Higgs Physics

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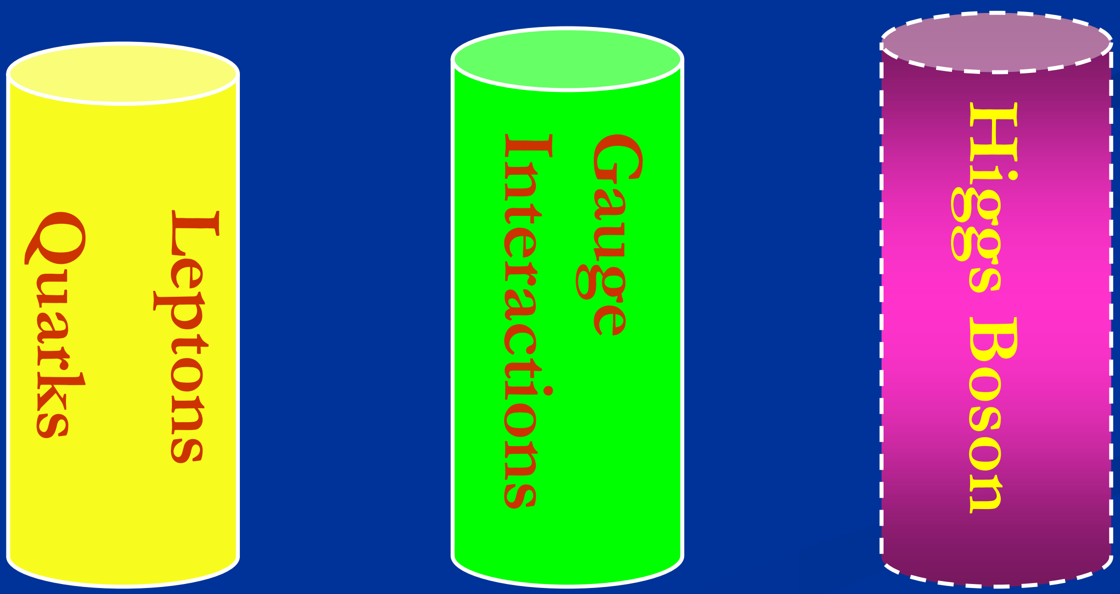
The Standard Model was established in the very end of the last millennium after remarkable interplays between experimentalists and theorists,
The Standard Model is made up of three pillars,

(1) The matter is made out of Quarks and Leptons.
They are All discovered. ☑

(2) 3 interactions are governed by gauge principle. Gauge bosons are all discovered & tested with high precision. ☑

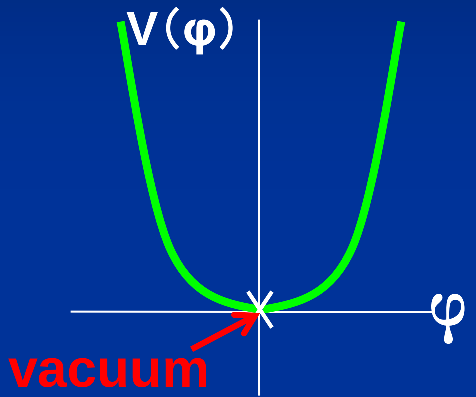
(3) Higgs Boson breaks SU(2) Gauge Symmetry.
⇒ Origin of Masses (not yet experimentally proven)



All the dark part of the SM is attributed to a single elementary particle = Higgs boson. (matches with the economic principle, but looks very artificial)

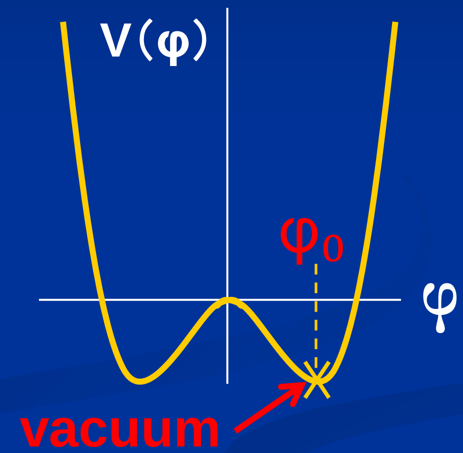
Higgs boson and vacuum

Higgs boson has quantum numbers which are the same as those of "vacuum"



The early universe

expansion cools down the universe



The lowest-energy position ≡ vacuum

φ_0 = vacuum expectation value of Higgs field

⇒ EW symmetry is broken.

The shape of the Higgs potential can be naturally realized with TeV scale supersymmetry (K. Inoue et al.)

Higgs Boson is a very unique spinless elementary particle

Its discovery is worth as much as that for the first gauge boson (γ) or for the first matter Fermion (e^-).

"No-lose theorem" was a driving force of the SSC project.

SSC experiments should have discovered either Higgs boson or other mechanism ($W_L W_L \rightarrow W_L W_L$) to explain EW symmetry breaking. But they lost project itself. ⇒ LHC (upgrade)

Higgs boson is an excellent tool to study TeV scale physics.

The theoretical constraints on Higgs are looser than for the gauge sector.

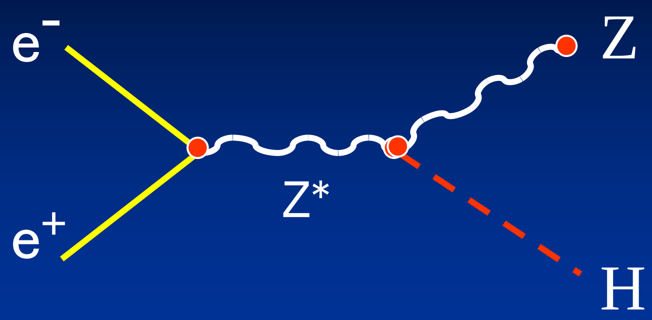
⇒ Its parameters should be experimentally determined.

Even based on very different models (MSSM, Little Higgs Model, …) the first discovered Higgs boson can be very similar to the SM Higgs boson (Y.Okada) .

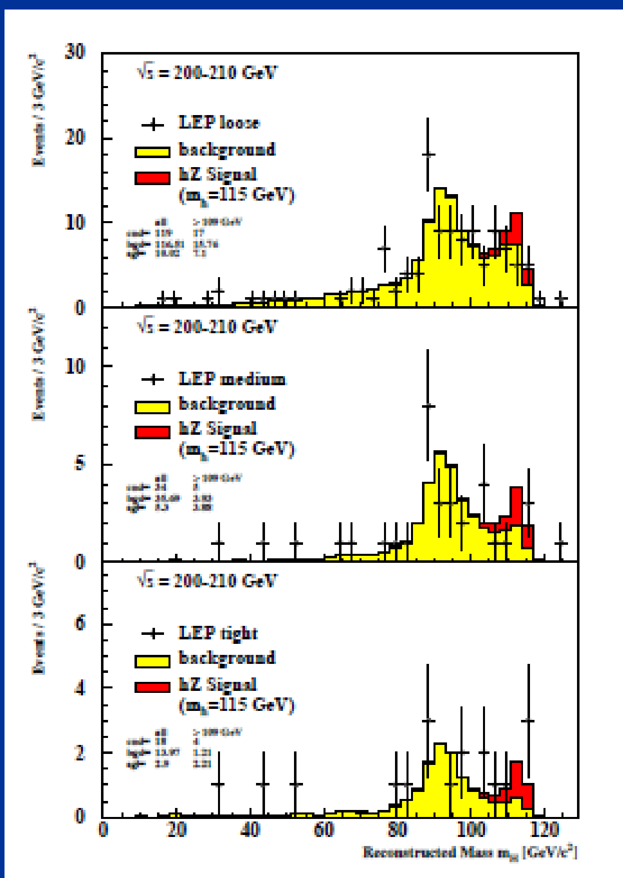
⇒ Its properties have to be thoroughly studied.

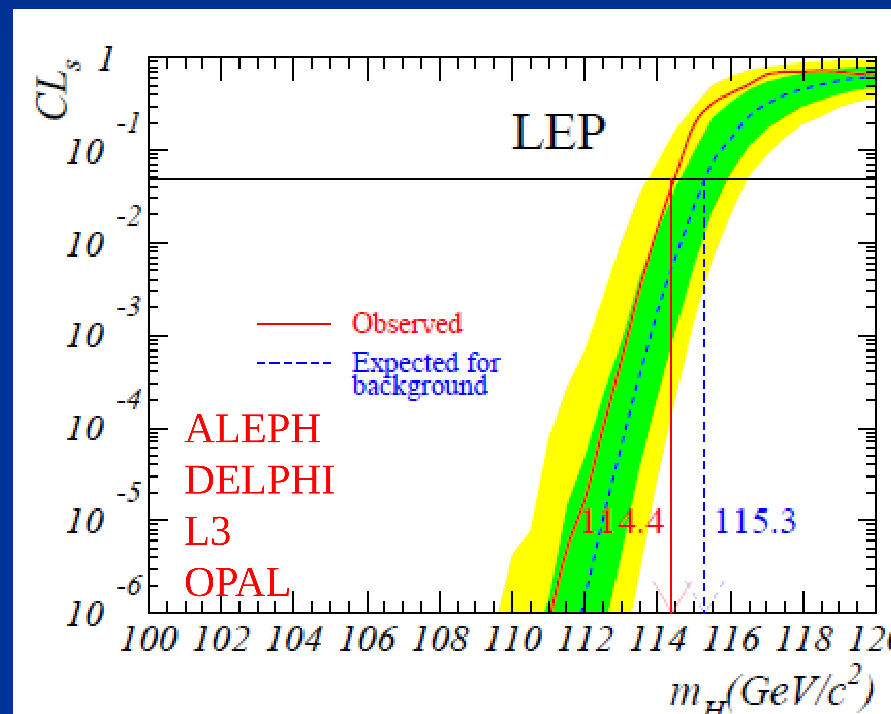
Higgs Search at LEPII

The lightest SUSY Higgs mass $M_h < M_Z$ (tree level calculation). But just before the LEP start , radiative corrections were calculated. $\Rightarrow$ h can be heavier than Z.



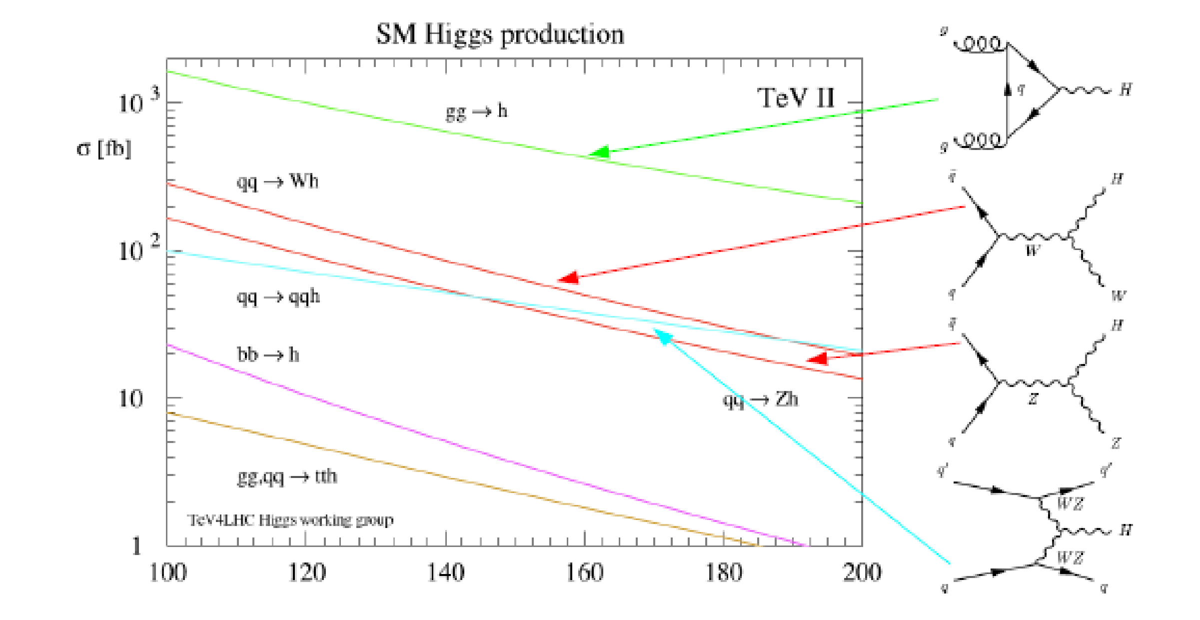
$Z \rightarrow q\bar{q}(70\%),\ l^+l^-(10\%),\ \nu\bar{\nu}(20\%)$
$H \rightarrow b\bar{b},\ \tau^+\tau^-$



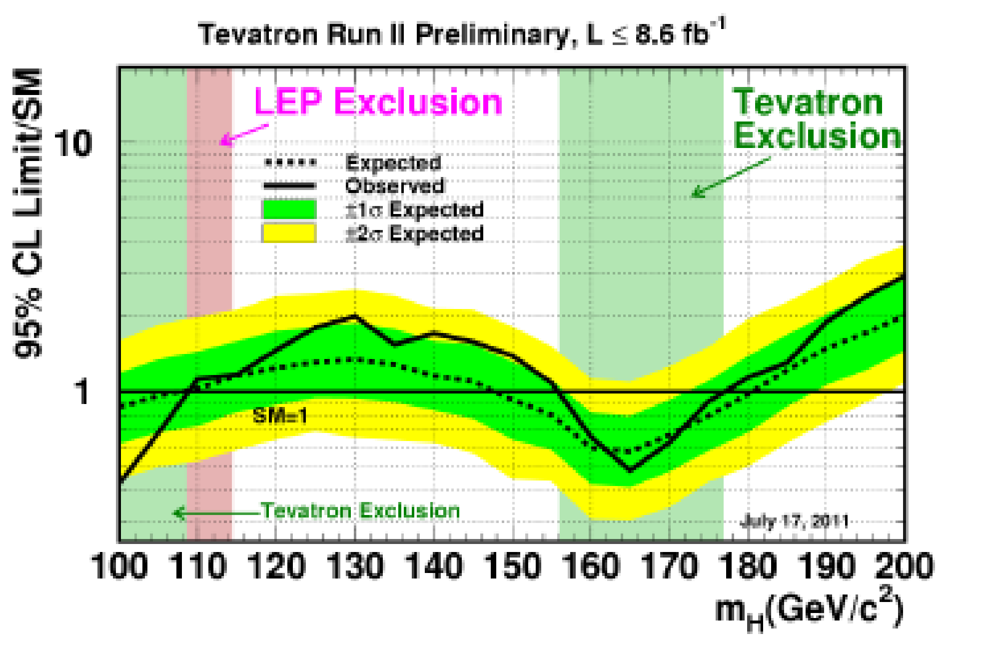


Direct search limit $m_H > 114.4$ GeV @ 95%CL
If LEP had operated one more year, life at LHC should have been much easier.

Higgs Searches at TEVATRON (CDF and D0)

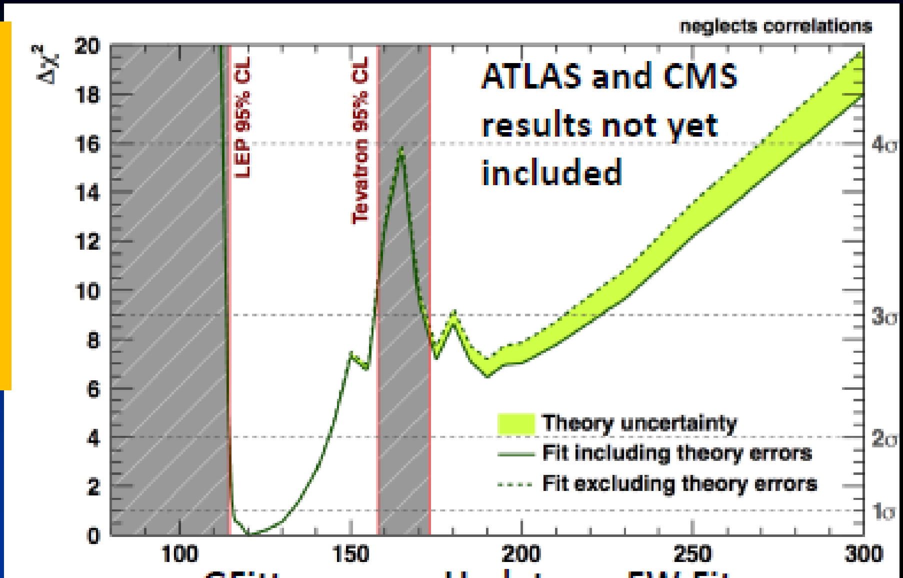


Cross sections for associate production with W or Z are large due to $p\bar{p}$ collision

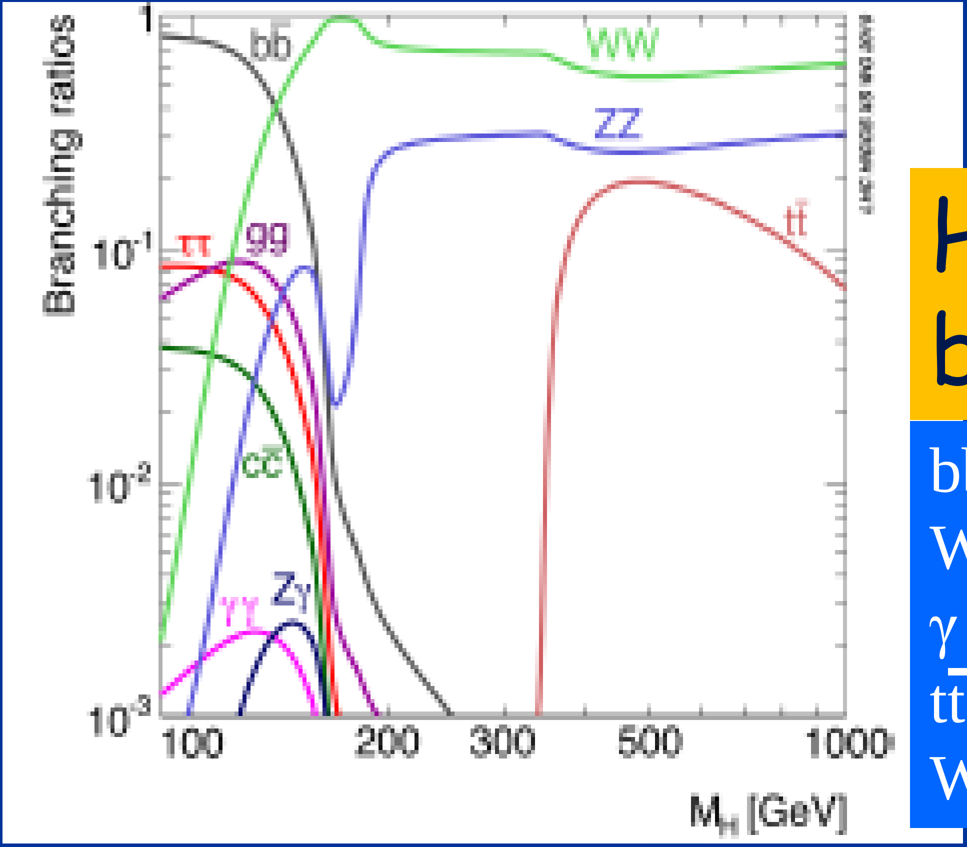


Although LHC takes over most of the mass ranges, TEVATRON sensitivity is still higher in the low mass region (close to the LEP limit). Analysis methods are inherited from TEVATRON to LHC.

Situation of the SM Higgs Boson before the advent of LHC



GFitter group, Update on EW Fit
http://arxiv.org/abs/1107.0975

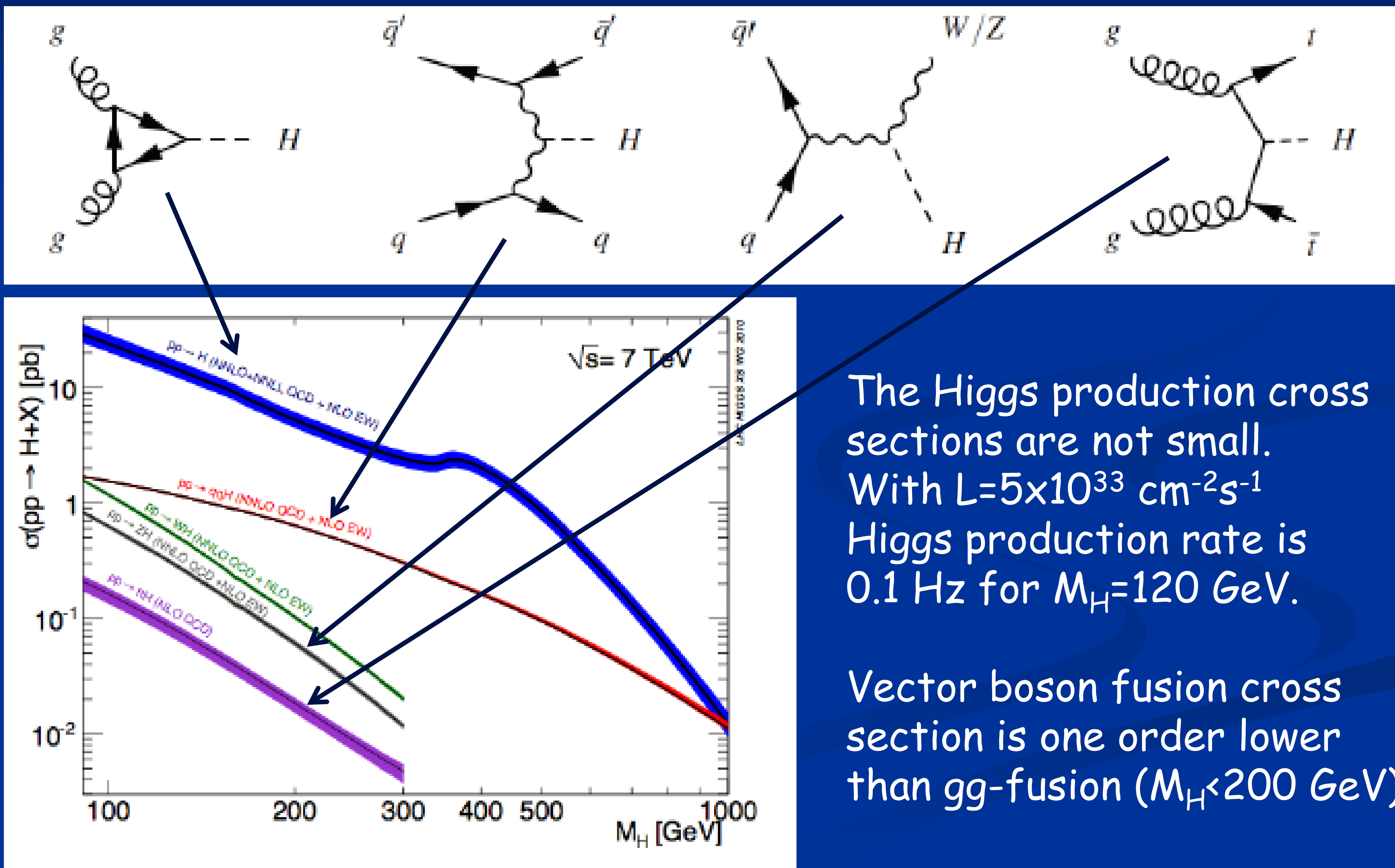


Higgs Boson decay branching fractions

$b\bar{b}$ is dominant in M_H<135 GeV
WW takes over in M_H>135 GeV
$\gamma\gamma$ is $O(10^{-3})$ M_H<150 GeV
$t\bar{t}$ becomes never domimant over WW or ZZ, even for M_H>$2M_t$

Higgs Boson Searches at LHC

Production mechanism and cross section



The Higgs production cross sections are not small.
With $L=5\times10^{33}$ $cm^{-2}s^{-1}$ Higgs production rate is 0.1 Hz for M_H=120 GeV.

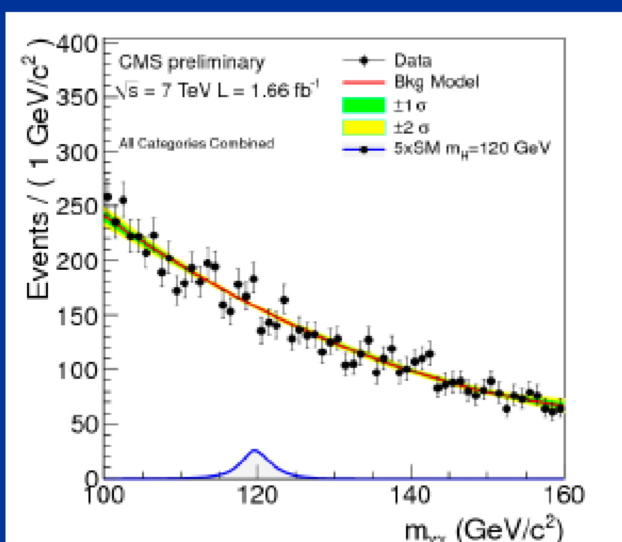
Vector boson fusion cross section is one order lower than gg-fusion (M_H<200 GeV).

Strategy@LHC

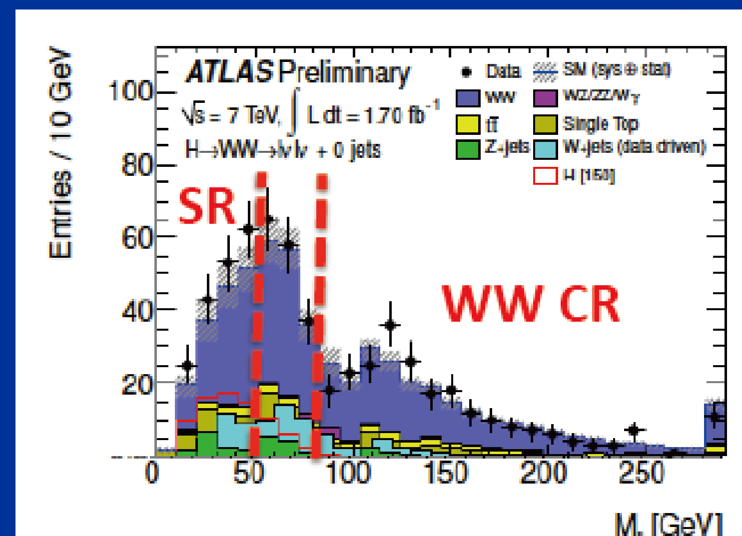
0) Identify Higgs production /decay processes with large sensitivity

1) Search for an invariant mass peak above a smooth background distribution

Narrow peak $\gamma\gamma$, $ZZ^{(*)} \rightarrow 4$leptons
Broad peak $\tau\tau$

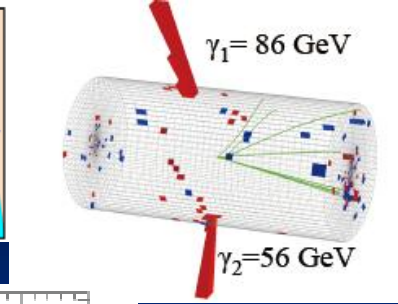


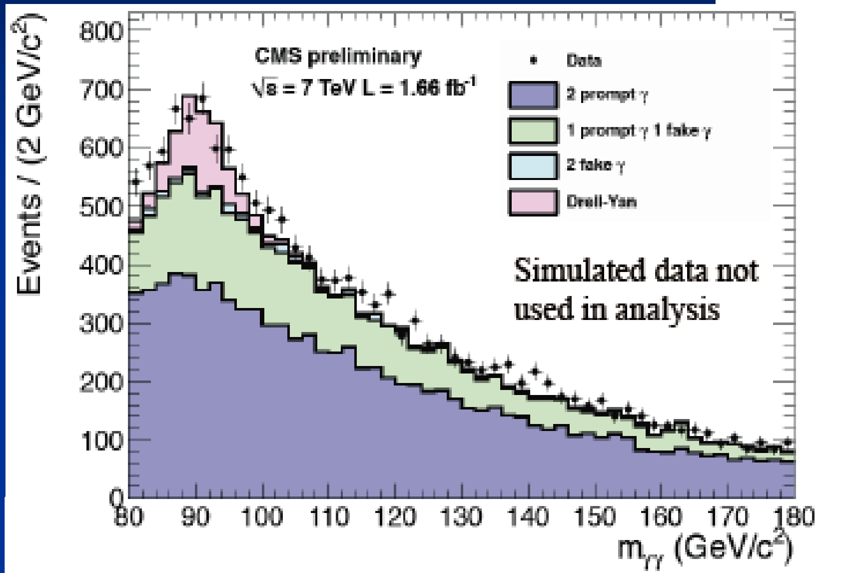
2) Search for excess of events on the understood background
Background processes have to be identified, the background is measured in "Control region" with data and estimated by extrapolation in the large signal region

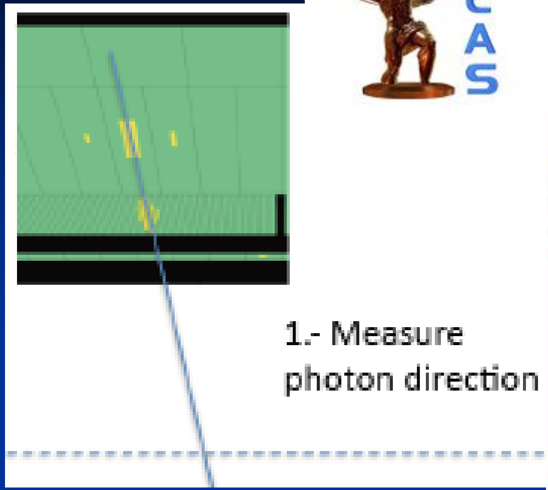


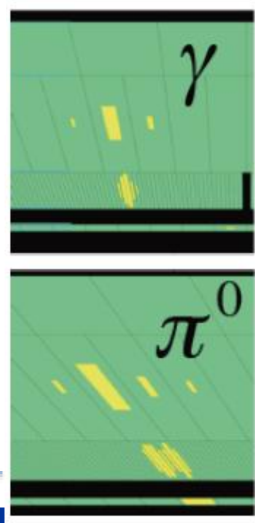
3) Tag forward high pt jet(s) from vector boson fusion to further reduce background
Large statistics is needed

H →γγ

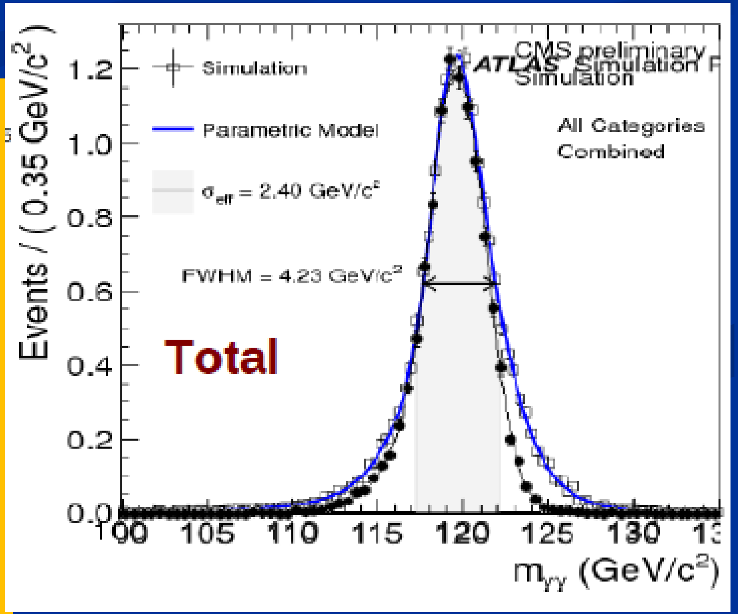




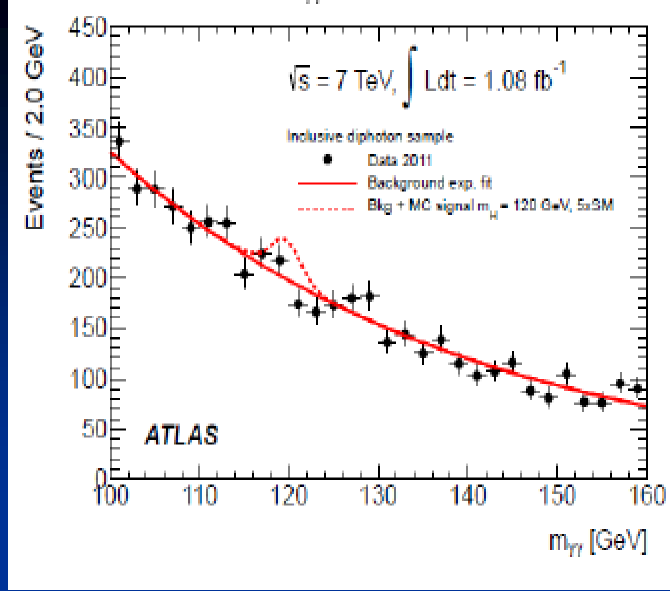


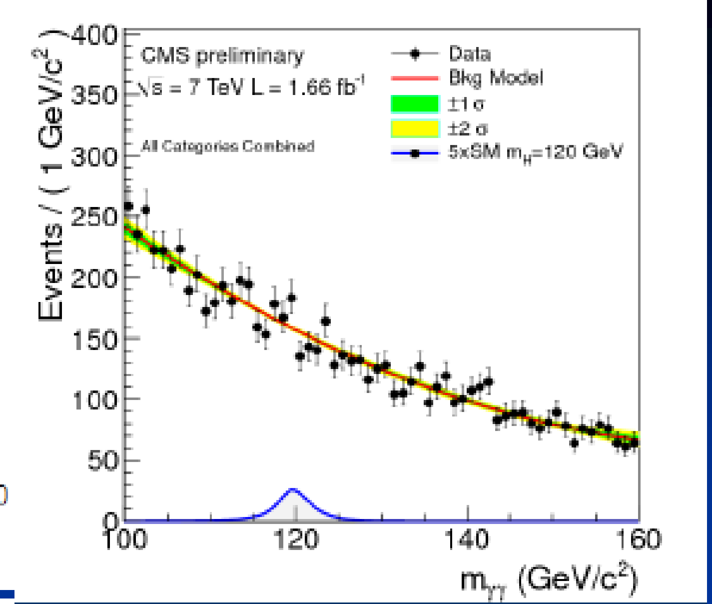


Branching fraction is small: for low mass Higgs O(0.1%) .
Background is well understood.
γγ mass resolution is essential for the background reduction. Currently FWHMs for both detectors are almost the same value.
CMS $PbWO_4$ calibration is not yet completed
ATLAS is using cluster pointing.

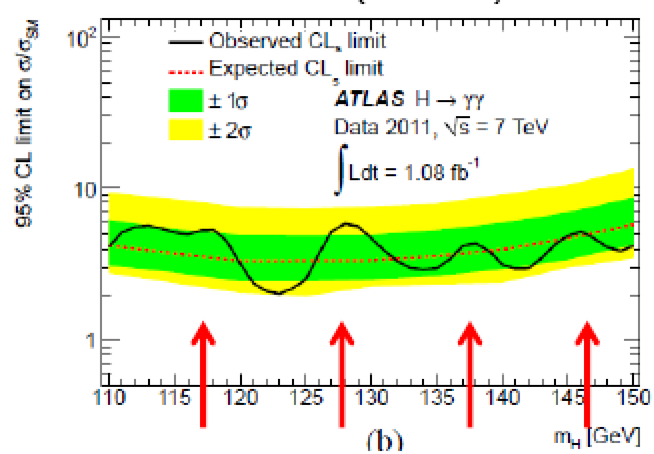


$H \to \gamma\gamma$

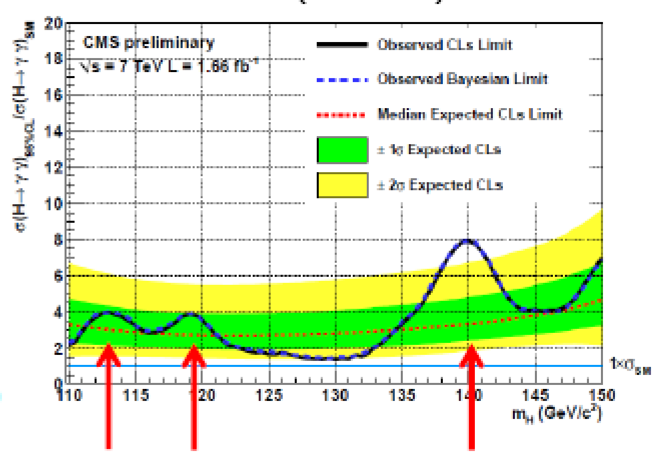




ATLAS(1.08 fb^{-1})



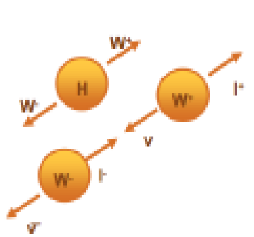
CMS(1.66 fb^{-1})



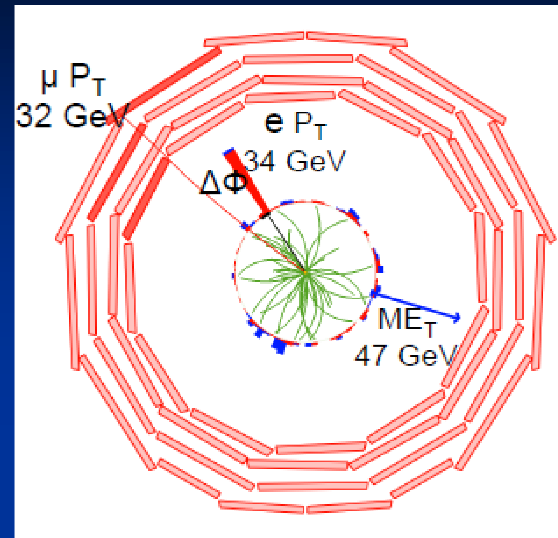
The γγ decay mode is only through charged particle loops. Even if other decay modes are consistent with SM, γγ branching fraction can be significantly smaller than SM prediction. ⇒ Hint of new physics (ex. SUSY) can be seen !

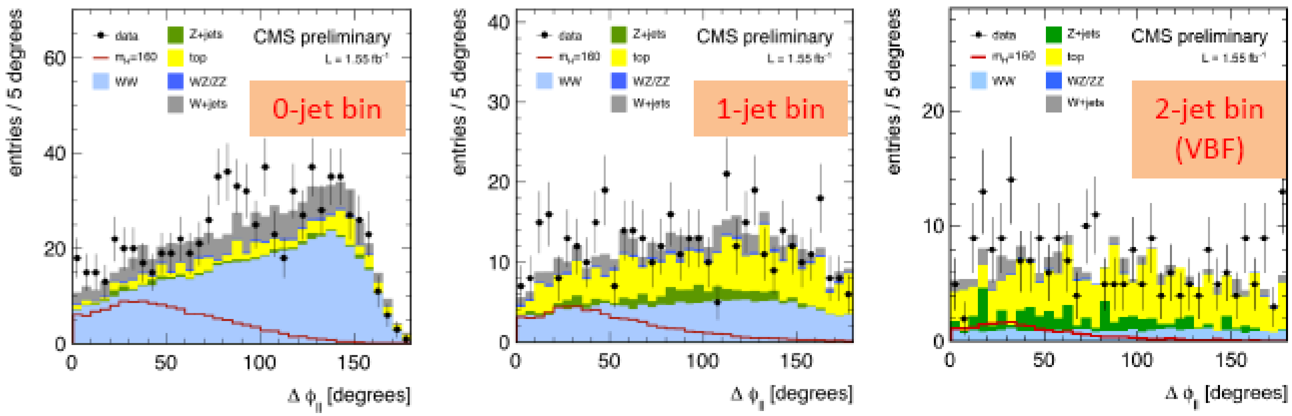
H→WW→lνlν

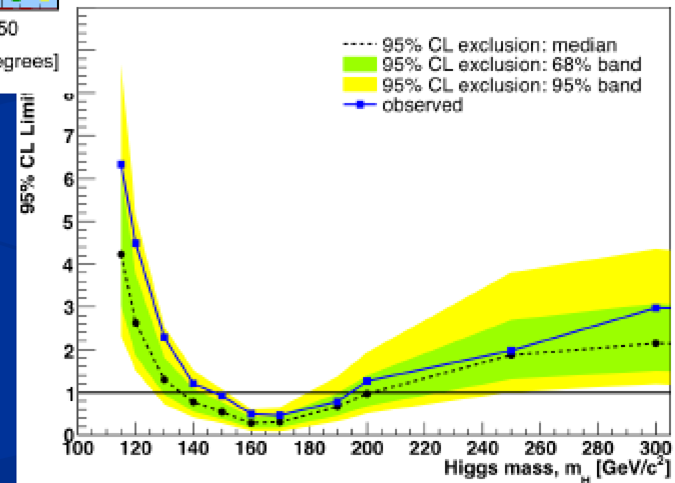
The most sensitive channel M_H<300GeV



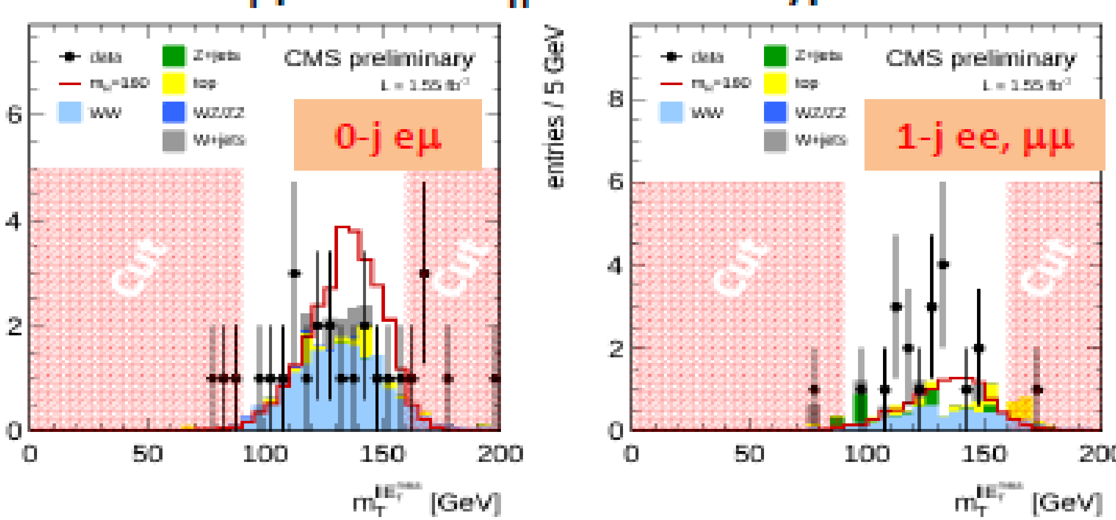
Higgs (J=0) with V-A W-decay,
two leptons (two neutrinos)
have small opening angle



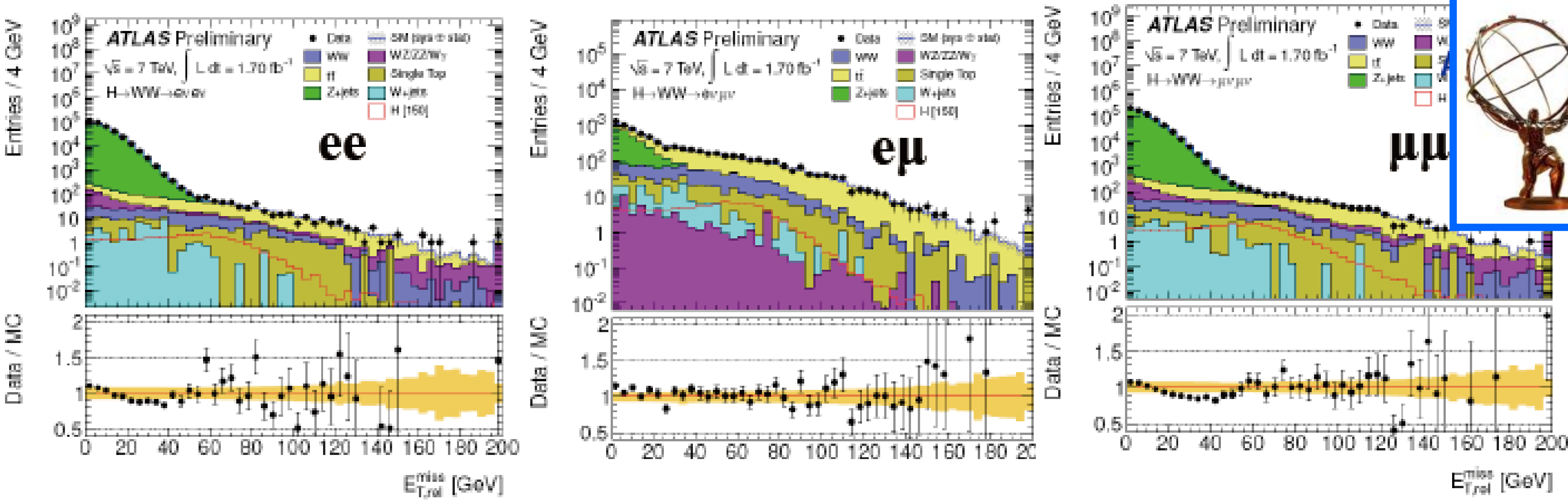




Final M_T plots for M_H=160 GeV hypothesis



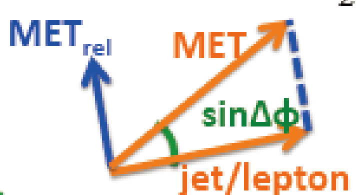
- Excluded (95% CL)
  $147 \le m_H \le 193$ GeV
  (expected: $136 \le m_H \le 200$GeV)



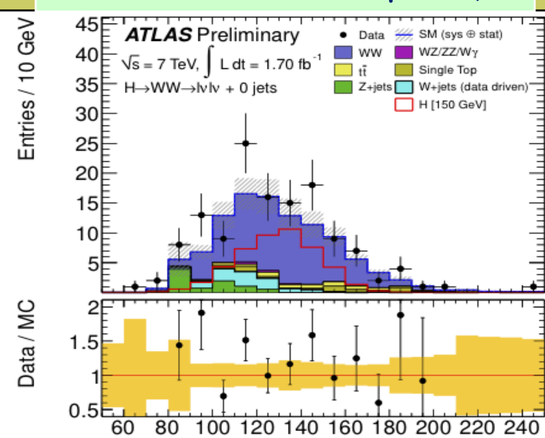
Distributions of E_T^{miss}rel after lepton p_T cuts

METrel

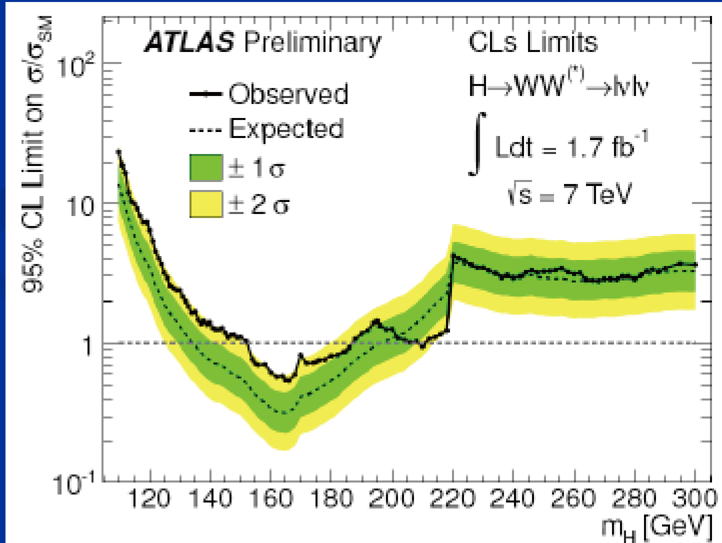
$$E_{T,rel}^{miss} = \begin{cases} E_T^{miss} & (\Delta\phi \geq \frac{\pi}{2}) \\ E_T^{miss}\sin\Delta\phi & (\Delta\phi \leq \frac{\pi}{2}) \end{cases}$$



After all cuts except M_T



$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$$

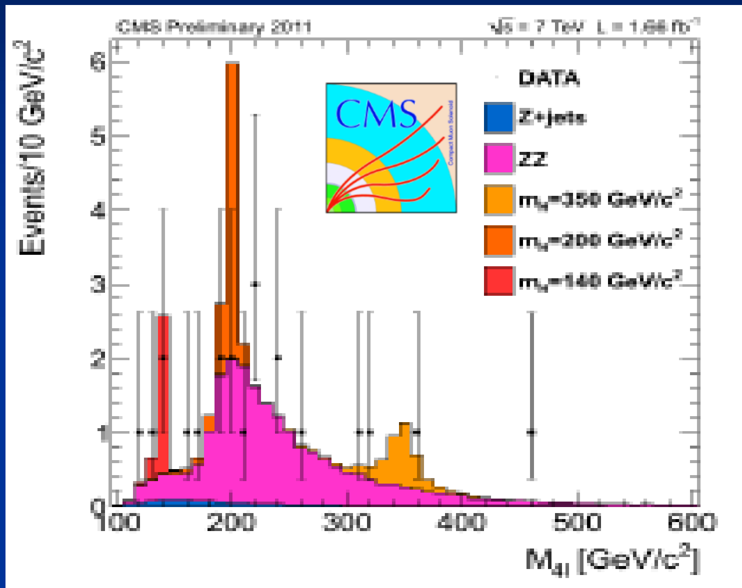


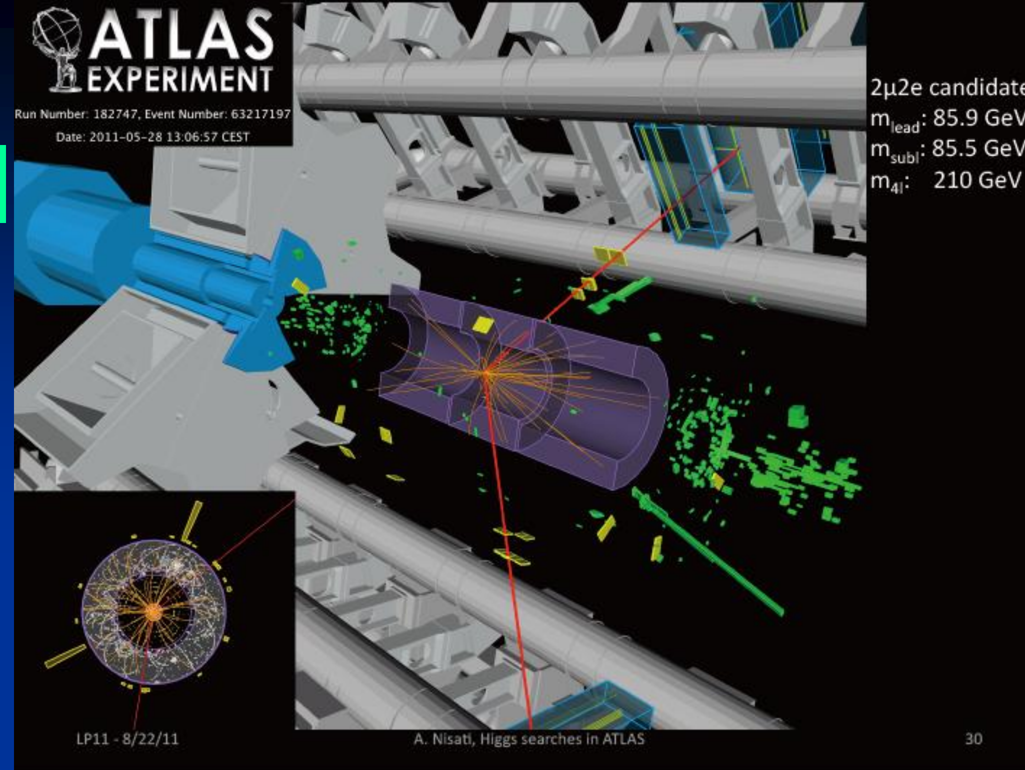
Observed in data 93 events [14 ee, 43 eμ, 36 μμ]
Expected from background 76 (±13)
Expected from signal m_H=150 GeV 46 (±10)

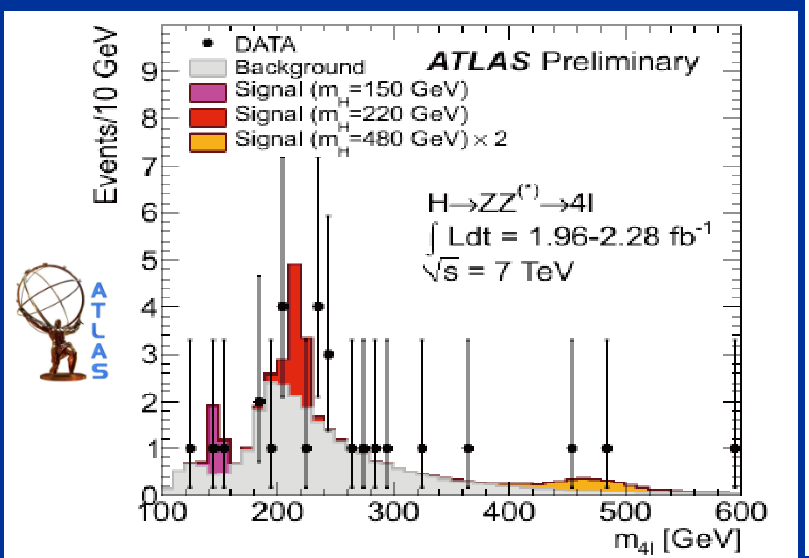
- Excluded (95% CL)
  $154 \leq m_H \leq 186$ GeV
  (expected: $135 \leq m_H \leq 196$ GeV)

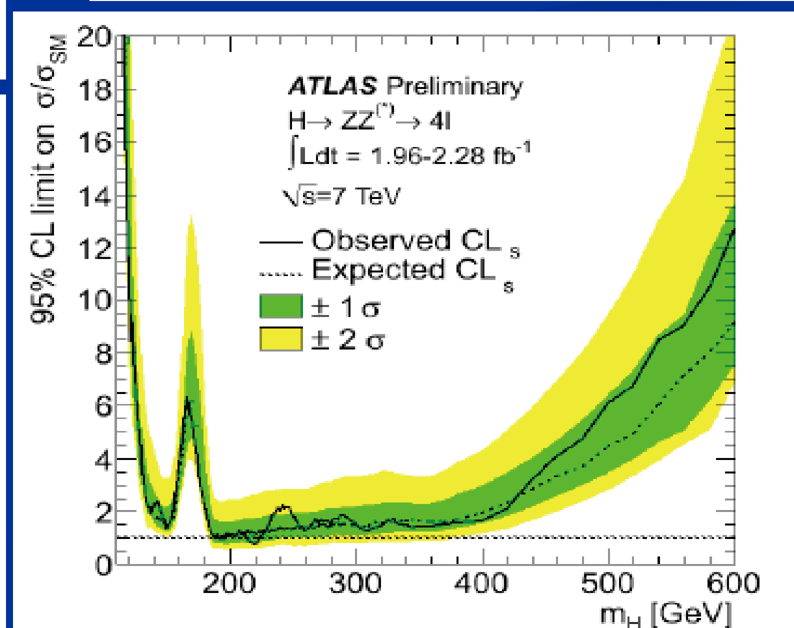
$H \rightarrow ZZ^{(*)} \rightarrow l^+l^-l^+l^-$

Gold-plated channel for heavy Higgs







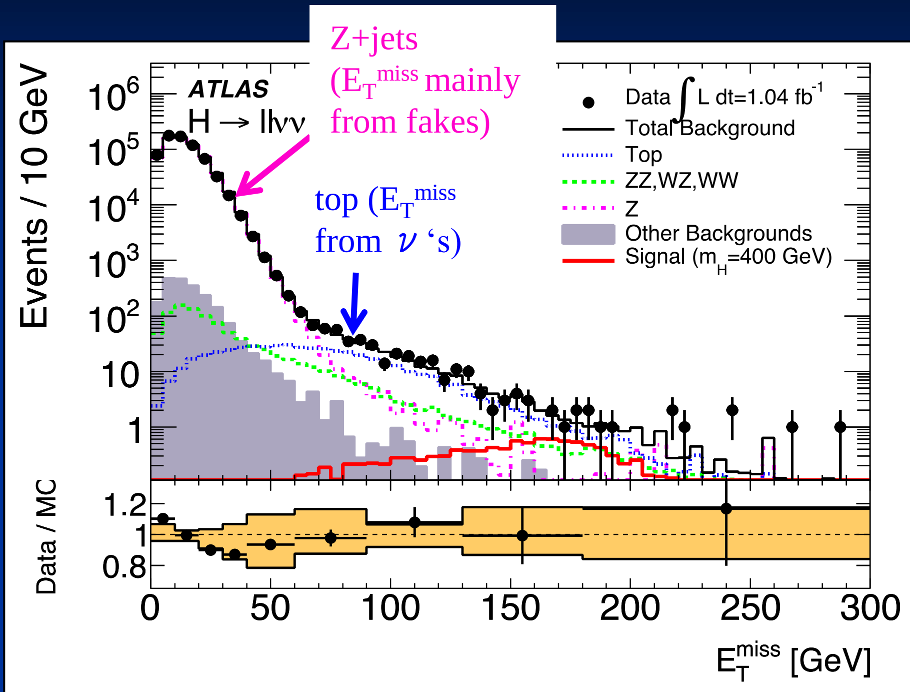


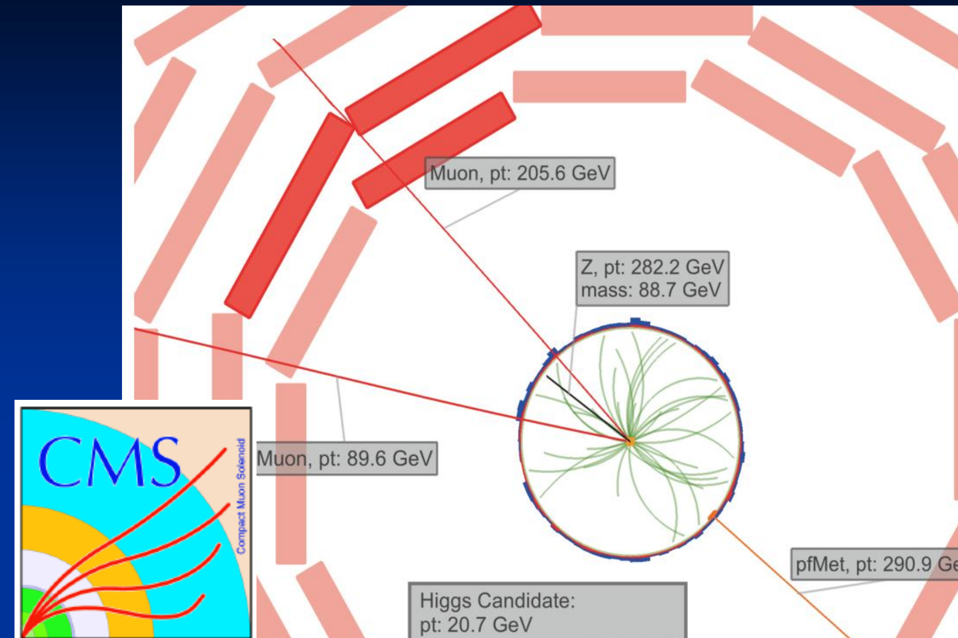
statistically limited

S/B~1

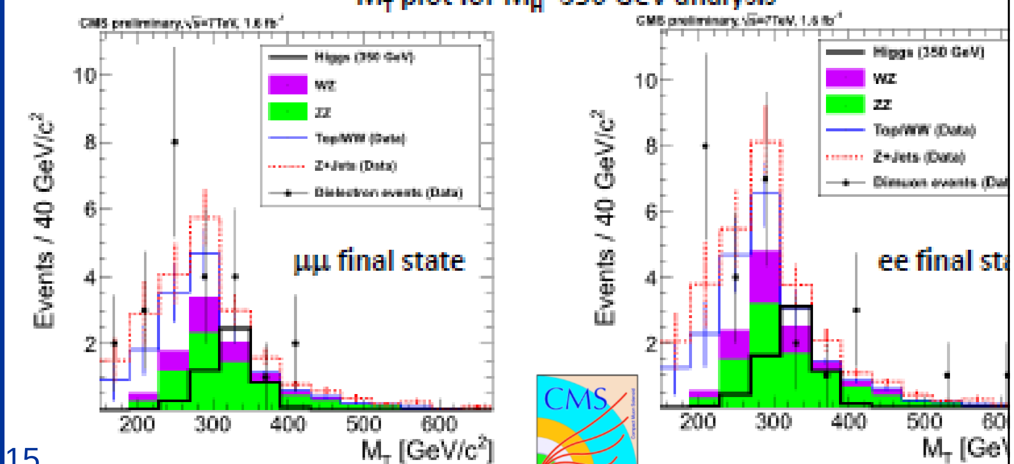
CMS result is similar
6 observed
2.8 ± 0.2 exp.
$M_H < 180$GeV

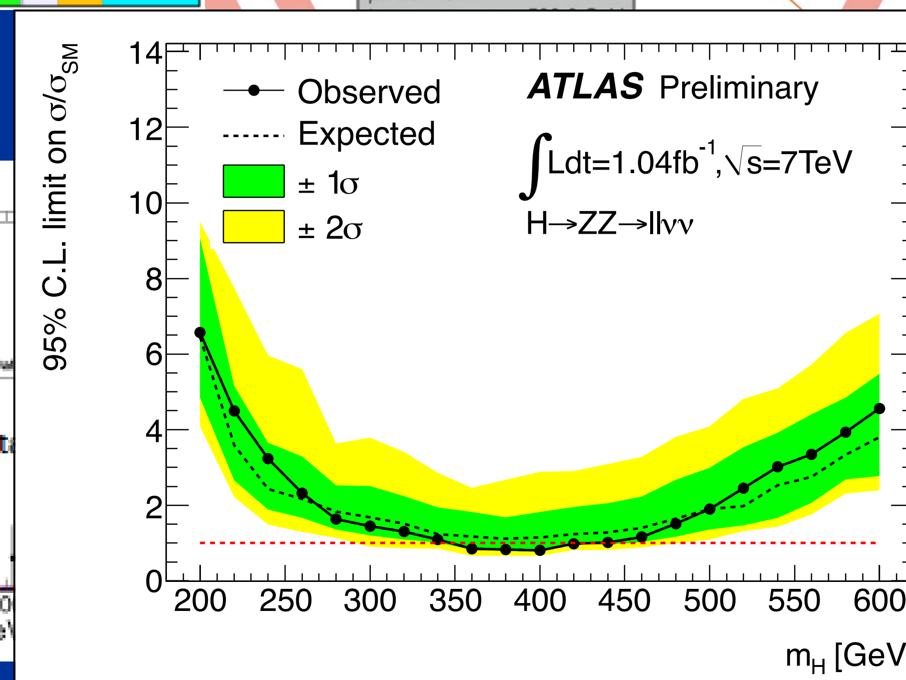
$H \to ZZ^{(*)} \to l^+l^-\nu\nu$ The most sensitive channel M_H>300GeV





M_T plot for M_H=350 GeV analysis





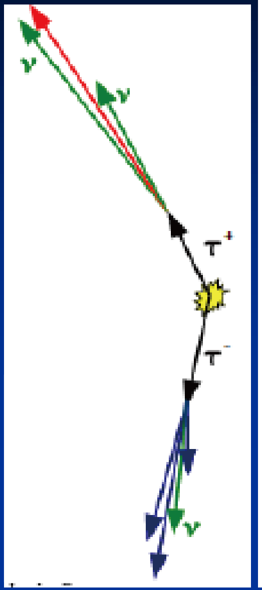
Decay through Yukawa Coupling

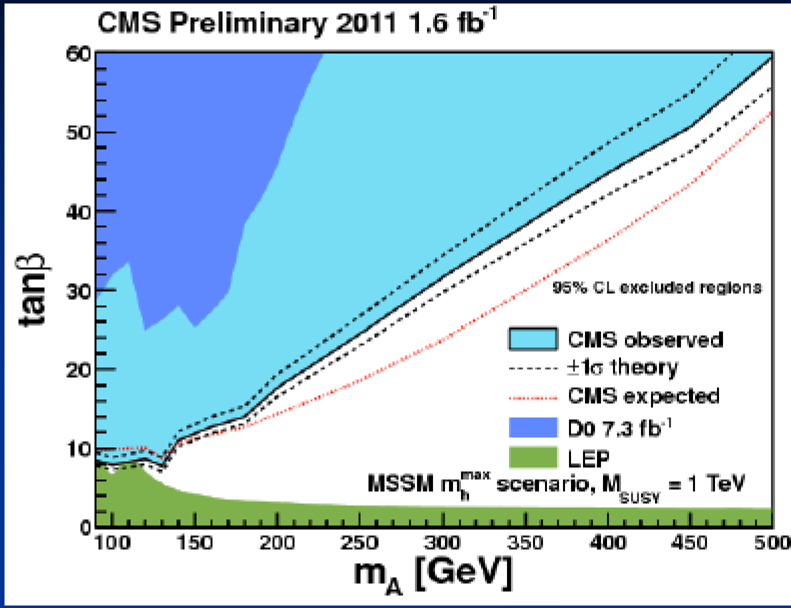
$H \rightarrow \tau\tau$

important for SUSY Higgs

Mass reconstruction is possible.
Etmiss vector can be shared by two taus, but this method does not work for back-to-back taus

Large M_A-tanβ space will be covered by the ττ mode

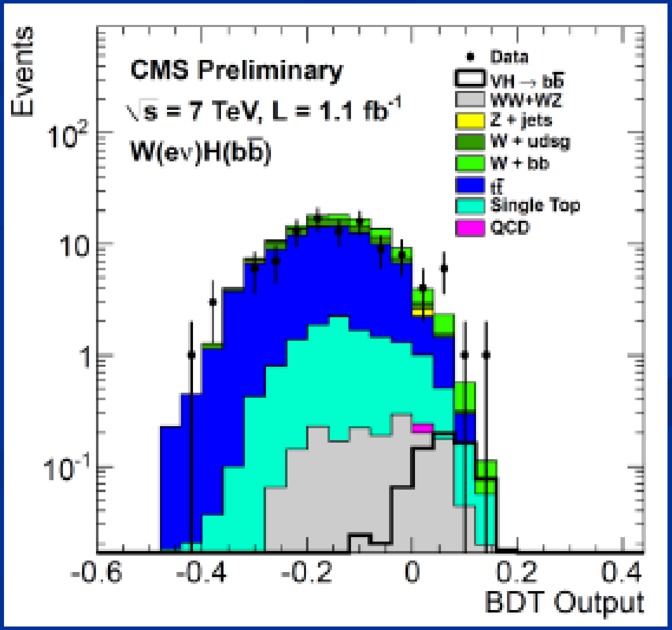




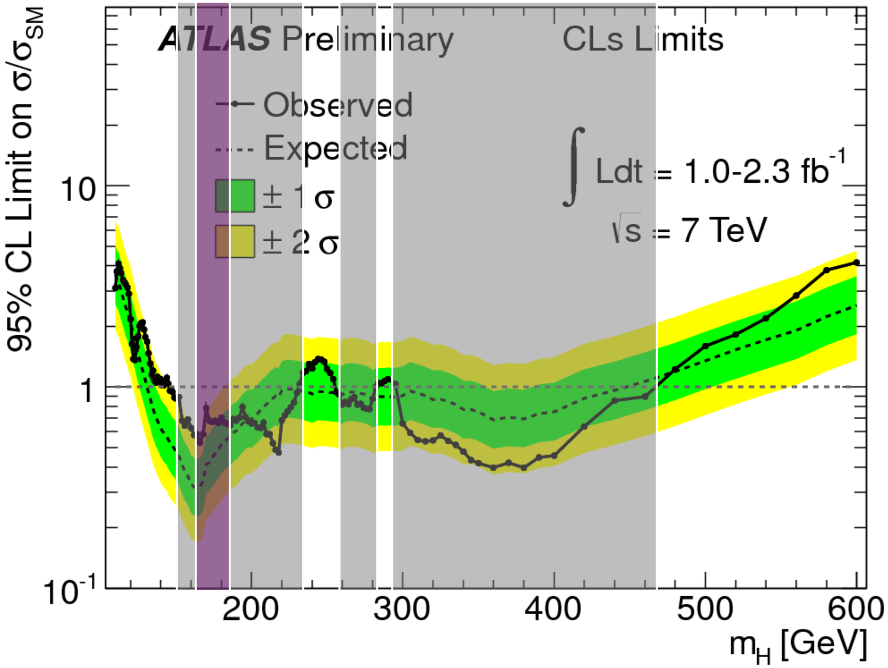
WH→lνbb, ZH→llbb

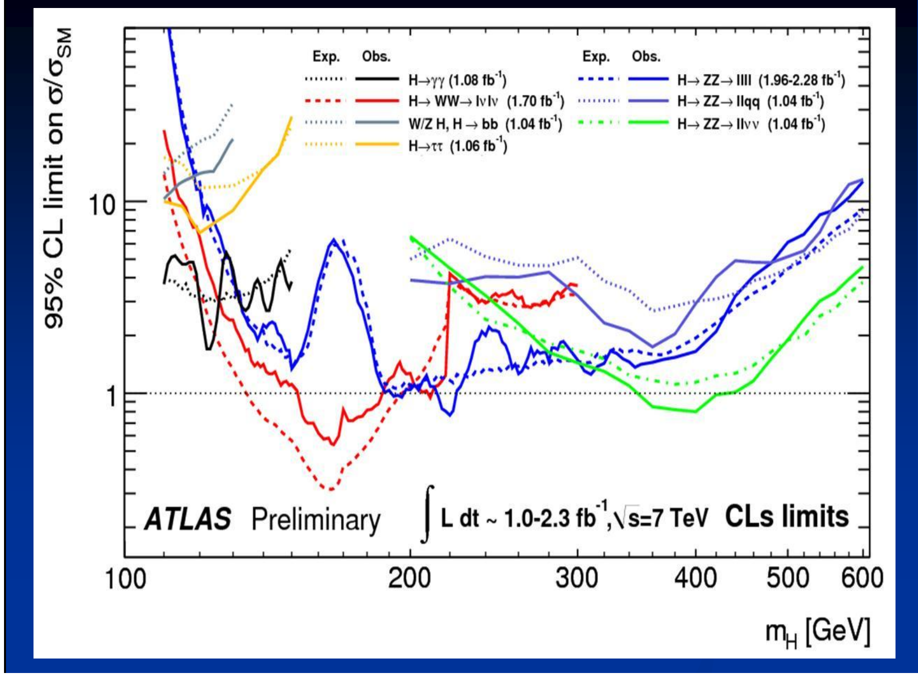
Select heavily boosted Higgs
Pt(bb)>100(150)GeV for ZH(WH)

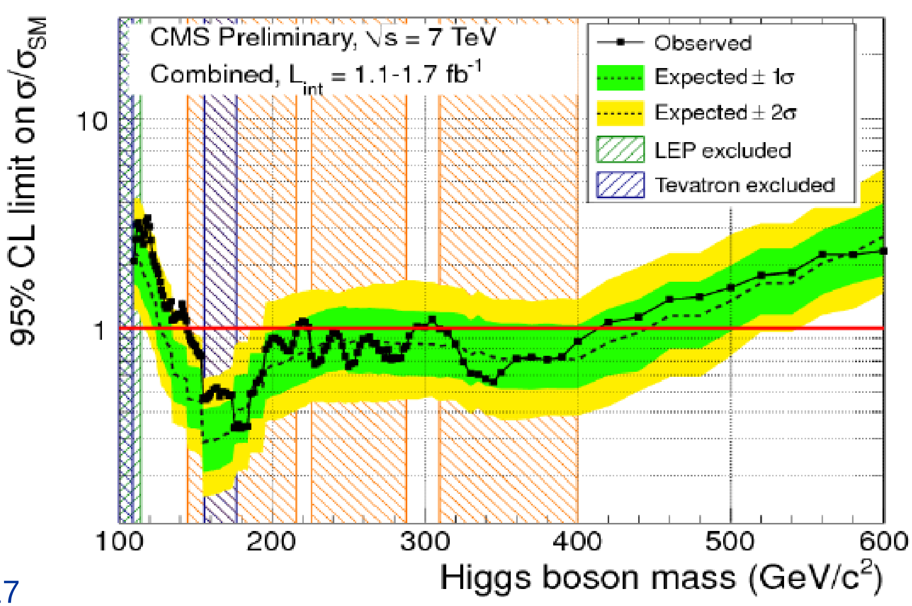
Still background from tt, W/Z+jets, WW+WZ
Results is based on the shape of multivariable analysis output (BDT)

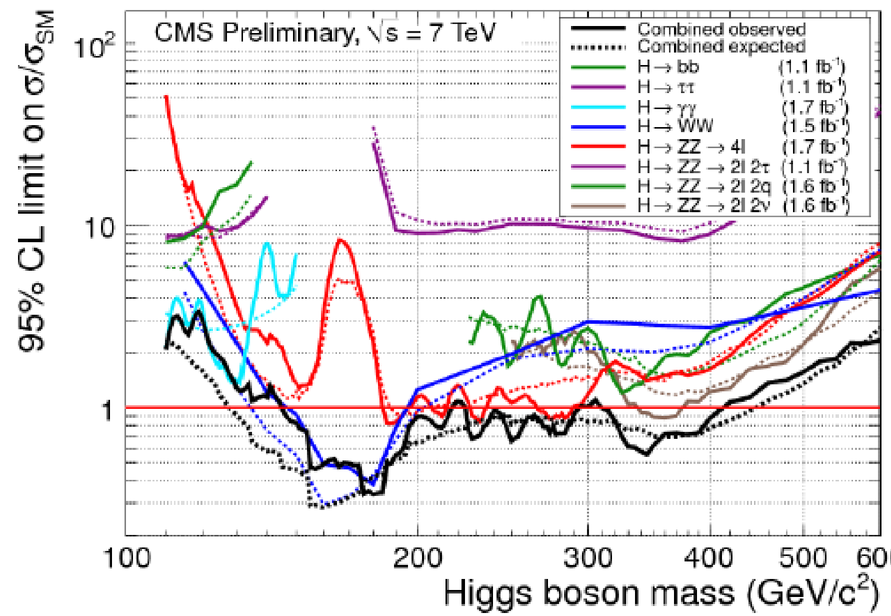


These processes are essential in the future.
For ττ VBF can be used to reduce background.







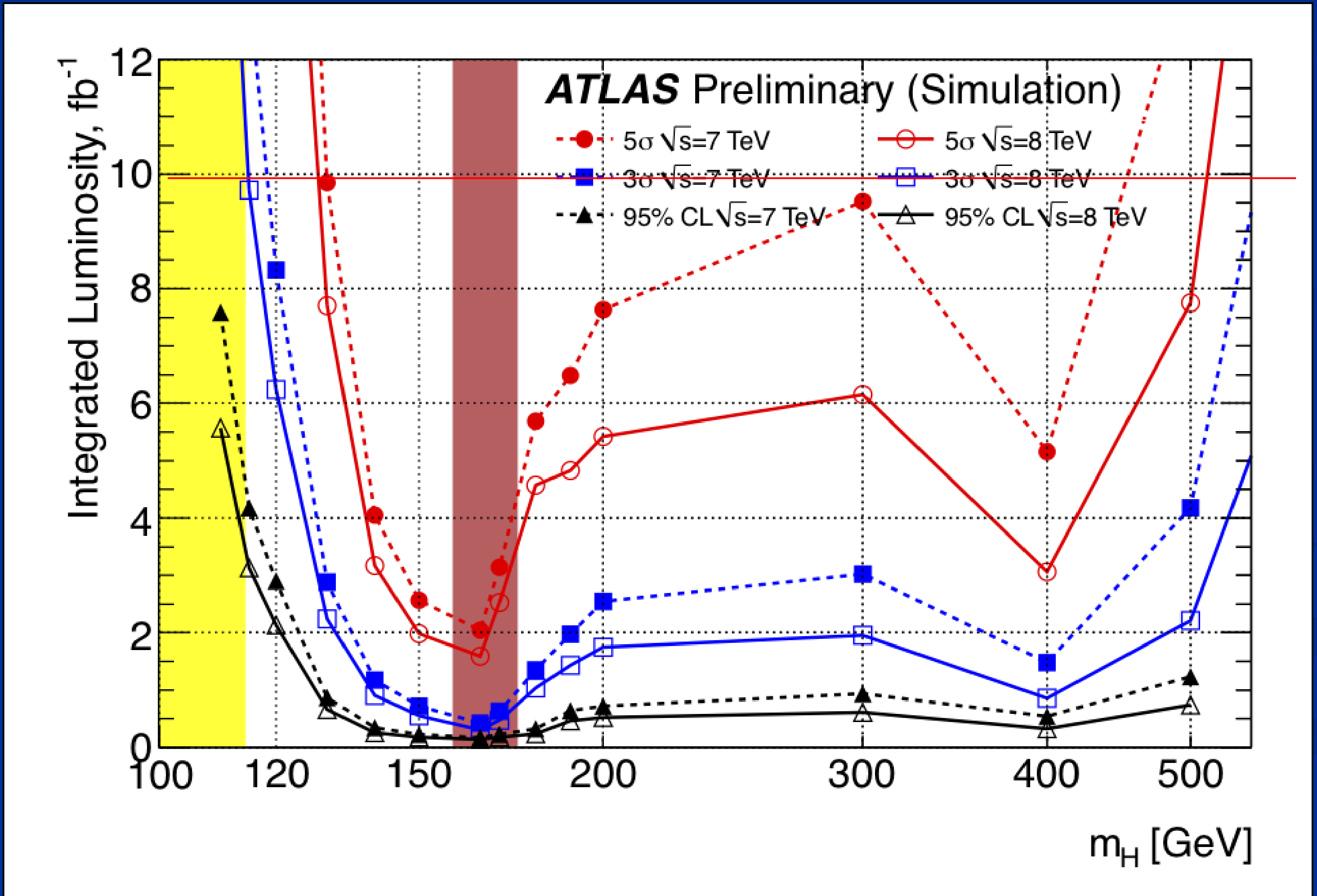


Excluded either by ATLAS or CMS 145-466 GeV (except 288-296 GeV) 95%CL

Prospects of Higgs discovery/studies at LHC

It is very hard to tell the future prospects without seeing Higgs.

Very short term (in the end of this year)



Integrated Luminosity in the end of 2011
~10 fb^{-1}
(CMS+ATLAS)

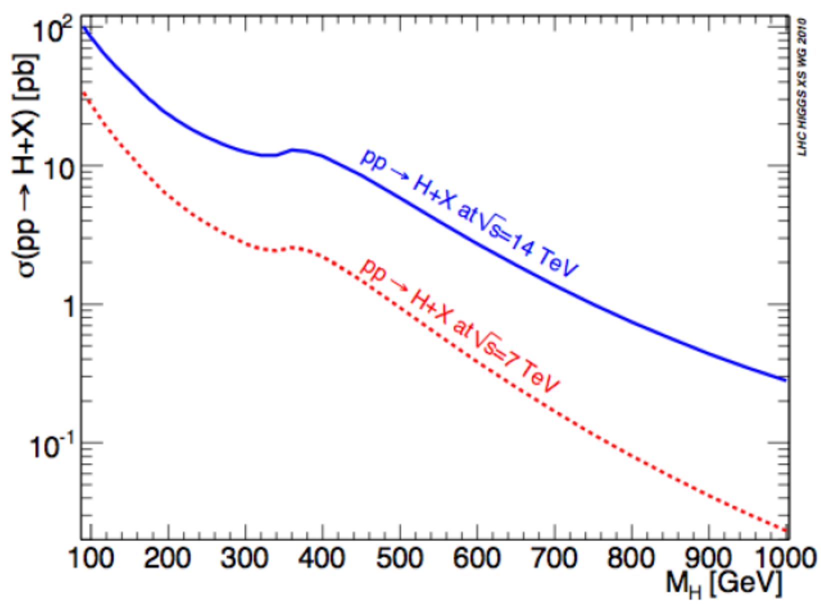
120 GeV SM Higgs can be seen with 3σ

114-600 GeV with 3σ
SPS 12.9.2011
F. Gianotti

Prospects of Higgs discovery/studies at LHC

Mid term

The first step is to increase CM energy to the nominal 14TeV. Cross section is increased by a factor of ~3 for 120 GeV Higgs. Study gauge/Yukawa coulpling.



Long term

Production rate of Higgs becomes significant for HL-LHC or HE-LHC. Detector upgrade is essential to handle higher background/radiation.

Phenomenological studies claim that the tri-linear Higgs self-coupling could be measured (never seen Realistic studies). In any case, LHC-upgrade is inevitable irrespective of physics scopes. (Huge community is behind the project)

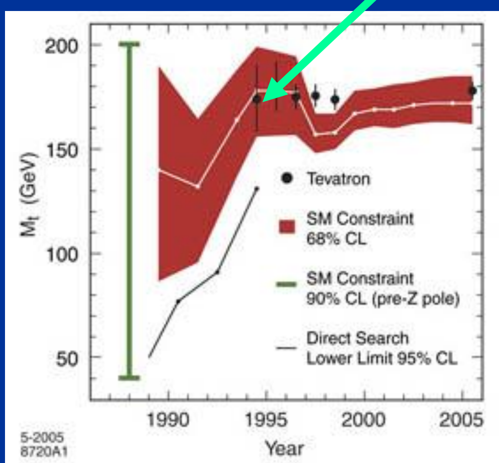
Story of Top Quark and Higgs Boson

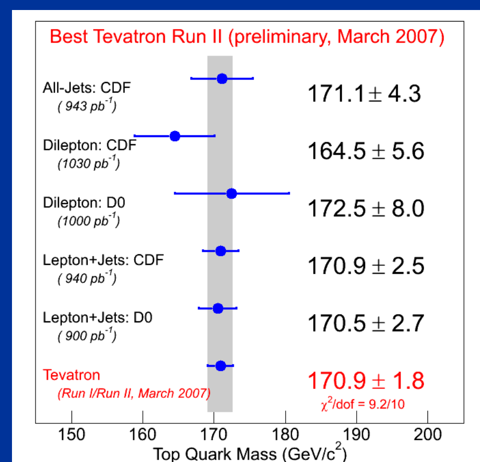
Importance of interplay between hadron and e^+e^- colliders

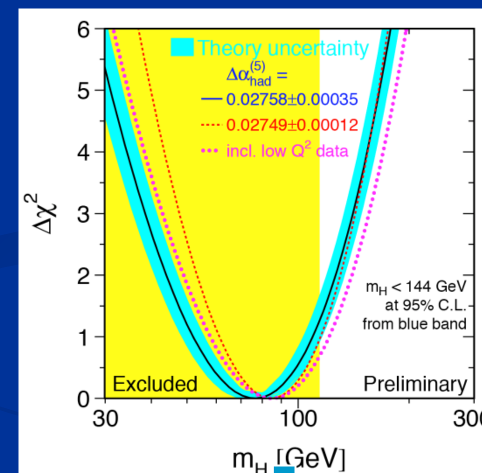
From precise electro-weak measurements at LEP, top mass was predicted → **Discovery to Top**

Precise Measurement of Top mass at the TEVATRON

→ Higgs mass is restricted into a narrow mass range using precise top mass and LEP/SLC electro-weak data
114 GeV $< M_H \lesssim 160$ GeV

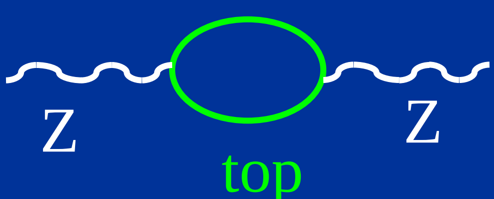






Discovery of Higgs at LHC

Precise measurements of Higgs properties at **ILC**



Studies on Higgs Boson Properties at ILC

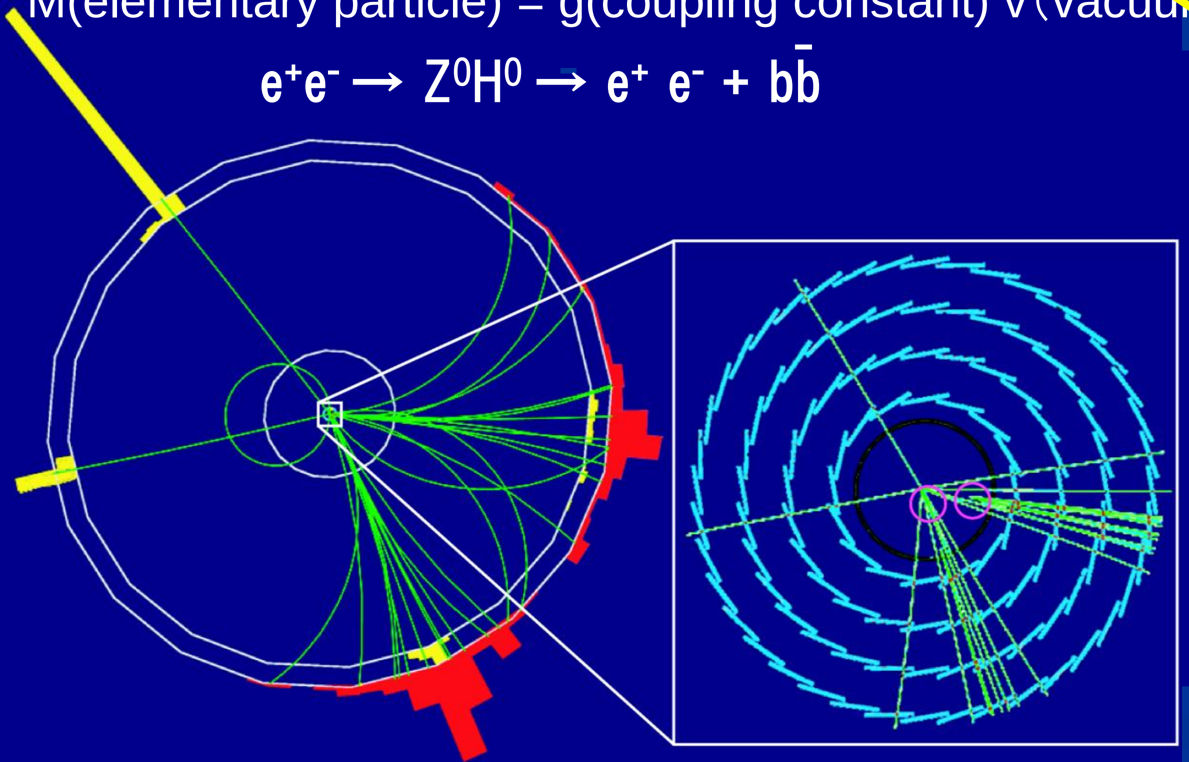
ILC is Super Higgs boson factory **Clean environment**

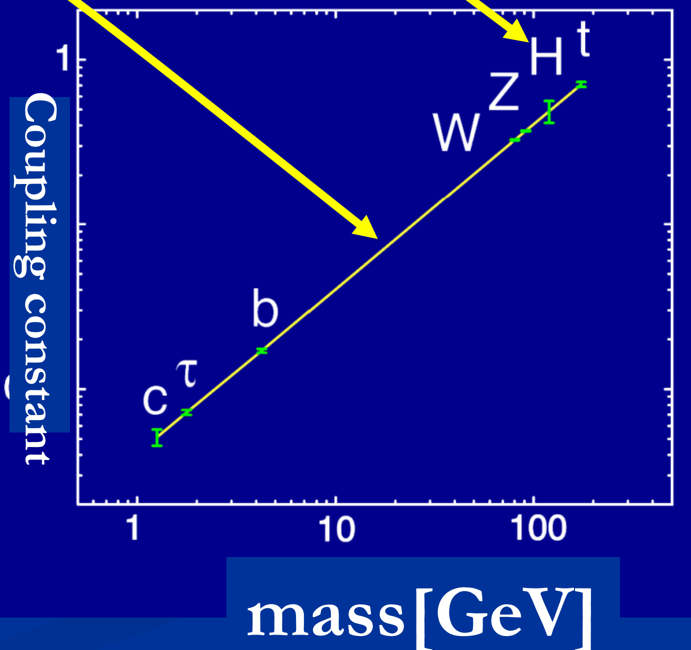
Detailed studies with O(10^5) Higgs events generated at ILC

the origin of mass ⟷ **the structure of vacuum**

M(elementary particle) = g(coupling constant) v（vacuum expectation value）

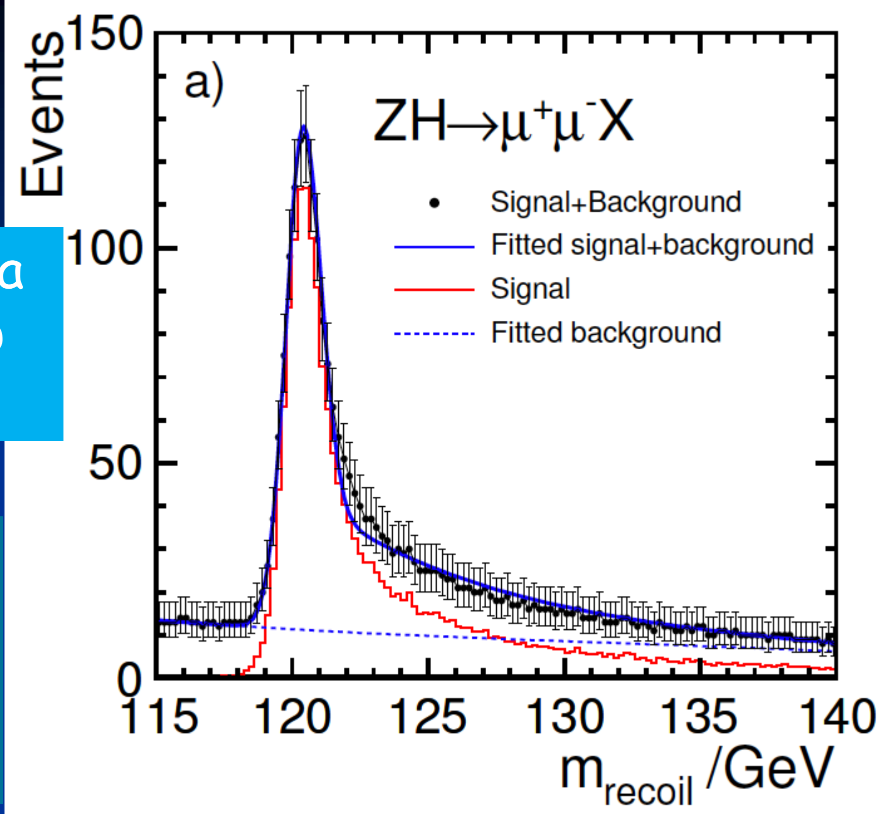
$e^+e^- \rightarrow Z^0H^0 \rightarrow e^+ e^- + b\bar{b}$



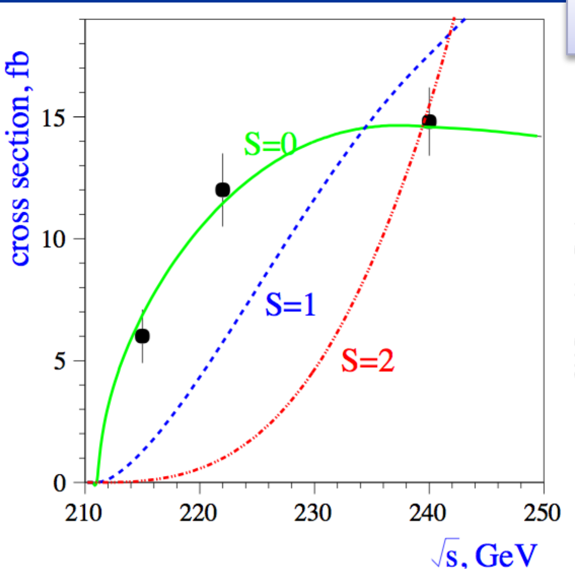


Measurements at ILC will be in future text books

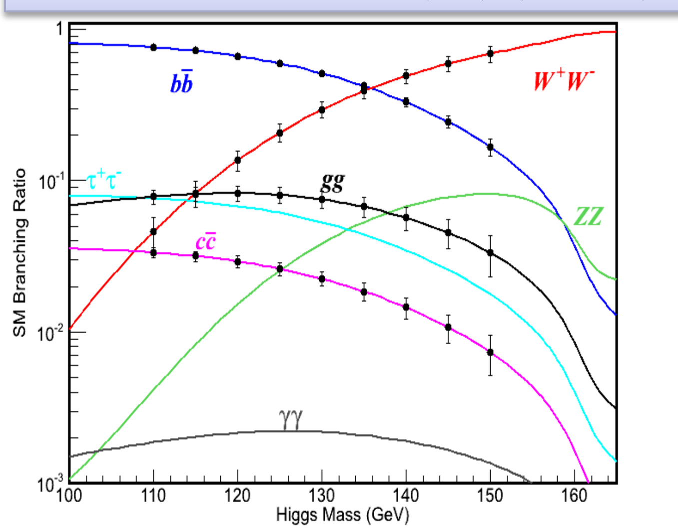
Even for an invisible Higgs boson, a missing (recoil) mass peak is sharp at ILC



Couplings, Spin and CP properties of Higgs boson can easily determined at ILC. Energy scan and electron polarization are important tools at ILC



Ecm=250 GeV, L=250 fb^{-1}, Pol(e$^+$,e$^-$)=(+0.3, -0.8)



We need to seriously study what are expected to be revealed on Higgs boson at the time ILC is constructed.

Summary

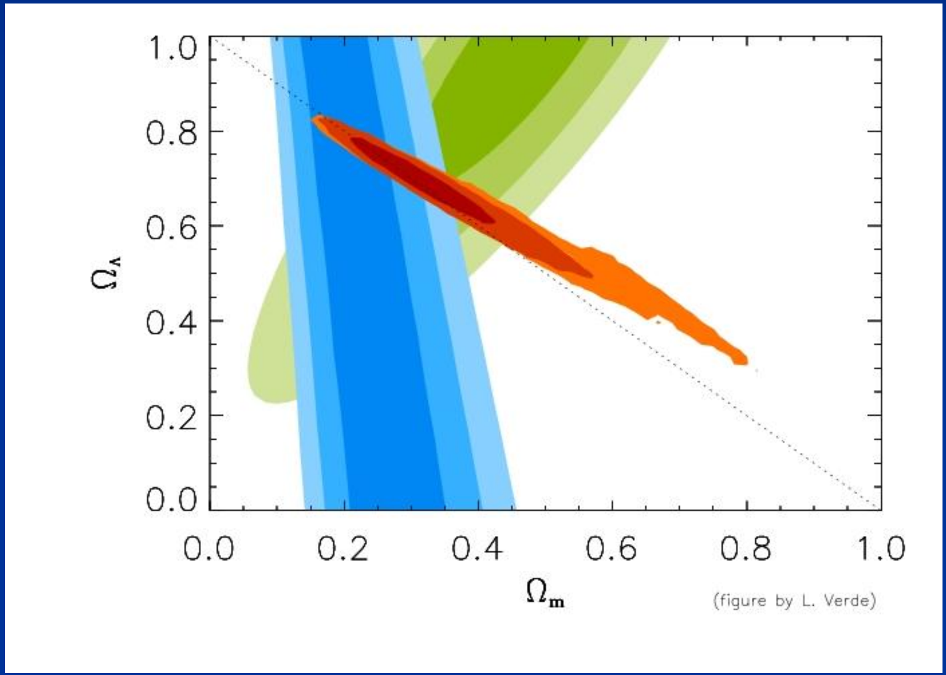
The dawn of a revolutionary era since 1974 (discovery of J/ψ)

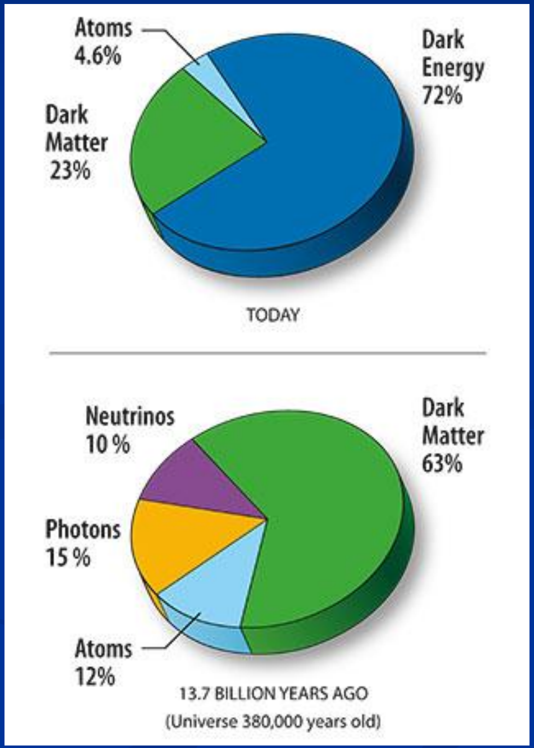
1) Higgs boson seems to be restricted in a narrow low mass region. LHC experiments will find it (3σ) in the end of this year and hopefully discover it (5σ) in a few years, if the mass is not very close to the LEP direct search limit.
2) The low mass Higgs can be very similar to the SM Higgs. The detailed investigations of its properties are essential to understand the physics in the TeV region.
3) Further precise measurements should be done at optimal Ecm at an e+e- linear collider (ILC), and the Higgs self-coupling has to be measured at higher energy at ILC to prove the connection between Higgs and the "vacuum".

excuses

4) If only a heavy Higgs is found at LHC, the SM is surely broken and there must be something else in the TeV region.
5) If Higgs is not found at all, this would be a real revolution ! But we need to seriously think about our future.

Investigation of Higgs boson (fundamental scalar, something to do with the vacuum) can be the zeroth step to understand inflation of the universe and dark energy.





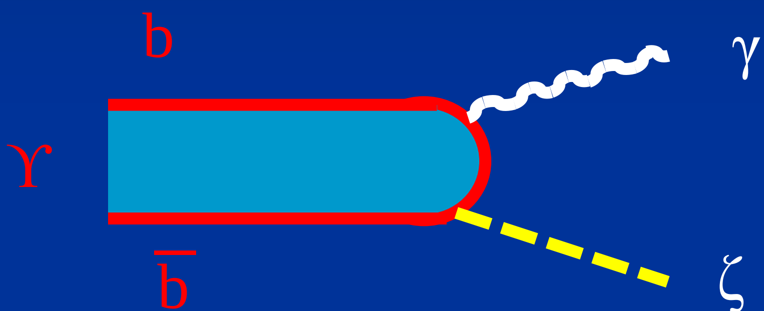
Most of the slides/figures are stolen from
LP2011 talks M.Verzocchi, A.Nisati, V.Sharma, A.Djouadi,
Recent talks F.Gianotti, M.Zanetti
My young Higgs hunter T.Masubuchi Many thanks to them

Spare

Higgs boson searches at prehistoric times

Higgs couples to the heaviest elementary particle available

$\Upsilon \to \gamma h$ Monochromatic γ searches at CESR and DORIS-II
(Wilczek mechanism 1980')

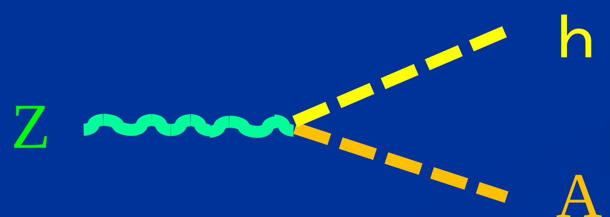


$\zeta \to cc, \tau\tau$

An experiment found a signal but it disappeared after increase the data x2.

Phenomenology of non-minimal (two doublet, SUSY) Higgs models was studied (8 degree of freedom $\to h, H, A, H^+, H^-$)

$Z \to hA$ 'UA1 monojet' could be a Higgs associate production
(Two doublet models Glashow-Manohar monojet)



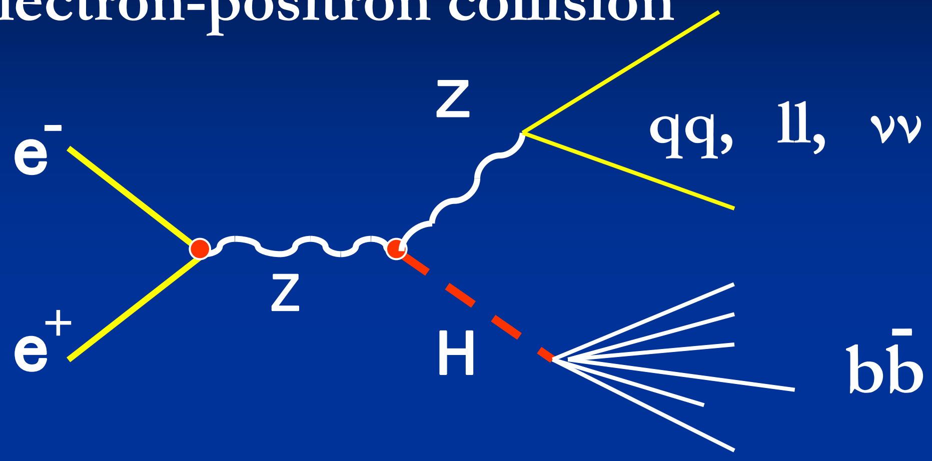
$h \to qq$
A: stable
Searches @PETRA

Reaction of theorists is very prompt.

electron-positron vs proton-proton collision

Ex. Higgs boson production

electron-positron collision

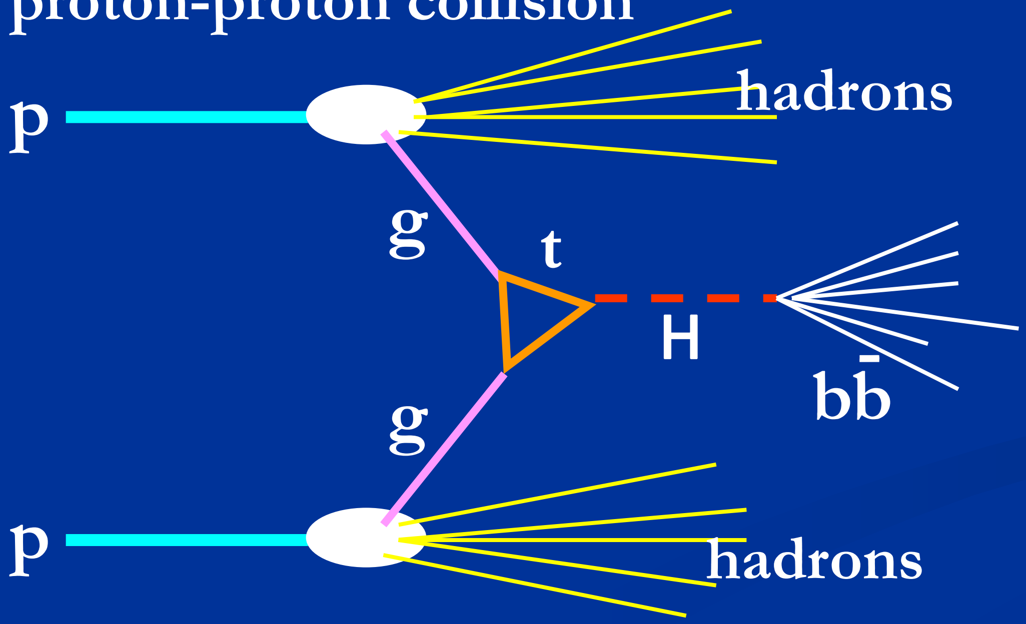


Electron-positron collision is an elementary process in particle physics
⇒ ideal detector can be designed

high precision experiments

Energy loss due to synchrotron radiation
⇒ Linear collider is inevitable

proton-proton collision



A proton is a composite particle

⇒ complicated interactions

high radiation environment
high event frequency
⇒ requires advanced detector technologies and smart ideas in the analyses.