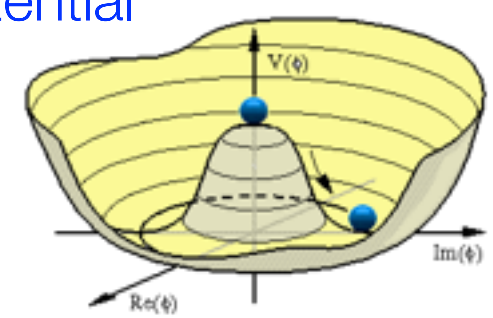
# The SM Lagrangian – Revised

Yukawa Couplings

Higgs Field

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}' + \mathcal{L}_{\text{Yuk}} + \mathcal{L}_{\phi'}$$

Higgs Potential




$$\mathcal{L}_\phi = (\partial_\mu \phi^\dagger)(\partial^\mu \phi) - V(\phi)$$

$$\mathcal{L}_{\text{Yuk}} = c_f(\bar{\psi}_L \psi_R \phi + \bar{\psi}_R \psi_L \phi)$$

Higgs Fermion Interaction

Gauge Boson masses: $i\partial_\mu \rightarrow i(\partial_\mu - ieA_\mu)$

Fermion masses: $c_f \bar{\psi}\psi\phi$

and $\phi' = \phi - \rho_0$

Vacuum expectation value

# SM Parameters

Determine experimentally

| | |
|---|---|
| 3 Couplings | $g_s,\ e,\ \sin\theta_W$ |
| 4 CKM parameters | $\vartheta_1,\ \vartheta_2,\ \vartheta_3,\ \delta$ |
| 2 Boson masses | $m_\mathrm{Z},\ m_\mathrm{H}$ |
| 3 Lepton masses | $m_\mathrm{e},\ m_\mu,\ m_\tau$ |
| 6 Quark masses | $m_\mathrm{u},\ m_\mathrm{d},\ m_\mathrm{s},\ m_\mathrm{c},\ m_\mathrm{t},\ m_\mathrm{b}\ .$ |

18 free SM parameters
no neutrino masses

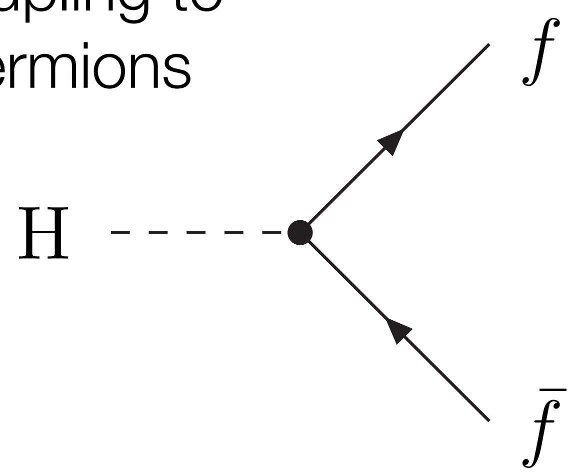
$$\begin{aligned} m_\mathrm{W}^2 &= \tfrac{1}{2}\, g^2\, \rho_0^2 \\ m_\mathrm{Z}^2 &= \tfrac{1}{2}\,(g^2 + {g'}^2)\, \rho_0^2 \\ m_\mathrm{H}^2 &= 4\,\lambda \rho_0^2 \end{aligned}$$

$$\begin{aligned} g &= e/\sin\theta_W \\ g' &= e/\cos\theta_W \end{aligned}$$

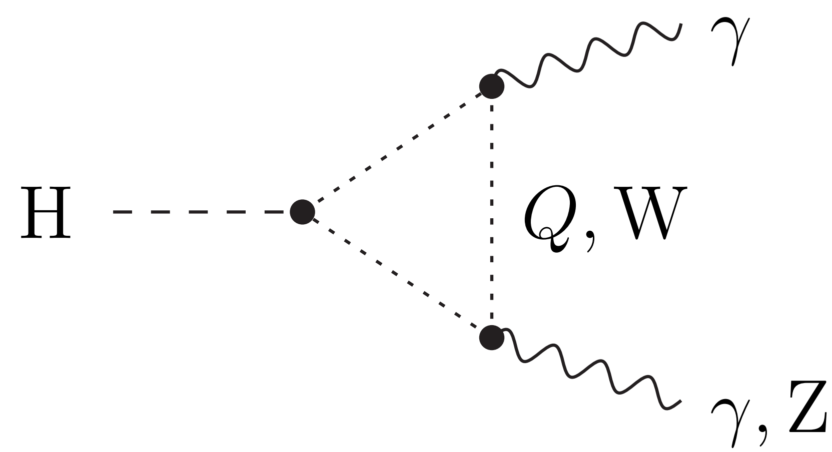
$$m_f = c_f \rho_0$$

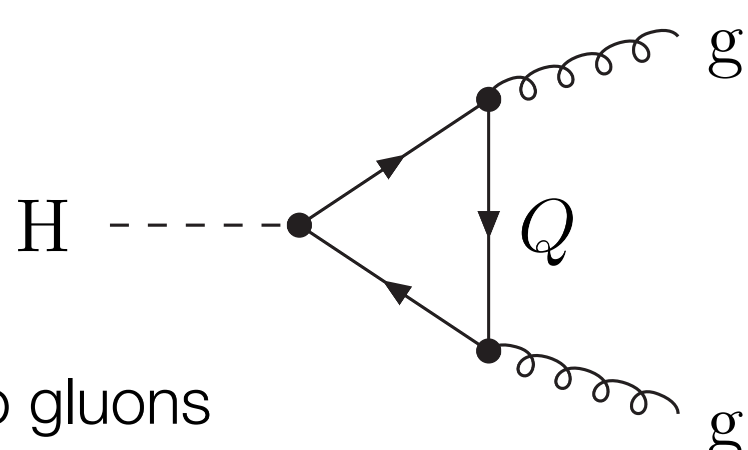
# Higgs Couplings – Examples

Coupling to
Fermions

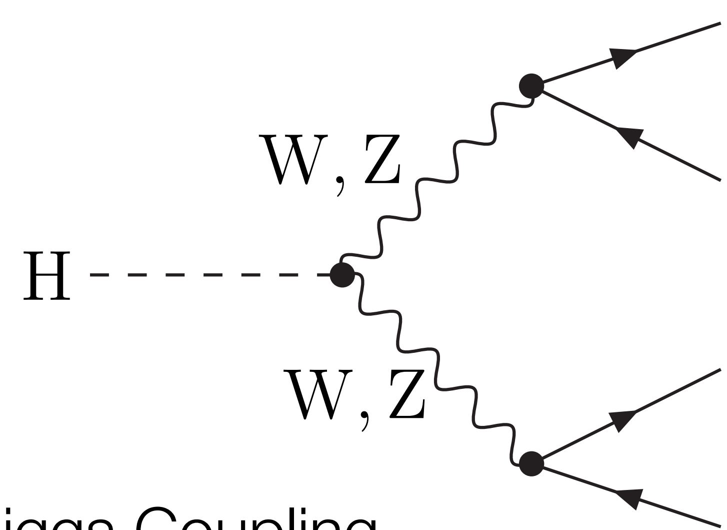



Coupling to photpns
[via charged particle loops]



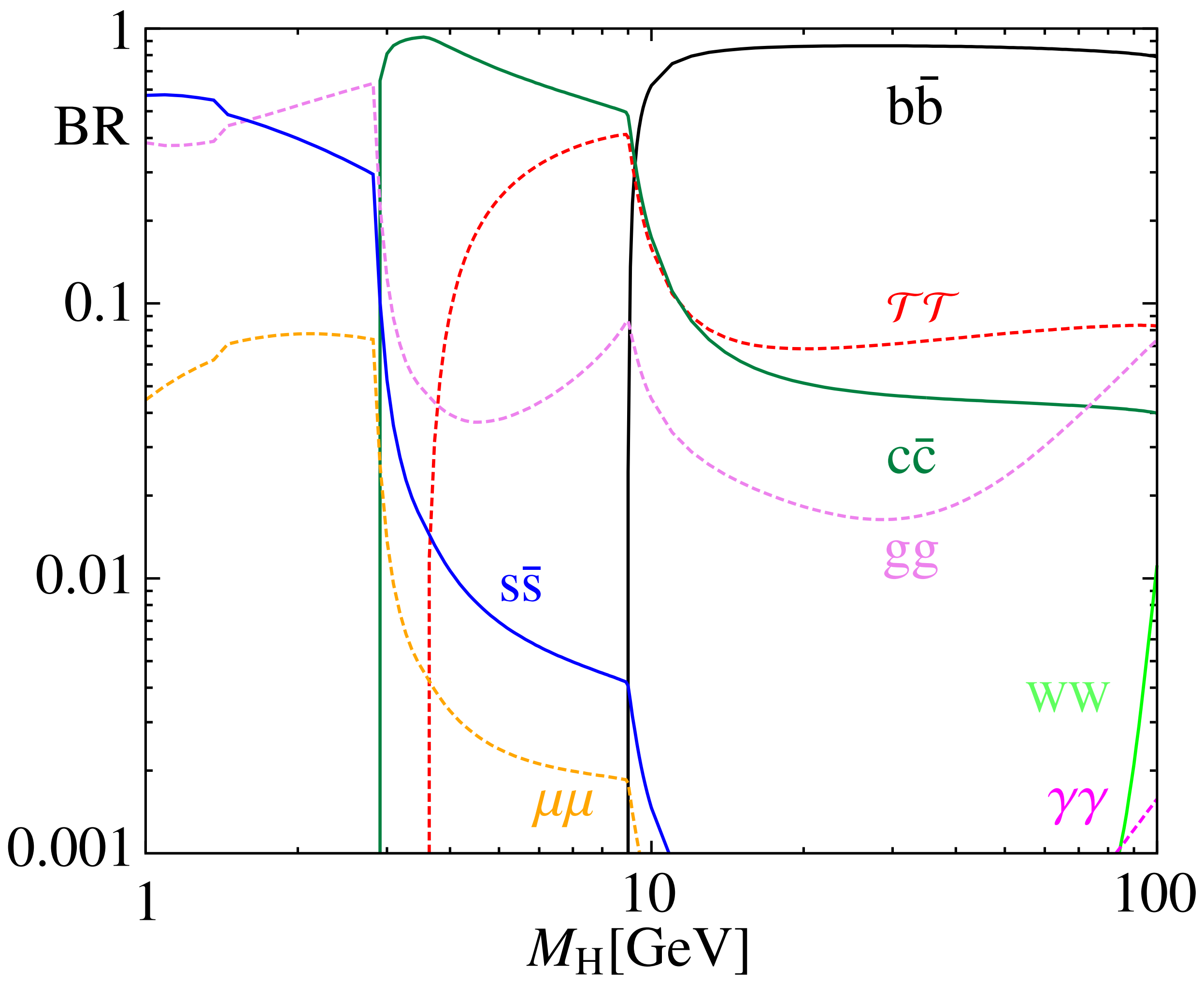

Coupling to gluons
[via heavy particle loops]




Higgs Coupling
to Gauge Boson

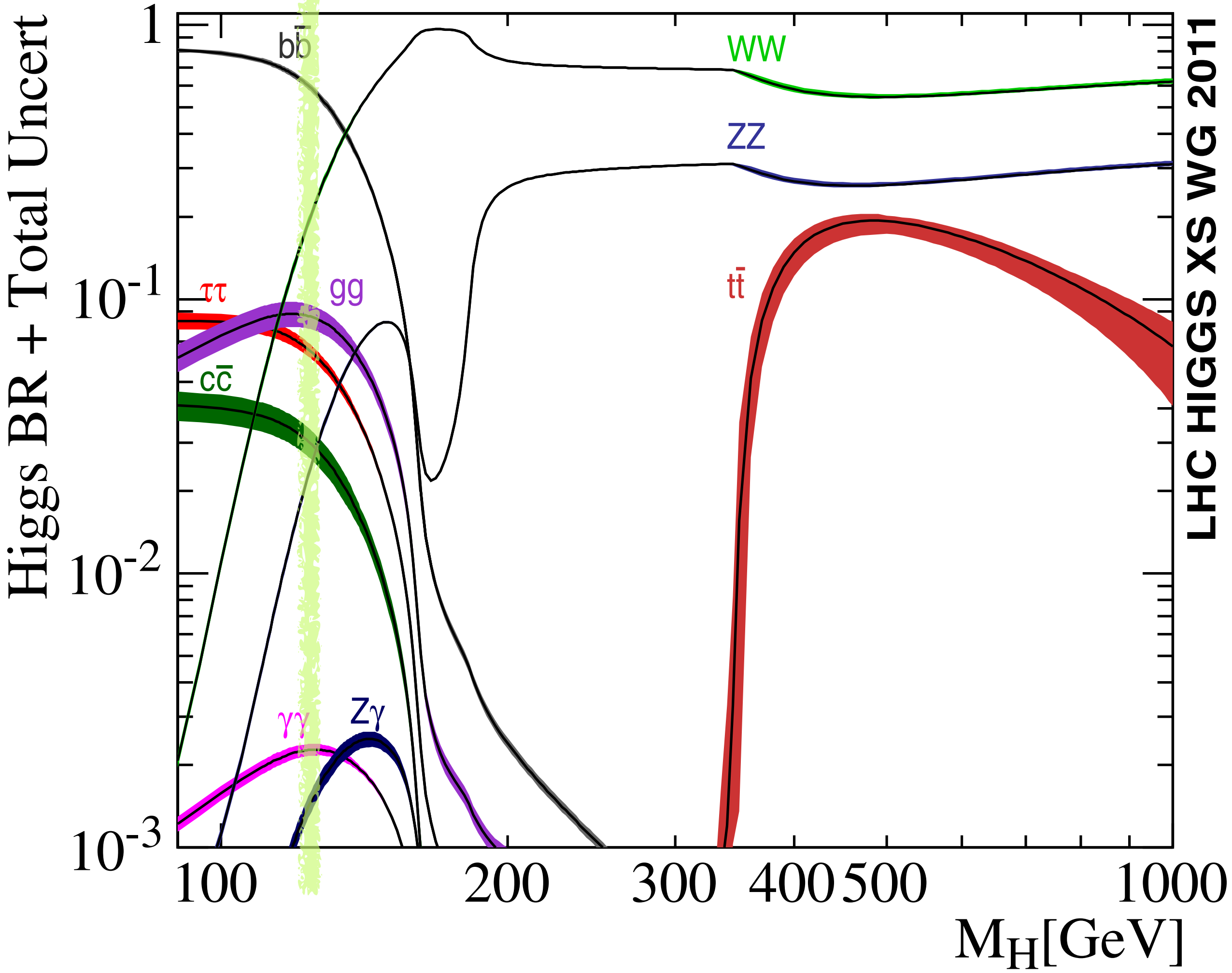
# Branching Ratios of the SM Higgs

Low Higgs Masses




Here it is

High Higgs Masses




A. Djouadi, et al., arXiv:1003.1643

S. Dittmaier et al., arXiv:1101.0593

S.Dittmaier and M. Schumacher, Progress in Particle and Nuclear Physics

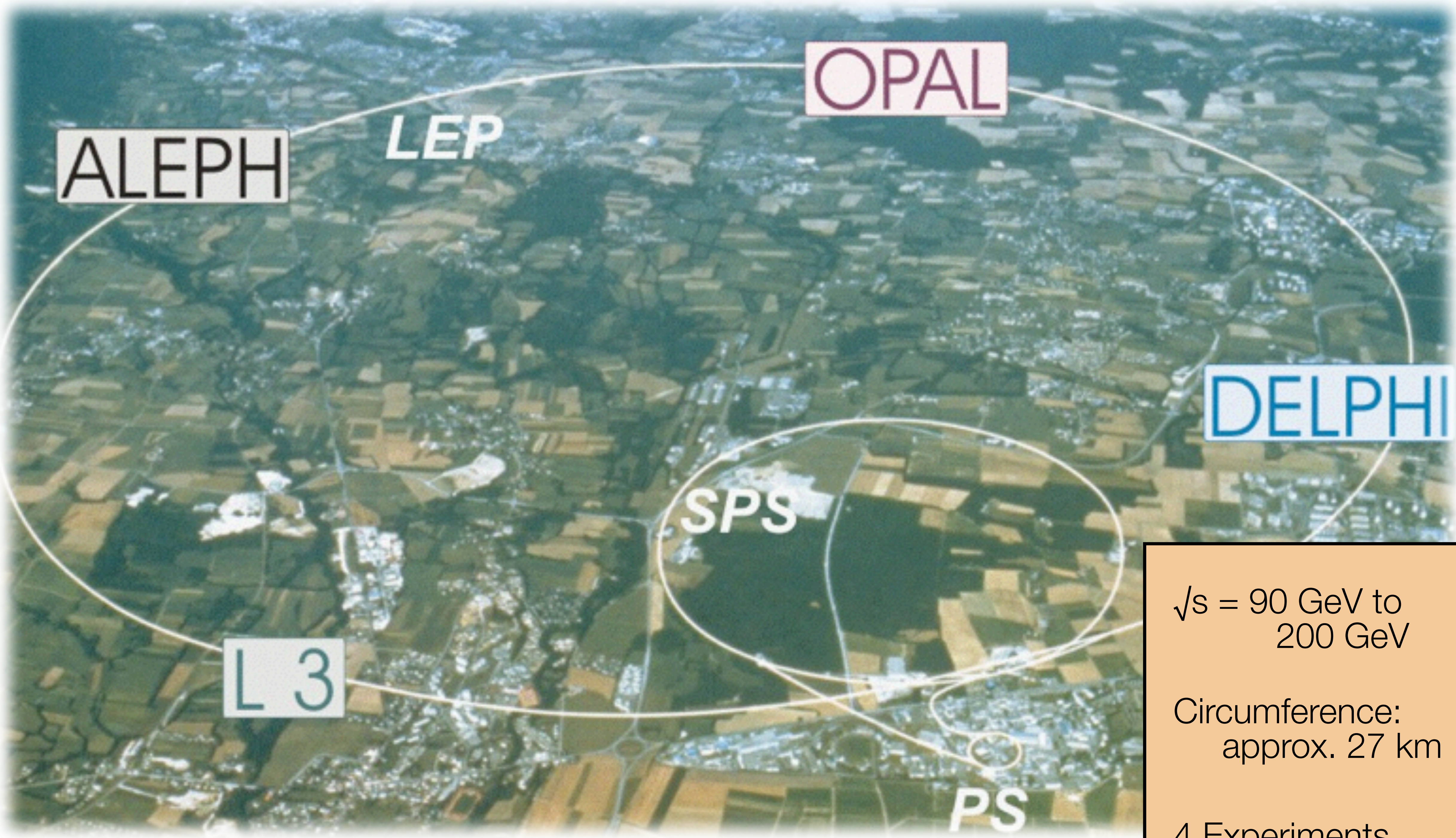
# Pre-LHC Status

[a very short history]

# Higgs Search

## at LEP

# The LEP Collider



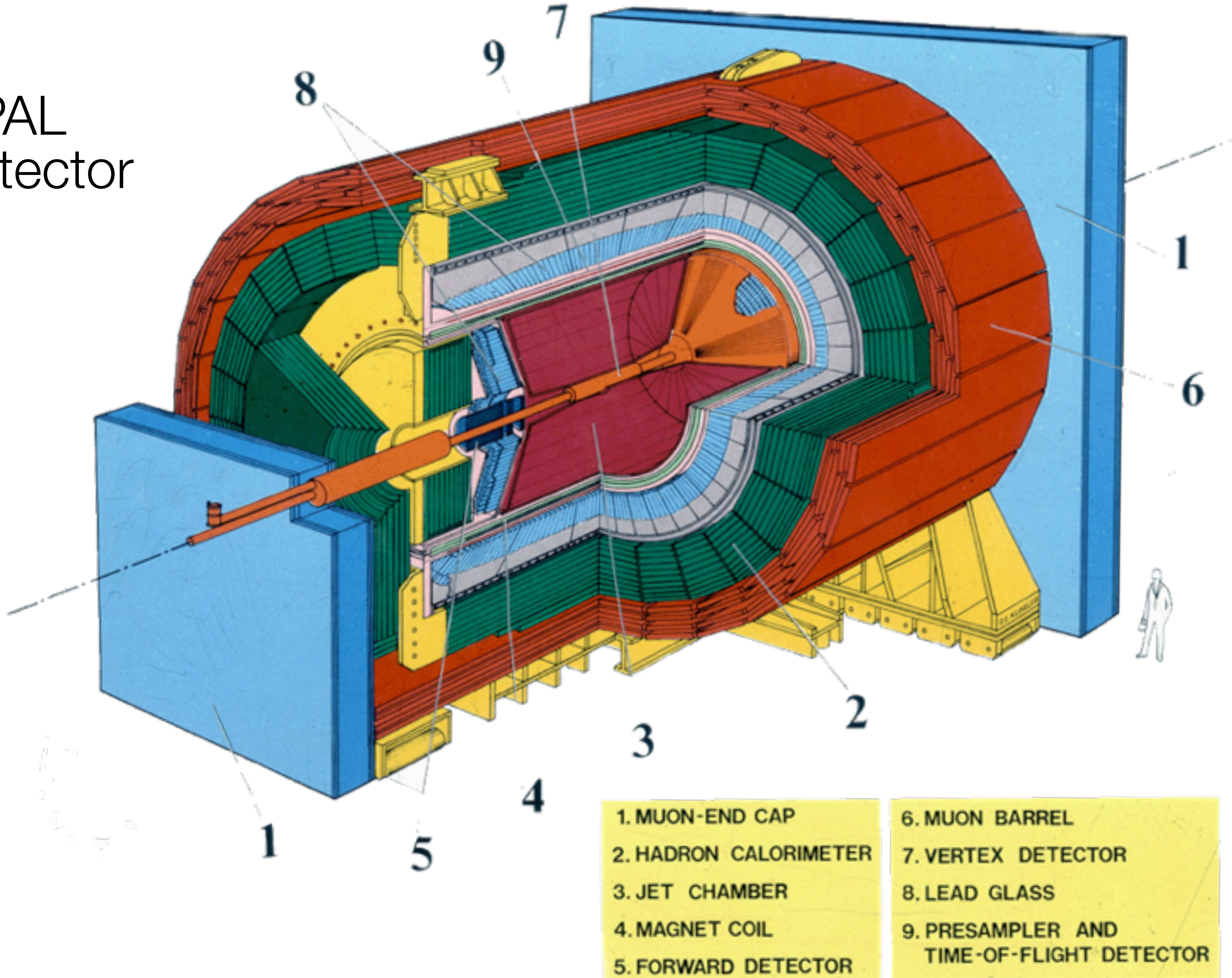

$\sqrt{s}$ = 90 GeV to 200 GeV

Circumference: approx. 27 km

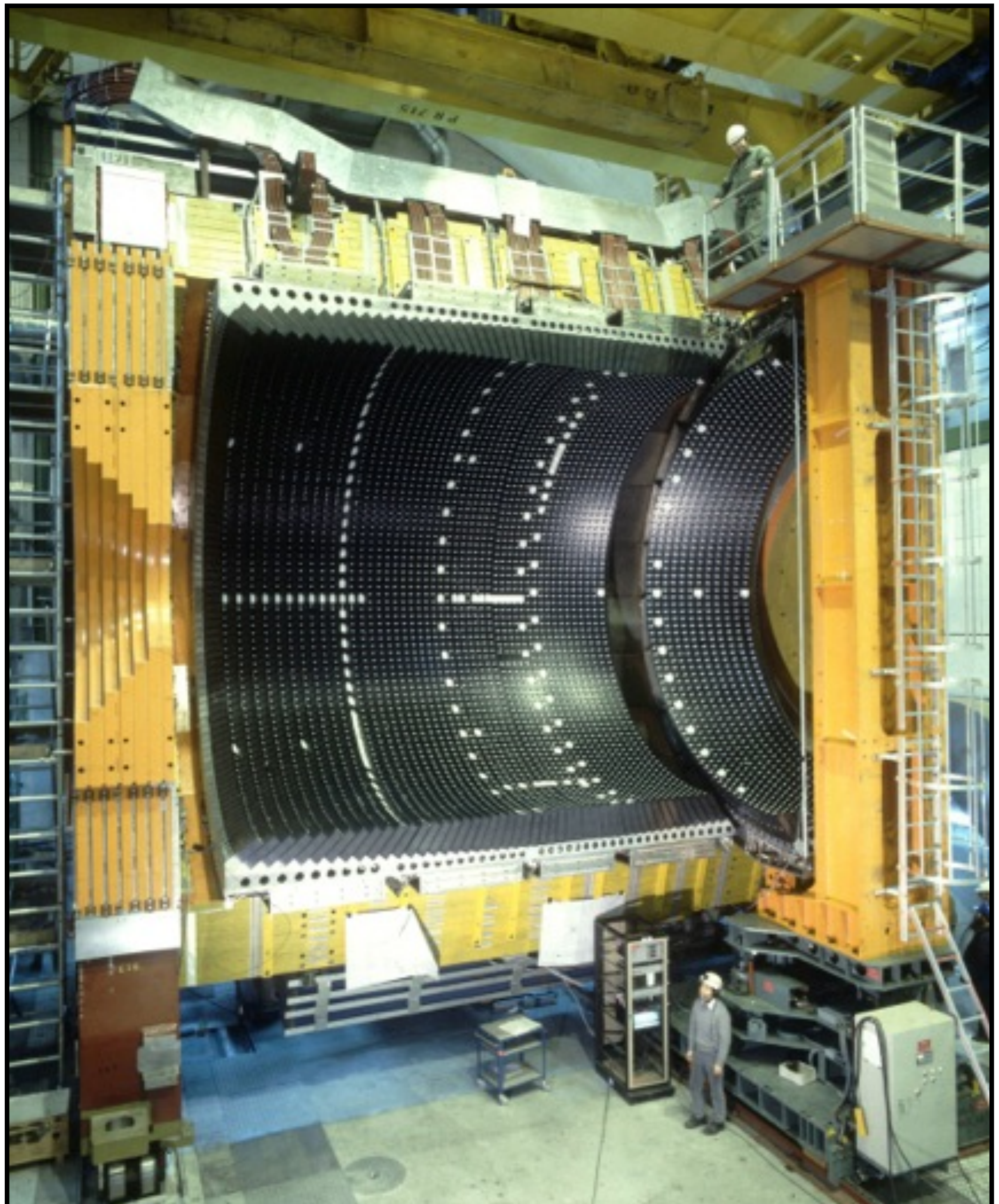
4 Experiments

# The LEP Experiments [Example: OPAL]

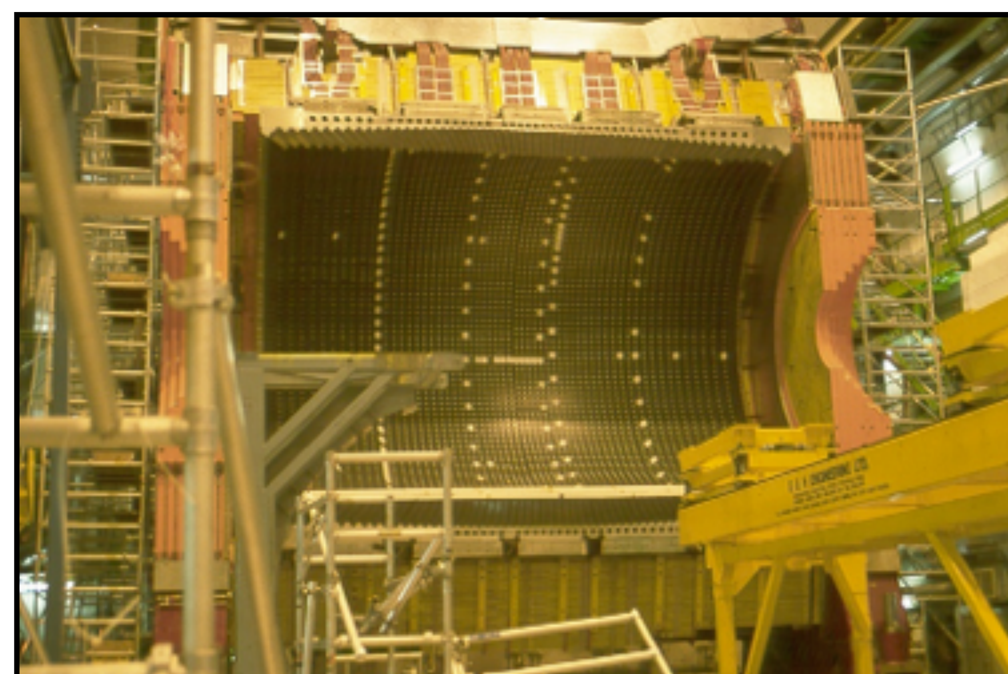
OPAL
Detector



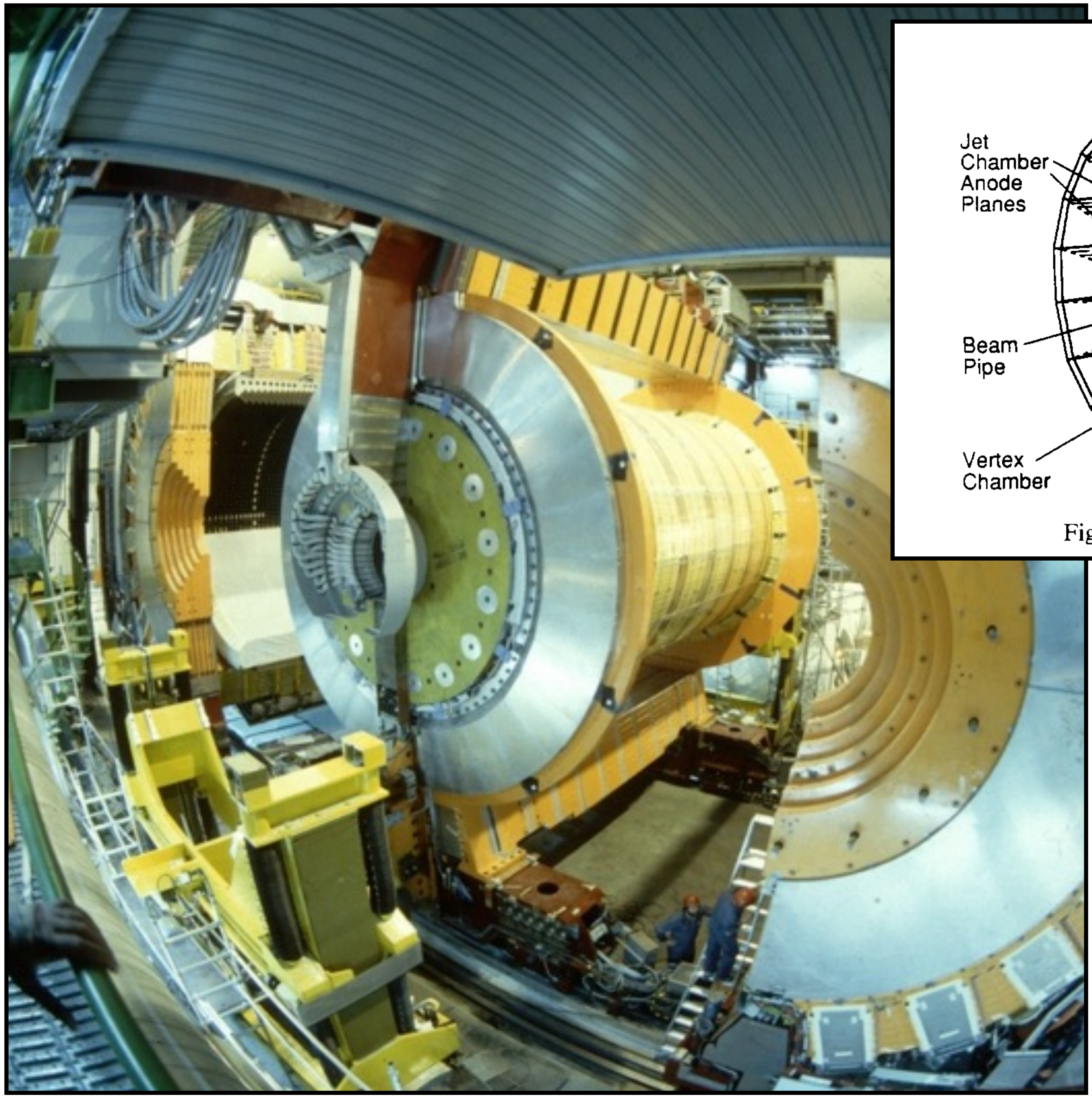
# The LEP Experiments [Example: OPAL]



OPAL Calorimeter



# The LEP Experiments [Example: OPAL]



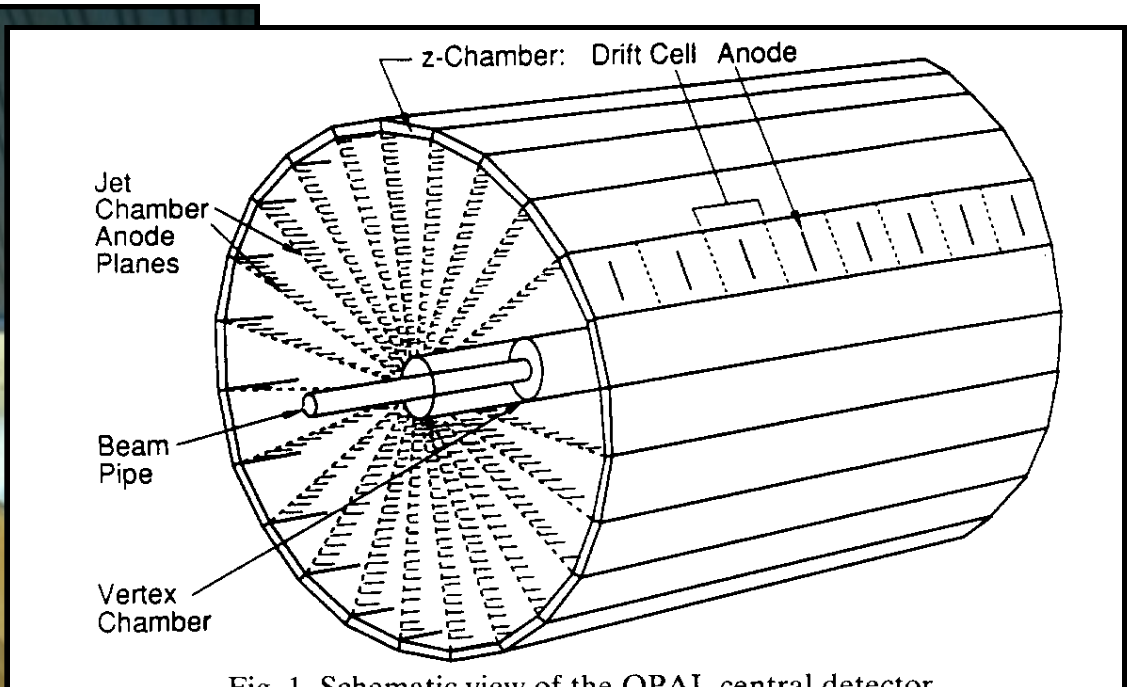
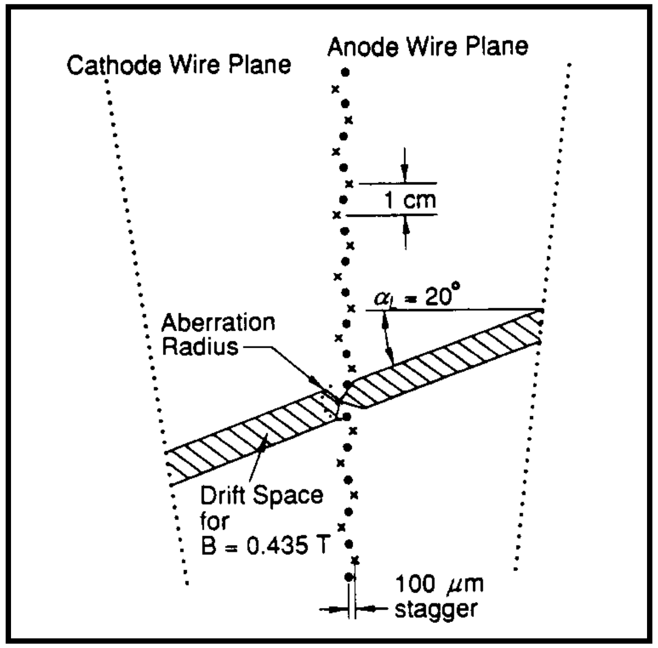
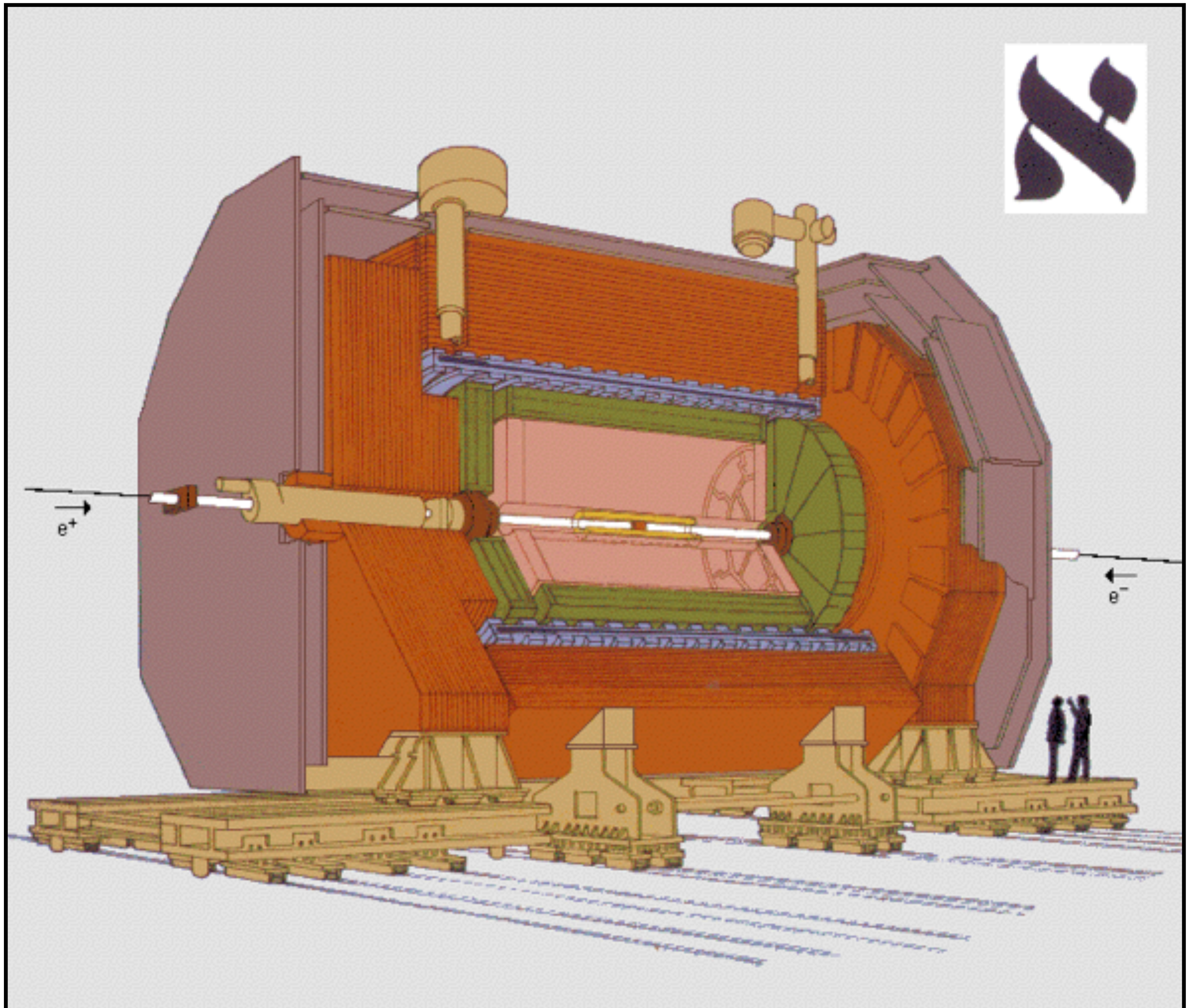


Fig. 1. Schematic view of the OPAL central detector.



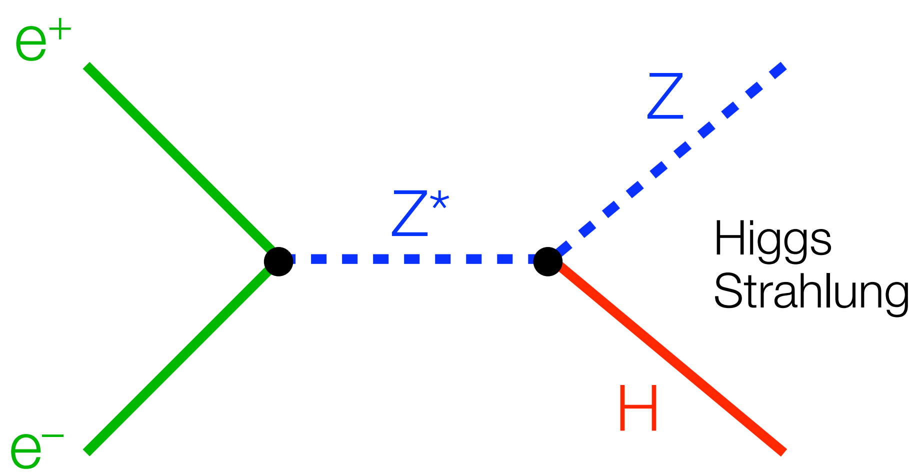

OPAL Jet Chamber

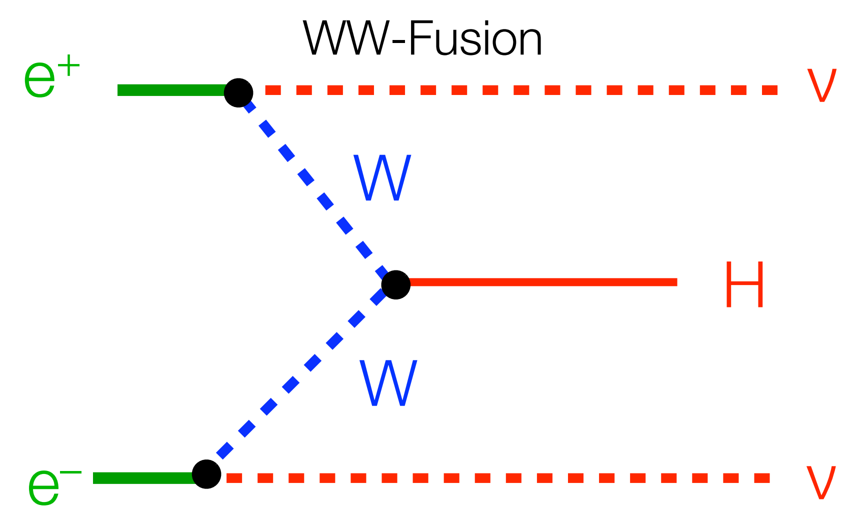
# The LEP Experiments [Example: ALEPH]

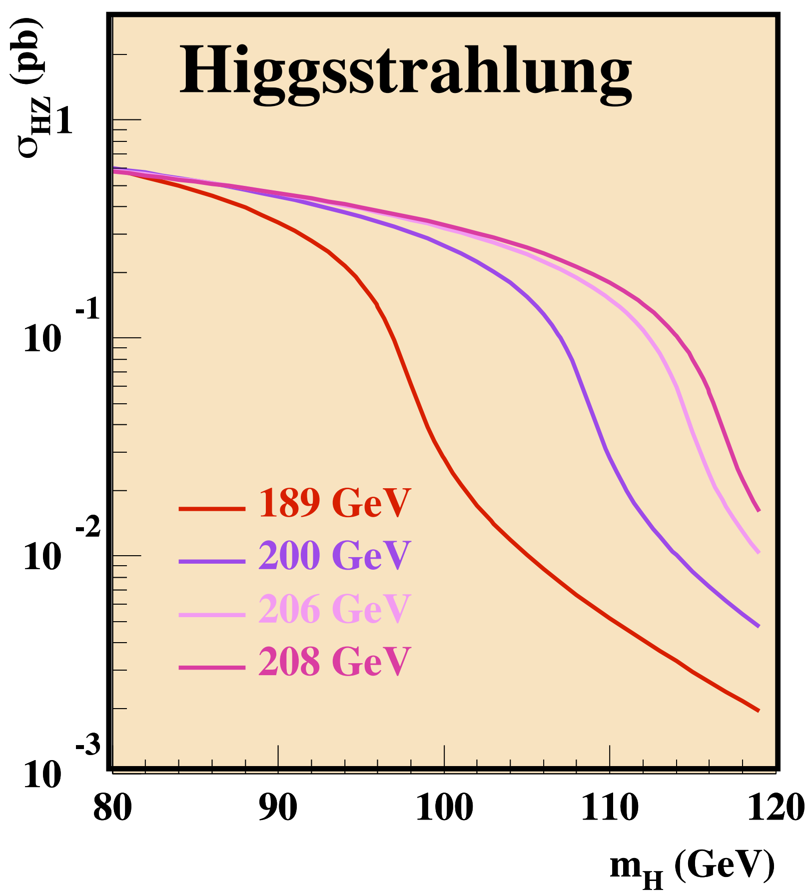


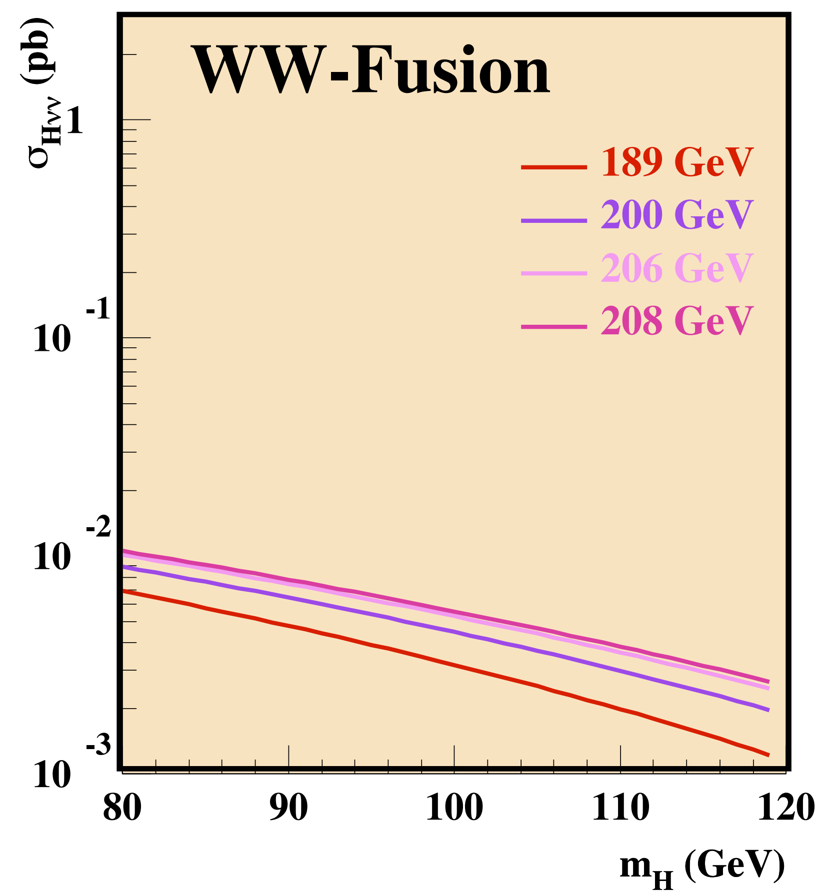

- Vertex Detector
- Inner Tracking Chamber
- Time Projection Chamber
- Electromagnetic Calorimeter
- Superconducting Magnet Coil
- Hadron Calorimeter
- Muon Chambers
- Luminosity Monitors

# SM Higgs Production at LEP

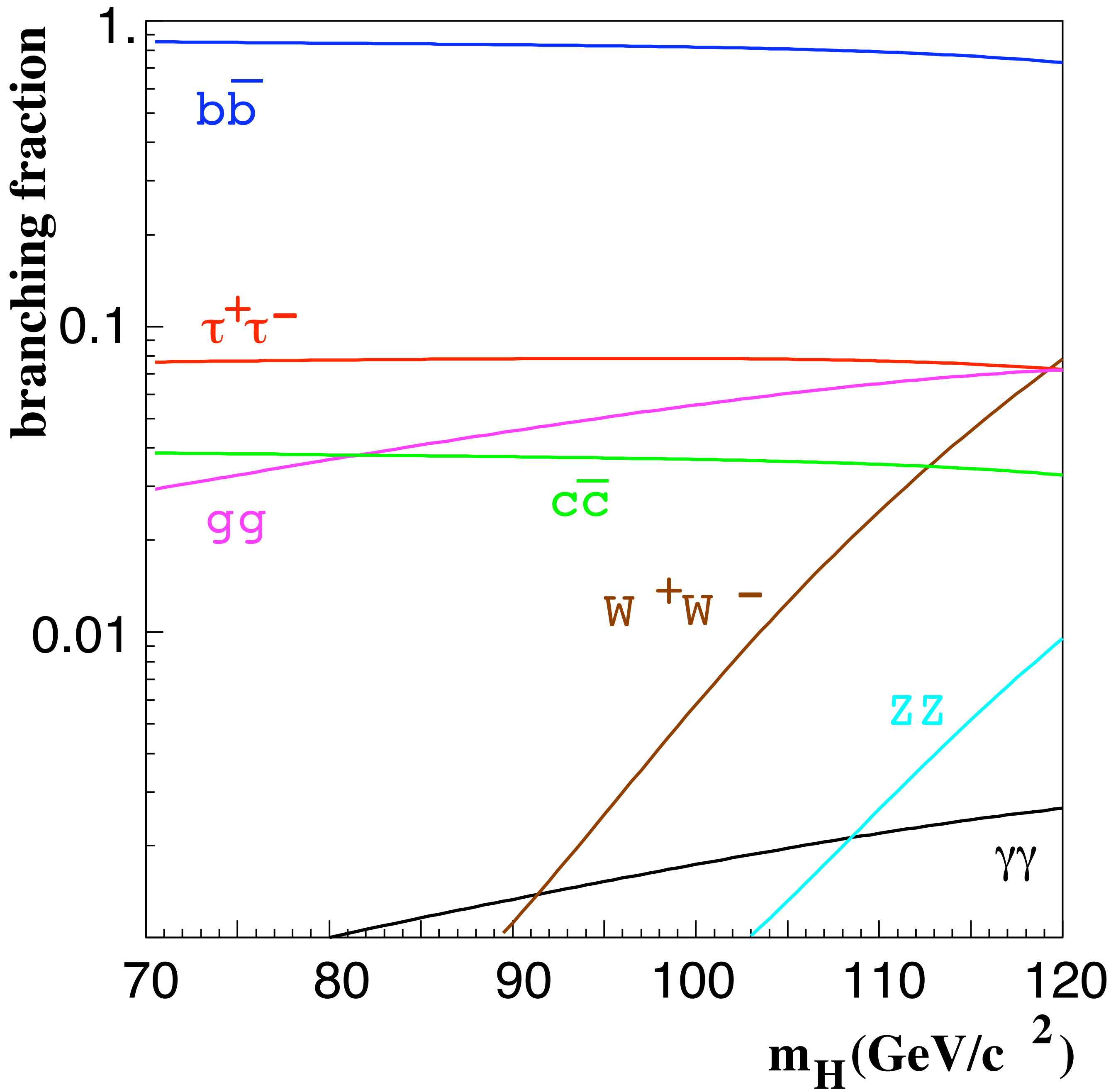


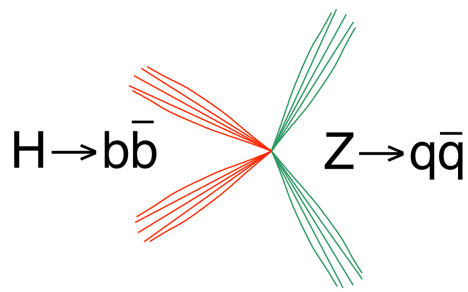



# Higgs Decay at LEP Energies




bb-decay
dominant !!

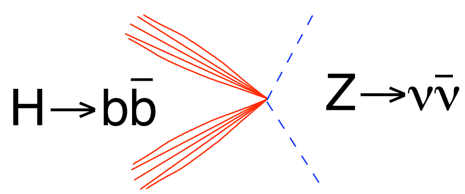
# LEP Higgs Signatures




4-jets

51%

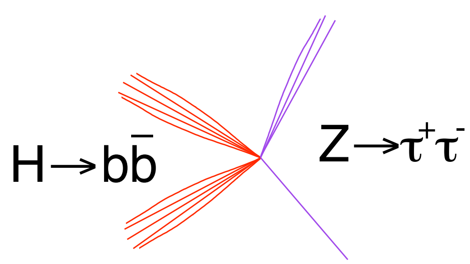
WW ➝ qqqq
ZZ ➝ qqqq
QCD 4-jets




missing energy

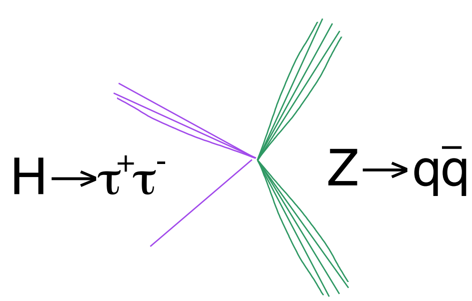
15%

WW ➝ qqlv
ZZ ➝ bbvv




τ-channel

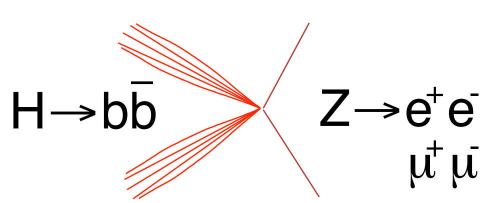
2.4%




τ-channel

5.1%

WW ➝ qqτv
ZZ ➝ bbττ
ZZ ➝ qqττ
QCD low mult. jets

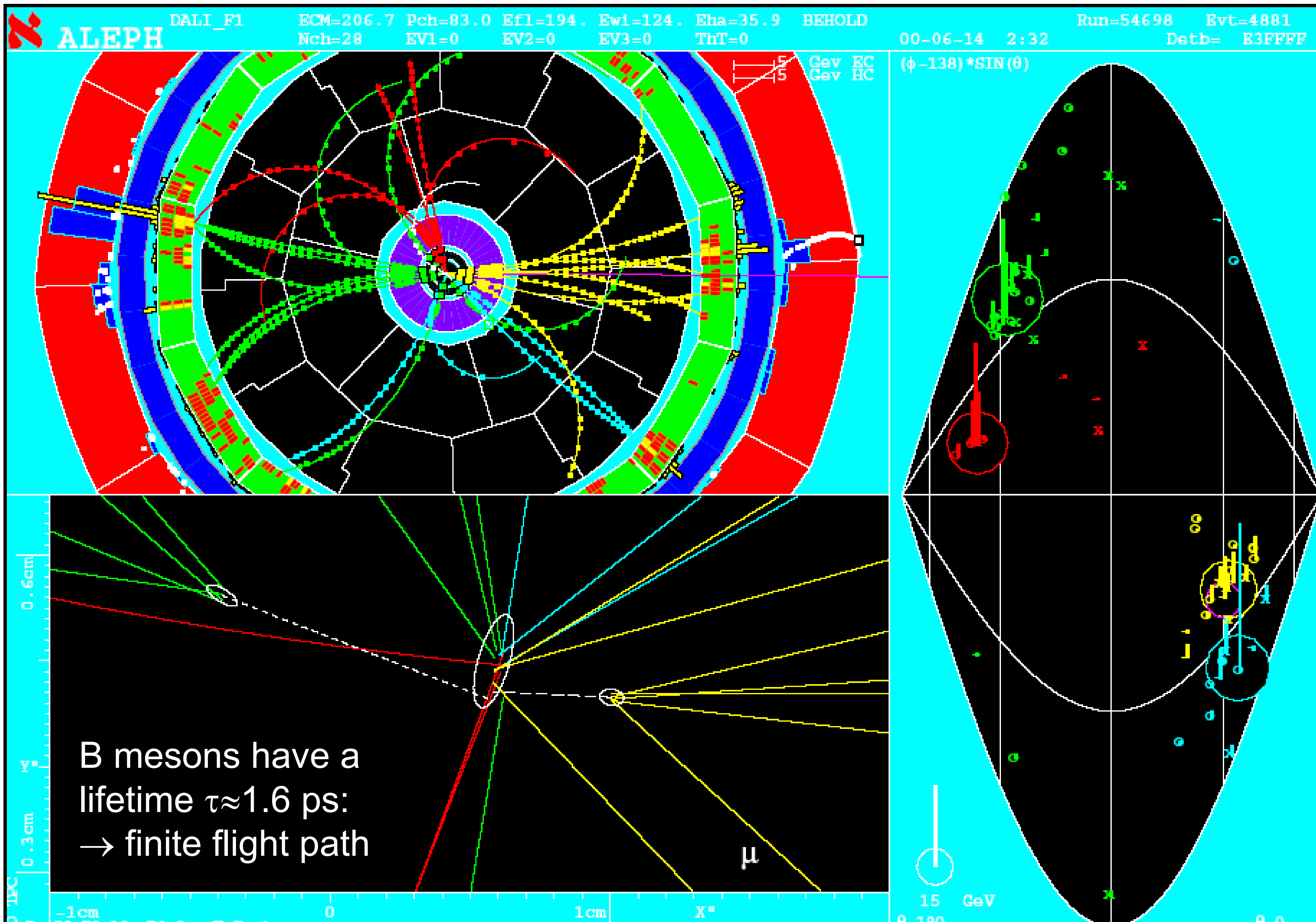



lepton channel

4.9%

ZZ ➝ bbee
ZZ ➝ bbμμ

# Higgs Candidate [$M_H$=114 GeV]



# LEP Higgs Candidates

LEP
final result

Observation:

17 candidate events

Expectation:

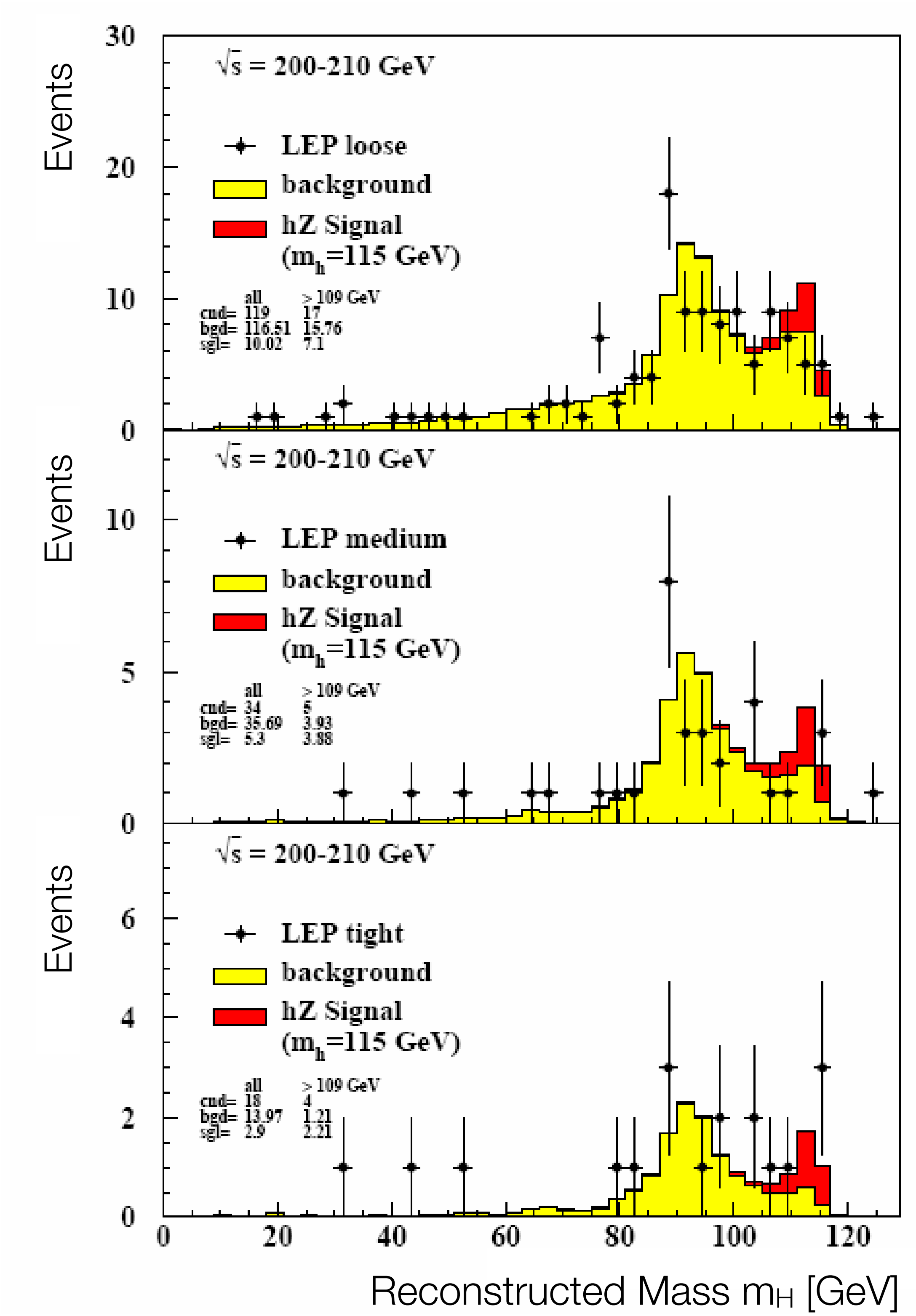
15.8 background events

8.4 signal events for $M_H$ =115 GeV

| | Expt | $E_{cm}$ | channel | $M^{rec}$ (GeV) | $\ln(1+s/b)$ @ 115 GeV | prev. rank. |
|---|---|---|---|---|---|---|
| 1 | A | 206.6 | 4 jet | 114.1 | 1.76 | 1 |
| 2 | A | 206.6 | 4 jet | 114.4 | 1.44 | 2 |
| 3 | A | 206.4 | 4 jet | 109.9 | 0.59 | 3 |
| 4 | L | 206.4 | Emiss | 115.0 | 0.53 | 4 |
| 5 | A | 205.1 | Lept. | 117.3 | 0.49 | 7 |
| 6 | A | 206.5 | Tau | 115.2 | 0.45 | 8 |
| 7 | O | 206.4 | 4 jet | 108.2 | 0.43 | 5 |
| 8 | A | 206.4 | 4 jet | 114.4 | 0.41 | 9 |
| 9 | L | 206.4 | 4 jet | 108.3 | 0.30 | 12 |
| 10 | D | 206.6 | 4 jet | 110.7 | 0.28 | |
| 11 | A | 207.4 | 4 jet | 102.8 | 0.27 | 14 |
| 12 | D | 206.6 | 4 jet | 97.4 | 0.23 | 11 |
| 13 | O | 201.5 | Emiss | 111.2 | 0.22 | |
| 14 | L | 206.0 | Emiss | 110.1 | 0.21 | 17 |
| 15 | A | 206.5 | 4 jet | 114.2 | 0.19 | |
| 16 | D | 206.6 | 4 jet | 108.2 | 0.19 | |
| 17 | L | 206.6 | 4 jet | 109.6 | 0.18 | |

Observation consistent with background !

# Final LEP Result




Invariant mass of Higgs candidates

LEP Summary:
No signal above background

$M_H > 114.4$ GeV @ 95% CL

# Blue Band Plot

[Indirect Information on SM Higgs]

# LEP "Zedometry"

Hadronic vaccuum polarization

Z Mass

Z Width

Had. Pole Cross Section

Lepton Asymmetries

Left/Right Asymmetries

Forw./Backw. Asymmetries

Ratios

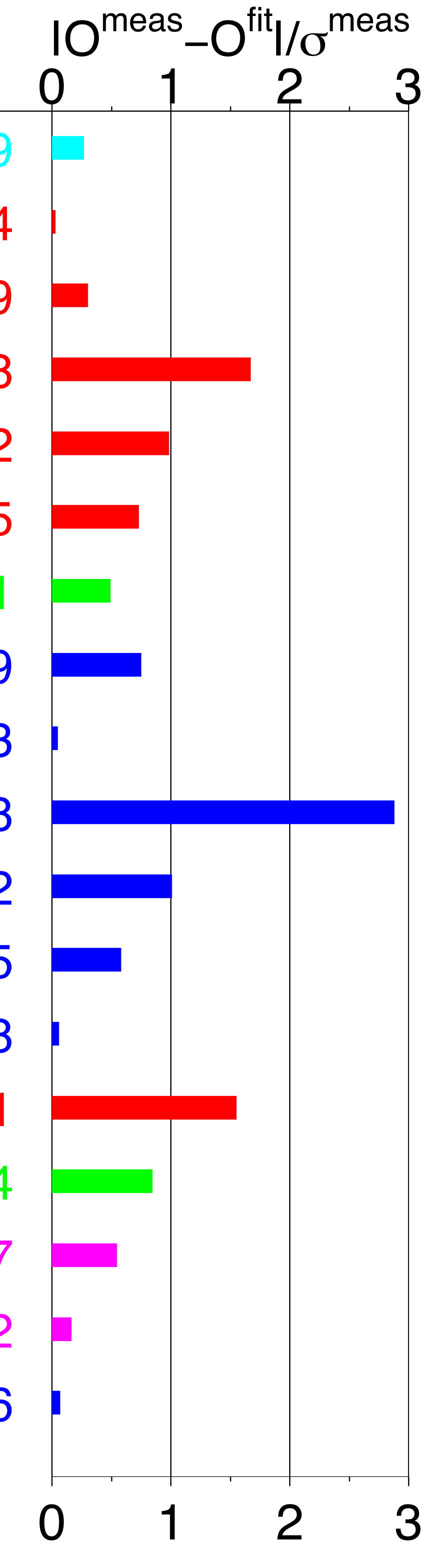
Effective mixing angle

W Mass

W Width

Top Mass

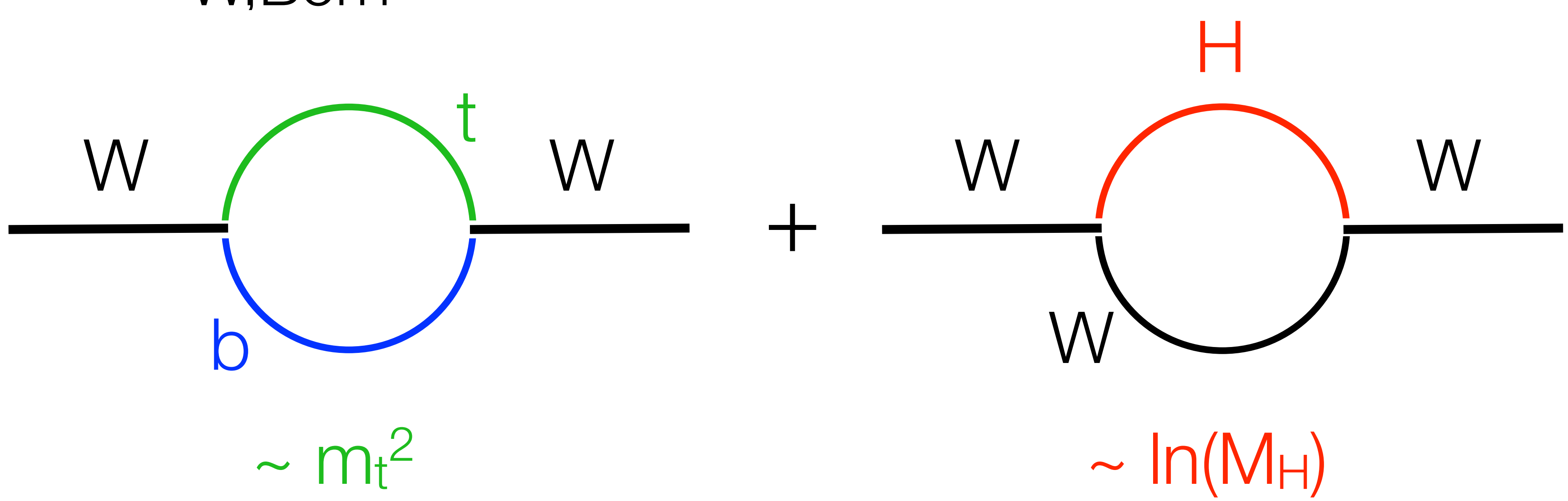
| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | 0.02750 ± 0.00033 | 0.02759 |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 |
| $\sigma_{had}^{0}$ [nb] | 41.540 ± 0.037 | 41.478 |
| $R_l$ | 20.767 ± 0.025 | 20.742 |
| $A_{fb}^{0,l}$ | 0.01714 ± 0.00095 | 0.01645 |
| $A_l(P_\tau)$ | 0.1465 ± 0.0032 | 0.1481 |
| $R_b$ | 0.21629 ± 0.00066 | 0.21579 |
| $R_c$ | 0.1721 ± 0.0030 | 0.1723 |
| $A_{fb}^{0,b}$ | 0.0992 ± 0.0016 | 0.1038 |
| $A_{fb}^{0,c}$ | 0.0707 ± 0.0035 | 0.0742 |
| $A_b$ | 0.923 ± 0.020 | 0.935 |
| $A_c$ | 0.670 ± 0.027 | 0.668 |
| $A_l$(SLD) | 0.1513 ± 0.0021 | 0.1481 |
| $\sin^2\theta_{eff}^{lept}(Q_{fb})$ | 0.2324 ± 0.0012 | 0.2314 |
| $m_W$ [GeV] | 80.385 ± 0.015 | 80.377 |
| $\Gamma_W$ [GeV] | 2.085 ± 0.042 | 2.092 |
| $m_t$ [GeV] | 173.20 ± 0.90 | 173.26 |

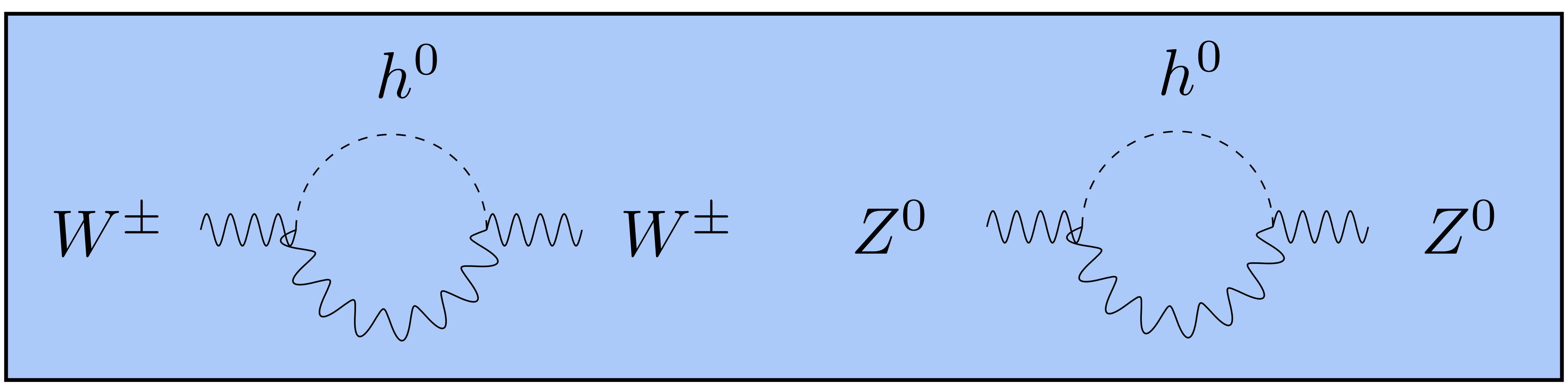



March 2012

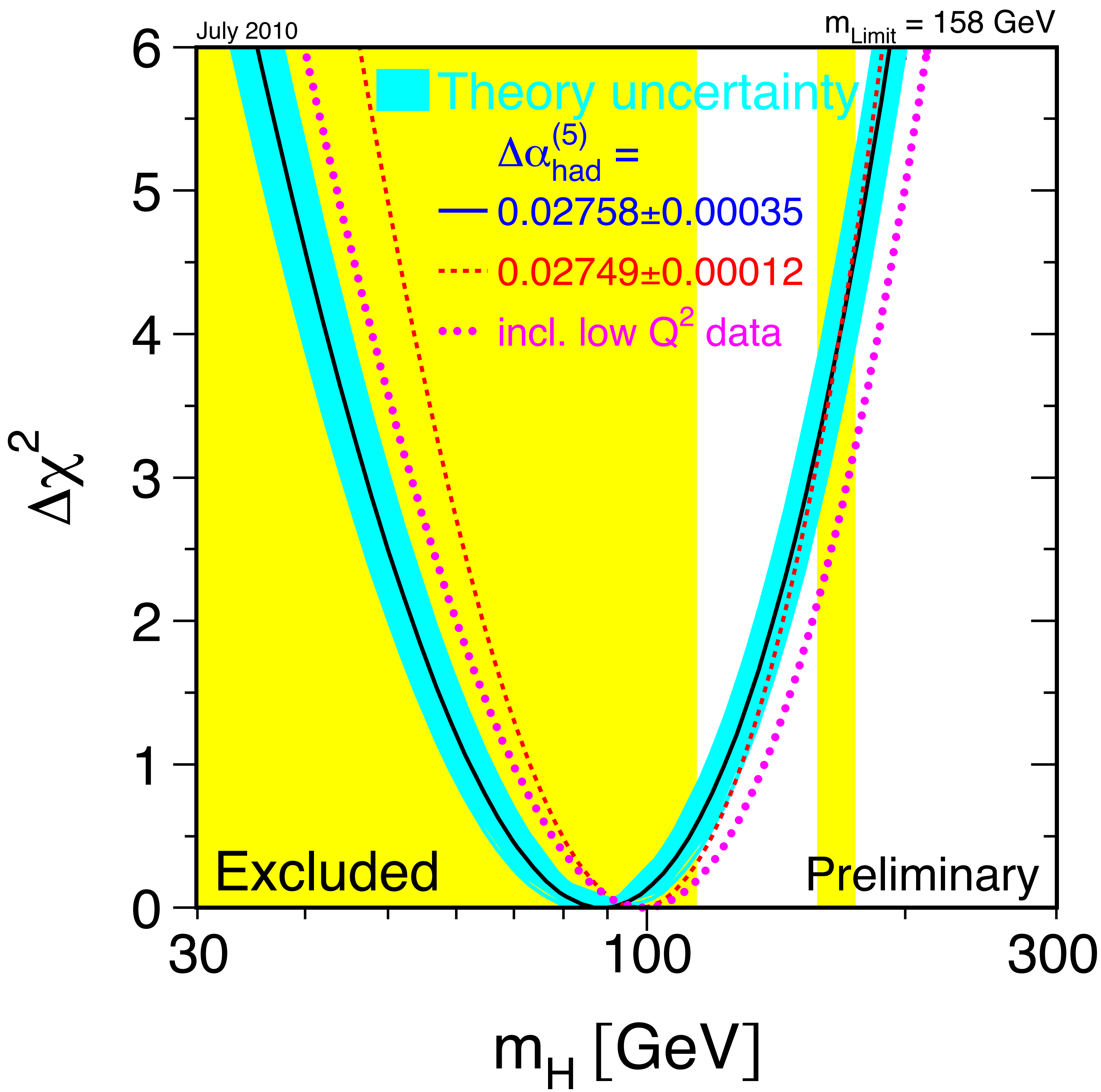
# The Higgs Influencing the SM

$$M_W = M_{W,\mathrm{Born}} + \ldots$$



# The Blue Band Plot 2010 ...




EW-Fits:

$M_H = 89^{+35}_{-26}$ GeV

$M_H < 158$ GeV @ 95% CL

From direct search at LEP:

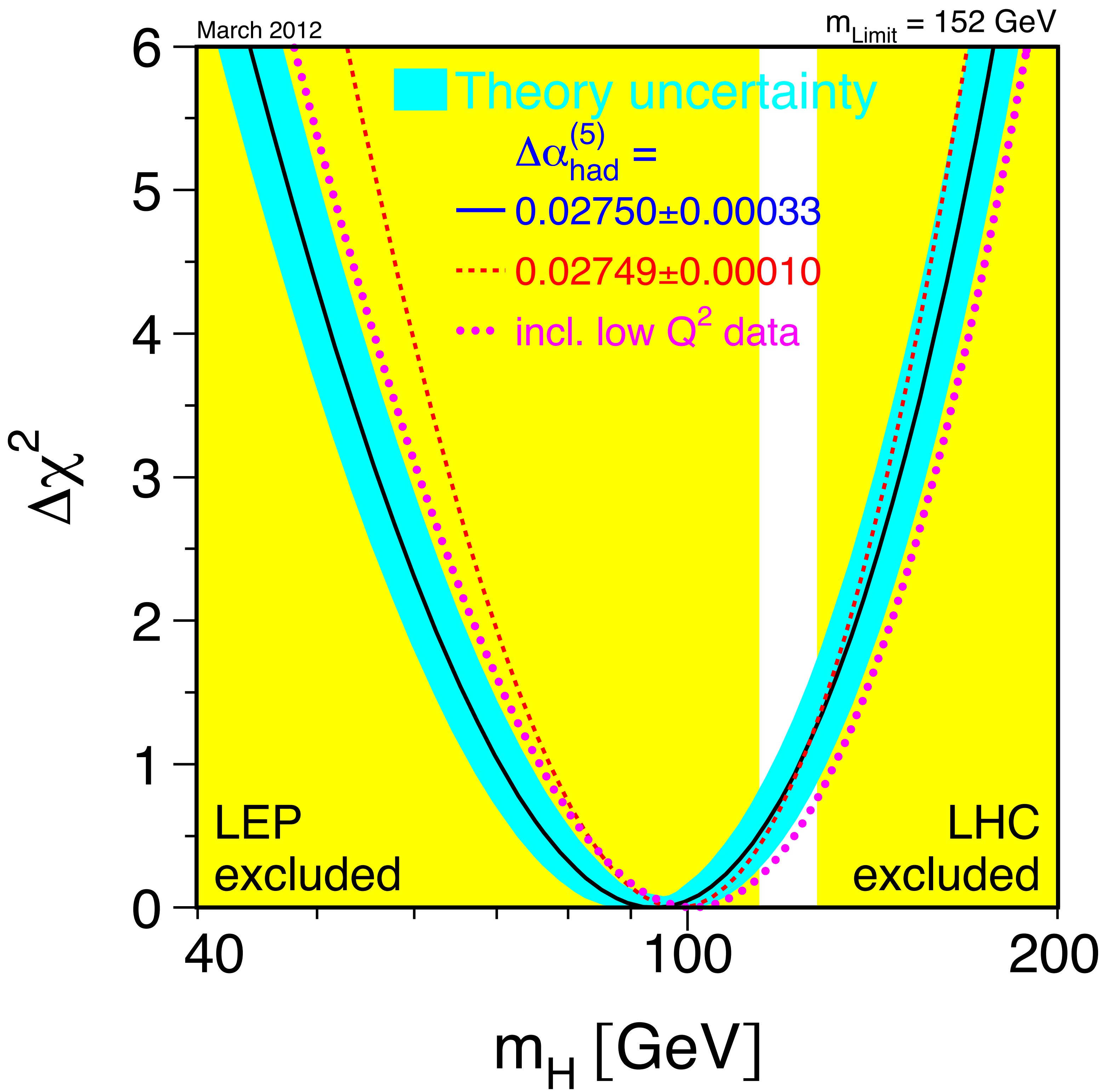
$M_H > 114$ GeV @ 95% CL

From direct search at Tevatron:

$158 < M_H < 175$ GeV @ 95% CL

[Status: Summer 2010]

# The Blue Band Plot 2012 ...




ATLAS:

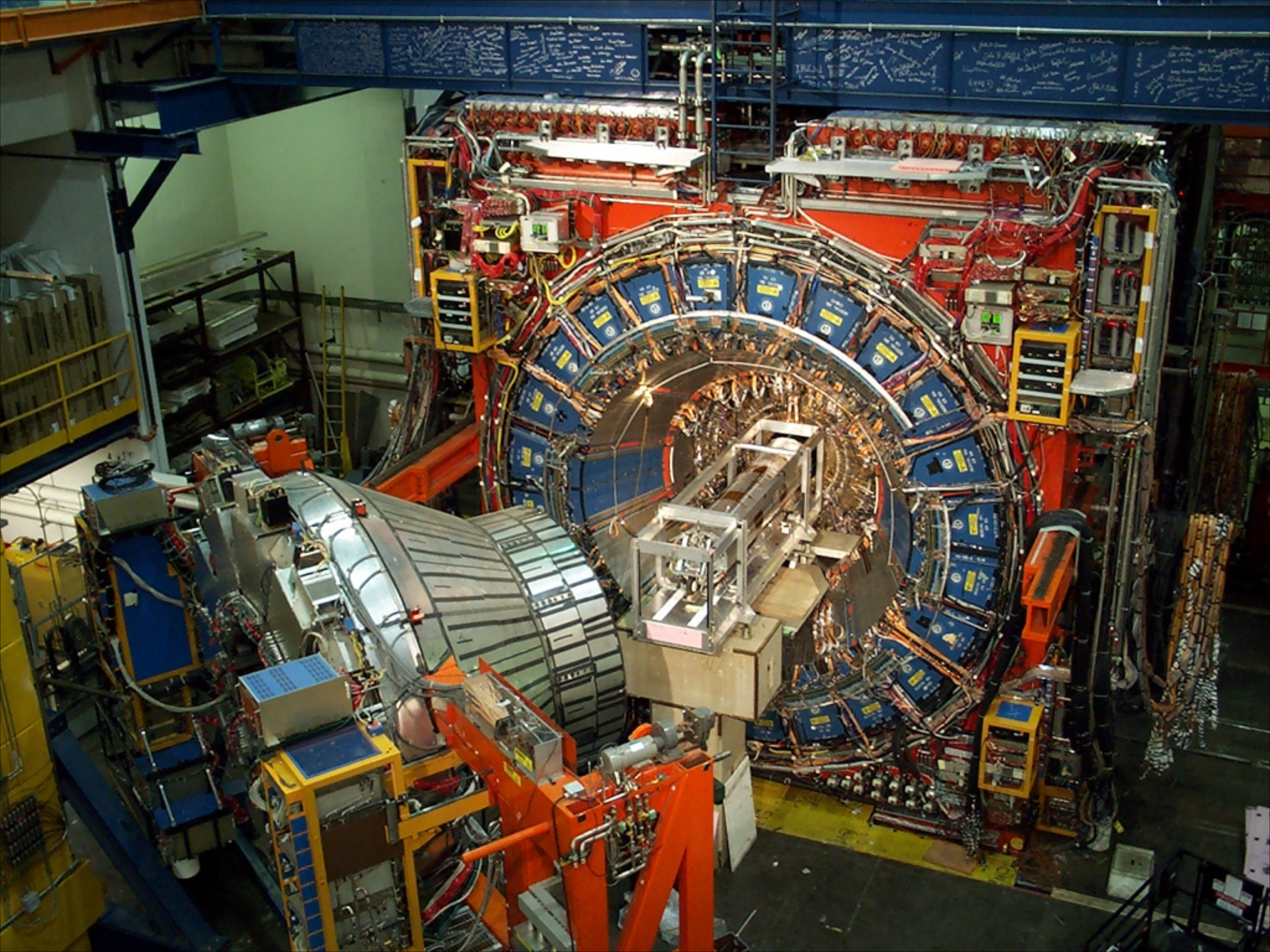
$$M_H = 125.5^{+0.5}_{-0.6}\ \text{GeV}$$

CMS:

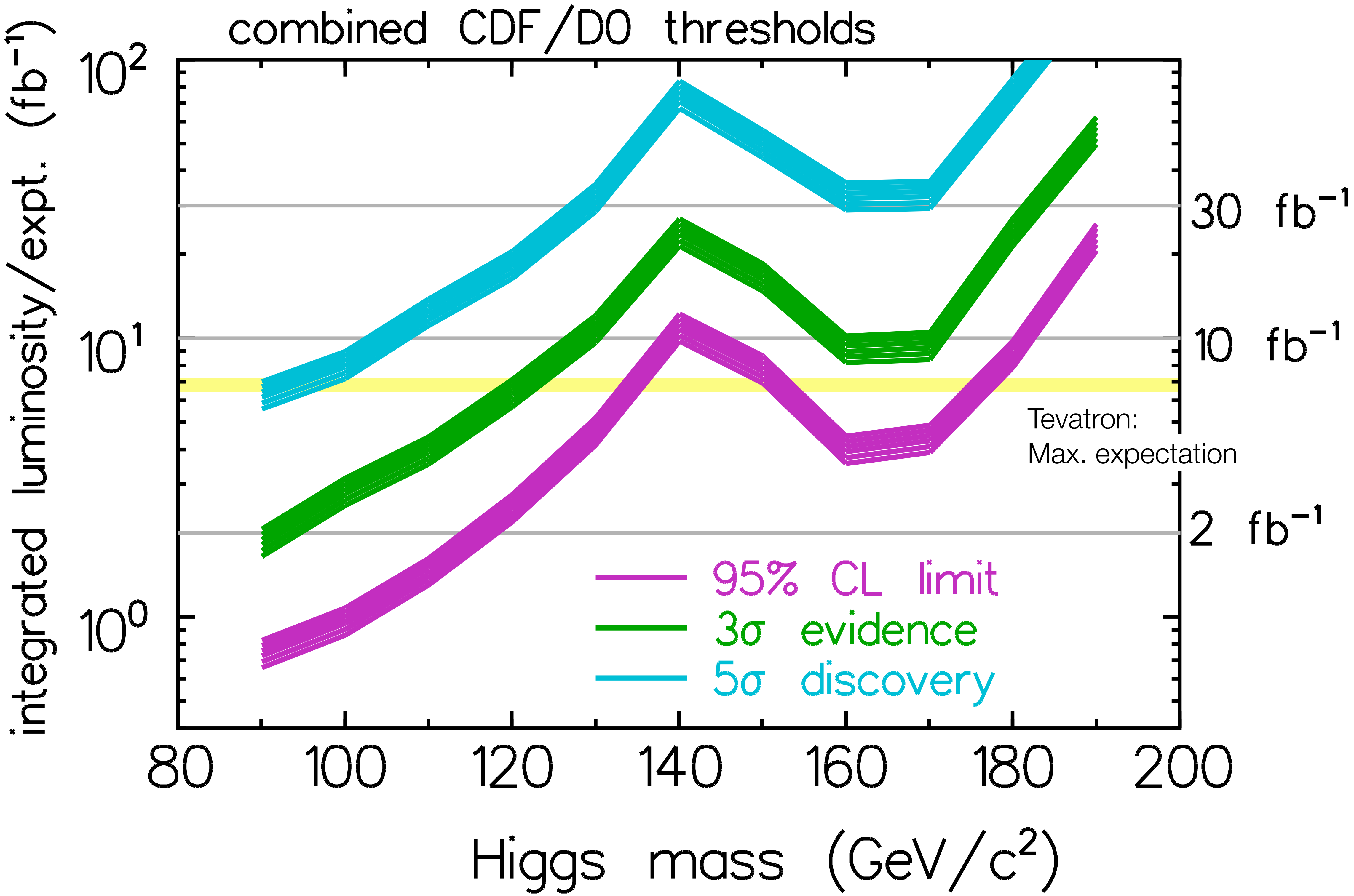
$$M_H = 125.3^{+0.6}_{-0.6}\ \text{GeV}$$

# Higgs Search

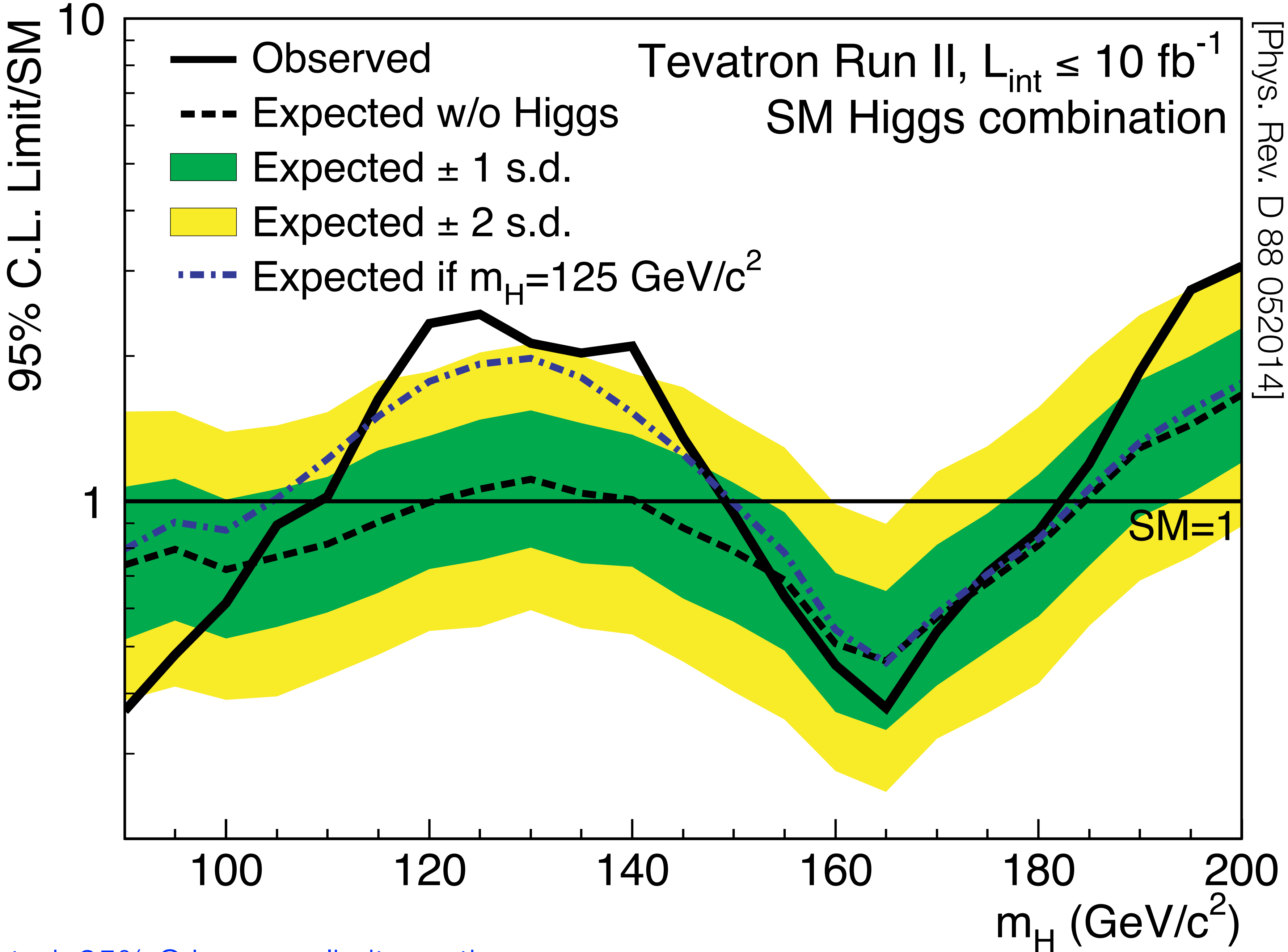
## at Tevatron



# Tevatron: Higgs Discovery Potential



# Tevatron: Latest Result




Observed and expected 95% C.L. upper limits on the ratios to the SM cross section, as functions of the Higgs boson mass for the combined CDF and D0 analyses ...

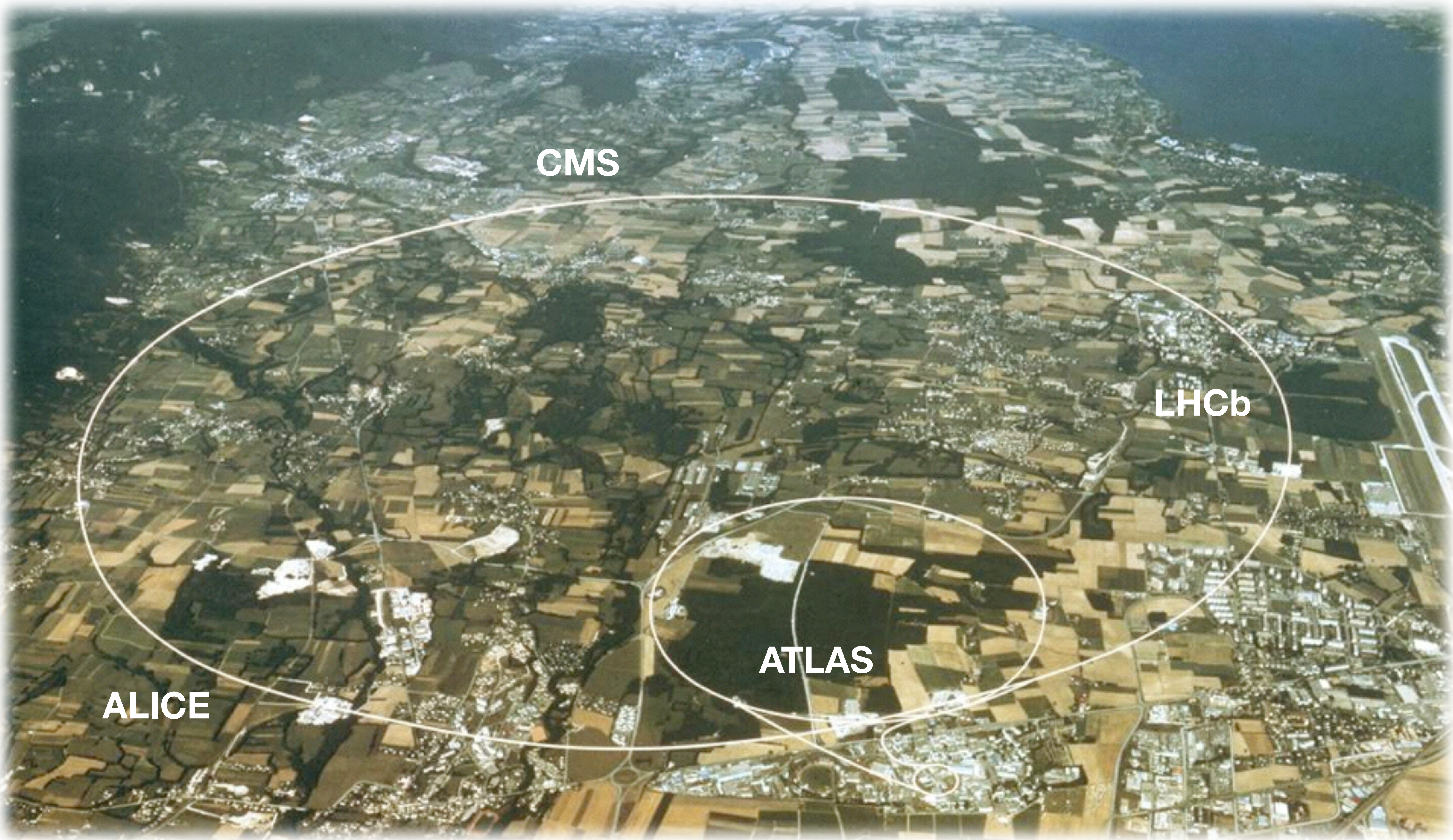
# Higgs Search

## at the LHC

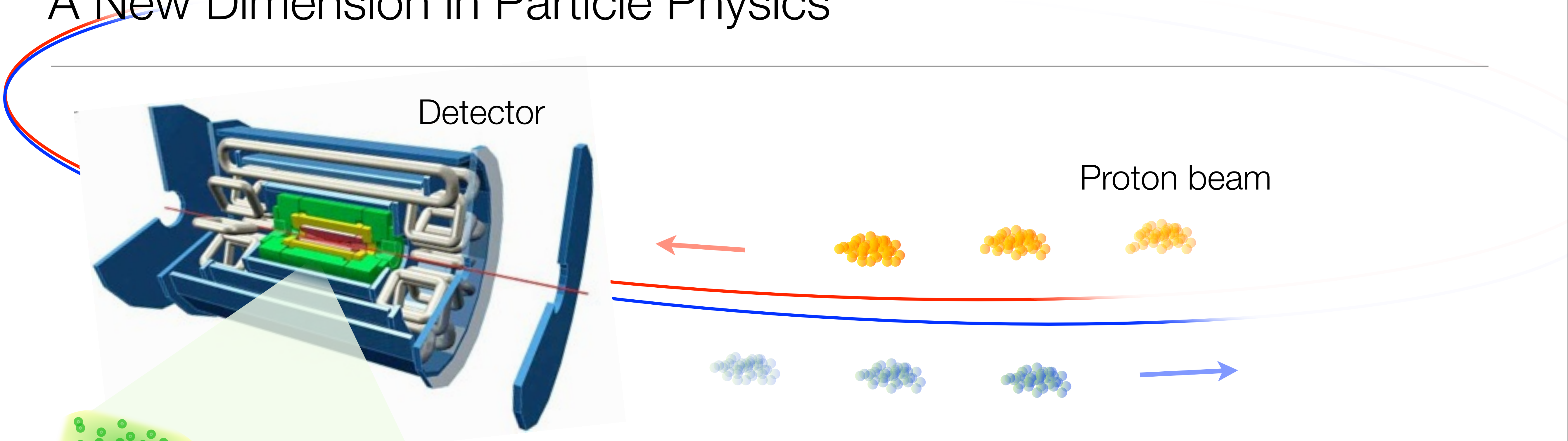
[The 2010 Perspective]

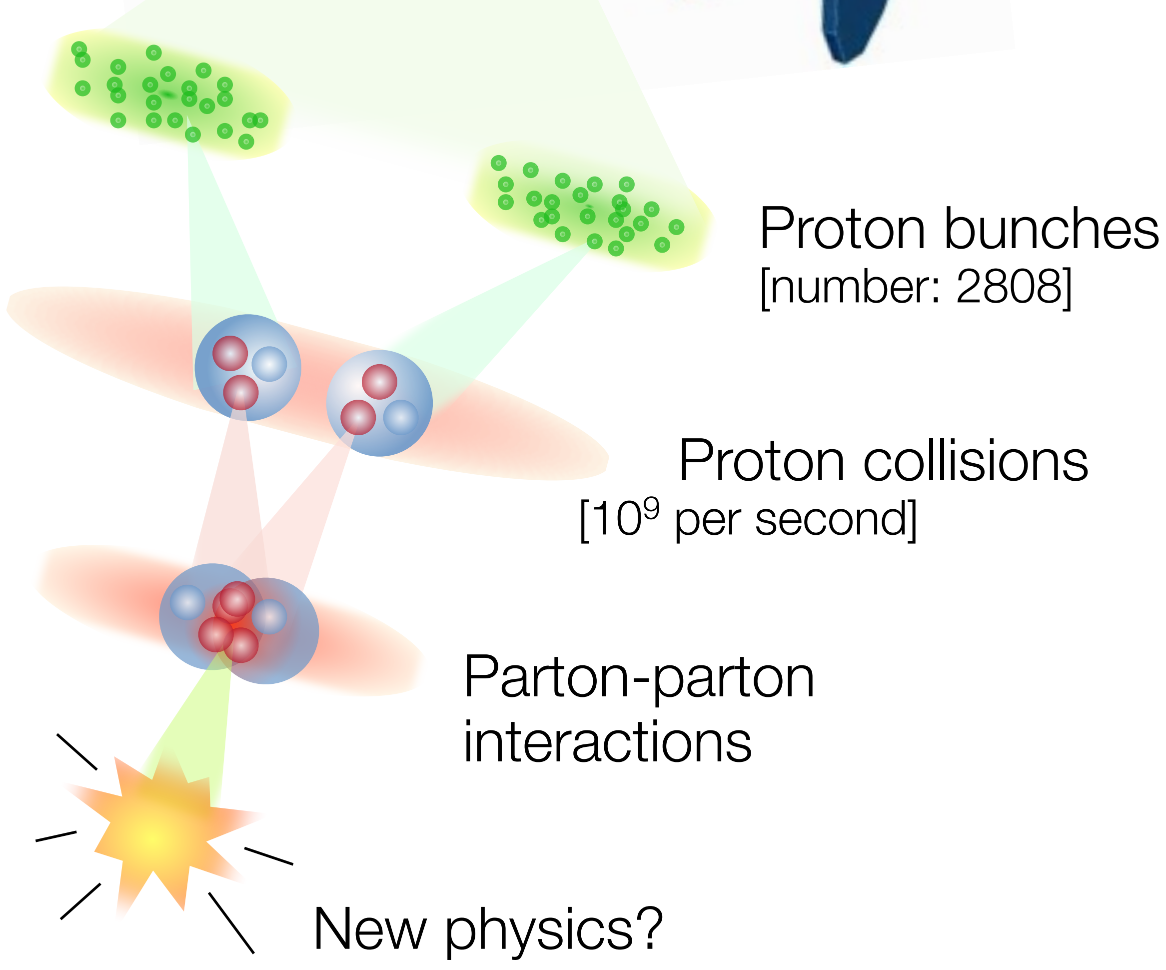
# The LHC

## A New Dimension in Particle Physics



# The LHC
## A New Dimension in Particle Physics

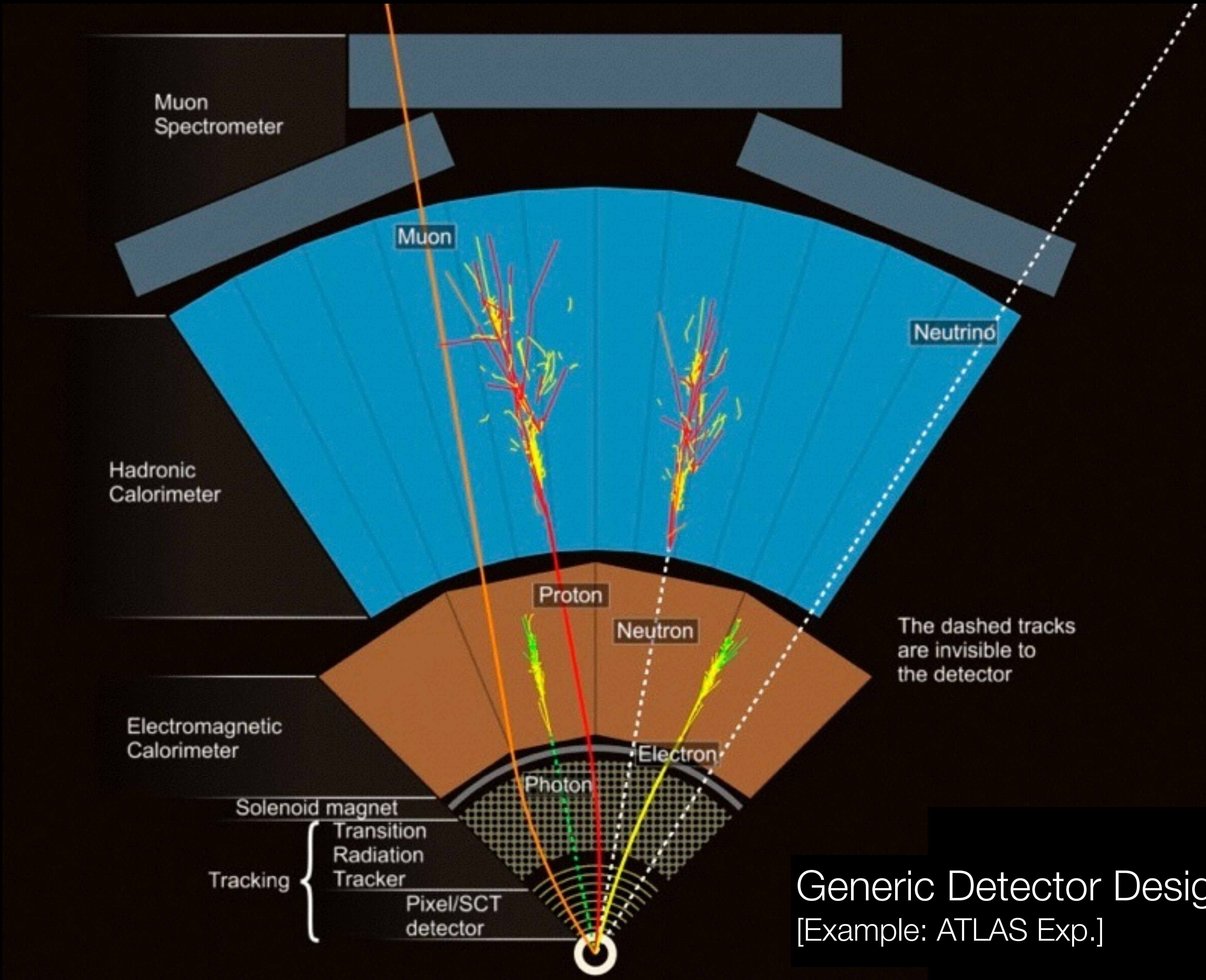



Circumference: 27 km
Collision rate: 40 MHz
CMS-Energy: 14 TeV

Dipols: ca. 1200

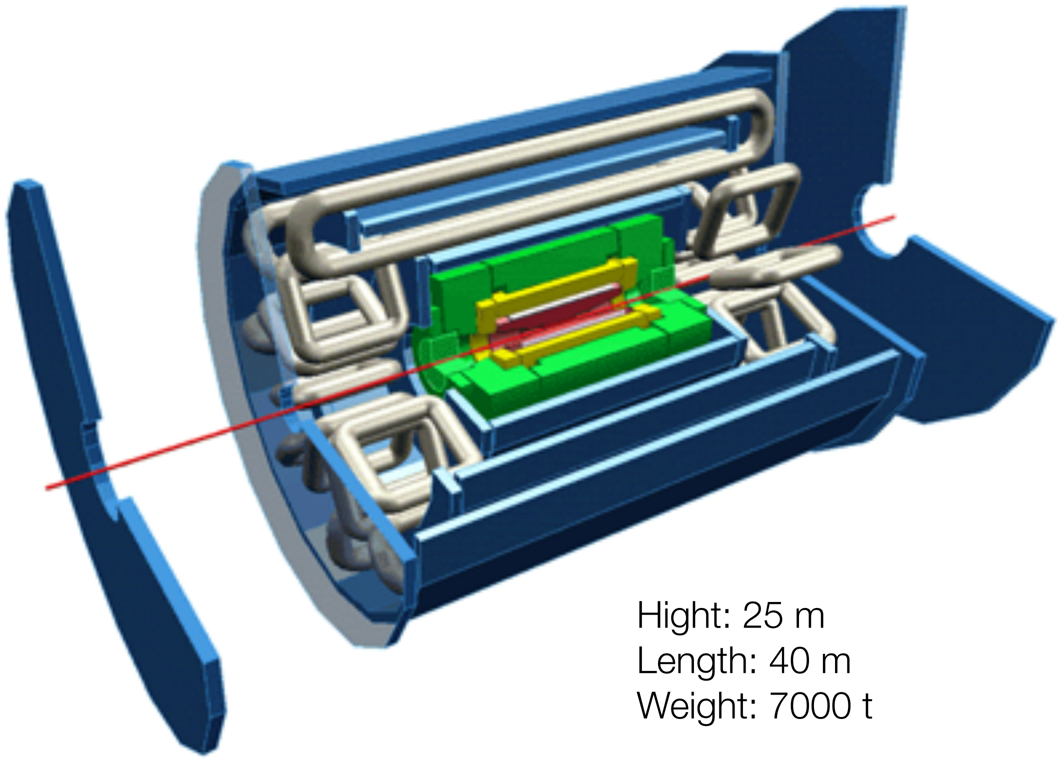
[Field: up to 8.3 T]
[Temperature: 1.9 K]
[Stored energy: 9.2 GJ]




Generic Detector Design
[Example: ATLAS Exp.]

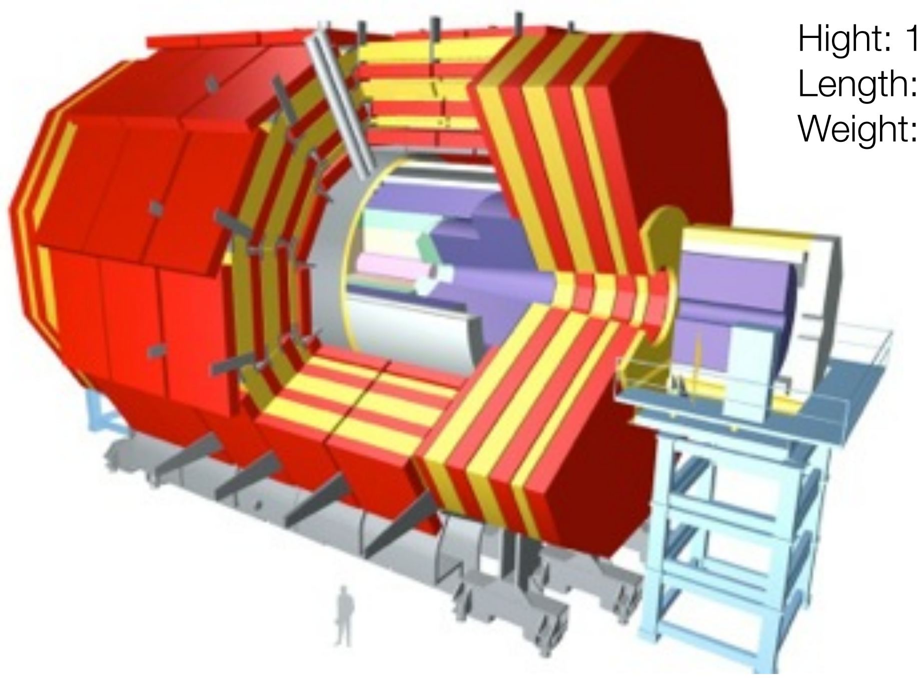
# Two Basic Architectures

ATLAS: A Toroidal LHC ApparatuS

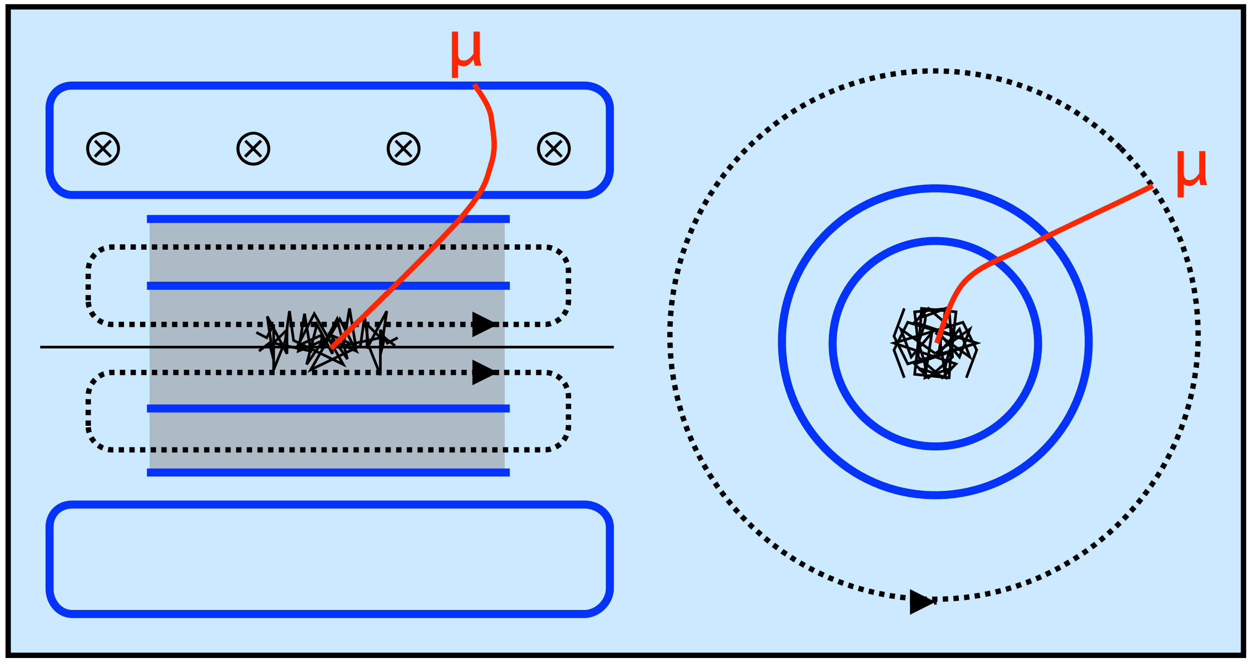


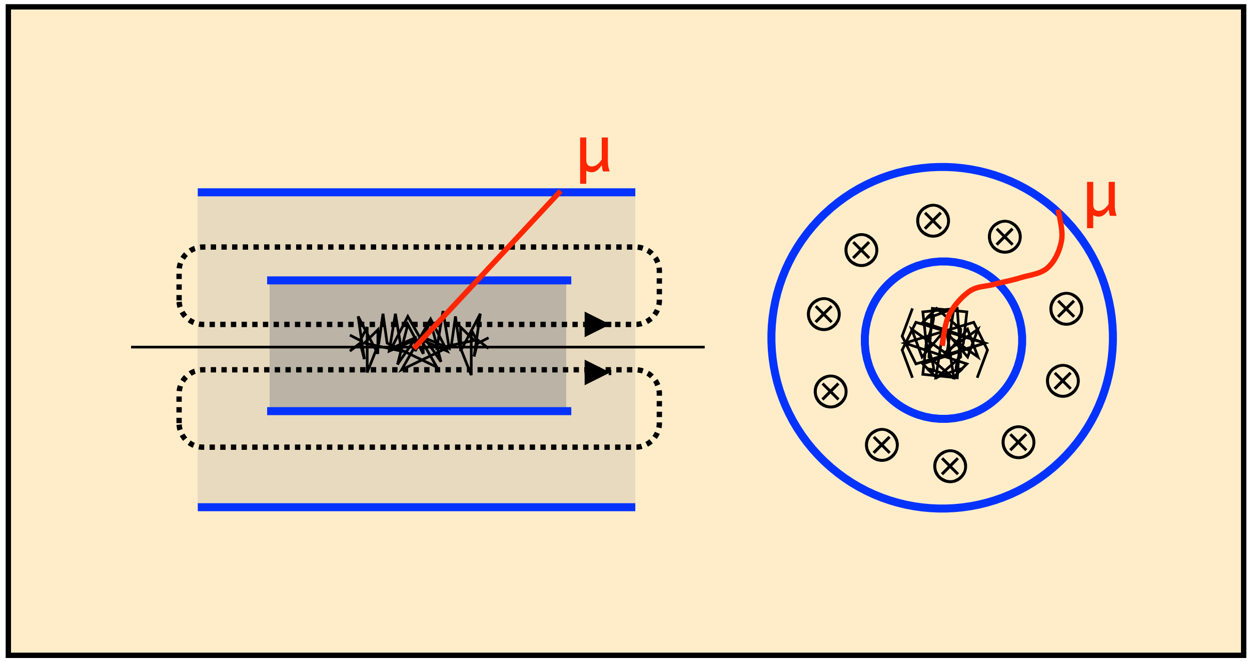
Hight: 25 m
Length: 40 m
Weight: 7000 t

CMS: Compact Muon Solenoid

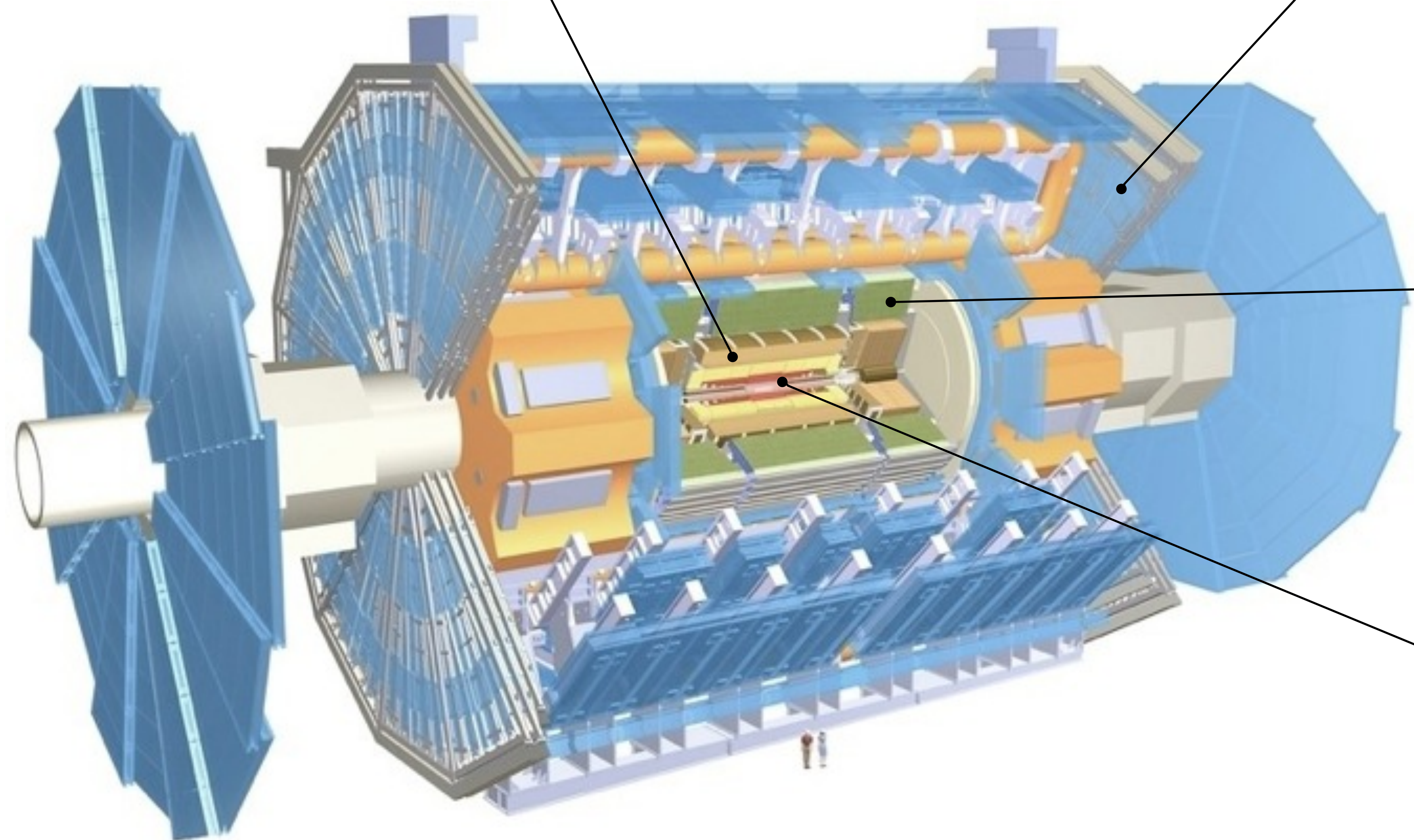


Hight: 15 m
Length: 22 m
Weight: 12500 t



# The ATLAS Detector



EM Calorimeters: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$
excellent $e/\gamma$ identification
good energy resolution (e.g. for $H \to \gamma\gamma$)

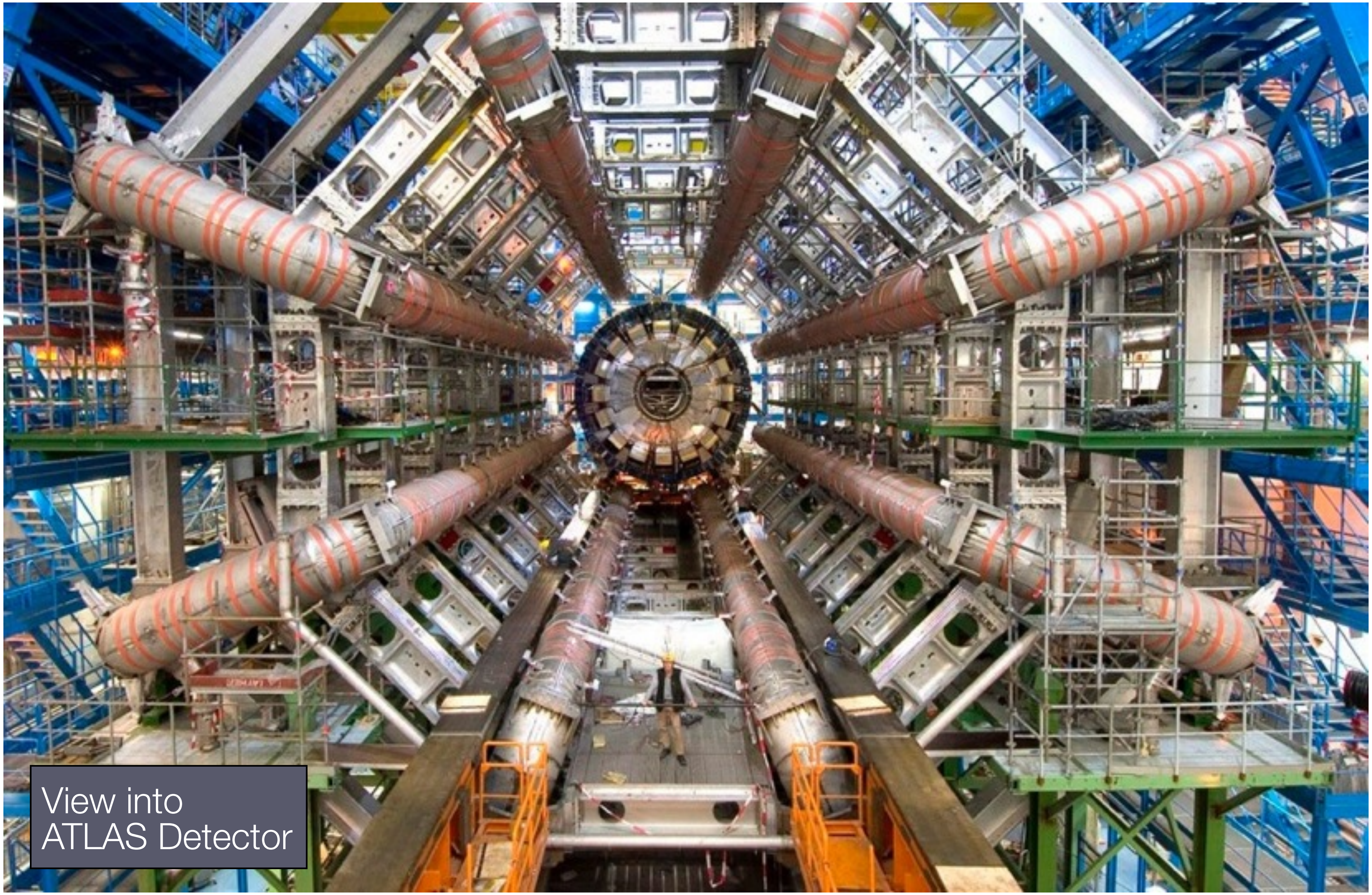
Prescision Muon Spectrometer: $\sigma/p_t \approx 10\%$ @ 1 TeV
fast trigger response
good momentum resolution
(e.g. $A/Z' \to \mu\mu$, $H \to 4\mu$)

Hadron Calorimeter:
$\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$
good jet resolution
good missing $E_T$ resolution
(e.g. $H \to \tau\tau$)

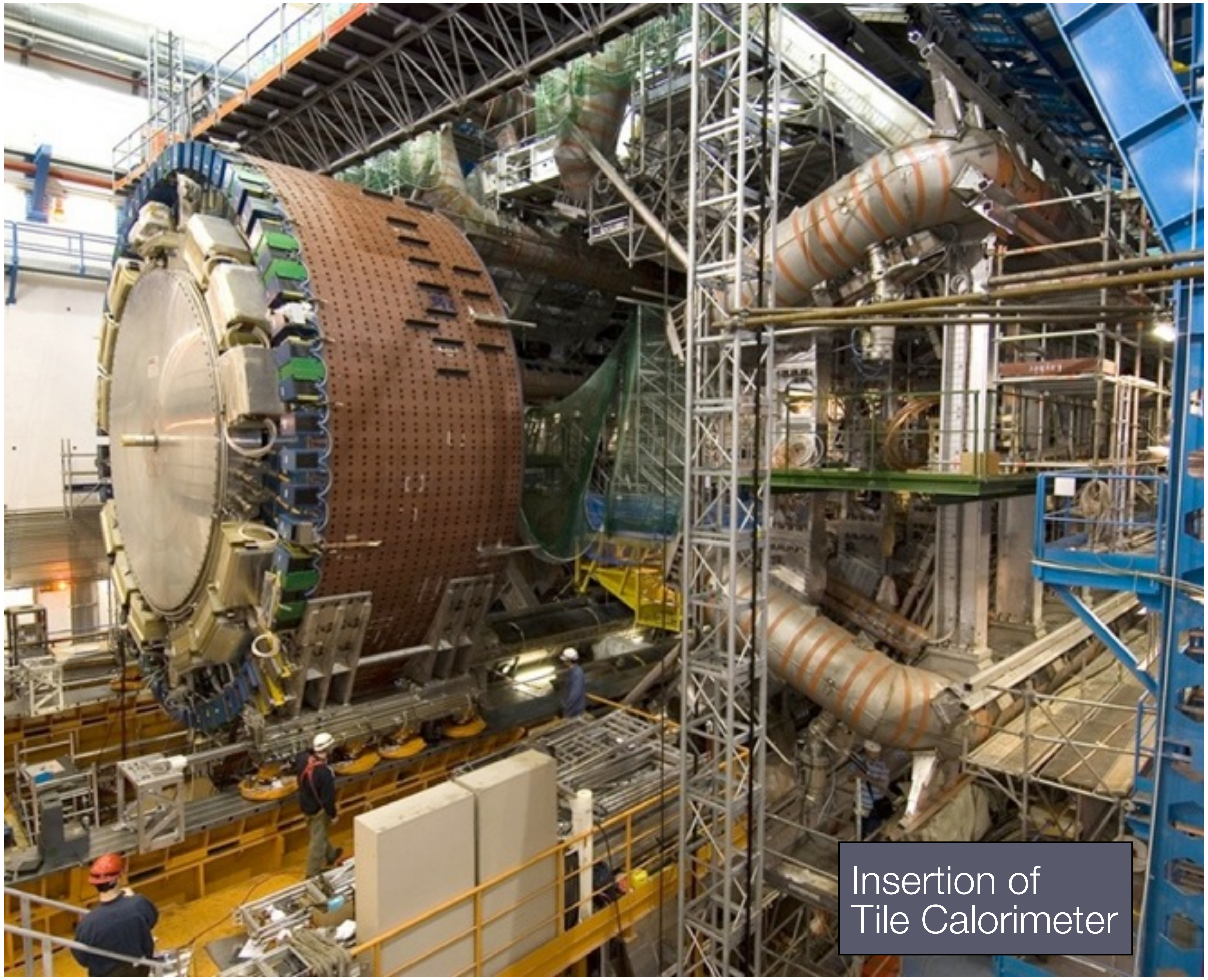
Inner Detector:
Si Pixel & strips; TRT
$\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$
good impact parameter res., i.e.
$\sigma(d_0) \approx 15\ \mu m$ @ 20 GeV
(e.g. $H \to bb$)

Magnets:
Solenoid (inner detector): 2 T
Toroid (muon spectrometer): 0.5 T

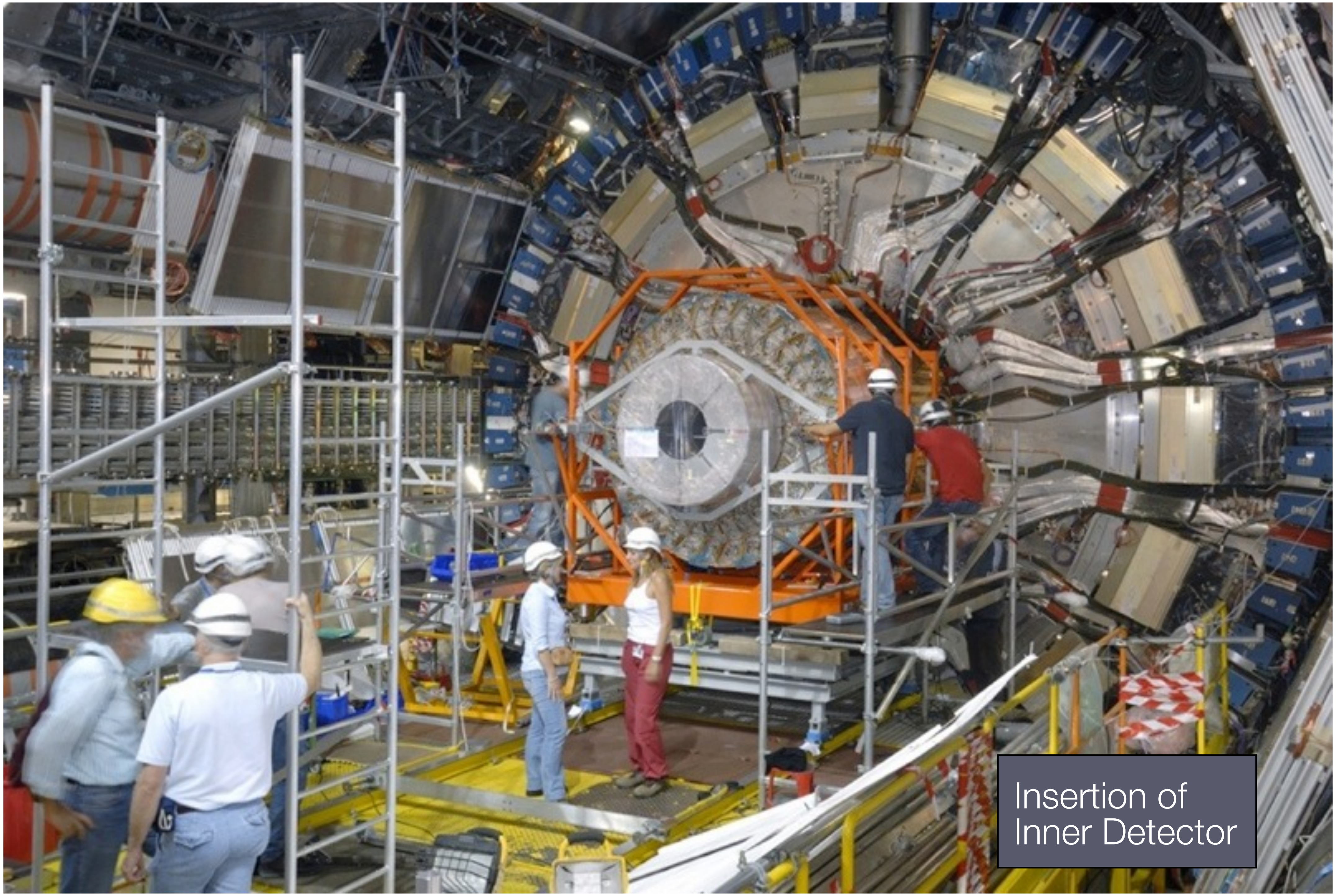
# ATLAS October 2005



# ATLAS July 2006



# ATLAS August 2006


Insertion of Inner Detector

# The CMS Detector

Inner Detector:

$\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$

[vergl. ATLAS $\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$]

EM Calorimeters:

$\sigma/E \approx 3\%/\sqrt{E} \oplus 0.5\%$

[vergl. ATLAS: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$]

Hadron Calorimeter:

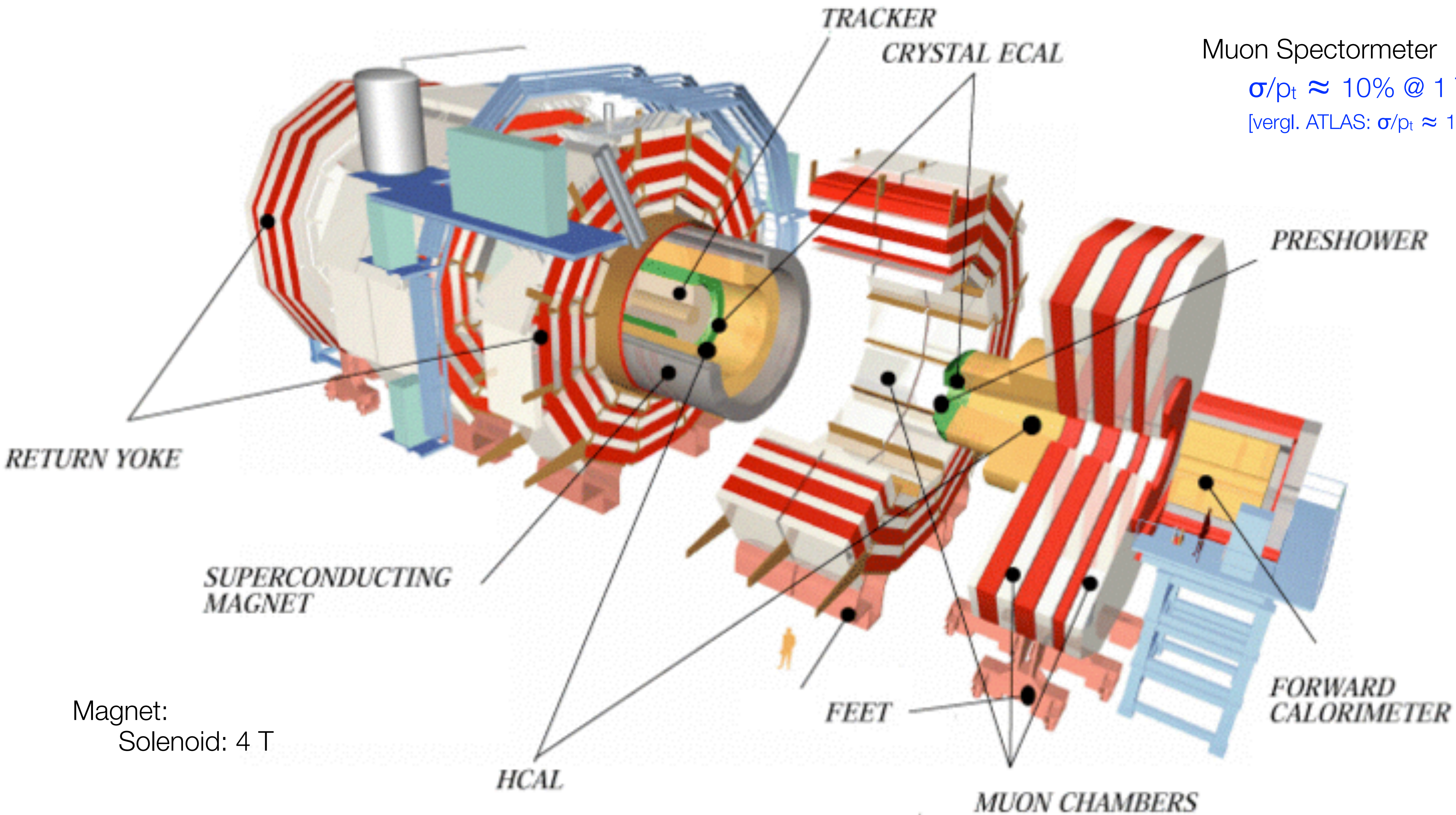
$\sigma/E \approx 100\%/\sqrt{E} \oplus 5\%$

[vergl. ATLAS: $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$]

Muon Spectormeter

$\sigma/p_t \approx 10\%$ @ 1 TeV

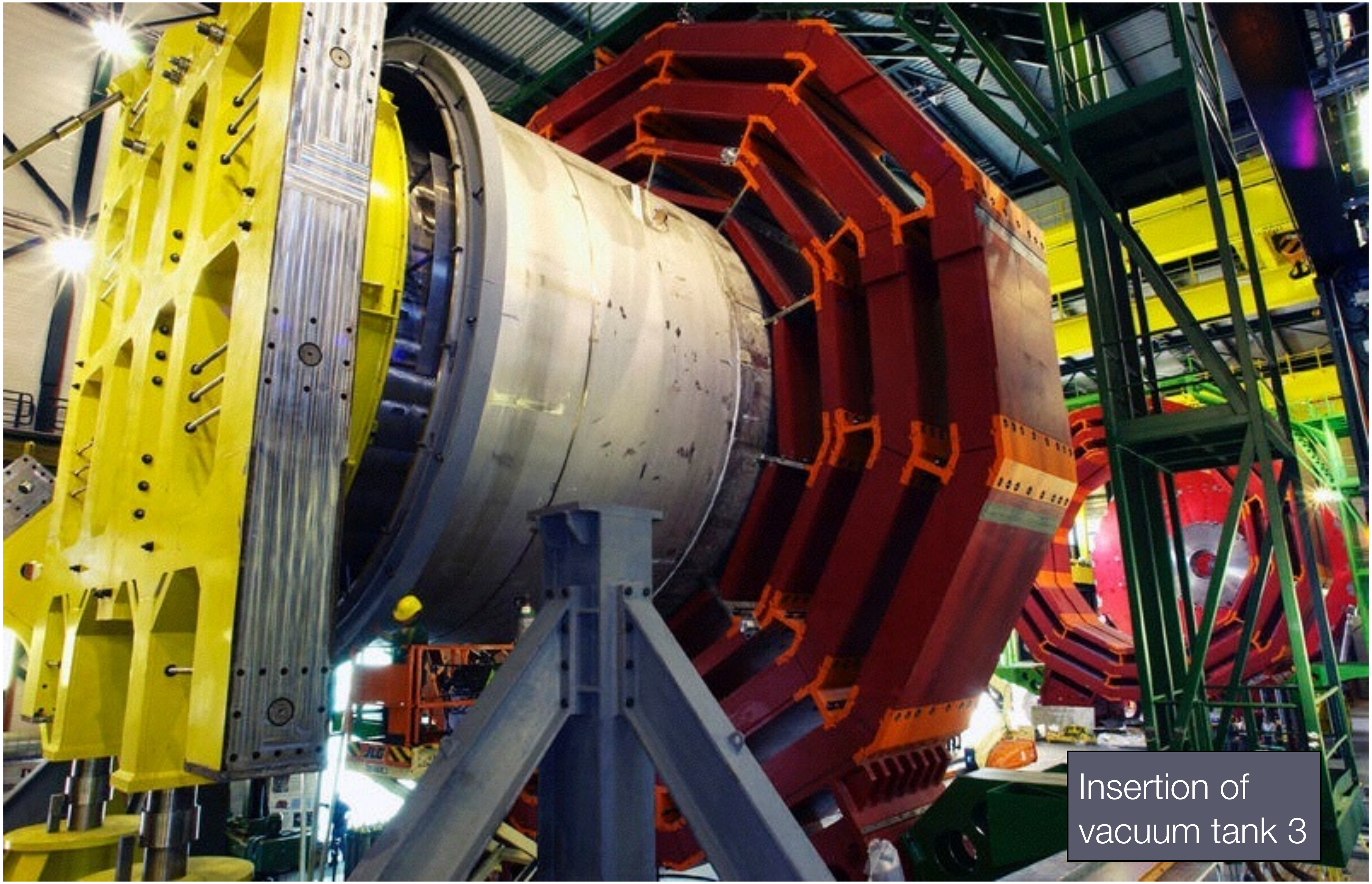
[vergl. ATLAS: $\sigma/p_t \approx 10\%$ @ 1 TeV]



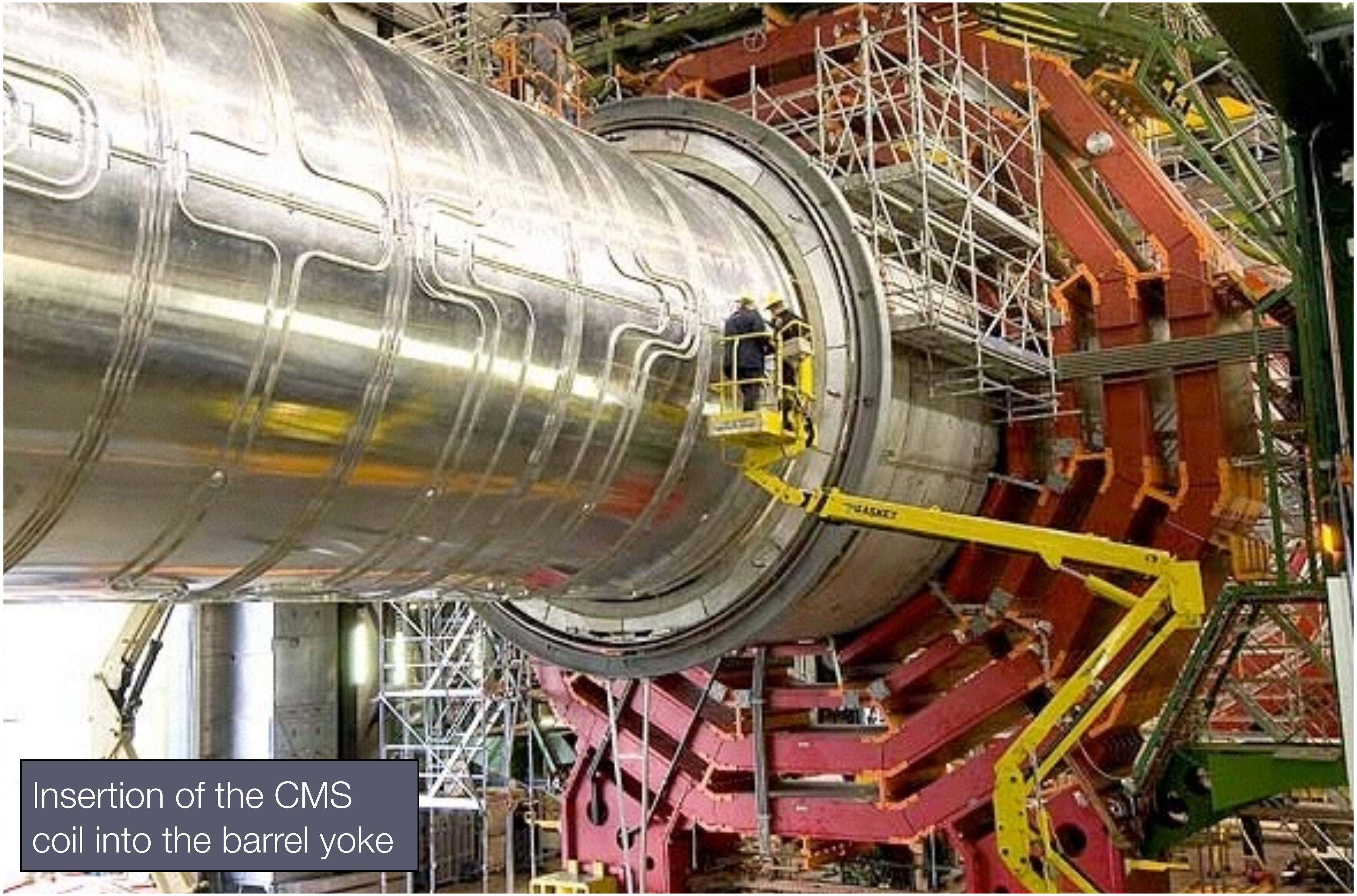

Magnet:

Solenoid: 4 T

# CMS June 2002

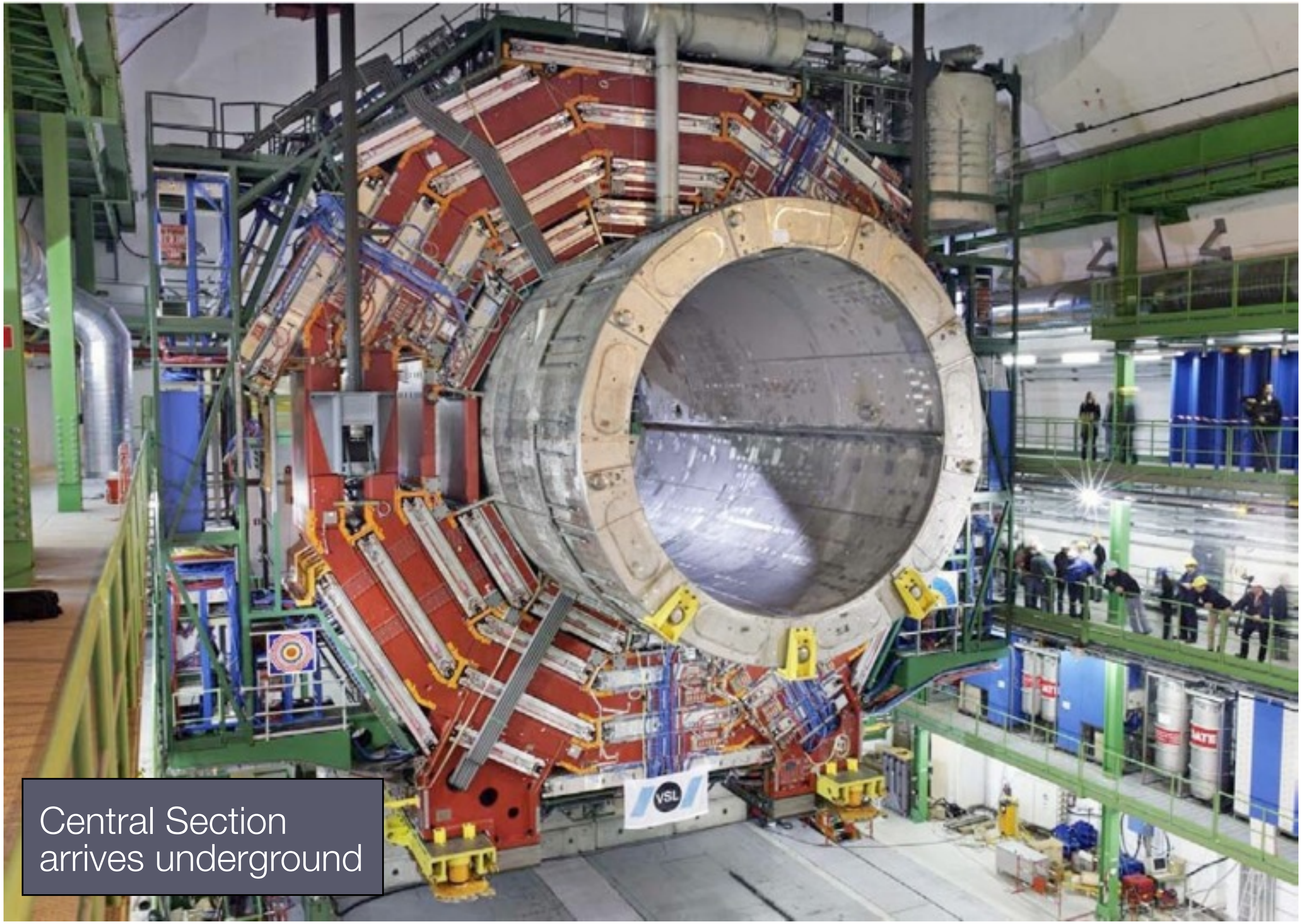


# CMS September 2005



Insertion of the CMS coil into the barrel yoke

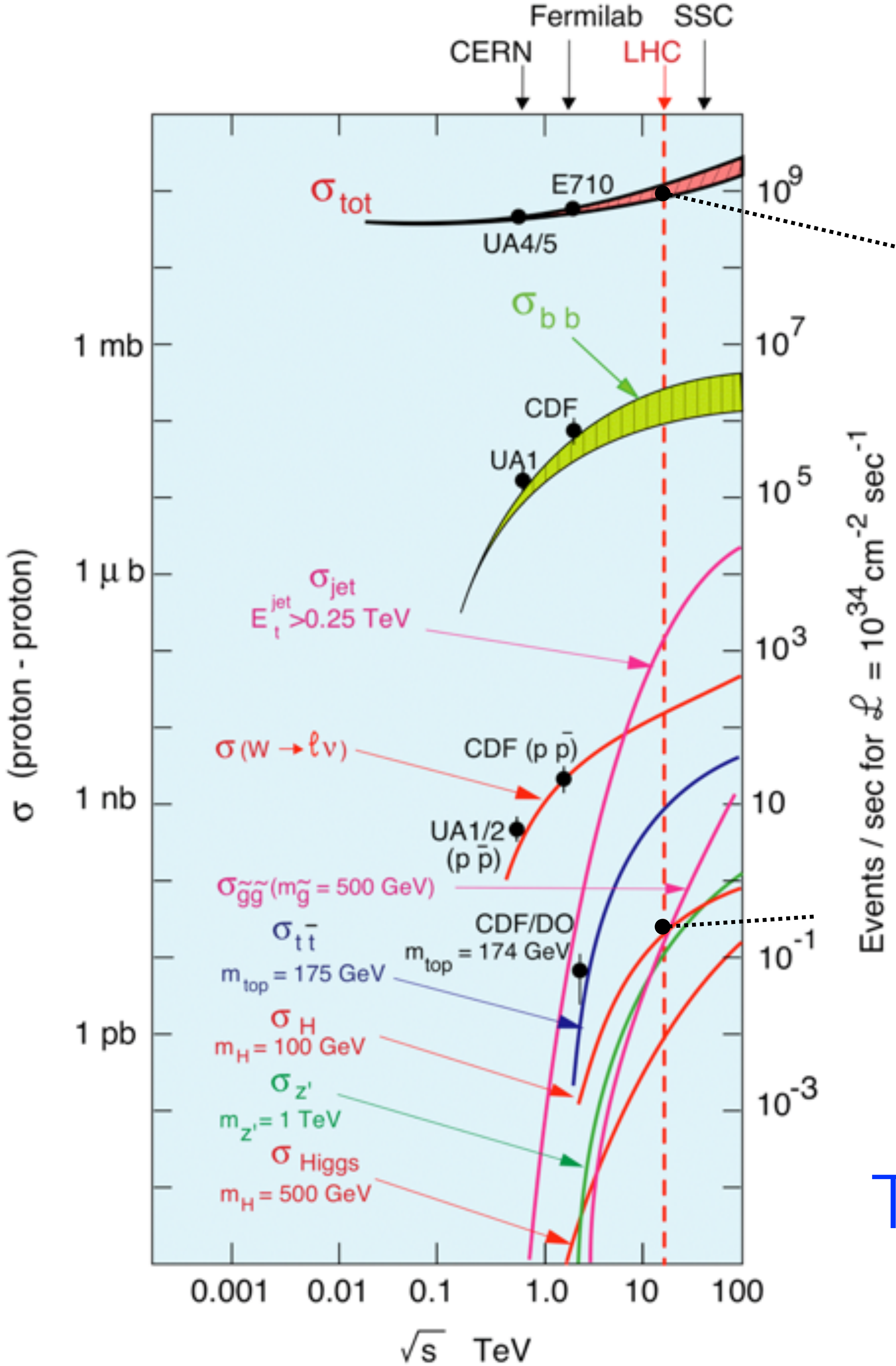
# CMS February 2007



# ATLAS vs. CMS

| ATLAS | | CMS |
|---|---|---|
| Silicon pixels; Silicon strips; Transition Radiation Tracker; 2 T magnetic field | Inner Detector | Silicon pixels, Silicon strips, 4 T magnetic field |
| Lead plates as absorbers; active medium: liquid argon; outside solenoid | Electrom. Kalorimeter | Lead tungsten ($PbWO_4$) crystals; both absorber and scintillator; inside solenoid |
| Central region: Iron absorber with plastic scintillating tiles; Endcaps: copper and tungsten absorber with liquid argon | Hadronic Calorimeter | Stainless steel and copper with plastic scintillating tiles |
| Large air-core toroid magnet; muon chambers: drift tubes and resistive plate chambers;0.5 T magnetic field | Muon Chambers | Magnetic field from return yoke (solenoid field: 4 T); muon chambers: drift tubes and resistive plate chambers |

# A Needle in a Haystack




$10^9$ Events/sec

[1 Mbyte/Event]

$10^{10}$

Efficient
rate reduction needed

[Storage rate: 100 Hz]

10 Events/min

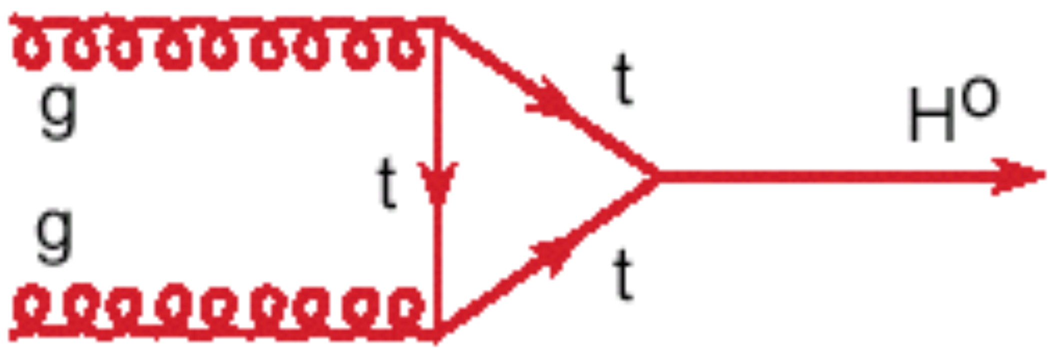
[$m_H \approx 100$ GeV]

with 0.2% $H \rightarrow \gamma\gamma$
1.5% $H \rightarrow ZZ$

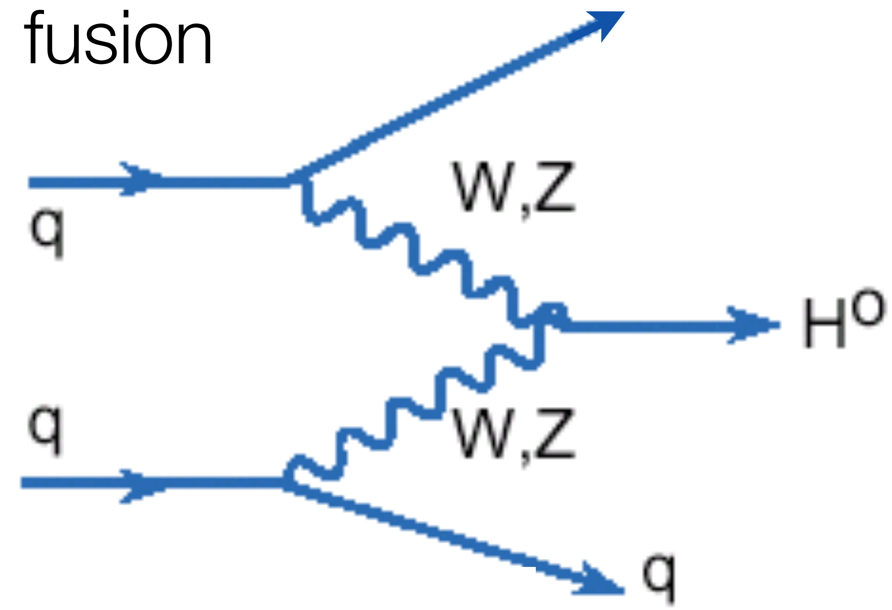
Trigger !

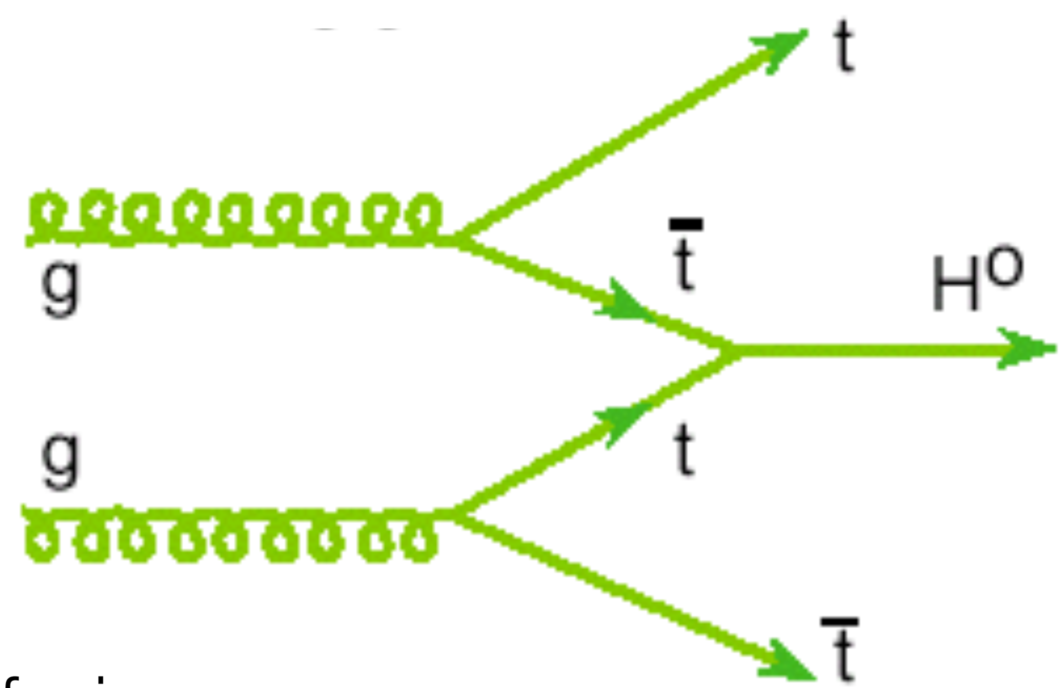
# Higgs Production Mechanisms

Gluon fusion

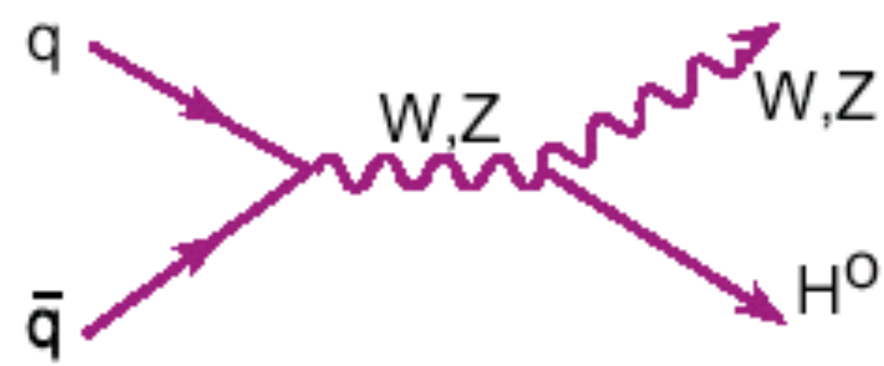



Vector boson fusion



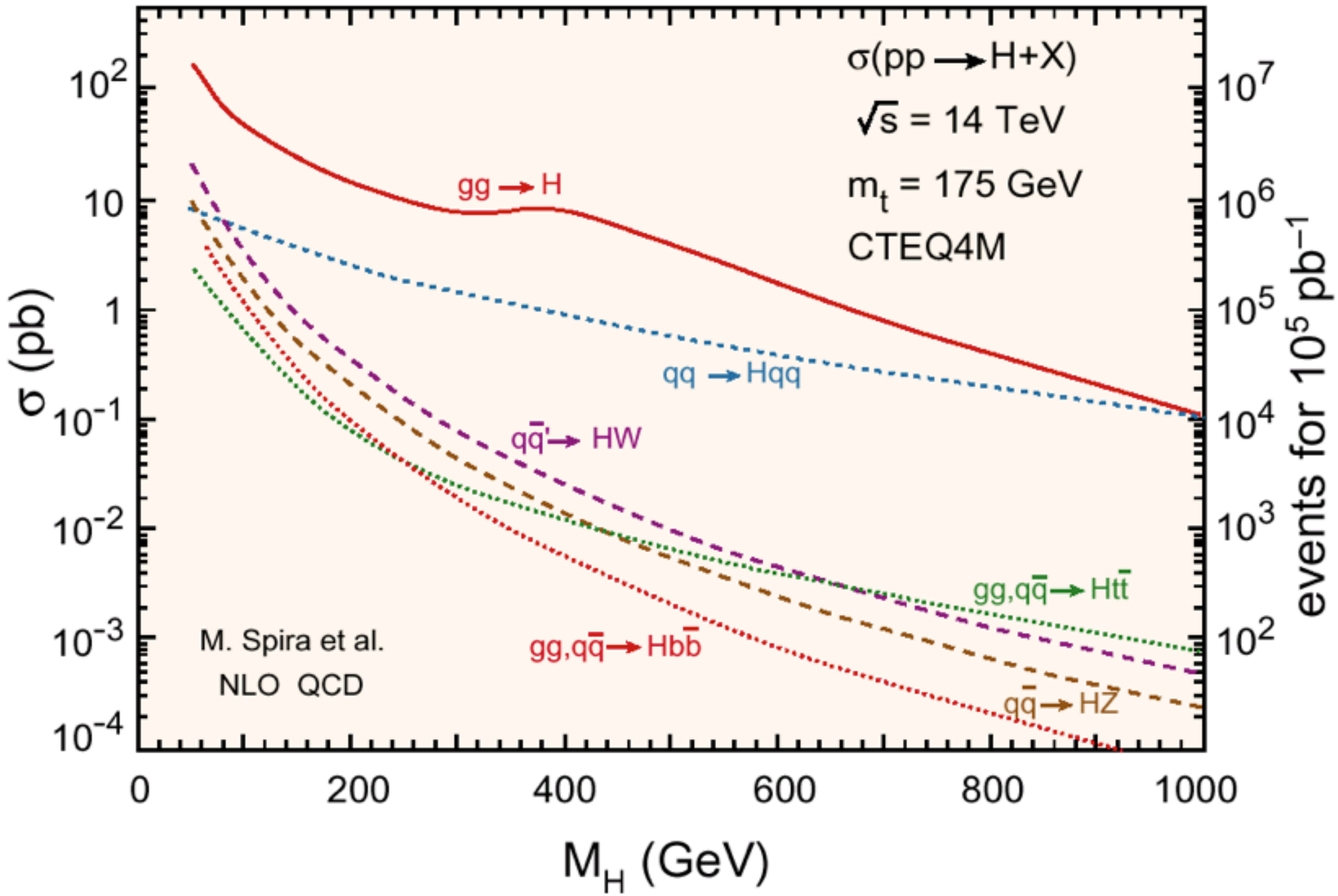




$t\bar{t}$-fusion

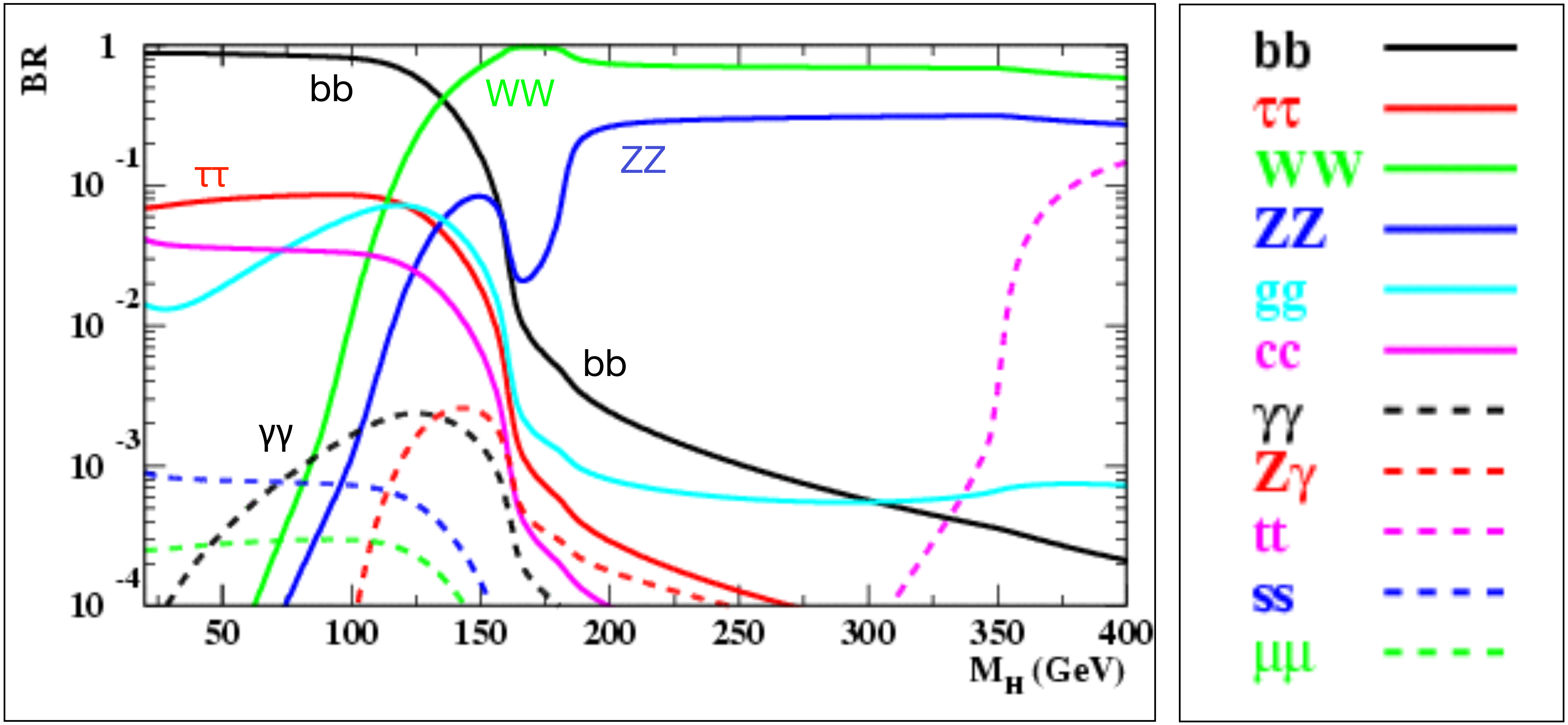



Associated production

# Higgs Production Cross Sections



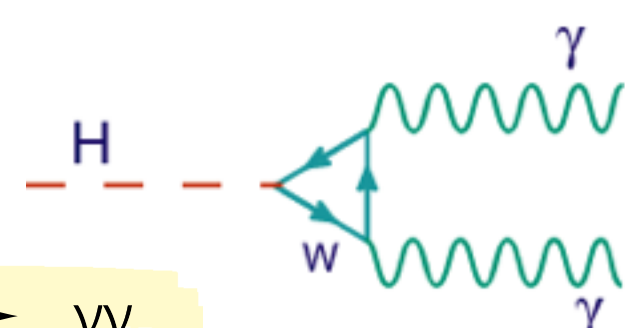
# Higgs Boson Decays




For M < 135 GeV: H ➛ bb, ττ dominant

For M > 135 GeV: H ➛ WW, ZZ dominant

Tiny but also important: H ➛ γγ



# Direct Higgs Channels

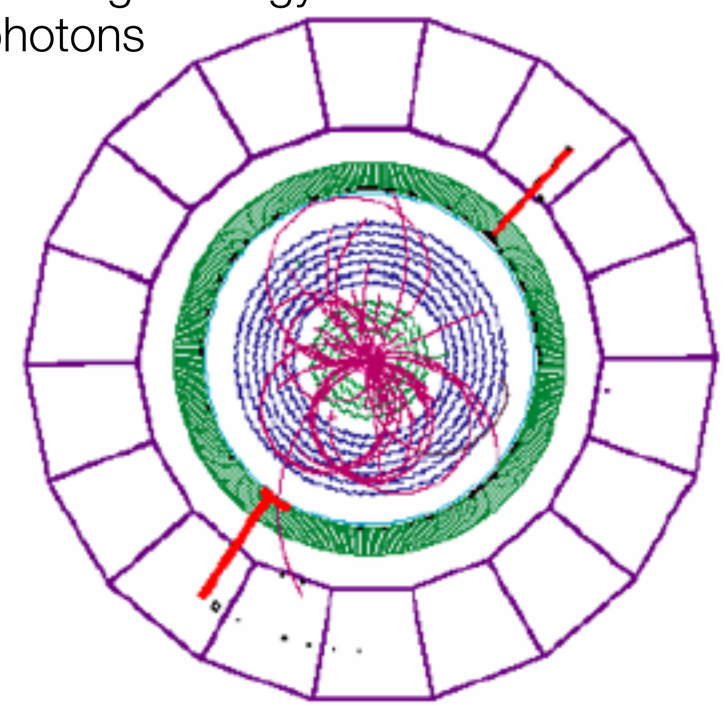
| Channel | LHC Potential |
|---|---|
| $gg \rightarrow H \rightarrow bb$ | Huge QCD background ($gg \rightarrow bb$); extremely difficult |
| $gg \rightarrow H \rightarrow \tau\tau$ | Higgs with low $p_T$, hard to discriminate from background; problematic |
| $gg \rightarrow H \rightarrow \gamma\gamma$ | Small rate, large combinatorial background, but excellent determination of $m_H$ (CMS: crystal calorimeter) |
| $gg \rightarrow H \rightarrow WW$ | Large rate, but 2 neutrinos in leptonic decay, Higgs spin accessible via lepton angular correlations |
| $gg \rightarrow H \rightarrow ZZ$ | $ZZ \rightarrow 4\mu$: "gold-plated" channel for high-mass Higgs (ATLAS: muon spectrometer) |

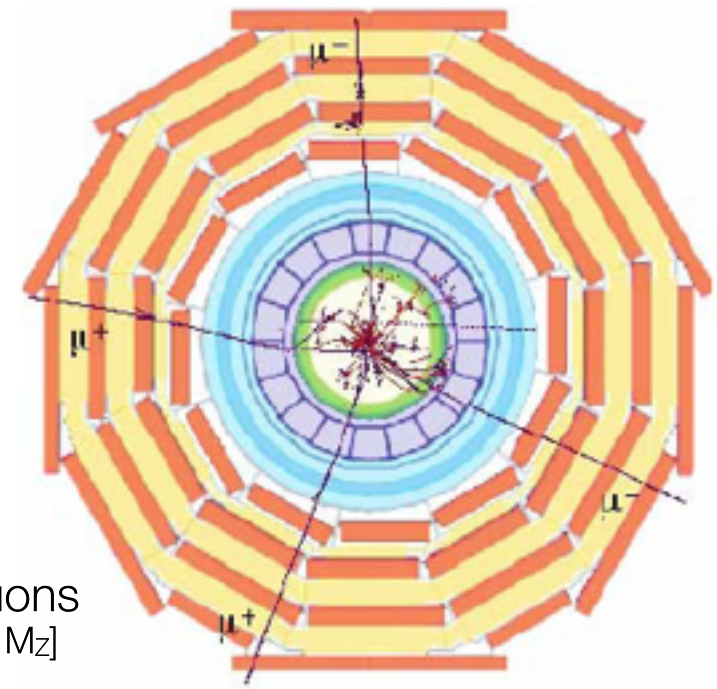
# Vector Boson Fusion

| Channel | LHC Potential |
| --- | --- |
| qq ➛ qq H [with H ➛ bb] | Very large QCD background (gg/qq ➛ bbqq); still very difficult |
| qq ➛ qq H [with H ➛ ττ] | Higher $p_T$ than direct channel; interesting discovery channel for $m_H < 135$ GeV |
| qq ➛ qq H [with H ➛ γγ] | Most likely combined with gg ➛ H ➛ γγ to inclusive diphoton signal |
| qq ➛ qq H [with H ➛ WW] | Additional background suppression w.r.t. direct channel; interesting discovery channel for $m_H > 135$ GeV |
| gg ➛ ttH [with H ➛ bb] | Top-associated production; Seemed very promising, but overwhelmed by SM ttbb production |

# Higgs Searches @ LHC: Examples

Two high-energy photons



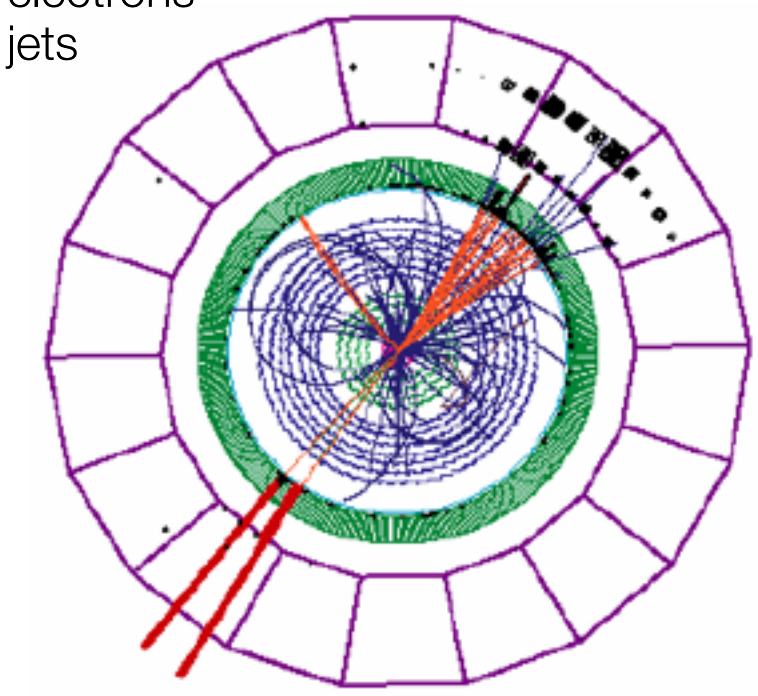


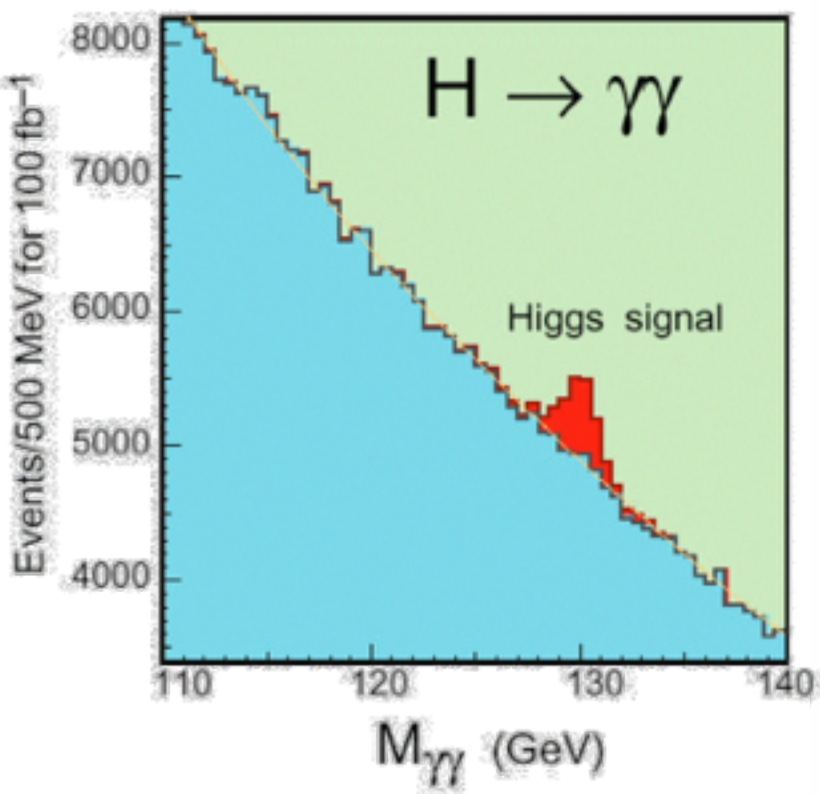

4 muons

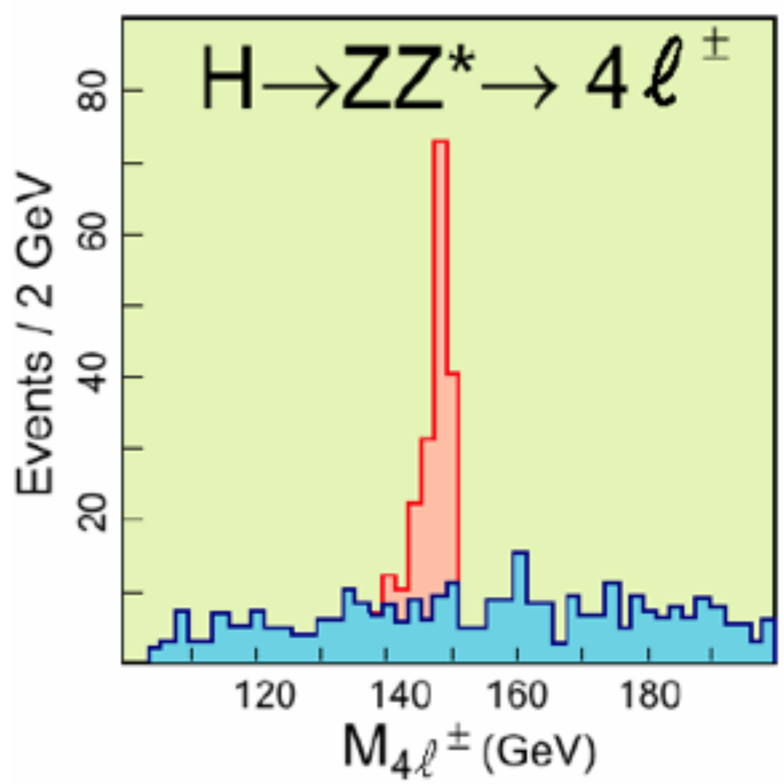
[$M_{\mu\mu} = M_Z$]

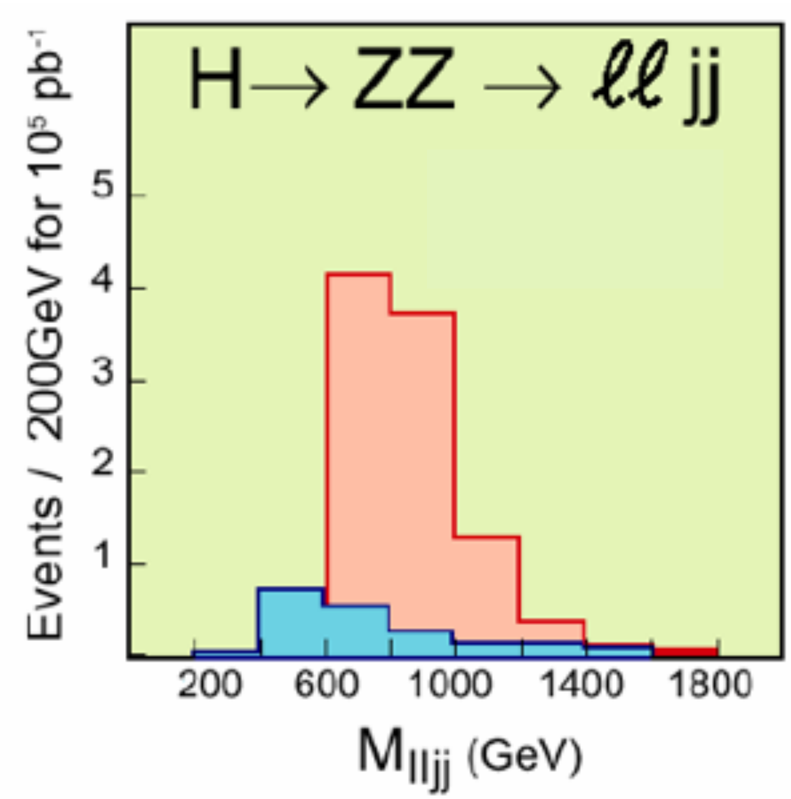
2 electrons

2 jets



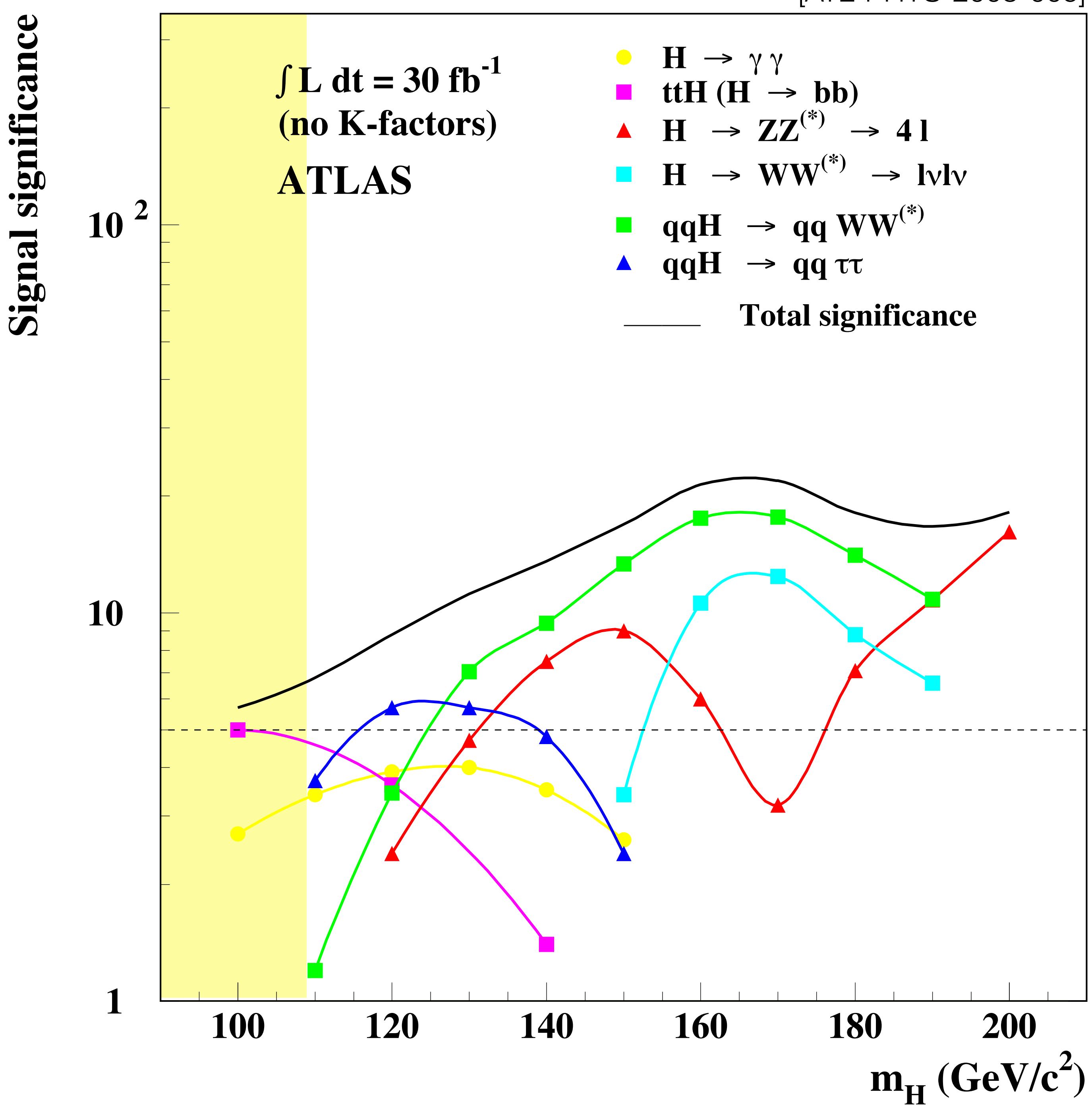


# LHC: Higgs Discovery Potential

[ATL-PHYS-2003-005]




Full mass range can already be covered after a few years at low luminosity

Several channels available over a large range of masses

Low mass discovery requires combination of three of the most demanding channels

Comparable situation for the CMS experiment