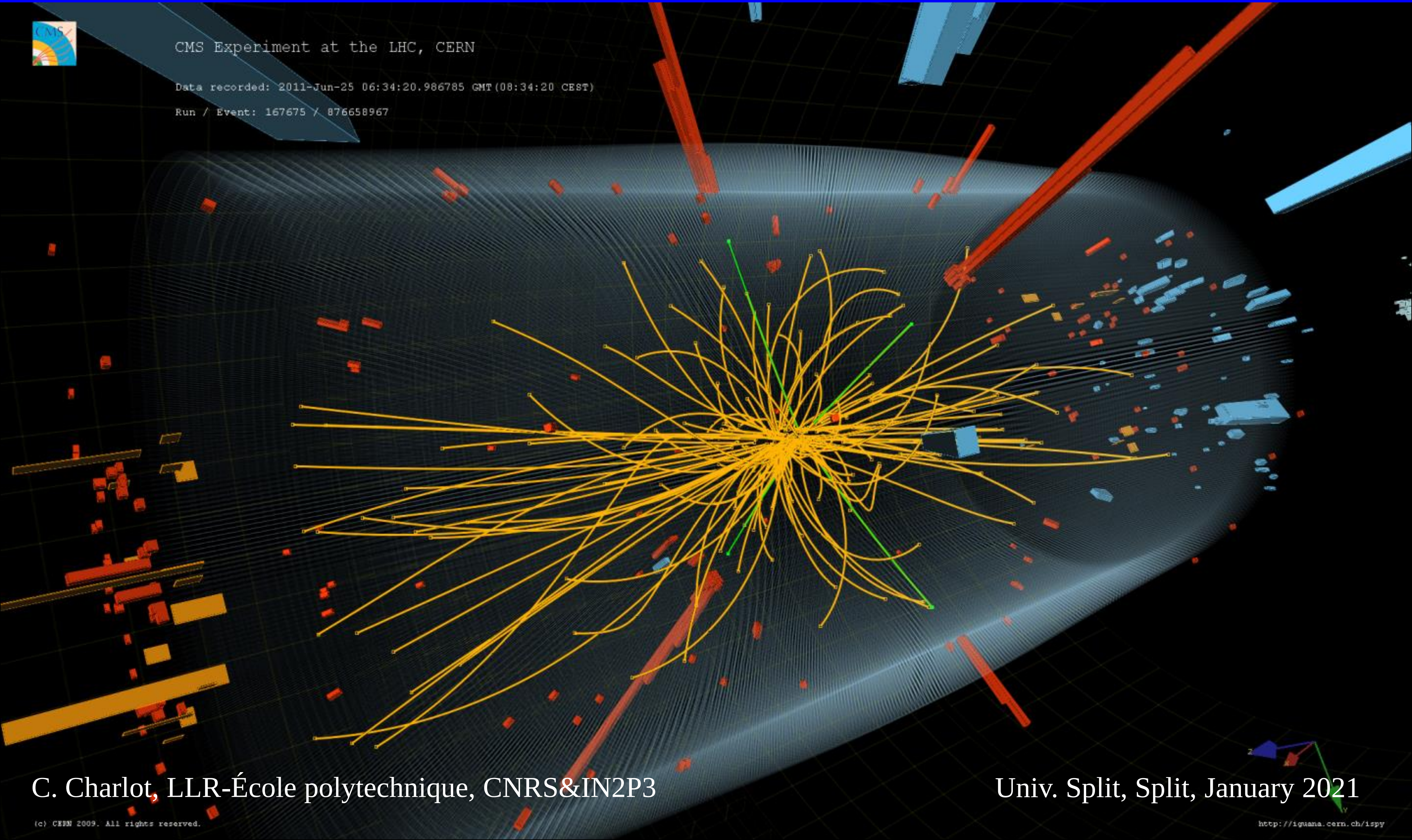
The Higgs boson: from concept to discovery



C. Charlot, LLR-École polytechnique, CNRS&IN2P3

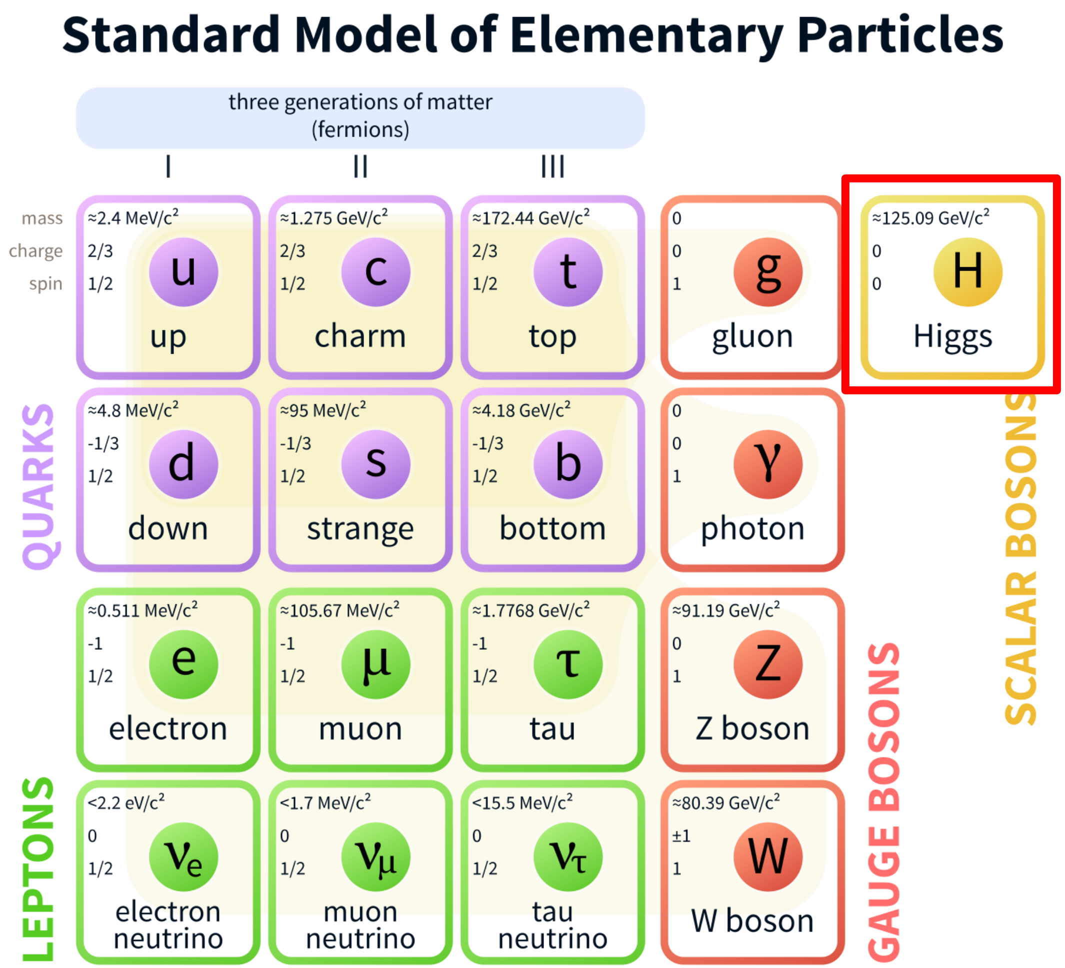
Univ. Split, Split, January 2021

From concept to discovery

- Why a Higgs boson?
- How did we search for and discover it?
- Status of current experimental measurements / knowledge
- What’s next?

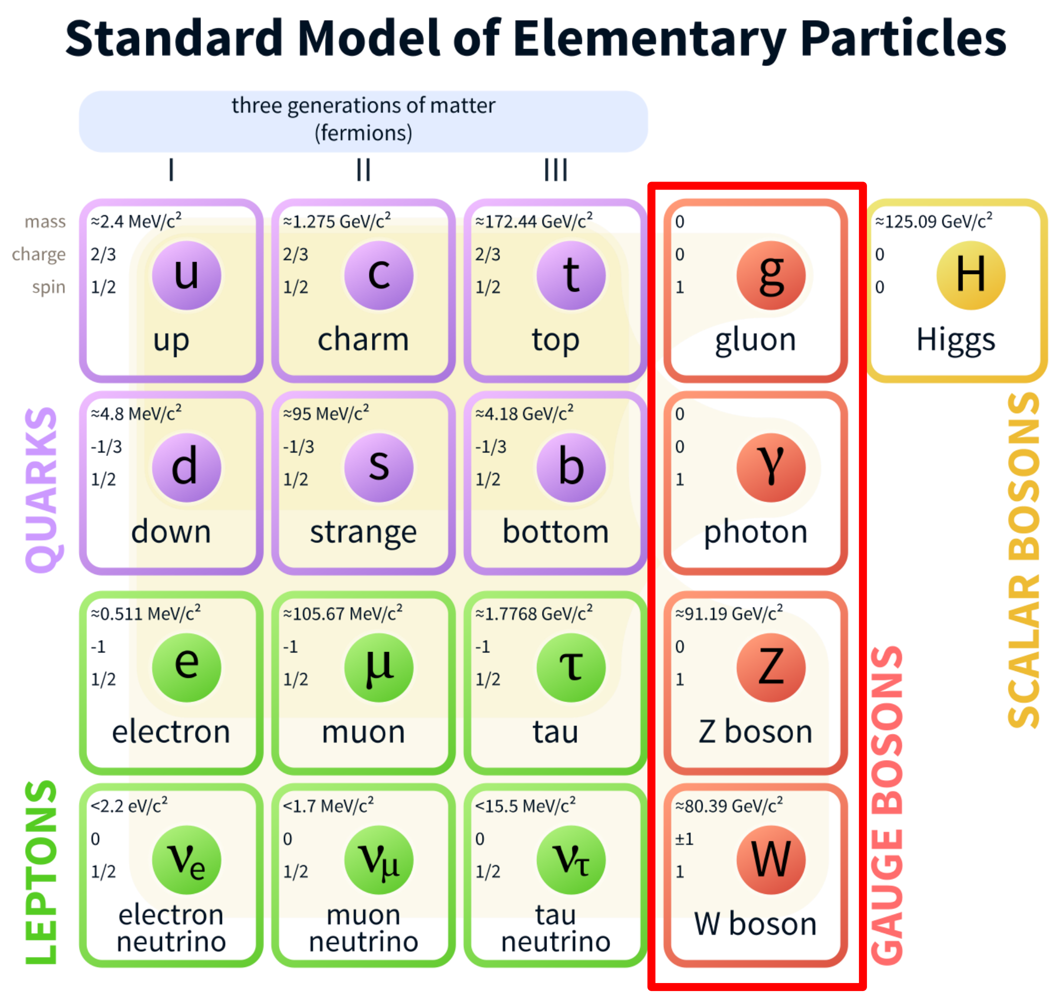
Fundamental particles & interactions

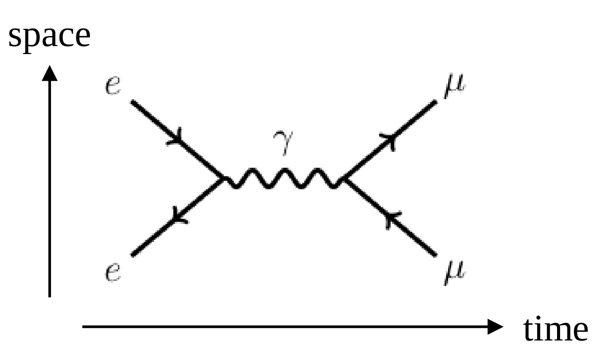
- Higgs boson: spin 0 (unique)
- Discovered in 2012 by ATLAS and CMS experiments
- Resolve conflict between gauge interactions and masses
- Totally new interaction
- It is the subject of this lecture!



Fundamental interactions

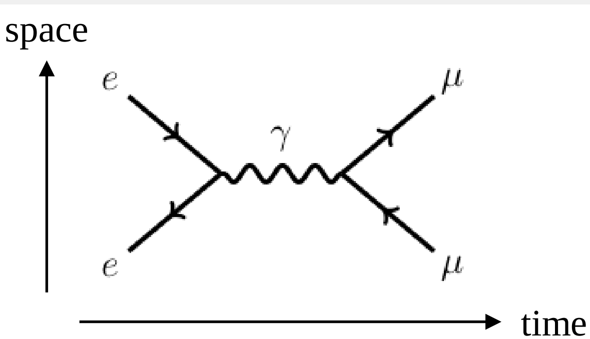
- Interactions: bosons, spin 1
- Electroweak, strong
- Gravity is too weak at our energies (spin 2 graviton, although consistent theory requires supersymmetry and higher space dimensions)
- Interaction = particle exchange, emerges in QFT from requiring local gauge invariance



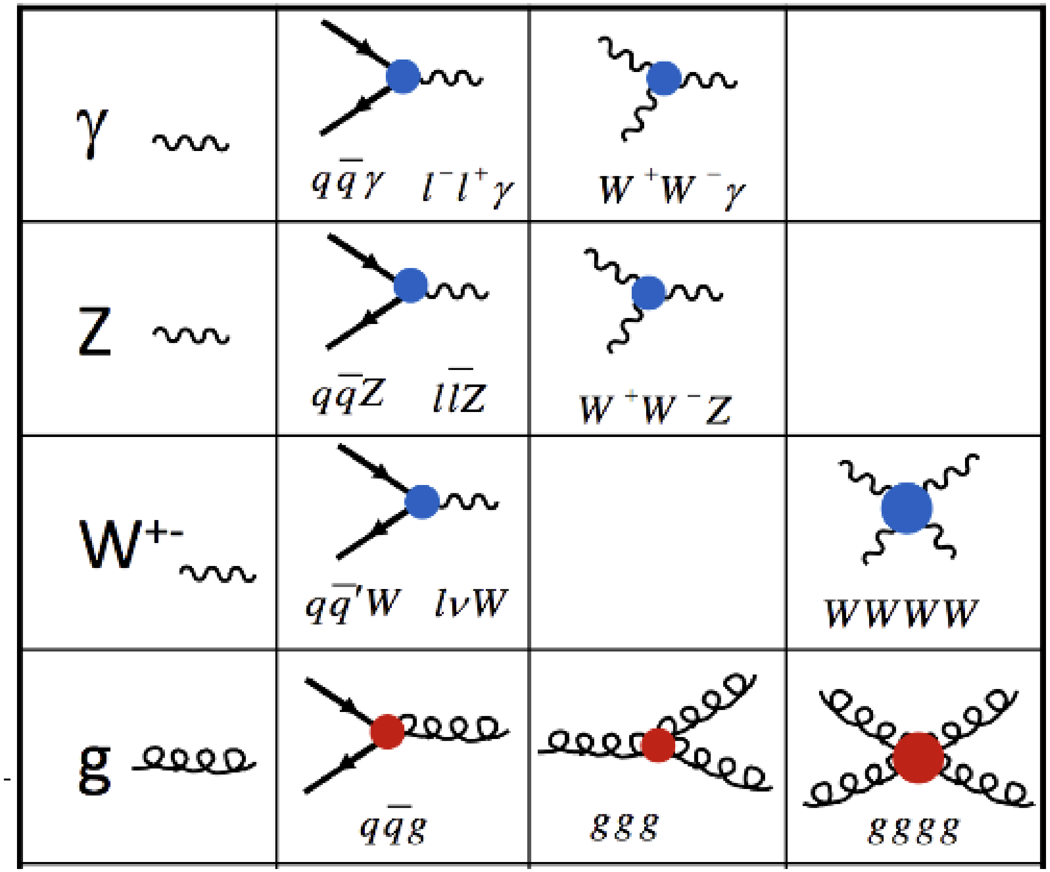


Fundamental particles & interactions

- Interactions: bosons, spin 1
- Electroweak, strong
- Gravitation is too weak at our energies (spin 2 graviton, although consistent theory requires supersymmetry and higher space dimensions)
- Interaction = particle exchange, emerge in QFT from requiring local gauge invariance



Gauge bosons' interactions



A problem of mass

- QFT that describes fundamental particles and their interactions is a theory of particles without mass
- A mass term in the Lagrangien breaks the local gauge symmetry, which is at the heart of the description of the interactions
- Therefore in QFT the gauge bosons must have m=
- For the photon, this is the case, so far so good

- But it is an **experimental fact** that the weak bosons are massive:
- m_W=80.4 GeV, m_Z=91.2 GeV (discovered at CERN in the early 80's)

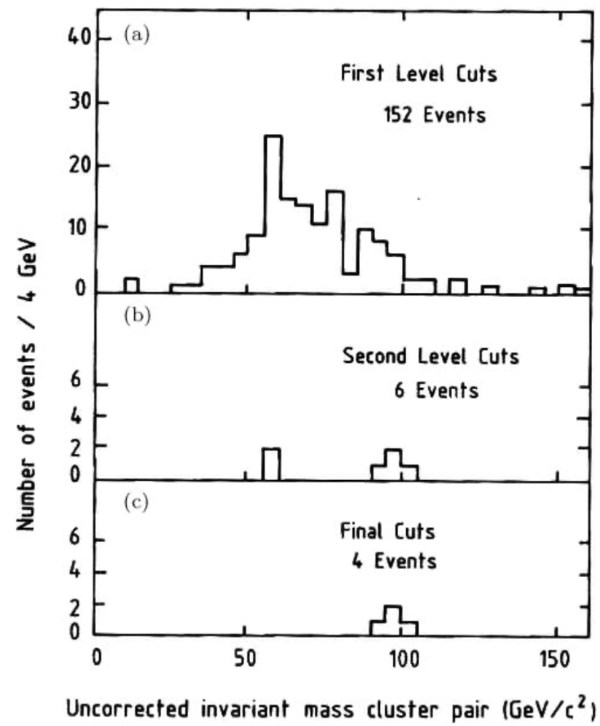


Fig. 14. Search for the decay $Z \rightarrow e^+e^-$ in UA1 (see text).

Gauge boson mass and interaction range

- The range of an interaction is related to the mass m of the exchanged particle
- A virtual particle can take an amount of energy DE=mc2 for a time Dt only according to the uncertainty principle

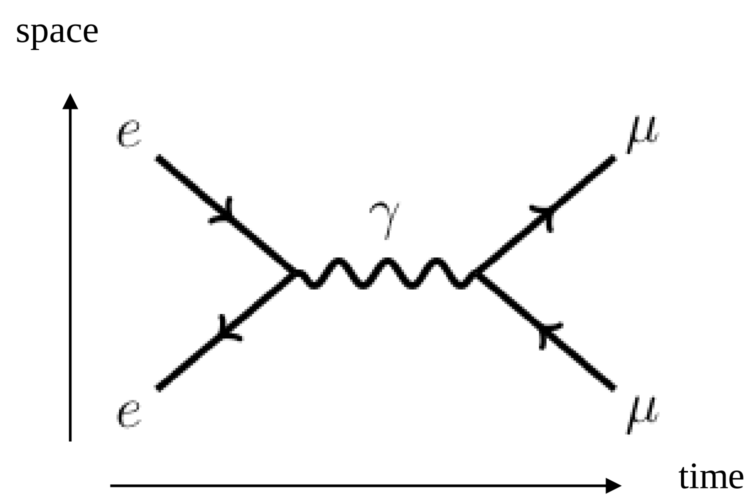
$$\Delta E \times \Delta t \sim \hbar$$

- The distance such particle can travel is at max $\Delta x = c\Delta t$, so that

$$\Delta x = \hbar c / \Delta E$$

$$\boxed{\Delta x = \hbar c / Mc^2}$$

- The photon has m=0 => e.m. interaction of infinite range
- The weak bosons W, Z are massive => **short range** of the weak interaction, fundamental difference with the other interactions



Why gauge bosons must have 0 mass?

- Suppose a gauge field theory on a lattice

$$\Psi(x) \Rightarrow \Psi_i \quad ; \quad \partial\Psi(x) \Rightarrow (\Psi_i - \Psi_{i+1})$$

$$\Psi(x) \rightarrow e^{i\theta}\Psi(x) \quad \Rightarrow \Psi_i \rightarrow e^{i\theta}\Psi_i$$

- Under a global phase transformation (θ constant), the following field terms

$$\bar{\Psi}_i\Psi_i \qquad \bar{\Psi}_i\Psi_{i+1}$$

are invariant.

- Under a local phase transformation, θ = θ(x), the term i,i+1 involving subsequent points on the lattice becomes

$$e^{-i\theta_i}\bar{\Psi}_i\Psi_{i+1}e^{i\theta_{i+1}}$$

- To cancel it we need a field that connects the phases at point i and i+1and transforms as

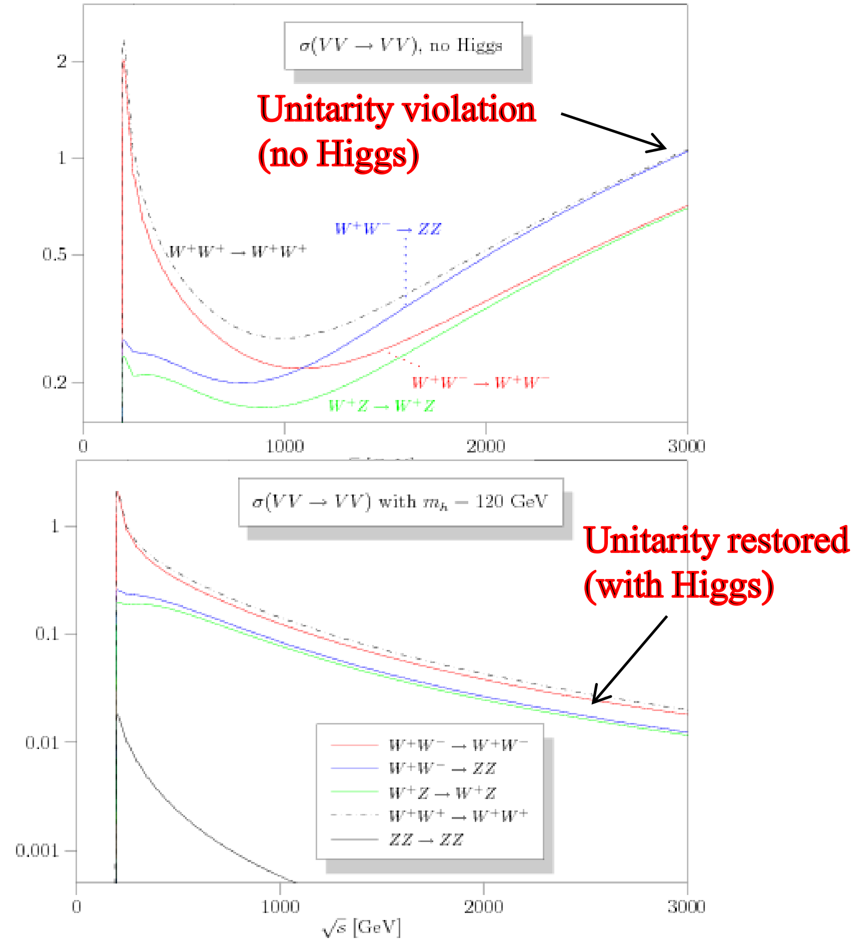
$$U_{i,i+1} \rightarrow e^{i\theta_i}U_{i,i+1}e^{-i\theta_{i+1}}$$

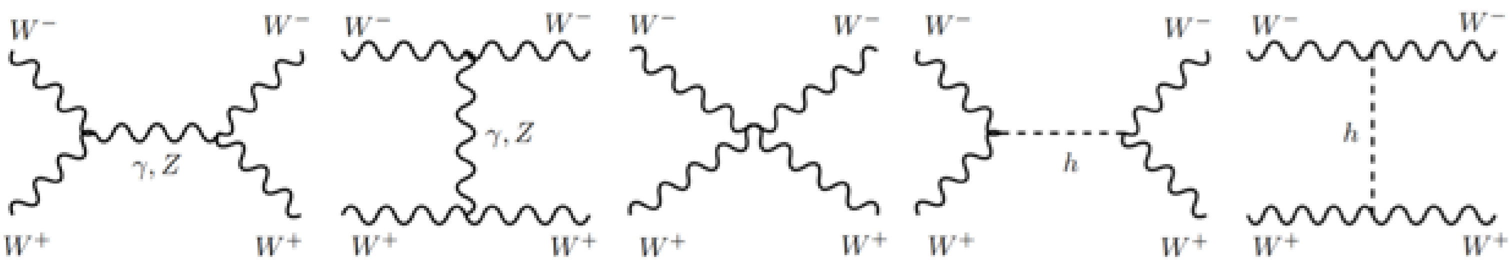
- Gauge invariance introduce a **long range correlation**

=> the gauge bosons have m=0! It is a **geometrical property**!

Another problem in the SM

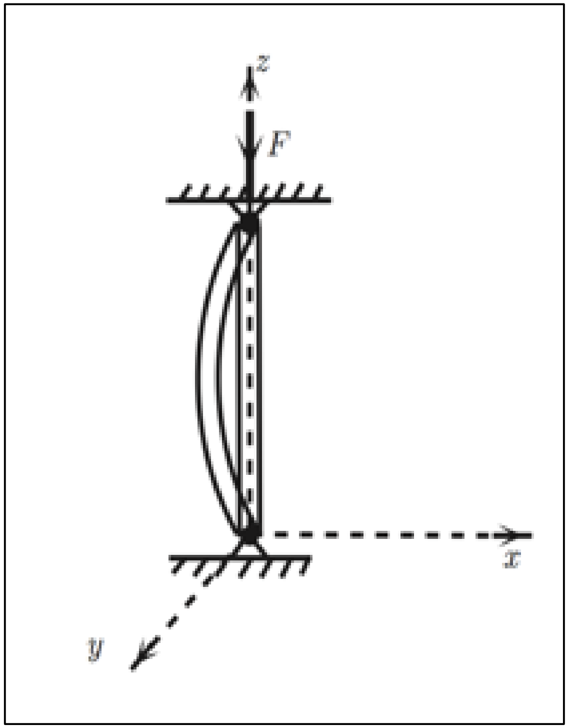
- In the absence of the Higgs, the cross section for **weak bosons longitudinal scattering** grows with energy and ultimately **breaks unitarity**!
- The addition of a scalar boson exchange regularizes the cross section through a **negative interference** with amplitudes involving triple and quartic gauge couplings
- This **cancellation** happens if and only if the coupling of the scalar boson to the gauge fields is that of the **Higgs boson** (ie ~m_V^2)





Spontaneous Symmetry breaking

- There are many cases in physics where the **system has symmetry** while the ground state (minimal energy) doesn't has the symmetry
- A stick with a vertical force applied on top of it will bend ($F<F_c$) to a state of lower energy that **breaks the azimuthal symmetry**
- The system has an **infinity of states** with lower energy
- The symmetry is still present in the equations but the ground state has a **non-0 energy**
- With a suitable choice of the potential it is then possible to 'generate' **quadratic terms** in the Lagrangian

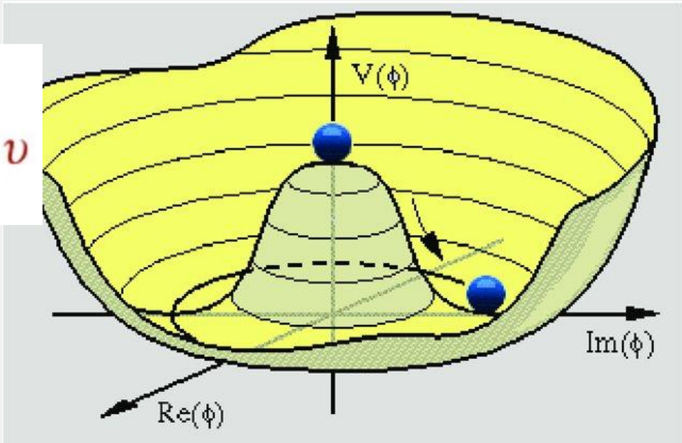


The BEH mechanism

- Introduce an SU(2) doublet of complex scalar fields
- The Lagrangian is $\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$
- And with a particular choice for the potential

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

- For $\lambda>0$ and $\mu^2>0$ there is a unique vacuum with $<0|\phi|0> = 0$
- For $\lambda>0$ and $\mu^2<0$ the true vacuum is at $|\phi_0| = \sqrt{\frac{-\mu^2}{\lambda}} \equiv \upsilon$
- The choice of the vacuum breaks the symmetry and 4 Goldstone bosons of 0 mass appear
- 3 GB combine with the gauge sector and reappear as longitudinal degree of freedom for the **Z and Ws, which become massive**
- The 4th Goldstone boson remains as a **new neutral scalar particle, the Higgs boson**

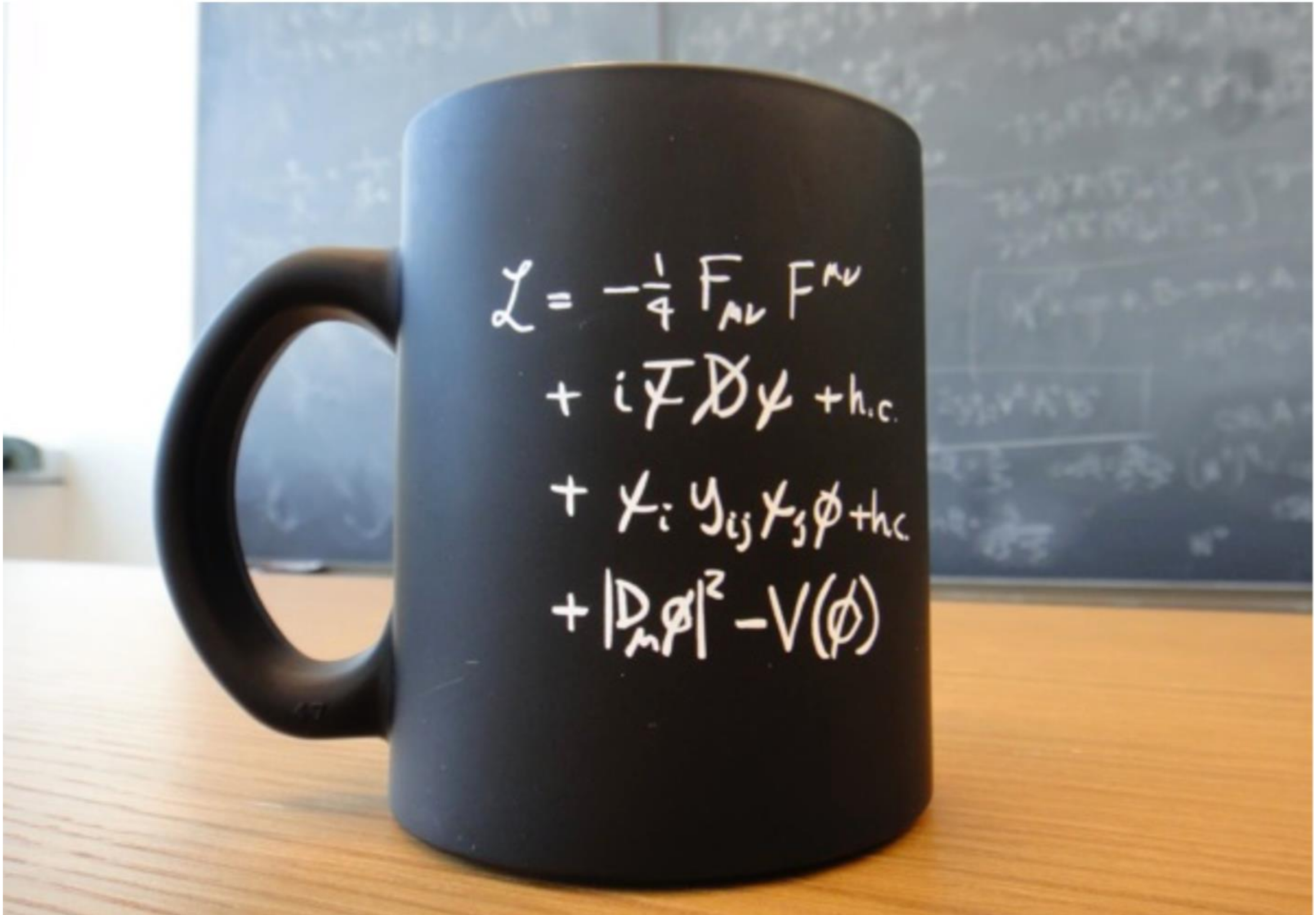


$$M_W^2 W_\mu^+ W^{-\mu} + \tfrac{1}{2} M_Z^2 Z_\mu Z^\mu$$

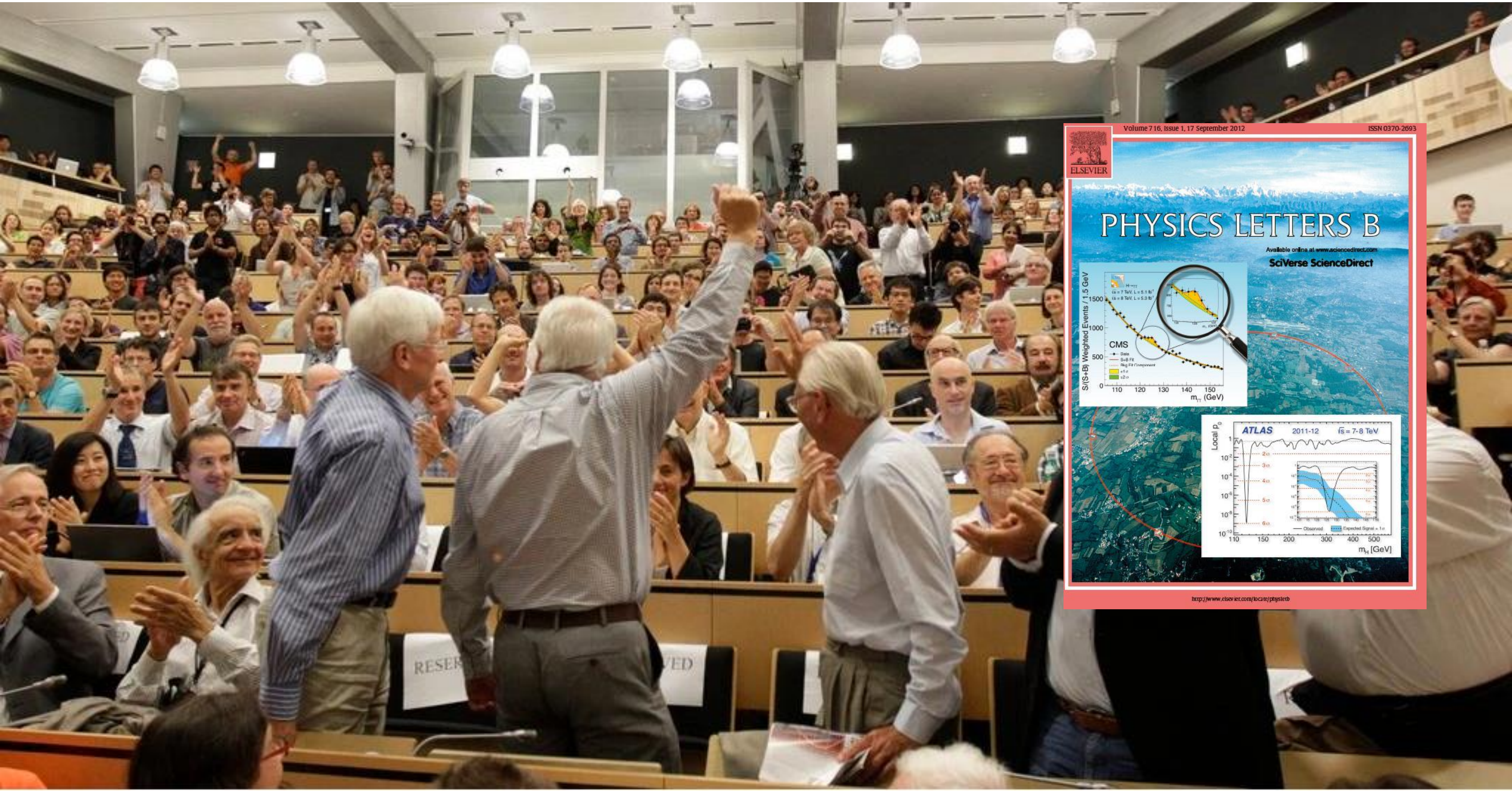
$$M_W = \tfrac{1}{2} g v$$

$$M_Z = \tfrac{1}{2} g_Z v = M_W / \cos\theta_W$$

Is this theory describing the reality?



Yes (july 4, 2012)!



Intermediate summary

- The SM is a **gauge theory** where interactions arise from gauge symmetries
- The natural mass for gauge bosons is 0, but **weak bosons are massive**!
- **SSB** allows to **reconcile mass** terms with gauge symmetries, introducing a doublet of scalar fields
- **EWSB** gives rise to 4 **Goldstone bosons**, three of them combine as longitudinal components with the transverse ones for the Ws and Z, ‘giving’ **mass to Ws and Z**
- A new scalar boson must **remain**, the Higgs boson
- Its mass is the only **unknown parameter** (assuming simplest possible field content and potential, and neglecting the mass parameters needed for fermions…)
- This description was put in place in the early 60’s, we now know that **it is reality**

Part 2: How did we get there?

First attempts at a systematic search

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

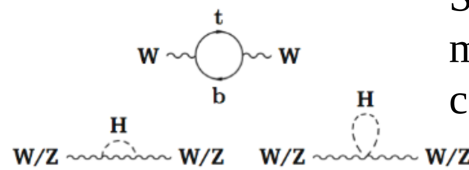
A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model.

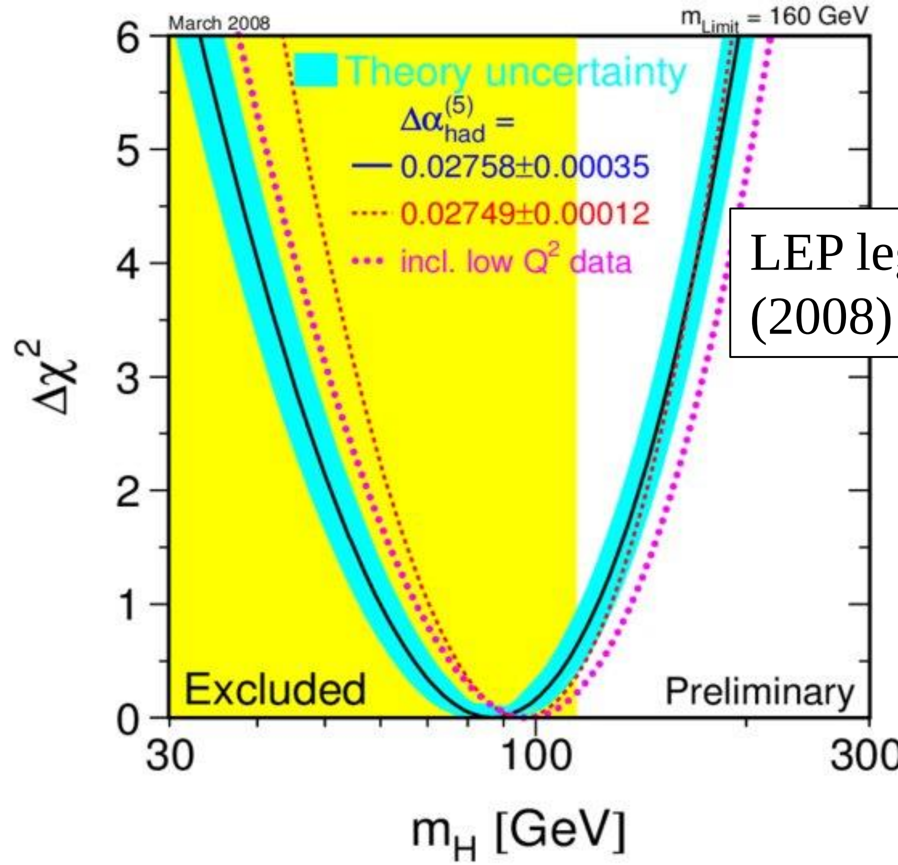
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

LEP searches (1981-2000)

- Direct searches: m_H>114.4GeV@95%CL
- Fits to EW data (indirect)
- m_H<160 GeV @95%CL and MPV = 87^{+38}_{-27} GeV (indirect)
- m_H<190 GeV if direct search result included
- Light Higgs favoured, assuming it exists and SM is correct!`

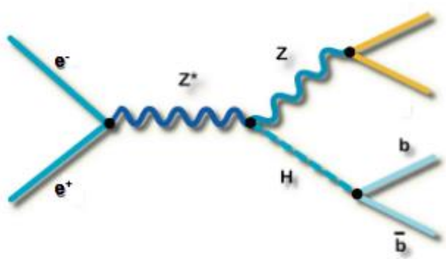
SM relates m_t, $m_{W/Z}$ and m_H through radiative corrections





LEP legacy (2008)

Higgstrahlung: pp → ZH

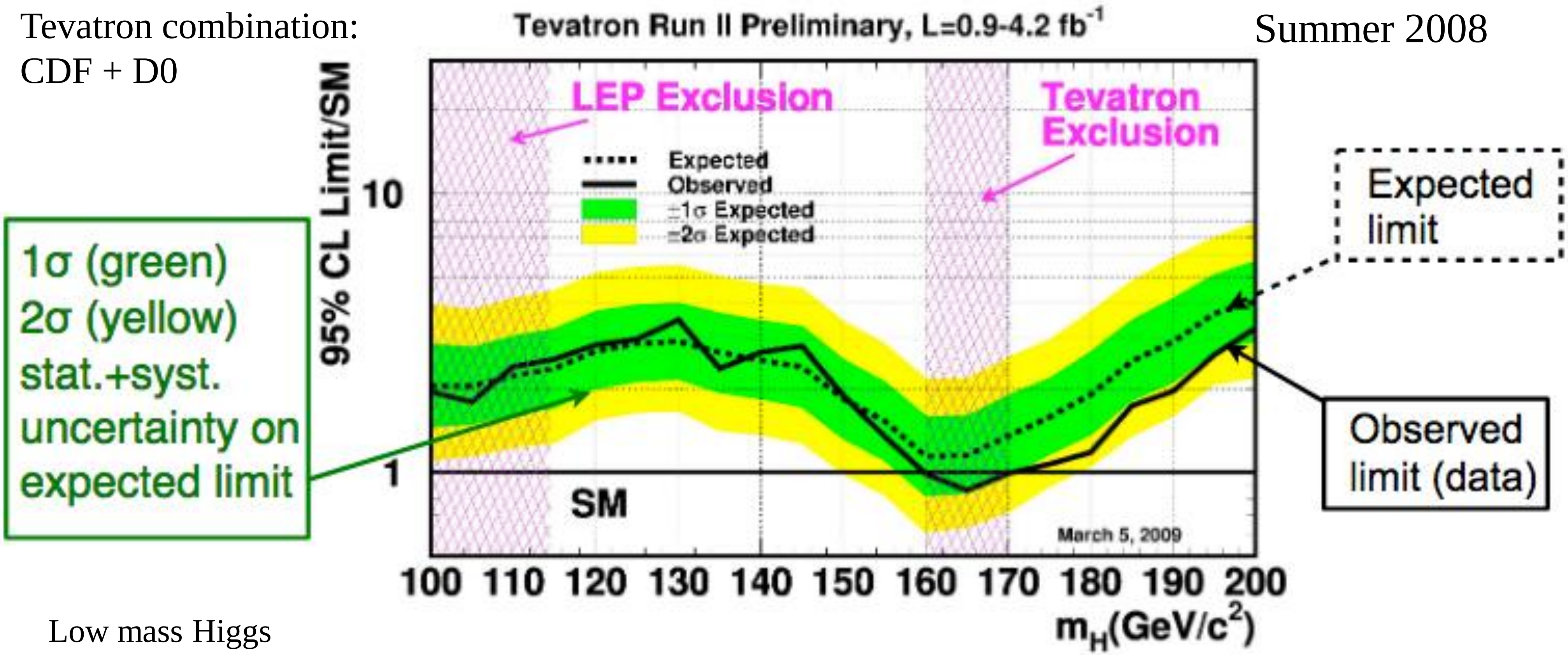


$\sqrt{s}$ - m_Z = 206.6 - 91.2 = 115.4 GeV

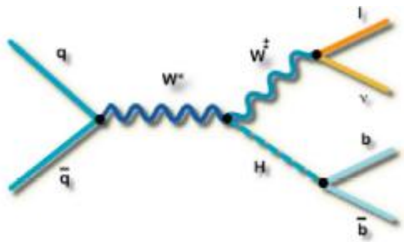
Tevatron results (2001-2011)

Tevatron combination:
CDF + D0

Summer 2008

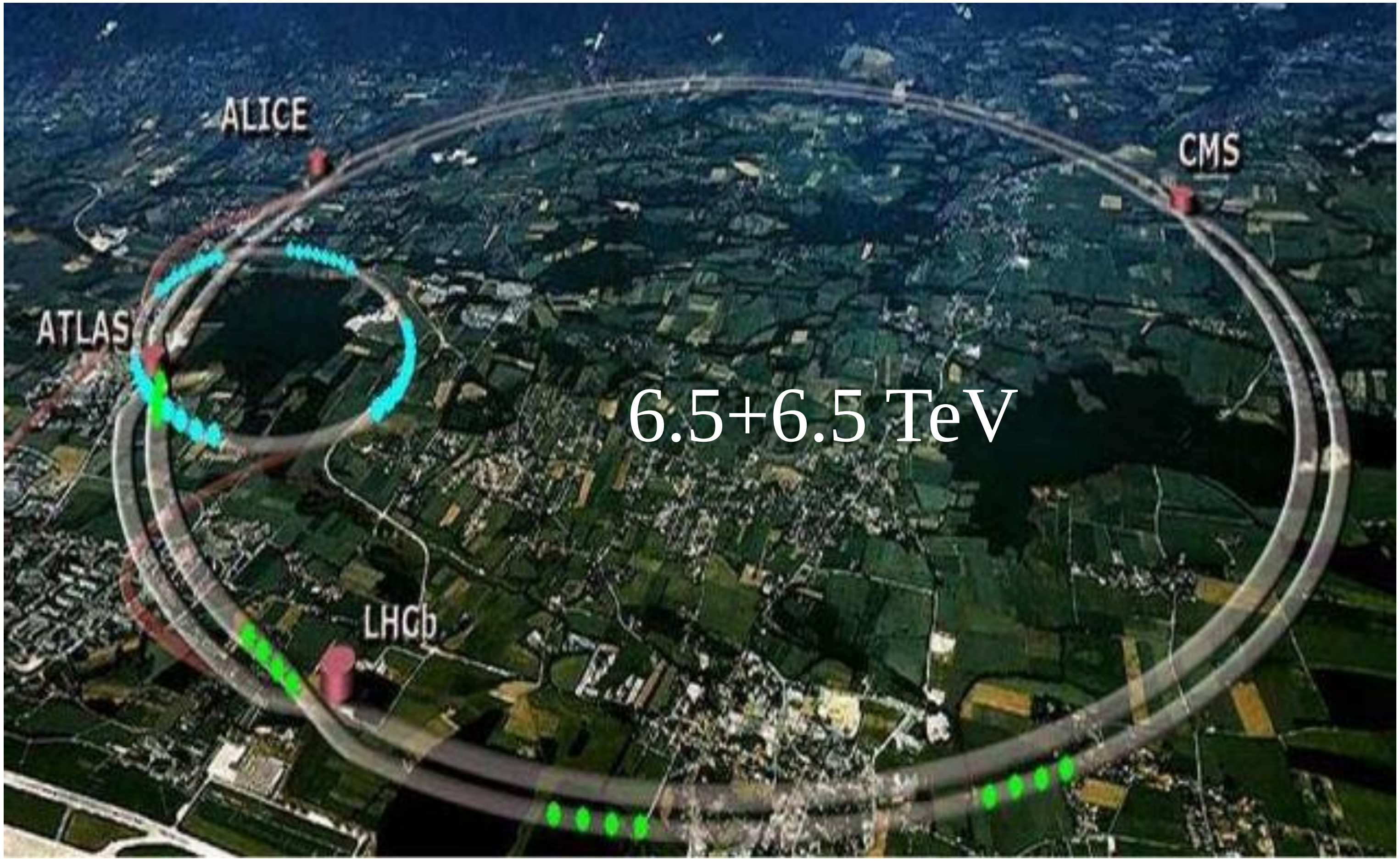


Low mass Higgs
(m_H<135 GeV)



- ❑ Low mass search: pp → VH in νvbb, llbb, lνbb, jjττ, ττbb
- ❑ Very sophisticated analyses, many channels, BDTs
- ❑ Discovery out of reach except ~2m_W (H → WW)

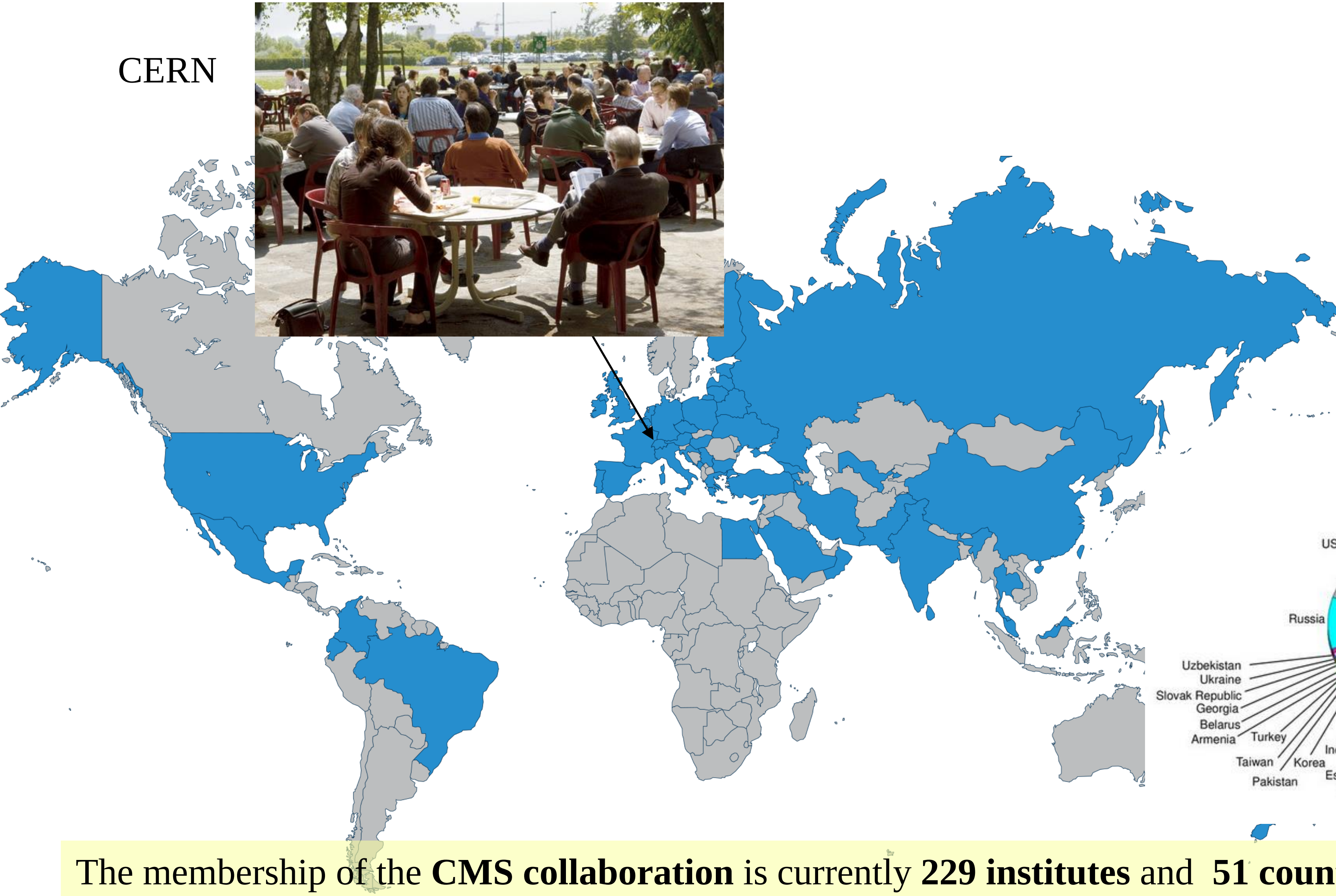
The Large Hadron Collider

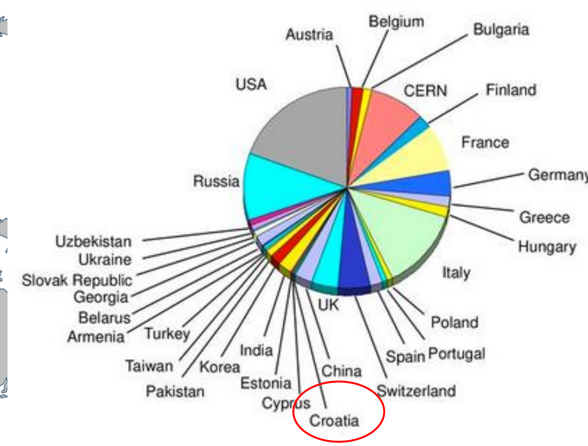


- A 27 km circumference accelerator located at the Franco-Swiss border, 100m underground
- Accelerates protons to *nearly* the speed of light, in two counter rotating beams

Experimental collaborations

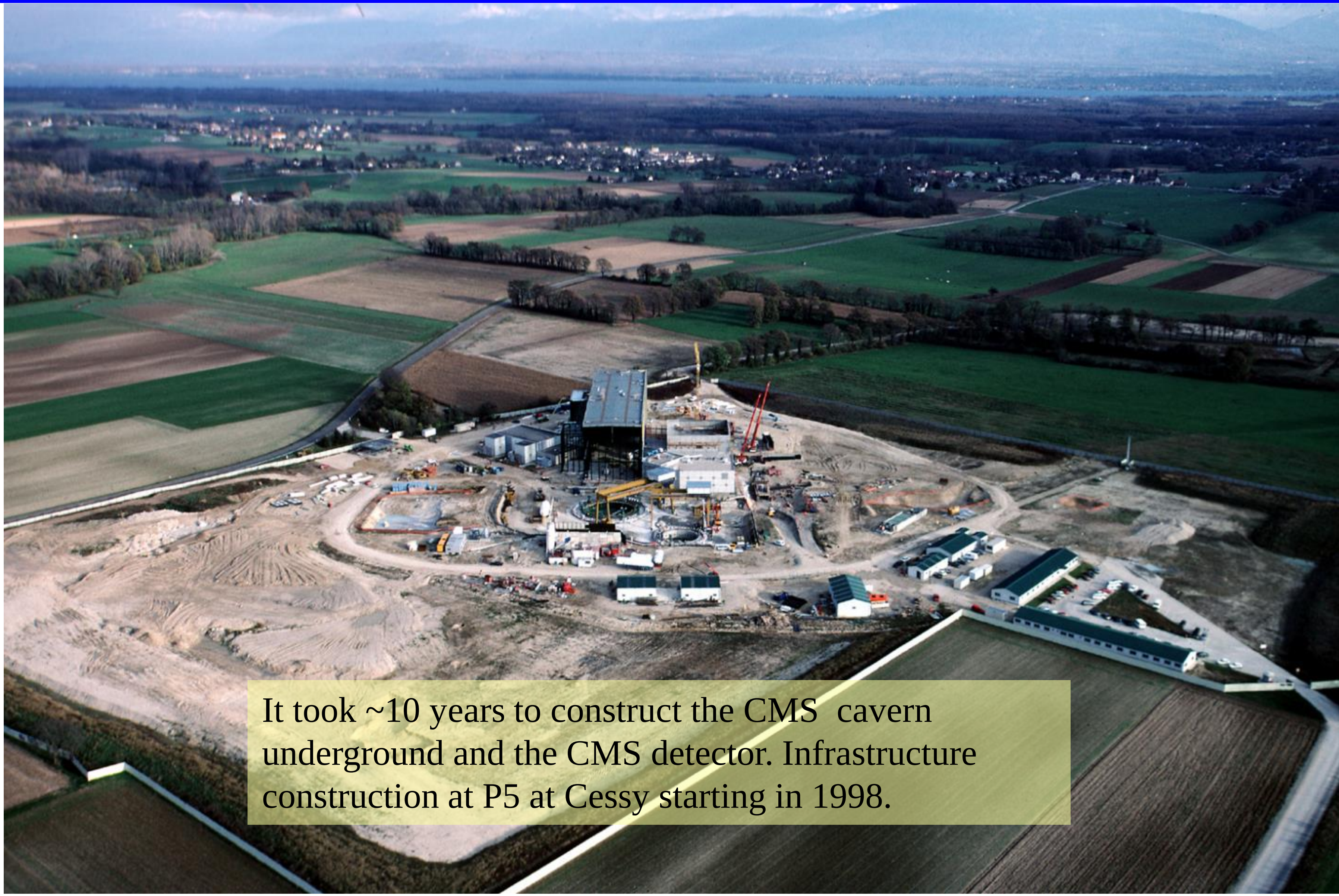
CERN



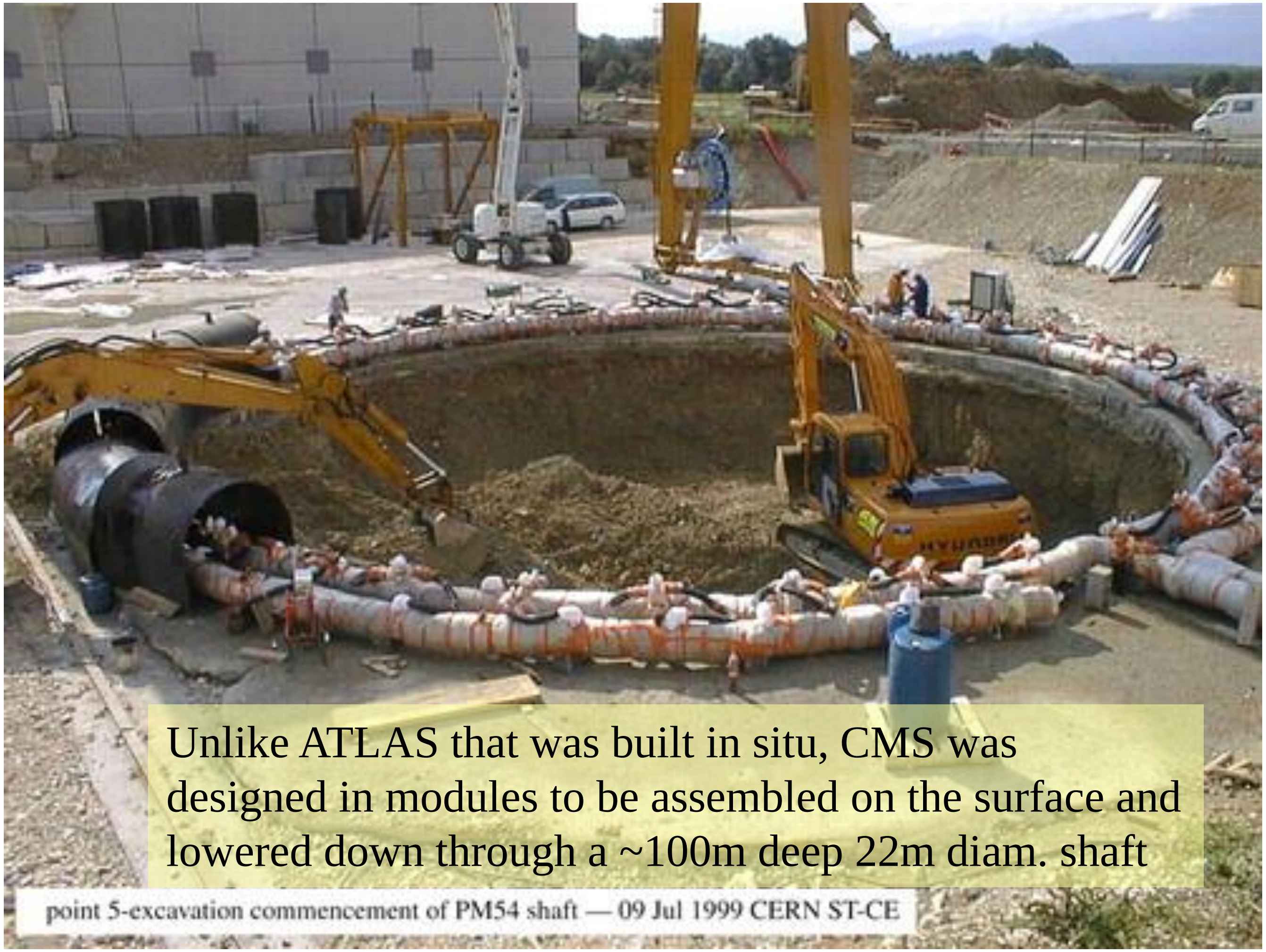


The membership of the **CMS collaboration** is currently **229 institutes** and **51 countries**
~3000 physicists (including ~1000 students) ~1300 engineers and technicians

CMS P5 construction (1998-2005)

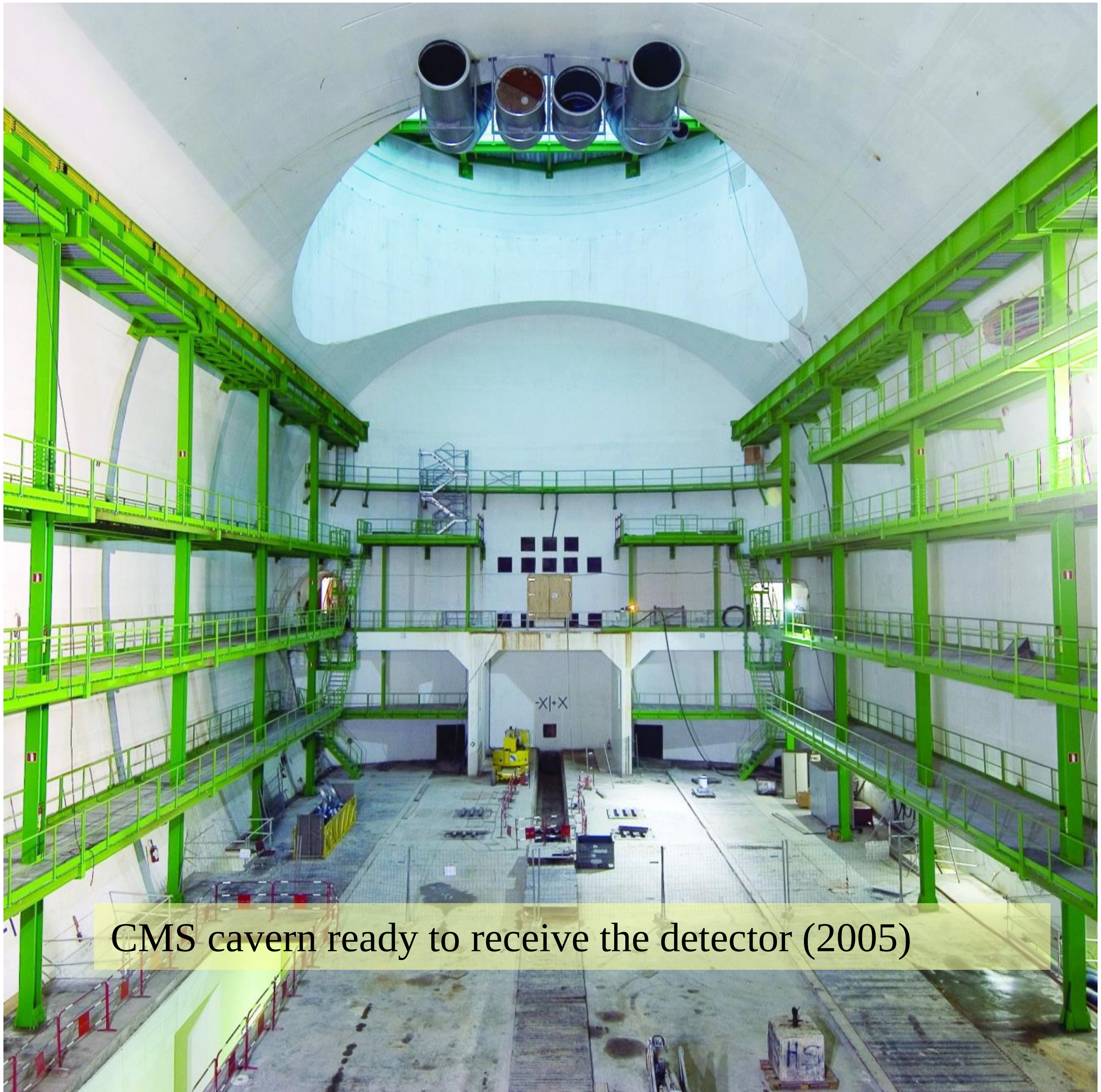


CMS P5 construction (1998-2005)



Unlike ATLAS that was built in situ, CMS was designed in modules to be assembled on the surface and lowered down through a ~100m deep 22m diam. shaft

CMS P5 construction (1998-2005)



CMS construction (2001-2008)

Transport of the vacuum tank of the CMS solenoid at P5 (2001). 1 week was necessary to transport it from Long-le-Saugnier (France) to Cessy CERN P5 (120km)

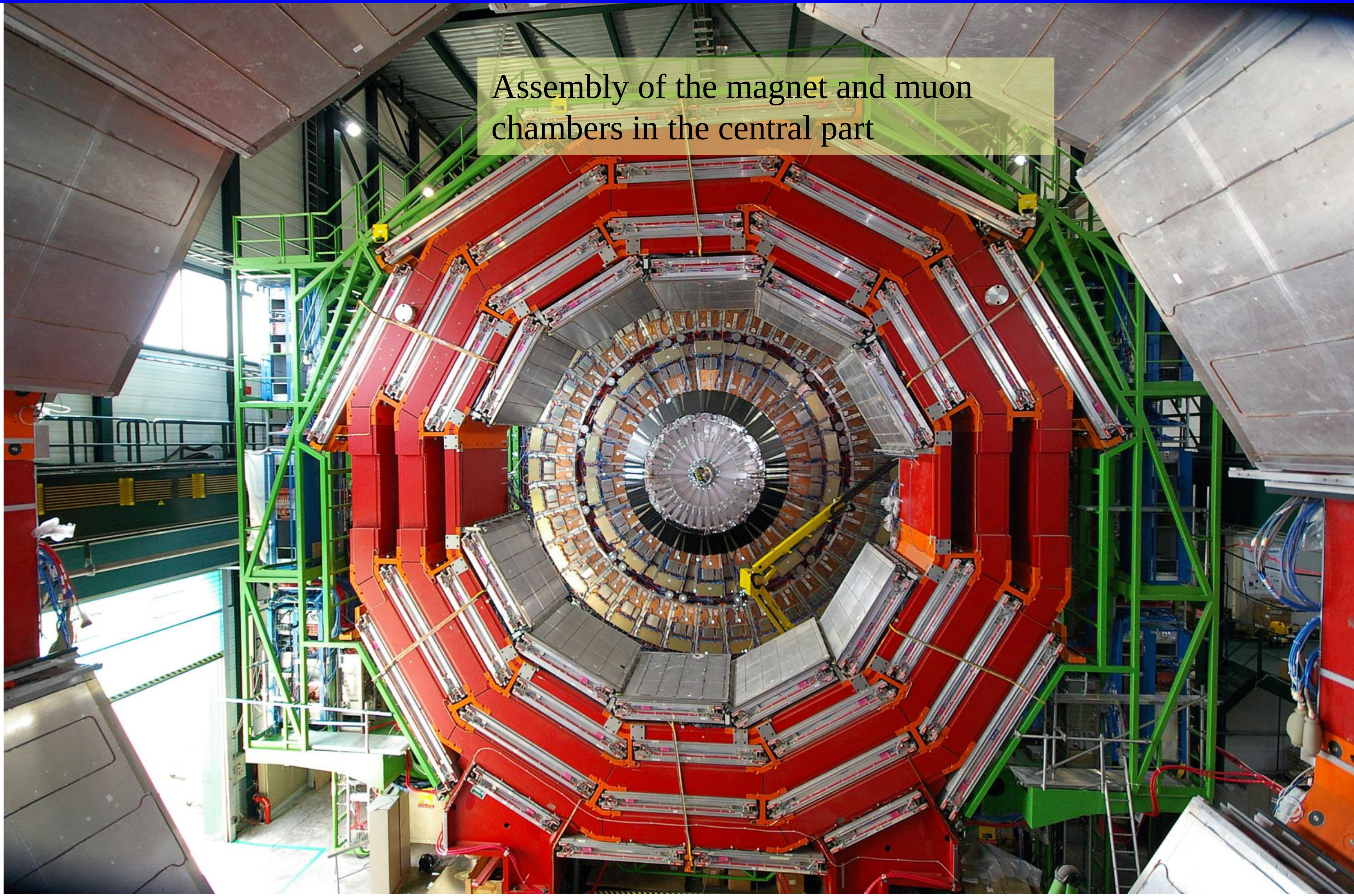
CMS Installation (2001-2008)

CMS magnet assembly. The vacuum tank consists of inner and outer stainless-steel cylinders and houses the superconducting coil (4K)

CMS Installation (2001-2008)

The first endcap disk of the magnetic field return-yoke, equipped with the endcap muon chambers is being lowered through the shaft!

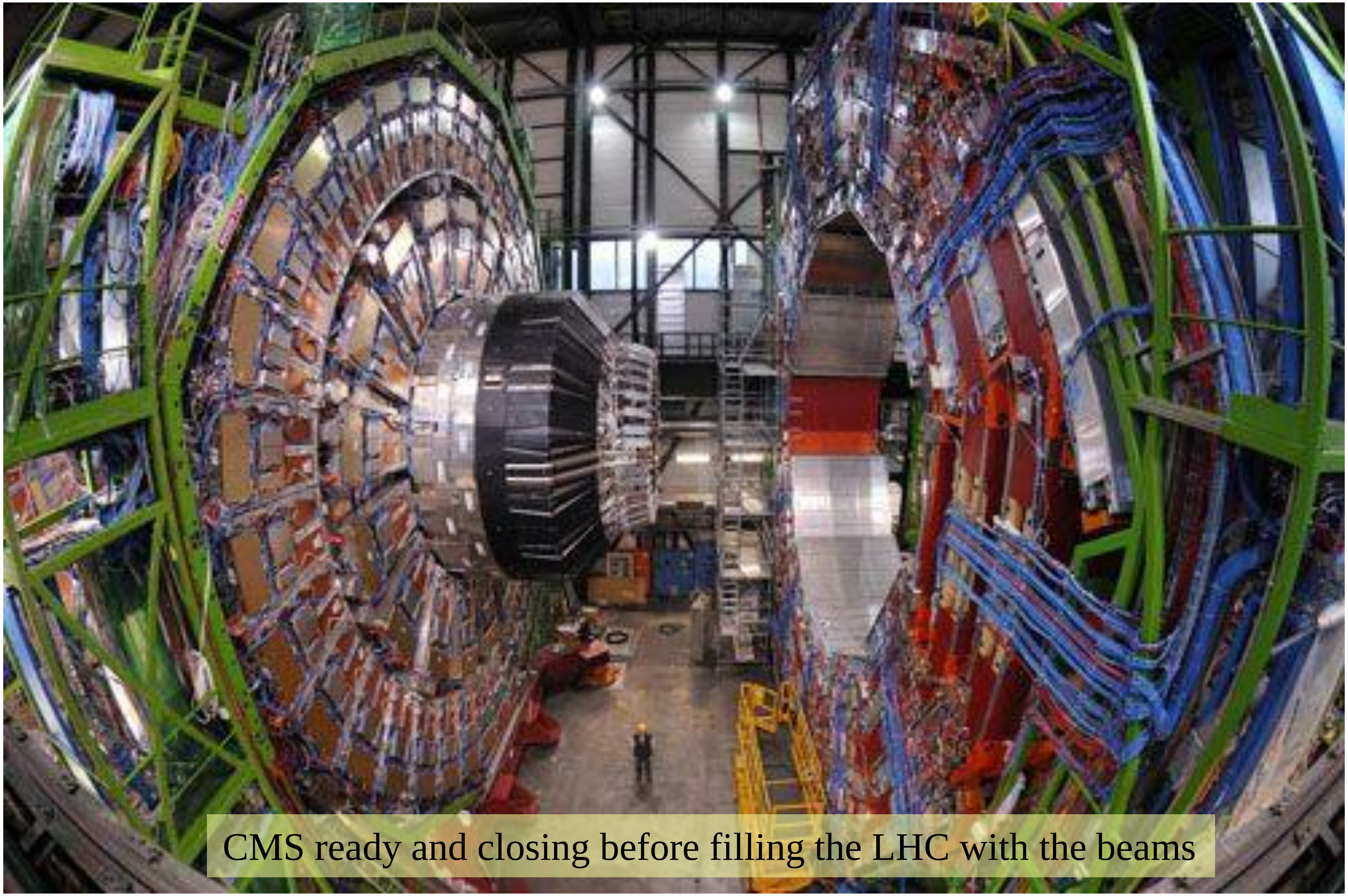
CMS Installation (2001-2008)



CMS Installation (2001-2008)

The solenoid is being installed inside the cryostat

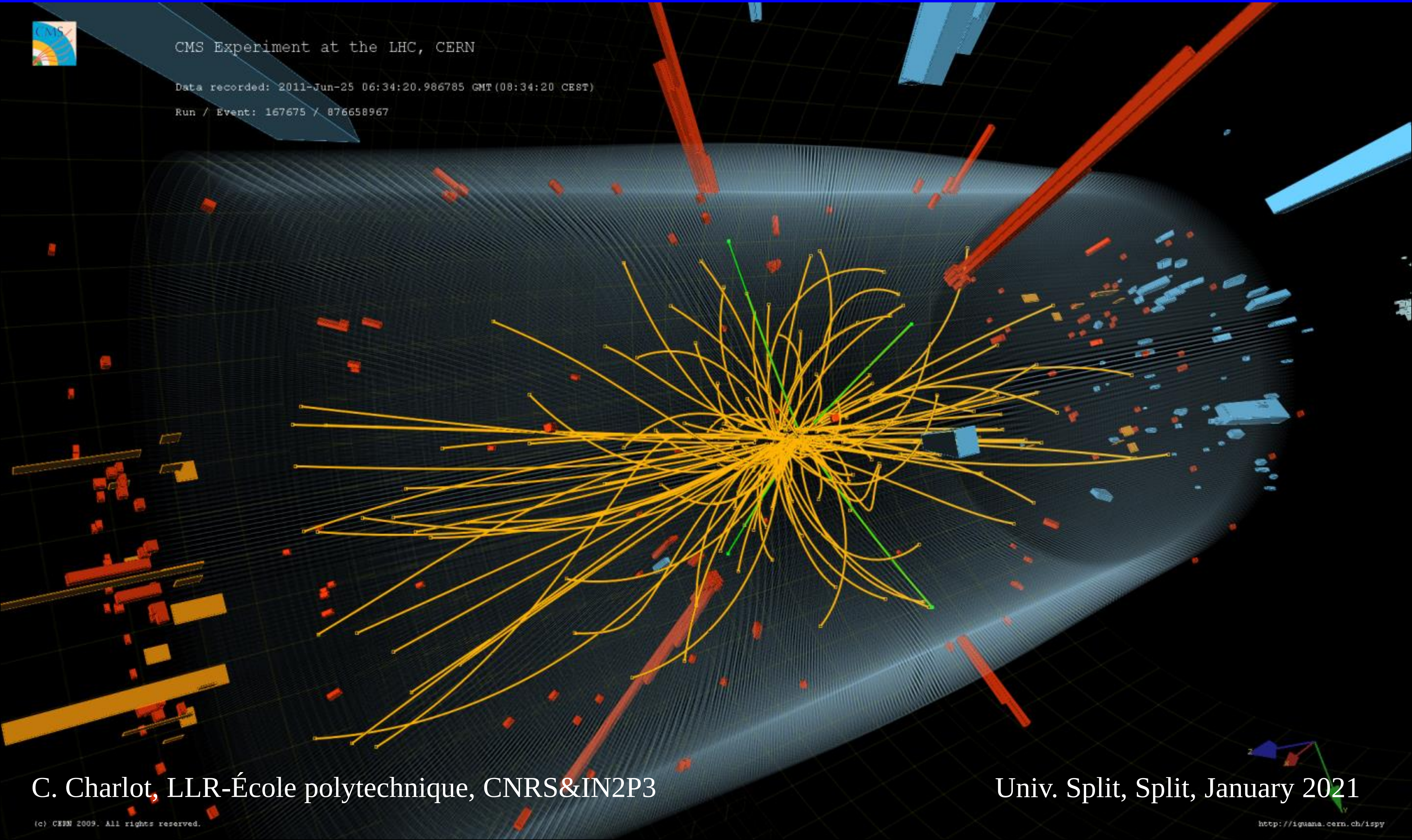
CMS Installation (2001-2008)



CMS ready and closing before filling the LHC with the beams

Bdg.40 at CERN

The Higgs boson: from concept to discovery



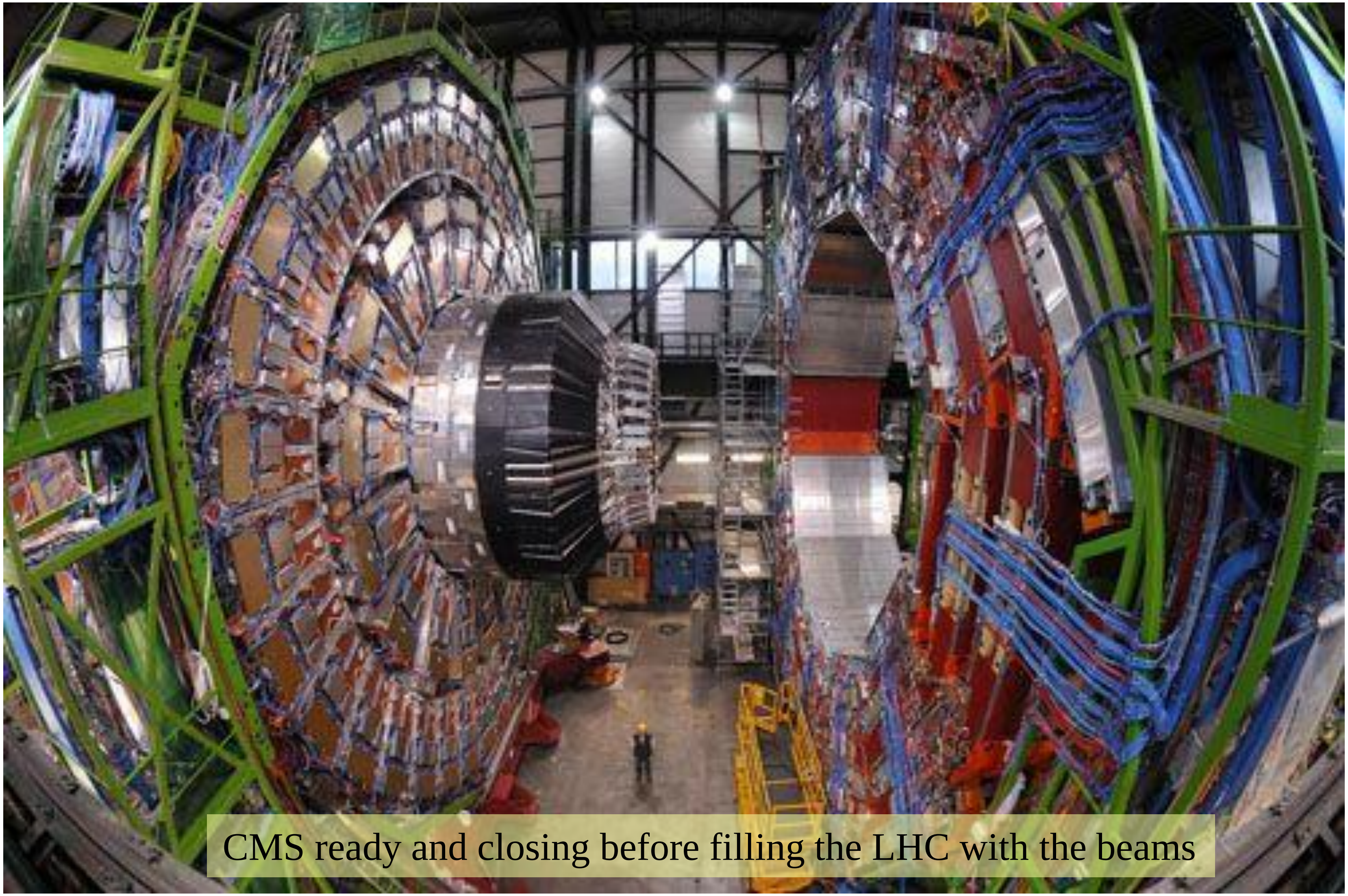
C. Charlot, LLR-École polytechnique, CNRS&IN2P3

Univ. Split, Split, January 2021

From concept to discovery

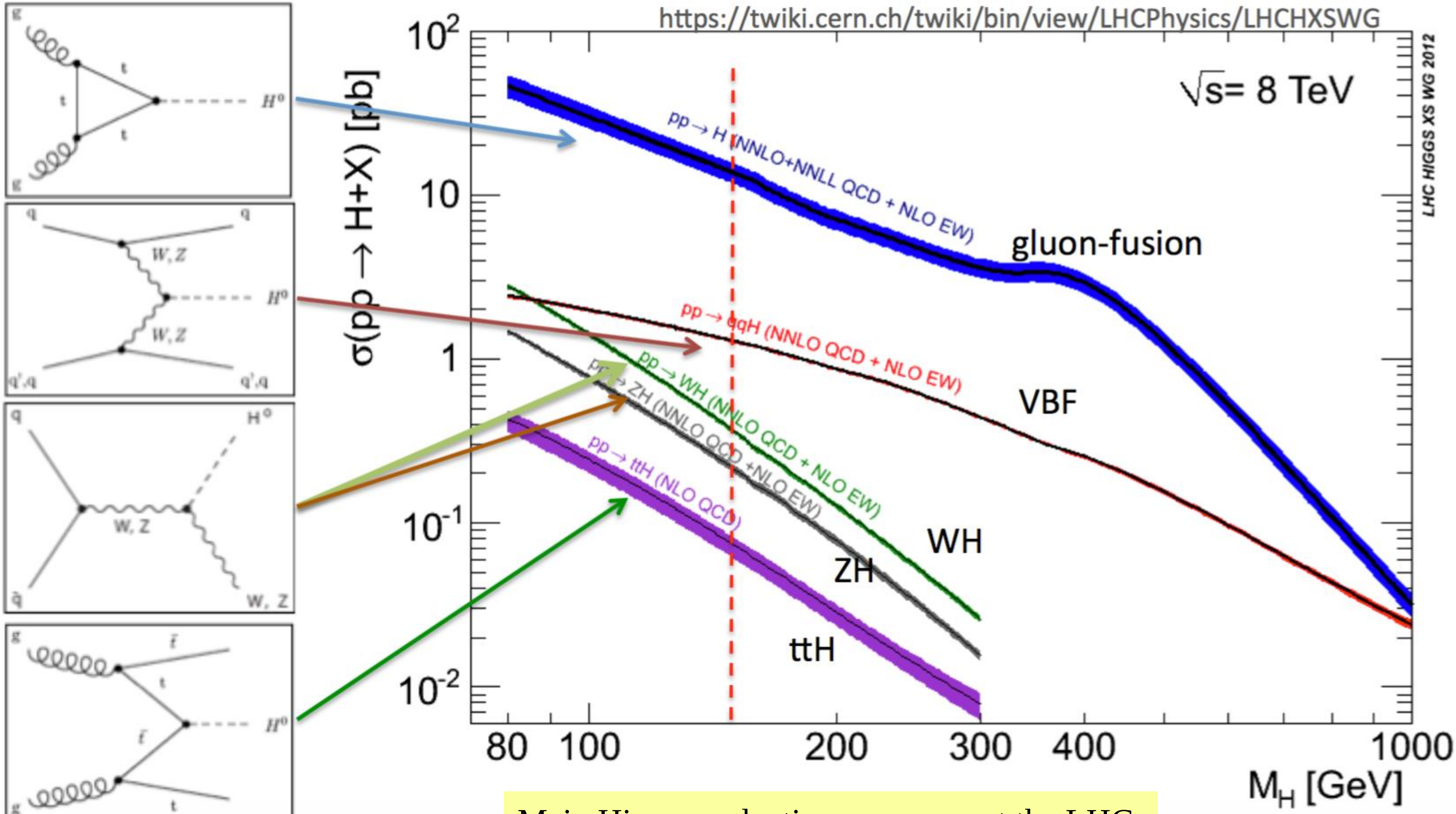
- ❑ Why a Higgs boson?
- ❑ **How did we search for and finally discover it?**
- ❑ Status of current experimental measurements / knowledge
- ❑ What’s next?

CMS Installation (2001-2008)



CMS ready and closing before filling the LHC with the beams

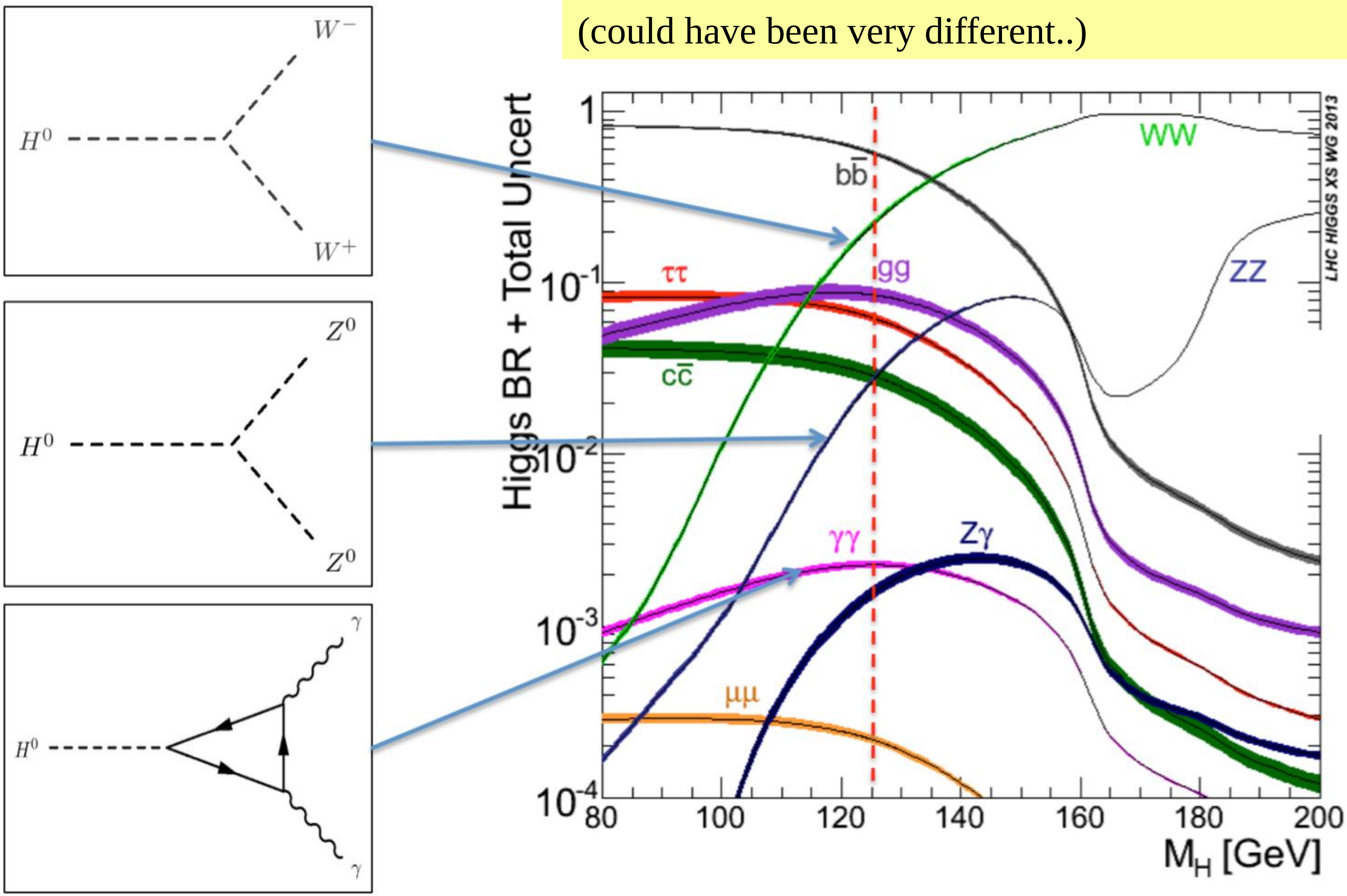
Higgs production at LHC



Main Higgs production processes at the LHC

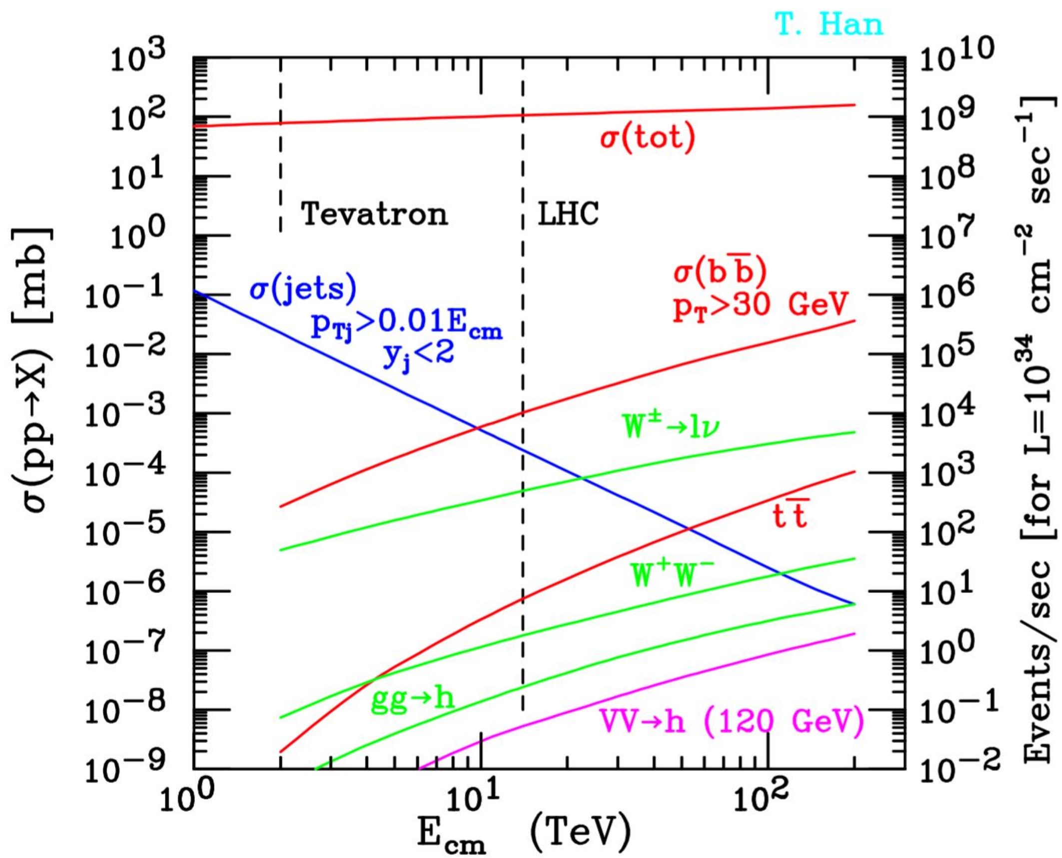
Higgs decay at LHC

Many decay channels accessible for m_H=125 GeV
(could have been very different..)



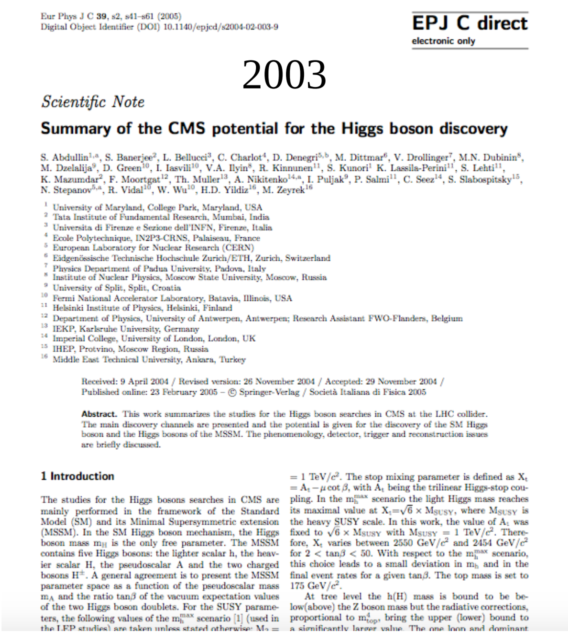
Higgs events do not come alone..

- High collision rate needed to produce enough Higgs events: **~10^9 interactions /sec**
- Corresponds to σ_{tot}~100mb
- b-quark (B factory)
- $W^\pm \to l^\pm \nu$, $Z^0 \to ll$, tt, dibosons, Higgs in gluon fusion, in VBF
- Rates **increase with energy**
- Higgs rather copiously produced, ~0.1/sec, the **problem is to identify it** from the many other processes



→ need to look for rare decays with less backgrounds: e.g.. $H \to ZZ \to llll$ with $H \to ZZ$ and $Z \to ll$ ~ 3% at m_H=125 GeV)

While CMS is being constructed ..



Eur Phys J C **39**, s2, s41–s61 (2005)
Digital Object Identifier (DOI) 10.1140/epjcd/s2004-02-003-9

EPJ C direct
electronic only

2003

Scientific Note

Summary of the CMS potential for the Higgs boson discovery

S. Abdullin[1,a], S. Banerjee[2], L. Bellucci[3], C. Charlot[4], D. Denegri[5,b], M. Dittmar[6], V. Drollinger[7], M.N. Dubinin[8], M. Dzelalija[9], D. Green[10], I. Iasvili[10], V.A. Ilyin[8], R. Kinnunen[11], S. Kunori[1] K. Lassila-Perini[11], S. Lehti[11], K. Mazumdar[2], F. Moortgat[12], Th. Muller[13], A. Nikitenko[14,a], I. Puljak[9], P. Salmi[11], C. Seez[14], S. Slabospitsky[15], N. Stepanov[5,a], R. Vidal[10], W. Wu[10], H.D. Yildiz[16], M. Zeyrek[16]

[1] University of Maryland, College Park, Maryland, USA
[2] Tata Institute of Fundamental Research, Mumbai, India
[3] Universita di Firenze e Sezione dell'INFN, Firenze, Italia
[4] Ecole Polytechnique, IN2P3-CRNS, Palaiseau, France
[5] European Laboratory for Nuclear Research (CERN)
[6] Eidgenössische Technische Hochschule Zurich/ETH, Zurich, Switzerland
[7] Physics Department of Padua University, Padova, Italy
[8] Institute of Nuclear Physics, Moscow State University, Moscow, Russia
[9] University of Split, Split, Croatia
[10] Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[11] Helsinki Institute of Physics, Helsinki, Finland
[12] Department of Physics, University of Antwerpen, Antwerpen; Research Assistant FWO-Flanders, Belgium
[13] IEKP, Karlsruhe University, Germany
[14] Imperial College, University of London, London, UK
[15] IHEP, Protvino, Moscow Region, Russia
[16] Middle East Technical University, Ankara, Turkey

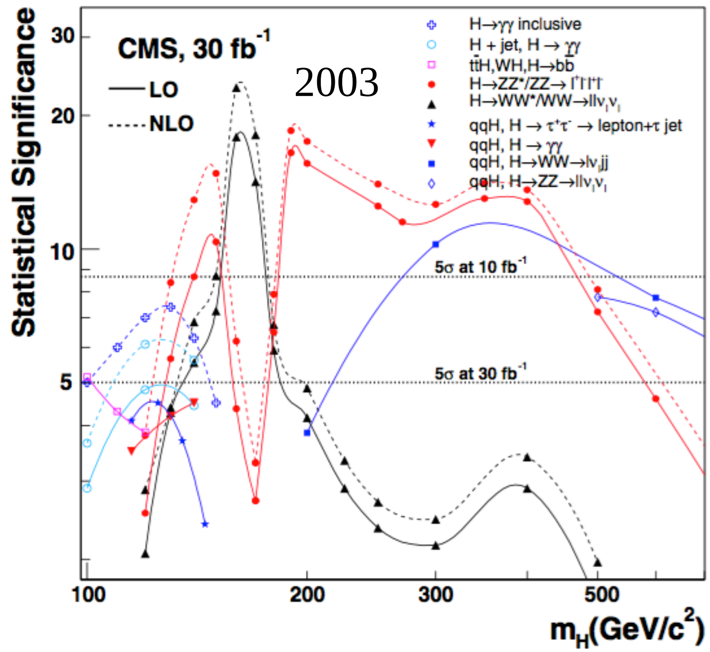
Received: 9 April 2004 / Revised version: 26 November 2004 / Accepted: 29 November 2004 /
Published online: 23 February 2005 – © Springer-Verlag / Società Italiana di Fisica 2005

Abstract. This work summarizes the studies for the Higgs boson searches in CMS at the LHC collider. The main discovery channels are presented and the potential is given for the discovery of the SM Higgs boson and the Higgs bosons of the MSSM. The phenomenology, detector, trigger and reconstruction issues are briefly discussed.

1 Introduction

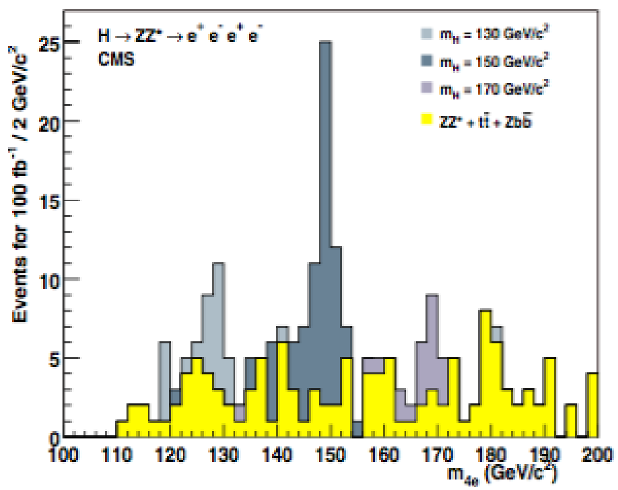
The studies for the Higgs bosons searches in CMS are mainly performed in the framework of the Standard Model (SM) and its Minimal Supersymmetric extension (MSSM). In the SM Higgs boson mechanism, the Higgs boson mass m_H is the only free parameter. The MSSM contains five Higgs bosons: the lighter scalar h, the heavier scalar H, the pseudoscalar A and the two charged bosons $H^{\pm}$. A general agreement is to present the MSSM parameter space as a function of the pseudoscalar mass m_A and the ratio $\tan\beta$ of the vacuum expectation values of the two Higgs boson doublets. For the SUSY parameters, the following values of the m_h^{max} scenario [1] (used in the LEP studies) are taken unless stated otherwise: M_2 = 1 TeV/c^2. The stop mixing parameter is defined as $X_t = A_t - \mu \cot\beta$, with A_t being the trilinear Higgs-stop coupling. In the m_h^{max} scenario the light Higgs mass reaches its maximal value at $X_t = \sqrt{6} \times M_{SUSY}$, where M_{SUSY} is the heavy SUSY scale. In this work, the value of A_t was fixed to $\sqrt{6} \times M_{SUSY}$ with M_{SUSY} = 1 TeV/c^2. Therefore, X_t varies between 2550 GeV/c^2 and 2454 GeV/c^2 for $2 < \tan\beta < 50$. With respect to the m_h^{max} scenario, this choice leads to a small deviation in m_h and in the final event rates for a given $\tan\beta$. The top mass is set to 175 GeV/c^2.

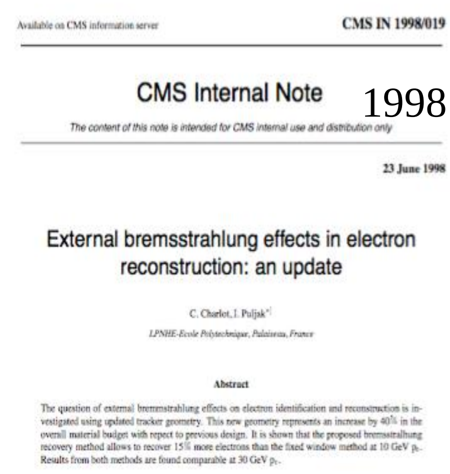
At tree level the h(H) mass is bound to be below(above) the Z boson mass but the radiative corrections, proportional to m_{top}^4, bring the upper (lower) bound to a significantly larger value. The one loop and dominant



- Many channels to look for, depending on Higgs mass
- $H \rightarrow ZZ \rightarrow 4l$ has high discovery potential, except for m_H<120 and m_H~170 GeV

- Realized very early that the efficiency of leptons detection would be the limited factor at low m_H
- Additional pb of electron bremsstrahlung in the tracker material





Available on CMS information server

CMS IN 1998/019

CMS Internal Note

1998

The content of this note is intended for CMS internal use and distribution only

23 June 1998

External bremsstrahlung effects in electron reconstruction: an update

C. Charlot, I. Puljak*[1]

LPNHE-Ecole Polytechnique, Palaiseau, France

Abstract

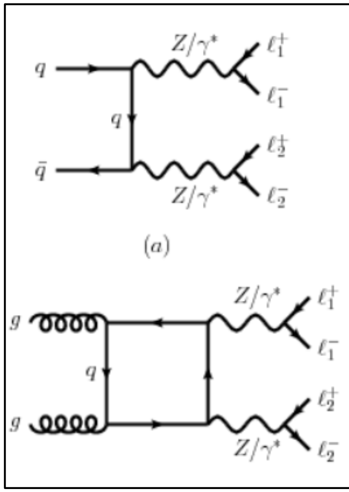
The question of external bremsstrahlung effects on electron identification and reconstruction is investigated using updated tracker geometry. This new geometry represents an increase by 40% in the overall material budget with repect to previous design. It is shown that the proposed bremsstralhung recovery method allows to recover 15% more electrons than the fixed window method at 10 GeV p_T. Results from both methods are found comparable at 30 GeV p_T.

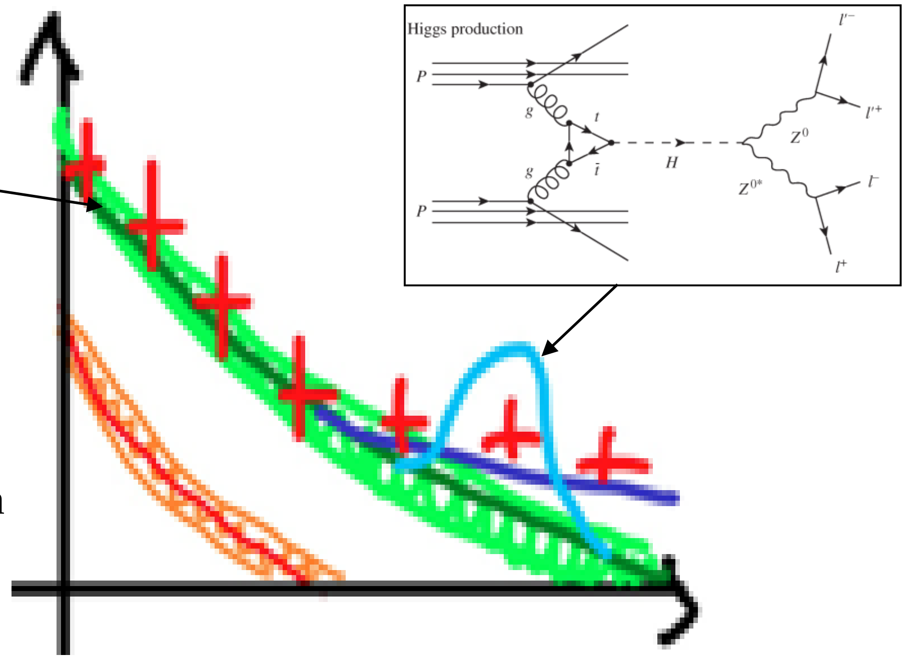
And also internal bremsstrahlung, see later..

The H → ZZ$^{(*)}$ → 4l channel

- **Simple analysis**: search for a localized excess in the four-lepton mass spectrum

Higgs signal





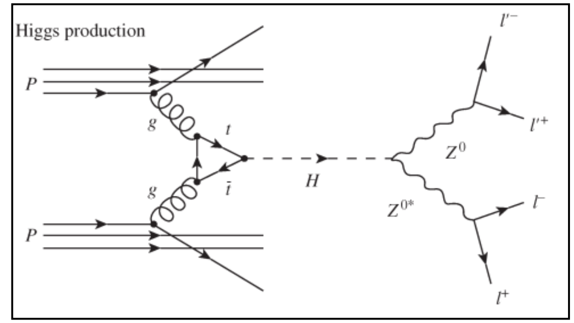
Background from non-resonant production
+ reducible background from WZ+jet,
Z+2jets where 1,2 jets fake a lepton

- Among the **cleanest** channels (S/B~1) over a wide mass range (m_H=120-800 GeV)
- But **low yield** from small BR(Z → ll)

=> should maximize detection efficiency, in particular at low m_H

The H → ZZ$^{(*)}$ → 4l channel

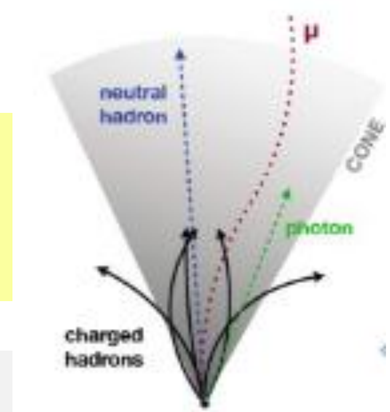
- Select events with **4 leptons** (e or μ), compatible with two $Z^{(*)}$
- Two opposite-sign same-flavour pairs with mass compatible with m_Z



signal

$$m_{ll} = \sqrt{2E_1E_2(1 - cos\theta_{12})}$$

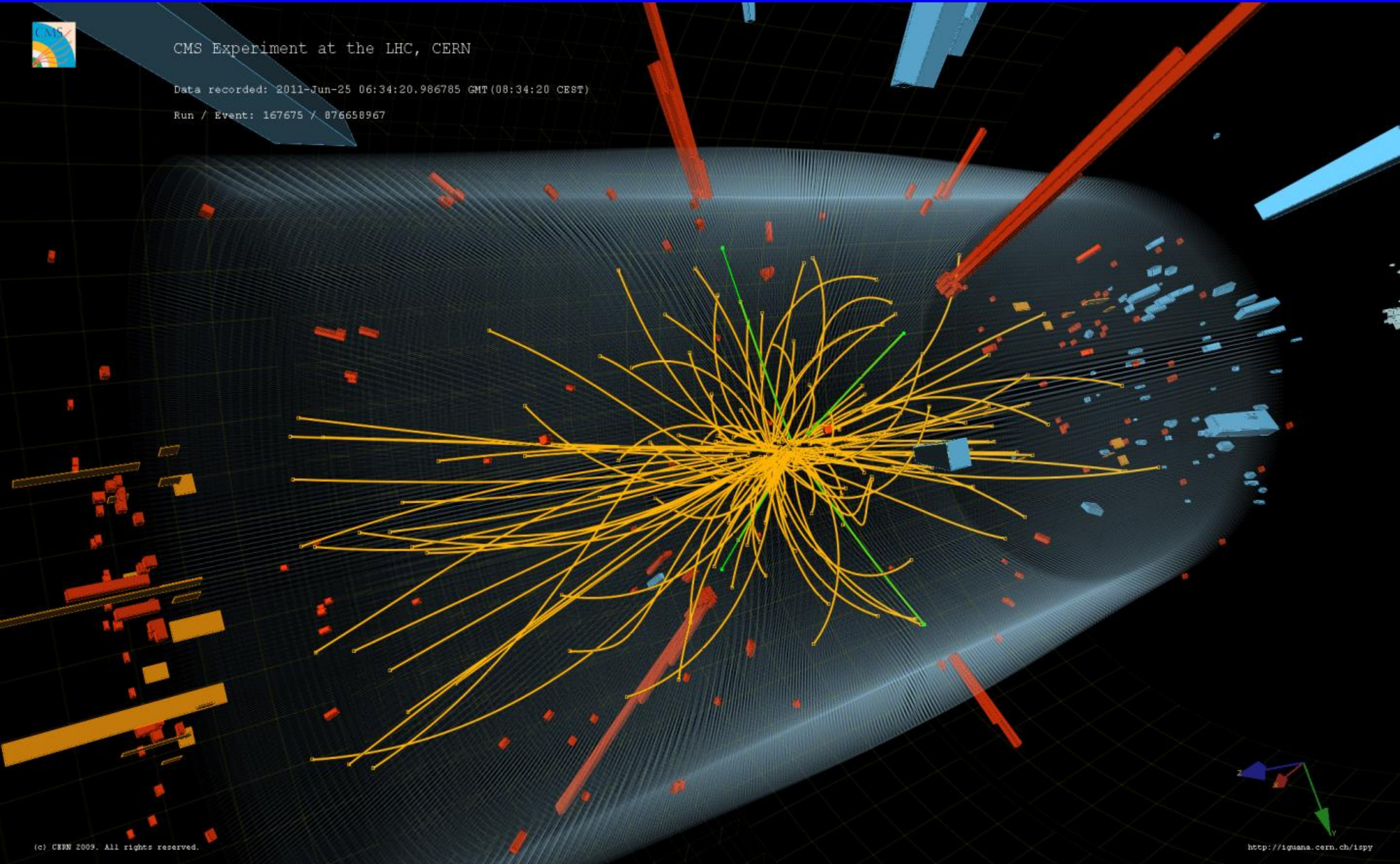
- Reject (reducible) WZ+jet and Z+2jets backgrounds where jet(s) fake(s) lepton(s) by requiring well **identified and isolated** leptons



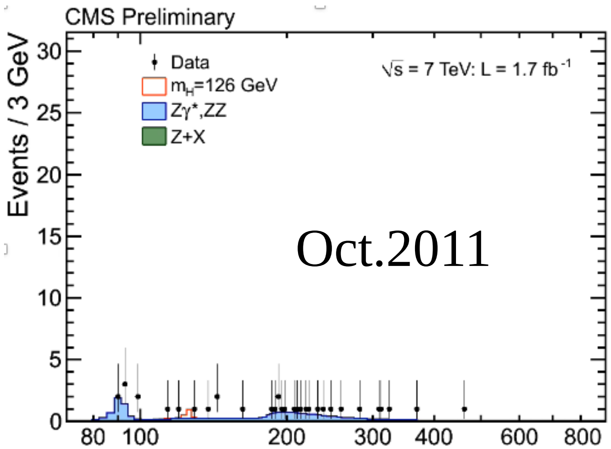
- **Data-driven** methods
  - Efficiency from Z → ll, WZ+jet and Z+jets backgrounds from data

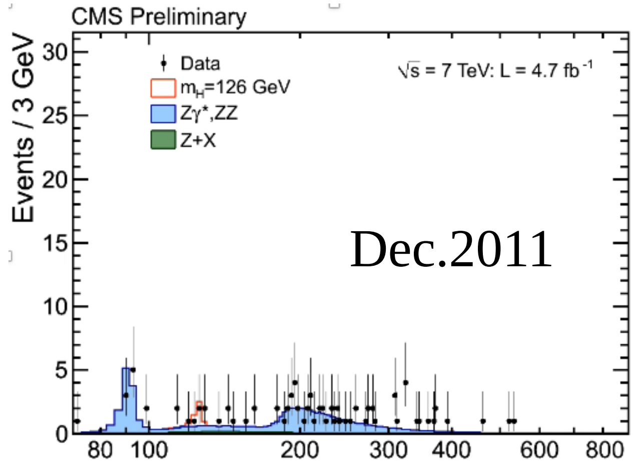
- **Analysis blind to the mass spectrum** in the search region up to preapproval and until efficiencies and background composition checked

A Higgs → 4l candidate event

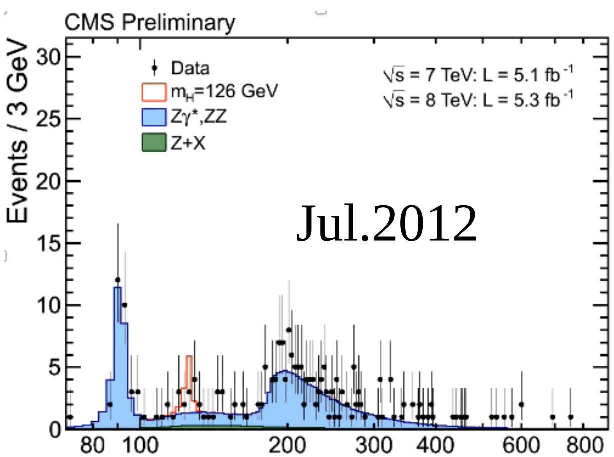


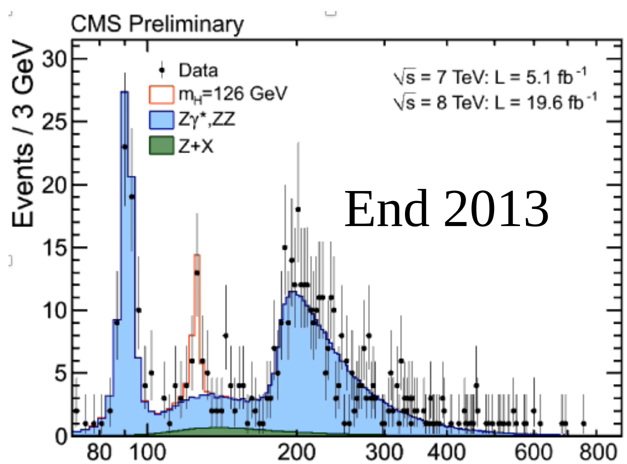
The growing signal

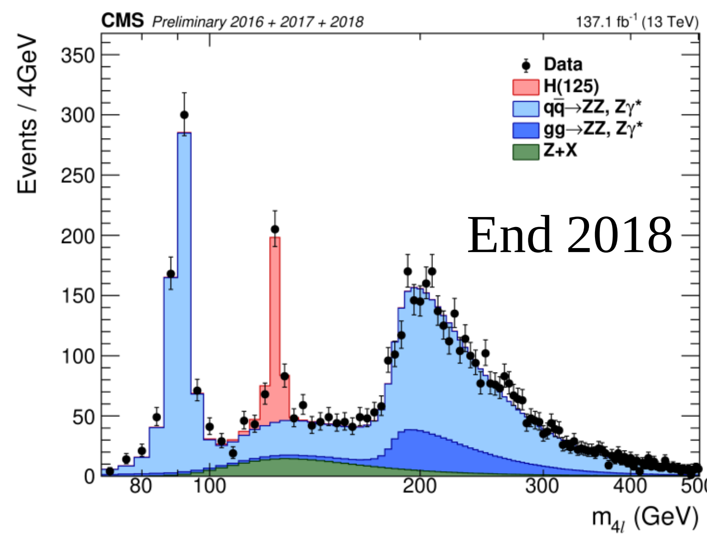




At the beginning only fluctuations here and there => more data needed!







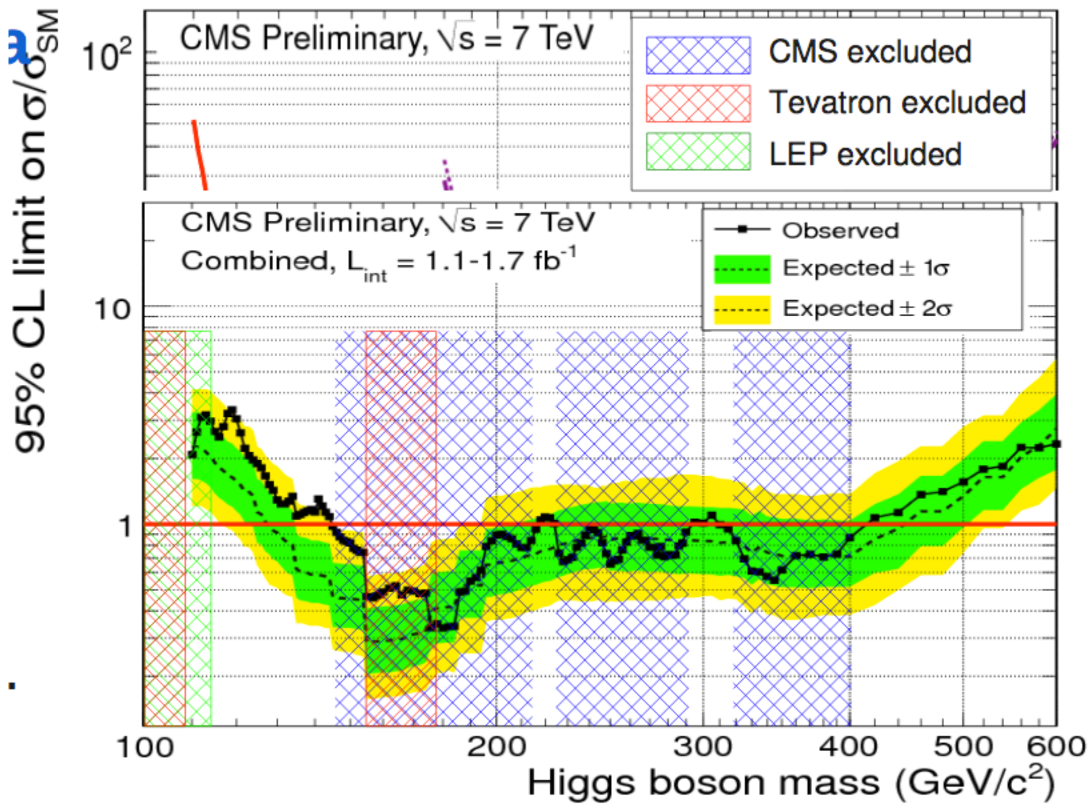
Accumulating data the signal started to show up, discovery announced in 2012 (together with other channels). Now the resonance is there and will stay forever.

HCP conference (nov. 2011)

- 1.1-1.7/fb in the combination from data up to summer
- ~5/fb planed by end of the year
- CMS and ATLAS preparing for discovery
- Agreement not to show updated result at HCP
- And to prepare a combination
- Results with the entire 2011 datasets to be shown at CERN jamboree in December

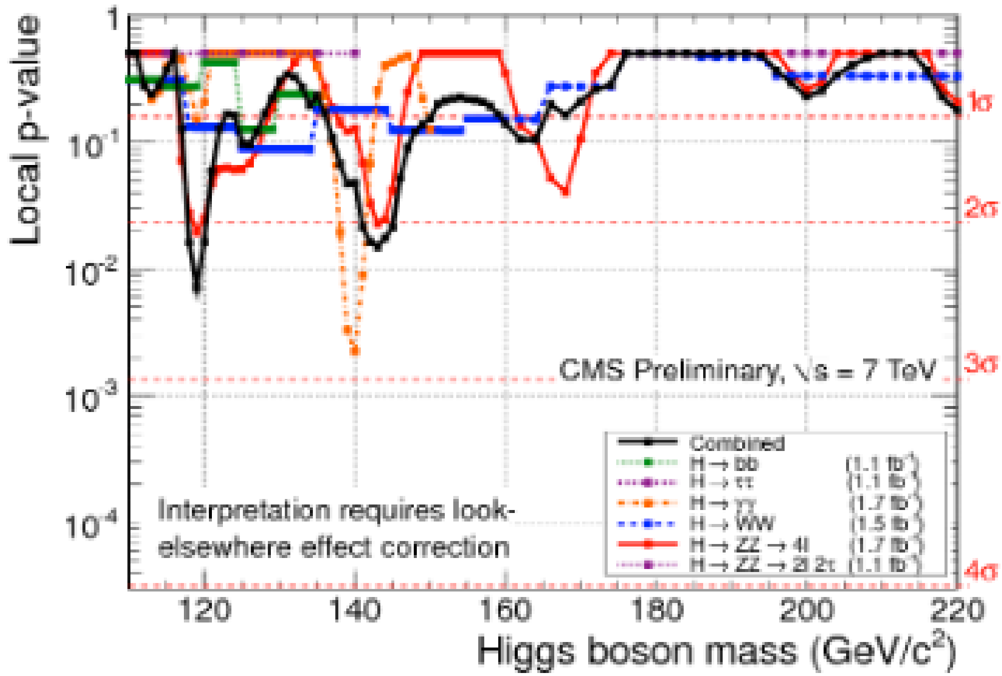
Combined limit (L = 1.1 – 1.7 fb^{-1})

• Solid – observed; dashed – expected

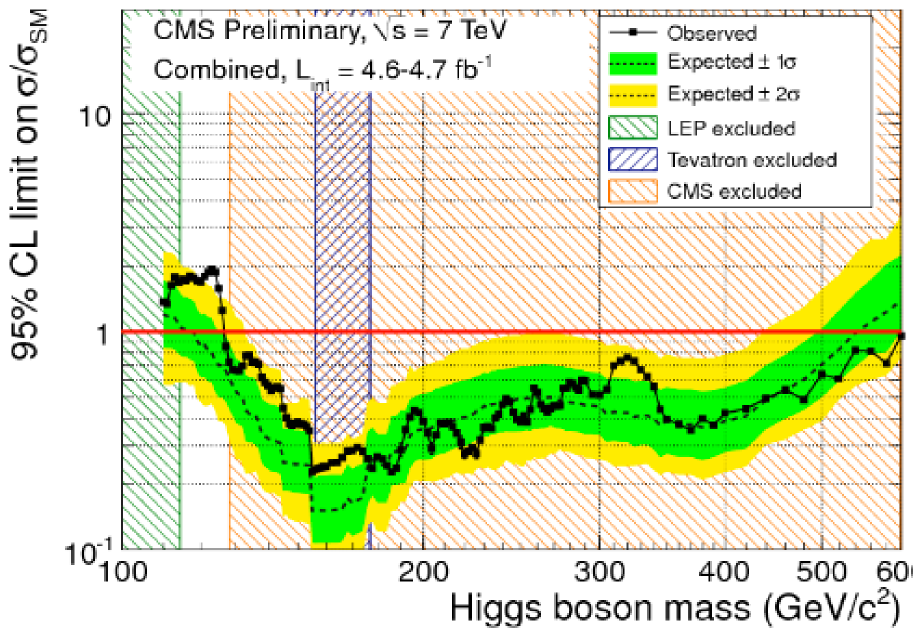


HCP conference (nov. 2011)

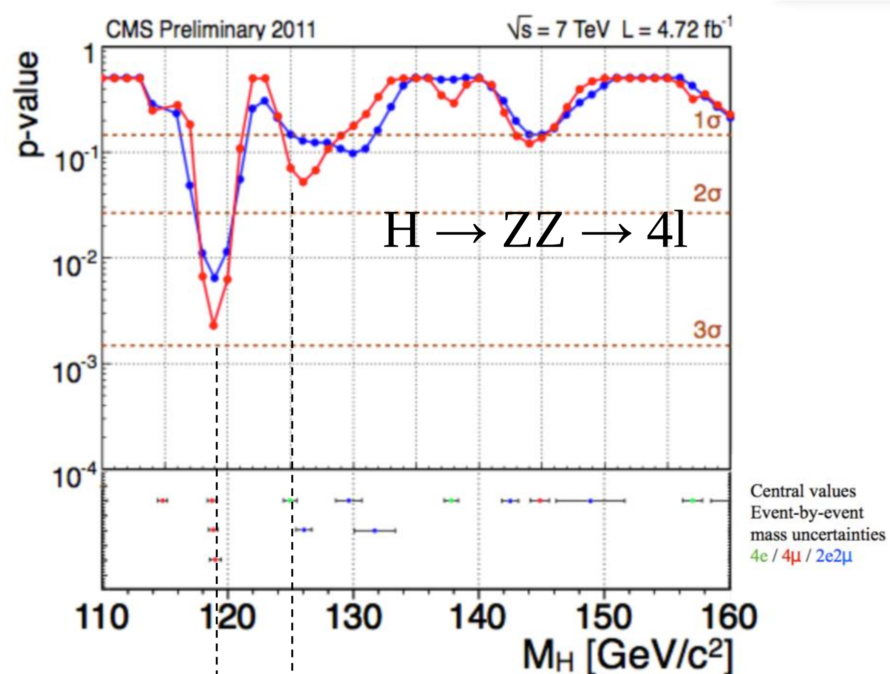
- >~2σ fluctuations at ~119 GeV and 140 GeV, but not significant
- That at ~119 GeV with rate consistent with expectation from SM Higgs…
- Full 2011 dataset being analyzed with x3-5 more statistics
- Exciting times!

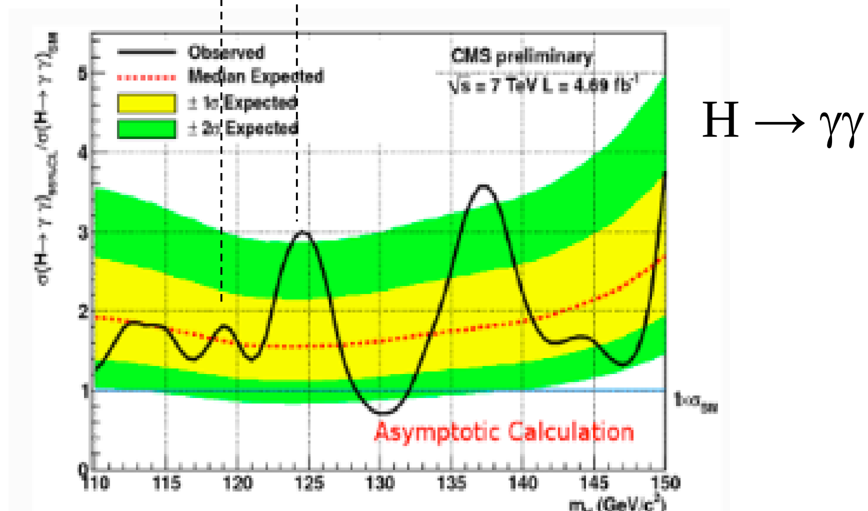


CERN december ‘11 jamboree



95% CL:	obs 127-600,	exp:117-543
99% CL:	obs 128-525,	exp:125-500



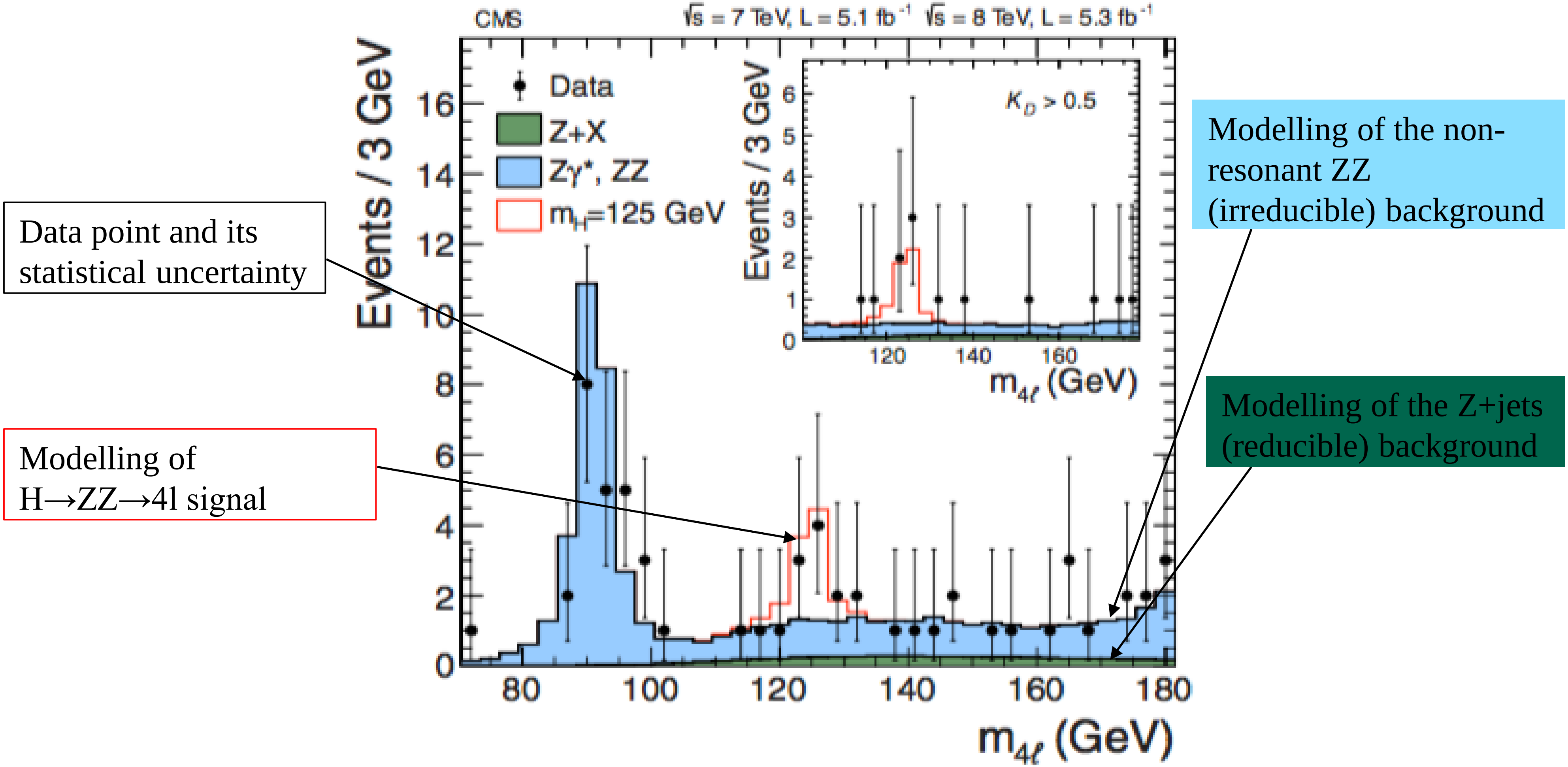


Mis-calibration pb? FSR?
Claude, are you there?
(phys. plenary meeting, Dec.1)

6 months later and ~3 months of 8 TeV data added

Discovery announced at CERN

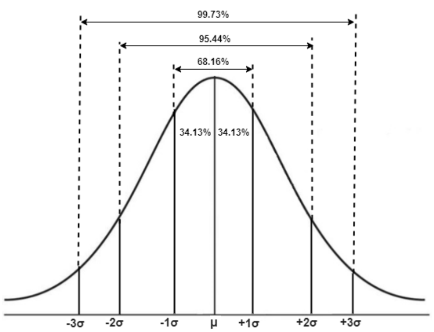
How do we extract the signal from data?

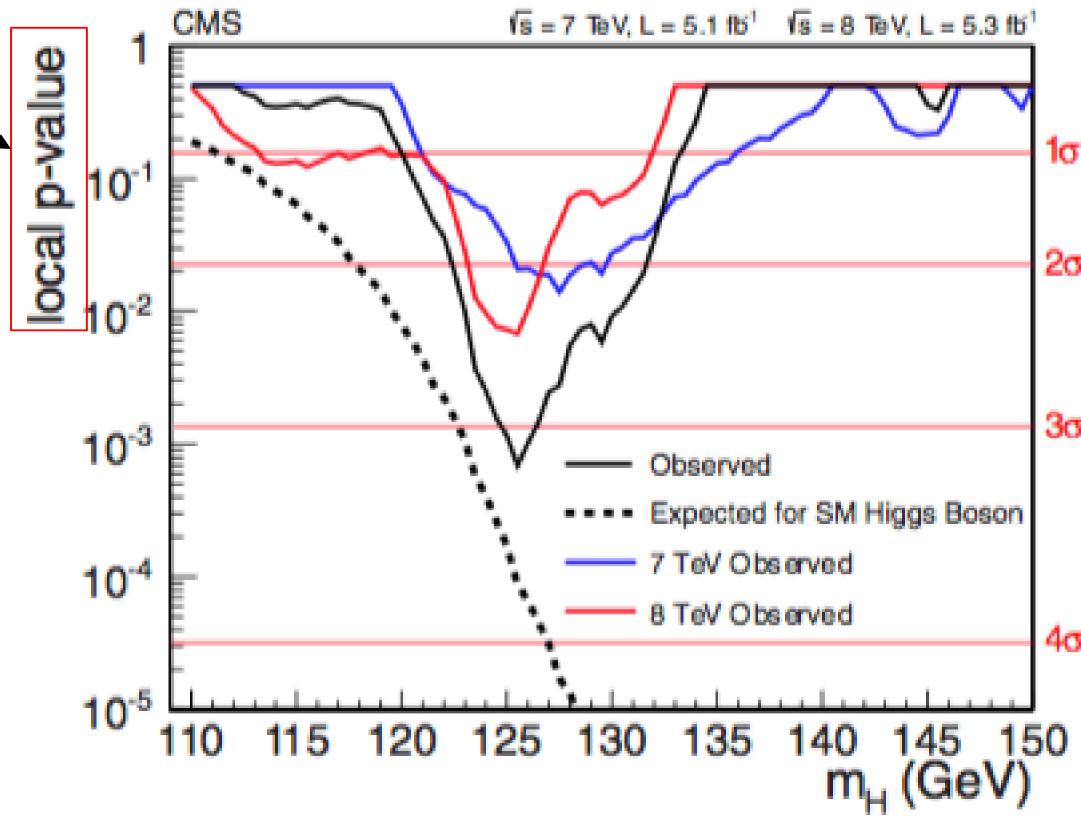


⇒ Around 125 GeV, **7 events in excess of backgrounds' predictions**, compatible with expectation from a Higgs signal. Is it enough? Need to quantify…

The Higgs discovery results

Probability that B accounts for the observed yields





Significance

⇒ In the excess region the probability that B only accounts for the observed data is very low..

⇒ The probability is often translated in Gaussian equivalents: 2σ=~5%, 3σ<~1%, … Here p_{min}~7.10^{-4}

⇒ Is this enough? No! HEP discovery requires 5σ, this is equivalent to p_{min}~0.3 per million for a false positive!!!

The Higgs discovery results

Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	2.7 ± 0.3	5.7 ± 0.6	7.2 ± 0.8	15.6 ± 1.4
$Z + X$	$1.2^{+1.1}_{-0.8}$	$0.9^{+0.7}_{-0.6}$	$2.3^{+1.8}_{-1.4}$	$4.4^{+2.2}_{-1.7}$
All backgrounds ($110 < m_{4\ell} < 160\,\mathrm{GeV}$)	4.0 ± 1.0	6.6 ± 0.9	9.7 ± 1.8	20 ± 3
Observed ($110 < m_{4\ell} < 160\,\mathrm{GeV}$)	6	6	9	21
Signal ($m_H = 125\,\mathrm{GeV}$)	1.36 ± 0.22	2.74 ± 0.32	3.44 ± 0.44	7.54 ± 0.78
All backgrounds (signal region)	0.7 ± 0.2	1.3 ± 0.1	1.9 ± 0.3	3.8 ± 0.5
Observed (signal region)	1	3	5	9

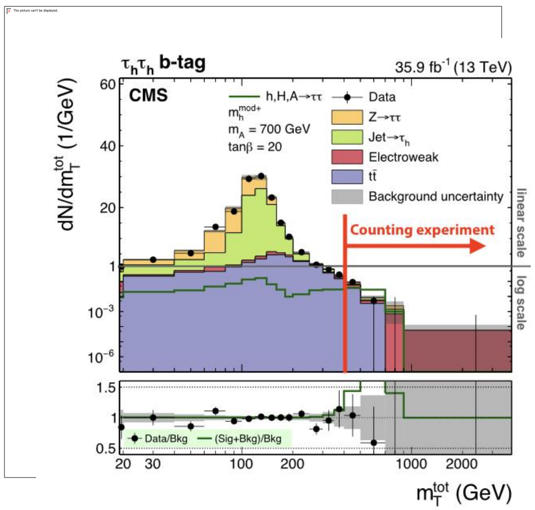
Remind: simple counting experiment, ΔN=sqrt(N) (only in the region of large N, else ΔN>sqrt(N))

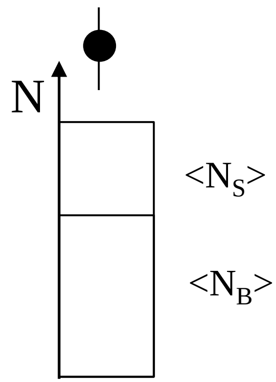
⇒ In the signal and background regions, observed yields are compatible with expectations from S+B in all subchannels 4e/2e2mu/2mu2e/4mu

⇒ Are they incompatible with expectations from B only?

More on Significance

- Simple example: counting experiment
- Assume we expect $\langle N_S \rangle$ signal events, $\langle N_B \rangle$ bkgd events
- Both S and B fluctuate and we measure only the sum: $N_{data}=N_S+N_B$
- Actual N_S and N_B in the measurement are unknown
- Approximate (Gaussian) significance:
- Exp.: significance = $\langle N_S \rangle/\Delta N_B = \langle N_S \rangle / \sqrt{\langle N_B \rangle}$
- Obs. Significance = $(N_{data} - \langle N_B \rangle)/\Delta N_B = (N_{data} - \langle N_B \rangle) / \sqrt{\langle N_B \rangle}$

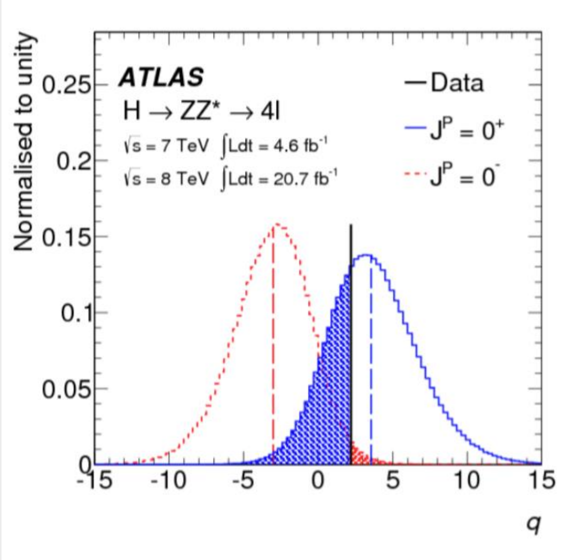




⇒ Only valid when N_S and N_B are high (>~10) for $\Delta N=\sqrt{N}$ to apply

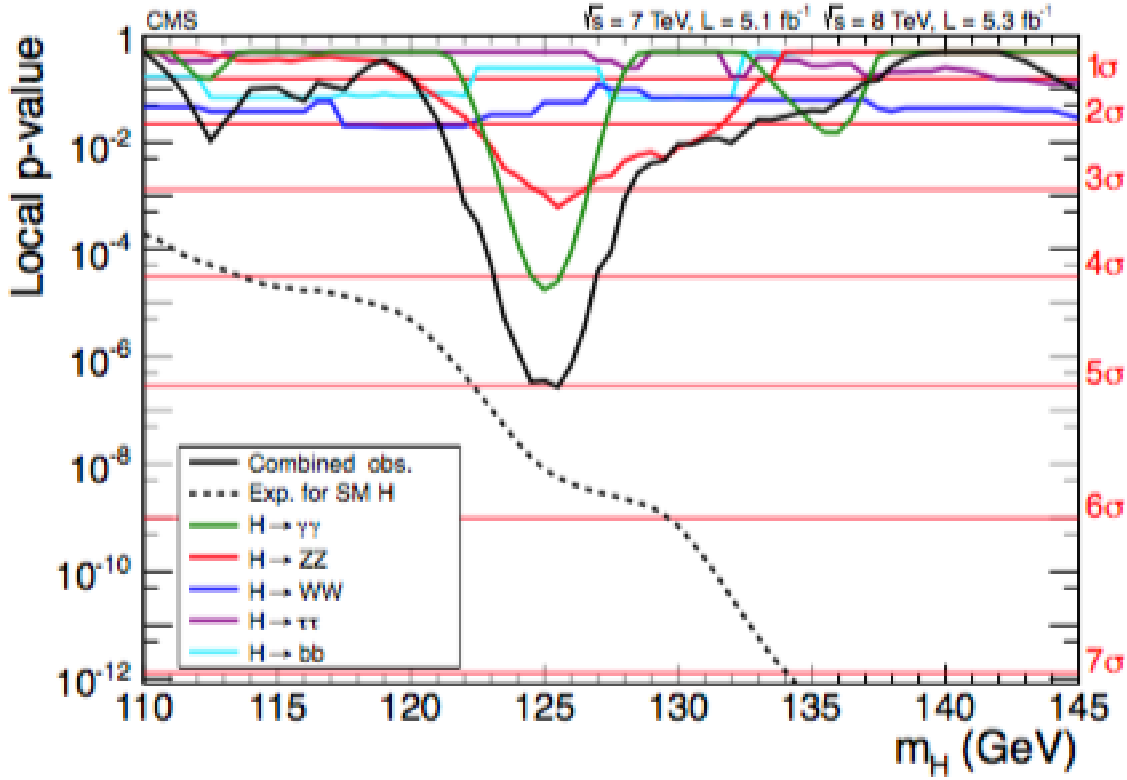
A better significance: log-likelihood ratio

- Likelihood function $\mathcal{L}$ measures the goodness of a fit to the data (N)
  - For Poisson probability, $\mathcal{L}$ is $\exp(-\lambda)\lambda^N$, where $\lambda = \langle N \rangle$ is the expectation (from model)
  - $\mathcal{L}$ for bkgd is $\exp(-\langle N_B \rangle) \langle N_B \rangle^N$
  - $\mathcal{L}$ for S+B is $\exp(-\langle N_S+N_B \rangle) \langle N_S+N_B \rangle^N$
- Likelihood ratio $Q = \exp(-\langle N_S+N_B \rangle) \langle N_S+N_B \rangle^N / \exp(-\langle N_B \rangle) \langle N_B \rangle^N$
  - so that $\ln Q = -\langle N_S \rangle + N \ln (1+\langle N_S \rangle/\langle N_B \rangle)$
- Significance = $\sqrt{(-2\ln Q)}$
  - Exp. Significance: $\ln Q = -\langle N_S \rangle + \langle N_S+N_B \rangle \ln (1+\langle N_S \rangle/\langle N_B \rangle)$
- If several bins:
- $\mathcal{L} = \Pi \ \mathcal{L}_i$ (independent probabilities)
  - $\ln Q = -\langle N_S \rangle + N \Sigma \ln (1+\langle N_S \rangle^i/\langle N_B \rangle^i)$



⇒ Formula more accurate and easily extended to many (independent) channels/bins
⇒ Each channel/bin contributes with weight: $\ln (1+\langle N_S \rangle^i/\langle N_B \rangle^i)$
⇒ Formalism also allows to include systematic uncertainties (not discussed here)

The Higgs discovery results



⇒ Combining with the other channels (and in particular H→γγ), we now get 5σ
⇒ Each channel contribute with his own sensitivity
⇒ Note: the observed sensitivity (p-values) are shown here individually, comparison of channels performance should be based on expected sensitivity (Asimov dataset)

Interlude: the HX (no) discovery result

- In mars 2019, a french immunologist and his team, who had forgotten their statistical lectures, pretended that HydroxyChloroquine (HQ) was able to cure Covid19
- HQ treatment: 14 patients
- HQ+Azythromicyn: 6 patients
- Wants to measure benefit of treatments when $<N_B>$ = ~80% (~90-95% if considering those patients in ICU, i.e. who need respiratory assistance)
- Q: what is the p-value here assuming all the 6 patients treated with HQ+A got cured? **Does it satisfies HEP discovery standards?**

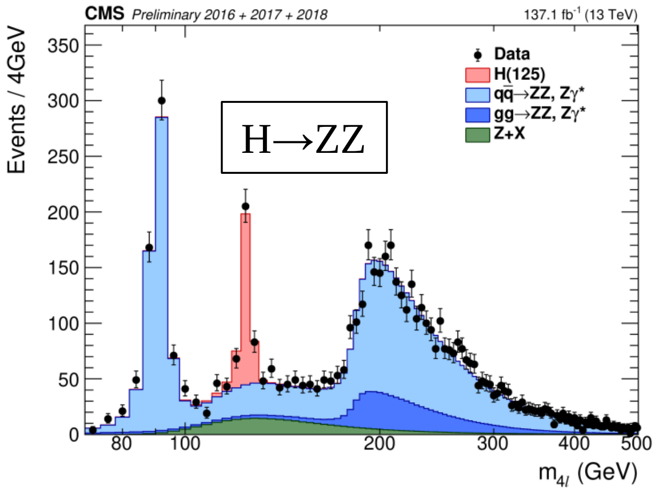
Hydroxychloroquine and azithromycin as a treatment of COVID-19: results of an open-label non-randomized clinical trial

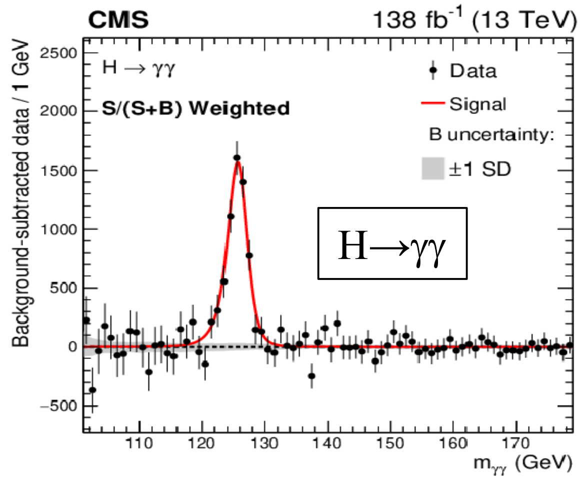
Philippe Gautret[a,b$], Jean-Christophe Lagier[a,c$], Philippe Parola[a,b], Van Thuan Hoang[a,b,d], Line Meddeb[a], Morgane Mailhe[a], Barbara Doudier[a], Johan Courjon[e,f,g], Valérie Giordanengo[h], Vera Esteves Vieira[a], Hervé Tissot Dupont[a,c], Stéphane Honoré[i,j], Philippe Colson[a,c], Eric Chabrière[a,c], Bernard La Scola[a,c], Jean-Marc Rolain[a,c], Philippe Brouqui[a,c], Didier Raoult[a,c*].

Despite its small sample size our survey shows that hydroxychloroquine treatment is significantly associated with viral load reduction/disappearance in COVID-19 patients and its effect is reinforced by azithromycin.

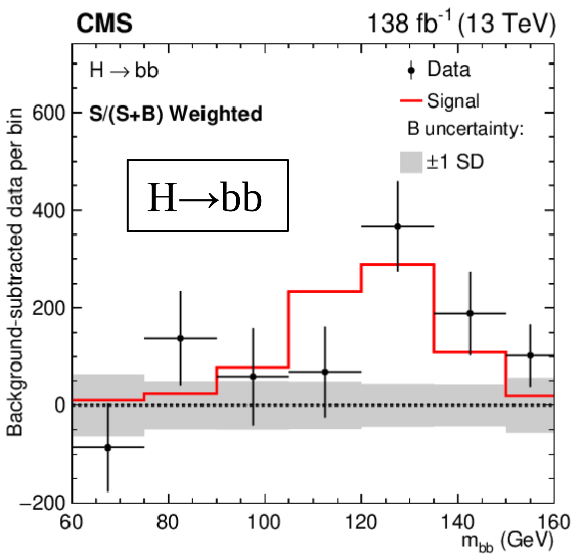
⇒ In low statistic processes one must be very careful before claiming a discovery
⇒ A background event can mimic a discovery, even if rare!
⇒ There is no other solution than to require a very low p-value, set based on the number of times you would have claimed wrongly for a discovery
⇒ 5σ is the adopted convention in HEP (though there are some physicists arguing it is not sufficiently low..)

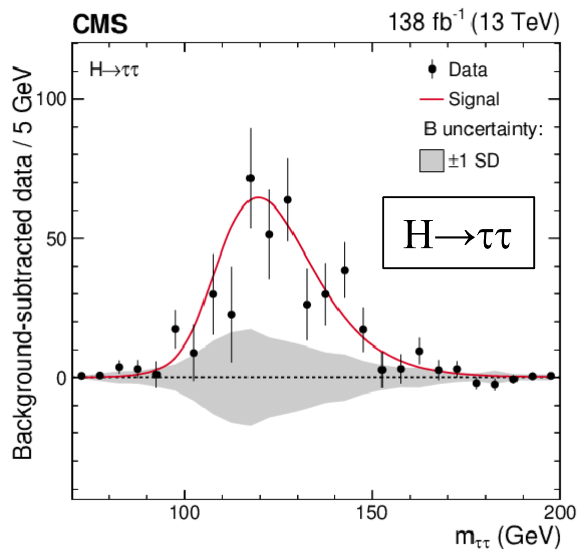
10 years after the discovery

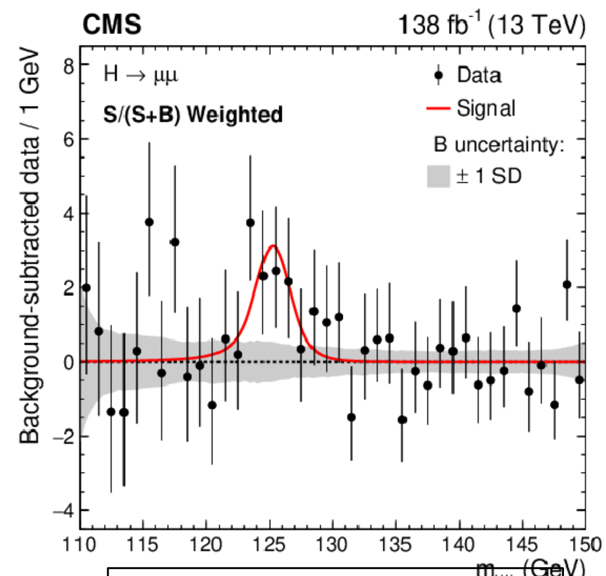




The Higgs is observed and measured now in many decay channels (also H→WW)





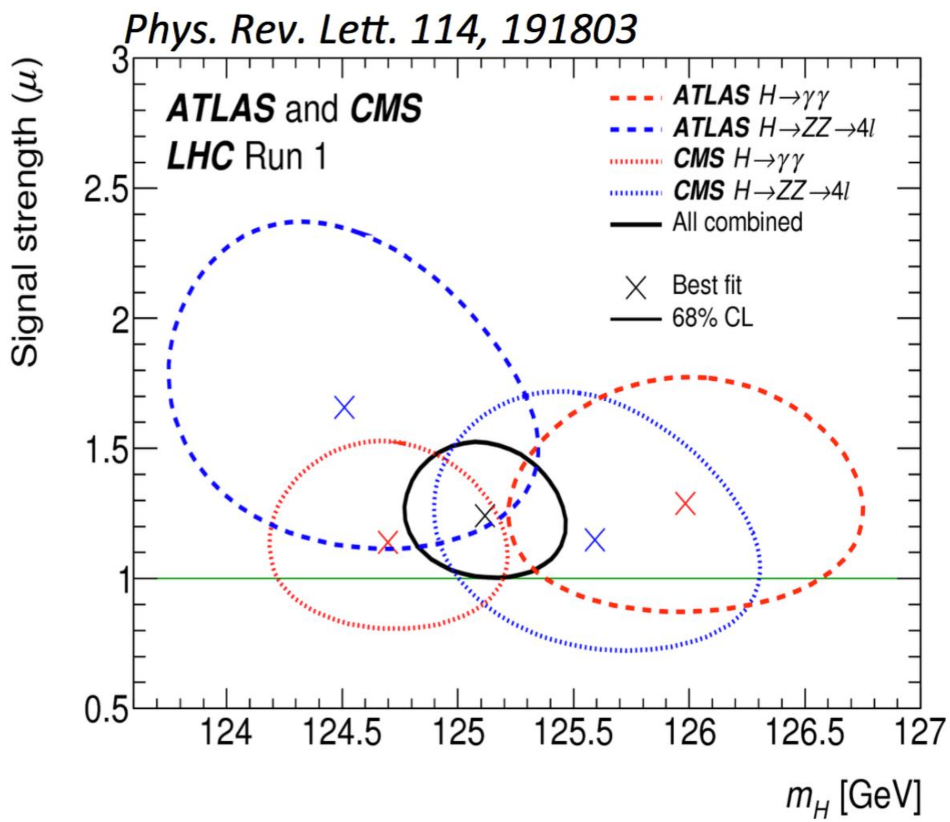


3σ evidence in H→ μμ!

Higgs mass

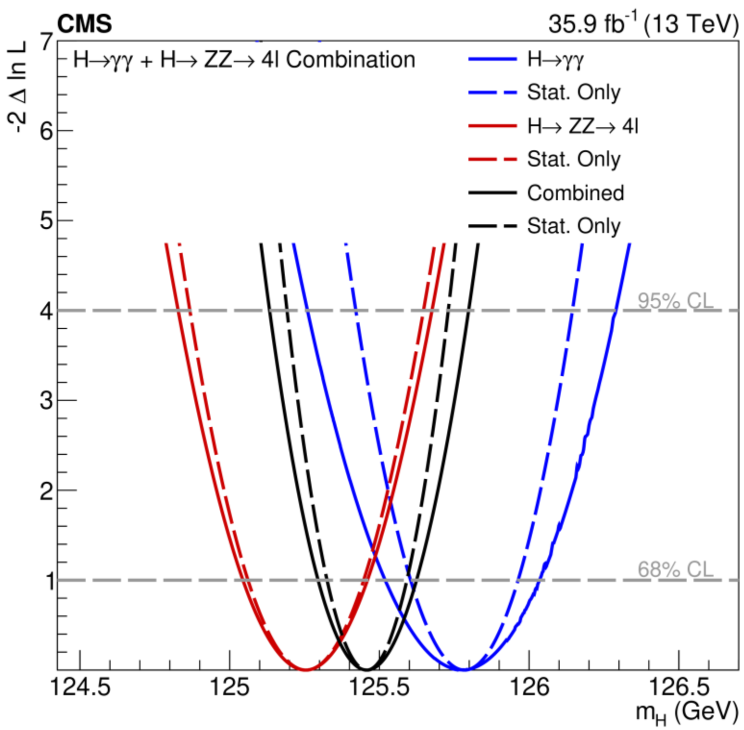
- The **only free** parameter of the Higgs (minimal) Lagrangian

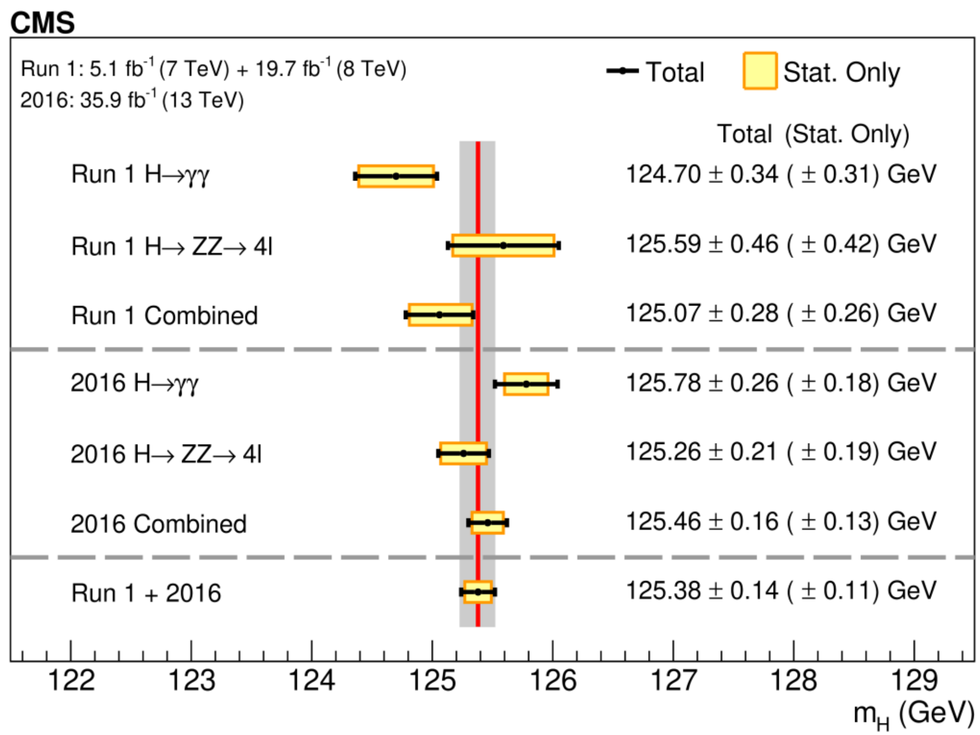
Result from Run I ATLAS+CMS combination



$$m_H = 125.09 \pm 0.24 \text{ GeV} = 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst) GeV}$$

Higgs mass (CMS 2016)

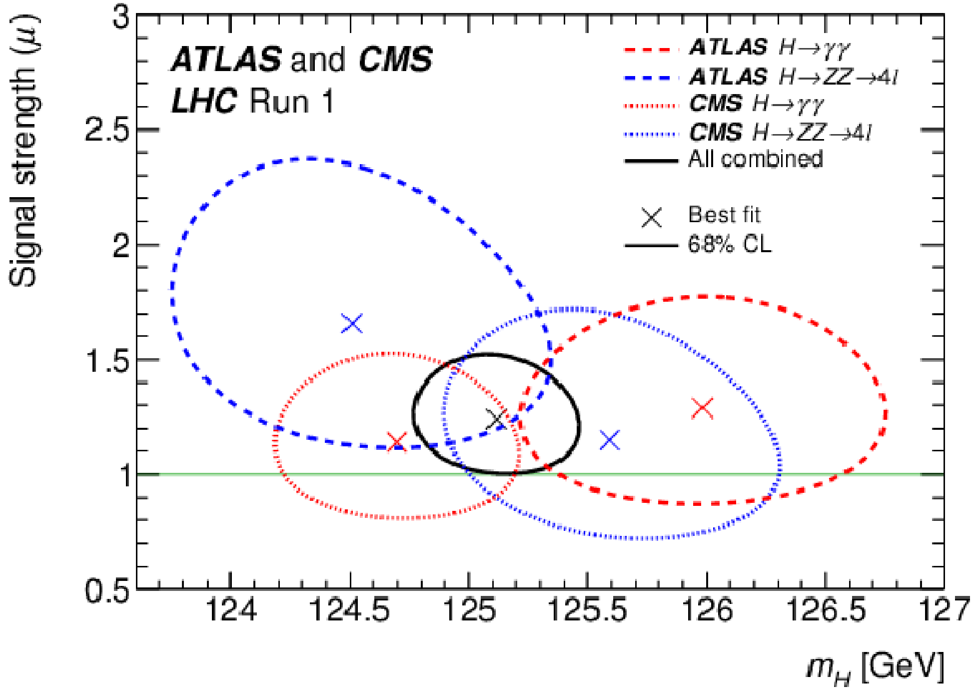




m_H = 125.38 +/- 0.11 (stat) +/- 0.08 (syst) GeV

Results from CMS Run I +2016 (run II) data

Higgs mass (CMS + ATLAS2016)

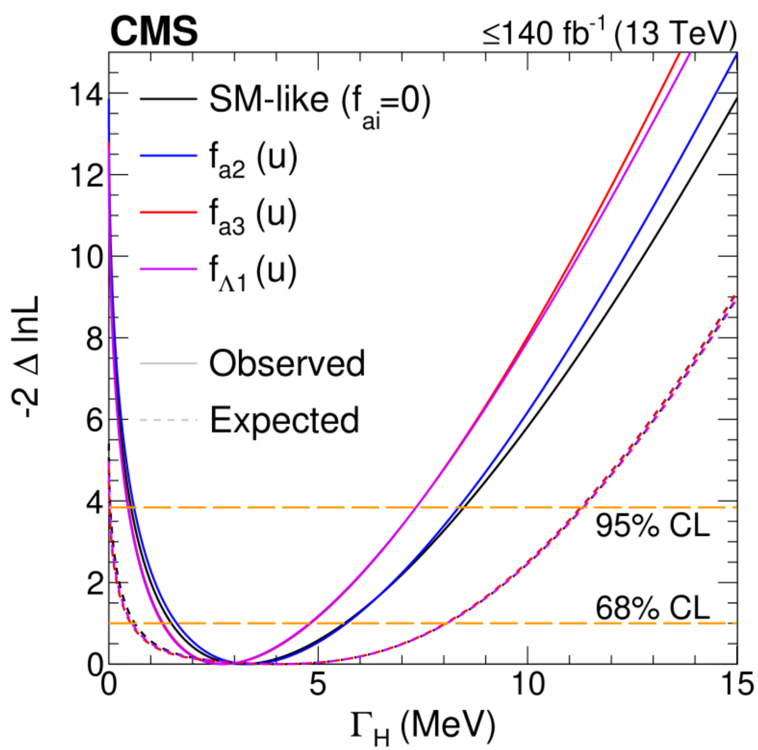


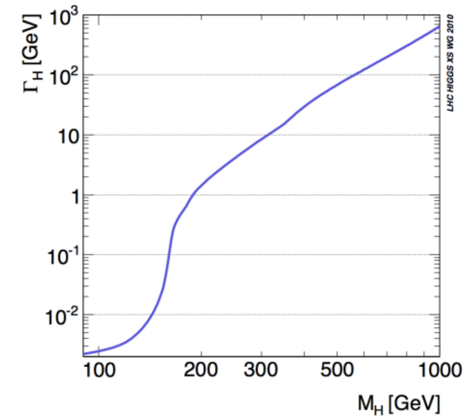
m_H = 125.38 +/- 0.11 (stat) +/- 0.08 (syst) GeV

Results from CMS Run I +2016 (run II) data

Higgs width

- The decay width is a fundamental parameter
  - Relates to the couplings to all (massive) particles in the spectrum, therefore sensitive to BSM physics and dark matter

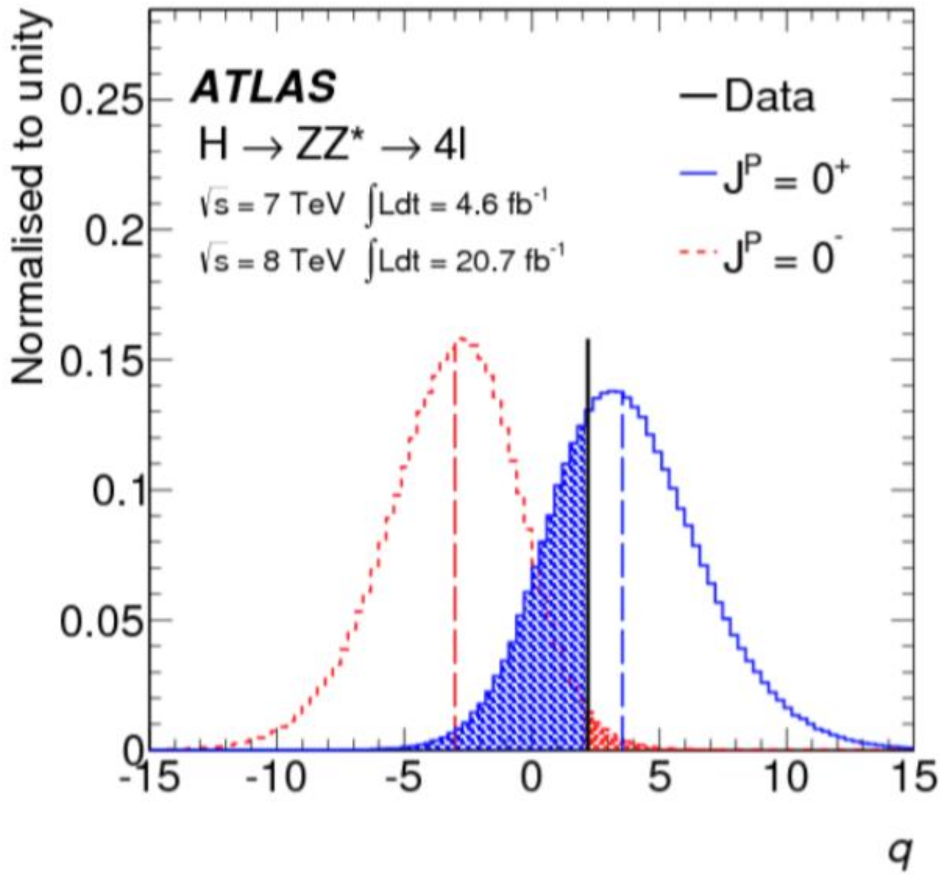




Measured $\Gamma_H=3.2^{+2.4}_{-1.7}$ MeV, [0.5-8.5] MeV at 95% CL
+ Various constraints with fitted anomalous couplings

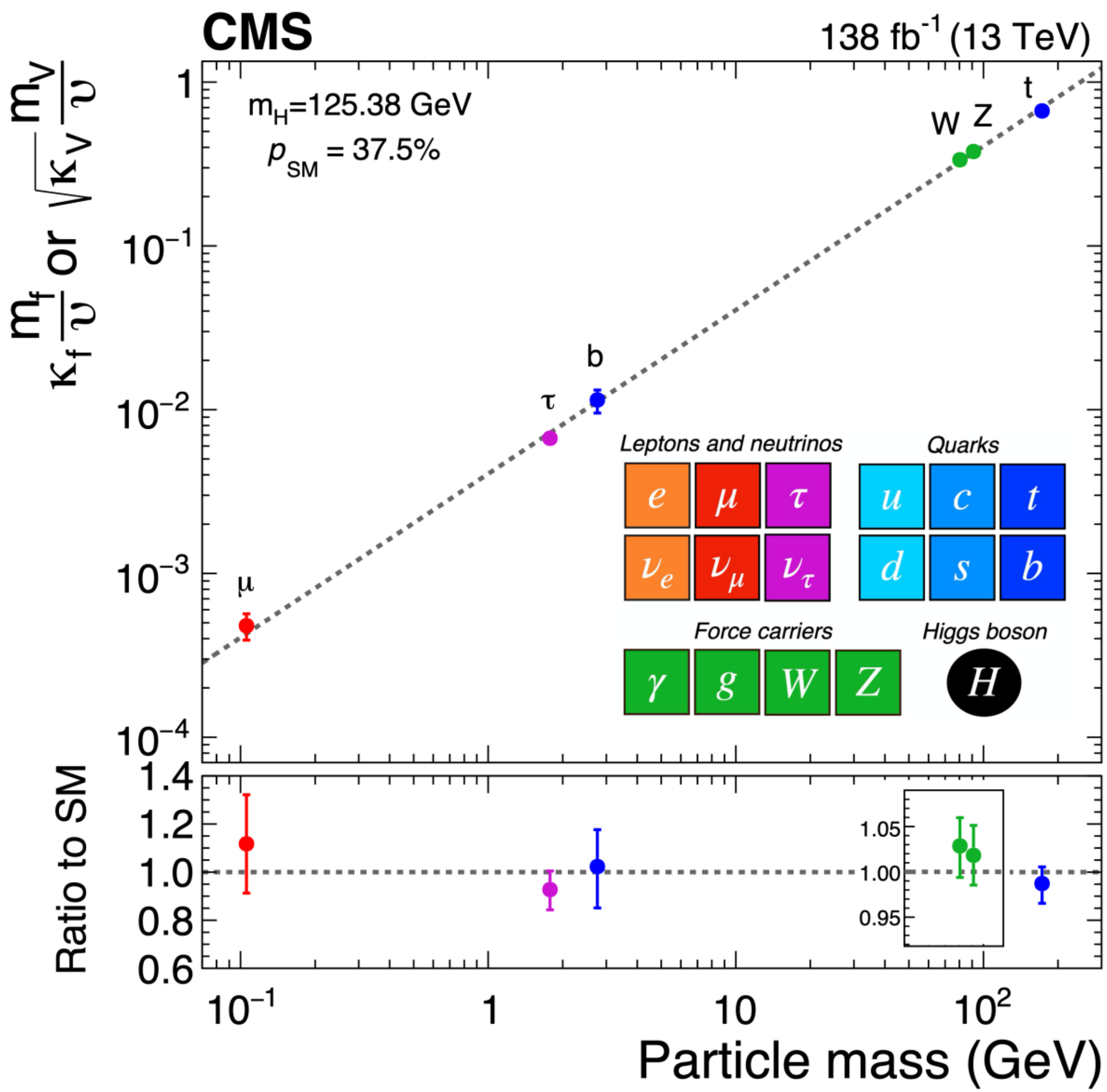
- Experimental resolution far off for a direct measurement
  - $\sigma_m/m \sim 1\%$ for $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ and m_H~4 MeV
- **New idea**: use off-shell production to constrain the Higgs decay width

Higgs Spin - parity



$J^P = 0^-$, 1+, 1-, 2+, .. excluded at >97.8% CL

Higgs Couplings



Most solid proof that the new particle is the Higgs boson

Uncertainties not better than ~10% though => room for discoveries!

Intermediate summary

- Higgs was discovered in 2012 based on ~5/fb at 7 TeV and ~5/fb at 8 TeV
- At the end of the run II we now have ~14 times more statistics at 13 TeV
- Statistical methods are used to quantify the excess and extract the key properties of the new particle: mass, spin, width, couplings from the data
- The Higgs boson is now seen in multiple decay channel at the 5σ level, and an observation in the extremely challenging $H \rightarrow \mu\mu$ channel is in reach
- So far all measurement are consistent with a SM Higgs
- Although with uncertainties of at best 5-15%

Going beyond: important unanswered questions

Data driven:

- Dark matter in the universe
- Neutrino masses, Dirac or Majorana neutrinos?
- Why do we observe more matter than antimatter in the universe, if there is a symmetry between the two?
  - New in 2020: evidence for CP violation in the ν sector!
- …

Theory driven:

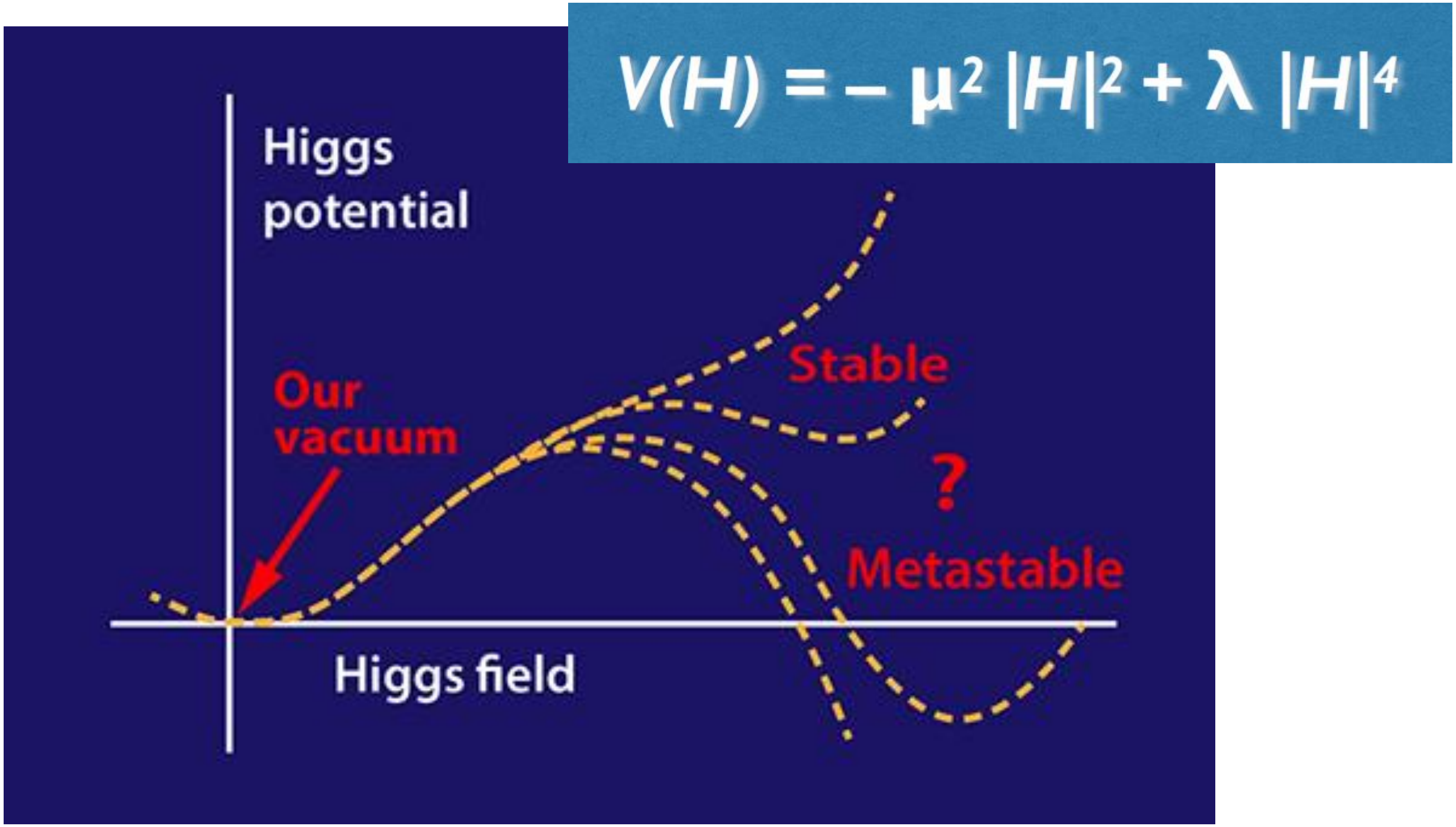
- Are quarks and leptons fundamental, or made up or more fundamental particles?
- How to include gravity?
- Why are there exactly three generations of quarks and leptons?
- Instability of the Higgs mass (naturalness and hierarchy problems)
- ...

How to deal with these questions?

- None have a clear path to answer (contrary to the case of EWSB)
- DM could be from 10^{-22} GeV scalars to O(TeV) WIMPs, axions or primordial BHs
- Neutrino masses could originate anywhere between the EW and GUT scales
- Still in the process of acquiring basic knowledge about neutrino sector: mass hierarchy, Majorana nature, sterile neutrinos, CP violations, ..
- No clear hierarchy from theory side although it is likely that several questions are tied together and will find answer in a common context (eg DM and hierarchy problem)

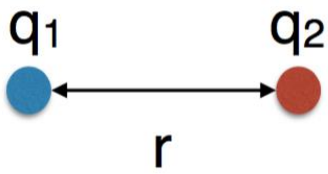
$\Rightarrow$ But one question has emerged from LHC run I-II, and points to a unique and well-defined direction…

The "immediate" next question



Where does it come from?

Electromagnetic vs Higgs dynamics

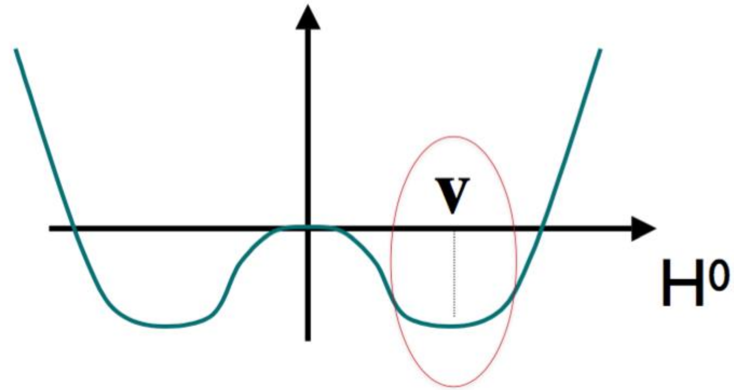


$$V(r) = + \frac{q_1 \times q_2}{r^{1}}$$

quantized, in units of fixed charge

sign fixed by photon spin

power determined by gauge invariance/charge conservation/Gauss theorem



any function of $|H|^2$ would be ok wrt known symmetries

$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

both sign and value totally arbitrary

>0 to ensure stability, but otherwise arbitrary

THE take away

- Aside from historical moments, experimental research is not about proving a theory is right or wrong, it is about finding how nature works
- We do not measure the Higgs couplings to find deviations from the SM but to know them
- Precision per se is not necessarily justified but currently we don't really know how important is a given measurement to build the future understanding
- The day a BSM signal is found, the precise coupling measurements will be crucial to establish the nature of the signal

$\Rightarrow$ At HL-LHC we will:

1. measure the H couplings to o(2-5%)
2. first assess the λ parameter of the Higgs potential
3. first assess EWSB though longitudinal VBS

$\Rightarrow$ A next machine is needed (eg FCC):

1. to measure with the best possible precision the Higgs and EWSB properties
2. to extend the mass reach of direct search by ~an order of magnitude

Additional slides

Lagrangien, symmetries and EWSB

This construction started back in the XVIIIth century!

Lagrangian in classical mechanics

- The equations of motion of a system can be derived from a scalar **Lagrangian** function of **generalized coordinates** and **time derivatives** of the coordinates (velocities)

$$L(q, \dot{q}) = T - V$$

- And from Euler-Lagrange equations

$$\frac{\partial L}{\partial q_j} - \frac{d}{dt}\frac{\partial L}{\partial \dot{q}_j} = 0$$

(from Hamiltonian variational principle)

Lagrangian in classical mechanics

- For a particle in a conservative potential V, the Lagragian is

$$L = \frac{1}{2}m(\dot{x}^2 + \dot{y}^2 + \dot{z}^2) - V(x, y, z)$$

So the derivatives are (here for x)

$$\frac{\partial L}{\partial x} = -\frac{\partial V}{\partial x}, \frac{\partial L}{\partial \dot{x}} = m\dot{x}, \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) = m\ddot{x}$$

and Euler-Lagrange's equations

$$\frac{\partial L}{\partial q_j} - \frac{d}{dt}\frac{\partial L}{\partial \dot{q}_j} = 0$$

finally give us the usual second Newton's law

$$m\ddot{x} = -\frac{\partial V}{\partial x}, m\ddot{y} = -\frac{\partial V}{\partial y}, m\ddot{z} = -\frac{\partial V}{\partial z} \Leftrightarrow m\vec{a} = \vec{F}$$

Symmetries and conserved quantities

- Noether's theorem: "to each infinitesimal transformation that leaves the Lagrangian invariant corresponds a quantity that is conserved in time"
- Simple case: coordinates not explicitly appearing in the Lagrangian => invariant under a continuous transformation of the coordinates
- Example: mass m orbiting in the gravitational field of a fixed mass M

$$L(r,\phi,\dot{r},\dot{\phi}) = T - V = \tfrac{1}{2}m\dot{r}^2 + \tfrac{1}{2}mr^2\dot{\phi}^2 + \frac{GMm}{r}$$

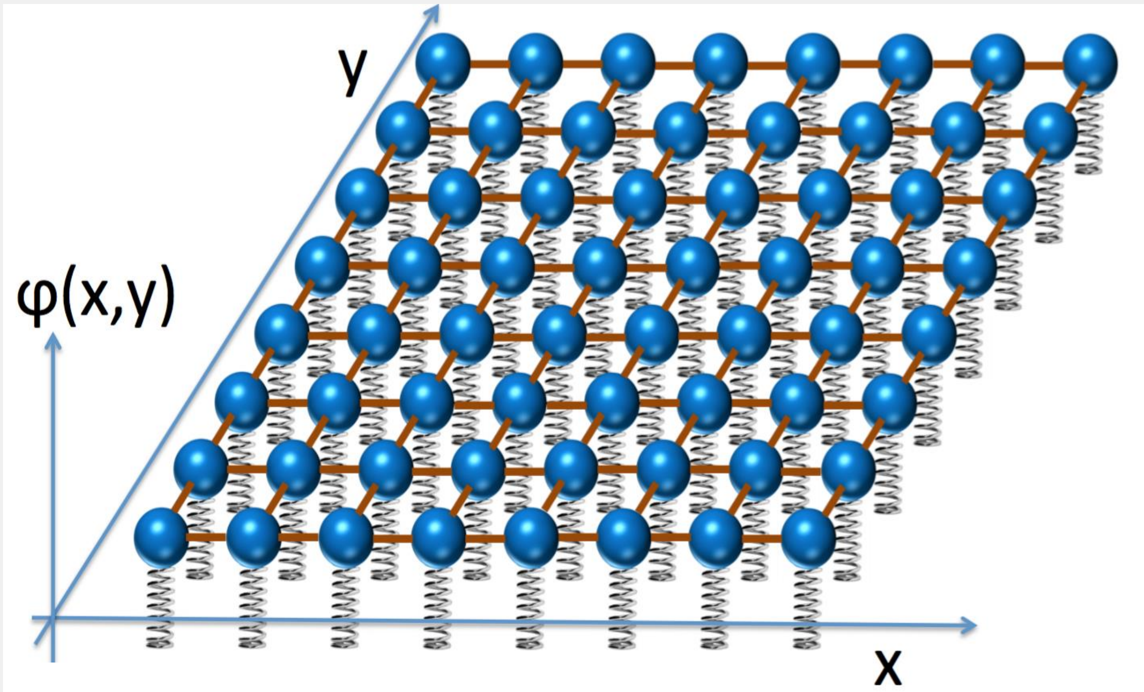
- Since the Lagrangian doesn't depend explicitly on ϕ (symmetry with respect to space rotations), the Euler-Lagrange equations give

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\phi}}\right) = 0 \Leftrightarrow \frac{\partial L}{\partial \dot{\phi}} = mr^2\dot{\phi} = J$$

- So that the angular momentum J is a constant of motion!

In quantum mechanics

- ❑ Imagine space as a continuum of springs and balls connected with its neighbors by elastic bands



=> Particles are excitation of the field

- ❑ Quantum fields allows to account for both QM and SR basic principles

In quantum field theory

- Generalized coordinates are now fields (each spring becomes a field)

$$q_i \rightarrow \phi_i(x^\mu)$$

- In a relativistic theory one must treat space and time on equal footing, so the derivatives in the classical equations are now

$$\frac{d}{dt}, \nabla \rightarrow \partial_\mu = (\frac{\partial}{\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z})$$

- Instead of Lagrangian we have a Lagrangian density (we also call it Lagrangian to make things more confusing ☺)

$$L(q_i, \frac{dq_i}{dt}) \rightarrow \mathcal{L}(\phi_i, \partial_\mu \phi_i) \quad \text{with:} \quad L = \int \mathcal{L} d^3x$$

- The new Euler-Lagrange equation becomes

$$\partial_\mu (\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_i)}) - \frac{\partial \mathcal{L}}{\partial \phi_i} = 0$$

Gauge invariance

- Consider the Dirac Lagrangian for a spinor field Ψ representing a spin-1/2 particle, for instance an electron

$$\mathcal{L} = i\hbar\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi$$

- It is invariant under a global gauge transformation like

$$\psi(x) \rightarrow \psi'(x) = e^{iq\chi}\psi(x)$$

- Where χ is constant

$$\mathcal{L}' = e^{-iq\chi}e^{iq\chi}(i\hbar\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi) = \mathcal{L}$$

Local gauge invariance

- If χ depends on the position, $\chi=\chi(x)$, we get extra terms in the Lagrangian

$$\begin{aligned}\mathcal{L}' &= ie^{-iq\chi}\bar{\psi}\gamma^\mu[e^{iq\chi}\partial_\mu\psi + iq(\partial_\mu\chi)e^{iq\chi}\psi] - me^{-iq\chi}e^{iq\chi}\bar{\psi}\psi \\ &= \mathcal{L}' - q\bar{\psi}\gamma^\mu(\partial_\mu\chi)\psi\end{aligned}$$

and to **preserve gauge invariance** we need to add a new field A_μ, that transforms as

$$A_\mu \rightarrow A'_\mu = A_\mu - \partial_\mu\chi$$

in such a way that

$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi - q\bar{\psi}\gamma^\mu A_\mu\psi$$

is invariant under the local gauge transformation

=> Interactions arise by enforcing **local gauge invariance**

=> The field A_μ is the photon field, mediator of em interaction

=> There is no mass term $A_\mu A^\mu$ as it would break gauge invariance, it is OK for the photon as $m_\gamma=0$, but is **not OK for the weak interaction** (m_W and m_Z ~100 GeV)