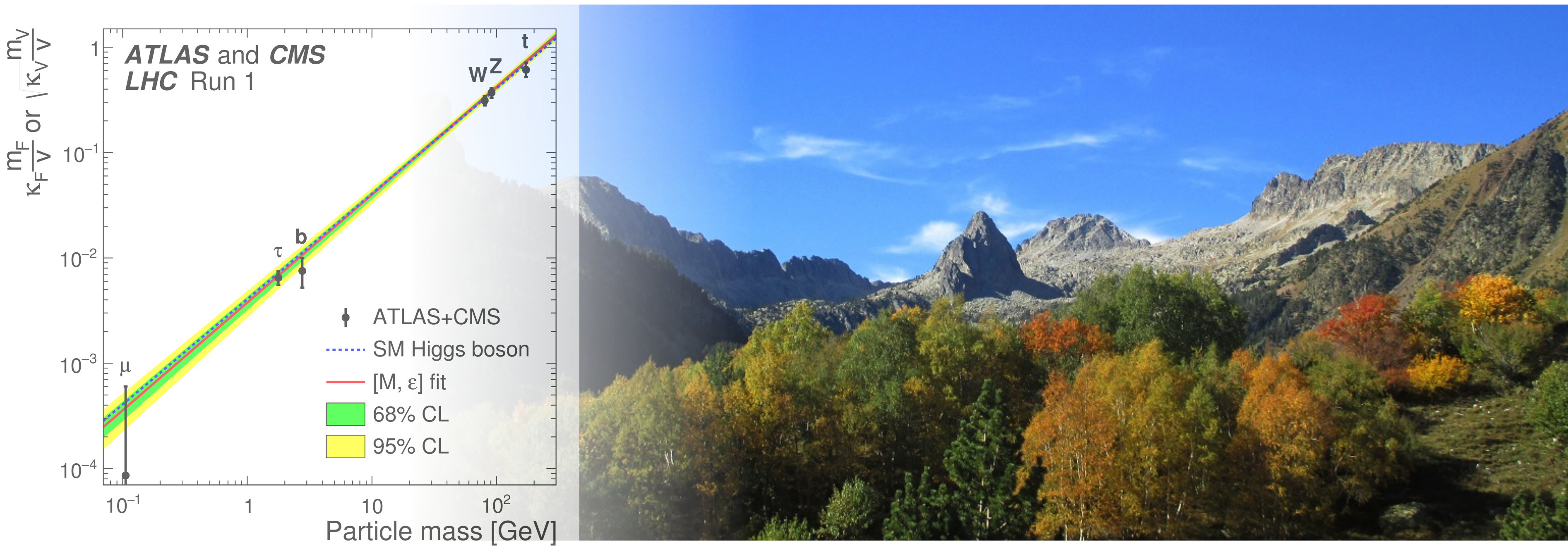
Higgs Physics at LHC

Lecture 1 –*Higgs Fundamentals* TAE 2017

The beauty and overwhelming success of the Standard Model



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LAL, Orsay

Benasque TAE
September, 2017

References and Disclaimer

Not an exhaustive review of all the latest results on Higgs physics

Exhaustive review of latest results available at latest specialised conference

- Higgs Hunting (July): http://higgshunting.fr
- Higgs couplings (Coming soon November): http://www.thphys.uni-heidelberg.de/~higgs/

All results from LHC experiments:

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic

CMS: http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html

Detailed overall review available in the PDG:

http://www-pdg.lbl.gov

Overall Contents

Lecture 1: Fundamentals, The beauty and overwhelming success of the Standard Model

Lecture 2: Complete experimental profile of the Higgs boson, current challenges

Lecture 3: Future challenges (and future machines), implications and searches for new physics beyond the Standard Model

Higgs Physics - Lecture 1

The beauty and overwhelming success of the Standard Model

1.- **Fundamentals**: The Standard Model and the Higgs mechanism

2.- **Direct constraints**: Before the LHC

3.- **Indirect constraints**: Before the LHC Era

4.- **The LHC Machine**

5.- **The General Purpose LHC Detectors:** ATLAS and CMS

6.- **LHC Higgs physics**: Discovery and discovery channel

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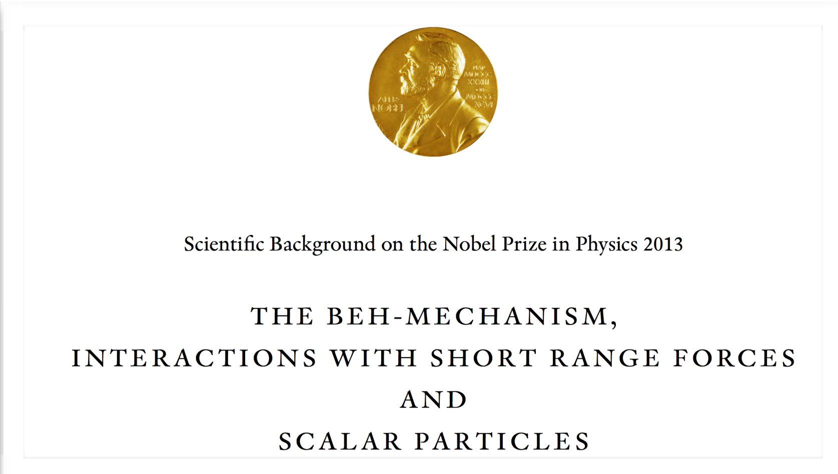
What is the Higgs mechanism about?



Scientific Background on the Nobel Prize in Physics 2013

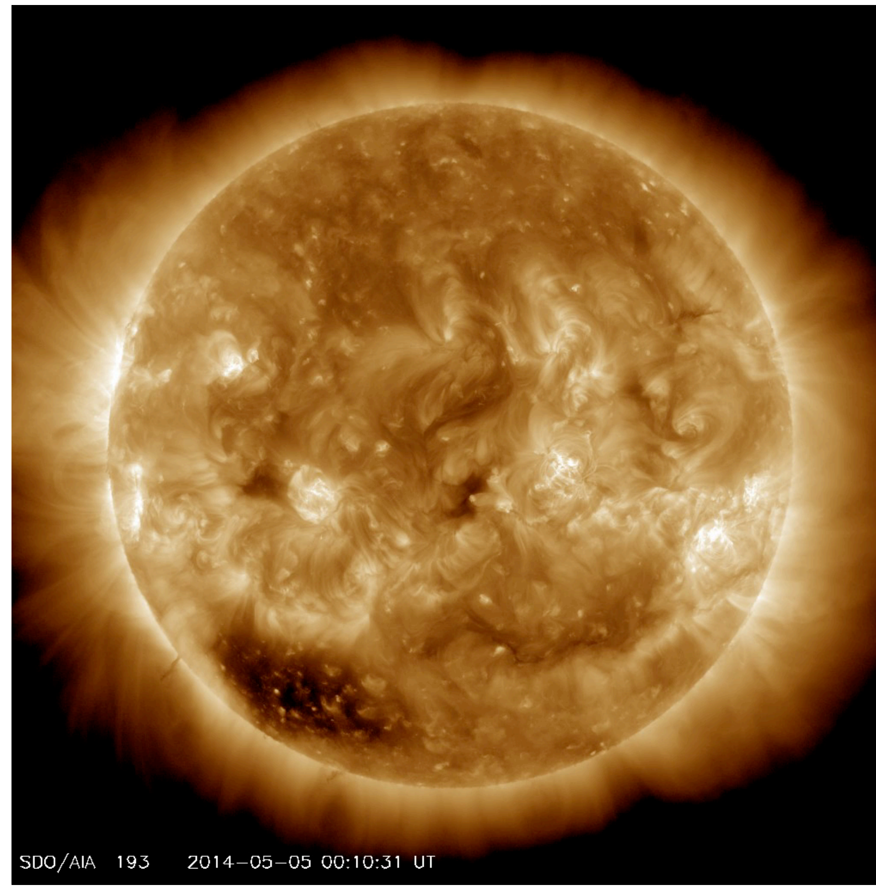
THE BEH-MECHANISM,
INTERACTIONS WITH SHORT RANGE FORCES
AND
SCALAR PARTICLES

"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"

W boson mass (m_W = 81 GeV)

$G_F \sim (M_W)^{-2}$

We will come back to this



If no or lower W mass : shorter combustion time at lower temperature

The Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi} \not{D} \psi + h.c.$$

The elegant gauge sector (tree parameters for EWK and one parameter for QCD)

$$\theta \frac{\alpha_s}{8\pi} F^{A}_{\mu\nu} \tilde{F}^{A\mu\nu}$$

$$\theta < 10^{-10}$$

From neutron electric dipole moment measurements

The strong CP problem

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

The less elegant Higgs sector:

- Carries the largest number of parameters of the theory
- Not governed by symmetries

- Gauge Hierarchy (and Naturalness)
- Flavor hierarchy
- Neutrino masses

Consequences of the Higgs mechanism in the Standard Model:

1.- Two massive charged vector bosons *(charged currents)* :

$$m_W^2 = \frac{g^2 v^2}{4}$$

Thus v = 246 GeV

The theory (and gauge group) was chosen to describe charged current interactions

2.- One massless vector boson : $m_\gamma = 0$

The photon corresponding to the unbroken $U(1)_{EM}$

Consequence of developing the Higgs field along the neutral and real part of the doublet

Predictions :

1.- One massive neutral vector **boson Z**:

$$m_Z^2 = \frac{v^2(g^2 + g'^2)}{4}$$

(Neutral currents not discovered at the time)

2.- One massive scalar particle: **The Higgs boson**

Higgs mass is an unknown parameter of the theory or equivalently the quartic coupling λ

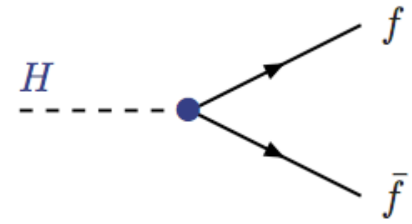
$$m_H^2 = \frac{4\lambda m_W^2}{g^2}$$

3.- Gauge couplings and masses (at tree level):

Protected by cutsodial symmetry at higher orders

$$\frac{m_W}{m_Z} = \rho \frac{g^2}{g^2 + g'^2}$$

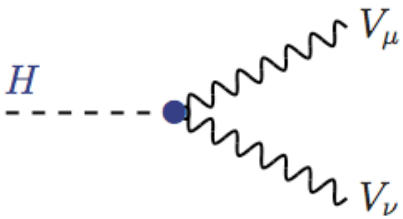
$$\rho = 1$$



$$g_{Hff} = m_f/v$$

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

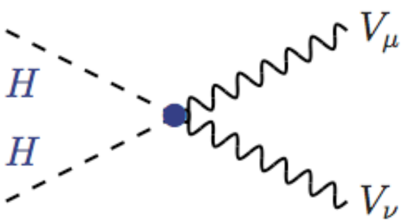
(and masses of fermions)



$$g_{HVV} = 2M_V^2/v$$

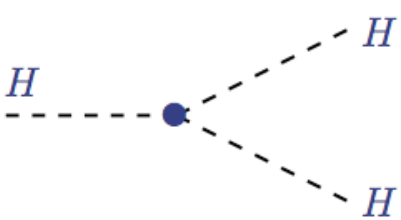
$$+ |D_\mu \phi|^2$$

(and masses of gauge bosons)



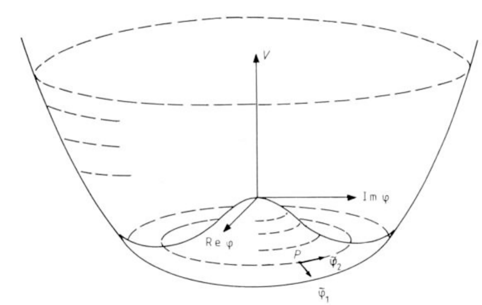
$$g_{HHVV} = 2M_V^2/v^2$$

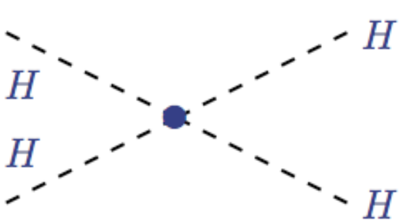
$$V(\phi)$$



$$g_{HHH} = 3M_H^2/v$$

$$v = -\frac{\mu^2}{\lambda}$$





$$g_{HHHH} = 3M_H^2/v^2$$

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

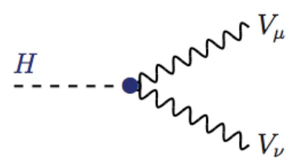
Prior to the Higgs discovery

$$\rho = 1$$

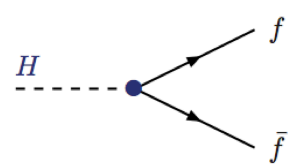
The Higgs mechanism is corroborated at 75% (F. Wilzcek)

- All couplings of the Higgs boson to vector bosons and the fermions were fully predicted from the Standard Model.

$$\frac{m_V^2}{v} H V^\mu V_\mu$$



$$\frac{m_\psi}{v} H \overline{\psi} \psi$$



Is the Higgs boson (alone) responsible for the masses of fermions?

What is the mass of the Higgs boson?

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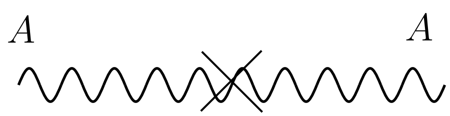
Without SSB

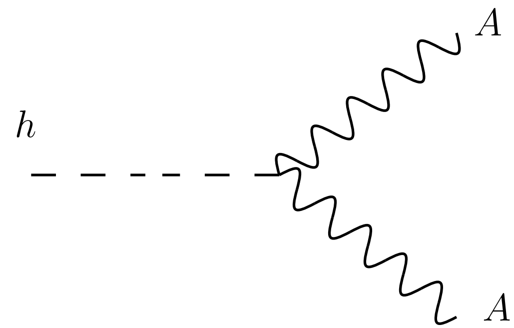
Not gauge invariant

$$m^2 A_\mu A^\mu$$



Not existing vertex
(Simple dimensional analysis)

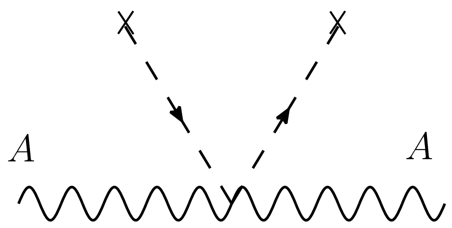
$$h A_\mu A^\mu$$



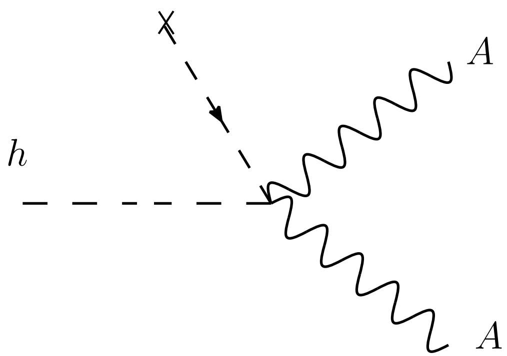
With the Higgs Mechanism (and after SSB)

Not only existing but also closely related!

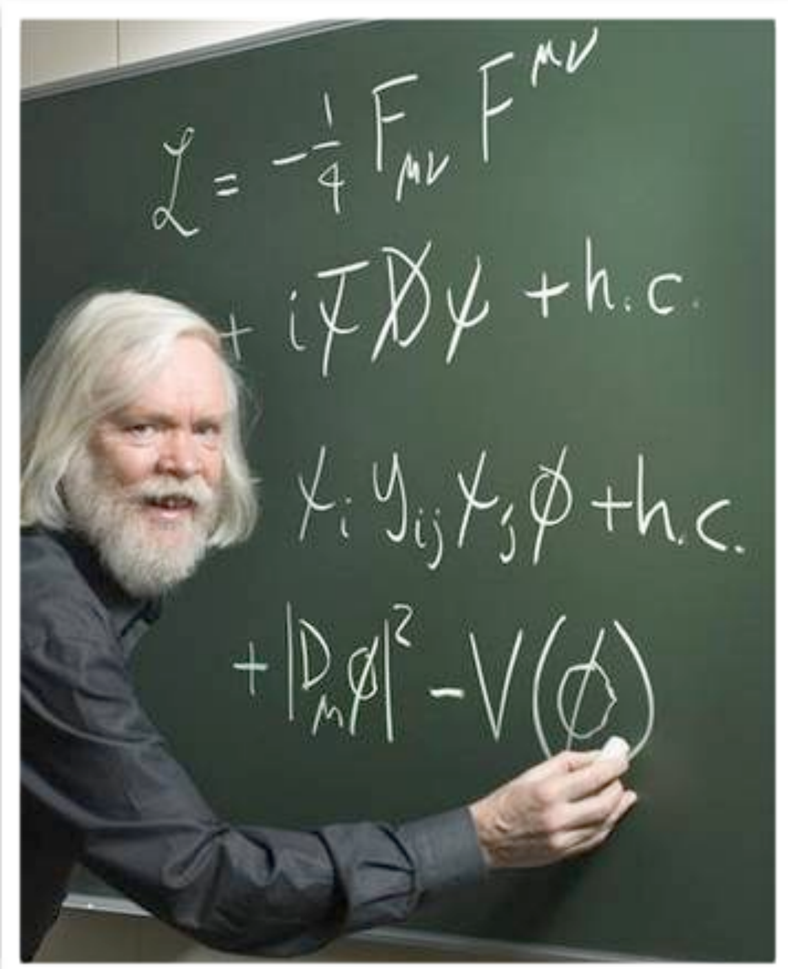
$$\frac{1}{2}e^2v^2A_\mu A^\mu$$



$$e^2vhA_\mu A^\mu$$



Proof of condensate !



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1976

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)

CERN -- Geneva

The Roadmap

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.

First Bounds

Skip

Astrophysical and Phenomenological

- Effect on Cosmic Microwave background (0.1 eV < m_H < 100 eV)

  (Sato and Sato, 1975)

- Emission from stars: $m_H > 0.7\ m_e$

  (Sato and Sato, 1975)

- Neutron-electron scattering: $m_H > 0.7$ MeV

  (Rafelski, Muller, Soff and Greiner; Watson and Sundaresan,1974)

- Neutron-electron scattering: $m_H > 0.7$ MeV

  (Adler, Dashen and Treiman; 1974)

- Neutron-nucleus scattering: $m_H > 13$ MeV

  (Barbieri and Ericson, 1975)

- Nuclear ^{16}O(6.05 MeV) to ground state (0^+ – 0^+) transitions (can occur through Higgs emission): $m_H > 18$ MeV

  (Kohler, Watson and Becker, 1974)

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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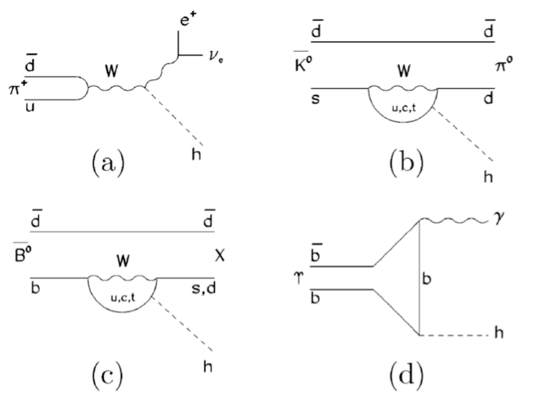
CERN -- Geneva

The situation with regard to Higgs bosons is unsatisfactory. First it should be stressed that they may well not exist. Higgs bosons

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.



Nano review of Pre-LHC Direct Constraints

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1976 – 2010

- SINDRUM Collaboration measured p to ev H (ee) Yielding a limit on very light Higgs
- CUSB Collaboration Y to Hgamma yielding limit of ~ 5-6 GeV (dependent on high order corrections)
- Jade and CLEO provided bounds on B to mm+X
- CERN-Edimbrgh-Orsay-Mainz-Pisa-Siegen K to p H (ee) below ~50 MeV
- Electron beam dump e to eH (ee) excluded 1.2 MeV to 52 MeV (TH uncertainties free)

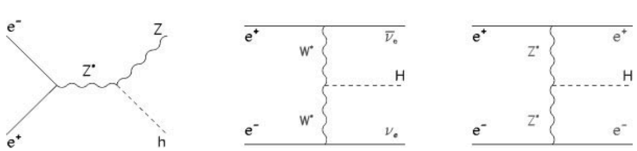
LEP1 e^+e^- at COM ~m_Z

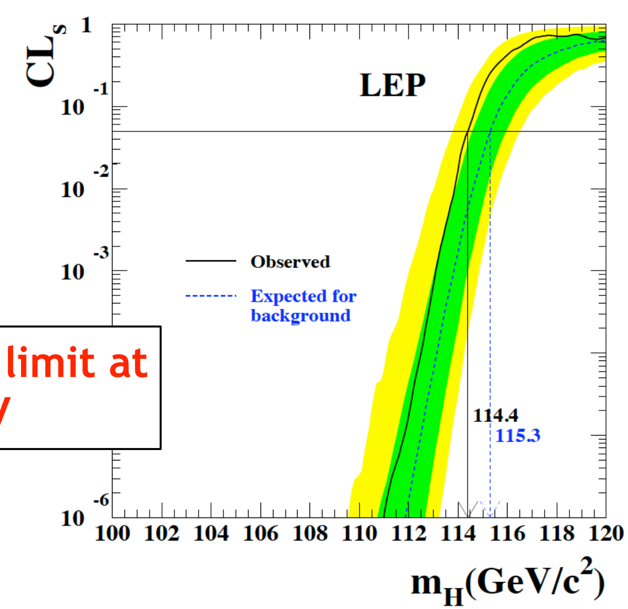
Various decays and topologies

Limit down to below $2m_e$ using acoplanar lepton pairs (Higgs is long lived)

LEP2 e^+e^- up to 209 GeV

(mostly bb and tt decays)





Absoute lower limit at 114 GeV

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Electroweak Precision Data Before the LHC

- The EW sector of the Standard Model (excluding the Yukawa sector and the Higgs potential) has only 3 parameters. The complete set of SM parameters include the Higgs mass the fermion masses and mixing and α_s.

- A useful (for precision) set of these 3 parameters are
  - The fine structure constant : $$\alpha = 1/137.035999679(94)$$ $\boxed{10^{-9}}$

    Determined at low energy by electron anomalous magnetic moment and quantum Hall effect

  - The Fermi constant : $$G_F = 1.166367(5) \times 10^{-5}\,\mathrm{Ge}V^{-2}$$ $\boxed{10^{-5}}$

    Determined from muon lifetime

  - The Z mass : $$M_Z = 91.1876(21)\,\mathrm{Ge}V$$ $\boxed{10^{-5}}$

    Measured from the Z lineshape scan at LEP

- At three level other parameters such as M_W are fully determined by the relation

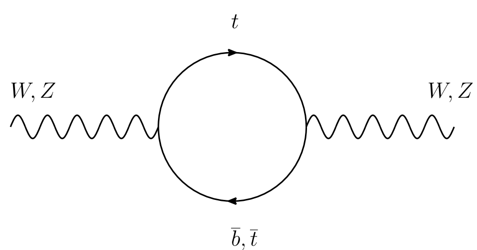
$$G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2(1 - \frac{M_W^2}{M_Z^2})}$$

- At loop level all parameters matter mix through (small) corrections, these corrections are parameterised by form factors e.g.:

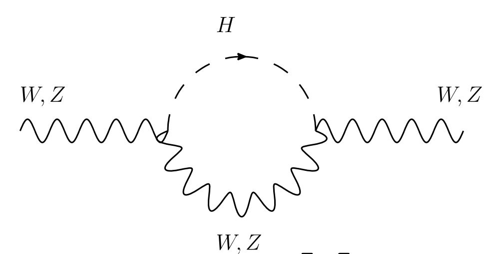
$$G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2(1-\frac{M_W^2}{M_Z^2})}(1+\Delta r)$$

- These form factors are computed at a very high level of precision (at two loops).

- In the Eq. above Δr also depends on M_W which requires an iterative method to solve. M_W has been computed including 3-loop QCD corrections.



$$\propto m_t^2$$



$$\propto \log\frac{M_H}{M_Z}$$

- Then use the SM quantum corrections to fit the model parameters to:
  - Determine Higgs mass and improve determination of the model parameters
  - Probe the consistency of the Standard Model

Main EW collider results before the LHC

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Observables

- Z-pole observables: LEP/SLD results
- MW and ΓW: LEP/Tevatron
- mt :Tevatron
- $\Delta\alpha_{had}(5)$
- mc, mb: world averages

Comments

- Numerous observables O(40)
- Numerous experiments/analyses (with different systematics)
- Numerous TH inputs

Fit Parameters

M_Z, M_H, $\Delta\alpha_{had}(5)$, α_s, m_c, m_b, m_t (and TH uncertainties)

M_W [GeV]	80.385 ± 0.015	Tevatron
Γ_W [GeV]	2.085 ± 0.042	
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	
R^0_ℓ	20.767 ± 0.025	
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	SLC
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	
A_c	0.670 ± 0.027	SLC
A_b	0.923 ± 0.020	
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	
R^0_c	0.1721 ± 0.0030	
R^0_b	0.21629 ± 0.00066	
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]	173.20 ± 0.87	Tevatron
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2757 ± 10	

From R. Kogler (Gfitter coll.)

Fit Results

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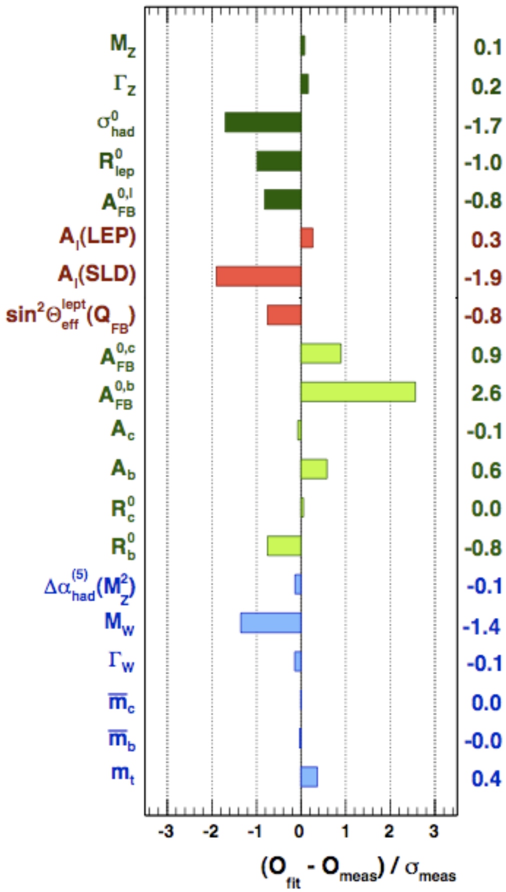
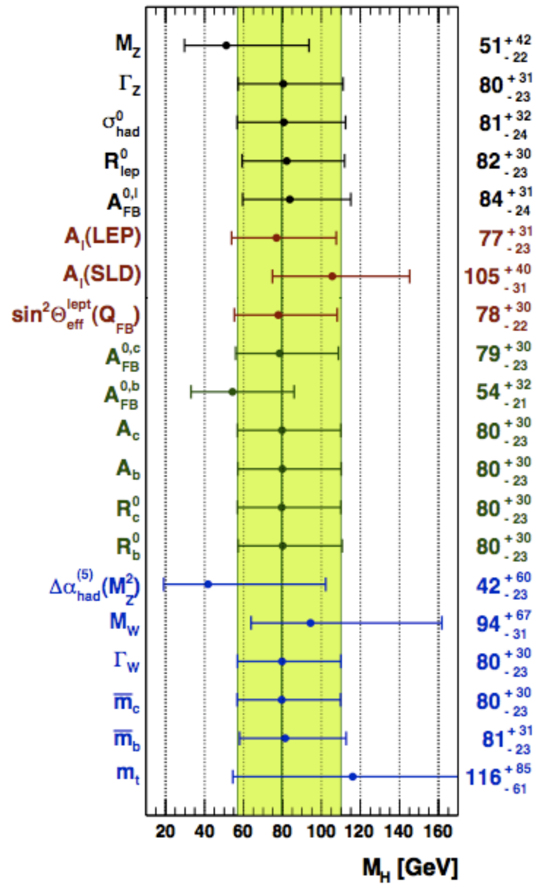
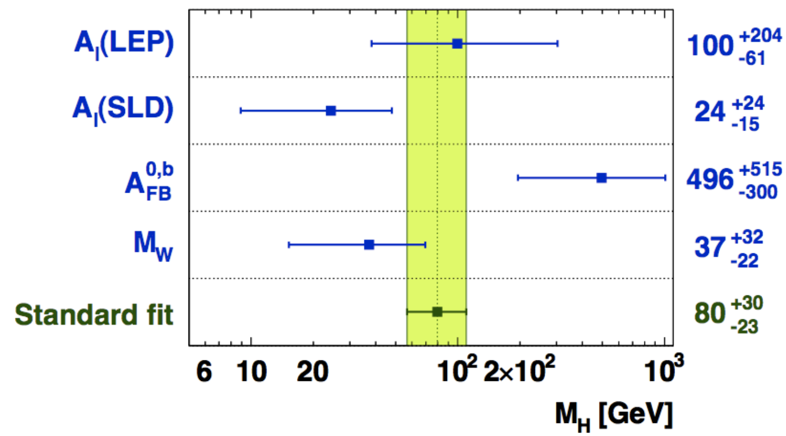


Comparing fit results to the measured values



MH fit excluding specific observables

$$\mathrm{Prob}(\chi^2, 13) = 0.23$$



MH from specific observables

Fit Results (partial)

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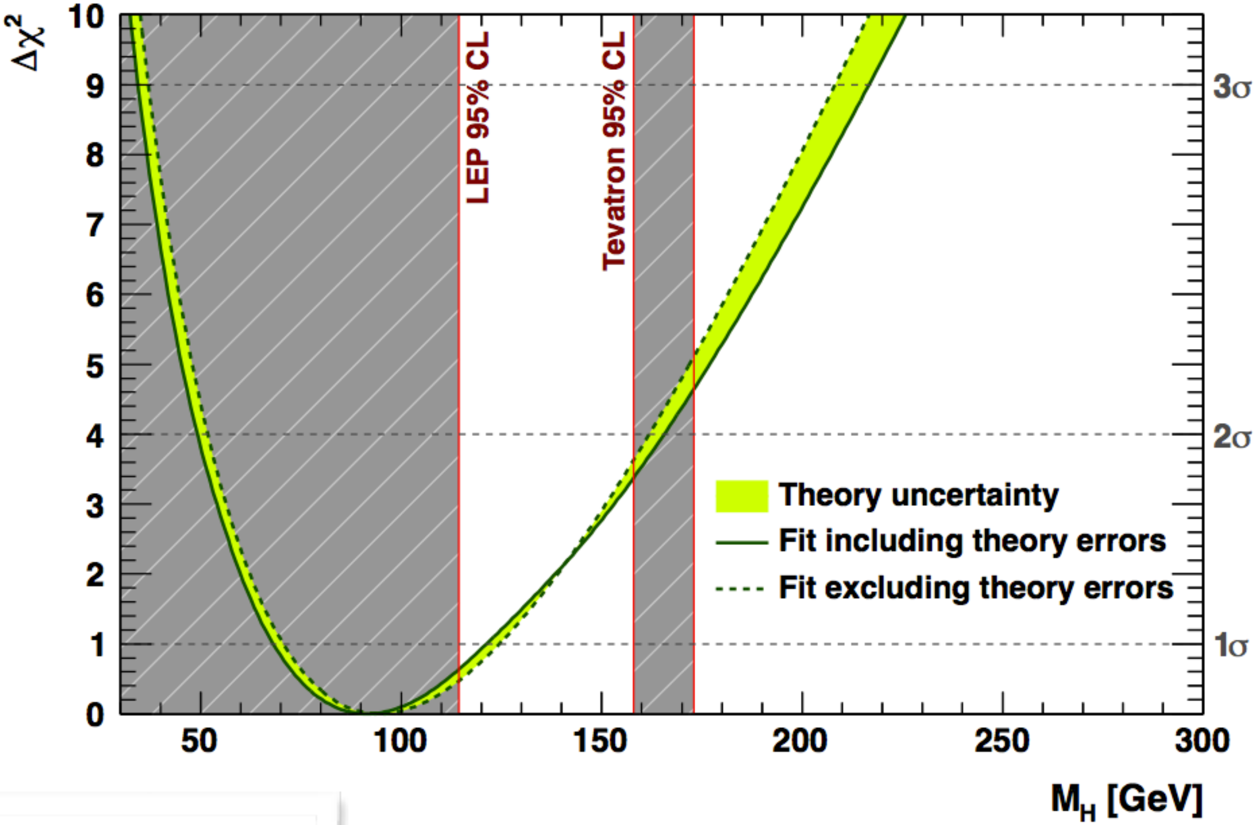
Parameter	Input value	Free in fit	Results from global EW fits: Standard fit	Complete fit	Complete fit w/o exp. input in line
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1874 ± 0.0021	91.1877 ± 0.0021	$91.2001^{+0.0174}_{-0.0178}$
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4959 ± 0.0015	2.4955 ± 0.0015	2.4950 ± 0.0017
σ^0_{had} [nb]	41.540 ± 0.037	–	41.477 ± 0.014	41.477 ± 0.014	41.468 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.018	20.742 ± 0.018	$20.717^{+0.029}_{-0.025}$
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	–	0.01638 ± 0.0002	0.01610 ± 0.9839	0.01616 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1478^{+0.0011}_{-0.0010}$	$0.1471^{+0.0008}_{-0.0009}$	–
A_c	0.670 ± 0.027	–	$0.6682^{+0.00046}_{-0.00045}$	$0.6680^{+0.00032}_{-0.00046}$	$0.6680^{+0.00032}_{-0.00047}$
A_b	0.923 ± 0.020	–	$0.93470^{+0.00011}_{-0.00012}$	$0.93464^{+0.00008}_{-0.00013}$	$0.93464^{+0.00008}_{-0.00011}$
$A^{0,c}_{\mathrm{FB}}$	0.0707 ± 0.0035	–	0.0741 ± 0.0006	$0.0737^{+0.0004}_{-0.0005}$	$0.0737^{+0.0004}_{-0.0005}$
$A^{0,b}_{\mathrm{FB}}$	0.0992 ± 0.0016	–	0.1036 ± 0.0007	$0.1031^{+0.0007}_{-0.0006}$	0.1036 ± 0.0005
R^0_c	0.1721 ± 0.0030	–	0.17224 ± 0.00006	0.17224 ± 0.00006	0.17225 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	$0.21581^{+0.00005}_{-0.00007}$	0.21580 ± 0.00006	0.21580 ± 0.00006
$\sin^2\theta^\ell_{\mathrm{eff}}(Q_{\mathrm{FB}})$	0.2324 ± 0.0012	–	0.23143 ± 0.00013	$0.23151^{+0.00012}_{-0.00010}$	$0.23149^{+0.00013}_{-0.00009}$
M_H [GeV] $^{(\circ)}$	Likelihood ratios	yes	$80^{+30[+75]}_{-23[-41]}$	$116.4^{+18.3[+28.4]}_{-1.3[-2.2]}$	$80^{+30[+75]}_{-23[-41]}$
M_W [GeV]	80.399 ± 0.025	–	$80.382^{+0.014}_{-0.016}$	80.364 ± 0.010	$80.359^{+0.010}_{-0.021}$
Γ_W [GeV]	2.098 ± 0.048	–	$2.092^{+0.001}_{-0.002}$	2.091 ± 0.001	$2.091^{+0.001}_{-0.002}$
m_t [GeV]	172.4 ± 1.2	yes	172.5 ± 1.2	172.9 ± 1.2	$178.2^{+9.8}_{-4.2}$
$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)$ $^{(\dagger\triangle)}$	2768 ± 22	yes	2772 ± 22	2767^{+19}_{-24}	2722^{+62}_{-53}
$\alpha_s(M_Z^2)$	–	yes	$0.1192^{+0.0028}_{-0.0027}$	$0.1193^{+0.0028}_{-0.0027}$	$0.1193^{+0.0028}_{-0.0027}$

The Standard Blue Band Plot

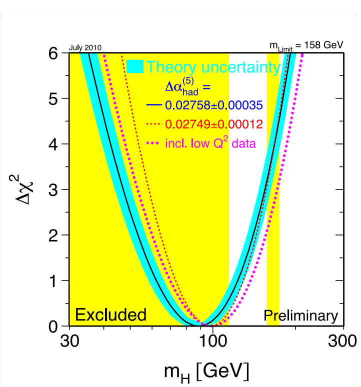


- The fit yielded :

$$91^{+30}_{-23}\ \mathrm{GeV}$$

- The 95% limit :

$$163\ \mathrm{GeV}$$



$$\alpha(m_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha_\ell(m_Z^2) - \Delta\alpha_{had}(m_Z^2) - \Delta\alpha_{top}(m_Z^2)}$$

As mentioned above $\alpha(0)$ measured with ~10^{-9} precision

The difficulty is how to evaluate : $\Delta\alpha_{had}(m_Z^2)$

$V(\phi)$

Running Quartic Coupling

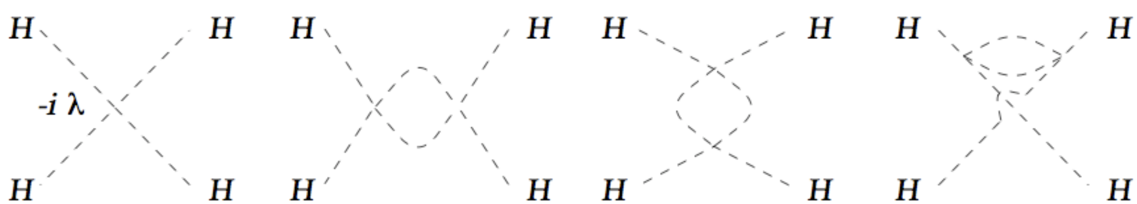
Triviality

The (non exhaustive though rather complete) evolution of the quartic coupling :

$$32\pi^2 \frac{d\lambda}{dt} = \boxed{24\lambda^2} - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 24y_t^4 + \cdots$$

If the Higgs mass had been large (large λ) :

The first term of the equation would have been dominant due to diagrams such as :



$$\frac{d\lambda(Q^2)}{dt} = \frac{3}{4\pi^2}\lambda^2(Q^2) \longrightarrow \frac{1}{\lambda(Q^2)} = \frac{1}{\lambda(Q_0^2)} - \frac{3}{4\pi^2}\ln\left(\frac{Q^2}{Q_0^2}\right)$$

$$M_H^2 = 2\lambda v^2$$

If Q can be high at will eventually lead to Landau pole

$$\boxed{M_H^2 < \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}}$$

Triviality condition to avoid such pole : $1/\lambda(Q) > 0$

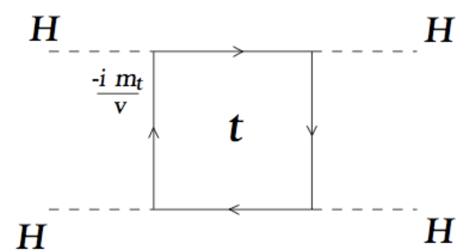
$V(\phi)$

Running Quartic Coupling
Vacuum stability

Looking closer into the limit where the Higgs boson mass is small:

$$32\pi^2\frac{d\lambda}{dt} = 24\lambda^2 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2g^2 + \frac{9}{8}g^4 - \boxed{24y_t^4} + \cdots$$

The last term of the equation is dominant and due to diagrams such as :



$$\sim \frac{m_t^4}{v^4}$$

The equation is then very simply solved : $\lambda(\Lambda) = \lambda(v) - \frac{3}{4\pi^2}y_t^2\log\left(\frac{\Lambda^2}{v^2}\right)$

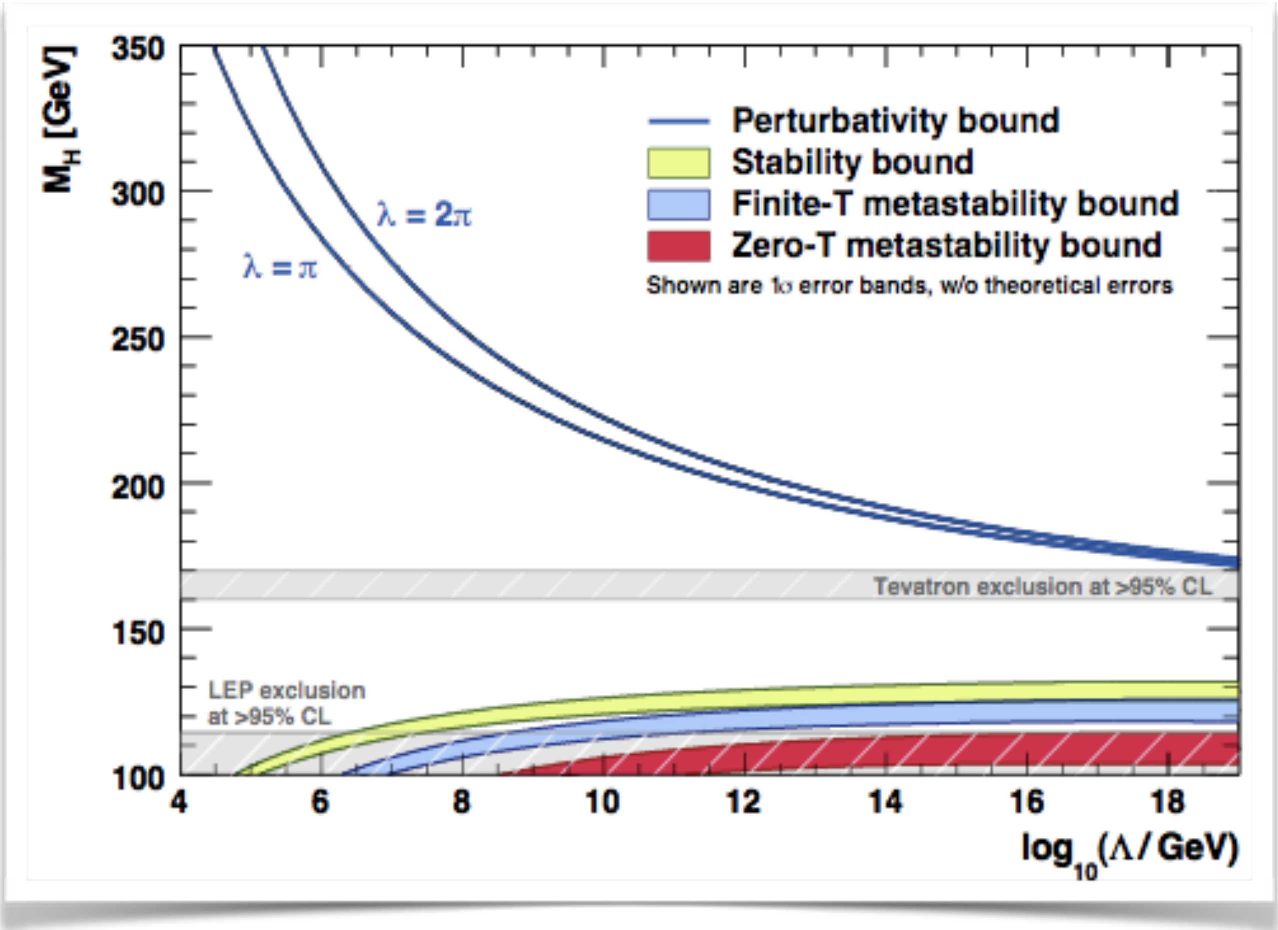
Requiring that the solutions are stable (non-negative quartic coupling) :

$\lambda(\Lambda) > 0$ then $\boxed{M_H^2 > \frac{3v^2}{2\pi^2}y_t^2\log\left(\frac{\Lambda^2}{v^2}\right)}$

$V(\phi)$

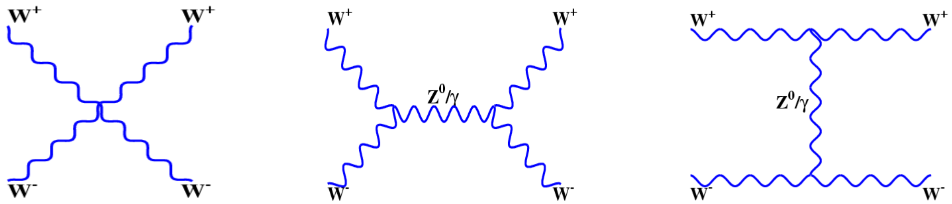
Running Quartic Coupling

Vacuum stability



The No-Loose Theorem at the LHC

$$W_L^+ W_L^- \rightarrow W_L^+ W_L^-$$



Without the Higgs boson the scattering amplitude is:

$$\mathcal{A} \sim \sqrt{2} G_F (s+t)$$

Where s and t are the Mandelstam variables: $1+2 \rightarrow 3+4$

$$s = (p_1 + p_2)^2$$
$$t = (p_1 - p_3)^2$$

The amplitude does therefore not preserve pertubative unitarity.

Introducing a Higgs boson modifies the amplitude as follows:

$$\mathcal{A} \sim -\sqrt{2} G_F m_H^2 \left(\frac{s}{s - m_H^2} + \frac{t}{t - m_H^2} \right)$$

To preserve perturbative unitarity the amplitude should not exceed O(1) for any large s and therefore :

$$G_F m_H^2 < \mathcal{O}(1) \qquad m_H < \mathcal{O}(1 TeV)$$

The origin of the No Loose theorem* at the LHC

**Approximate*

Higgs Physics - Lecture 1

The beauty and overwhelming success of the Standard Model

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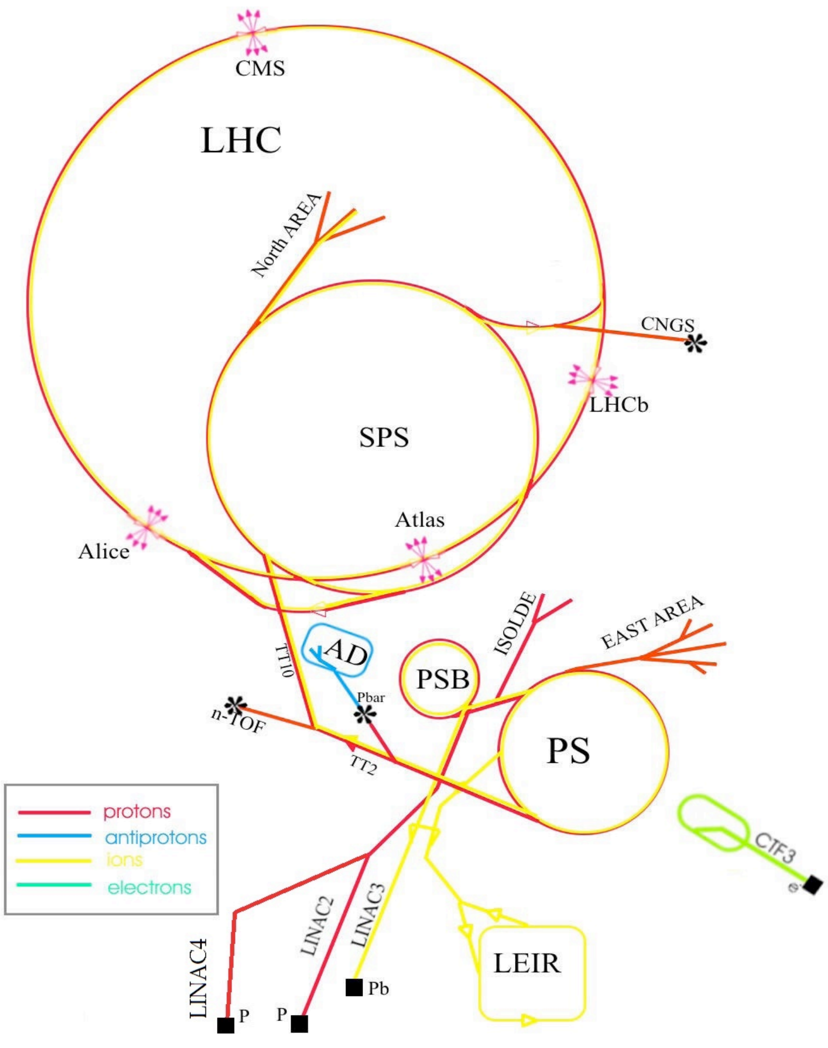
4.- **The LHC Machine**

5.- **The General Purpose LHC Detectors:** ATLAS and CMS

6.- **LHC Higgs physics:** Discovery and discovery channel

The LHC

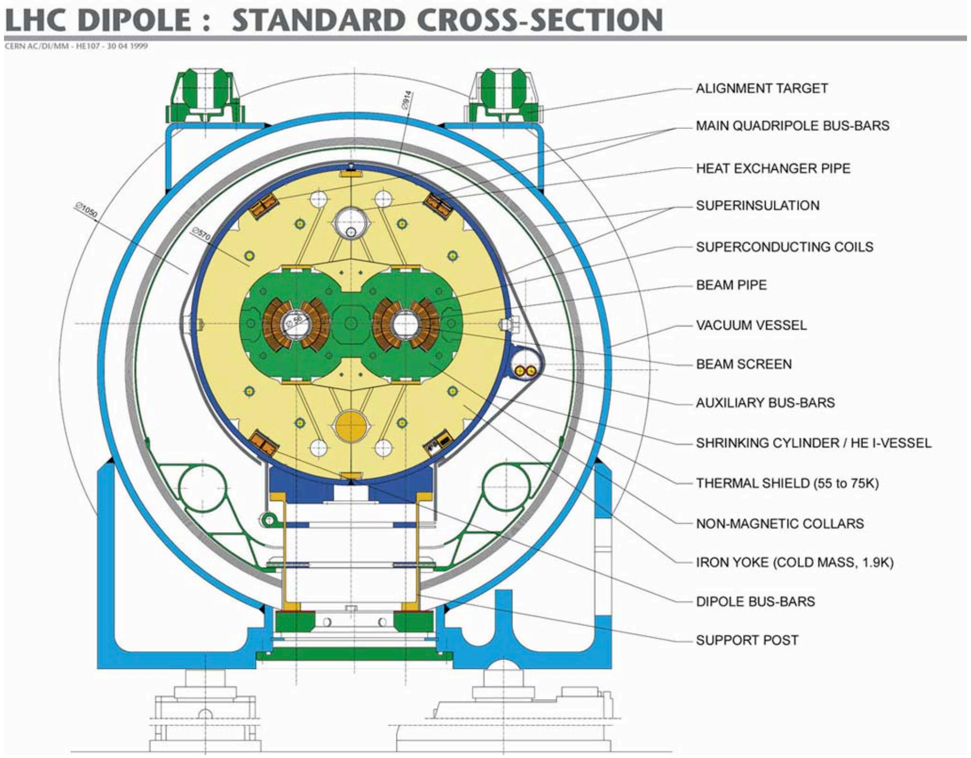


- Hydrogen (gas) is ionized in a duoplasmotron.
- First accelerated with a RF quadrupole at 750 keV.
- Accelerated at 50 MeV in a LINAC
- The booster accelerates protons at 1.4 GeV.
- PS brings them to 26 GeV, it is in the PS that bunches are formed with a 25ns spacing.
- SPS accelerates protons to 450 GeV, bunches before injection in the LHC.

The maximum number of bunches (2808) not reached at Run 2 is limited by the injection kickers (~1 μs) and by the beam dump extraction (~3 μs)

The LHC

FF

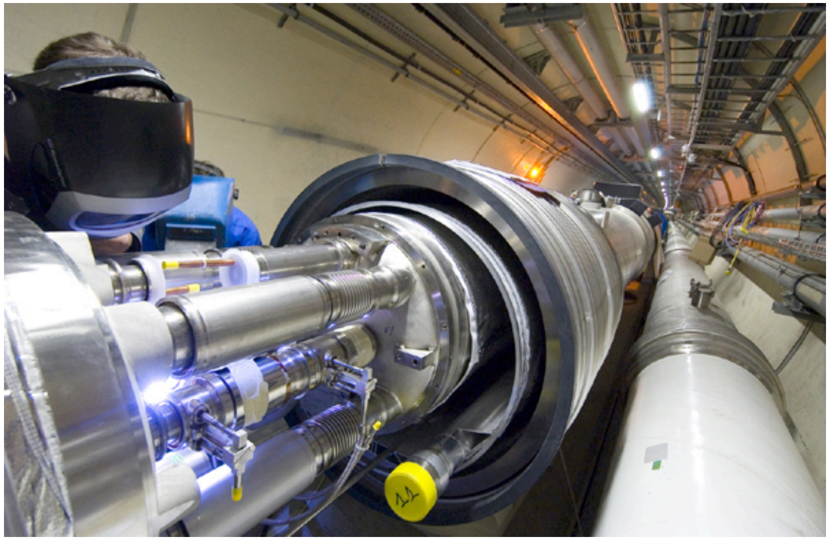


9300 Magnets (among which 1232 bending dipoles) reaching 8.3T with current of 11,400 A.

Beams are made of trains with a total nominal number of bunches of 2808 each containing approximately 100 Bilion protons. Bunches are separated within trains by 25ns (approximately 7m).

Each proton has the kinetic energy of a mosquito and the total energy of the beams is 350 MJ ~ 1 TGV à 150 km/h.

Design, Construction and Commissioning of the LHC



Operation challenge: Unprecedented beam energy and luminosities (for a hadron machine)

- Main challenge : Stored beam energy 2 orders of magnitude higher than existing machines… 350 MJ
- Total stored energy in the magnets (11 GJ, enough to melt 15 tons of copper)

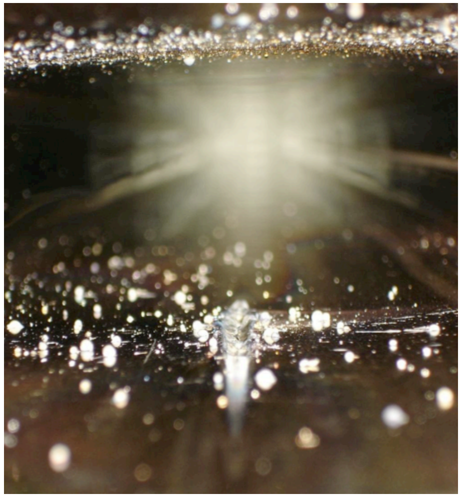
Risk of damage is the main concern :

- From the stored beam energy

(few cm groove in an SPS vacuum chamber from a beam 1% of nominal LHC beam, vacuum chamber ripped open)

- From the stored energy in the magnets

The November 19 2008 incident… (700 m damage area with 39 dipoles and 14 quadrupoles and beam vacuum affected over 2.7 km, 1 year repair)



LHC Luminosity

FF

- Using the normalized emittance (Lorentz invariant, conserved during acceleration phase)

$$\varepsilon_N = \gamma\varepsilon$$

- Beams made of trains of k_b bunches
- With a revolution frequency of f_{rev} (11 kHz)

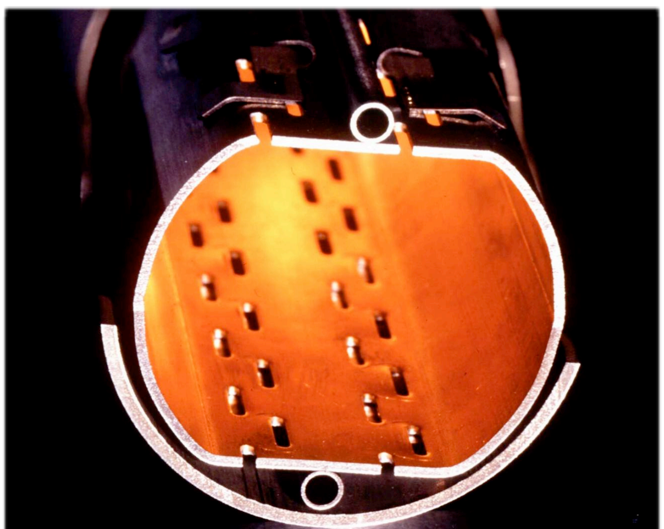
$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi\beta^* \varepsilon_N} F$$

Parameter	2010	2011	2012	2016	Nominal
C.O.M Energy	7 TeV	7 TeV	8 TeV	13 TeV	14 TeV
N_p	1.1 10^{11}	1.4 10^{11}	1.6 10^{11}	1.2 10^{11}	1.15 10^{11}
Bunch spacing / k	150 ns / 368	50 ns / 1380	50 ns /1380	25ns /2300	25 ns /2808
ε (mm rad)	2.4-4	1.9-2.3	2.5	2.6	3.75
β^* (m)	3.5	1.5-1	0.6	0.4	0.55
L ($cm^{-2}s^{-1}$)	$2x10^{32}$	$3.3x10^{33}$	~$7x10^{33}$	$1.5x10^{33}$	10^{34}
PU	~2	~10	~30	~30	~25

Limitations in the Luminosity

FF

- **Electron cloud:** major intensity limiting factor! Photons from synchotron radiation off protons hit the beam pipe inducing the emission of photo-electrons. The electrons are then accelerated by the subsequent bunches and will hit the beam pipe generating secondary electron, and so on. This will generate a cloud of electrons (an issue seen at other colliders with bunches and small bunch spacing), inducing:
  - Beam instabilities
  - Increase in the pressure
  - Heat in the vacuum pipes

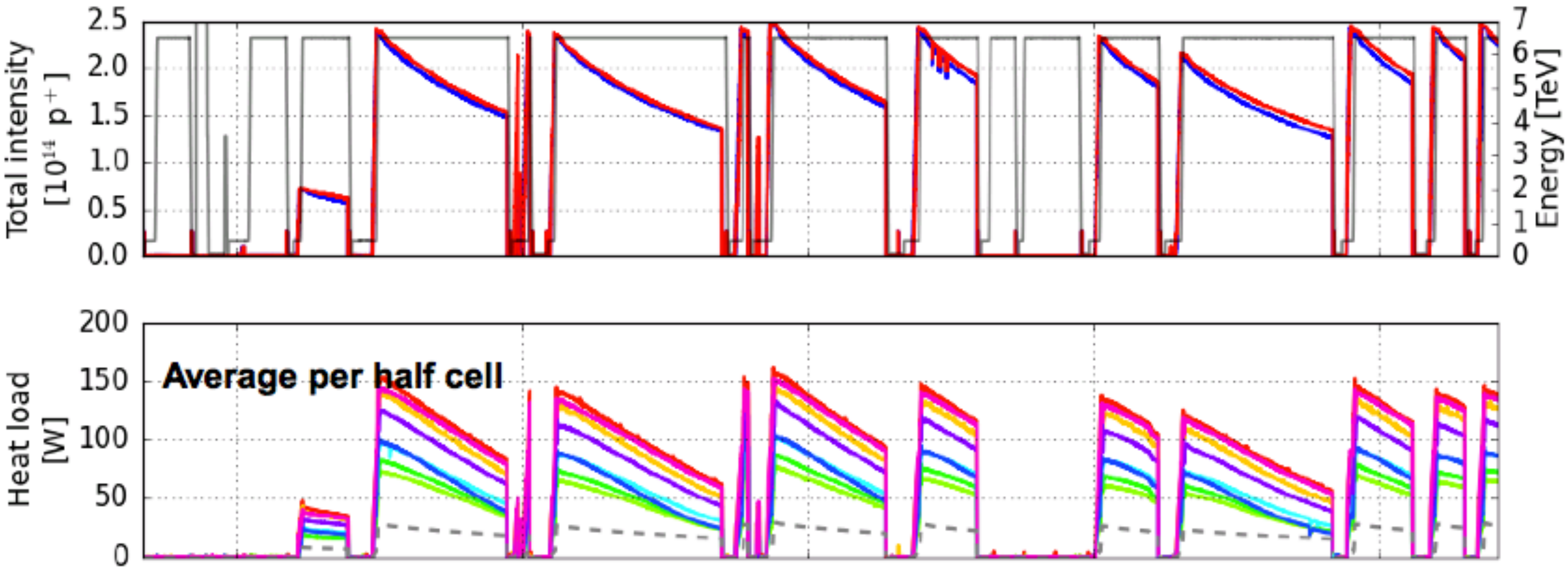


- At LHC beam screen primarily in place to remove heat from synchotron radiation also help to remove heat originating from EC.
- Effect increases with the bunch frequency.
- Scrapping necessary to reach stable beam conditions. At 50ns scrapping at 25ns was efficient, recent operations were uncertain at 25ns, heat load kept under control.

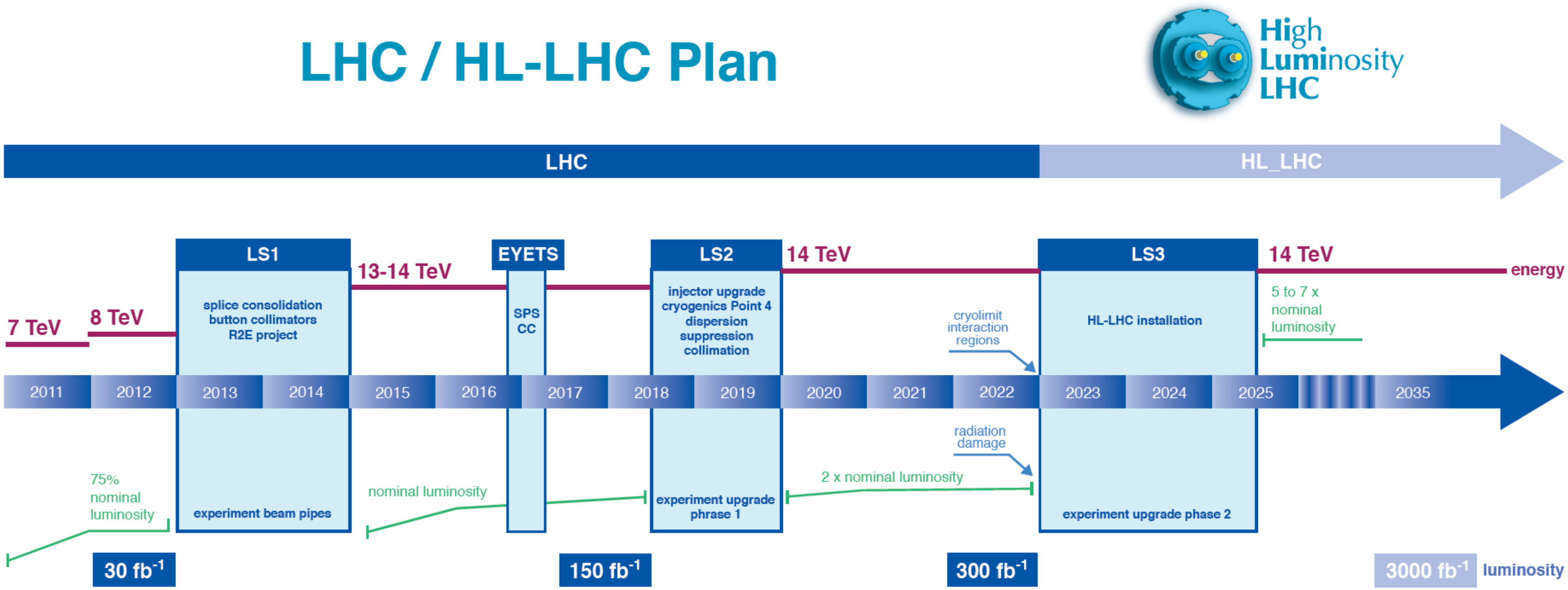
Limitations in the Luminosity

FF

Monitoring of the Heat Load during typical excellent Run 2 week at high intensity



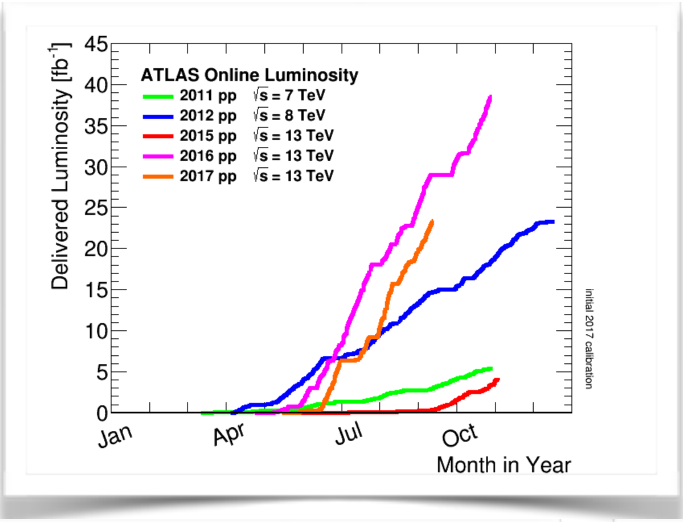
LHC Complete (Latest) Overview

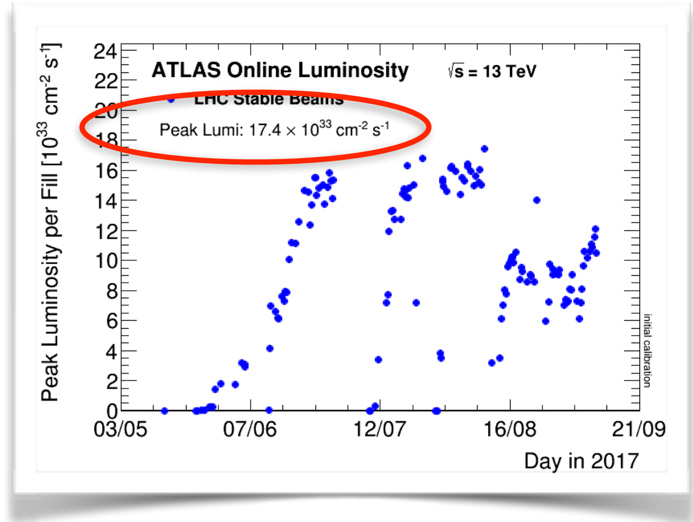


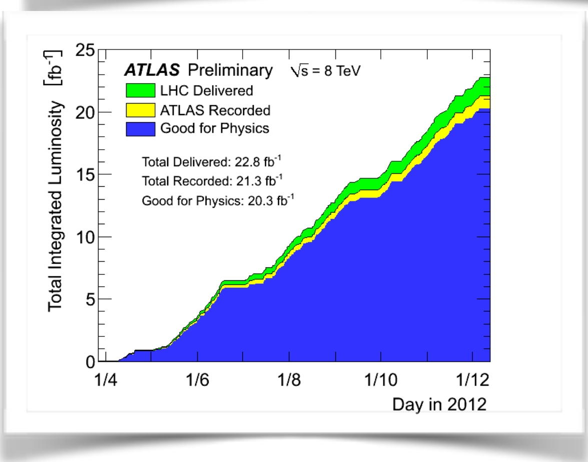
Where do we stand?

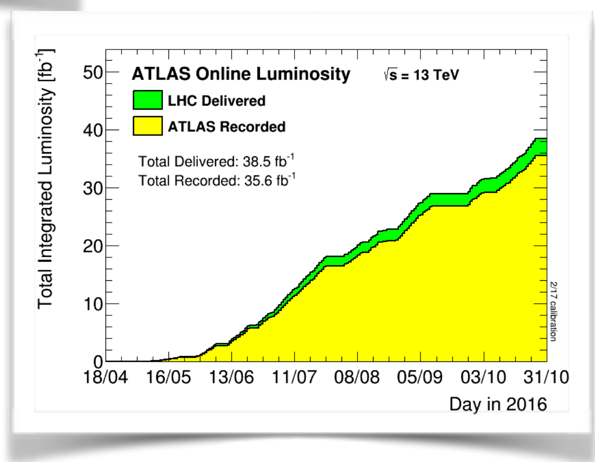
- 8th year of the (25 year) program. Reaching almost nominal centre-of-mass energy and surpassed nominal luminosity estimates.
- Extended YETS: replacement of CMS inner pixel detector.

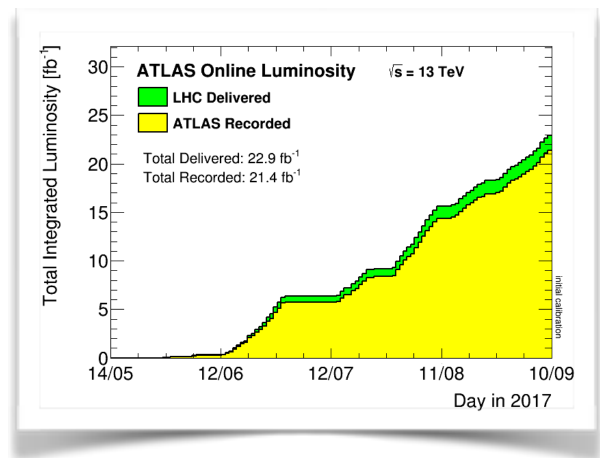
Datasets











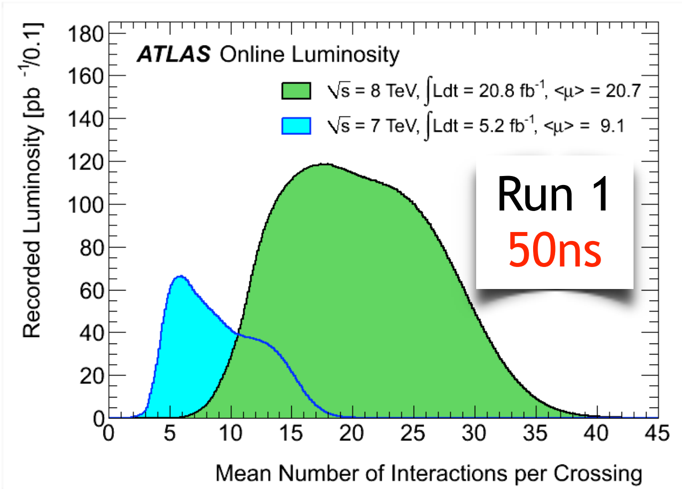
Run 1 dataset
- (illustrating data taking and data quality efficiency
- 2010-2012: ~25 fb-1

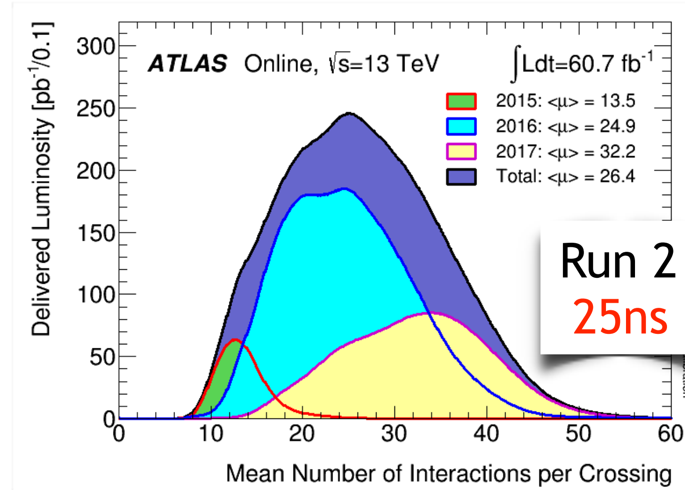
Run 2 dataset
2015-2016: ~35 fb-1

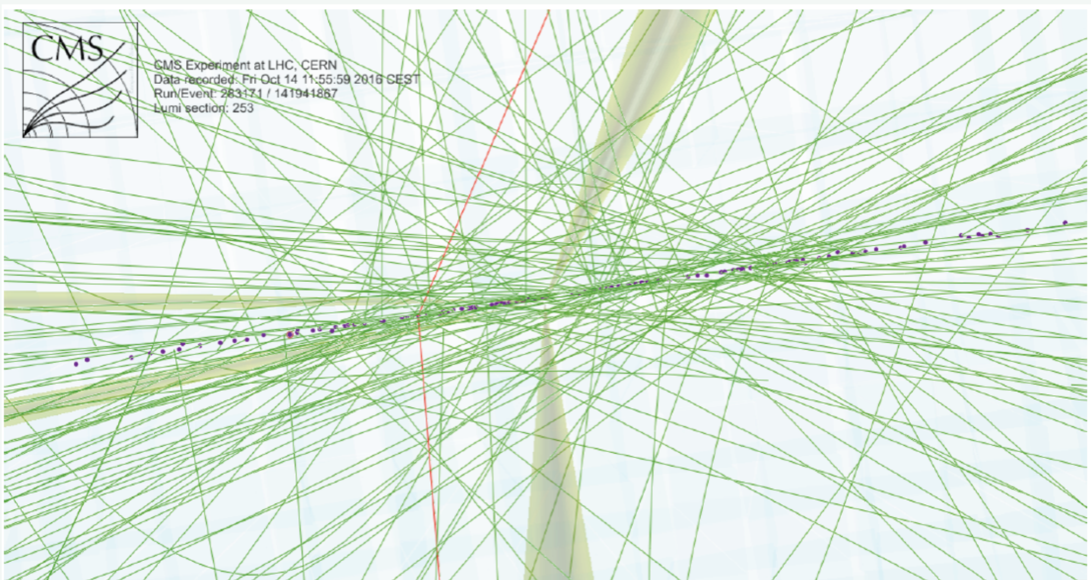
Run 2 dataset
This year, as of this week: ~23 fb-1

Doubling time of luminosity is now O(1 year)

The Run 2 Dataset







Z+jets event in high PU data recorded in 2016, with 103 number of vertices, tracks of $p_T > 1.5$ GeV are shown.

- Number of PU events per bunch crossing has not very significantly increased from Run 1 to Run 2
- The inter-bunch spacing though has been reduced by half from 50ns to 25ns
- Impact on the out-of-time PU significant.

The Success of the LHC

Since 2016 an outstanding success for the LHC, noticeable changes:

- A lower β^* of 40cm instead of 80cm in 2015.
- A smaller bunch spacing of 25ns

(Some of) **the reasons behind the outstanding luminosity reach in 2016**:

- High machine availability (less UFOs, many fixes and tunings)
- High luminosity lifetime (tunes, couplings and bunch length)
- High peak luminosity (low emittance with BCMS, low beta*, and crossing angle)

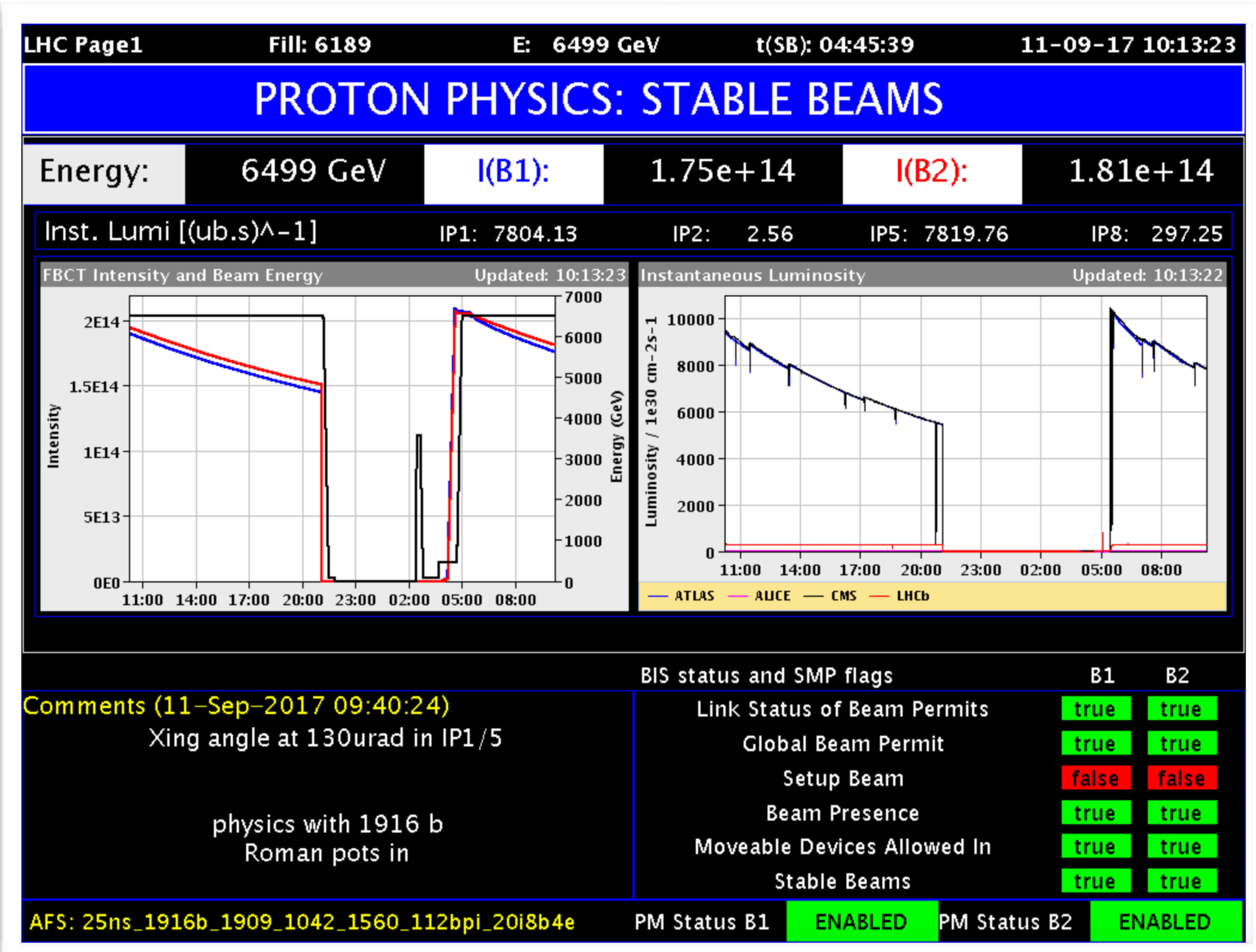
For more details see talk by B. Salvant at the LHCC (December 2016)

Such a complex project encountered various issues, very prompt solutions were found: **Congratulations to the Machine operations and coordination teams!**

Possible goals for next year and for Run 2

- Peak luminosity from 1.4 - 2 10^{34} $cm^{-2}s^{-1}$ (depending on BCMS scheme).
- Peak PU from 37 to 56.
- Integrated luminosity between 45 and 60 fb^{-1}.
- For the entire Run 2 between 120 and 150 fb^{-1}.

LHC Page 1



LHC Page1
Fill: 6189
E: 6499 GeV
t(SB): 04:45:39
11-09-17 10:13:23
PROTON PHYSICS: STABLE BEAMS
Energy:
6499 GeV
I(B1):
1.75e+14
I(B2):
1.81e+14
Inst. Lumi [(ub.s)^-1]
IP1: 7804.13
IP2: 2.56
IP5: 7819.76
IP8: 297.25
FBCT Intensity and Beam Energy
Updated: 10:13:23
Intensity
Energy (GeV)
2E14
1.5E14
1E14
5E13
0E0
7000
6000
5000
4000
3000
2000
1000
0
11:00 14:00 17:00 20:00 23:00 02:00 05:00 08:00
Instantaneous Luminosity
Updated: 10:13:22
Luminosity / 1e30 cm-2s-1
10000
8000
6000
4000
2000
0
11:00 14:00 17:00 20:00 23:00 02:00 05:00 08:00
ATLAS
ALICE
CMS
LHCb
BIS status and SMP flags
B1
B2
Comments (11-Sep-2017 09:40:24)
Xing angle at 130urad in IP1/5
physics with 1916 b
Roman pots in
Link Status of Beam Permits true true
Global Beam Permit true true
Setup Beam false false
Beam Presence true true
Moveable Devices Allowed In true true
Stable Beams true true
AFS: 25ns_1916b_1909_1042_1560_112bpi_20i8b4e
PM Status B1 ENABLED
PM Status B2 ENABLED

Higgs Physics - Lecture 1

The beauty and overwhelming success of the Standard Model

1.- **Fundamentals**: The Standard Model and the Higgs mechanism

2.- **Direct constraints**: Before the LHC

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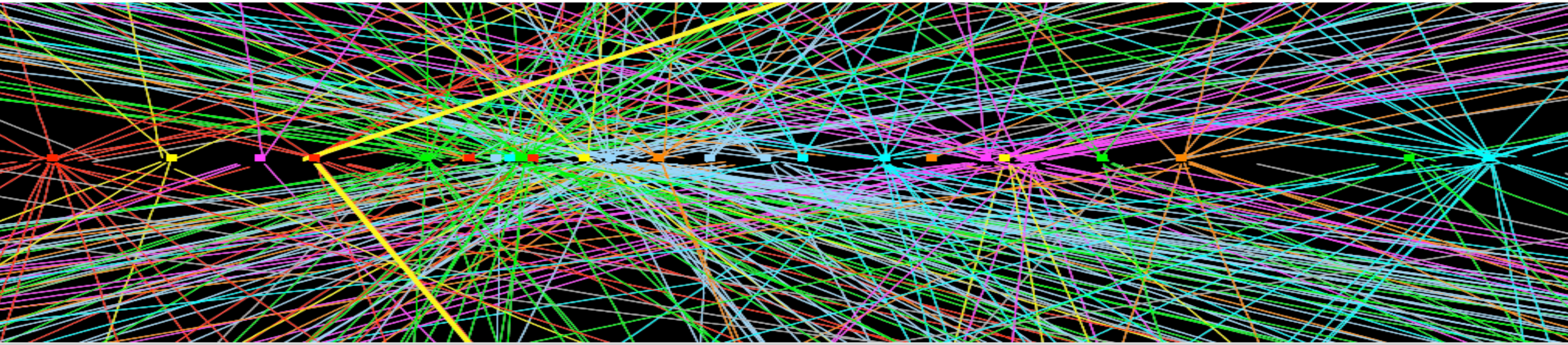
5.- **The General Purpose LHC Detectors:** ATLAS and CMS

6.- **LHC Higgs physics:** Discovery and discovery channel

Detector Challenges (ATLAS Example)

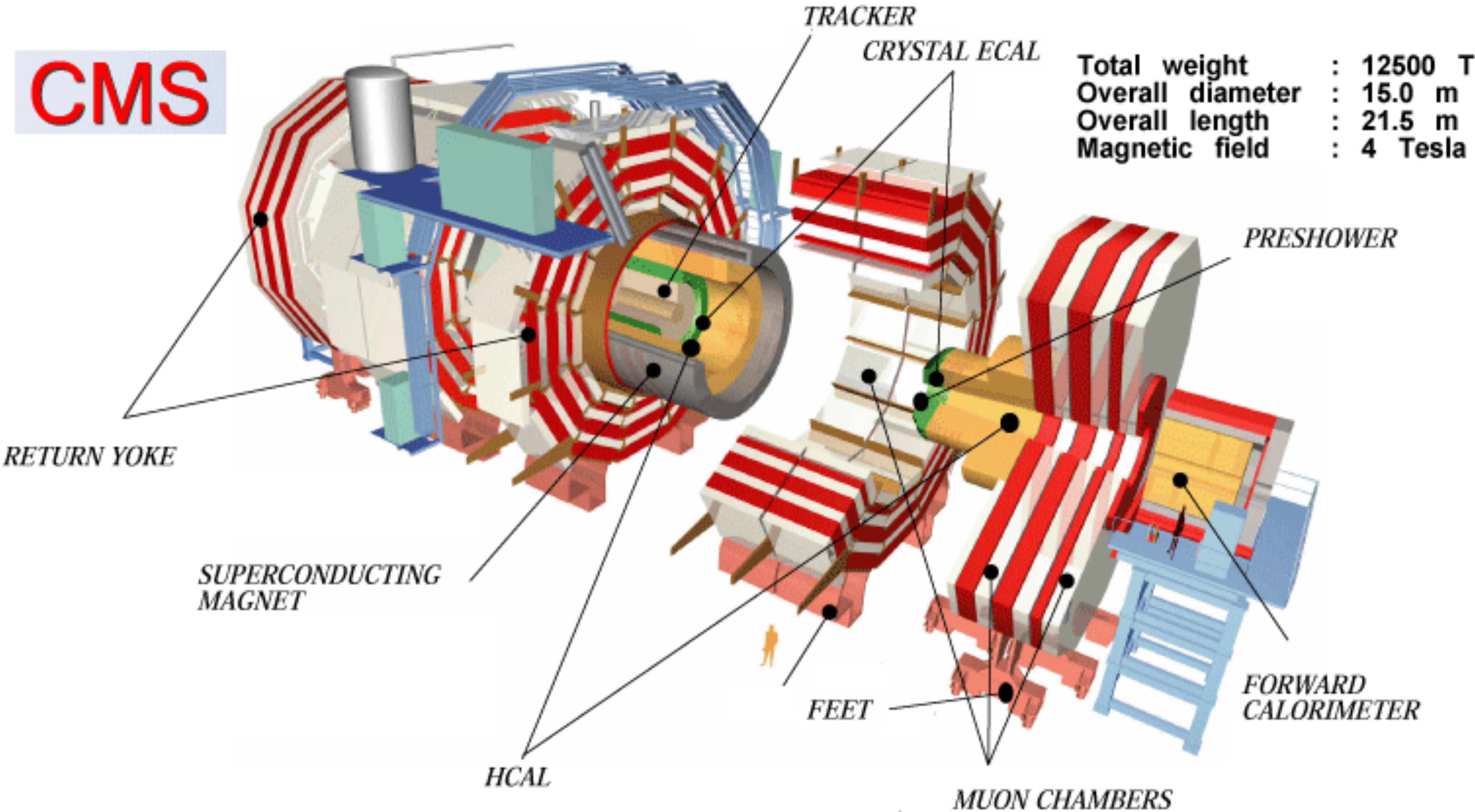


- **Trigger Challenge**: How to select 1000 out of 20M events per second while keeping the interesting (including unknown) physics

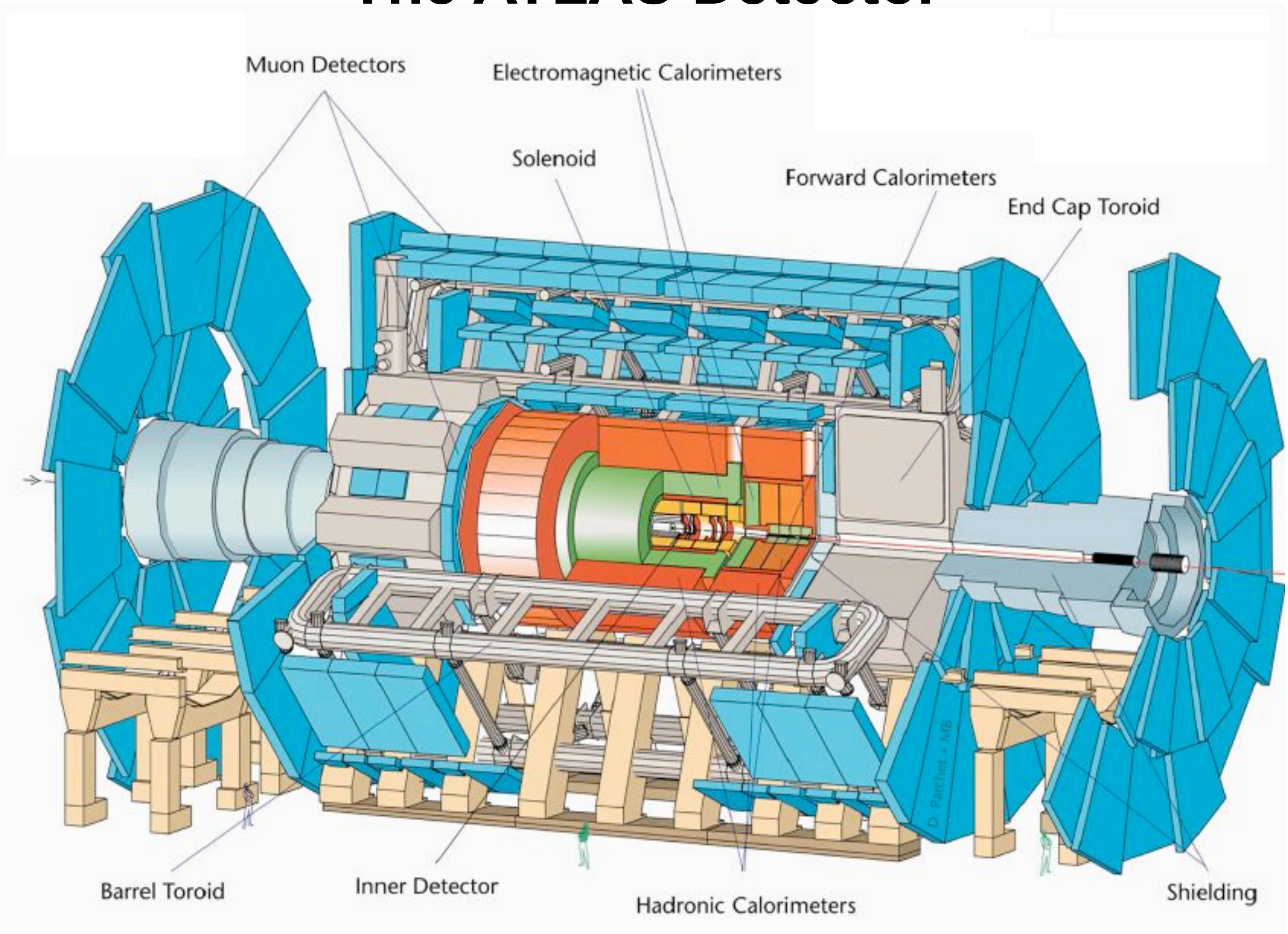
- **Computing Challenge**: How to reconstruct, store and distribute 400 increasingly complex events per second (over 100 PB per experiment)

- **Analysis Challenge**: Maintain high (and as much as possible stable) reconstruction and identification efficiency for physics objects (e, μ, τ, jets, E^{T}_{mis}, b-jets) up to the highest pile-up

The CMS Detector

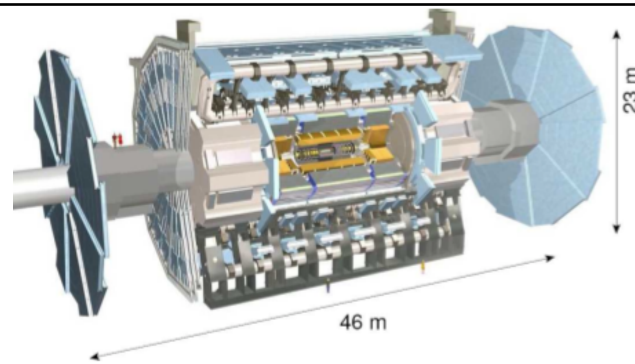
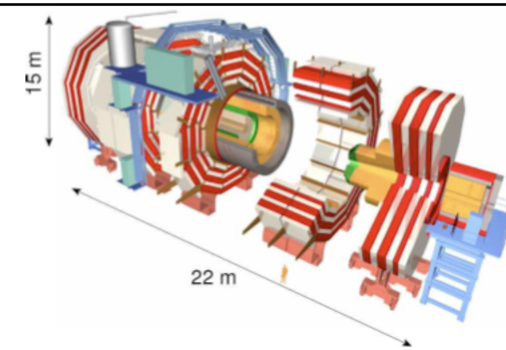


The ATLAS Detector



The ATLAS and CMS Detectors In a Nutshell

FF

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 $\sigma_{p_T}/p_T \sim 5\times 10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5\times 10^{-4} p_T \oplus 0.005$
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)

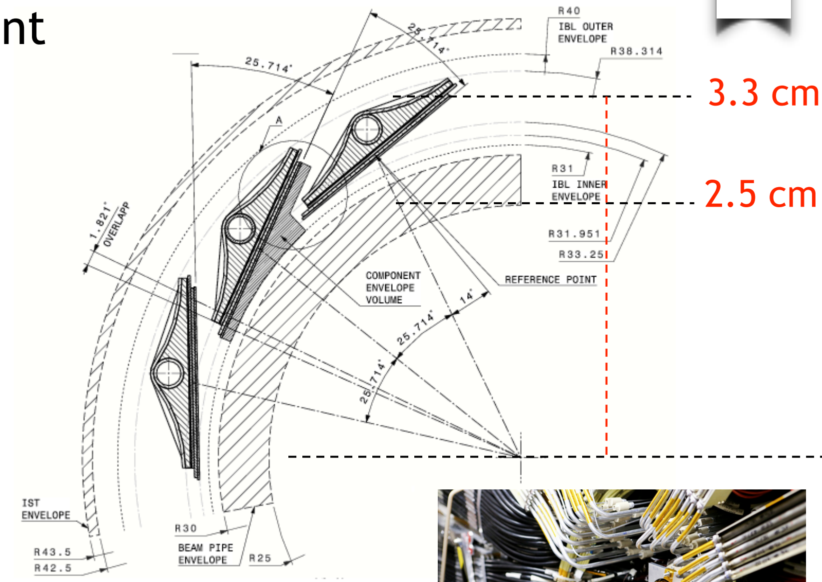
Main (phase 0) Detector Improvements

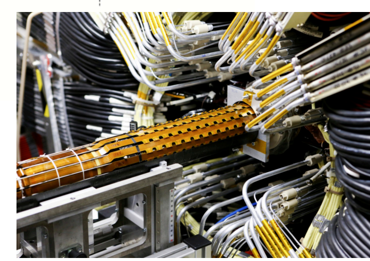
FF

Important changes in all areas of the experiment

ATLAS - Phase 0

- 4th innermost layer of pixels (3.3 cm, 2nd layer at 5.05 cm)
- Consolidation: Complete muon coverage, Luminosity detectors, Repairs (LAr and Tile), Beam Condition. Monitors
- Infrastructure: New Beam Pipe, Magnets and Cryogenic system, Muon Chamber shielding, New pixel services
- Trigger/DAQ: Increase max L1 rate from 75kHz to 100kHz, new Central Trigger Processor, Merge L2 and HLT farms, Additional SFOs for higher output rate.
- Topological L1 triggers
- Fast Track Trigger



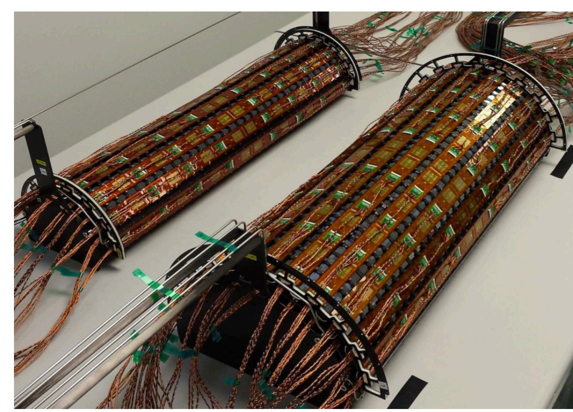


Inserted during LS1

CMS - Phase 0

- Complete muon coverage
- Replace HCAL photodetectors
- During LS1 L1 Triger upgrade
- New Pixel detector: to be inserted during the EYETS
- L1 Trigger upgrade

Both for ATLAS and CMS Reconstruction and analysis software are regularly updated.



To be inserted during EYETS

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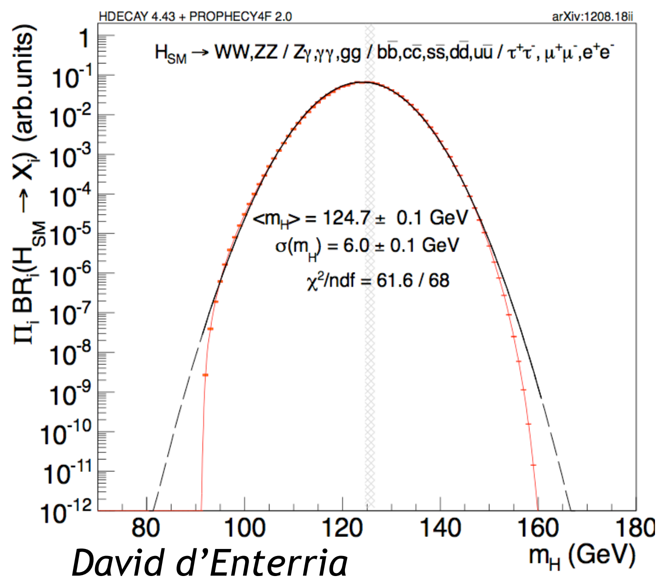
A Gift of Nature!



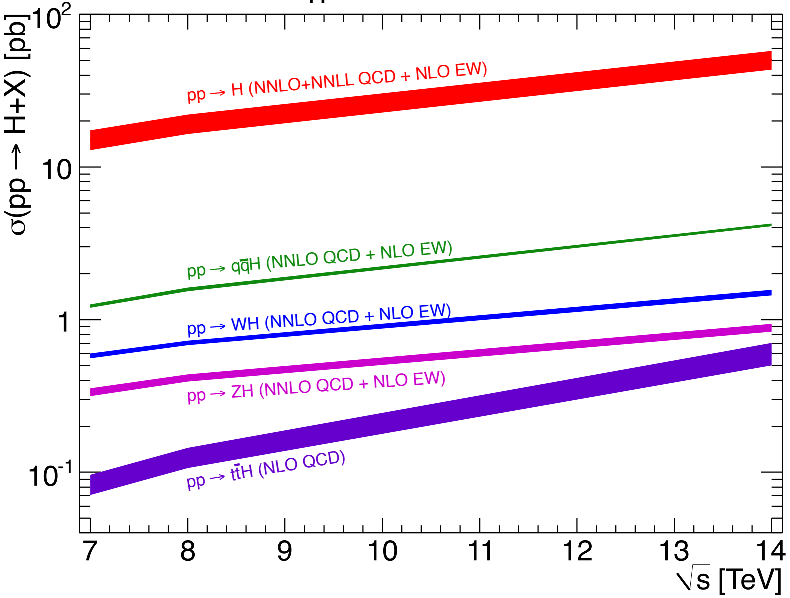
David d'Enterria

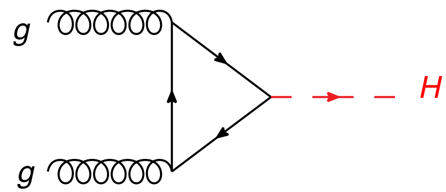
"A Gift of Nature"

Fabiola Gianotti
(July 4, 2012 CERN)

Higgs Production Modes

k for m_H = 125.5 GeV

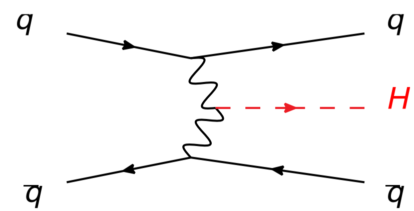




Gluon fusion process

NNnLO ~O(10%)

~0.5 M events produced

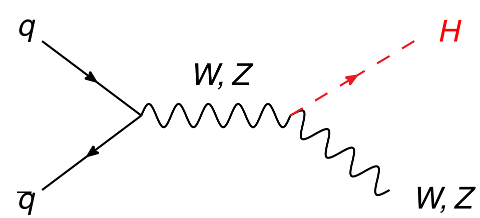


Vector Boson Fusion

NLO TH uncertainty ~O(5%)

Two forward jets and a large rapidity gap

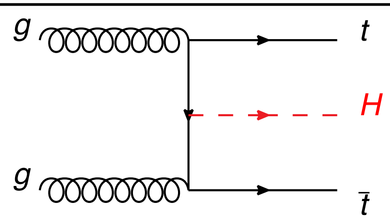
~40 k events produced



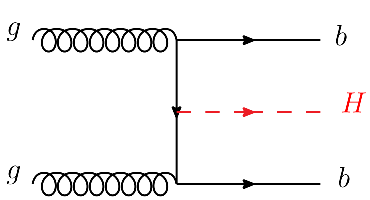
W and Z Associated Production

NNLO TH uncertainty ~O(5%)

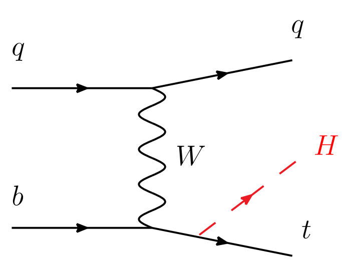
~20 k events produced



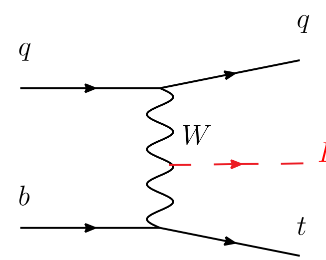
Top Assoc. Prod. ~3 k evts produced



B-quark Assoc. Prod. ~5 k evts produced



tH



Two diagrams interfering

Higgs Decay Channels

- Dominant: bb (57%)

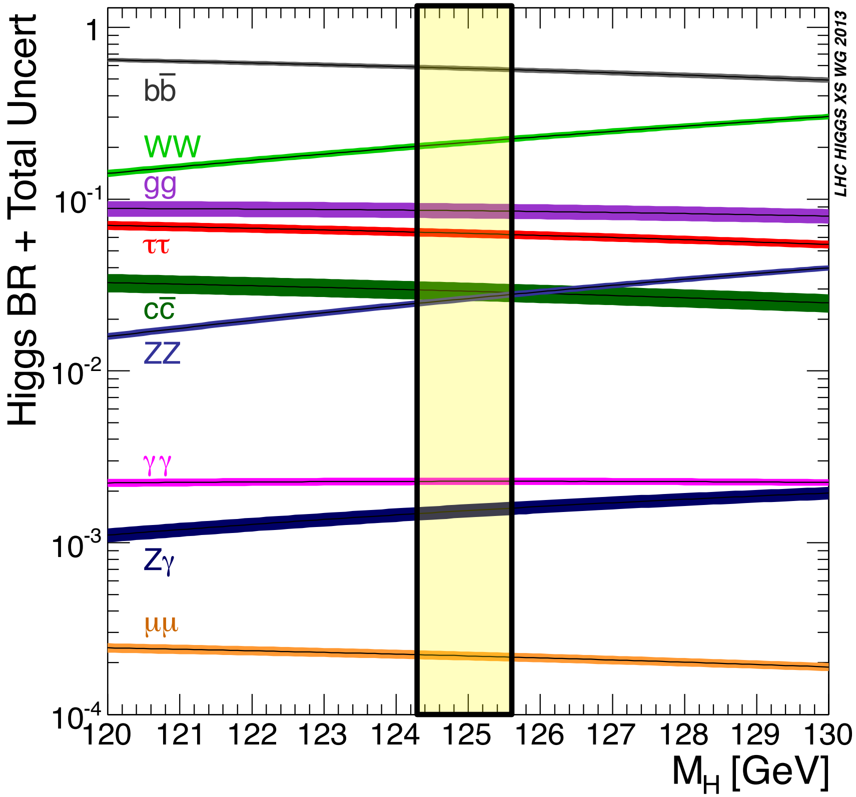
- WW channel (22%)

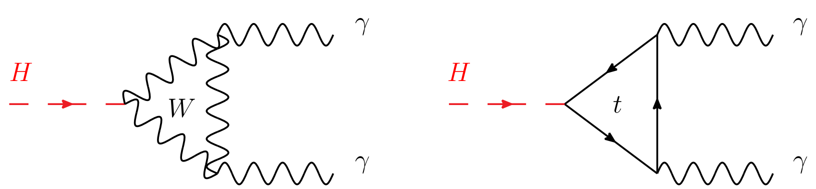
- ττ channel (6.3%)

- ZZ channel (3%)

- cc channel (3%)
  Extremely difficult

- The γγ channel (0.2%)





Two diagrams interfering

- The Zγ (0.2%)

- The μμ channel (0.02%)

The κ Formalism

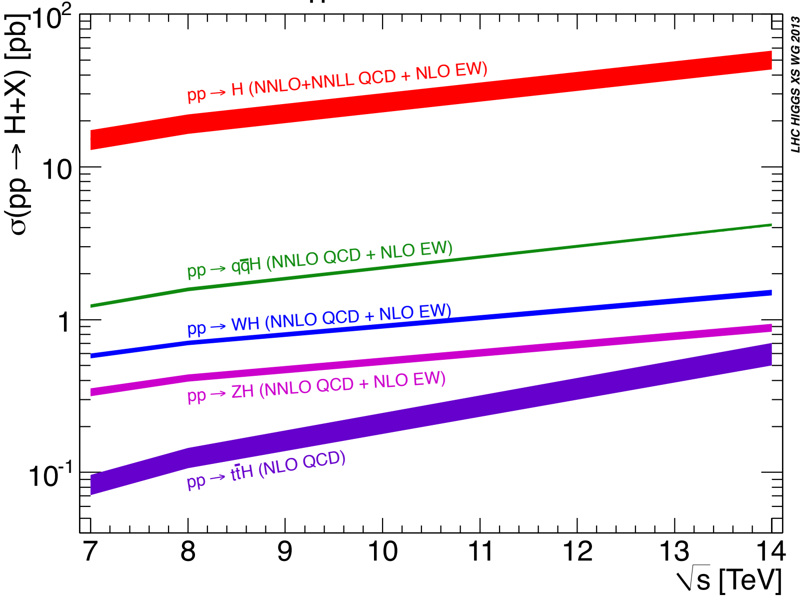
The k factors are fully defined as coefficients of dimension-6 operators, and is therefore a valid effective field theory.

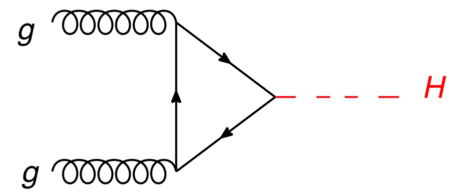
However the parameterisation of the branching fractions and the cross sections does not take into account all loop level mixing of parameters.

$$
\begin{aligned}
\mathcal{L} = {} & \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\
& + \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\
& + \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W_{\mu\nu}^+ W^{-\mu\nu} \right) H \\
& - \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H.
\end{aligned}
$$

Higgs Production Modes

k for m_H = 125.5 GeV



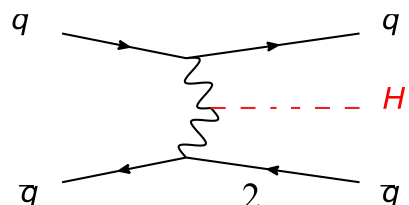


Gluon fusion process

NNnLO ~O(10%)

~0.5 M events produced

$$\kappa_g \propto 1.\times 06\kappa_t^2 - 0.07\times\kappa_t\kappa_b + 0.01\times\kappa_b^2$$



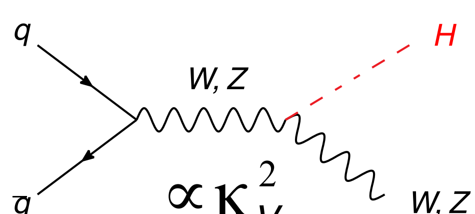
$$\propto \kappa_V^2$$

Vector Boson Fusion

NLO TH uncertainty ~O(5%)

Two forward jets and a large rapidity gap

~40 k events produced

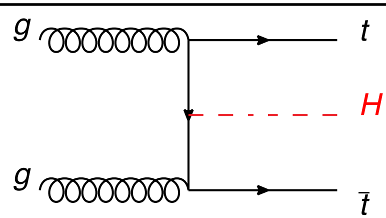


$$\propto \kappa_V^2$$

W and Z Associated Production

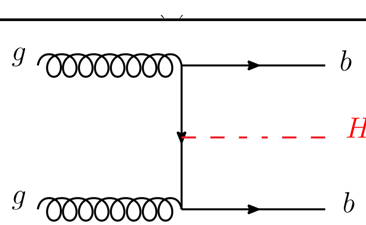
NNLO TH uncertainty ~O(5%)

~20 k events produced



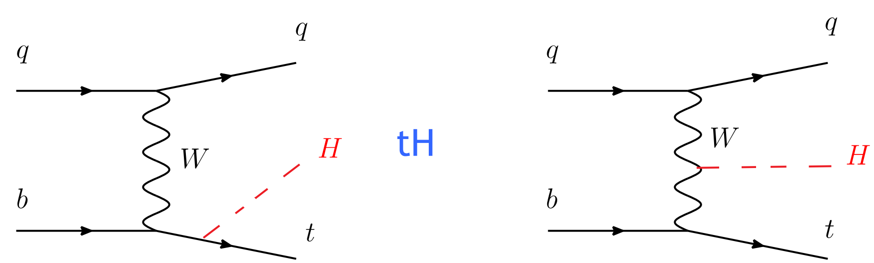
$$\propto \kappa_t^2$$

Top Assoc. Prod. ~3 k evts produced



$$\propto \kappa_b^2$$

B-quark Assoc. Prod. ~5 k evts produced

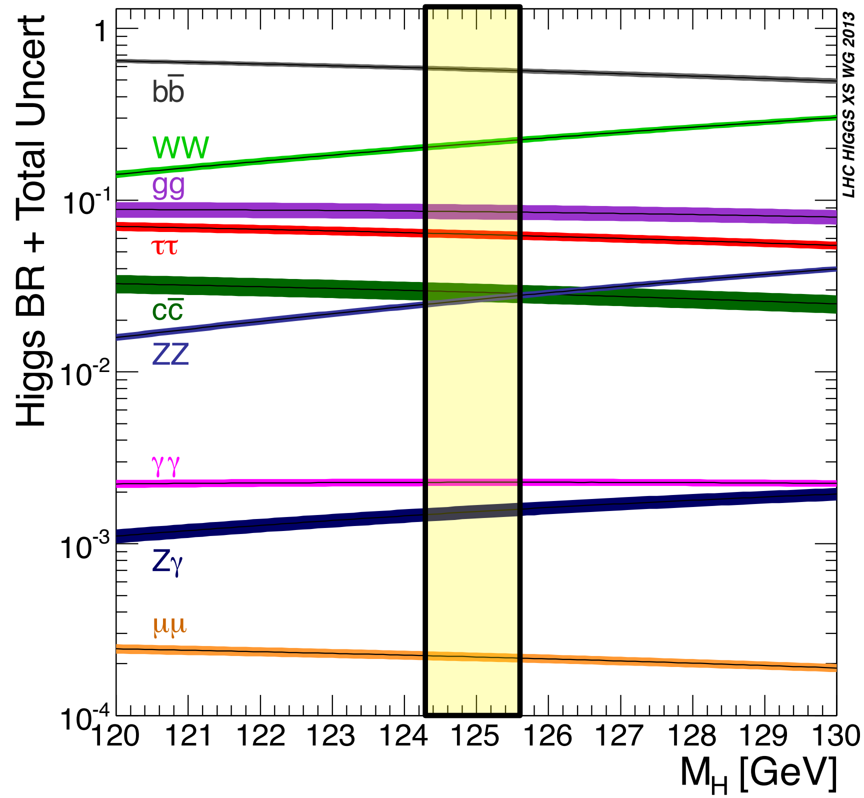


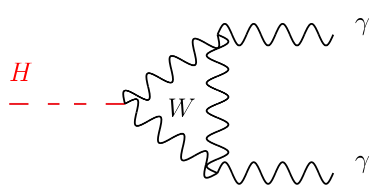
$$\propto 3.3\times\kappa_W^2 - 5.1\times\kappa_t\kappa_W + 2.8\times\kappa_t^2$$

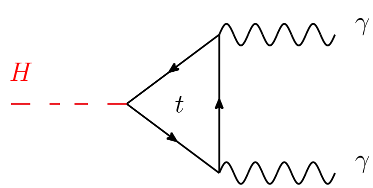
Higgs Decay Channels

- Dominant: bb (57%) $\propto \kappa_b^2 / \kappa_H^2$
- WW channel (22%) $\propto \kappa_W^2 / \kappa_H^2$
- $\tau\tau$ channel (6.3%) $\propto \kappa_\tau^2 / \kappa_H^2$
- ZZ channel (3%) $\propto \kappa_Z^2 / \kappa_H^2$
- cc channel (3%) $\propto \kappa_c^2 / \kappa_H^2$

  Extremely difficult
- The $\gamma\gamma$ channel (0.2%) $\propto \kappa_\gamma^2 / \kappa_H^2$







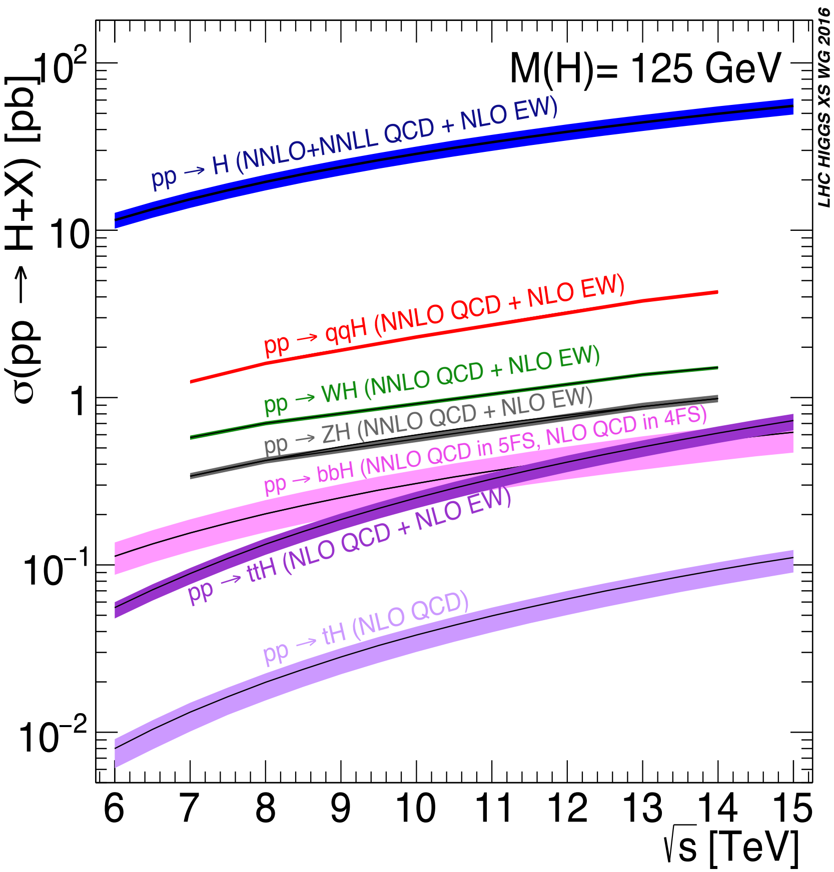
$$\kappa_\gamma \propto 1.6\times\kappa_W^2 - 0.7\times\kappa_t\kappa_W + 0.1\times\kappa_t^2$$

(when assuming no BSM charged in the loop)

- The $Z\gamma$ (0.2%) $\kappa_{Z\gamma} \propto 1.12\times\kappa_W^2 - 0.15\times\kappa_t\kappa_W + 0.03\times\kappa^2$
- The $\mu\mu$ channel (0.02%) $\propto \kappa_\mu^2 / \kappa_H^2$

$$\kappa_H^2 = \frac{\sum_f \Gamma_f}{\Gamma_{SM}} = 0.75\times\kappa_F^2 + 0.25\times\kappa_V^2$$

The gains of LHC Run 2



Increase in production cross section from 7 TeV to 13 TeV

ggH ~ 2.3

VBF ~ 2.4

VH ~ 2.9

ttH ~ 3.9

Ratio of parton-parton luminosities!

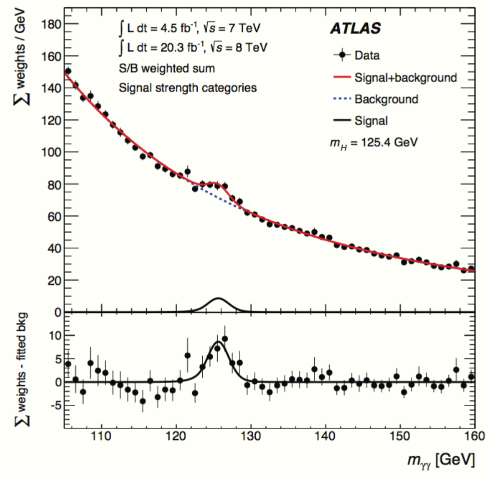
The discovery of the Higgs boson

The Economist

« A Giant Leap for Science »

The Discovery Channels

$pp\ (\rightarrow H)\ \rightarrow \gamma\gamma$



« Bread and Butter » Mass peak signals

Photon decay modes of the intermediate mass Higgs
ECFA Higgs working group
C.Seez and T. Virdee
L. DiLella, R. Kleiss, Z. Kunszt and W. J.Stirling

Presented at the LHC Workshop, Aachen, 4 - 9 October 1990
by C. Seez, Imperial College, London.

A report is given of studies of:
(a) H -> $\gamma\gamma$ (work done by C. Seez and T. Virdee)
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for Higgs bosons in the intermediate mass range ($90 < m_H < 150$ GeV/c^2).
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The decay channel $H^0 \to Z\gamma$ also appears to be potentially attractive, but, after requiring that the Z decay into electrons or muons, the combined branching fraction times cross-section is very small. The intrinsic background (i.e. the background with the same final state as the signal) is large and rules out the possibility of detecting the Higgs boson in this channel.

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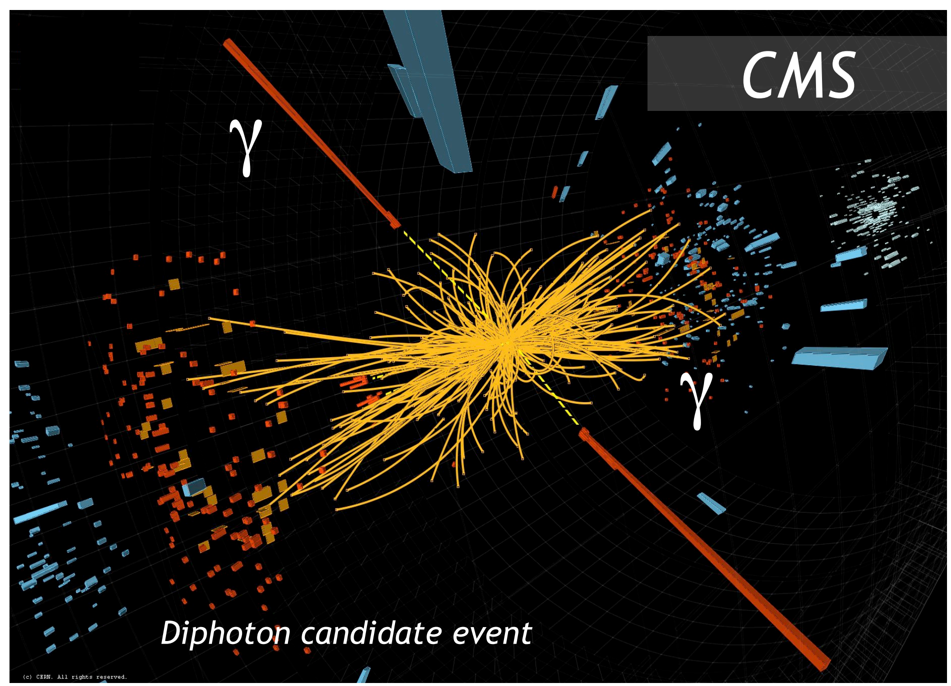
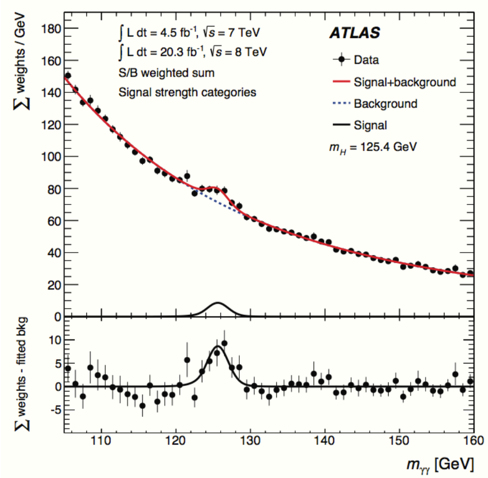


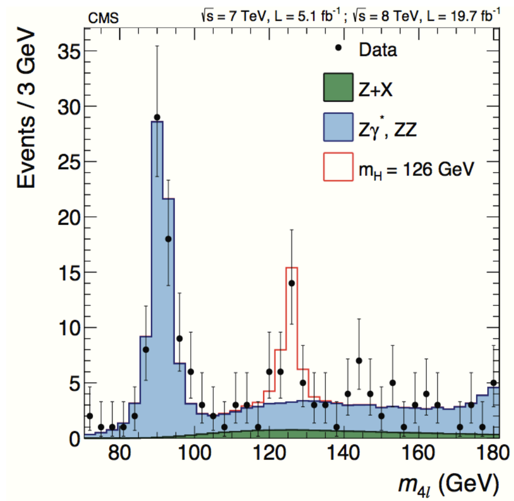
The Discovery Channels

FF

$pp\ (\to H) \to \gamma\gamma$



$pp\ (\to H) \to ZZ \to 4l$



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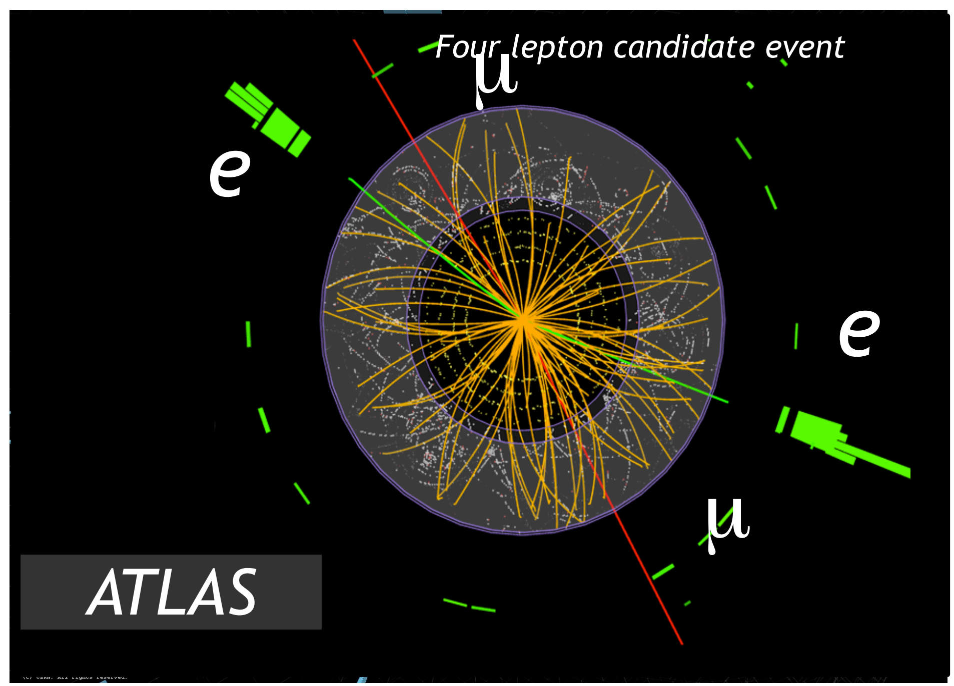

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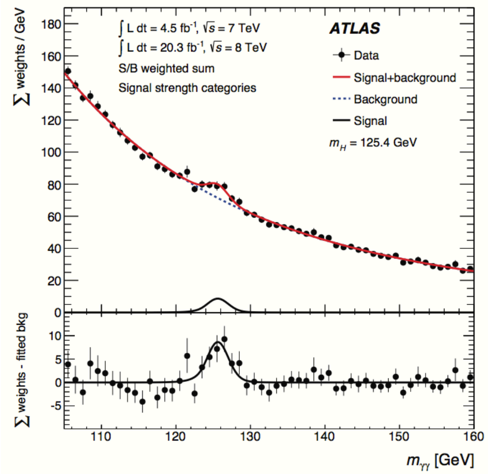

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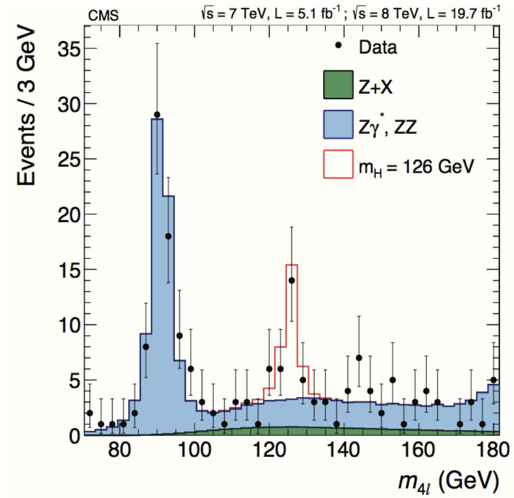
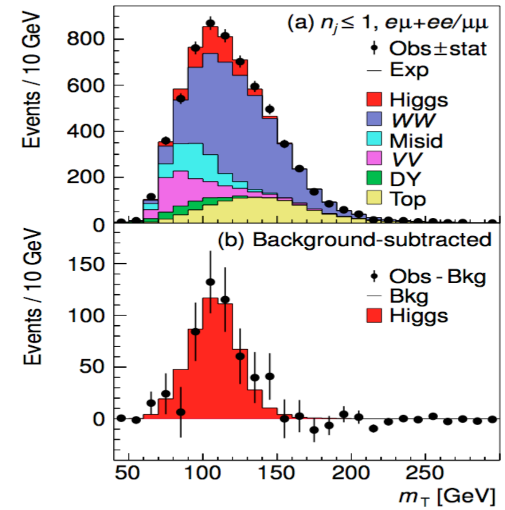


$pp\,(\rightarrow H) \rightarrow WW \rightarrow l\nu\, l\nu$



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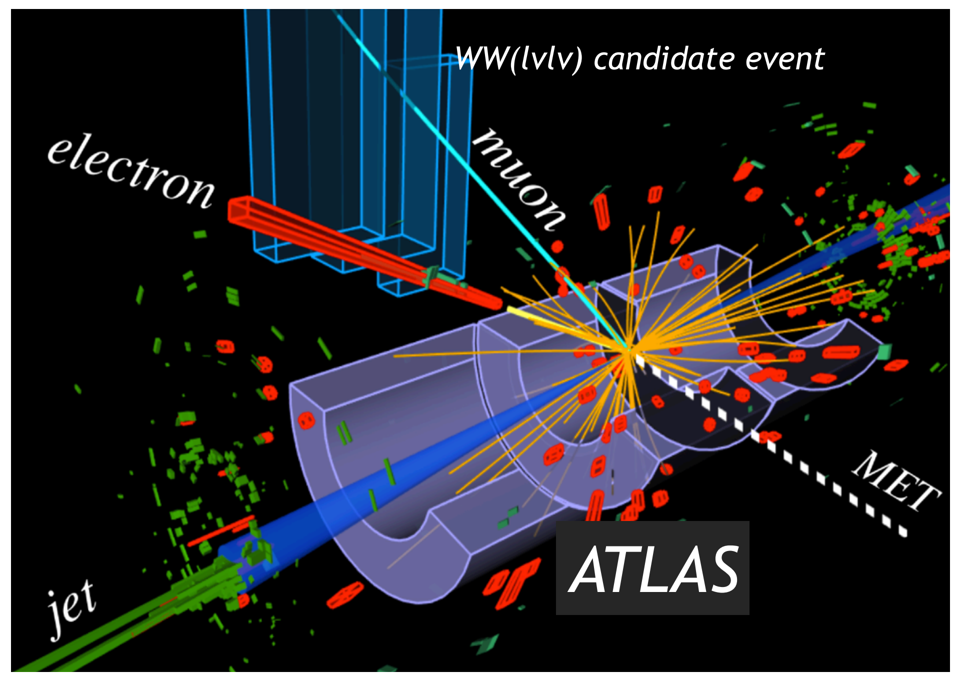
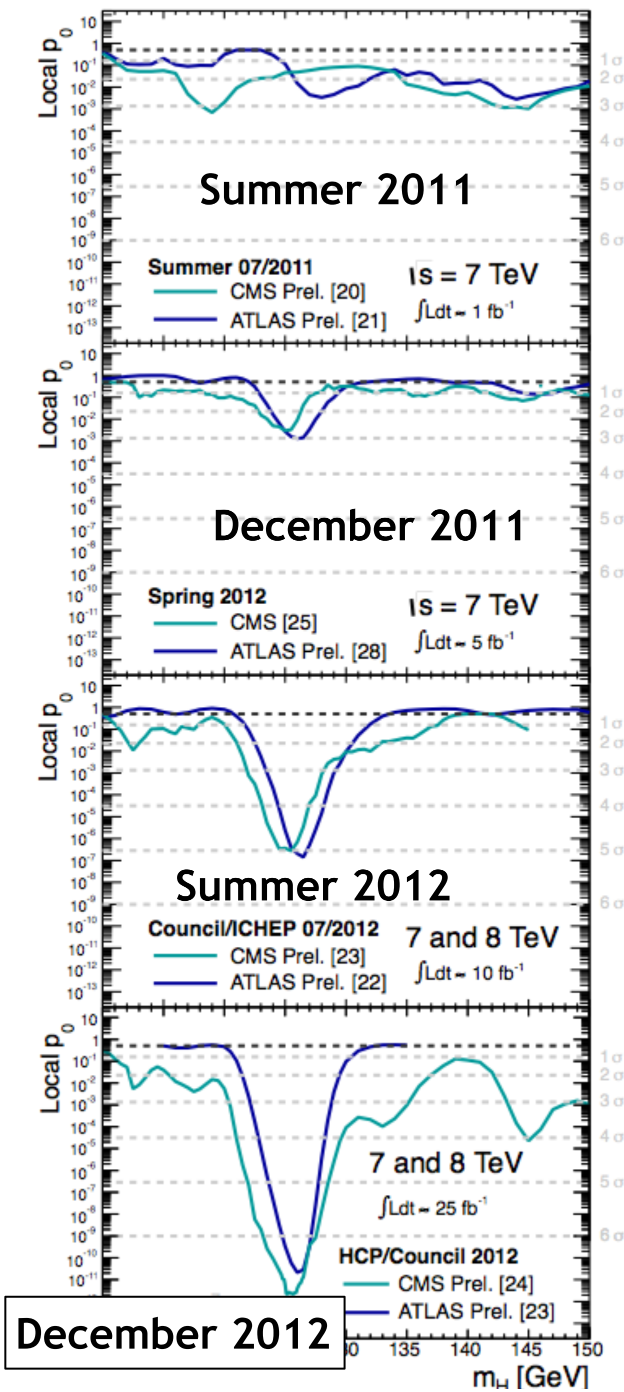


PDG, review of Particle Physics



A Textbook and Timely Discovery

- Summer 2011: EPS and Lepton-Photon
  First (and last) focus on limits (scrutiny of the p_0)
- December 2011: CERN Council
  First hints
- Summer 2012: CERN Council and ICHEP
  Discovery!
- December 2012: CERN Council
  Begining of a new era

✓ Strongly Motivated

✓ Significance increased with luminosity to reach unambiguous levels

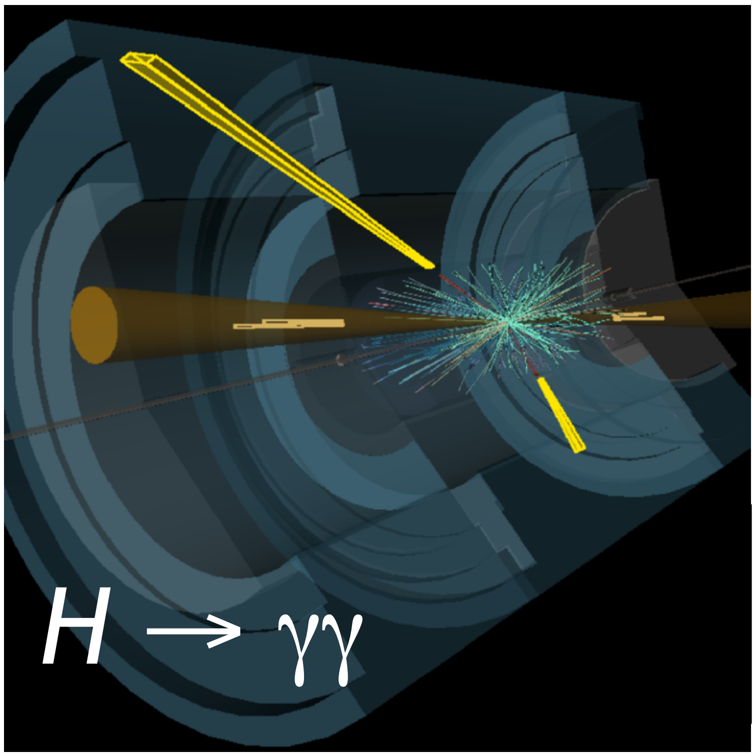
✓ Two experiments

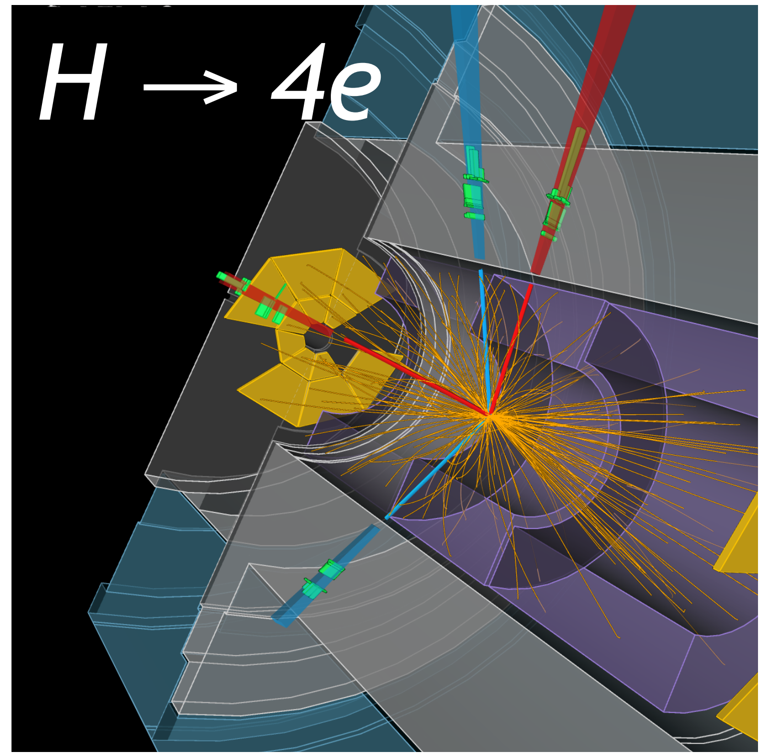
✓ Several channels

The two Main discovery Chanels

An excellent chanel for a Higgs boson near 125 GeV

The Golden chanel over a large range in mass

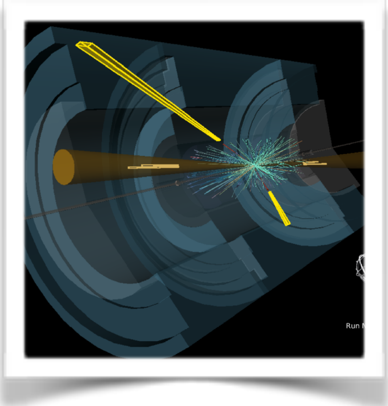




Inclusive approximate number of selected signal events

(at Run 1) $n_s \sim 500$ $n_s \sim 20-30$

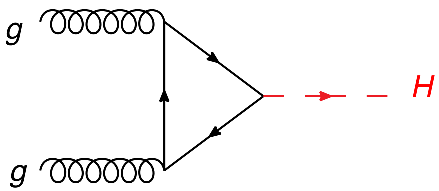
Very simple channels, with excellent mass resolution (unambiguous signatures)

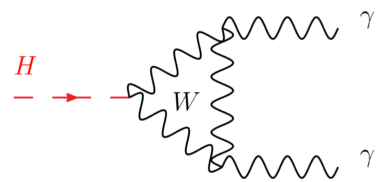


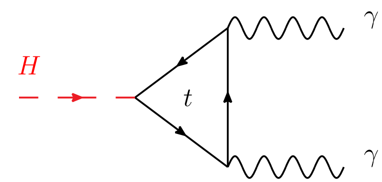
The γγ Channel

- Main production and decay processes occur through loops :

Excellent probe for new physics !







A priori potentially large possible enhancement…

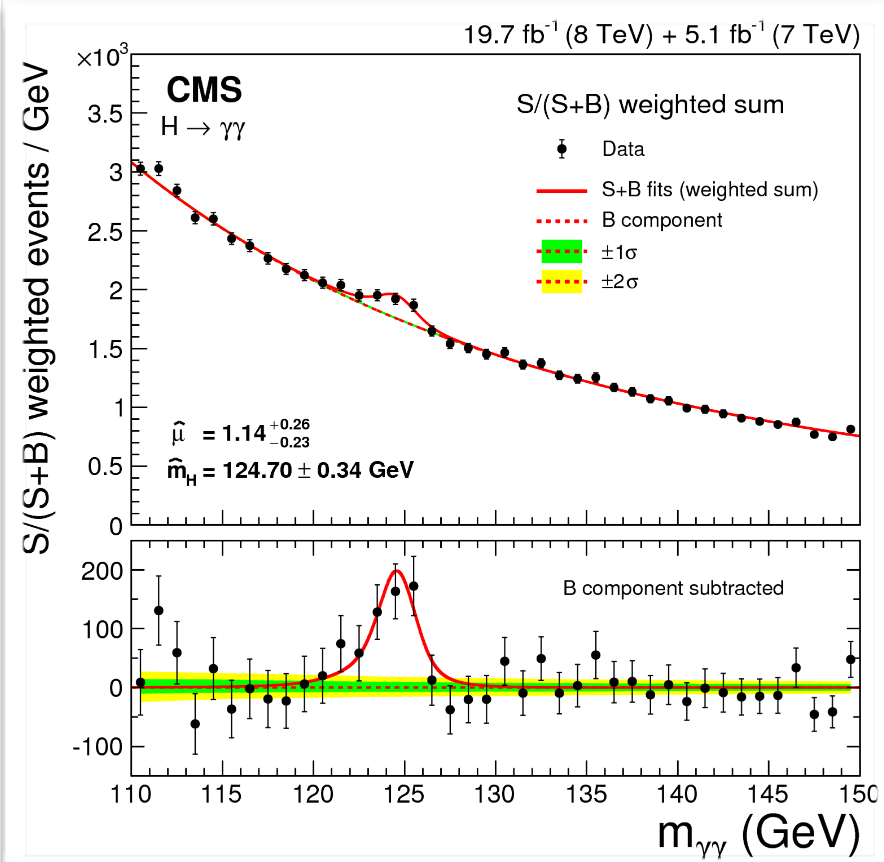
$$\kappa_\gamma \propto 1.6 \times \kappa_W^2 - 0.7 \times \kappa_t \kappa_W + 0.1 \times \kappa_t^2$$

… Not so obviously enhanced (e.g. SM4)

Seldom larger yields : e.g. NMSSM up to x6, large stau mixing, Fermiophobia…

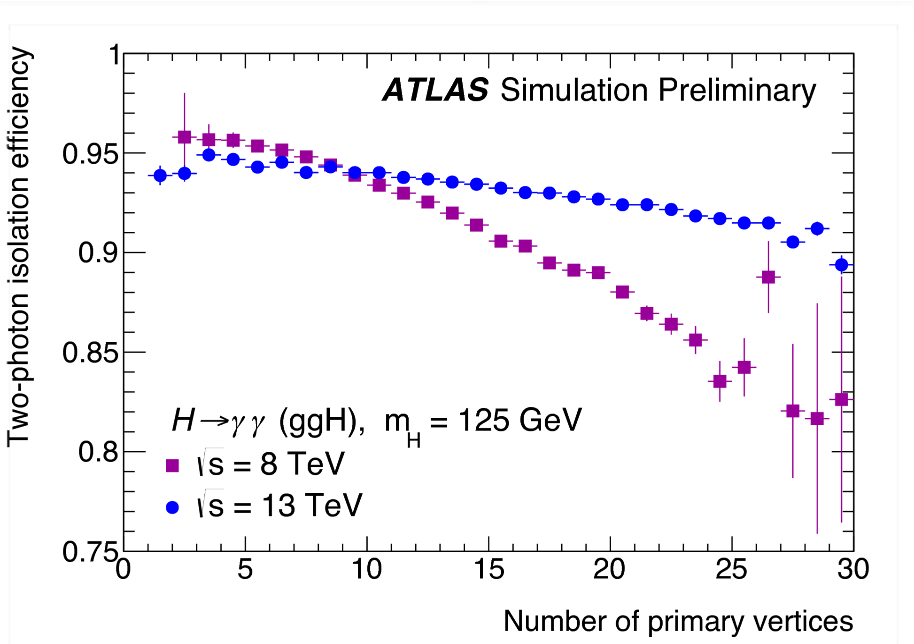
- High mass resolution channel
- If observed implies that it does not originate from spin 1 : Landau-Yang theorem
- If observed implies that its Charge Conjugation is +1 (assuming C and P separately conserved)

The Discovery and the Measurement are fully lead by two channels

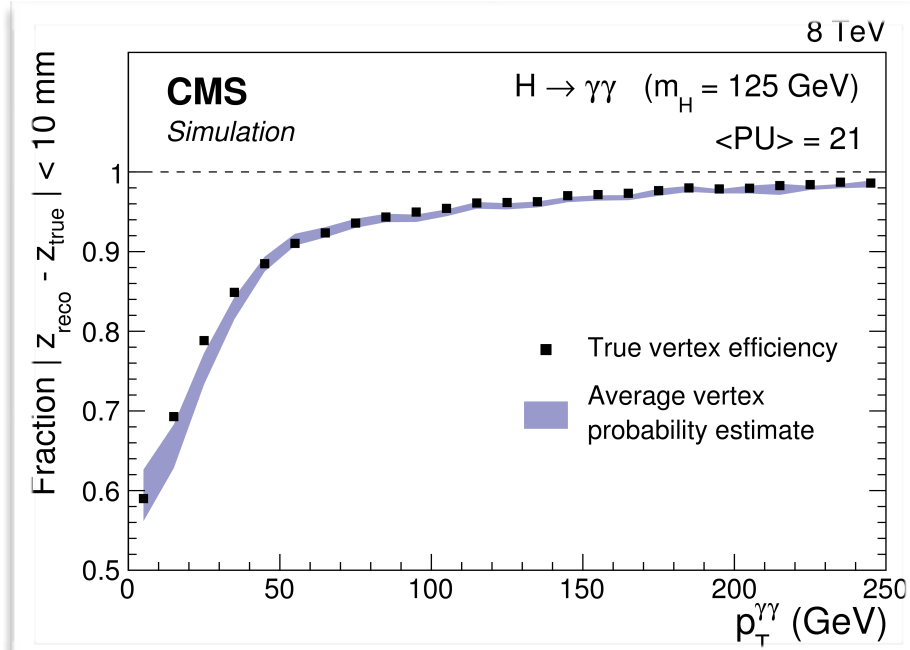


- s/b ratio ranging from few % to approximately 30%
- Uses exclusive production (VBF,VH and ttH) not for the mass measurement
- Uses Higgs pT as discriminating variable

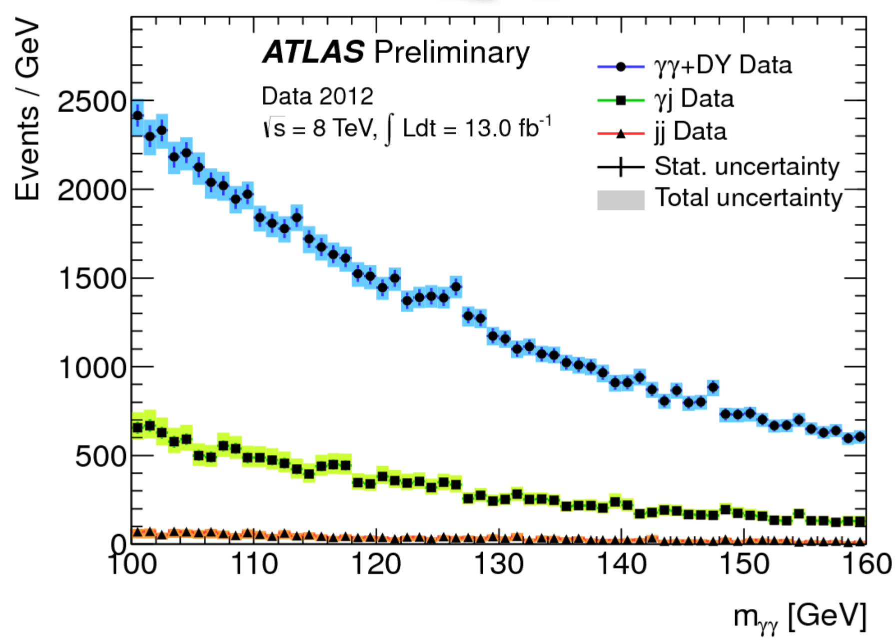
Isolated Photon Identification

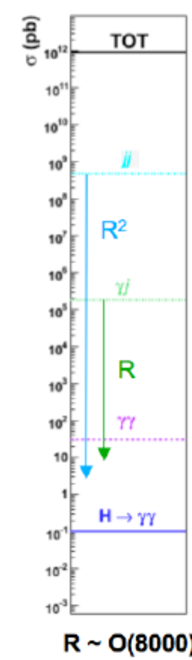


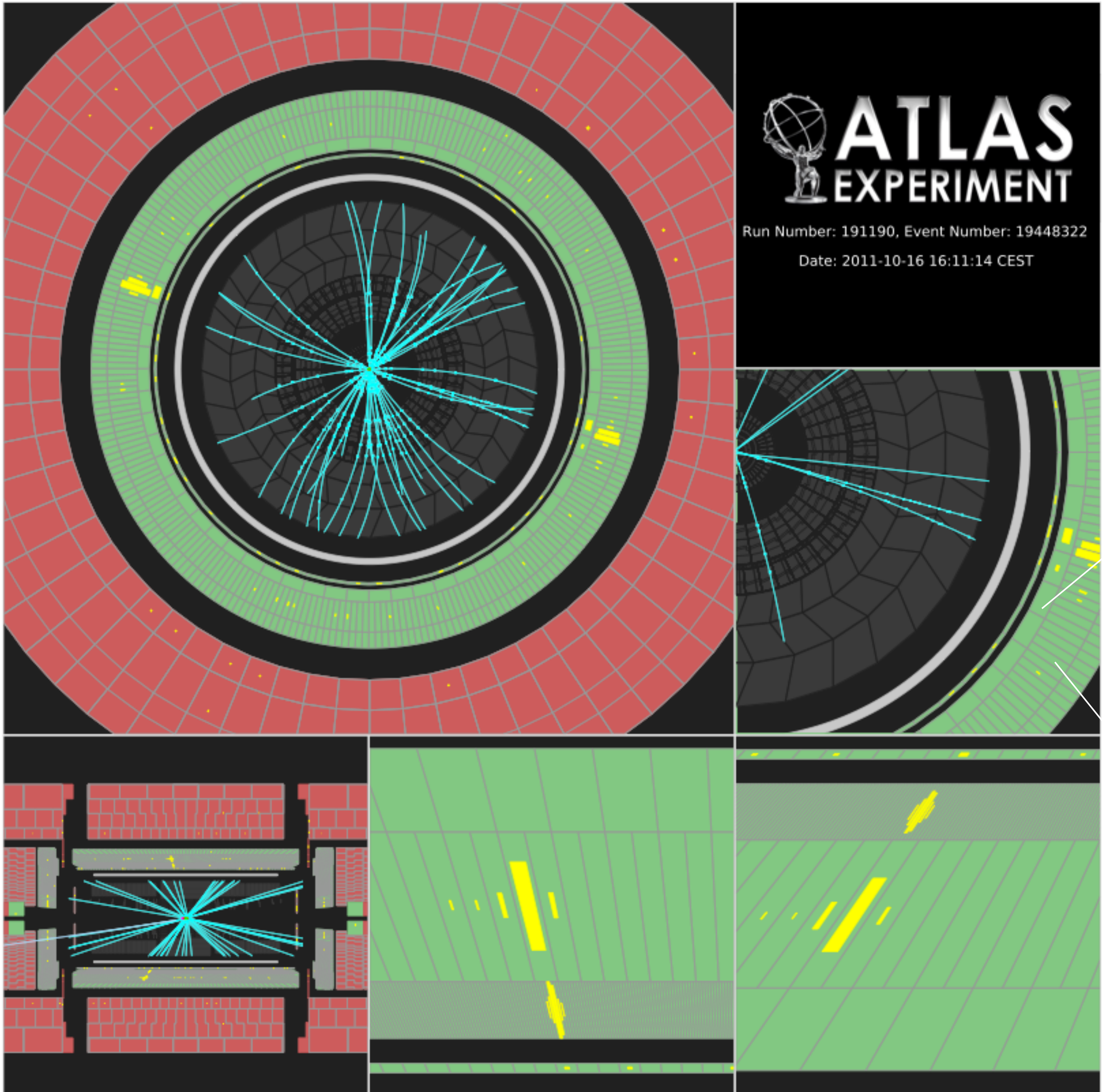
Primary vertex reconstruction



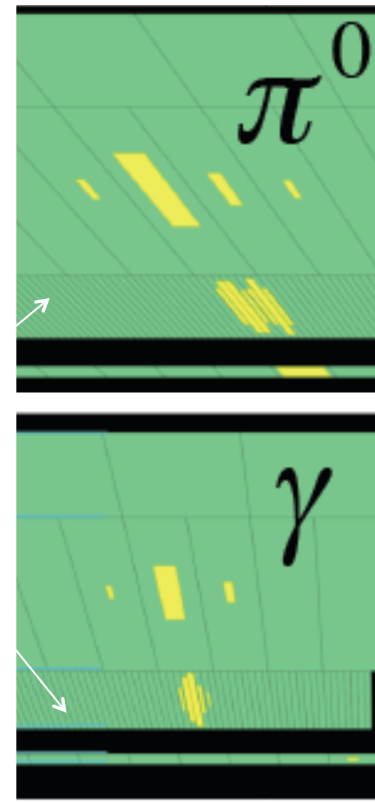
Bkg rejection





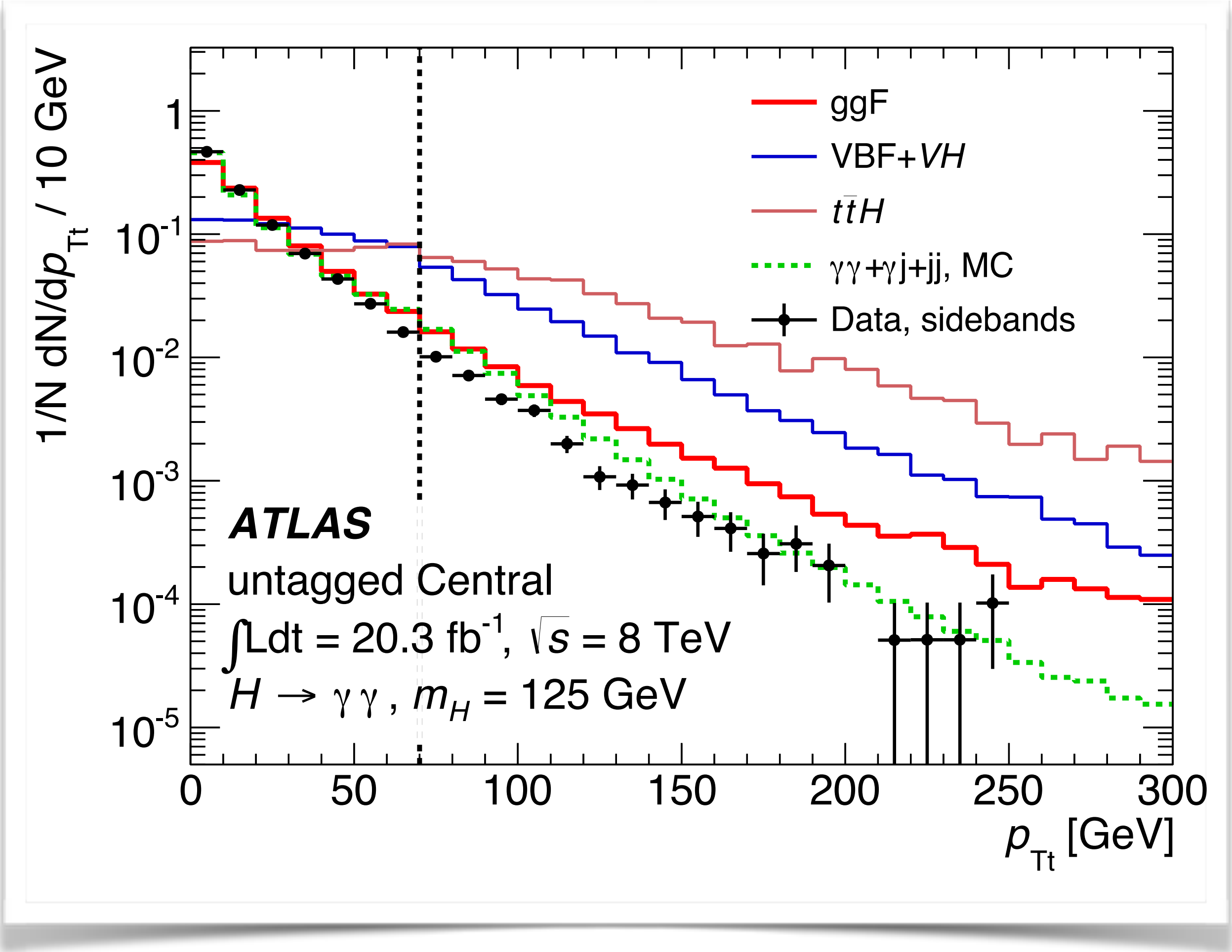


Background
From jets

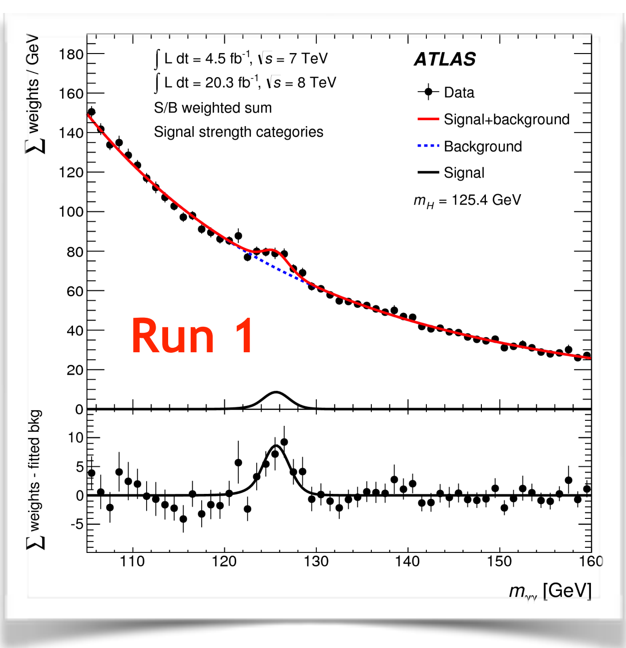


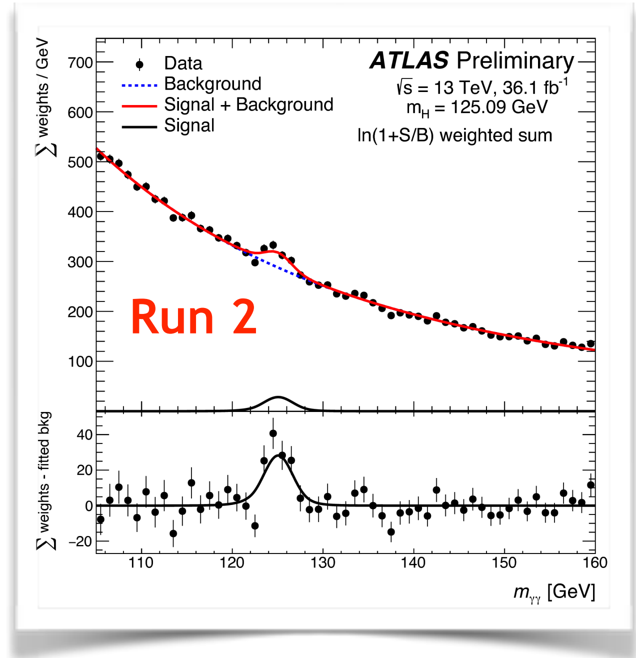
Signal

The Importance of the Higgs Boson Transverse Momentum



From Run 1 to Run 2

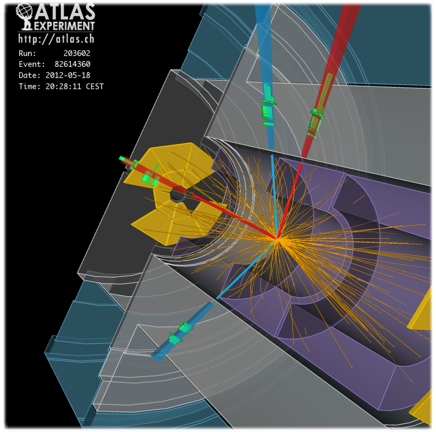




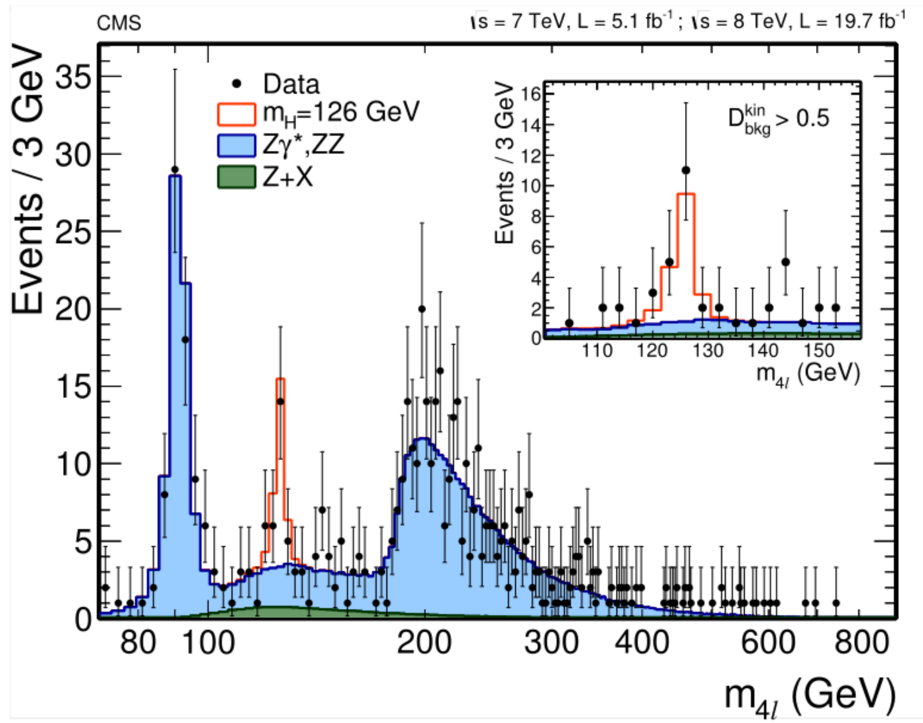
Comparison of results from CMS Run 2 vs. Run 1

Run 1 $$1.14 \pm 0.21\,(stat)\,{}^{+0.09}_{-0.05}\,(exp)\,{}^{+0.13}_{-0.09}\,(th)$$

Run 2 $$1.16^{+0.11}_{-0.10}\,(stat)\,{}^{+0.09}_{-0.08}\,(exp)\,{}^{+0.06}_{-0.05}\,(th)$$



The four lepton channel



- High s/b ratio from approximately 1.5 up to more than 10
- Uses exclusive production (VBF,VH and ttH)
- Uses Higgs pT as discriminating variable
- Uses angular variables to discriminate background

Key features

- One Z on mass shell

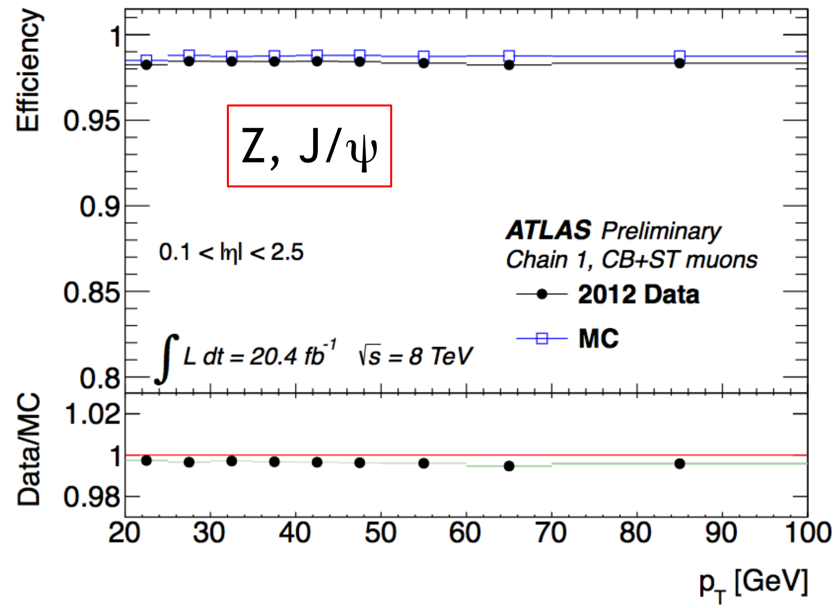
- Reconstruction and ID efficiencies from data with tag-and-probe analyses.

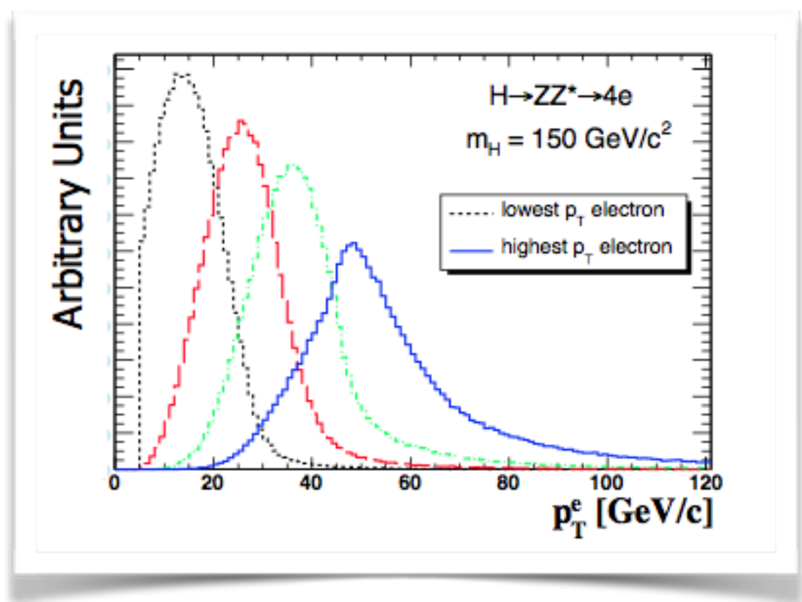
- low p_T lepton reconstruction very important

- Main Background ZZ from Monte Carlo or from high mass data

- Other backgrounds (Zbb and top) data driven (small)

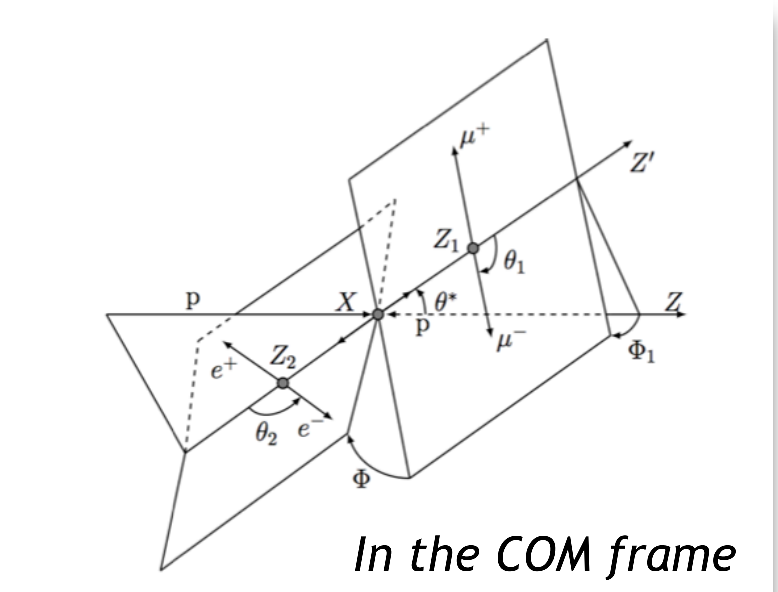
Muons

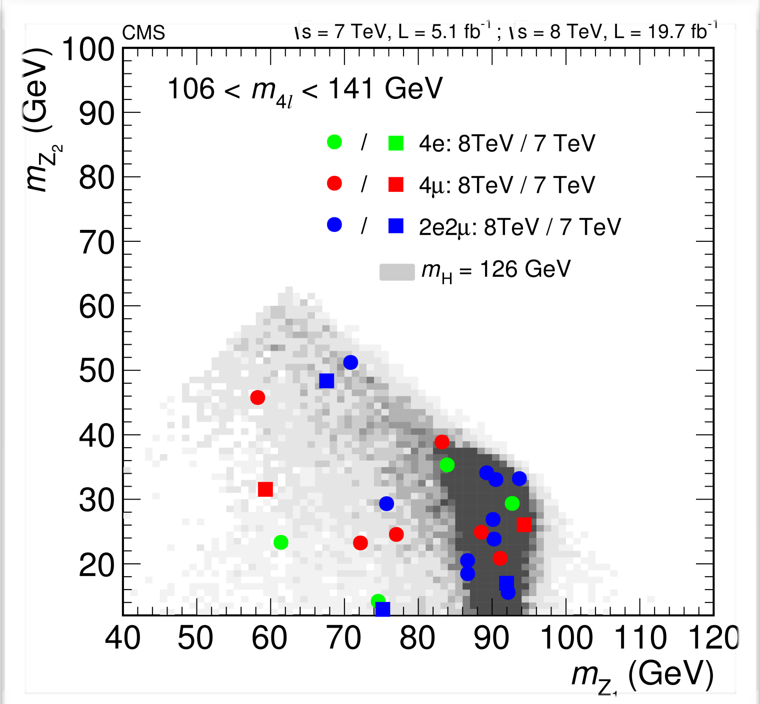


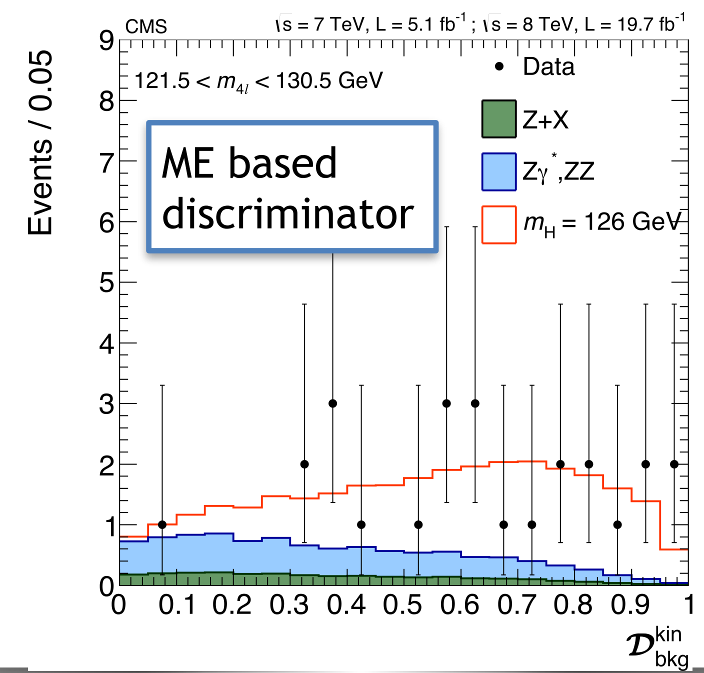


- Use distributions of 2 production and 3 decay angles
- … and the Z_1 and Z_2 masses

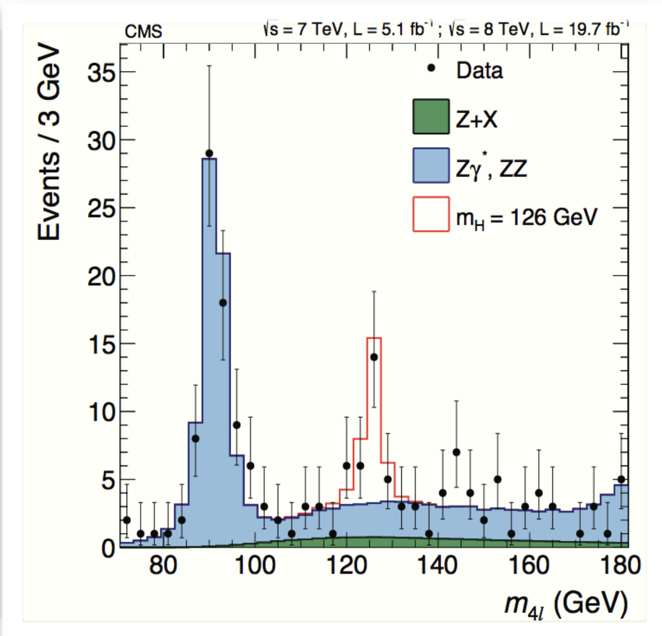
Combination of this information through LO Matrix Element based event probabilities or MVA

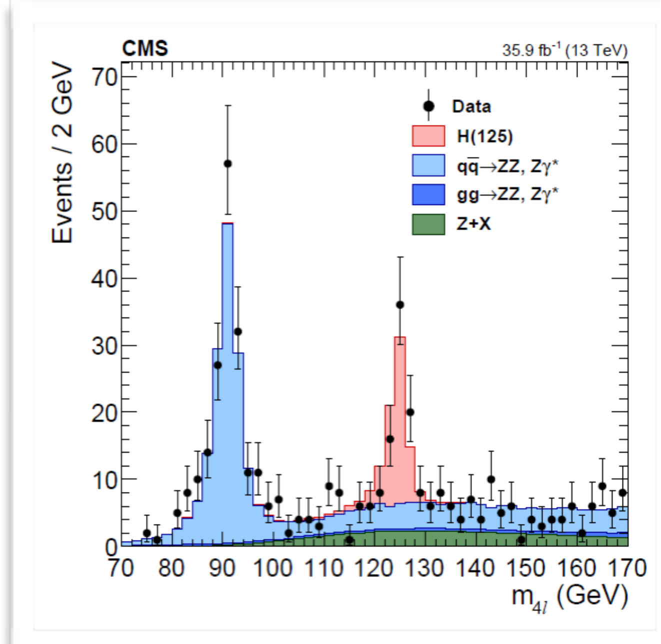






New Run 2 results





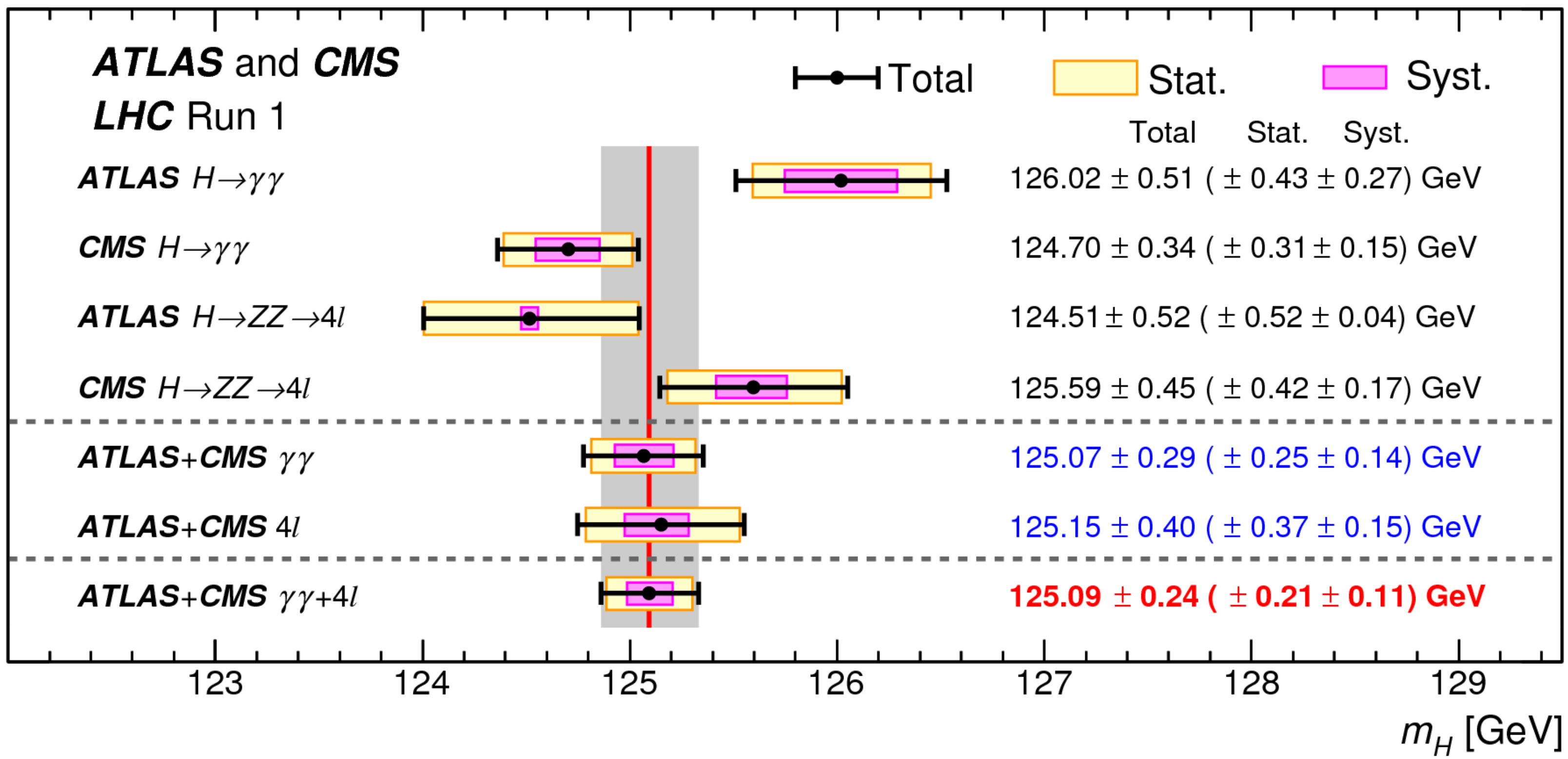
Comparison of results from ATLAS Run 2 vs. Run 1

Run 1 $$1.44^{+0.34}_{-0.31}\,(stat)\,^{+0.21}_{-0.11}\,(syst)$$

Run 2 $$1.73^{+0.24}_{-0.23}\,(stat)\,^{+0.10}_{-0.08}\,(exp)\;\pm 0.04\,(th)$$

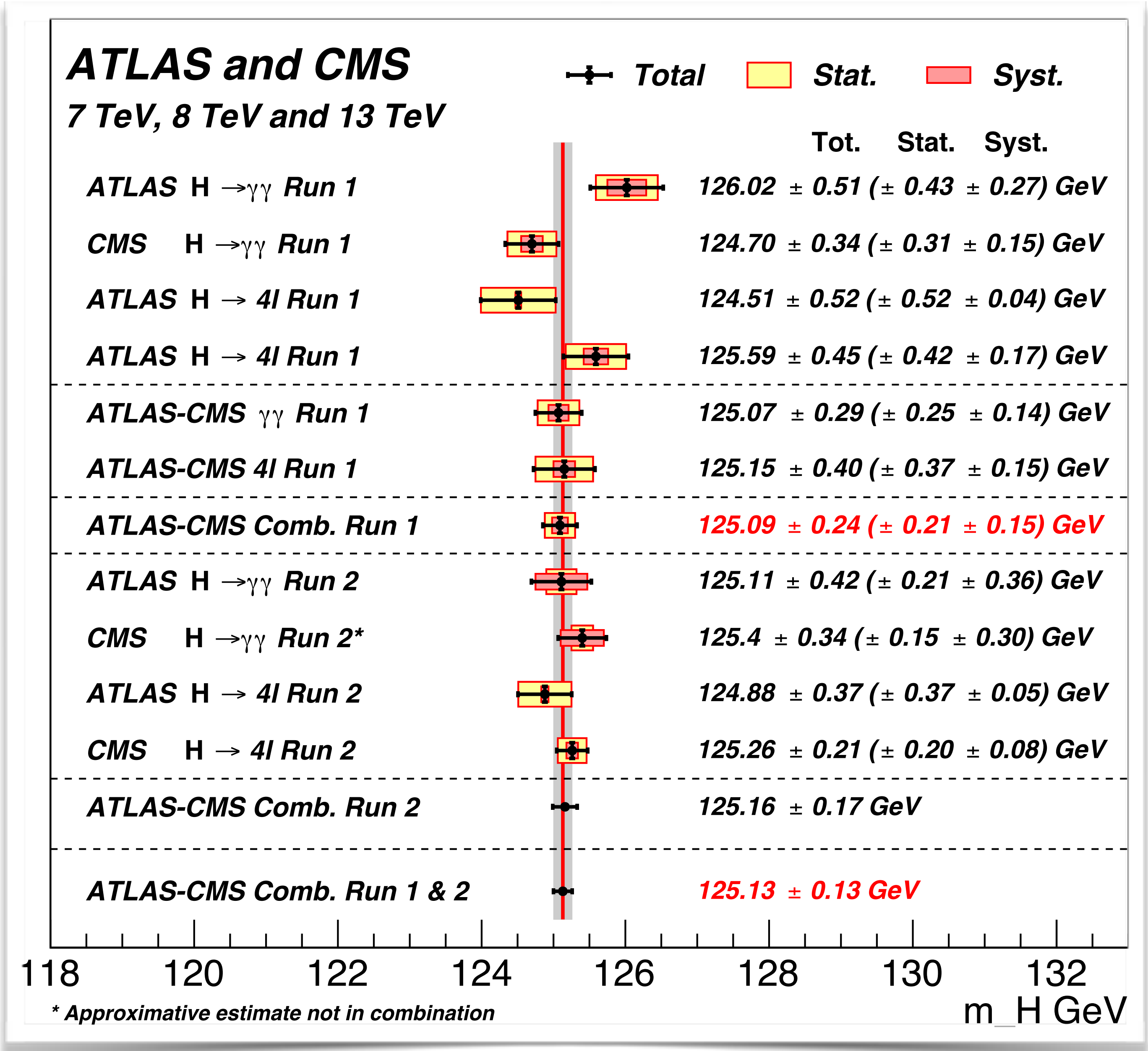
A measurement of fundamental importance

The fundamental new parameter that we learned is its mass (and if the Higgs potential is SM-like also its self coupling).



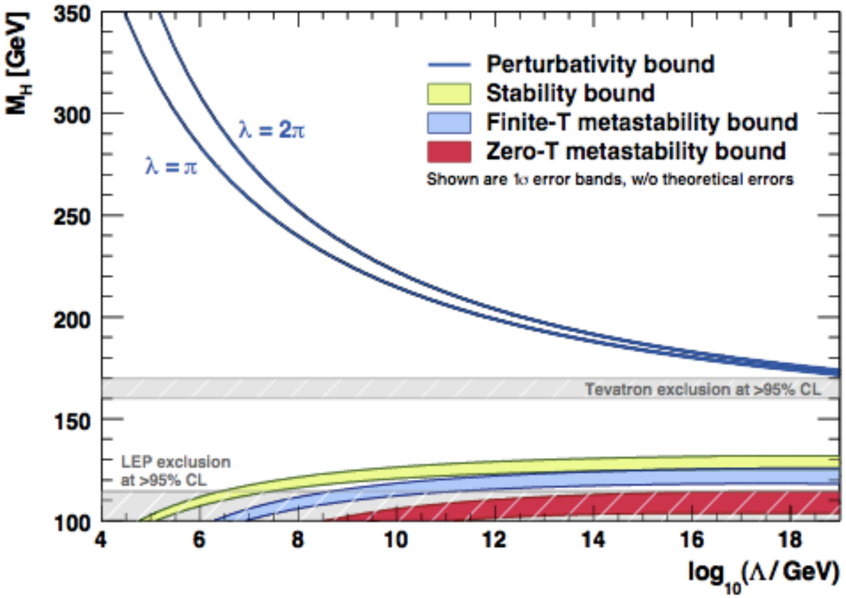
Run 1 2 per-mille precision Measurement, most precise measurement at the LHC until recently (W-boson mass)

From Run 1 to Run 2



1 per-mille precision Measurement.

Implications - TH consistency



With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.

Nima Arkani Hamed

- From the running of the self coupling (in the SM There is no need (or indication) that to preserve vacuum stability and avoid Landau pole (triviality) new physics is needed anywhere soon. With the measured value of the Higgs boson mass and **the top mass**, the self-coupling of the Higgs is vanishing at the Planck scale (is there an underlying principle to this?).

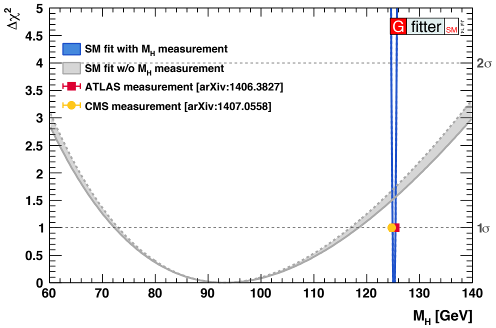
- With the Higgs discovery there is **no No Loose theorem anymore.**

Implications

$$\rho = 1$$

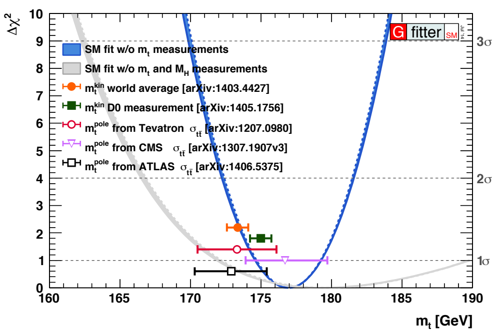
At tree level the EW gauge sector of the SM relies only on three free parameters (the fourth is determined, e.g. W mass from the precise knowledge of α, m_Z, G_F).

Higher order corrections introduce dependence on parameters from the Higgs and the fermion sectors, allowing precision electroweak data to yield indirect measurements (assuming SM)



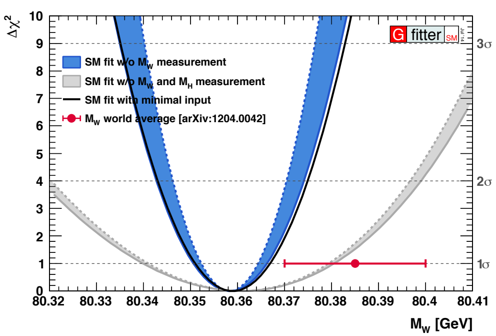
Higgs corrections are logarithmic in Higgs mass and yield indirect measurement in agreement with the direct one. Precise knowledge of the Higgs mass will not change this picture

$$\Delta\rho = -\frac{\alpha}{4\pi}\log\frac{m_H^2}{m_Z^2}$$



The larger corrections from the top and the knowledge of the Higgs mass yield a precise indirect constraint, however not competitive with the direct measurement.

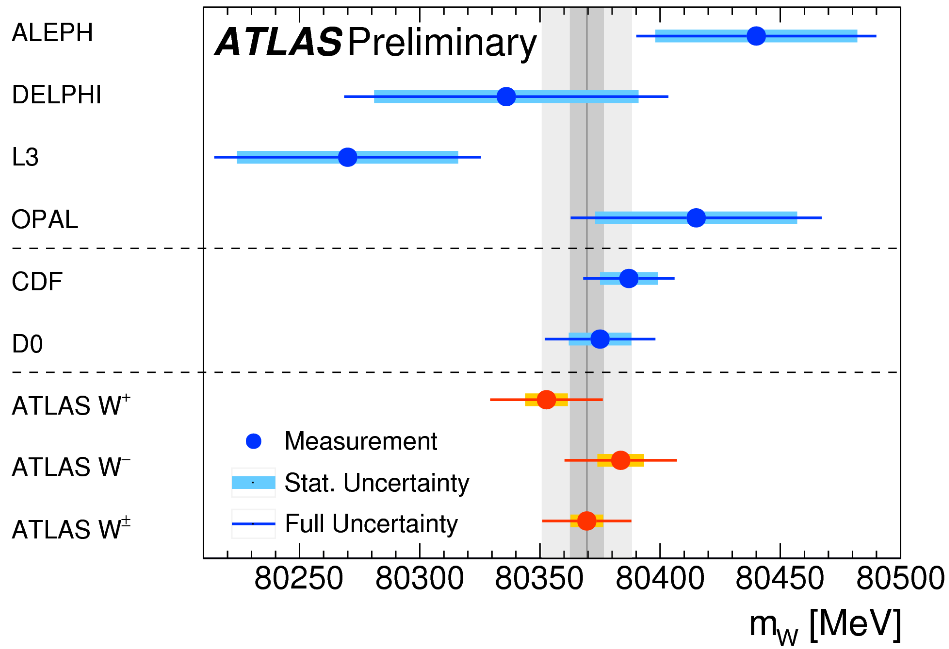
$$\Delta\rho = \frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2}$$



The knowledge of the Higgs mass has also improved the indirect W mass measurement at a precision (8 MeV) tice better than the WA (15 MeV) as of two weeks ago…

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

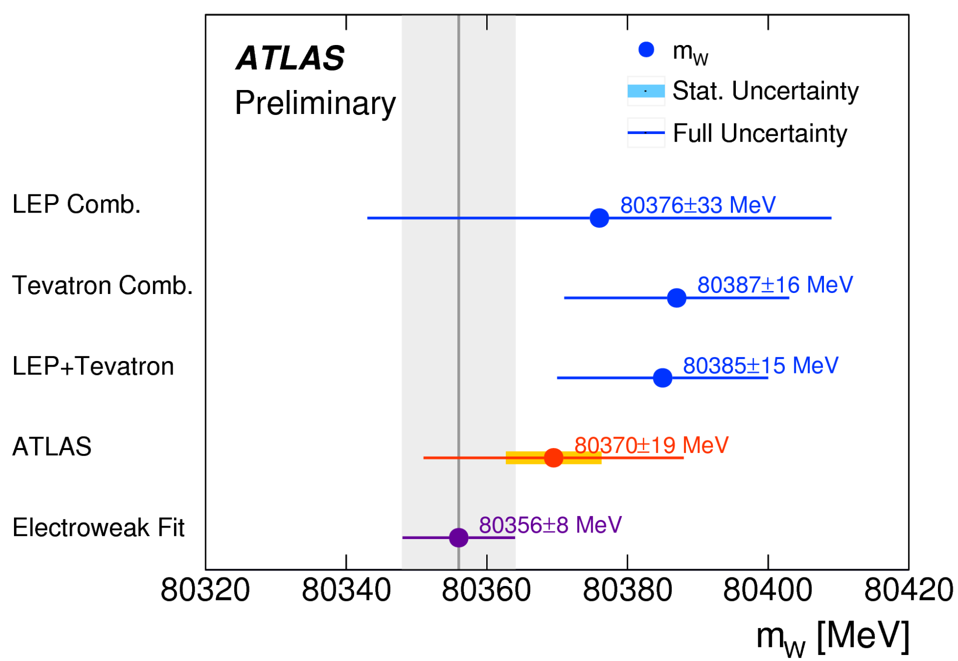
More precise measurement of the Higgs mass will not change this picture.



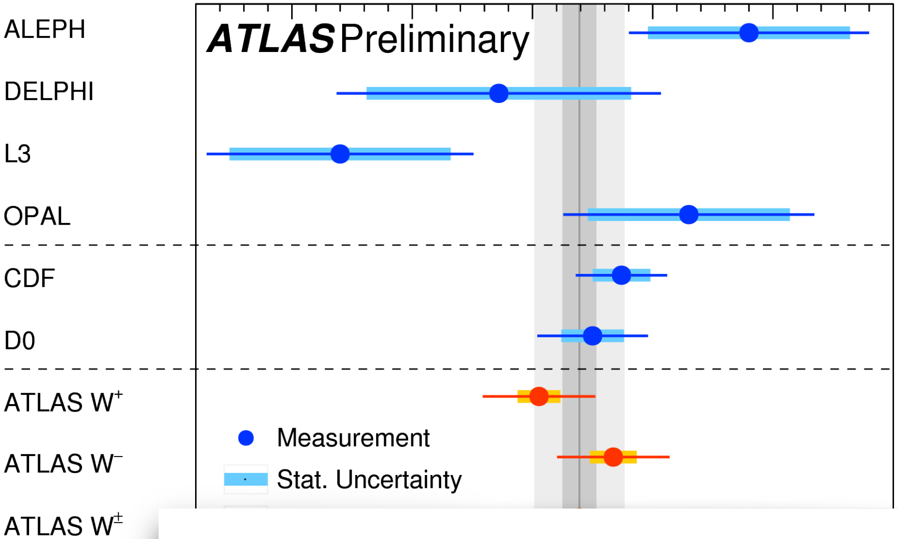
$$m_W = 80369.5 \pm 18.5 MeV$$
$$(\pm 6.8\,(Stat)$$
$$\pm 10.6\,(Exp.\,Sys.)$$
$$\pm 13.6\,(Mod.\,Sys.)\,MeV)$$

Best individual experiment ex-aequo with CDF measurement (CDF measurement has larger statistical component 12 MeV smaller systematics - still dominated by PDFs)

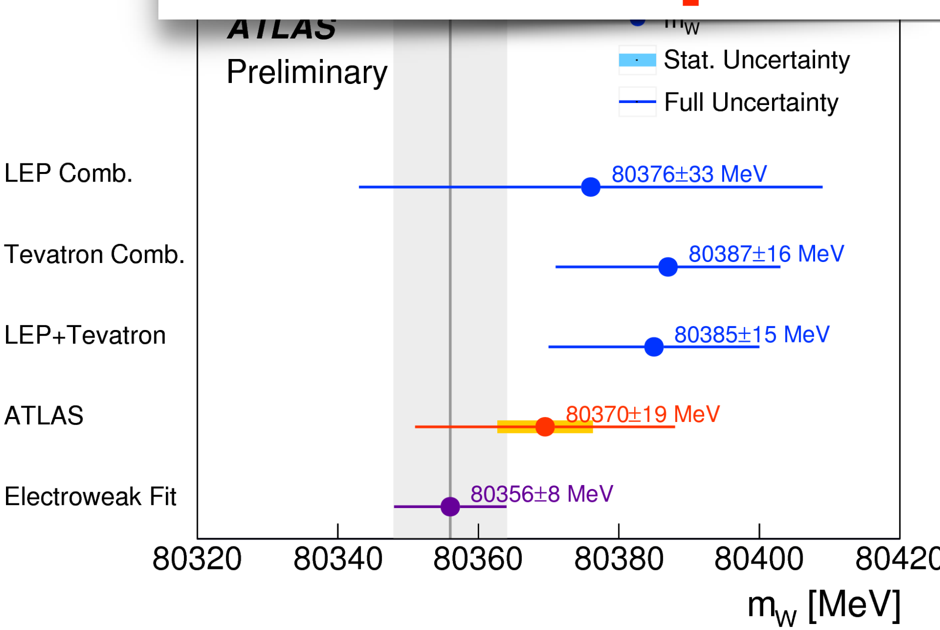
- Muon channel weighs 57% in the measurement
- The pT lepton measurement dominates weighing 86%
- Charges contribute similarly 52% vs 48%



- Modeling systematic uncertainties are largest (PDF uncertainties are dominant among modeling systematics)
- Experimental calibration systematics not negligible.



Triumph of the SM



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Backup

QCD Unbroken "simplicity"

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\Psi} \not{D} \psi \quad + h.c.$$

$SU(3)$ Color is an exact symmetry

Unbroken: gluons are massless

Simplicity: Only one free parameter g_s

QCD is flavor blind

The QCD Lagrangian:

$$\mathcal{L} = -\frac{1}{4} \sum_i F^i_{\mu\nu} F^{i\mu\nu} + \sum_r \overline{q}_{r\alpha} (i \not{D}^\alpha_\beta - m_r) q^\beta_r$$

Field strength (including gluon self interaction):

$$F^i_{\mu\nu} = \partial_\mu G^i_\nu - \partial_\nu G^i_\mu - g_s f_{ijk} G^j_\mu G^k_\nu$$

Covariant derivative – interaction with quarks (t^a_{ij} color matrices)

$$\not{D}^\mu_{ij} = \partial^\mu \delta_{ij} + i g_s t^a_{ij} G^\mu_a$$

From SC to SSB in Particle Physics

SC (BCS) Theory

1950 – Landau and Ginzburg
JETP 20 (1950) 1064

1957 – Bardeen, Cooper and Schrieffer
Phys. Rev. 108 (1957) 1175

1958 – P. W. Anderson
Phys. Rev. 112 (1958) 1900
SC and gauge invariance

1963 – P. W. Anderson
Phys. Rev. 130 (1963) 439
Gauge field with mass (non relativistic)

Particle Theory

1954 - Yang-Mills theories for non abelian gauge interactions

1957-59 – Schwinger, Bludman and Glashow introduce W bosons for the weak charged currents...

... but local gauge symmetry forbids gauge bosons masses.

1962 – J. Schwinger
Phys. Rev. 125 (1962) 397
Gauge invariance and mass

1964 – W. Gilbert Phs. Rev. Lett 12 (1964) 713

Thought to be impossible in relativistic theories !

Spontaneous Symmetry Breaking (SSB)

Nambu (1960) and Goldstone (1961)

Massless scalars occur in a theory with SSB… but not only
The symmetry is not apparent (hidden) in the ground state

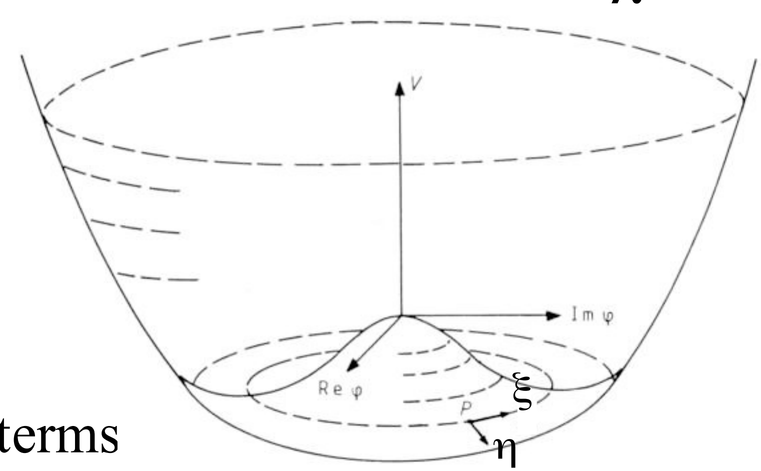
From a simple (complex) scalar theory with a U(1) symmetry

$$\varphi = \frac{\phi_1 + i\phi_2}{\sqrt{2}} \qquad L = \partial_\nu \varphi^* \partial^\nu \varphi - V(\varphi) \qquad V(\varphi) = \mu^2 \varphi^* \varphi + \lambda(\varphi^* \varphi)^2$$

The Lagrangian is invariant under : $\varphi \rightarrow e^{i\alpha}\varphi$

$$v = -\frac{\mu^2}{\lambda}$$

Shape of the potential if $\mu^2<0$ and $\lambda>0$ necessary for SSB and be bounded from below.



Change frame to local minimum frame :

$$\varphi = \frac{v + \eta + i\xi}{\sqrt{2}}$$

No loss in generality.

$$L = \underbrace{\frac{1}{2}\partial_\nu \xi \partial^\nu \xi}_{\text{Massless scalar}} + \frac{1}{2}\partial_\nu \eta \partial^\nu \eta + \underbrace{\mu^2 \eta^2}_{\text{Massive scalar}} + \text{interaction terms}$$

Digression on Chiral Symmetry

In the massless quarks approximation : $SU(2)_L x SU(2)_R$ the chiral symmetry is an (approximate) global symmetry of QCD

The chiral symmetry is broken by means of coherent states of quarks (which play a role similar to the cooper pairs in the BCS superconductivity theory)

It is a Dynamical Symmetry Breaking where the pseudo-goldstone bosons are the π^+, π^0, π^- mesons

And the massive scalar is also there : the sigma!

This is the basis of the construction of an effective field theory ChPT allowing for strong interaction calculations at rather low energy

$|D_\mu \phi|^2$

EW Spontaneous Symmetry Breaking

$$SU(2)_L \times U(1)_Y$$

Introducing a double of complex scalar fields (4 d.o.f.) : $\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^o \end{pmatrix}$

Setting aside the gauge kinematic terms the Lagrangian can be written :

$$\mathcal{L} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi) \qquad \begin{cases} D_\mu = \partial_\mu - ig\vec{W}_\mu.\vec{\sigma} - ig'\frac{Y}{2}B_\mu \\ V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 \end{cases}$$

The next step is to develop the Lagrangian near : $<\phi>= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

Choosing the specific real direction of charge 0 of the doublet is not fortuitous : $\phi = e^{-i\vec{\sigma}.\vec{\xi}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H + v \end{pmatrix}$ Non electrically charged vacuum

Again choosing the gauge that will absorb the Goldstone bosons ξ…

Spontaneous Local Symmetry Breaking (SSB)

Let the aforementioned continuous symmetry U(1) be local : $\alpha(x)$ now depends on the space-time x.

$$\varphi \to e^{i\alpha(x)}\varphi$$

The Lagrangian can now be written : $L = (D_\nu \varphi)^* D^\nu \varphi - V(\varphi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$

In terms of the covariant derivative : $D_\nu = \partial_\nu - ieA_\nu$

The gauge invariant field strength tensor : $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$

And the Higgs potential : $V(\varphi) = \mu^2 \varphi^* \varphi + \lambda(\varphi^* \varphi)^2$

Here the gauge field transforms as : $A_\mu \to A_\mu + \frac{1}{e}\partial_\mu \alpha$

Again translate to local minimum frame : $\varphi = \dfrac{v + \eta + i\xi}{\sqrt{2}}$

$$L = \frac{1}{2}\partial_\nu \xi \partial^\nu \xi + \frac{1}{2}\partial_\nu \eta \partial^\nu \eta + \mu^2 \eta^2 - v^2 \lambda \eta^2 + \frac{1}{2}\underbrace{e^2 v^2 A_\mu A^\mu} - evA_\mu \partial^\mu \xi - F^{\mu\nu} F_{\mu\nu} + \mathrm{ITs}$$

Mass term for the gauge field! But…

Then developing the covariant derivative for the Higgs field :

Just replacing the Pauli matrices :

$$D_\mu\varphi = \partial_\mu\varphi - \frac{i}{2}\begin{pmatrix} gW_\mu^3 + g'B_\mu & g(W_\mu^1 - iW_\mu^2) \\ g(W_\mu^1 + iW_\mu^2) & -gW_\mu^3 + g'B_\mu \end{pmatrix}\varphi$$

Then using : $W_\mu^\pm = \dfrac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}}$

$$D_\mu\varphi = \partial_\mu\varphi - \frac{i}{2}\begin{pmatrix} gW_\mu^3 + g'B_\mu & \sqrt{2}gW_\mu^+ \\ \sqrt{2}gW_\mu^- & -gW_\mu^3 + g'B_\mu \end{pmatrix}\varphi = \begin{pmatrix} 0 \\ \partial_\mu h \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \sqrt{2}gvW_\mu^+ + \sqrt{2}ghW_\mu^+ \\ -gvW_\mu^3 + g'vB_\mu - ghW_\mu^3 + g'hB_\mu \end{pmatrix}$$

For the mass terms only :

$$(D_\mu\varphi)^+ D^\mu\varphi = \partial_\mu h\partial^\mu h + \frac{1}{4}g^2v^2W_\mu^+W^{-\mu} + \frac{1}{8}(W_\mu^3 \quad B_\mu)\begin{pmatrix} g^2v^2 & -gg'v^2 \\ -gg'v^2 & g'^2v^2 \end{pmatrix}\begin{pmatrix} W^{3\mu} \\ B^\mu \end{pmatrix}$$

Explicit mixing of W^3 and B.

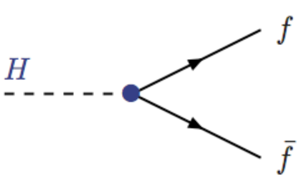
The Lagrangian can then be written :

$$
\begin{aligned}
\mathcal{L} \;=\;& \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}\lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4}H^4 \\
&+ \frac{1}{2}\left[\frac{g'^2 v^2}{4} B_\mu B^\mu - \frac{g g' v^2}{2} W^3_\mu B^\mu + \frac{g^2 v^2}{4}\vec{W}_\mu . \vec{W}^\mu\right] \\
&+ \frac{1}{v}\left[\frac{g'^2 v^2}{4} B_\mu B^\mu H - \frac{g g' v^2}{2} W^3_\mu B^\mu H + \frac{g^2 v^2}{4}\vec{W}_\mu . \vec{W}^\mu H\right] \\
&+ \frac{1}{2v^2}\left[\frac{g'^2 v^2}{4} B_\mu B^\mu H^2 - \frac{g g' v^2}{2} W^3_\mu B^\mu H^2 + \frac{g^2 v^2}{4}\vec{W}_\mu . \vec{W}^\mu H^2\right]
\end{aligned}
$$

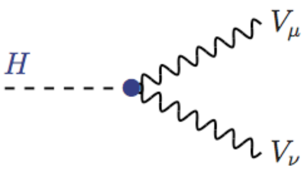
Massive scalar : The Higgs boson

Massive gauge bosons

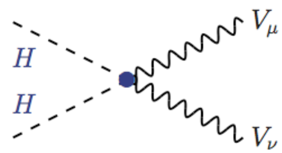
Gauge-Higgs interaction



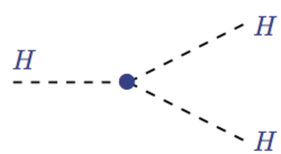
$$g_{Hff} = m_f/v$$



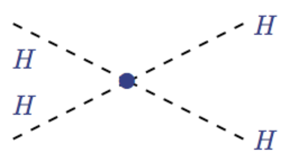
$$g_{HVV} = 2M_V^2/v$$



$$g_{HHVV} = 2M_V^2/v^2$$



$$g_{HHH} = 3M_H^2/v$$



$$g_{HHHH} = 3M_H^2/v^2$$

Keep this in mind for the next lectures…

What about the field content?

A massless Goldstone boson ξ a massive scalar η and a massive gauge boson!

Number of d.o.f. : 1 1 1

Number of initial d.o.f. : 2 Does not match!

But wait! The term $evA_\mu \partial^\mu \xi$ is unphysical

The Lagrangian should be re-written using a more appropriate expression of the translated scalar field choosing a particular gauge where h(x) is real :

$$\varphi = (v + h(x))e^{i\frac{\theta(x)}{v}}$$

Gauge fixed to absorb θ

Then the gauge transformations are : $\varphi \rightarrow e^{-i\frac{\theta(x)}{v}}\varphi \qquad A_\mu \rightarrow A_\mu + \frac{1}{ev}\partial_\mu \theta$

$$L = \frac{1}{2}\partial_\nu h \partial^\nu h - \lambda v^2 h^2 - \lambda v h^3 - \frac{1}{4}\lambda h^4$$ Massive scalar : The Higgs boson

$$+(1/2)e^2 v^2 A_\mu A^\mu - F^{\mu\nu}F_{\mu\nu}$$ Massive gauge boson

$$+(1/2)e^2 A_\mu A^\mu h^2 + ve^2 A_\mu A^\mu h$$ Gauge-Higgs interaction

The Goldstone boson does not appear anymore in the Lagrangian

Consequences of the mechanism :

1.- Two massive charged vector bosons *(charged currents)* :

$$m_W^2 = \frac{g^2 v^2}{4}$$

Thus v = 246 GeV

The theory (and gauge group) was chosen to describe charged current interactions

2.- One massless vector boson : $m_\gamma = 0$

The photon corresponding to the unbroken $U(1)_{EM}$

Consequence of developing the Higgs field along the neutral and real part of the doublet

Predictions :

1.- One massive neutral vector boson Z: *(Neutral currents not discovered at the t*

$$m_Z^2 = (g^2 + g'^2)v^2/4$$

2.- One massive scalar particle: **The Higgs bosor**

Higgs mass is an unknown parameter of the theory or equivalently the quartic coupling λ

$$m_H^2 = \frac{4\lambda(v) m_W^2}{g^2}$$

3.- Gauge couplings and masses (at tree level) :

$$\rho = 1 \qquad \frac{M_W}{M_Z} = \rho \frac{g^2}{g^2 + g'^2} = \rho \cos^2\theta_W$$

Protected by cutsodial symmetry at higher orders

$$+\ \bar{\psi}_i\, y_{ij}\, \psi_j \phi + h.c.$$

The Sector of Fermions

Another important consequence of the Weinberg Salam Model…

A specific $SU(2)_L x U(1)_Y$ problem : $m\bar{\psi}\psi$ manifestly not gauge invariant

$$m\bar{\psi}\psi = m\bar{\psi}\left(\frac{1}{2}(1-\gamma^5) + \frac{1}{2}(1+\gamma^5)\right)\psi = m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$

- neither under $SU(2)_L$ doublet and singlet terms together
- nor under $U(1)_Y$ do not have the same hypercharge

Not the case when using Yukawa couplings to the Higgs doublet

$$\frac{\lambda_\psi v}{\sqrt{2}}\bar{\psi}\psi + \frac{\lambda_\psi}{\sqrt{2}}H\bar{\psi}\psi$$

Which is invariant under $U(1)_{EM}$

The Higgs mechanism DOES NOT predict fermion masses

…Yet the coupling of the Higgs to fermions is proportional to their masses

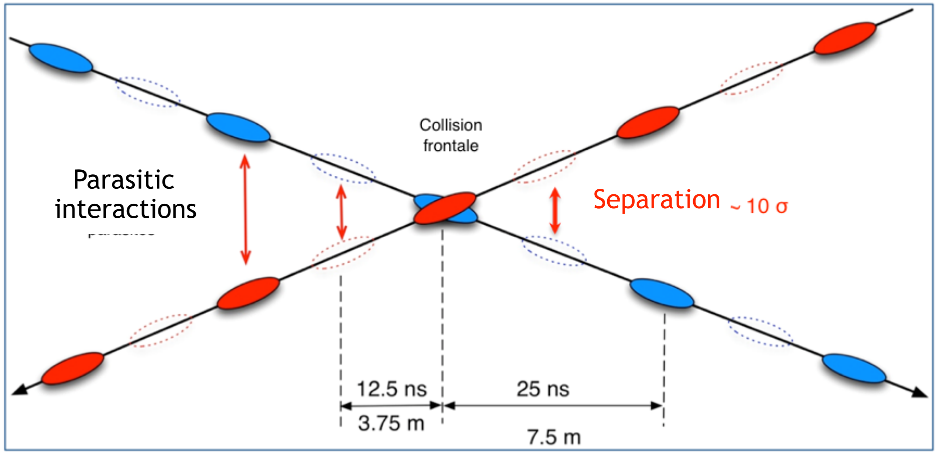
Limitations in the Luminosity

Beams are circulating for ~120m in the same vacuum pipe around Ips, to minimize long distance beam-beam effects beams cross with an angle.

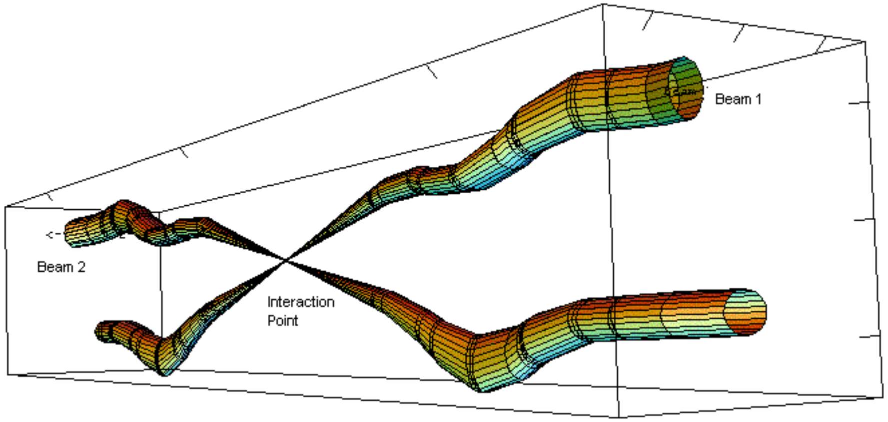
- Crossing angle affects the luminosity by a factor of:

$$F = \frac{1}{\sqrt{1 + (\frac{\theta\sigma_z}{2\sigma_x})}} \sim 0.8$$

$$\theta = 285\mu\text{rad}$$



- Beam-beam effects still at IPs, where beams are see the effect of the presence of the crossing beam. A limitation for the emittance.



Relative beam sizes around IP1 (Atlas) in collision

- Another limiting factorQuadrupole aperture at lowest b*

Wait…

The coupling to the Higgs fields is the following :

$$\lambda_d(\bar{u}_L, \bar{d}_L)\begin{pmatrix} 0 \\ v+h \end{pmatrix} d_R + H.C. = \lambda_d \bar{Q}_L \, \phi \, d_R$$

Can be seen as giving mass to down type fermions…

To give mass to up type fermions, need to use a slightly different coupling term:

$$\phi^C = i\sigma_2\phi^* \qquad \lambda_u Q_L \, \phi^C \, \bar{u}_R = \lambda_u(\bar{u}_L, \bar{d}_L)\begin{pmatrix} v+h \\ 0 \end{pmatrix} d_R + H.C.$$

One doublet of complex scalar fields is sufficient to accommodate mass terms for gauge bosons and fermions !

... But not necessary.