Introduction to the Standard Model

New Horizons in Lattice Field Theory
IIP Natal, March 2013

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Successes of Standard Model

Standard Model describes almost all the experimental data produced over many decades in many different experiments (not only particle accelerators).

Describe a few of the tests in this lecture:

- muon magnetic moment
- electron magnetic moment
- Z line shape and the number of neutrinos
- precision measurements at LEP
- hadron collider results
- the discovery of the "Higgs"

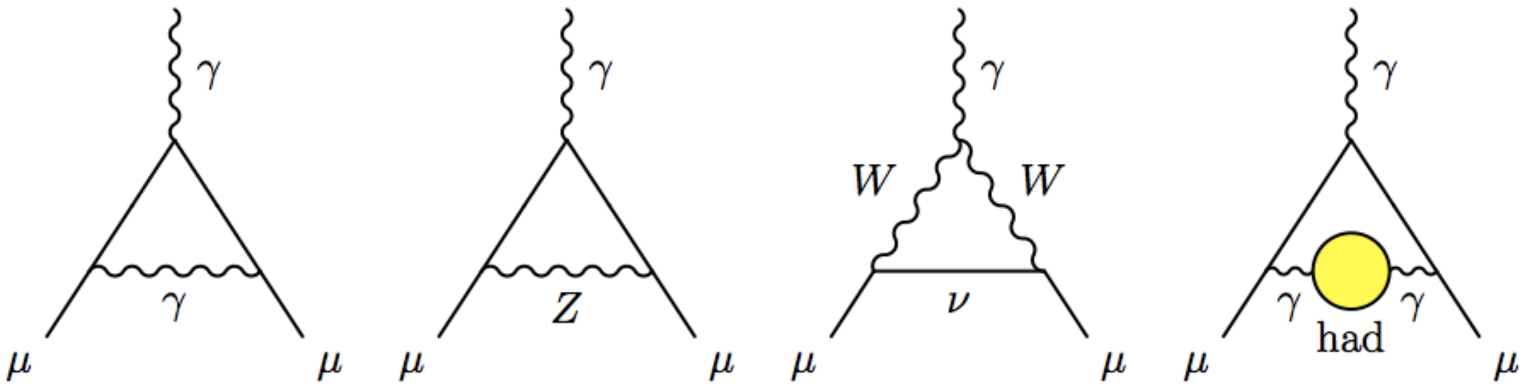
Muon anomalous magnetic moment

de Rafael, 0809.3085

g-factor: relation between spin and magnetic moment

$$\vec{\mu} = g_\mu \frac{e\hbar}{2m_\mu c}\vec{s}, \qquad \underbrace{g_\mu = 2}_{\text{Dirac}}(1 + a_\mu)$$

$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm Had}$$



Perturbation theory at work – 5 loop calculation!

$$a_\mu^{\rm QED} = \frac{\alpha}{2\pi} + 0.765857410(27)\left(\frac{\alpha}{\pi}\right)^2 + 24.05050964(43)\left(\frac{\alpha}{\pi}\right)^3 + 130.8055(80)\left(\frac{\alpha}{\pi}\right)^4 + 663(20)\left(\frac{\alpha}{\pi}\right)^5 + \cdots \quad (5)$$

Table 2 Standard Model Contributions

CONTRIBUTION	RESULT IN 10^{-11} UNITS
QED (leptons)	$11\,6584\,718.09 \pm 0.14 \pm 0.04_\alpha$
HVP(lo)	$6\,908 \pm 39_{\rm exp} \pm 19_{\rm rad} \pm 7_{\rm pQCD}$
HVP(ho)	$-97.9 \pm 0.9_{\rm exp} \pm 0.3_{\rm rad}$
HLxL	105 ± 26
EW	$152 \pm 2 \pm 1$
Total SM	$116\,591\,785 \pm 51$

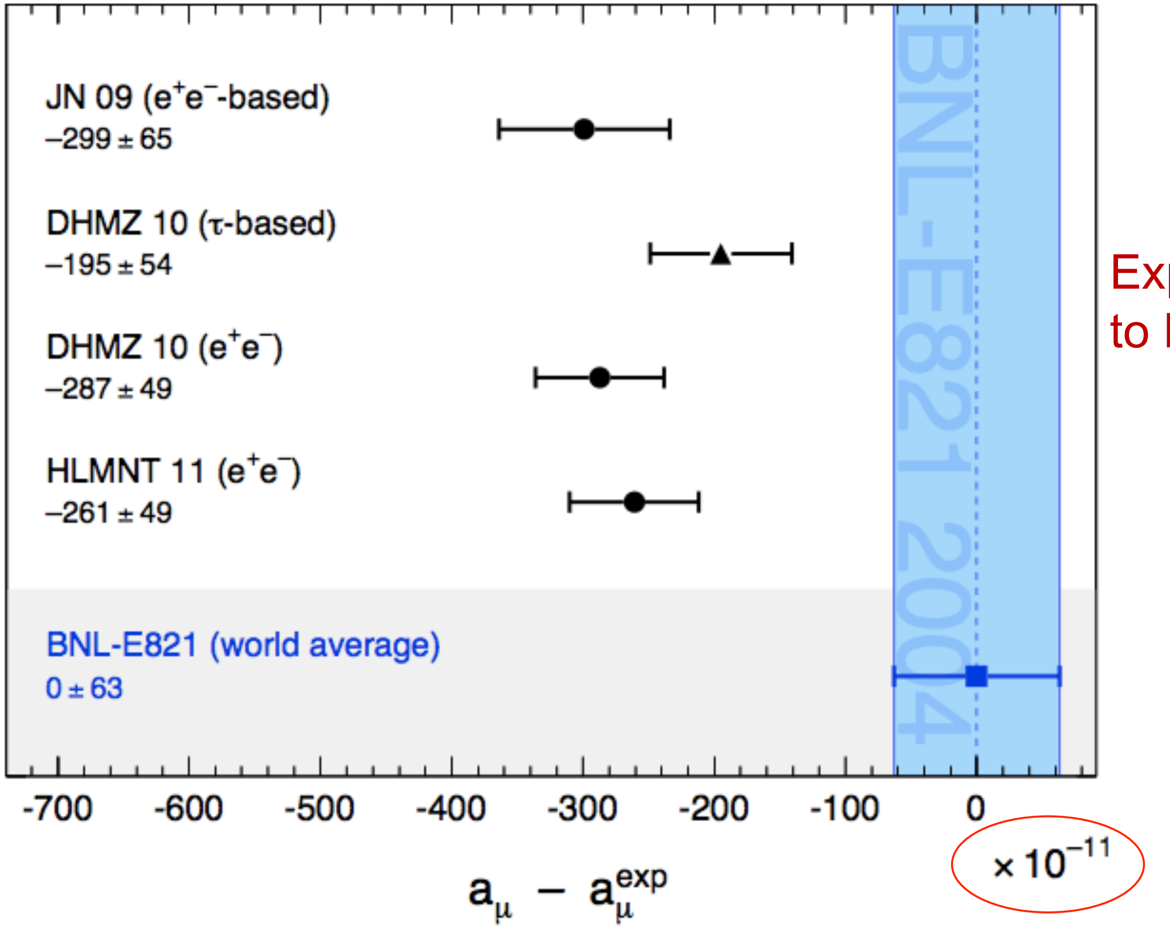
$$a_\mu^{\rm SM} = 116\,591\,802(2)(42)(26) \times 10^{-11}$$

$$a_\mu^{\rm exp} = 116\,592\,089(54)(33) \times 10^{-11}$$

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 287(63)(49) \times 10^{-11}$$

3 parts in a billion!

PDG 2012



Experiment moving to Fermilab

$$a_\mu^{\rm SUSY} \simeq \pm 130 \times 10^{-11} \cdot \left(\frac{100 \text{ GeV}}{m_{\rm SUSY}}\right)^2 \tan\beta$$

Electron anomalous magnetic moment

Kinoshita 2010

Following Dyson we can write a_e as
$a_e = a_e(\text{QED}) + a_e(\text{hadron}) + a_e(\text{electroweak})$, where

$$a_e(\text{QED}) = A_1 + A_2(m_e/m_\mu) + A_2(m_e/m_\tau) + A_3(m_e/m_\mu, m_e/m_\tau)$$

$$A_i = A_i^{(2)}\left(\frac{\alpha}{\pi}\right) + A_i^{(4)}\left(\frac{\alpha}{\pi}\right)^2 + A_i^{(6)}\left(\frac{\alpha}{\pi}\right)^3 + \ldots, i = 1, 2, 3$$

- First four A_1 terms are known analytically or by numerical integration

$A_1^{(2)} = 0.5$ — 1 Feynman diagram (analytic)
$A_1^{(4)} = -0.328\,478\,965\ldots$ — 7 Feynman diagrams (analytic)
$A_1^{(6)} = 1.181\,241\,456\ldots$ — 72 Feynman diagrams (analytic,numerical)

Laporta, Remiddi, PLB 379, 283 (1996)
Kinoshita, PRL 75, 4728 (1995)

$A_1^{(8)} = -1.914\,4\,(35)$ — 891 Feynman diagrams (numerical)

Kinoshita,Nio, PRD 73, 013003 (2006)
Aoyama,Hayakawa,Kinoshita,Nio, PRD 77, 053012 (2008)

$a_e(\text{exp}) = 1\,159\,652\,180.73\,(0.28) \times 10^{-12}$ [0.24 *ppb*]

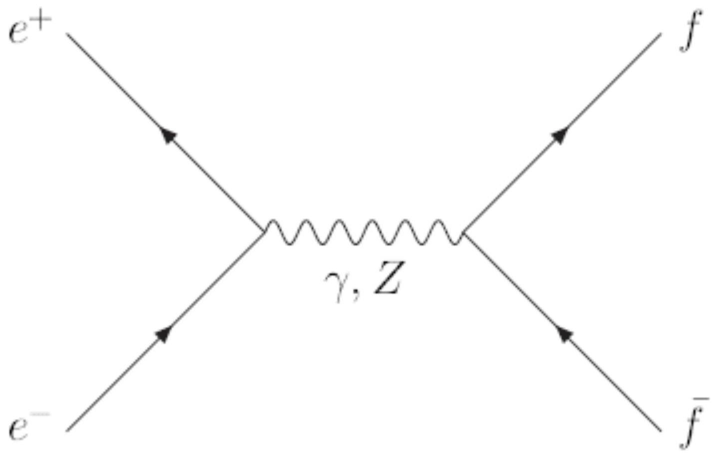
Hanneke,Fogwell,Gabrielse, PRL 100, 120801 (2008)

Table top experiment

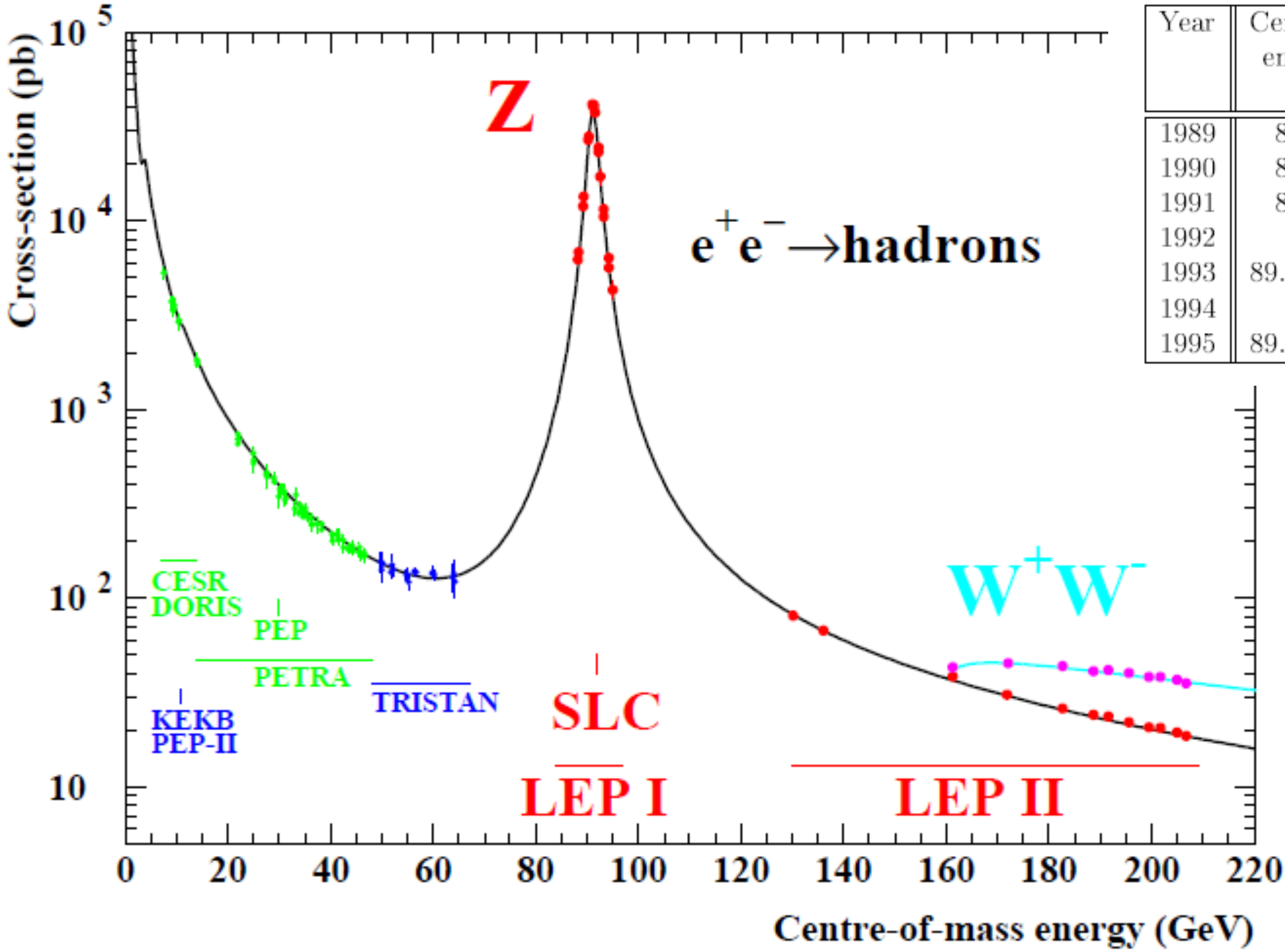
Best determination of fine structure constant
$\alpha^{-1}(a_e) = 137.035\,999\,085\,(12)(37)(33)$ [0.37 *ppb*]

Z-boson and the number of neutrinos

More than 15 million Z-bosons were produced and detected at LEP through the process:

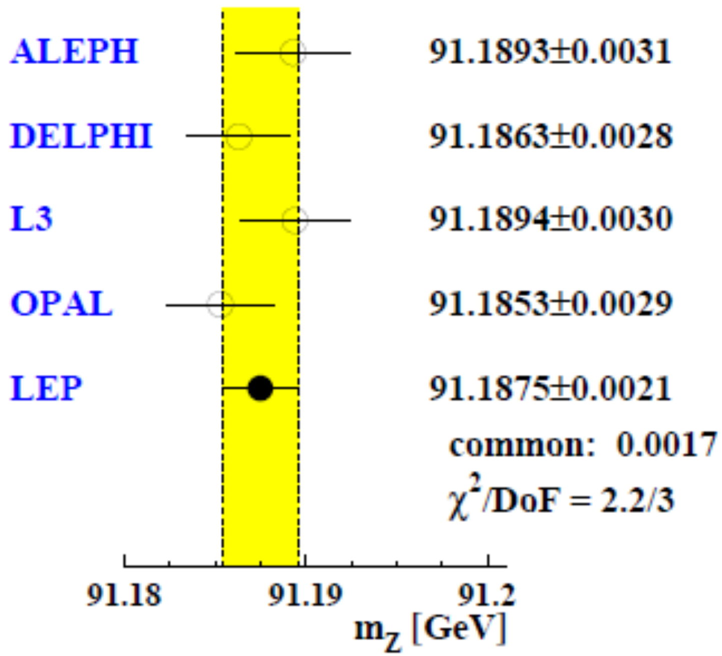


The Z-boson shows up as a resonance in e^+e^- collisions in the LEP collider:



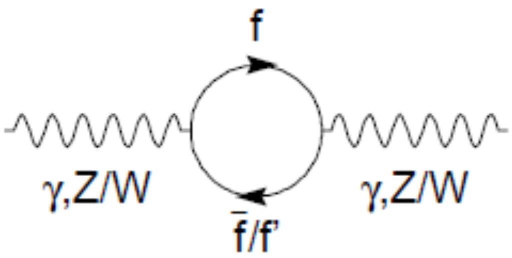
Year	Centre-of-mass energy range [GeV]	Integrated luminosity [pb^{-1}]
1989	88.2 – 94.2	1.7
1990	88.2 – 94.2	8.6
1991	88.5 – 93.7	18.9
1992	91.3	28.6
1993	89.4, 91.2, 93.0	40.0
1994	91.2	64.5
1995	89.4, 91.3, 93.0	39.8

The Z-boson mass is one of the best measured quantities in the SM:



LEPEWW

The resonance line shape is a consequence of the Z-boson propagator which must include quantum corrections due to its decay such as the diagram



which leads to a cross section proportional to the so-called Breit-Wigner factor:

$$\left| \frac{1}{s - M_Z^2 + i \underbrace{\Gamma_Z}_{\text{Z widht}} M_Z} \right|^2$$

Partial Z width in lowest order (tree-level):

$$\Gamma(Z \to f\bar{f}) = \frac{4G_F}{3\pi\sqrt{2}} M_Z^3 (a_L^2 + a_R^2) N_C$$

Channel	$a_L^2 + a_R^2$
$\nu\bar{\nu}$	$\frac{1}{16}$
$l\bar{l}$	$\frac{1}{4}\left(\frac{1}{4} - \sin^2\theta_W + 2\sin^4\theta_W\right)$
$u\bar{u}$	$\frac{1}{4}\left(\frac{1}{4} - \frac{2}{3}\sin^2\theta_W + \frac{8}{9}\sin^4\theta_W\right)$
$d\bar{d}$	$\frac{1}{4}\left(\frac{1}{4} - \frac{1}{3}\sin^2\theta_W + \frac{2}{9}\sin^4\theta_W\right)$

Total Z width given by (why?):

$$\Gamma(Z) = 2\times\Gamma(Z \to u\bar{u}) + 3\times\Gamma(Z \to d\bar{d}) + 3\times\Gamma(Z \to l^+l^-) + N_\nu \times\Gamma(Z \to \nu\bar{\nu})$$

Using $G_F = 1.166 \times 10^{-5}\ \mathrm{GeV}^{-2}$ $\sin^2\theta_W = 0.231$

I get

$$\Gamma(Z \to u\bar{u}) = 0.2854\ \mathrm{GeV}, \quad \Gamma(Z \to d\bar{d}) = 0.3679\ \mathrm{GeV},$$
$$\Gamma(Z \to l^+ l^-) = 0.0834\ \mathrm{GeV}, \quad \Gamma(Z \to \nu\bar{\nu}) = 0.1658\ \mathrm{GeV}$$

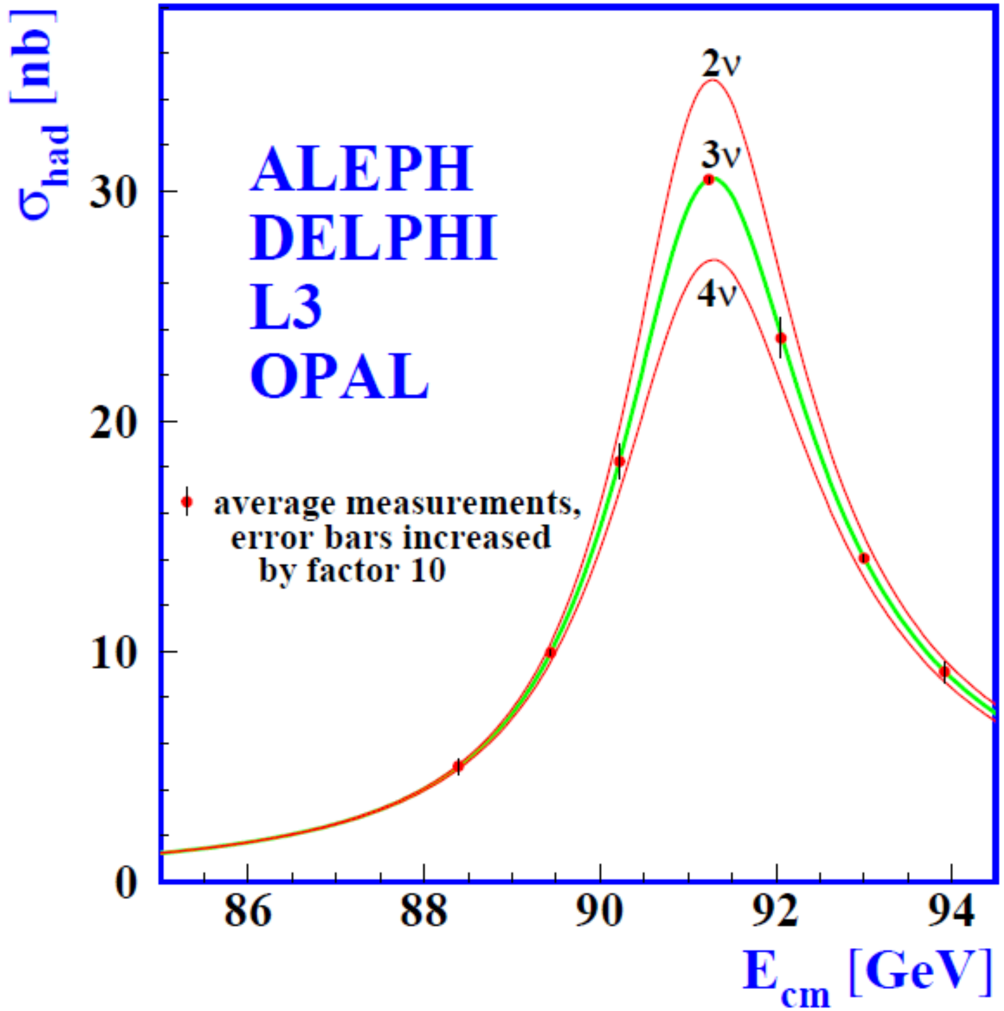
and hence $\Gamma(Z) = 2.423\ \mathrm{GeV}$ for $N_\nu = 3$

to be compared with experimental result:

$$\Gamma(Z) = 2.4952 \pm 0.0023\ \mathrm{GeV}$$

No room for an extra neutrino!

Agrees with cosmology (BBN)



Effective number of near massless neutrinos

$$N_\nu = 2.984 \pm 0.008$$

$N_{eff} = 3.84 \pm 0.40$ from WMAP9

Dark radiation? Wait for Planck.

Precision measurements at LEP

Many observables were measured that depend on the fundamental parameters of the SM.

At tree level, only g_1, g_2 and v are necessary to calculate electroweak processes.

Other parameters appear at the loop-level and are important since the measurements are very precise.

New physics could be the cause if there are poor fits between SM and measurements – but there are NOT.

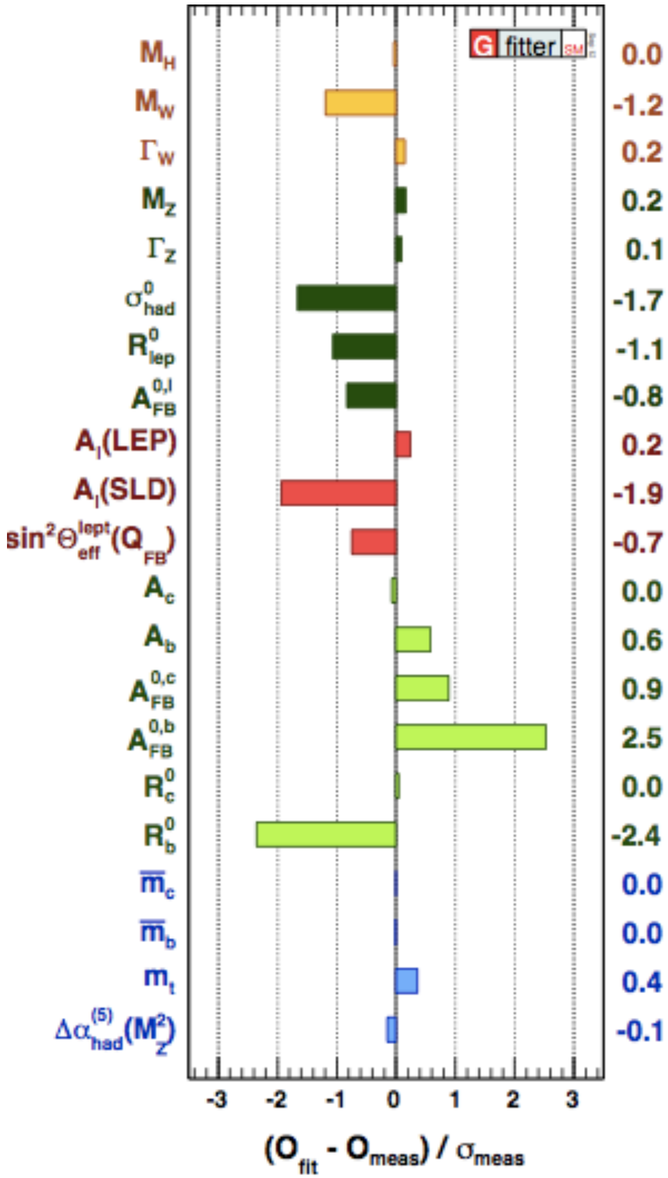
Gfitter group provides a global fit of electroweak observables

http://gfitter.desy.de/Standard_Model/

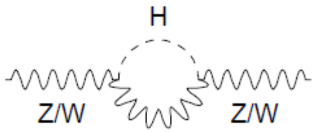
Parameter	Input value	Free in fit	Fit result incl. M_H	Fit result not incl. M_H	Fit result incl. M_H but not exp. input in row
M_H [GeV] $^{(\circ)}$	125.7 ± 0.4	yes	125.7 ± 0.4	$94\,^{+25}_{-22}$	$94\,^{+25}_{-22}$
M_W [GeV]	80.385 ± 0.015	–	80.367 ± 0.007	80.380 ± 0.012	80.359 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.092 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1874 ± 0.0021	91.1983 ± 0.0116
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4958 ± 0.0015	2.4951 ± 0.0017
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.478 ± 0.014	41.470 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.743 ± 0.018	20.716 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01627 ± 0.0002	0.01637 ± 0.0002	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1473\,^{+0.0006}_{-0.0008}$	0.1477 ± 0.0009	$0.1468 \pm 0.0005^{(\dagger)}$
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23148\,^{+0.00011}_{-0.00007}$	$0.23143\,^{+0.00010}_{-0.00012}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6680\,^{+0.00025}_{-0.00038}$	$0.6682\,^{+0.00042}_{-0.00035}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464\,^{+0.00004}_{-0.00007}$	0.93468 ± 0.00008	0.93463 ± 0.00006
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0739\,^{+0.0003}_{-0.0005}$	0.0740 ± 0.0005	0.0738 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	$0.1032\,^{+0.0004}_{-0.0006}$	0.1036 ± 0.0007	0.1034 ± 0.0004
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21474 ± 0.00003	0.21475 ± 0.00003	0.21473 ± 0.00003
$\overline{m}_c$ [GeV]	$1.27\,^{+0.07}_{-0.11}$	yes	$1.27\,^{+0.07}_{-0.11}$	$1.27\,^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20\,^{+0.17}_{-0.07}$	yes	$4.20\,^{+0.17}_{-0.07}$	$4.20\,^{+0.17}_{-0.07}$	–
m_t [GeV]	173.18 ± 0.94	yes	173.52 ± 0.88	173.14 ± 0.93	$175.8\,^{+2.7}_{-2.4}$
$\Delta\alpha^{(5)}_{\rm had}(M^2_Z)$ $^{(\triangle\triangledown)}$	2757 ± 10	yes	2755 ± 11	2757 ± 11	$2716\,^{+49}_{-43}$
$\alpha_s(M^2_Z)$	–	yes	0.1191 ± 0.0028	0.1192 ± 0.0028	0.1191 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\triangle)}$	$[-4.7, 4.7]_{\rm theo}$	yes	-1.4	4.7	–

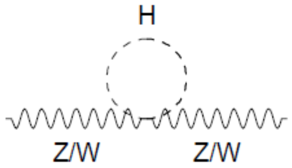
$^{(\circ)}$Average of ATLAS ($M_H = 126.0 \pm 0.4$ (stat) ± 0.4 (sys)) and CMS ($M_H = 125.3 \pm 0.4$ (stat) ± 0.5 (sys)) measurement assuming no correlation of the systematic uncertainties. $^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm$ 0.0021) measurements, used as two measurements in the fit. $^{(\dagger)}$The fit w/o the LEP (SLD) measurement gives $A_\ell = 0.1474\,^{+0.0005}_{-0.0009}$ ($A_\ell = 0.1467\,^{+0.0006}_{-0.0004}$). $^{(\triangle)}$In units of 10^{-5}. $^{(\triangledown)}$Rescaled due to α_s dependency.

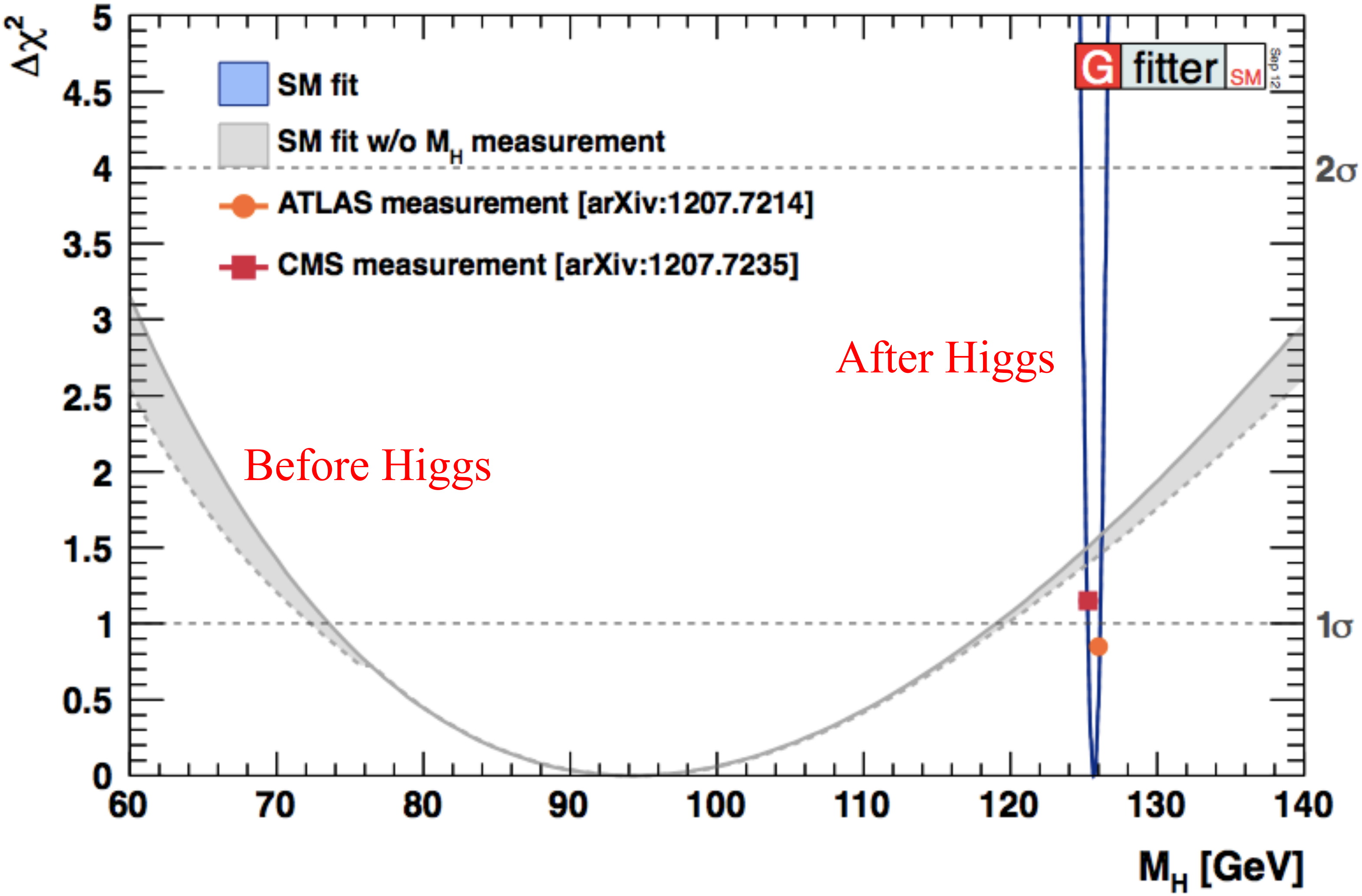
The famous "pull" diagram - SM works beautifully



Indirect limits on the Higgs mass

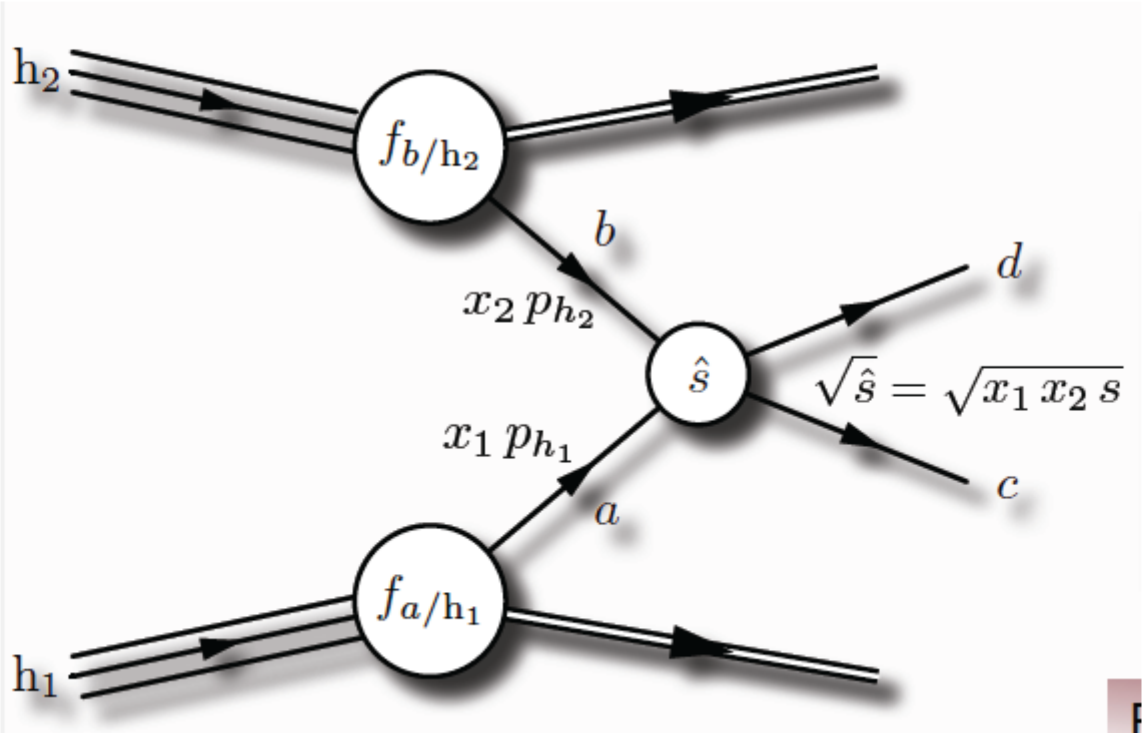






Particle production at hadron colliders

Protons are made out of quarks and gluons. What really participate in the collision are the proton constituents, called generically partons. Partonic center-of-mass energy is not fixed!



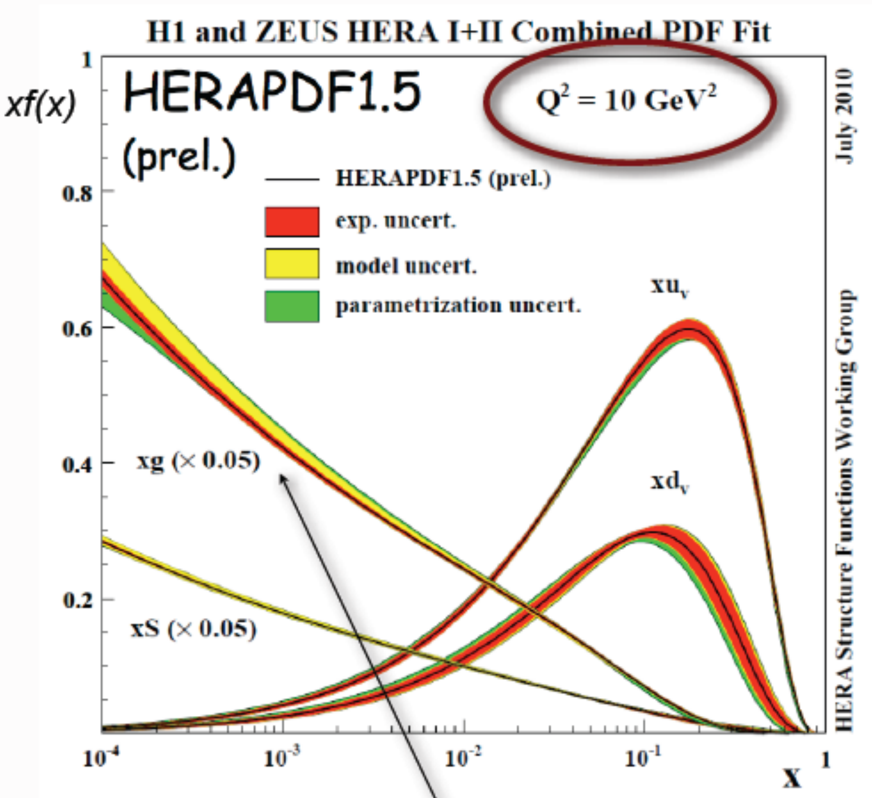
Cross section:

Factorization at work!

Parton distribution functions (PDFs)

$$d\sigma(h_1 h_2 \to cd) = \int_0^1 dx_1 dx_2 \sum_{a,b} f_{a/h_1}(x_1,\mu_F^2) f_{b/h_2}(x_2,\mu_F^2) d\hat{\sigma}^{(ab\to cd)}(Q^2,\mu_F^2)$$

Partonic cross section



gluons dominate at low x !

To produce (at central rapidity, ie. $x_1 \sim x_2$) a mass of

	LHC (7 TeV)	TEVATRON
100 GeV	x~0.014	0.05
3 TeV	x~0.43	--

Cross sections and event rates

Productions of particles are characterized by cross sections σ with units of area:

barn	b	10^{-24} cm^2
millibarn	mb	10^{-27}
microbarn	μb	10^{-30}
nanobarn	nb	10^{-33}
picobarn	pb	10^{-36}
femtobarn	fb	10^{-39}
attobarn	ab	10^{-42}

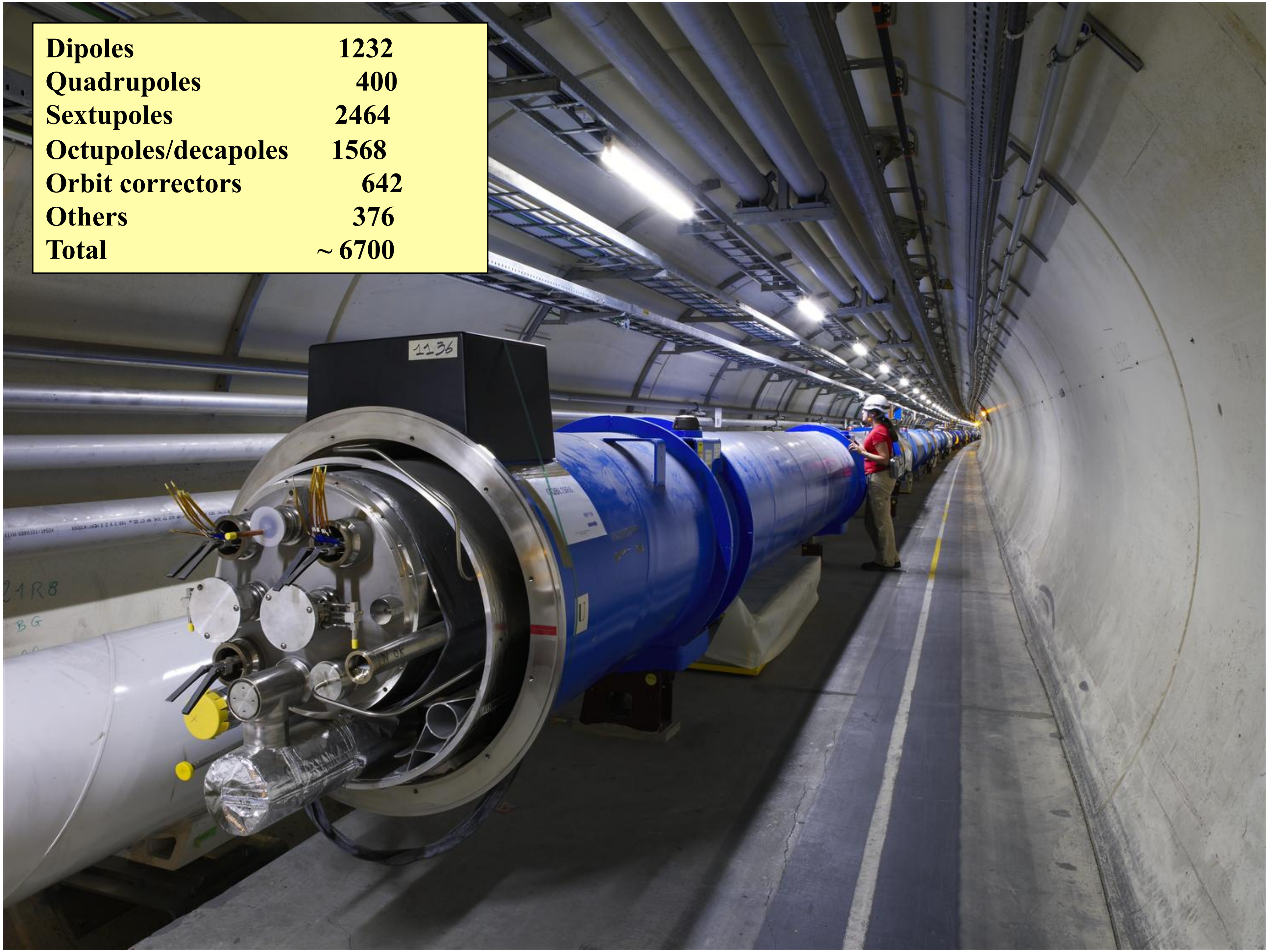
Accelerators are characterized by their center-of-mass energy and luminosity. Luminosity has dimensions of inverse of an area (or inverse cross section).

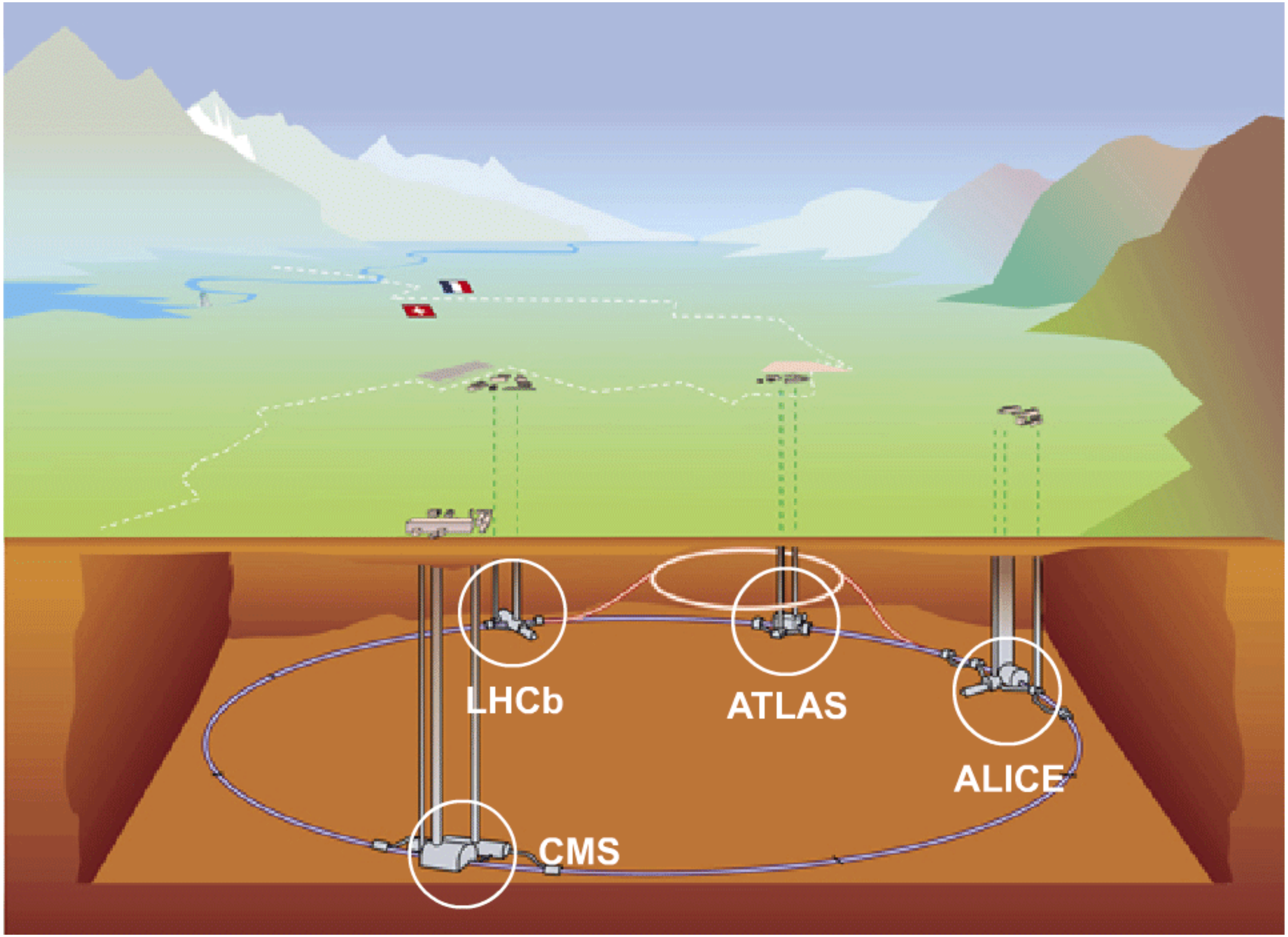
The product of cross section with luminosity gives the number of events that would be produced.

Large Hadron Collider at CERN

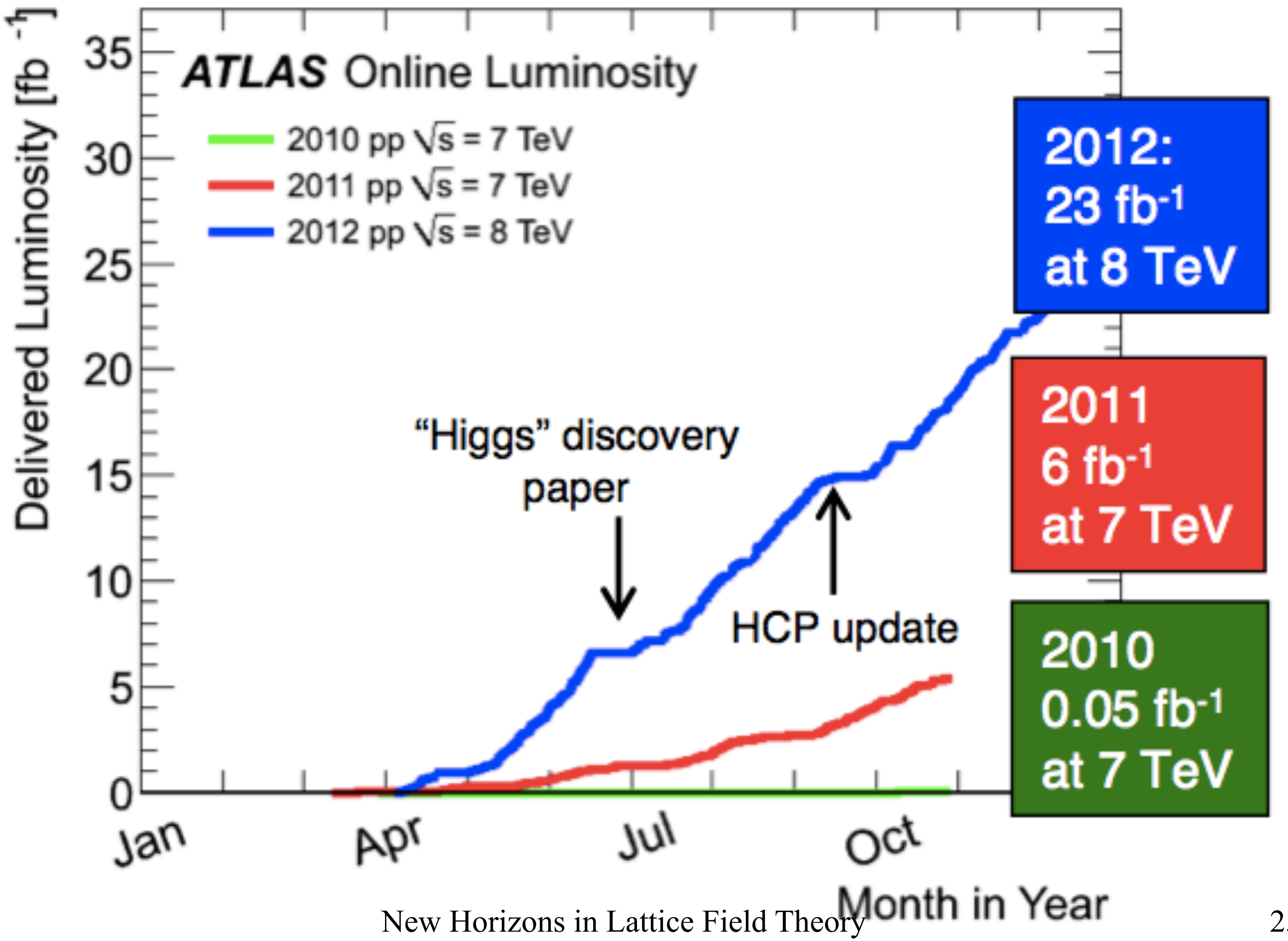
27 km circumference – largest experiment ever

Dipoles	**1232**
Quadrupoles	**400**
Sextupoles	**2464**
Octupoles/decapoles	**1568**
Orbit correctors	**642**
Others	**376**
Total	**~ 6700**




LHCb
ATLAS
ALICE
CMS

Outstanding LHC performance: 2010, 11 and 12



http://lhc-statistics.web.cern.ch/LHC-Statistics/index.php

LHC Performance and Statistics

Quick search

Fill number :

Overview | Run Details | Fill Summaries | Supertable

Filters: 2012 | 4TeV | proton - proton | Stable Beams | Apply filt

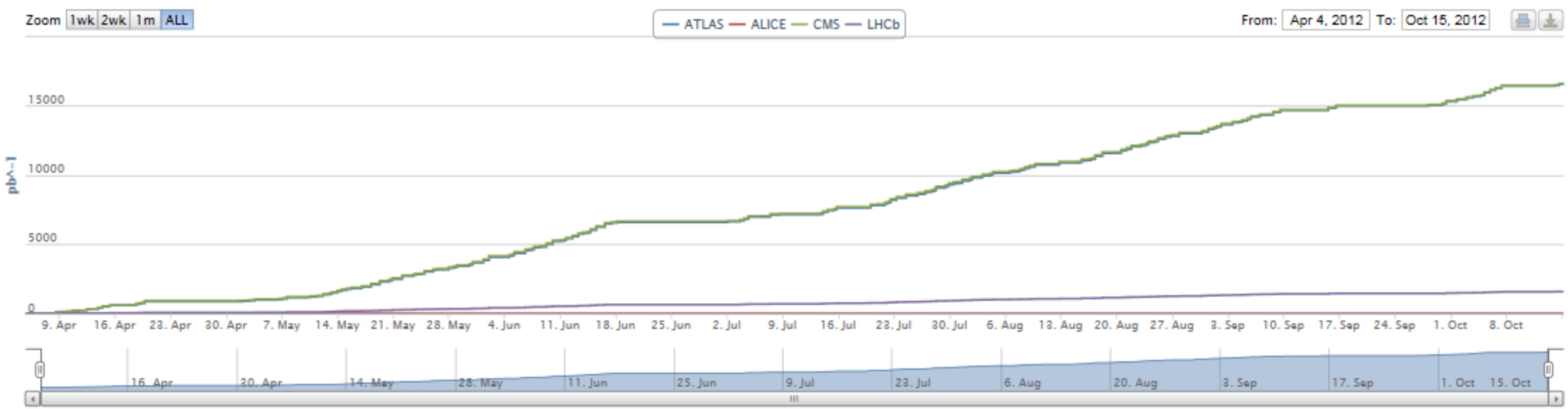
Online Integrated Luminosity

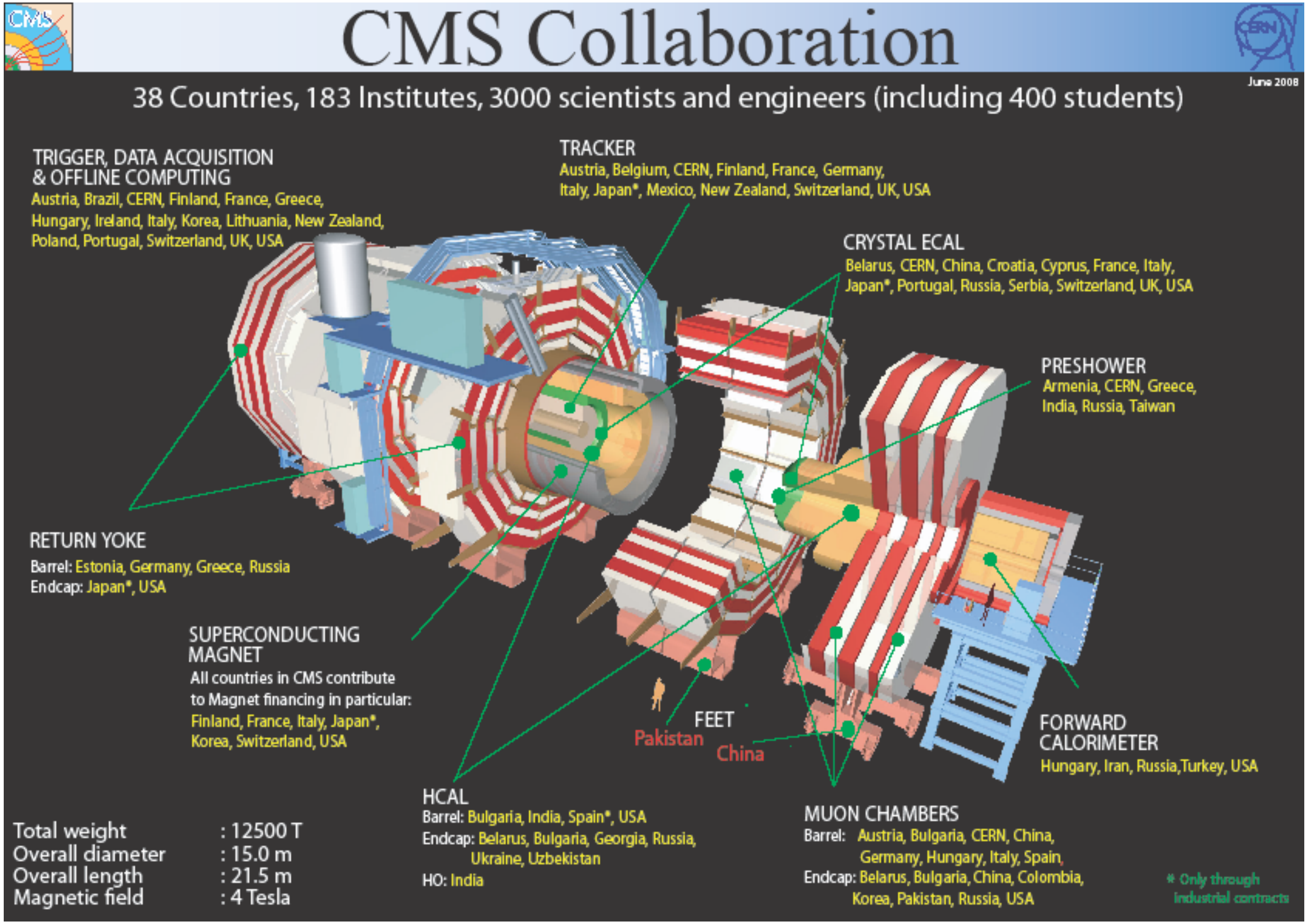
ALICE: 3.77 pb^{-1} ATLAS: 16.64 fb^{-1} CMS: 16.68 fb^{-1} LHCb: 1.6 fb^{-1}

Latest 5 LHC Fills

Fill	Fill Times			Energy [Gev]	Intensity		Bunches		Bunch Collision Scheme [IPI&5/2/8]	Peak Luminosity [Hz/ub] = [10^{30} $cm^{-2}s^{-1}$]				Delivered Luminosity [nb^{-1}] = [10^{33} cm^{-2}]			
	Fill Start	SB Start [hh:mm]	SB Duration [hh:mm]		B1 [10^{12}]	B2 [10^{12}]	Number	Norm Emitt [um]		ATLAS	ALICE	CMS	LHCb	ATLAS	ALICE	CMS	LHCb
3185	08:23 15/10/2012	12:43	7:45	4000	210.47	210.89	1374	2.72	1368/0/1262	6941	18.76	6914	405	121907	190.84	122362	10901
3182	18:00 14/10/2012	22:58	4:15	4000	210.18	208.38	1374	2.78	1368/0/1262	6729	15.72	6981	425	77181	107.14	78422	5915
3178	05:05 14/10/2012	07:49	2:21	4000	213.03	209.45	1374	2.39	1368/0/1262	6856	13.56	6915	411	47747	66.8	48779	3231
3169	16:22 13/10/2012	18:21	0:25	4000	11.08	11.91	78	2.76	72/0/48	334	0	341	54	479	0	473	53
3138	13:02 07/10/2012	17:03	9:54	4000	219	215.07	1374	2.51	1368/0/1262	7310	10.27	7244	411	149374	112.66	149403	13978

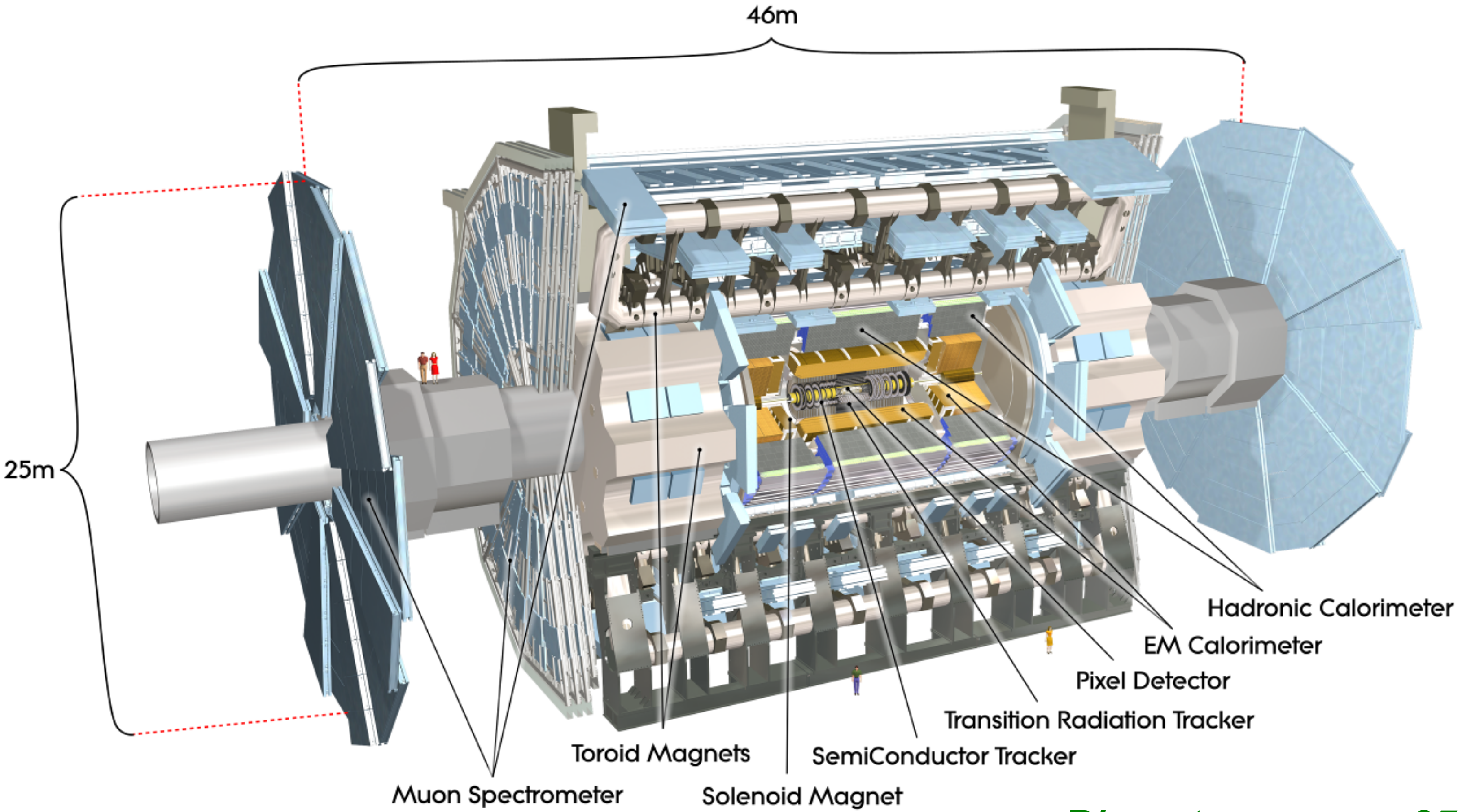
Integrated Luminosity Evolution





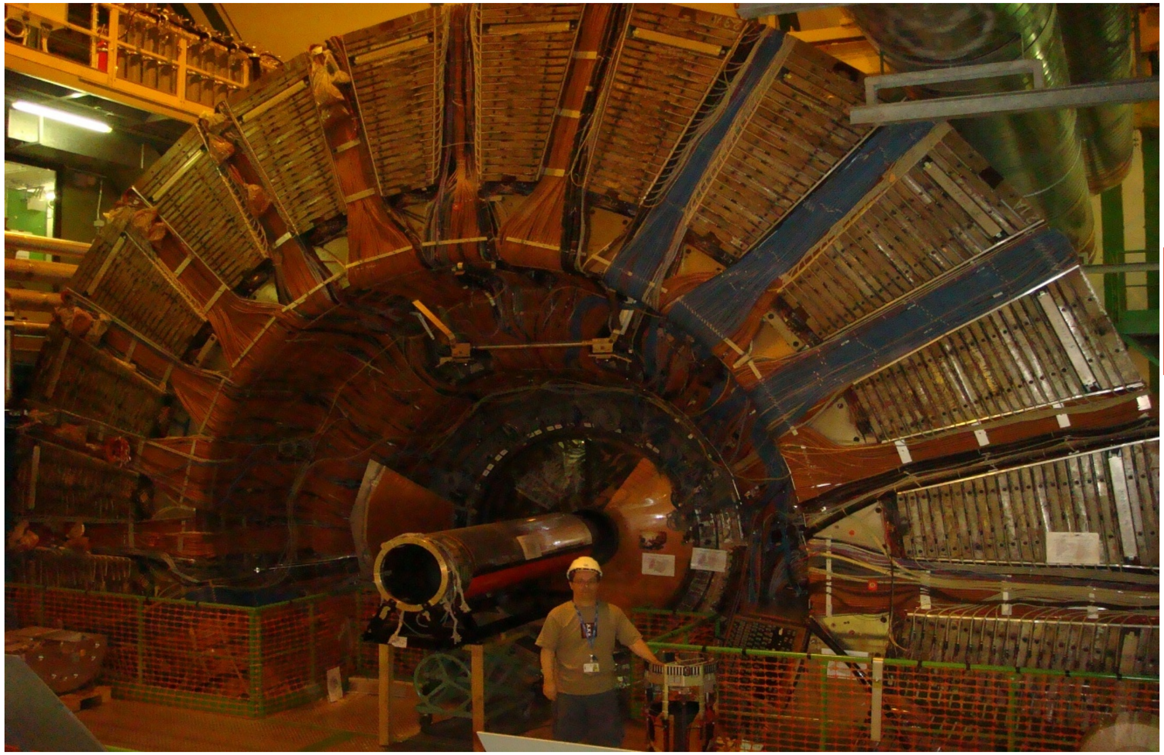
CBPF, UERJ and IFT-UNESP

ATLAS Collaboration



UFRJ and USP

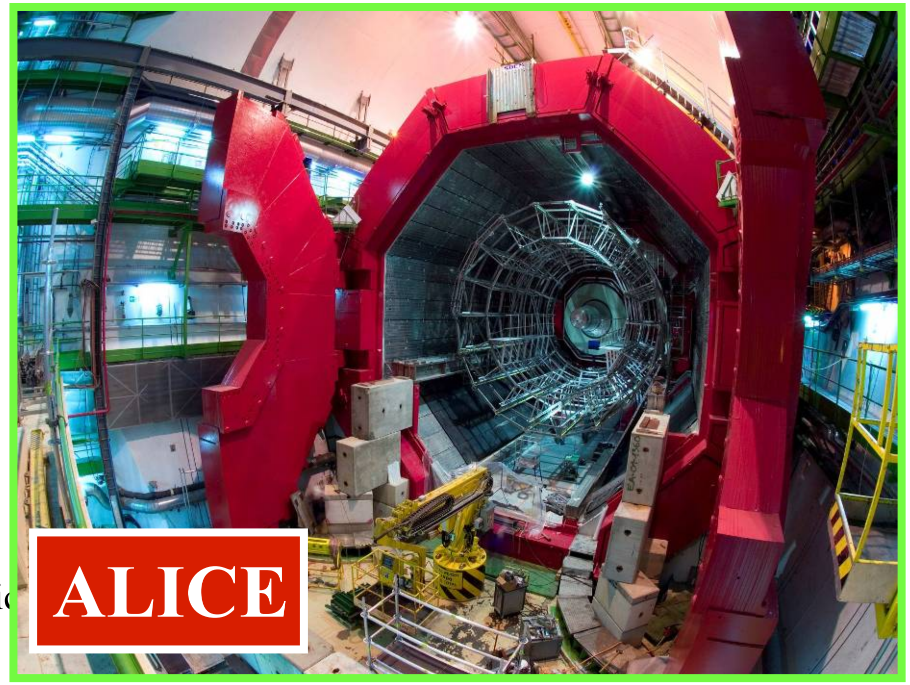
Diameter	*25 m*
Length	*46 m*
Weight	*7000 Tons*



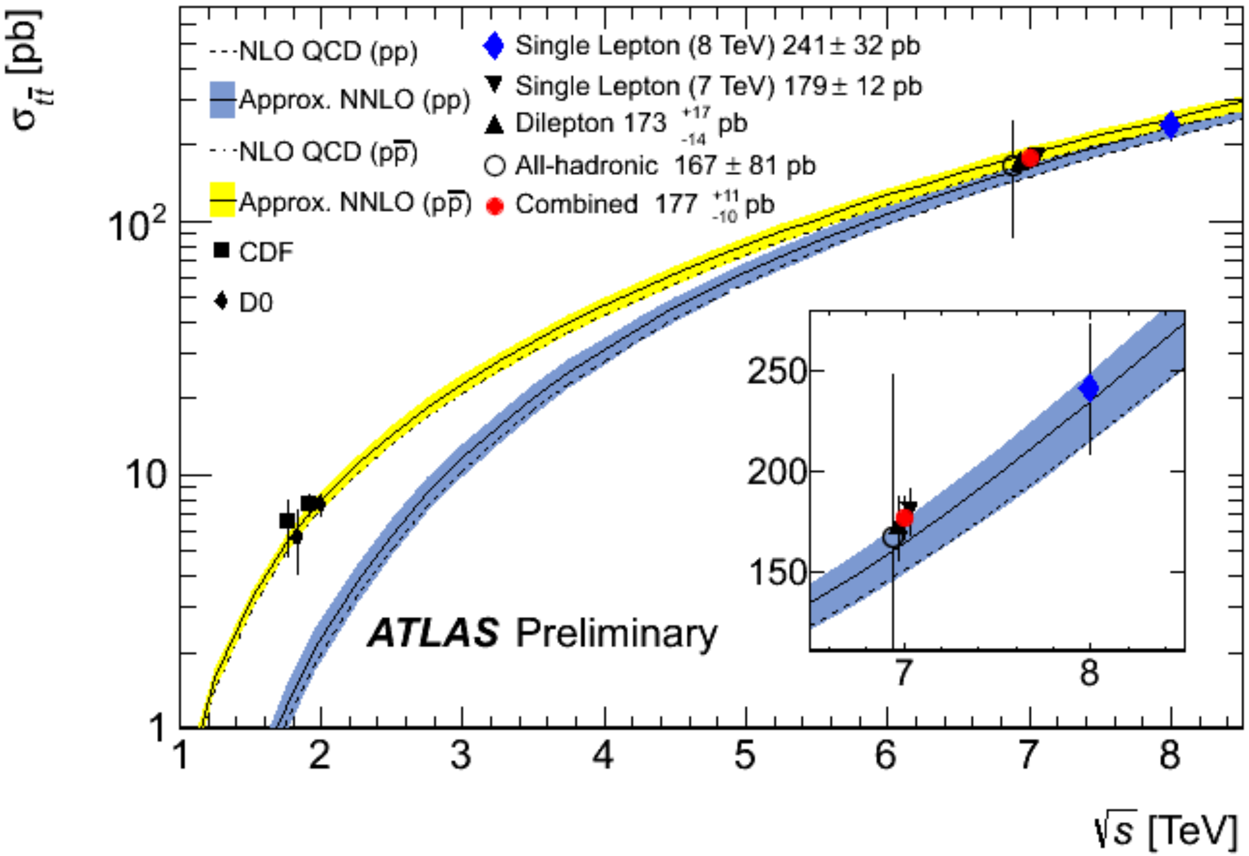
LHCb

LHCb focus on b-physics
(UFRJ and CBPF).

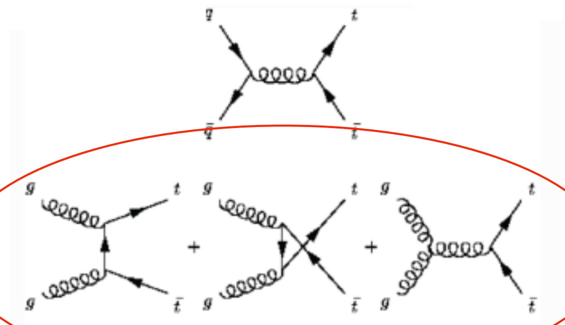
ALICE is dedicated to heavy ion collisions
(USP and UNICAMP)



Example: top quark pair production

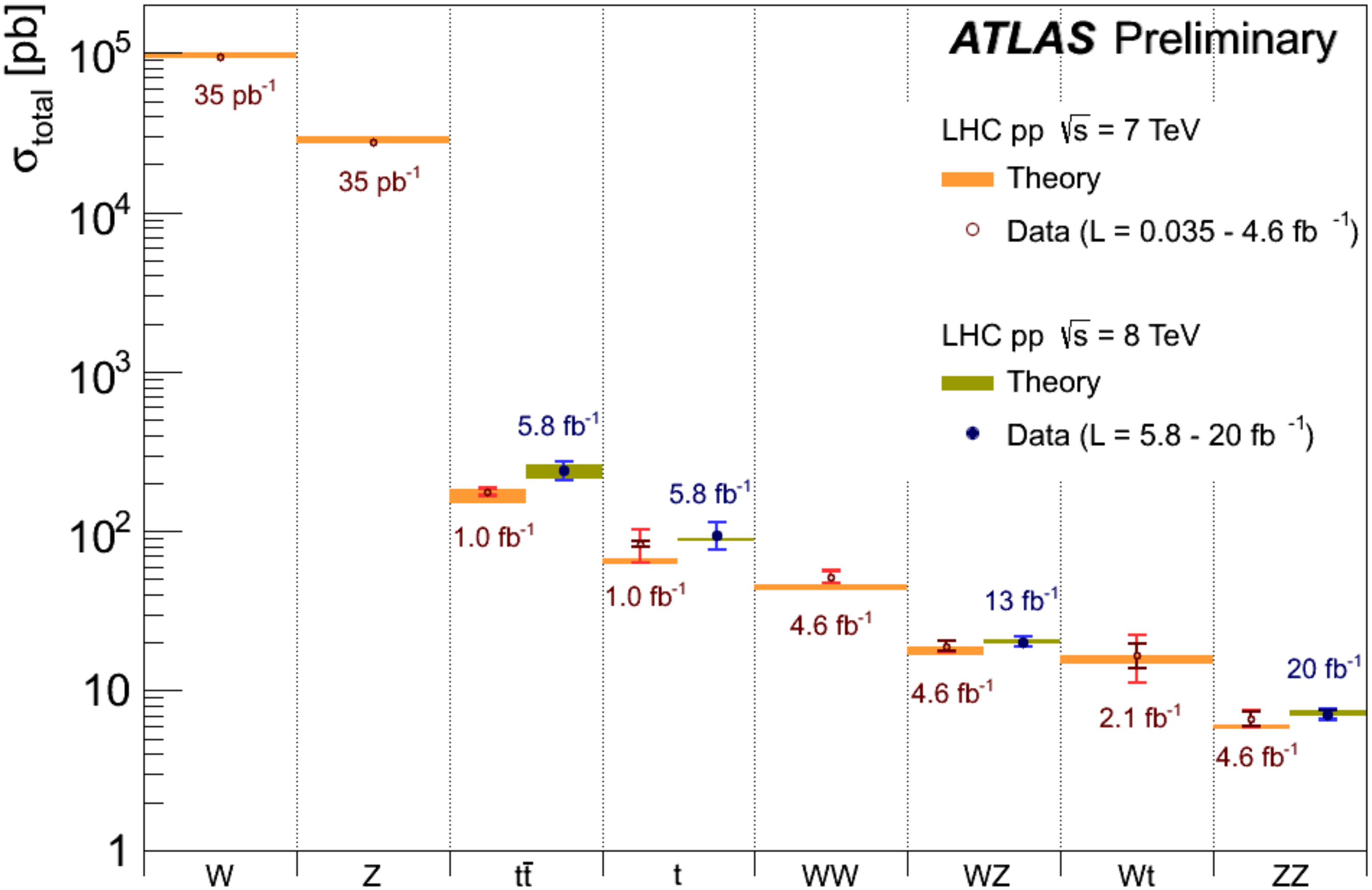


Leading order



dominant

Standard Model at the LHC

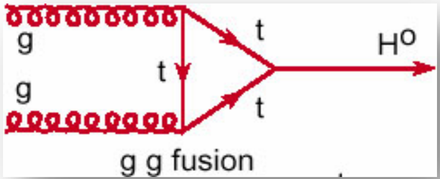


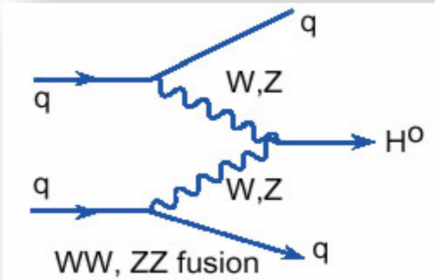
2012: a Hi(gg)storical year

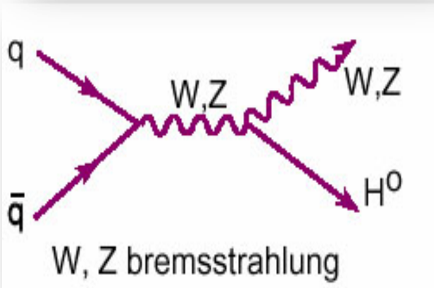
July 4th at CERN

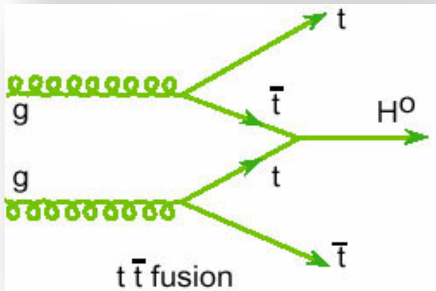
"At the beginning I had no idea a discovery would be made in my lifetime,"

Finding the Higgs

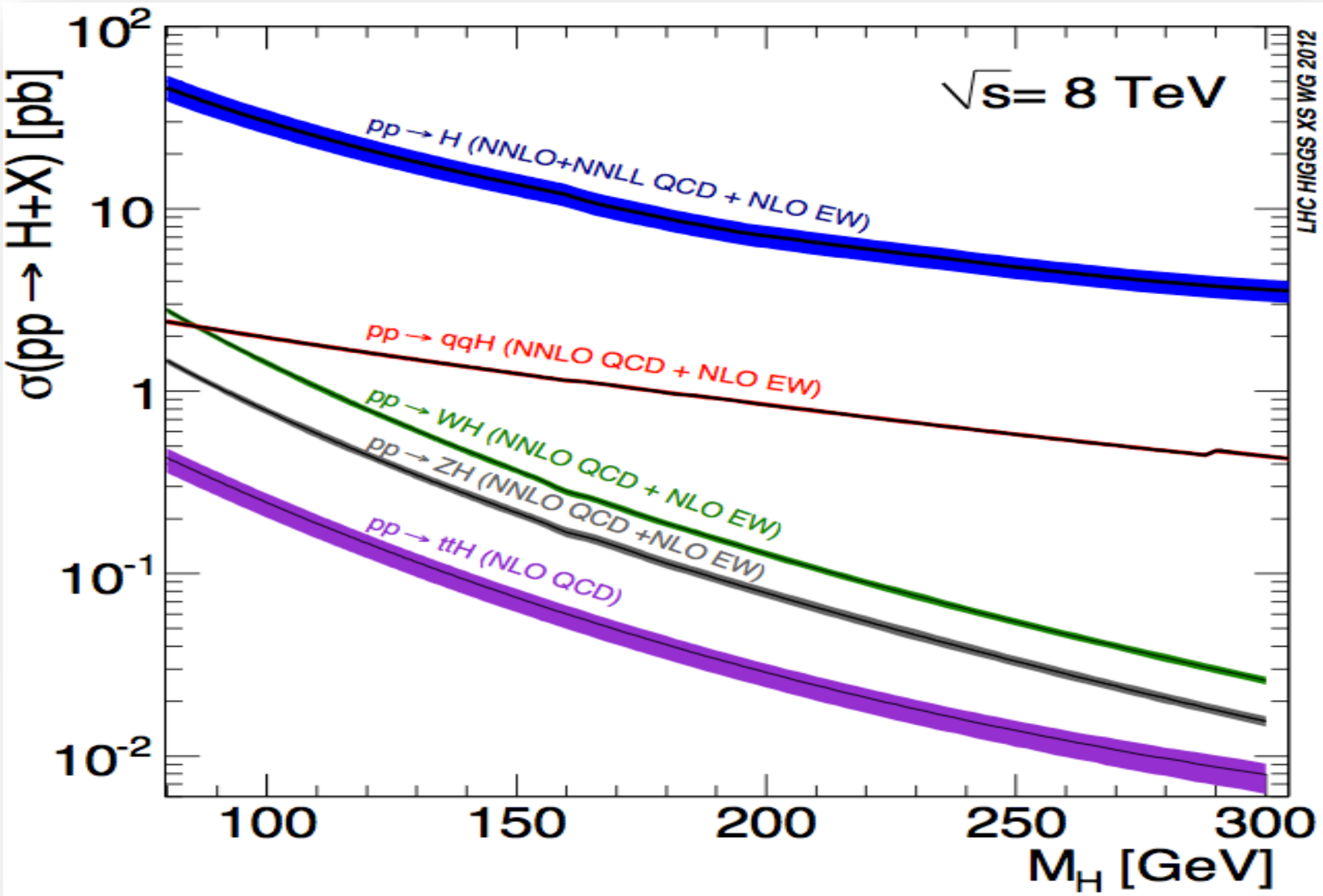








Higgs production at the LHC

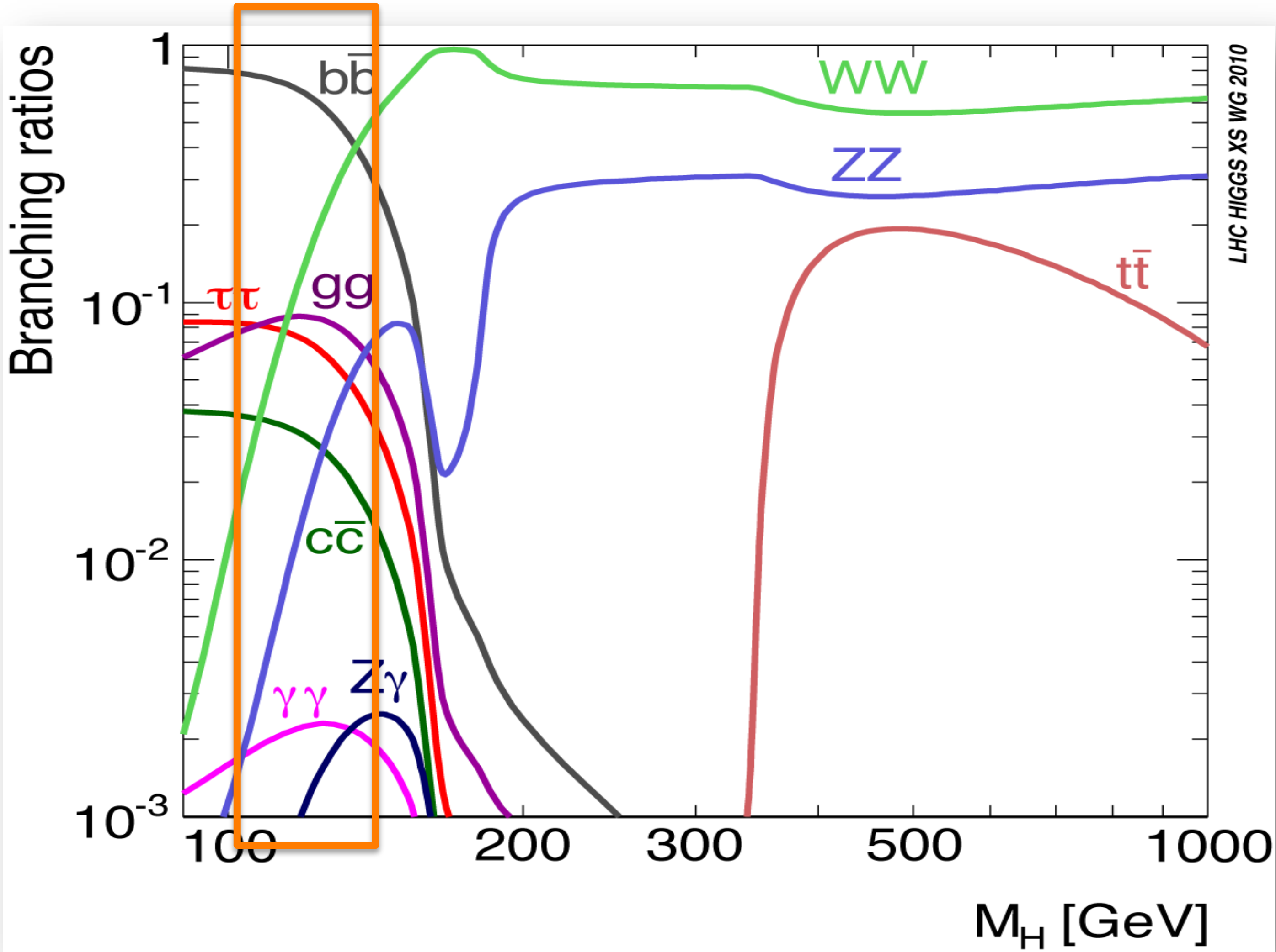


Exercises:

1. Given that the instantaneous luminosity at the LHC is approximately $7 \times 10^{33} \mathrm{cm}^{-2} s^{-1}$ how many Higgs bosons are produced in one hour if its mass is 120 GeV?

2. Why **~2** Higgs bosons @ 125GeV produced at LHC out of 10^{10} pp collisions?

Higgs decays



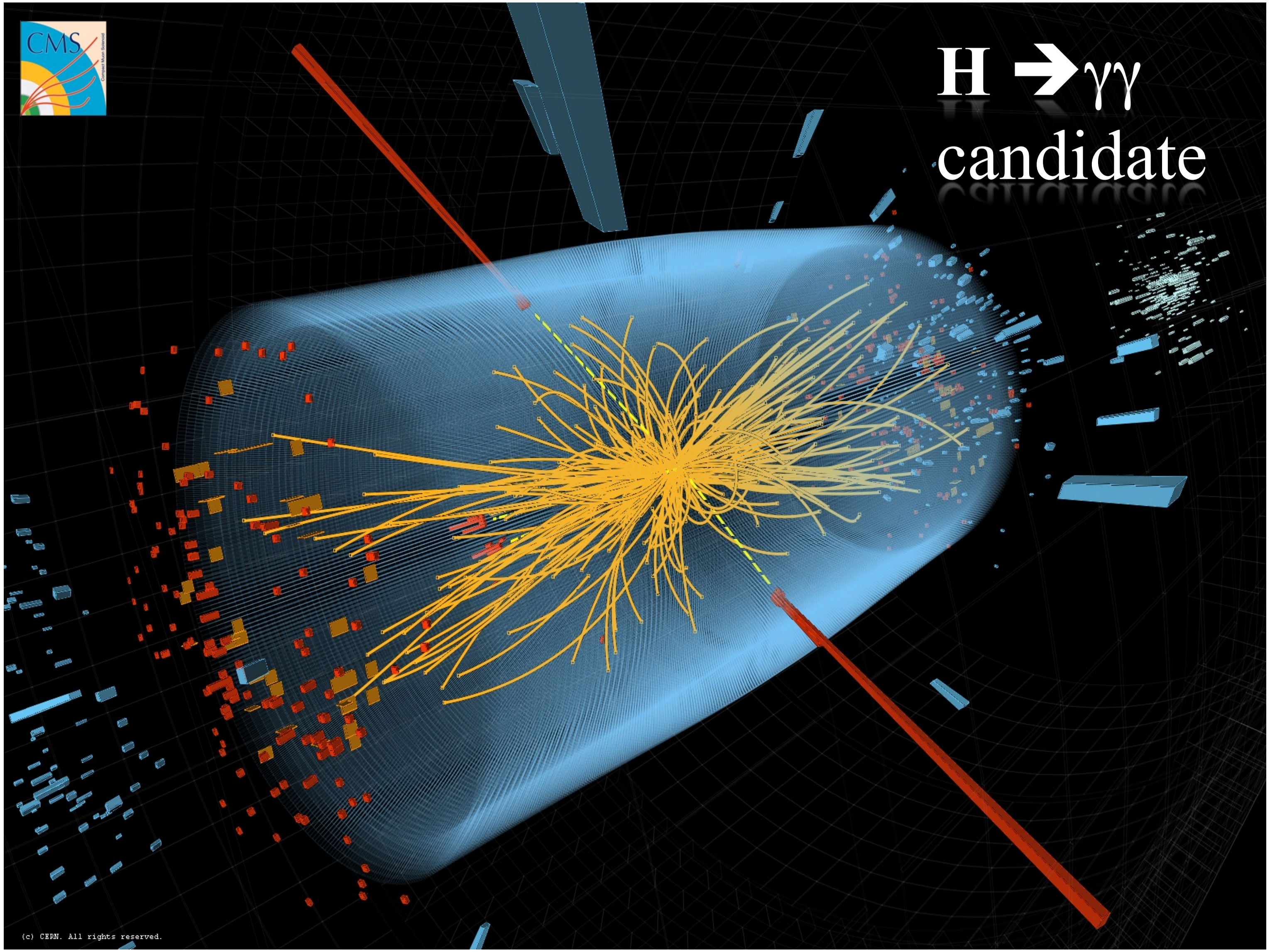
Main search channels

H-> $\gamma\gamma$

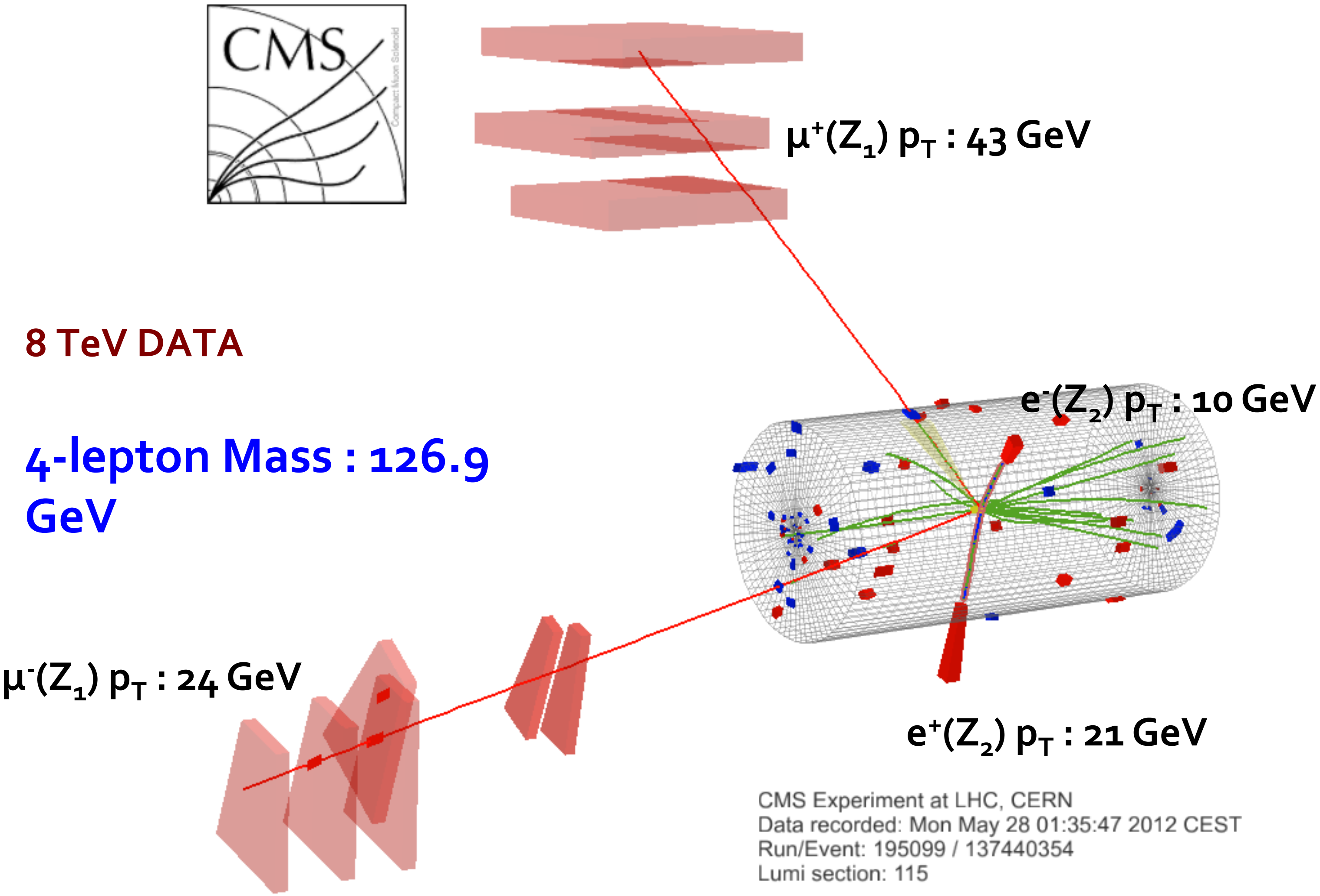
H-> Z Z -> 4 charged leptons

Backgrounds are manageable

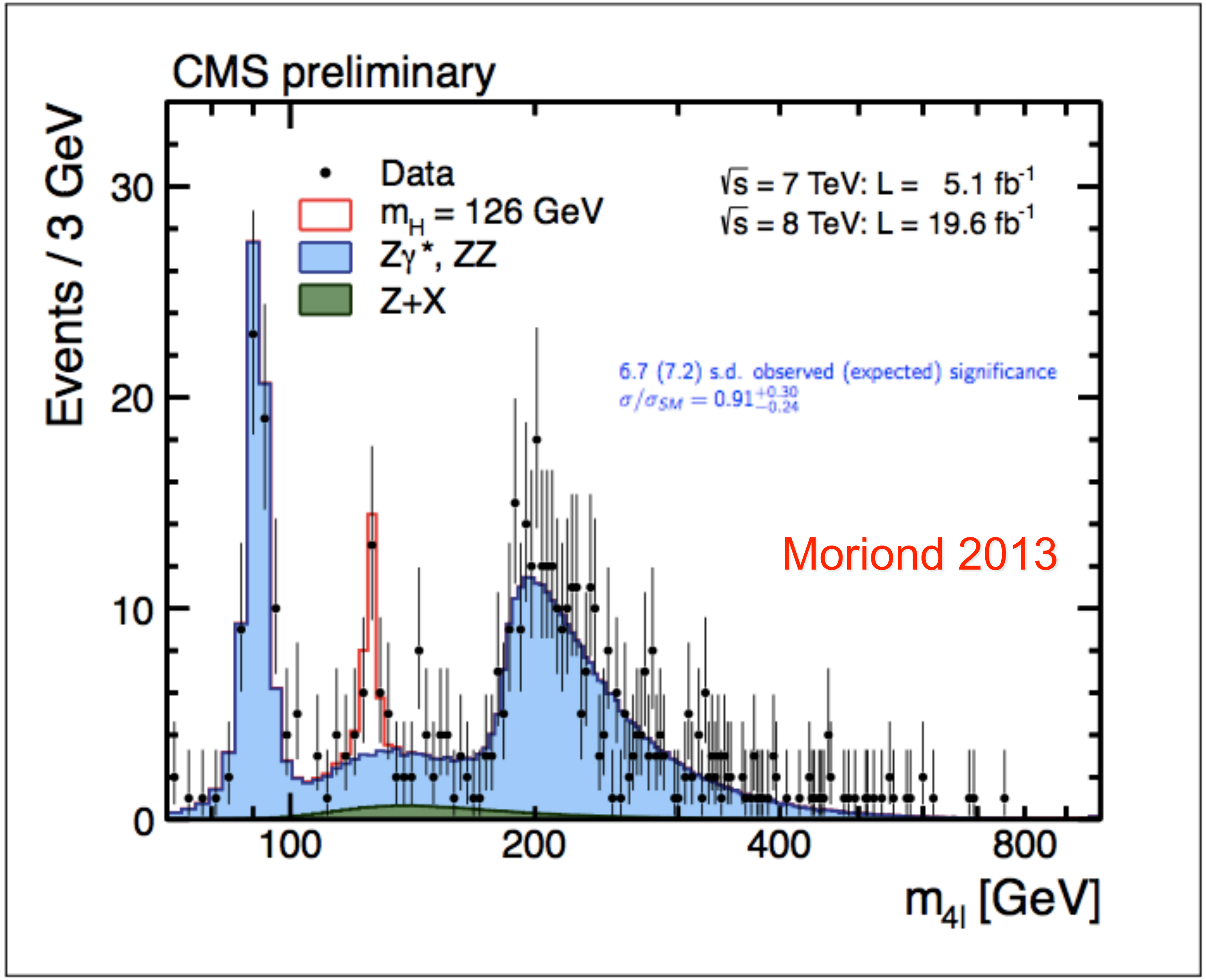
H-> $\gamma\gamma$

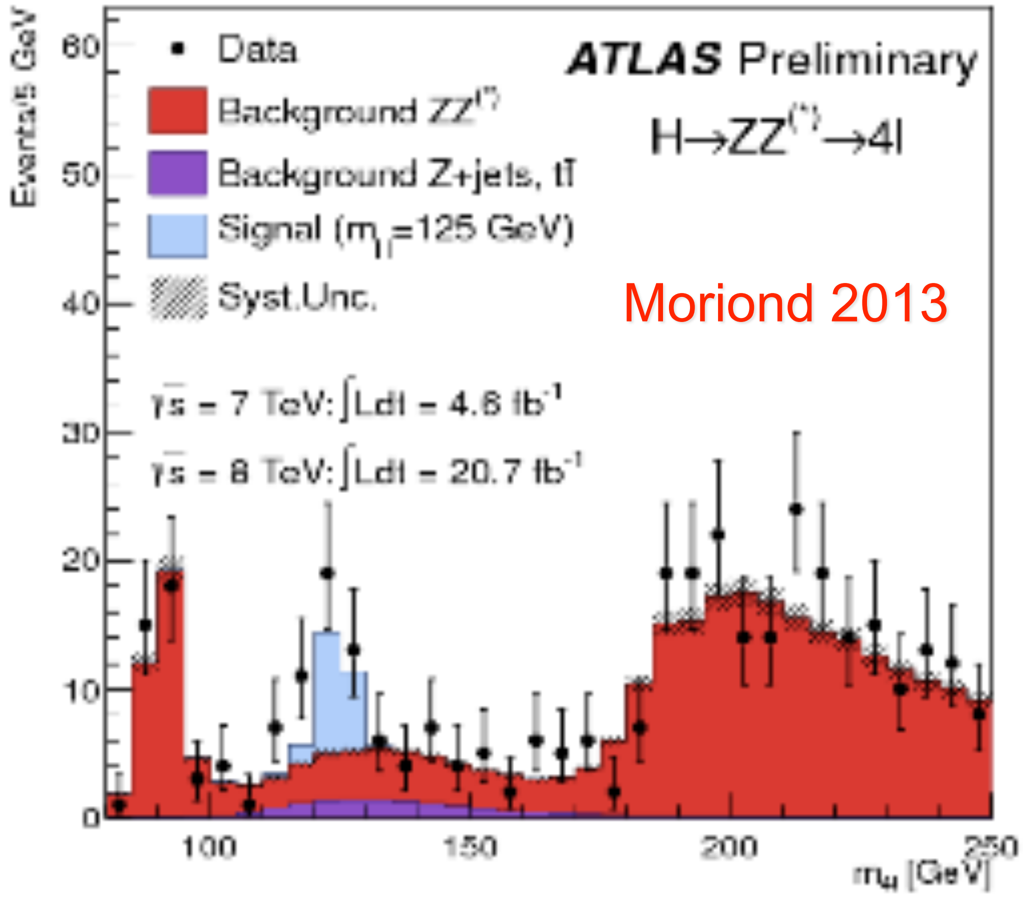


H-> Z Z$^{(*)}$ -> 4 charged leptons



H-> Z Z$^{(*)}$ -> 4 charged leptons

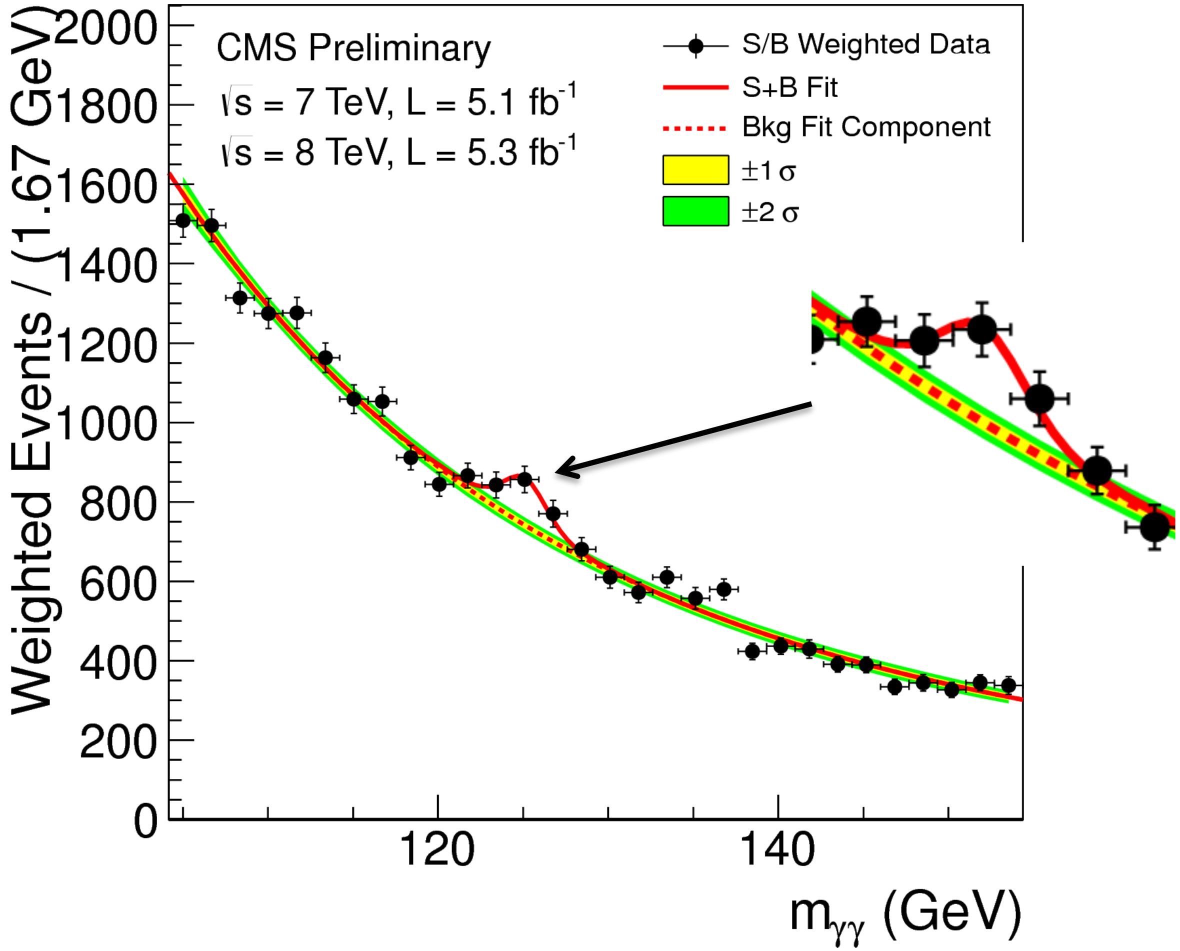


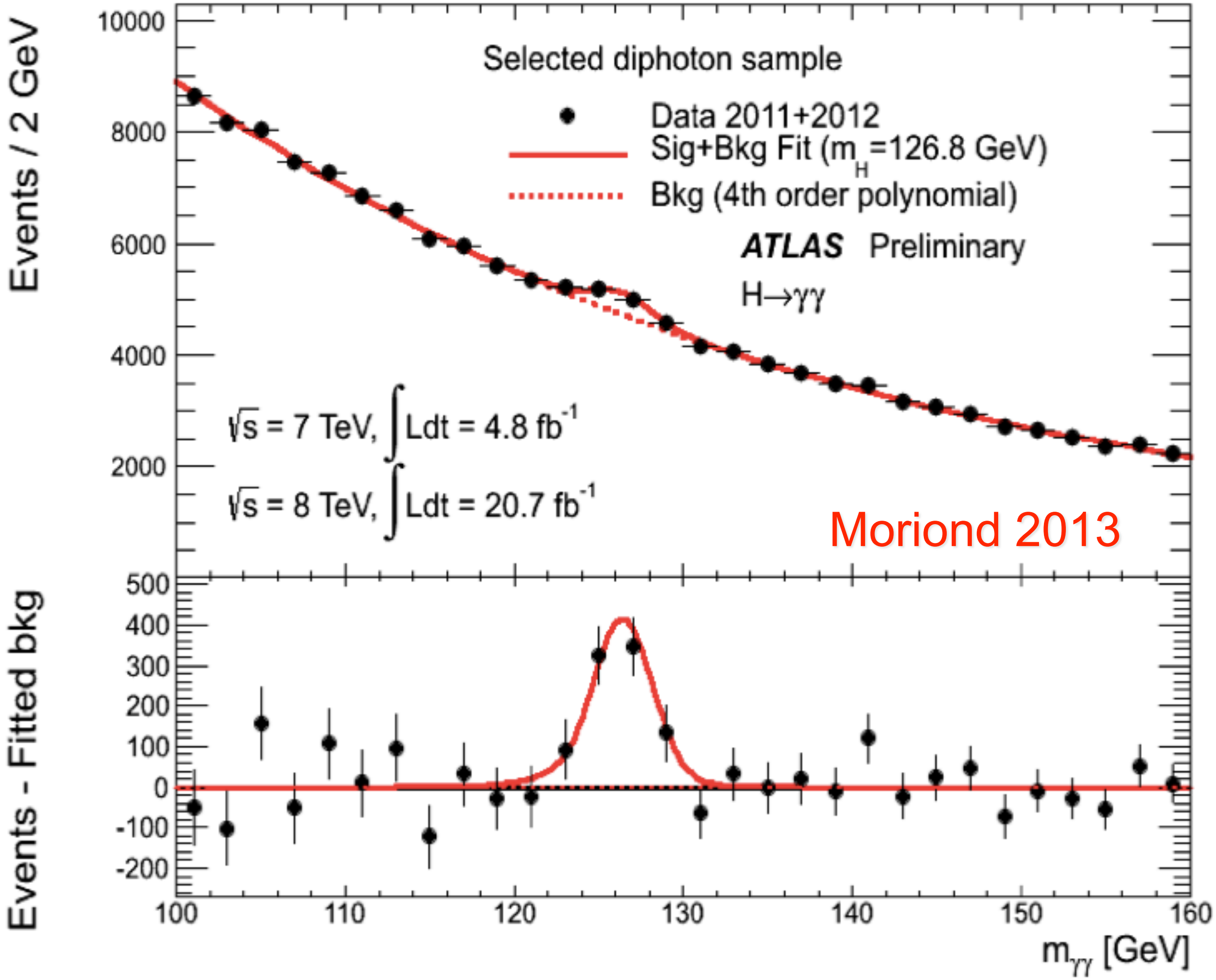


- Observed local significance of the excess: **6.6σ**
  (4.4σ expected for SM Higgs)
- Best mass fit **$124.3^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) GeV**
  [measurement dominated by 4μ – 0.2% systematics from p_T-scale]
- Signal strength @ this mass: **$\mu=1.7^{+0.5}_{-0.4}$**
  [@ 125.5 GeV: μ =1.5 ± 0.4]

H-> γγ

- Sum of mass distributions for each event class, weighted by S/B
  - B is integral of background model over a constant signal fraction interval





- Observed local significance of the excess: **7.4σ** (4.1σ expected for SM Higgs)
- Best mass fit: **126.8 ± 0.2 (stat) ± 0.7 (syst) GeV** → Systematics fully dominated by γ-energy scale
- Best fit of signal strength @ this mass $\mu = 1.65^{+0.34}_{-0.30} = 1.65 \pm 0.24\ (stat)\ ^{+0.25}_{-0.18}\ (syst)$
  [consistent across various categories]

➔ 2.3σ from SM Higgs + background hypothesis

Summary of Higgs mass

$$M_h = 125.66 \pm 0.34 \ \text{GeV} = \begin{cases} 125.4 \pm 0.5_{\text{stat}} \pm 0.6_{\text{syst}} \ \text{GeV} & \text{CMS } \gamma\gamma \\ 125.8 \pm 0.5_{\text{stat}} \pm 0.2_{\text{syst}} \ \text{GeV} & \text{CMS } ZZ \\ 126.8 \pm 0.2_{\text{stat}} \pm 0.7_{\text{syst}} \ \text{GeV} & \text{ATLAS } \gamma\gamma \\ 124.3 \pm 0.6_{\text{stat}} \pm 0.5_{\text{syst}} \ \text{GeV} & \text{ATLAS } ZZ \end{cases}$$

I’m not an experimentalist but I also found the Higgs at CERN...

Have we found THE Higgs?

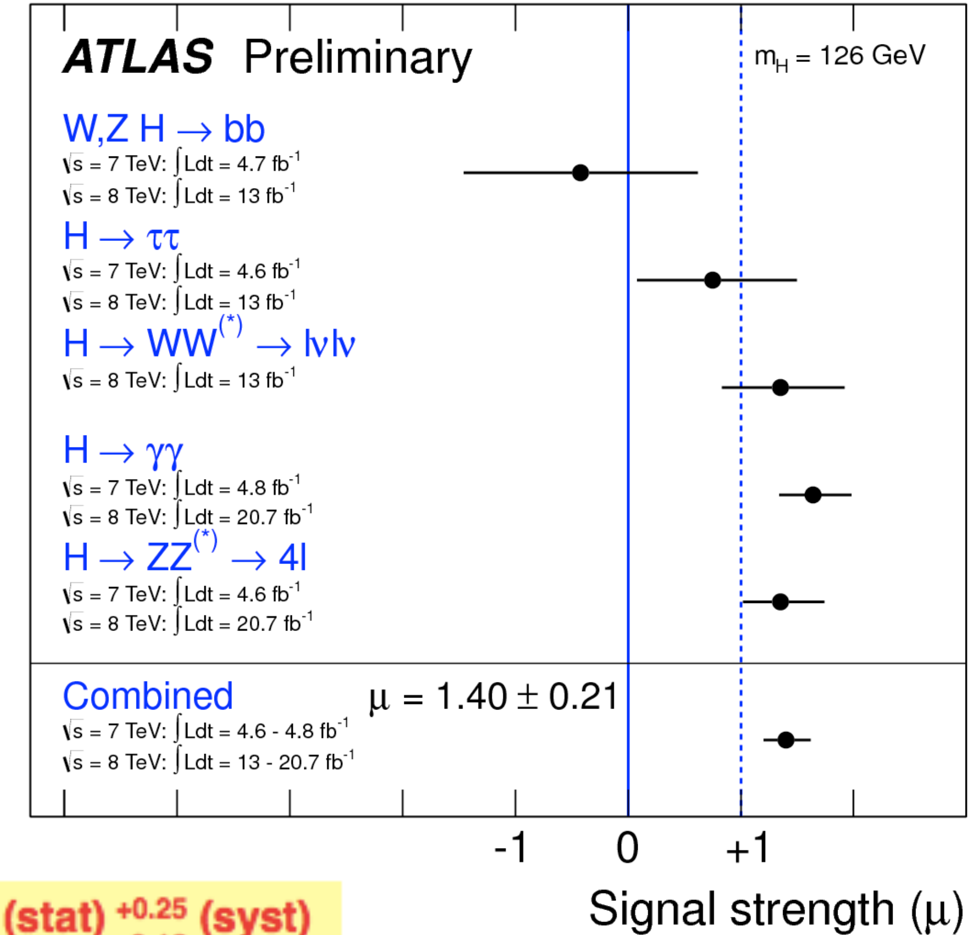
Given the Higgs mass in the SM, all parameters are known!

Strategy: measure Higgs cross sections and compare with SM predictions.

In particular, define “signal strength”:

$$\mu \equiv \frac{\sigma}{\sigma_{SM}}$$

An example of signal strength



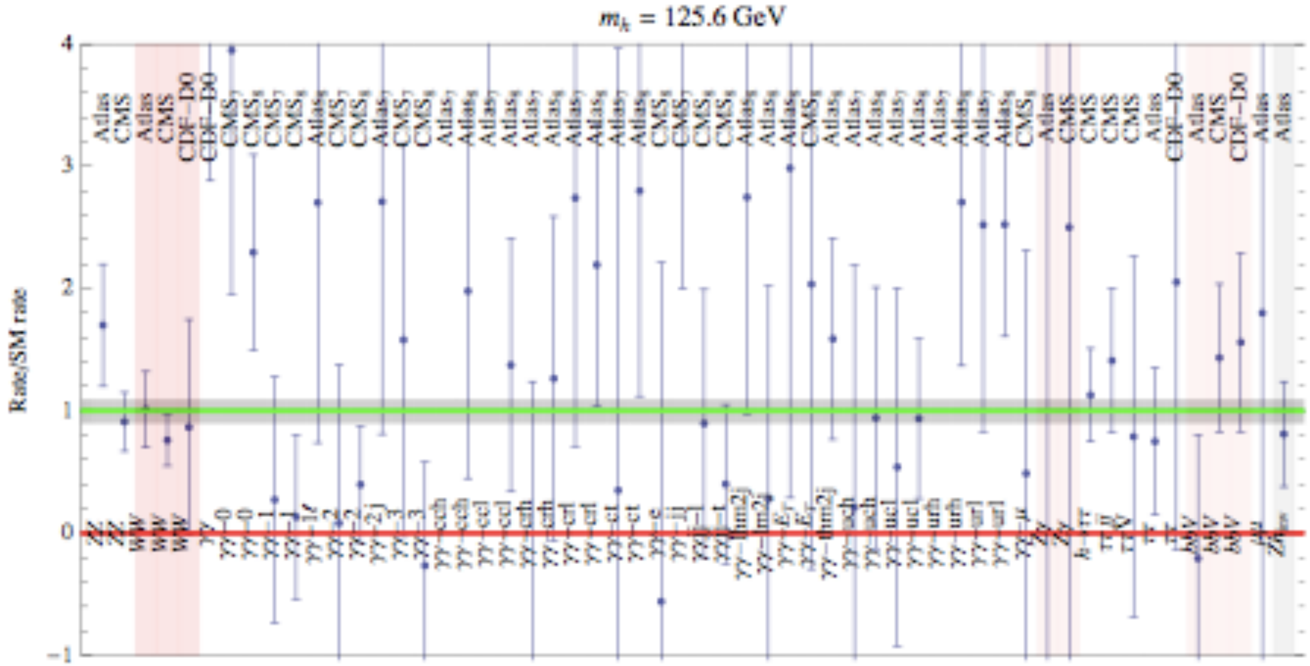
Photons only

$\mu = 1.65^{+0.34}_{-0.30} = 1.65 \pm 0.24\,(\text{stat})\,^{+0.25}_{-0.18}\,(\text{syst})$

➔ 2.3σ from SM Higgs + background hypothesis

Many papers have been written to explain this "excess" – but CMS has a deficit!

Many measurements on Higgs
(but large error bars)



arXiv:1303.3570

Figure 1: *Measured Higgs boson rates at ATLAS, CMS, CDF, D0 and their average (horizontal gray band at $\pm 1\sigma$). Here 0 (red line) corresponds to no Higgs boson, 1 (green line) to the SM Higgs boson (including the latest data point, which describes the invisible Higgs rate).*

The universal fit

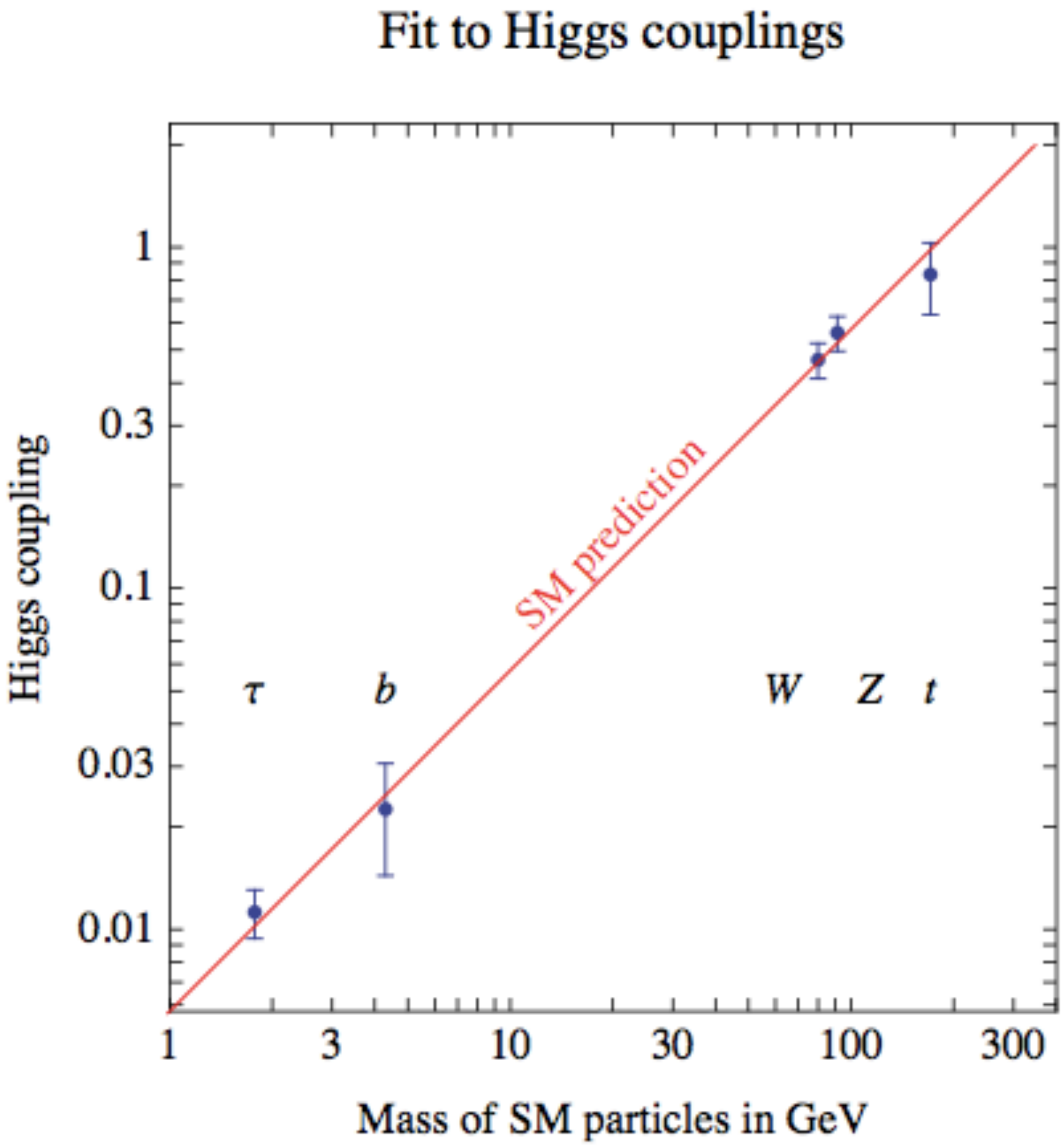
Parametrize new physics with an effective lagrangian (9 free parameters – r's - that are equal to 1 in SM):

$$\mathcal{L}_h = r_t \frac{m_t}{V} h\bar{t}t + r_b \frac{m_b}{V} h\bar{b}b + r_\tau \frac{m_\tau}{V} h\bar{\tau}\tau + r_\mu \frac{m_\tau}{V} h\bar{\mu}\mu + r_Z \frac{M_Z^2}{V} hZ_\mu^2 + r_W \frac{2M_W^2}{V} hW_\mu^+ W_\mu^- + \\ + r_\gamma c_{\rm SM}^{\gamma\gamma} \frac{\alpha}{\pi V} hF_{\mu\nu}F_{\mu\nu} + r_g c_{\rm SM}^{gg} \frac{\alpha_s}{12\pi V} hG_{\mu\nu}^a G_{\mu\nu}^a + r_{Z\gamma} c_{\rm SM}^{Z\gamma} \frac{\alpha}{\pi V} hF_{\mu\nu}Z_{\mu\nu}.$$

Use all available data do minimize

$$\chi^2(r_t, r_b, r_\tau, r_W, r_Z, r_g, r_\gamma, r_{Z\gamma}, r_\mu, \mathrm{BR}_{\rm inv})$$

OBS: given a model, parameters are correlated.



Assumption:
no new particles.

arXiv:1303.3570

Are you convinced it is THE Higgs?

Another fit paper – yesterday!

Higgs At Last

Adam Falkowski[a], **Francesco Riva**[b], **Alfredo Urbano**[c]

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[b] *Institut de Théorie des Phénomènes Physiques, EPFL,1015 Lausanne, Switzerland.*

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Abstract

We update the experimental constraints on the parameters of the Higgs effective Lagrangian. We combine the most recent LHC Higgs data in all available search channels with electroweak precision observables from SLC, LEP-1, LEP-2, and the Tevatron. Overall, the data are perfectly consistent with the 126 GeV particle being the Standard Model Higgs boson. The Higgs coupling to W and Z bosons relative to the Standard Model one is constrained in the range [0.98, 1.09] at 95% confidence level, independently of the values of other Higgs couplings. Higher-order Higgs couplings to electroweak gauge bosons are also well constrained by a combination of LHC Higgs data and electroweak precision tests.

Conclusion for the successes:

All measurements performed so far at accelerators are in good agreement with predictions of the Standard Model.

Why we are not totally happy with the SM?

Shortcomings of the Standard Model

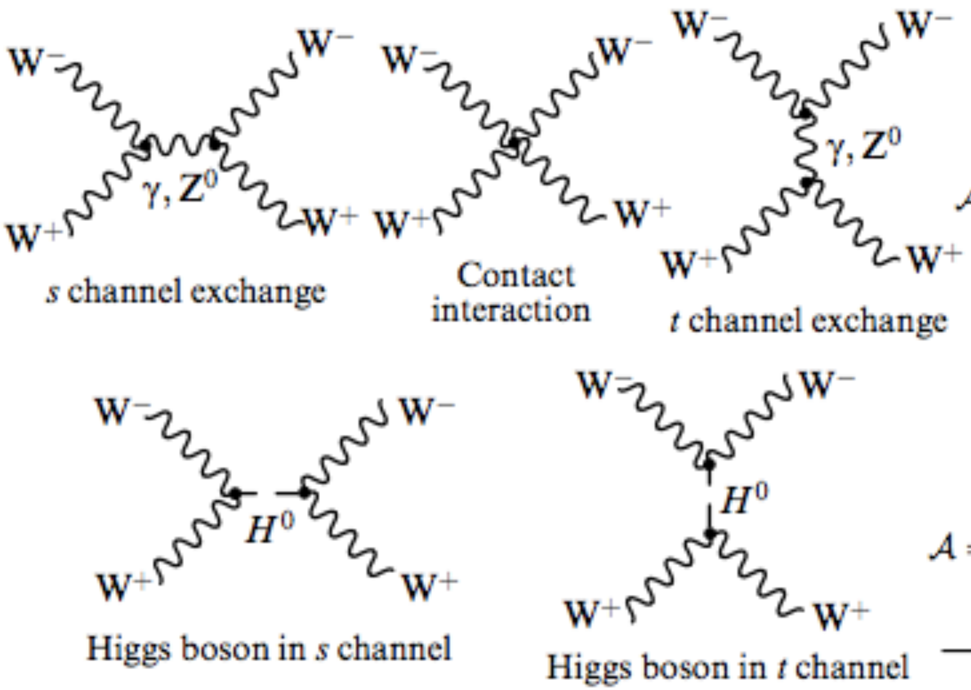
Many free parameters – mostly associated with the Higgs
New non-gauge interactions:
Higgs self-couplings λ
Yukawa couplings between Higgs and leptons – Flavor problem

Conceptual problems related to the scalar sector

- Perturbative unitarity
- Triviality
- Vacuum stability
- Hierarchy and naturalness

I. Perturbative unitarity

SM is “sick” without the Higgs boson – WW scattering violates perturbative unitarity



$$A = g^2\left(\frac{E}{M_W}\right)^2$$

$$A = -g^2\left(\frac{E}{M_W}\right)^2$$

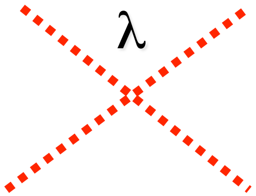
$$A = g^2\left(\frac{M_H}{2M_W}\right)^2$$

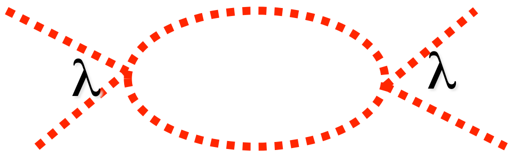
Bad energy behaviour is cancelled by the Higgs

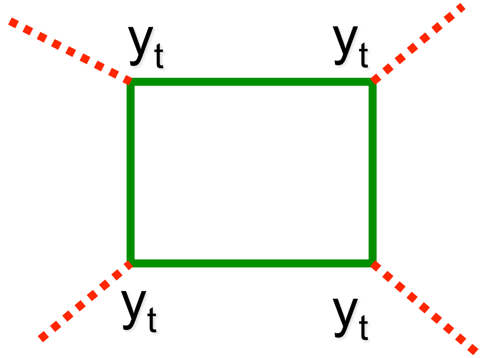
II. Triviality: upper bound on M_H

$$V(\phi) = \lambda \left(\phi^\dagger \phi - \frac{v^2}{2} \right)^2$$

"Running" λ:







$$\frac{d\lambda(\mu^2)}{d \ln \mu^2} \approx \frac{3}{8\pi^2} \lambda^2$$

for large λ

"Running" λ:

$$\lambda\left(\Lambda^2\right) = \frac{\lambda\left(v^2\right)}{1 - \frac{3\lambda\left(v^2\right)}{8\pi^2}\ln\left(\Lambda^2 / v^2\right)}$$

Landau pole: coupling constant <u>diverges</u> at an energy scale Λ:

$$\frac{3\lambda\left(v^2\right)}{8\pi^2}\ln\left(\Lambda^2 / v^2\right) = 1$$

Only way to have a weel defined theory at all scales is to have a vanishing coupling: theory is trivial!

Lesson to be learned:
Higgs sector is an effective theory, valid only up to a given energy scale Λ.

Given a cutoff scale Λ there is an upper limit in the Higgs mass:

$$\frac{3\lambda\left(\mathrm{v}^2\right)}{8\pi^2}\ln\left(\Lambda^2/\mathrm{v}^2\right)<1\Rightarrow$$

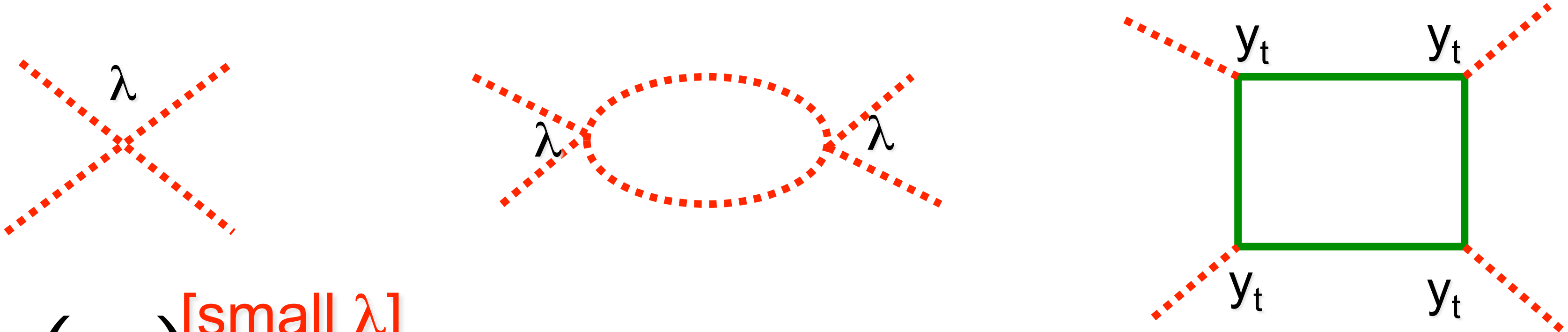
$$M_H^2=2\lambda\left(\mathrm{v}^2\right)\mathrm{v}^2<\frac{16\pi^2\mathrm{v}^2}{3\ln\left(\Lambda^2/\mathrm{v}^2\right)}$$

III. Vacuum stability: λ >0

Higgs can't be too light (small λ):

"Running" λ:

$$V(\phi) = \lambda \left(\phi^\dagger \phi - \frac{v^2}{2} \right)^2$$



[small λ]

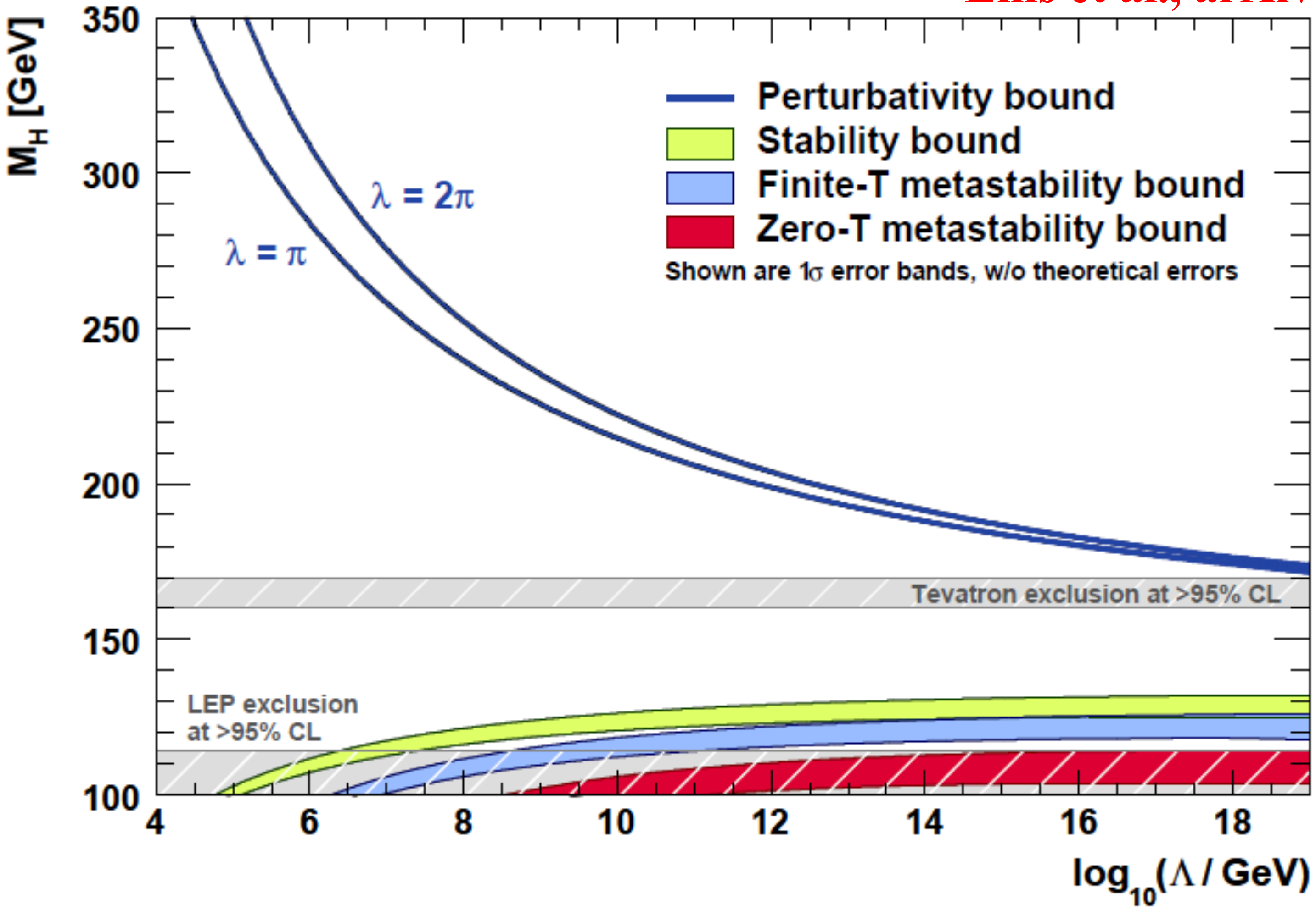
$$\frac{d\lambda(\mu^2)}{d\ln \mu^2} \approx -\frac{3}{8\pi^2} y_t^4 \Rightarrow \lambda(\Lambda^2) = \lambda(\mathrm{v}^2) - \frac{3 y_t^4}{8\pi^2} \ln(\Lambda^2 / \mathrm{v}^2)$$

Vacumm stability (λ>0) implies a lower bound:

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

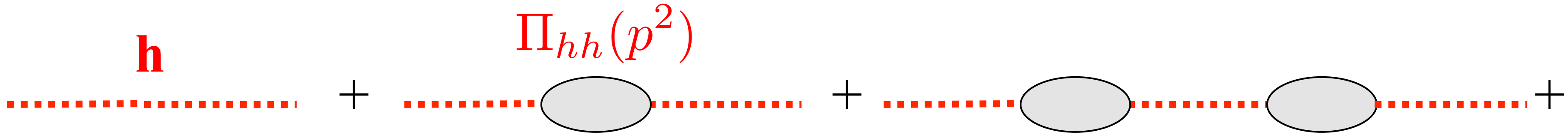
Higgs sector is an effective theory valid up to an energy scale Λ

Ellis et al., arXiv:0906.0954



Recent results on vacuum stability

Condition for absolute stability up to the Planck scale is



Pole equation $$M_h^2 = 2\lambda v^2 + \Pi_{hh}(M_h^2)$$

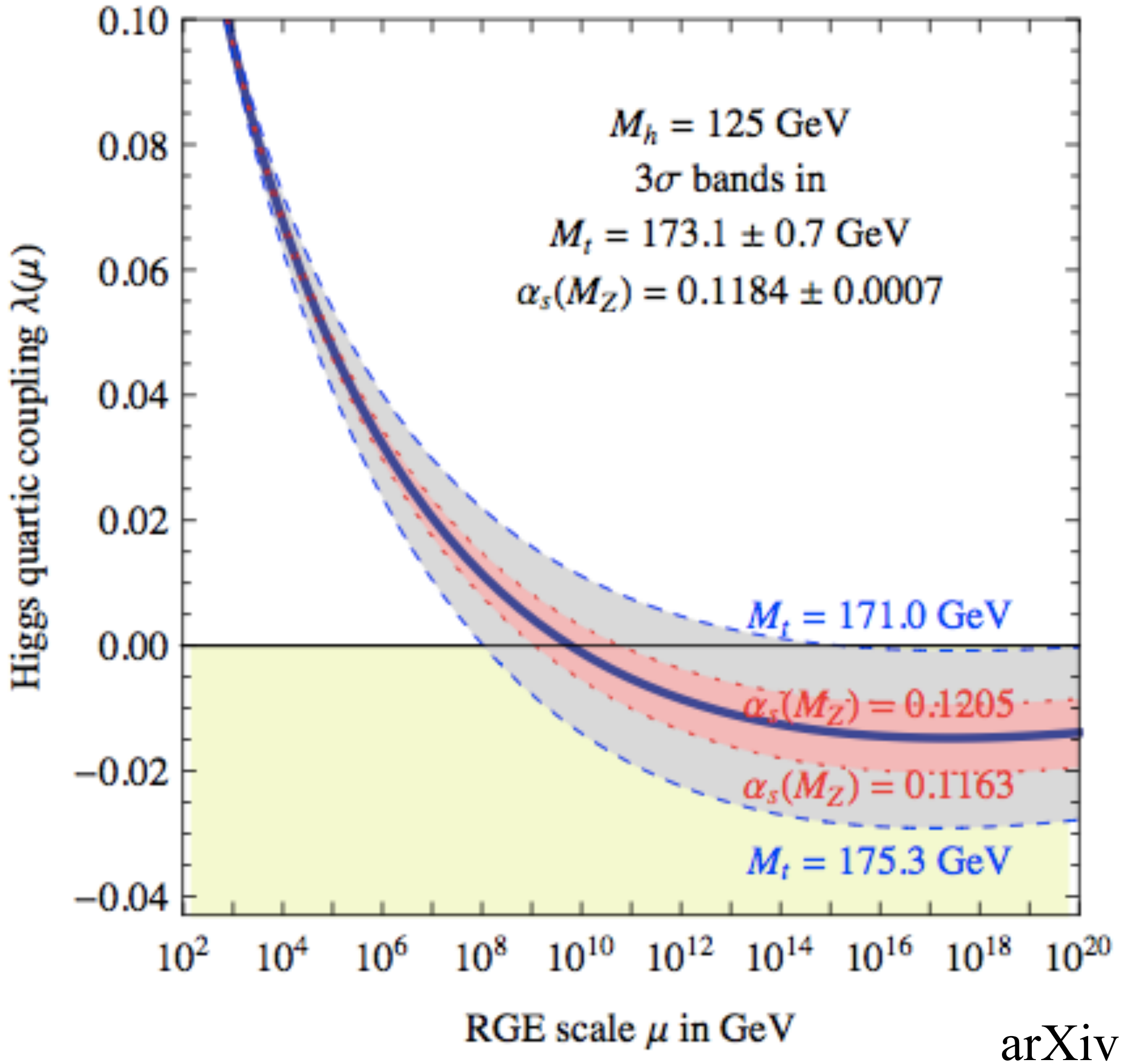
Higgs pole mass at NNLO (independent of μ)

$$M_h\ [\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}$$

$$M_h > 129.4 \pm 1.8\ \mathrm{GeV}$$

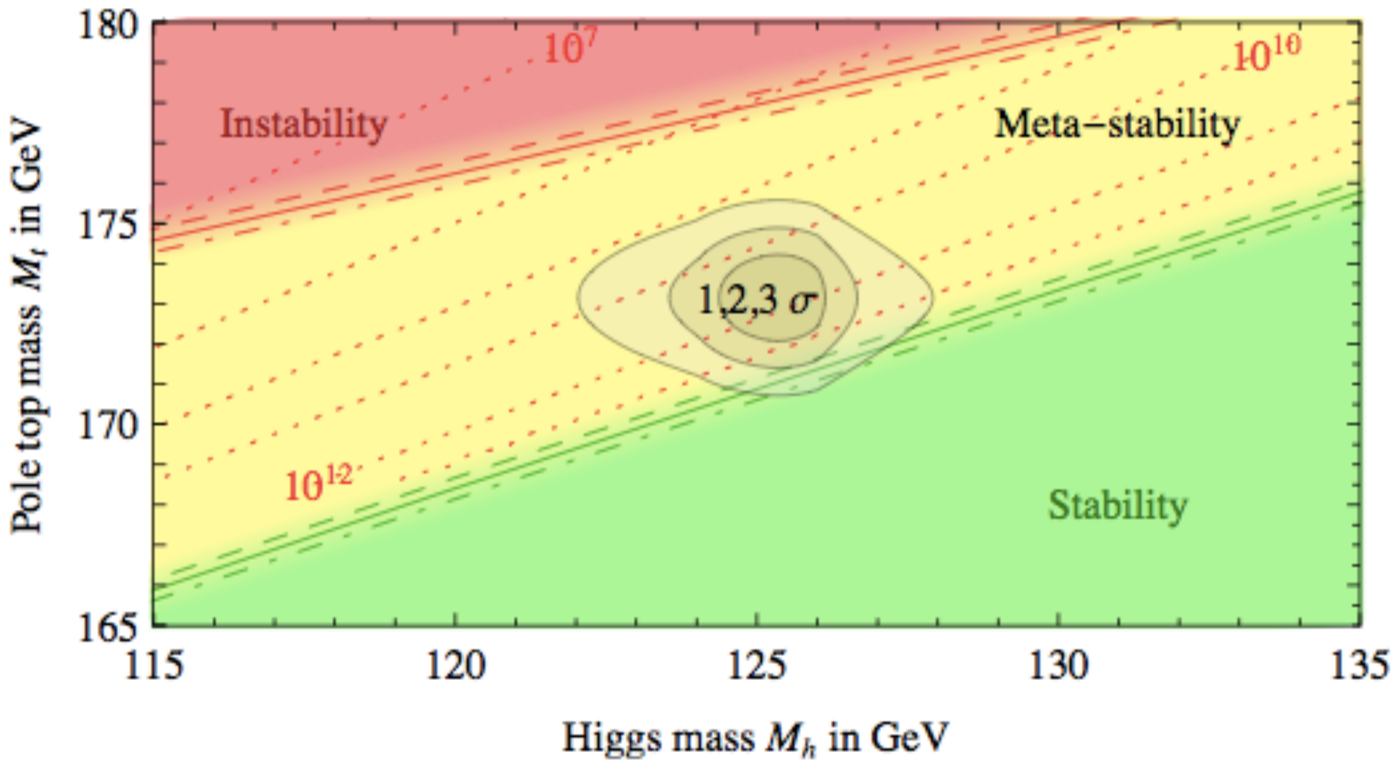
arXiv:1205.6497

Quartic coupling becomes negative: unstable vacuum



arXiv:1205.6497

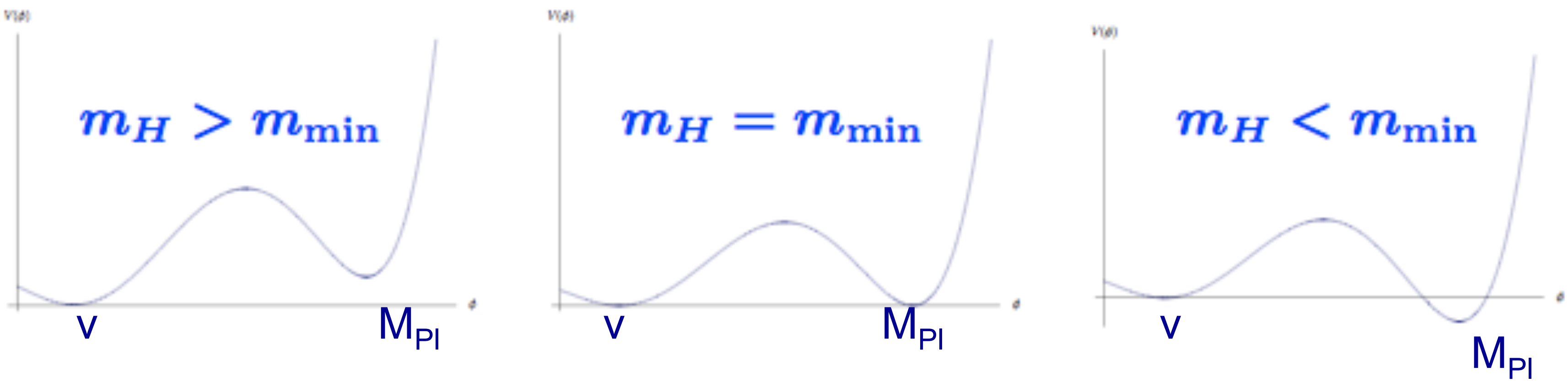
We live in a dangerous universe



arXiv:1205.6497

We live in a dangerous universe

If $m_H < m_{\mathrm{min}}$, there is a deeper vacuum with the Higgs vacuum expectation value larger than the EW vev.



The life-time of our vacuum is smaller than the age of the Universe if $m_H < m_{\mathrm{meta}}$, with $m_{\mathrm{meta}} \simeq 111$ GeV Espinosa, Giudice, Riotto '07

It is curious that the Higgs mass is such that the theory is stable almost up to the Planck mass!

Is this a coincidence? Is there any deep reason?

Asymptotic safety of gravity and the Higgs boson mass

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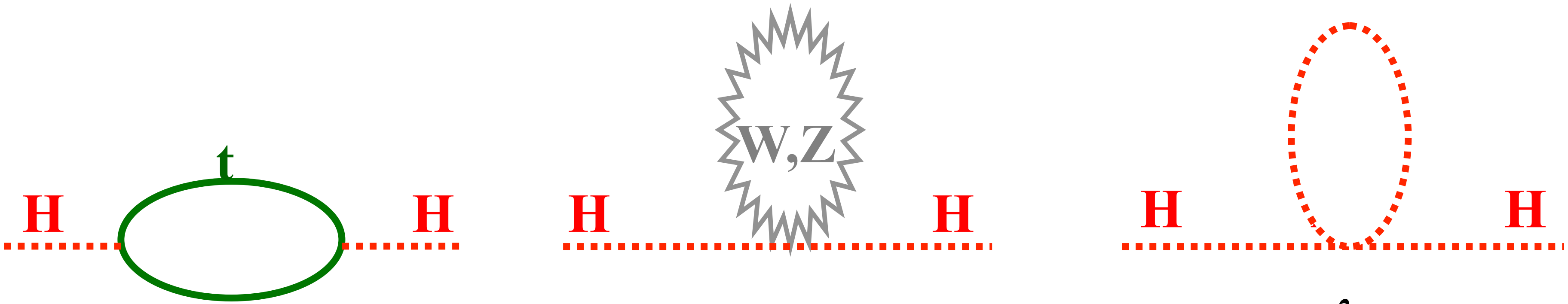
12 January 2010

Abstract

There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson m_H can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction λ at scales beyond the Planck mass is determined by a fixed point at zero. This results in $m_H = m_{\text{min}} = 126$ GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well. For $A_\lambda < 0$ one finds m_H in the interval $m_{\text{min}} < m_H < m_{\text{max}} \simeq 174$ GeV, now sensitive to A_λ and other properties of the short distance running. The case $A_\lambda > 0$ is favored by explicit computations existing in the literature.

IV. Hierarchy and naturalness

Higgs boson mass receives quantum corrections the takes it to be of the order of the largest scale in the theory.
The origin of this behaviour is in the presence of quadratic divergences in the Higgs 2 point function:



$$-\frac{3g_t^2}{8\pi^2}\Lambda^2 \qquad +\frac{9g^2}{64\pi^2}\Lambda^2 \qquad +\frac{\lambda}{16\pi^2}\Lambda^2$$

Physical Higgs mass:

$$M_H^{2(\text{phys.})} \approx \Lambda^2 - M_H^{2(\text{bare})} = \Lambda^2 \left(1 - \frac{M_H^{2(\text{bare})}}{\Lambda^2} \right)$$

Example:

$$M_H^{(\text{phys.})} = 100 \text{ GeV}$$
$$\Lambda = 10^{15} \text{ GeV}$$

$\Longrightarrow$

$$\left(1 - \frac{M_H^{2(\text{bare})}}{\Lambda^2} \right) \approx 10^{-26}!$$

Huge fine tuning of the bare Higgs mass: huge differences in energy scales are not natural.

3 possibilities for natural Higgs:

- New symmetries to protect Higgs mass from quadratic divergences:

✓ SUSY
✓ Shift symmetry (Higgs~NG boson?)
✓ Conformal symmetry (Higgs~dilaton?)

- SM valid only up to Λ~1TeV

 Symmetry is broken by new strong interactions.

- Extra dimensions:

lower Planck scale (UED) or use warped geometries (R-S).

Any substitute to the Higgs sector should:

- break SM symmetries down to EM
- generate masses for particles
- unitarize WW scattering
- explain hierarchy between electroweak and Planck scales.

Beyond the Standard Model

- explain hierarchy between electroweak and Planck scales.
- explain dark matter
- explain neutrino masses
- explain baryon asymmetry in the universe

All candidates predict new particles at the TeV scale! On to the LHC!!