Higgs Physics – Lecture 1

Higgs Physics at the LHC – Introduction

Ricardo Gonçalo – LIP

IDPASC Course on Physics at the LHC – LIP, 3 April 2017

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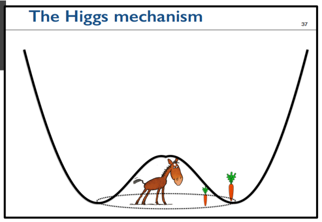
Higgs Lectures

Monday, 3 April

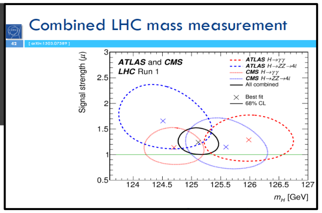


18:00 → 19:30 **Higgs Physics 1**

Introduction
Reminder of some shortcomings of the SM: masses, WW scattering.
The Higgs mechanism. Production and decay of the Higgs boson at colliders: LEP, Tevatron and LHC.
Previous searches at LEP and the Tevatron.

Speaker: Ricardo Jose Morais Silva Goncalo (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part)

Wednesday, 5 April

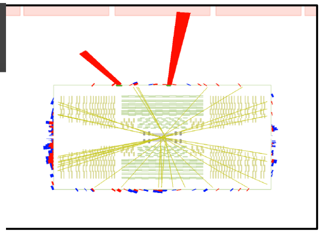


18:00 → 19:30 **Higgs Physics 2**

Discovery of the Higgs boson in the different final states
Case-study of the H->WW search
Algorithms, challenges, tools
Combination of search results

Speaker: Dr. Patricia Conde Muino (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part)

Monday, 10 April



18:00 → 19:30 **Higgs Physics 3**

Models, properties, and interpretation.
Case-study of the coupling strengths.
Case-study of the hypothesis test for different spin-parity assignments.

Speaker: Pedro Vieira De Castro Ferreira Da Silva (CERN)

Wednesday, 12 April

18:00 → 19:30 **Higgs Physics 4**

- Search for new physics in the Higgs sector.
- The Higgs boson and processes beyond the SM.
- Extensions of the SM, minimal and non-minimal extensions.
- High mass searches.
- MSSM Higgs searches: neutral, charged.
- Light pseudoscalar, resonant and non-resonant Higgs pair production.

Speaker: Michele Gallinaro (LIP Lisbon)

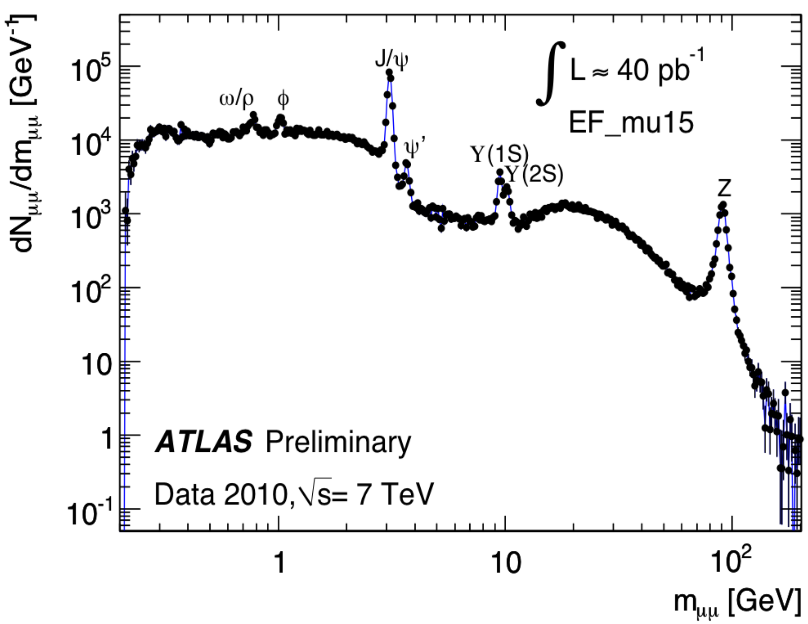
Outlook

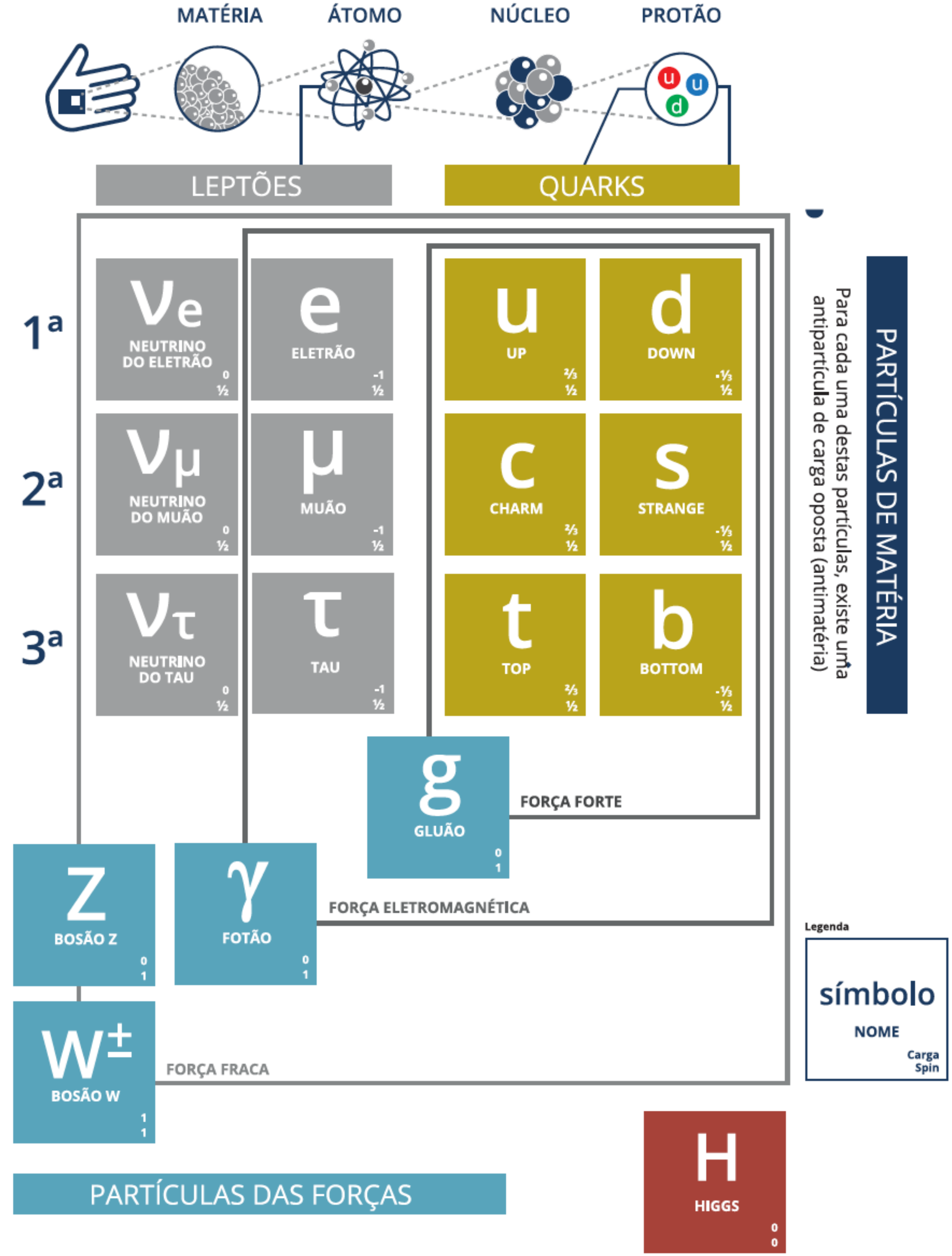
- Introduction
- Hard-core theory
  - Lagrangians and symmetries
  - Quantum fields
  - Problems with the Standard Model
- The Higgs mechanism
- The long way to discovery
  - LEP experiments
  - Tevatron experiments
  - Higgs production and decay at the LHC
  - Discovery!
- Since the discovery
- Open questions

Introduction

Standard Model particles, interactions, and hard-core theory to set the scene…

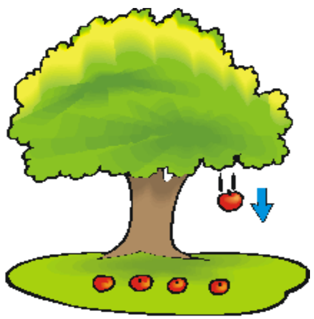
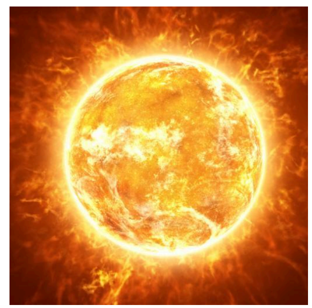
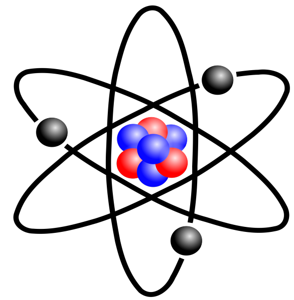
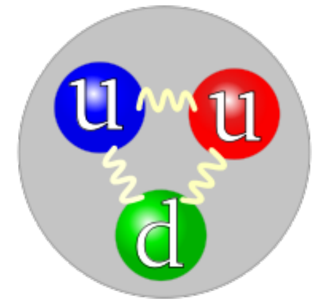
The Standard Model of particle physics





Fundamental interactions

- Four known interactions
- Carried by messenger particles (gauge bosons)
  - As far as we know... We don't know about gravity (too weak)

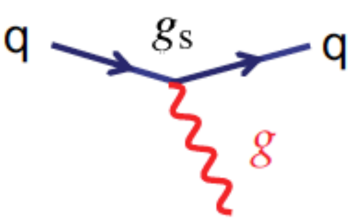





Interaction	Gravitation	Weak	Electromagnetic	Strong
Carrier	Graviton??	W^+, W^-, Z	photon	8 gluons
Acts on	Mass - energy	Weak isospin	Electric charge	Colour
Strength at quark scale	10^{-41}	10^{-4}	10^0	10^2
Characteristic range	∞	10^{-18} m	∞	10^{-15} m
Characteristic system	Apples, galaxies, etc	Beta decay, nuclear fusion	Light, atoms, chemistry	Hadrons (protons etc)

Standard model interactions

The interaction of gauge bosons with fermions is (very) well described by the Standard Model

STRONG



Only quarks

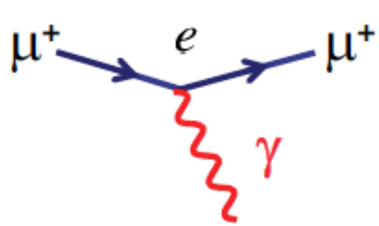
Never changes flavour

$\alpha_S \sim 1$

Gluons

massless

EM



All charged fermions

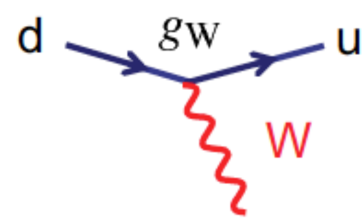
Never changes flavour

$\alpha \simeq 1/137$

Photon

massless

WEAK CC



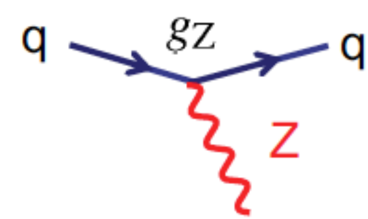
All fermions

Always changes flavour

W+, W-

very massive

WEAK NC



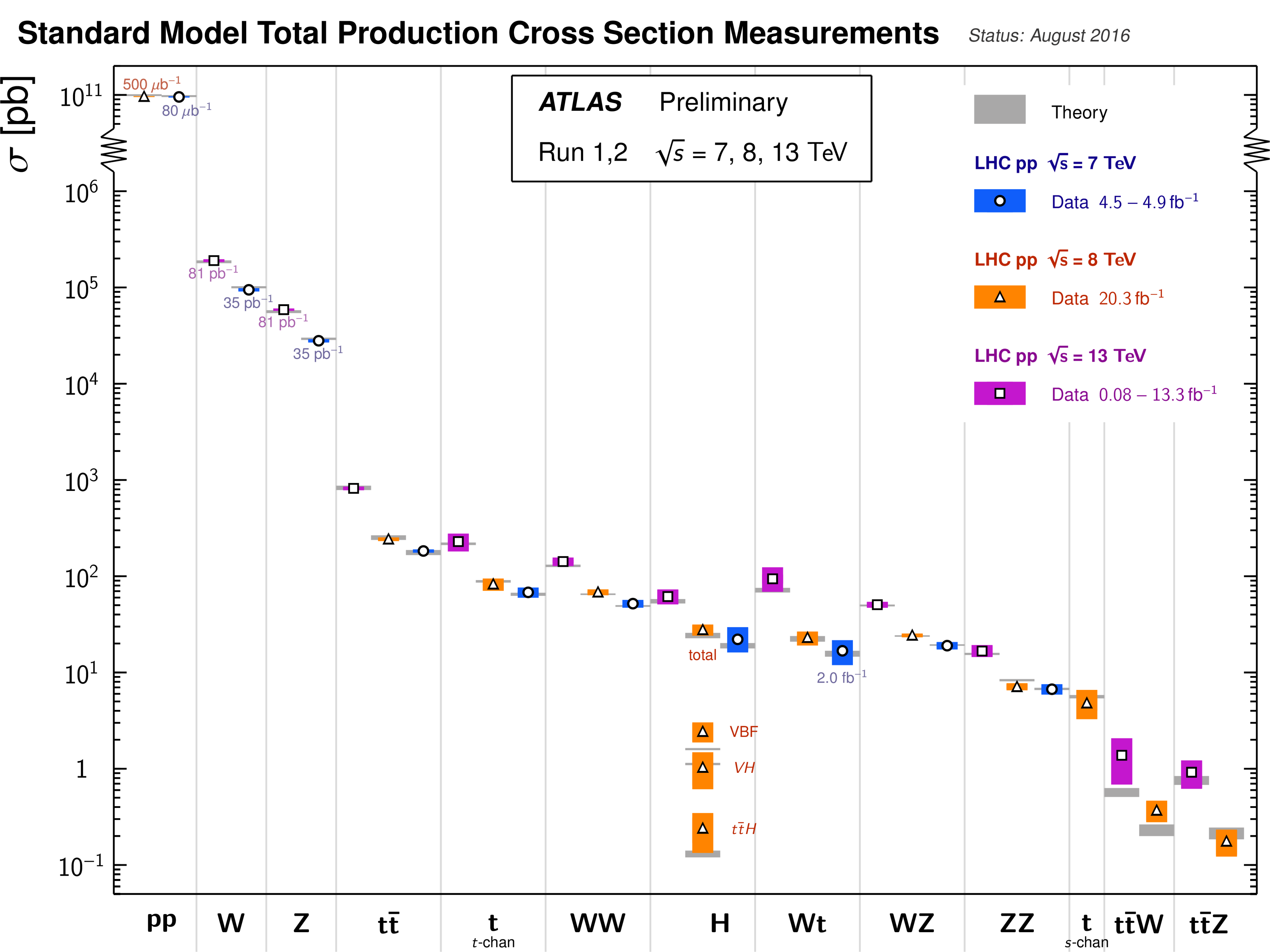
All fermions

Never changes flavour

$\alpha_{W/Z} \sim 1/40$

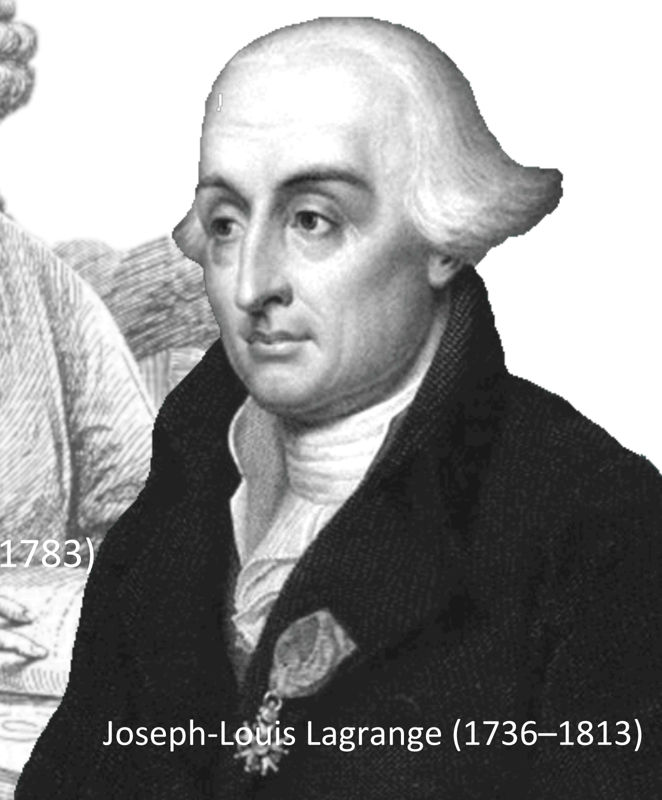
Z^0

very massive



Standard Model Total Production Cross Section Measurements
Status: August 2016
σ [pb]
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 0.08 – 13.3 fb⁻¹
500 μb⁻¹
80 μb⁻¹
81 pb⁻¹
35 pb⁻¹
81 pb⁻¹
35 pb⁻¹
total
2.0 fb⁻¹
VBF
VH
tt̄H
pp
W
Z
tt̄
t
t-chan
WW
H
Wt
WZ
ZZ
t
s-chan
tt̄W
tt̄Z

Lagrangians, symmetries and all that



Reminder: Lagrangians in classical mechanics

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

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

and from the **Euler-Lagrange's equations**:

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

Example

Particle in a conservative potential V. The Lagrangian

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

has derivatives (e.g. for *x*)

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

and Euler-Lagrange's equations

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

finally give us Newton's familiar 2nd law!

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

Symmetries and conservation laws

Noether's theorem:

If a system has a continuous symmetry property, then there are corresponding quantities whose values are conserved in time.

Simplest case: Coordinates not explicitly appearing in the Lagrangian

$\Rightarrow$ Lagrangian invariant over a continuous transformation of the coordinates

Example: mass **m** orbiting in the field of a fixed mass **M**

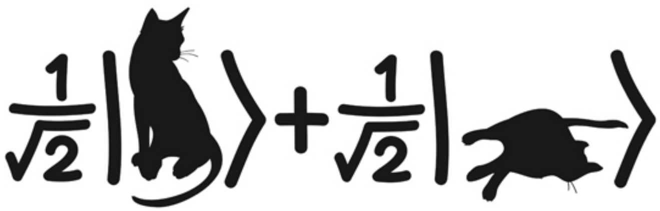
$$L(r,\phi,\dot{r},\dot{\phi}) = T - V = \frac{1}{2}m\dot{r}^2 + \frac{1}{2}mr^2\dot{\phi}^2 + \frac{GMm}{r}$$

Since the lagrangian doesn't depend explicitly on **ϕ** (symmetry with respect to rotations in space), the Euler-Lagrange equation gives

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

Where the **angular momentum J** is a constant of motion!

Let’s go to quantum fields...



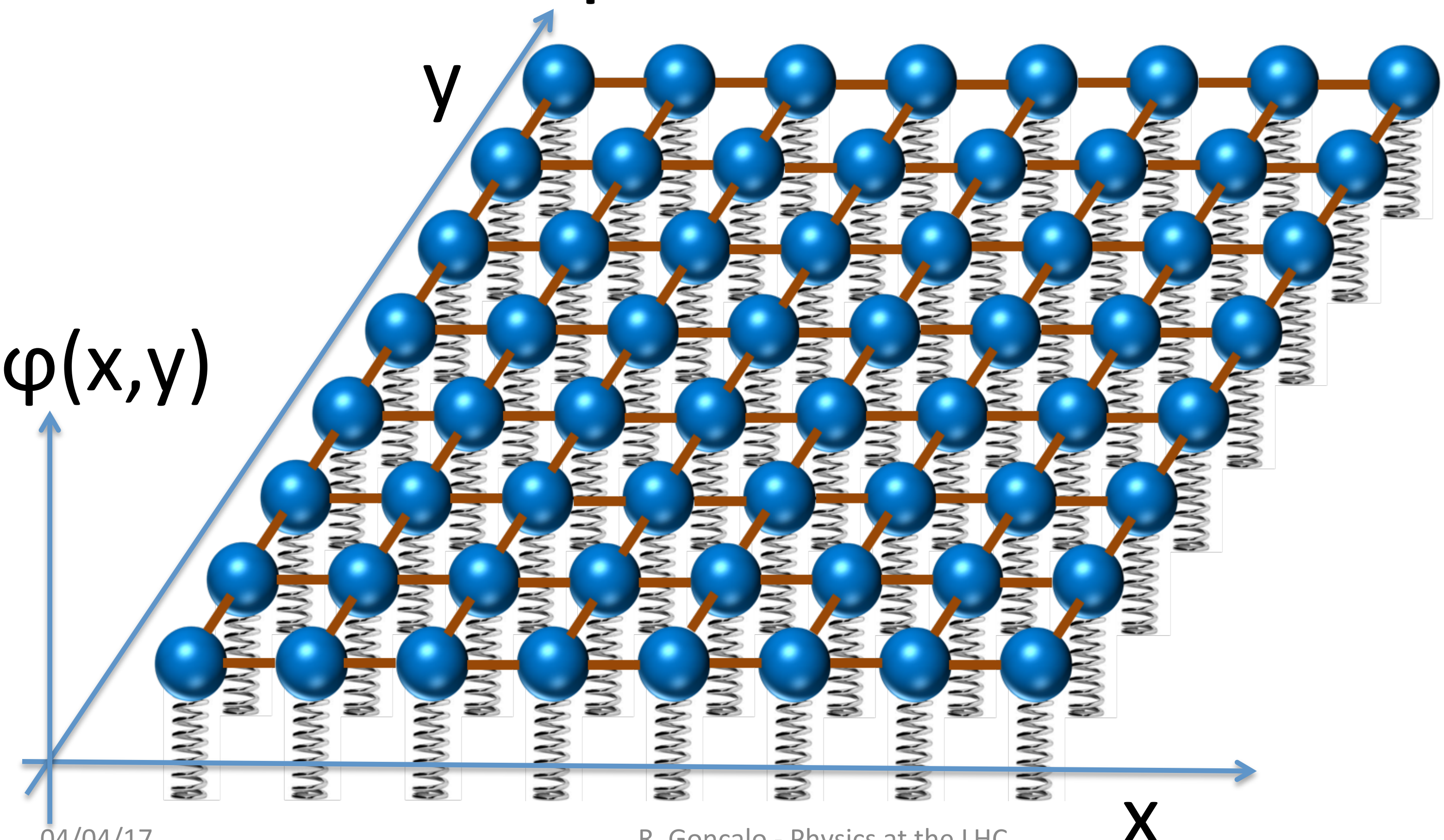
Richard Feynman
(1918 - 1988)

Schrödinger’s cat (?-?)

Erwin
Schrödinger
(1887 - 1961)

Now in quantum field theory…

Imagine space as an infinite continuum of balls and springs, where each ball is connected to its neighbours by elastic bands. **Particles are perturbations of this field**



Generalized coordinates are now **fields** (dislocation of each spring)

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

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

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

In place of a Lagrangian we have a **Lagrangian density** (we call it Lagrangian anyway, just to be confusing)

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

The new Euler-Lagrange equation now becomes

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

Gauge invariance

Take the Dirac Lagrangian for a field ψ representing a spin-½ particle, for example an electron:

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

It is invariant under a global U(1) phase transformation like:

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

Where **χ** is a constant

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

Local gauge invariance and interactions

If $\chi = \chi(x)$ then we get extra terms in the Lagrangian:

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

But we can now make the Lagrangian invariant by adding an ***interaction term*** with a new **gauge** field A_μ which transforms as:

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

We get:

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

A few things to note:

1. Gauge theories are renormalizable, i.e. calculable without infinities popping up everywhere (Nobel prize of t'Hooft and Veltman)
2. The new gauge field A_μ is the photon in QED
3. The mass of the fermion is the coefficient of the term on $\psi\bar{\psi}$
4. There is no term in $A_\mu A^\mu$ (the photon has zero mass) → this is the beginning of the Higgs story…

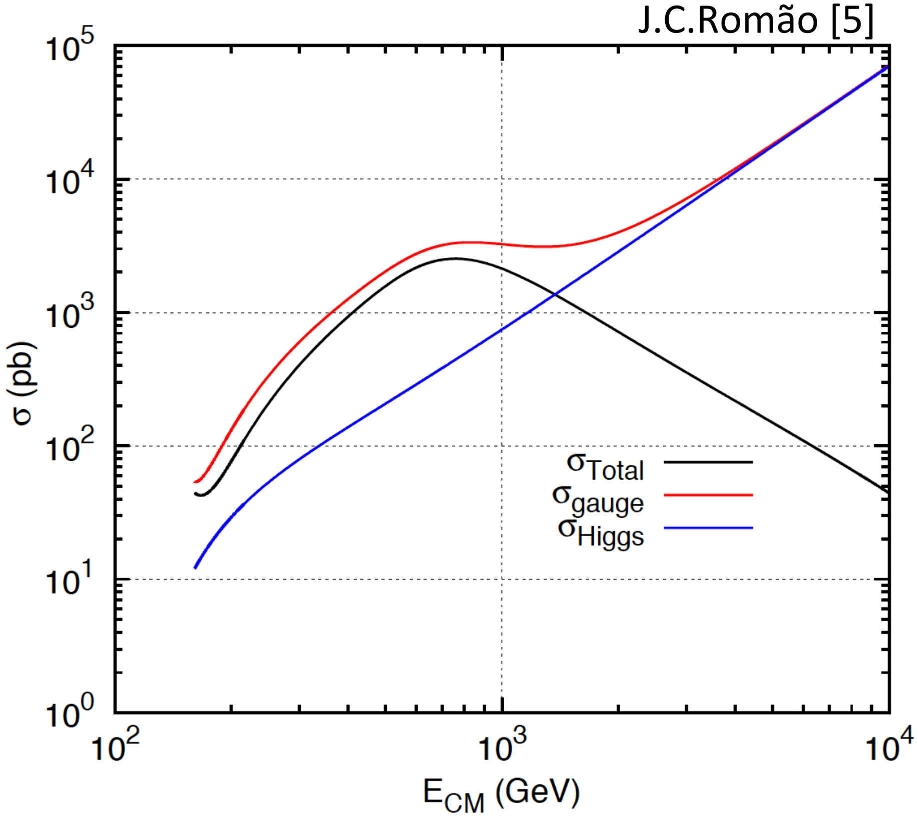
Now for the problems...

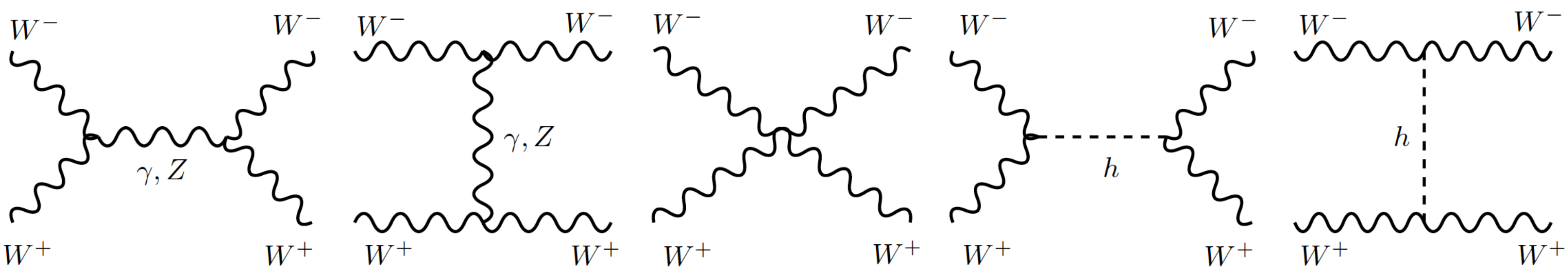
1: Longitudinal gauge-boson scattering

The cross section of a process quantifies the probability that this process occurs in a collision

In the absence of the Higgs, some processes have cross sections that grow with the centre of mass energy of the collision… i.e. breaks unitarity!

The Higgs regulates the cross section through negative interference





Feynman diagrams contributing to longitudinal WW scattering

2: Mass of elementary particles and gauge bosons

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu \partial_\mu - m_e)\psi - e\bar{\psi}\gamma^\mu \psi A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\gamma A_\mu A^\mu$$

To keep the Lagrangian gauge invariant (against a U(1) local phase transformation) the photon field transforms as:

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

But the $\boldsymbol{A^\mu}$ mass term breaks the invariance of the Lagrangian:

$$\frac{1}{2}m_\gamma A_\mu A^\mu \rightarrow \frac{1}{2}m_\gamma (A_\mu - \partial_\mu)(A^\mu - \partial^\mu \chi) \neq \frac{1}{2}m_\gamma A_\mu A^\mu$$

For the $SU(2)_L$ gauge symmetry transformations of the **weak interaction** the fermion mass term $\mathbf{m_e \bar{\psi}\psi}$ also breaks invariance!

Bottom line: **the SM (without the Higgs mechanism) results in wrong calculations and breaks down for massive particles**

The Higgs Mechanism

- Introduce a SU(2) doublet of spin-0 complex fields

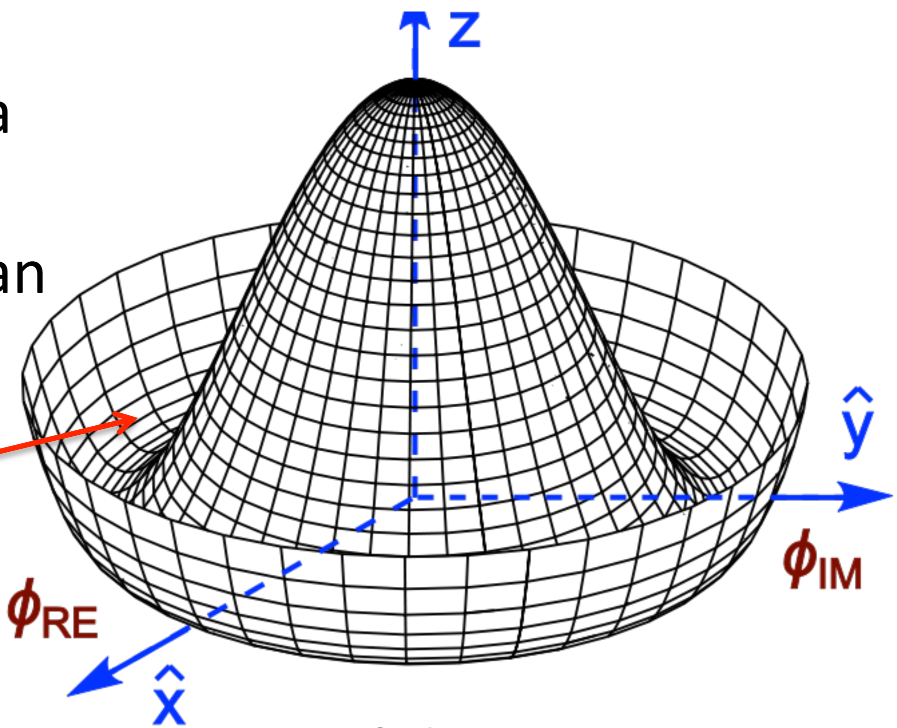
$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi 4 \end{pmatrix}$$

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

- With a potential $V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$

- For λ>0, μ^2<0 the potential has a minimum at the origin
- For λ>0, μ^2<0 the potential has an infinite number of minima at:

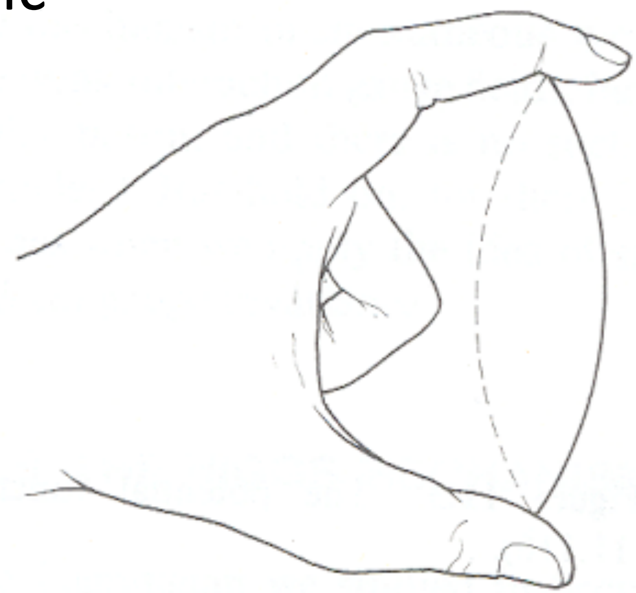
$$|\phi| = \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}}$$



The choice of vacuum (lowest energy state of the field) breaks the symmetry of the Lagrangian

Electroweak symmetry breaking

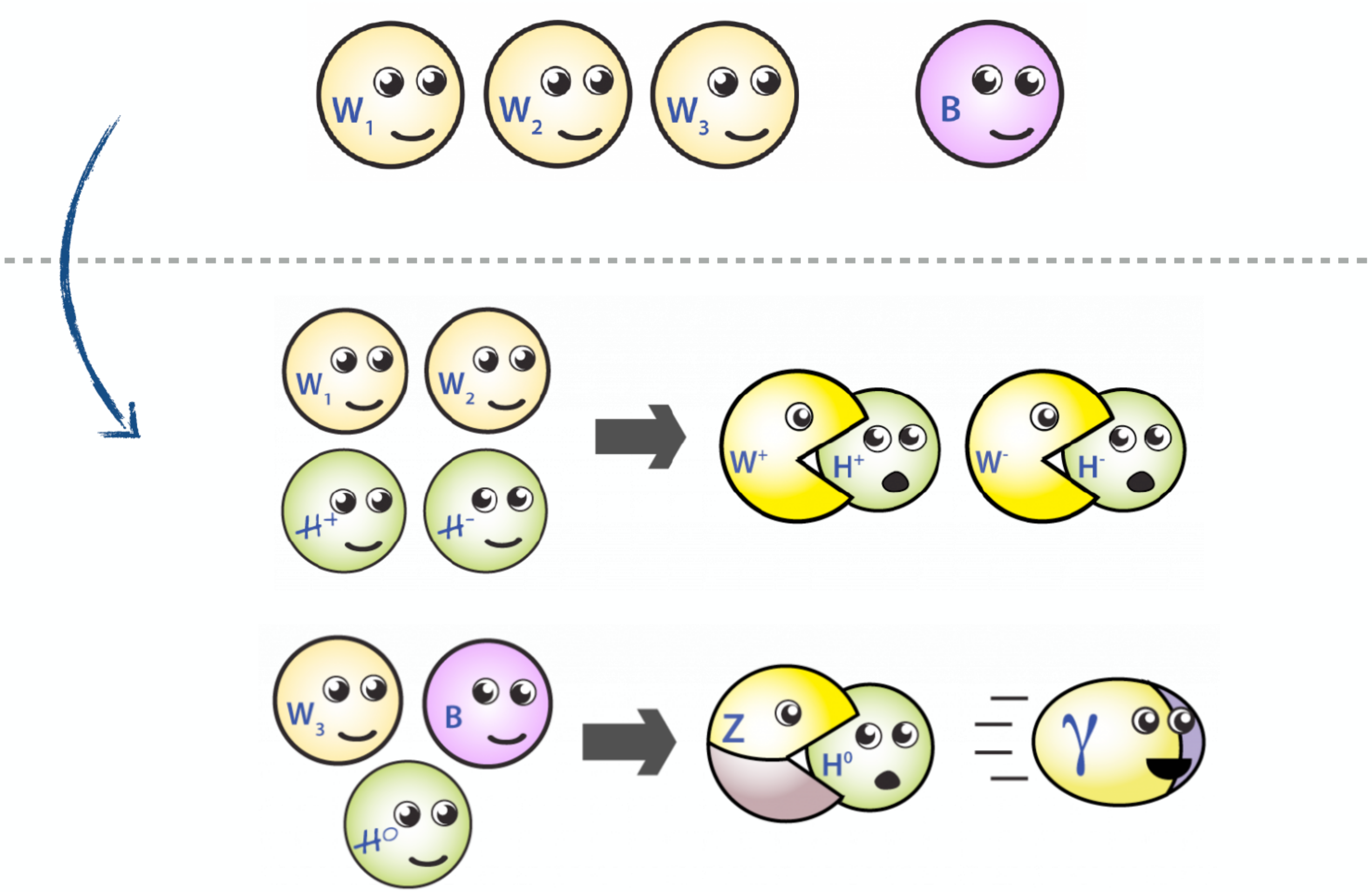
- In the Standard Model with no Higgs mechanism, interactions are symmetric and particles do not have mass



- Electroweak symmetry is broken:
  – Photon does not have mass
  – W, Z have a large mass
- Higgs mechanism: mass of W and Z results from the Higgs mechanism
- Masses of fermions come from a direct interaction with the Higgs field

see J.Varela's lecture

EWK Symmetry Breaking in Pictures



- We have at this point a massive scalar field with vacuum expectation value ***v*** and mass

$$m_h = \sqrt{2\lambda} v$$

- 4 gauge fields: $W^{(1)}$, $W^{(2)}$, $W^{(3)}$, and $B^{(1)}$ which transform to give the massive W^+, W^- and Z, and massless A (the photon)

$$m_{W^{(1)}} = m_{W^{(2)}} = m_W = \frac{1}{2} g_W v$$

$$m_A = 0 \qquad \Leftrightarrow v = 246\text{GeV}$$

$$m_Z = \frac{1}{2} v \sqrt{g_W^2 + g^2}$$

with g, g_W the couplings of electromagnetic and weak forces

- Defining the Weinberg angle as

$$\frac{g}{g_W} = \tan \theta_W$$

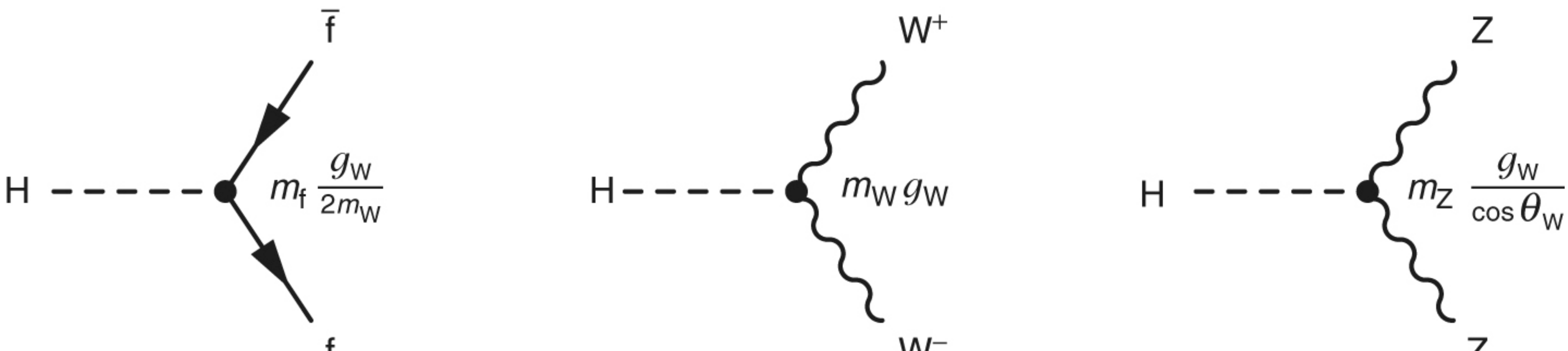
we also get the relation between the masses of W and Z

$$\frac{m_W}{m_Z} = \cos \theta_W$$

- Fermions get their masses from interaction terms with the Higgs field (Yukawa coupling)

Finally! What we think we know:

- Higgs mass (was) the only unknown parameter $$m_h = \sqrt{2\lambda}v$$
- We can give mass to $W^{\pm}$ and Z while keeping the photon massless
- Relation between masses of W and Z $$\frac{m_W}{m_Z} = \cos\theta_W$$
- Higgs couples to W and Z with strengths proportional to their masses
- Higgs couples to all fermions with a strength proportional to their mass $$g_f = \sqrt{2}\frac{m_f}{v}$$

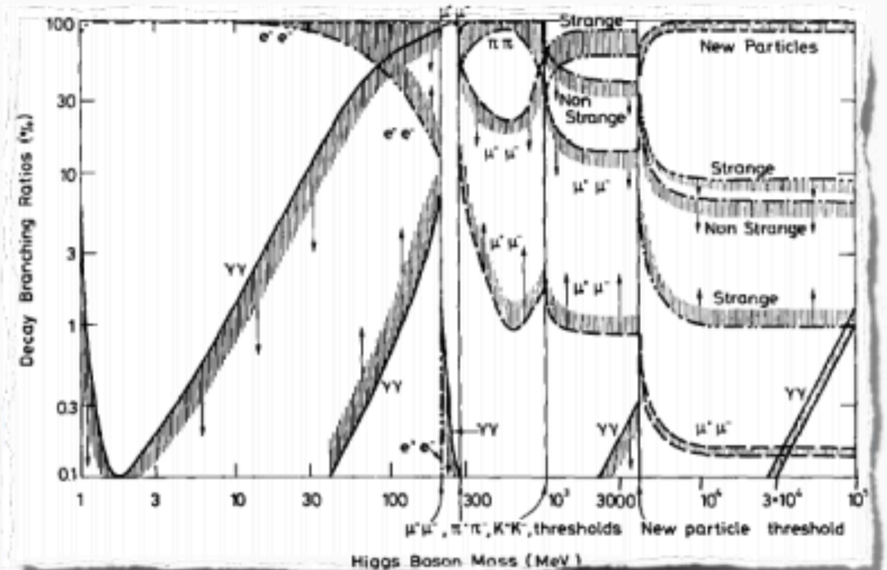


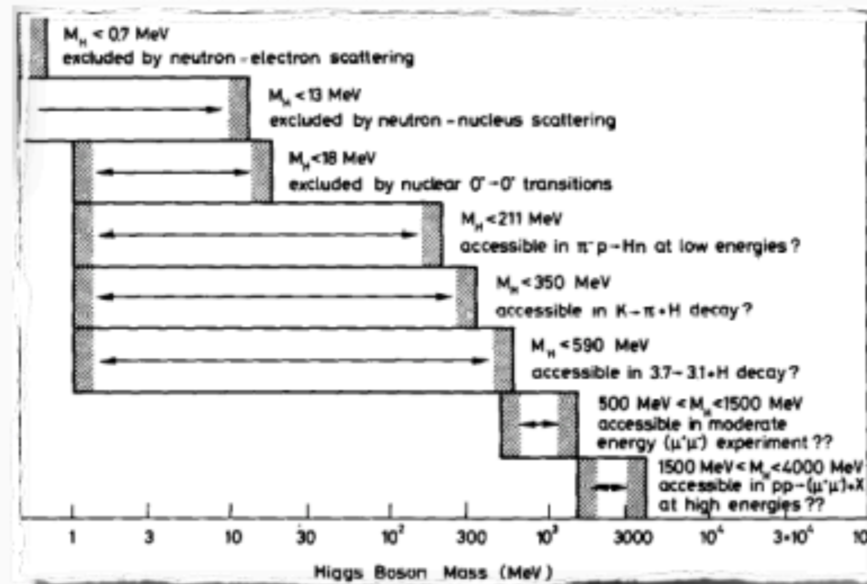
The Long Way to Discovery

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

Received 7 November 1975





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.

Searches in nuclear physics

The beginning of the 1970s started of with great excitement!

Two groups observed deviations in the X-ray spectrum of muonic atoms wrt QED expectations.

Dixit et al., Experimental test of the theory of muonic atoms, Phys.Rev.Lett. 27 (1971) 878-881

Walter et al., Test of quantum-electrodynamical corrections in muonic atoms, Phys.Lett. B40 (1972) 197-199

VOLUME 27, NUMBER 13 PHYSICAL REVIEW LETTERS 27 SEPTEMBER 1971

Experimental Test of the Theory of Muonic Atoms*†

M. S. Dixit and H. L. Anderson
Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637

and

C. K. Hargrove and R. J. McKee
National Research Council of Canada, Ottawa, Canada

and

D. Kessler, H. Mes, and A. C. Thompson
Department of Physics, Carleton University, Ottawa, Canada

(Received 28 June 1971)

We have measured muonic x rays in the energy region 150 to 440 keV in nine elements with an absolute precision of 15 to 21 eV for transitions with small nuclear effects. Calculated transition energies were found to be consistently larger than those measured by an amount that varied from 15±16 eV at 157 keV to 137±22 eV at 438 keV. For these transitions, the principal correction to the Dirac energy is the vacuum polarization. The discrepancy, however, lies outside the expected validity of quantum-electrodynamic calculations and we are unable, at present, to offer an explanation for this effect.

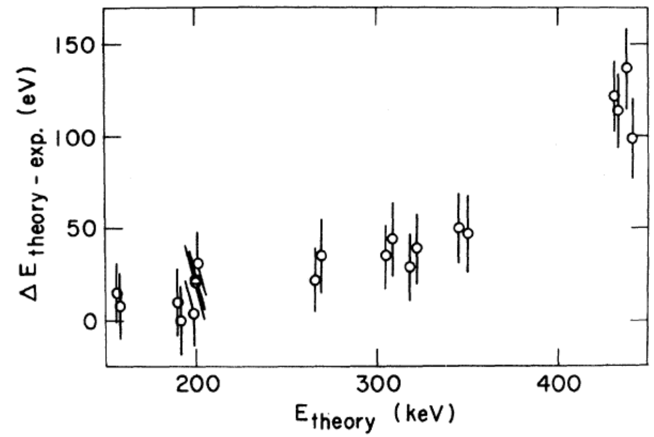


FIG. 1. The discrepancy $\Delta E_{theo-expt}$ (eV) plotted against the theoretical transition energies for 20 muonic x-ray transitions.

As expected a number of theory papers followed discussing potential sources of this effect, one being the production of a low mass Higgs boson, m_H~20 MeV

[1] S. Weinberg, Phys. Rev. Lett. 27, 1688 (1971).
[2] R. Jakiw and S. Weinberg, Phys. Rev. D 5, 2396 (1972).
[3] L. Resnick, M. K. Sundaresan, and P. J. S. Watson, Phys. Rev. D 8, 172 (1973).
[4] M. K. Sundaresan and P. J. S. Watson, Phys. Rev. Lett. 29, 15 (1972).

Searches in particle decays

- SINDRUM Collaboration measured $\pi^+ \to e^+ \nu e^+ e^-$ and searched for $H \to e^+ e^-$

[excluded 10 MeV < M_H < 110 MeV]
SINDRUM spectrometer experiment at the Paul Scherrer Institute (PSI) 590 MeV proton cyclotron.
Measurement of the Decay $\pi^+ \to e^+ \nu e^+ e^-$ and Search for a Light Higgs Boson
SINDRUM Collaboration (S. Egli (Zurich U.) et al.), Phys.Lett. B**222** (1989) 533

- CUSB Collaboration $\Upsilon \to H\gamma$

[excluded $2m_\mu < M_H$ < 5-6 GeV]
Investigated the radiative decay dependent on high order corrections of various states of the Y into a Higgs boson.
The search for a monochromatic photon sample from the decay $\Upsilon \to \gamma + X$.
It turned out that first order QCD corrections reduce the lowest order calculation by about 50%, and the effects of higher order corrections or relativistic corrections were not known.
CUSB also searched for Y decays to a photon plus a massless, invisible scalar.

- Crystal Ball collaboration looked for $J/\psi \to \gamma$+ massless scalar

The data were collected with the Crystal Ball Detector at the Stanford Linear Accelerator Center e^+e^- storage ring facility SPEAR at the peak of the J/ψ resonance

[Edwards et al, Upper Limit for $J/\psi \to \gamma$+Axion, Phys.Rev.Lett. 48 (1982) 903]
These two results CUSB and Crystal Ball together excluded a massless and very light Higgs, which is also subject to radiative correction uncertainties

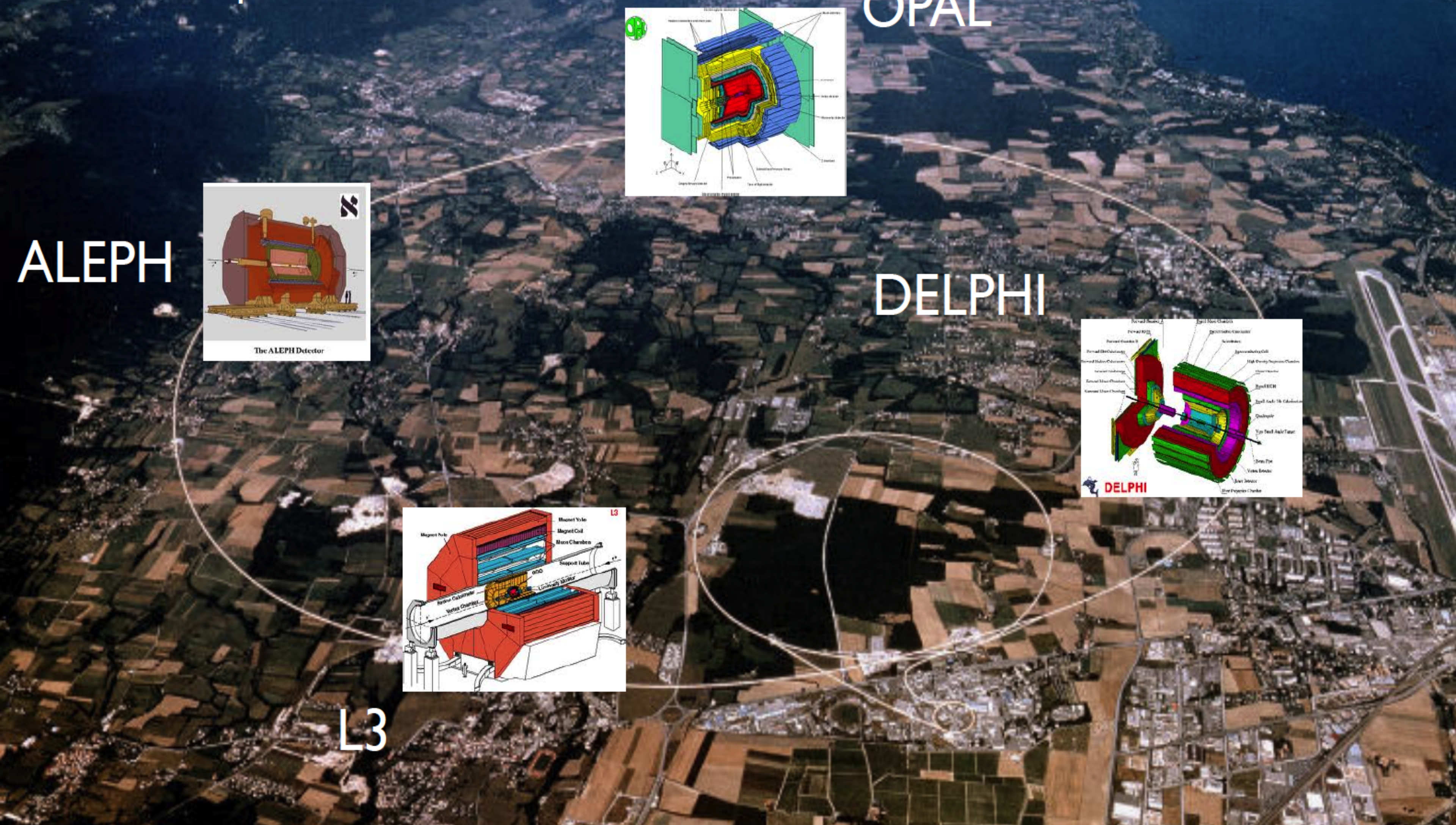
- CERN-Edinburgh-Orsay-Mainz-Pisa-Siegen (NA31) $K^0_L \to \pi^0 H(\to ee)$

[excluded M_H < 50 MeV]
The NA31 experiment at the CERN Super Proton Synchrotron (SPS) searched for Higgs boson decays in e^+e^- in the decay $K^0_L \to \pi^0 H$.
These searches severely constrain the Higgs boson mass in the domain below 50 MeV by conferring an upper limit on the product of the branching ratios $Br(K^0_L \to \pi^0 H) \times Br(H \to e^+ e^-)$ of approximately 2×10^{-8}
Search for a Neutral Higgs Particle in the Decay Sequence $K^0_L \to \pi^0 H$ and $H \to e^+ e$
NA31 Collaboration (G.D. Barr (CERN) et al.), Phys.Lett. B235 (1990) 356

Searches at LEP

Electron-positron collider up to $s^{1/2}$= 209 GeV
Integrated luminosity: ~700 pb^{-1}

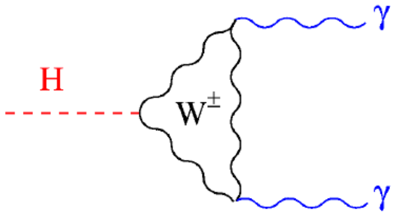
Shutdown: September 2000



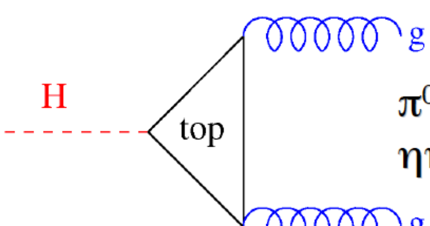
Low-mass searches at LEP

The decay branching ratios depend only on m_H:

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



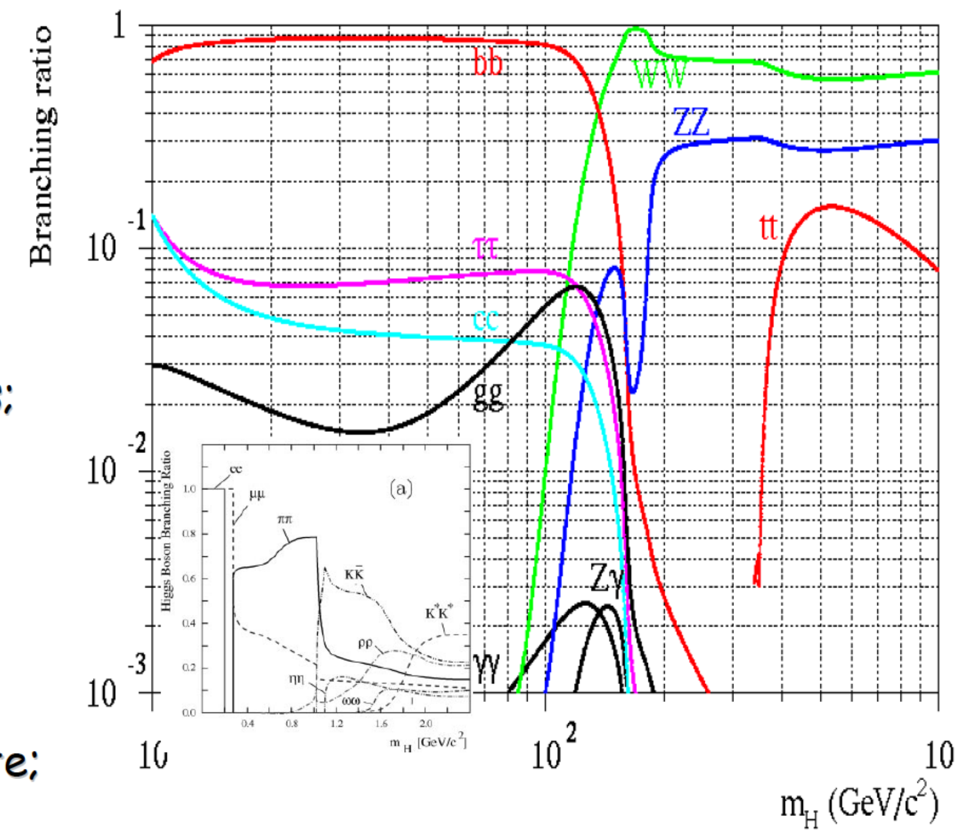
- ❑ $m_H < 2m_\mu$: $H \rightarrow e^+e^-$ dominates;
- ❑ $m_H < 2m_\pi$: $H \rightarrow \mu^+\mu^-$ dominates;
- ❑ $m_H < 3$ - 4 GeV: $H \rightarrow gg$ dominates;



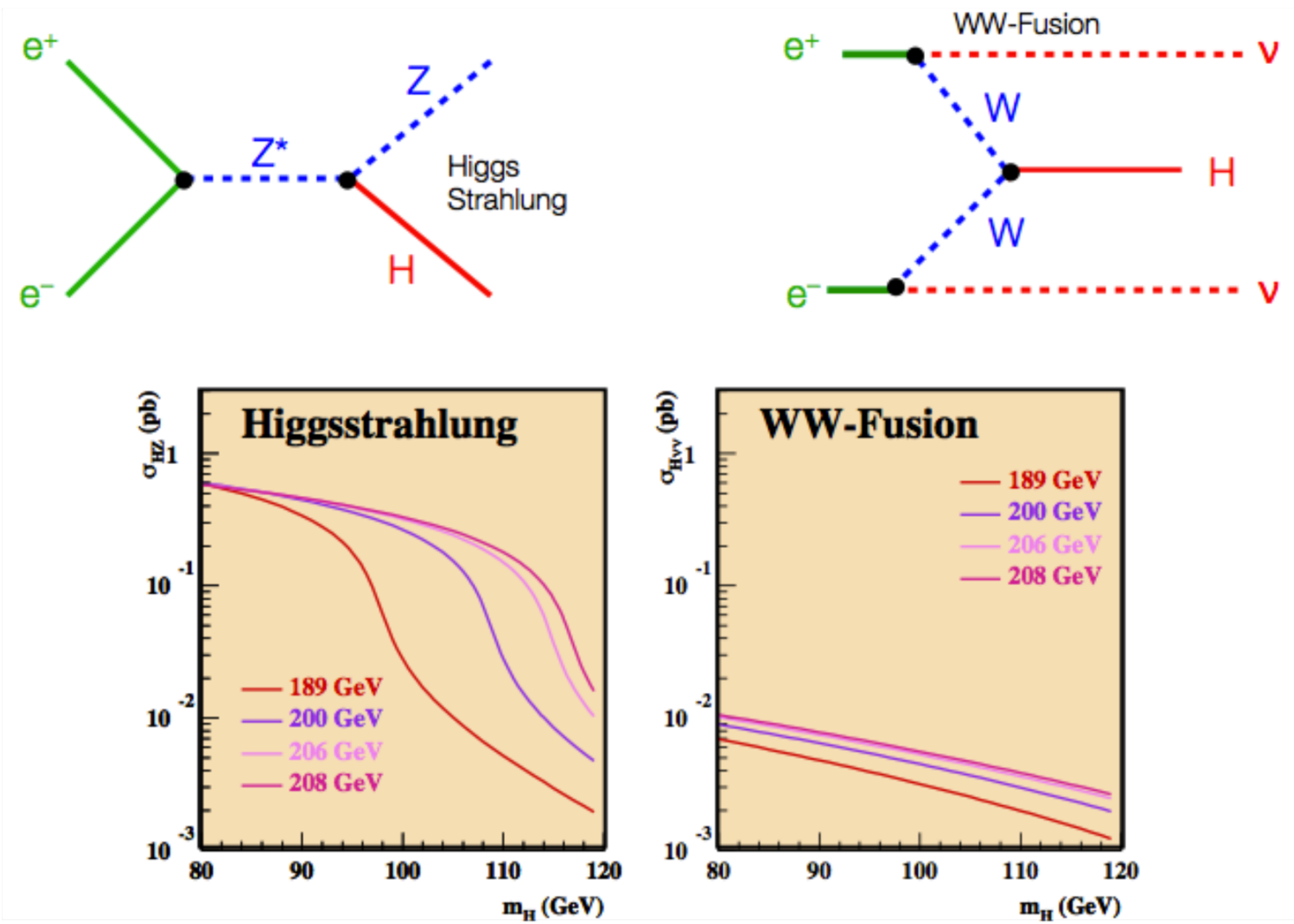
$\pi^0\pi^0$, $\pi^+\pi^-$, KK, $\eta\eta$, ... etc

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

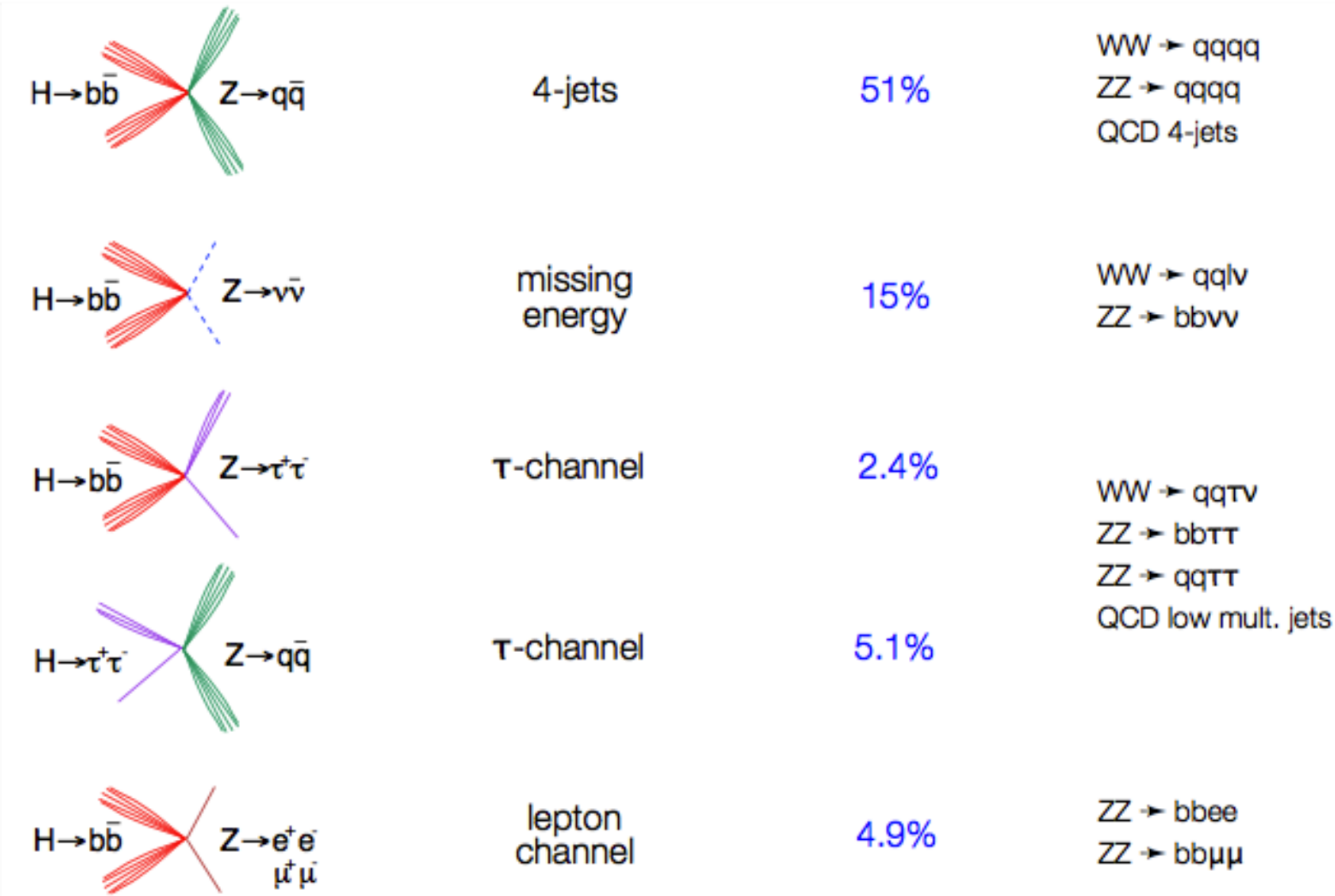
- ❑ $m_H > 2m_b$ up to 1000 GeV/c^2:



Higher-mass Higgs production at LEP



Higgs decays: focus on 3rd generation



Summary of all Higgs candidates found at LEP

Invariant mass of all candidates

In total 17 candidates selected

- 15.8 background events expected

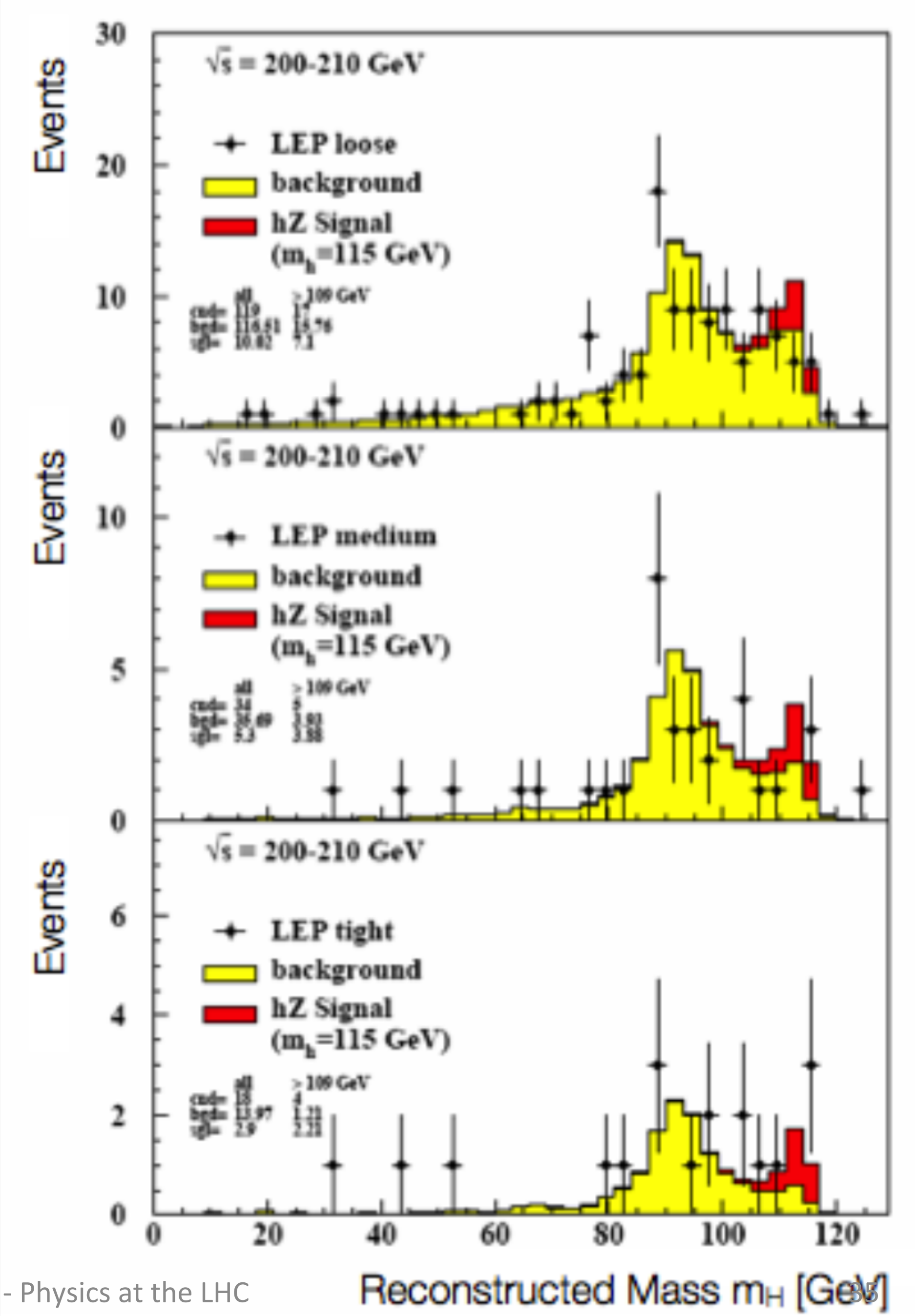
Expectation for m_H=115 GeV

- 8.4 events

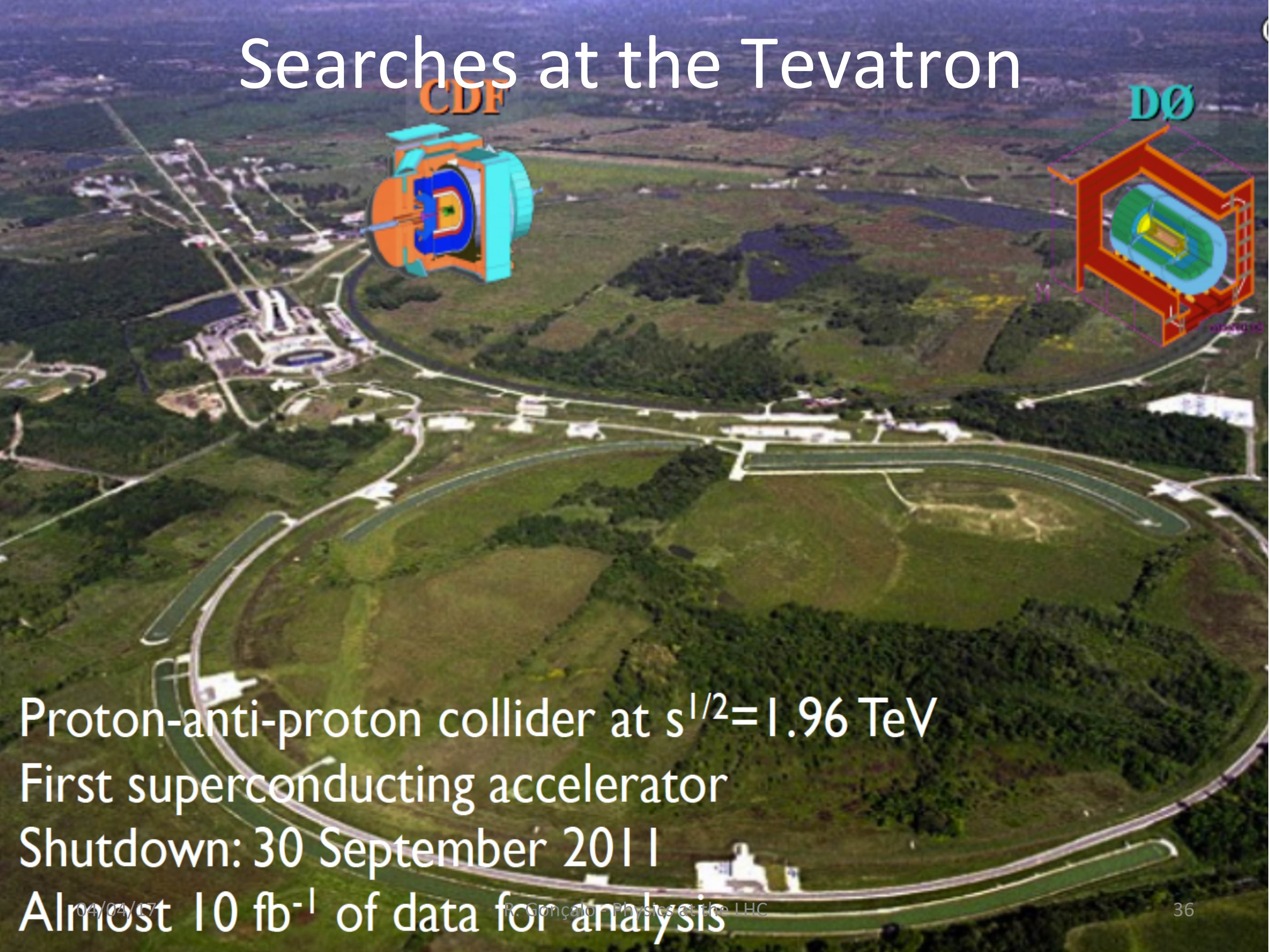
Corresponding excess was not observed

Final verdict from LEP

m_H>114.4 GeV @ 95% CL

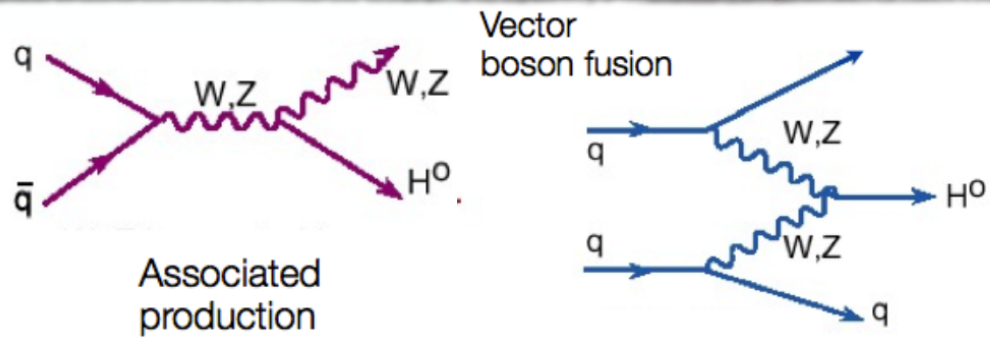


Searches at the Tevatron



Proton-anti-proton collider at $s^{1/2}$=1.96 TeV
First superconducting accelerator
Shutdown: 30 September 2011
Almost 10 fb^{-1} of data for analysis

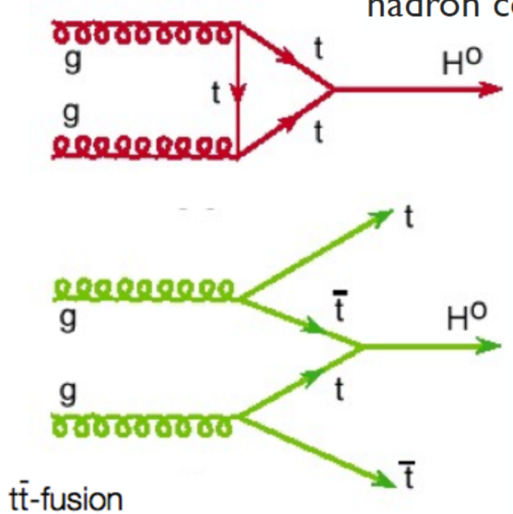
Higgs production at the Tevatron

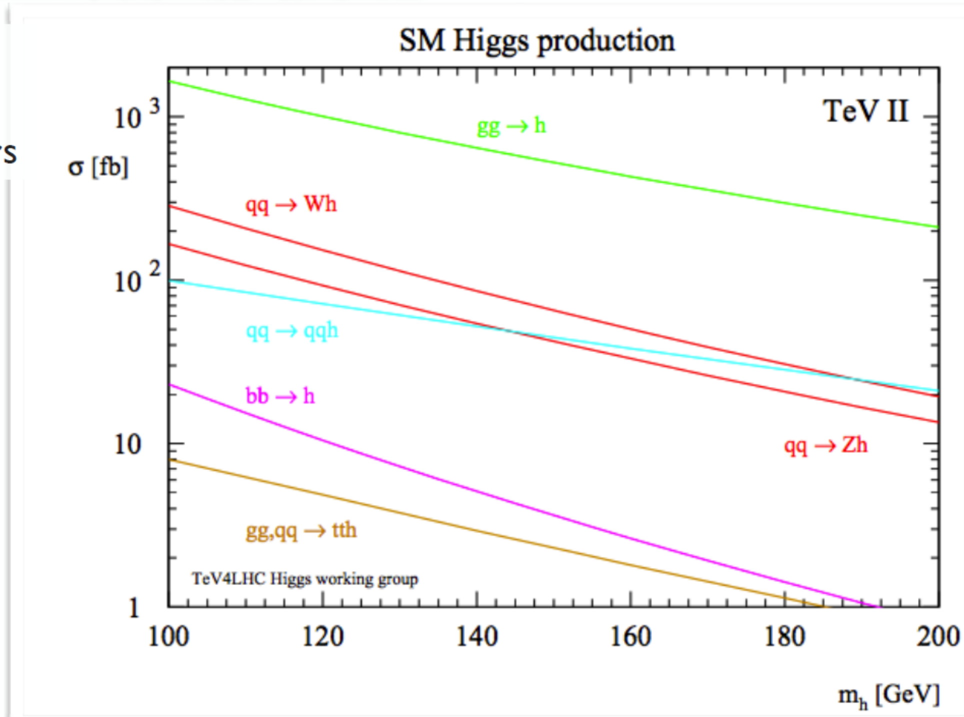


← (fermion annihilation and vector boson scattering)

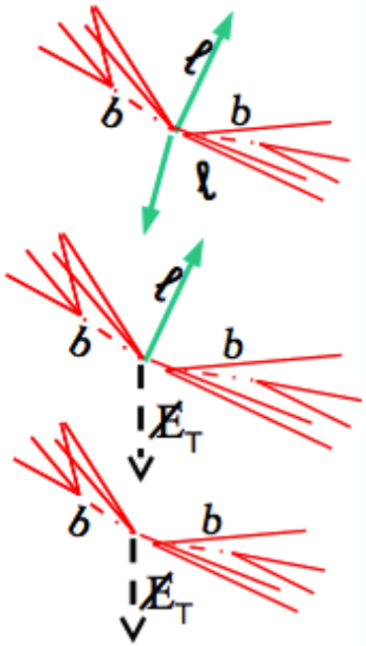
Gluon fusion

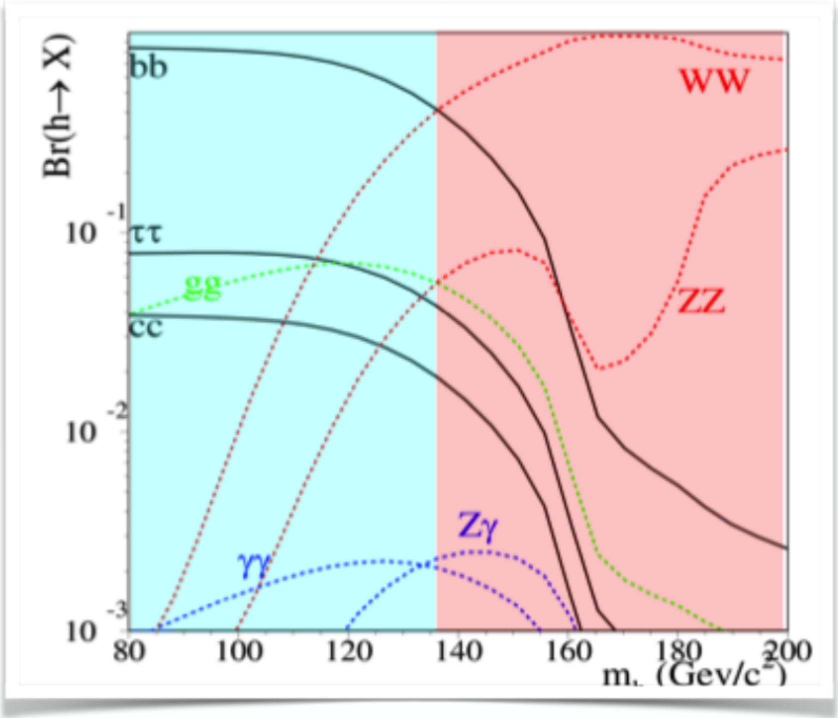
← Only available at hadron colliders





Most sensitive searches

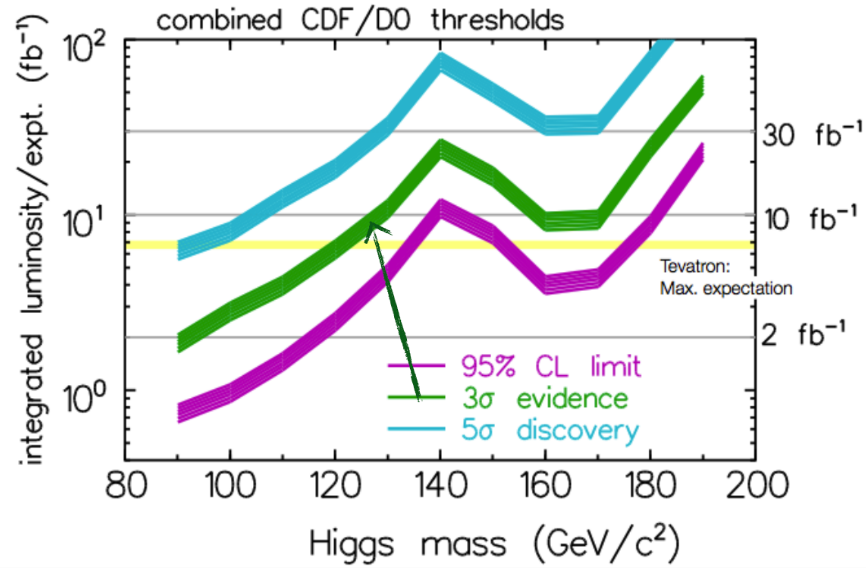


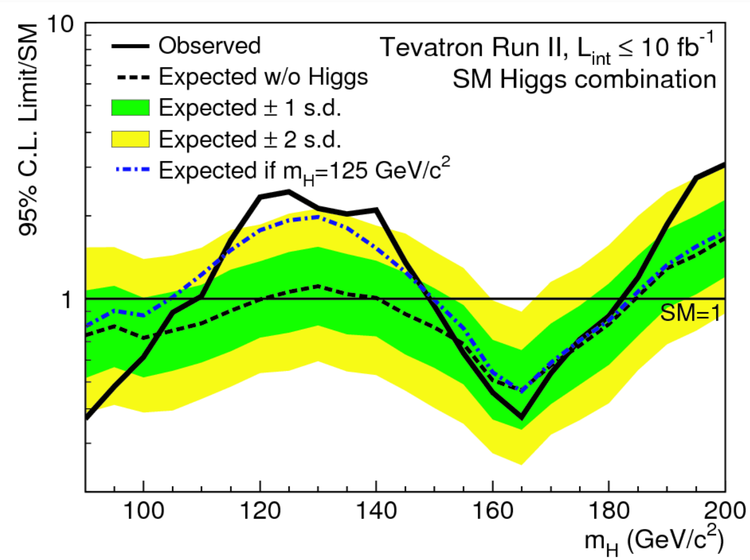


- At **low mass use h→bb final states**
  - associated production with W or Z
  - challenging: b-tagging, jet resolution
  - backgrounds: top, W/Z+heavy flavour di-bosons
- At **high mass use H→WW final states**
  - benefit from high gluon-gluon cross section
  - challenging: lepton acceptance, missing energy
  - backgrounds: top, di-bosons

The final stand of the Tevatron

- By the end of its lifetime, the Tevatron had very sophisticated analyses of a huge number of channels
- By that time the LHC was collecting data and analysing it very fast
- The CDF and D0 experiments obtained a significant excess of around 3 standard deviations in the mass range $115<M_H<140$ GeV
- Not enough to claim discovery, but consistent with the LHC results

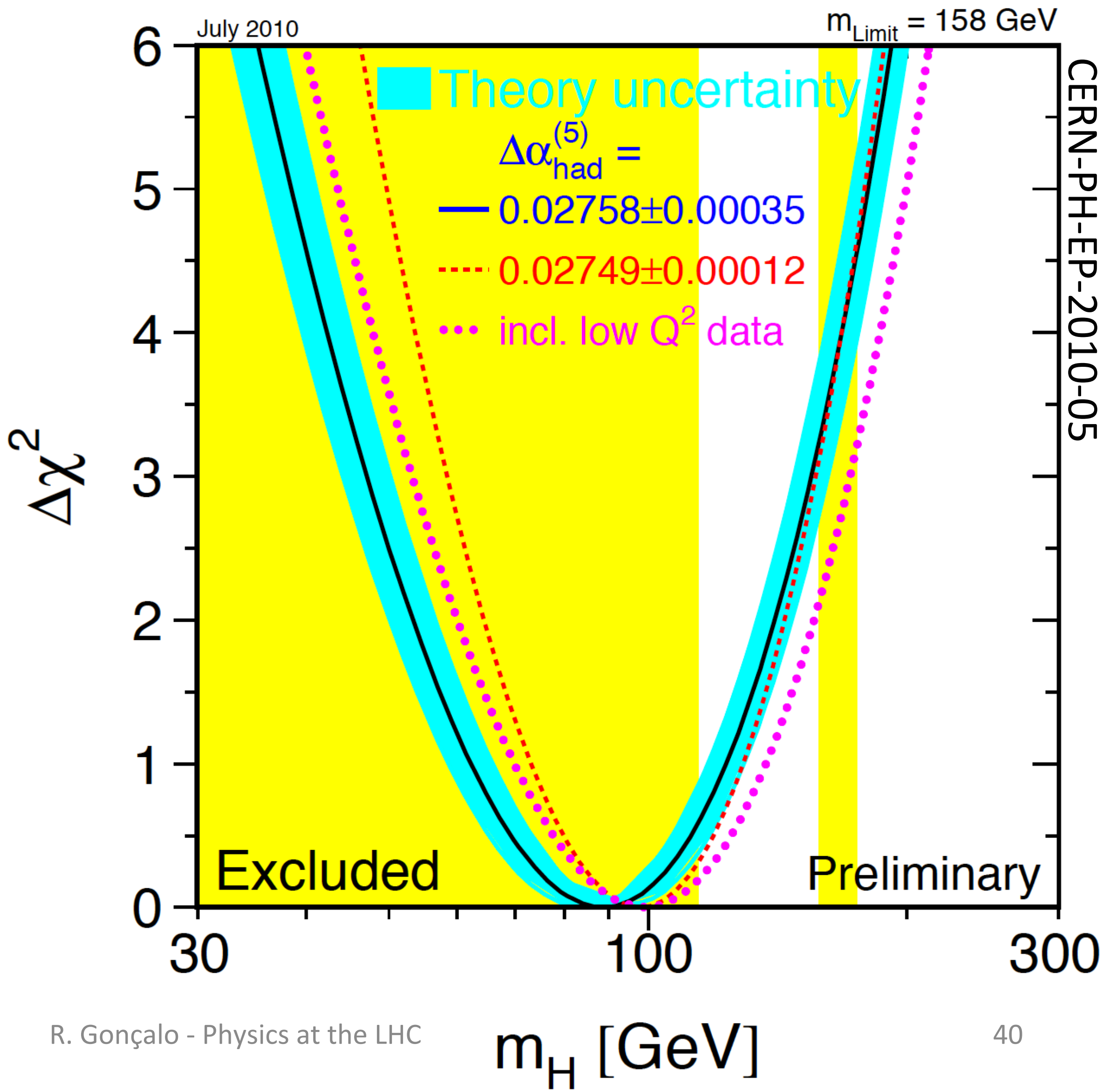




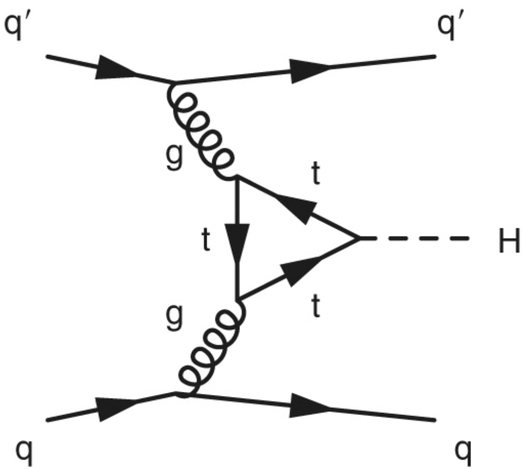
Setting the Scene for the LHC

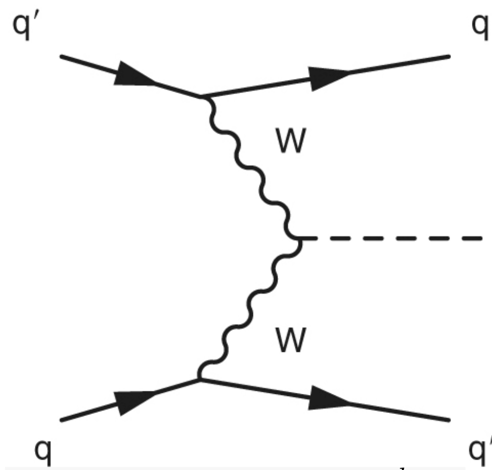
- Decades of searches in many experiments...

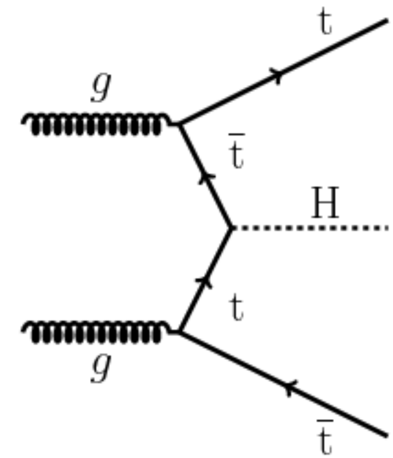
- By July 2010:
  - LEP+Tevatron+SLD limits
  - Higgs excluded m_h<114.4 GeV at 95% CL
  - Plus between 158 and 175 GeV

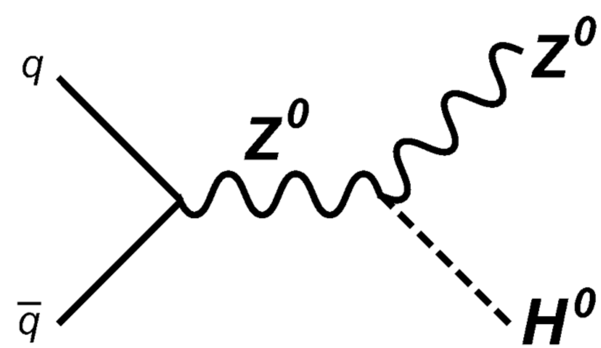


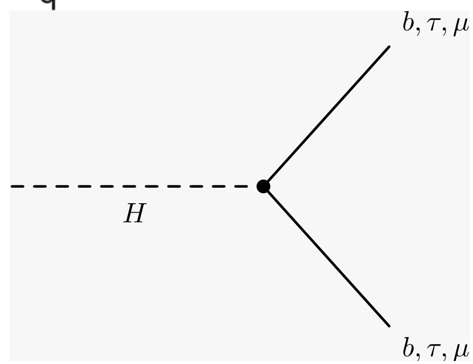
Production and decay at the LHC

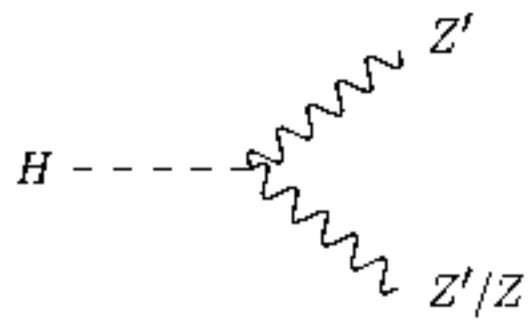


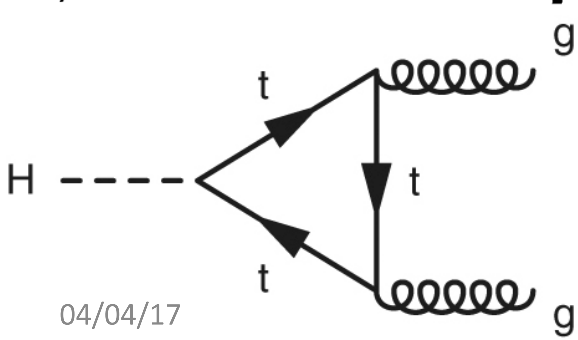


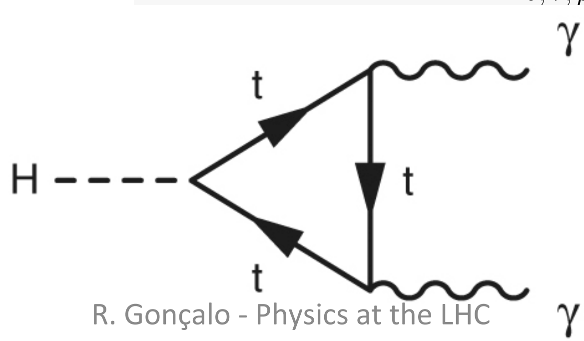


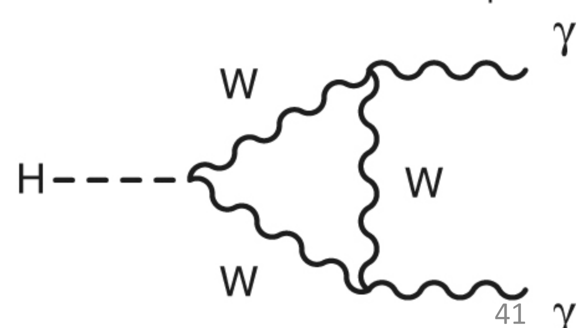




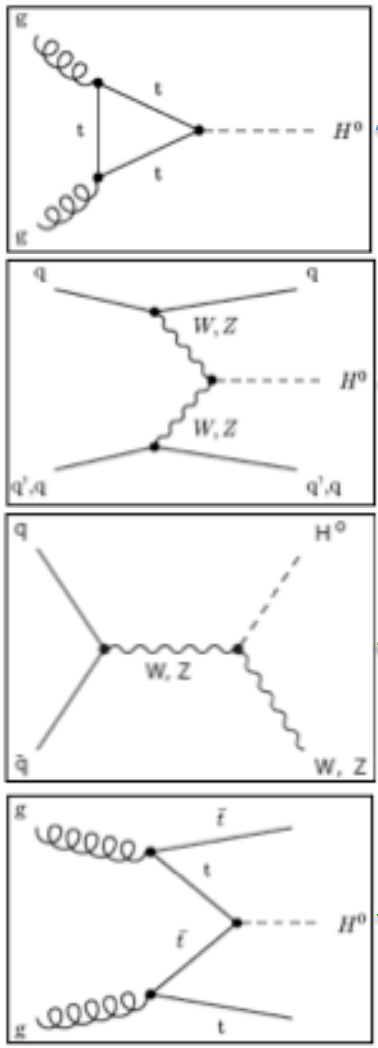




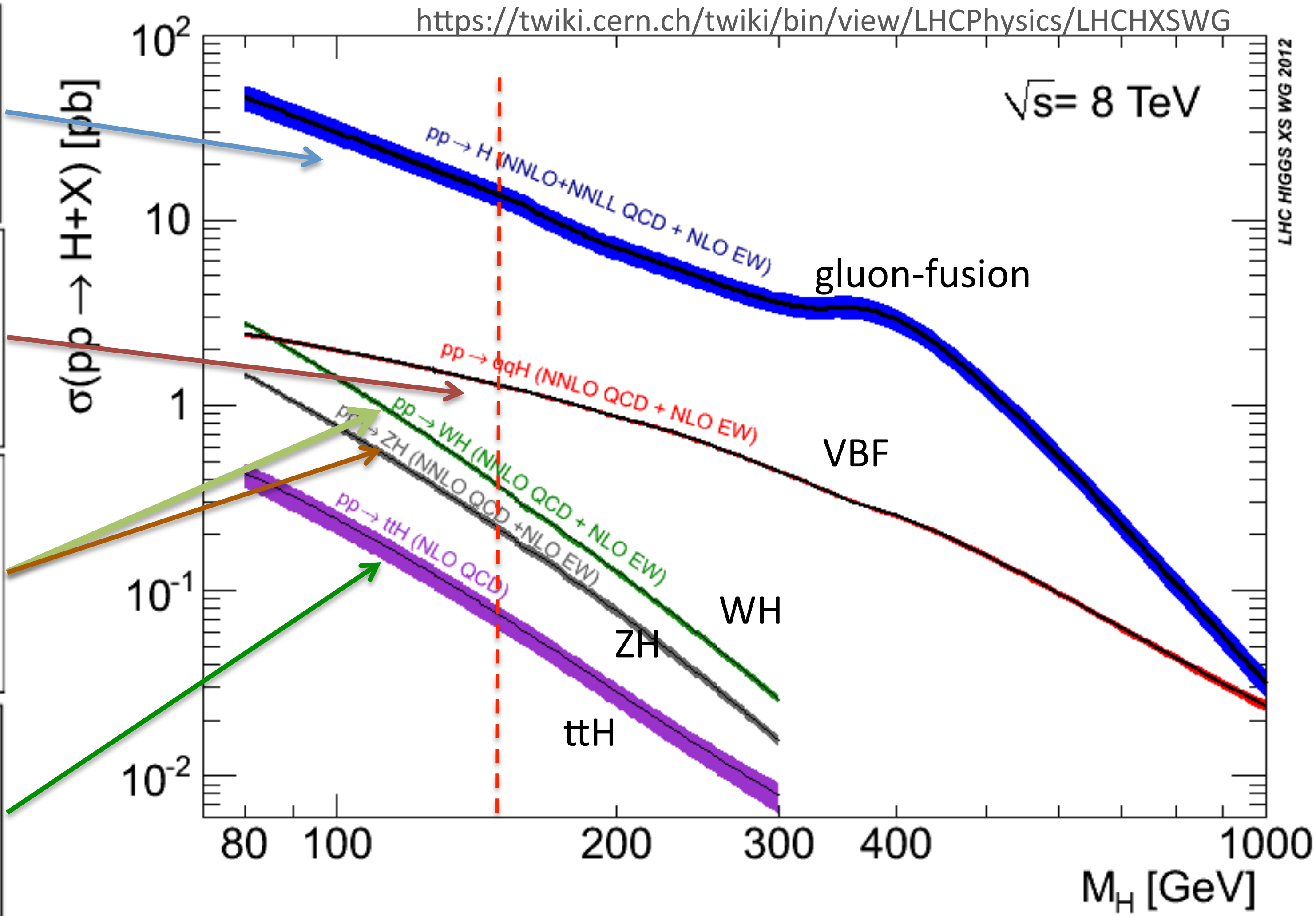




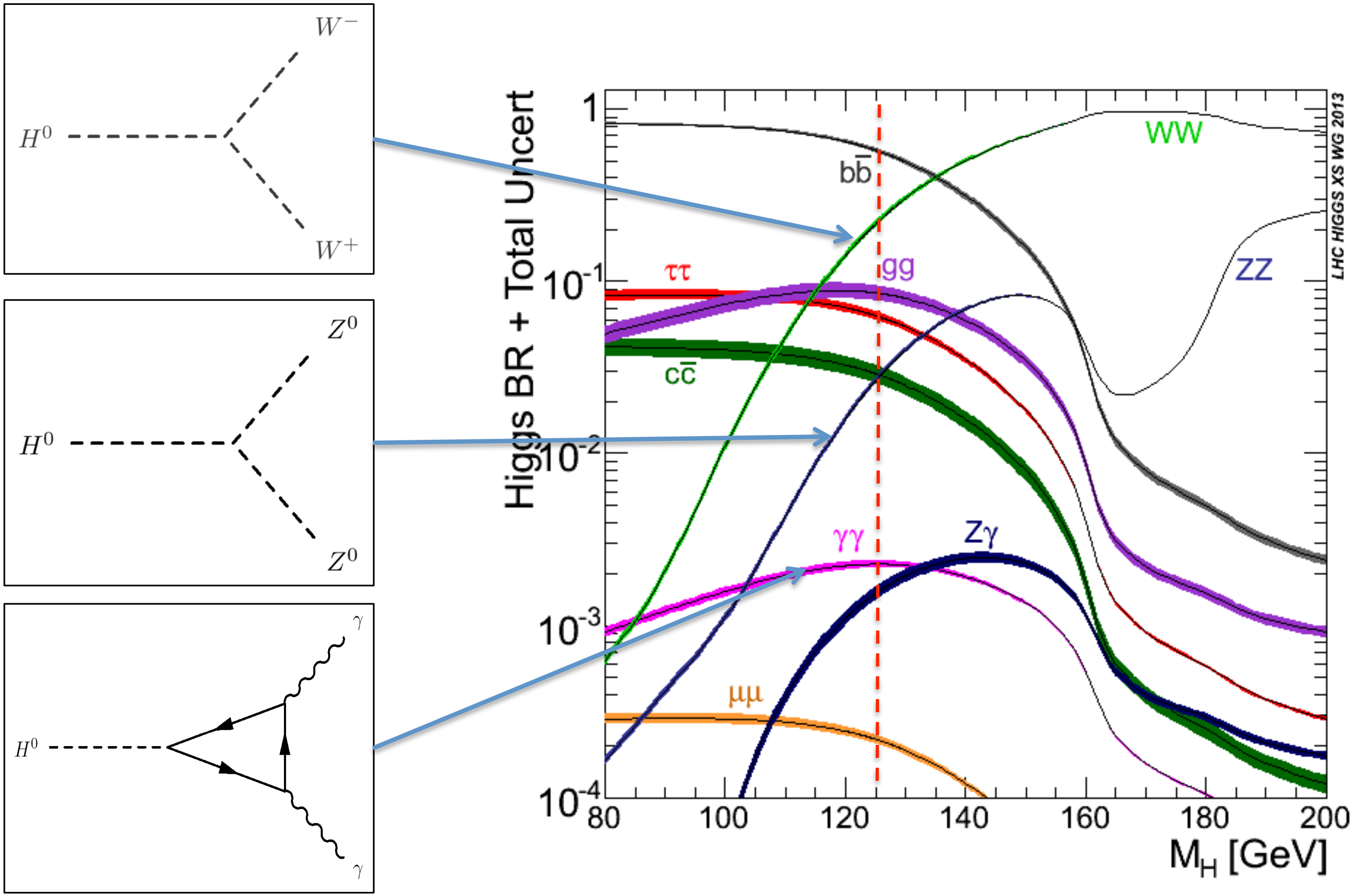
At the LHC



g
t
t
t
H^0
g
q
q
W, Z
H^0
W, Z
q', q
q', q
q
H^0
W, Z
$\bar{q}$
W, Z
g
$\bar{t}$
t
$\bar{t}$
H^0
g
t



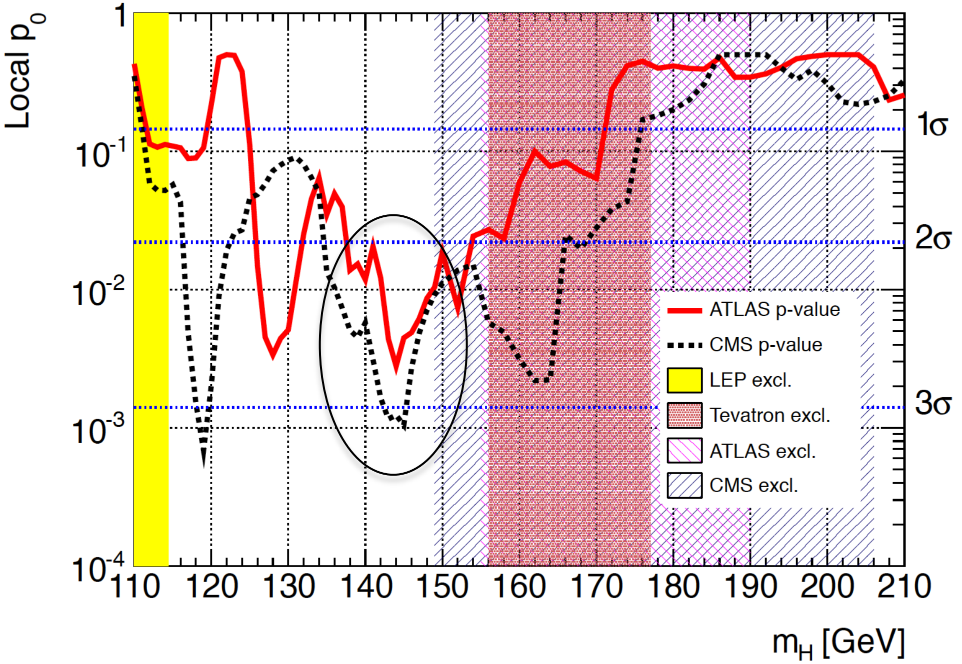
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG
$\sqrt{s}$= 8 TeV
LHC HIGGS XS WG 2012
σ(pp → H+X) [pb]
pp → H (NNLO+NNLL QCD + NLO EW)
gluon-fusion
pp → qqH (NNLO QCD + NLO EW)
VBF
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
WH
ZH
ttH
M_H [GeV]



H^0
W^-
W^+
H^0
Z^0
Z^0
H^0
γ
γ
Higgs BR + Total Uncert
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
80
100
120
140
160
180
200
M_H [GeV]
LHC HIGGS XS WG 2013
$b\bar{b}$
WW
ZZ
ττ
gg
$c\bar{c}$
γγ
Zγ
μμ

It takes time to get it right

EPS-HEP 2011 conference [6]



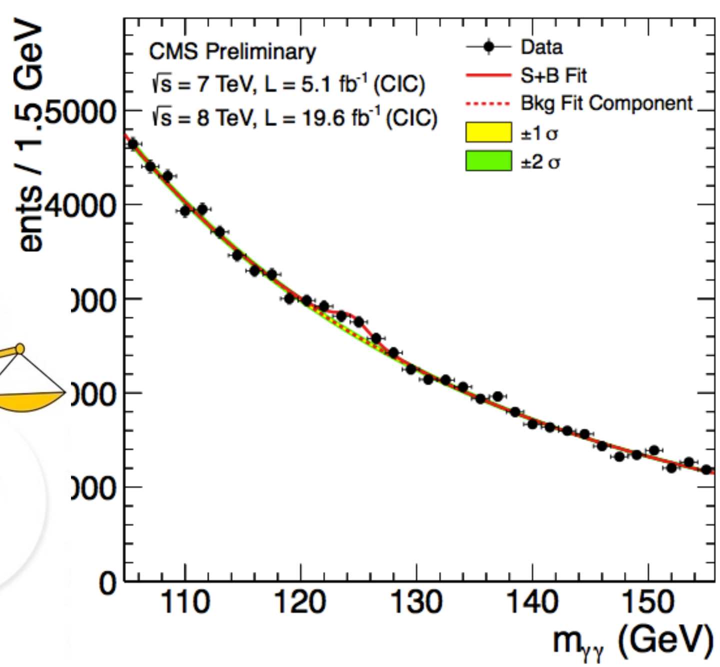
Discovery time!

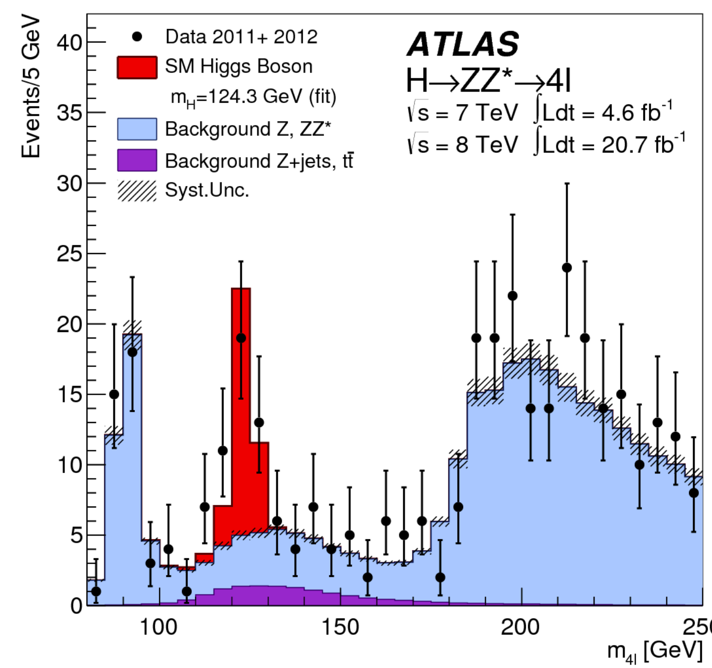
Discovery channels

- Discovery was made in ATLAS and CMS with about 5 fb^{-1} of 7TeV data and 20 fb^{-1} of 8TeV data per experiment; several channels combined

$$h \to \gamma\gamma; h \to ZZ^* \to 4\ell; h \to WW^*; h \to \tau^+\tau^-; h \to b\bar{b}$$

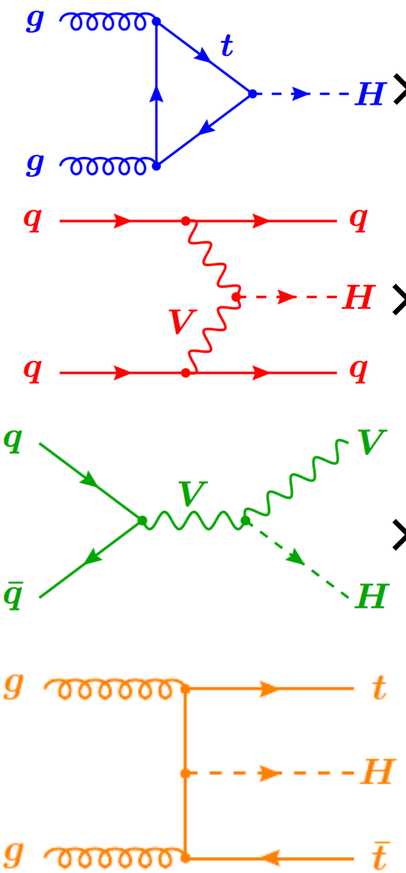
- This means about 400 000 Higgs bosons produced in about 8 000 000 000 000 000 proton collisions
  - Only about 4000 events with Higgs bosons contributed to the discovery





Combining Higgs Channels

Production



$\times\kappa_g^2$

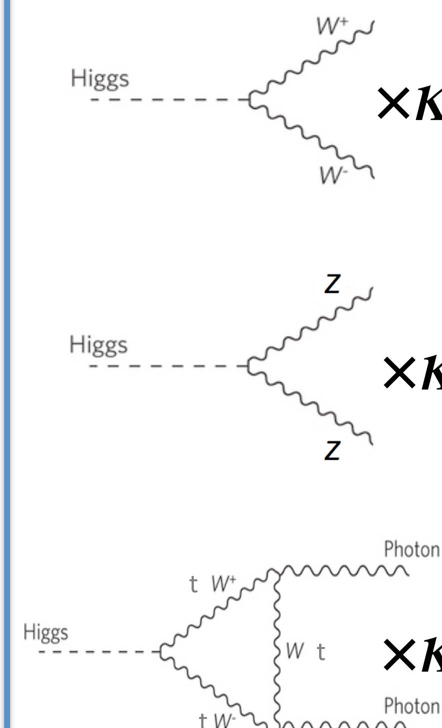
$\times\kappa_{W/Z}^2$

$\times\kappa_{W/Z}^2$

$\times\kappa_t^2$

$\times$

Decay



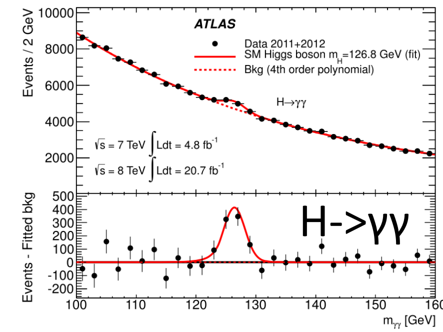
$\times\kappa_W^2$

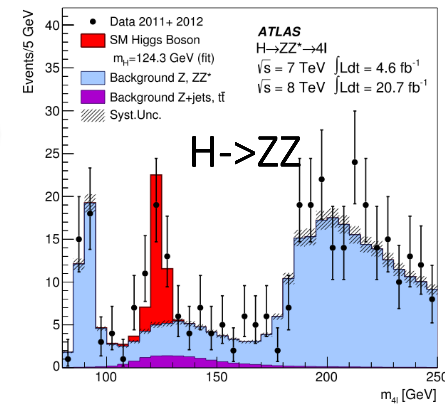
$\times\kappa_Z^2$

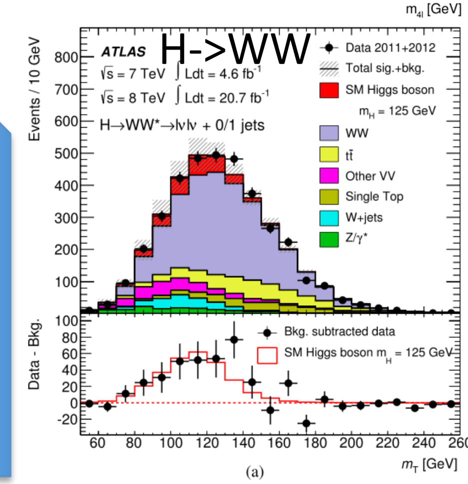
$\times\kappa_\gamma^2$

FIT

Backgrounds +

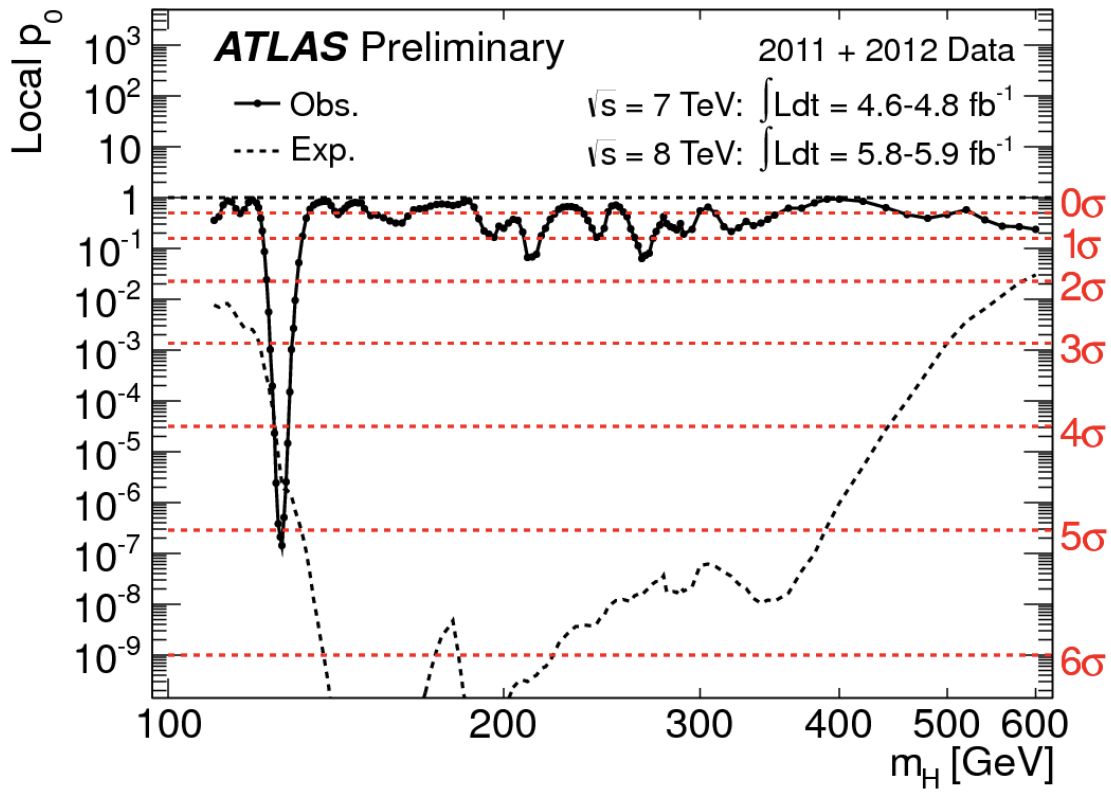




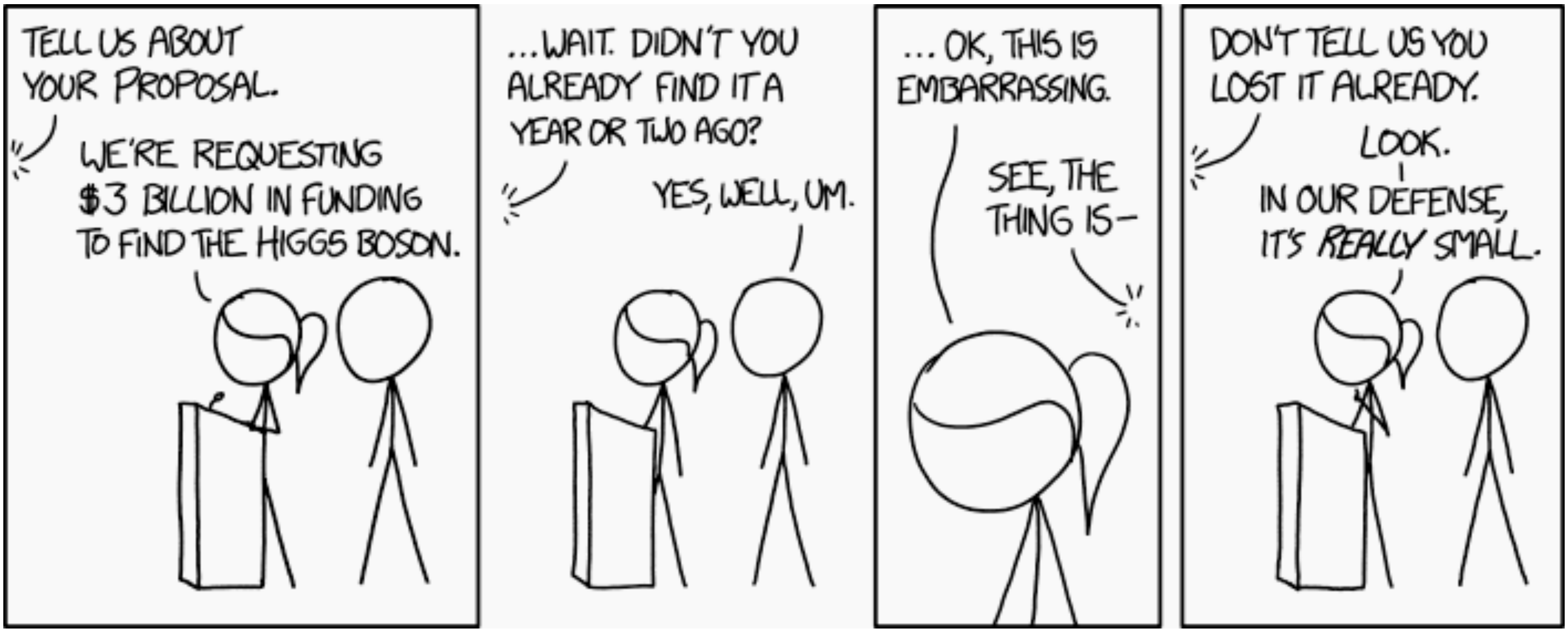


The p_0 Discovery Plot

- **p_0** is the combined probability that the background fluctuates to look like signal
- Translated into the one-sided Gaussian probability



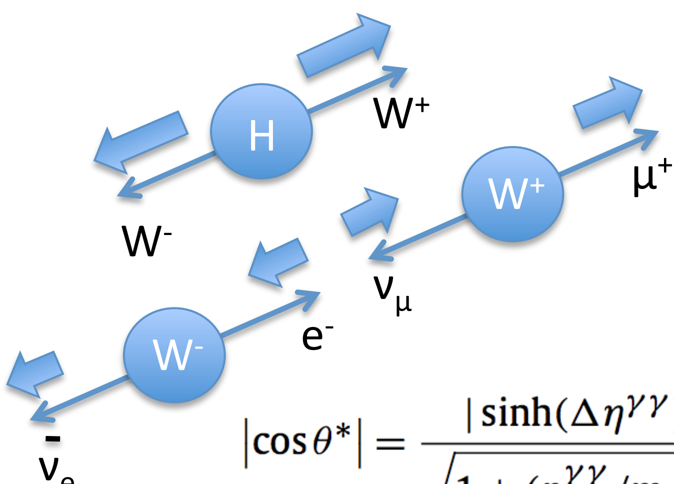
- This corresponds to a probability of **1 in 3.5 million** that this was a false positive from fluctuating backgrounds


TELL US ABOUT YOUR PROPOSAL.
WE'RE REQUESTING $3 BILLION IN FUNDING TO FIND THE HIGGS BOSON.
...WAIT. DIDN'T YOU ALREADY FIND IT A YEAR OR TWO AGO?
YES, WELL, UM.
... OK, THIS IS EMBARRASSING.
SEE, THE THING IS–
DON'T TELL US YOU LOST IT ALREADY.
LOOK.
IN OUR DEFENSE, IT'S REALLY SMALL.

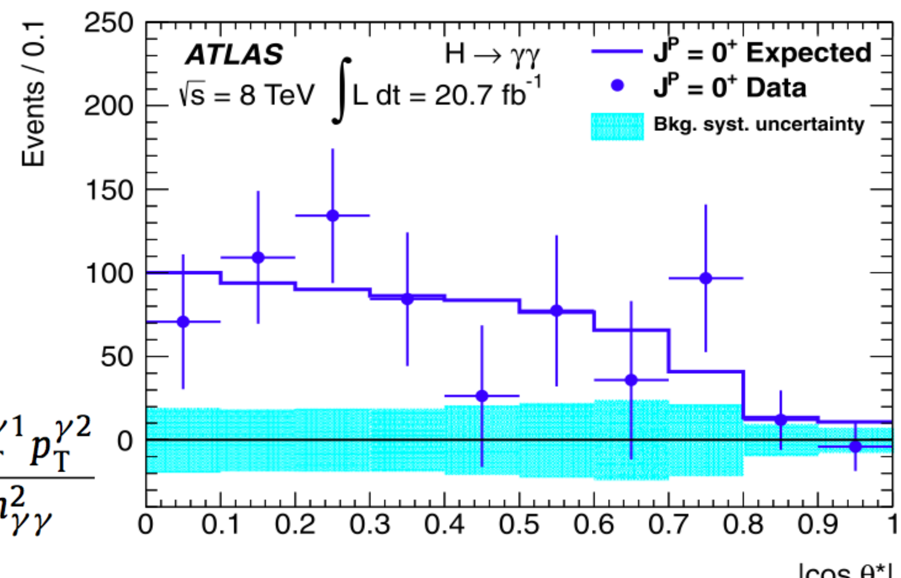
What we have found out since
A (quick) foretaste of the next few lectures

Spin and Parity

- First concern after observation!
- Some observable quantities sensitive to J^P: for example angle between leptons from W decay in H->WW
- Pure $J^P = 0^-, 1^+, 1^-$, and 2^+ excluded with 97.8, 99.97, 99.7, and 99.9% Confidence Level (ATLAS arXiv 1307.1432; CMS Phys. Rev. D 92, 012004)



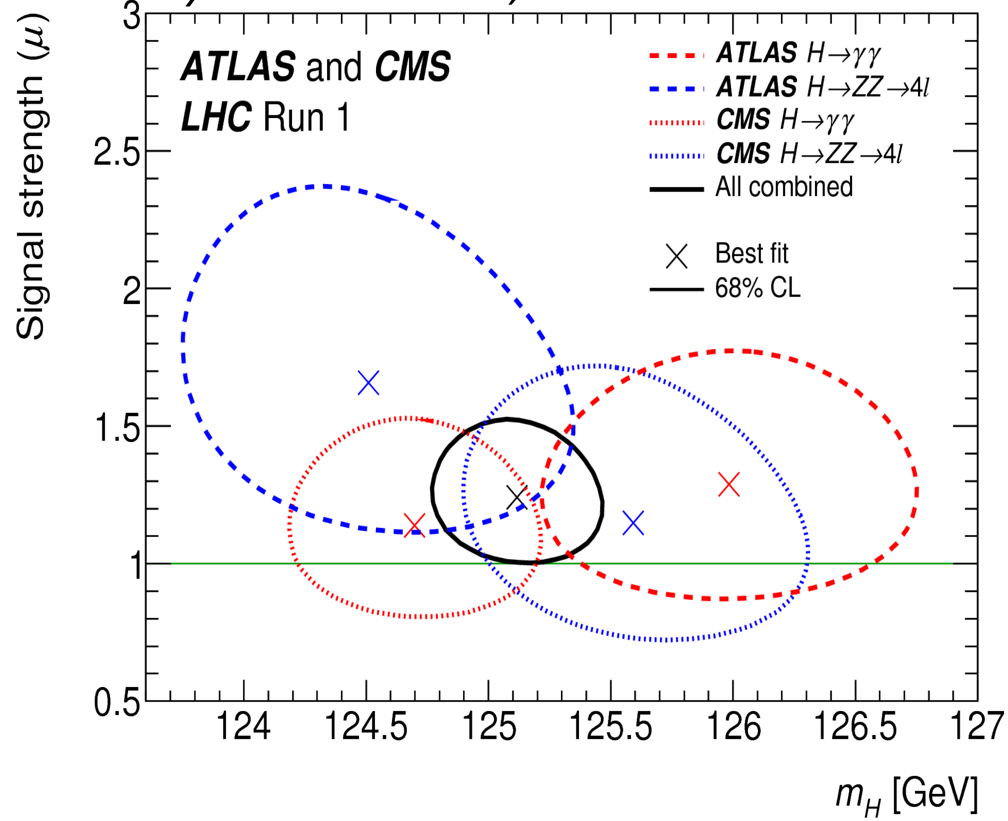
$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1} p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$



Higgs boson mass

- **Mass:** around 125GeV
  Used to be the only unknown SM-Higgs parameter, remember? ☺
- For a while, different mass values were being measured in ATLAS and CMS, and in different channels
- Numbers evolved with accumulated statistics
- Current most precise value from ATLAS+CMS has 0.2% precision!

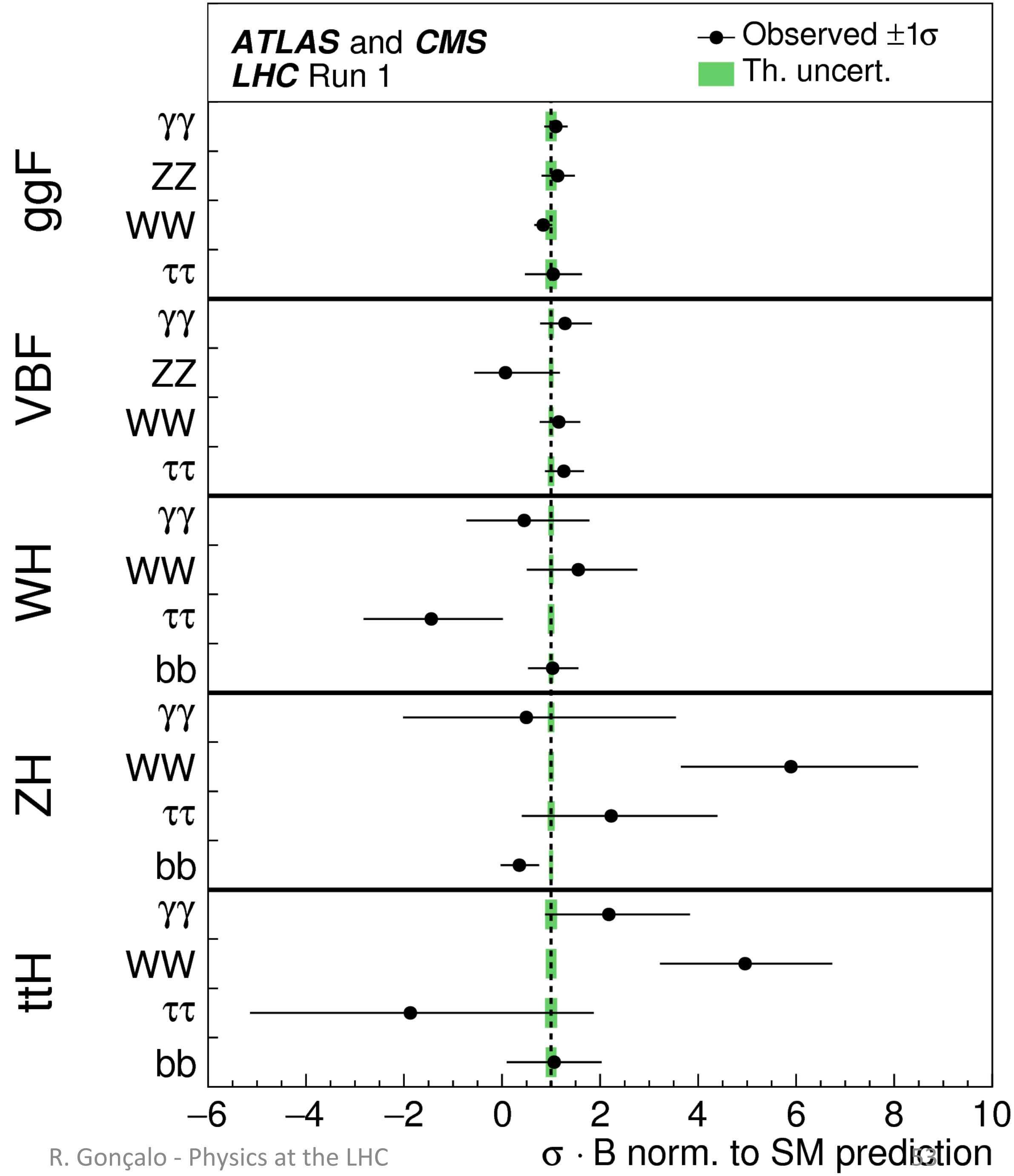
Phys. Rev. Lett. 114, 191803



m_H=125.09±0.21 (stat)±0.11 (syst) GeV

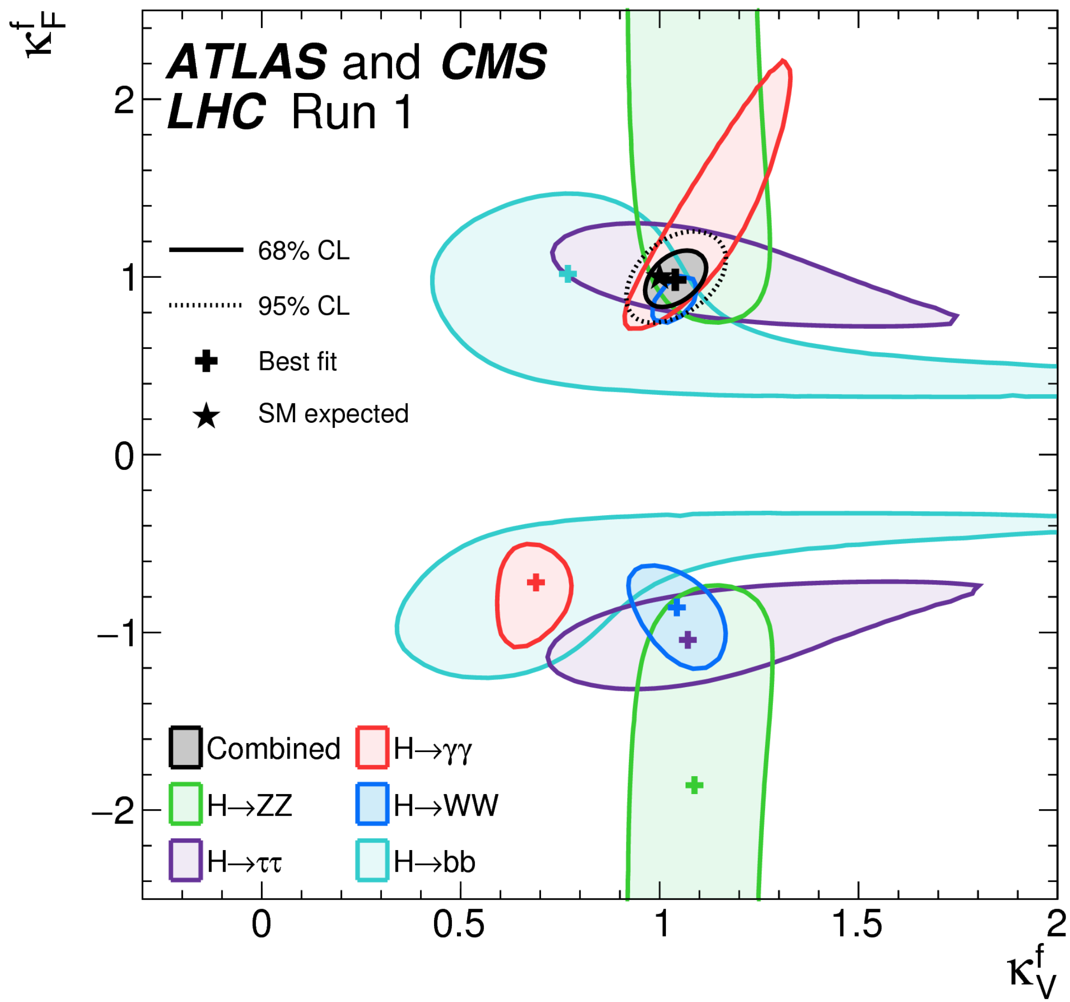
Cross section compared to SM expectation

$$\frac{\sigma_{meas}.BR}{\sigma_{SM}.BR}$$



Fermion and Boson couplings from fit

- Set one scale factor for all fermions (**κ_F** = κ_t = κ_b= κ_τ =…) and one for all vector bosons (**κ_V** = κ_Z = κ_W)
- Assume **no new physics**
- Strongest constraint to κ_F comes from loops and interference effects
- Note several couplings can still be negative!



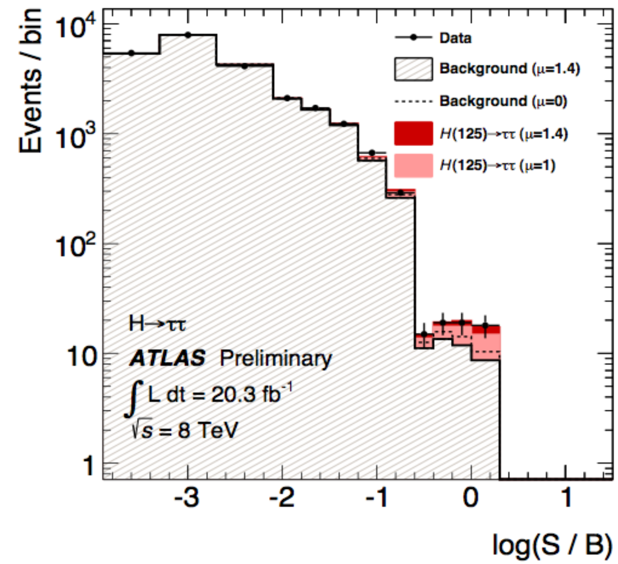
Direct Evidence of Fermion Couplings

- **Challenging** channels at the LHC!
  - Huge backgrounds (H->bb,H->ττ)
  - Or low rate: H->μμ

- ATLAS:

  4.1σ evidence of H->ττ decay 3.2σ exp.

  $\mu = \boldsymbol{\sigma_{obs.}/\sigma_{SM}} = 1.4 \pm 0.3(\text{stat}) \pm 0.4(\text{sys})$



ATLAS-CONF-2013-108

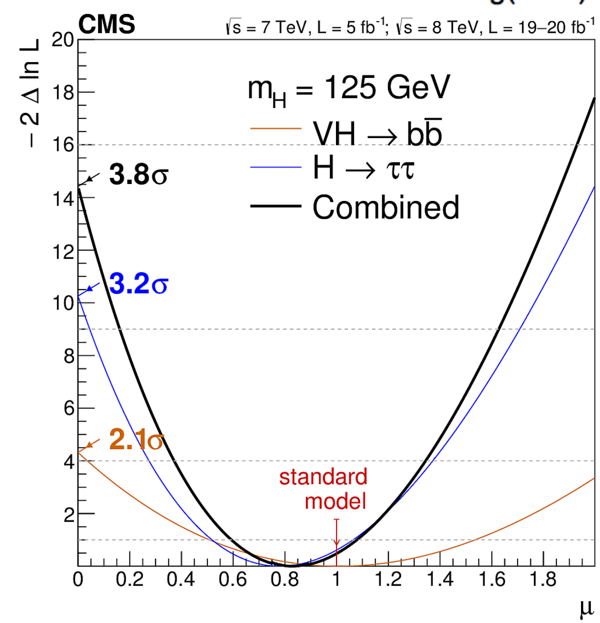
- CMS:
  - Combination of H->bb and H->ττ:

  3.8σ evidence (obs.) 4.4σ (expected)

  $\mu = \boldsymbol{\sigma_{obs.}/\sigma_{SM}} = 0.83 \pm 0.24$

CMS 1401.6527

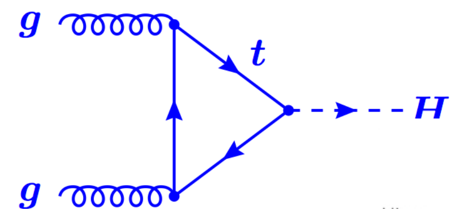
Channel ($m_H = 125\,\text{GeV}$)	Significance (σ) Expected	Significance (σ) Observed	Best-fit μ
$VH \to b\bar{b}$	2.3	2.1	1.0 ± 0.5
$H \to \tau\tau$	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24

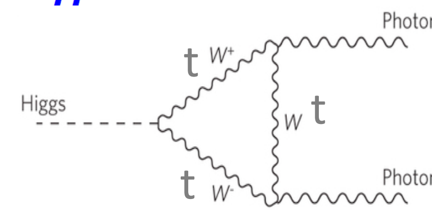


CMS 1401.6527

New Physics in the Loops?

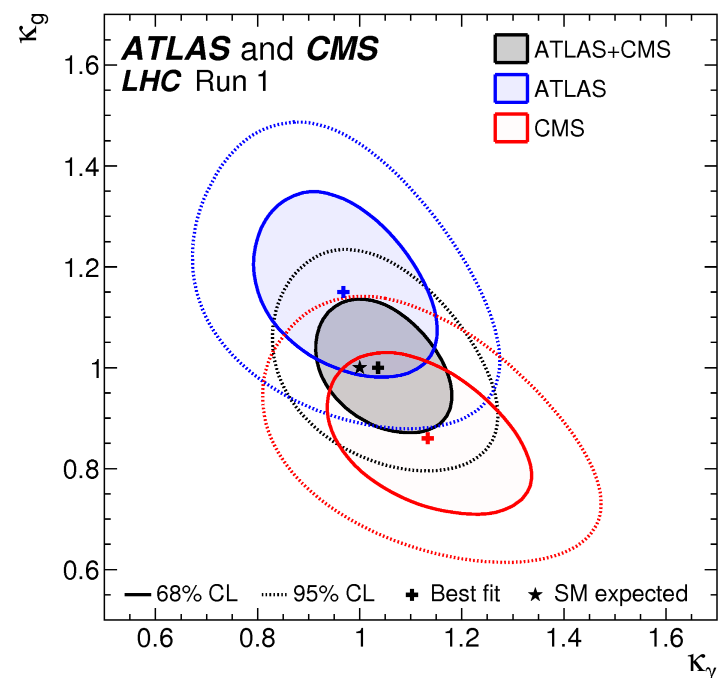
- New heavy particles may show up in **loops**
  - Dominant **gluon-fusion** through a (mostly) top loop production for H->ZZ, H->WW and H->γγ
  - **H->γγ decay** through top and W loops (and interference)





- Assume no change in Higgs width and SM couplings to known particles

- Introduce effective coupling scale factors:
  - κ_g and κ_γ for ggH and Hγγ loops



Couplings versus mass

- Reduced coupling modifiers as a function of the particle mass:

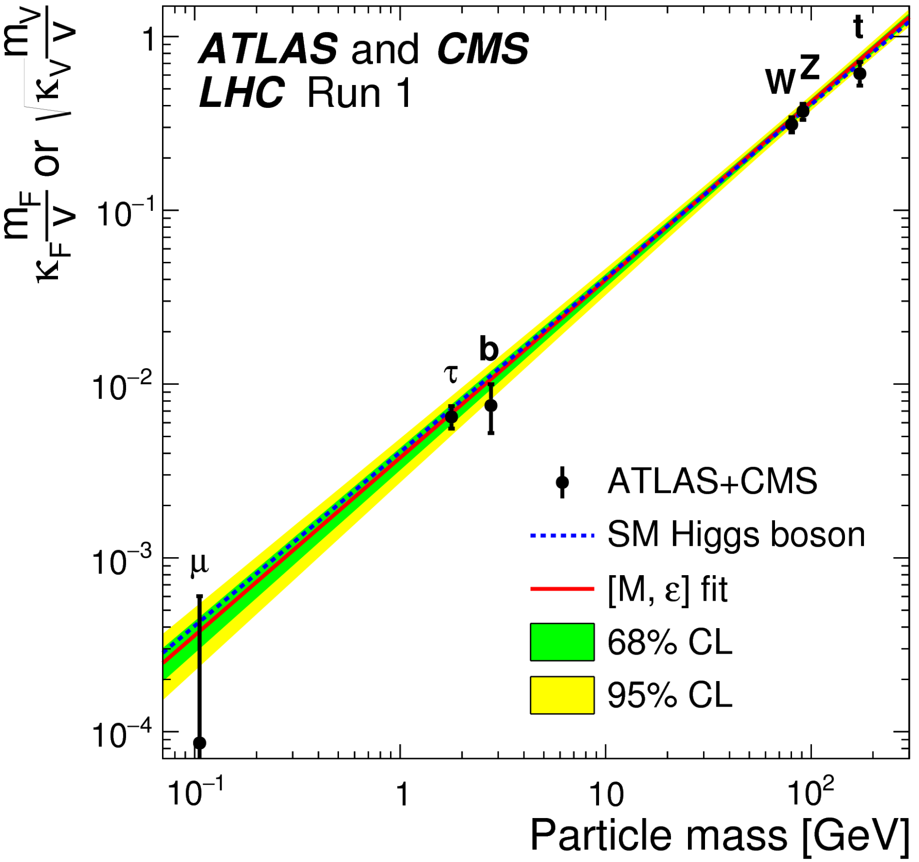
- For weak vector bosons:

$y_{V,i} = \sqrt{\kappa_{V,i}}\, g_{V/i}/2v = \sqrt{\kappa_{V,i}}\, m_{V/i}/v$

- For fermions:

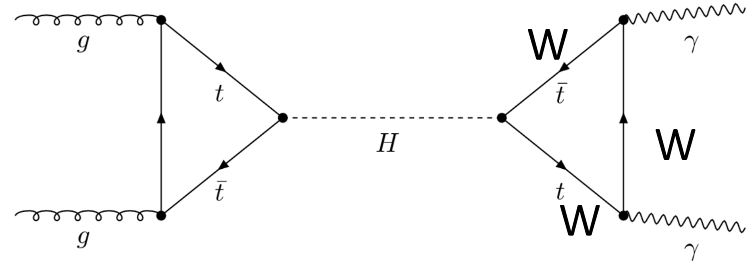
$y_{F,i} = \kappa_{F,i} g_{F/i}/\sqrt{2} = \kappa_{F,i} m_{F/i}/v$

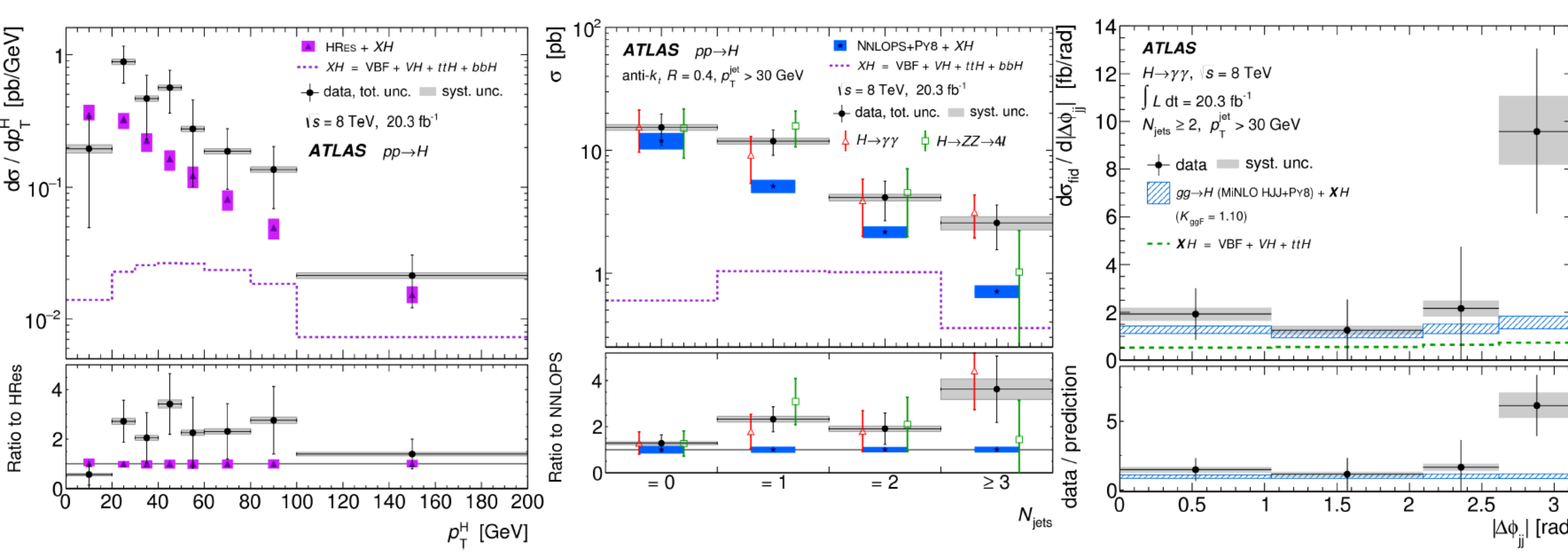
- Line indicates the predicted dependence on the particle mass for the SM Higgs boson



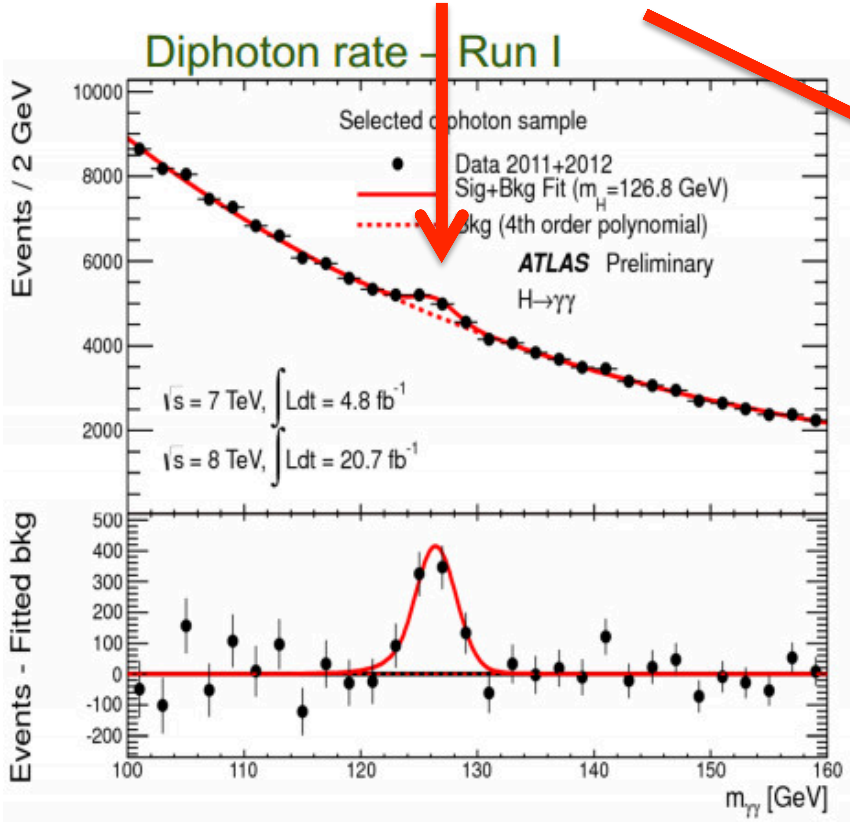
Higgs differential cross sections

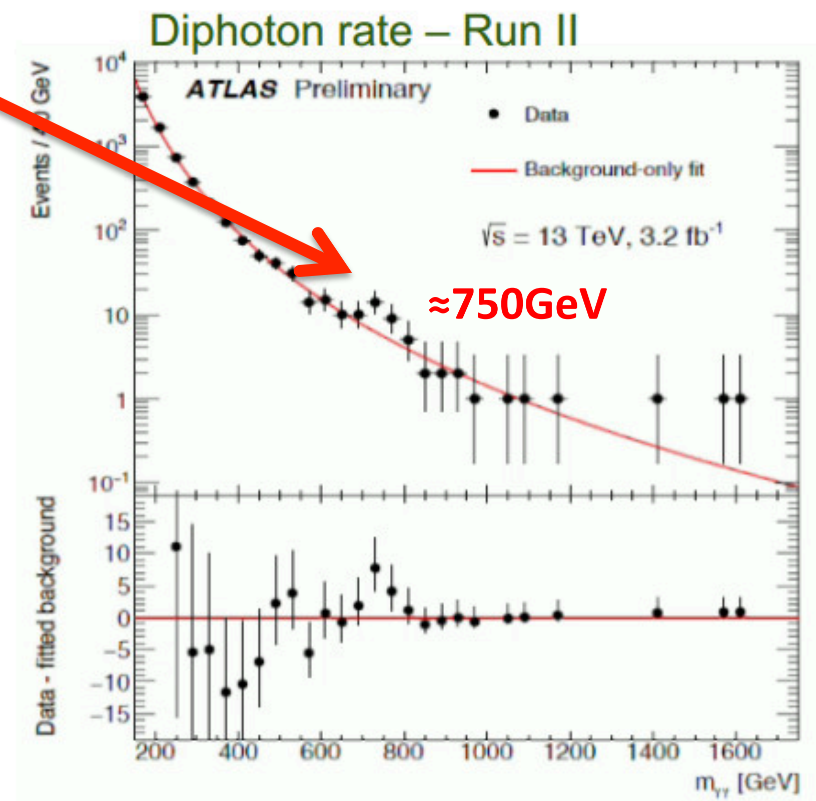
- Get access to the loop structure where there may be new physics
- ATLAS H→γγ and ZZ and more coming





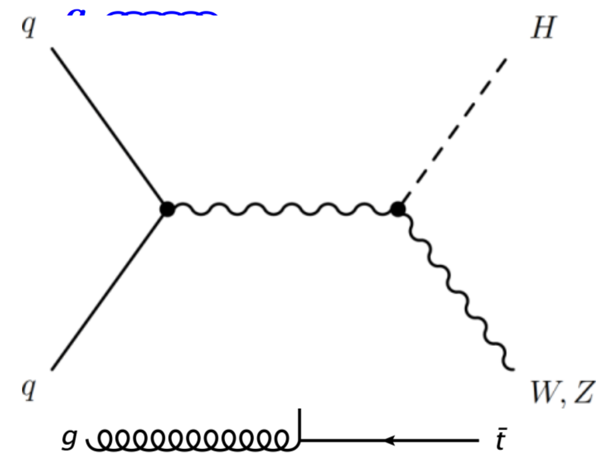
Anything new on the $m_{\gamma\gamma}$ = 750 front?



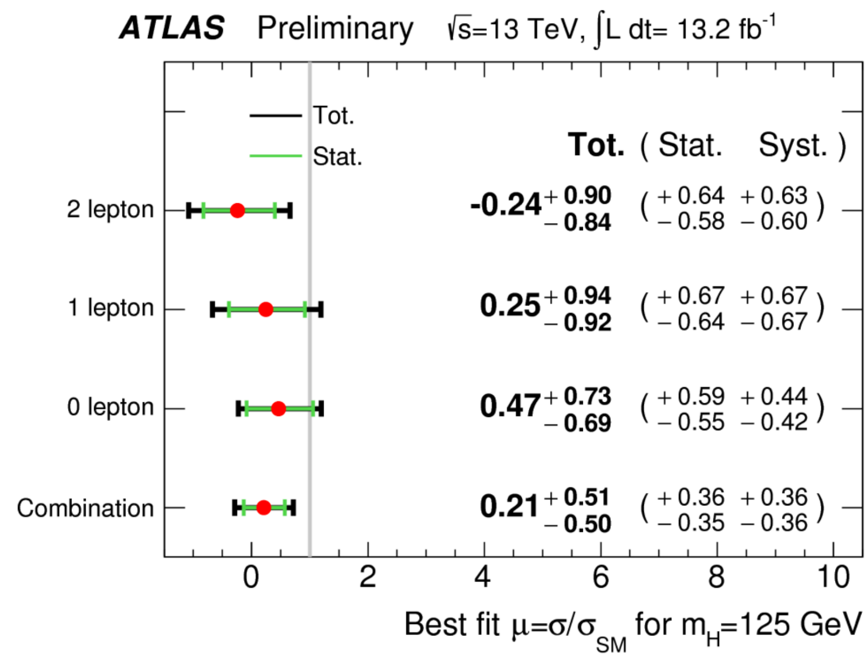


Coupling to quarks: our pet channels at LIP

- Important channels and still poorly known!
  - ttH – direct coupling to top quarks
  - VH->bb – coupling with b quarks
  - Can tell us about CP-violation in Higgs sector? Time will tell.



- ttH: μ_{ttH} = 1.7 ± 0.8
  - ttH(γγ) low – large statistical uncertainty
  - tth(ML) high – driven by 2lep0τ and 2lep1τ
  - tth(bb) high - driven by dilepton



- VH(bb): μ_{VH} = 0.21 ± 0.51
  - Low in all channels (WH, ZH)

- But nothing to get excited about
  - …YET!

Going beyond the standard model

But the Standard Model is not complete; there are still many unanswered questions.

Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

What is this "dark matter" that we can't see but has visible gravitational effects in the cosmos?

Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

Why are there exactly three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

How does gravity fit into all of this?

Many possible theories

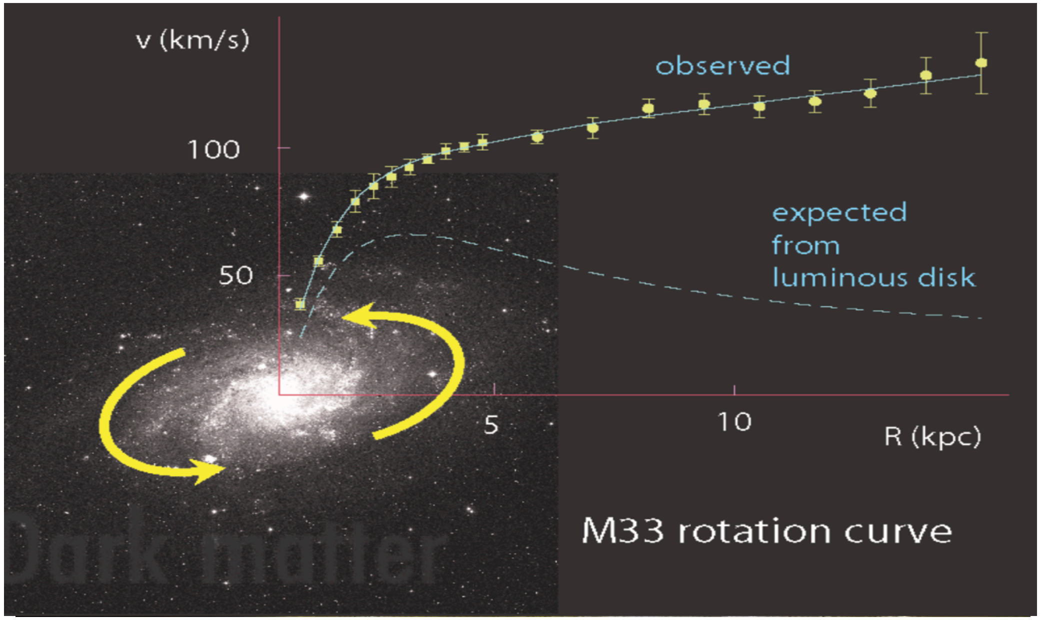
There are a large number of models which predict new physics at the TeV scale accessible at the LHC:

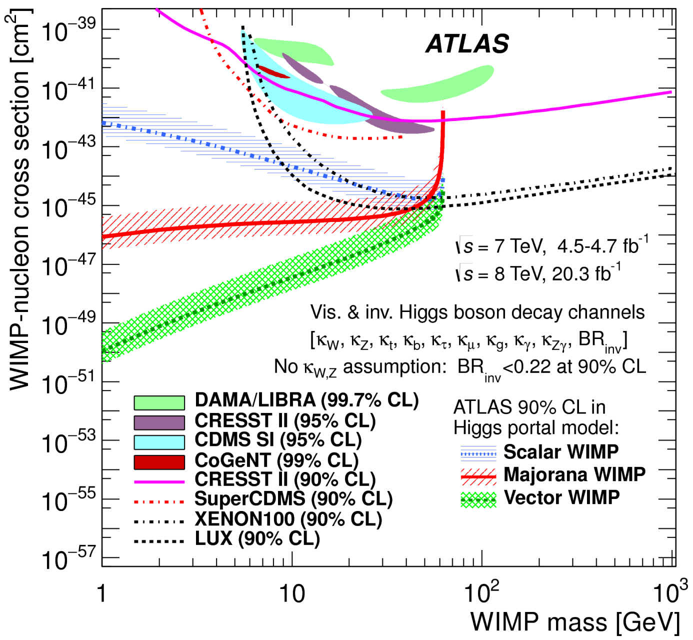
- Supersymmetry (SUSY)
- Extra dimensions
- Extended Higgs Sector e.g. in SUSY Models
- Grand Unified Theories (SU(5), O(10), E6, …)
- Leptoquarks
- New Heavy Gauge Bosons
- Technicolour
- Compositeness

Any of this could still be found at the LHC and most have a connection to the Higgs boson

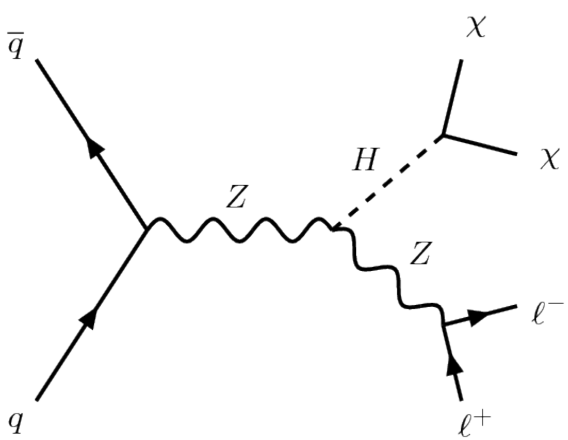
Invisible Higgs

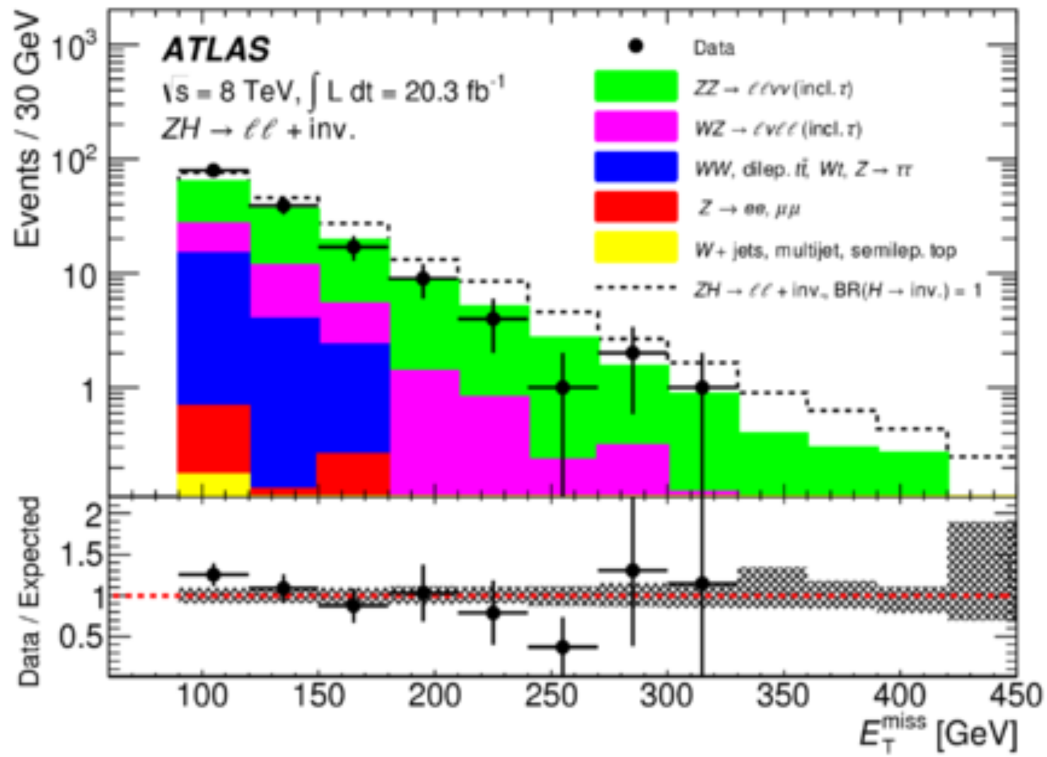
- Direct searches for Dark Matter usually hidden in deep caverns for low noise. But there is another way…
  - Dark matter has mass! Should couple to the Higgs. Do we see it?
  - Weakly interacting particles would leave no trace in detector – "Invisible" Higgs decays
  - Could be e.g. neutralinos in SUSY scenario
  - Would contribute to total Higgs width – we can search it at the LHC





Invisible Higgs





Require dileptons from Z

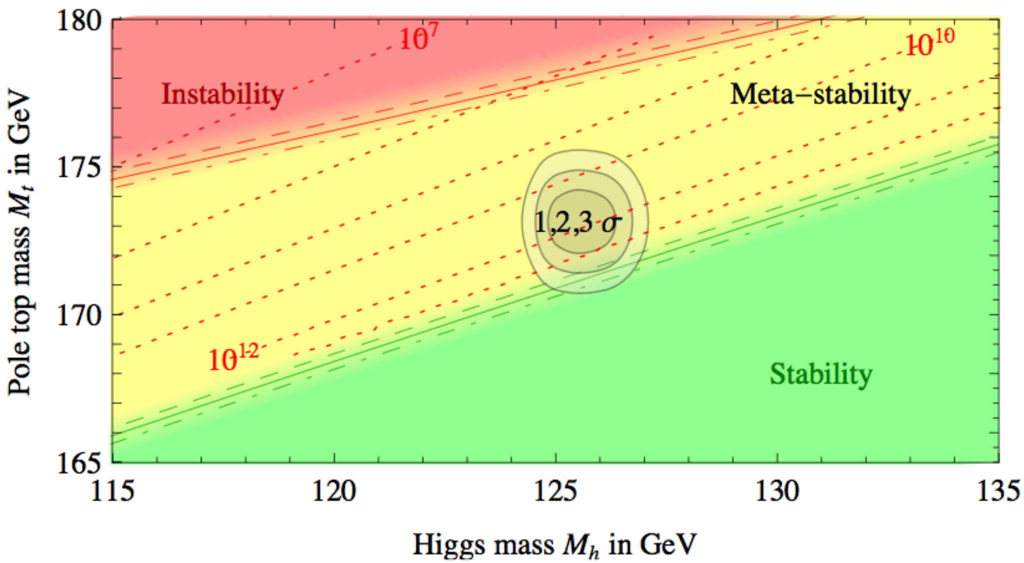
Back to back with Missing E_T and $p_T(\ell\ell)$

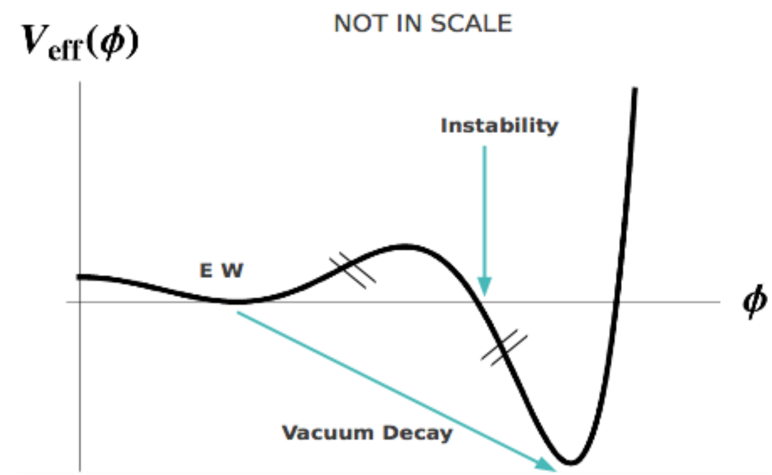
No jets

Main backgrounds ZZ, WZ

Claire Shepherd-Themistocleous - 26th Rencontres de Blois 2014

A bit of fun…





RG-improved potential

- What if…
  - At higher orders, Higgs potential doesn't have to be stable
  - Depending on m_t and m_H second minimum can be lower than EW minimum ⇒ tunneling between EW vacuum and true vacuum?!
- "For a narrow band of values of the top quark and Higgs boson masses, the Standard Model Higgs potential develops a shallow local minimum at energies of about 10^{16} GeV, where primordial inflation could have started in a cold metastable state", I. Masina, arXiv:1403.5244 [astro-ph.CO]
  - See also: V. Brachina, Moriond 2014 (Phys.Rev.Lett.111, 241801 (2013)), G. Degrassi et al, arXiv:1205.6497v2; R.Contino, Workshop sulla fisica p-p a LHC, 2013

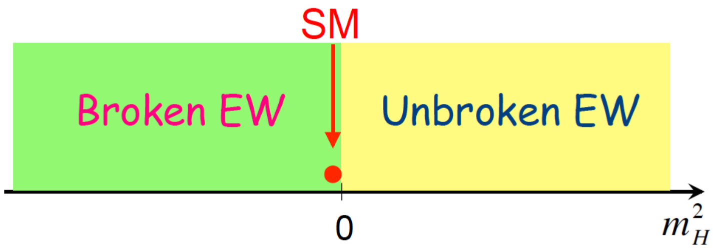
The universe seems to live near a critical condition

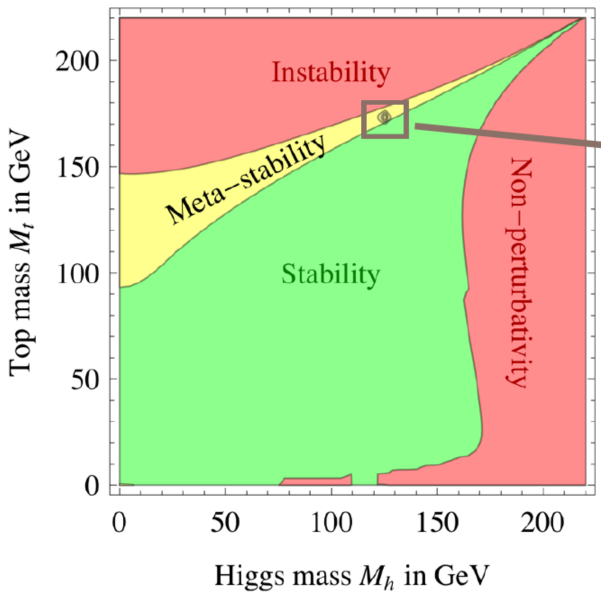
JHEP 1208 (2012) 098

Why?!

Explained by underlying theory?

Anthropic principle?





Where we stand now?

- The Higgs may very well be a window into the new physics which we know must exist
- We now have very precise results from the Higgs sector
- And no surprises (yet?)

- **But the truth is out there! Must keep looking!**

The End

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6. J. Butterworth, Smashing Physics – inside the world's biggest experiment, Headline Publishing Group, 2014
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9. LEP Electroweak Working Group, Precision Electroweak Measurements and Constraints on the Standard Model, CERN-PH-EP-2010-095, July 2010
10. LHC Higgs Cross Section Working Group: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG
11. CMS Collaboration, Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV, Phys. Rev. D 92, 012004, 2015
12. ATLAS and CMS Collaborations, Combined Measurement of the Higgs Boson Mass in pp Collisions at s√=7 and 8 TeV with the ATLAS and CMS Experiments, Phys. Rev. Lett. 114, 191803
13. I. Masina, arXiv:1403.5244 [astro-ph.CO], V. Brachina, Moriond 2014 (Phys.Rev.Lett.111, 241801 (2013)), G. Degrassi et al, arXiv:1205.6497v2; R.Contino, Workshop sulla fisica p-p a LHC, 2013


KEEP
CALM
AND
CHECK
BACKUP SLIDES

Portugal at the LHC

Experimental groups from LIP in ATLAS and CMS

- 20-30 researchers, students, engineers per group, from universities of Lisboa, Coimbra, Minho
- Dedicated to tasks from detector operation and upgrade to physics analysis
- Both groups made major contributions to the detector development, construction and exploitation over more than 20 years.

Current interests :

- ATLAS: detector control; calorimeter calibration and upgrade; jet trigger operation and upgrade; Physics analysis: Higgs; top quark; Exotic; Heavy ions
- CMS: calorimeter electronics; trigger/DAQ; Physics analysis: SUSY; top quark; Higgs.

How we know what we know?

The LHC and its experiments

The Large Hadron Collider

- Four main experiments:
  - ATLAS and CMS general-purpose
  - LHCb – B physics
  - ALICE – heavy-ion physics

CM energy	**14 TeV (design)**
Luminosity ($cm^{-2}s^{-1}$)	Low: $2x10^{33}$ High: 10^{34}
Bunch crossing	24.95 ns
Overlaid events	23 @ $10^{34}cm^{-2}s^{-1}$
Beam radius	16.7 μm
Particles/bunch	$1.15x10^{11}$
Bunches/beam	2808 (design)
Stored energy	362 MJ/beam

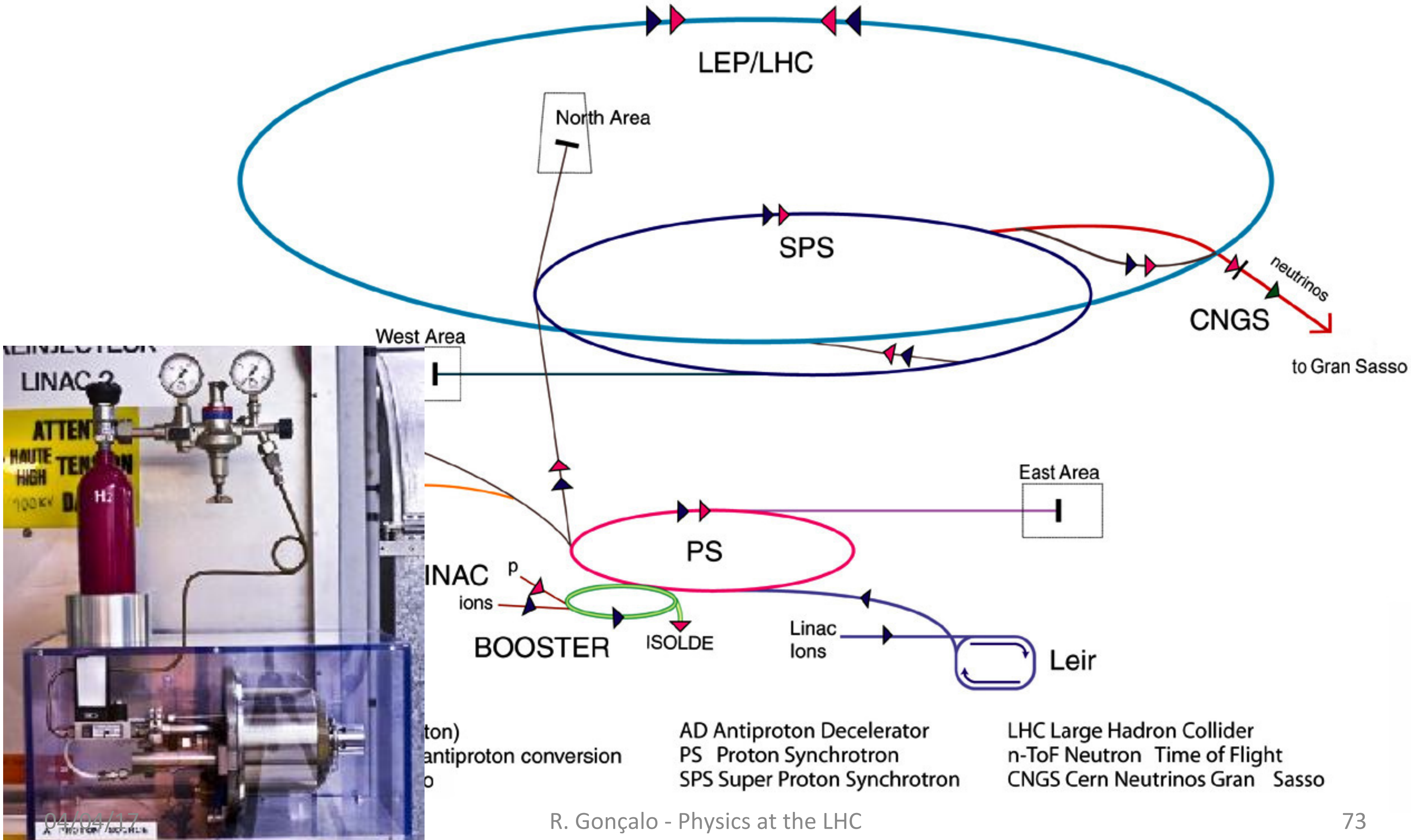
LINAC2 → **50 MeV**

Booster → **1.4 GeV**

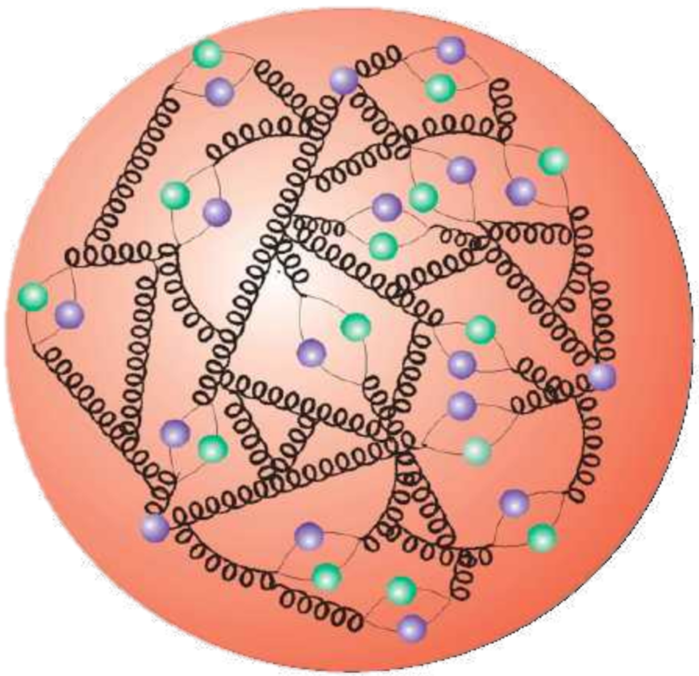
Proton Synchroton (PS) → **25 GeV**

Super Proton Synchrotron (SPS) → **450 GeV**

Large Hadron Collider (LHC)→ **7 TeV**



What do we talk about when we talk about colliding protons?

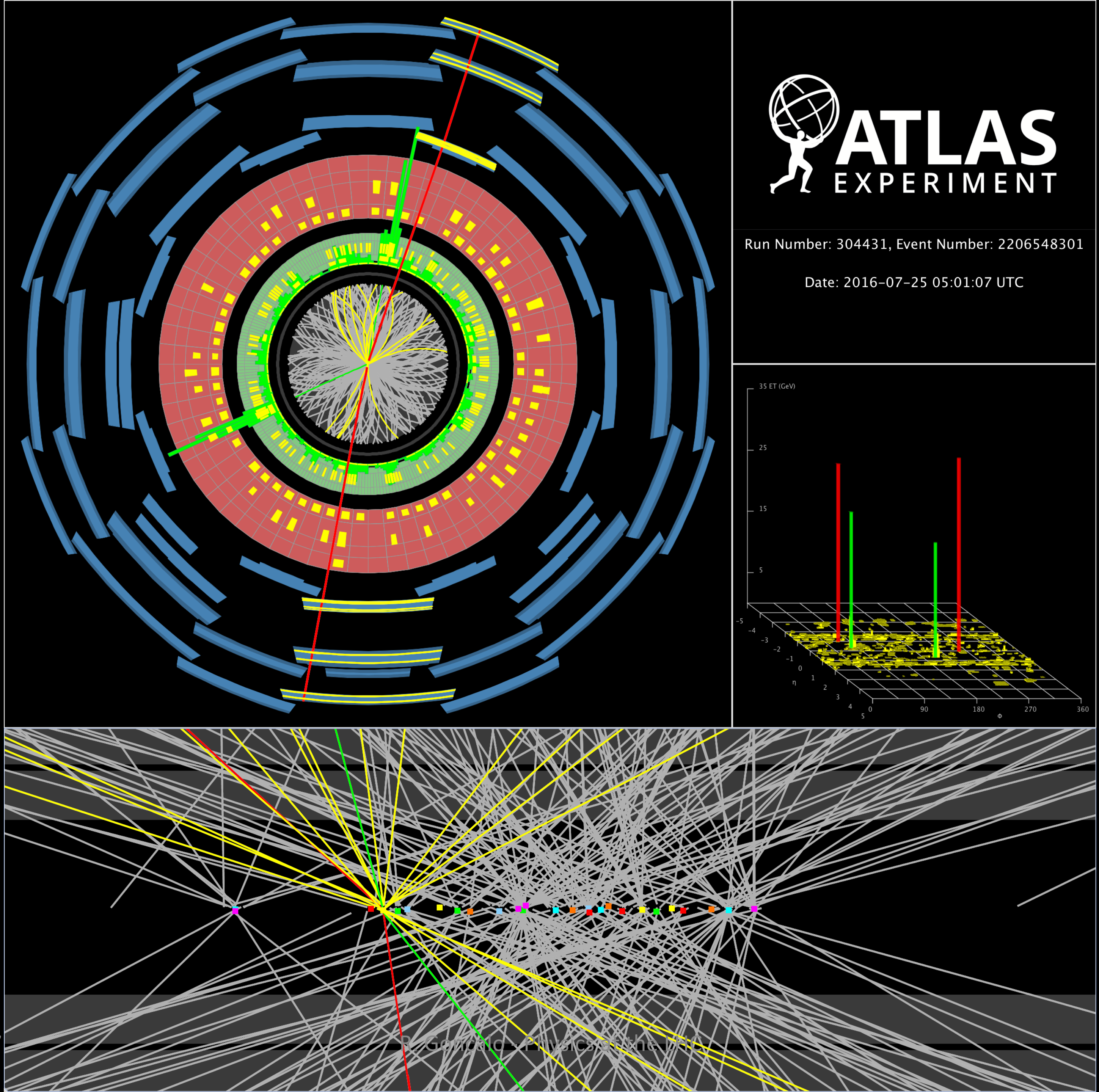


- The LHC collides the beams at the centre of the experiments
- Quarks or gluons from colliding protons carry a fraction of the proton's energy
- LHC centre of mass energy:
  - 7TeV in 2011
  - 8 TeV in 2012 (2013-2015 shutdown)
  - 13 TeV from 2015

- Both beam **energy** and **luminosity** are important

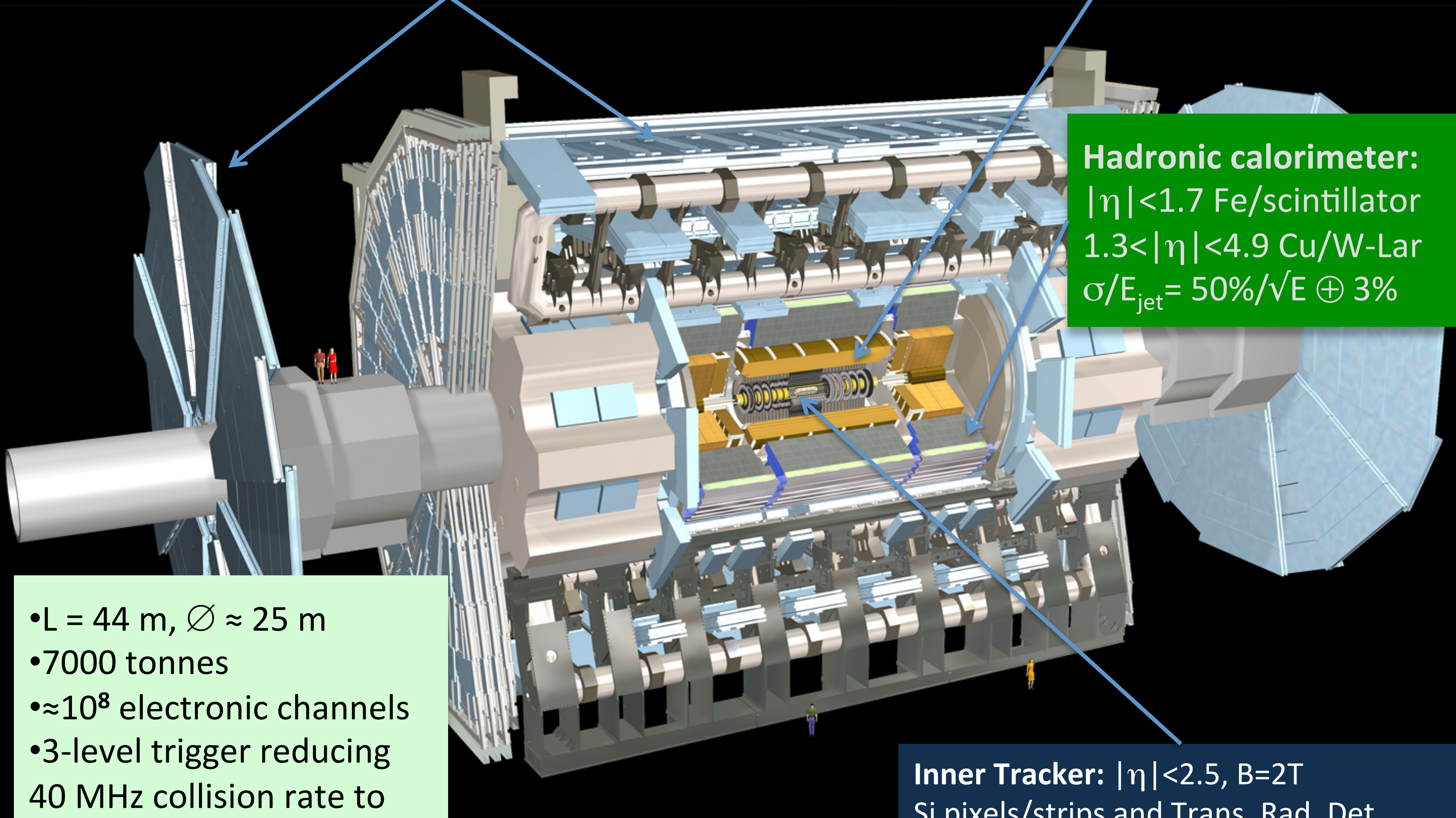
$$N = \sigma \mathcal{L}$$

Number of events — Process cross section — Collider luminosity


ATLAS
EXPERIMENT
Run Number: 304431, Event Number: 2206548301
Date: 2016-07-25 05:01:07 UTC
35 ET (GeV)
25
15
5
η
Φ
0
90
180
270
360

Muon Spectrometer: $|\eta|<2.7$
Air-core toroids and gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)

EM calorimeter: $|\eta|<3.2$
Pb-LAr Accordion
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$

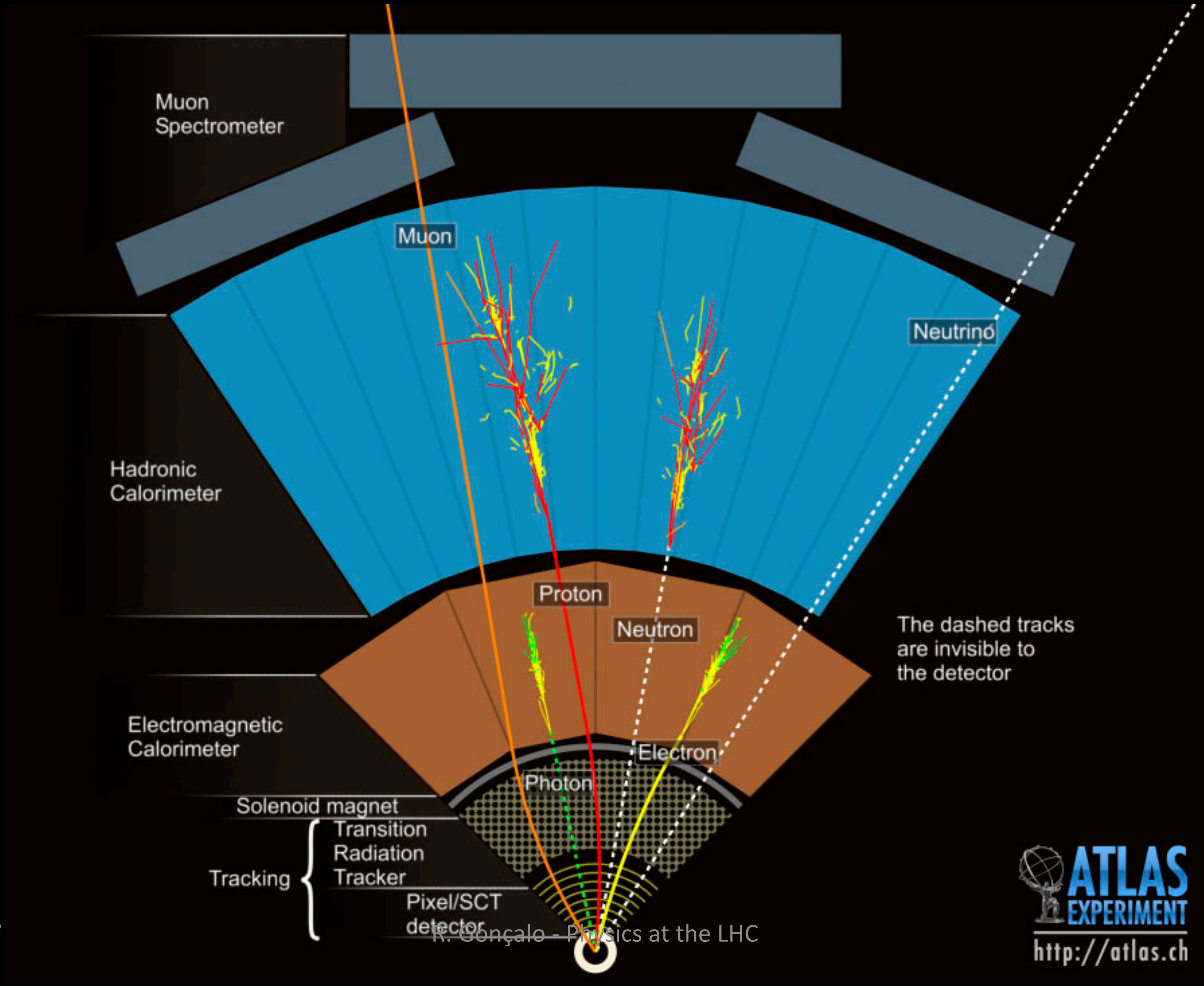


Hadronic calorimeter:
$|\eta|<1.7$ Fe/scintillator
$1.3<|\eta|<4.9$ Cu/W-Lar
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$

- L = 44 m, ∅ ≈ 25 m
- 7000 tonnes
- ≈10^8 electronic channels
- 3-level trigger reducing 40 MHz collision rate to 200 Hz of events to tape

Inner Tracker: $|\eta|<2.5$, B=2T
Si pixels/strips and Trans. Rad. Det.
$\sigma/p_T = 0.05\%\ p_T\,(\text{GeV}) \oplus 1\%$

Particle identification



Channel combination with gory details

- **Assumptions:**
  - Single resonance (at $m_H = 125.5$GeV)
  - No modification of tensor structure of SM Lagrangian:
    - i.e. H has $J^P = 0^+$
  - Narrow width approximation holds
    - i.e. rate for process i ➔ H ➔ f is:

$$\sigma \times BR = \frac{\sigma_{i\to H} \times \Gamma_{H\to f}}{\Gamma_H}$$

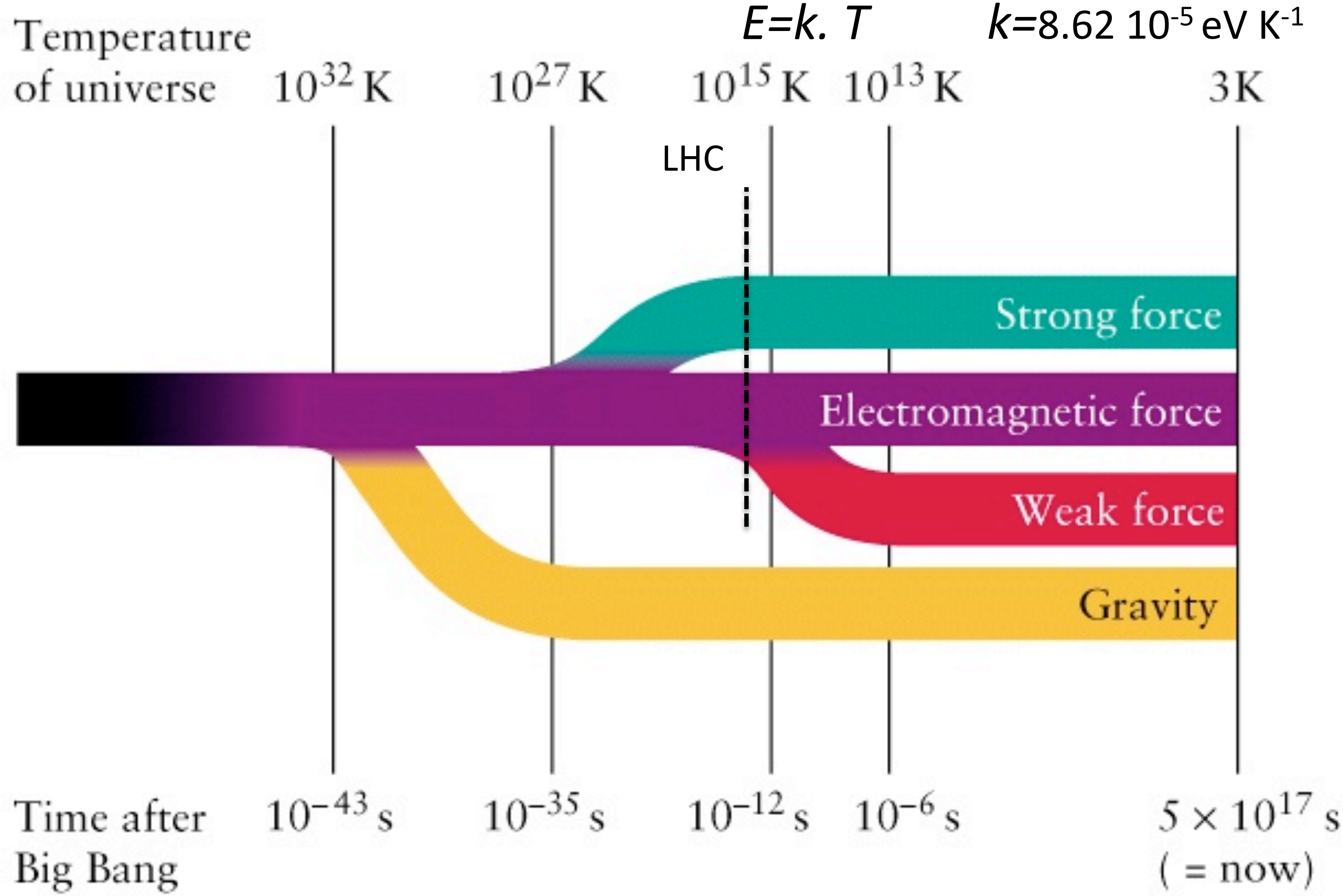
- **Free parameters** in framework:
  - Coupling scale factors: κ_j^2
  - Total Higgs width: κ_H^2
  - Or ratios of coupling scale factors: $\lambda_{ij} = \kappa_i / \kappa_j$

$$\sigma_i = \kappa_i^2 \cdot \sigma_i^{SM}; \Gamma_f = \kappa_f^2 \cdot \Gamma_f^{SM}; \Gamma_H = \kappa_H^2 \cdot \Gamma_H^{SM}$$

- Tree-level motivated framework
  - Useful for **studying deviations** in data with respect to expectations
    - E.g. extract coupling scale factor to weak bosons κ_V by setting $\kappa_W = \kappa_Z = \kappa_V$
  - Not same thing as fitting a new model to the data

Forces and expansion of the Universe

$E = k.\,T$ $k = 8.62\ 10^{-5}$ eV K^{-1}



Two Higgs Doublet Model (2HDM)

- No reason for simplest Higgs sector scenario to be true!
- One of the simplest alternatives: 2 Higgs doublets

$$\Phi_j = \begin{pmatrix} \phi_j^+ \\ (v_j + \rho_j + i\eta_j)/\sqrt{2} \end{pmatrix}$$

- Leads to 5 different Higgs bosons:
  - CP even (scalar): h, H
  - CP odd (pseudoscalar): A
  - charged: H^+, H^-
- Two doublets => two vacuum expectation values (mean field strength in the vacuum) – $\boldsymbol{v_1}$ **and** $\boldsymbol{v_2}$

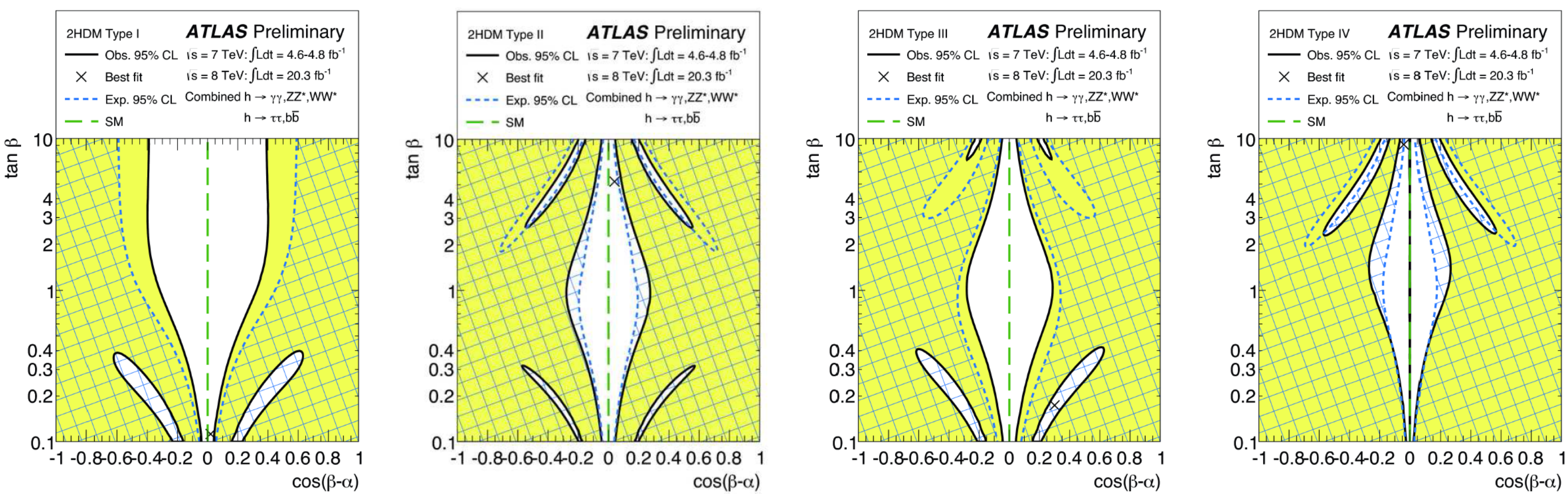
Two Higgs Doublet Model (2HDM)

- Free parameters:
  - 4 masses (Do we know one? Assume it's m_h)
  - $\tan\beta = v_1/v_2$ ratio of v.e.v.'s
  - Mixing angle of h and H: α
- 4 possible Yukawa coupling arrangements ("types")
- Most common SUSY benchmark (MSSM) is based on Type II
- If cos(β-α) = 0, h = Standard Model H^0

	Type I	Type II	Lepton Specific	Flipped
κ_V	sin(β-α)	sin(β-α)	sin(β-α)	sin(β-α)
κ_u	cos(α)/sin(β)	cos(α)/sin(β)	cos(α)/sin(β)	cos(α)/sin(β)
κ_d	cos(α)/sin(β)	-sin(α)/cos(β)	cos(α)/sin(β)	-sin(α)/cos(β)
κ_l	cos(α)/sin(β)	-sin(α)/cos(β)	-sin(α)/cos(β)	cos(α)/sin(β)

Constraints from SM channels

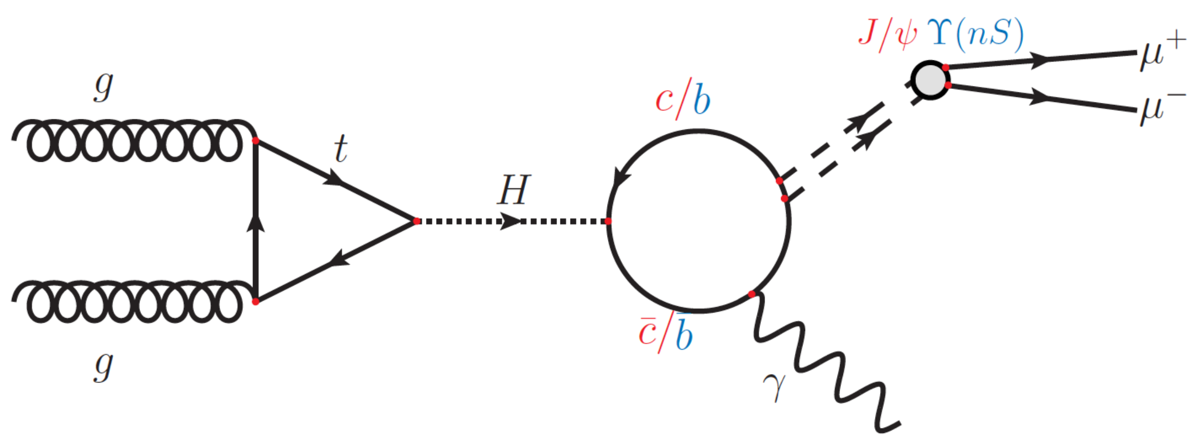
- What can our data already say about the 2HDM?
  - If it exists in Nature, then some of the measured rates (signal strength) are modified
  - Existing measurements can already rule out many possibilities
  - Used final states γγ, ZZ, WW, bb, ττ



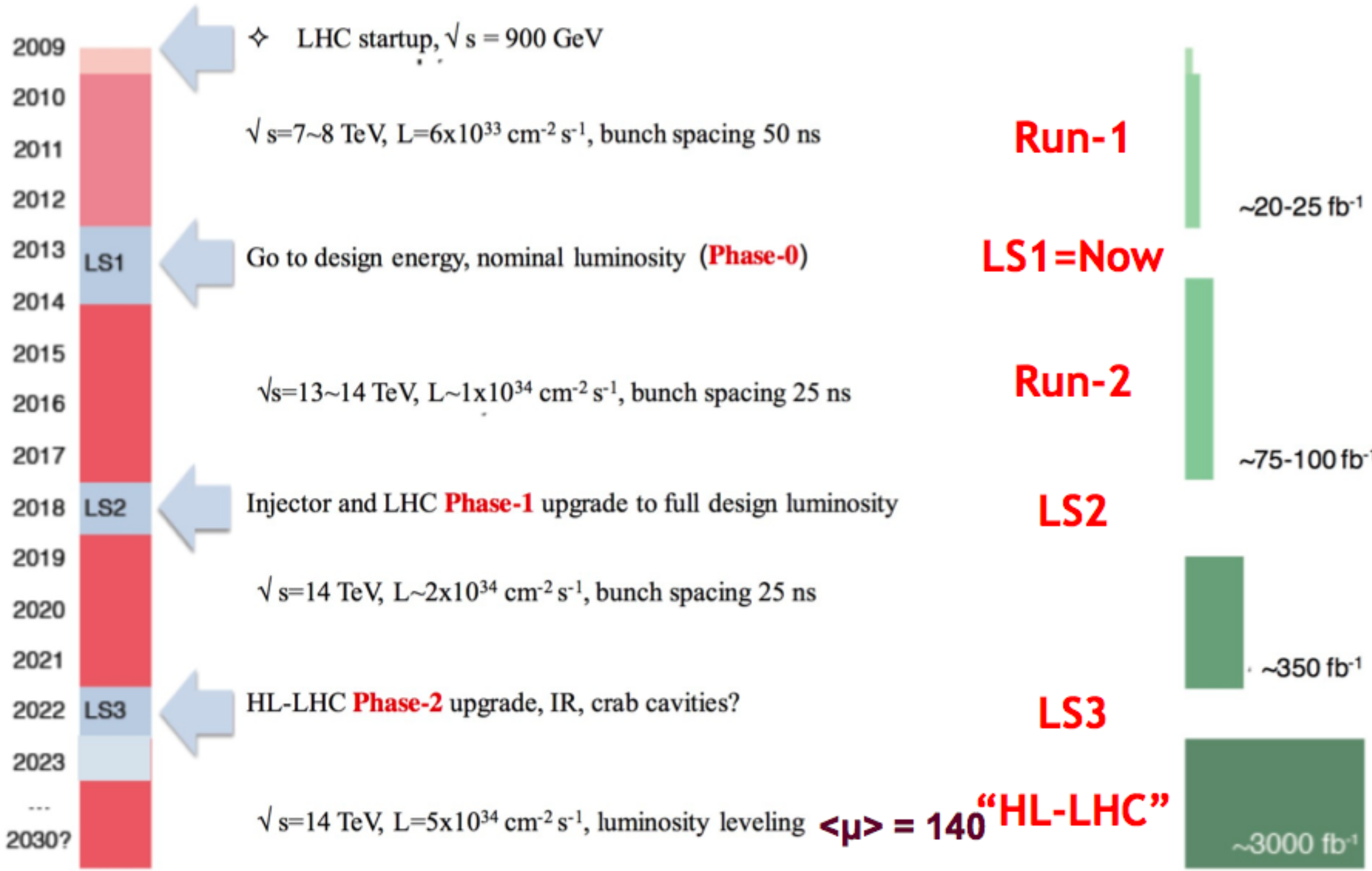
ATLAS-CONF-2014-010

Rare decays

- Only way to probe Higgs decays to charm – charm Yukawa coupling – at LHC
- Deviations in coupling from SM value can lead to increase in branching fraction
- Analysis also probes Z decays to J/Ψ or ϒ(nS) plus γ – improved LEP limits by 2

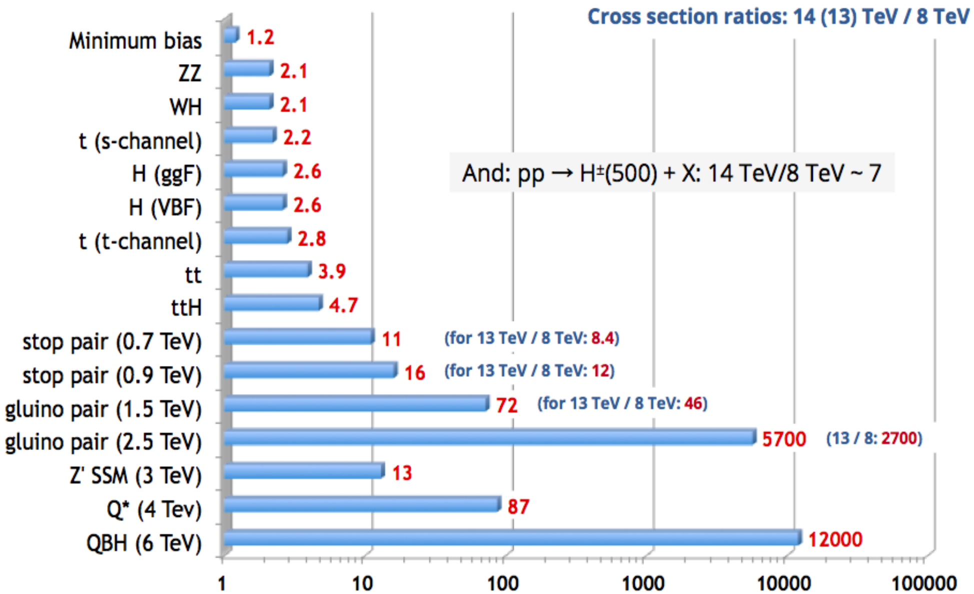


Future LHC Running

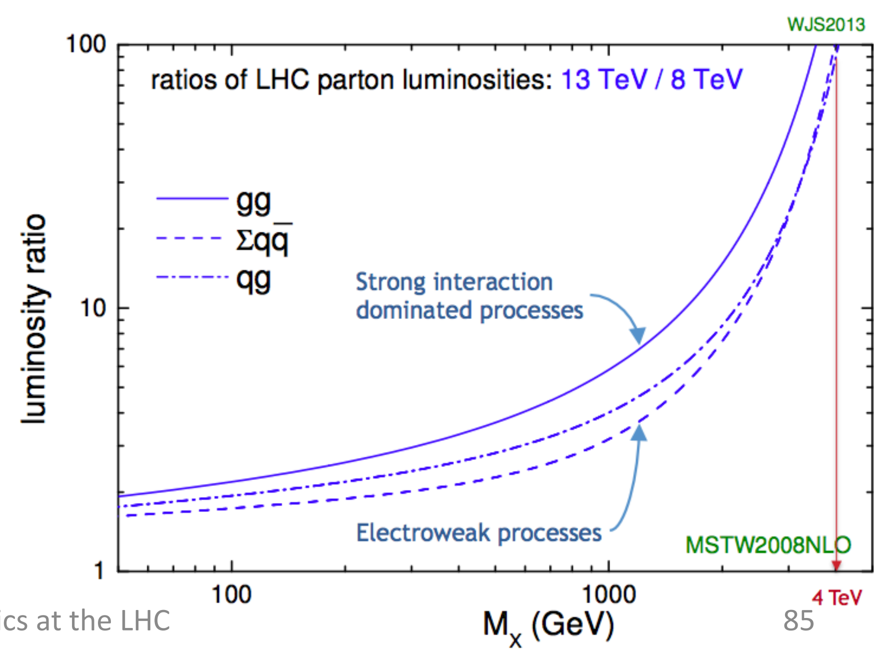


Not only more luminosity

- Higher centre of mass energy gives access to higher masses
- Hugely improves potential for discovery of heavy particles
- Increases cross sections limited by phase space
  - E.g. ttH increases faster than background (factor 4)
- But may make life harder for light states
  - E.g. only factor 2 increase for WH/ZH, H➞bb and more pileup
  - Could be compensated by use of boosted jet techniques (jet substructure)



http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html



Run II/High-Lumi LHC Programme

Precision AND searches!

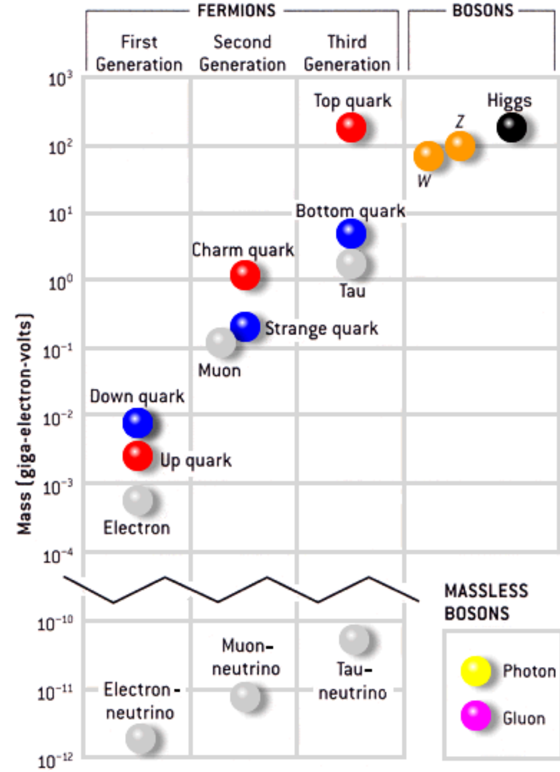
- Precision:
  - Continue to look for deviations wrt Standard Model
- Differential cross sections:
  - New physics in loops could modify event kinematics
- Complete measurement of properties:
  - E.g. CP quantum numbers:
  - Sensitivity in $H \rightarrow ZZ$ and VBF
  - Search for CP violation in Higgs sector
- Search for rare decay modes:
  - $H \rightarrow HH$ to access self coupling (long term!)
- Search for additional Higgs bosons:
  - E.g. 2-Higgs Doublet Model is a natural extension and predicted in SUSY

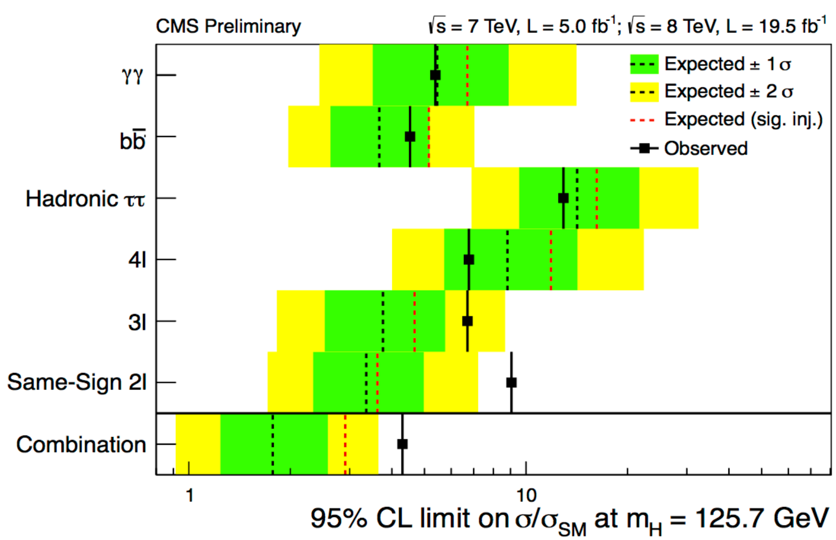
Luminosity	$H \rightarrow Z\gamma$	$H \rightarrow \mu\mu$	$H \rightarrow$ Invisible
$300 fb^{-1}$	$2.3\ \sigma$	$2.3\ \sigma$	$Br < 23\%$
$3000 fb^{-1}$ HL-LHC	$3.9\ \sigma$	$7.0\ \sigma$	$Br < 8\%$

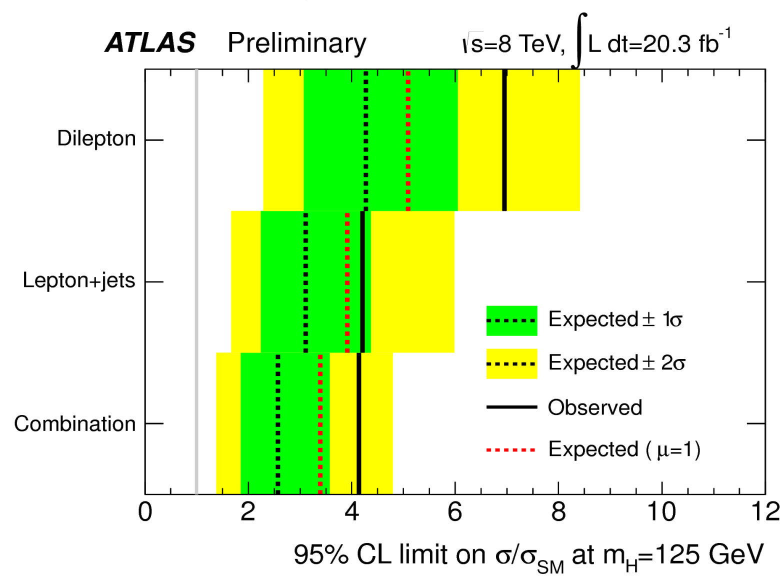
ATL-PHYS-PUB-2014-006 ATL-PHYS-PUB-2013-014 ATL-PHYS-PUB-2013-014

Another example: ttH

- Indirect constraints on top-Higgs Yukawa coupling from loops in ggH and ttH vertices
  - Assumes no new particles contribute to loops
- Top-Higgs Yukawa coupling can be measured directly
  - Allows probing for New Physics contributions in the ggH and γγH vertices
- Top Yukawa coupling $Y_t = \sqrt{2}M_t/vev = 0.996 \pm 0.005$
  - Does this mean top plays a special role in EWSB?

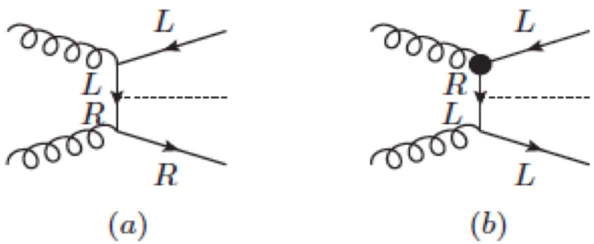




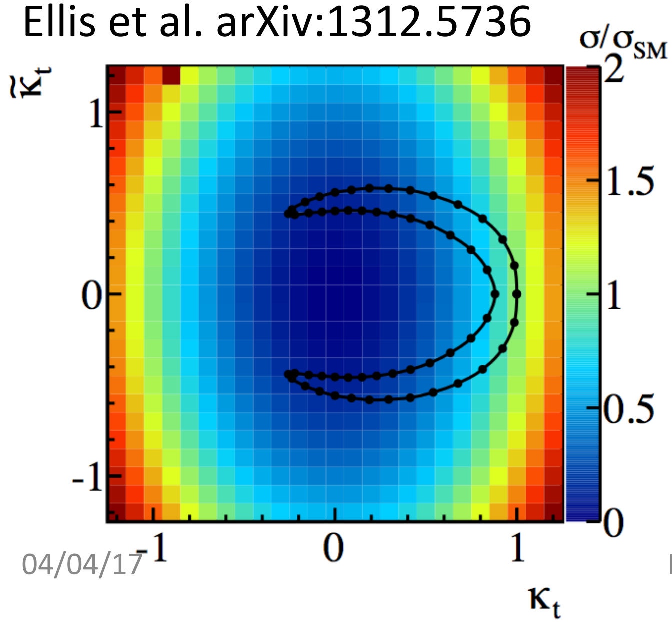


Sensitivity to New Physics

Degrande et al. arXiv:1205.1065



Ellis et al. arXiv:1312.5736



- Effective top-Higgs Yukawa coupling may deviate from SM due to new higher-dimension operators
  - Change **event kinematics –** go differential!
- ttH sensitive new physics: little Higgs, composite Higgs, Extra Dimensions,…
- In the presence of CP violation, Higgs-top coupling have scalar (κ_t)and pseudoscalar ($\tilde{\kappa}_t$)components
  - Strong dependence on ttH cross section
  - Note: Indirect constraints from electron electric dipole moment not taken into account (give $|\tilde{\kappa}_t| < 0.01$)

Summary

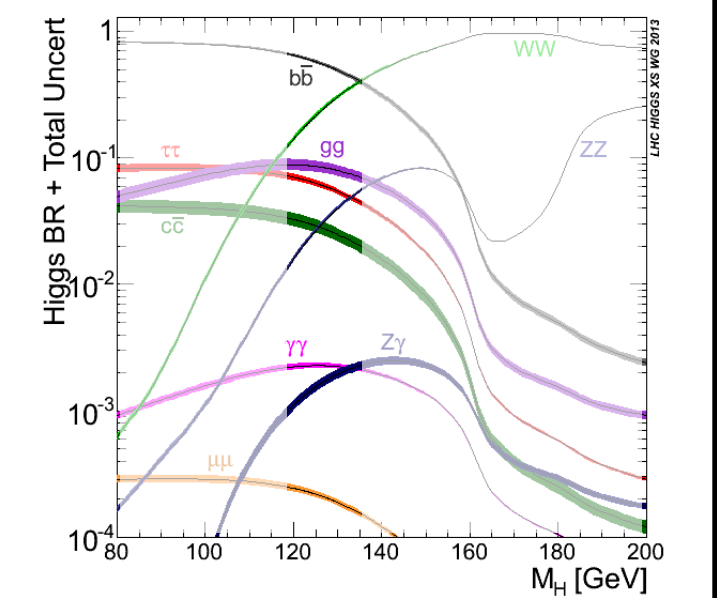
- Recapitulation:
  - Electroweak symmetry breaking
  - Higgs boson in Electroweak Lagrangian
  - Higgs boson production and decay at the LHC
  - The landscape at the end of LHC run I

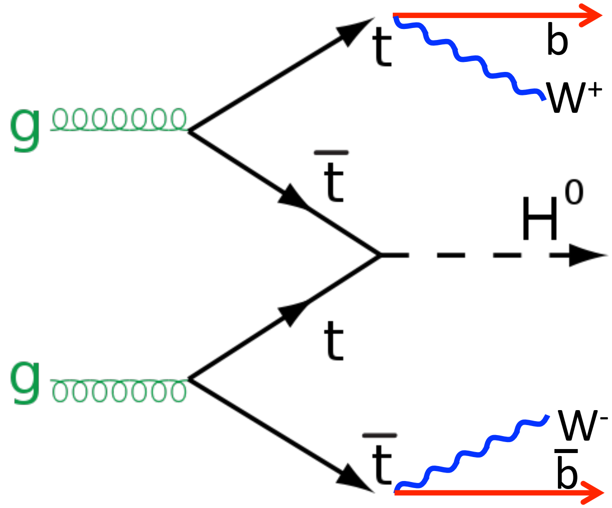
- The Higgs sector beyond the Standard Model
  - Constraints from current data
  - Examples of rare and exotic channels

- Future Higgs measurements at LHC and beyond
  - Fundamental questions at the end of run I
  - Future LHC running – luminosity, energy, and physics reach
  - Higgs physics in future LHC analyses – Precision and Searches
  - An example: associated production with top-quark pair – SM and BSM

Introduction

- Why should we care about ttH?
  - Measure largest SM Yukawa coupling ($y_{top} \approx 1$)
  - Direct measurement of y_{top} – unlike gluon-fusion!
  - y_{top} connected to the scale of new physics (arXiv: 1411.1923 [hep-ph])
  - Complementary channel to extract Higgs CP (arXiv:1501.03157 [hep-ph], arXiv:hep-ph/9602226, arXiv:1312.5736 [hep-ph])
- But :
  - Small cross section:
    - 0.506pb @ 13 TeV, 0.136pb @ 8 TeV
    - ≈ 0.7% – 1.1% of gluon-fusion Higgs production
  - Complicated final states: many possible Higgs and top decay combinations
  - Draws on all detector capabilities
  - Problematic combinatorial issues in event reconstruction for most channels
- So:
  - Favour high branching ratio decays: bb, WW, ττ
  - Or H->γγ (low BR but no comb. issues there)
  - Make analyses orthogonal to ease combination

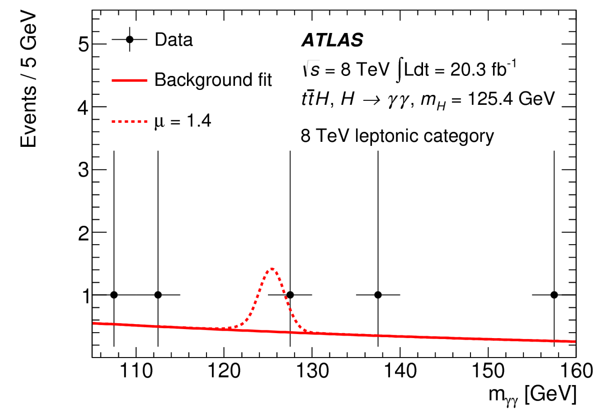


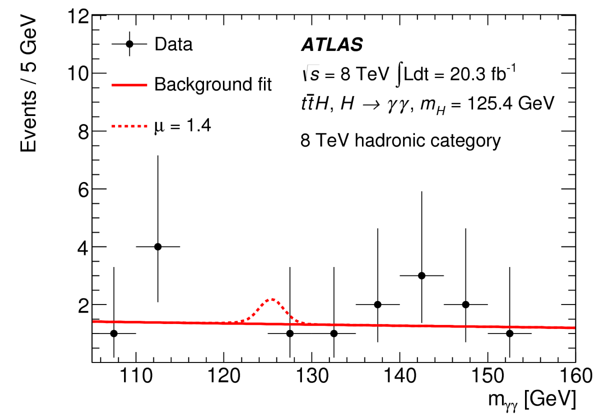


Phys.Lett. B 740 (2015) 222-242

ttH, H→γγ analysis

- Analysis targets ttH and tH production (tHqb, tHW)
- Data: 4.5 fb^{-1} at √s = 7 TeV and 20 fb^{-1} at √s = 8 TeV
- Very small BR(H → γγ) = 0.0023
  - Event yields: ≈0.2 at 7 TeV; ≈1 at 8 TeV
  - But good di-photon mass resolution and small backgrounds
- Analysis driven by ttH, but cuts loose enough to accommodate tH
  - Efficiency ≈15% for ttH, ≈6% to 12% for tH
- Selection:
- 2 photons with 105 GeV < $m_{\gamma\gamma}$ < 160 GeV
  - Diphoton vertex reconstructed from longitudinal shower profile (un-converted) or tracks (converted photons)
  - Leading (subleading) photon: $E_T > 0.35 \times m_{\gamma\gamma}$ ($0.25 \times m_{\gamma\gamma}$)
- 2 event categories:
  - Leptonic: ≥ 1 e/μ + ≥ 1 b-tagged jet + E_T^{miss} > 20 GeV; $m_{\ell e} \neq m_Z$
  - Hadronic: no e or μ; high jet and b-tag multiplicity





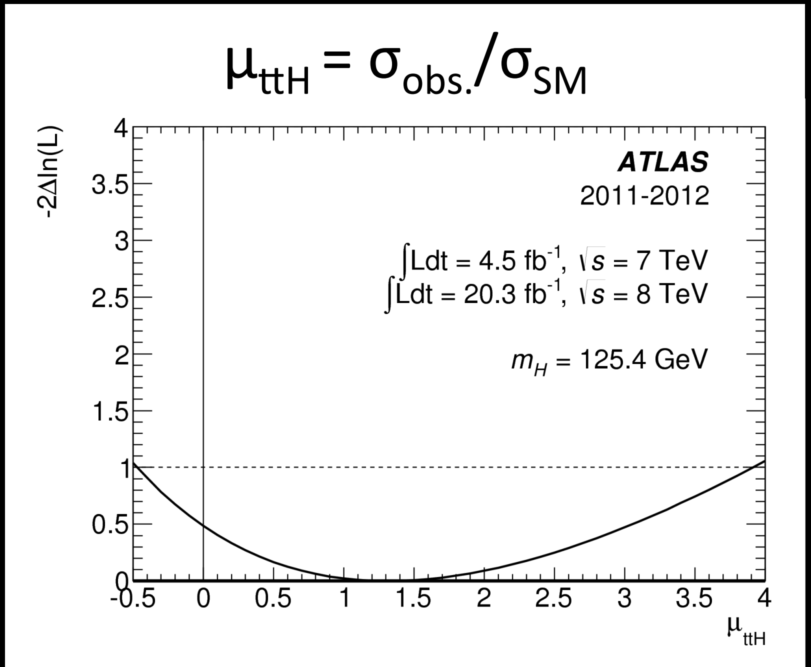
Category	N_H	% of signal: ggF	VBF	WH	ZH	$t\bar{t}H$	$tHqb$	WtH	N_B
7 TeV leptonic selection	0.10	0.6	0.1	14.9	4.0	72.6	5.3	2.5	$0.5^{+0.5}_{-0.3}$
7 TeV hadronic selection	0.07	10.5	1.3	1.3	1.4	80.9	2.6	1.9	$0.5^{+0.5}_{-0.3}$
8 TeV leptonic selection	0.58	1.0	0.2	8.1	2.3	80.3	5.6	2.6	$0.9^{+0.6}_{-0.4}$
8 TeV hadronic selection	0.49	7.3	1.0	0.7	1.3	84.2	3.4	2.1	$2.7^{+0.9}_{-0.7}$

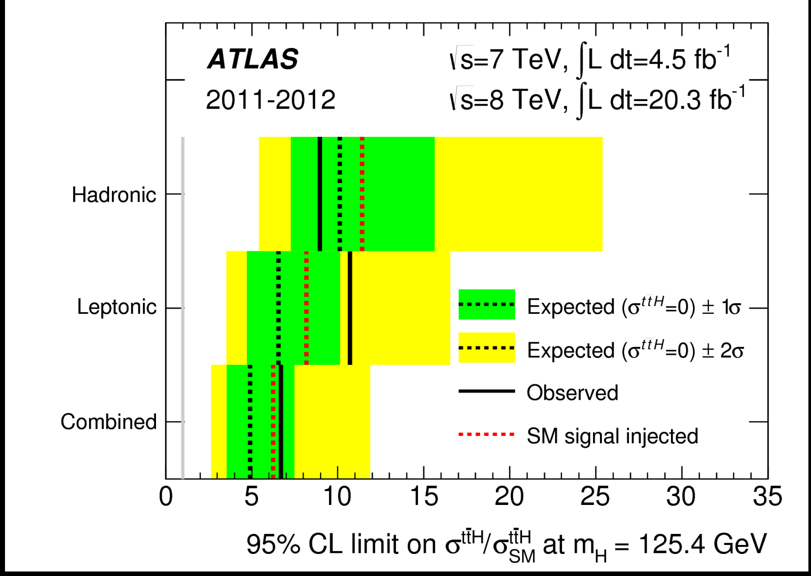
Phys.Lett. B 740 (2015) 222-242

Analysis & Results

- Discriminant parameter: $m_{\gamma\gamma}$
  - Search excess around 125.4 GeV using S + B likelihood fit
  - Signal modelling: Crystal Ball + Gaussian (from simulation)
  - Continuum background: exponential fit to sideband
  - Fit function validated in loose photon-ID control regions dominated by jets
- Signal strength ($\mu_{ttH} = \sigma_{obs.}/\sigma_{SM}$) best fit:
  - Overall ($H \to \gamma\gamma$): $1.4^{+2.1}_{-1.4}(\text{stat.})^{+0.6}_{-0.3}(\text{syst.})$
  - ttH only: $1.3^{+2.5}_{-1.7}(\text{stat.})^{+0.8}_{-0.4}(\text{syst.})$
- Combined limits on signal strength

  $\mu < 6.7$ (4.9 expected)
- Interpreting the data as 95% CL interval of a constant κ_t multiplying the top Yukawa coupling ($y_t = \kappa_t\, y_t^{SM}$):
  - Observed: $-1.3 < \kappa_t < 8.0$
  - Expected: $-1.2 < \kappa_t < 7.8$



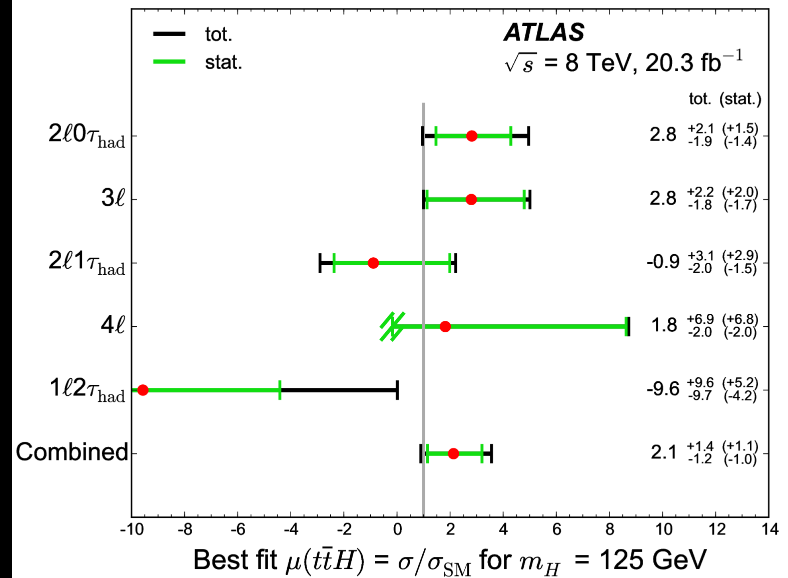


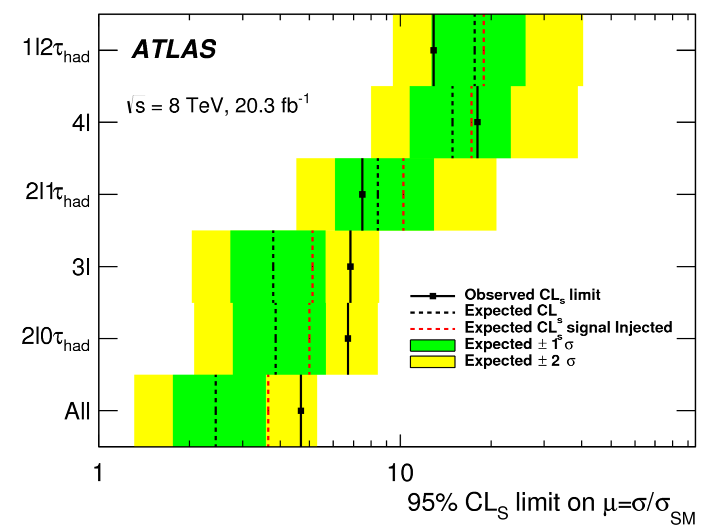
Phys.Lett. B 749 (2015) 519-541

Results

- Signal strength $\mu_{ttH} = \sigma_{obs.}/\sigma_{SM}$ from maximum-likelihood fit to yields in all categories
  - Systematic uncertainties are nuisance parameters in fit
  - μ_{ttH}=1 assumes SM x-sections and BR, and m_H = 125 GeV
  - Fit constrains statistically-limited non-prompt leptons
- Small excess in combined signal strength from $2\ell 0\tau_{had}$, 3ℓ categories – compatible with SM
- Combined 95% CL exclusion limit on is $\mu_{ttH} < 4.7$ ($\mu_{ttH} < 2.4$ expected)
- Single top tH production was set to SM value
  - Setting it to zero gives a variation Δμ of 0.04

$\mu_{ttH} = \sigma_{obs.}/\sigma_{SM}$



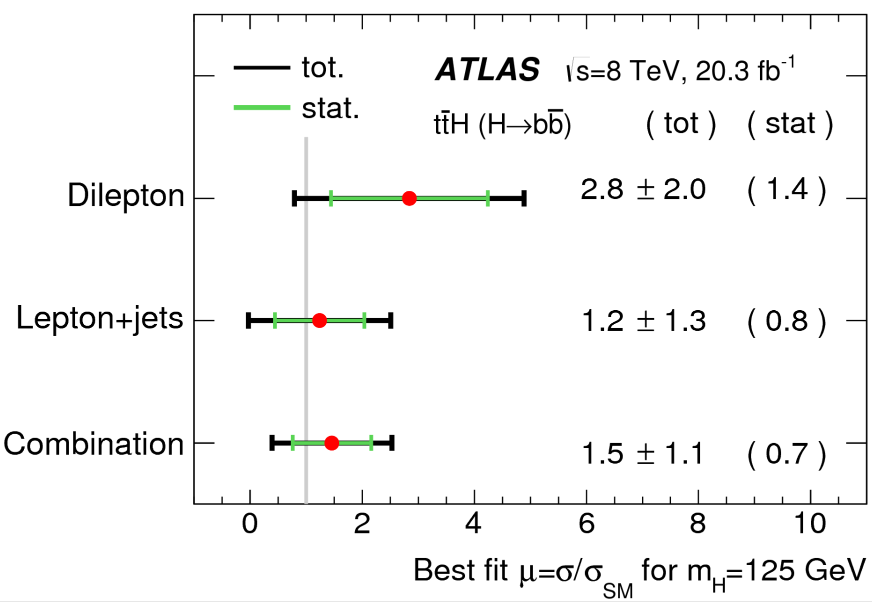


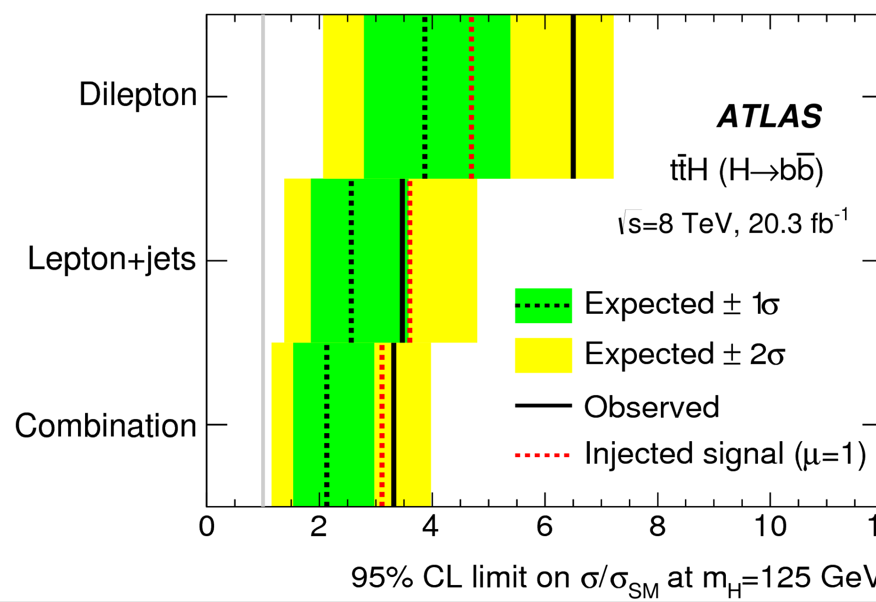
Source	Combination of all categories	$\Delta\mu$	
$2\ell 0\tau_{\rm had}$ non-prompt muon transfer factor		+0.38	−0.35
$t\bar{t}W$ acceptance		+0.26	−0.21
$t\bar{t}H$ inclusive cross section		+0.28	−0.15
Jet energy scale		+0.24	−0.18
$2\ell 0\tau_{\rm had}$ non-prompt electron transfer factor		+0.26	−0.16
$t\bar{t}H$ acceptance		+0.22	−0.15
$t\bar{t}Z$ inclusive cross section		+0.19	−0.17
$t\bar{t}W$ inclusive cross section		+0.18	−0.15
Muon isolation efficiency		+0.19	−0.14
Luminosity		+0.18	−0.14

Eur. Phys. J. C (2015) 75:349

Results

- Signal strength from combined H→bb single-lepton and dilepton channels: $\mu_{ttH} = \sigma_{obs.}/\sigma_{SM} = 1.5 \pm 1.1$
- Exclusion limits at 95% CL: $\mu < 3.4$ (2.2 expected)
- Most important uncertainties:
  - tt + Heavy Flavour modeling
  - Jet energy scale
  - ttV cross section





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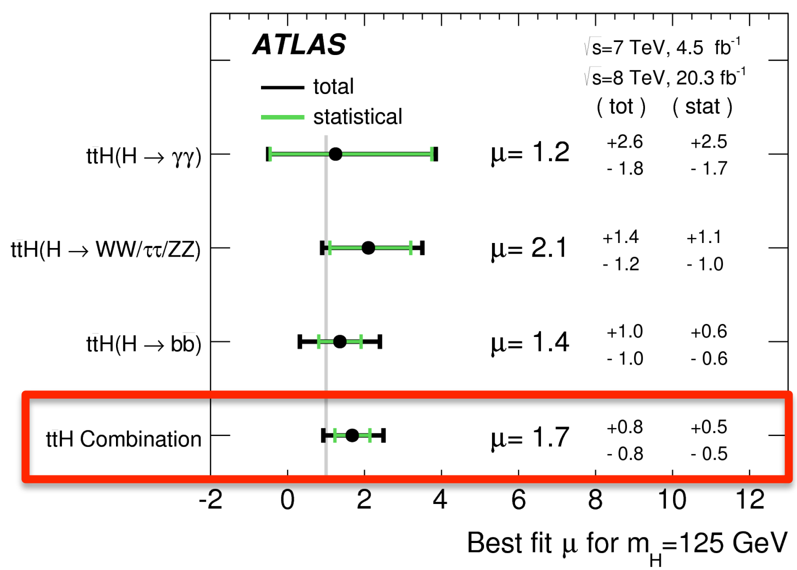
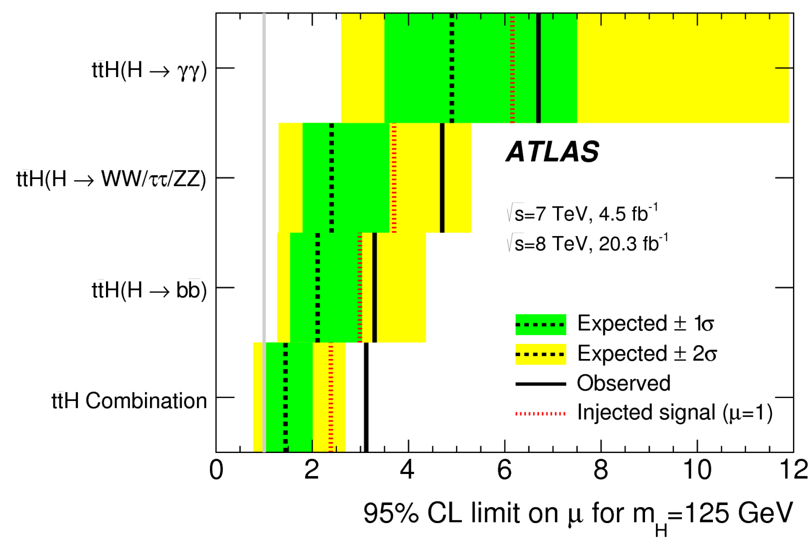
ttH combination

- ATLAS combined all above analyses to get final LHC Run 1 sensitivity
- LHC Run 1 ATLAS best fit: $\mu_{ttH} = 1.7 \pm 0.8$
- Compatible with SM signal ($\mu_{ttH} = 1$) within 1σ
- 2σ above $\mu_{ttH} = 0$ (background-only hypothesis)
- 95% CL limit: $\mu_{ttH} < 3.1 \times$ SM (obs) / $1.4 \times$ SM (exp)

Representative/best analysis category

ttH channel	S/B	S/√B
H→γγ	64%	0.6
multilepton	20%	0.69
H→bb 1ℓ	4%	0.8
H→bb 2ℓ	6%	0.4
H→bb all-had.	1%	0.4



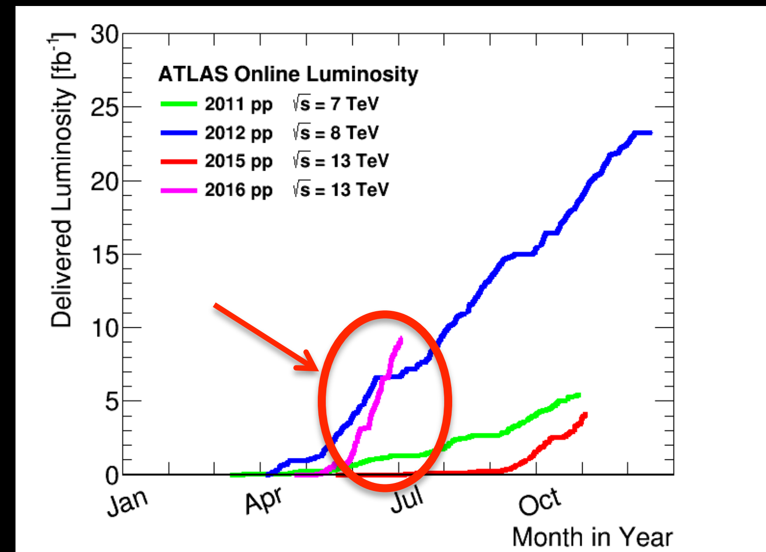


Conclusions and outlook

- ttH production provides unique, direct access to top Yukawa coupling and Higgs properties
  - Covered H→γγ, H→WW, H→ττ, H→ZZ, H→bb decay channels
- Combined signal strength 2σ above background-only hypothesis and compatible with SM expectations

$$\mu_{ttH} = 1.7 \pm 0.8$$

- Better sensitivity expected soon :
  - Higher luminosity (ramping up quickly!)
  - Better S/B ratio(*) with respect to some backgrounds



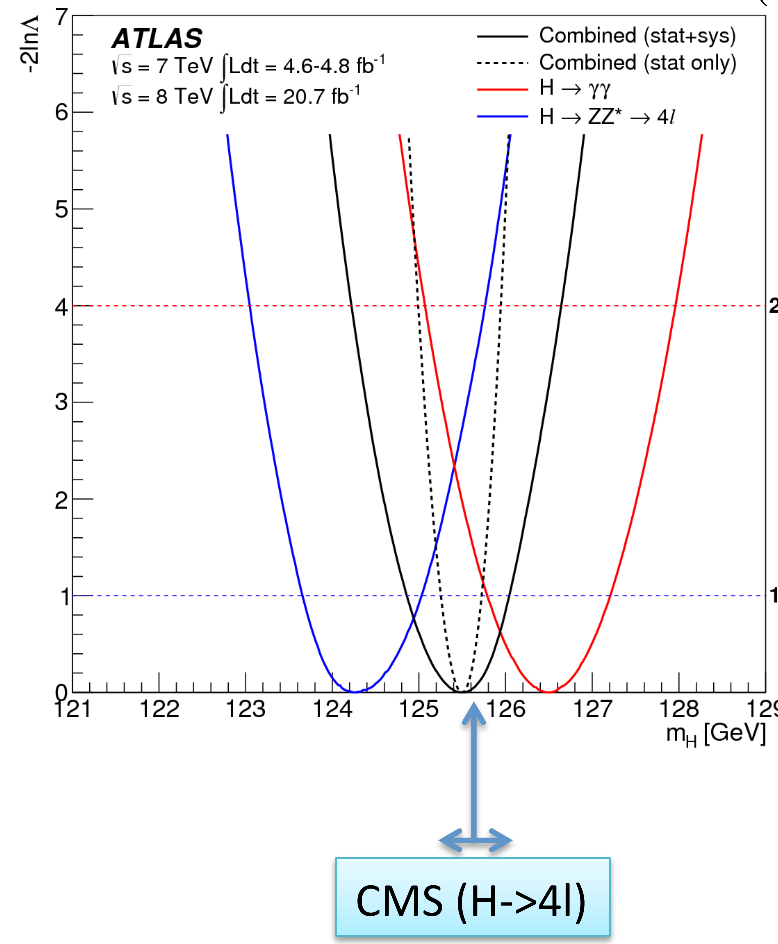
(*) Before cuts and for inclusive tt+jets; not necessarily true after cuts for all channels and jet flavours

How much have we learned since then?

- **Mass:** around 125GeV
  - Used to be the only unknown SM-Higgs parameter, remember? ☺
- ATLAS: arXiv:1307.1427
  - $m_H^{H\to 4l} = 124.3 \pm 0.6(stat) \pm 0.5(sys)$
  - $m_H^{H\to \gamma\gamma} = 126.8 \pm 0.2(stat) \pm 0.7(sys)$
  - Assuming single resonance: $m_H = 125.5 \pm 0.2(stat)\ ^{+0.5}_{-0.6}(sys)$
- Tension between channels!
  - Compatibility P=1.5% (2.4σ)
  - Rises to 8% with square syst.prior
- CMS: arXiv:1312.5353
  - $m_H^{H\to 4l} = 125.6 \pm 0.4(stat) \pm 0.6(sys)$
- Doesn't look like two different resonances!...

ATLAS: arXiv:1307.1427

$$\Lambda = \frac{L(m_H)}{L(\hat{m}_H)}$$

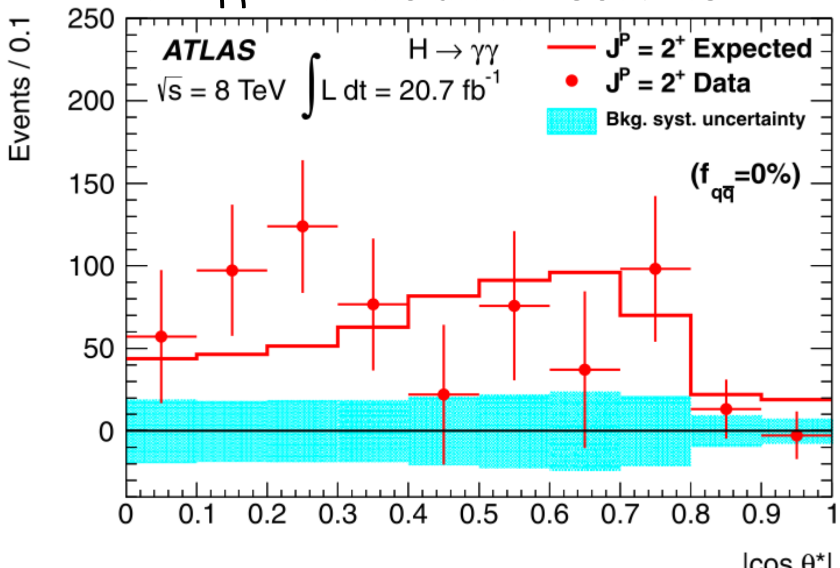


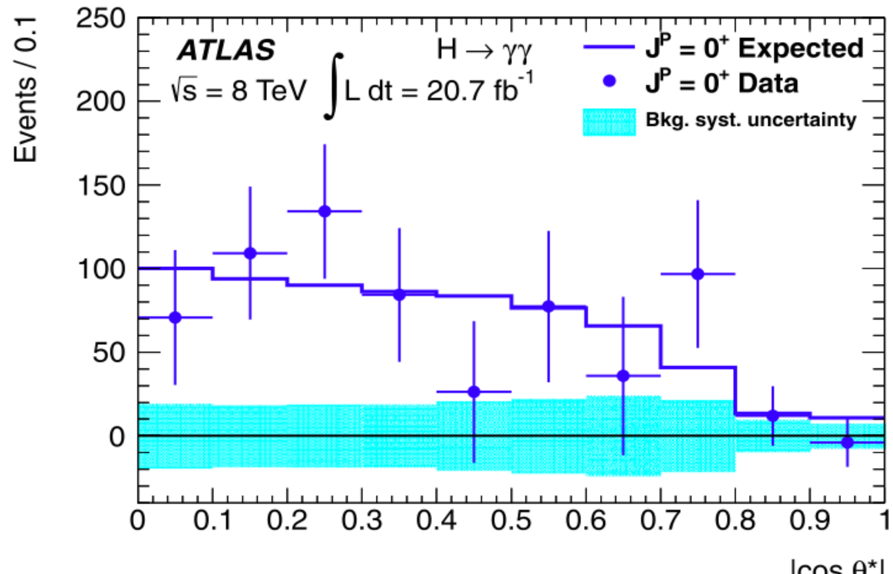
Spin and Parity

- Pure $J^P = 0^-, 1^+, 1^-$, and 2^+ excluded with 97.8, 99.97, 99.7, and 99.9% Confidence Level (ATLAS arXiv 1307.1432)
- But note: Higgs could have CP-violating component!

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1} p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

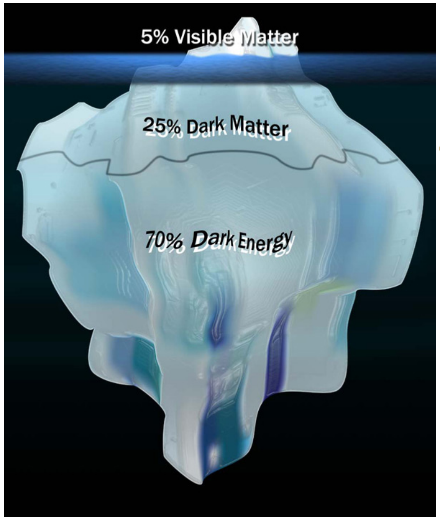
H->γγ – ATLAS arXiv 1307.1432



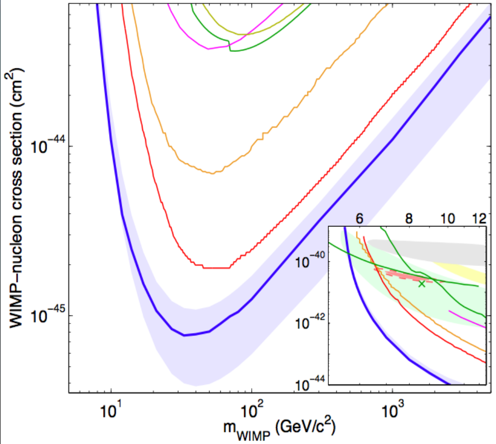


So, where do we stand?

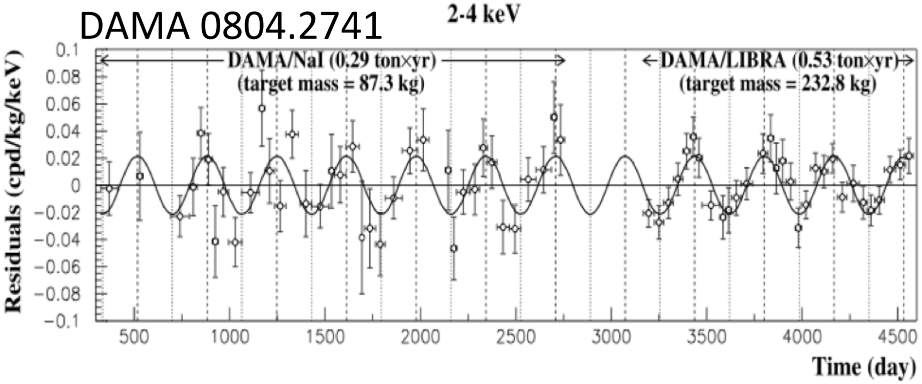
- We have found the **missing piece** of the Standard Model puzzle
- The current data show us a **SM-like** Higgs boson
  - Each channel not so well measured
  - But combination fits well with expectations
- **Is this the end of the story?**



LUX 1310.8214



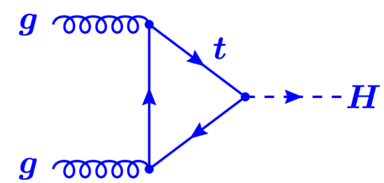
DAMA 0804.2741

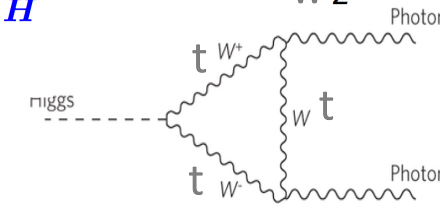


Discovery → Precision! (& a few more channels)

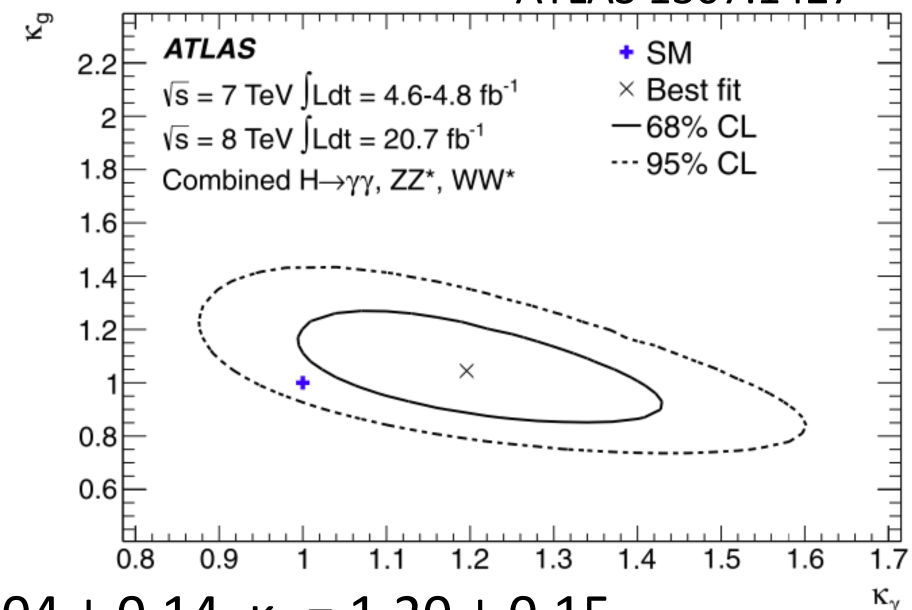
New Physics in the Loops?

- New heavy particles may show up in **loops**
  - Dominant **gluon-fusion** through a (mostly) top loop production for H->ZZ, H->WW and H->γγ
  - **H->γγ decay** through top and W loops (and interference)





ATLAS 1307.1427



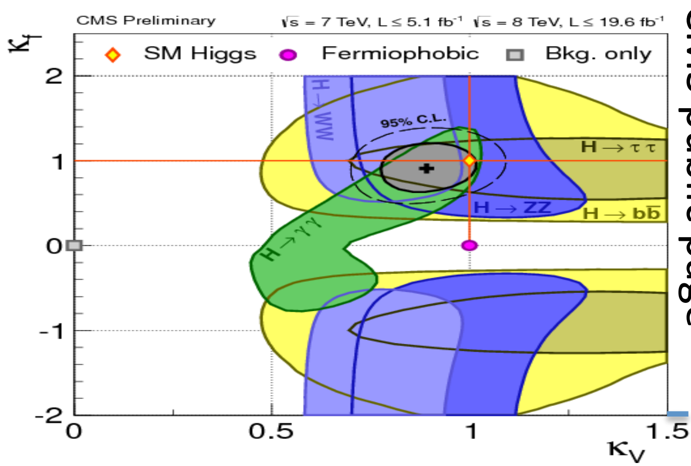
- Assume no change in Higgs width and SM couplings to known particles

- Introduce effective coupling scale factors:
  - κ_g and κ_γ for ggH and Hγγ loops

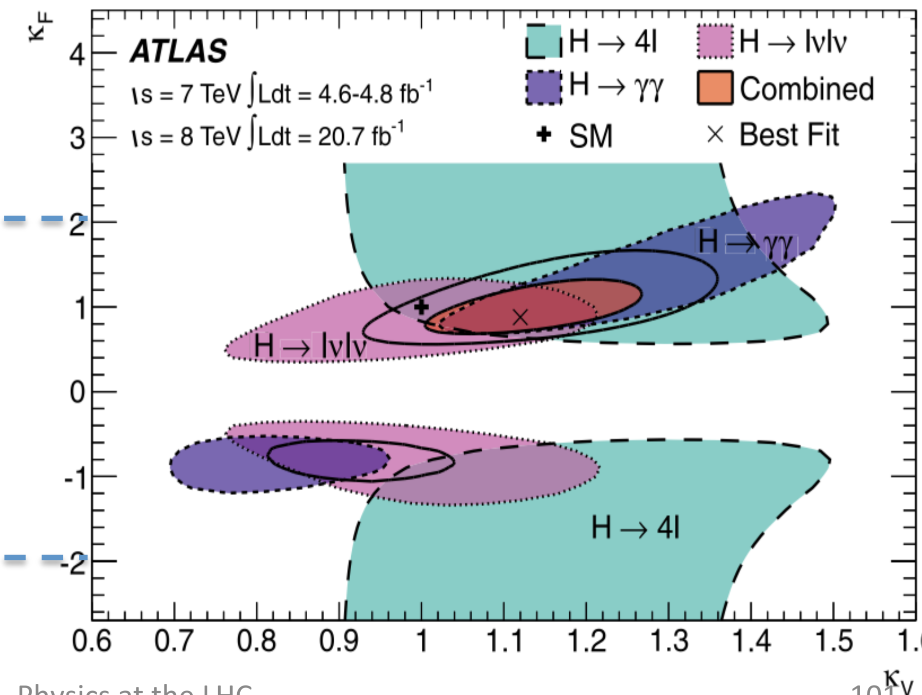
- Best fit values: $\kappa_g = 1.04 \pm 0.14$, $\kappa_\gamma = 1.20 \pm 0.15$
- Fit within 2σ of SM (compatibility P=14%)

Fermion and Boson couplings from fit

- Set one scale factor for all fermions (**κ_F** = κ_t = κ_b= κ_τ =…) and one for all vector bosons (**κ_V** = κ_Z = κ_W)
- Assume **no new physics**
- Strongest constraint to κ_F comes form gg->H loop
- ATLAS and CMS fits within 1-2σ of SM expectation (compatibility P=12%)
- Note ATLAS and CMS κ_V different – see signal strength below



CMS public page



ATLAS 1307.1427

Direct Evidence of Fermion Couplings

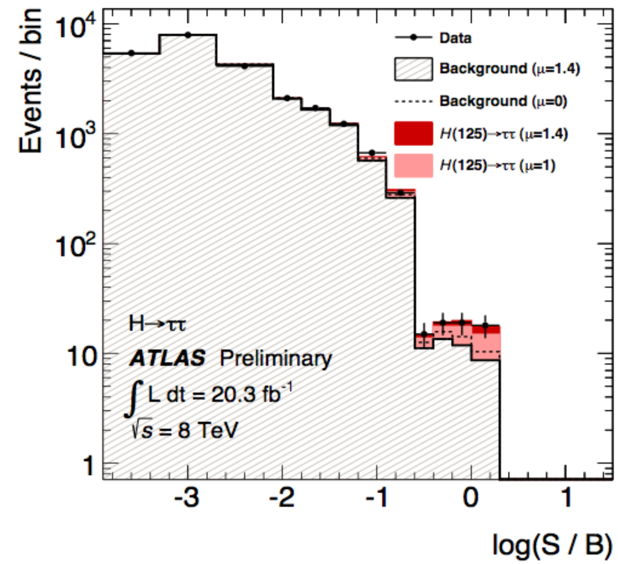
- **Challenging** channels at the LHC!
  - Huge backgrounds (H->bb,H->ττ)
  - Or low rate: H->μμ

New results!

- ATLAS:

  4.1σ evidence of H->ττ decay 3.2σ exp.

  $\mu = \boldsymbol{\sigma_{obs.}/\sigma_{SM}} = 1.4 \pm 0.3(\text{stat}) \pm 0.4(\text{sys})$



ATLAS-CONF-2013-108

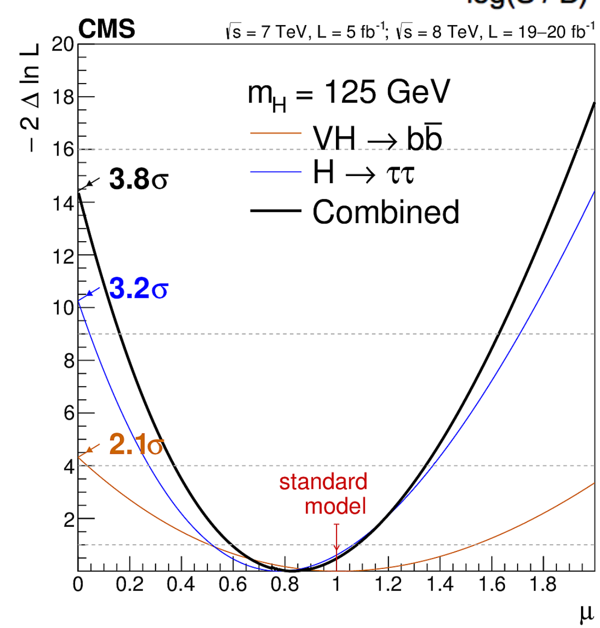
- CMS: **hot off the press!**
  - Combination of H->bb and H->ττ:

  3.8σ evidence (obs.) 4.4σ (expected)

  $\mu = \boldsymbol{\sigma_{obs.}/\sigma_{SM}} = 0.83 \pm 0.24$

CMS 1401.6527

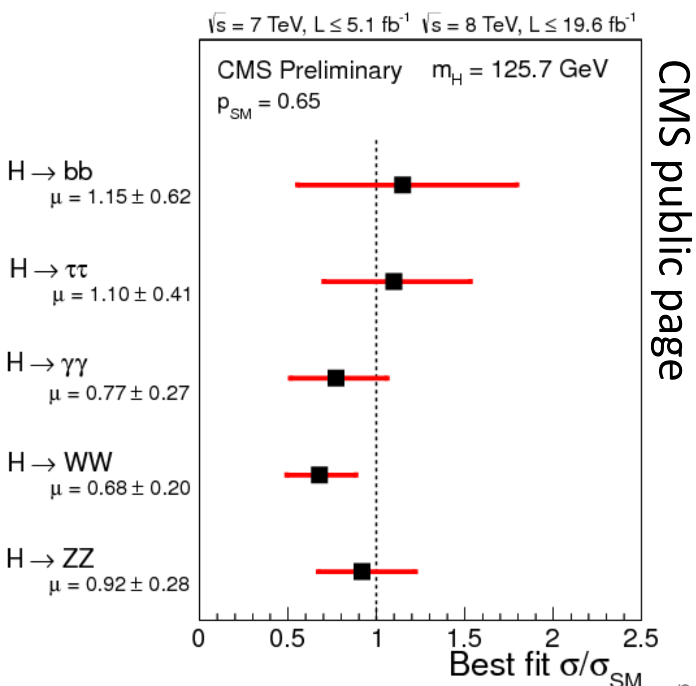
Channel ($m_H = 125\,\text{GeV}$)	Significance (σ) Expected	Observed	Best-fit μ
$VH \to b\bar{b}$	2.3	2.1	1.0 ± 0.5
$H \to \tau\tau$	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24

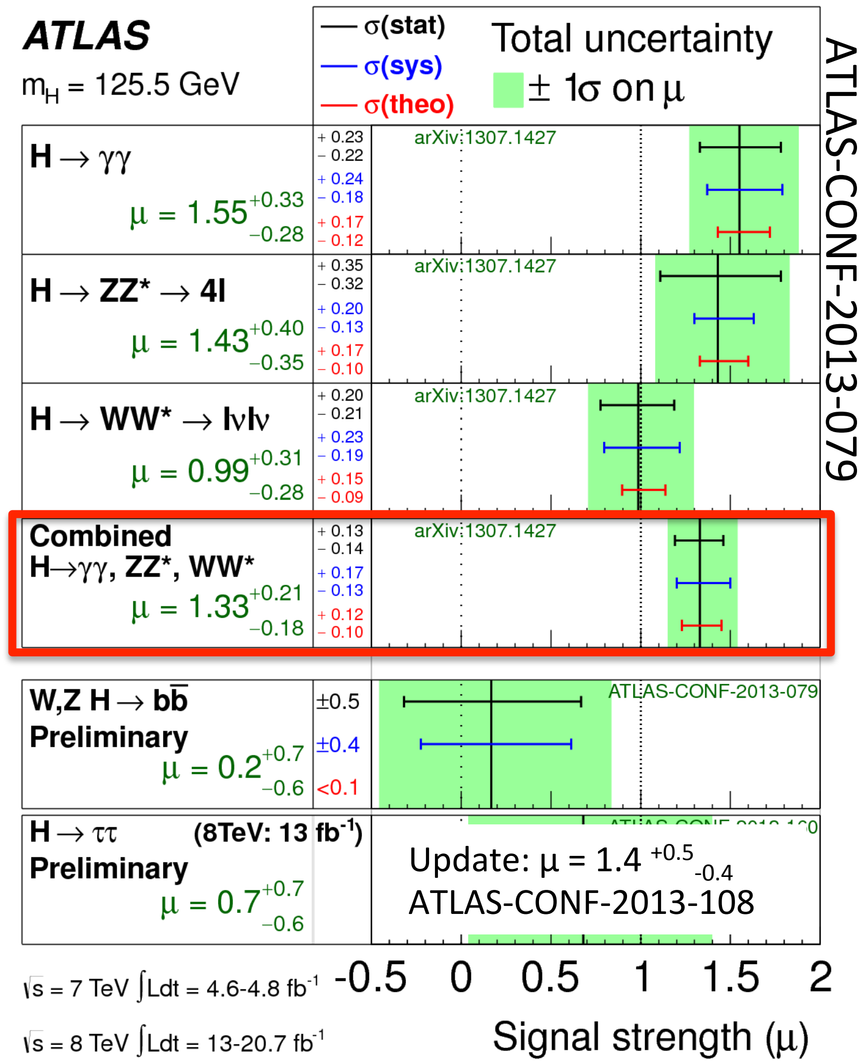


CMS 1401.6527

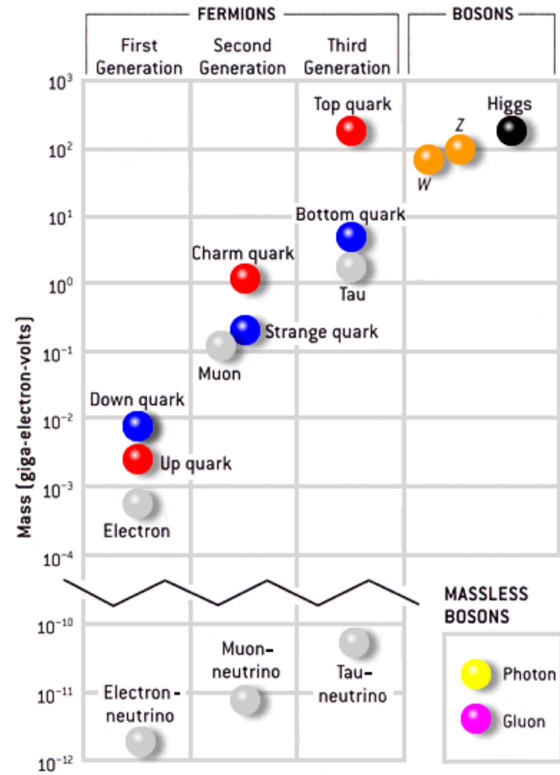
Signal Strength

- Signal strength: **$\mu = \sigma_{obs.}/\sigma_{SM}$**
- ATLAS: global excess in H->γγ and H->ZZ
  μ = 1.33 ±0.14(stat) ±0.15(sys)
  - Largest deviation in H->γγ (1.9σ)
  - When H->bb and (old) H->ττ added:
    μ = 1.33 ±0.14(stat) ±0.15(sys)
- CMS: under-fluctuation in H->WW/γγ



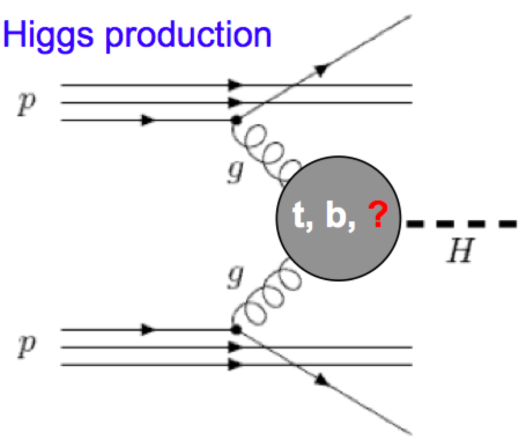


A favourite of mine: ttH

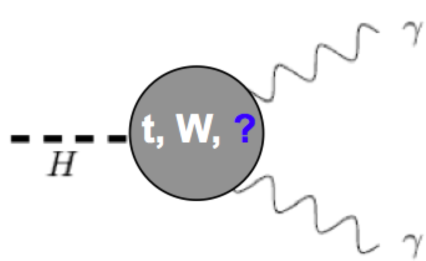


- Indirect constraints on top-Higgs Yukawa coupling from loops in ggH and ttH vertices
  - Assumes no new particles contribute to loops
- Top-Higgs Yukawa coupling can be measured directly
  - Allows probing for New Physics contributions in the ggH and γγH vertices
- Top Yukawa coupling $Y_t = \sqrt{2}M_t/vev = 0.996\pm0.005$
  - Does this mean top plays a special role in EWSB?

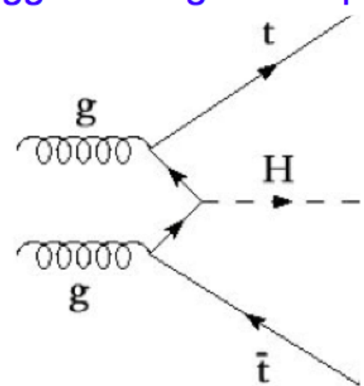
Higgs production



Higgs decay to photons



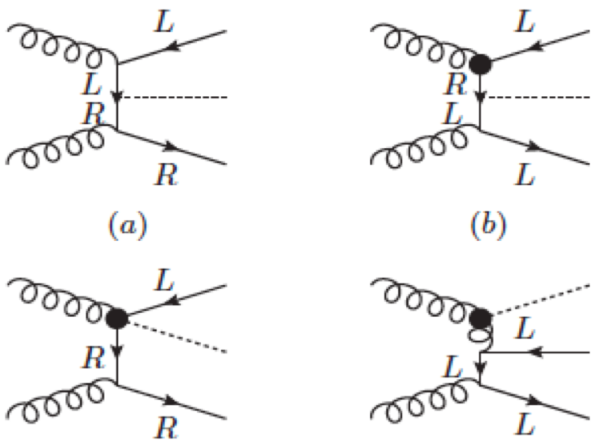
Higgsstrahlung from top quark



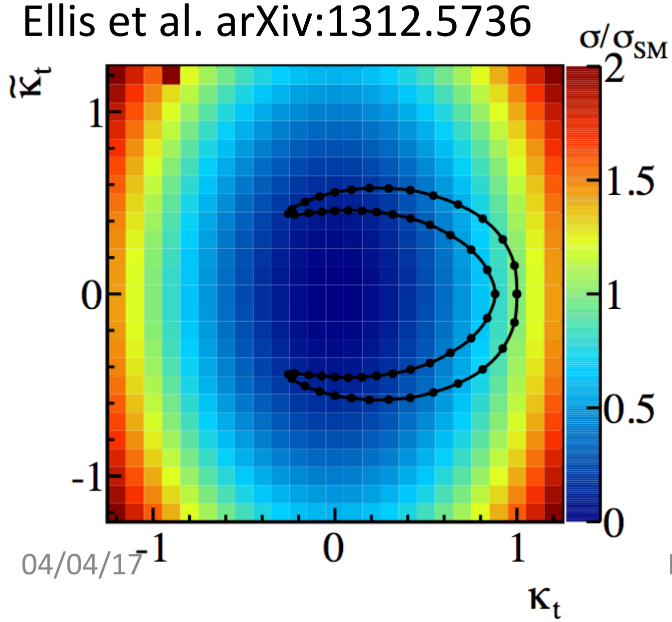
$$\sigma(t\bar{t}H) \propto g_{ttH}^2$$

Sensitivity to New Physics

Degrande et al. arXiv:1205.1065



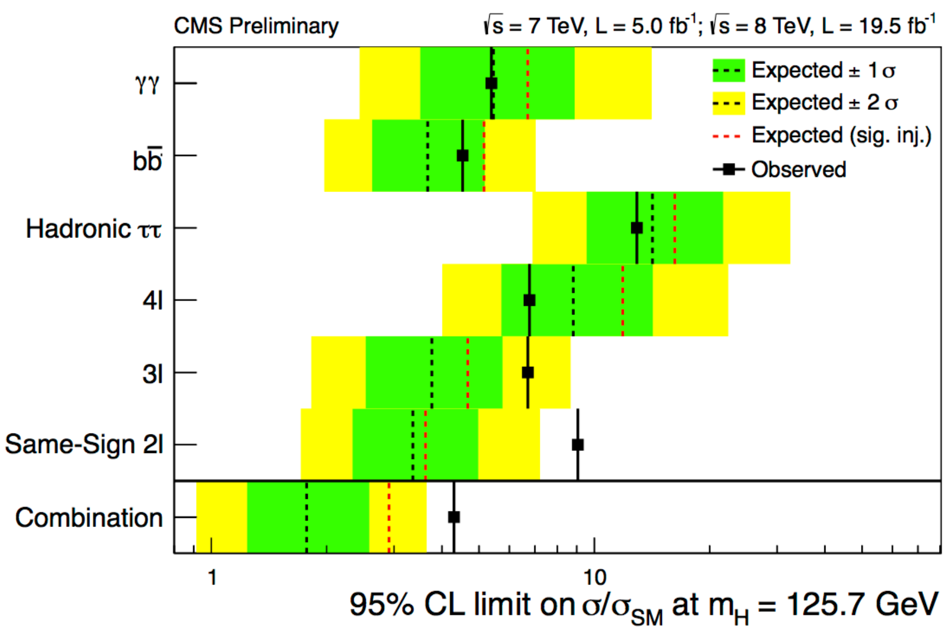
Ellis et al. arXiv:1312.5736

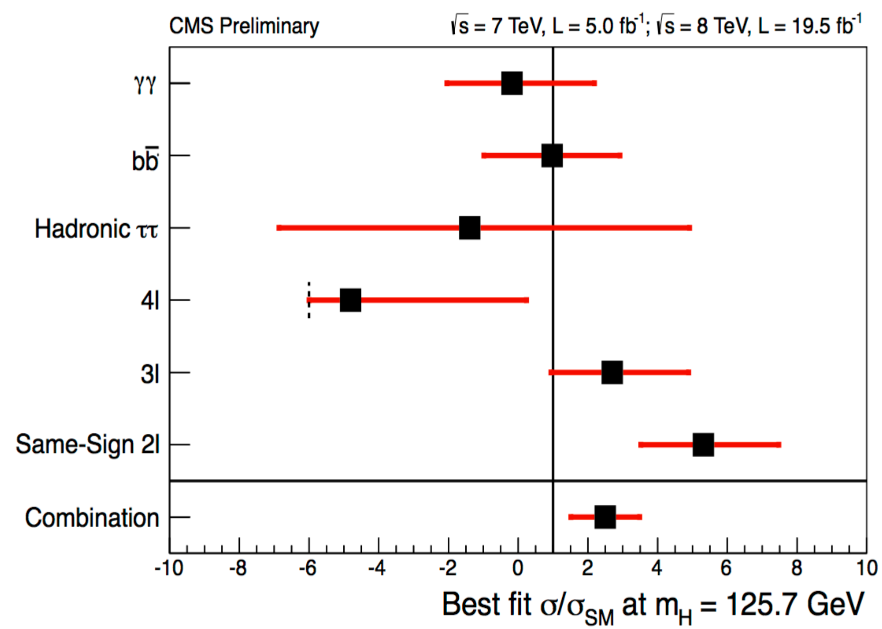


- Effective top-Higgs Yukawa coupling may deviate from SM due to new higher-dimension operators
  - Change **event kinematics –** go differential!
- ttH sensitive new physics: little Higgs, composite Higgs, Extra Dimensions,…
- In the presence of CP violation, Higgs-top coupling have scalar (κ_t)and pseudoscalar ($\tilde{\kappa}_t$)components
  - Strong dependence on ttH cross section
  - Note: Indirect constraints from electron electric dipole moment not taken into account (give $|\tilde{\kappa}_t| < 0.01$)

Status: latest ttH results from CMS

- Combination of H -> bb, H -> ττ, H -> γγ and multilepton (H->WW/ZZ)
  - HIG-12-035, HIG-13-015, HIG-13-019, CMS public page
- No statistically significant excess over background predictions
  - Need LHC run II data!

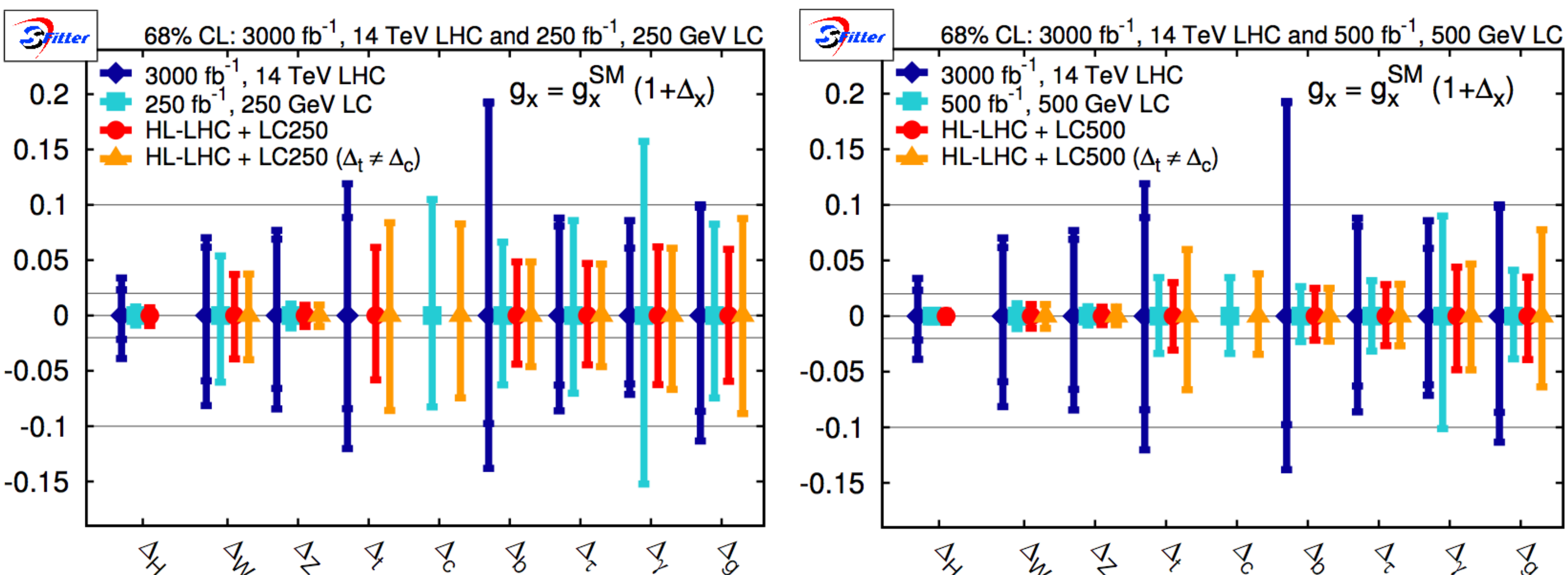




The Far Future

High-Luminosity LHC plus Linear Collider are "**dream team**" for Higgs properties!

- LHC ($\sqrt{s}$=14TeV and L=3000fb^{-1}) **systematics limited**
- Total width only at Linear Collider ($\sqrt{s}$=250GeV, L=250fb^{-1}: ≈10% accuracy)
- 2nd generation couplings (Δ_c, Δ_μ) challenging at LHC but possible at LC
- Δ_{top} opens up for LC500 ($\sqrt{s}$=500GeV, L=500fb^{-1}): ≈3-7% from HL-LHC + LC500
- Precision of **HL-LHC + LC** limited by LC statistical uncertainty, not systematics!



Klute et al, arXiv: 1301.1322

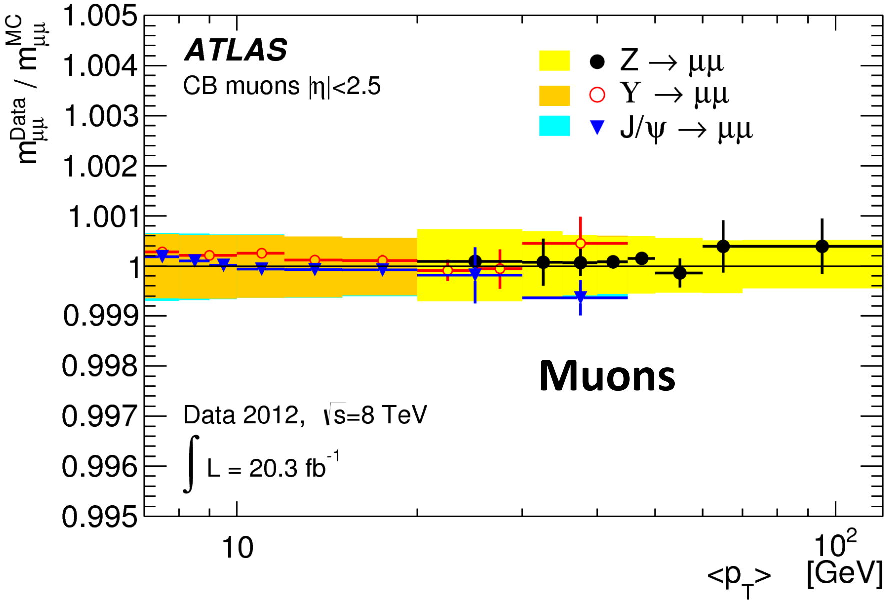
Conclusions & Outlook

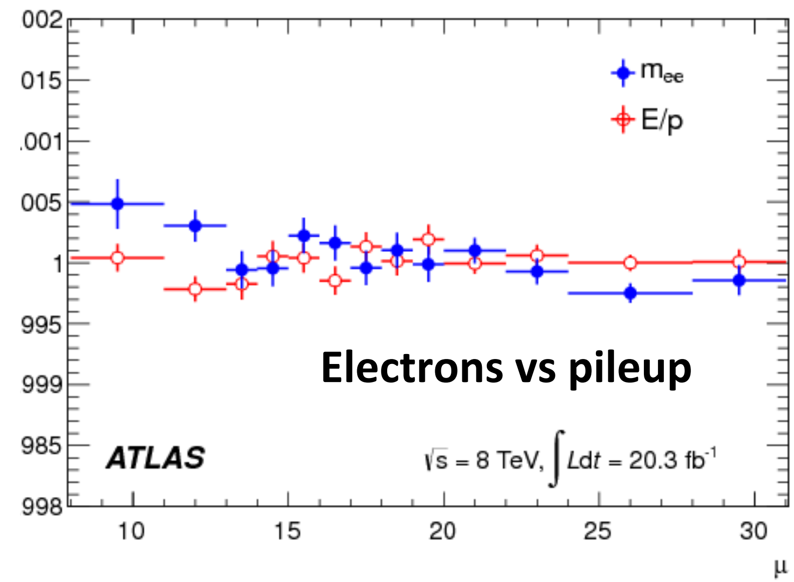
- **Milestone discovery (finally!) opened field of Higgs properties**
  - Measurement precision increasing but still limited
  - So far it looks like it says in the SM book… but we like surprises!
  - New results from challenging fermion channels
  - Will benefit enormously from future LHC data!

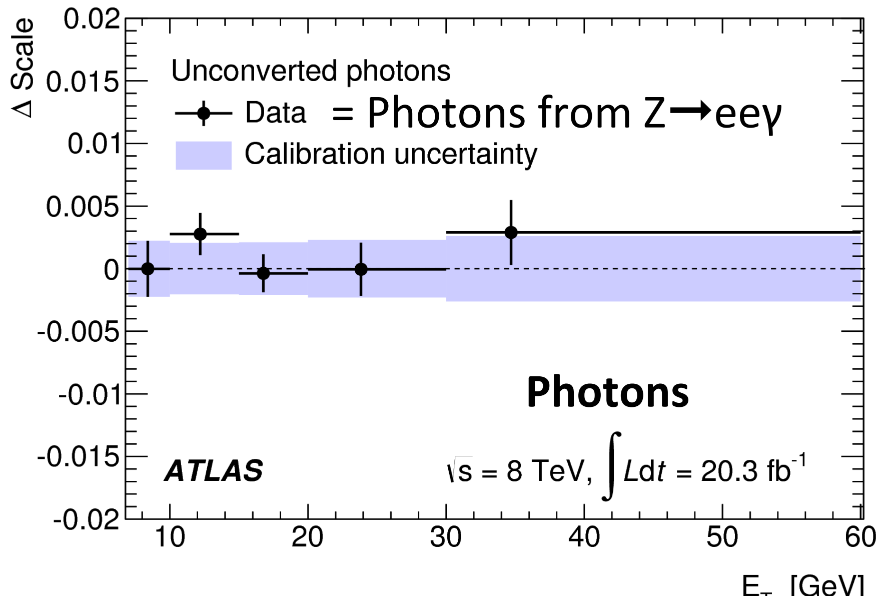
- **New Physics is out there!**
  - Aim for precision analyses: can constrain a lot of model space
  - Look at more difficult SM channels: ttH, VH->Vbb, H->ττ, H->μμ
  - Keep looking for Beyond SM Higgs signals
  - Will benefit enormously from future LHC data! (did I mention this?)

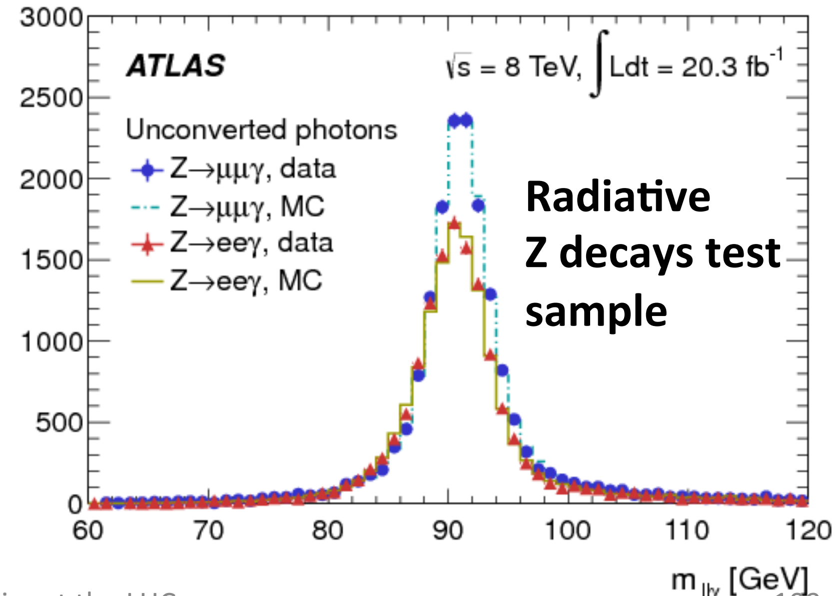
- **Don't forget longer term**
  - HL-LHC + Linear Collider are our dream team

arXiv:1406.3827, CERN-PH-EP-2014-153

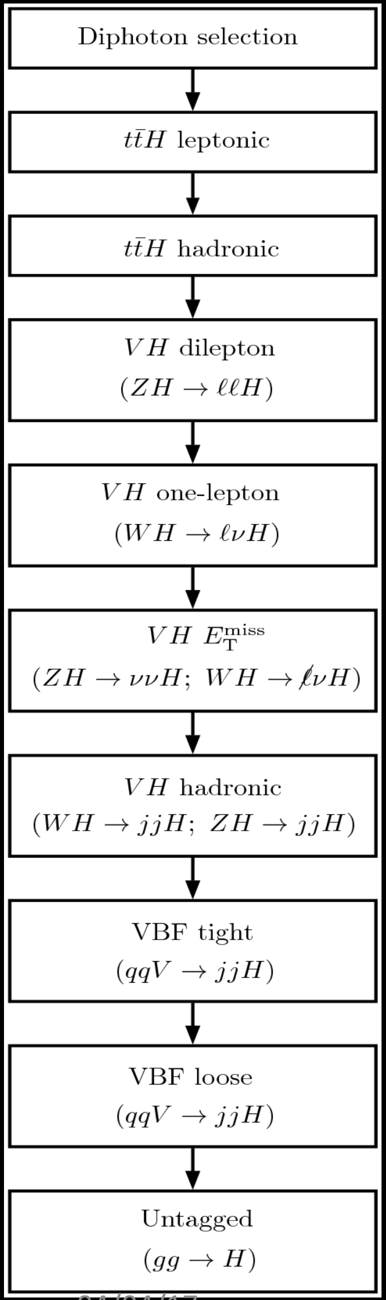








H→γγ Analysis



γγ, $105 < m_{\gamma\gamma} < 160$GeV

1 e/μ and b-jets

No e/μ,
5-6 jets incl. b-jets

2 e/μ, $m_{ee/\mu\mu} \approx m_Z$

1 e/μ, E_t^{miss}

High E_t^{miss}

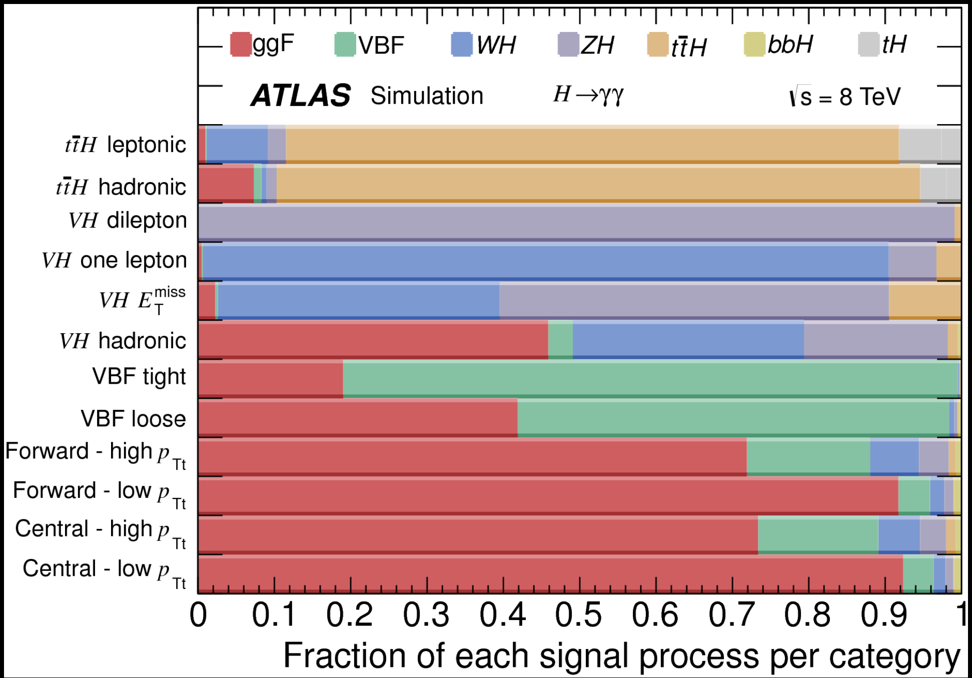
2 jets, $m_{jj} \approx m_{Z/W}$

|Δη(lead jets)|>2, BDT tight

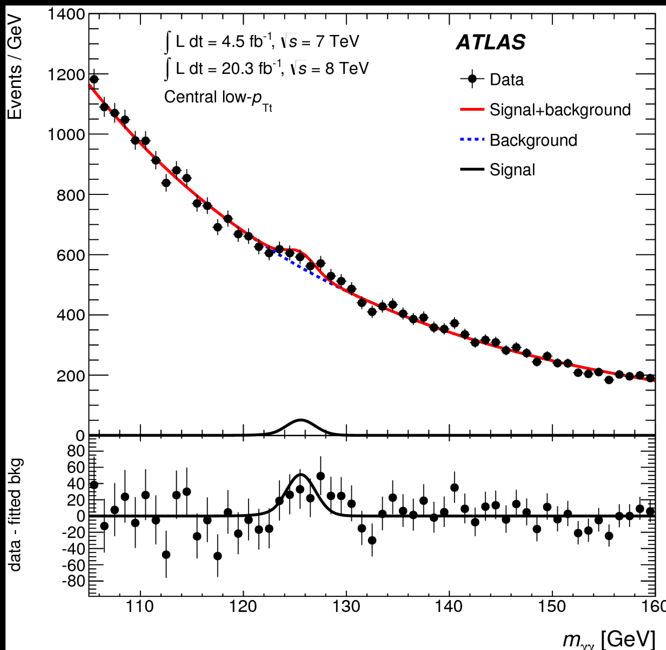
|Δη(lead jets)|>2, BDT loose

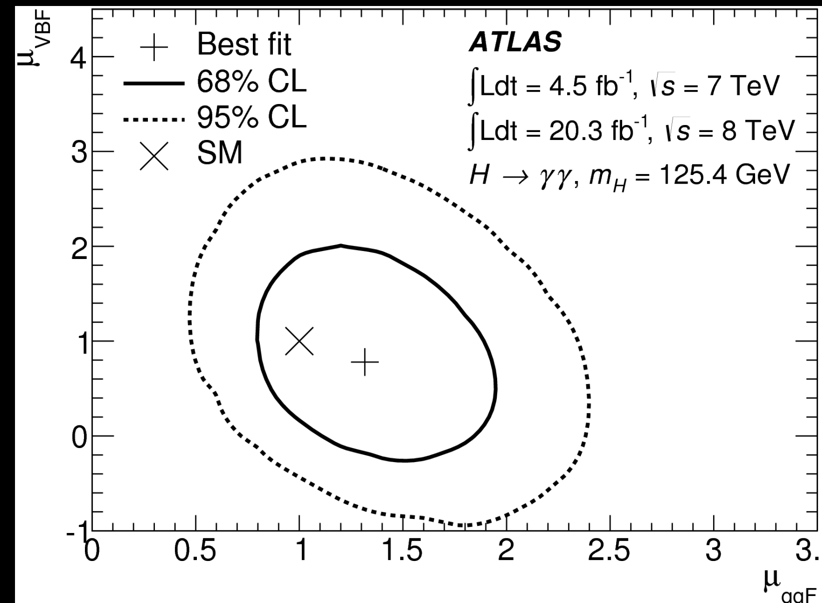
Untagged: 4 categories
Dominated by ggF

- Analysis categories optimized for measuring signal strength
- m_H set to 125.4 GeV, as determined in arXiv:1406.3827
- 20% reduction in total uncertainty with respect to an inclusive analysis



H→γγ Analysis (cont.)





$$\mu_{ggF} = 1.32 \pm 0.32\ (\text{stat.})\ ^{+0.13}_{-0.09}\ (\text{syst.})\ ^{+0.19}_{-0.11}\ (\text{theory}) = 1.32 \pm 0.38,$$

$$\mu_{VBF} = 0.8 \pm 0.7\ (\text{stat.})\ ^{+0.2}_{-0.1}\ (\text{syst.})\ ^{+0.2}_{-0.3}\ (\text{theory}) = 0.8 \pm 0.7,$$

$$\mu_{WH} = 1.0 \pm 1.5\ (\text{stat.})\ ^{+0.3}_{-0.2}\ (\text{syst.})\ ^{+0.2}_{-0.1}\ (\text{theory}) = 1.0 \pm 1.6,$$

$$\mu_{ZH} = 0.1\ ^{+3.6}_{-0.1}\ (\text{stat.})\ ^{+0.7}_{-0.0}\ (\text{syst.})\ ^{+0.1}_{-0.0}\ (\text{theory}) = 0.1\ ^{+3.7}_{-0.1},$$

$$\mu_{t\bar{t}H} = 1.6\ ^{+2.6}_{-1.8}\ (\text{stat.})\ ^{+0.6}_{-0.4}\ (\text{syst.})\ ^{+0.5}_{-0.2}\ (\text{theory}) = 1.6\ ^{+2.7}_{-1.8}.$$

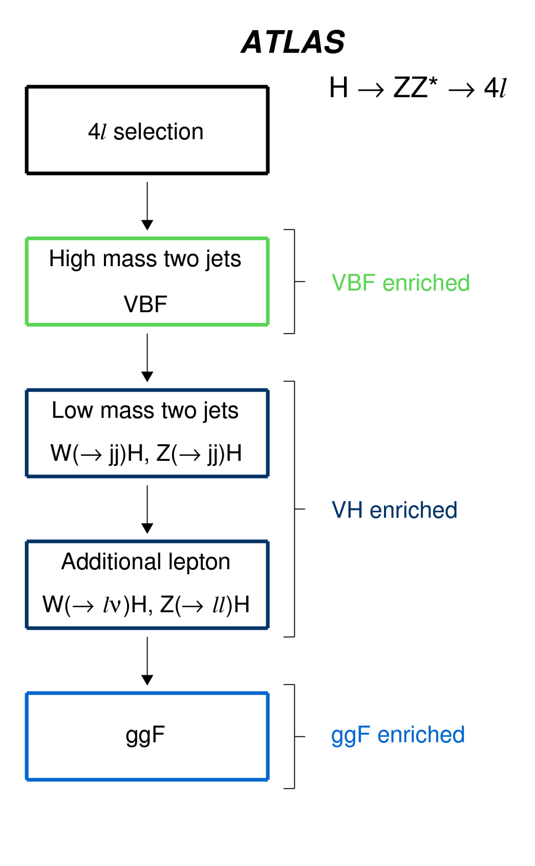
- m_H fixed at 125.4 GeV
- $\mu_{\gamma\gamma} = \sigma/\sigma_{SM} = 1.17 \pm 0.27 =$

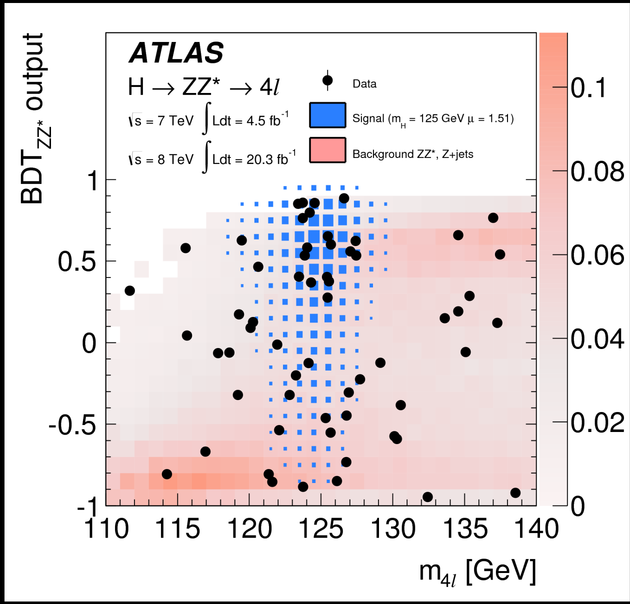
$1.17 \pm 0.23\ (\text{stat})\ ^{+0.10}_{-0.08}\ (\text{syst})\ ^{+0.12}_{-0.08}\ (\text{theory})$

- Increased statistical uncertainty due to:
  - Lower signal rate
  - Fluctuation – expected uncertainty 0.35 GeV

H→ZZ Analysis

- Also benefits from improved:
  - Electron identification and energy measurement
  - Muon momentum scale
- Plus:
  - New VH category
  - Multivariate method to discriminate ZZ* (BDT_{ZZ*})
  - Improved treatment of FSR photons
  - 2D fit to m(4l) and BDT_{ZZ*}



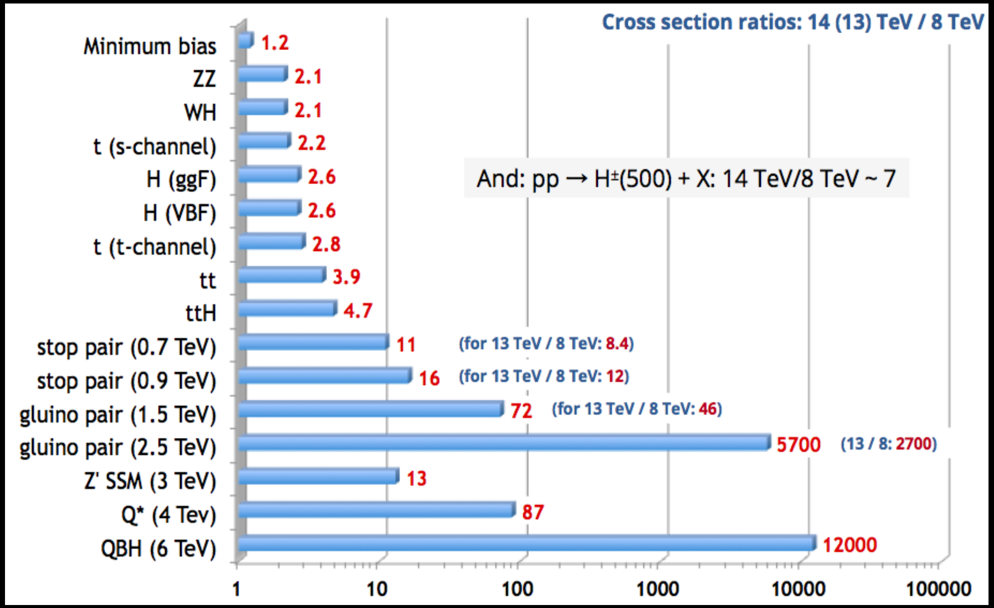


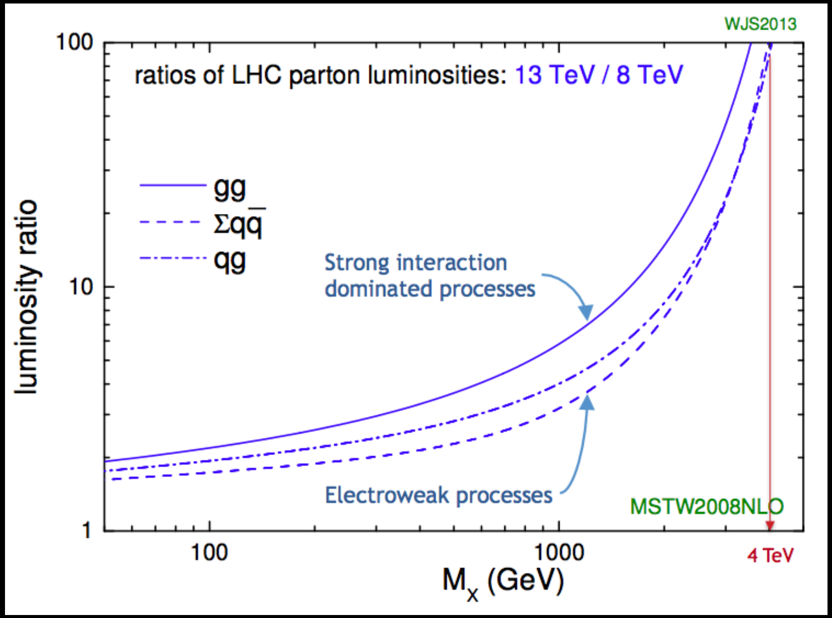
- Signal strength: $\mu = \sigma/\sigma_{SM}$
- Inclusive:
  - $\mu_{ZZ} = 1.44\ ^{+0.34}_{-0.21}$ (stat) $^{+0.21}_{-0.11}$ (syst)
- ggF and VBF categories:
  - $\mu_{ggF} = 1.66\ ^{+0.45}_{-0.41}$ (stat) $^{+0.26}_{-0.16}$ (syst)
  - $\mu_{VBF} = 0.26\ ^{+1.60}_{-0.91}$ (stat) $^{+0.38}_{-0.23}$ (syst)

Run II – Not only more luminosity

- Higher centre of mass energy gives access to higher masses
- Hugely improves potential for discovery of heavy particles
- Increases cross sections limited by phase space
  - E.g. ttH increases faster than background (factor 4)
- But may make life harder for light states
  - E.g. only factor 2 increase for WH/ZH, H→bb and more pileup
  - Could be compensated by use of boosted jet techniques (jet substructure)

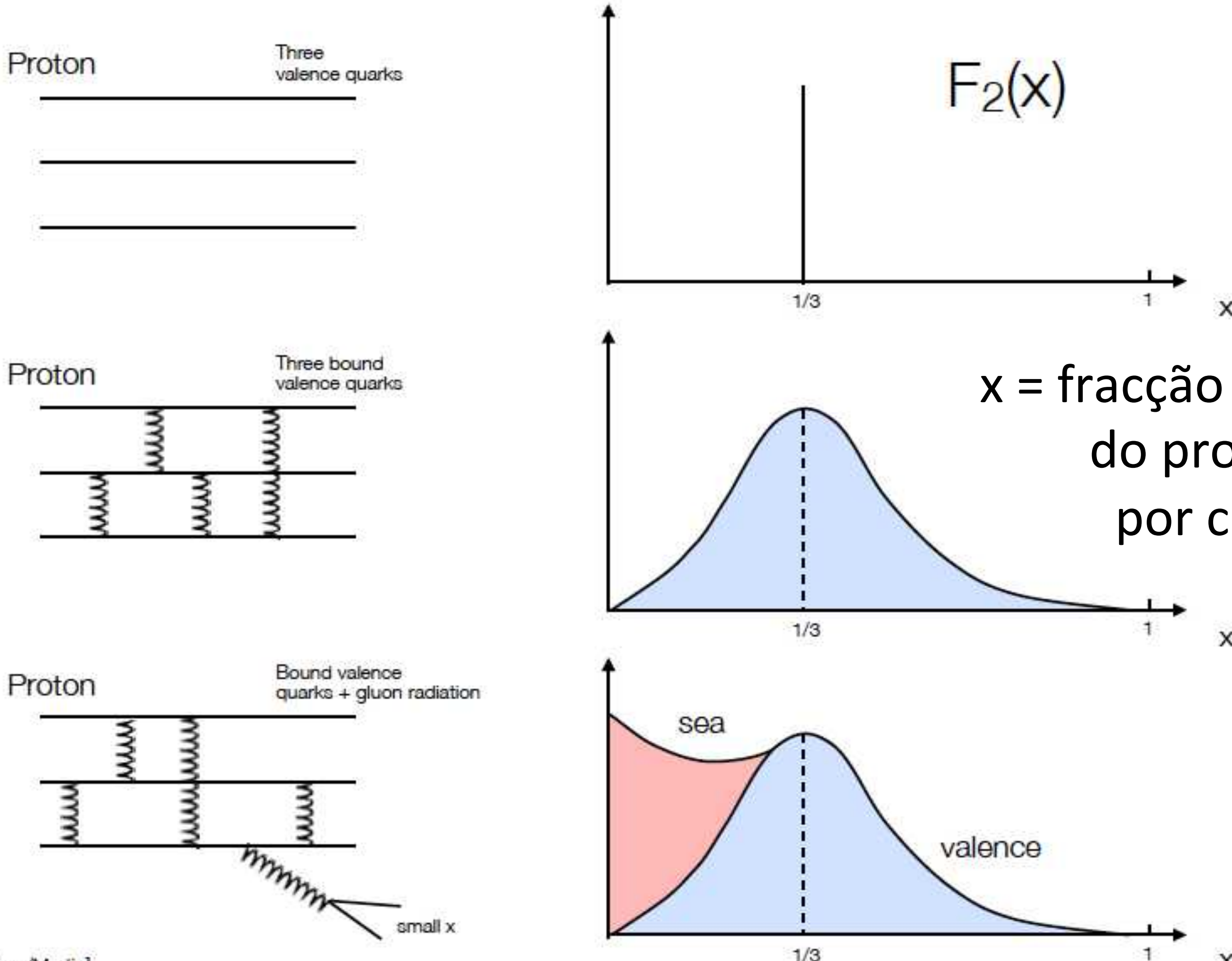
http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html





Como se distribui a energia dentro dos protões

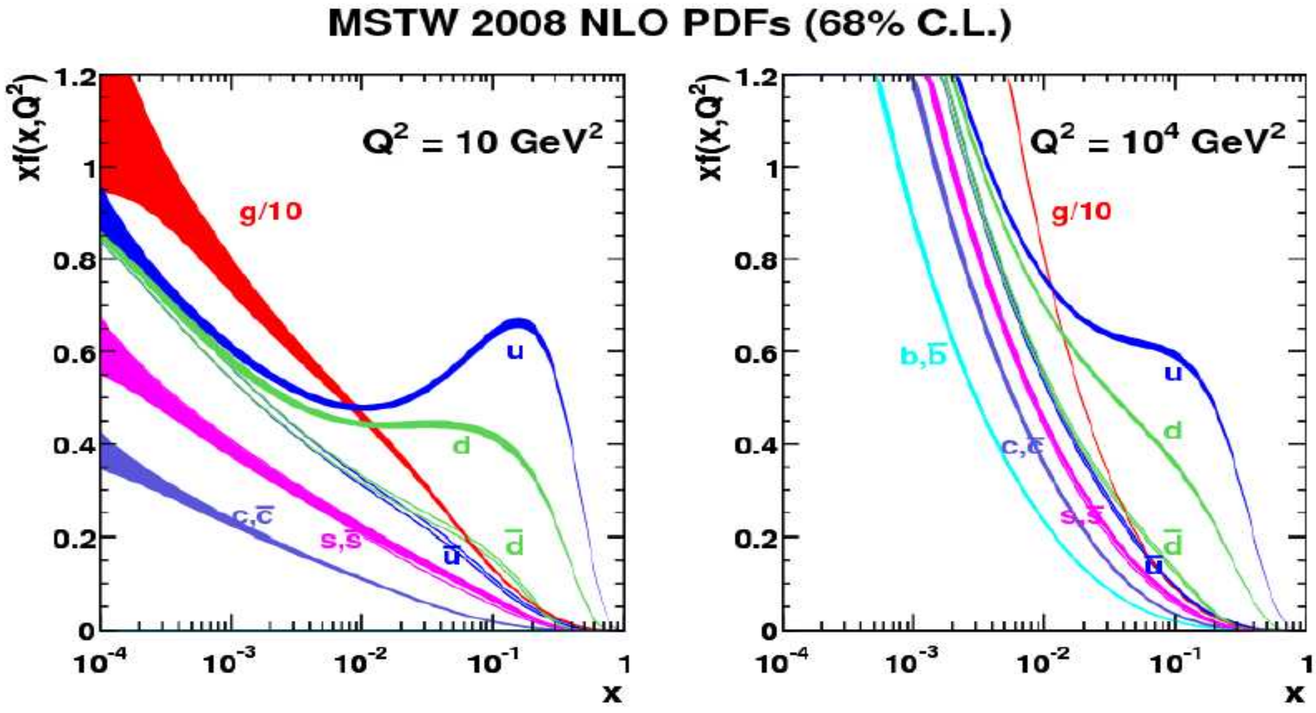
Partões: quarks e gluões constituintes dos hadrões



x = fracção da energia do protão levada por cada partão

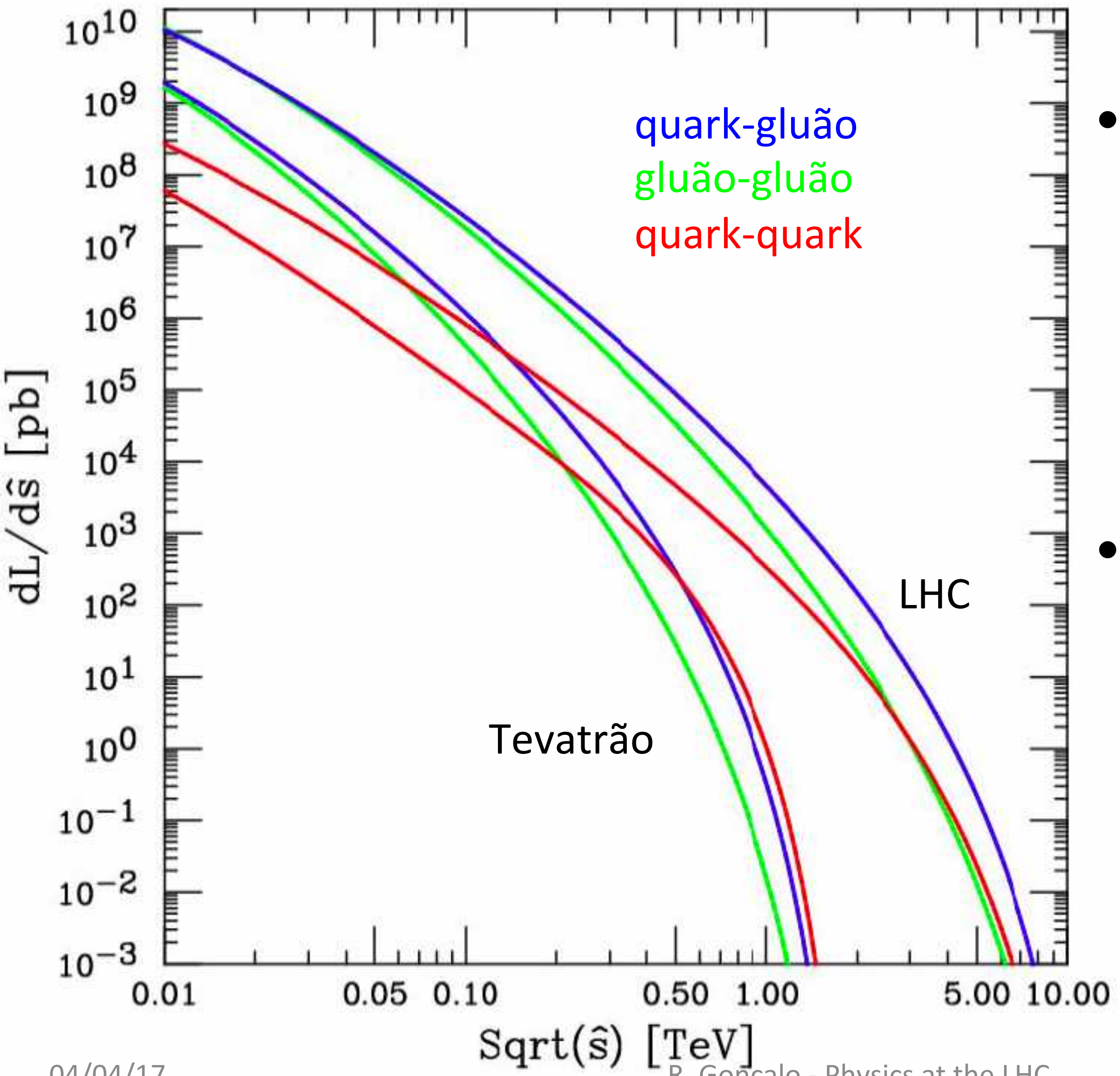
[see e.g. Halzen/Martin]

Em detalhe: funções de distribuição dos partões



A energias maiores, como as do LHC, a contribuição dos gluões e dos quarks de "mar" aumenta – o LHC colide quarks e gluões!

Energia efetiva das colisões

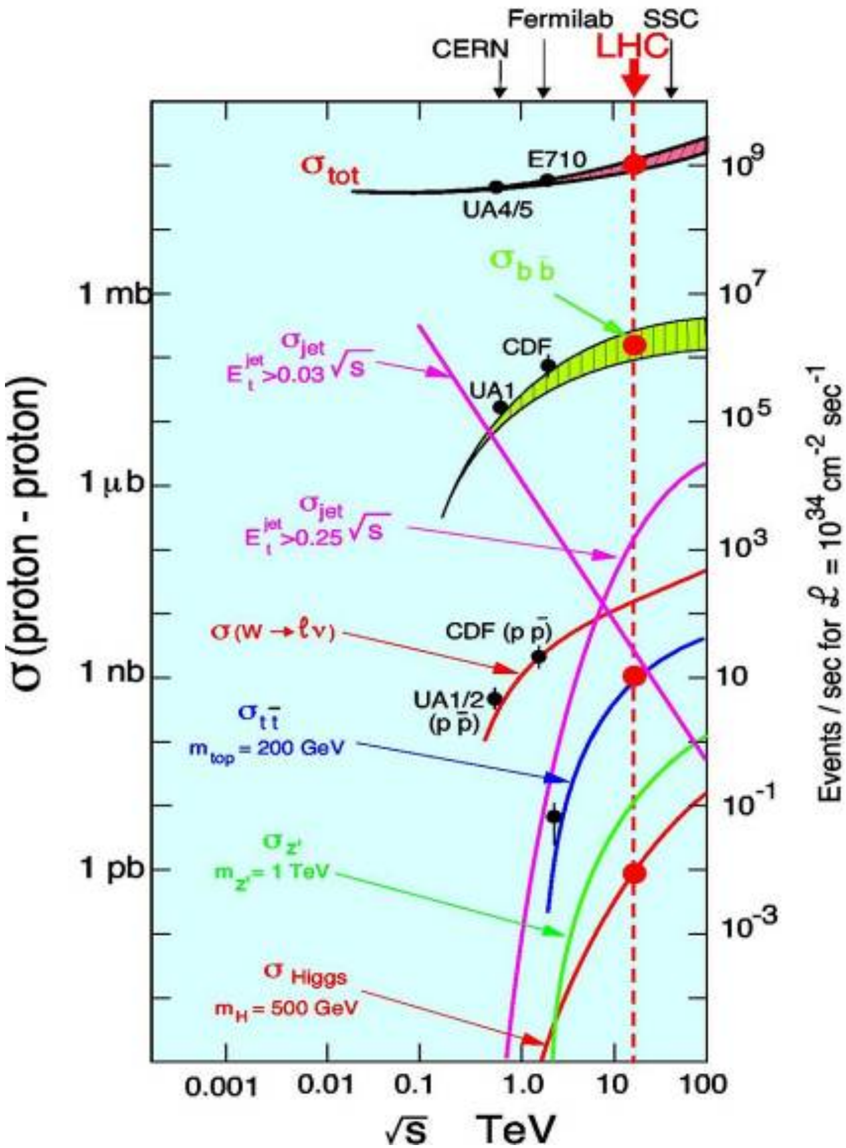


- Energia de colisão no centro de massa dos protões é 14TeV (8TeV em 2012)

- Colisões entre os constituintes elementares (quarks e gluões) são a energias mais baixas

Challenges faced by the ATLAS trigger

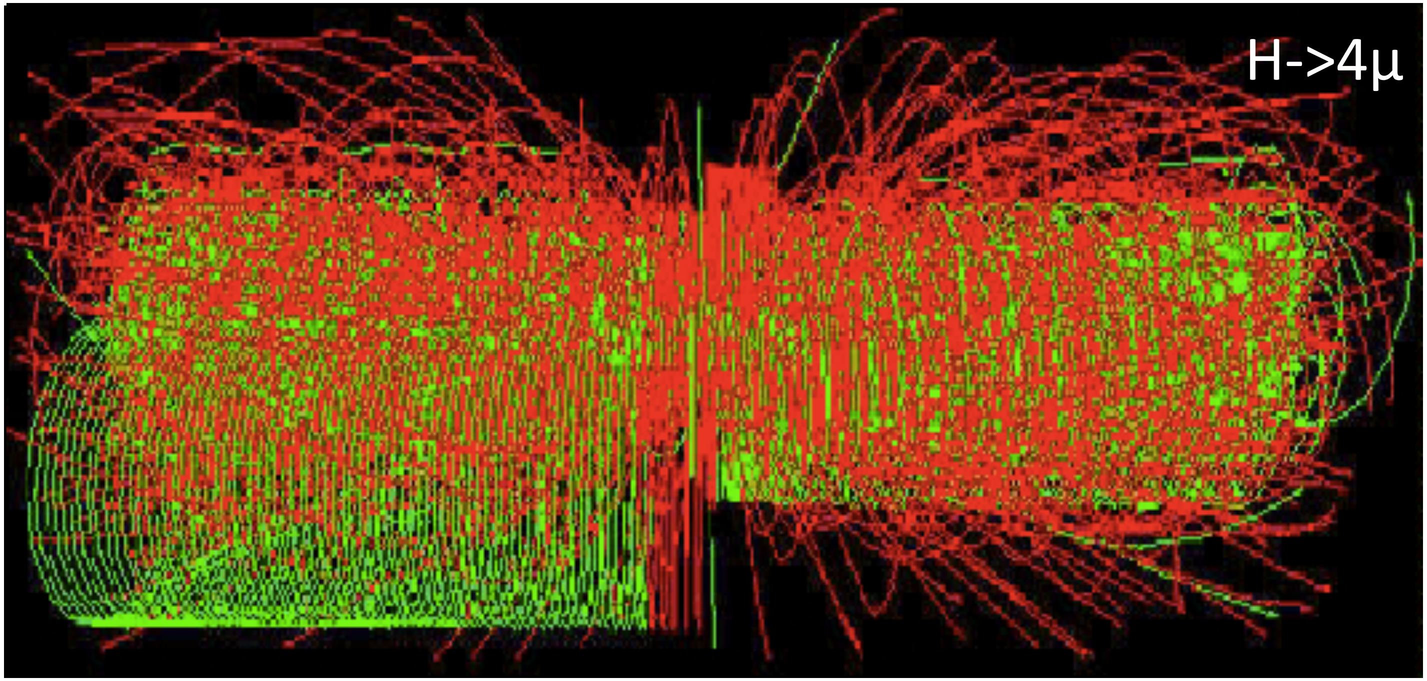
- Much of ATLAS physics means cross sections at least ~10^6 times smaller than total cross section
- 25ns bunch crossing interval (40 MHz)
- Event size 1.5 MB (x 40 MHz = 60 TB/s)
- Offline storing/processing: ~200 Hz
  - ~5 events per million crossings!
- In one second at design luminosity:
  - 40 000 000 bunch crossings
  - ~2000 W events
  - ~500 Z events
  - ~10 top events
  - ~0.1 Higgs events?
  - **200 events written out**
- We'd like the right 200 events to be written out!...



- Ok, so we reject background and take only signal events

Maybe not so simple:

- Bunch spacing is 25ns: not much time to decide! (25ns x c = 7.5m)
- Put event fragments in memory pipeline to buy time for Level 1 decision
- Pileup of minimum-bias events means longer reconstruction time and higher occupancy
- Not only pileup from same bunch crossing! ATLAS sub-detector response varies from a few ns to about 700 ns (= 28 bunch crossings!)
- Try to rely mostly on high-pT particles

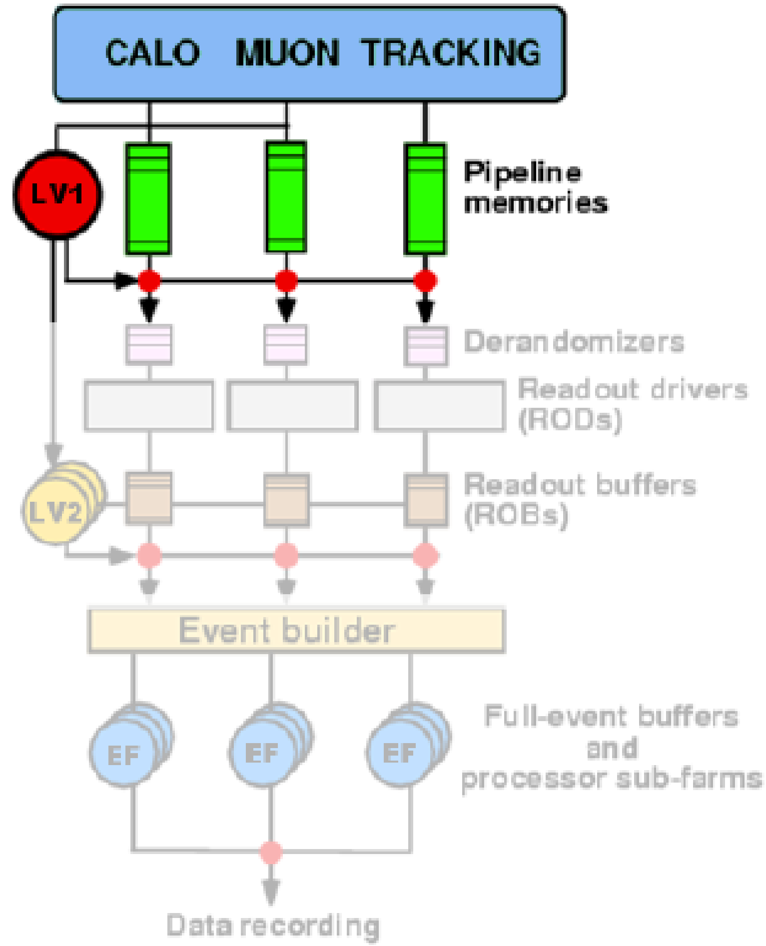


The ATLAS trigger

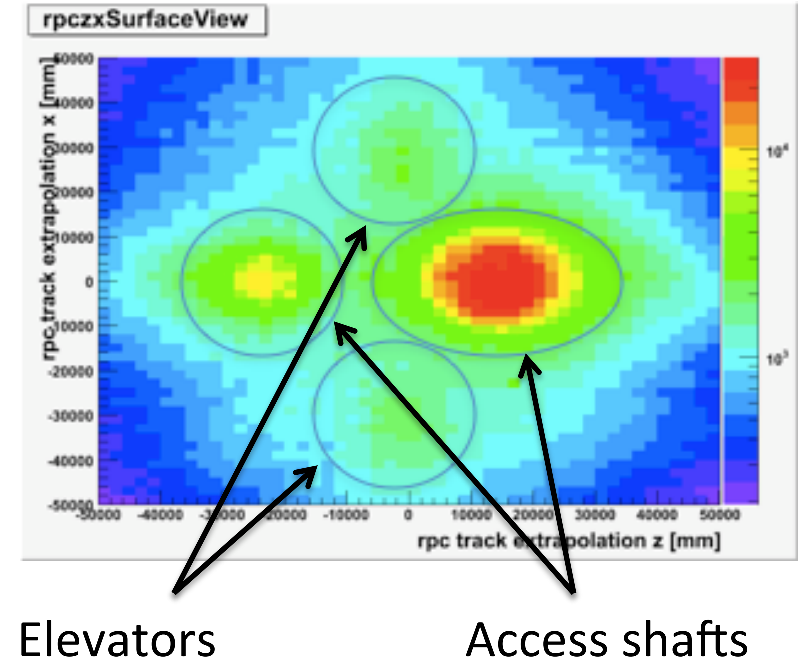
Three trigger levels:

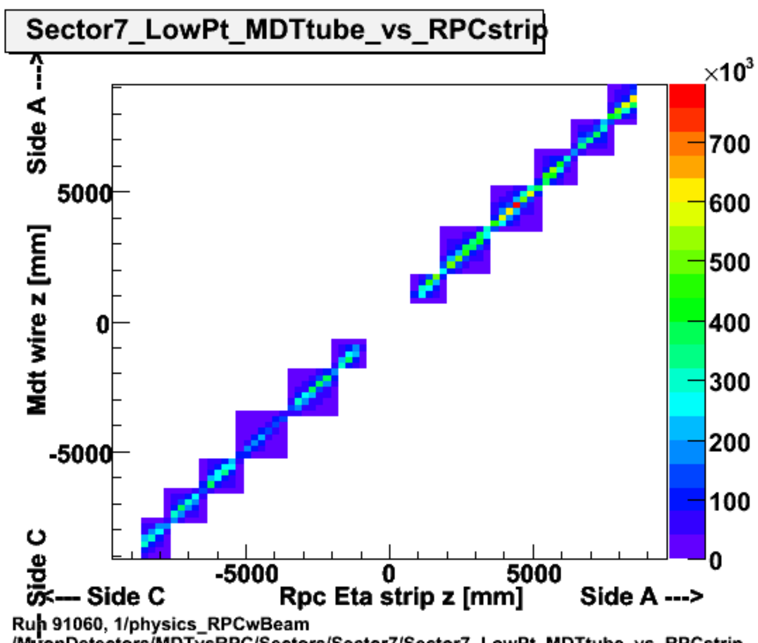
- Level 1:
  - Hardware based (FPGA/ASIC)
  - Coarse granularity detector data
  - Calorimeter and muon spectrometer only
  - Latency 2.5 μs (buffer length)
  - Output rate ~75 kHz (limit ~100 kHz)
- Level 2:
  - Software based
  - Only detector sub-regions processed (Regions of Interest) seeded by level 1
  - Full detector granularity in RoIs
  - Fast tracking and calorimetry
  - Average execution time ~40 ms
  - Output rate ~1 kHz
- Event Filter (EF):
  - Seeded by level 2
  - Full detector granularity
  - Potential full event access
  - Offline algorithms
  - Average execution time ~1 s
  - Output rate ~200 Hz

High-Level Trigger



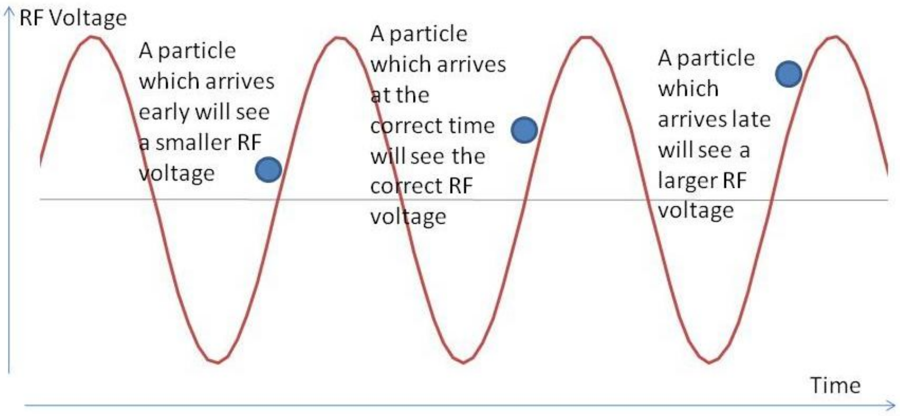
X-ray of the ATLAS cavern with cosmic muons

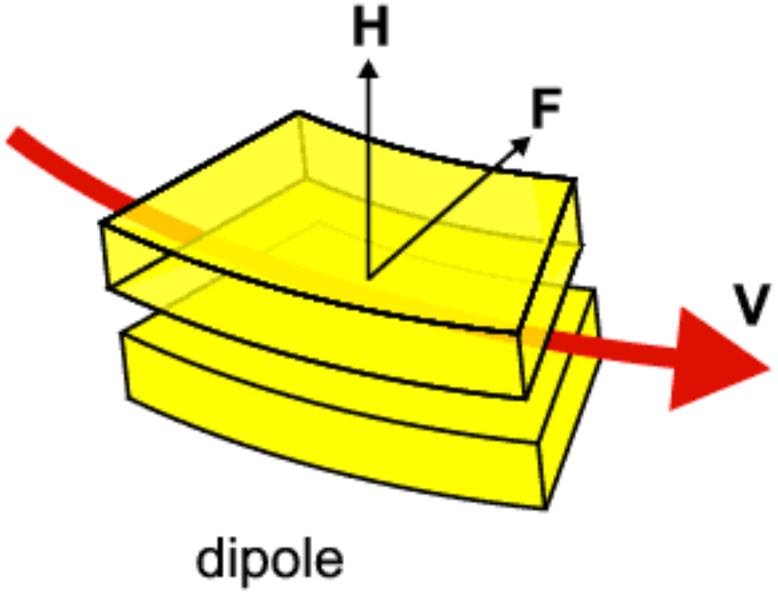


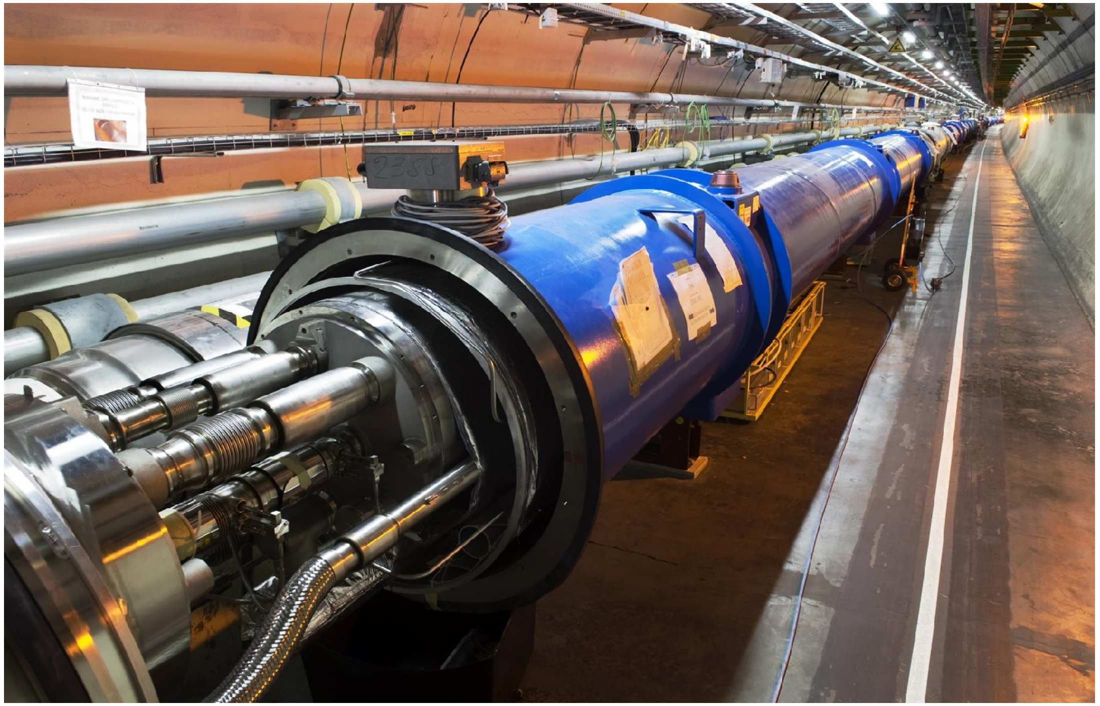


Very good correlation between RPC (trigger chambers) and MDT (precision chambers) hits

Feixes de protões

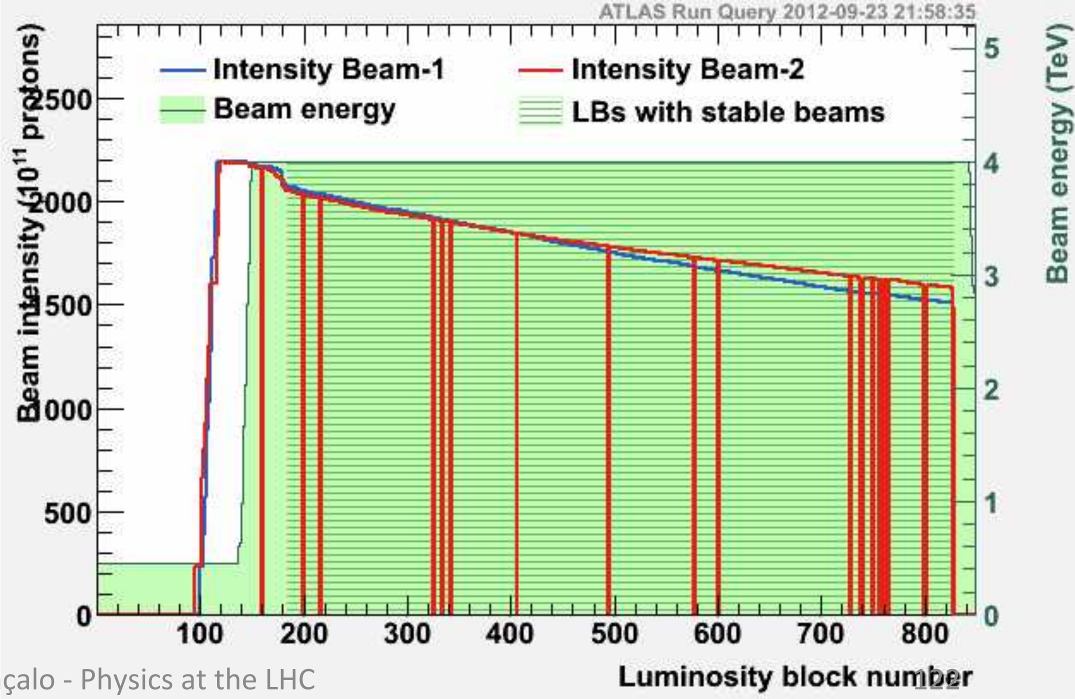




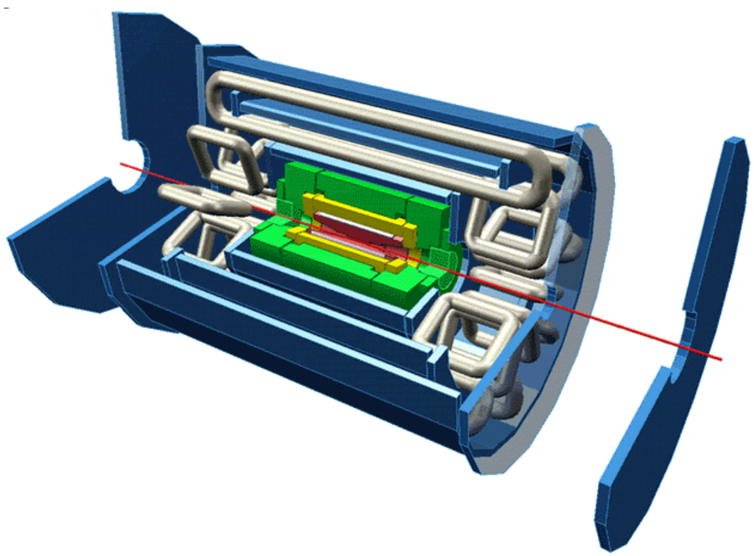


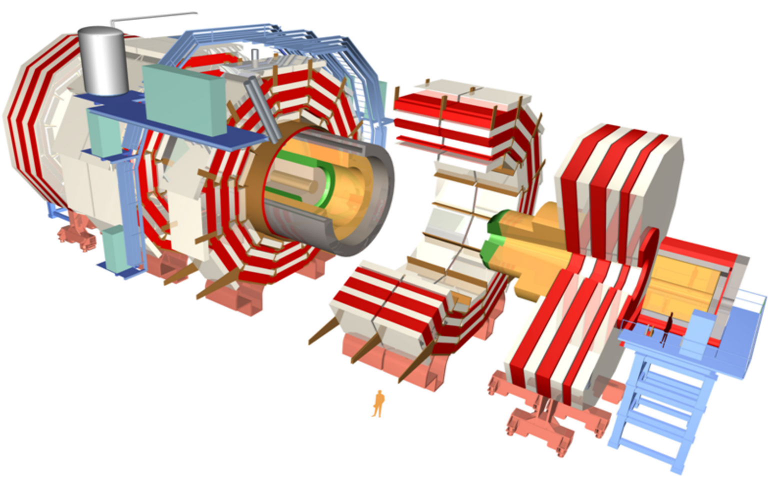
- Energia do feixe:
- 2802 bunches de 1.15×10^{11} protões
- 7TeV / protão (2015) = $7 \times 10^{12} \times 1.602 \times 10^{-19}$ J
- Dá 362 MJ por feixe…
- Igual à energia cinética de um porta-aviões de 20,000t a viajar a 11,7 nós (21.7 km/h)

- Tudo contido num feixe de ≈16μm
- Runs típicos duram cerca de 8 horas
- Intensidade diminui devido a perdas
- Depois voltamos a injectar novos feixes



	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5\text{x}10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\text{x}10^{-4} p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 2\text{-}5\%/\sqrt{E} + 0.005$
Hadronic calorimeter	Fe+scint. / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Cu+scintillator (5.8λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (ID+MS)	$\sigma/p_T \approx 1\%$ @ 50GeV to 5% @ 1TeV (ID+MS)
Trigger	L1 + RoI-based HLT (L2+EF)	L1+HLT (L2 + L3)





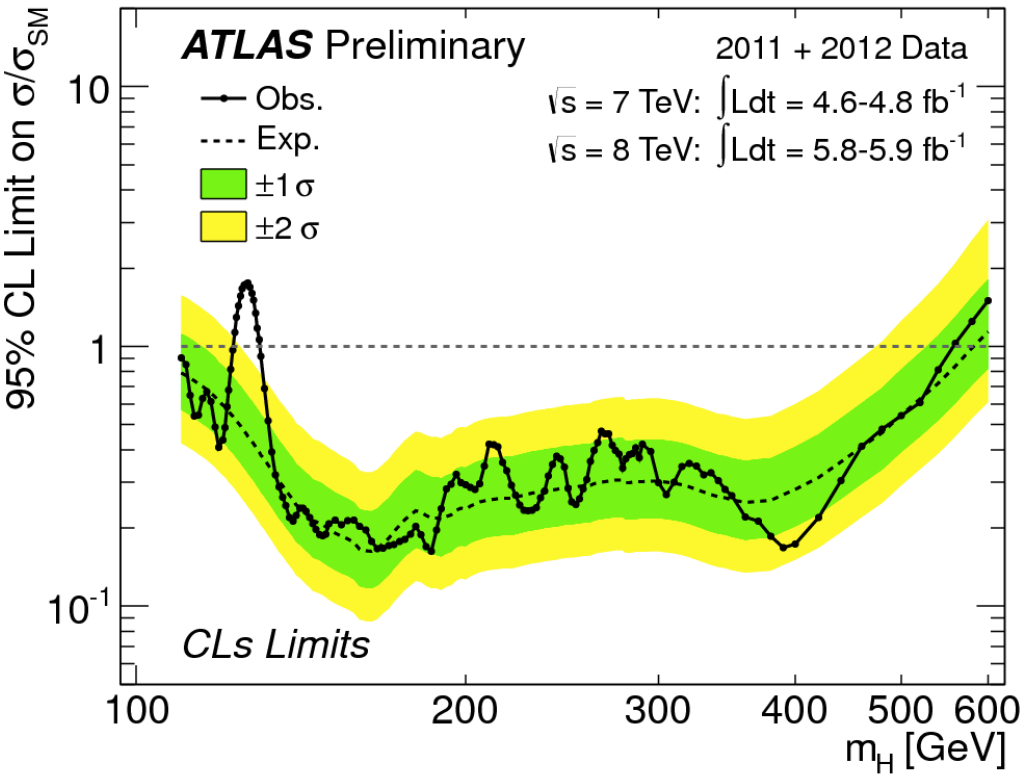
The Brazil Plot

Expected:

- Upper limit on σ(S+B)/σ(B) at 95% CL in Monte Carlo assuming B-only hypothesis

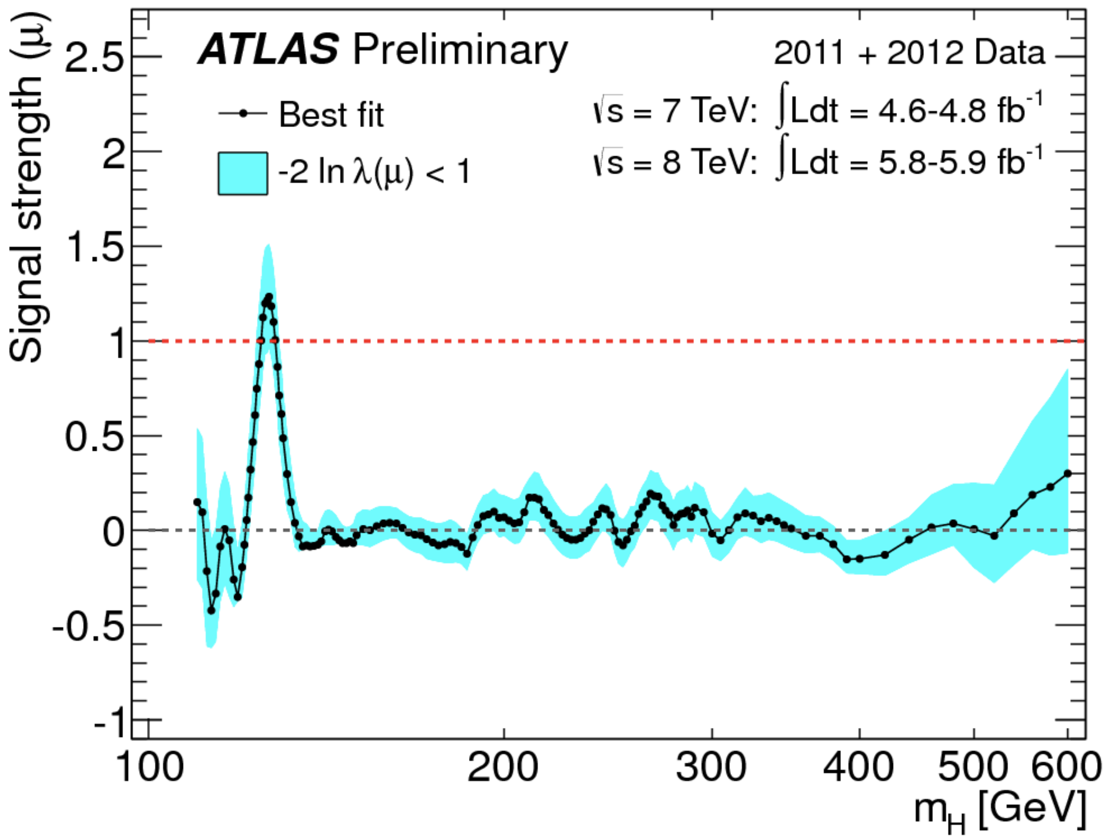
Observed:

- Upper limit on σ(S+B)/σ(B) at 95% CL seen in data assuming B-only hypothesis



The Cyan Band Plot – signal strength

- Best fit of μ=σ(S+B)/σ(B) to data
- Error bands important…. As usual!



Blind Analysis

- To avoid unintended experimenter's bias in search for the Higgs boson
- The analysis strategy, event selection & optimization criteria for each Higgs search channel were **fixed** by looking at data control samples before looking at the signal sensitive region
  - Logistically quite painful
  - But the right thing to do !