Higgs physics: Theory and recent results

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Introduction

- We have seen yesterday that the standard model is a well verified theory.
- However by having a closer look at some equations we will realise that we had left aside a problem: The interactions Lagrangians do not permit particles to have a mass!
- To solve this problem Higgs proposed an extra mechanism that gives mass to the SM particles.
- The Higgs mechanism is the only part of the SM that still awaits experimental confirmation…

Motivations: Gauge invariance

- In any physical theory there are "phases" through which the theory should be invariant.
- For example, the phase of an EM wave or the referential mechanics.
- In Field Theory this is called "gauge invariance". Lagrangians for interactions must be "gauge invariant".
- There is one gauge for each degree of freedom in a Lagragian.

Gauge invariance in QED

- The QED Lagrangian is:

$$\mathcal{L} = -\hbar c \bar{\psi}\left(\gamma_\mu \frac{\partial}{\partial x_\mu} + \frac{mc}{\hbar}\right)\psi - \frac{1}{4}F_{\mu\nu}F_{\mu\nu} - ie\bar{\psi}\gamma_\mu A_\mu \psi$$

- It is gauge invariant, that is, it is invariant under the transformation:

$$\psi \rightarrow e^{i\lambda(x)}\psi$$

$$A_\mu \rightarrow A_\mu - \frac{\hbar c}{e}\frac{\partial \lambda(x)}{\partial x_\mu}$$

- However, adding a mass term would not be Gauge invariant:

$$-m^2 A_\mu A_\mu$$

- Therefore to keep the QED Lagragian Gauge invariant one needs set the mass of the photon to zero (as observed experimentally).

Gauge invariance in the Electroweak interaction

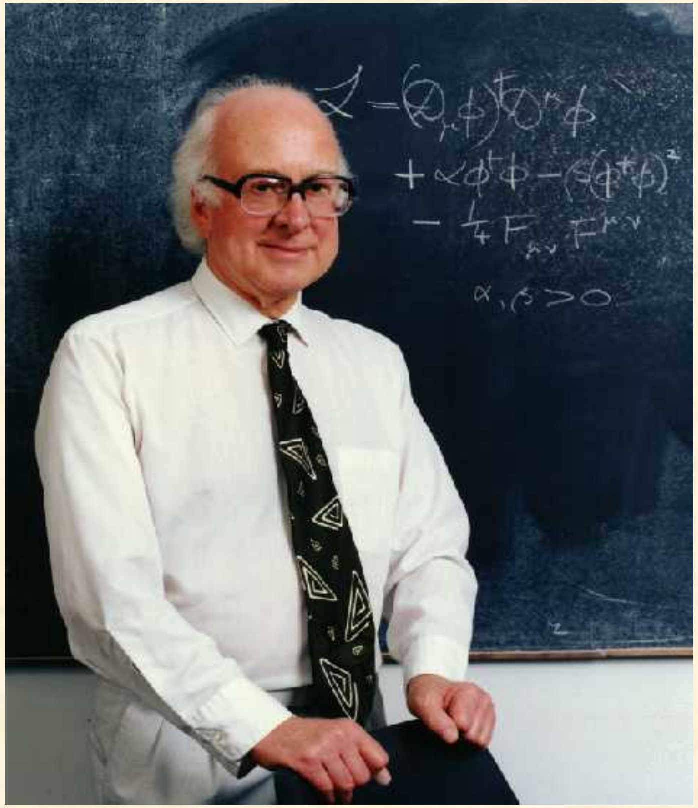
- The EM and weak interactions can be unified ("electroweak interaction") with symmetry group $SU(2)_L \times U(1)_Y$.
- The resulting Lagrangian must be Gauge invariant, however the term $L_M = \frac{1}{2} m_\gamma^2 A^\mu A_\mu$ is not.
- This is fine with photons but the same argument applies to all bosons.
- W and Z must also be massless!
- And fermions also!

The Higgs Mechanism

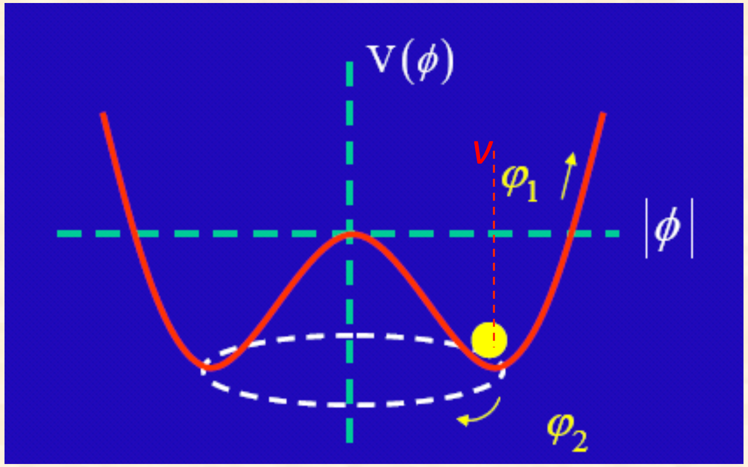
- To bring the SM in agreement with experimental observations a mechanism has been proposed by Peter Higgs.
- A scalar fields should be added to the fermions mass term to make it gauge invariant: $f_R f_L \phi$

$$\phi = \begin{pmatrix} \phi^{+} \\ \phi^{0} \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2) \\ \frac{1}{\sqrt{2}}(\phi_3 + i\phi_4) \end{pmatrix}$$

- Any choice that breaks the symmetry will generate mass for the associated bosons.



Symmetry breaking



Lagrangian a complex scalar field $\phi = 1/\sqrt{2}(\phi_1 + i\phi_2)$

$$L = (\partial_\mu \phi^+)(\partial^\mu \phi) - \lambda(\phi^+\phi)^2 - \mu^2\phi^+\phi$$

L has a global U(1) symmetry ($\Phi \rightarrow e^{-i\alpha}\,\Phi$)

Minimum : $\dfrac{\partial V(\phi)}{\partial \phi} = 0$

If $\lambda>0$ and $\mu^2< 0$

Degenerate minima : $\phi_1^2 + \phi_2^2 = v$ with $v=\sqrt{\dfrac{-\mu^2}{\lambda}}$

Perturbative calculations : expand around the minimum energy which we choose at Φ_1=v and Φ_2=0 :

$$\phi = \frac{1}{\sqrt{2}}\left[v + \phi_1(x)\right]e^{i\phi_2(x)/v}$$

And we replace in L so that we get $L' = \dfrac{1}{2}(\partial_\mu\phi_1)(\partial^\mu\phi_1) + \dfrac{1}{2}\left(1 + \dfrac{\phi_1}{v}\right)^2(\partial_\mu\phi_2)(\partial^\mu\phi_2) - V(\phi)$

$$V(\phi) = V(\phi_0) + \frac{1}{2}M_{\phi_1}^2\phi_1^2 + \lambda v\phi_1^3 + \frac{1}{4}\lambda\phi_1^4$$

$M_{\phi_1}^2 = -2\mu^2 > 0$ The Φ_1 field has a mass

$M_{\phi_2}^2 = 0$ No corresponding mass term for the Φ_2 field : the theory has a massless scalar : the Goldstone boson.

In Φ_1 and Φ_2 directions the potential behaves differently : flat in $\Phi_2 \Rightarrow$ massless boson electroweak unification + spontaneous symmetry breaking :

$$L = (D_\mu \phi^+)(D^\mu \phi) - \lambda(\phi^+\phi)^2 - \mu^2\phi^+\phi$$

$$D^\mu \phi = \left[\partial^\mu + igW^\mu + ig' y_\phi B^\mu\right]\phi$$

Λ>0 and μ^2<0 ⇒ degenerate vacuum states $\left|\langle 0|\phi^0|0\rangle\right| = \sqrt{\frac{-\mu^2}{2\lambda}} = \frac{v}{\sqrt{2}}$ and $\left|\langle 0|\phi^+|0\rangle\right| = 0$

spontaneous symmetry breaking : $\phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$

keep $U(1)_{em}$ invariance

The coupling to the gauge boson is obtained via the covariant derivatives (rather long calculation) :

$$L = (D_\mu \phi^+)(D^\mu \phi) = \frac{1}{2}\partial_\mu H \partial^\mu H + \frac{g^2}{4}(v+H)^2\left[W_\mu^+ W^\mu + \frac{1}{\cos^2\theta_W} Z_\mu^+ Z^\mu\right]$$

No $A_\mu A^\mu$ term : $M_\gamma = 0$

Massive weak gauge bosons :

$$M_W = \frac{1}{2}vg$$

$$M_Z = \frac{1}{2}\frac{vg}{\cos\theta_W}$$

v is not known it can be computed using the muon decay rate

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{1}{2v^2} \quad \Rightarrow v \sim 246 \text{ GeV}$$

Experiments :

M_Z = 91.1876 ± 0.0021 GeV (precision 10^{-5} !)

M_W = 80.403 ± 0.029 GeV

$$\Rightarrow \quad \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} \sim 0.223$$

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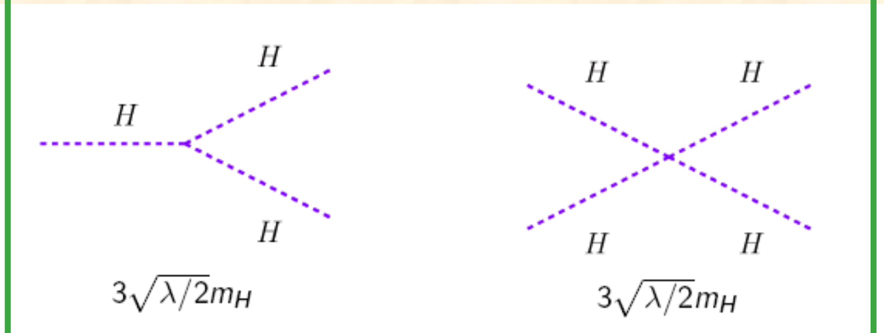
The Higgs boson

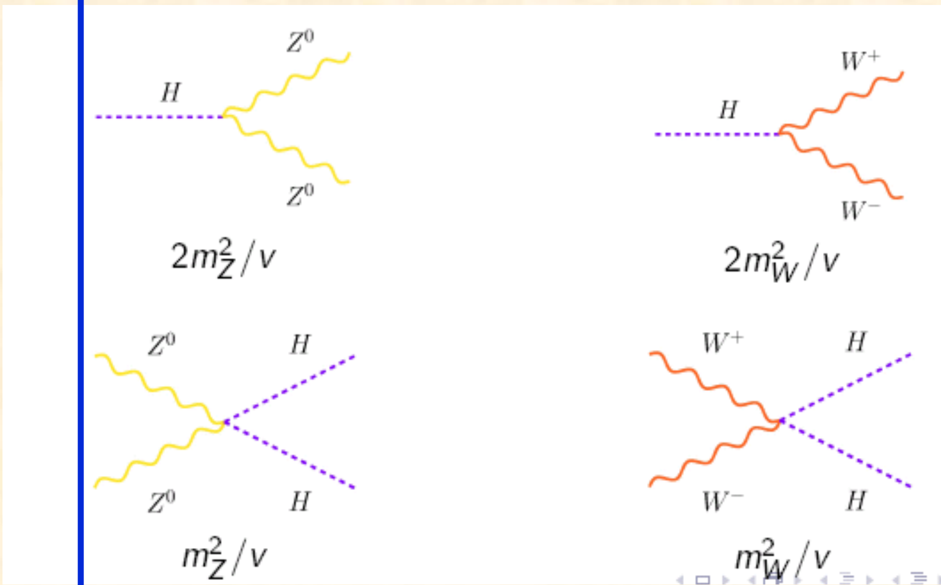
As shown before $M_H=\sqrt{-2\mu^2}$ it is a free parameter

If one writes the full lagrangian one sees Higgs self coupling and Higgs coupling to the gauge bosons

Higgs self coupling

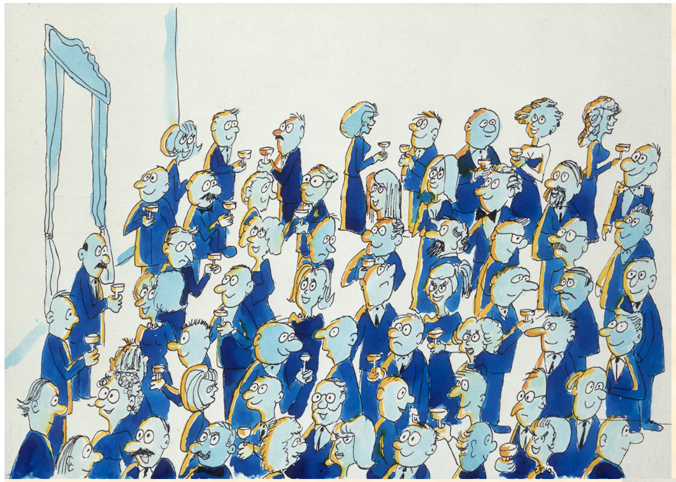


Higgs coupling to the gauge bosons

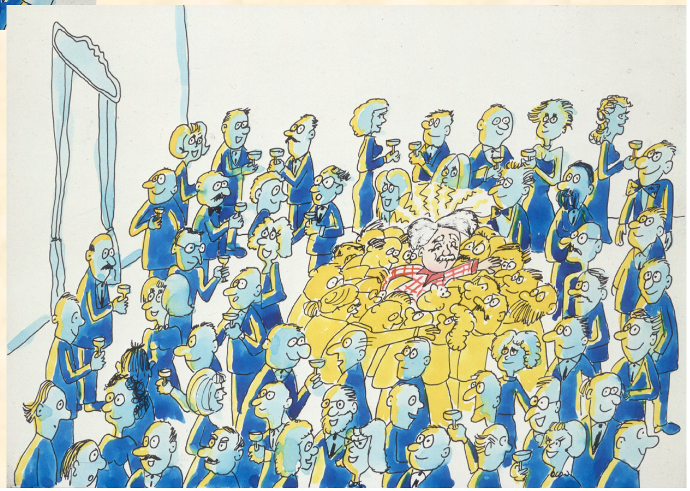


These couplings are proportional to the masses

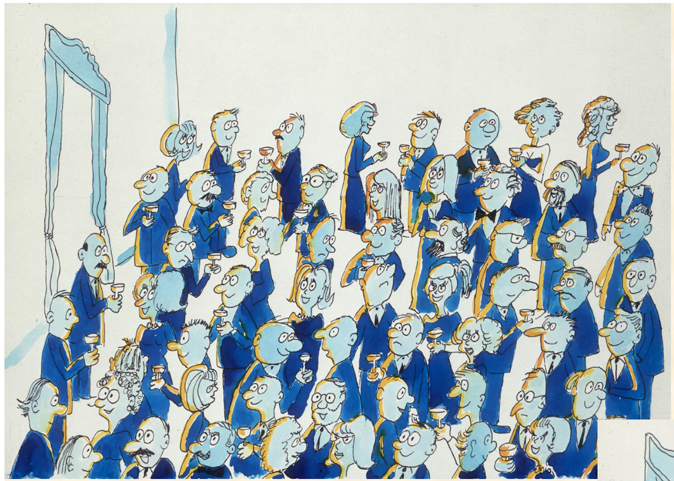
Higgs field in pictures



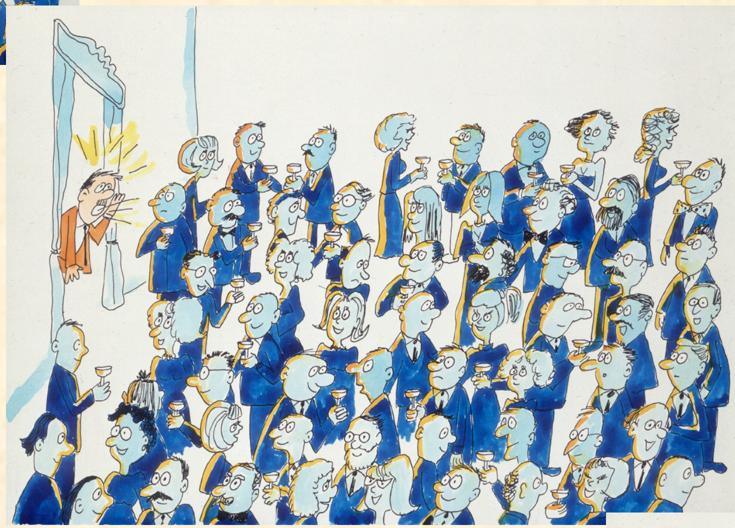
Adapted from D. Miller, © CERN



- During a party people are uniformly spread in a room.
- The arrival of a famous person will create a cluster around him/her.
- This will his/her progression in the room.
- The more famous, the slower he will become.



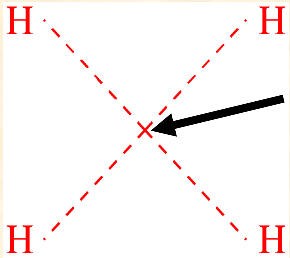
Higgs Boson



Adapted from D. Miller,

- A rumour will spread in the room in a similar fashion but without physical support.
- It is like the Higgs boson created by the field coupling to itself.

"Theoretical basics": are there bounds on m_H?



$\lambda = m_H^2/v^2$

As for any other coupling constant, the particle content of the Standard Model determines the running of λ up to a scale Λ, at which the model is no longer valid.

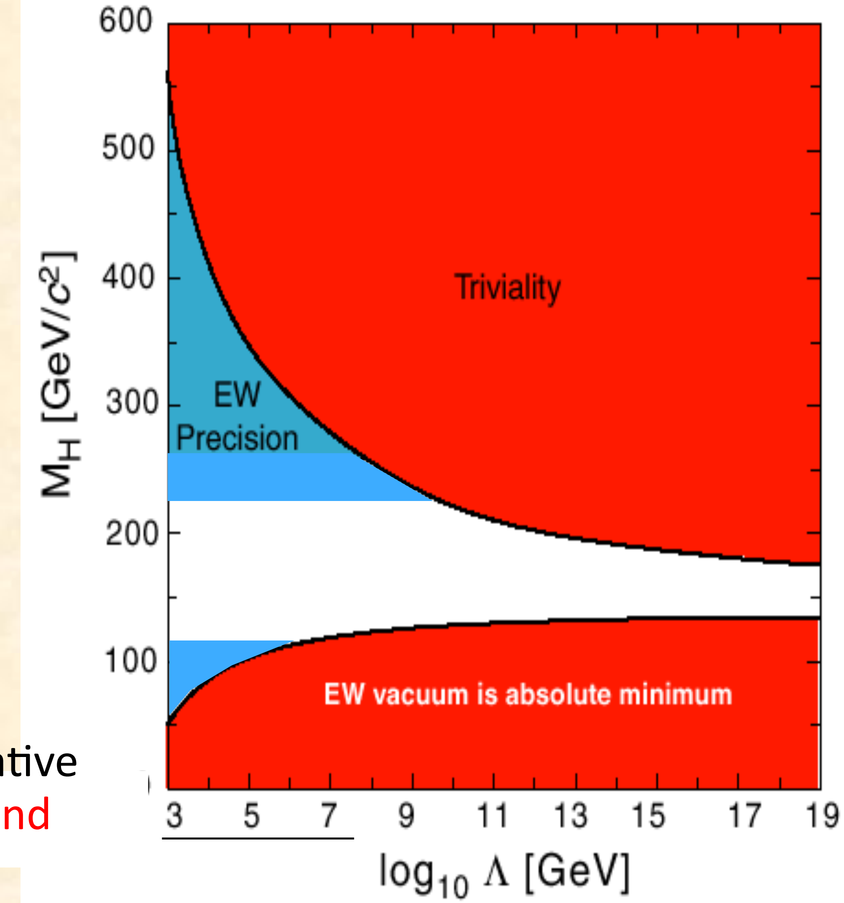
$$0 \leq \lambda(\Lambda) \leq \infty$$

$\lambda > 0$: $V(\phi)$ with a minimum up to the scale Λ

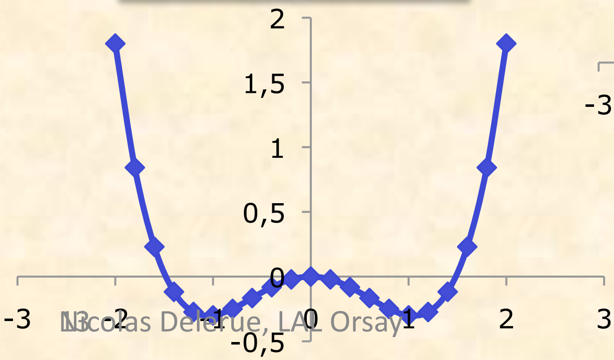
Vacuum stability

λ small : SM perturbative up to Λ

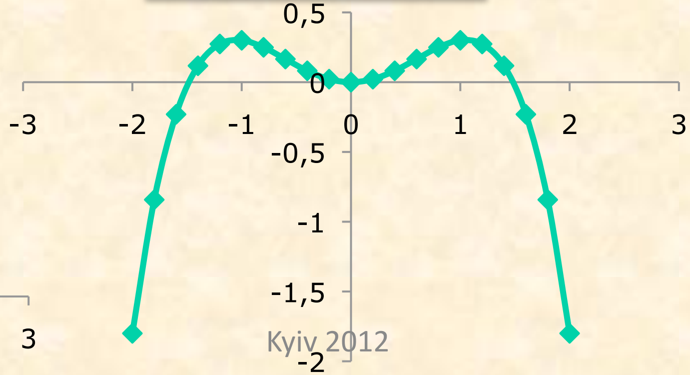
Triviality bound



If $\lambda>0$ and $\mu^2< 0$



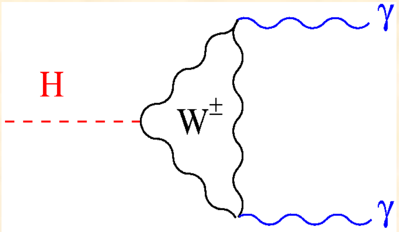
If $\lambda<0$ and $\mu^2>0$



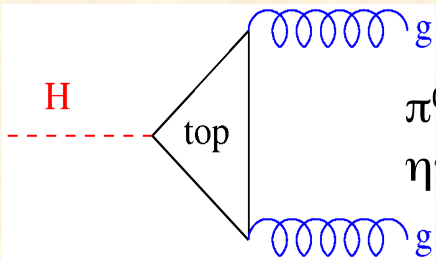
Higgs boson decay

The decay branching ratios depend only on m_H:

- $m_H < 2m_e$: $H \rightarrow \gamma\gamma$ + large lifetime;



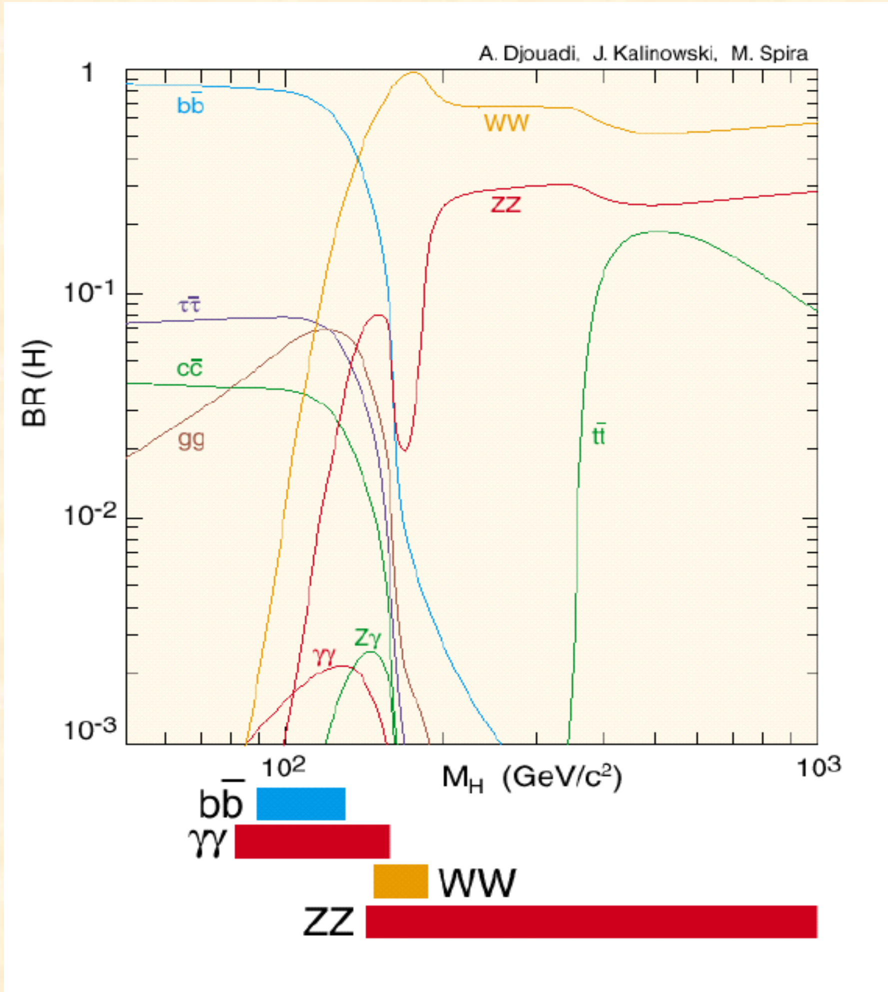
- $m_H < 2m_\mu$: $H \rightarrow e^+e^-$ dominates;
- $m_H < 2m_\pi$: $H \rightarrow \mu^+\mu^-$ dominates;
- $m_H <$ 3 - 4 GeV: $H \rightarrow gg$ dominates;



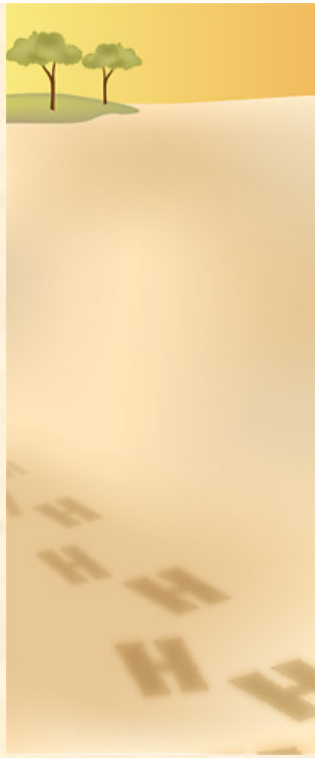
$\pi^0\pi^0$, $\pi^+\pi^-$, KK, $\eta\eta$, … etc

- $m_H < 2m_b$: $H \rightarrow \tau^+\tau^-$ and $c\bar{c}$ dominate;

- $m_H > 2m_b$ up to ~100 GeV/c^2:



SEARCH FOR THE HIGGS BOSON



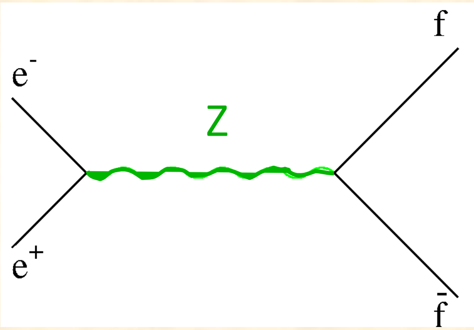
Higgs searches at LEP/SLD : indirect informations

• Precision measurements at LEP/SLD ⇒ evidence for virtual particles contributions

Radiative corrections : take into account higher order diagrams in power of α

⇒ Good agreement with the SM predictions at higher orders

These higher order corrections are sensitive to the top mass (and to a smaller extend to the Higgs mass) ⇒ indirect constraints on m_{top} and m_{Higgs}



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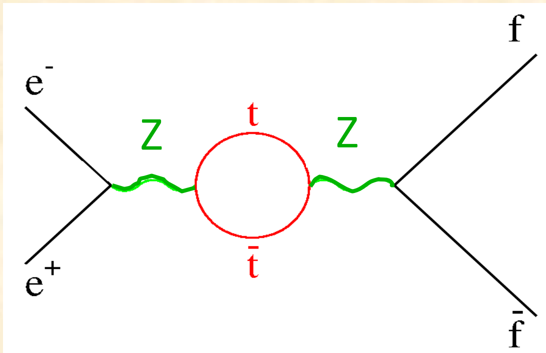

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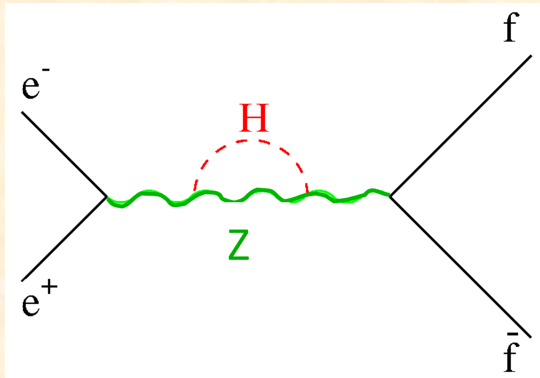
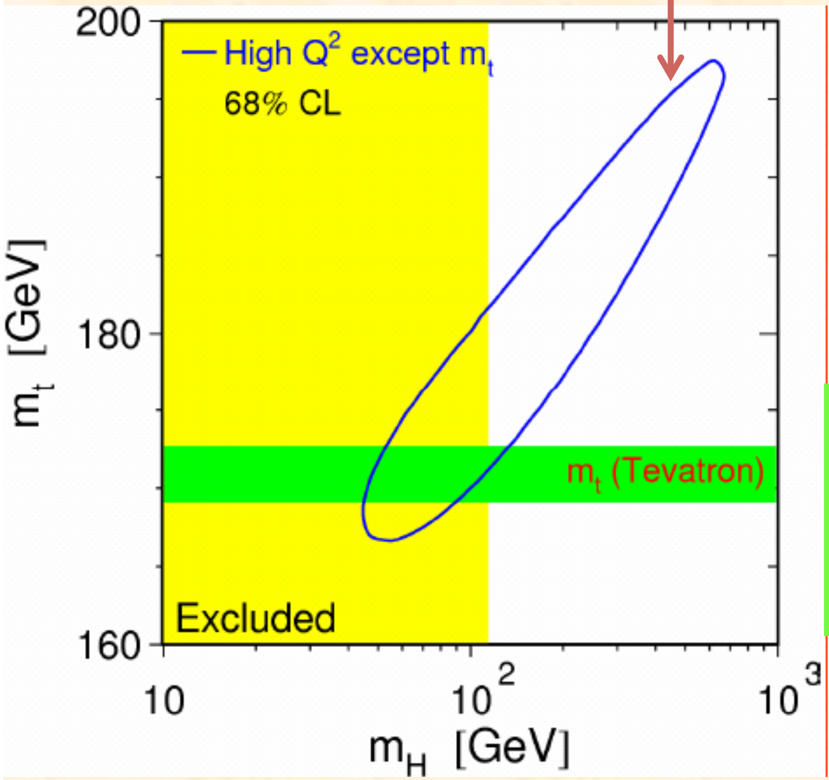


$$\frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} \approx 1\%$$

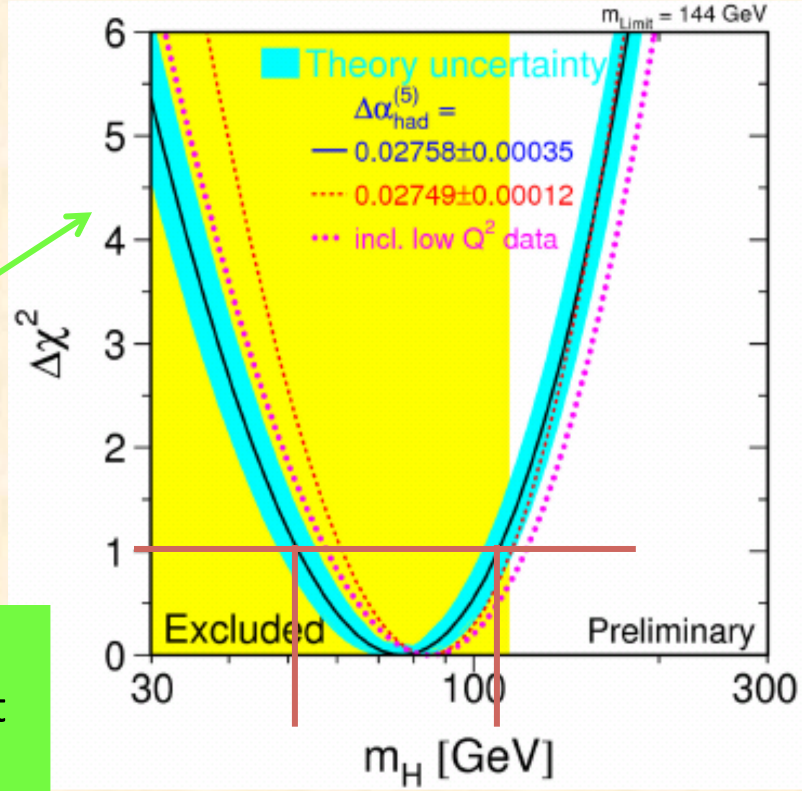
$$-\frac{\alpha}{4\pi}\mathrm{Log}\frac{m_H^2}{m_Z^2}$$

0.1% precision needed… and achieved!!

Combining many electroweak measurements and having as free parameters m_t and m_H



Adding the measurement of m_t by CDF and D0



⇒ Indirect prediction of m_H:

$$m_H = 76^{+33}_{-24}\ \text{GeV}$$

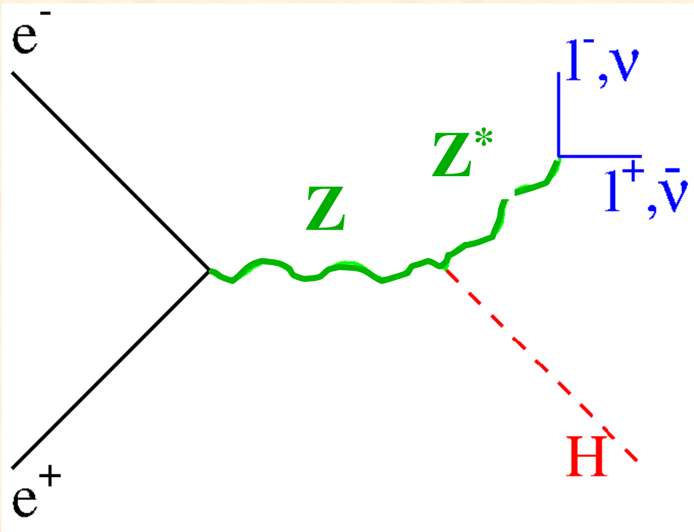
Direct search for the Higgs boson at LEP

Dominant production process at LEP: "Higgs-strahlung"

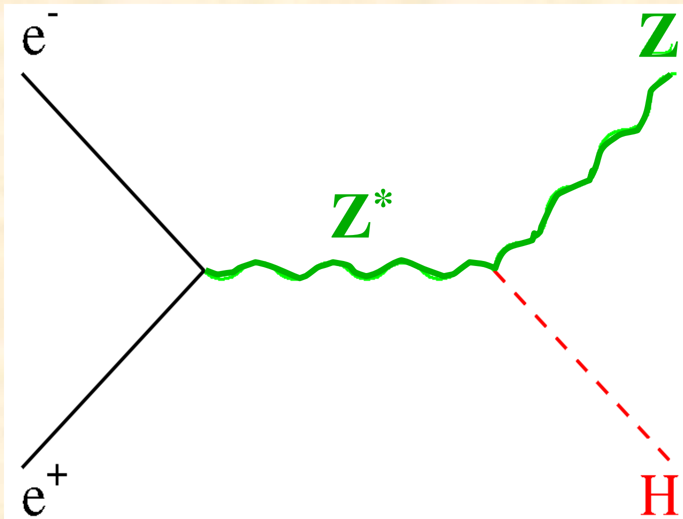
The production cross section depends only on m_H

Large coupling to the Z ⇒ all other processes negligible

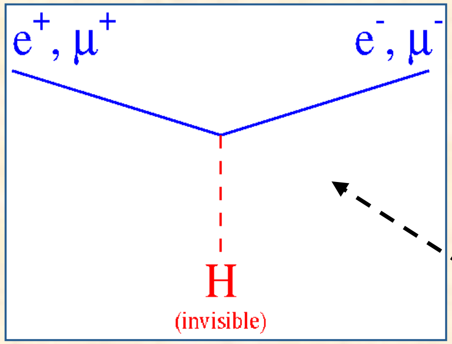
LEP 1: $\sqrt{s} \sim m_Z$



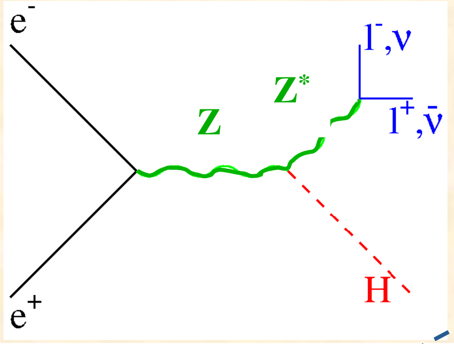
LEP 2: $\sqrt{s} \geq m_Z + m_H$

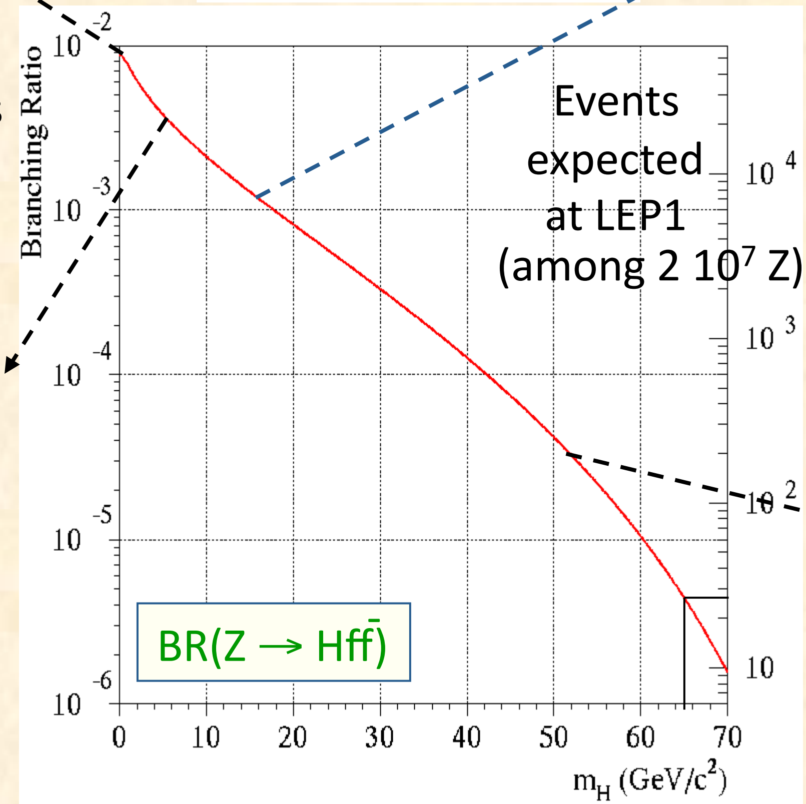


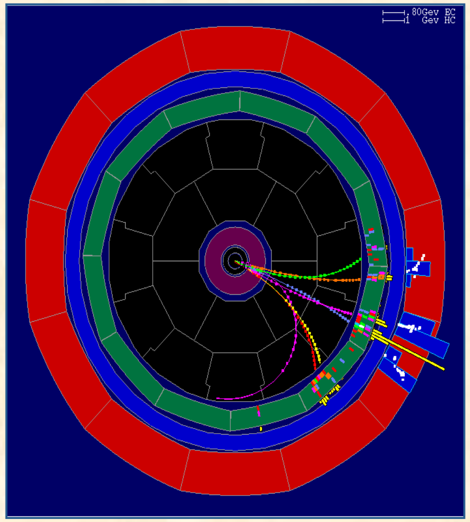
Higgs searches at LEP1



Acoplanar lepton pairs

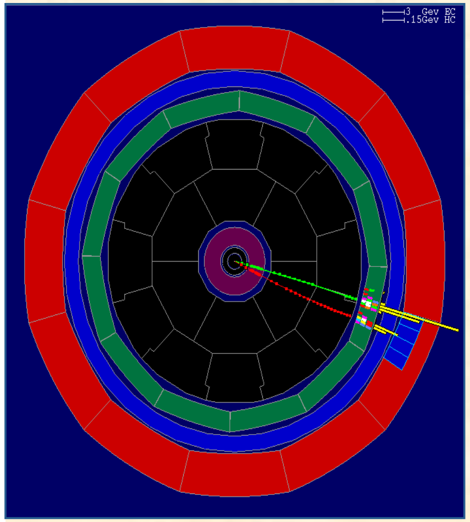




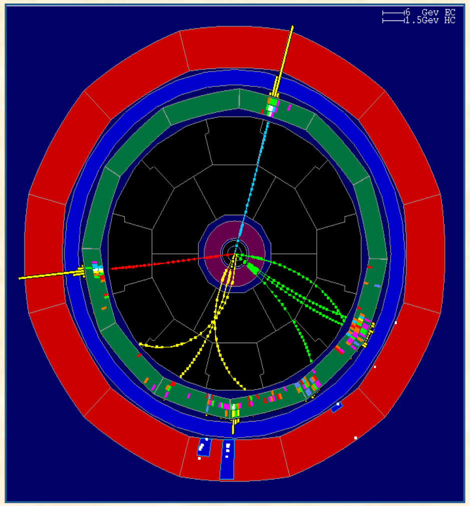


Monojets

Acoplanar pairs

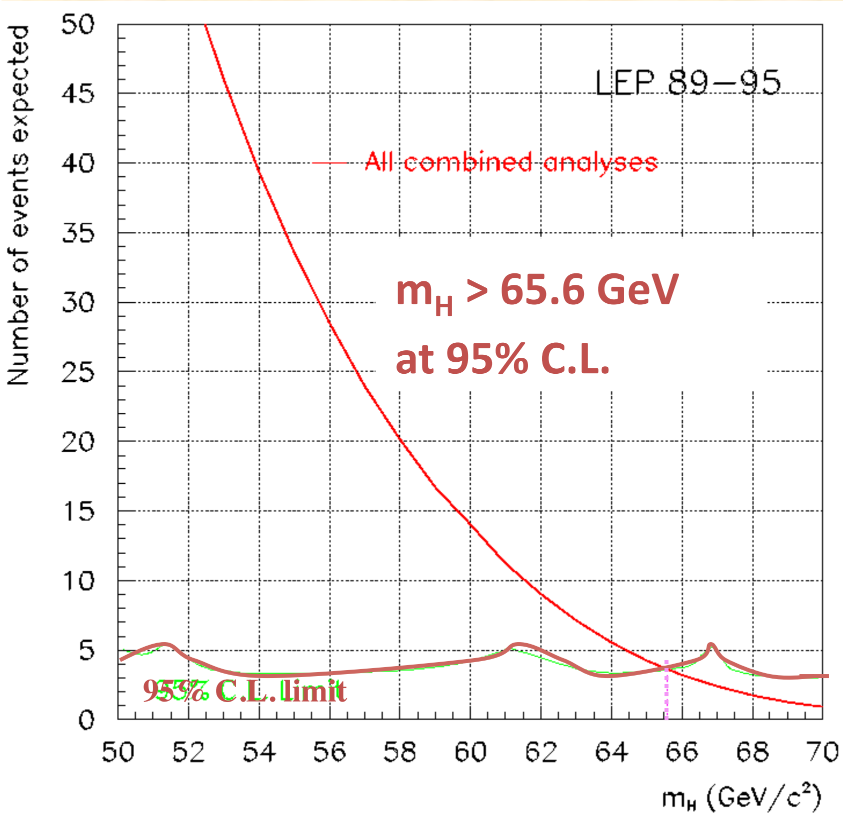


Acoplanar jets

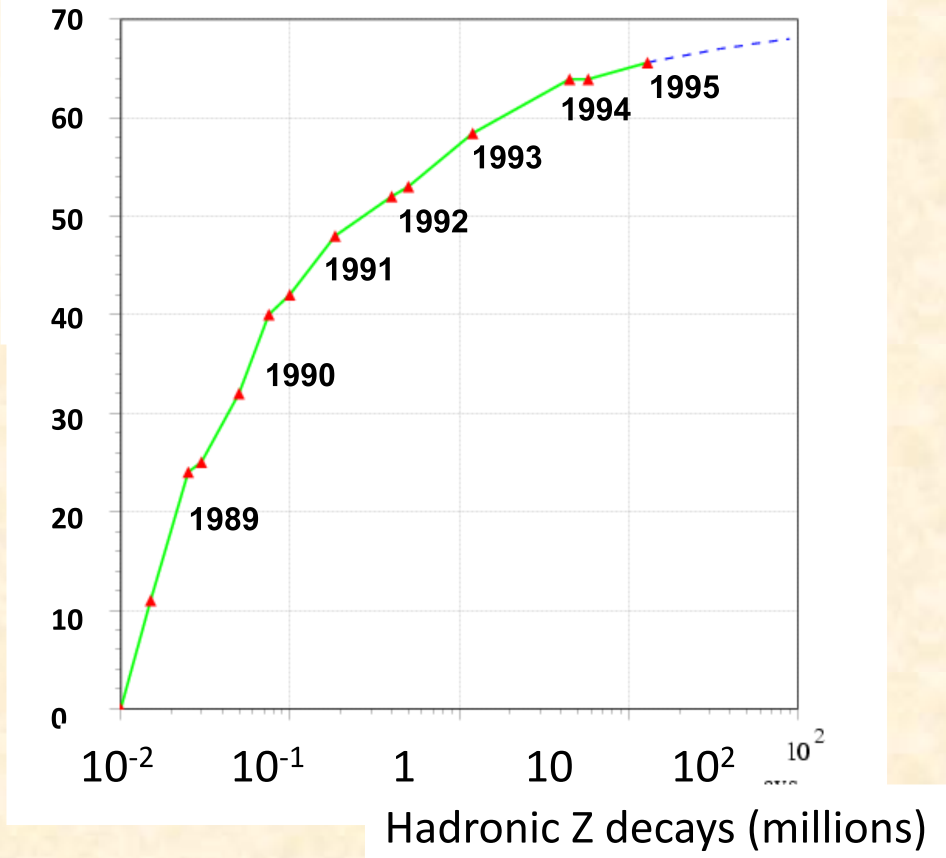


Very little background expected

Combination of the 4 LEP experiments :
4.0 signal events expected (for m_H~65 GeV)
none were observed ⇒ lower limit is set



Saturation was being reached
for lower limit on m_H



⇒ Limits

Setting limits

- If you play 5 times with one dice and do not get the number 6, does that mean that the dice has no number 6?
- Even if you play 10 times or 20 times you many not get a number 6 out.
- This will not allow you for sure to know if the dice has a side with a number 6 or not.
- The probability of not getting 6 in 20 throws is $(5/6)^{20}$ ~2%
- While searching new particles similar phenomena may happen: even if the particle exists, it may not appear immediately.
- If no event is found, one has to look at the probability for the particle to be present in the dataset.
- It becomes even more complicated when a background can mimic the expected signal: one must then compare the probability of what is observed with what would have been observed if the particle existed.

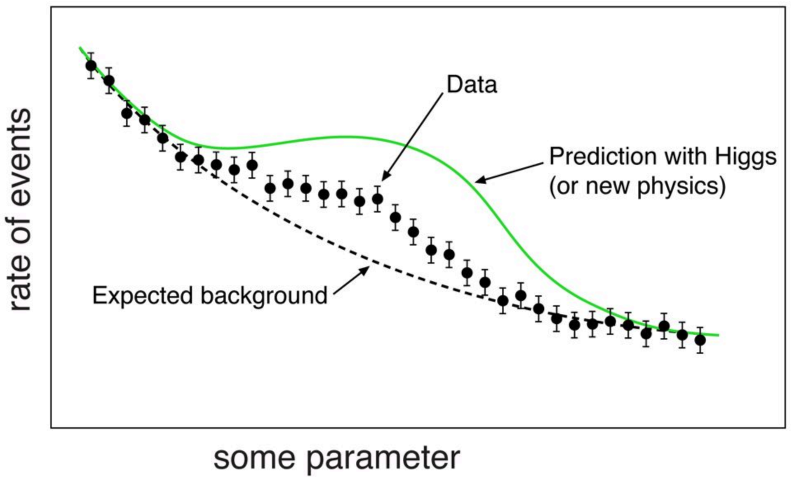


Figure B

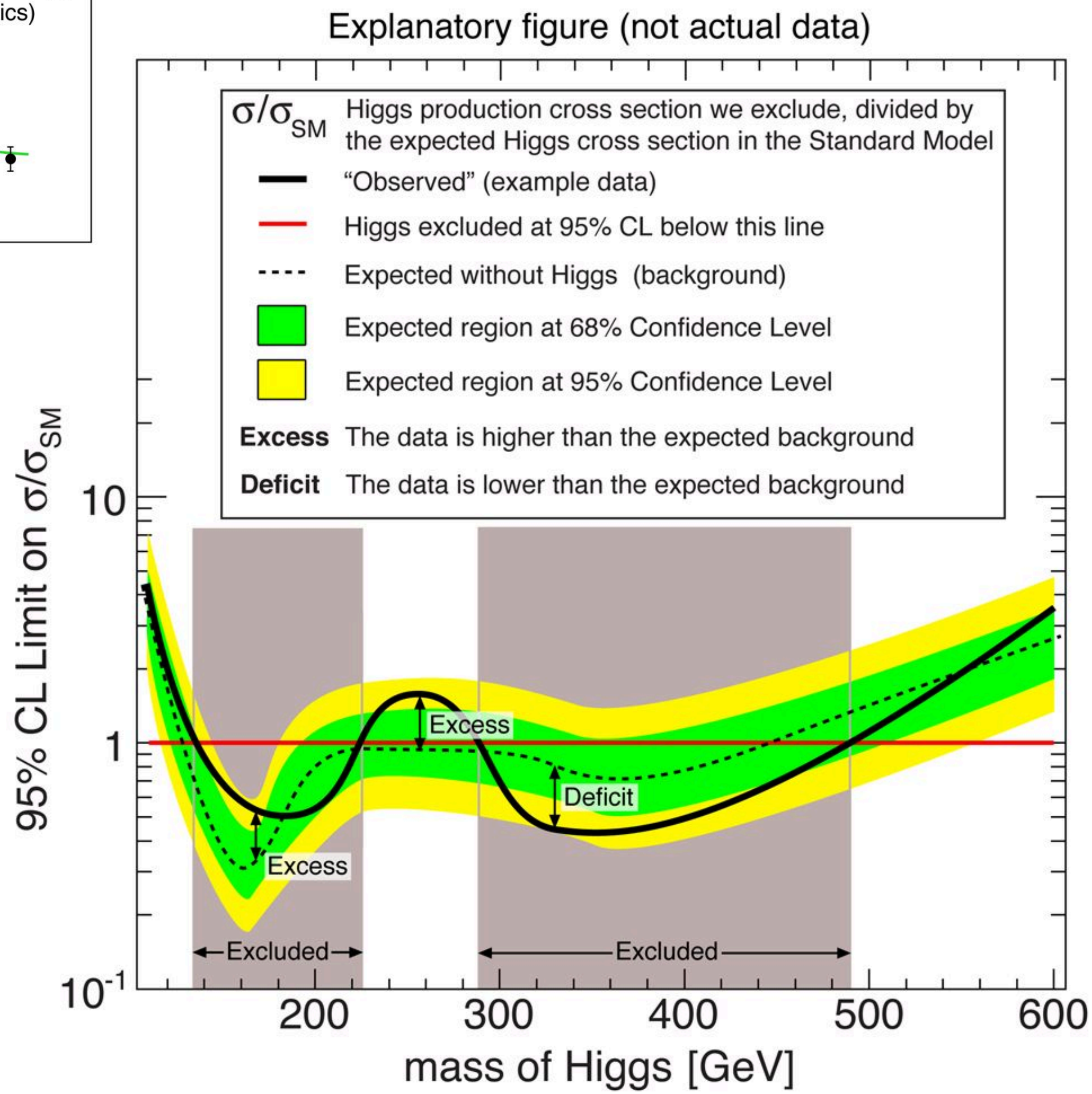
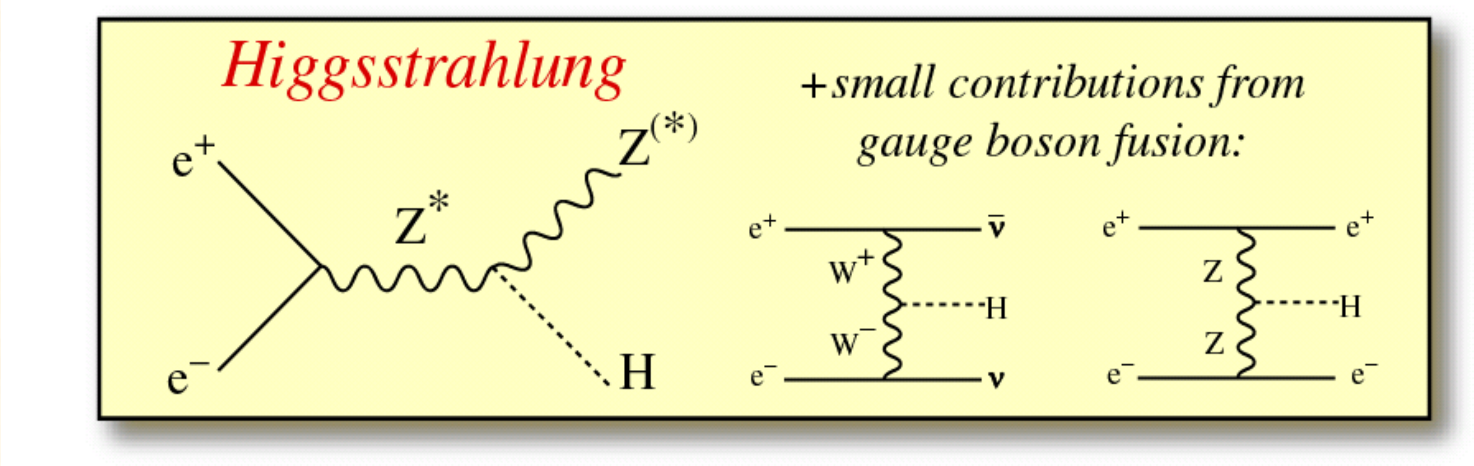
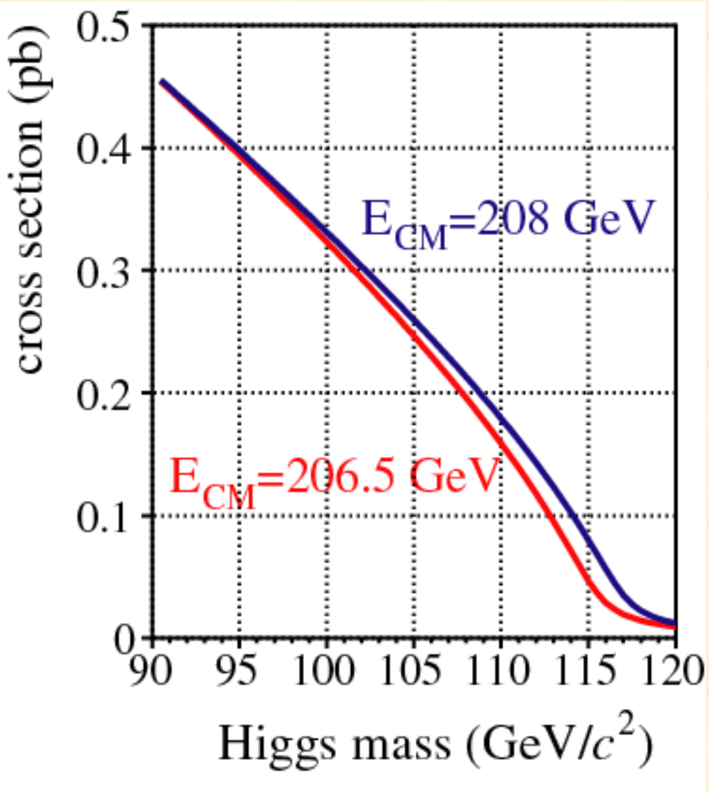
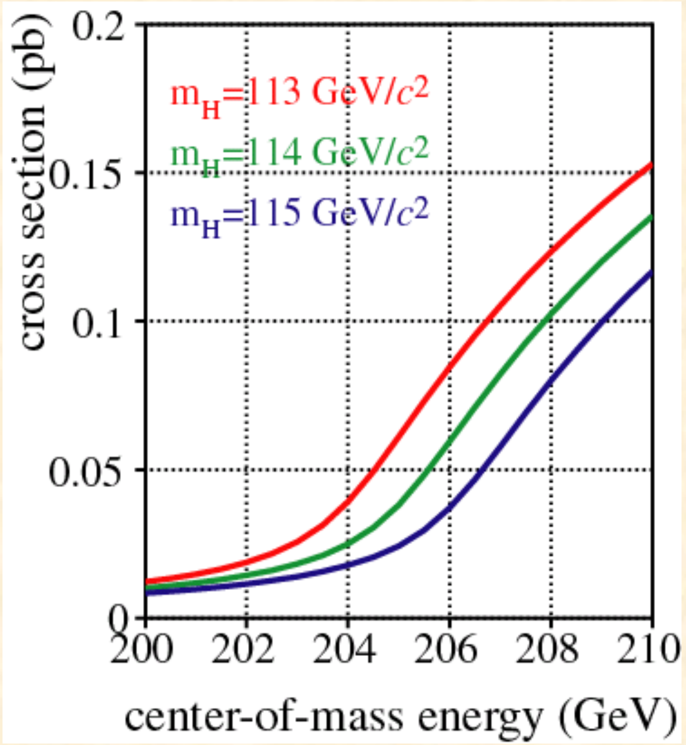


Figure A

Higgs searches at LEP2



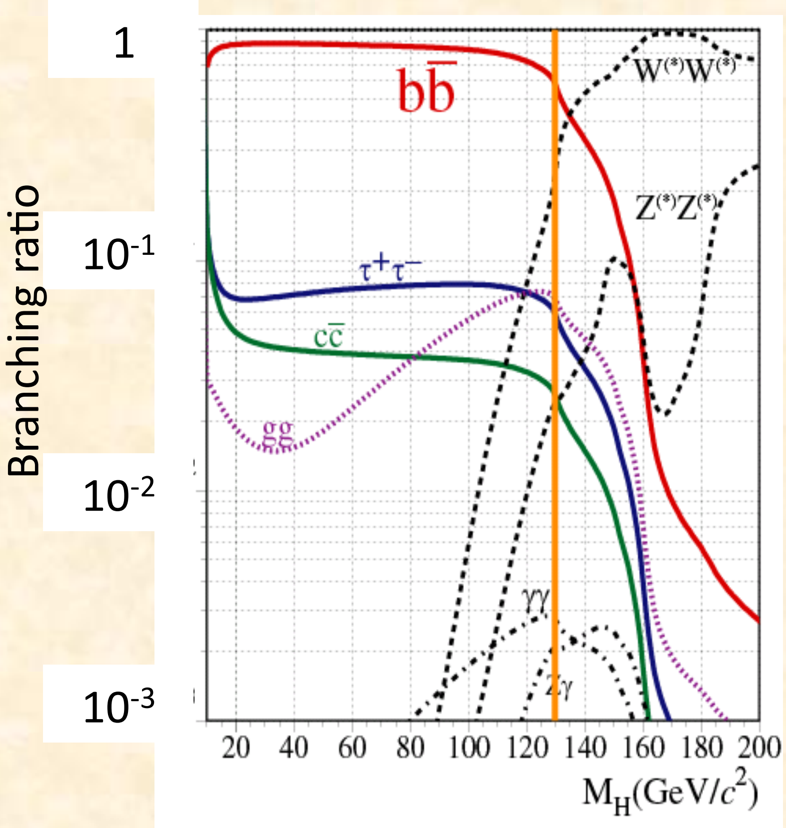


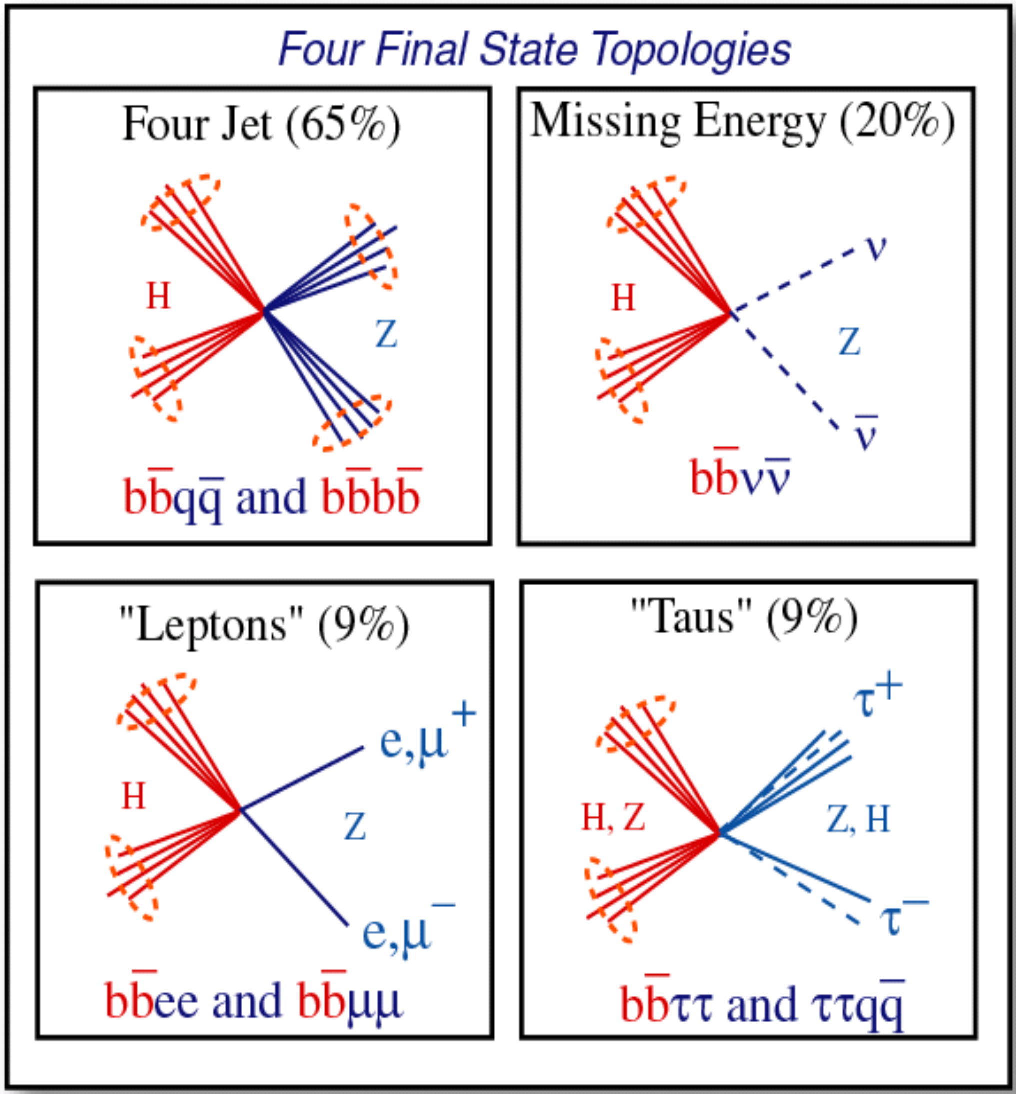


Extreme sensitivity to centre-of-mass energy and Higgs mass

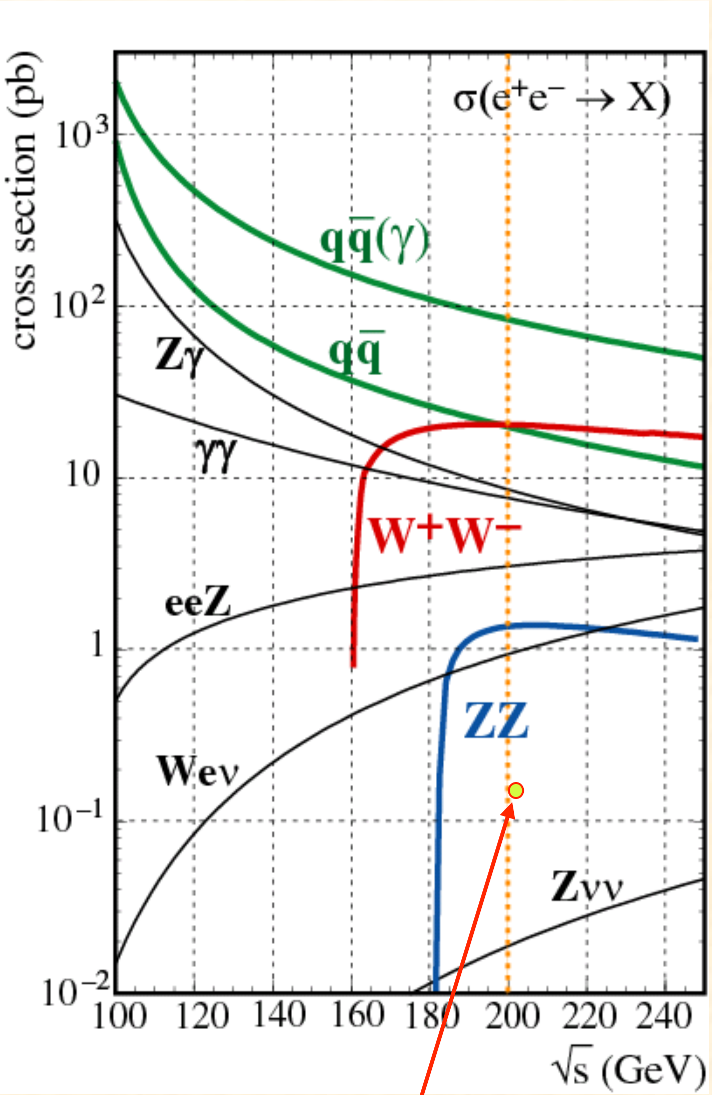
The Higgs couplings are proportional to the mass

⇒ It decays predominantly to bb pairs



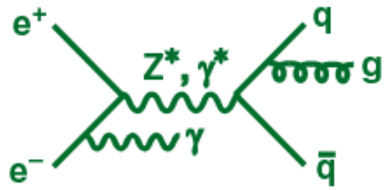


LEP2 Higgs search : background processes



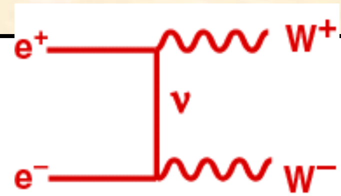
Higgs prod. cross section for m_H=110 GeV

Two fermions (includes rad. return to the Z)



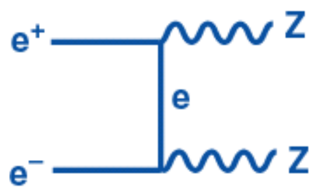
4-jet quality
jet-jet angles
b-tagging of jets

Four-Fermions



W-pair Production

b-tagging of jets

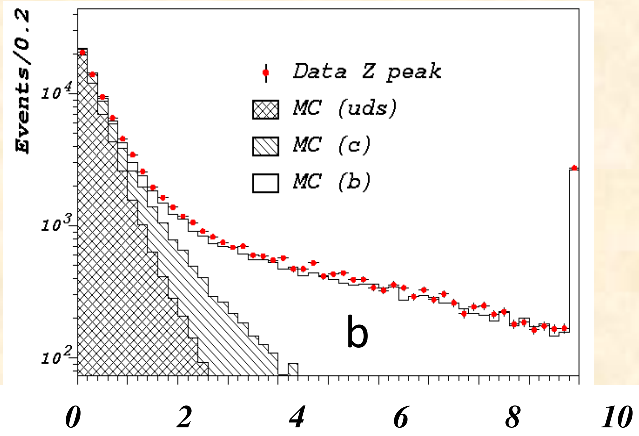


Z-pair Production

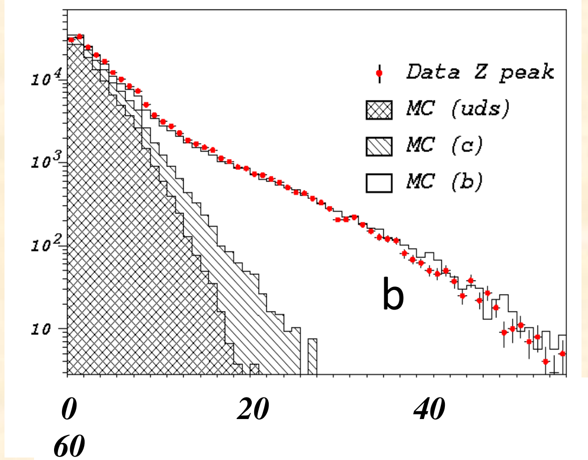
ZZ → qq qq: b-tagging

ZZ → bb qq: irreducible!

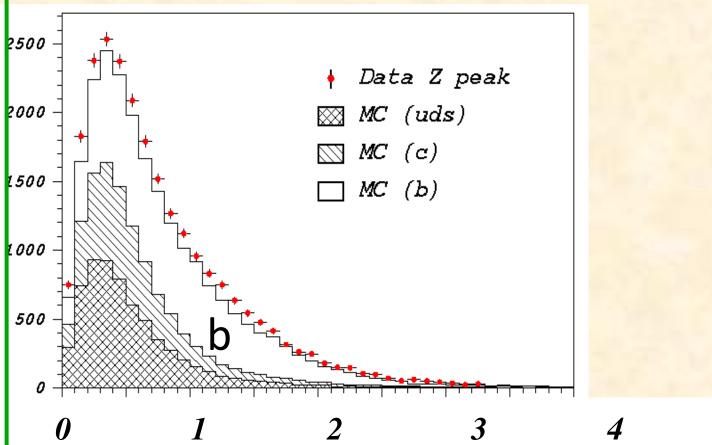
b-tagging : example of ALEPH



Impact parameter with respect to primary vertex ($-\log_{10}(P_{evt})$)



χ^2 decrease with a secondary vertex



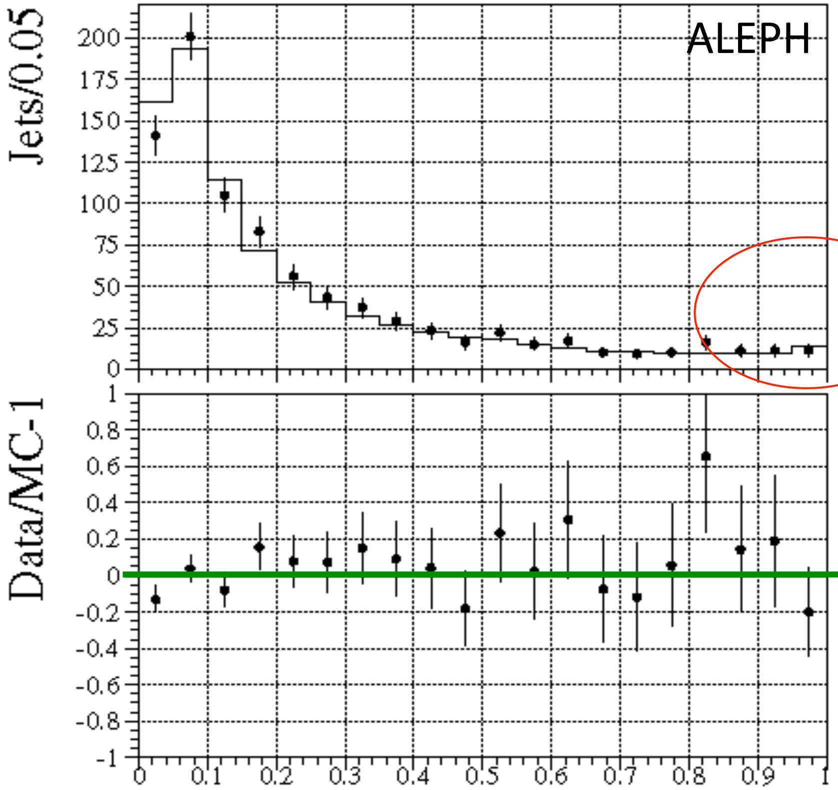
Lepton transverse momentum with respect to b-jet axis (GeV)

Combine with neural networks likelihoods, …

Other jet-shape variables (multiplicity, mass, sphericity)

This b-tagging is crucial ⇒ check on data :

Result on jets from hadronic W decays (from semi-leptonic $e^+e^- \rightarrow W^+W^-$ events)

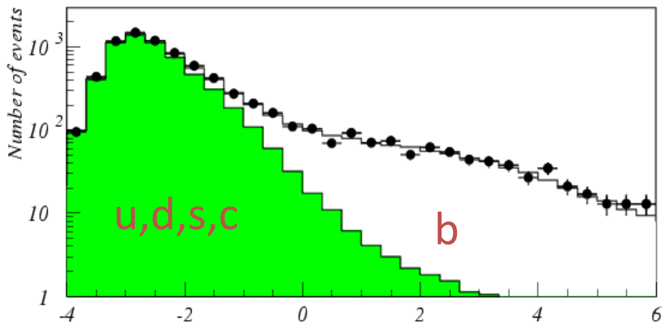


No b-jets in W decays

Simulation reproduces well the data (essential!)

Global b-tagging variable

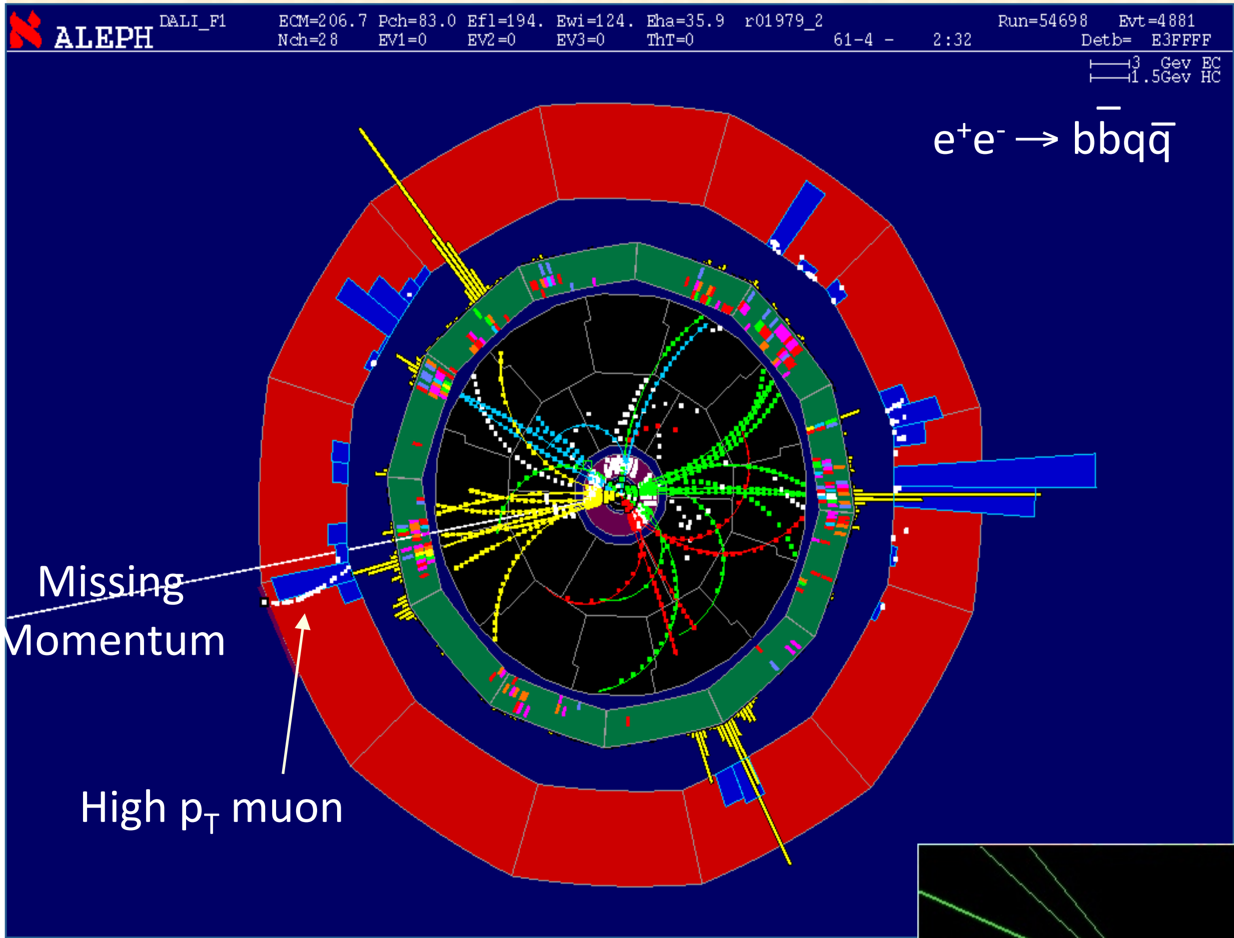
DELPHI : Z hadronic decays



Global b-tagging variable

b-jets and light-quark jets are well separated

Golden 4-jet event (ALEPH, 14/06/00, 206.7 GeV)

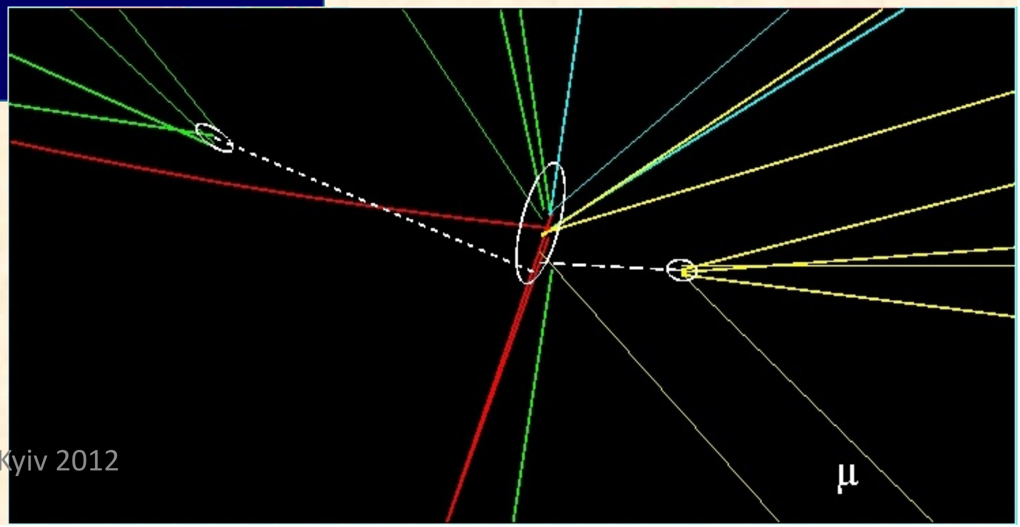


- Mass 114 ± 3 GeV
- Good HZ fit
- Poor WW and ZZ fits
- P(Background) ≈ 2%
- s/b(115) = 4.6

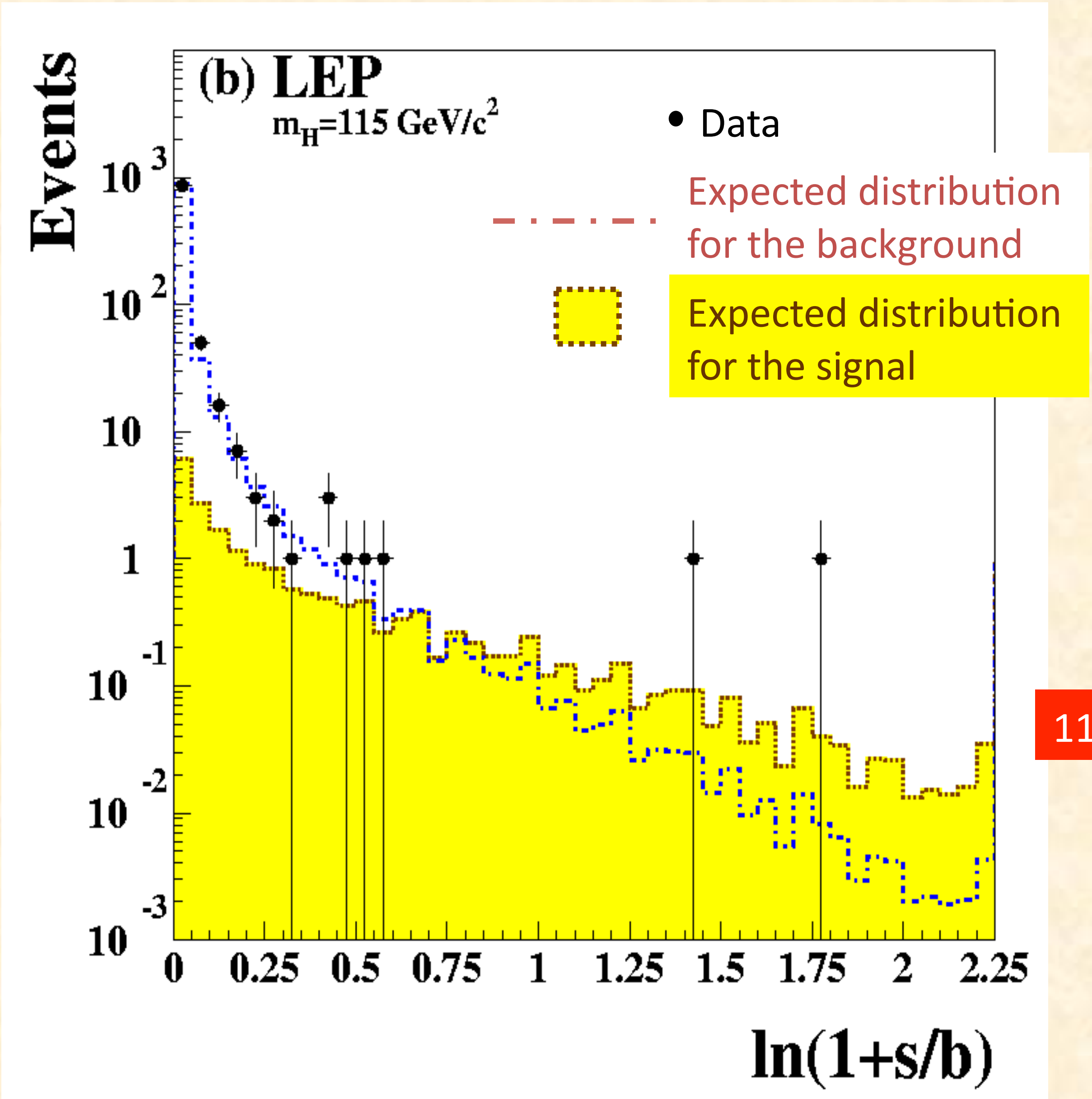
<u>b-tagging</u>

(0 = light quarks, 1 = b quarks)

- Higgs jets: 0.99 and 0.99;
- Z jets: 0.14 and 0.01.

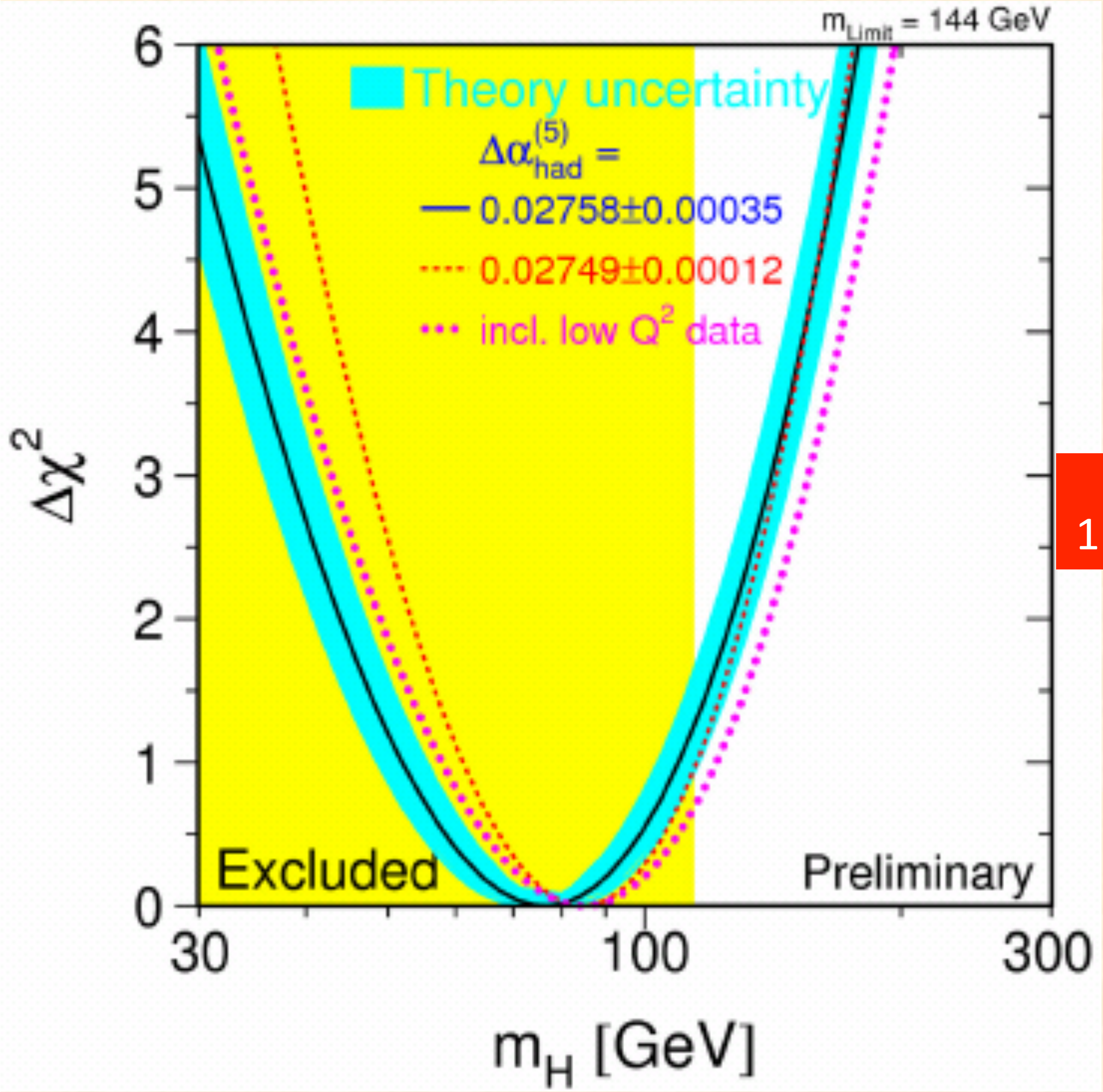


But combining all experiments :



114.4 GeV < M_{Higgs} at 95 %CL

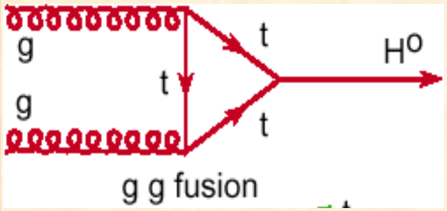
LEP result on the Higgs mass prediction combining direct and indirect searches :



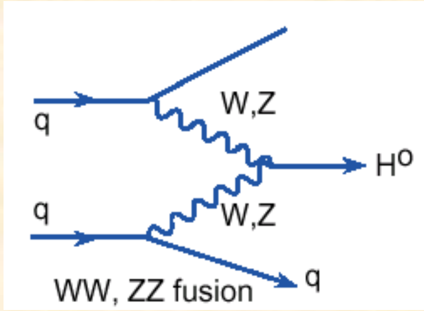
114.4 GeV < M_{Higgs} < 182 GeV at 95%CL

Higgs production at hadronic colliders

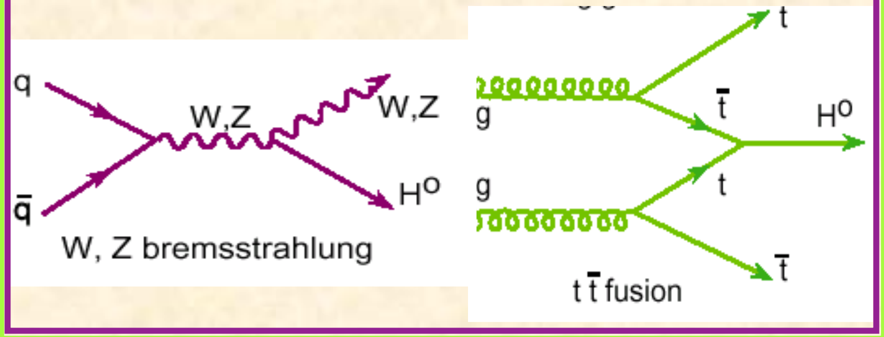
(i) Gluon fusion



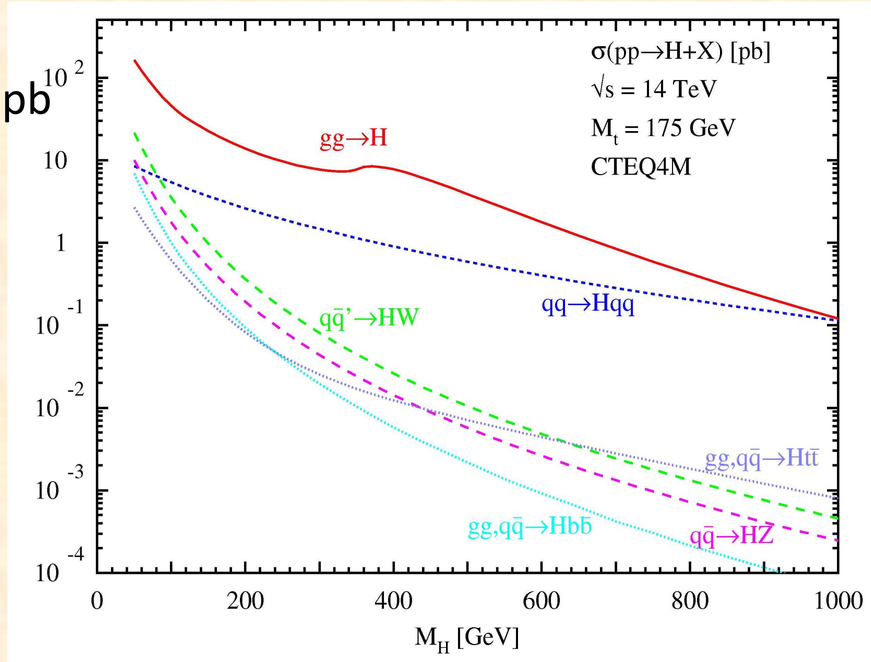
(ii) Vector boson fusion



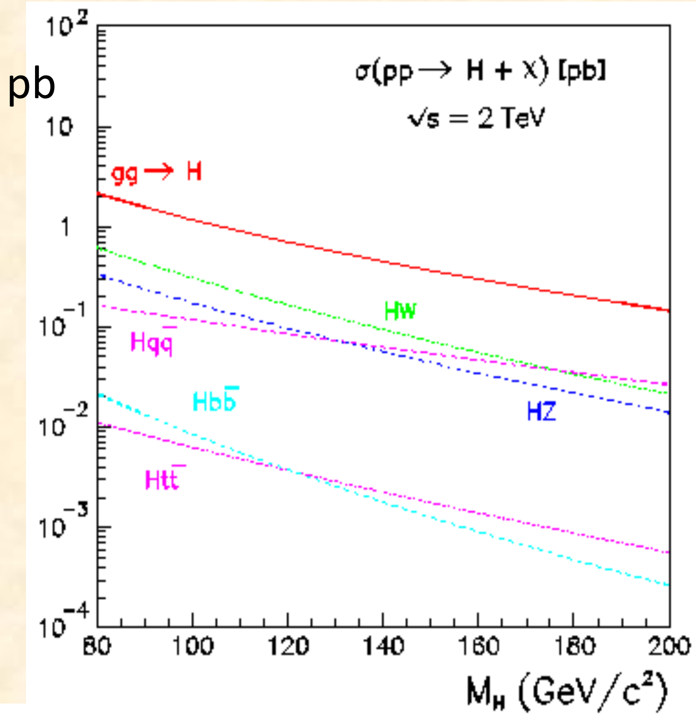
(iii) Associated production (W/Z, tt)



LHC



Tevatron



qq → W/Z + H   cross sections   ~10 x larger at the LHC
gg → H   ~70-80 x larger at the LHC

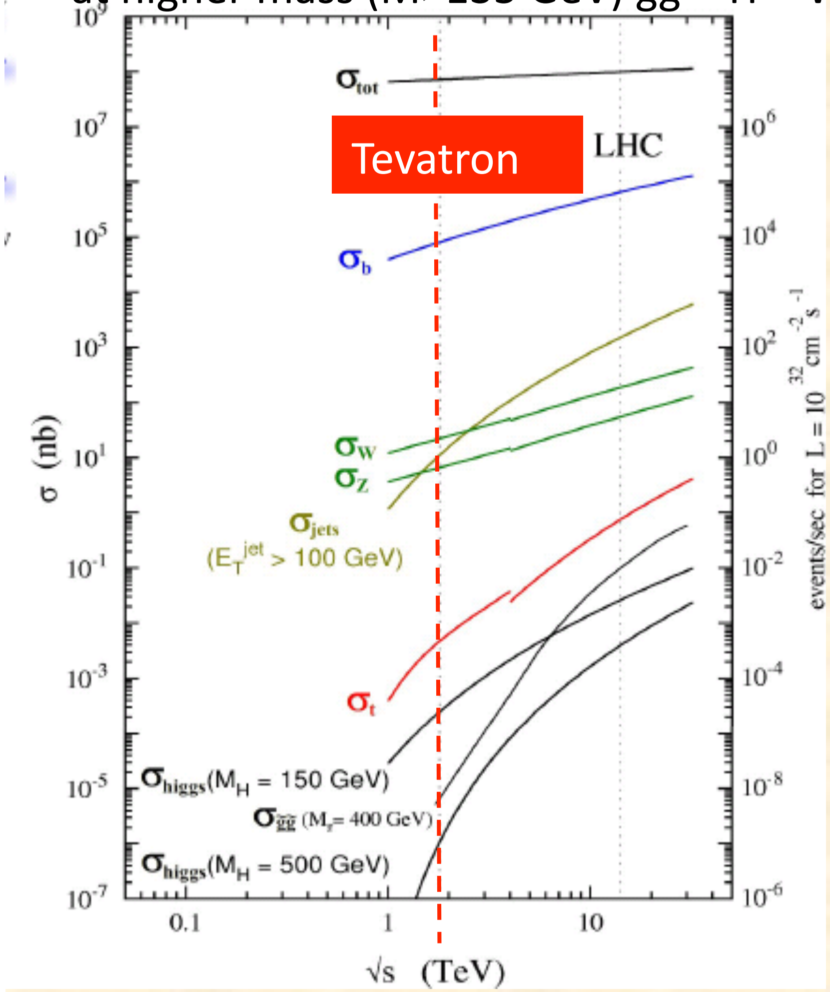
Backgrounds >> signal

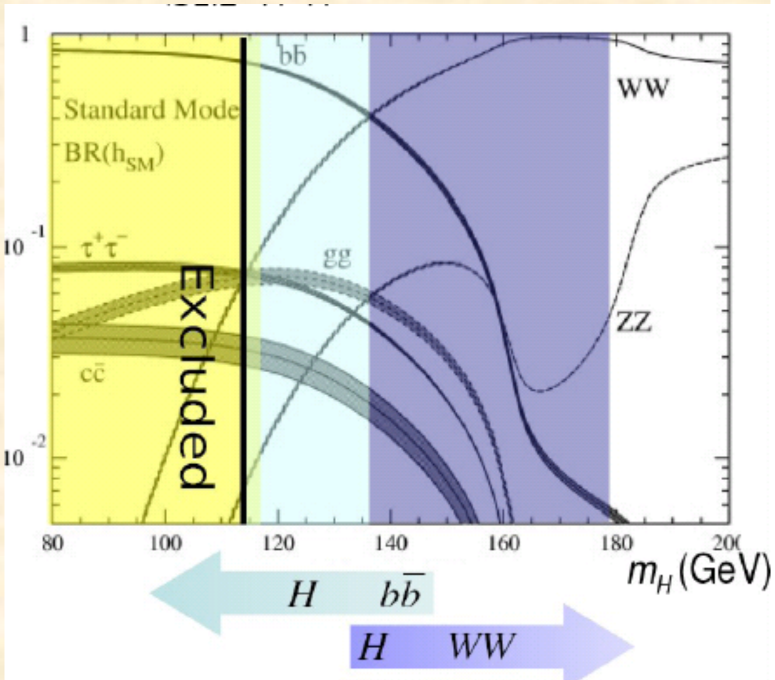
Higgs searches at the Tevatron

The background dictate the search strategy :

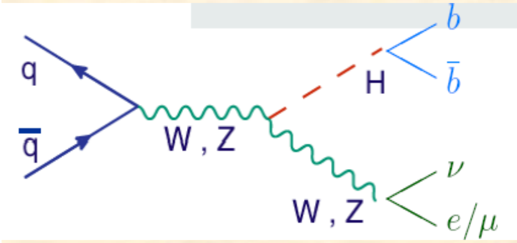
• at low mass the background in the channel gg→H→bb is too large ⇒ use the associated production (WH, ttH). The main backgrounds : W/Z + jets, top, WW, WZ

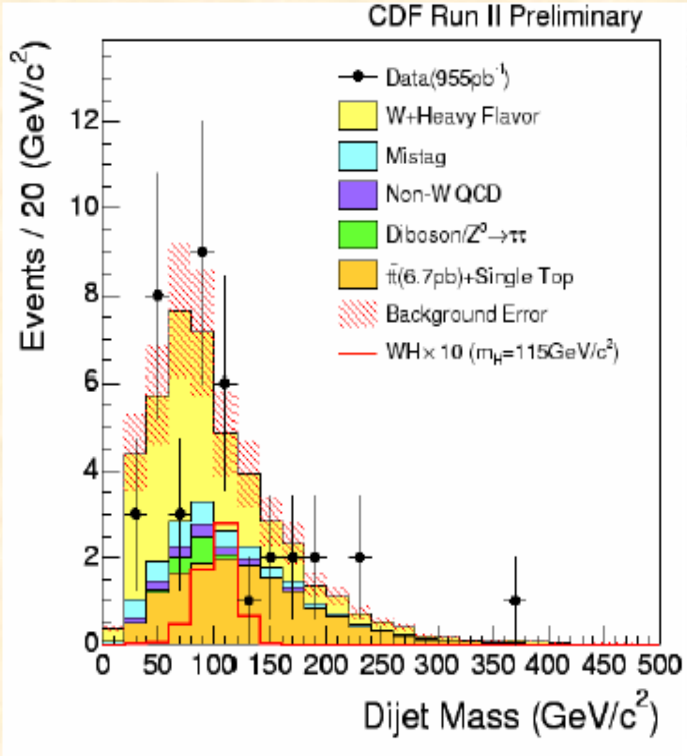
• at higher mass (M>135 GeV) gg→H→WW. Main background : SM WW

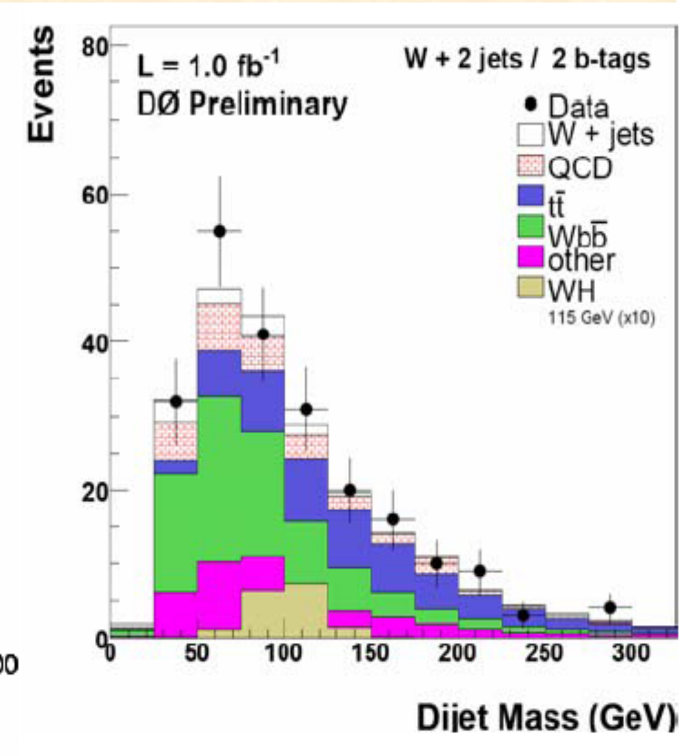




Example of the low mass range searches : WH → e/μ ν bb







Run II data: ~ 1 fb^{-1}

Event selection:

- 1 e or μ with large P_T
- P_T^{miss} > 20 GeV/c
- 2 jets, b-tagged

Backgrounds:

- Wbb, Wcc, Wjj
- WW, WZ, ZZ, Z→ ττ
- tt, t
- Jet production (from QCD processes)

Data are consistent with backgrounds from Standard Model processes:

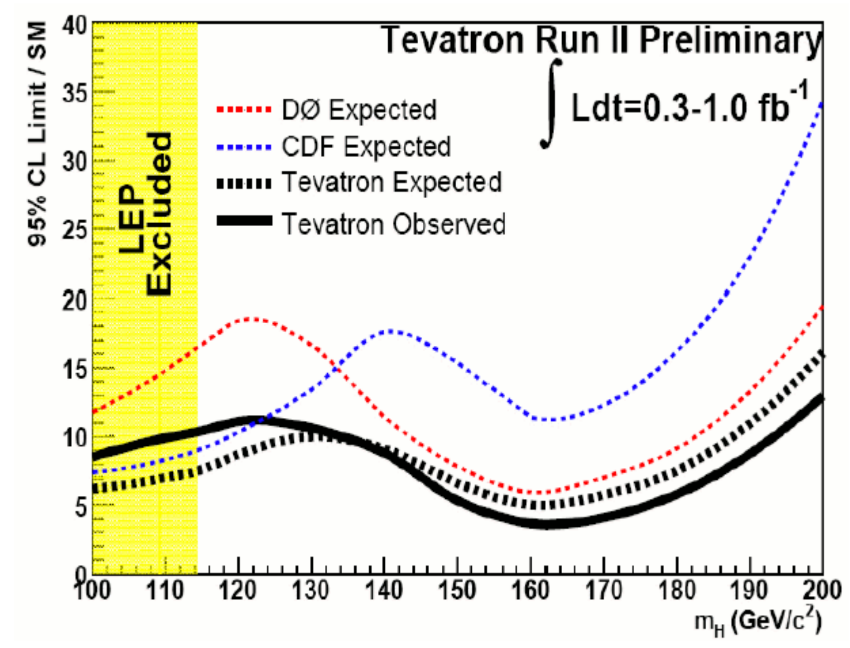
Limits on the Higgs boson production cross section:

CDF: σ(H) < 3.4 pb (95 % CL)
DØ: σ(H) < 1.3 pb (95 % CL)

Standard Model value: σ(H) ~ 0.13 pb

D0 and CDF combination :

95% CL Limit / SM value



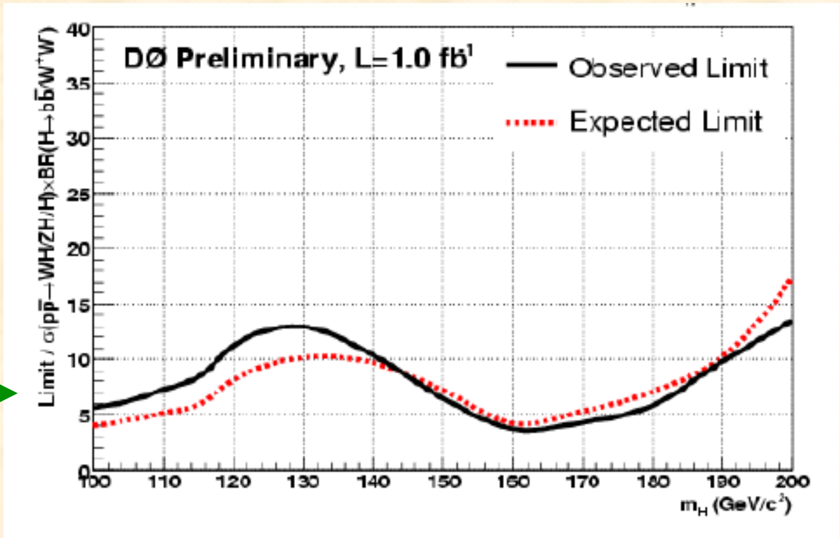
WH → ℓ ν bb
ZH → ℓ ℓ bb
ZH → νν bb

H → WW → ℓν ℓν
WH → WWW → ℓν ℓν + …

- The expected combined limits are still a factor of 7.5 (m_H=115 GeV/c²) and 4 (m_H=160 GeV/c²) away from the Standard Model expectation

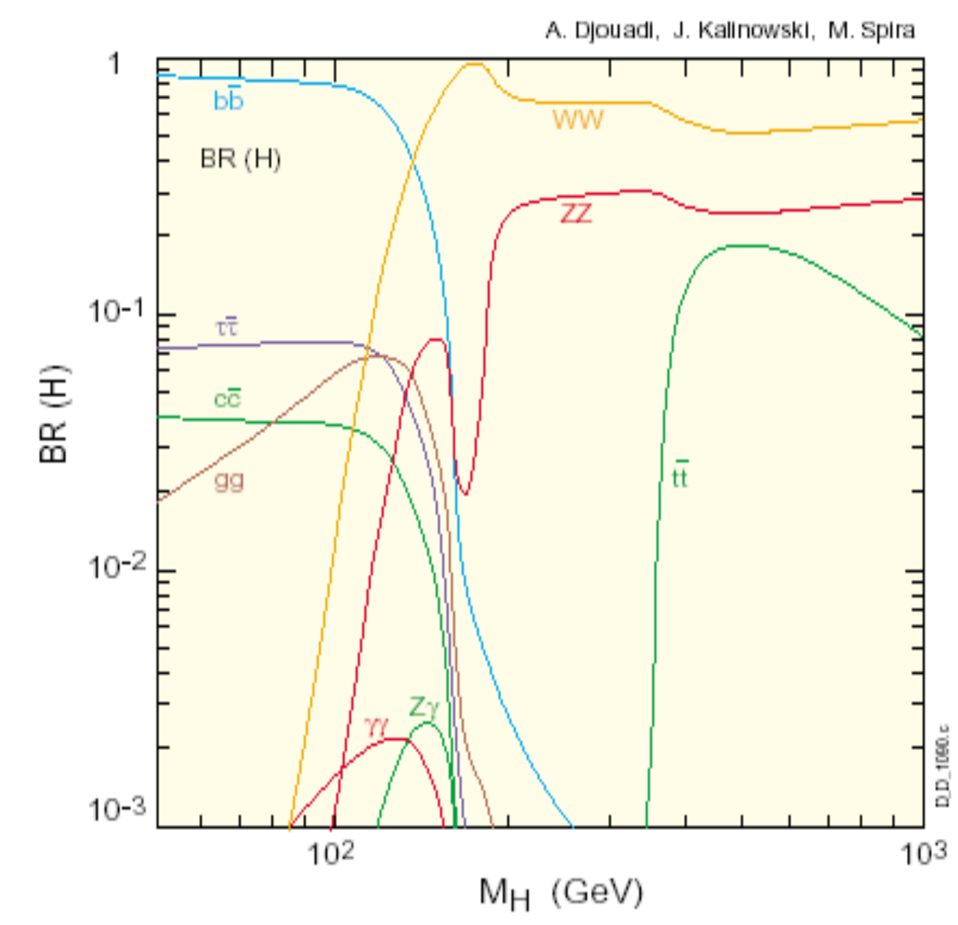
- However, not all results included yet (CDF 1fb^{-1} results at high mass and DØ 1fb^{-1} result at low mass are missing)

- Many improvements have been made during the past year



Higgs searches at the LHC

Once again the search modes choice is dictated by the interplay between production cross sections in various channels, BR values and backgrounds…



at low mass:

Lepton and Photon final states

M<120 GeV WH→ ℓν bb or tt H → ℓXν bb

M<150 GeV H →γγ

~130 <M<2 M_Z H→WW* → ℓν ℓν

~130 <M<2 M_Z H→ZZ* → ℓ ℓ ℓ ℓ

+ Tau final states

The dominant bb decay mode is only useable in the associated production mode (ttH) (due to the huge QCD jet background)

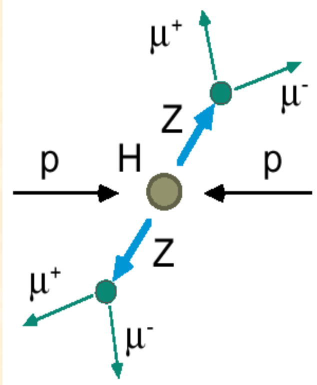
at high mass:

H→ZZ → ℓ ℓ ℓ ℓ

H→WW → ℓ ν jet jet

…

Example of the high mass range searches : H → ZZ(*) → ℓ ℓ ℓ ℓ



Background: Top production

tt → Wb Wb → ℓν cℓν ℓν cℓν

~ 200 times larger than signal

Associated production Z bb

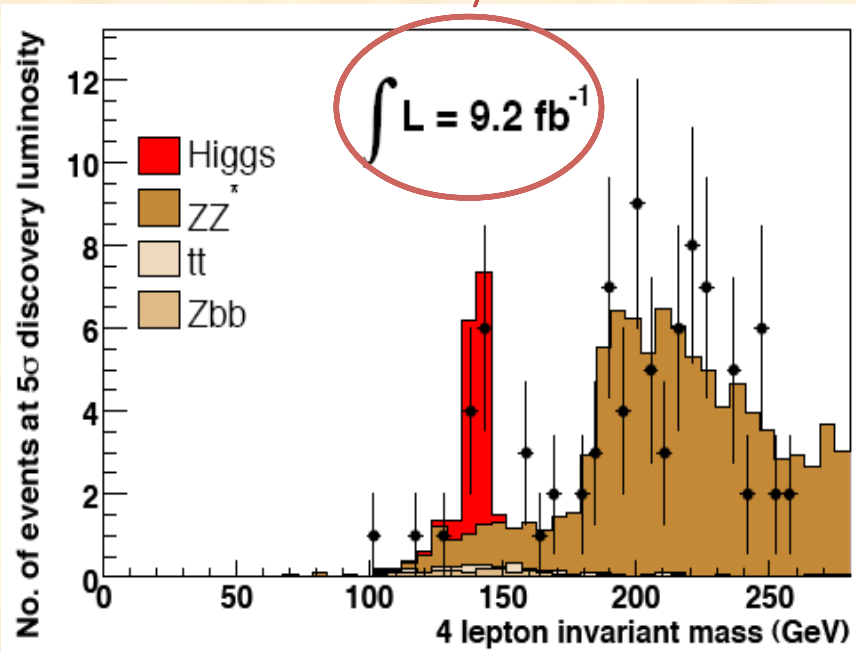
Z bb → ℓℓ cℓν cℓν

Background rejection: Leptons from b-quark decays

→ non isolated

→ do not originate from primary vertex (τ(B-meson) ~ 1.5 ps)

A nominal year : 30 fb^{-1}

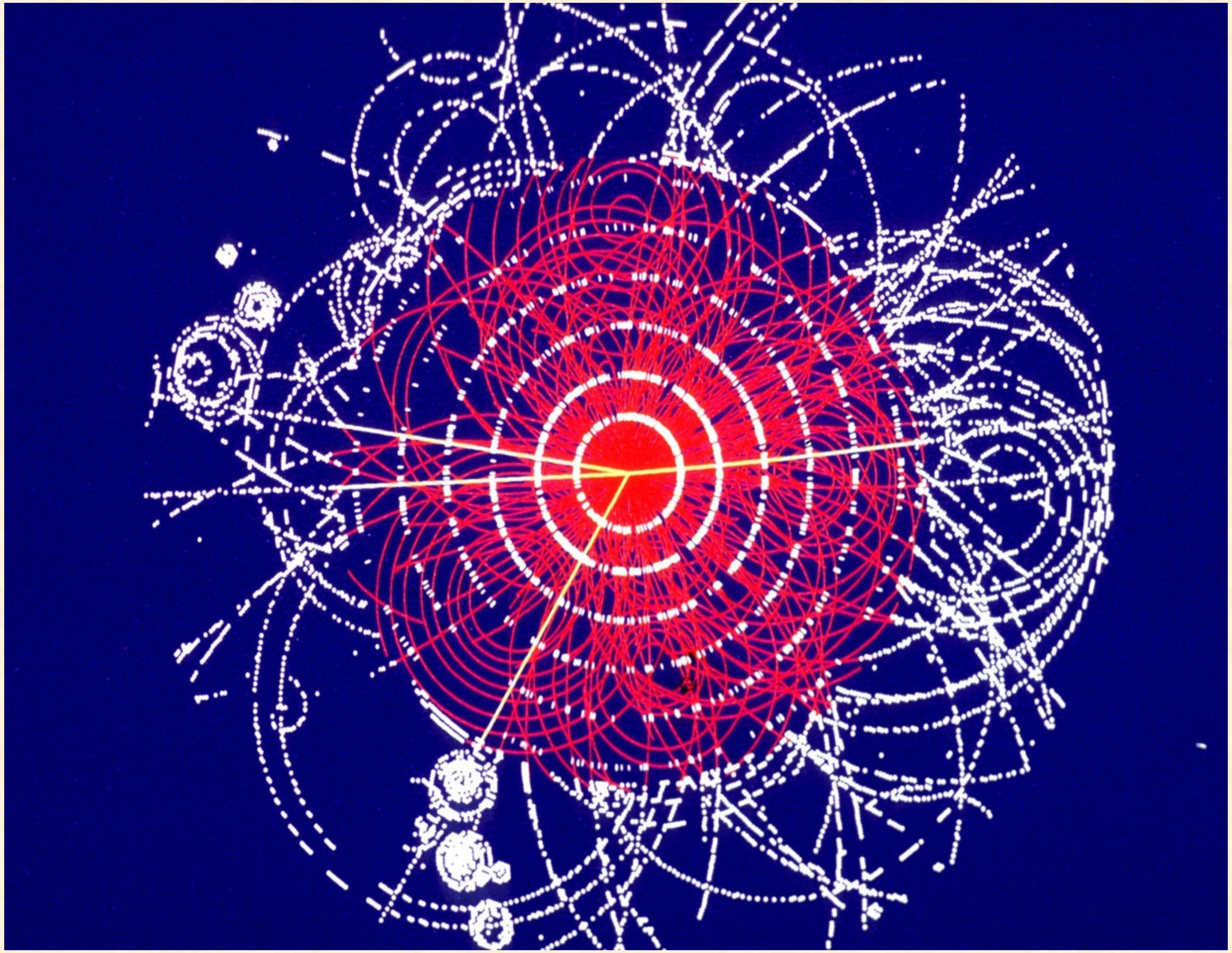


Dominant background after isolation cuts:

ZZ continuum

Discovery potential in mass range from ~130 to ~600 GeV/c^2

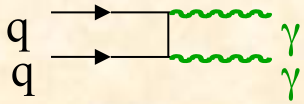
<u>A simulated H → ZZ → ℓℓℓℓ event</u>



Example of the low mass range searches : H → γ γ

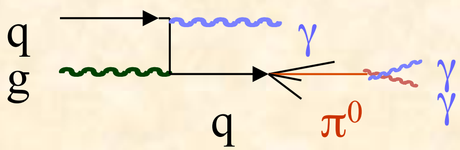
Main backgrounds:

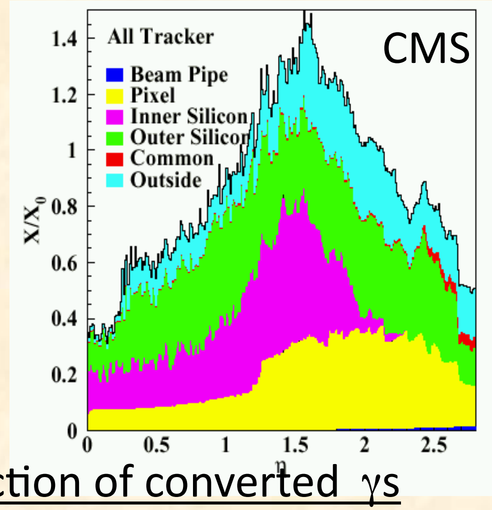
- γγ irreducible background



$\sigma_{\gamma j+jj} \sim 10^6\, \sigma_{\gamma\gamma}$ with large uncertainties ⇒ $R_j > 10^3$

- γ-jet and jet-jet (reducible)





fraction of converted γs

Barrel region: 42.0 %

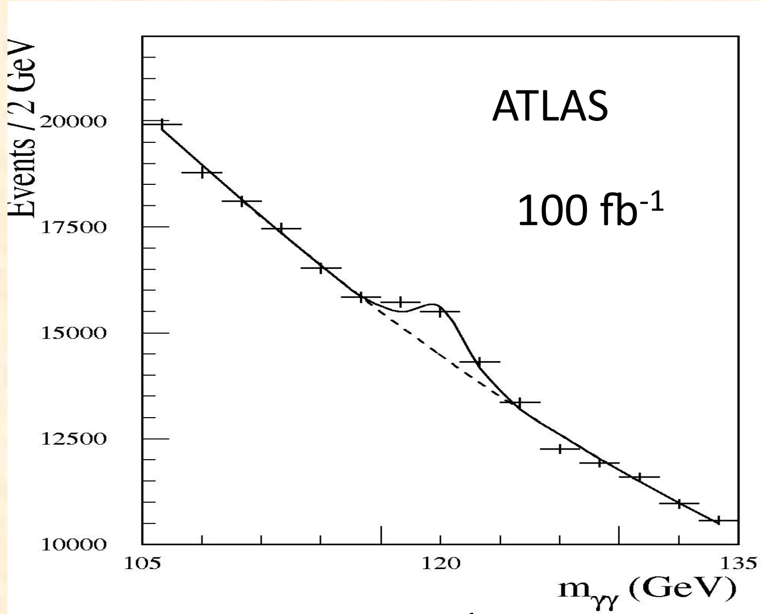
Endcap region: 59.5 %

⇒ Should be reconstructed

Main exp. tools for background suppression:

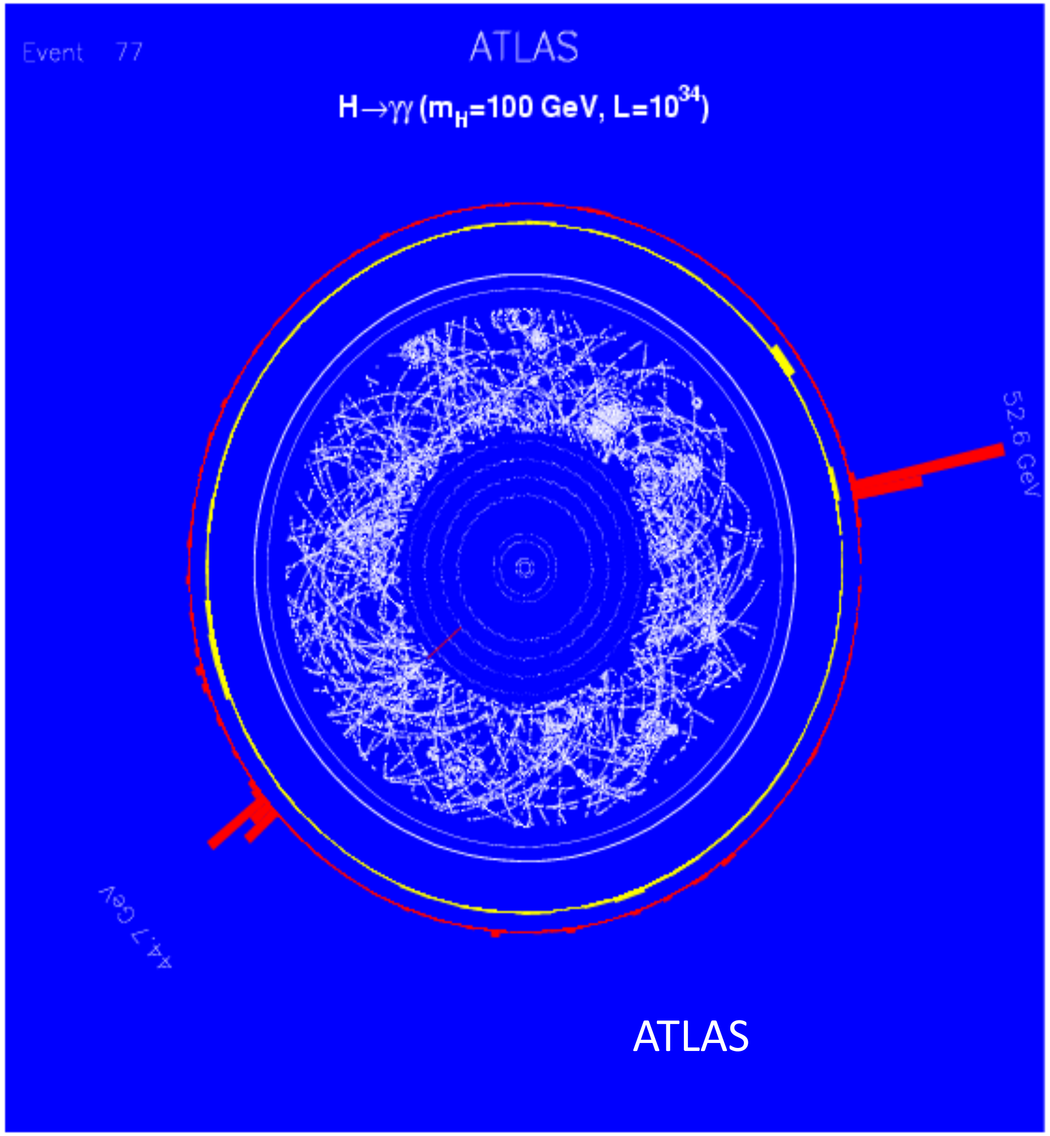
- photon identification
- γ / jet separation (calorimeter + tracker)

→ most demanding channel for EM calorimeter performance : energy and angle resolution, acceptance, γ /jet and γ / π^0 separation



1 nominal year : 30 fb^{-1}

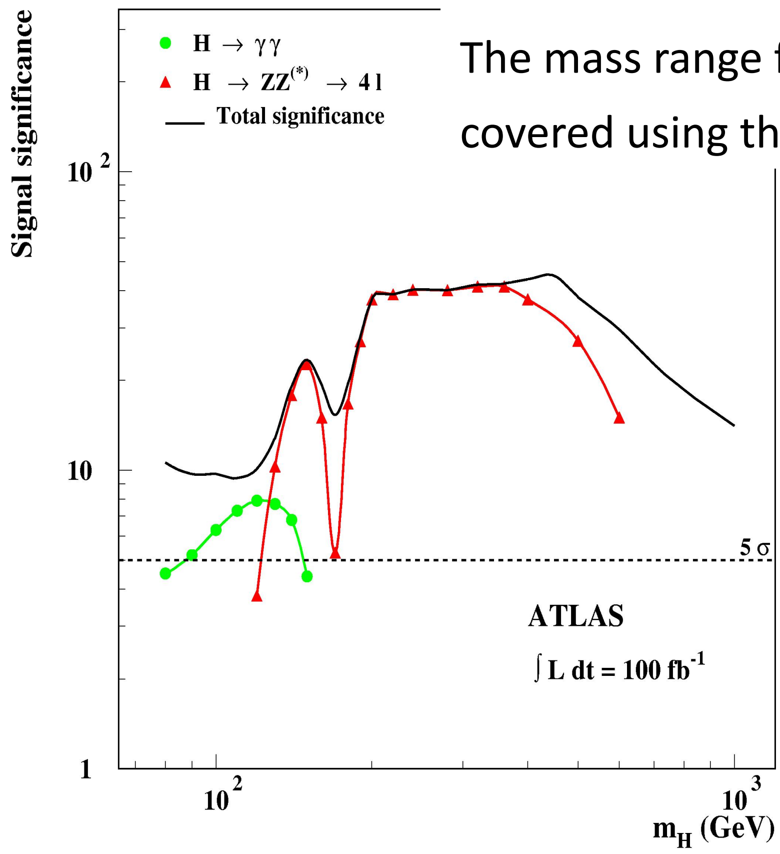
A simulated $H \rightarrow \gamma\gamma$ event in ATLAS

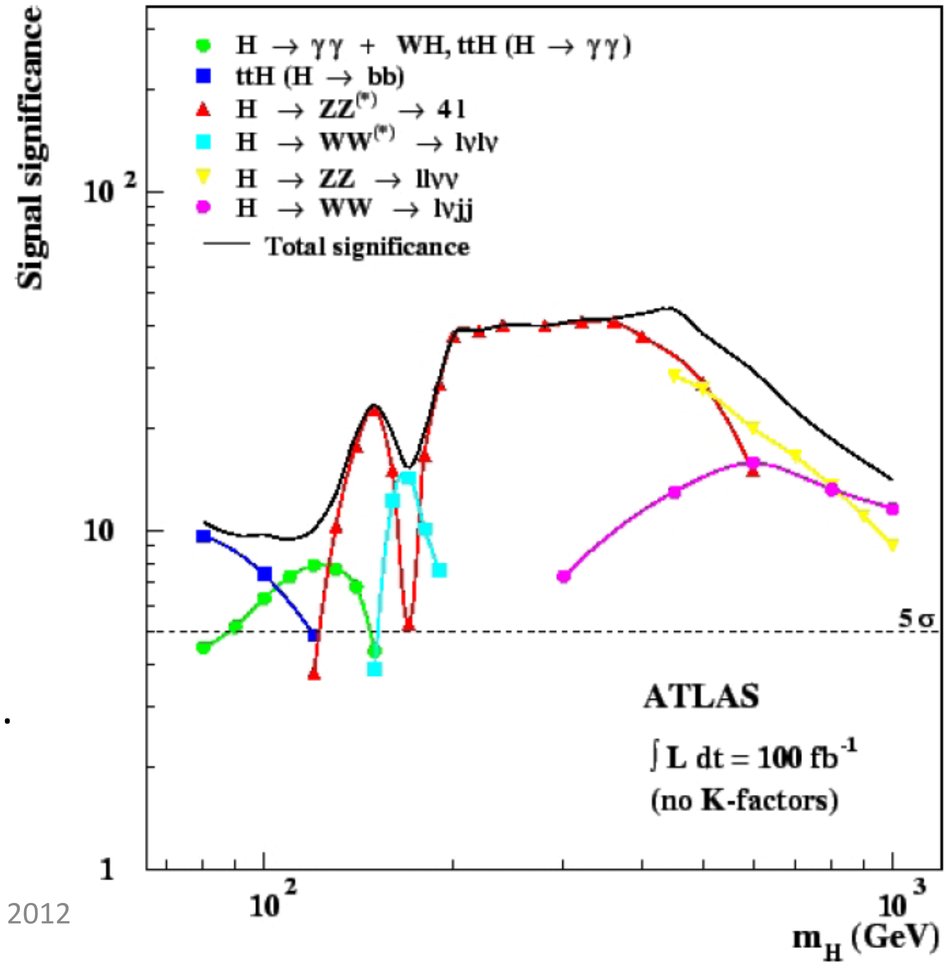


Signal significance for m_H = 130 GeV/c^2 and 30 fb^{-1}

~8 σ for ATLAS and CMS

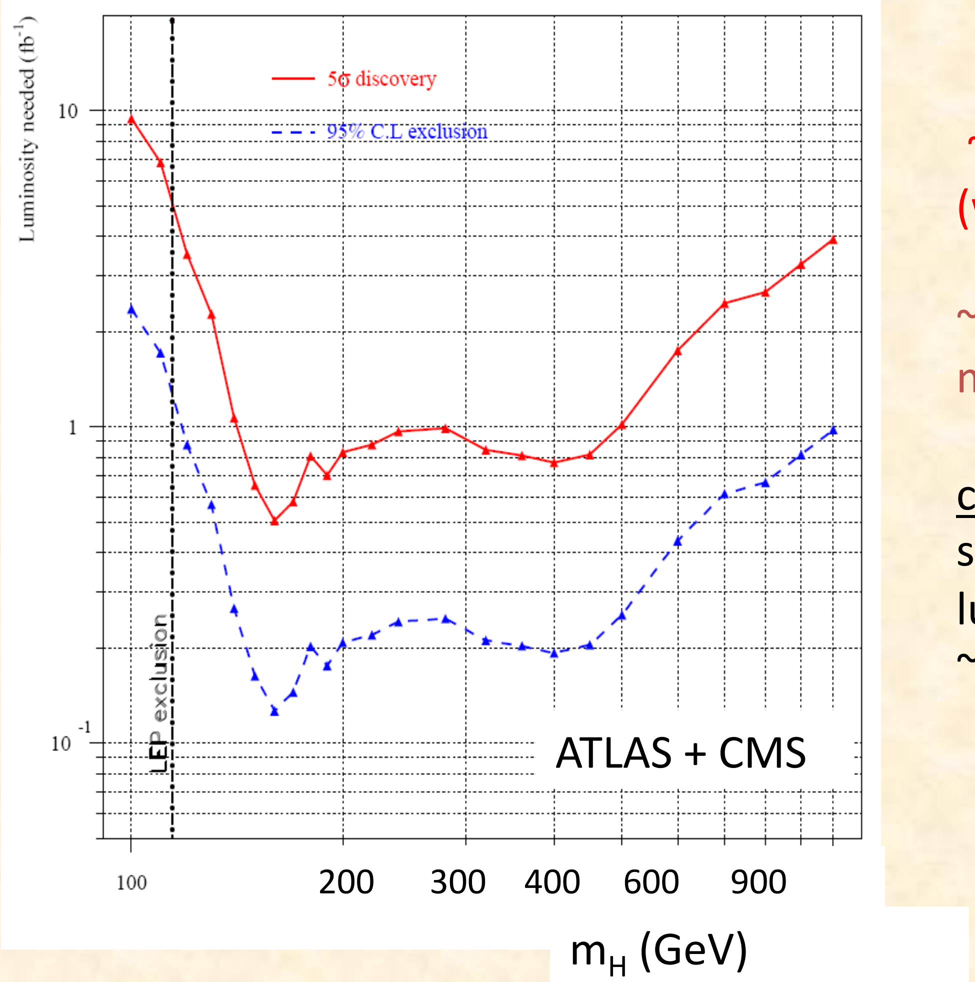
The mass range from 114.4 GeV (LEP limit) to 1 TeV ("theory") can be covered using the two "safe" channels H → ZZ → ℓℓ ℓℓ and H → γγ





But many other modes are also studied …

Combined ATLAS + CMS discovery potential : luminosity required for a 5 σ discovery or a 95% CL exclusion

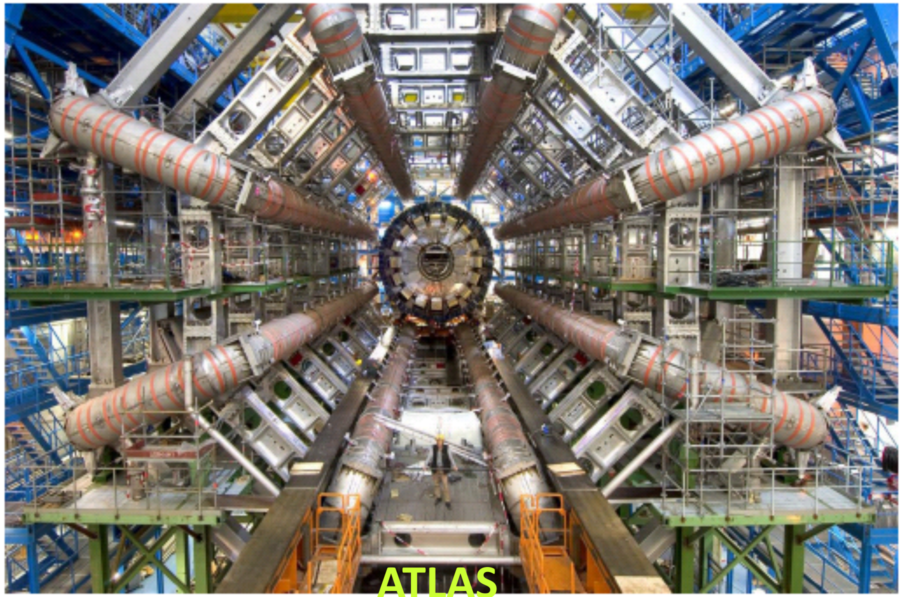


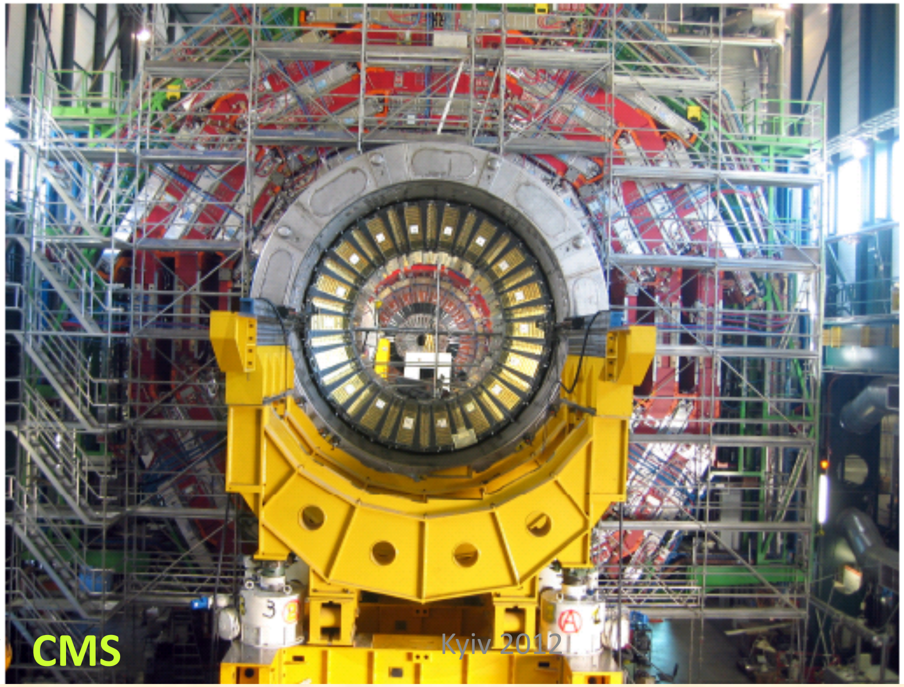
~ 5 fb^{-1} needed to achieve a 5σ discovery (well understood and calibrated detector)

~ < 1 fb^{-1} needed to set a 95% CL limit (low mass ~ 115 GeV/c^2 more difficult)

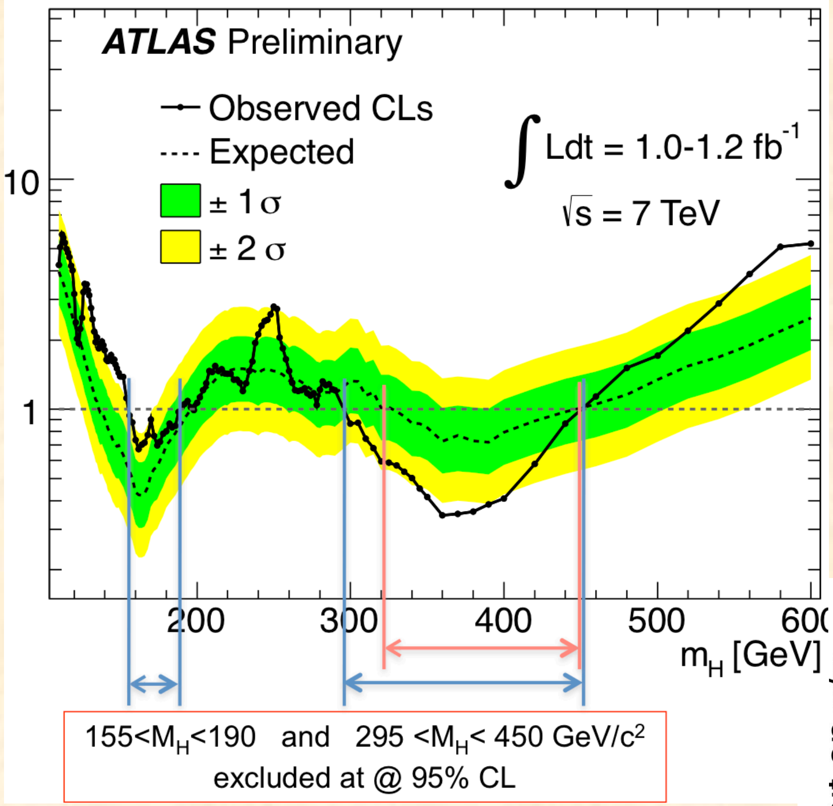
<u>comments:</u>
systematic uncertainties assumed to be luminosity dependent (no simple scaling, $\sigma \sim \sqrt{L}$, possible)

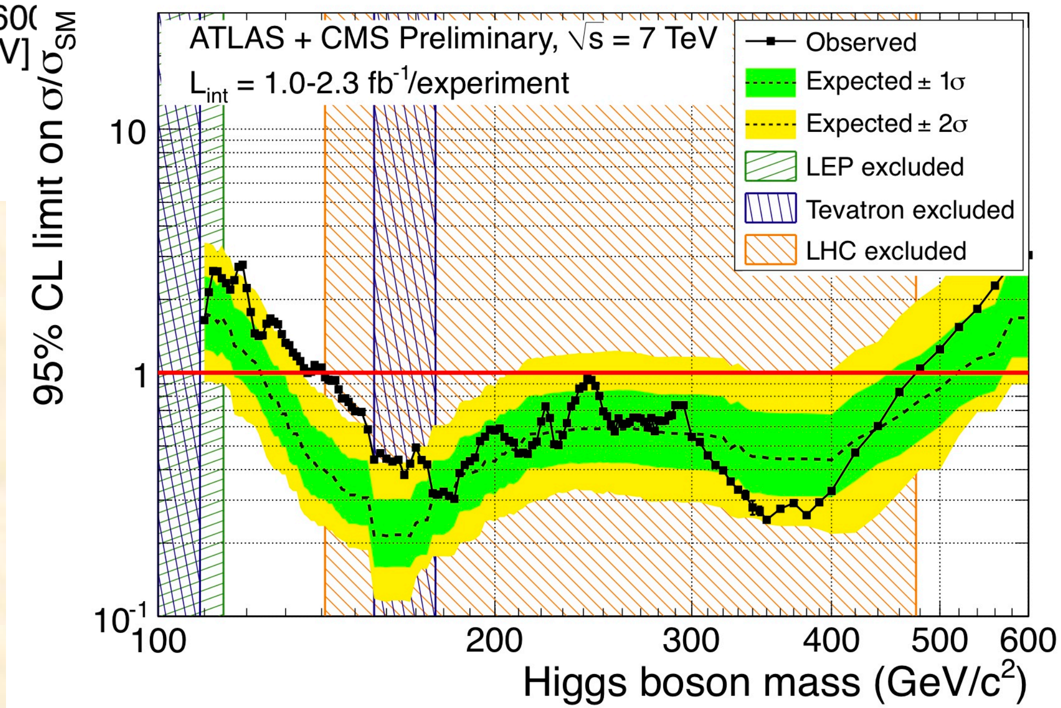
LHC (ATLAS and CMS) should be able to find the Higgs if it exists !





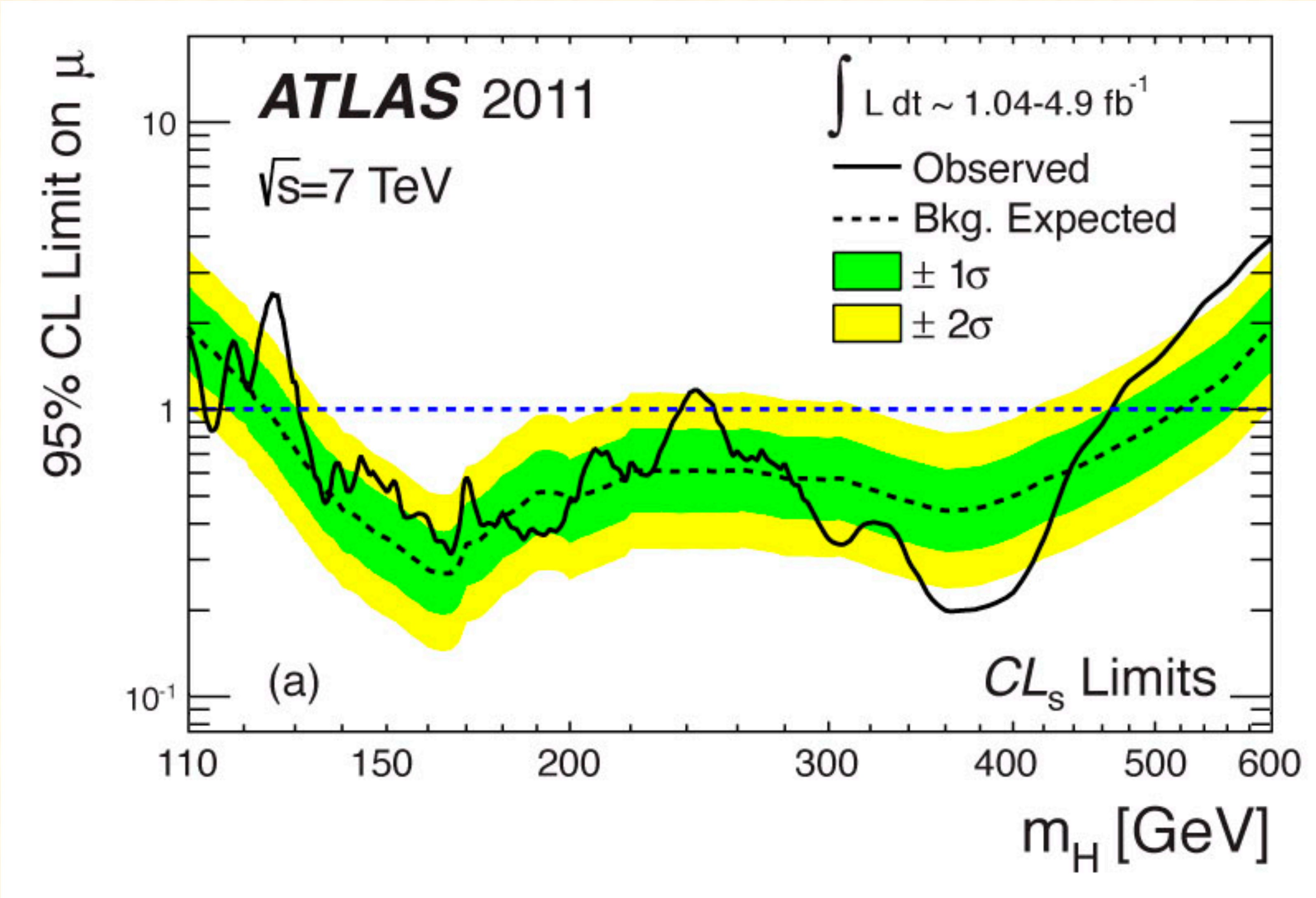
Higgs limits at the LHC



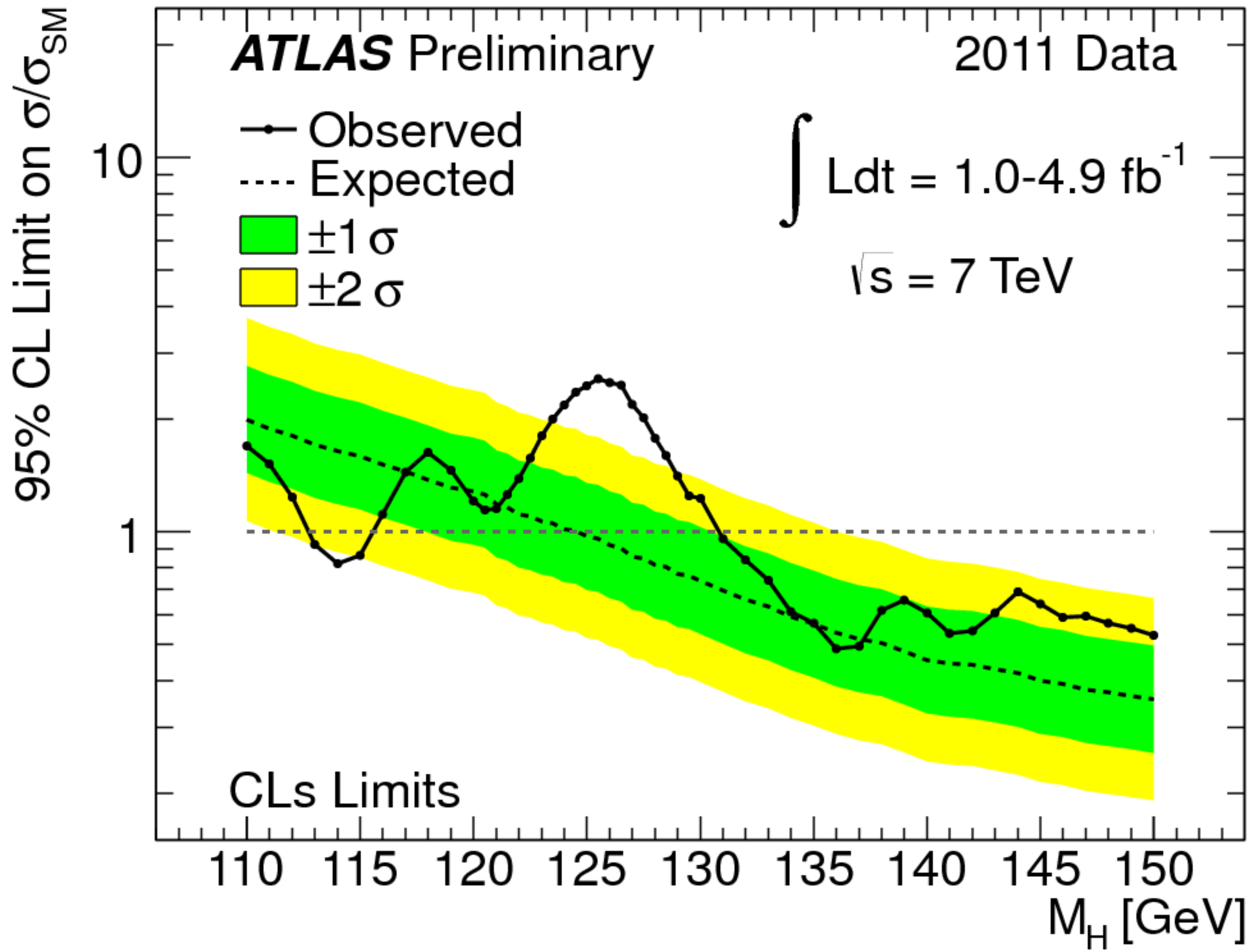


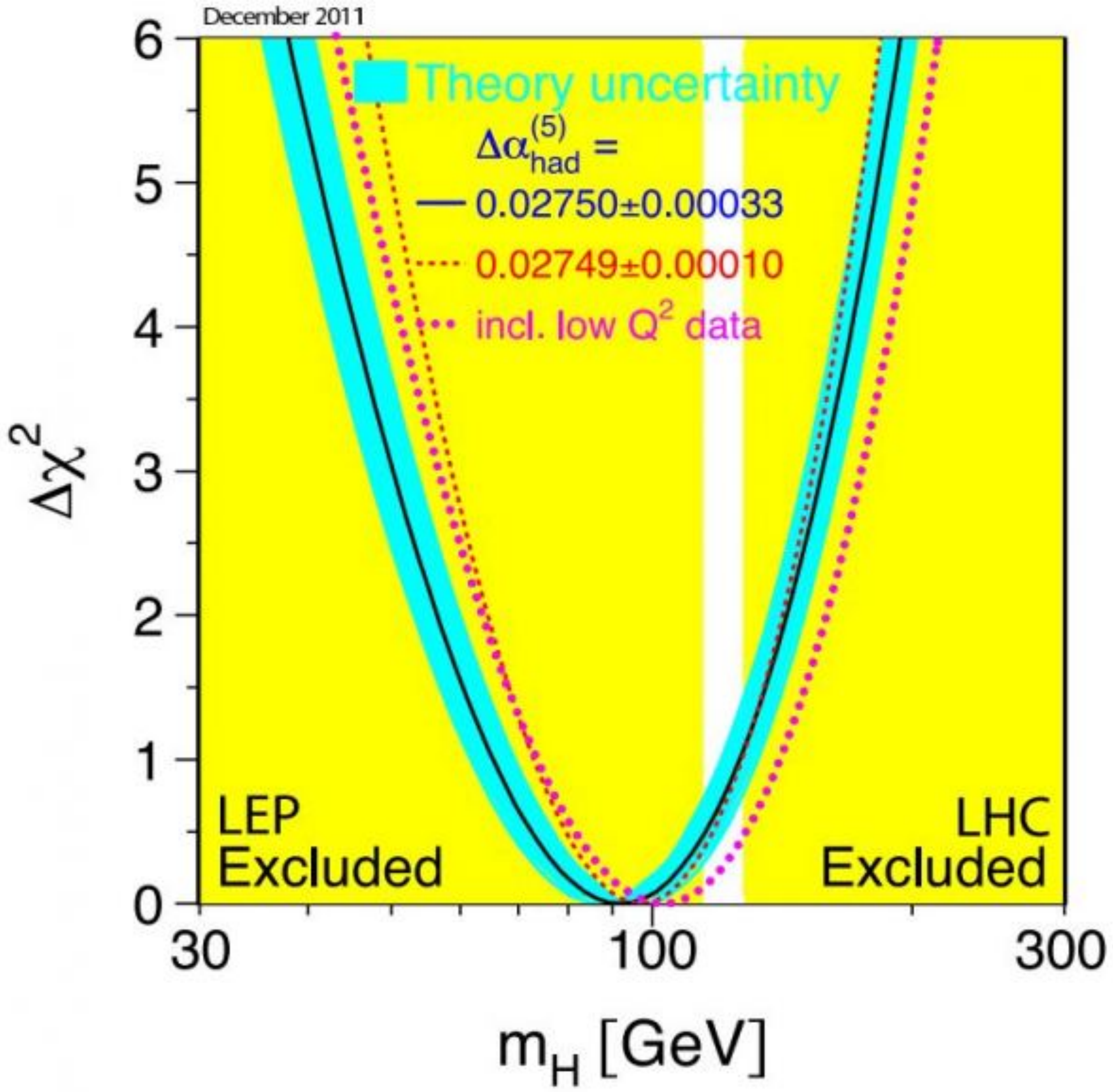
LATEST HIGGS RESULTS FROM THE LHC

Latest limits

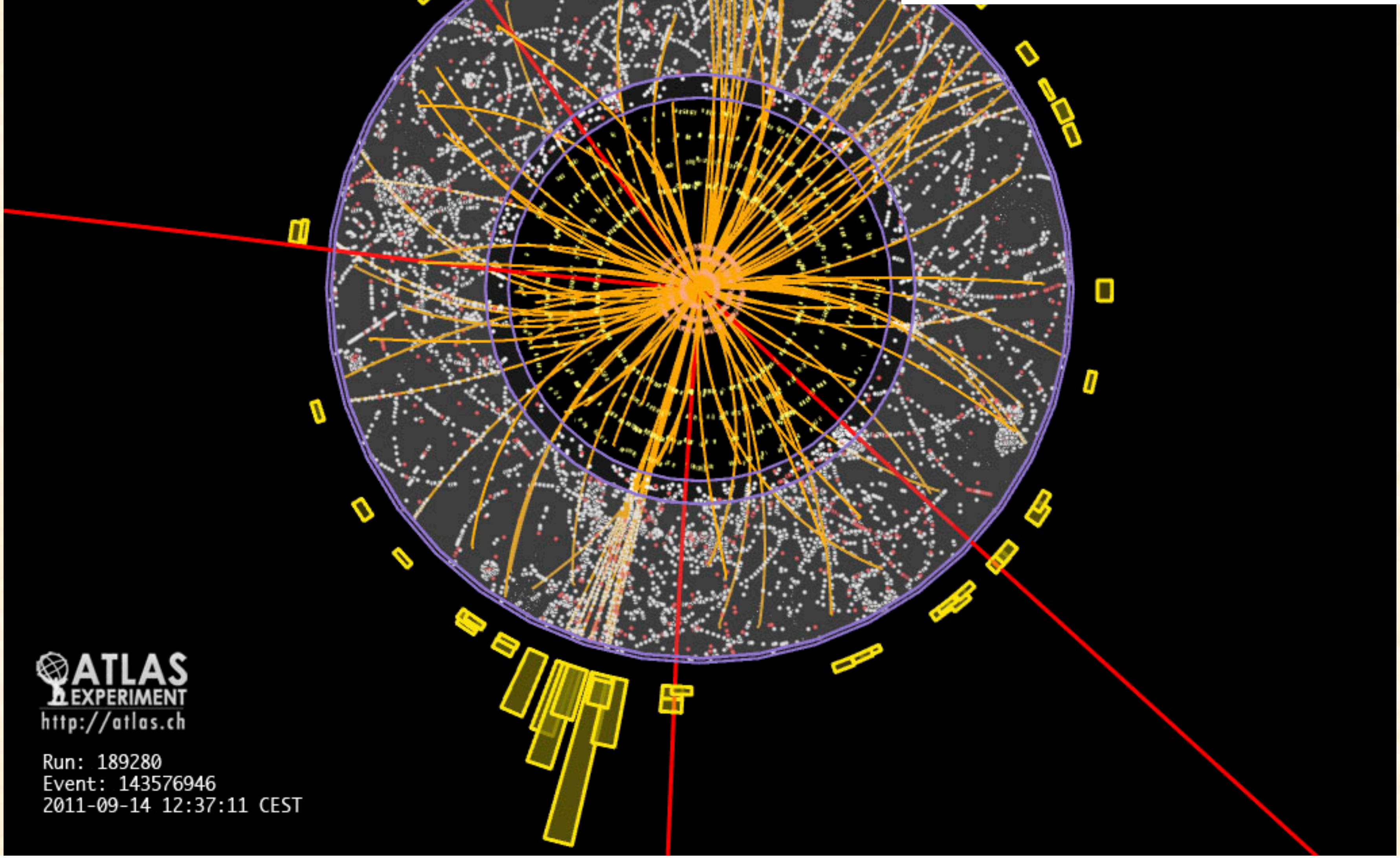


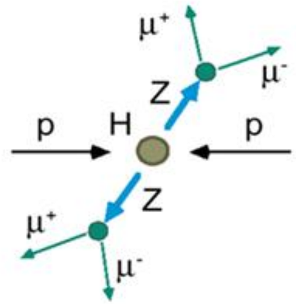
Only a small range is not excluded with a slight excess of events around 125 GeV

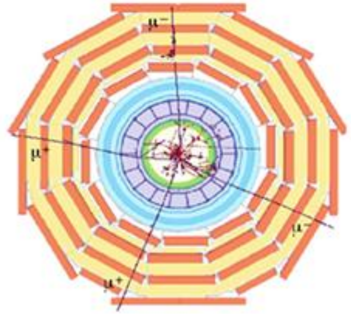

ATLAS Preliminary
2011 Data
Observed
Expected
±1 σ
±2 σ
∫ Ldt = 1.0-4.9 fb^-1
√s = 7 TeV
CLs Limits
95% CL Limit on σ/σ_SM
10
1
110
115
120
125
130
135
140
145
150
M_H [GeV]

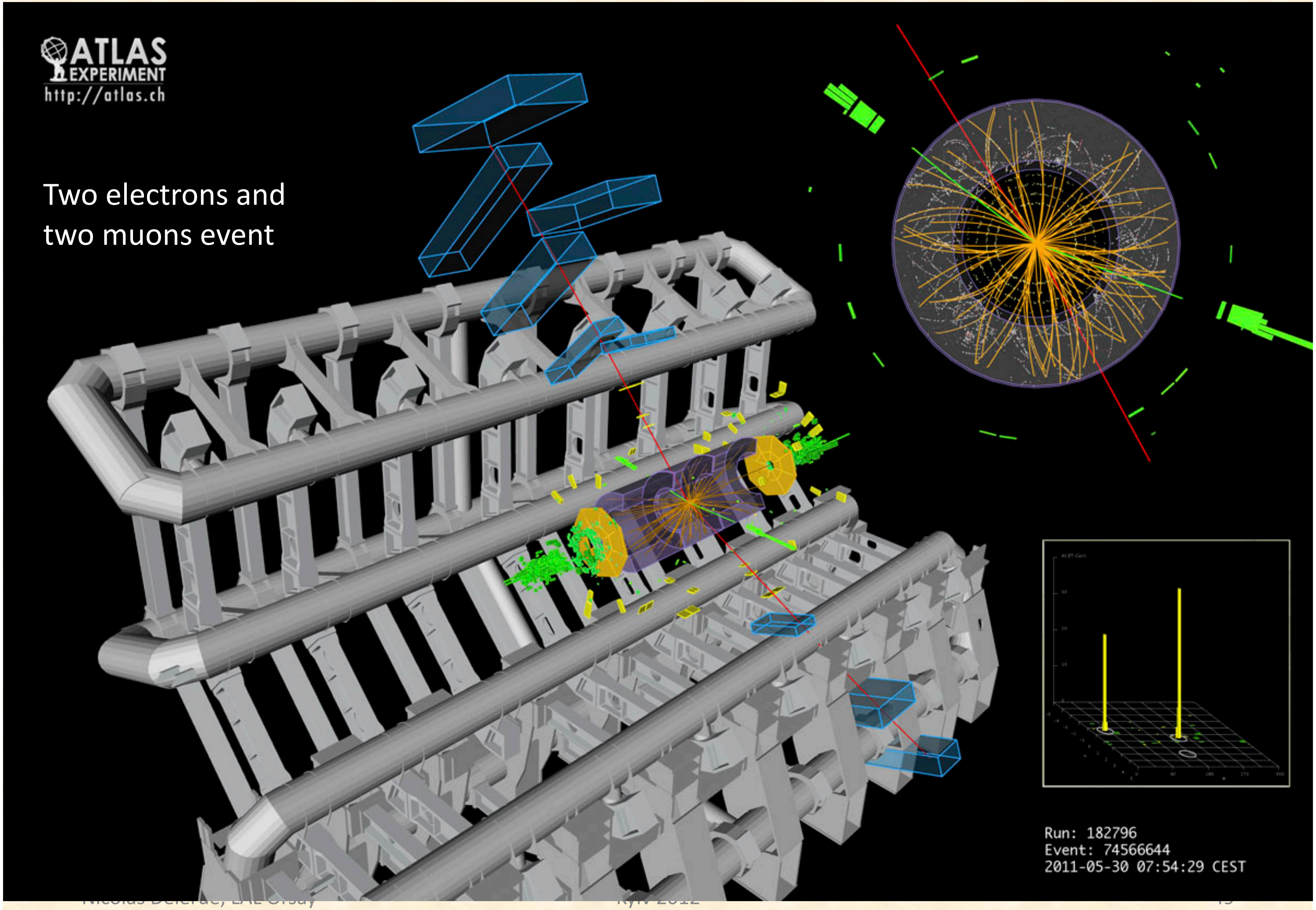

December 2011
Theory uncertainty
$\Delta\alpha_{had}^{(5)}$ =
0.02750±0.00033
0.02749±0.00010
incl. low Q^2 data
LEP
Excluded
LHC
Excluded
$\Delta\chi^2$
6
5
4
3
2
1
0
30
100
300
m_H [GeV]

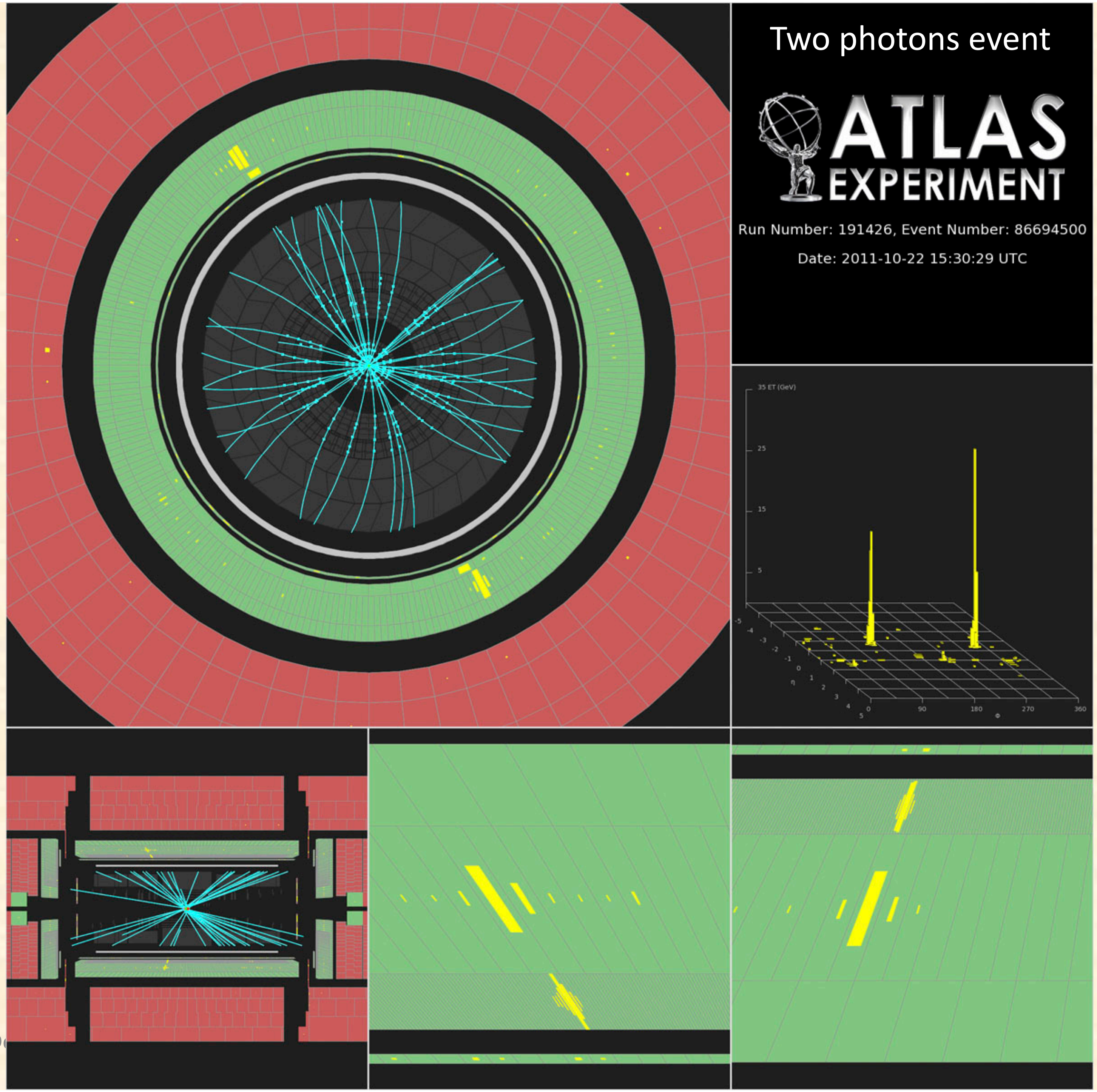
Four muons event

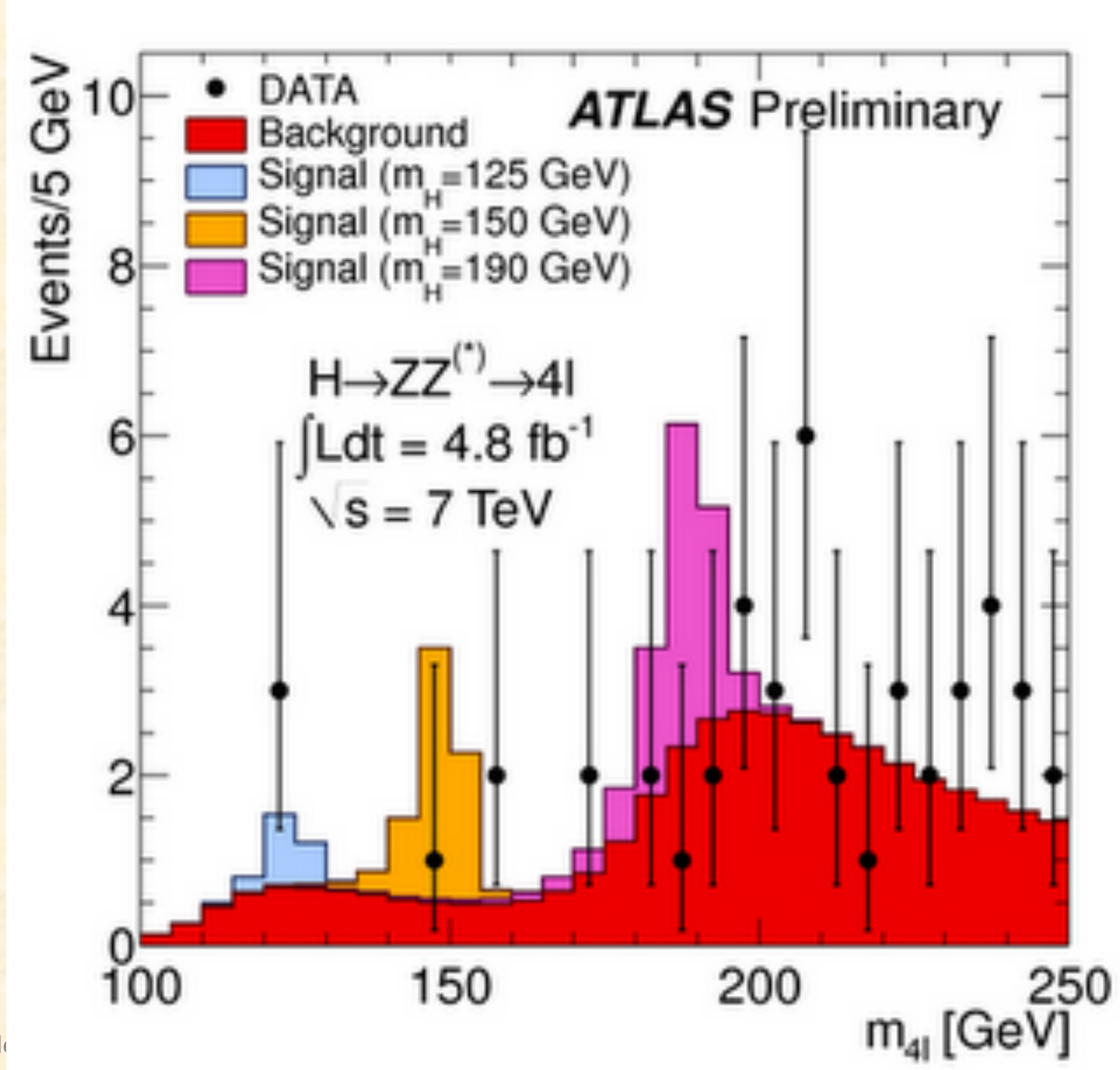







ATLAS EXPERIMENT
http://atlas.ch
Two electrons and
two muons event
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST


Two photons event
ATLAS EXPERIMENT
Run Number: 191426, Event Number: 86694500
Date: 2011-10-22 15:30:29 UTC
35 ET (GeV)
25
15
5
0
90
180
270
360



DATA
Background
Signal (m_H=125 GeV)
Signal (m_H=150 GeV)
Signal (m_H=190 GeV)
ATLAS Preliminary
H→ZZ(*)→4l
∫Ldt = 4.8 fb⁻¹
√s = 7 TeV
Events/5 GeV
m_4l [GeV]

Outlook

- The Higgs mechanism is a possible explanation of why particles have mass.
- It has not yet been confirmed experimentally.
- However, the mass range where the Higgs boson may be is very narrow.
- Both CMS and ATLAS observe possible candidates.
- Answer probably by the summer or by the end of the year at the latest!