⇒	$\Delta\lambda_{HHH} / \lambda_{HHH}$ = 19 % (stat.)	(for m_H = 170 GeV)
	$\Delta\lambda_{HHH} / \lambda_{HHH}$ = 25 % (stat.)	(for m_H = 200 GeV)

BACKUP

Measurement of Higgs-Boson Coupling Ratios

assumptions: only SM particles couple to Higgs boson,

no large couplings of light fermions

Global fit (ATLAS study)

(all channels at a given mass point)

Fit parameters:

$$\frac{g_Z^2}{g_W^2} \quad \frac{g_\tau^2}{g_W^2} \quad \frac{g_b^2}{g_W^2} \quad \frac{g_t^2}{g_W^2} \quad \frac{g_W^2}{\sqrt{\Gamma_H}}$$

Production cross sections

$$\sigma_{ggH} = \alpha_{ggH} \bullet g_t^2$$

$$\sigma_{VBF} = \alpha_{WF} \bullet g_W^2 + \alpha_{ZF} \bullet g_Z^2$$

$$\sigma_{ttH} = \alpha_{ttH} \bullet g_t^2$$

$$\sigma_{WH} = \alpha_{WH} \bullet g_W^2$$

$$\sigma_{ZH} = \alpha_{ZH} \bullet g_Z^2$$

b loop neglected for now in ggH

α from theory with assumed uncertainty $\Delta\alpha$

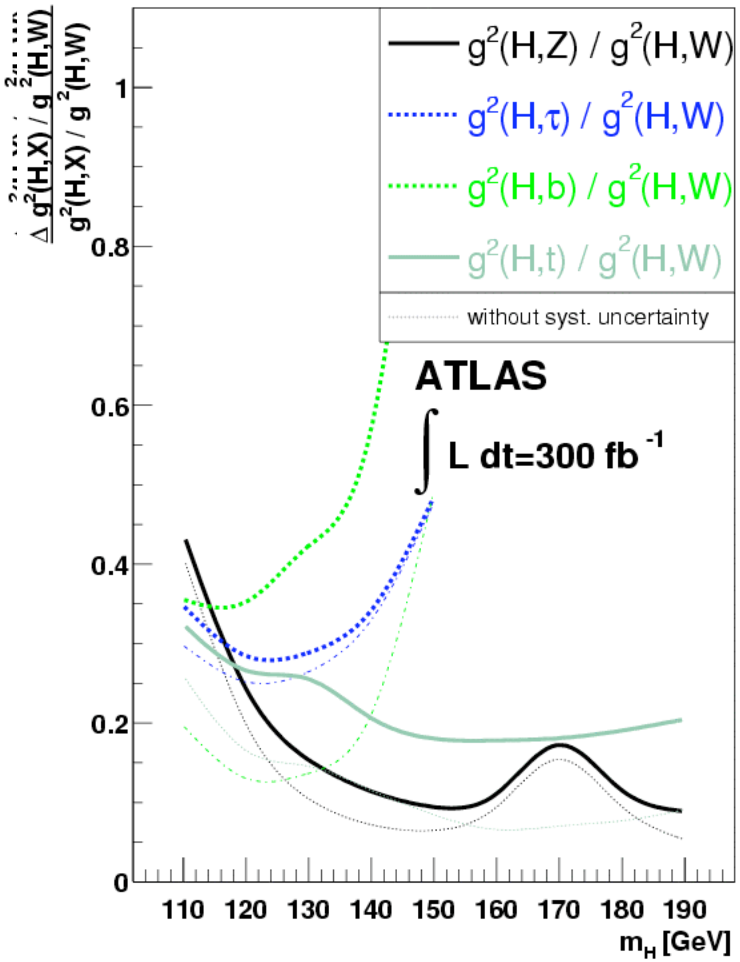
$$\Delta\alpha_{ggH} = 20\%$$

$$\Delta\alpha_{WF} = \alpha_{ZF} = 4\%$$

$$\Delta\alpha_{ttH} = 15\%$$

$$\Delta\alpha_{WH} = \Delta\alpha_{ZH} = 7\%$$

Ratio of Higgs-Boson Couplings



Branching ratios

$$BR(H \to WW) = \beta_W \frac{g_W^2}{\Gamma_H}$$

$$BR(H \to ZZ) = \beta_Z \frac{g_Z^2}{\Gamma_H}$$

$$BR(H \to \gamma\gamma) = \frac{\left(\beta_{\gamma(W)} g_W - \beta_{\gamma(t)} g_t\right)^2}{\Gamma_H}$$

$$BR(H \to \tau\tau) = \beta_\tau \frac{g_\tau^2}{\Gamma_H}$$

$$BR(H \to bb) = \beta_b \frac{g_b^2}{\Gamma_H}$$

$\Delta\beta = 1\%$

Rate as function of x_i, e.g.

$$(\sigma \bullet BR)_{ggH, H \to ZZ} = \alpha_{ggH} \frac{g_t^2}{g_W^2} \frac{g_W^2}{\sqrt{\Gamma_H}} \beta_Z \frac{g_Z^2}{g_W^2} \frac{g_W^2}{\sqrt{\Gamma_H}}$$