BEH mechanism & Higgs searches/discovery

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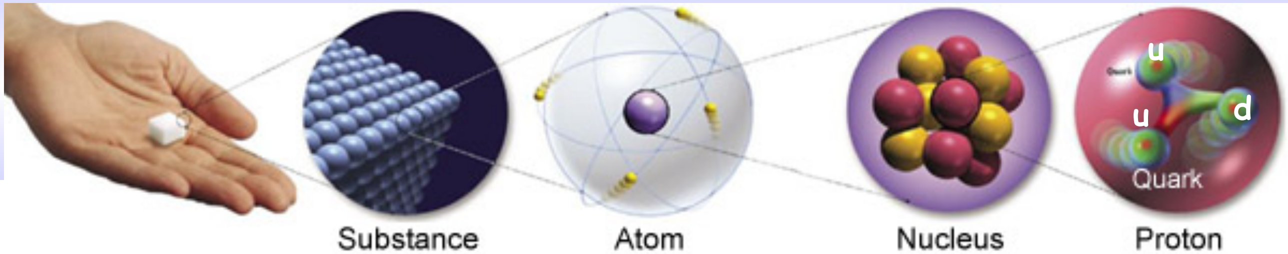
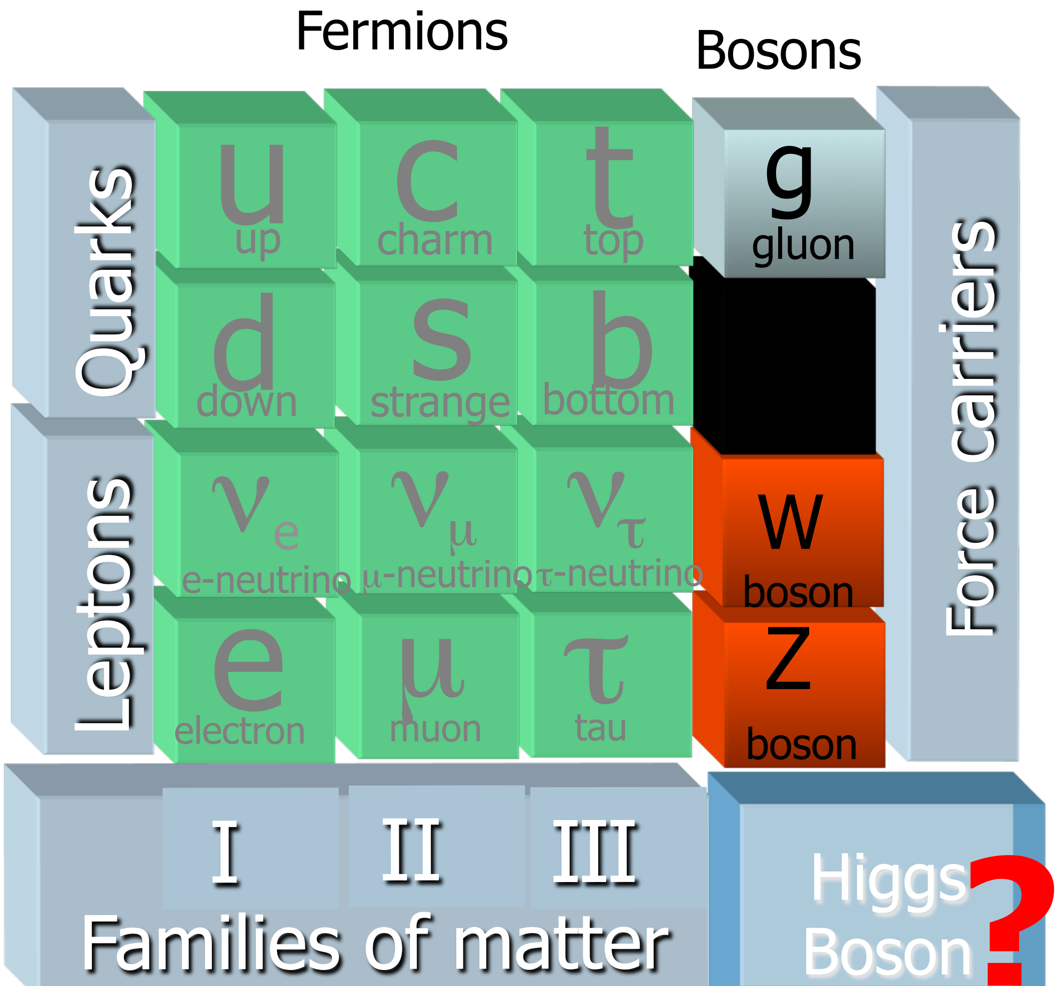
4th Egyptian School on High Energy Physics,
26th April - 5th May 2014
The British University and Ain-Shams University

Outline

- Introduction to BEH mechanism
- Searches for SM Higgs:
  - at LEP
  - at TEVATRON
  - at LHC
- History of the Higgs discovery



The Standard Model



Questions:

why masses of matter particles and forces carriers are so different ? The bare SM could be consistent with massless particles but matter particles range from almost 0 to about 170 GeV while force carriers range from 0 to about 90 GeV.

The simplest solution:

all particles are massless !!

A new scalar field pervades the Universe (the Higgs field). Particles interacting with this field acquire mass: the stronger the interaction the larger the mass...

04/07/2012

the Higgs boson has been found !

The origin of the BEH mechanism

	Article	Reception date	Publication date
1	F. Englert and R. Brout Phys. Rev. Letters **13-[9]** (1964) 321	26/06/1964	31/08/1964
2	P.W. Higgs Phys. Letters **12** (1964) 132	27/07/1964	15/09/1964
3	P.W. Higgs Phys. Rev. Letters **13-[16]** (1964) 508	31/08/1964	19/10/1964
4	G.S. Guralnik, C.R. Hagen and T.W.B. Kibble Phys. Rev. Letters **13-[20]** (1964) 585	12/10/1964	16/11/1964

"Theory": introduction (1)

1. Why Higgs?

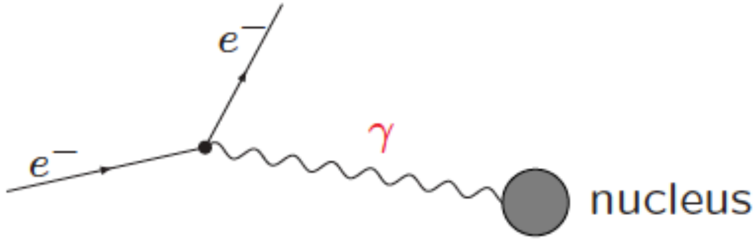
Standard Model (SM) of the electroweak and strong interaction

SM: Quantum field theory $\Rightarrow$ interaction: exchange of field quanta

Construction principle of the SM: gauge invariance

Example: Quantum electro-dynamics (QED)

field quanta: photon A_μ



$\mathcal{L}_{\text{QED}}$ invariant under gauge transformation:

$\Psi \rightarrow e^{i\,e\,\lambda(x)}\Psi,\ A_\mu \rightarrow A_\mu + \partial_\mu \lambda(x)$

mass term for photon: $m^2 A^\mu A_\mu$ not gauge invariant

$\Rightarrow A_\mu$ is massless gauge field

"Theory": Higgs mechanism

Problem:

Gauge fields Z, W^+, W^- are massive

explicite mass terms in the Lagrangian $\Leftrightarrow$ breaking of gauge invariance

Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

Higgs sector in the Standard Model:

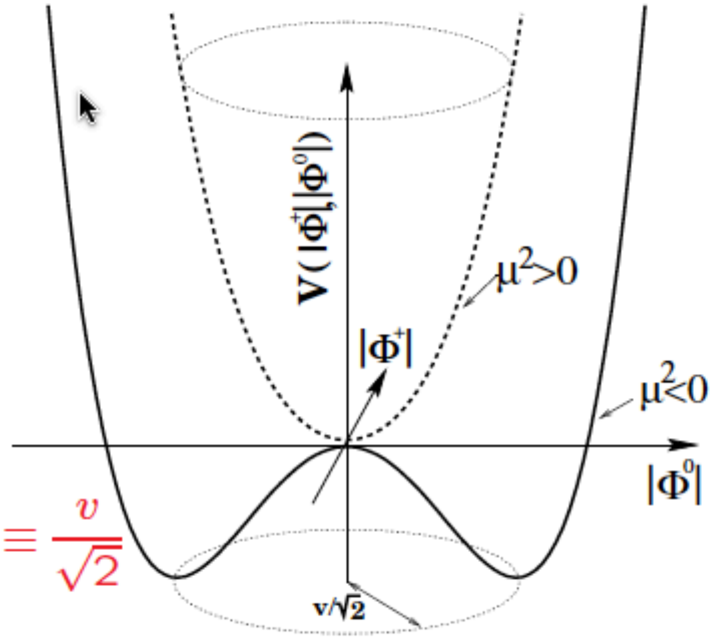
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 \left|\Phi^\dagger\Phi\right| + \lambda \left|\Phi^\dagger\Phi\right|^2, \quad \lambda > 0$$

$\mu^2 < 0$: Spontaneous symmetry breaking

minimum of potential at $|\langle\Phi_0\rangle| = \sqrt{\frac{-\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$



"Theory": Higgs mechanism(2)

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad \text{(unitary gauge)}$$

H: elementary scalar field, Higgs boson

Lagrange density:

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = \quad & (D_\mu \Phi)^\dagger (D^\mu \Phi) \\ & - g_d \bar{Q}_L \Phi d_R \; - \; g_u \bar{Q}_L \Phi_c u_R \\ & - V(\Phi) \end{aligned}$$

with

$$\begin{aligned} iD_\mu &= i\partial_\mu - g_2 \vec{I}\vec{W}_\mu - g_1 Y B_\mu \\ \Phi_c &= i\sigma_2 \Phi^\dagger \qquad Q_L \sim \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \; \Phi \sim \begin{pmatrix} 0 \\ v \end{pmatrix}, \; \Phi_c \sim \begin{pmatrix} v \\ 0 \end{pmatrix} \end{aligned}$$

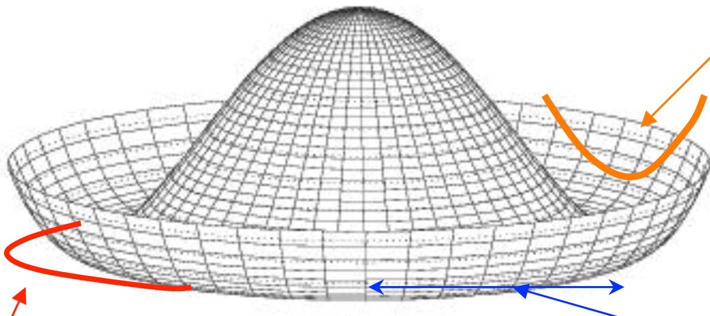
Gauge invariant coupling to gauge fields

$\Rightarrow$ mass terms for gauge bosons and fermions

"Theory": Higgs mechanism in a nutshell

$m_W, m_Z = 0$

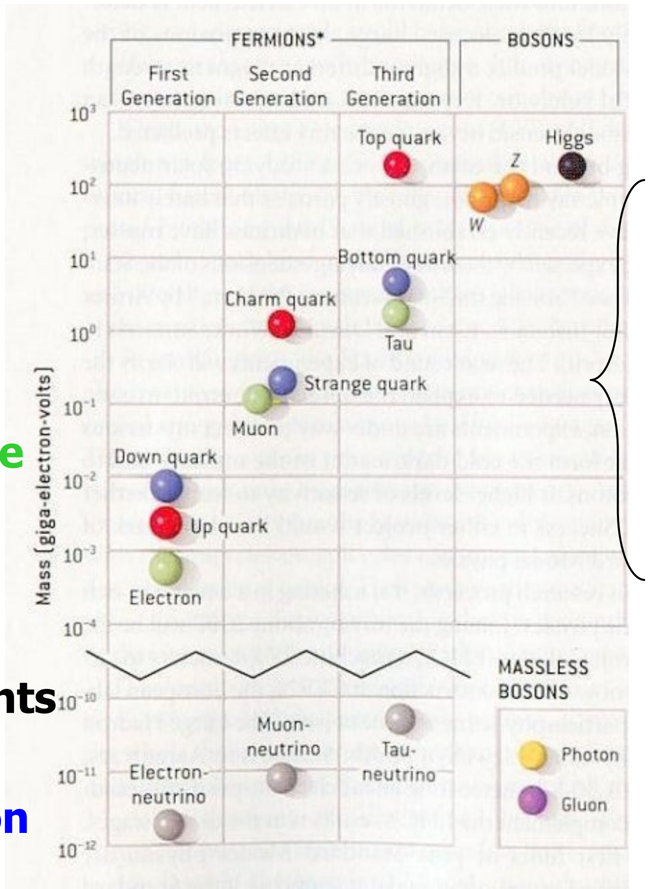
physical Higgs boson



v

$m_W, m_Z \neq 0$

modes "eaten" by *W,Z*



all masses due to Higgs

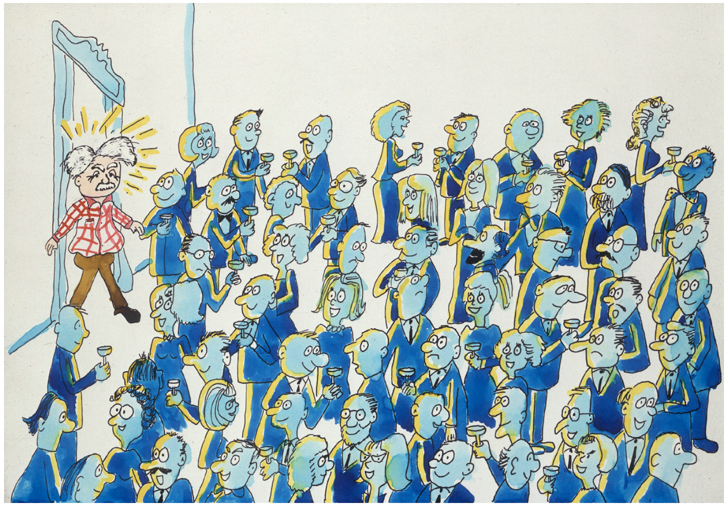
- **Breaks symmetry while maintaining local gauge invariance (→renormalizability)**
- **Add complex weak isospin doublet with "mexican hat" potential V = $\lambda|\Phi|^4 - \mu^2|\Phi|^2$**
- **3 components of Φ form longitudinal components of $W^{\pm}$ and Z (→massive)**
- **1 component → real scalar particle: Higgs boson**
- Couple fermion fields to Φ → fermion mass terms

"Theory": Higgs mechanism cartoon

Let's imagine a room with many physicists talking each other →

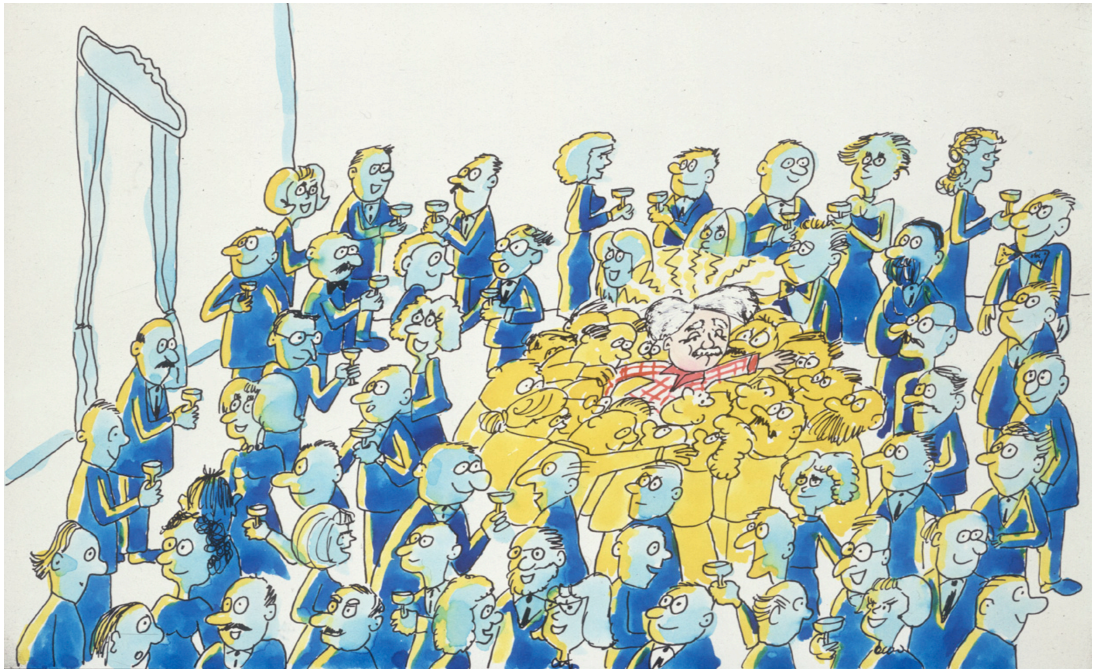
space filled with the Higgs field

A well know scientist starts to move in the room creating disturbance and attracting clusters of admirers at each step.



“Theory”: Higgs mechanism cartoon (2)

That increases the resistance to the motion and so he gets mass like a particle moving in the higgs field



"Theory": Higgs decays

2. The SM Higgs boson

1.) Decay to fermions:

coupling:

$$g_{f\bar{f}H} = \left[\sqrt{2}\,G_\mu\right]^{1/2} m_f$$

decay width:

$$\Gamma(H \to f\bar{f}) = N_c \frac{G_\mu M_H}{4\sqrt{2}\,\pi} m_f^2(M_H^2) \left(1 - 4\frac{m_f^2}{M_H^2}\right)^{3/2}$$

with N_c = number of colors

Bulk of QCD corrections for decays to quarks are mapped into

$$m_q^2(\text{pole}) \to m_q^2(M_H^2)$$

Dominant decay process: $H \to b\bar{b}$

"Theory": Higgs decays (2)

2.) Decay to heavy gauge bosons ($V = W, Z$):

coupling:

$$g_{VVH} = 2\left[\sqrt{2}\,G_\mu\right]^{1/2} M_V^2$$

on-shell decay width ($M_H > 2M_V$):

$$\Gamma(H \to VV) = \delta_V \frac{G_\mu M_H^3}{16\sqrt{2}\,\pi}\left(1 - 4\frac{M_V^2}{M_H^2} + 12\frac{M_V^4}{M_H^4}\right)\left(1 - 4\frac{M_V^2}{M_H^2}\right)^{1/2}$$

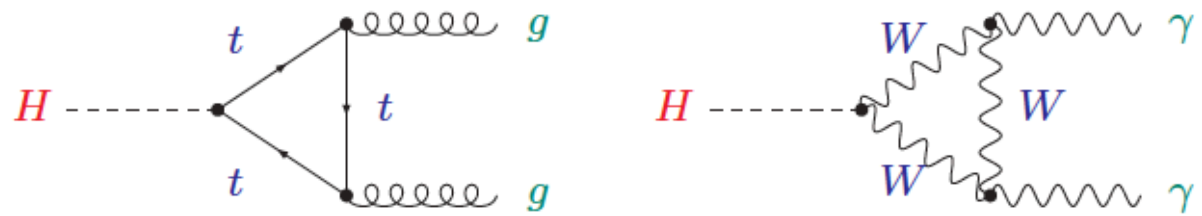
with $\delta_{W,Z} = 2, 1$

off-shell decay width ($M_H < 2M_V$):

$$\Gamma(H \to VV^*) = \delta'_V \frac{3G_\mu^2 M_H}{16\,\pi^3} M_V^4 \times \text{Integral}$$

"Theory": Higgs decays (3)

3.) Decay to massless gauge bosons (gg, $\gamma\gamma$):



$$\Gamma(H \to gg) = \frac{G_\mu \alpha_s^2(M_H^2) M_H^3}{36\sqrt{2}\pi^3}\left[1 + C\frac{\alpha_s(\mu)}{\pi}\right]$$

via the top quark loop with

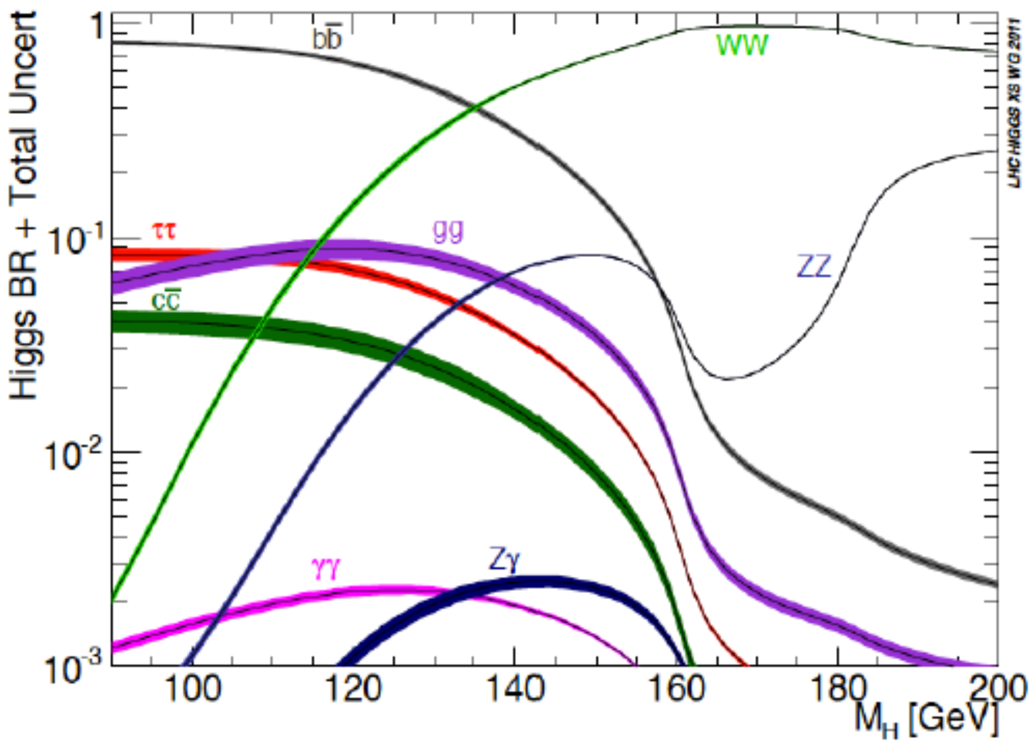
$$C = \frac{215}{12} - \frac{23}{6}\log\left(\frac{\mu^2}{M_H^2}\right) + \mathcal{O}(\alpha_s)$$

⇒ huge QCD corrections

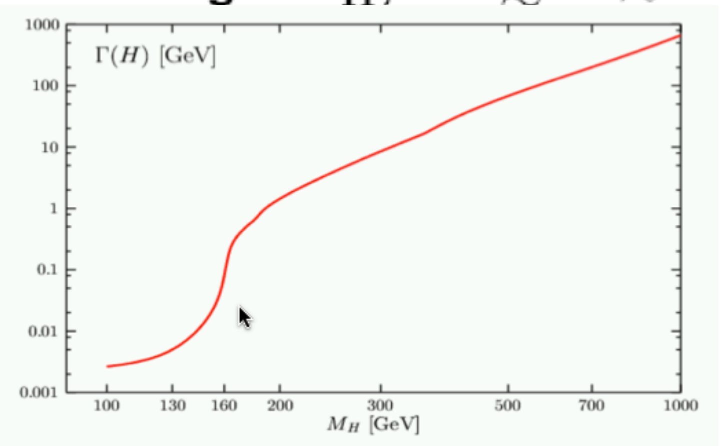
$$\Gamma(H \to \gamma\gamma) = \frac{G_\mu \alpha^2 M_H^3}{128\sqrt{2}\pi^3}\left|\frac{4}{3}e_t^2 - 7\right|^2$$

via the top quark and W boson loop

"Theory": Higgs decays (4)



- 'Low mass range', $M_H \lesssim 130$ GeV:
  - $H \to b\bar{b}$ dominant, BR = 60–90%
  - $H \to \tau^+\tau^-, c\bar{c}, gg$ BR= a few %
  - $H \to \gamma\gamma, \gamma Z$, BR = a few permille.
- 'High mass range', $M_H \gtrsim 130$ GeV:
  - $H \to WW^*, ZZ^*$ up to $\gtrsim 2M_W$
  - $H \to WW, ZZ$ above (BR $\to \frac{2}{3}, \frac{1}{3}$)
  - $H \to t\bar{t}$ for high M_H; BR $\lesssim 20\%$.

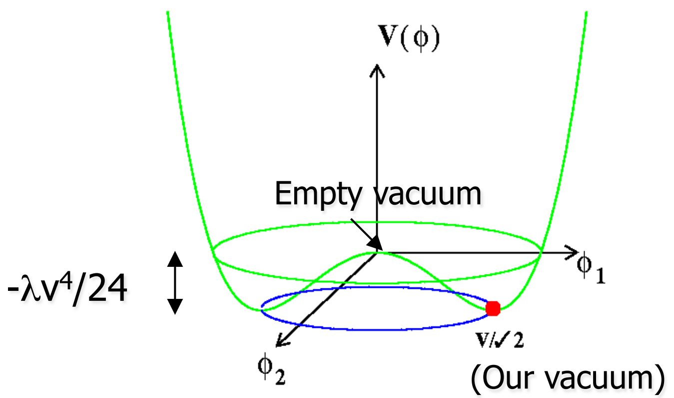


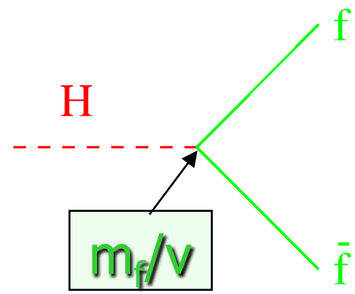
"Theory": Higgs mass and couplings

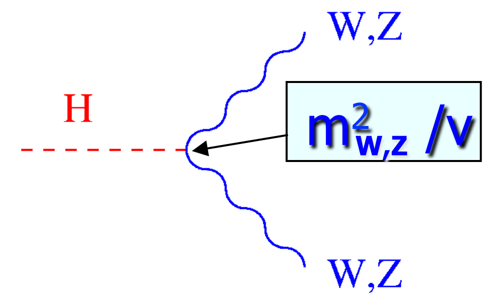
From the Higgs Mechanism … and from Gauge Invariance :

$m_Z = m_W/\cos\vartheta_W$; $m_W = gv/2$; ($\rightarrow$ v ~ 250 GeV).

vacuum expectation value







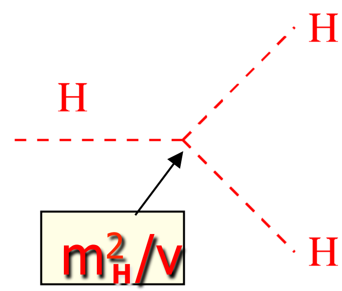
All couplings predicted

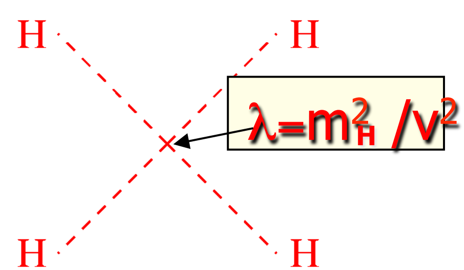
$$V(\phi) = \frac{\lambda}{3!}\left\{\bar{\phi}\phi - v^2/2\right\}^2$$

$$= \frac{1}{2}\frac{\lambda v^2}{3}H^2 + \frac{\lambda v}{3!}H^3 + \frac{\lambda}{4!}H^4$$

(unknown)

$m^2_H = \lambda v^2/3$



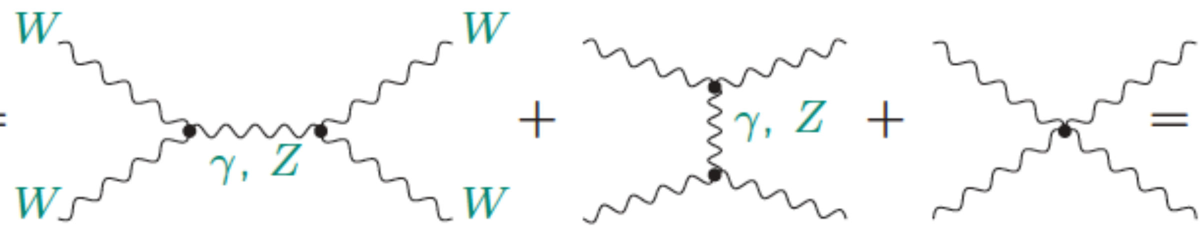


"Theory": impact of Higgs

Another effect of the Higgs field:

Scattering of longitudinal W bosons: $W_L W_L \to W_L W_L$

$\mathcal{M}_V =$



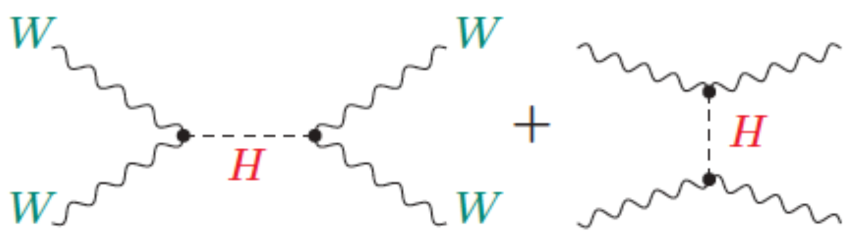
$$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$$

for $E \to \infty$

$\Rightarrow$ violation of unitarity

Contribution of a scalar particle with couplings prop. to the mass:

$\mathcal{M}_S =$



$$= g_{WWH}^2 \frac{E^2}{M_W^4} + \mathcal{O}(1)$$

for $E \to \infty$

$$\mathcal{M}_{\text{tot}} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4}\left(g_{WWH}^2 - g^2 M_W^2\right) + \ldots$$

$\Rightarrow$ compensation of terms with bad high-energy behavior for

$$g_{WWH} = g\, M_W$$

Unitarity constraint

The Higgs boson allows to regulate calculations at high energies

$$A\left(W_L^+ W_L^- \to Z_L Z_L\right) = \frac{G_F E^2}{8\sqrt{2}\pi}\left(1 - \frac{E^2}{E^2 - m_H^2}\right)$$

To avoid unitarity violation (scattering propability > 1 !)

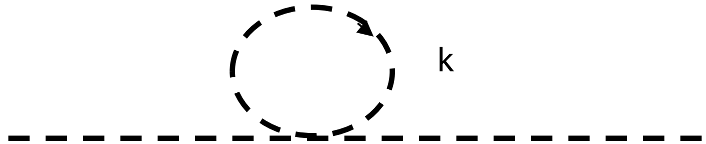
Without Higgs ⇨ SM limited to E < 1.2 TeV

SM applicable ⇨ $M_H < 780$ GeV/c^2

… or else there must ∃ new physics at the O(TeV) to regulate the scattering amplitudes

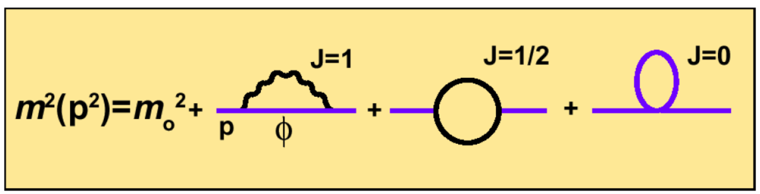
Instability of Higgs mass

General problem: the introduction of a scalar field in a quantum field theory generates quadratic divergencies as soon a one introduces a cut-off Λ



$$m^2 = m_0^2 + \alpha\lambda \frac{\Lambda^2}{16\pi^2}$$

e.g. If the SM is valid as an effective theory up to a « mass scale » Λ for new physics, M_H unavoidably receives radiative corrections from loops involving the top quark, the gauge bosons or from self-couplings …



$$M_H^2 \to M_H^2\,(\text{bare}) + c\,\Lambda^2$$

$$\partial M_H = \frac{3}{8\pi^2}\lambda_t^2\Lambda^2 \quad \text{… from top quark}$$

$$\partial M_H \propto a_W \Lambda^2 \quad \text{… from gauge bosons}$$

$$\partial M_H \approx \frac{\lambda}{16\pi^2}\Lambda^2$$

Dramatic problem if $\Lambda \sim M_{GUT}$

The difference scales between the Fermi scale and the scale for new physics (e.g. at M_{GUT}) is not natural !

Corrections of O(100) GeV at O(1) TeV already for $\Lambda \sim 10$ TeV !

$\Rightarrow$ Fine tuning to keep $M_H \sim O(100)$ GeV

Is the SM enough? Open questions

- How to solve the problem of the hierarchy between the EWK scale and the GUT or Planck scale ?

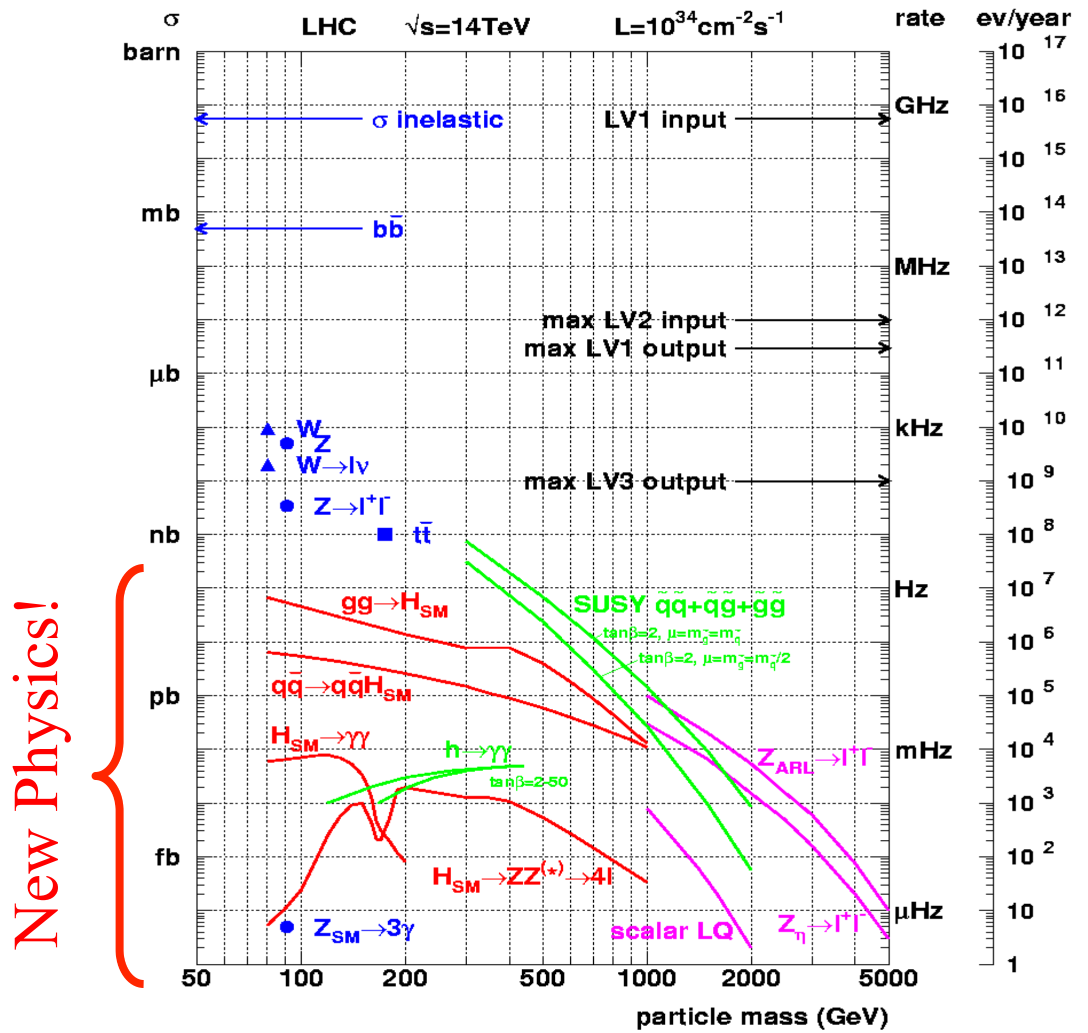
- Are the electroweak and strong forces unified at some GUT scale

- Is the SUSY realized in nature ? Do the SUSY particles exist ? Can they explain the dark matter ?

- Do extra dimensions exist?

- ….etc..

LHC can provide some answers



"Theory": supersymmetry

3. The MSSM Higgs sector

Supersymmetry (SUSY) : Symmetry between

$$\text{Bosons} \leftrightarrow \text{Fermions}$$

$$Q\ |\text{Fermion}\rangle \rightarrow |\text{Boson}\rangle$$
$$Q\ |\text{Boson}\rangle \rightarrow |\text{Fermion}\rangle$$

Simplified examples:

$$Q\ |\text{top},\ t\rangle \rightarrow |\text{scalar top},\ \tilde{t}\rangle$$
$$Q\ |\text{gluon},\ g\rangle \rightarrow |\text{gluino},\ \tilde{g}\rangle$$

$\Rightarrow$ each SM multiplet is enlarged to its double size

Unbroken SUSY: All particles in a multiplet have the same mass

Reality: $m_e \neq m_{\tilde{e}} \Rightarrow$ SUSY is broken . . .

. . . via soft SUSY-breaking terms in the Lagrangian (added by hand)

SUSY particles are made heavy: $M_{\text{SUSY}} = \mathcal{O}(1\ \text{TeV})$

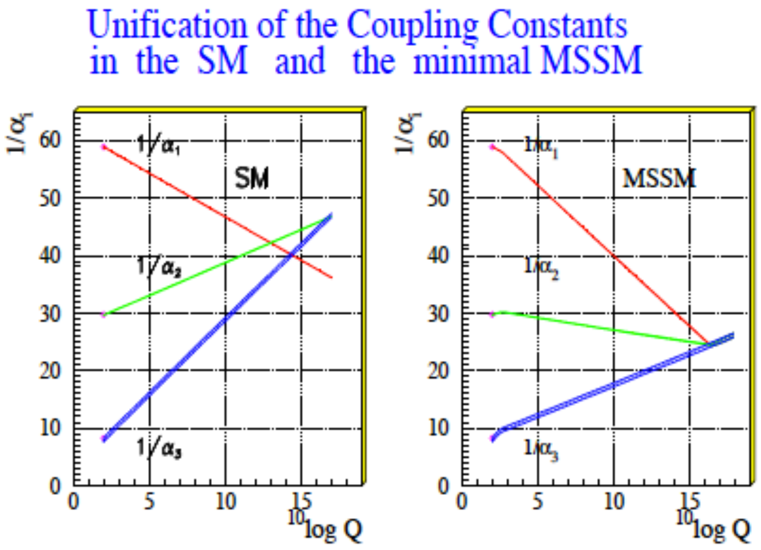
"Theory": supersymmetry (2)

Five reasons as a SUSY motivation

The SM is in a pretty good shape.

Why MSSM? (Is it worth to double the particle spectrum?)

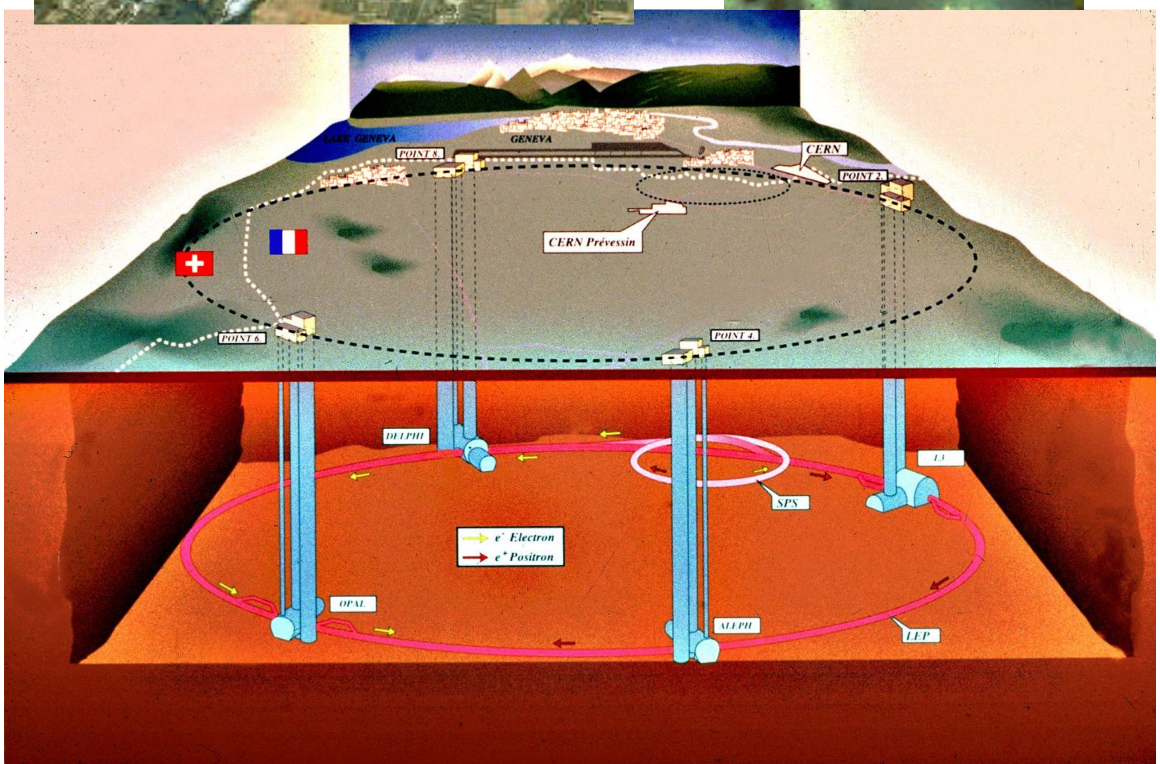
1.) Stability of the Higgs mass against higher-order corr.
2.) Unification of gauge couplings: Not possible in the SM, but in the MSSM (although it was not designed for it.)
3.) Spontaneous symmetry breaking via Higgs mechanism is automatic in SUSY GUTs
4.) SUSY provides CDM candidate
5.) . . .



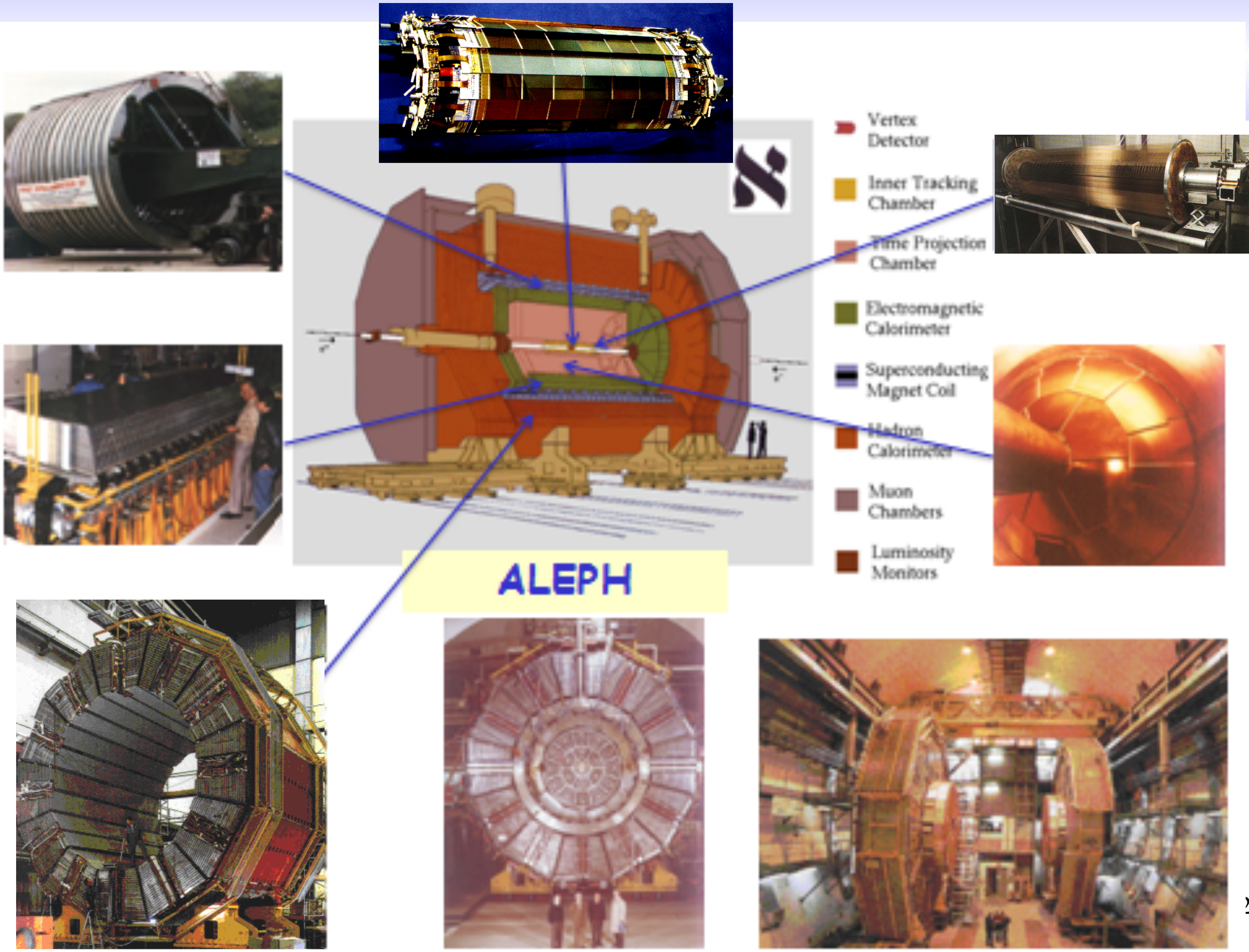
[Amaldi, de Boer, Fürstenau '92]

Higgs searches at LEP

LEP



- Operation
  1989 - 2000, CERN, Geneva
- Circumference
  27 km
- Particles
  electrons - positrons
- Beam energy
  45 GeV → 104.5 GeV
- Luminosity
  10^{31} - 10^{32} cm^{-2} sec^{-1}
- L_{int}
  1000 pb^{-1}
- Experiments
  ALEPH, DELPHI, L3, OPAL
- Characteristics:
  - very clean environment
  - very small backgrounds


Vertex Detector
Inner Tracking Chamber
Time Projection Chamber
Electromagnetic Calorimeter
Superconducting Magnet Coil
Hadron Calorimeter
Muon Chambers
Luminosity Monitors
ALEPH

LEP data and luminosity

- LEP: e+e- collider at CERN

  four experiments: ALEPH, DELPHI, L3, OPAL
- LEP1: 1989-1995, $\sqrt{s}$=91 GeV,

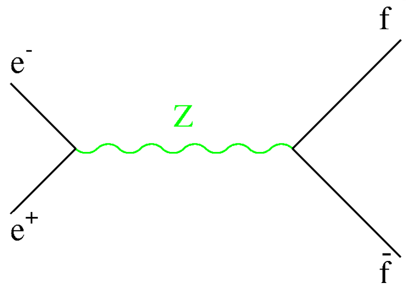
  precision measurement of Z boson parameters
- LEP2: 1995-2000, $\sqrt{s}$ =130-208 GeV

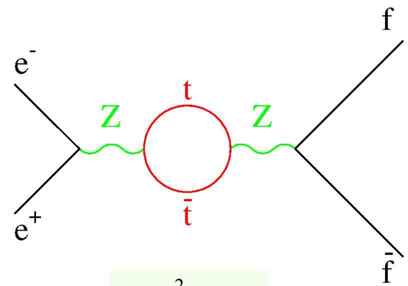
year	'95	'96	'97	'98	'99	2000
$\sqrt{s}$	130-136	161-172	183	189	192 196 200 202	204 205 207 208
Lum (pb^{-1})	3 3	11 11	55	160	25 80 80 40	9 72 130 8
Lum x4 exp	24	88	220	640	900	875

>2.5 fb^{-1} @ E_{cm}>180 GeV

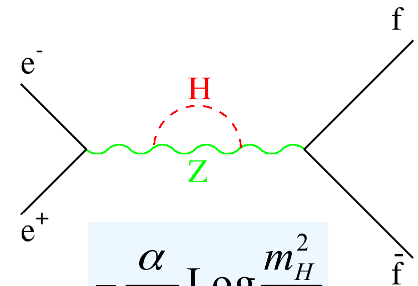
Dependence of EWK observables on m_{top} and m_H

Electroweak Observables (i.e., related to W and Z) sensitive to vacuum polarization effects:

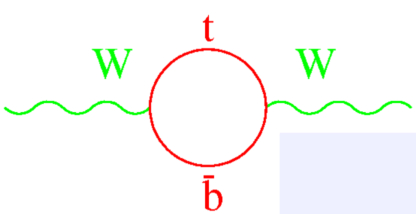




$$\frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} \approx 1\%$$



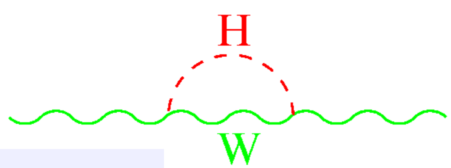
$$-\frac{\alpha}{4\pi}\,\mathrm{Log}\,\frac{m_H^2}{m_Z^2}$$



$(m_W/m_Z)^2$

↓

$(m_W/m_Z)^2 \times (1+\Delta r)$



Radiative corrections :

$\Delta r_{top} \sim m^2_{top}$

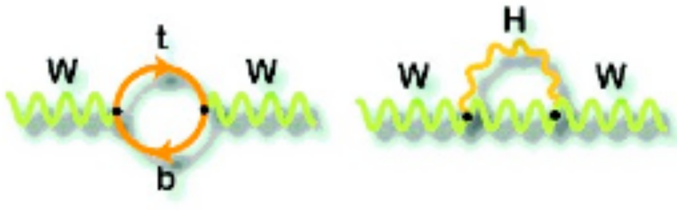
$\Delta r_H \sim \log m_H$

From precision electroweak measurements :

- **Predict m_{top} (and m_W) and compare with direct measurements;**
- **Predict m_H ....and compare with direct measurements.**

Global fit of the Standard Model to m_H

Precision electroweak data are sensitive to Higgs mass

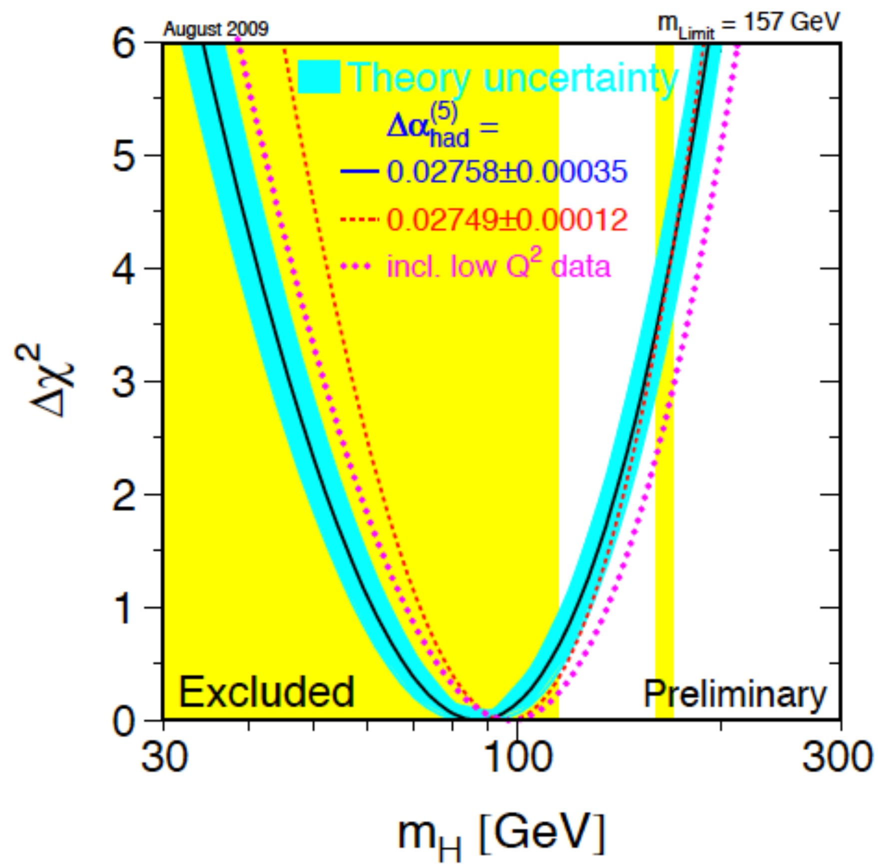


$$m_W = \left(\frac{\pi\alpha_{em}}{\sqrt{2}G_F}\right)\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$

$$\Delta r = f(m^2_{top}, \log m_H)$$

Global SM electroweak fits provide upper limit :

$M_H = 91\pm^{45}_{32} < 186$ GeV @ 95% C.L.



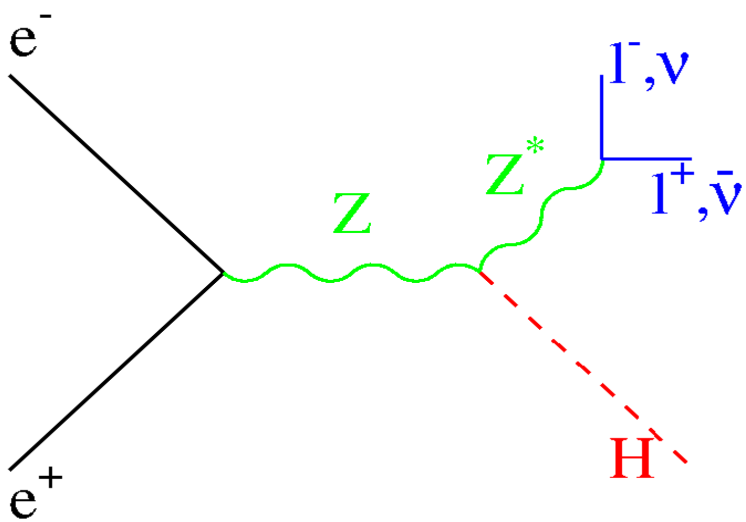
SM Higgs production at LEP

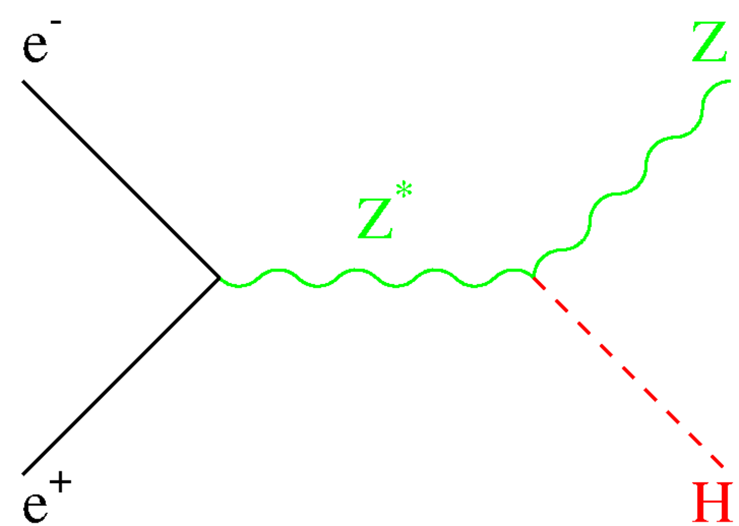
Dominant at LEP: The Higgs-strahlung process

(The production cross section depends only on m_H)

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

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



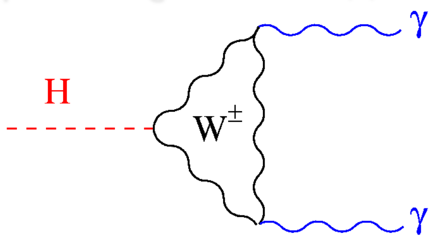


(Large coupling to the Z ⇒ Only sizeable cross section)

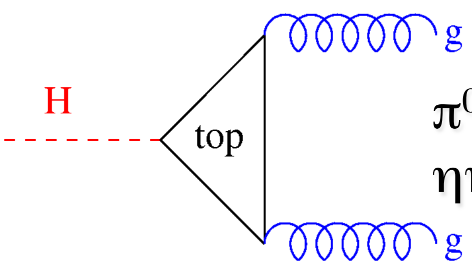
SM Higgs decay at LEP

The decay branching ratios depend only on m_H:

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



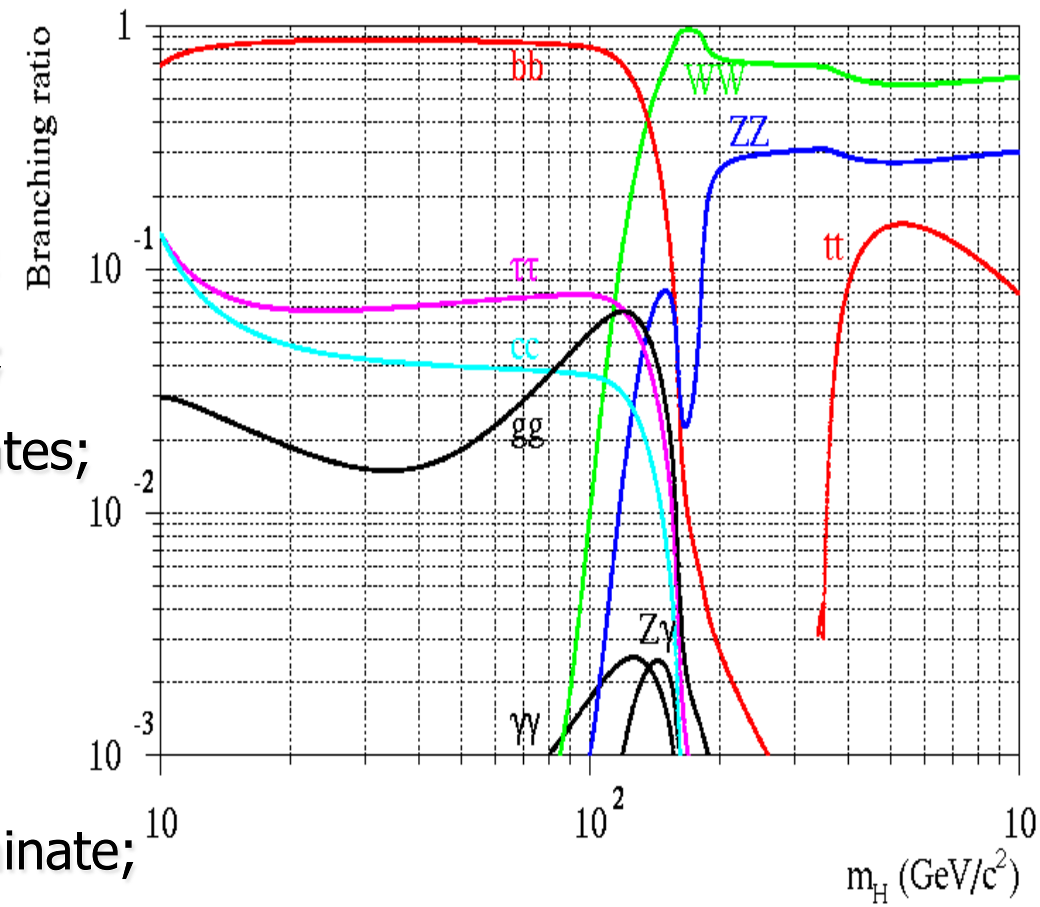
- $m_H < 2m_\mu$: $H \rightarrow e^+e^-$ dominates;
- $m_H < 2m_\pi$: $H \rightarrow \mu^+\mu^-$ dominates;
- $m_H < 3 - 4$ GeV: $H \rightarrow gg$ dominates;



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

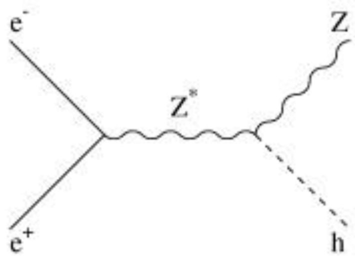
- $m_H < 2m_b$: $H \rightarrow \tau^+\tau^-$ and $c\bar{c}$ dominate;

- $m_H > 2m_b$ up to 1000 GeV/c^2:

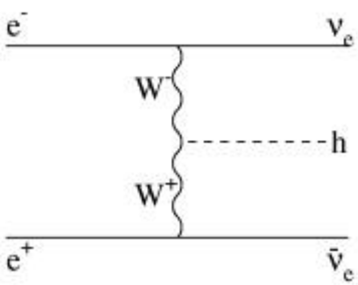


Direct search of SM Higgs @LEP2

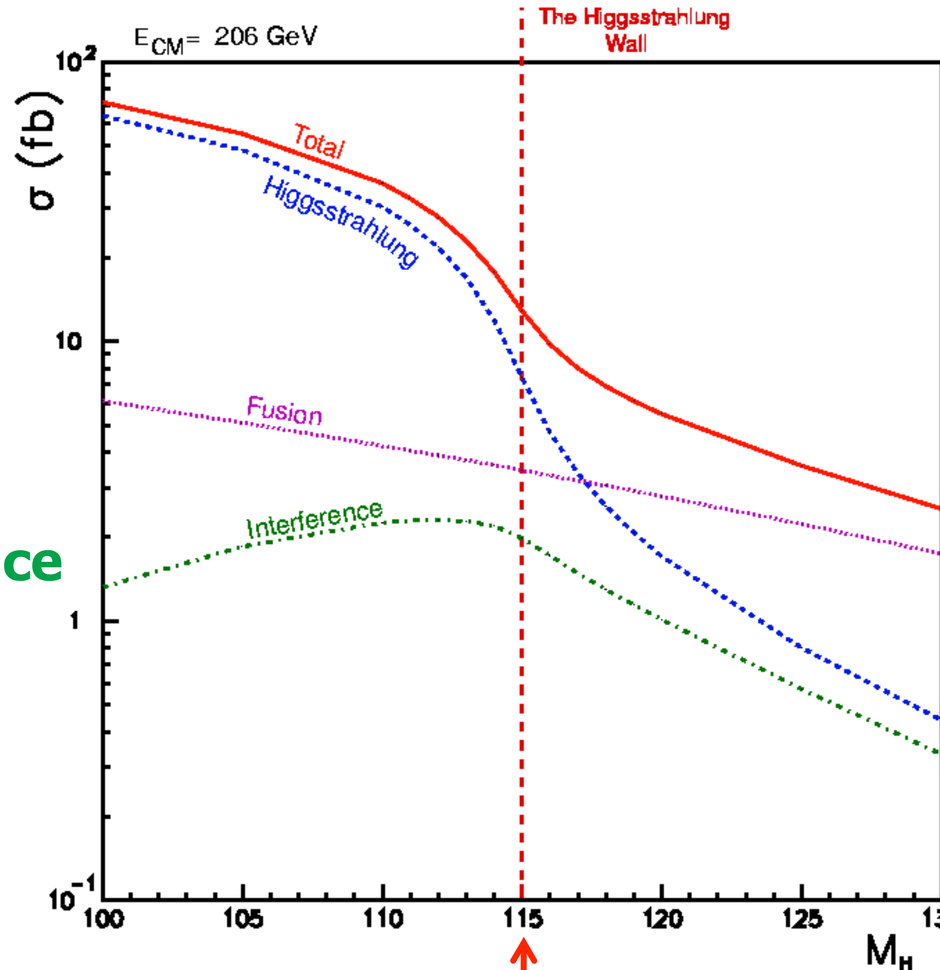
Higgsstrahlung
(dominant mode)



WW fusion

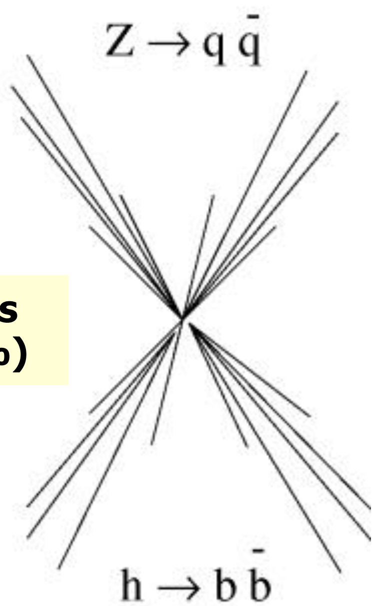


+ positive interference

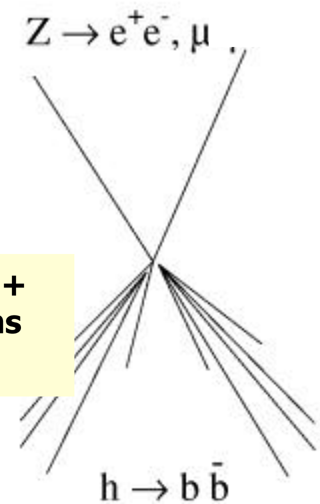


$M_H \leq \sqrt{s} - M_Z$

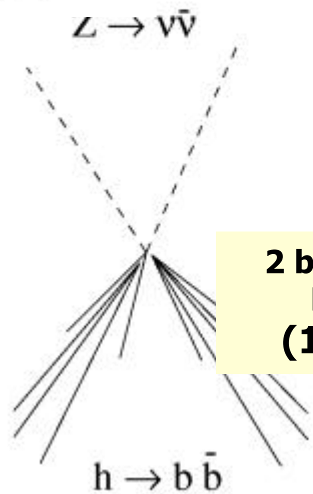
Higgs searches at LEP2



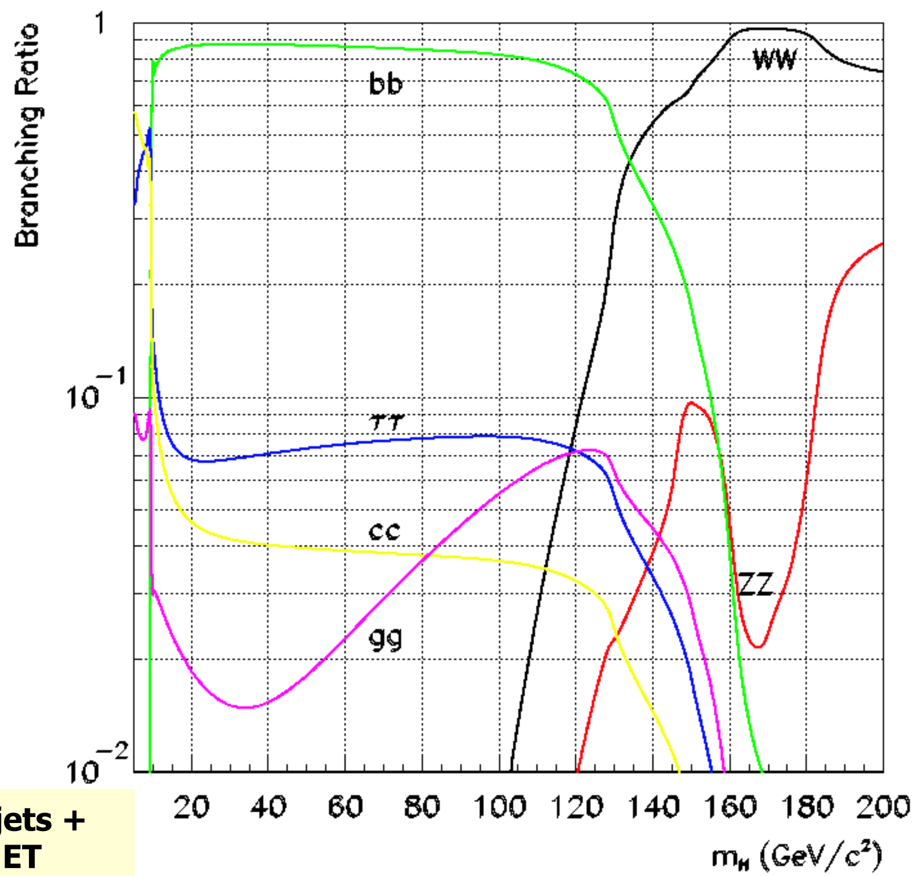
4 jets (60%)



2 b-jets + 2 leptons (6%)



2 b-jets + MET (19%)

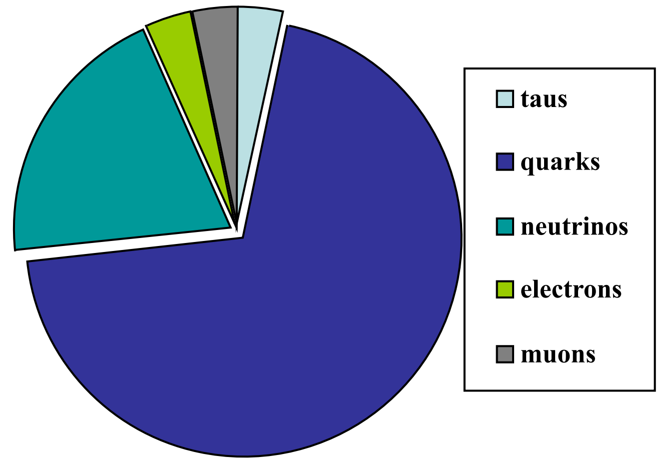


+ a contribution (7%) h → ττ (also WW*, gg)

Higgs event signatures

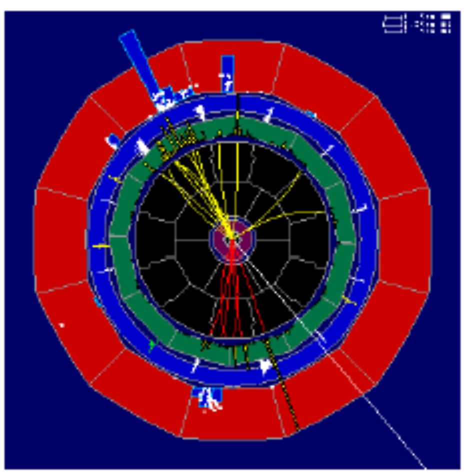
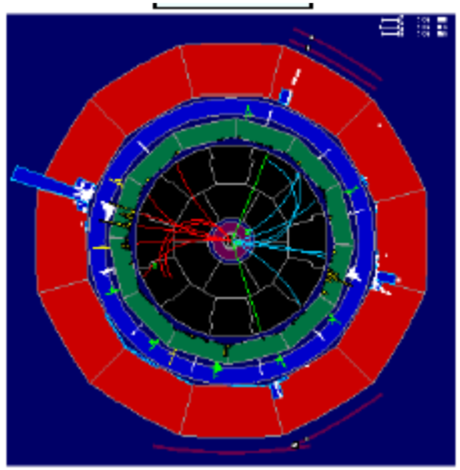
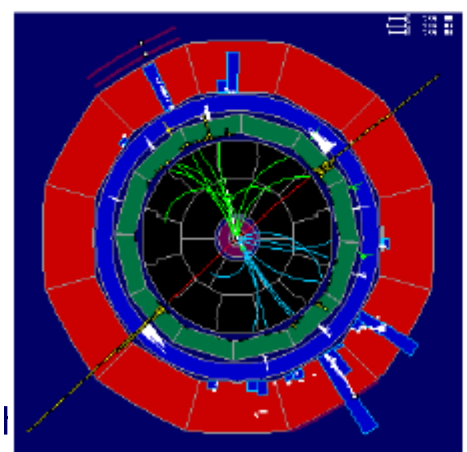
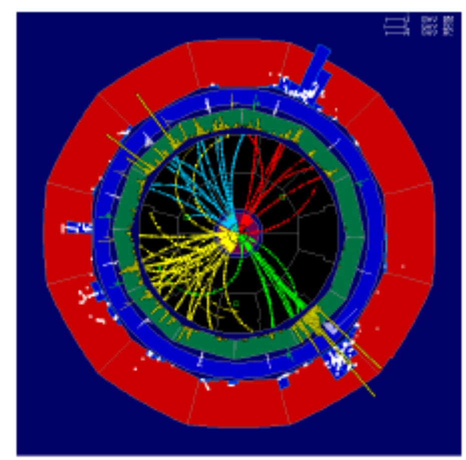
- Defined by the Z decay mode:

Higgs	Z	Fraction
bb	qq	51.5%
bb	$\nu\nu$	14.7%
Any	ll	6.7%
bb	$\tau\tau$	2.5%
$\tau\tau$	qq	5.0%
Total		80.9%



"missing E" "leptons" "4-jets"

$H\nu\bar{\nu}$ $H\mu^{+}\mu^{-}$ $He^{+}e^{-}$ $Hb\bar{b}$

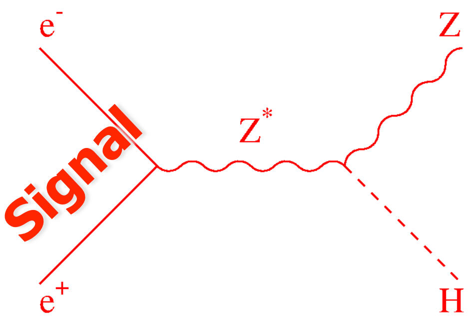





Signal vs Background (I)

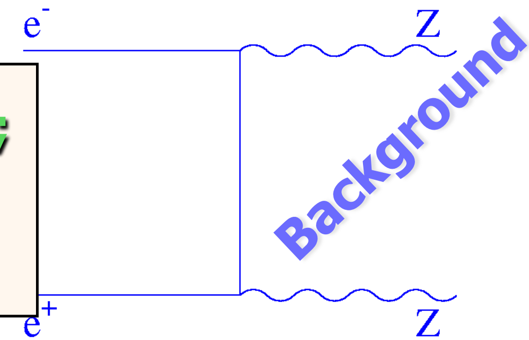
$e^+e^- \to HZ$
$\sigma = 0.1$ pb

Must evaluate the "signal-ness", s/b, of the candidate events

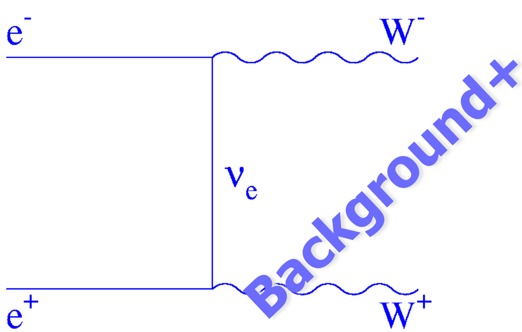
$e^+e^- \to ZZ$
$\sigma \sim 2$ pb

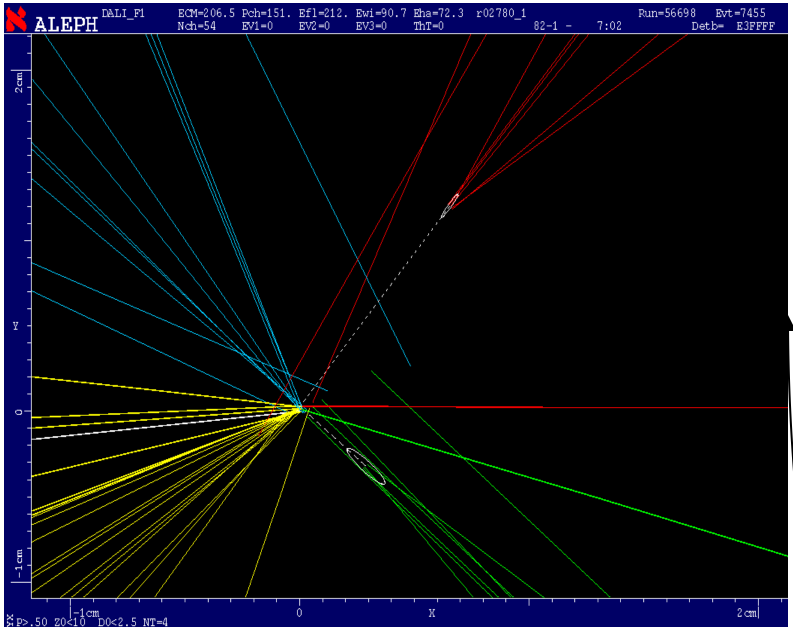


- **Reconstructed Higgs boson mass;**
- **Other kinematic variables;**
- **b-tagging (lifetime, leptons, ...);**

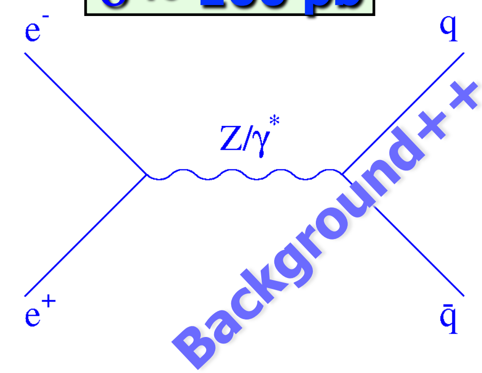


$e^+e^- \to W^+W^-$
$\sigma \sim 20$ pb





$e^+e^- \to q\bar{q}$
$\sigma \sim 100$ pb



Zoom of ±1cm around the interaction point

Signal topologies and background

Four-jet channel:

$Z \to qq$ $H \to bb$

70% x 80% > 50%

Kinematics & b-tag

ZZ "irreducible background"

$Z \to qq/\nu\nu/ll$ $Z \to bb$

$\sigma \sim 1$ pb (x 30% if bb)

"The Reference"

Missing energy channel:

$Z \to \nu\nu$ $H \to bb$

20% x 80% **> 15%**

Energy flow & b-tag

→

WW background

$WW \to qqqq$ $WW \to qq\tau\nu$

$\sigma \sim 18$ pb

"No b-tag (except Vcb)"

Leptonic channels:

$Z \to ll(e/\mu/\tau)$ $H \to bb$

$Z \to qq$ $H \to \tau\tau$ (70% x 7% **~ 5%**)

Lepton id (& b-tag)

→

Two fermion (Z/γ) background

ISR (single/double)

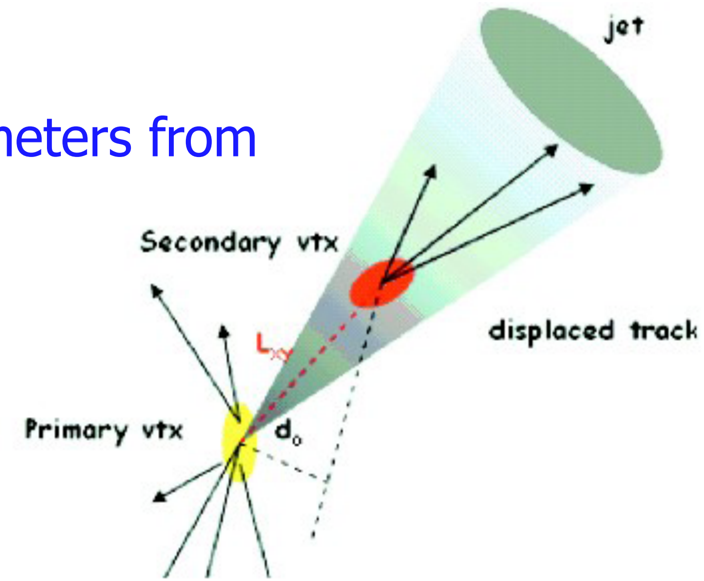
QCD: qq (g)(g)

B tagging

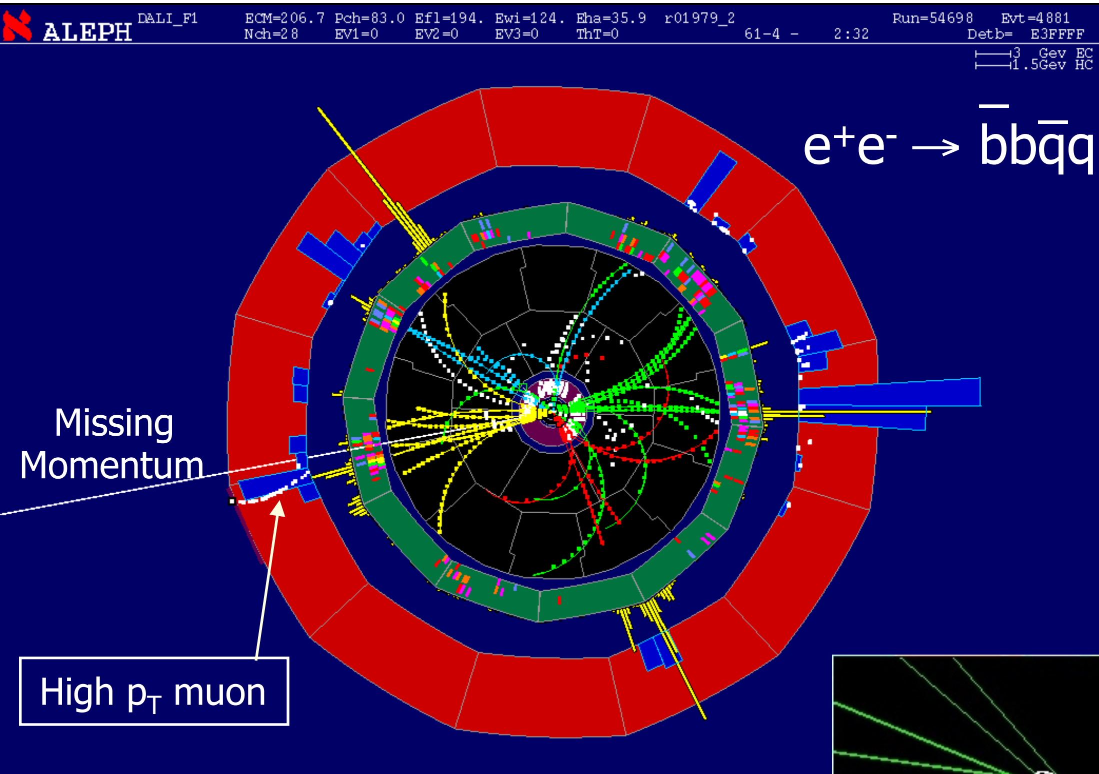
❑ b-tagging is crucial for Higgs searches at LEP

B hadron properties can be exploited to tag b-jets:

- long B lifetime (1.57±0.01 ps)
  - Can travel few millimeters before the decay
  - Secondary vertex displaced few millimeters from the interaction vertex
- high mass (~ 5.2 GeV/c^2)
- high charged decay multiplicity (4.97 ± 0.06)



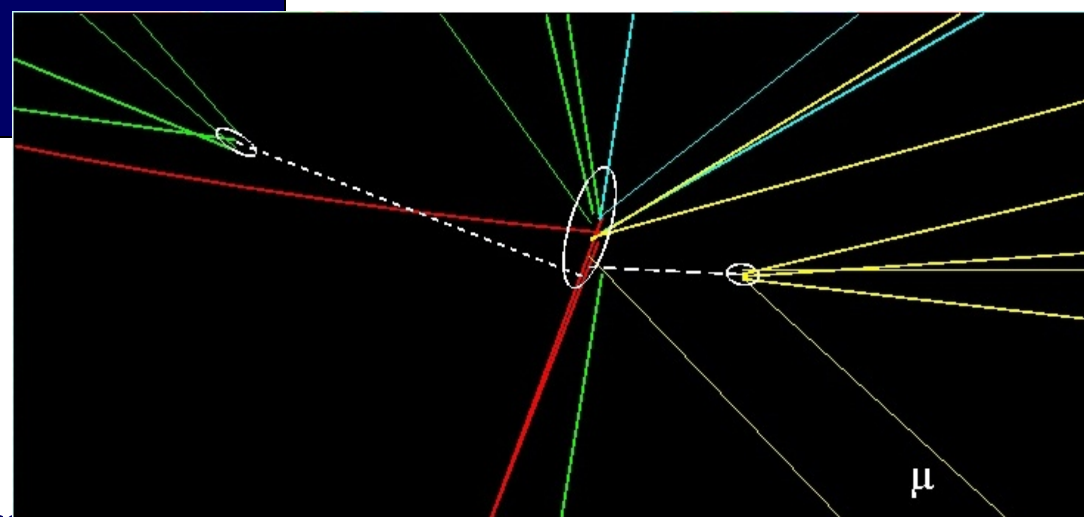
First pb^{-1}'s above 206 GeV:
First thrills at 115 GeV/c^2



First Candidate Event
(14-Jun-2000, 206.7 GeV)

- Mass 114.3 GeV/c2;
- Good HZ fit;
- Poor WW and ZZ fits;
- P(Background) : 2%
- s/b(115) = 4.7

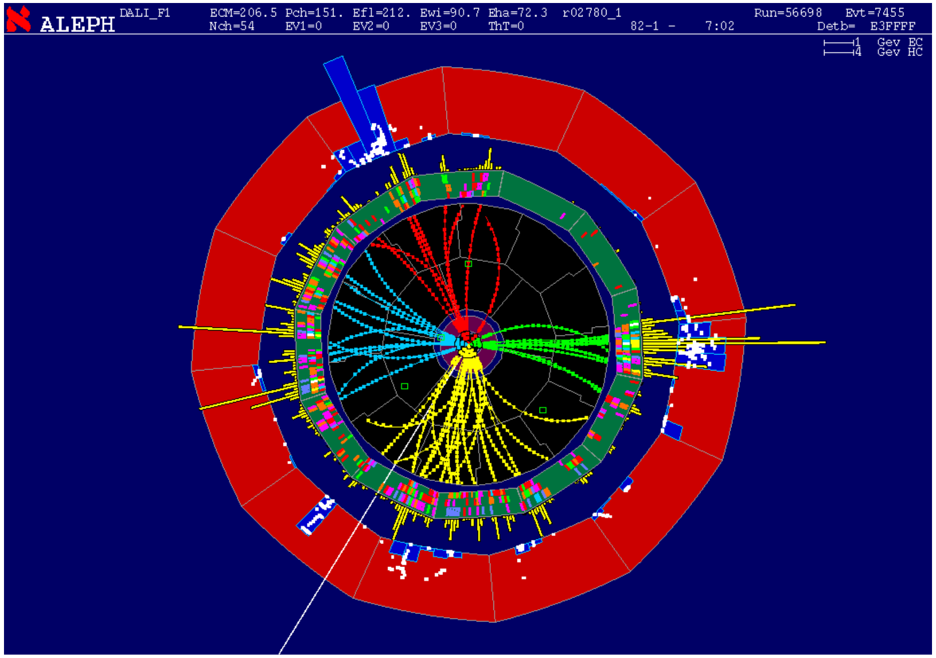
The purest candidate event ever!

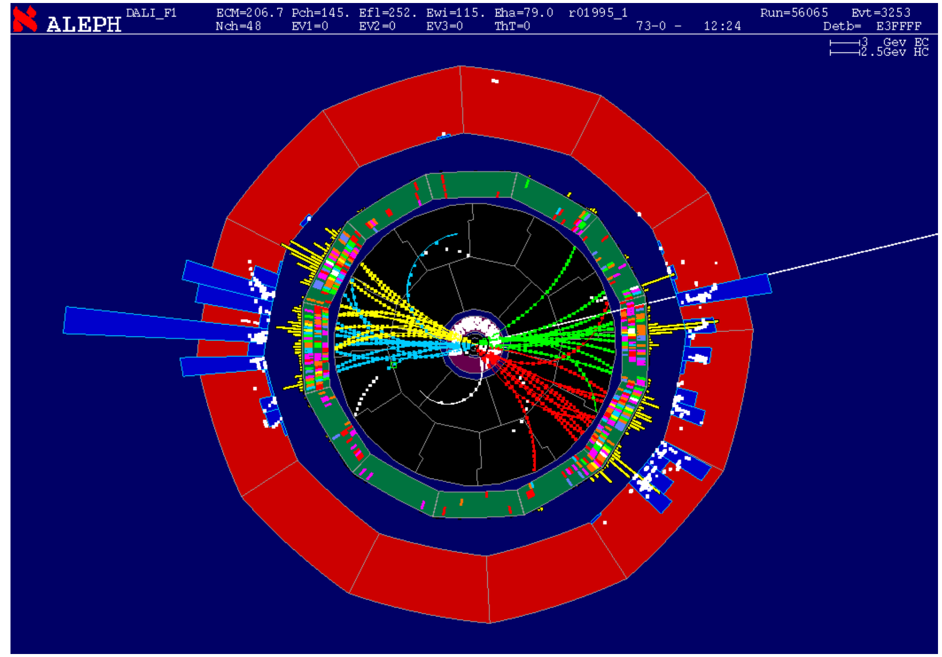


b-tagging
(0 = light quarks, 1 = b quarks)

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

ALEPH: four-jet bbbb candidates

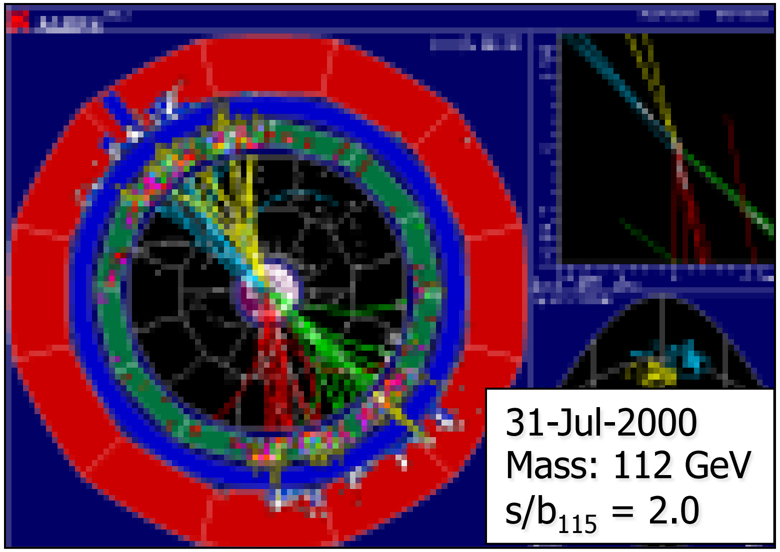


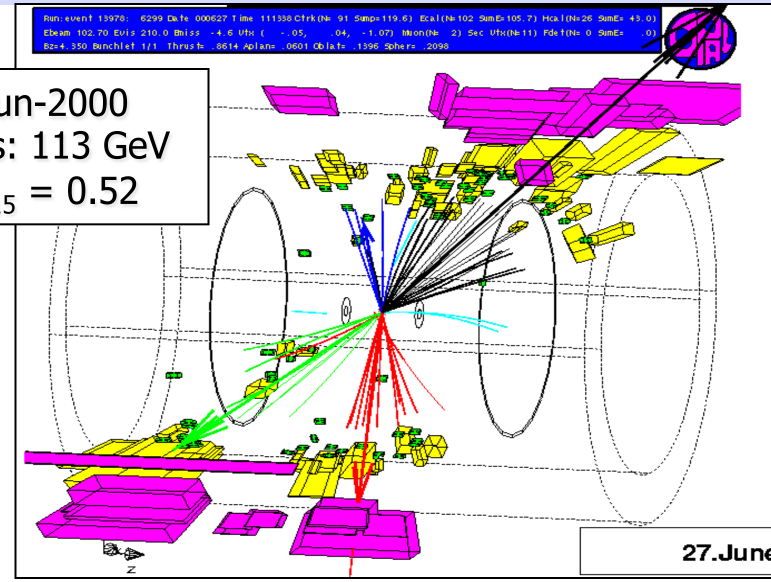


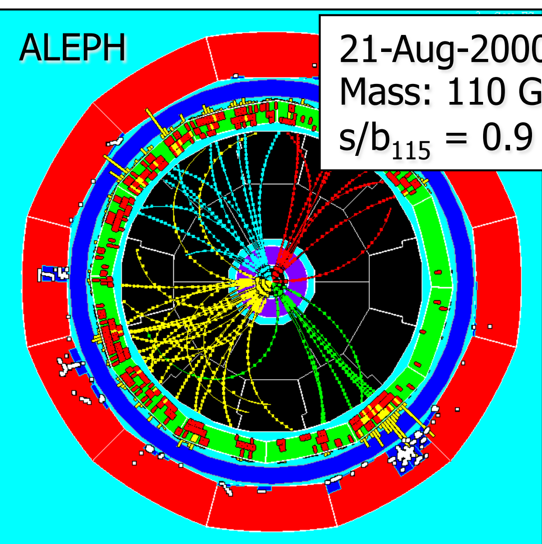
Two strong candidates, m=113, 110 GeV/c^2

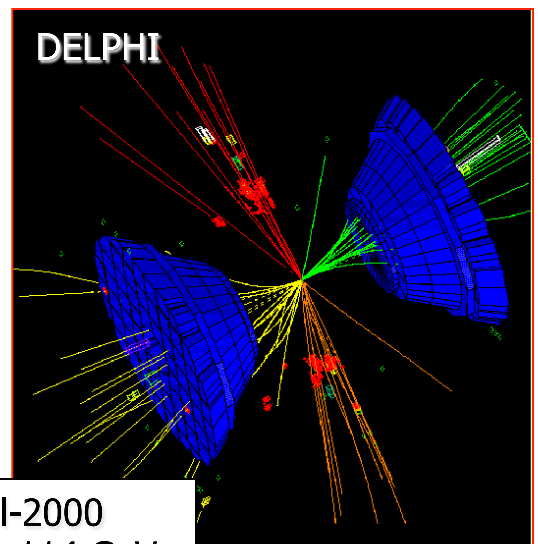
"Only" possible background: ZZ (+wrong pairing/undetected ISR)

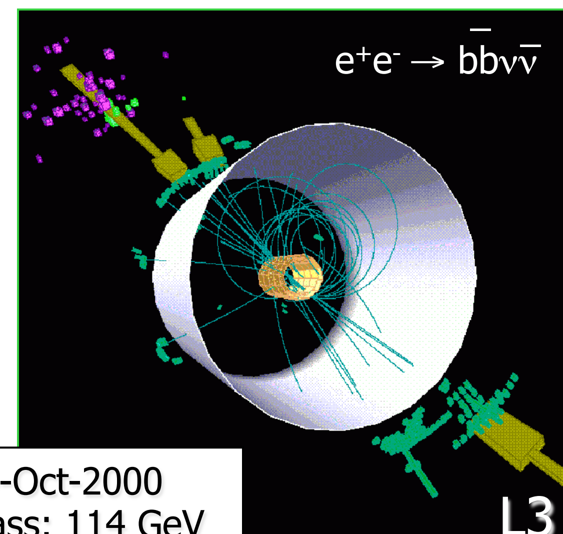
A few candidate events at 115 GeV/c^2











The 14 Most Significant Events

s/b > 0.3: Expected signal-to-noise ratio of ~1

Expected: 7
Observed: 14

Number of events compatible with s+b

Number of events in each experiment compatible with being democratic (~1.6 bkg expected)

In ALEPH: 6
In L3: 3
In OPAL: 3
In DELPHI: 2

In $Hq\bar{q}$: 9 (70%)
In $H\nu\bar{\nu}$: 3 (20%)
In Hl^+l^-: 2 (10%)

Number of events in each Z decay compatible with HZ predictions

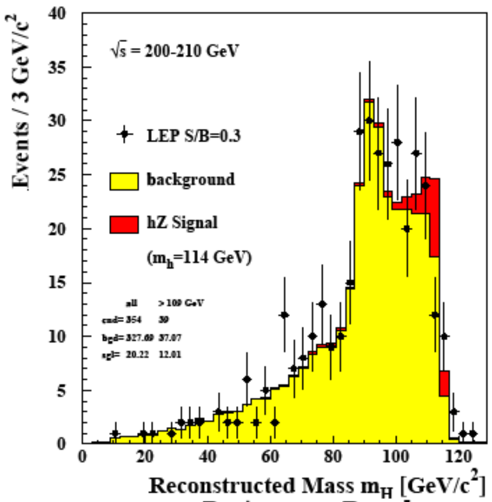
s/b	Rec. mass (GeV/c^2)	Channel	Expt
4.7	114	Hqq	ALEPH
2.3	112	Hqq	ALEPH
~~2.0~~ 0.7	~~114~~ 115	$H\nu\nu$	L3
0.90	110	Hqq	ALEPH
0.60	118	Hee	ALEPH
0.52	113	Hqq	OPAL
~~0.50~~ 0.7	111	Hqq	OPAL
0.50	115	$H\tau\tau$	ALEPH
0.50	115	Hqq	ALEPH
0.49	114	$H\nu\nu$	L3
0.47	115	Hqq	L3
0.45	97	Hqq	DELPHI
0.40	114	Hqq	DELPHI
0.32	104	$H\nu\nu$	OPAL

Values as of Nov 5th, 2000

Mass Reconstruction

Reconstructed m_H of selected candidates

Have to cut somewhere. For illustration only.
Cut on mass independent variables (like b-tags) so that $\frac{s_{expected}}{b_{expected}} \approx 0.3$ For m_{rec}>109 GeV for a 114 GeV Higgs

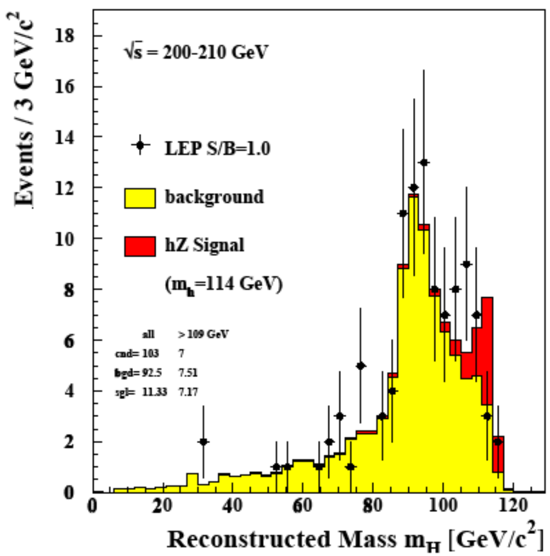


All 2000 Data

	Data	Backg	Signal
All m_{rec}	354	328	20.2
m_{rec}>109 GeV	39	37.1	12.0

Cutting a Little Harder

This time, adjust cuts so that $\frac{s_{expected}}{b_{expected}} \approx 1.0$ For m_{rec}>109 GeV for a 114 GeV Higgs



	Data	Backg	Signal
All m_{rec}	103	92.5	11.3
m_{rec}>109 GeV	7	7.5	7.2

The statistical procedure

LEP HIGGS WG

The data from all channels (**Hqq, Hνν, Hll, qqττ**) at all E_{cm} are combined in a 2-Dimensional space:

- reconstructed Higgs mass M_H^{rec}
- discriminant variable **G** (b-tag, kinematical info..)

In each bin of M_H^{rec} and G:

- Background (MC) b_i
- Signal (MC) s_i
- Num. of candidates N_i

For each "test mass" m(H)

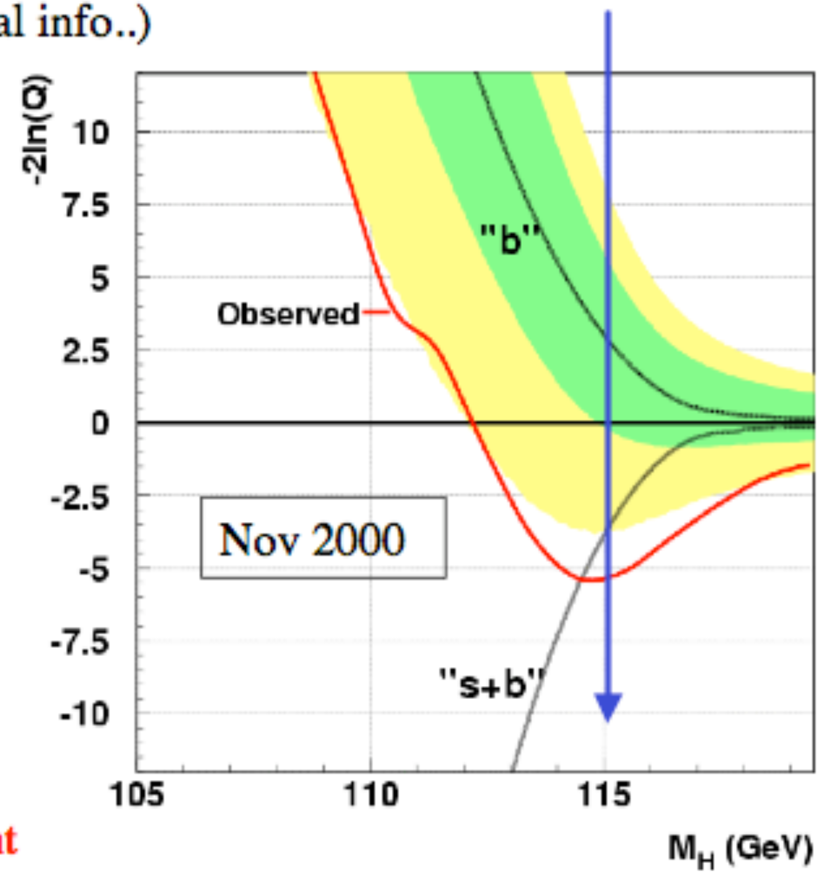
LIKELIHOOD TEST :

"sig+bkgr " ⇔ 'bkgr"

$$\ln Q(m(H)) = -S_{tot} + \sum N_i \ln[1+\underbrace{s_i(m(H))/b_i}_{W_i}]$$

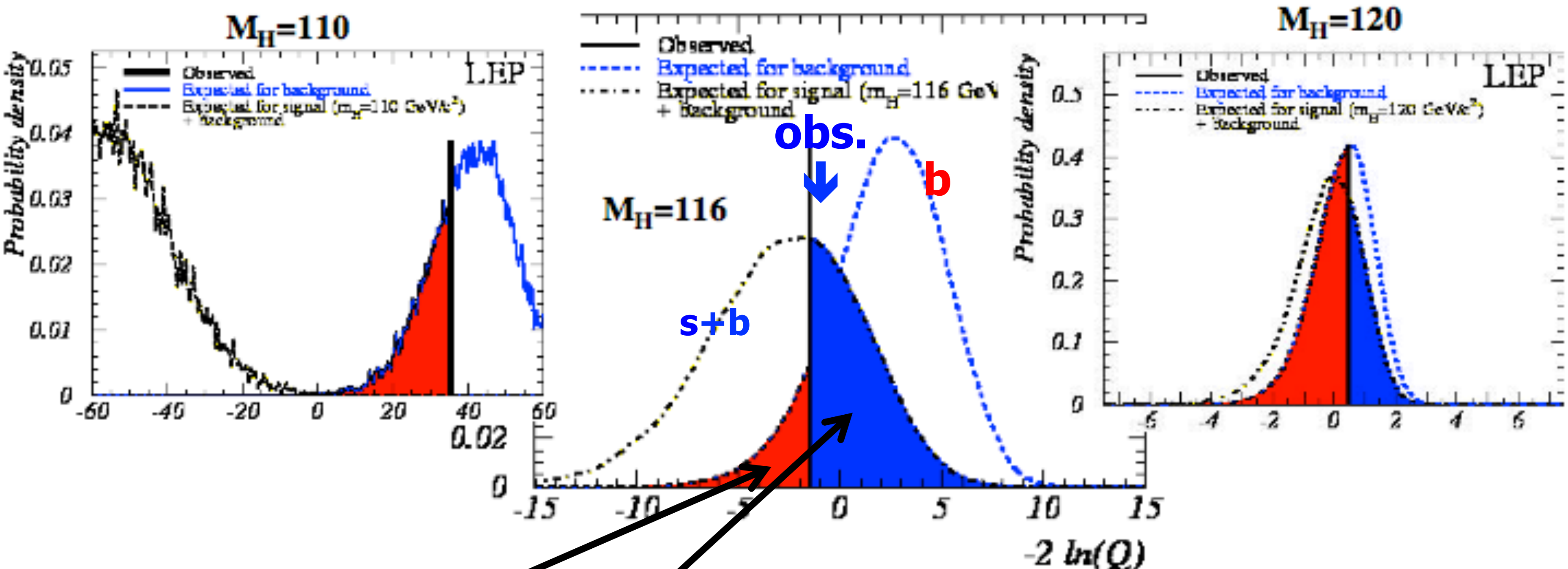
W_i of the event

$$Q(m(H)) = \mathcal{L}(s+b) / \mathcal{L}(b)$$ **"test statistic"**



How significant is it ?

Confidence Level



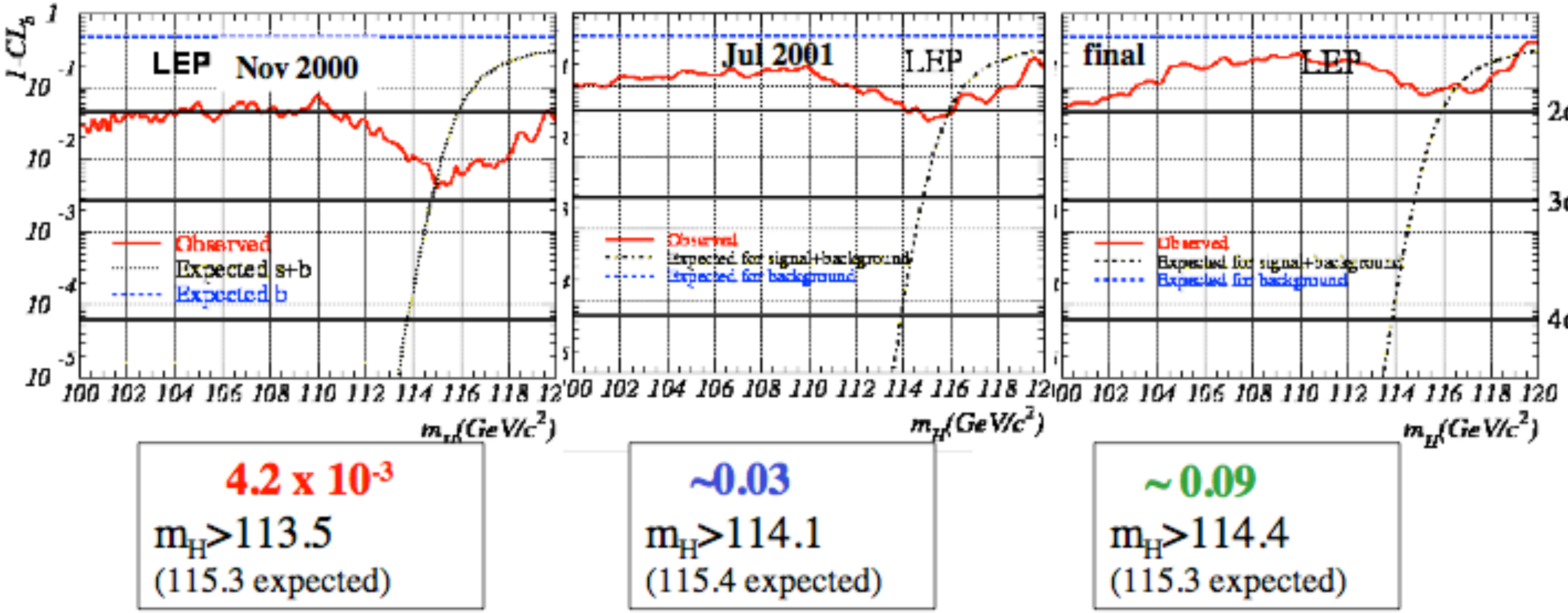
$1 - CL_b$: a measure of incompatibility with "b"

$1 - CL_b$	0.32	0.064	2.7×10^{-3}	6.3×10^{-5}	5.7×10^{-7}
	1σ	2σ	3σ	4σ	5σ

CL_{s+b} : a measure of compatibility with "s+b"

$CL_s = CL_{s+b} / CL_b$ gives the lower bound on Higgs mass

Higgs discovery?
from end of 2000 to the final results…



$1-CL_b$ confidence for background hypo. (if < $5.7*10^{-7}$ is a 5σ discovery)

CL_{s+b} confidence for signal+backg. hypo. (exclusion at 95% C.L. if < 0.05)

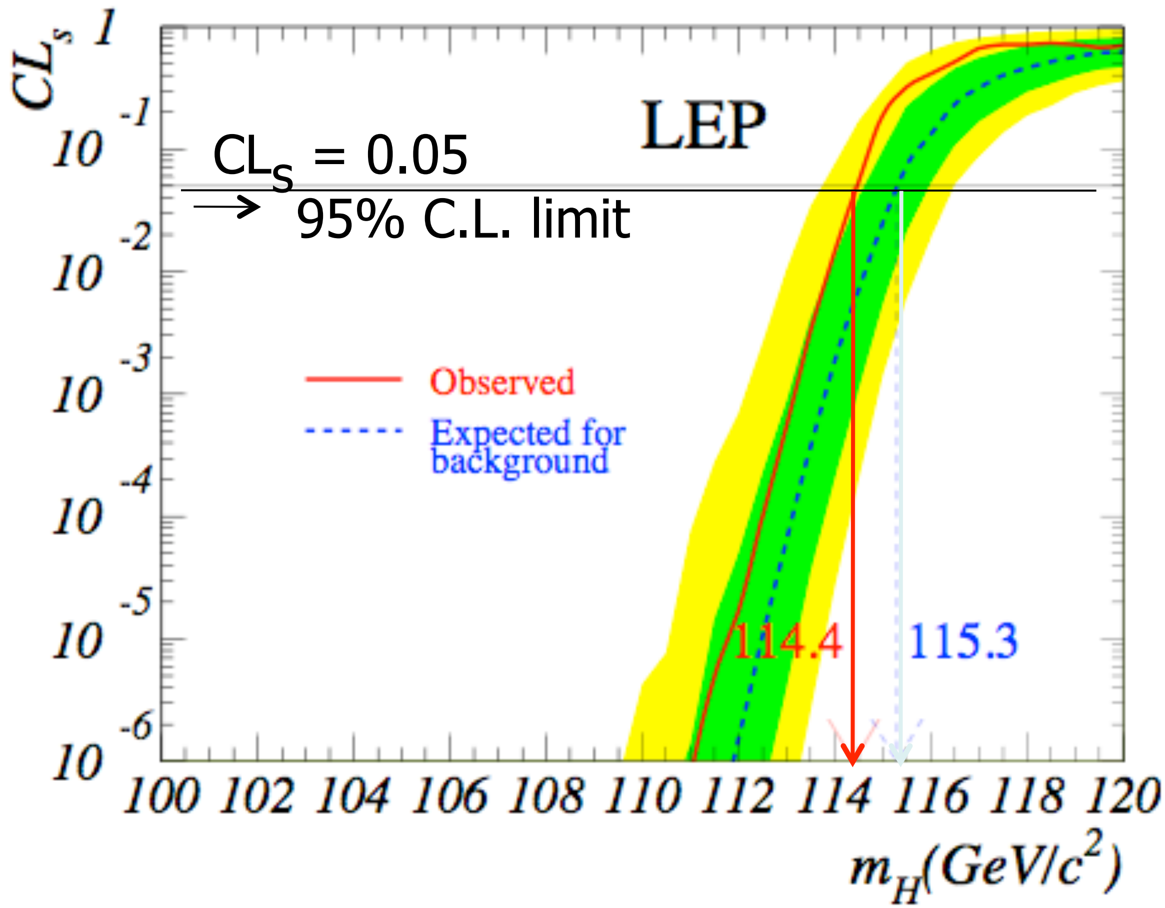
CL_s < 0.05 signal hypothesis ruled out at 95% C.L.

Higgs Mass Lower Bound

$CL_s = CL_{sb}/CL_b < 0.05$ for 95% C.L.
$m_{Higgs} > 114.4 GeV/c^2$

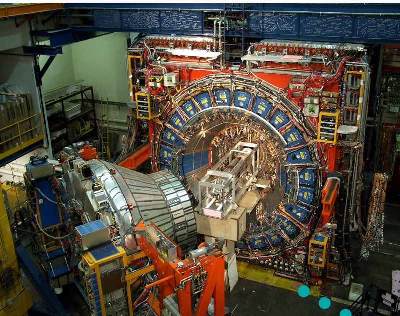
LEP excludes a 114.4 GeV Higgs boson @ 95% CL. (expected 115.3 GeV)

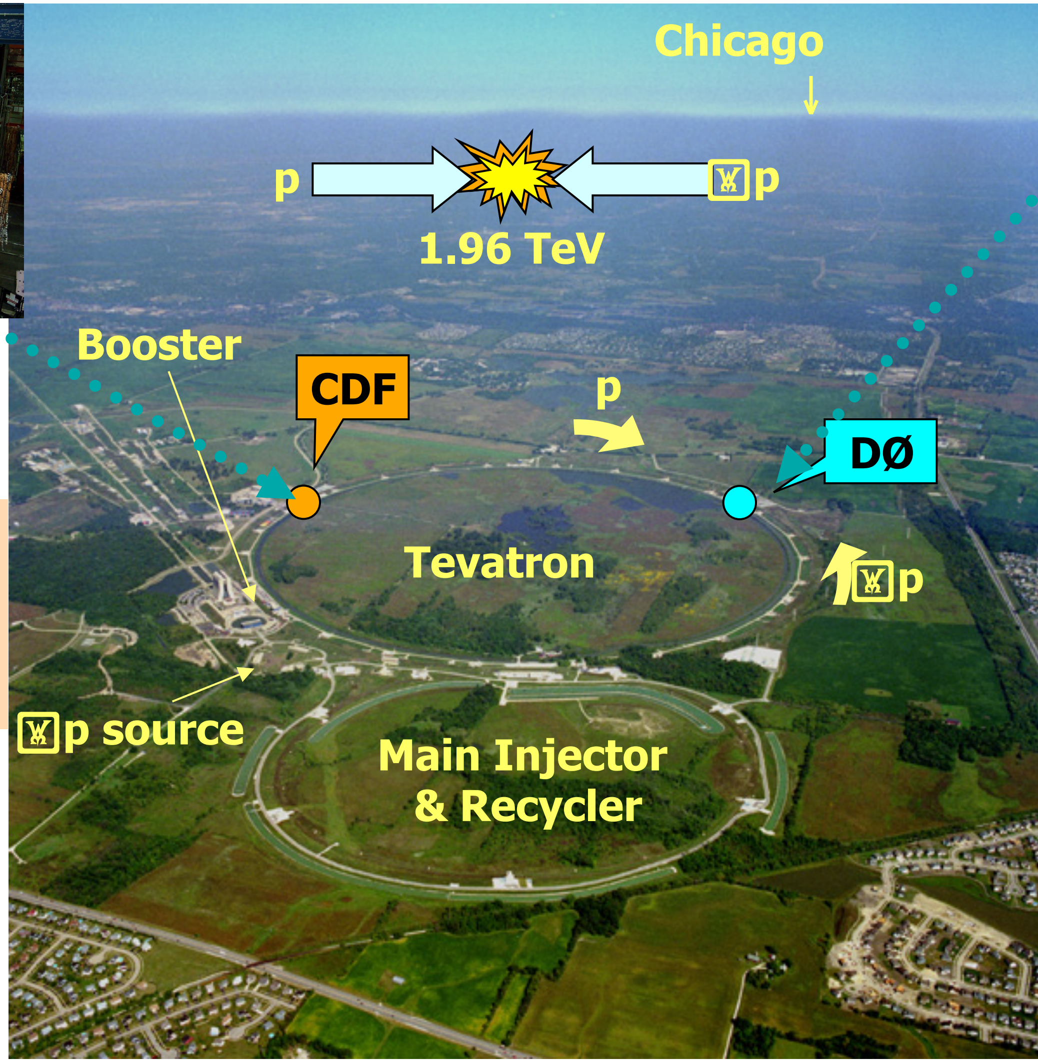
	Exp.	Obs.
ALEPH	113.5	111.4
DELPHI	113.3	114.1
L3	112.4	112.0
OPAL	112.7	112.7

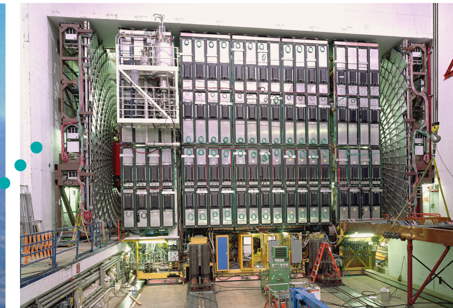


Higgs searches at TEVATRON

Fermilab TeVatron







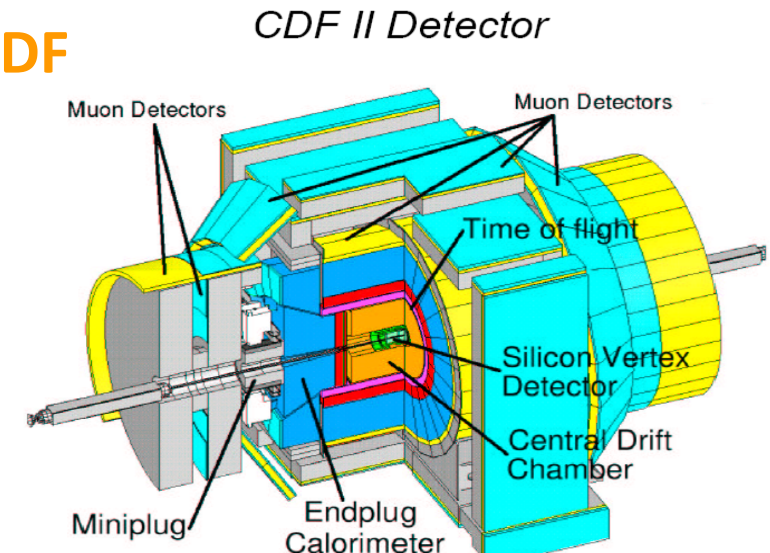
Run I
1992-1996
E_{CM} = 1.8 TeV
~120 pb^{-1}
(0.63 TeV ~600 nb^{-1})

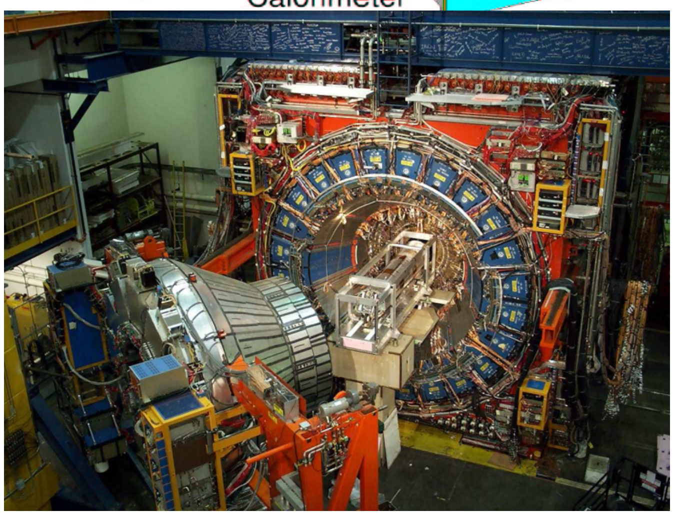
Run IIa
2001-2005
E_{CM} = 1.96 TeV
~ 1.2 fb^{-1}

Run IIb
2006-2009
E_{CM} = 1.96 TeV
expected~8 fb^{-1}

The detectors

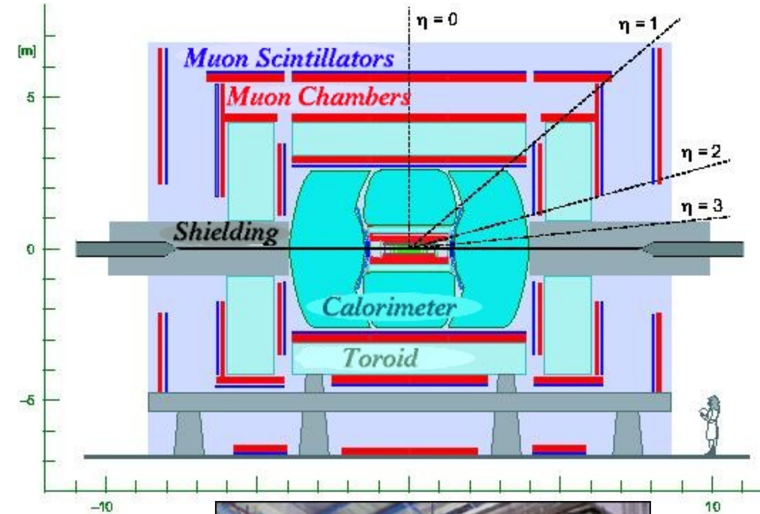
CDF





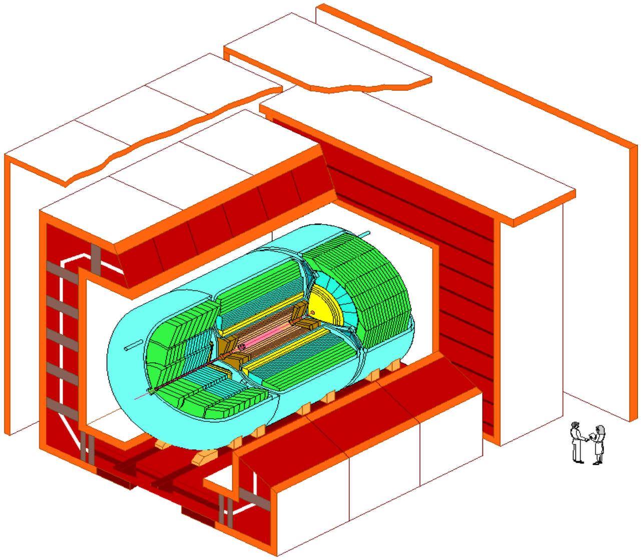
- Large tracking volume
- Vertex trigger
- Large trigger bandwidth

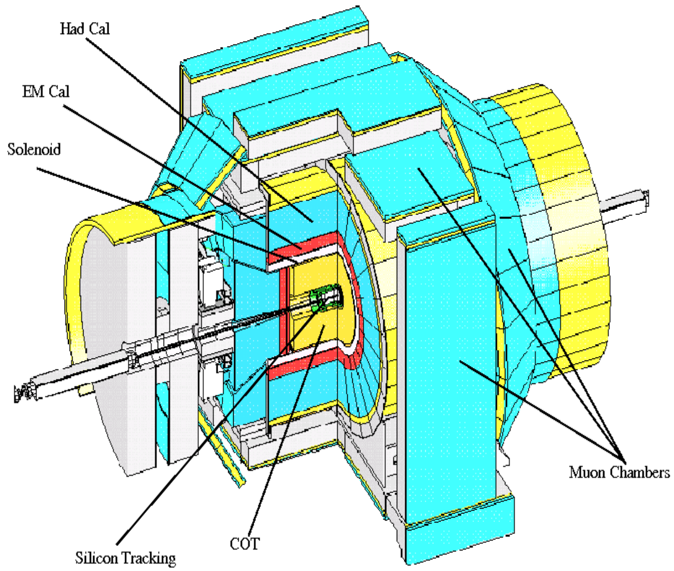
DØ



- Compact tracker,
- Large muon coverage

D0 and CDF Detectors





- Silicon Tracking
- Fibre Tracker
- L Ar Calo. $|\eta|<4$
- Muon: $|\eta|<2$

- Silicon Tracking
- Open drift Cell Tracker
- Scintillator Calo. $|\eta|<3.2$
- Muon coverage $|\eta|<1.5$

Results for 5.3-5.4 fb^{-1}

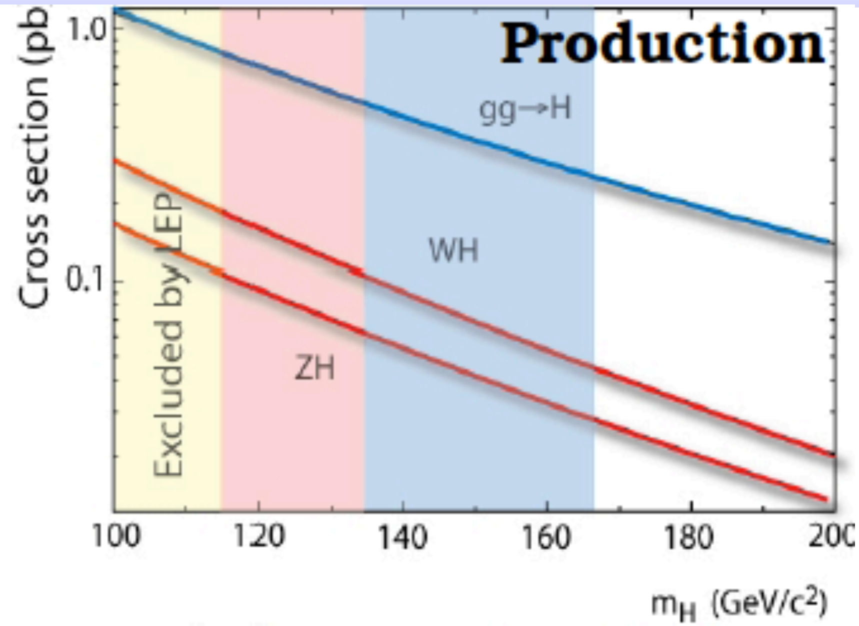
Higgs production and decay

Higgs production via gluon fusion dominates at the Tevatron

- Large multijet background makes fully hadronic searches difficult

Next largest rate is associated production of W/Z bosons + Higgs

- Leptonic decays of W/Z bosons provide a tag for triggering and analysis

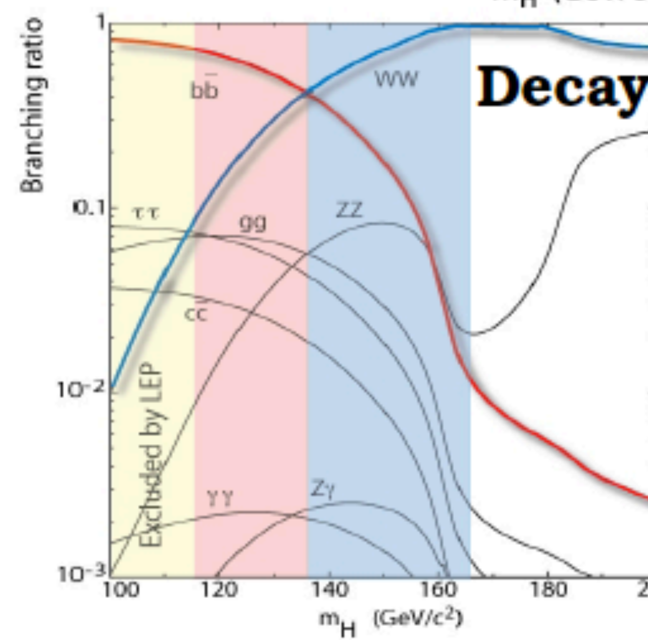


A low-mass Higgs (M_H<135 GeV) prefers to decay to bottom-quark pairs

- Need efficient identification of bottom quarks to reduce backgrounds

At high mass (M_H>135 GeV), search for $H \rightarrow WW^*$

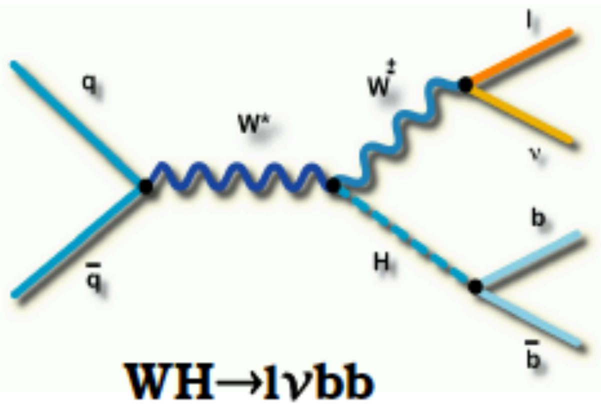
- Potential for an off-shell W boson allows non-resonant production

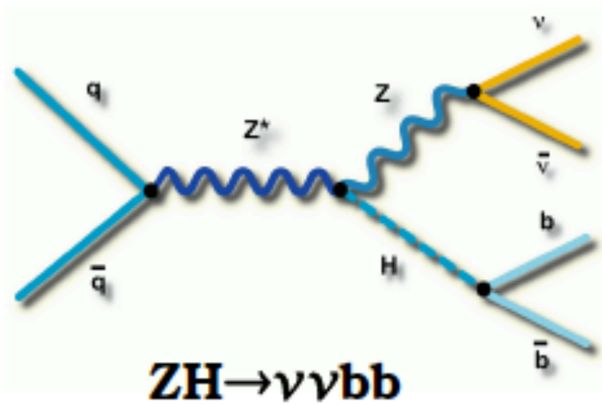


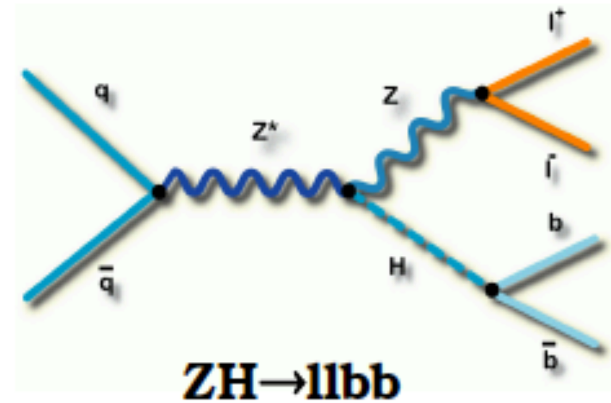
The Tevatron's Search for Low Mass Higgs Bosons

Higgs production processes

Associated Production: Low mass only, 3 dominant final states



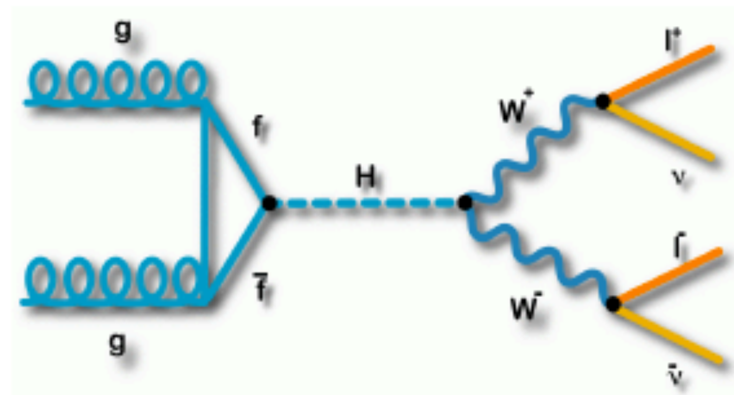




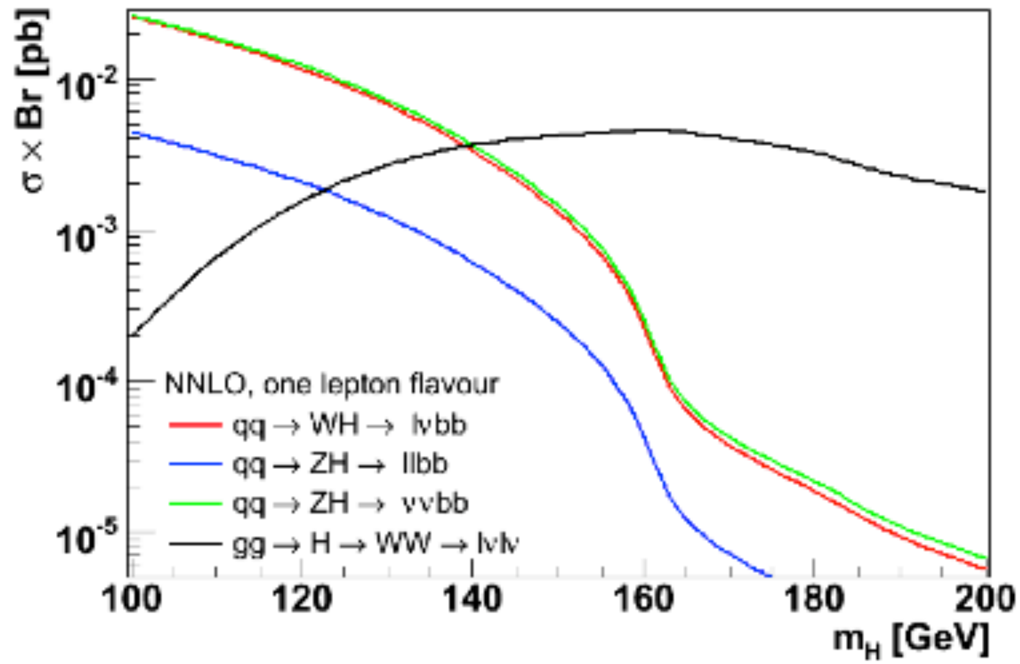
Gluon Fusion Production:

Maximum sensitivity at high mass,
also useful at low mass

Discussed in the next talk



How to search higgs at low mass?



ZH→νν bb	WH→lν bb	ZH→ll bb
MET+bb	l+MET+bb	2l(e/μ)+bb
Rich signal	Rich signal	less signal
0-lepton	1-lepton	2-lepton

Multi-Jet (MJ) BG:
HIGH → LOW

Extension:
- H→ γγ
- VH→τ + jets
- ttH→ttbb
- Signal from gg->H, VH, VBF

Low Mass SM Higgs Searches

- WH → e(μ)ν +bb
- ZH → (ee/μμ)νν + bb
- Measurements rely on
  - b-tagging
  - Lepton identification + Missing-E_T resolution
  - Dijet mass resolution and light/b-jet calibration
    - Z → bb
  - Understanding of backgrounds
    - W/Z + heavy-flavor/light jets

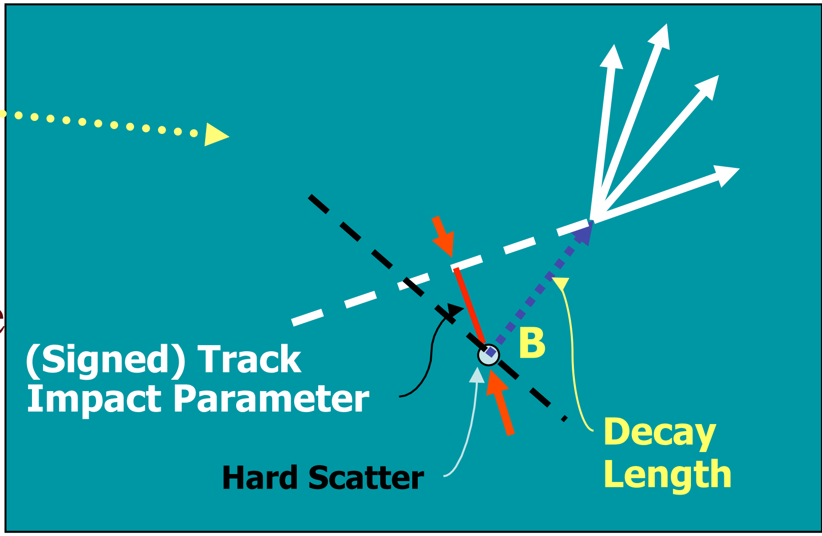
b-tagging (B lifetime (1.57±0.01 ps)

Based on signed impact parameter resolution

Jet Lifetime Impact Parameter algorithm

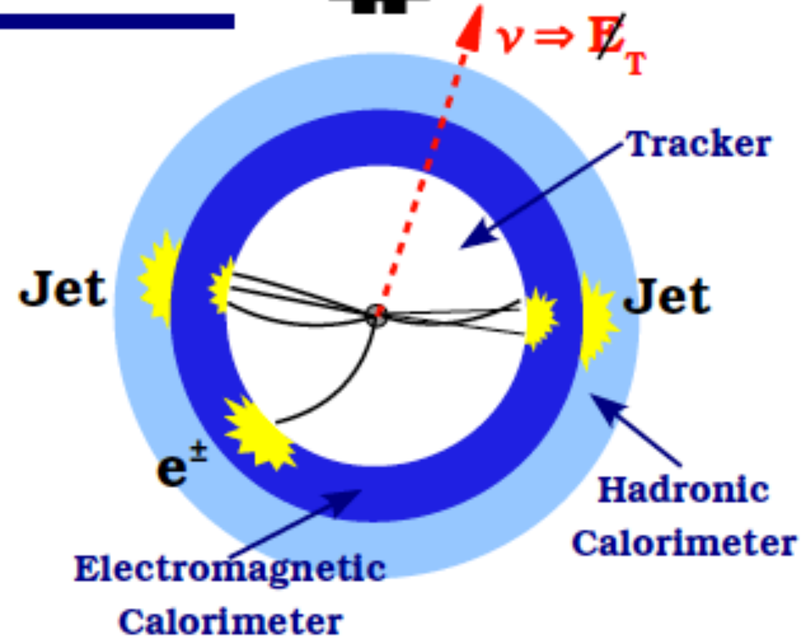
Based on decay length resolution

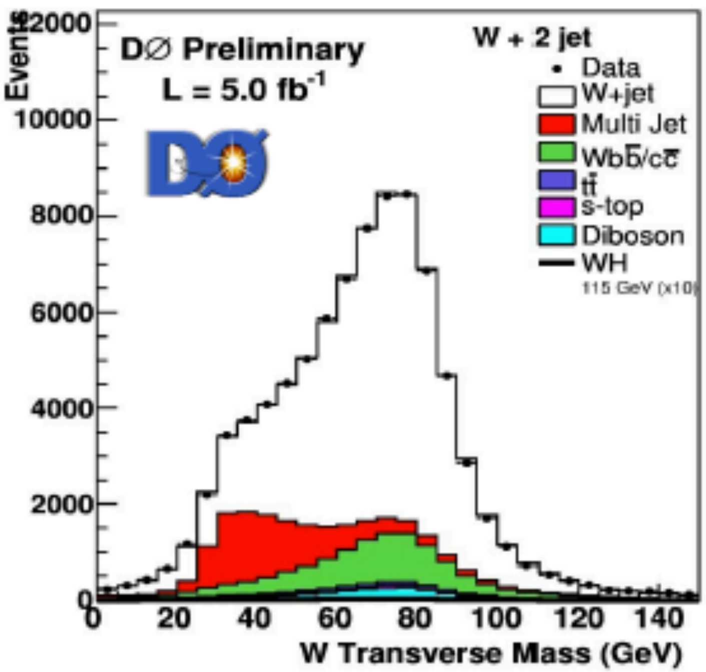
Secondary Vertex Algorithm

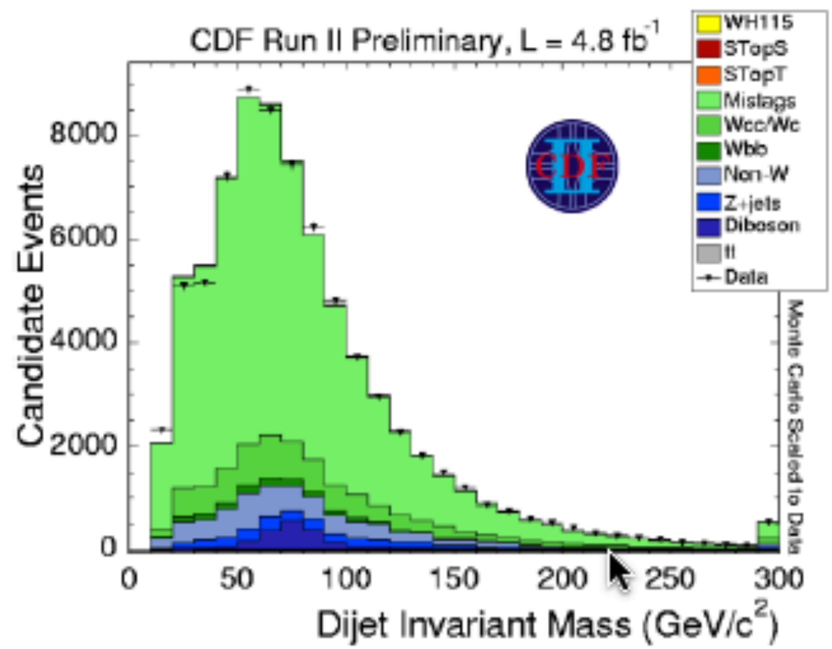


$WH \rightarrow l\nu bb$

- Identify events consistent with W decays
  - Trigger on **electrons** or **muons**
  - Select significant missing transverse energy (MET) as a signature for neutrinos
- Select events with 2 or 3 jets
  - Modeling of dijet invariant mass is crucial for detection of H→bb mass resonance

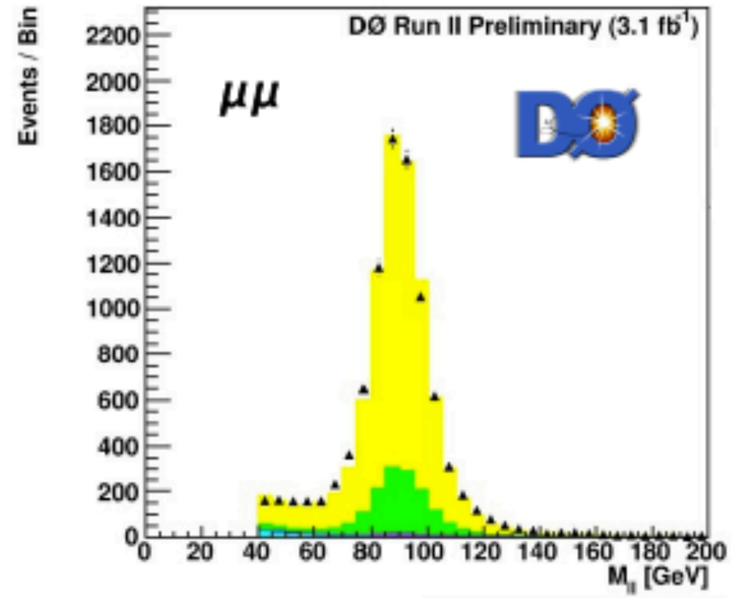


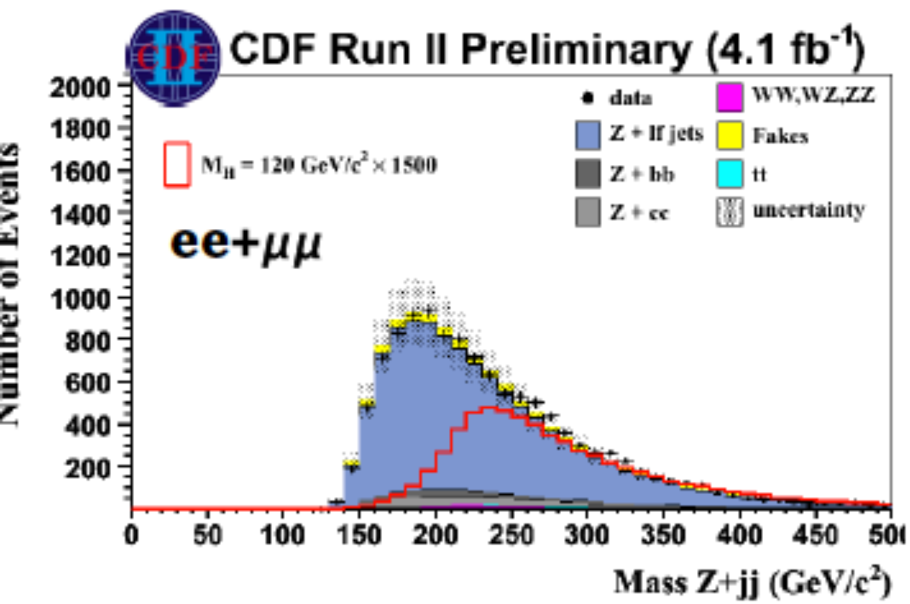


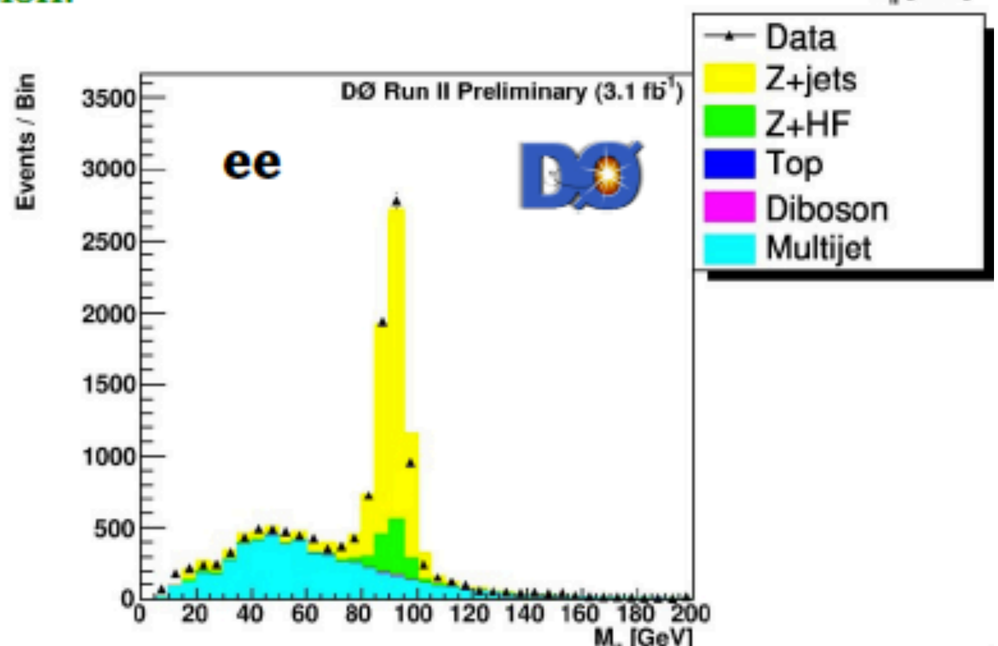


$ZH \rightarrow llbb$

- Di-lepton Z boson decays make this channel:
  - Easier: More efficient trigger, smaller multi-jet background, reconstructed Z mass provides reliable handle on event.
  - Harder: Very small signal rate, more sensitive to lepton ID efficiency loss.
- Select two leptons & at least two jets
  - Low MET final state enables the use of kinematic fitting to improve dijet mass resolution.

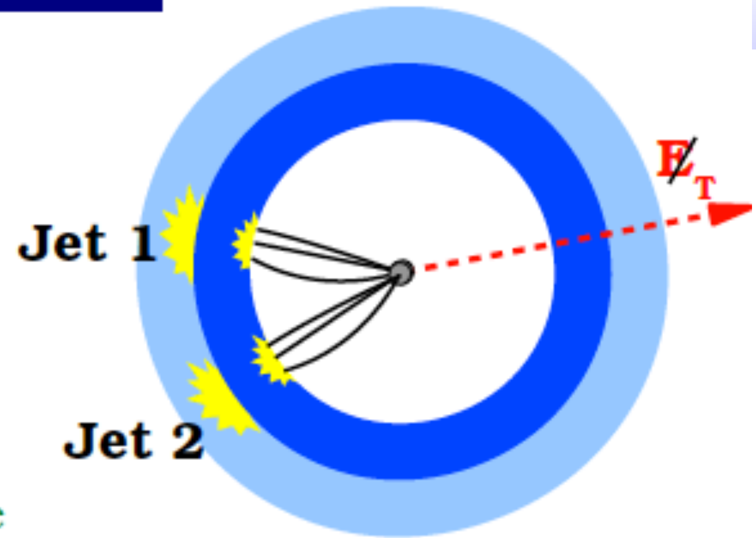


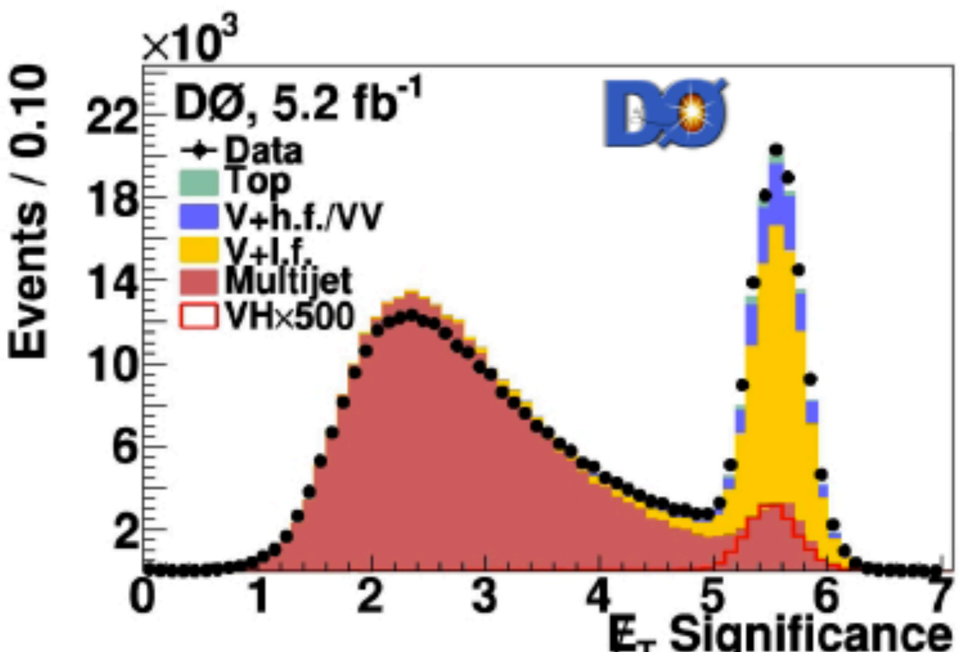


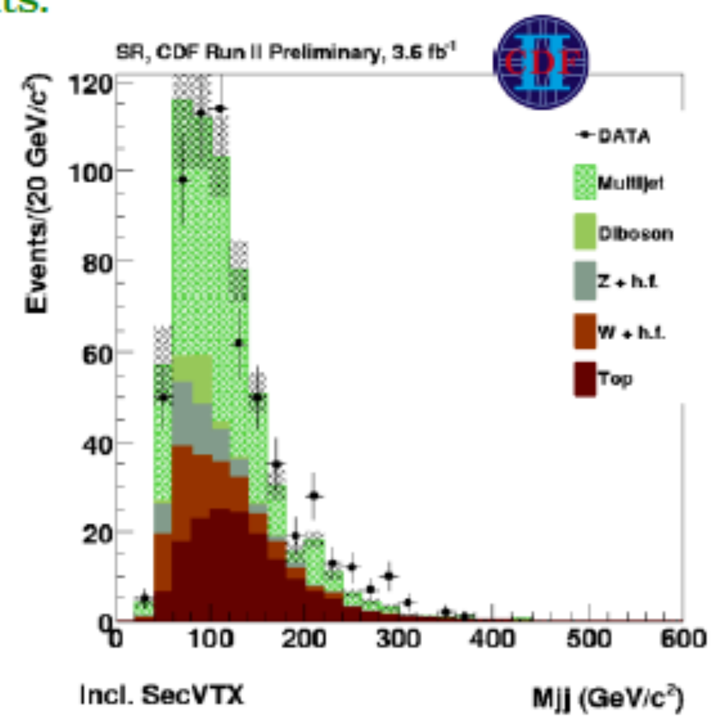


ZH → ννbb

- ✗ For ZH→ννbb the search is more difficult: no charged leptons!
  - Rely on large MET (neutrinos!)
  - Backgrounds:
  - <u>"Physics":</u> Z+jets, W+jets, top-pair, ZZ, WZ
  - <u>"Instrumental":</u> Multijets with mis-measured jets
- Trigger on large MET + 2 jets, veto on leptons, improve multijet prediction by refining MET measurements.







Latest results from Tevatron

Legacy results from FNAL
25 years of work on Higgs searches !

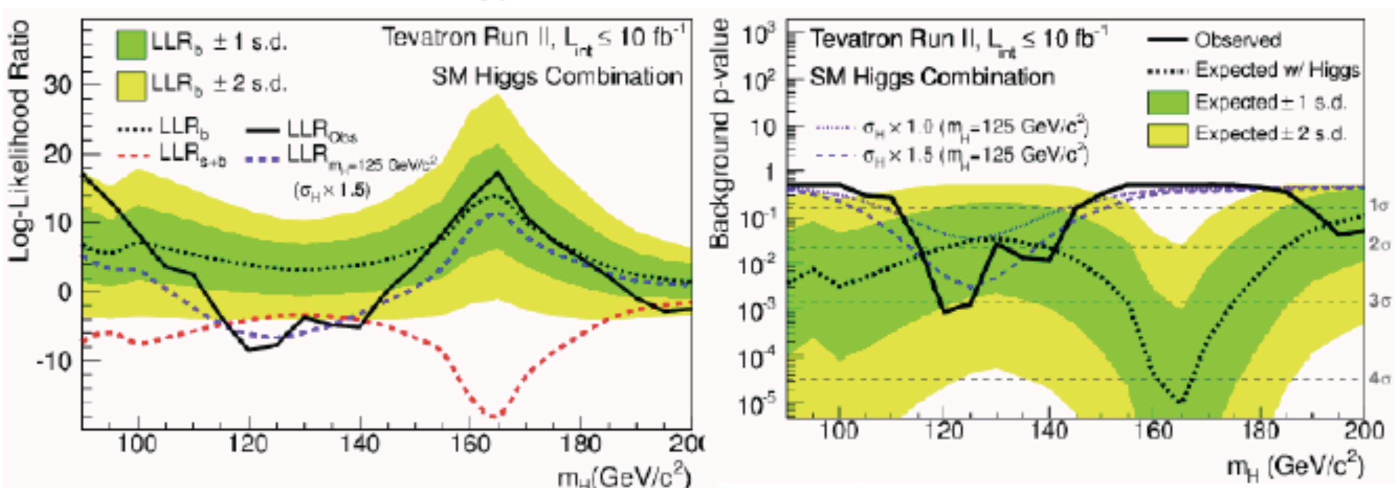
PHYSICAL REVIEW D VOLUME 41, NUMBER 5 1 MARCH 1990

Rapid Communications

Search for a light Higgs boson at the Fermilab Tevatron proton-antiproton collider

Combined SM Higgs results

- Combine ~300 sub-channels
- Build Likelihood based on all multivariate discriminant distributions to test S and S+B hypotheses



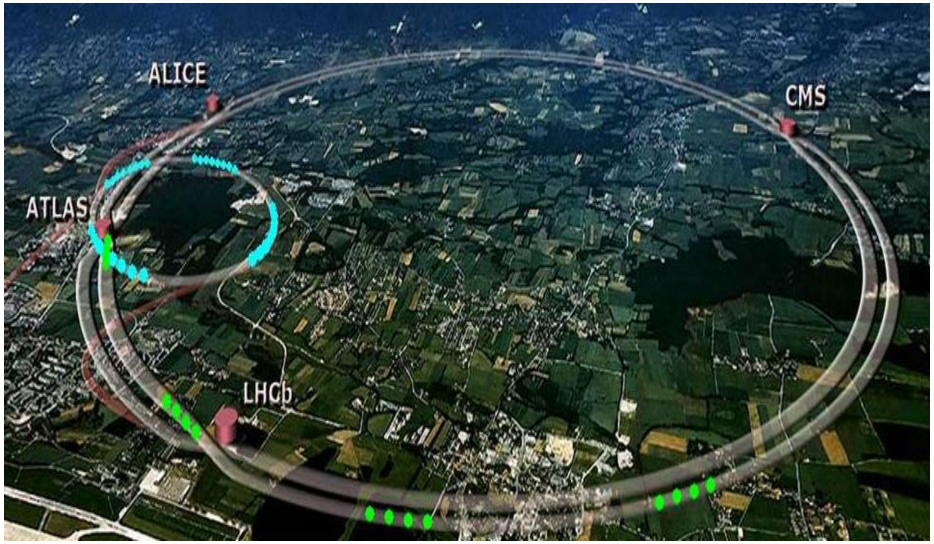
- Broad excess in the low mass range around 115-140 GeV
- Local p-value corresponding to 3.0 sigma for M_H=125 GeV
  - D0 1.7 sigma @ 125 GeV
  - CDF 2.0 sigma @ 125 GeV
- Consistent with a Higgs boson of 125 GeV at x1.5 SM rate

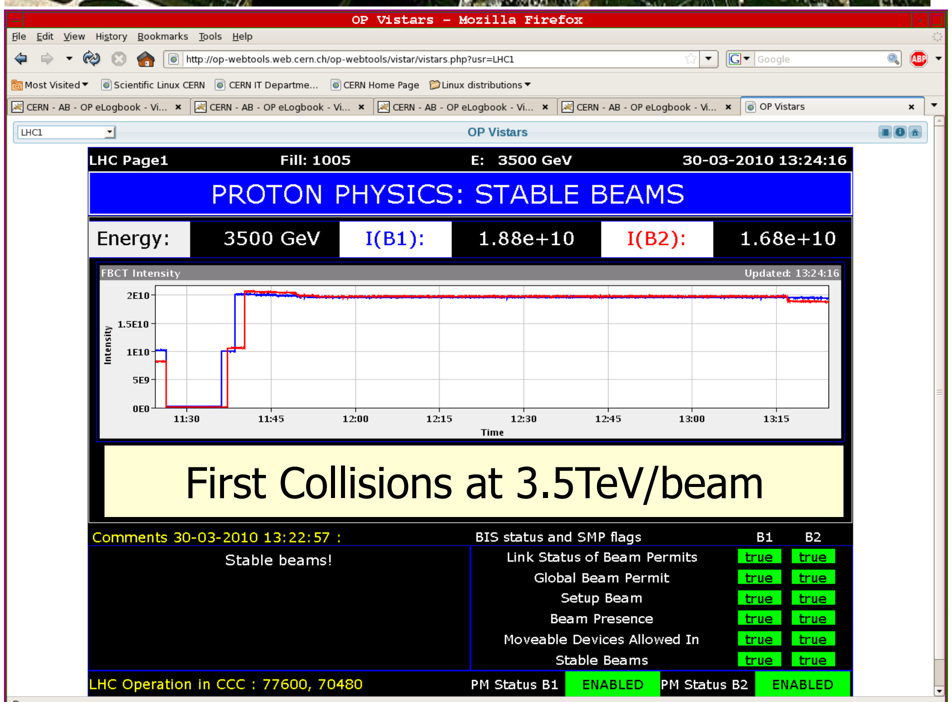
bb: a nice channel at FNAL

- $H \rightarrow b\bar{b}$ results: R=1.6 ± 0.7
  - Atlas R= 0.2±0.6
  - CMS R= 1.0±0.5

Higgs searches at LHC

The LHC machine





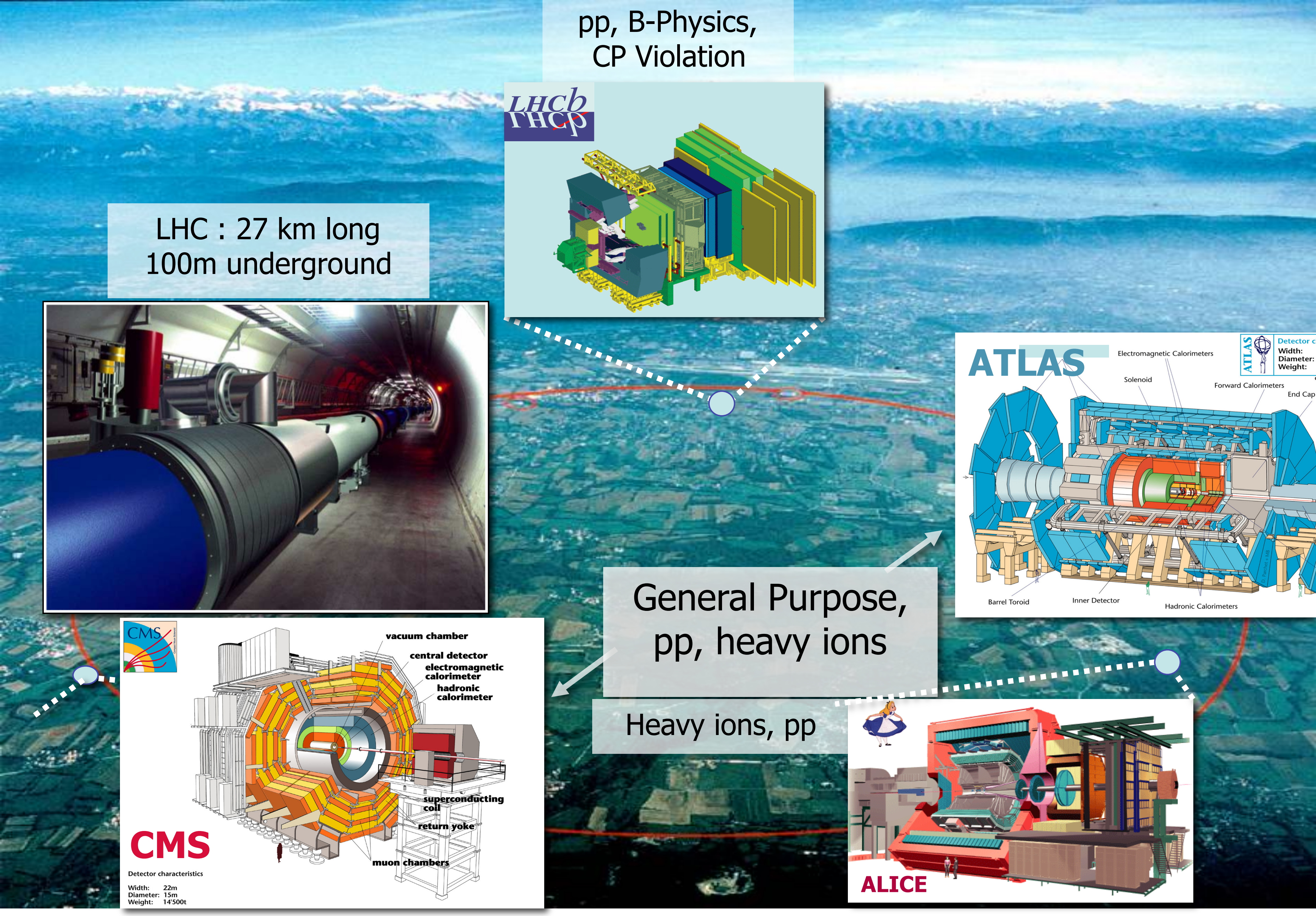
Circumference (km)	26.7
Number of superconducting Dipoles	1232
Length of Dipole (m)	14.3
Dipole Field Strength (Tesla)	8.4
Operating Temperature (K)	1.9
Current in dipole sc coils (A)	13000
Beam Intensity (A)	0.5
Beam Stored Energy (MJoules)	362
Number of particles per bunch	1.15×10^{11}
Number of bunches per beam	2808
Crossing angle (μrad)	285
Bunch length (cm)	7.55
Norm transverse emittance (μm rad)	3.75
Beta function at IP 1,2,5,8 (m)	0.55,10,0.55,10

$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \varepsilon_n \beta *} F$$

N_b = number of proton per bunch
n_b = number of bunches

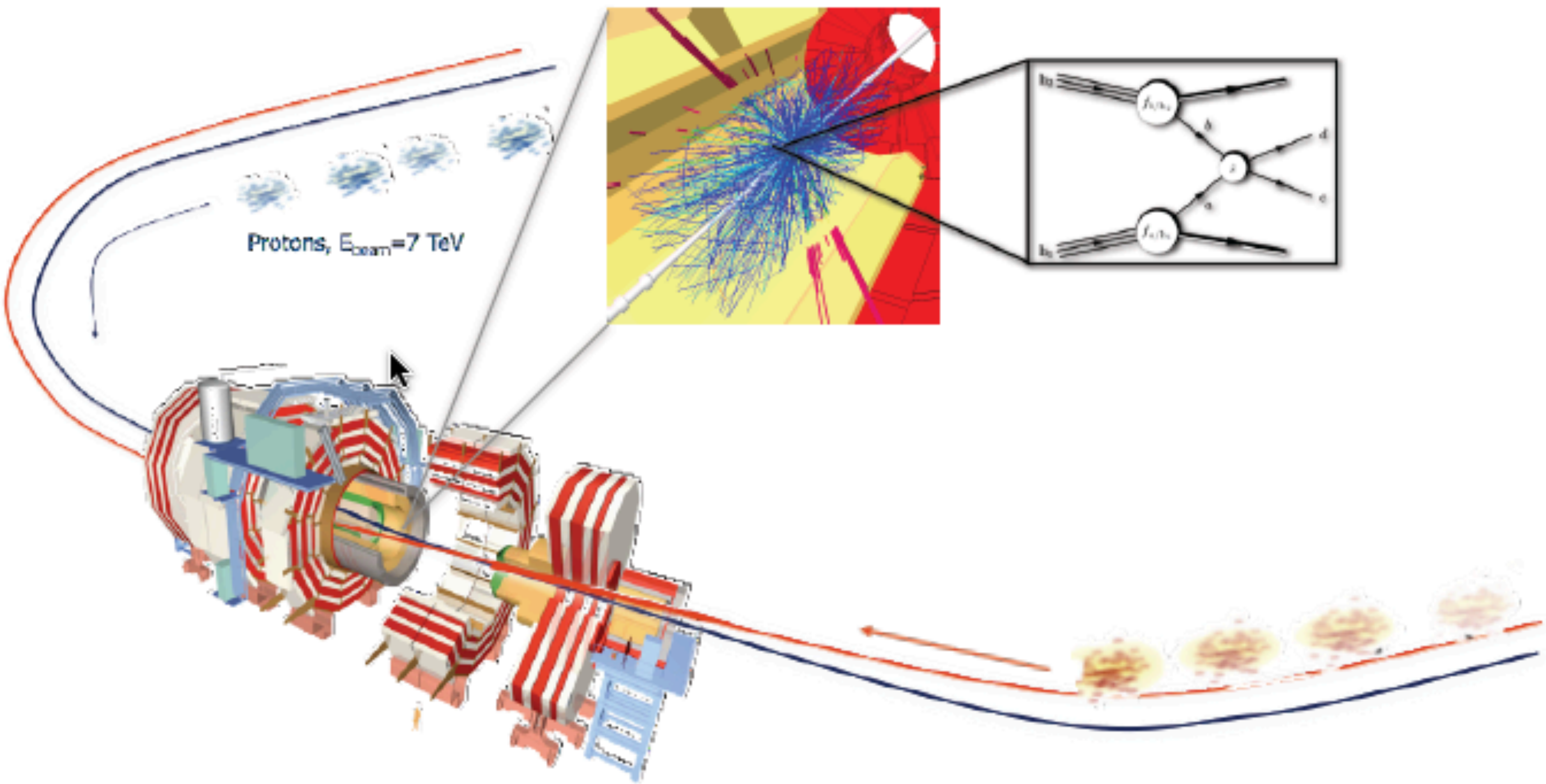
f_{rev} = rotation frequency (~ 11Hz)
F = crossing angle factor

Rms transverse beam size $=\sqrt{\varepsilon\ \beta / \gamma}$
ε_n = renorm. transverse emittance
$\beta *$ = optics at beam crossing (m)
γ_r = relativistic factor

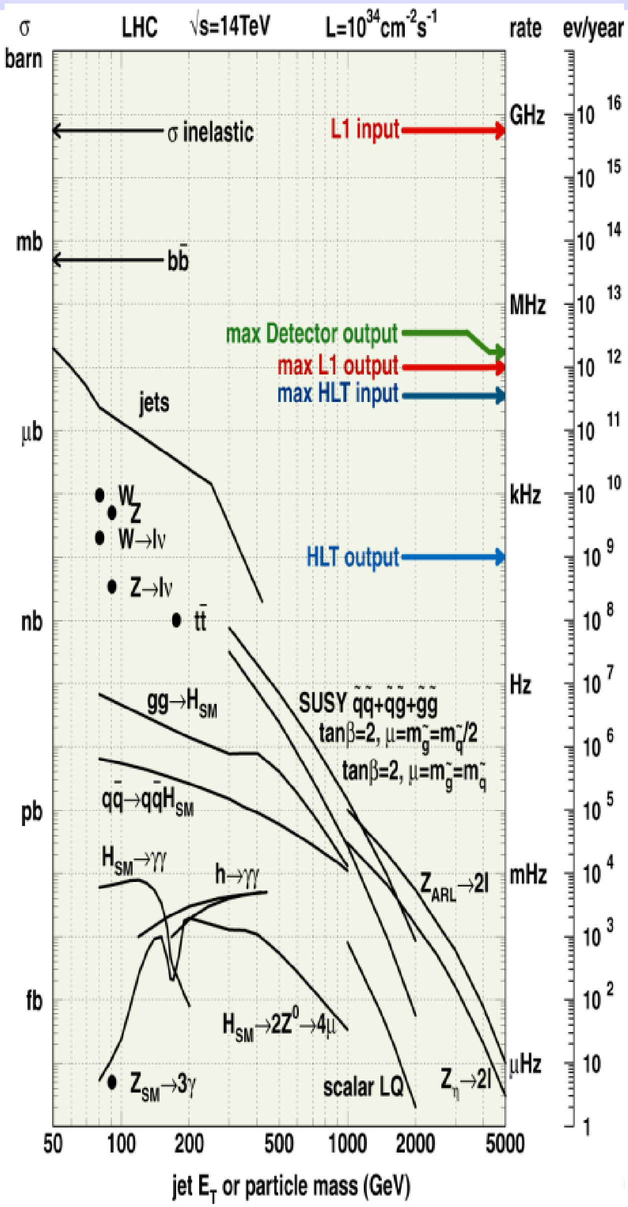

pp, B-Physics,
CP Violation
LHCb
LHC : 27 km long
100m underground
ATLAS
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap
Barrel Toroid
Inner Detector
Hadronic Calorimeters
General Purpose,
pp, heavy ions
Heavy ions, pp
CMS
vacuum chamber
central detector
electromagnetic calorimeter
hadronic calorimeter
superconducting coil
return yoke
muon chambers
Detector characteristics
Width: 22m
Diameter: 15m
Weight: 14'500t
ALICE

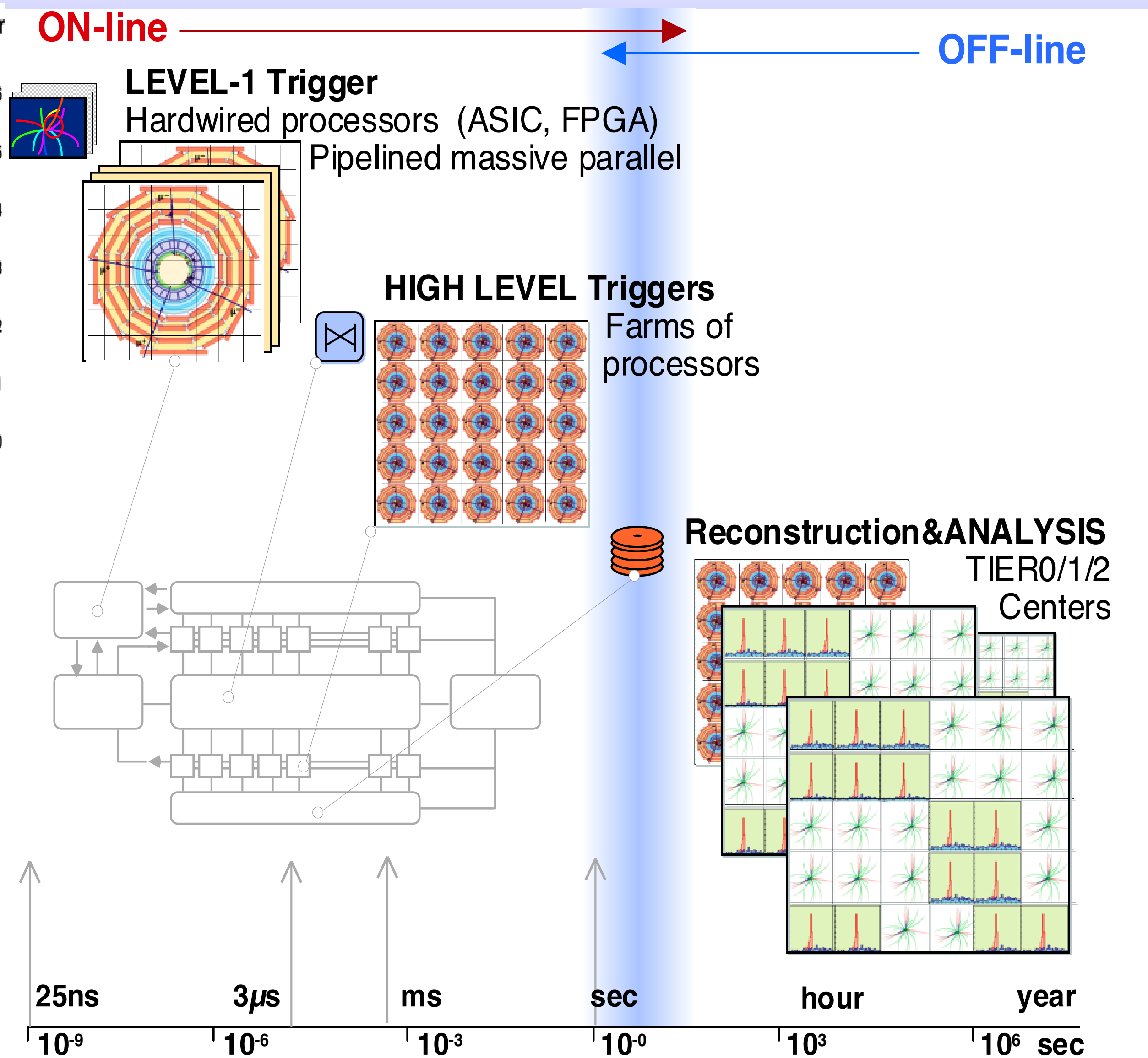
The LHC achievements

2010: $\sqrt{s}$= 7 TeV , peak L = 2.0x10^{32}, integrated L= 44.2 pb^{-1}, collision rate= 7 MHz
2011: $\sqrt{s}$= 7 TeV , peak L = 4.0x10^{33}, integrated L=6.1 fb^{-1}, collision rate= 20 MHz
2012: $\sqrt{s}$= 8 TeV , peak L= 7.7x10^{33}, integrated L=23.3 fb^{-1}, collision rate= 20 MHz

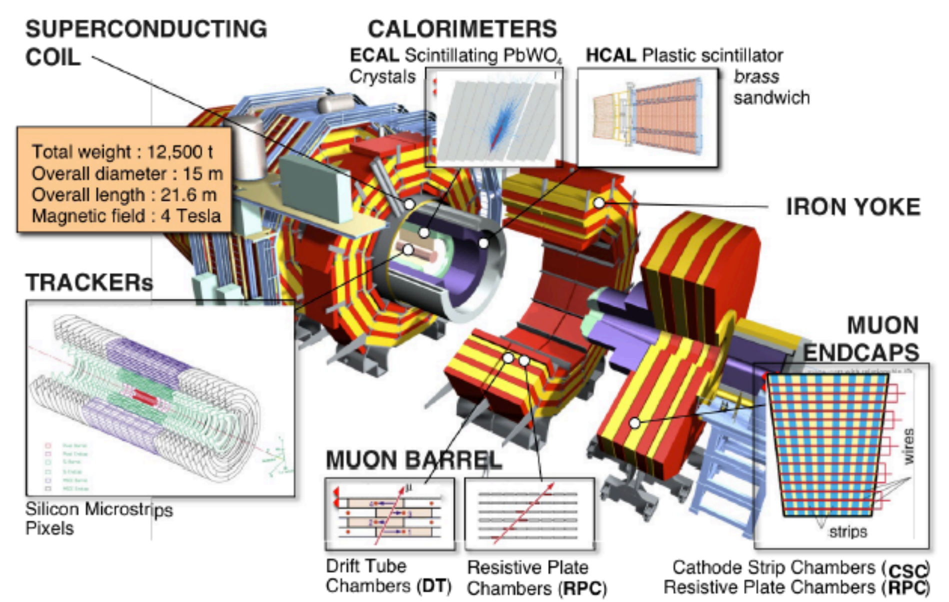


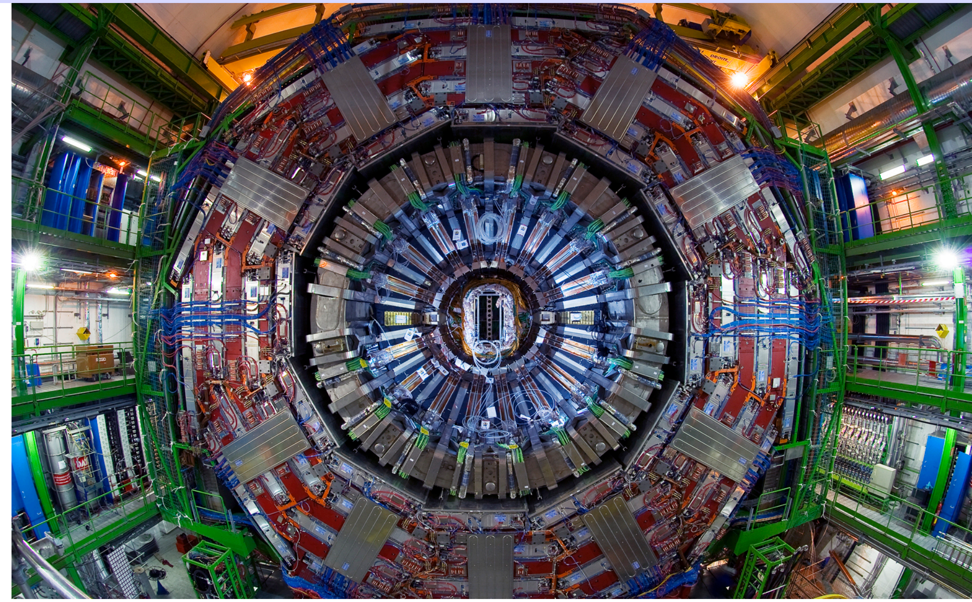
Event selection stages

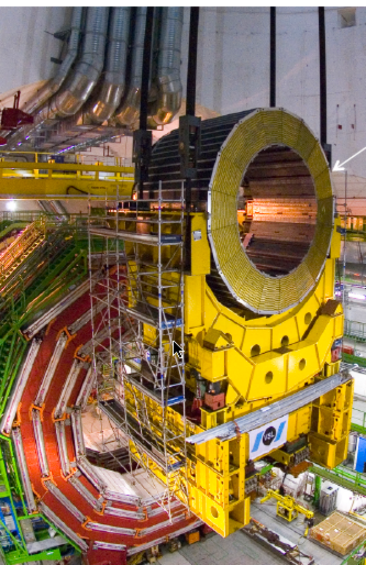




CMS in a nutshell







|η|<2.5 : Tracker

$\sigma/p_T \approx 10^{-4} p_T \oplus 0.005$

|η|<4.9 : EM Calorimeter

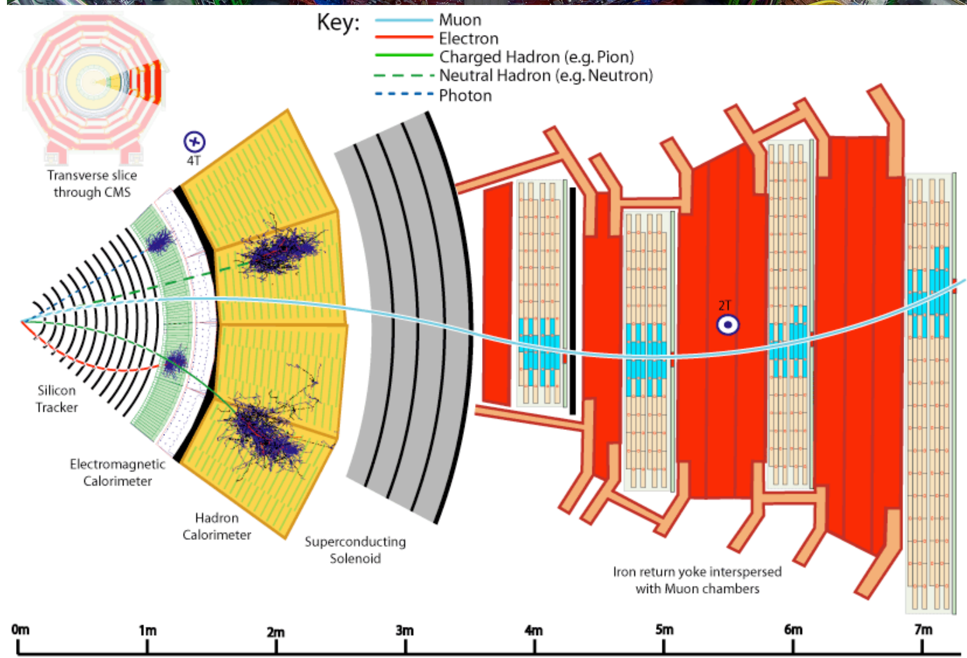
$\sigma/E \approx 0.03/\sqrt{E} + 0.003$

|η|<4.9 : HAD Calorimeter

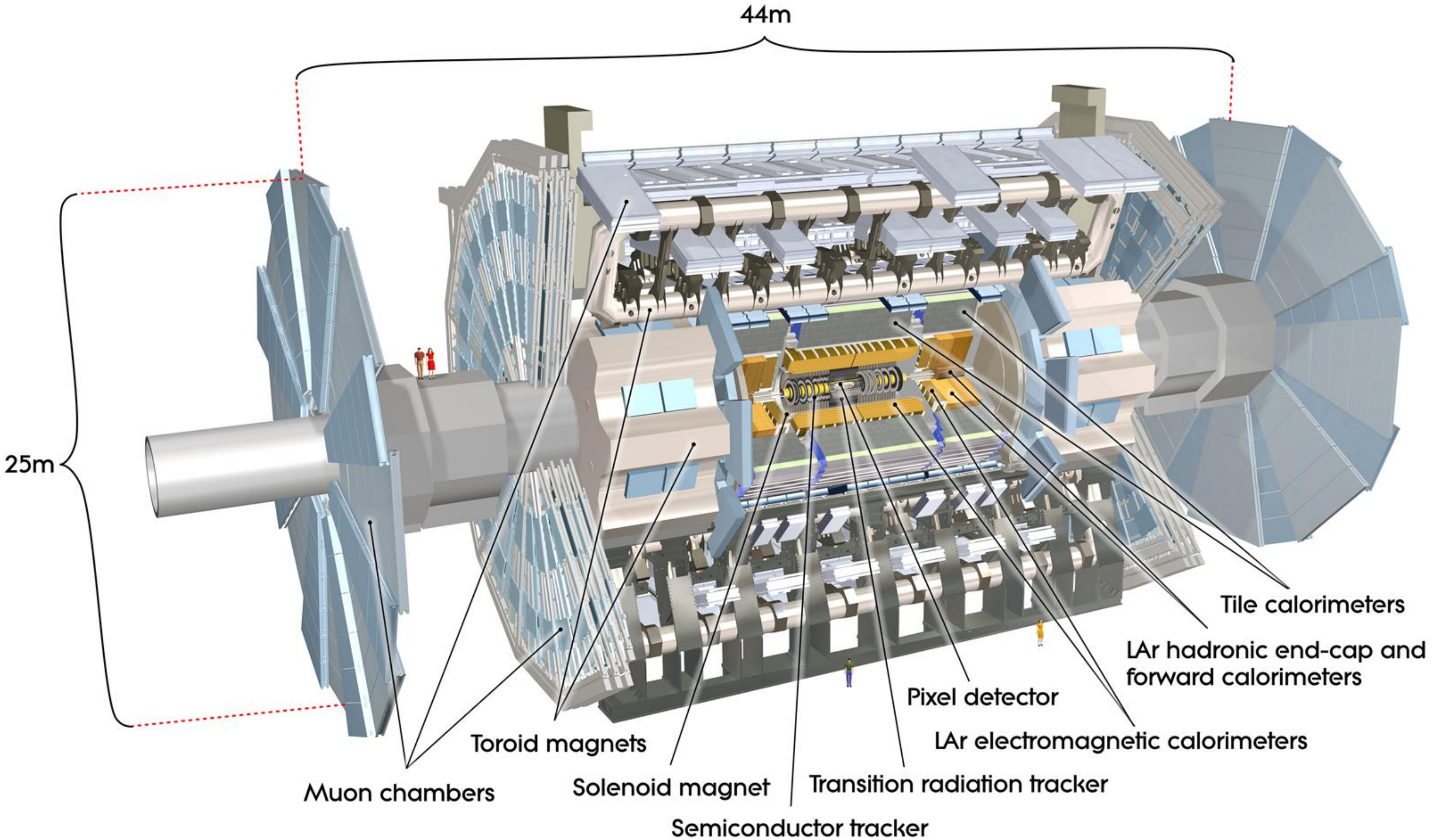
$\sigma/E \approx 1.0/\sqrt{E} + 0.05$

|η|<2.4 : Muon spectrometer

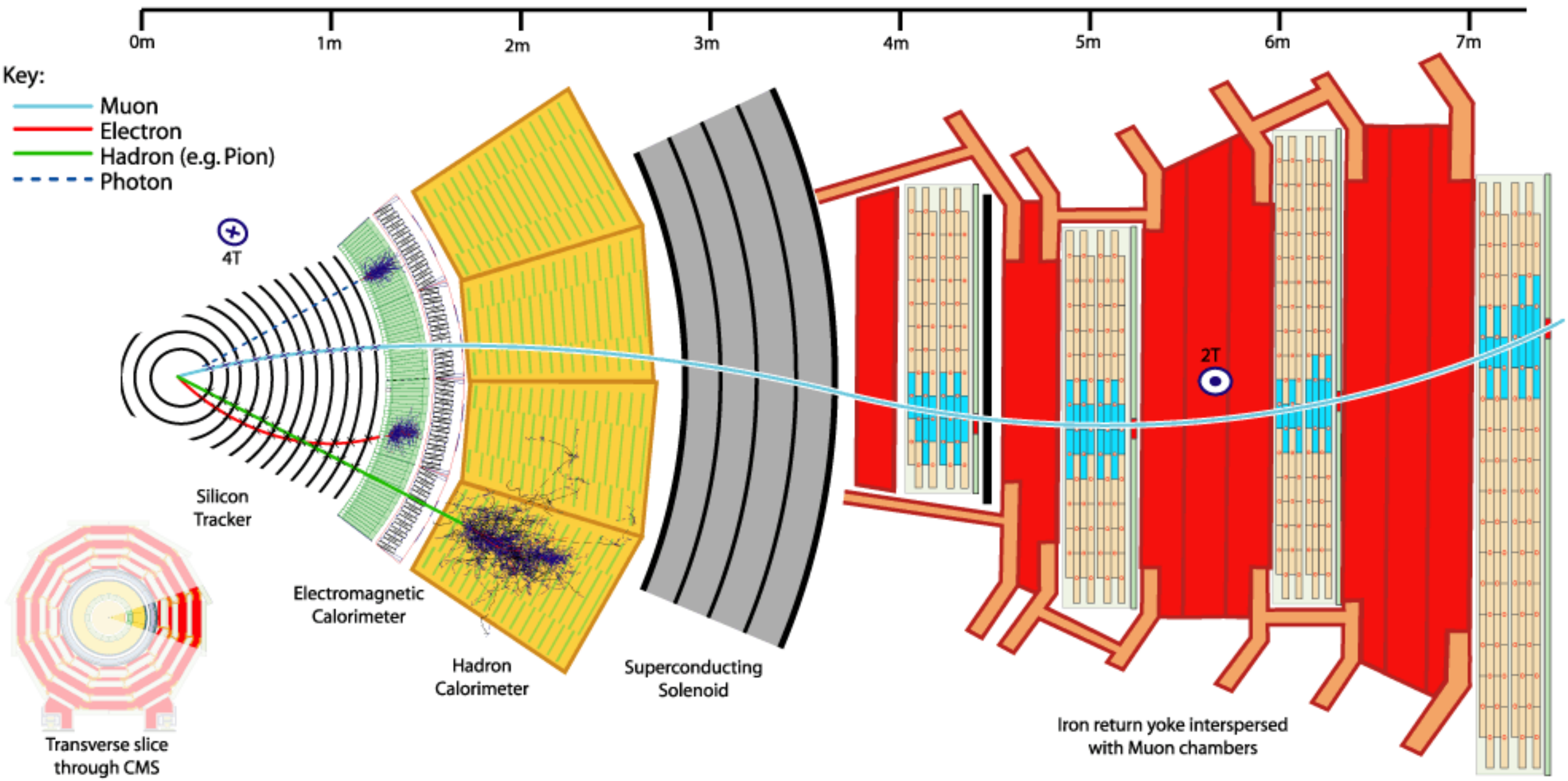
$\sigma/p_T \approx 0.10$ *(1TeV muons)*



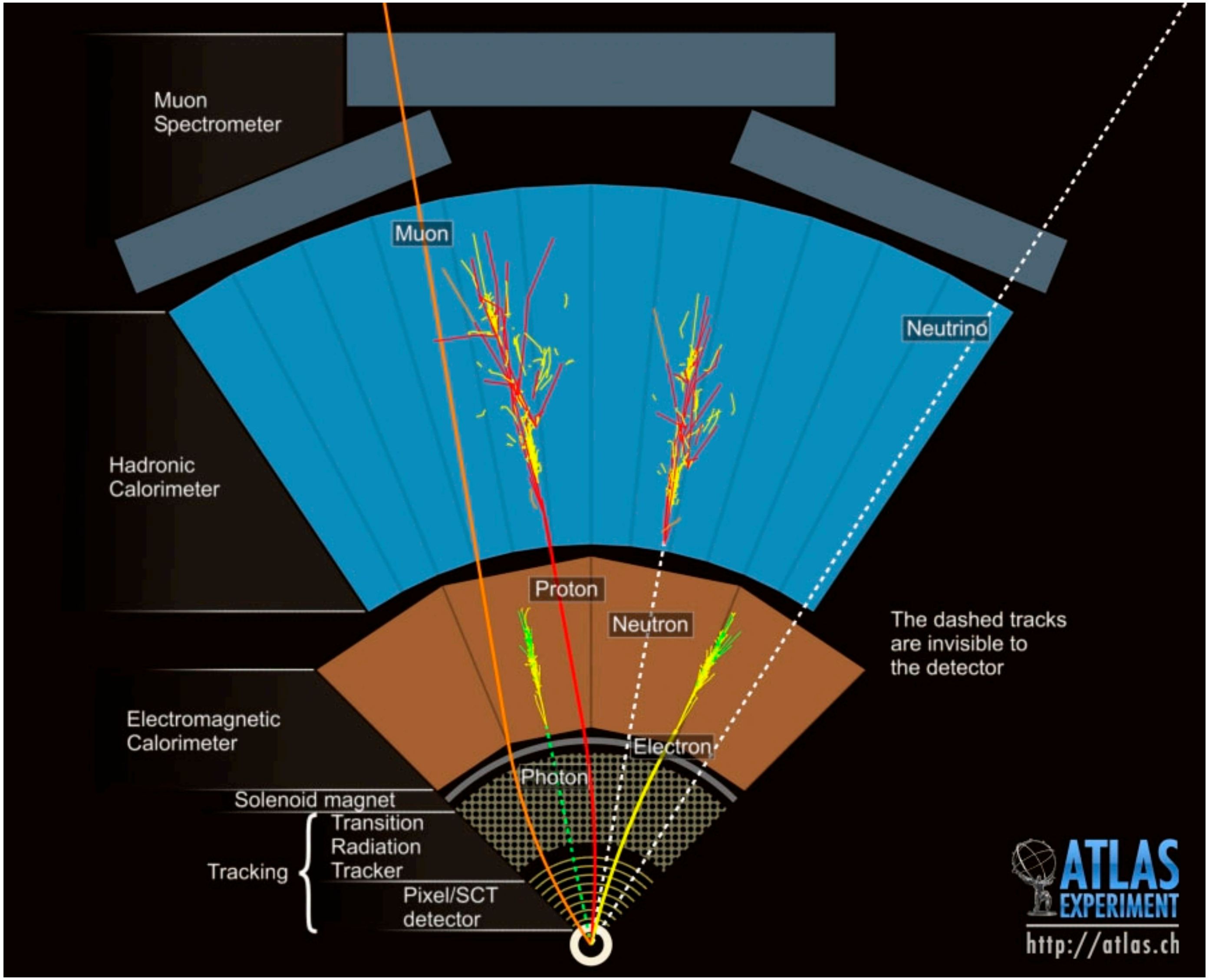
ATLAS in a nutshell



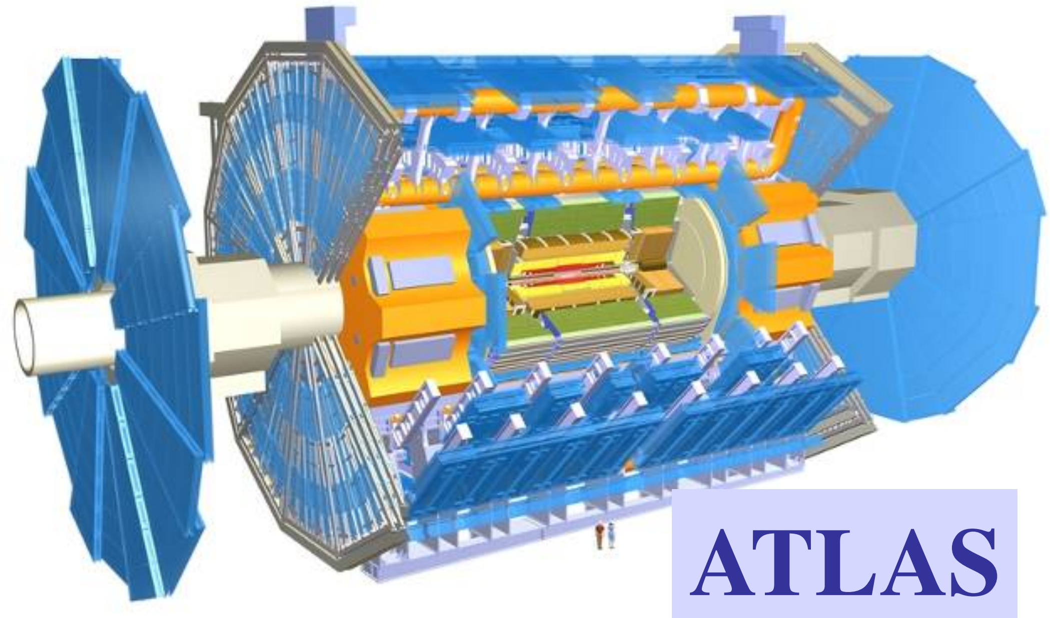
Particles as seen in CMS

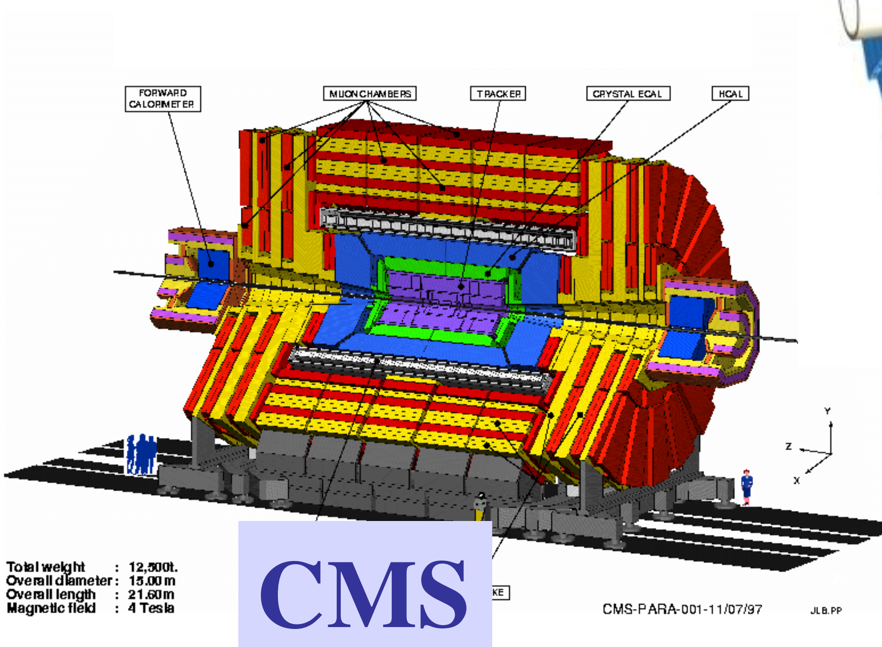


Particles as seen in ATLAS

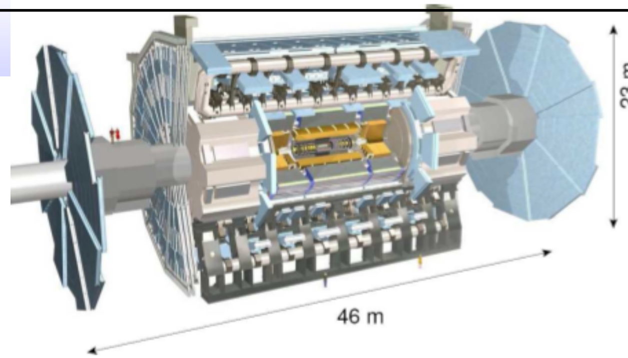
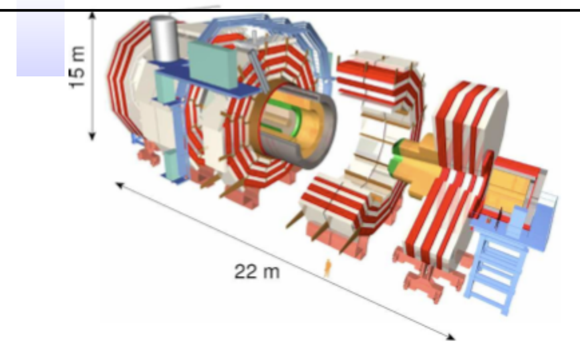


How big are ATLAS and CMS?



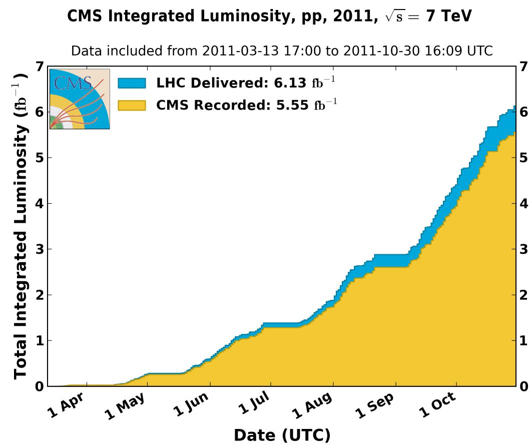


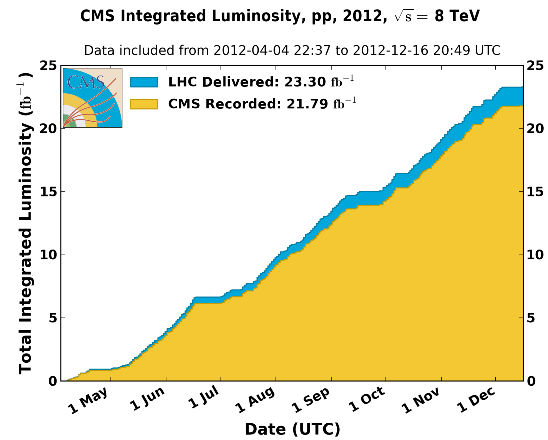
	ATLAS	CMS
Weight (tons)	7000	12500
Diameter	22 m	15 m
Lenght	46 m	22 m
Magnetic field	2 T	4 T

Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5\times10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5\times10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ & Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\,\%$ (at 50 GeV) $\sim 11\,\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

Data samples: CMS / ATLAS

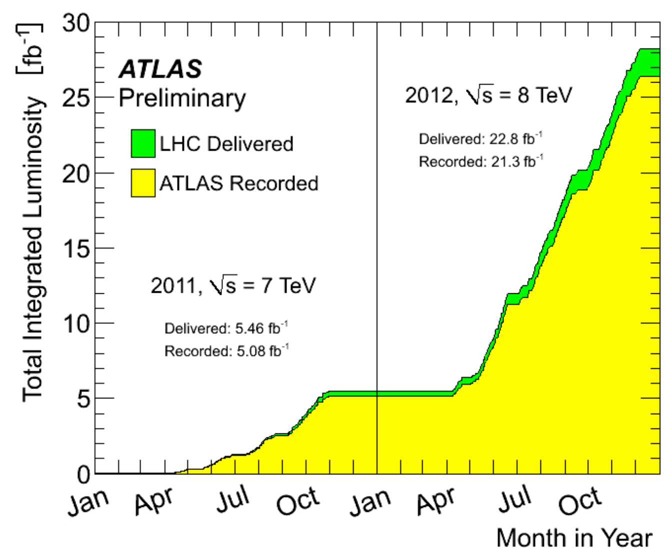
- Excellent machine and detector performance
- Very high quality data
  - ≈ 95% of delivered data were recorded
  - ≈ 90% certified and used in physics analyses



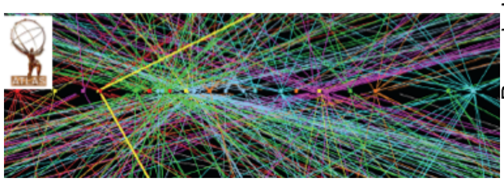


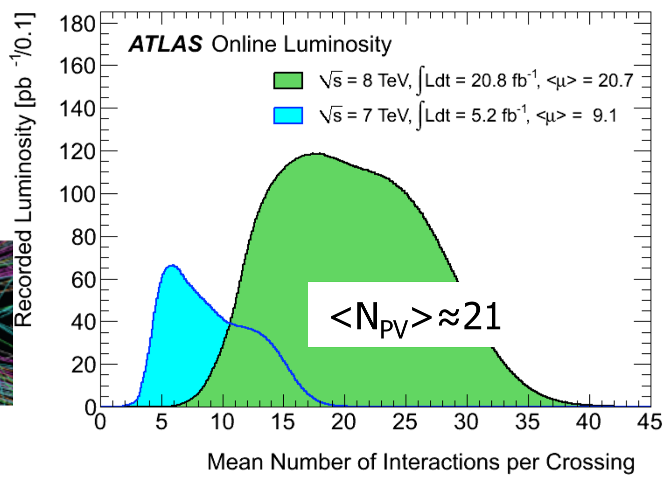
- Dataset of 2011-2012 of :

L = 5.1 (CMS) – 4.7 (ATLAS) fb^{-1} (7 TeV)
L = 19.7 (CMS) – 20.7 (ATLAS) fb^{-1} (8 TeV)

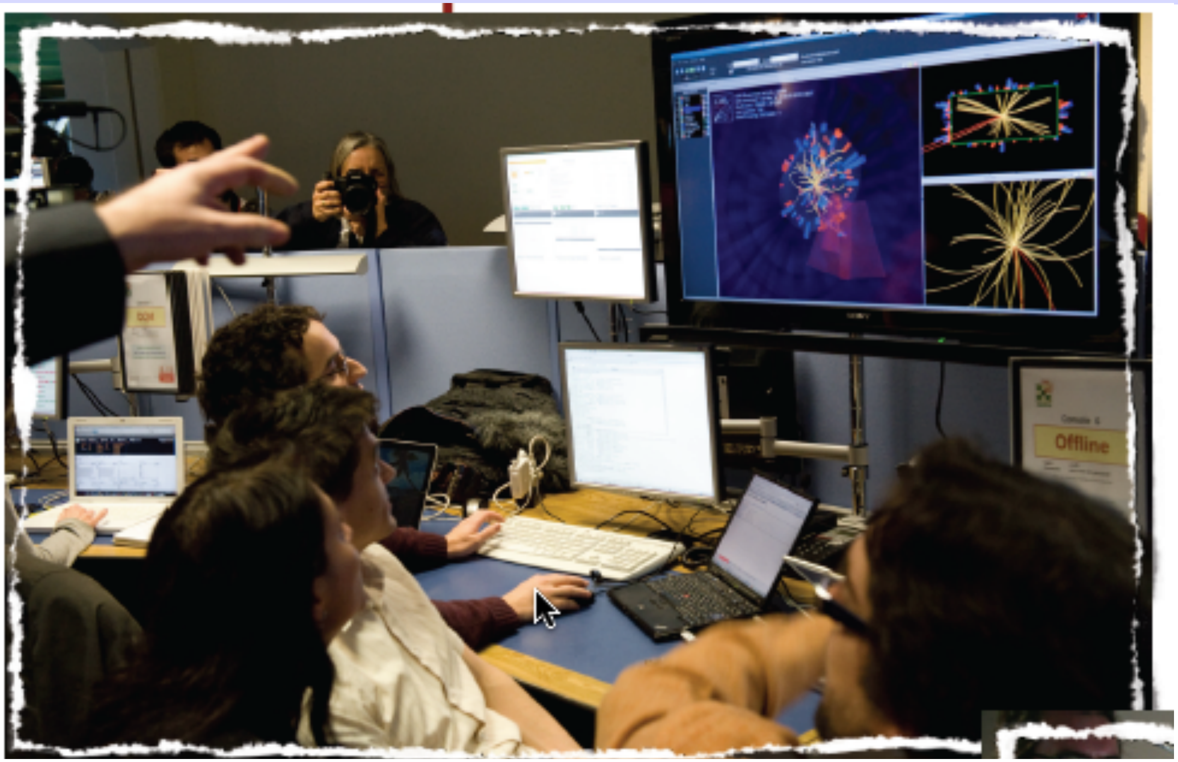


- Successfull pileup handling

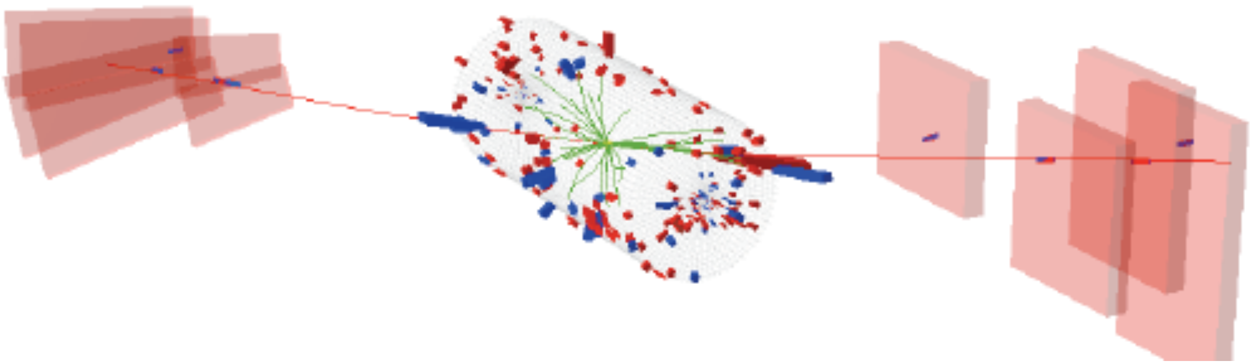




First collisions at 7 TeV

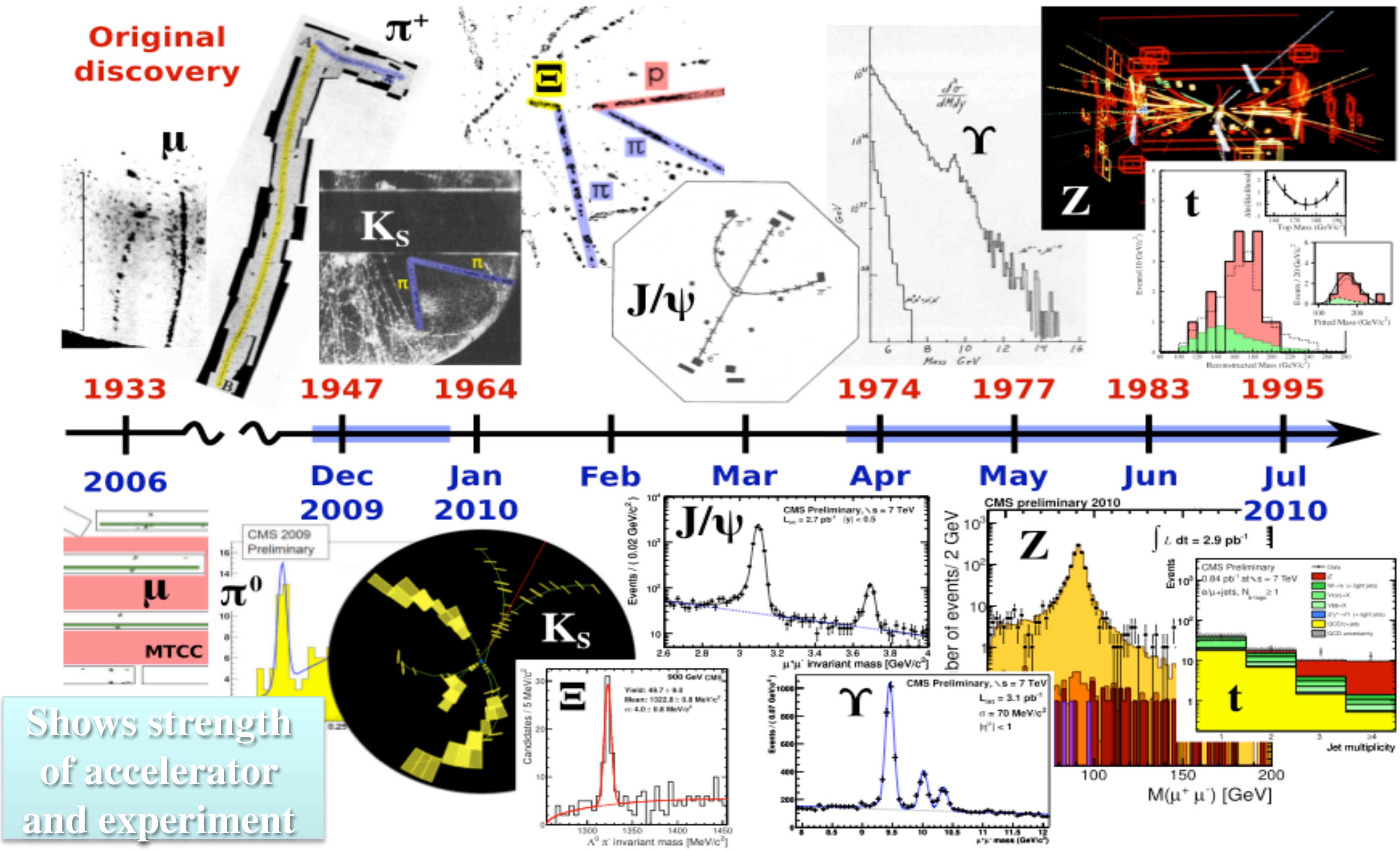


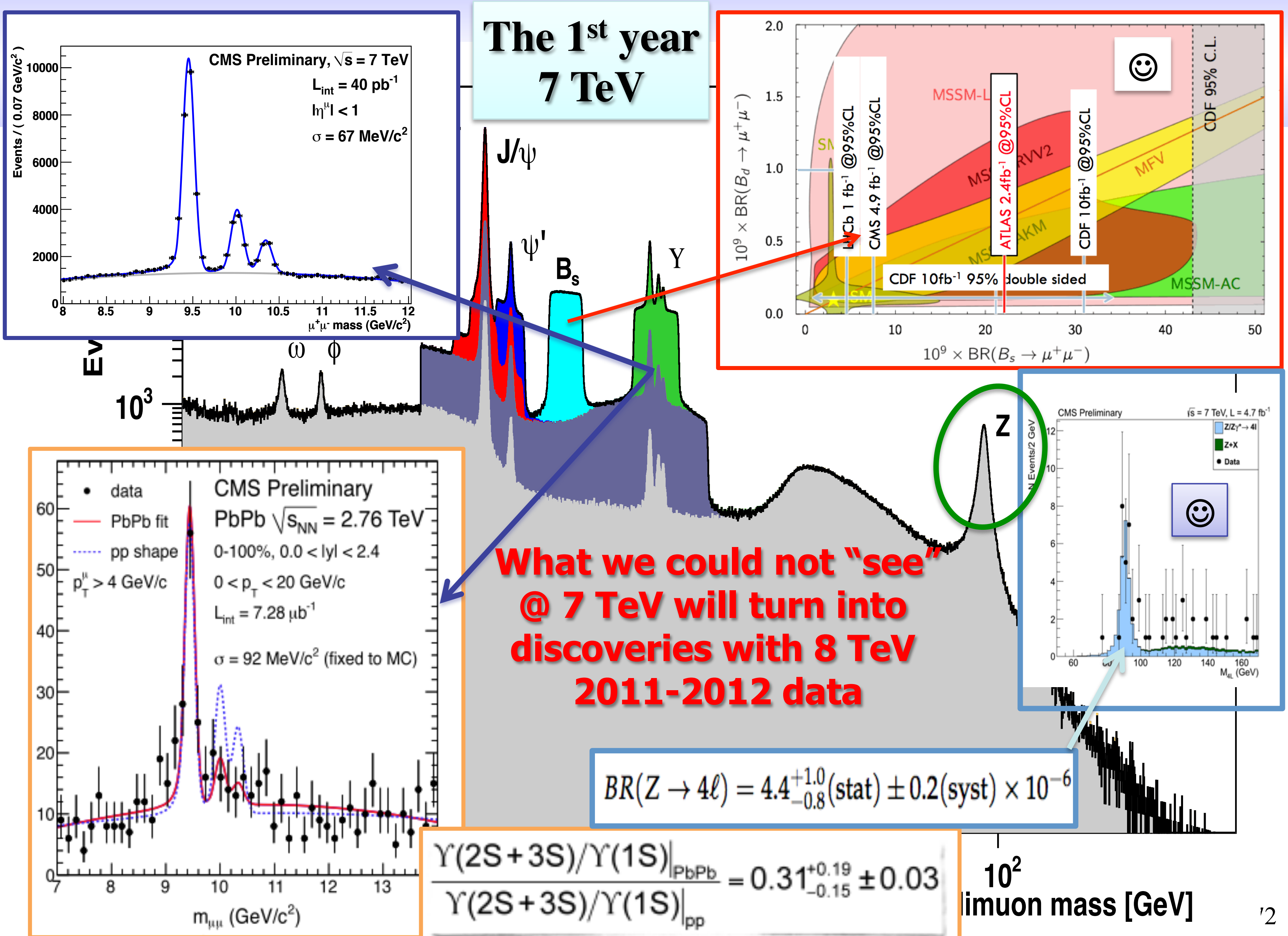
March 2010:
Collisions at 7 TeV.
LHC delivered: 44.22 pb-1
CMS recorded: 40.56 pb-



The first Z→μμ Candidate

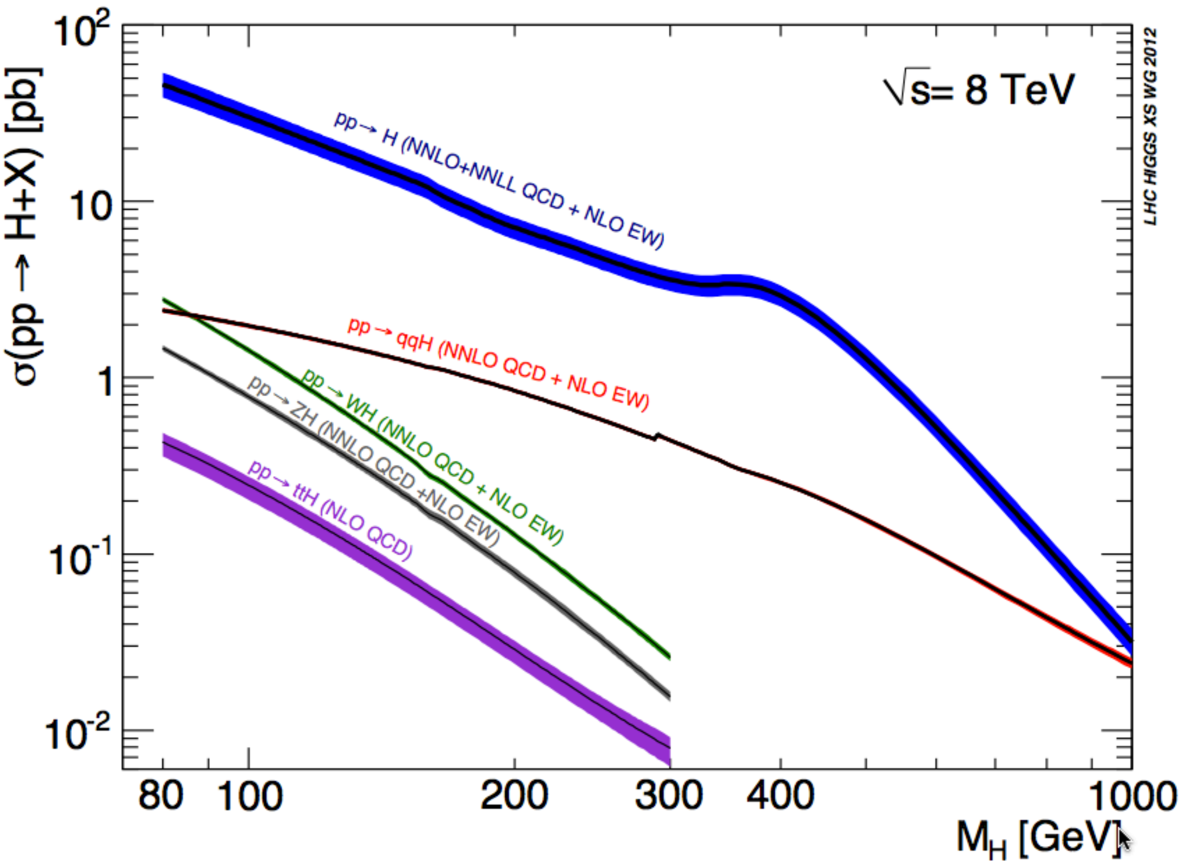
2010: CMS "re-discovers" the Standard Model in Particle Physics





The 1st year
7 TeV
CMS Preliminary, √s = 7 TeV
L_int = 40 pb^-1
|η^μ| < 1
σ = 67 MeV/c^2
Events / (0.07 GeV/c^2)
μ+μ- mass (GeV/c^2)
J/ψ
ψ'
Bs
Υ
ω
φ
Z
10^3
10^2
dimuon mass [GeV]
10^9 × BR(Bd → μ+μ−)
10^9 × BR(Bs → μ+μ−)
LHCb 1 fb^-1 @95%CL
CMS 4.9 fb^-1 @95%CL
ATLAS 2.4fb^-1 @95%CL
CDF 10fb^-1 @95%CL
CDF 95% C.L.
CDF 10fb^-1 95% double sided
MSSM-L
MSSM-RVV2
MFV
MSSM-AKM
MSSM-AC
SM
CMS Preliminary
√s = 7 TeV, L = 4.7 fb^-1
N Events/2 GeV
Z/Zγ*→ 4l
Z+X
Data
M_4L (GeV)
data
PbPb fit
pp shape
p_T^μ > 4 GeV/c
CMS Preliminary
PbPb √s_NN = 2.76 TeV
0-100%, 0.0 < |y| < 2.4
0 < p_T < 20 GeV/c
L_int = 7.28 μb^-1
σ = 92 MeV/c^2 (fixed to MC)
m_μμ (GeV/c^2)
What we could not "see" @ 7 TeV will turn into discoveries with 8 TeV 2011-2012 data
BR(Z → 4ℓ) = 4.4 +1.0 −0.8 (stat) ± 0.2(syst) × 10^−6
Υ(2S+3S)/Υ(1S)|PbPb / Υ(2S+3S)/Υ(1S)|pp = 0.31 +0.19 −0.15 ± 0.03

SM Higgs production at LHC

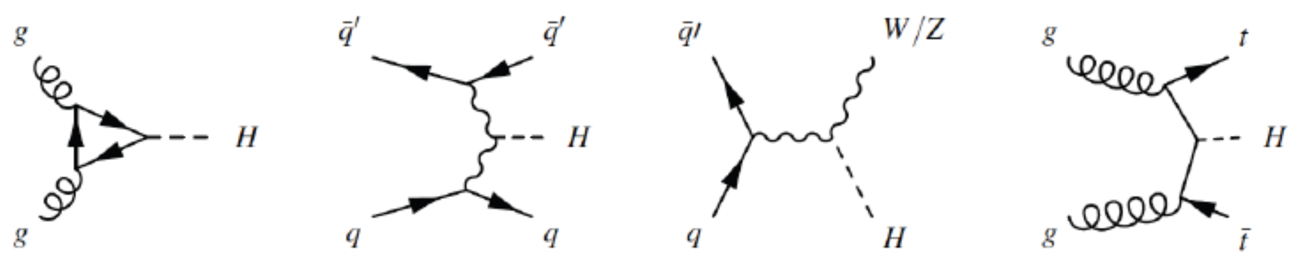


Gluon-gluon fusion:

→ radiative corrections at:

- NLO QCD
- NNLO QCD
- NNLL QCD
- NLO EW

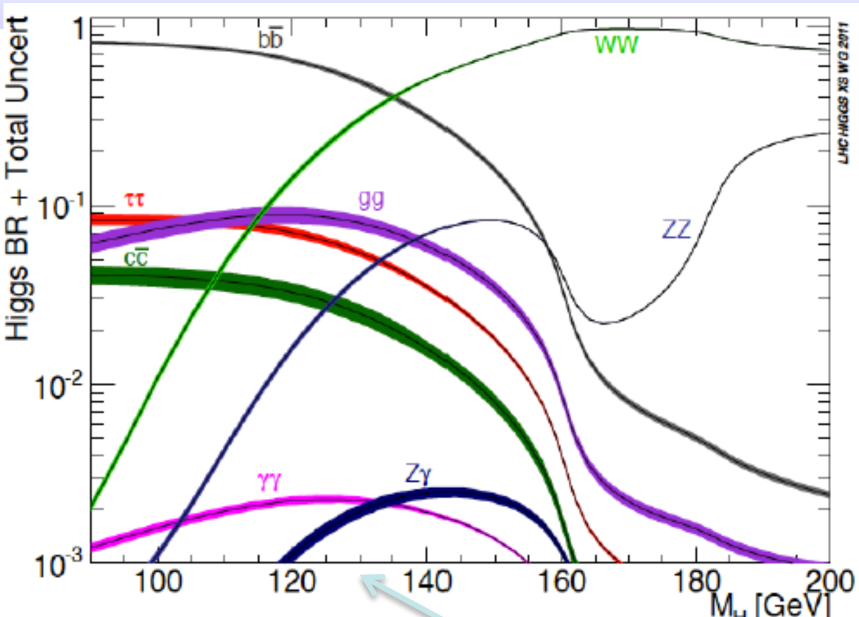
	$K_{NNLO/NLO}$ ($K_{NLO/LO}$)	Scale	PDF+a_s	Total error
ggF	+25% (+100%)	+12% -7%	±8%	+20 -15%
VBF	<1% (+5-10%)	±1%	±4%	±5%
WH/ ZH	+2-6% (+30%)	±1%	±4%	±5%
ttH	- (+5-20%)	+4% -10%	±8%	+12 -18%

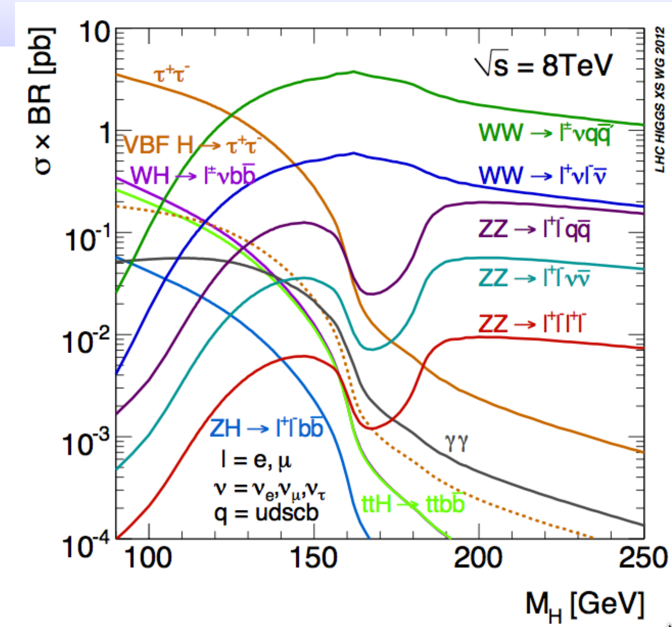


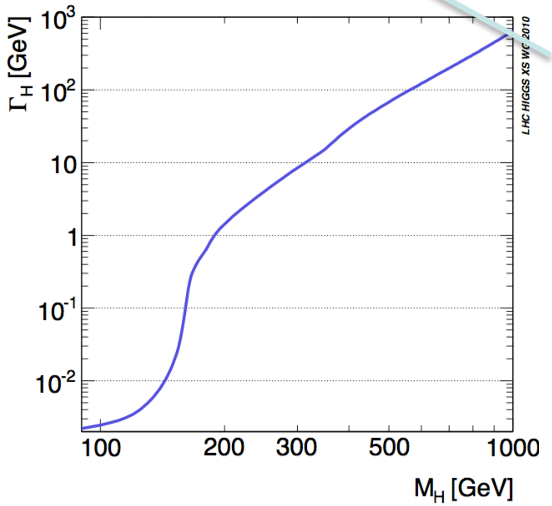
(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$

LHC Higgs Xsection WG

Higgs decay channels







At m_H =125 GeV:

- H(bb) ≈ 57%
- H(WW) ≈ 22%
- H(ττ) ≈ 6.2%
- H(ZZ) ≈ 2.8%
- H(γγ) ≈ 0.23%

Channel	m_H resolution
$H \to \gamma\gamma$	1–2%
$H \to \tau\tau \to e\tau_h/\mu\tau_h/e\mu + X$	20%
$H \to \tau\tau \to \mu\mu + X$	20%
$WH \to e\mu\tau_h/\mu\mu\tau_h + \nu's$	20%
$(W/Z)H \to (e\nu/\mu\nu/ee/\mu\mu/\nu\nu$	10%
$H \to WW^* \to 2\ell 2\nu$	20%
$WH \to W(WW^*) \to 3\ell 3\nu$	20%
$H \to ZZ^{(*)} \to 4\ell$	1–2%
$H \to ZZ^{(*)} \to 2\ell 2q$	3% 3%
$H \to ZZ \to 2\ell 2\tau$	10–15%
$H \to ZZ \to 2\ell 2\nu$	7%

Main discovery channels at LHC

$H \rightarrow ZZ \rightarrow 4l$ - golden channel

- clean experimental signature, four isolated leptons
- benefits from excellent electron and muon resolution
- narrow resonance in four lepton mass spectrum

$H \rightarrow \gamma\gamma$

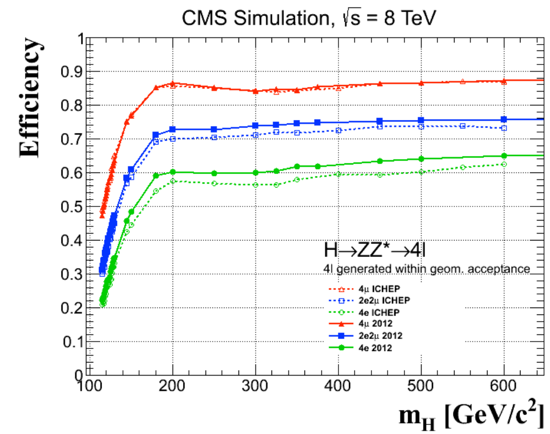
- clean signature of two energetic and isolated photons
- benefits from good photon resolution
- narrow peak in di-photon mass spectrum on the top of continuous background

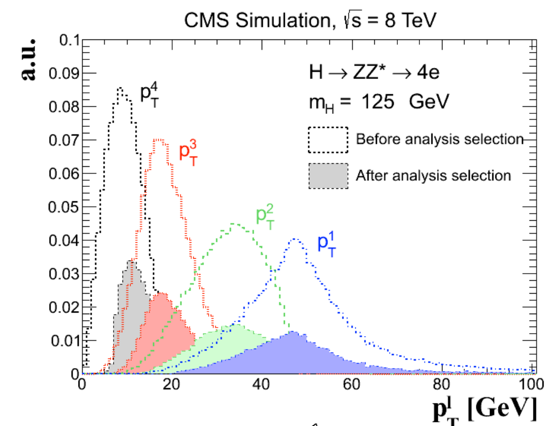
Both the channels:

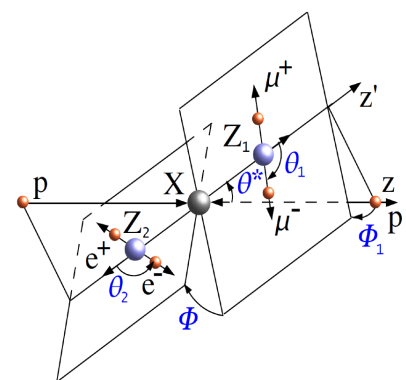
- suffer from low signal rate because of small BR
- allow to reconstruct the mass peak

H→ZZ→4l in a nutshell

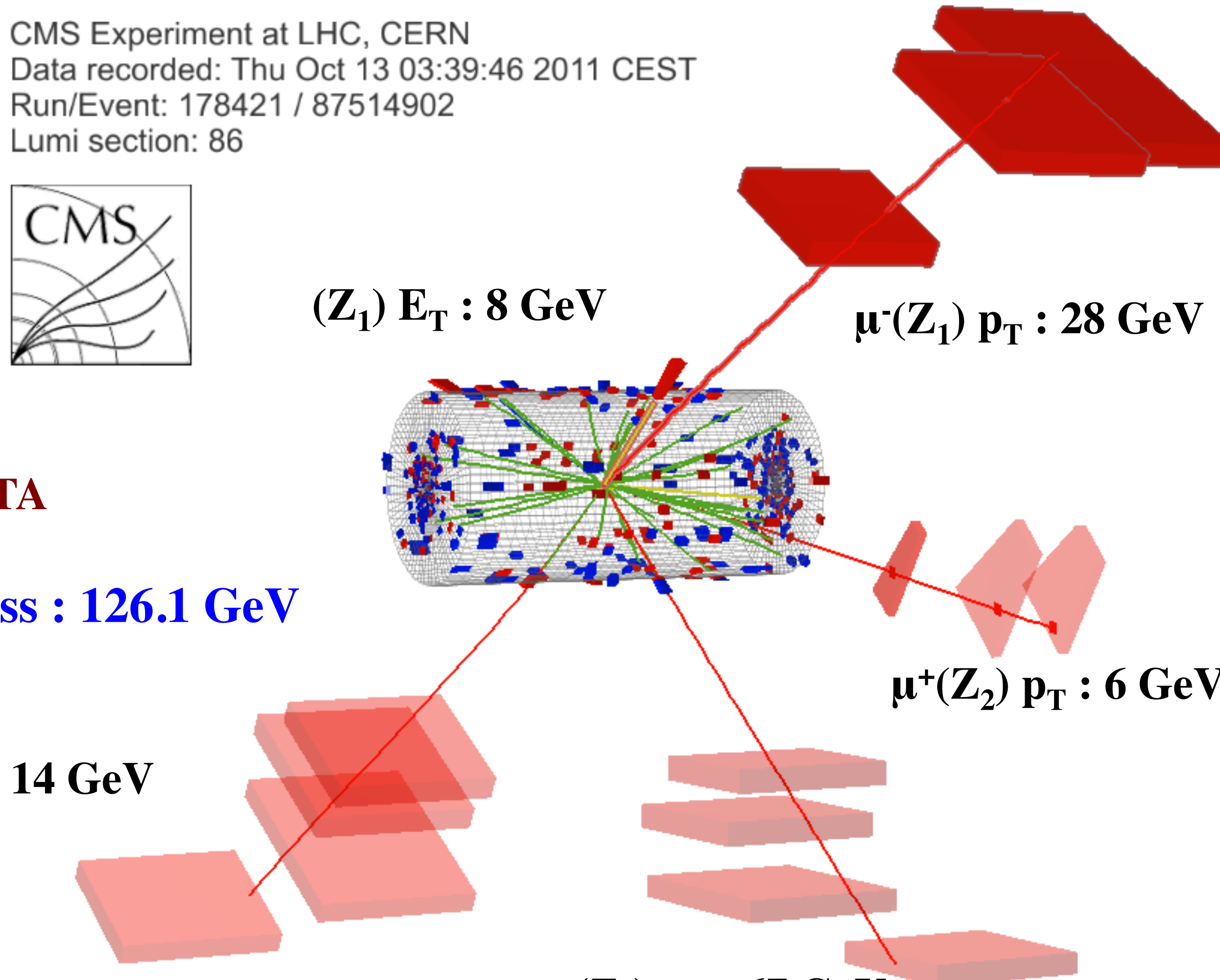
- Signatures: 4e, 4μ and 2e2μ final state
  - clean but demanding the highest lept. eff.
  - σxBR ≈ few fb but is the most sensitive channel
  - mass peak is reconstructed with resolution 1-2%
- ggF, VBF, VH, ttH all considered
- Backgrounds:
  - Irreducible: ZZ*
- Selection strategy:
  - triggering on 1/2/3 leptons
  - latest calibration for lept. pT and resolution
  - reco, ID and isolation (PU-corrected) of leptons
  - recovery of FSR photons
  - use of impact parameter
  - m_Z and m_{Z*} constraint
  - appliying jet reco and ID for VBF tagging
  - angular analysis via MELA (CMS) and BDT (ATLAS)
  - calculation of per event mass error (CMS)







Candidate event

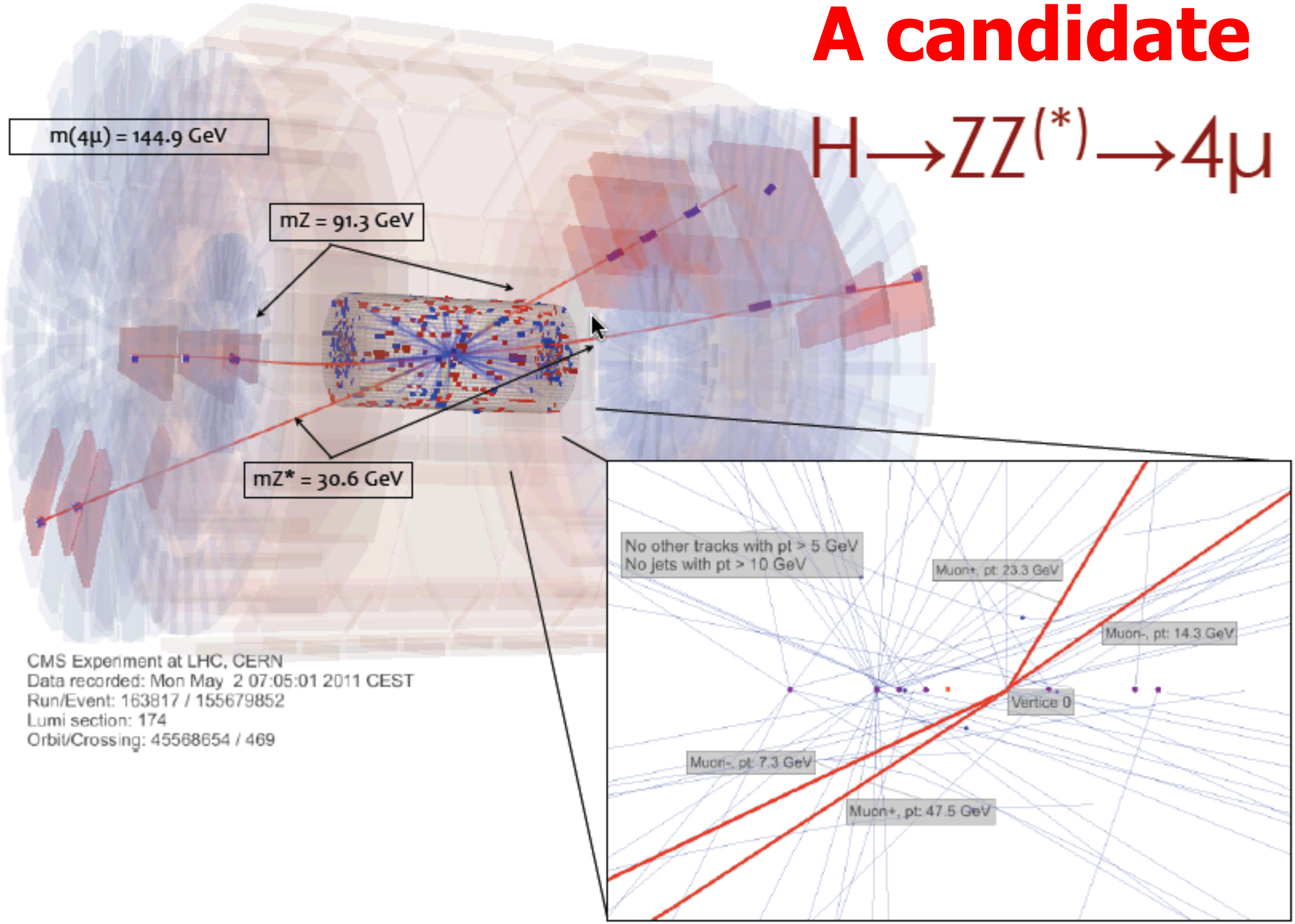


7 TeV DATA

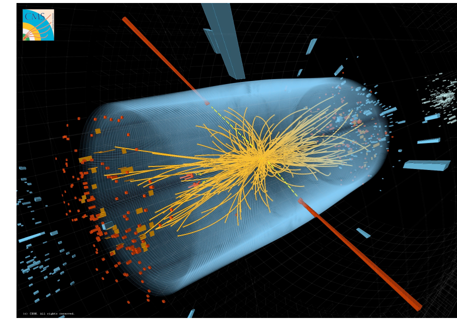
4μ+γ Mass : 126.1 GeV

A candidate

$H \rightarrow ZZ^{(*)} \rightarrow 4\mu$

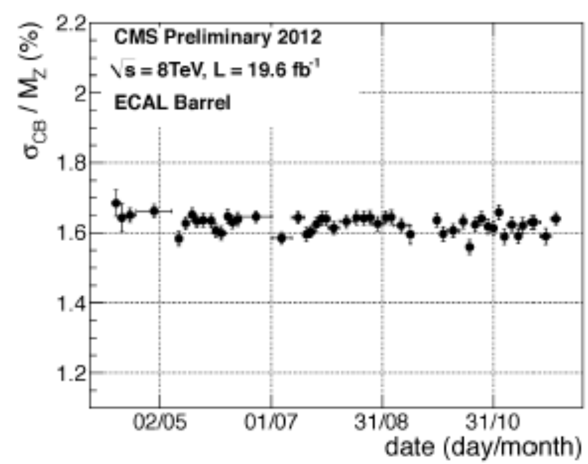


H→γγ in a nutshell



Important channel for Higgs with $110 < m_H < 140$ GeV
- clear signature of two isolated high E_T photons
- small B.R. (0.2%)
- narrow mass peak with very good mass resolution 1-2%
- Challenging electron/photon extrapolation for E-scale

Energy resolution of ECAL stable at ‰



Background:
- irreducible : γγ→γγ, qqbar, qg→γγ from QCD
- reducible: pp → γ+jets (1 prompt γ + 1 fake γ)
  pp → jets (2 fake γ), fake γ

Analysis strategy based on:
- trigger (double photon HLT)
- vertex ID via likelihood discriminant (ATLAS) / MVA (CMS), photon reconstruction, photon ID cut-based (ATLAS) / MVA (CMS) and isolation via MVA
- categories of events based on S/B, resolution and production modes
- look for a peak with MVA techniques and cut-based (CMS)

Statistical approach –ATLAS and CMS

- Hypothesis testing using the Profile likelihood ratio and CL_S method

$$\mathcal{L}(data \mid \mu,\theta) = Poisson(data \mid \mu \cdot s(\theta) + b(\theta)) \cdot p(\tilde{\theta} \mid \theta)$$

$$\tilde{q}_\mu = -2 \ln \frac{\mathcal{L}(\text{data}|\mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})}$$

Is the test statistics

$$CL_S(\mu) = \frac{P\left(q_\mu \geq q_\mu^{obs} \mid \mu s\left(\hat{\theta}_\mu^{obs}\right) + b\left(\hat{\theta}_\mu^{obs}\right)\right)}{P\left(q_\mu \geq q_\mu^{obs} \mid b\left(\hat{\theta}_0^{obs}\right)\right)}$$

for exclusion

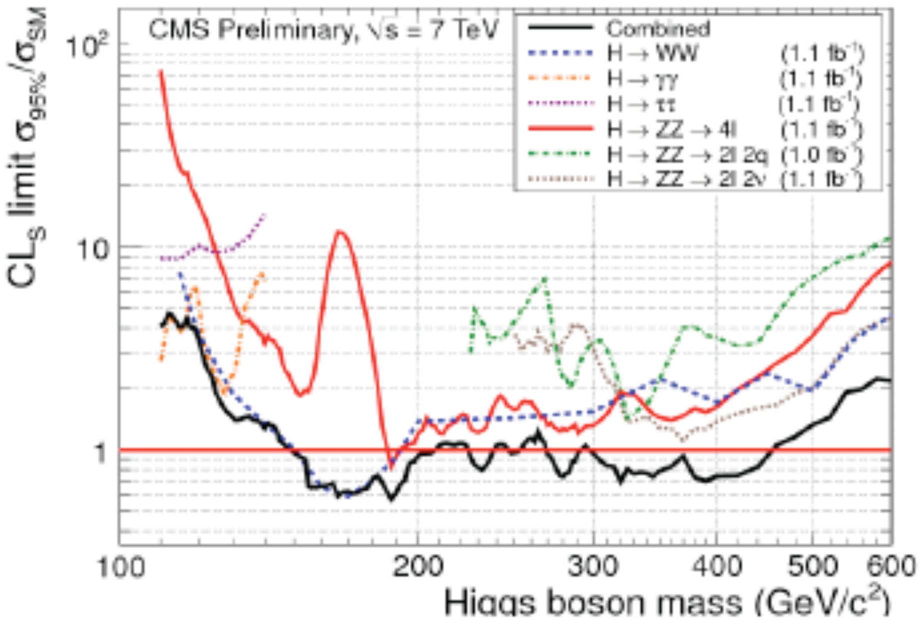
p-value: probability that the background can fluctuate to give an excess of events equal or larger than what observed

$$p_0 = P(q_0 \geq q_0^{obs}) \qquad q_0 = -2 \ln \frac{\mathcal{L}(\text{data}|0, \hat{\theta}_0)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})}$$

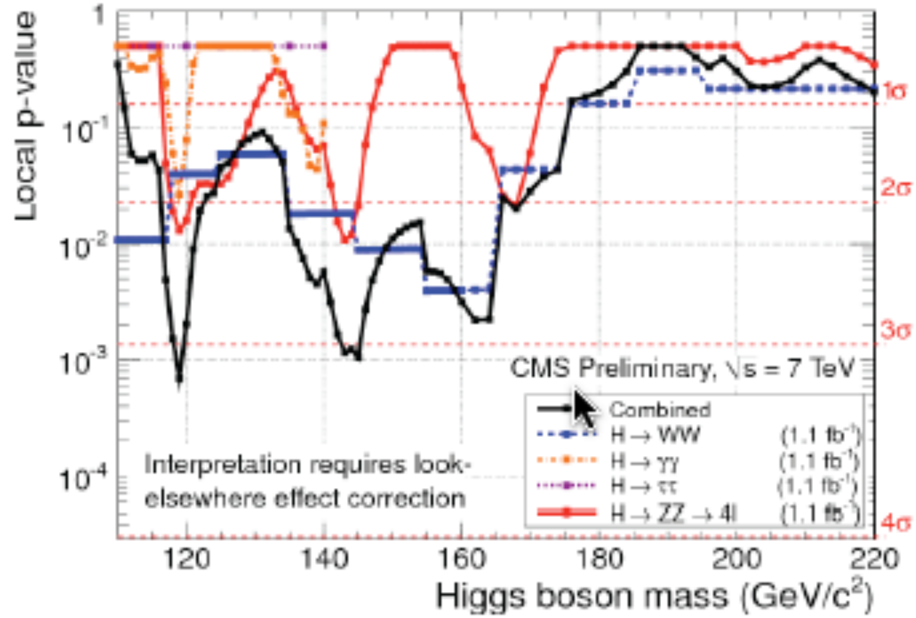
- Sistematic uncertainties and correlations modelled by introduction nuisance parameters θ with related distribution

- Choice of parameters of interest depends on test with the remaining parameters being "profiled" (set to the values that maximise the likelihood function for the given fixed values of the parameter of interest)

EPS in July 2011 at Grenoble



Observed combined upper limit on $\mu=\sigma/\sigma_{SM}$



Overall combined local p-values

CMS able to exclude the existence of Higgs in the mass range 149-206 GeV and 300-440 GeV (expected esclusion in 145-480 GeV).

December 2011

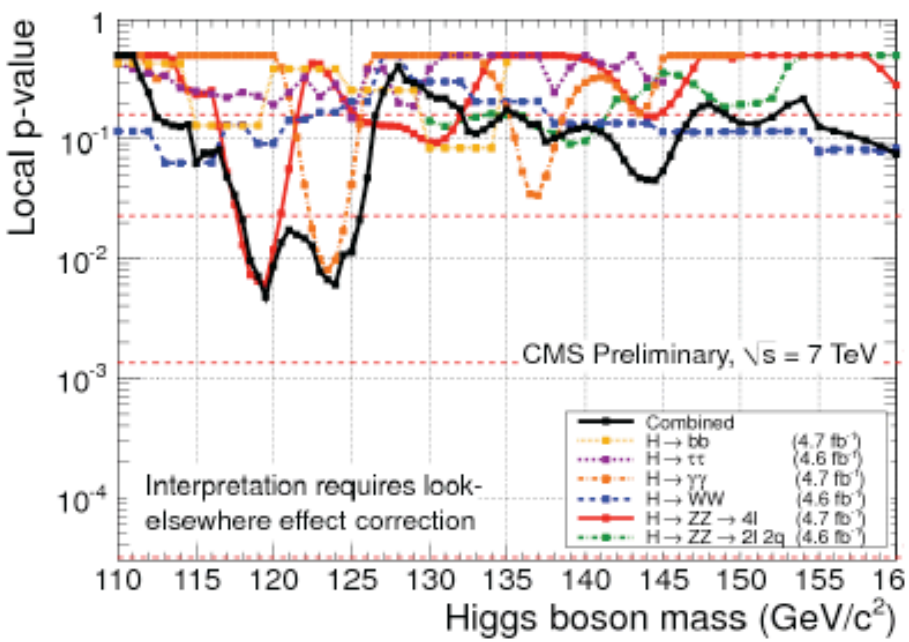
Analysed samples of data: 4.7 fb^{-1}

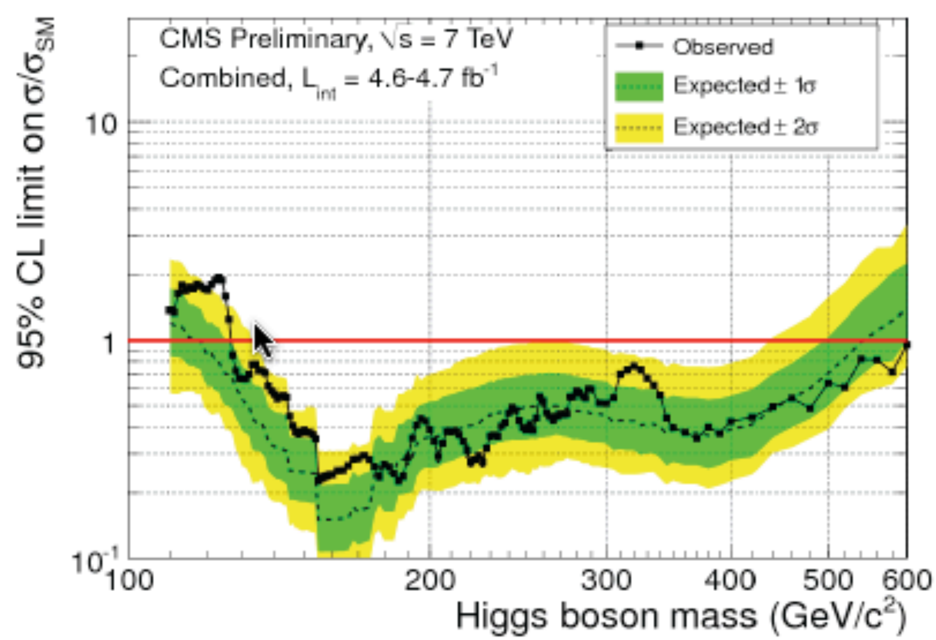
Excluded range of masses with combination of all Higgs analyses:

observed [127-600] GeV

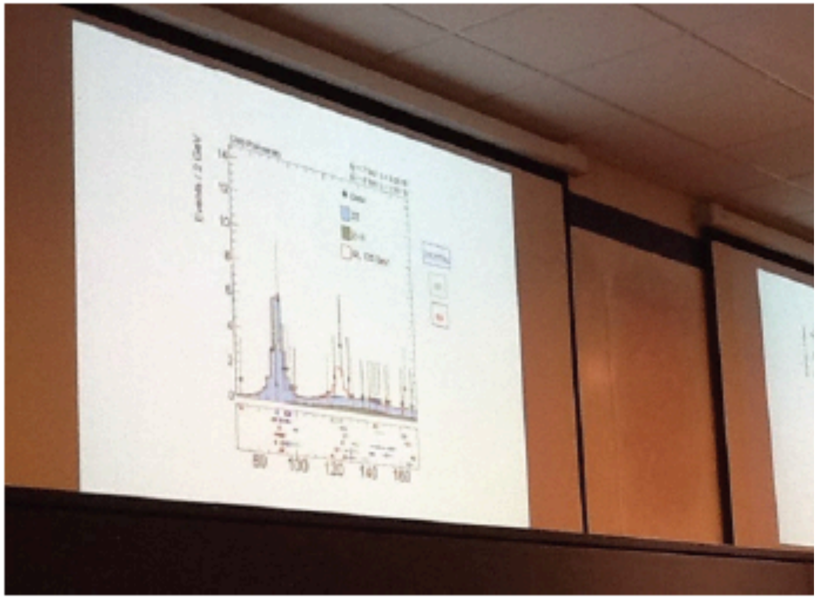
expected [117-543] GeV

With an excess in the range 120-127 GeV

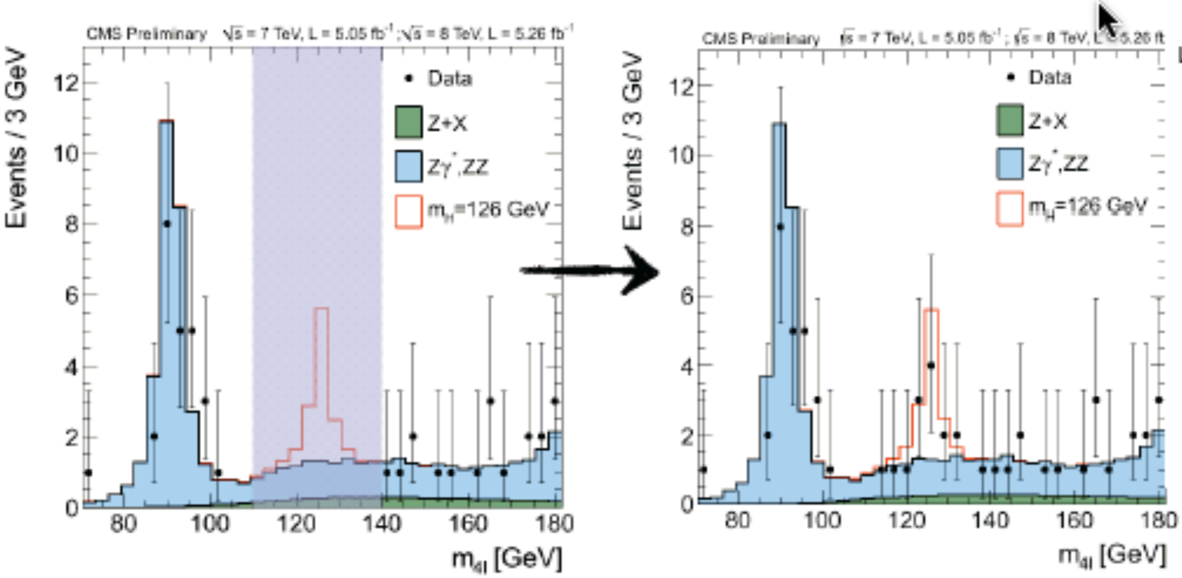


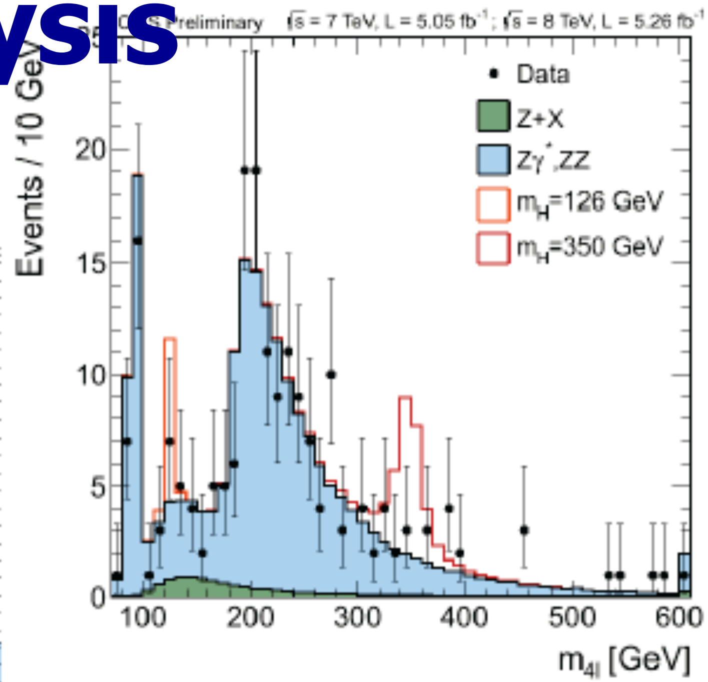


June 2012:

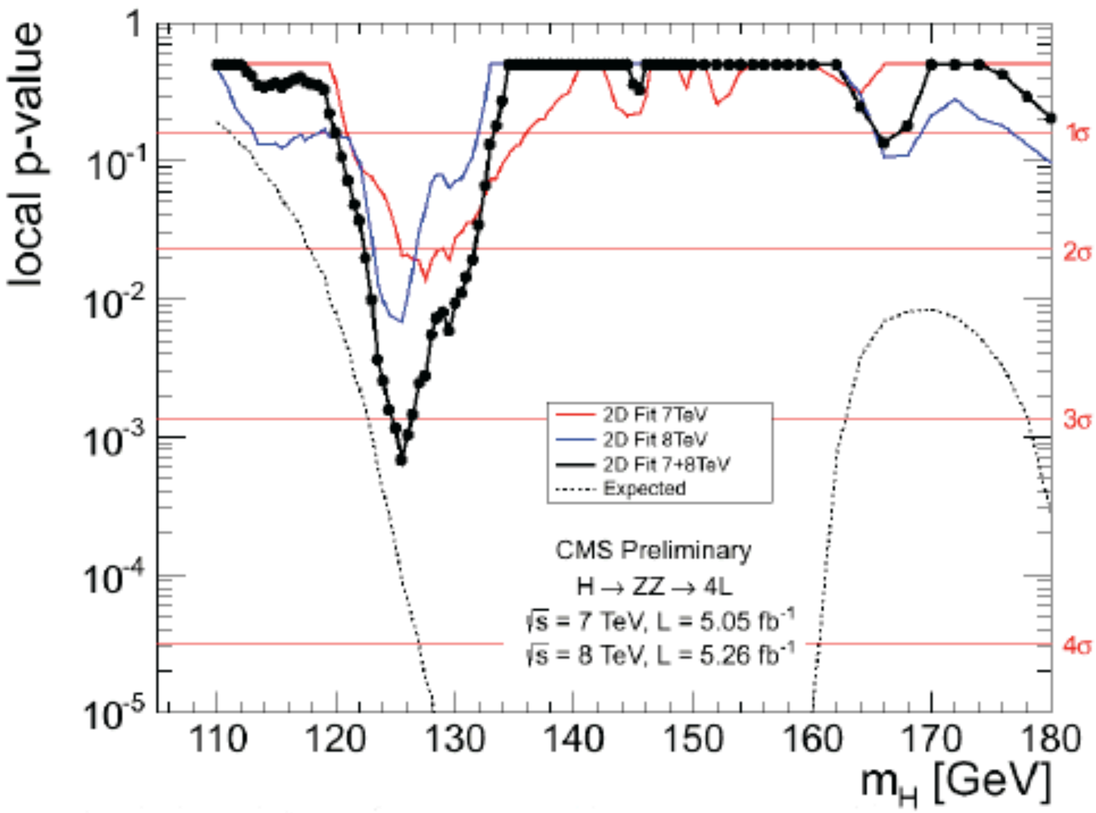


14.6.2012:
Approval of
H→ZZ→4l
analysis





Evidence of a new state

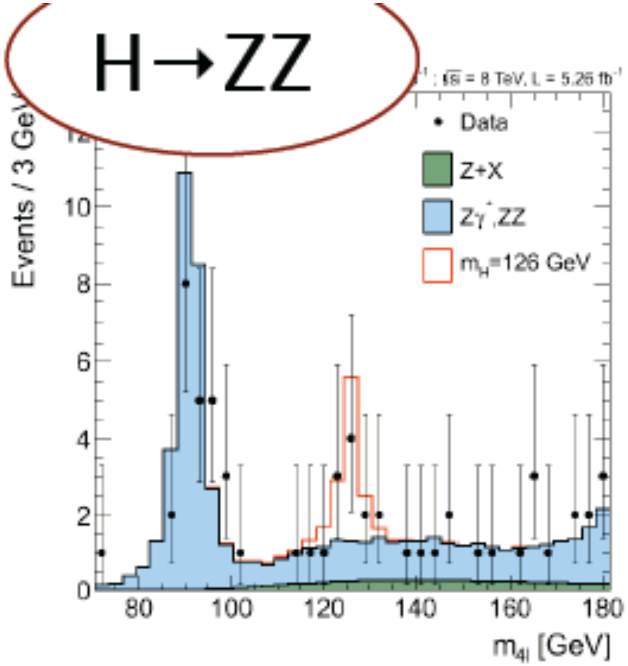


Evidence for a new state in the search for the standard model Higgs boson in the $H \to ZZ \to 4\ell$ channel in pp collisions at $\sqrt{s} = 7$ and 8 TeV

The CMS Collaboration

Excess at $m_{4l} \approx 126$ GeV with a p-value of **3.2σ**

July 4: seminar at CERN



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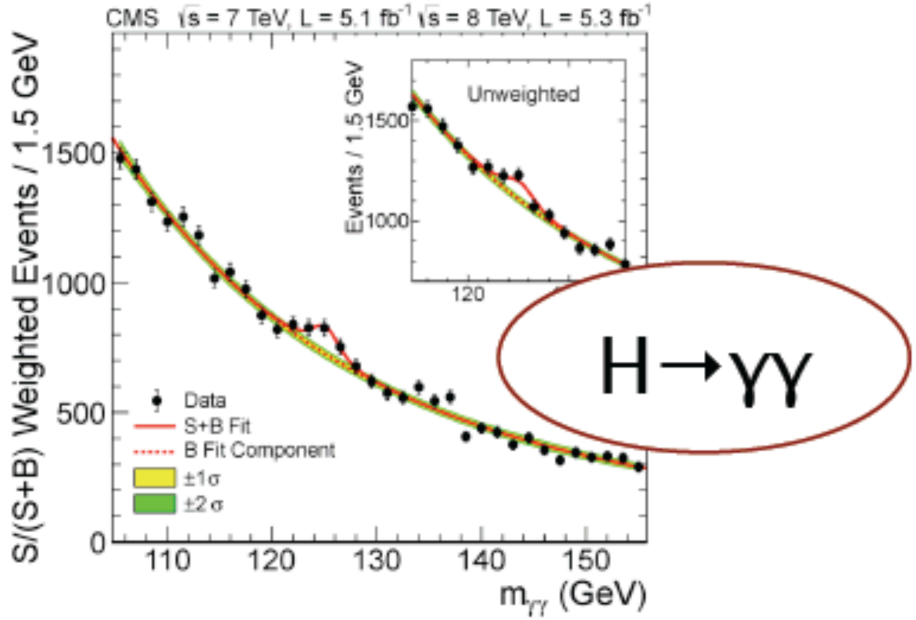

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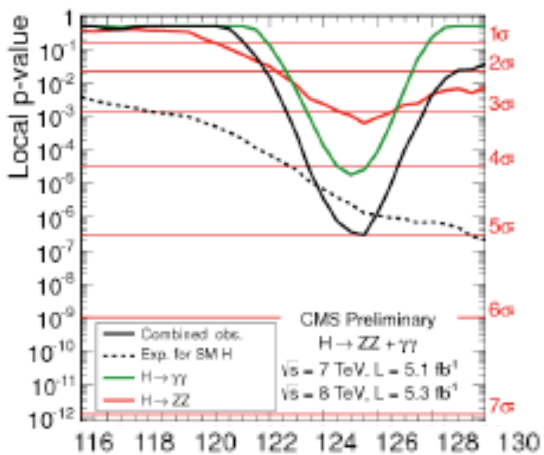
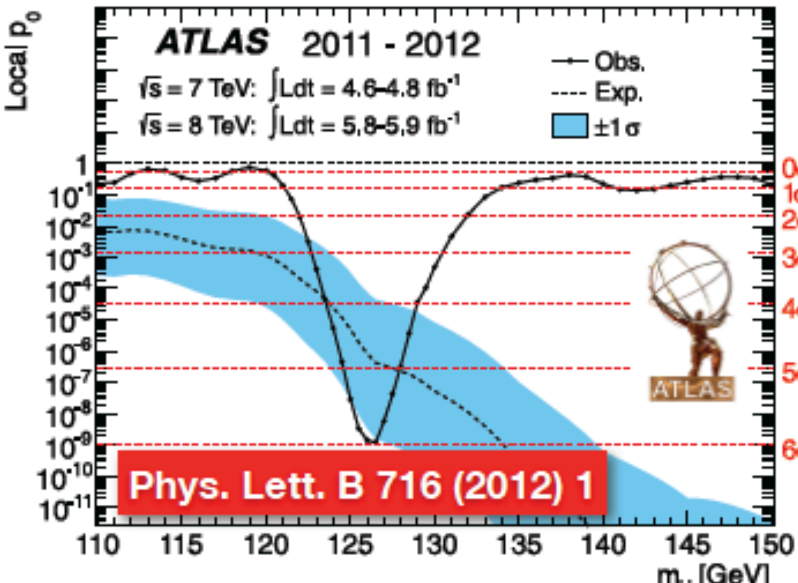
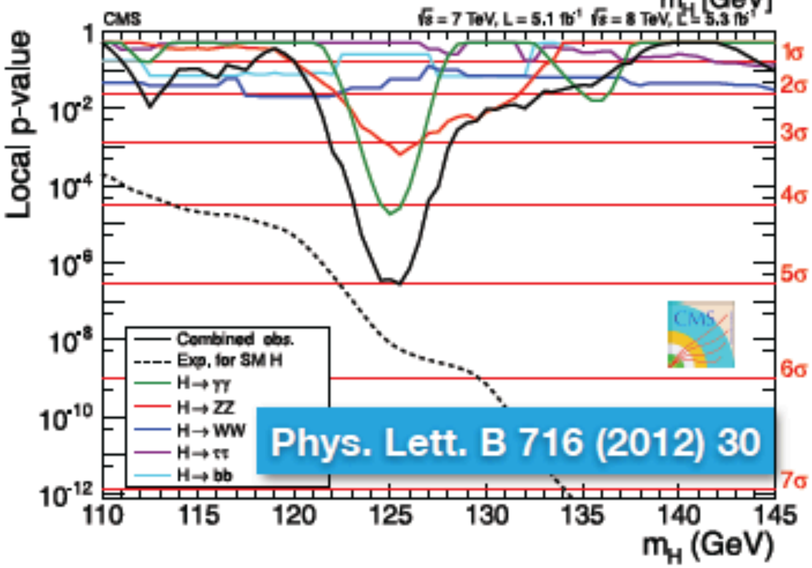
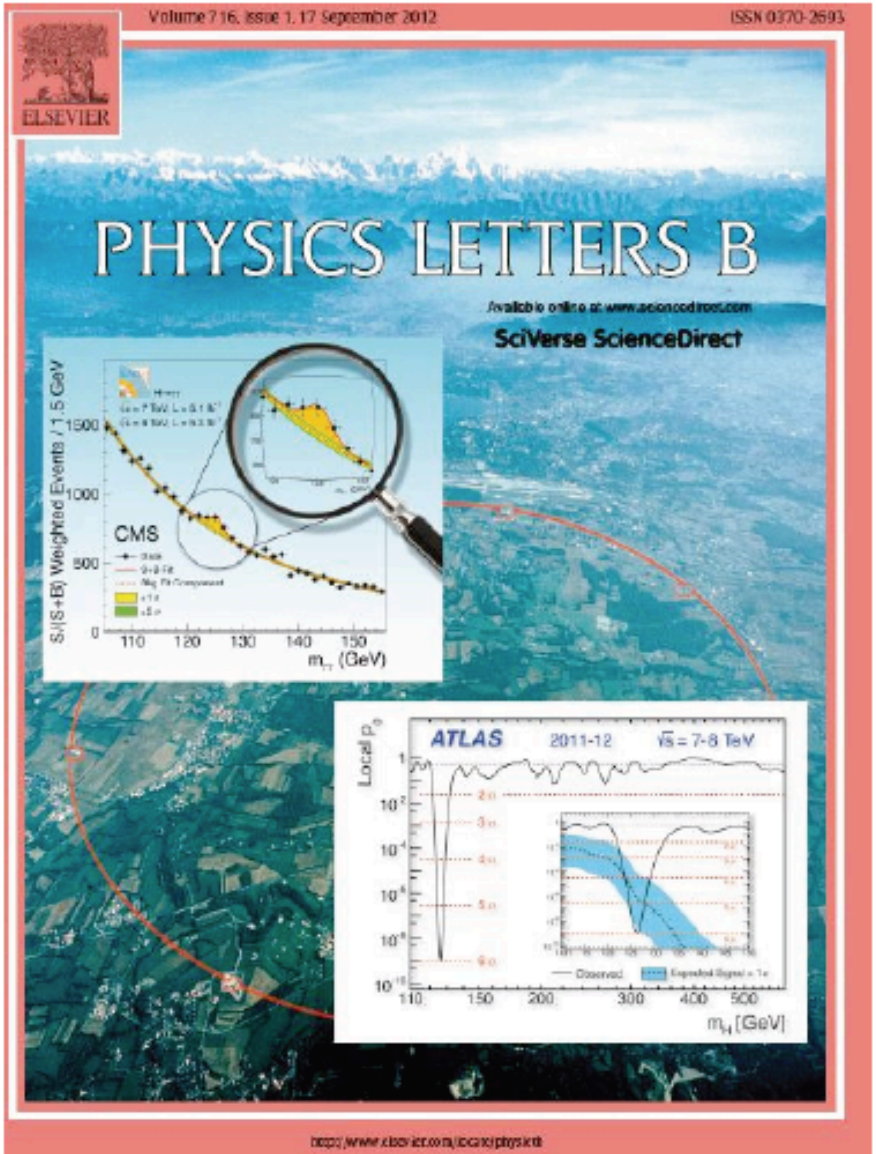


We have observed a new boson with a mass of **125.3 ± 0.6 GeV**

A new boson discovery: 4th of July 2012







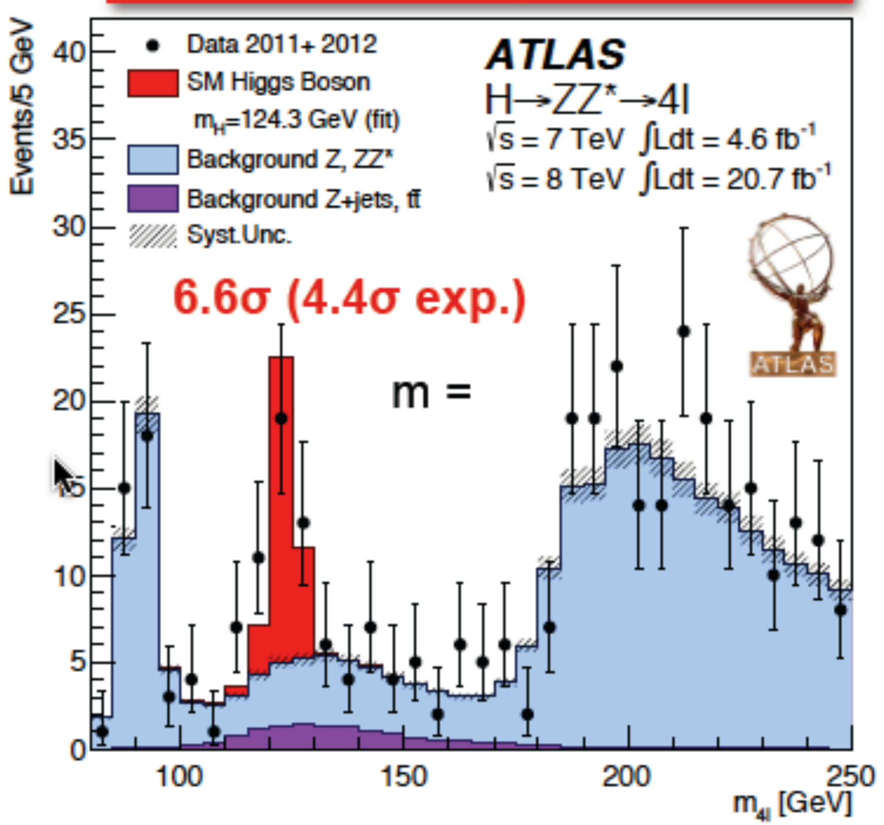
4th of July Fireworks

Moriond 2013 - What a Week!

H(ZZ→4l)

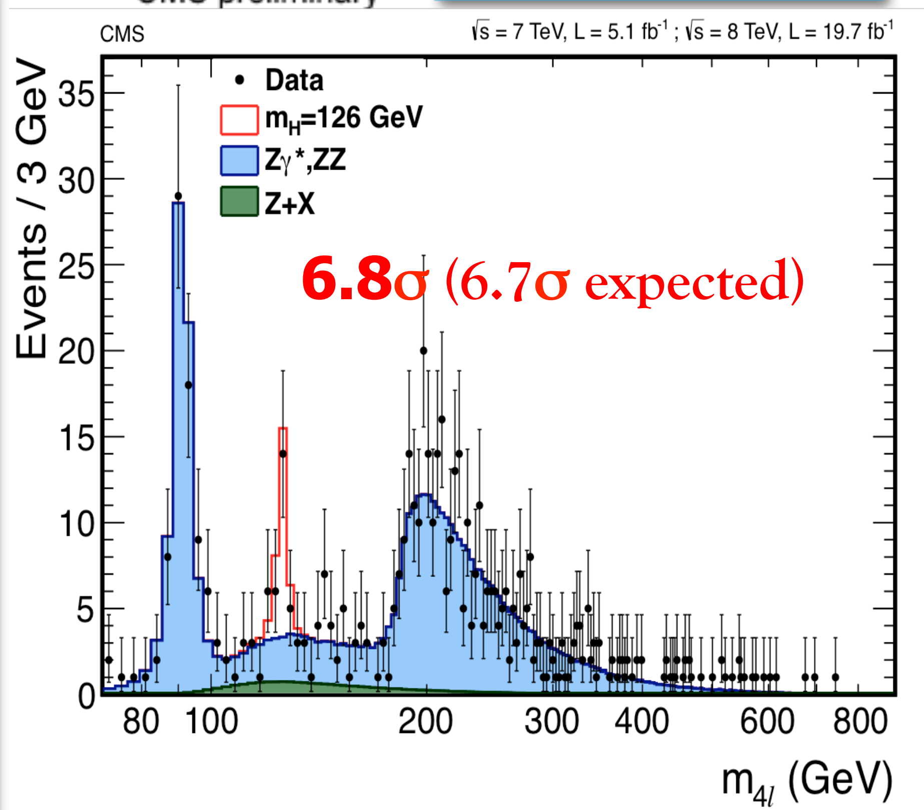
- Most sensitive, high-resolution channel for a 125 GeV Higgs!
  - ATLAS: Cut-in-categories, FSR accounting, untagged + VBF+ VH
  - CMS: MELA (angular analysis), FSR recovery, untagged + VBF

ATLAS Collaboration, arXiv:1307.1427



CMS preliminary

CMS PAS HIG-13-002

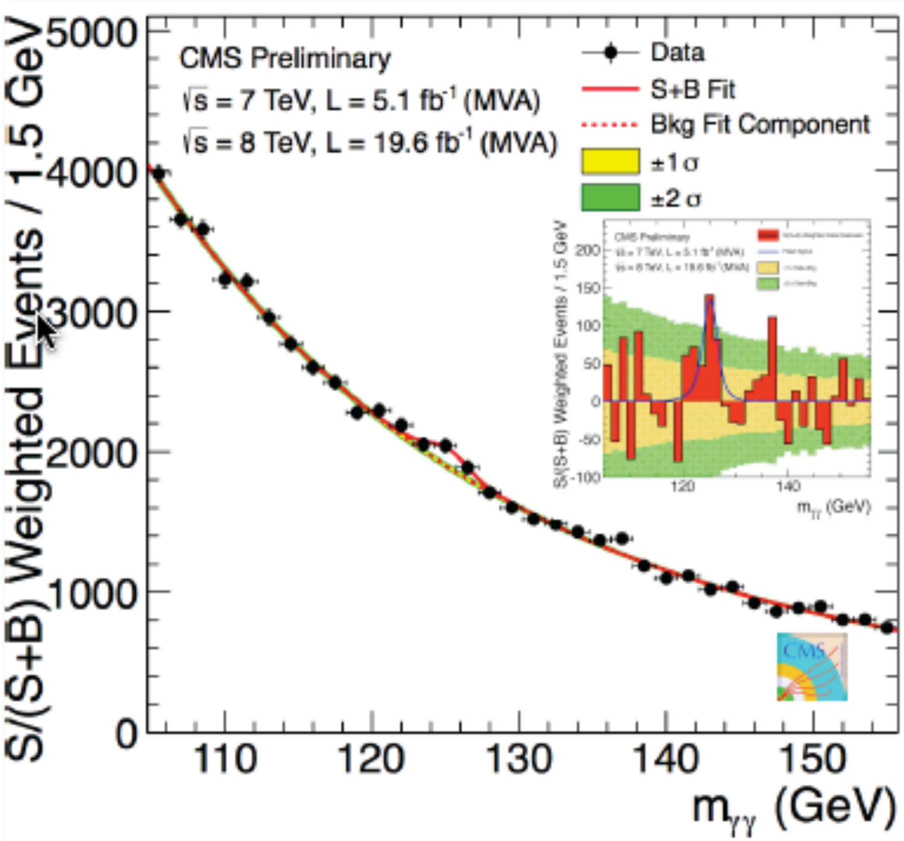


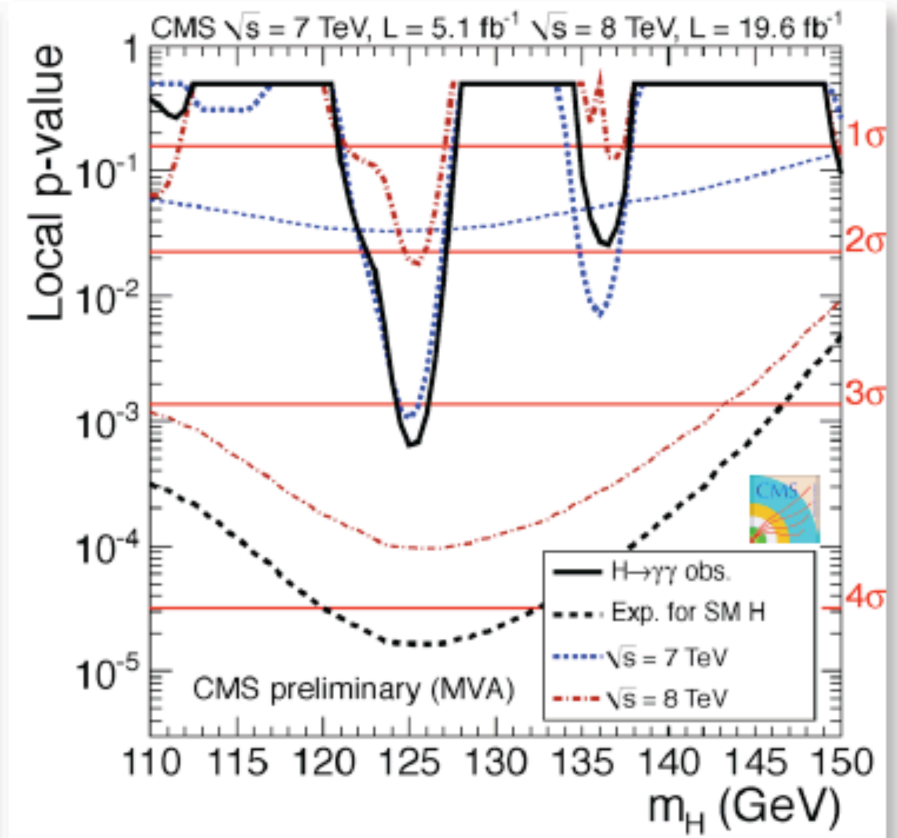
CMS H(γγ) Results

- Main analysis: MVA; cross-check: cut-in-categories (CiC)
  - Significances:
    - MVA: 3.2σ (4.2σ expected)
    - CiC: 3.9σ (3.5σ expected)
  - Mass: **125.4 ± 0.8 GeV**

μ-values:

	MVA analysis (at m_H=125 GeV)	cut-based analysis (at m_H=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$





October 8, 2013: Nobel Prize

Nobel Prizes and Laureates

Physics Prizes ‹ 2013 ›

▾ About the Nobel Prize in Physics 2013

- Summary
- Prize Announcement
- Press Release
- Advanced Information
- Popular Information
- Greetings

▸ François Englert

▸ Peter Higgs

All Nobel Prizes in Physics

All Nobel Prizes in 2013

The Nobel Prize in Physics 2013

François Englert, Peter Higgs

The Nobel Prize in Physics 2013

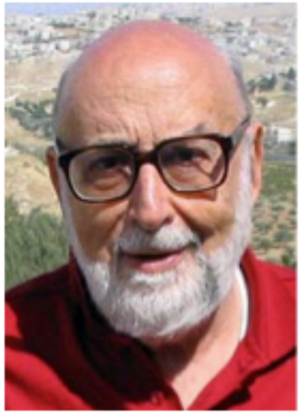


Photo: Pnicolet via Wikimedia Commons

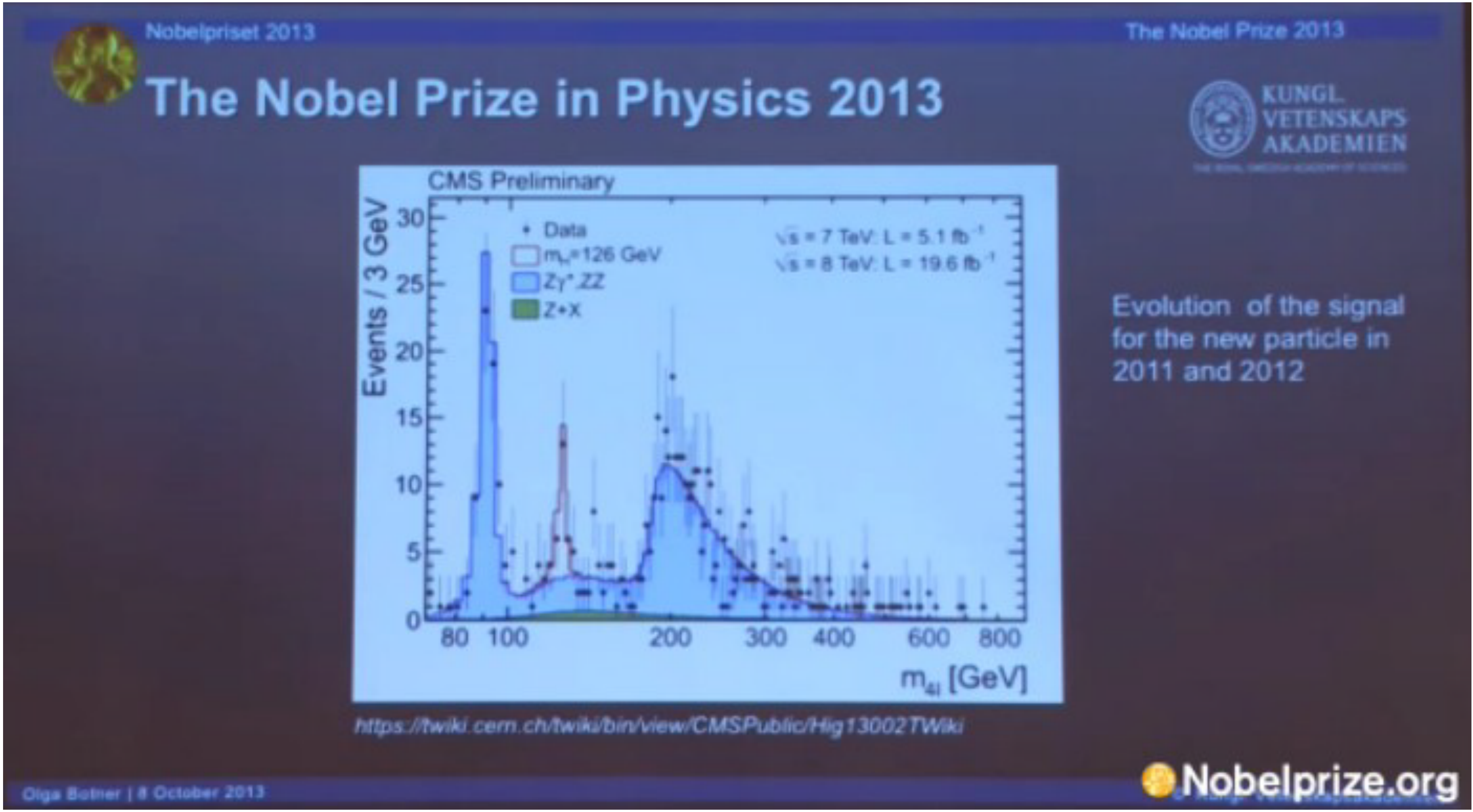
François Englert

Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

October 8, 2013: Nobel Prize



CERN congratulates Englert and Higgs on Nobel in physics

François Englert (left) and Peter Higgs at CERN on 4 July 2012, on the occasion of the announcement of the discovery of a Higgs boson by the ATLAS and CMS experiments (Image: Maximilien Brice/CERN)

ABOUT CERN

- About CERN
- Computing
- Engineering
- Experiments
- How a detector works
- *more →*

UPDATES

CERN hosts international conference on thorium technologies

29 Oct 2013 – CERN is currently hosting the Thorium Energy Conference ThEC13, running from 27 to 31 October, watch the webcast

CERN receives the Prince of Asturias Award

25 Oct 2013 – CERN, along with Peter Higgs and François Englert, today receives the Prince of Asturias Award during a ceremony in Spain

Backup

Theoretical constraints

Recall: 1 doublet of Higgs fields ⇒ 1 physical boson (CP-even)
M_H is a free parameter … $M_H^2 = 2\lambda v^2$; $v \sim 246$ GeV

Theory Constraints:

Unitarity:

$$M_H < 700 - 800\ GeV/c^2$$

''Triviality'' (Higgs self-coupling remains finite :)

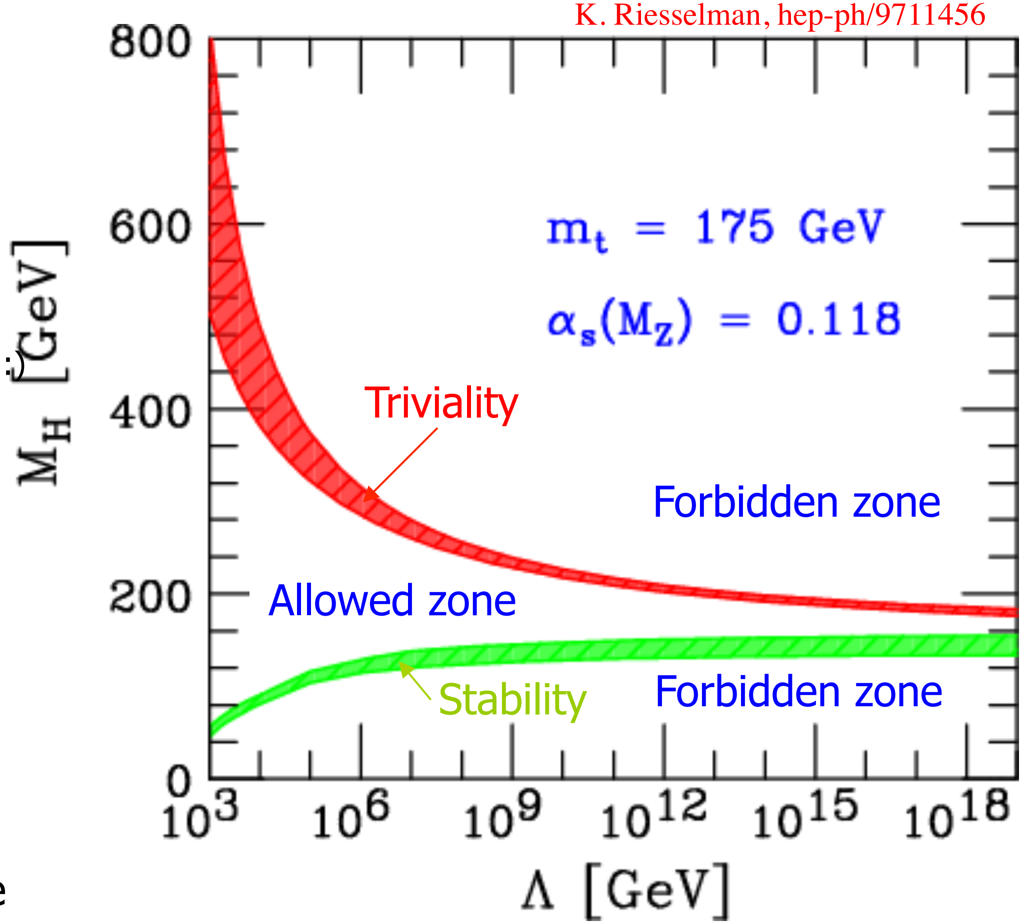
$$M_H^2 < \frac{4\pi^2 v^2}{3\ln(\Lambda/v)}$$

''Stability'' of vacuum:

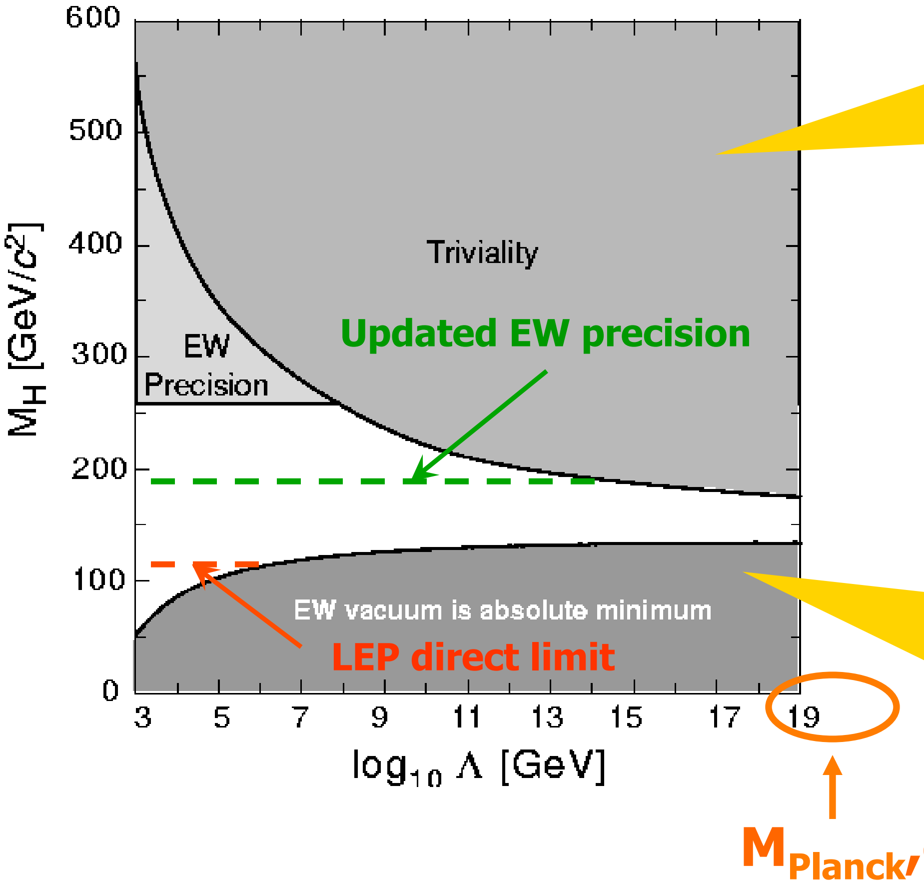
$$M_H^2 > \frac{4m_t^4}{\pi^2 v^2}\ln(\Lambda/v)$$

Λ = cut-off scale

K. Riesselman, hep-ph/9711456



Theoretical limits on Higgs mass



M_H too large:
Higgs self coupling blows up at some scale Λ

M_H too small:
for scalar field values O(Λ) the Higgs potential becomes unstable

- If SM is valid up to Planck Scale
  - $130 < M_H < 180$ GeV