



Higgs Physics

IST – 5 December 2022

Topics in Particle Physics, Astrophysics and Cosmology

Ricardo Gonalo – UC/LIP

Outlook



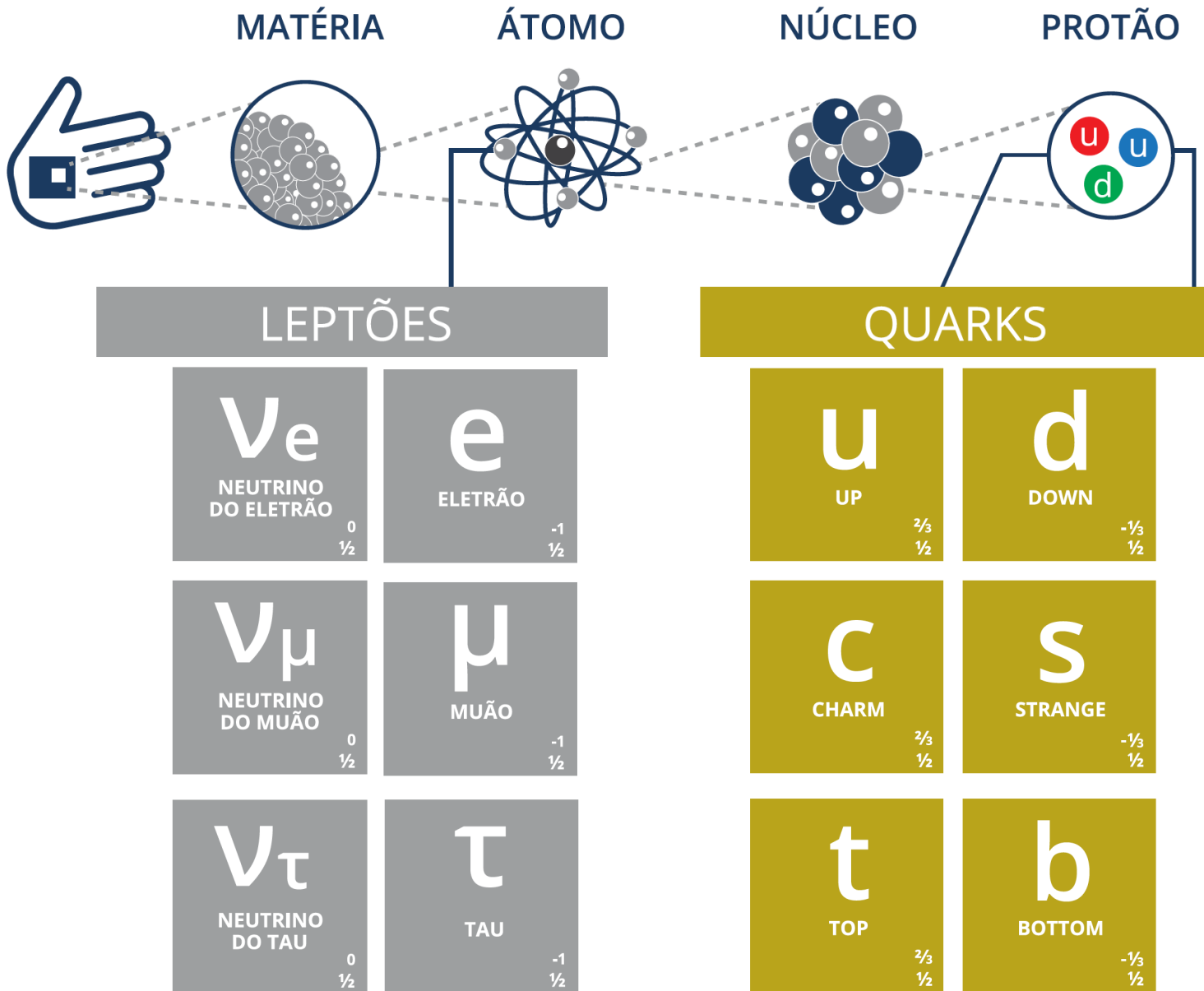
- What is the Higgs boson and what is it good for?
- How did we find it?
- Why do we care?
- And what comes next?

Introduction

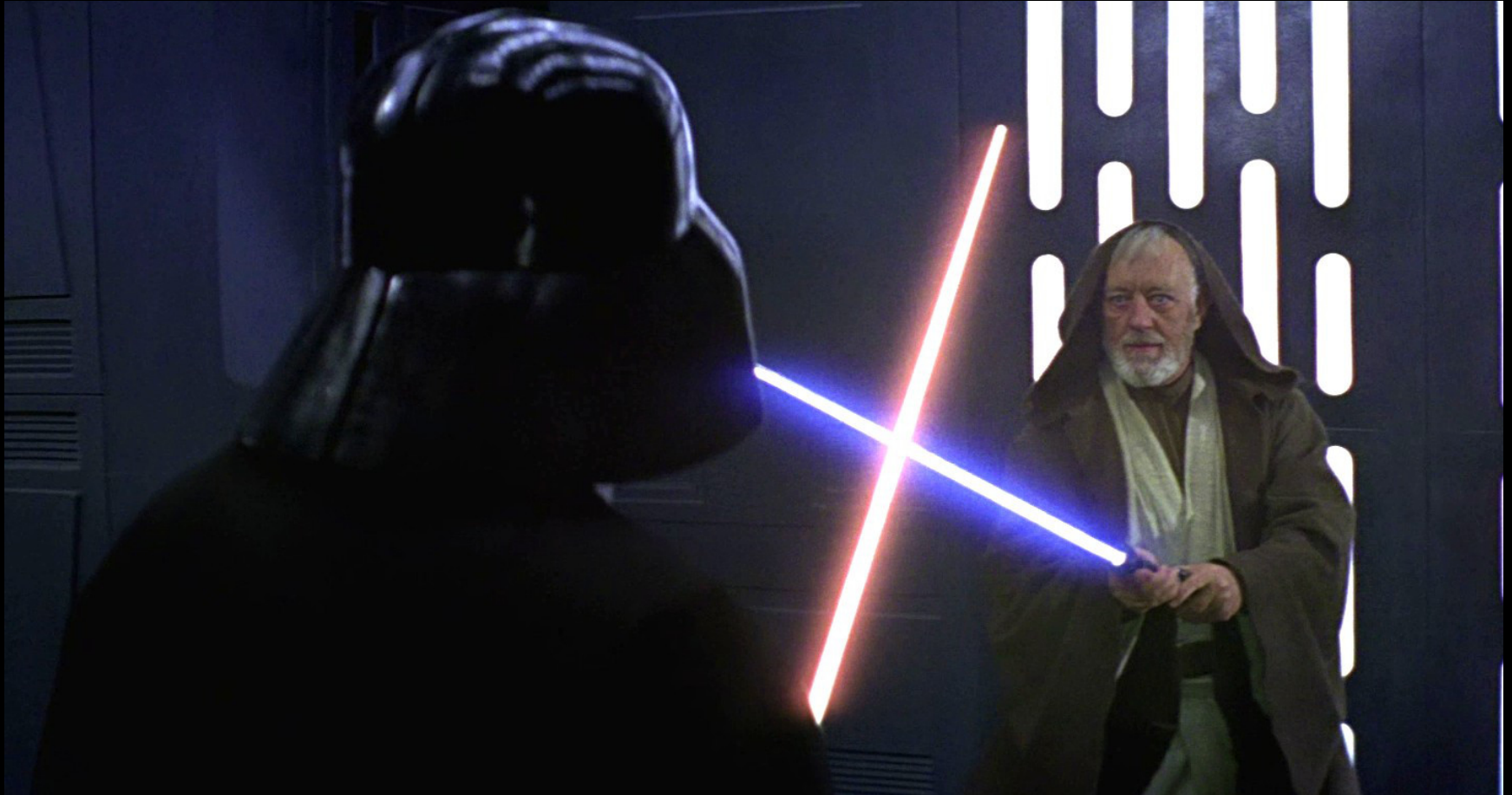
The Standard Model particles and interactions, and some theory to set the scene...

What is everything made of???



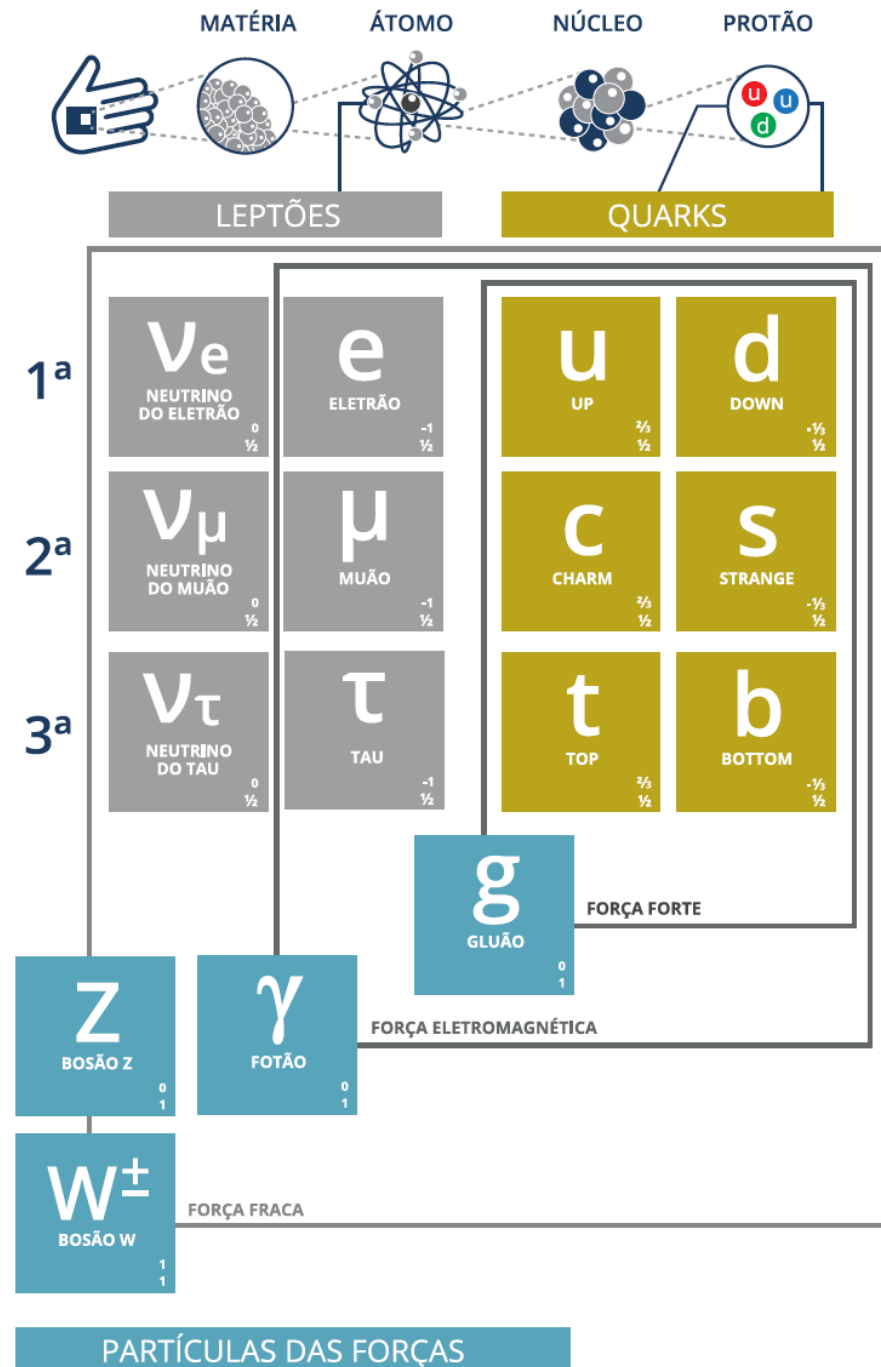


Fundamental Forces



Fundamental forces

- Electromagnetic:
 - Carried by photons
 - Acts on electrical charge
- Weak:
 - Carried by:
 - W^\pm (charged current)
 - Z^0 (neutral current)
 - Acts on weak isospin
- Strong:
 - Carried by 8 gluons
 - Acts on colour



Para cada uma destas partículas, existe uma antipartícula de carga oposta (antimatéria)

PARTÍCULAS DE MATÉRIA

PARTÍCULAS DAS FORÇAS

Lagrangians, symmetries and all that



Leonhard Euler (1707–1783)



Emmy Noether (1882 – 1935)



Joseph-Louis Lagrange (1736–1813)

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 of the coordinates)

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

From minimizing the action S , get the **Euler-Lagrange equations**:

$$S = \int dt L(q_i, \dot{q}_i) \qquad \frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = 0$$

For a point particle in a potential U , with $q_i = x, y, z$

$$L = \frac{1}{2} m \dot{q}_i^2 - U(q_i) \qquad \frac{d}{dt} (m \dot{q}_i) + \frac{\partial U}{\partial q_i} = 0 \qquad m \ddot{q}_i = - \frac{\partial U}{\partial q_i}$$

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 =>
Lagrangian invariant over a transformation of these coordinates

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

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

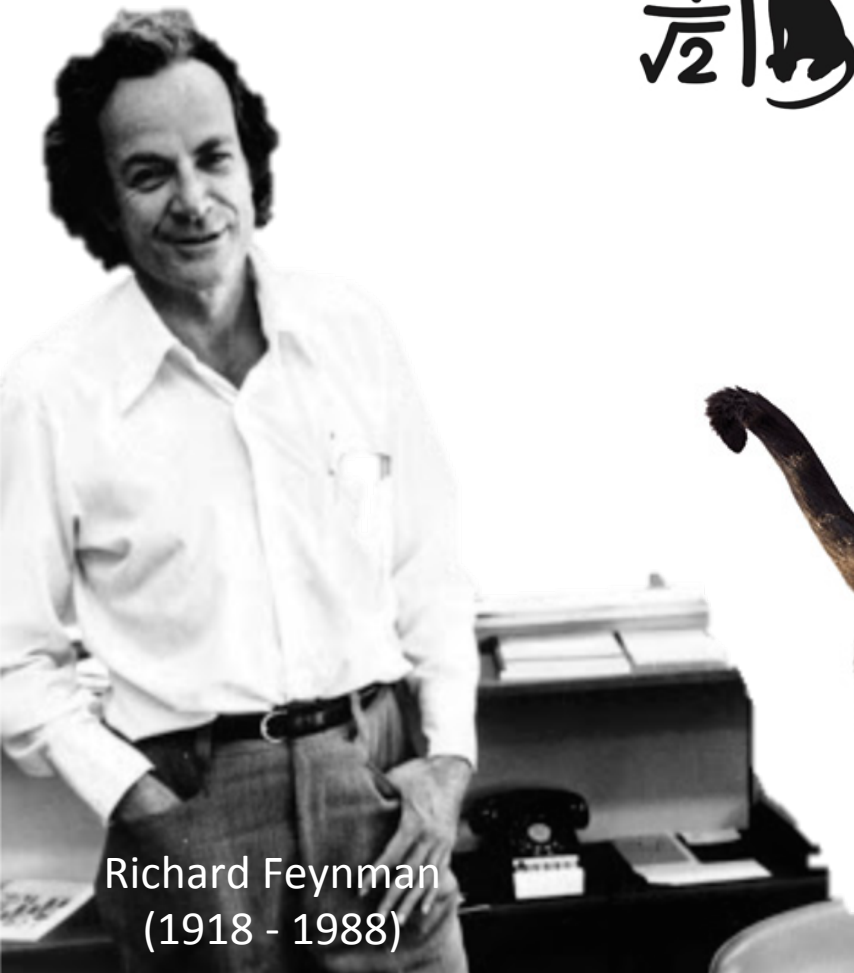
Since the lagrangian doesn't depend explicitly on ϕ (symmetry with respect to rotations in space), the Euler-Lagrange equation gives

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

Where the angular momentum J is a constant of motion!

Let's go to quantum fields...

$$\frac{1}{\sqrt{2}}|\text{cat up}\rangle + \frac{1}{\sqrt{2}}|\text{cat down}\rangle$$



Richard Feynman
(1918 - 1988)



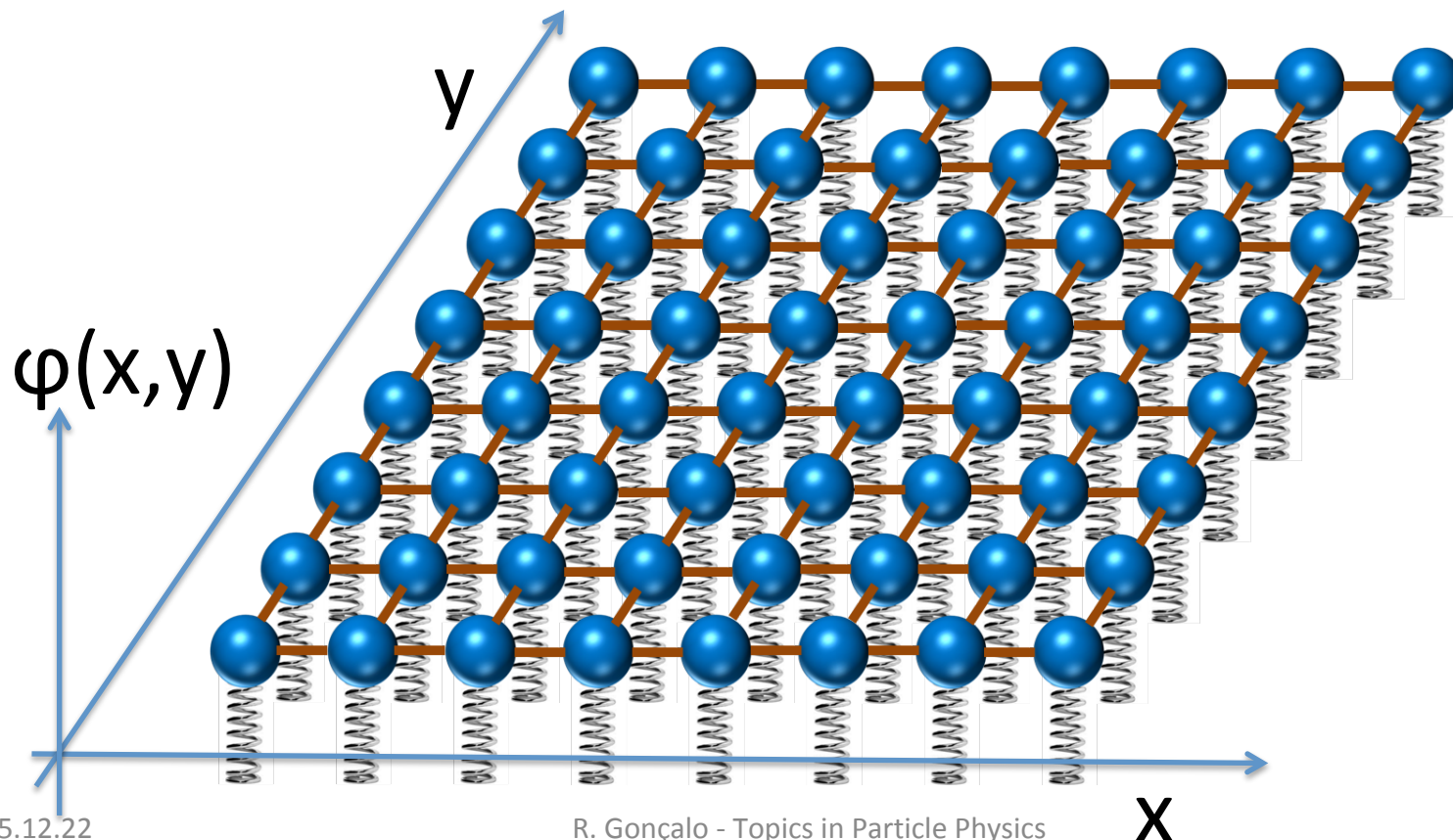
Fluffy (?-?)



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

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

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

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

The new Euler-Lagrange equation now becomes

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

- Example Lagrangians and equations of motion:
- Klein-Gordon Lagrangian for spin 0 particles (scalars):

$$\mathcal{L}_{KG} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}m^2 \phi^2$$

$$\partial_\mu \partial^\mu \phi + m^2 \phi = 0$$

- Dirac Lagrangian for spin ½ particles (fermions):

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

$$i\gamma^\mu \partial_\mu \psi - m\psi = 0$$

- Proca Lagrangian for spin 1 (vector) particles:

$$\mathcal{L}_P = \frac{-1}{16\pi}(\partial^\mu A^\nu - \partial^\nu A^\mu)(\partial_\mu A_\nu - \partial_\nu A_\mu) + \frac{1}{8\pi}m^2 A^\nu A_\nu$$

$$\partial_\mu(\partial^\mu A^\nu - \partial^\nu A^\mu) + m^2 A^\nu = 0$$

- Important:

Mass terms in Lagrangian are quadratic in the fields

Global gauge invariance

Take the Dirac Lagrangian for a spinor field ψ representing a spin- $\frac{1}{2}$ 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:

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

Where χ is a constant

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

Note: gauge invariance of the Dirac equation can be demonstrated to lead to conservation of probability current j^μ

$$j^\mu = (\rho, \mathbf{J}) = \bar{\psi}\gamma^\mu\psi$$

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 \mathbf{A}_μ which transforms as:

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

We get:

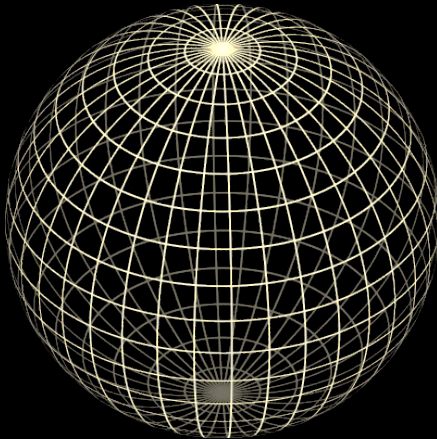
$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi - q\bar{\psi}\gamma^\mu A_\mu\psi$$

Note:

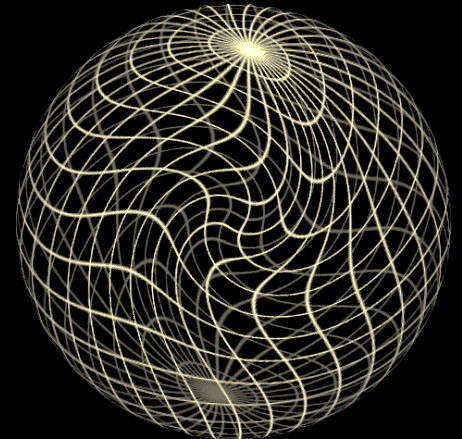
1. The new gauge field A_μ is the photon in QED
2. The mass of the fermion is the coefficient of the term on $\bar{\psi}\psi$
3. There is no term in $A_\mu A^\mu$ (the photon has zero mass)

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

Original sphere



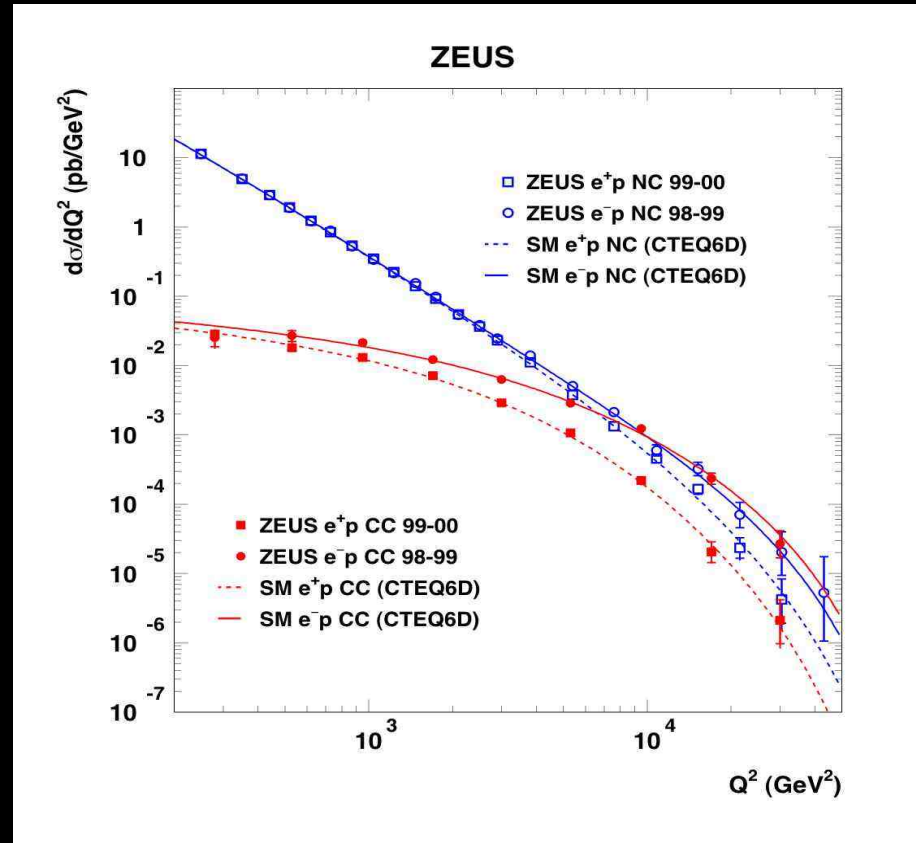
Local transformação



$$\chi = \text{constant}$$

$$\chi = \chi(x)$$

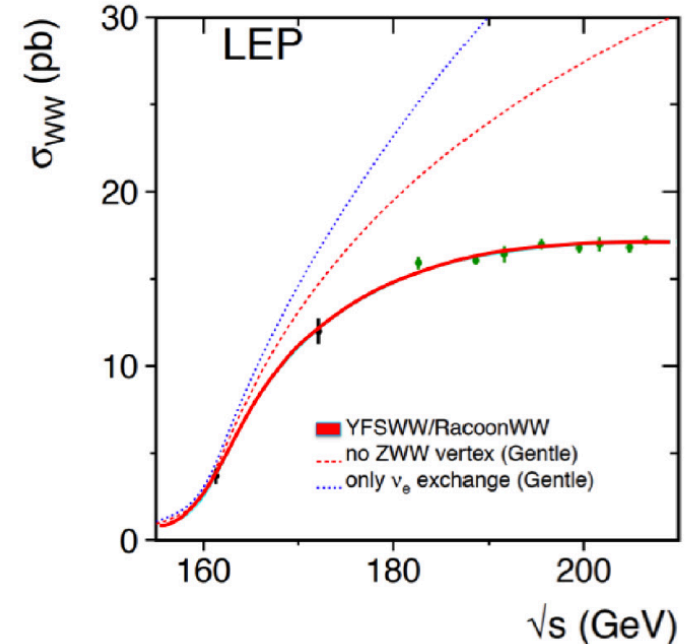
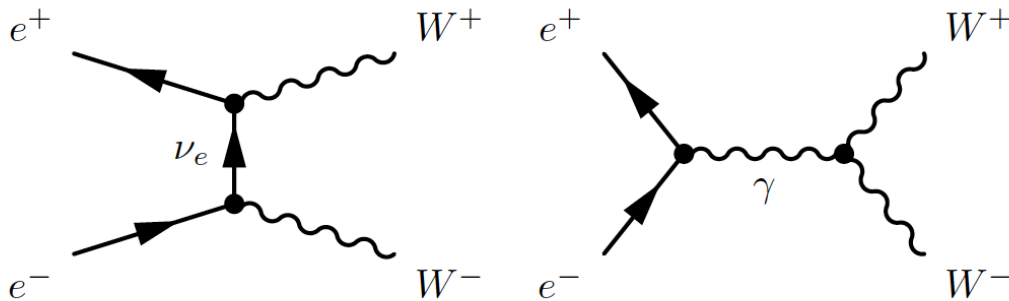
Weak Neutral Currents and Electroweak Unification



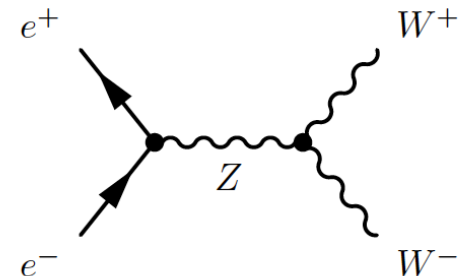
Weak Charged and Neutral Currents

- Weak CC interactions explained by W^\pm boson exchange
- W^\pm bosons are charged, thus they couple to the γ

Consider $e^-e^+ \rightarrow W^+W^-$: 2 diagrams (+interference)



- Cross-section **diverges** at high energy
- Divergence cured by introducing Z boson
- Extra diagram for $e^-e^+ \rightarrow W^+W^-$
- Idea only works if γ , W^\pm , Z couplings are related



Weak Gauge Theory

- Postulate invariance under a gauge transformation like:

$$\psi \rightarrow \psi' = e^{ig\vec{\sigma}\cdot\vec{\Lambda}(\vec{r},t)}\psi$$

an “SU(2)” transformation (σ are 2x2 matrices).

- Operates on the state of “weak isospin” – a “rotation” of the isospin state.
- Invariance under SU(2) transformations \Rightarrow three massless gauge bosons (W_1, W_2, W_3) whose couplings are well specified.
- They also have self-couplings.

But this doesn't quite work...

Predicts W and Z have the same couplings – not seen experimentally!

Sheldon Glashow's “stumbling block”

- There are hints that EM and weak interactions have a common origin
 - Similar gauge structure
 - W^\pm couples to charge
- But there are obvious differences:
 - Different masses of W^\pm , Z and photon
 - Structure of the vertex is different

PARTIAL-SYMMETRIES OF WEAK INTERACTIONS

SHELDON L. GLASHOW†

Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

Received 9 September 1980

Abstract: Weak and electromagnetic interactions of the leptons are examined under the hypothesis that the weak interactions are mediated by vector bosons. With only an isotopic triplet of leptons coupled to a triplet of vector bosons (two charged decay-intermediaries and the photon) the theory possesses no partial-symmetries. Such symmetries may be established if additional vector bosons or additional leptons are introduced. Since the latter possibility yields a theory disagreeing with experiment, the simplest partially-symmetric model reproducing the observed electromagnetic and weak interactions of leptons requires the existence of at least four vector-boson fields (including the photon). Corresponding partially-conserved quantities suggest leptonic analogues to the conserved quantities associated with strong interactions: strangeness and isobaric spin.

1. Introduction

At first sight there may be little or no similarity between electromagnetic effects and the phenomena associated with weak interactions. Yet certain remarkable parallels emerge with the supposition that the weak interactions are mediated by unstable bosons. Both interactions are universal, for only a single coupling constant suffices to describe a wide class of phenomena: both interactions are generated by vectorial Yukawa couplings of spin-one fields ^{††}. Schwinger first suggested the existence of an “isotopic” triplet of vector fields whose universal couplings would generate both the weak interactions and electromagnetism — the two oppositely charged fields mediate weak interactions and the neutral field is light ²⁾. A certain ambiguity beclouds the self-interactions among the three vector bosons; these can equivalently be interpreted as weak or electromagnetic couplings. The more recent accumulation of experimental evidence supporting the $\Delta I = \frac{1}{2}$ rule characterizing the non-leptonic decay modes of strange particles indicates a need for at least one additional neutral intermediary ³⁾.

The mass of the charged intermediaries must be greater than the K-meson mass, but the photon mass is zero — surely this is the principal stumbling block in any pursuit of the analogy between hypothetical vector mesons and photons. It is a stumbling block we must overlook. To say that the decay intermediaries

Electroweak Gauge Theory

The solution...

- Unify QED and the weak force \Rightarrow electroweak model
- “SU(2)xU(1)” transformation
U(1) operates on the “weak hypercharge” $Y = 2(Q - I_3)$
SU(2) operates on the state of “weak isospin, I ”
- Invariance under SU(2)xU(1) transformations \Rightarrow four massless gauge bosons W^+, W^-, W_3, B
- The two neutral bosons W_3 and B then **mix** to produce the physical bosons Z and γ
- Photon properties must be the same as QED \Rightarrow predictions of the couplings of the Z in terms of those of the W and γ
- Still need to account for the **masses** of the W and Z . This is the job of the **Higgs mechanism** (later).

The GWS Model



The **G**lashow, **W**einberg and **S**alam model treats **EM** and **weak** interactions as different manifestations of a single **unified electroweak** force (Nobel Prize 1979)

Start with 4 massless bosons W^+ , W_3 , W^- and B . The neutral bosons **mix** to give physical bosons (the particles we see), i.e. the W^\pm , Z , and γ .

$$\begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}; B \rightarrow \begin{pmatrix} W^+ \\ Z \\ W^- \end{pmatrix}; \gamma$$

Physical fields: W^+ , Z , W^- and A (photon).

$$Z = W_3 \cos \theta_W - B \sin \theta_W$$

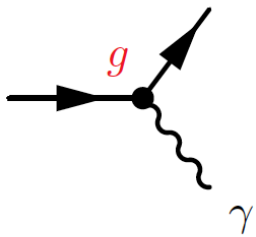
$$A = W_3 \sin \theta_W + B \cos \theta_W \quad \theta_W \text{ Weak Mixing Angle}$$

W^\pm , Z “acquire” mass via the **Higgs mechanism**.

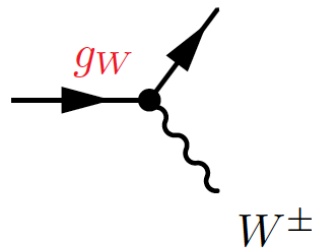
The GWS Model

The beauty of the **GWS** model is that it makes **exact** predictions of the W^\pm and Z masses and of their couplings with **only 3** free parameters.

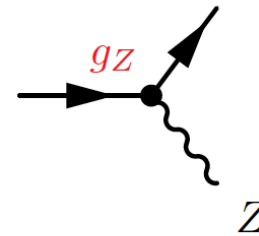
Couplings given by α_{EM} and θ_W



$$\alpha_{EM} = \frac{e^2}{4\pi} \quad g \sim e$$



$$g_W = \frac{e}{\sin \theta_W}$$



$$g_Z = \frac{e}{\sin \theta_W \cos \theta_W} = \frac{g_W}{\cos \theta_W}$$

Masses also given by G_F and θ_W

From Fermi theory

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2} = \frac{e^2}{8m_W^2 \sin^2 \theta_W} \quad m_{W^\pm} = \left(\frac{\sqrt{2}e^2}{8G_F \sin^2 \theta_W} \right)^{1/2} \quad m_Z = \frac{m_W}{\cos \theta_W}$$

If we know α_{EM} , G_F , $\sin \theta_W$ (from experiment), everything else is defined.

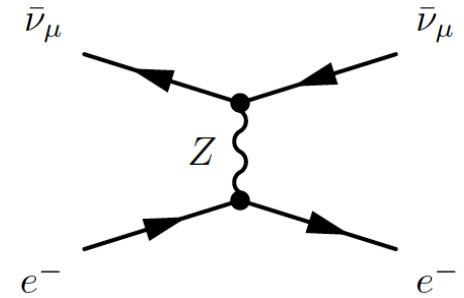
Evidence for the GWS model

- **Discovery of Neutral Currents (1973)**

The process $\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$ was observed.

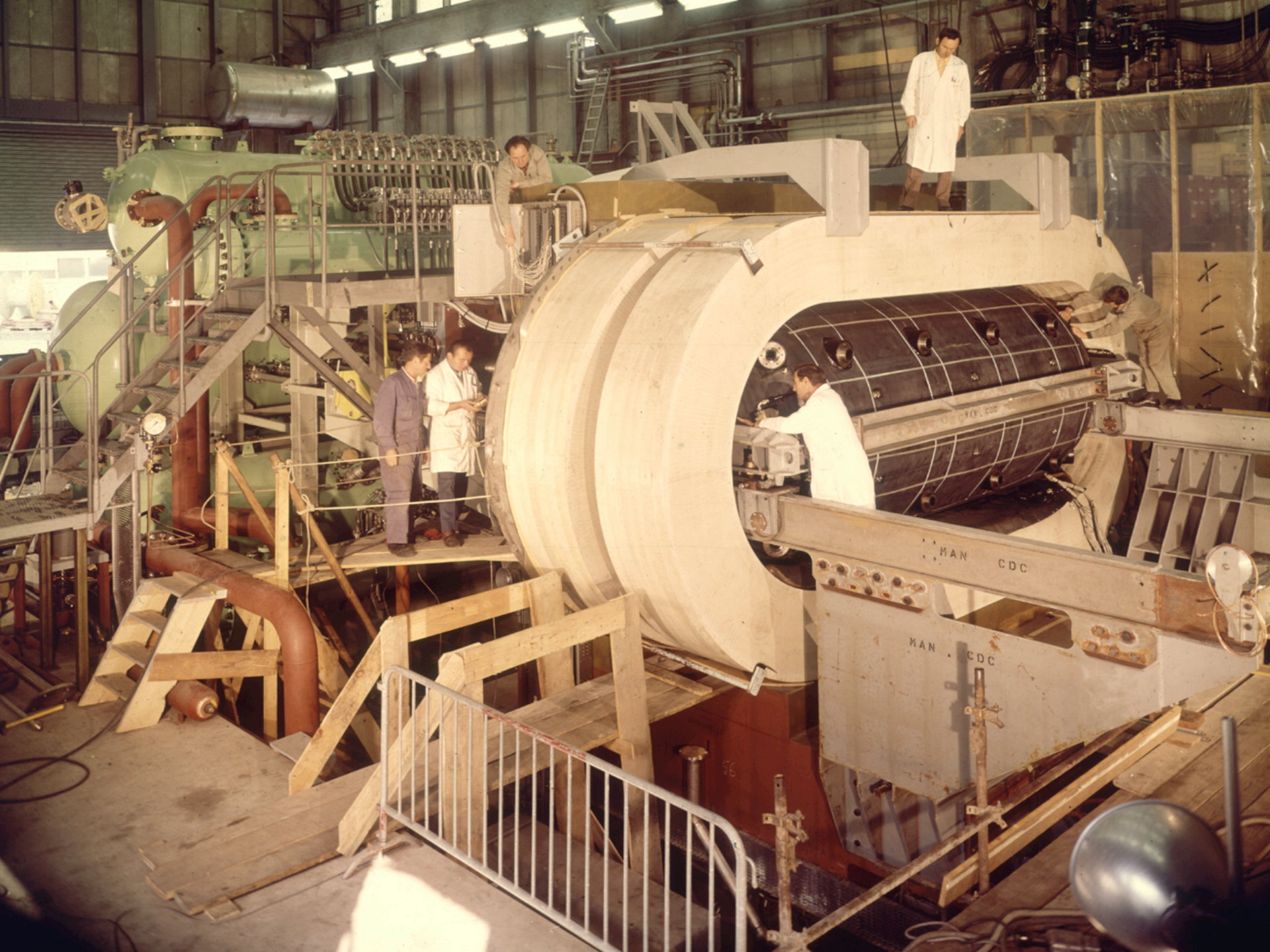
Only possible Feynman diagram (no W^\pm diagram).

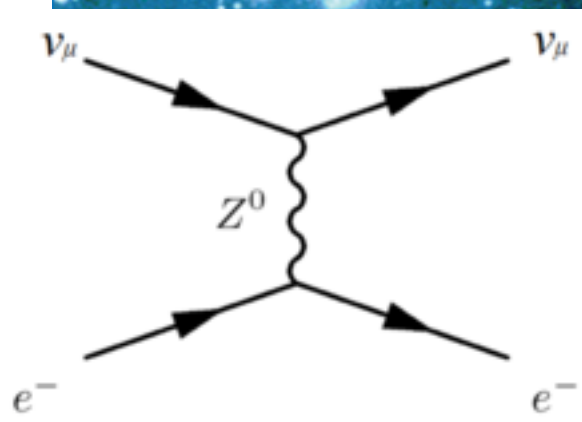
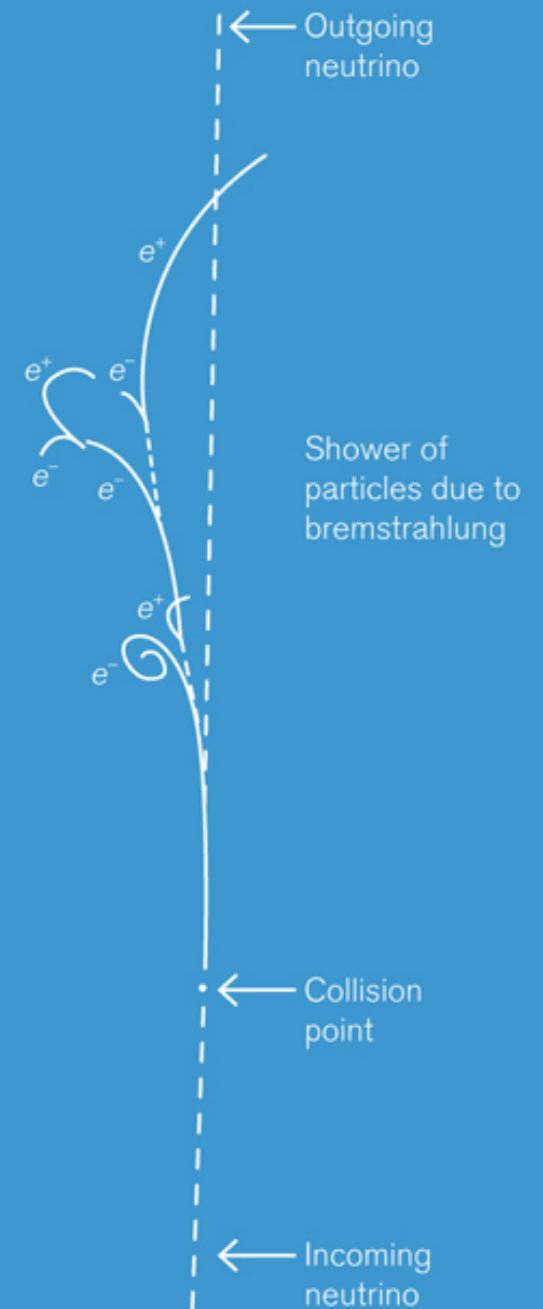
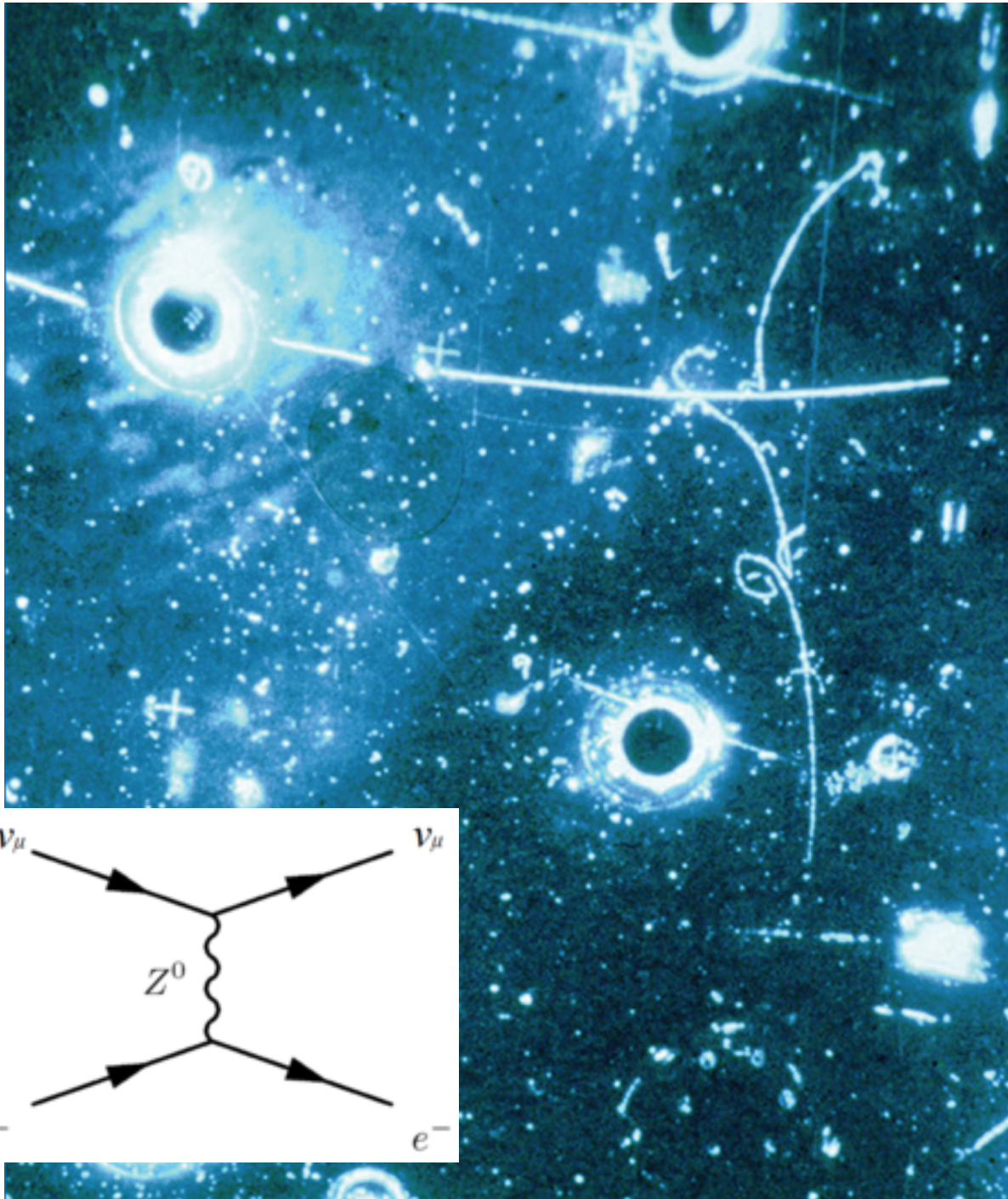
Indirect evidence for Z .



Gargamelle Bubble
Chamber at CERN







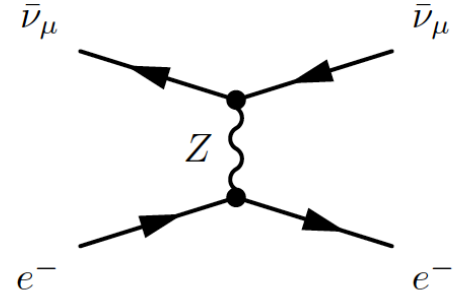
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- **Direct Observation of W^\pm and Z (1983)**

First **direct** observation in $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV via decays into leptons

$$p\bar{p} \rightarrow W^\pm + X$$

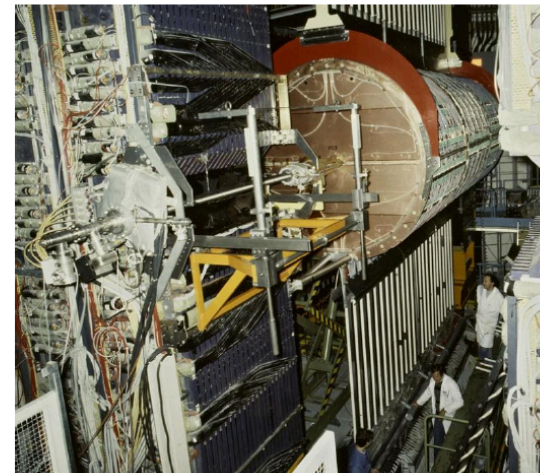
$$\hookrightarrow e^\pm \nu_e, \mu^\pm \nu_\mu$$

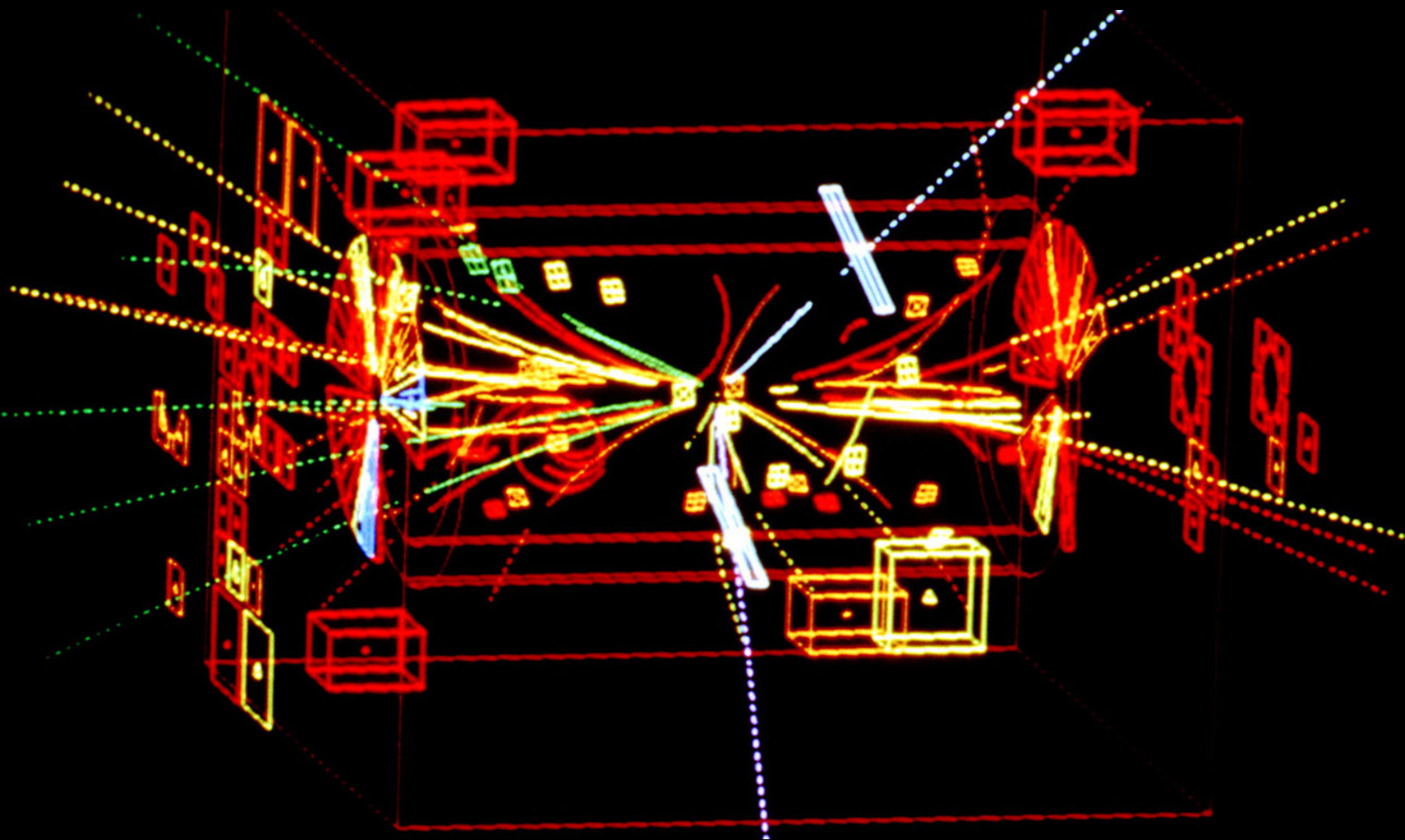
$$p\bar{p} \rightarrow Z + X$$

$$\hookrightarrow e^+ e^-, \mu^+ \mu^-$$

UA1 Experiment at CERN

Used Super Proton Synchrotron
(now part of LHC!)





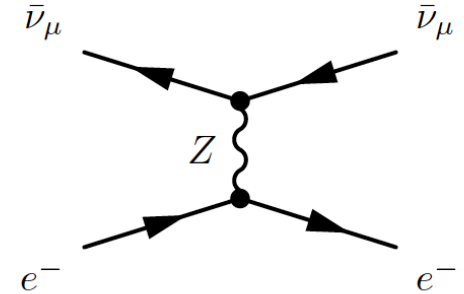
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$$p\bar{p} \rightarrow Z + X$$

$$\hookrightarrow e^+ e^-, \mu^+ \mu^-$$

- **Precision Measurements of the Standard Model (1989-2000)**

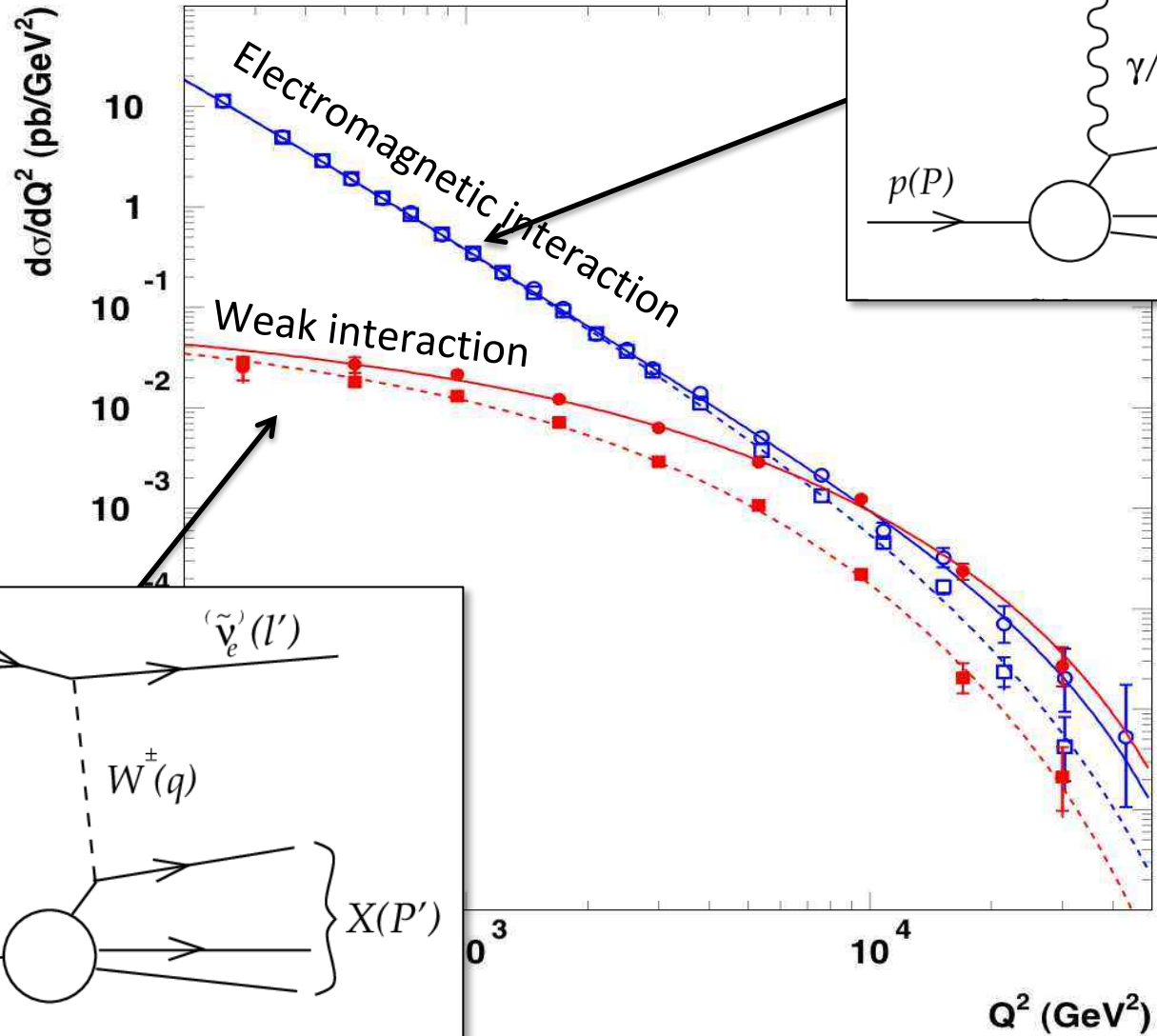
LEP e^+e^- collider provided many precision measurements of the Standard Model.

- Wide variety of different processes consistent with GWS model predictions and measure **same value** of

$$\sin^2 \theta_W = 0.23113 \pm 0.00015$$

$$\theta_W \sim 29^\circ$$

ZEUS



Now for the problems...



Problem 1: Mass of elementary particles and gauge bosons

What if we add a photon mass term to the QED Lagrangian?

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

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

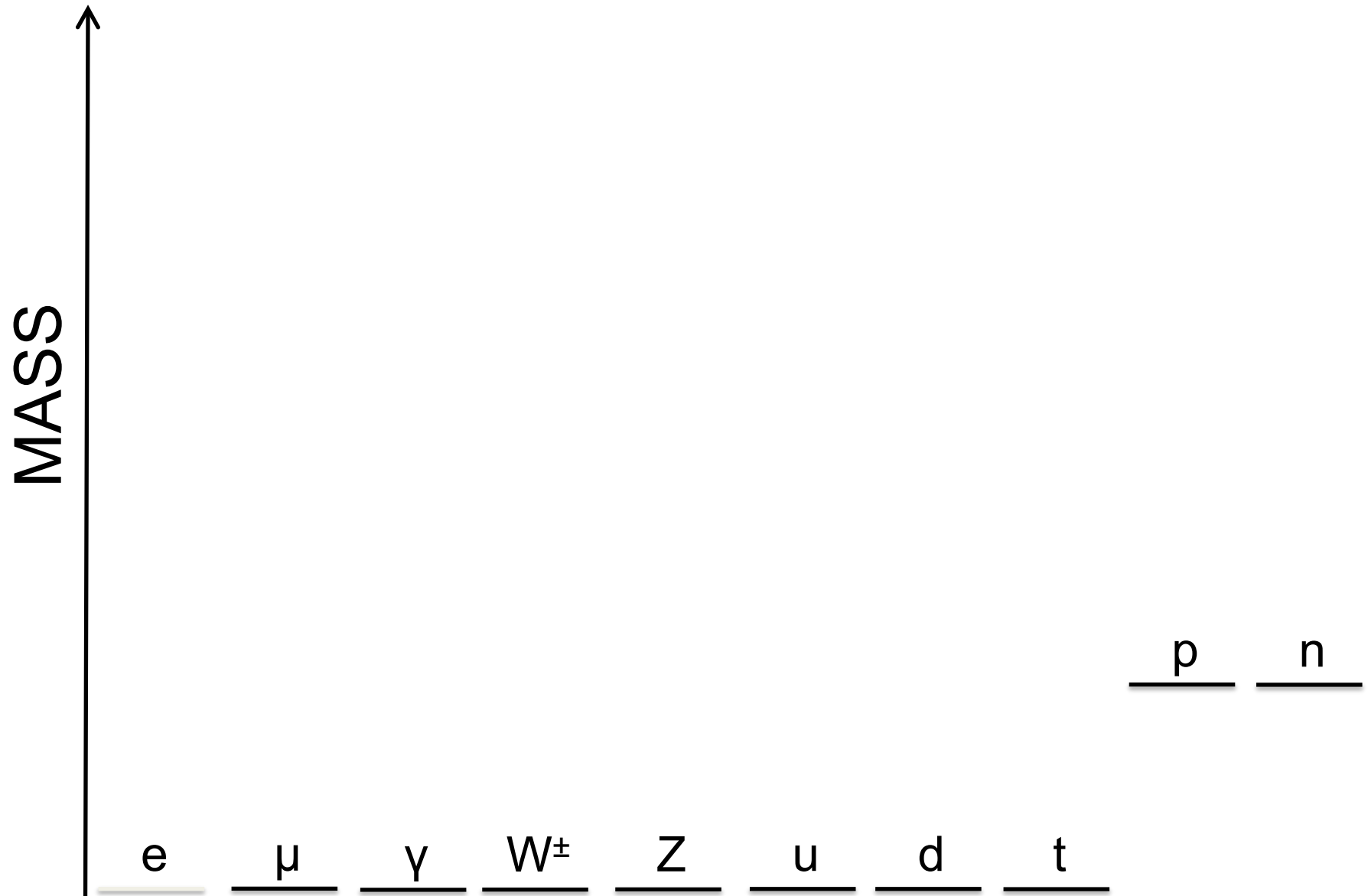
$$A_\mu \rightarrow A'_\mu = A_\mu - \partial_\mu\chi$$

But the A^μ mass term breaks the Lagrangian invariance:

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

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

It should not work...



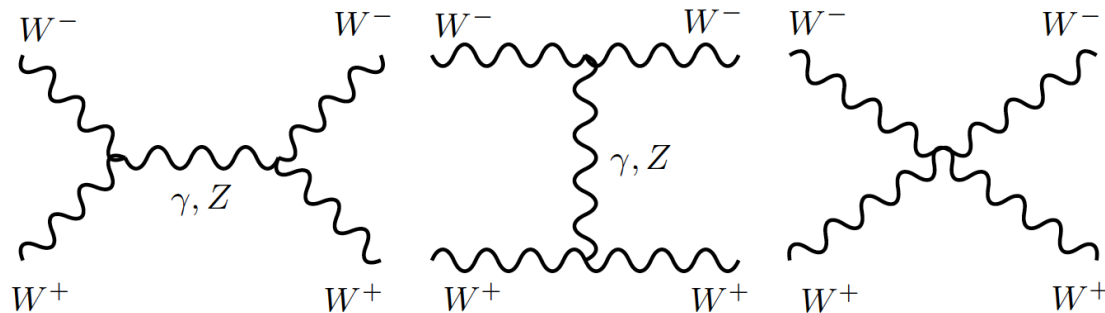
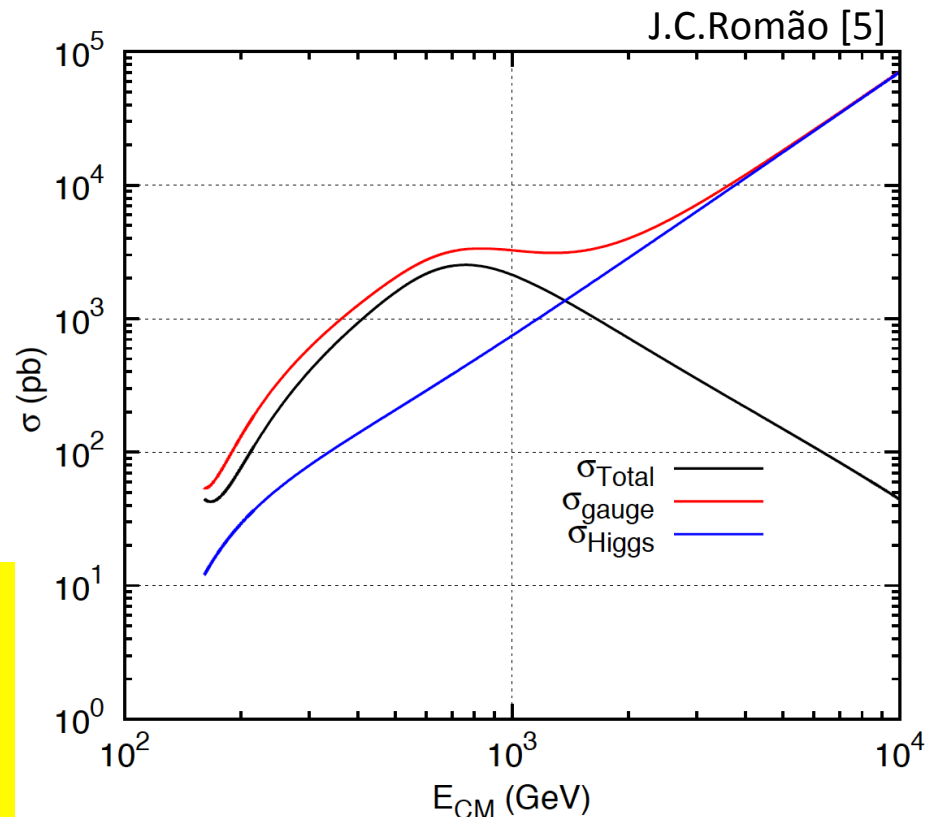
Problem 2:

Longitudinal gauge-boson scattering

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

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



Feynman diagrams contributing to longitudinal WW scattering

The Higgs Mechanism



Robert Brout (1928 – 2011)

Peter Higgs (b. 1929)

François Englert
(b. 1932)

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

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

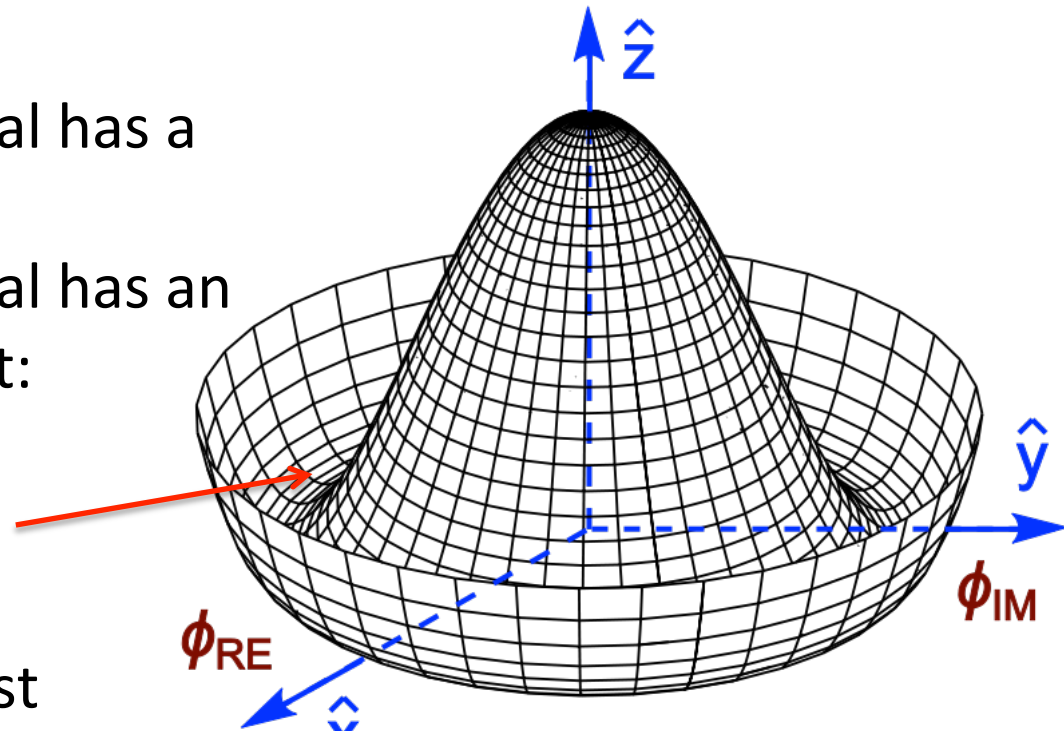
- New Lagrangian term: $\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$

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

- With a potential

- For $\lambda > 0, \mu^2 > 0$ the potential has a minimum at the origin
- For $\lambda > 0, \mu^2 < 0$ the potential has an infinite number of minima at:

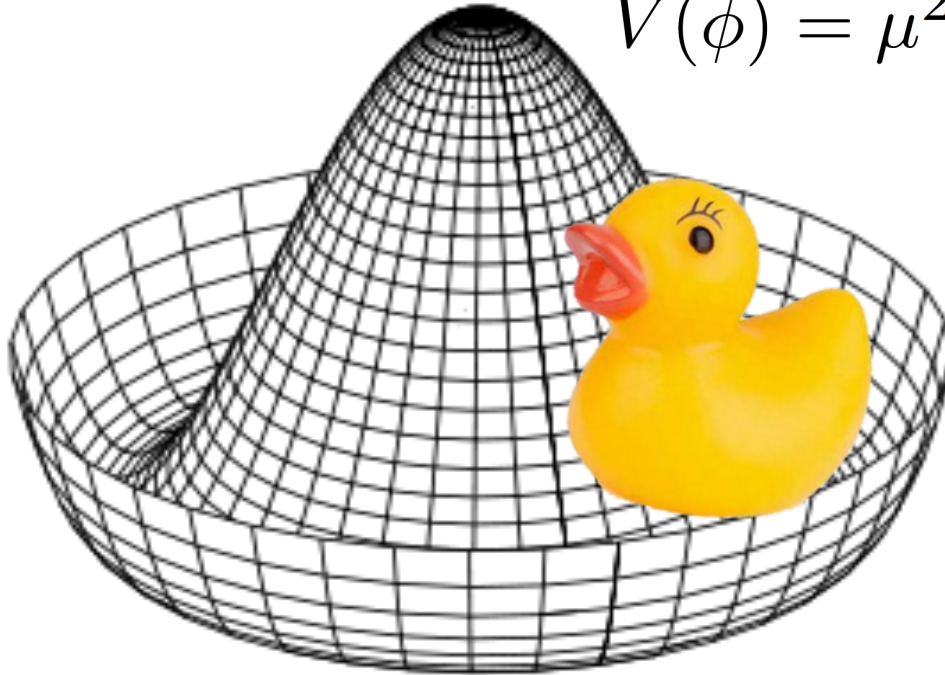
$$|\phi| = \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}}$$



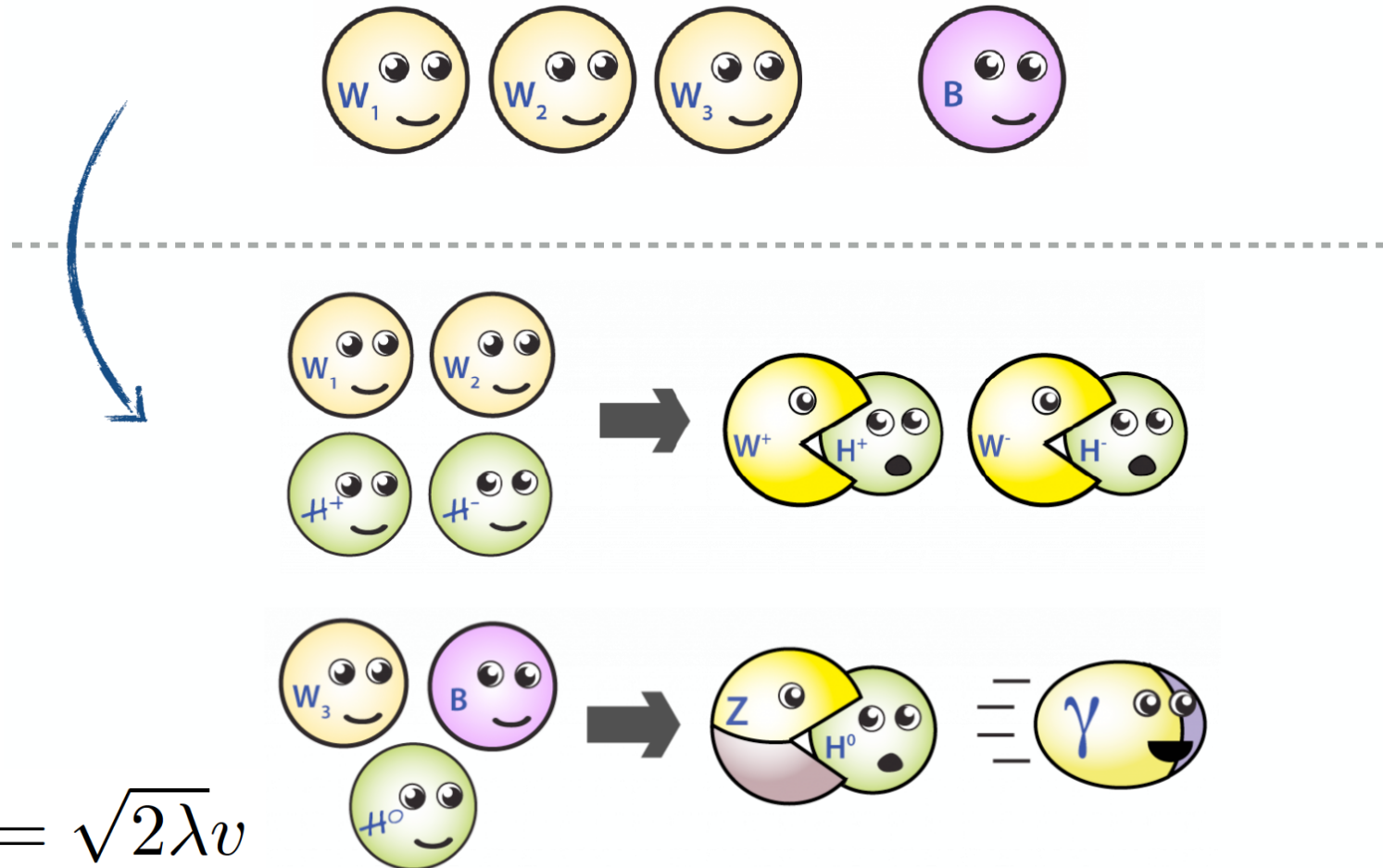
The choice of vacuum (lowest energy state of the field) breaks the symmetry of the Lagrangian



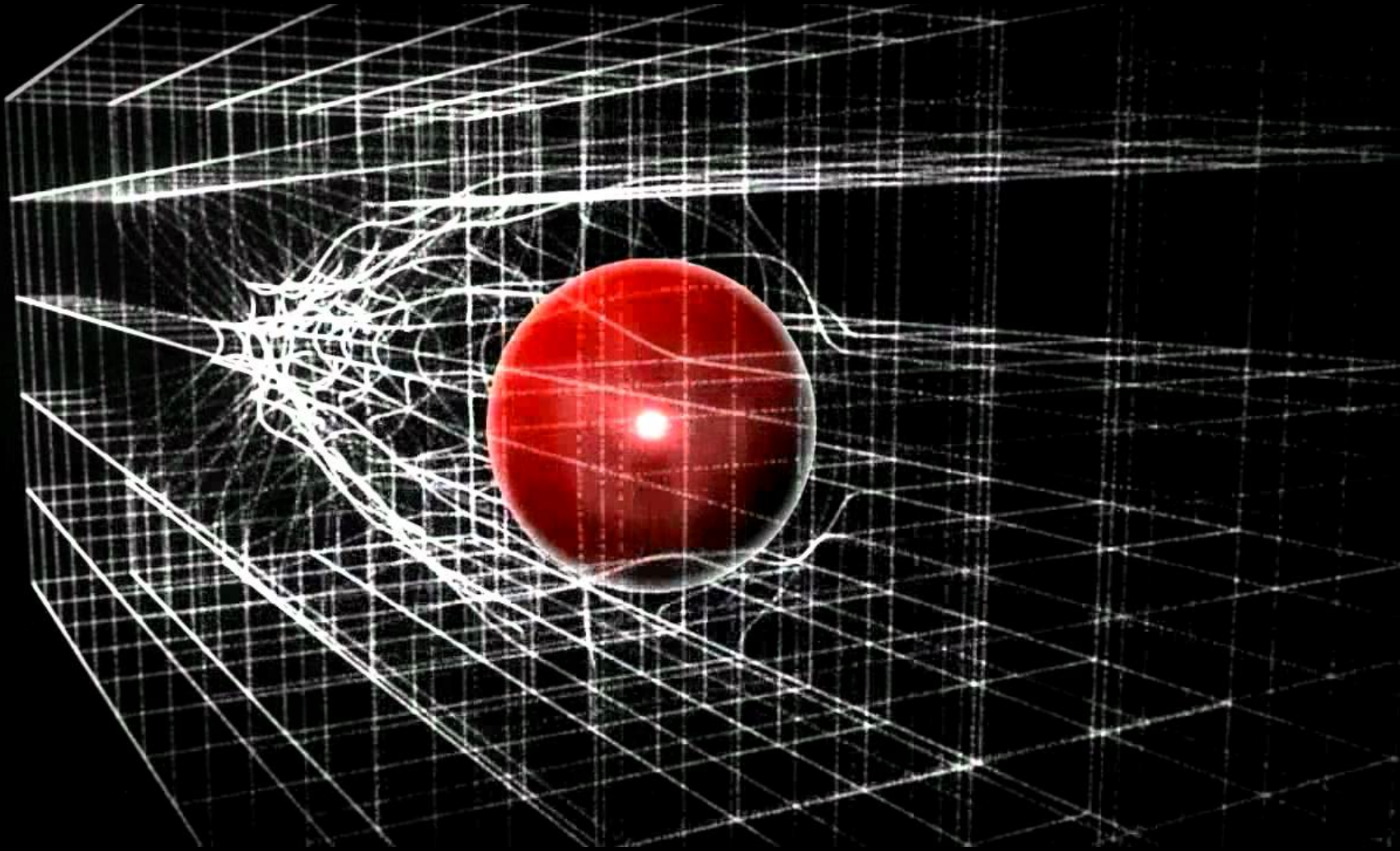
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$



EWK Symmetry Breaking in Pictures



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



Higgs Properties

- Mass $m_h = \sqrt{2\lambda}v$
- Spin: 1 degree of freedom $\Rightarrow 0$
- Couplings:
- To gauge bosons

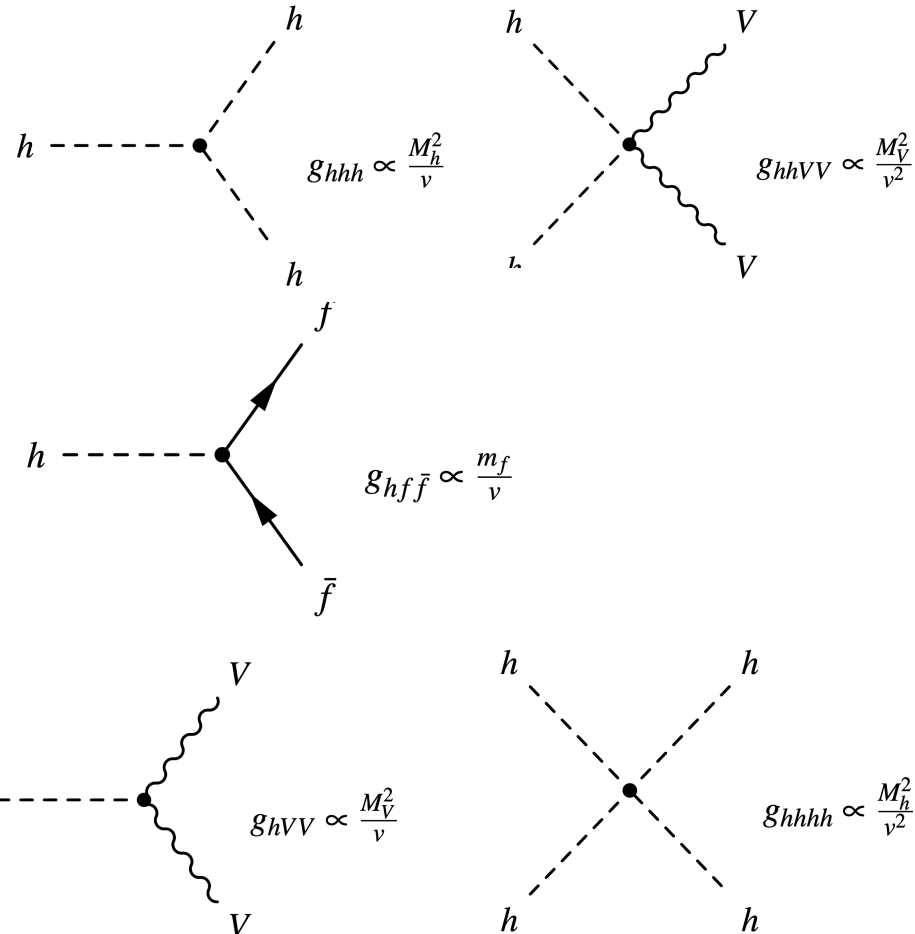
$$g_{hVV} \propto \frac{M_V^2}{v} \quad g_{hhVV} \propto \frac{M_V^2}{v^2}$$

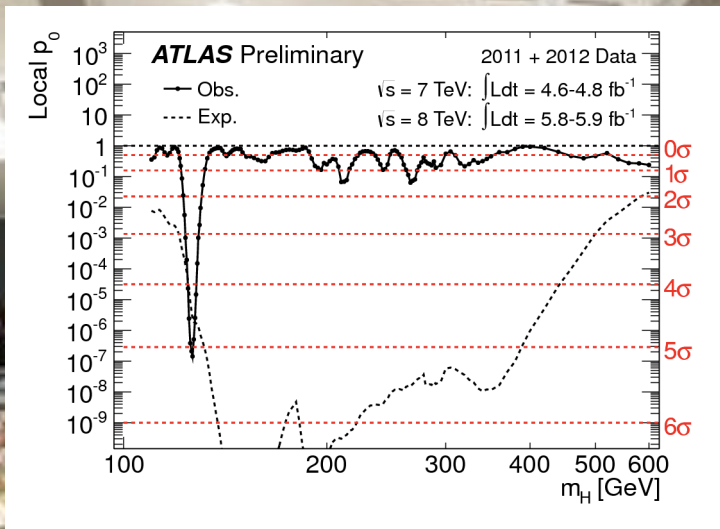
- Yukawa couplings to fermions

$$g_{hf\bar{f}} \propto \frac{m_f}{v}$$

- Self-couplings

$$g_{hhh} \propto \frac{M_h^2}{v} \quad g_{hhhh} \propto \frac{M_h^2}{v^2}$$





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



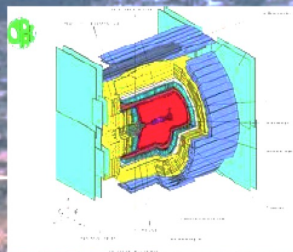
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm^{3),4)} and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons 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.

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

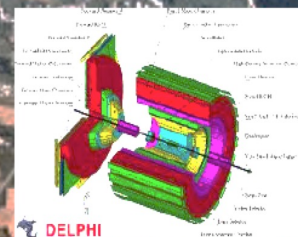
Shutdown: September 2000

Searches at LEP

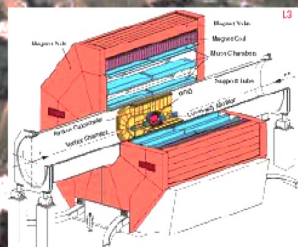
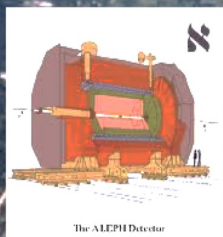
OPAL



DELPHI



ALEPH

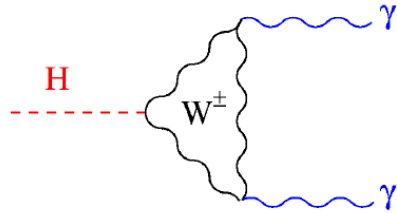


L3

Low-mass searches at LEP

The decay branching ratios depend only on m_H :

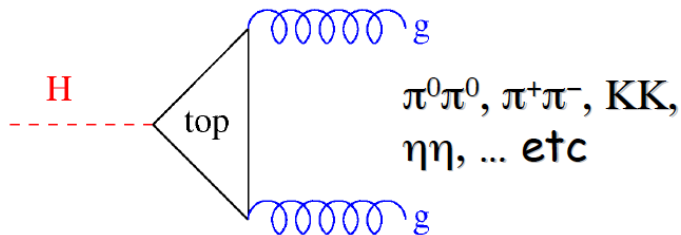
□ $m_H < 2m_e$: $H \rightarrow \gamma\gamma$ + large lifetime;



□ $m_H < 2m_\mu$: $H \rightarrow e^+e^-$ dominates;

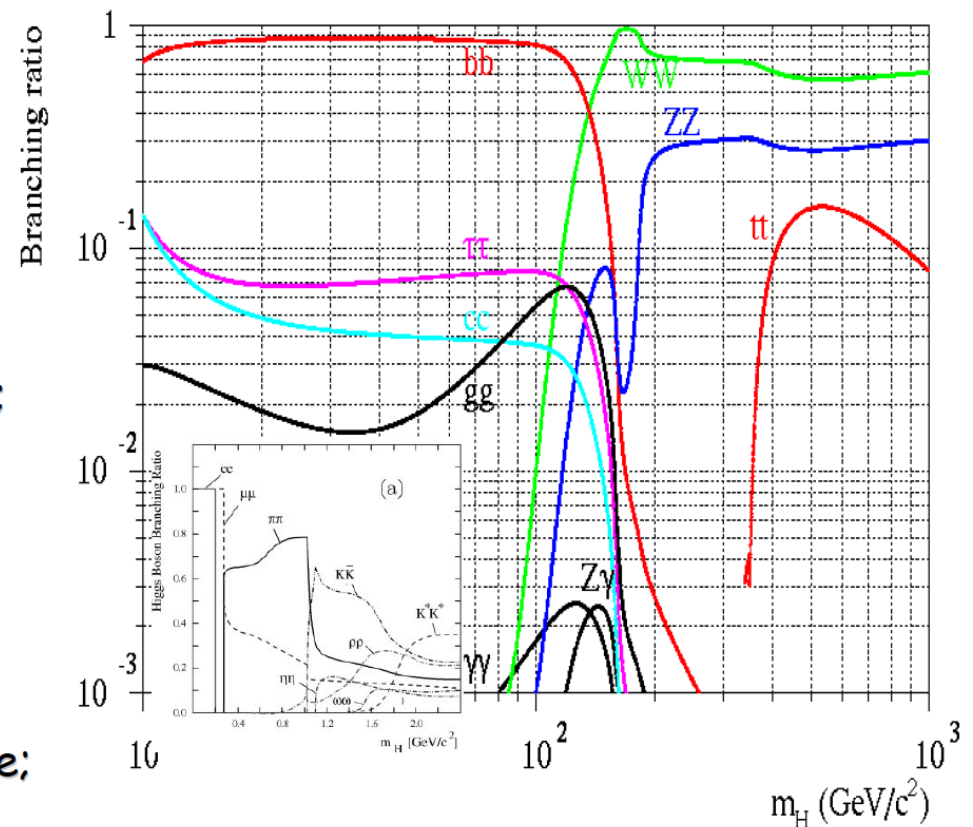
□ $m_H < 2m_\pi$: $H \rightarrow \mu^+\mu^-$ dominates;

□ $m_H < 3 - 4 \text{ GeV}$: $H \rightarrow gg$ dominates;

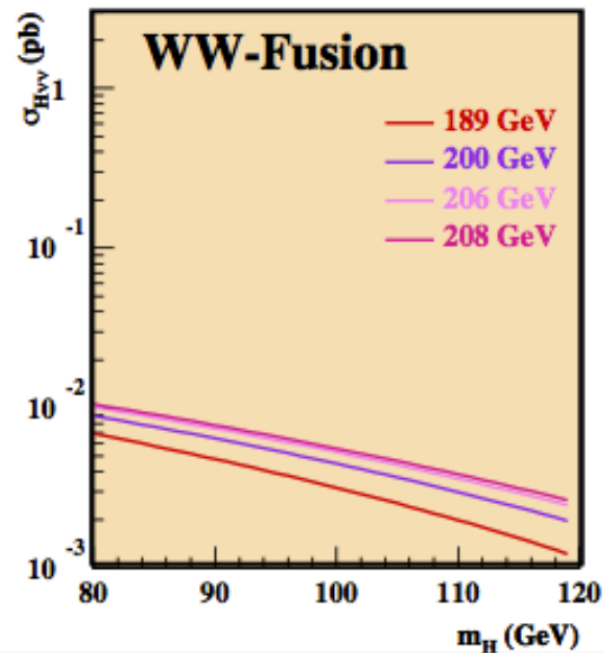
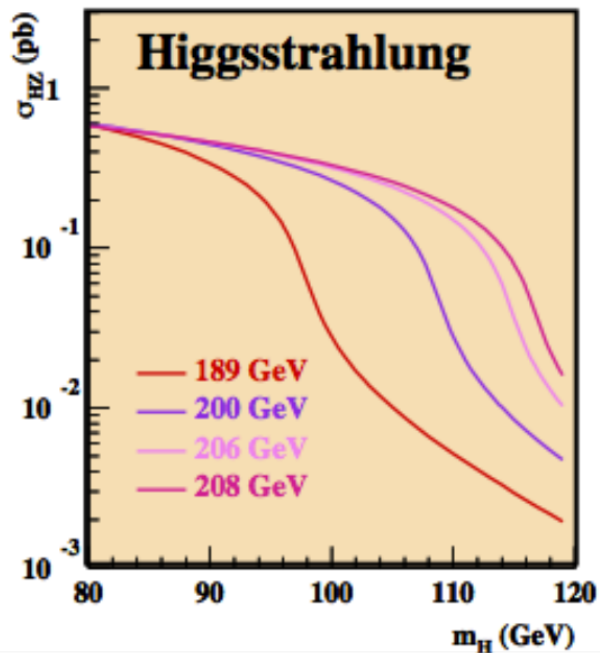
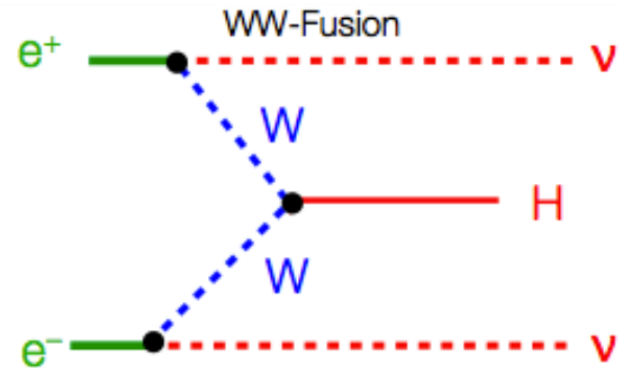
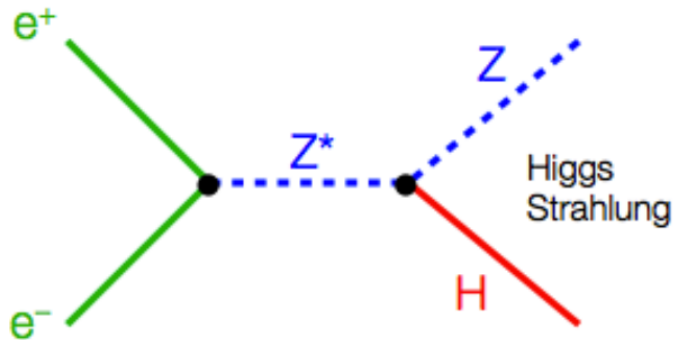


□ $m_H < 2m_b$: $H \rightarrow \tau^+\tau^-$ and $c\bar{c}$ dominate;

□ $m_H > 2m_b$ up to $1000 \text{ GeV}/c^2$:



Higher-mass Higgs production at LEP



Summary of all Higgs candidates found at LEP

Invariant mass of all candidates

In total 17 candidates selected

- 15.8 background events expected

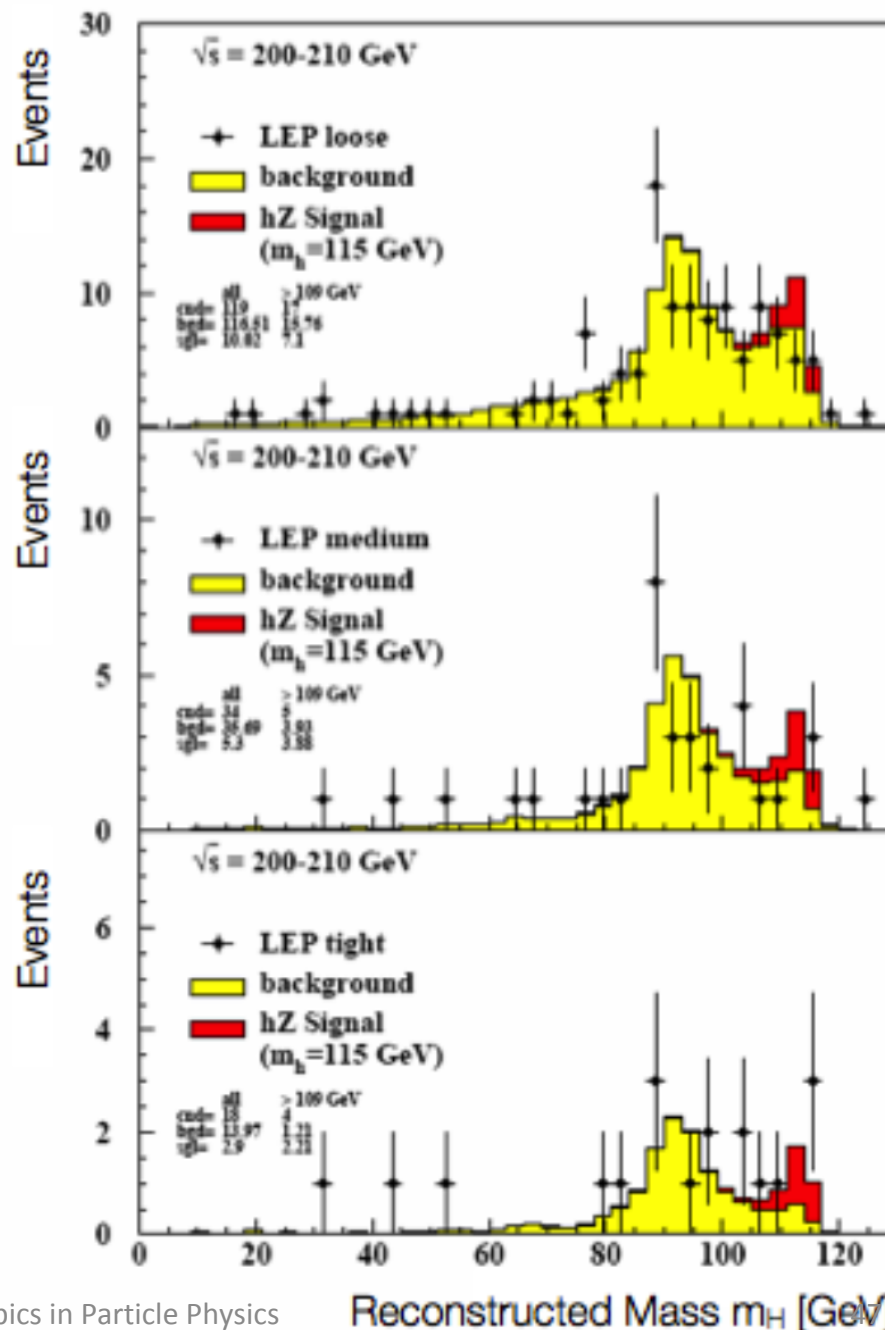
Expectation for $m_H = 115$ GeV

- 8.4 events

Corresponding excess was not observed

Final verdict from LEP

$m_H > 114.4$ GeV @ 95% CL

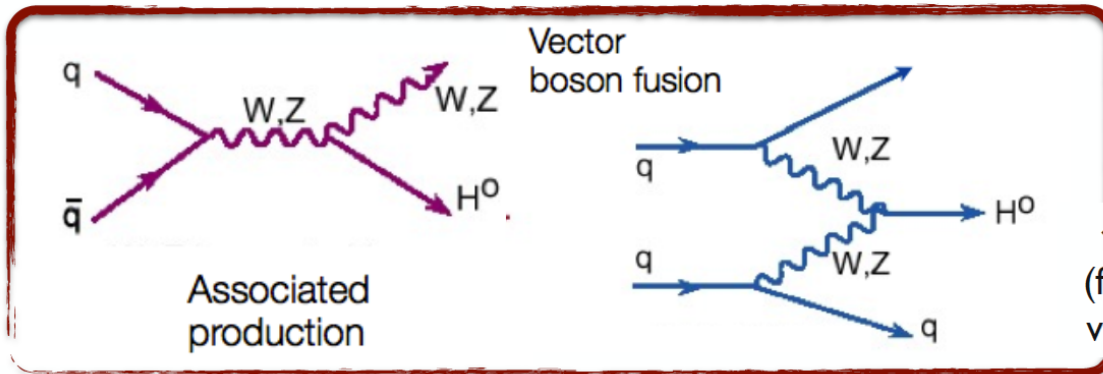


Searches at the Tevatron

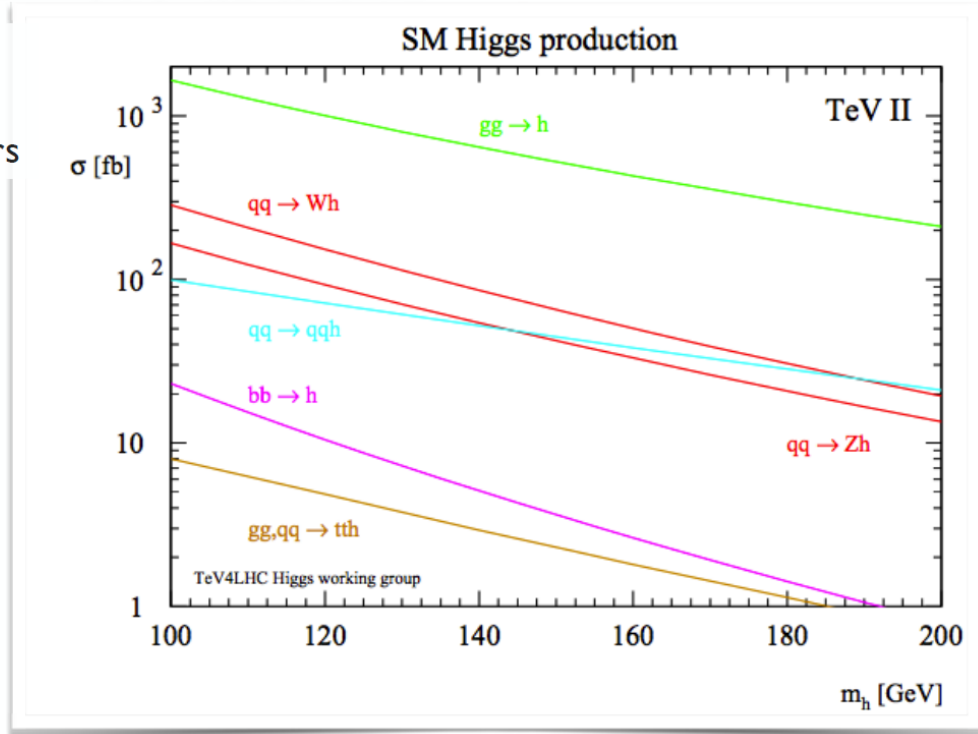
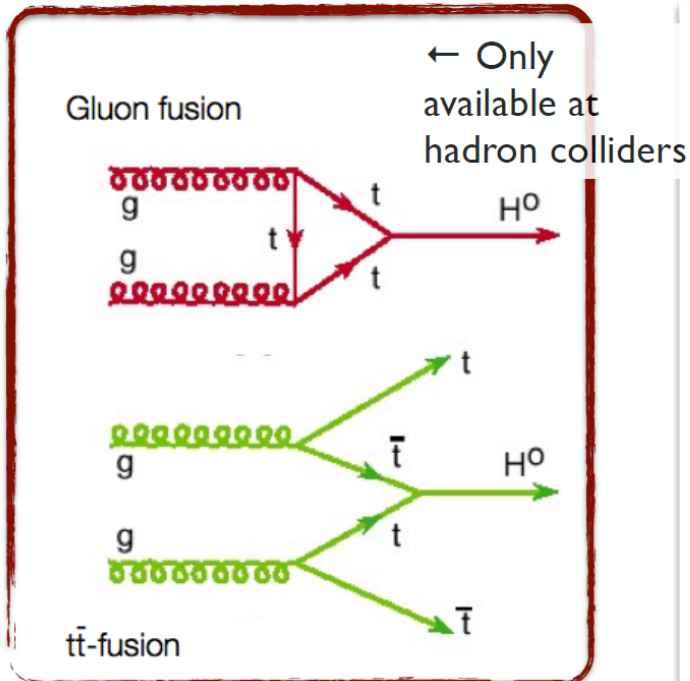


Proton-anti-proton collider at $s^{1/2}=1.96$ TeV
First superconducting accelerator
Shutdown: 30 September 2011
Almost 10 fb^{-1} of data for analysis

Higgs production at the Tevatron

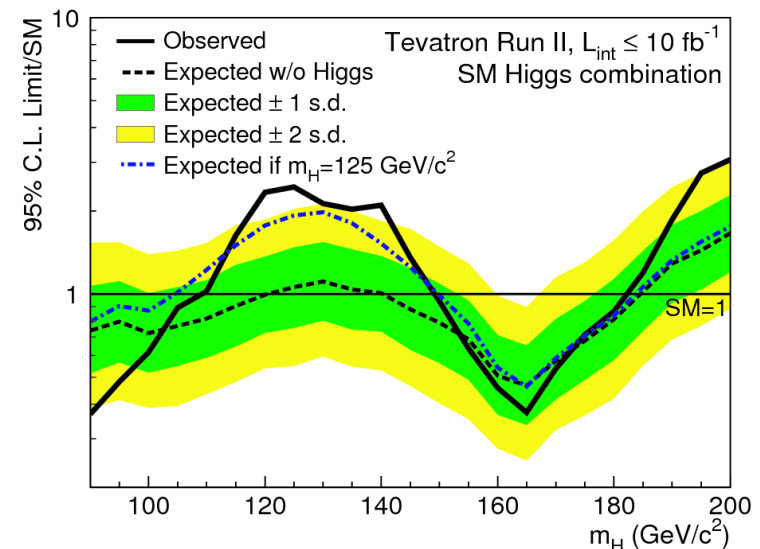
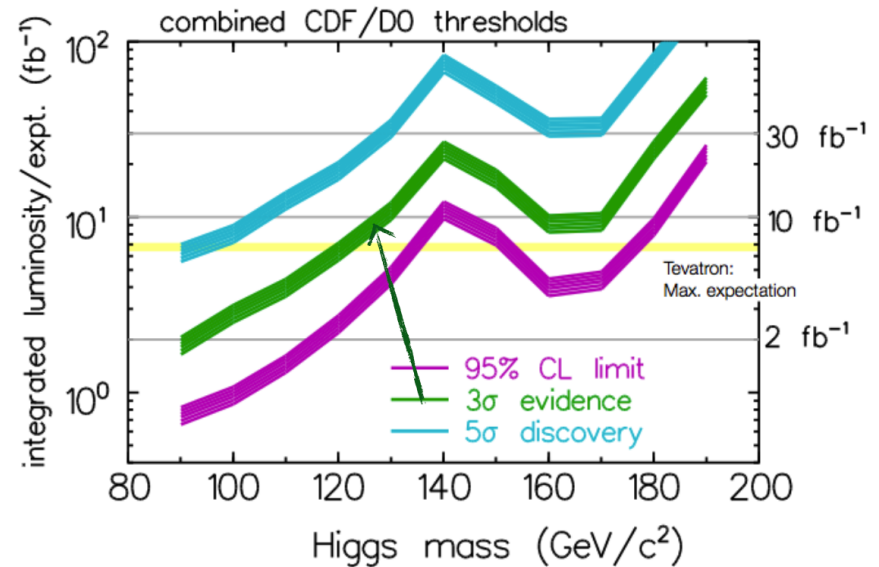


(fermion annihilation and vector boson scattering)



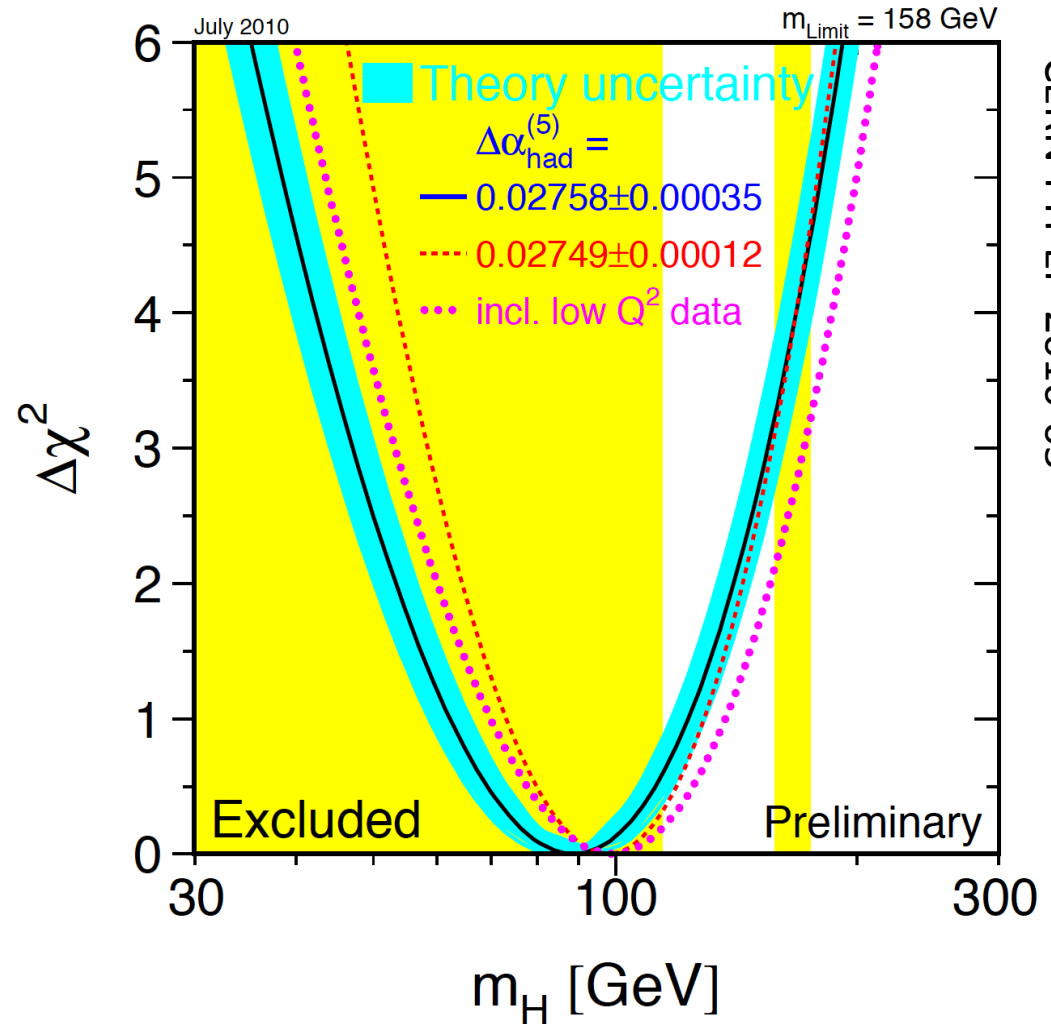
The final stand of the Tevatron

- 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 an 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



LEP and Tevatron: the Blue Band Plot

- Decades of searches in several experiments...
- By July 2010:
 - LEP+Tevatron+SLD limits
 - Higgs excluded for $m_h < 114.4$ GeV at 95% CL
 - Plus between 158 and 175 GeV



Discovery at the LHC

Design (p-p run):

$\sqrt{s} = 14 \text{ TeV}$ (design)

$N_p = 1.2 \times 10^{11} \text{ p/bunch}$

2780 bunches

Peak $L = 1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (design)

$\beta^* = 55 \text{ cm}$

Run 1: 2009 – 2013 $\sqrt{s} = 7/8 \text{ TeV}$

Run 2: 2015 – 2018 $\sqrt{s} = 13 \text{ TeV}$

Mont Blanc

ATLAS

ALICE

LHCb

CERN Prévessin

LHC 27 km

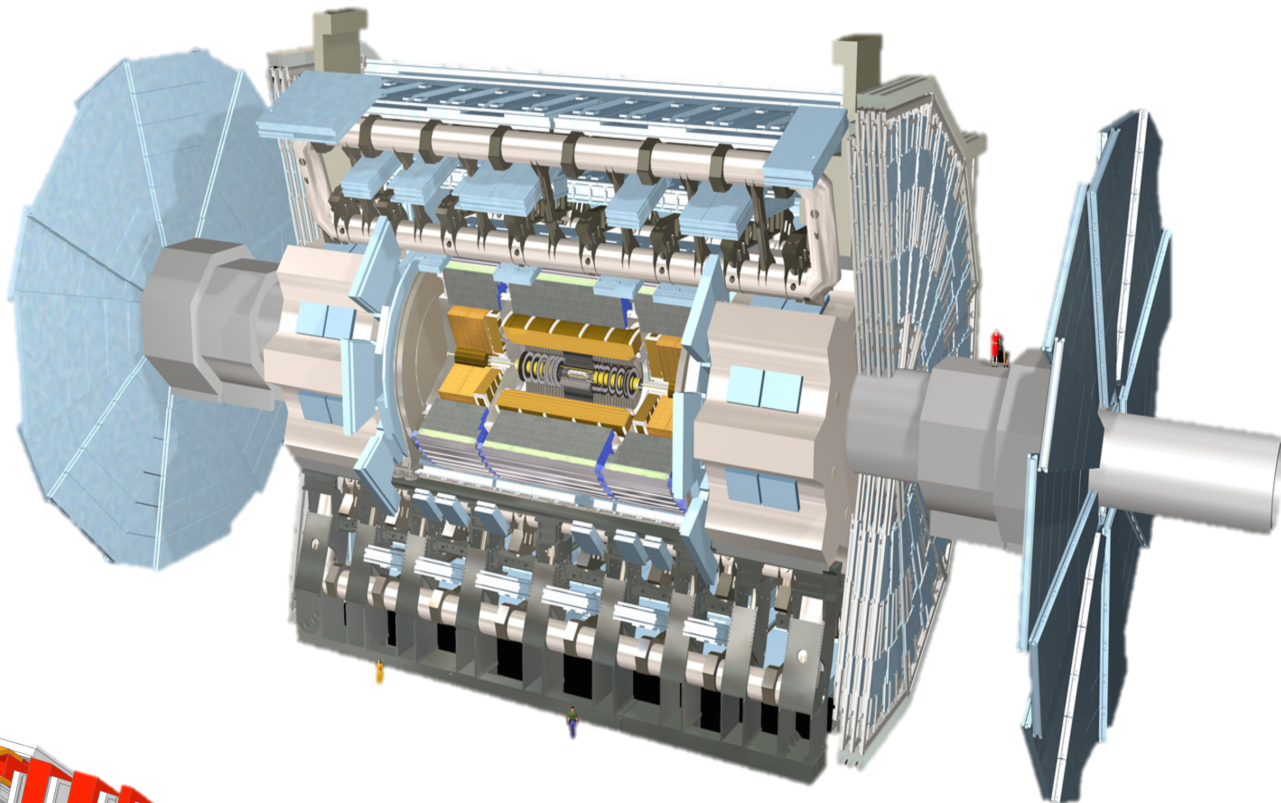
CMS

ATLAS

3000 colaboradores

175 institutos de 38 países

$L = 44 \text{ m}$, $\varnothing \approx 25 \text{ m}$, 7 000 t

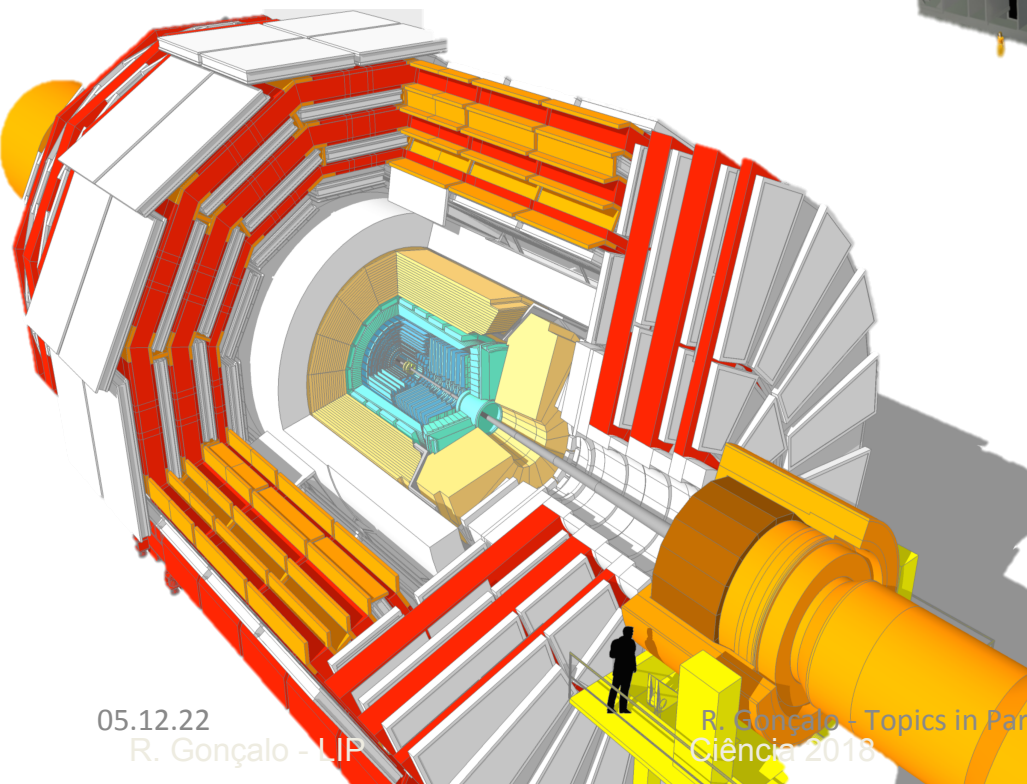


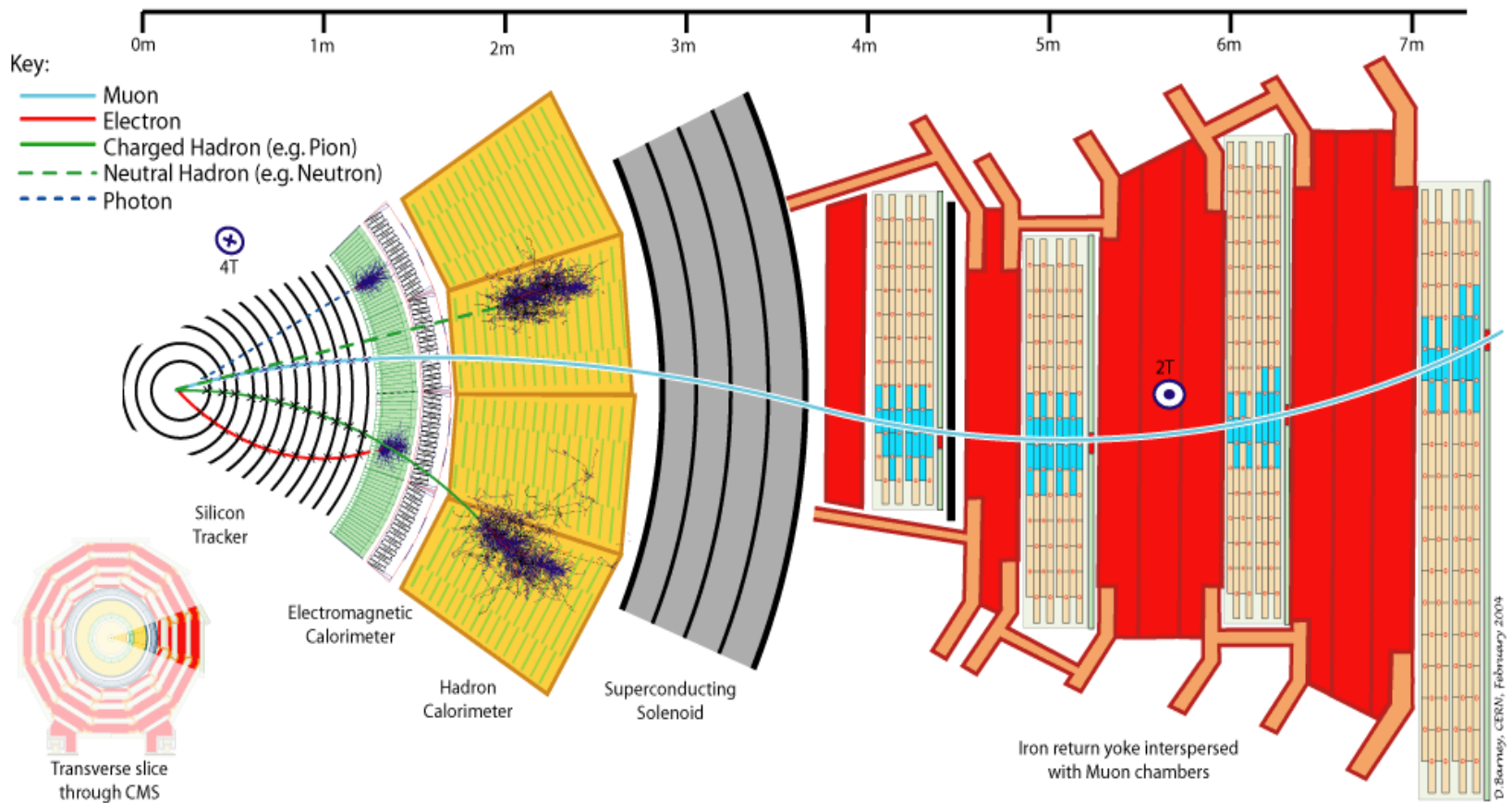
CMS

3800 colaboradores

199 institutos de 43 países

$L = 22 \text{ m}$, $\varnothing \approx 15 \text{ m}$, 14 000 t





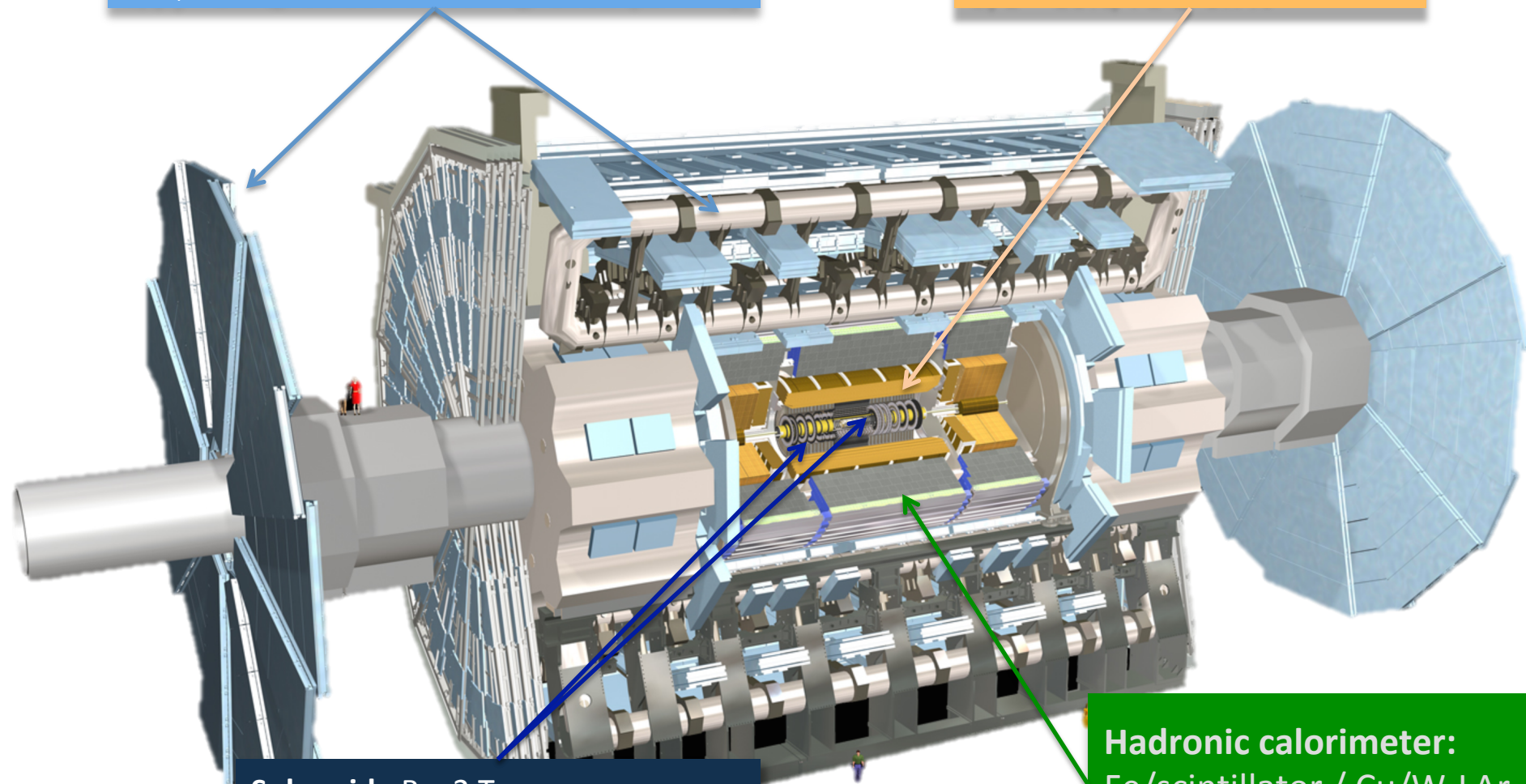
D. Barney, CERN, February 2004

Muon Spectrometer: $|\eta| < 2.7$

Air-core toroid + gas-based muon chambers
 $\sigma/p_T = 2\% @ 50\text{GeV}$ to $10\% @ 1\text{TeV}$ (ID+MS)

EM calorimeter: $|\eta| < 2.5$ (3.2)

Pb-LAr accordion sampling
 $\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$



Solenoid: $B = 2\text{ T}$

Inner Tracker: $|\eta| < 2.5$

Si pixels/strips and Trans. Rad. Det.
 $\sigma/p_T = 0.05\% p_T (\text{GeV}) \oplus 1\%$

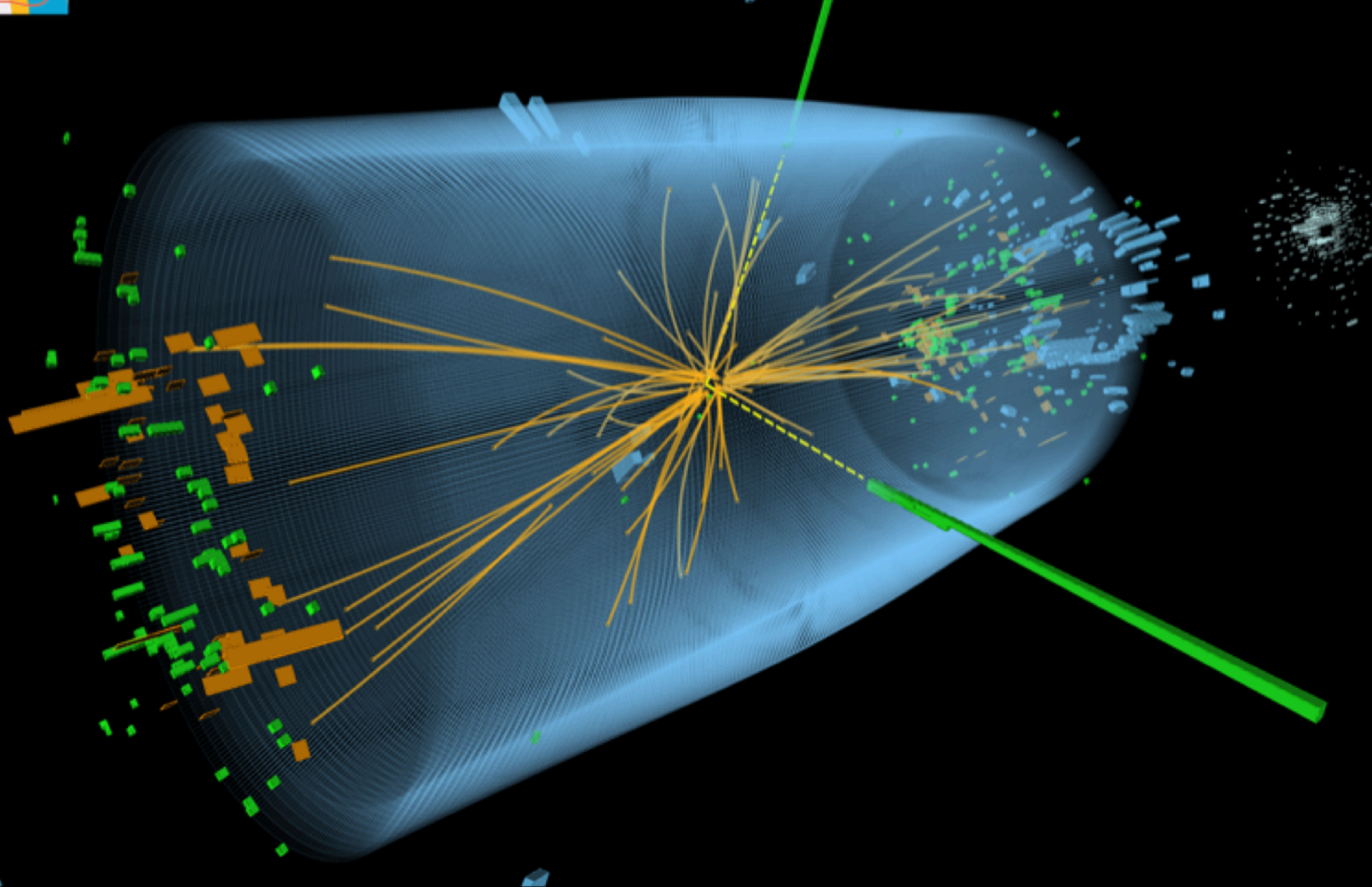
Hadronic calorimeter:
Fe/scintillator / Cu/W-LAr
 $\sigma/E_{\text{jet}} = 50\%/\sqrt{E} \oplus 3\%$



CMS Experiment at the LHC, CERN

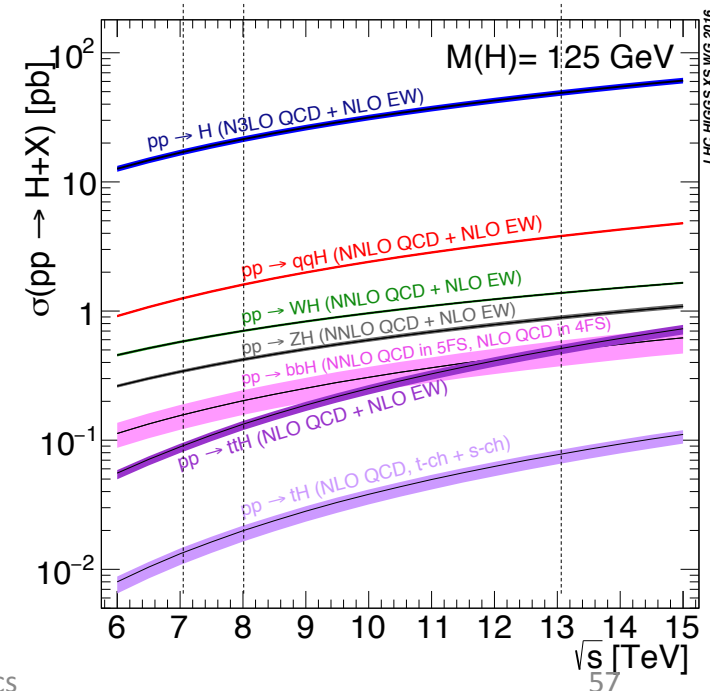
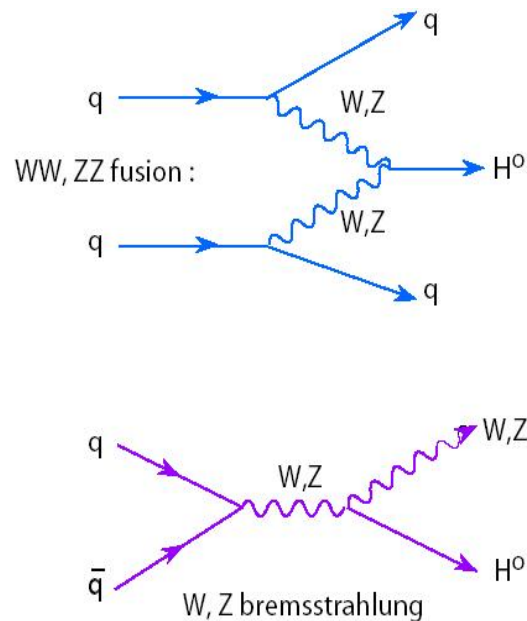
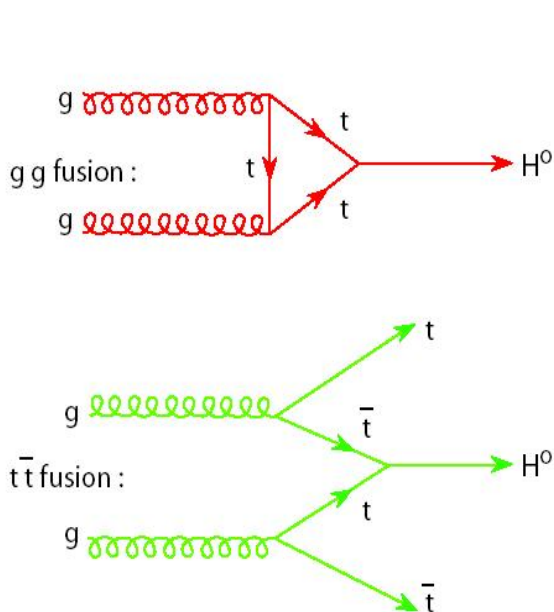
Data recorded: 2012-May-13 20:08:14.621490 GMT

Run/Event: 194108 / 564224000



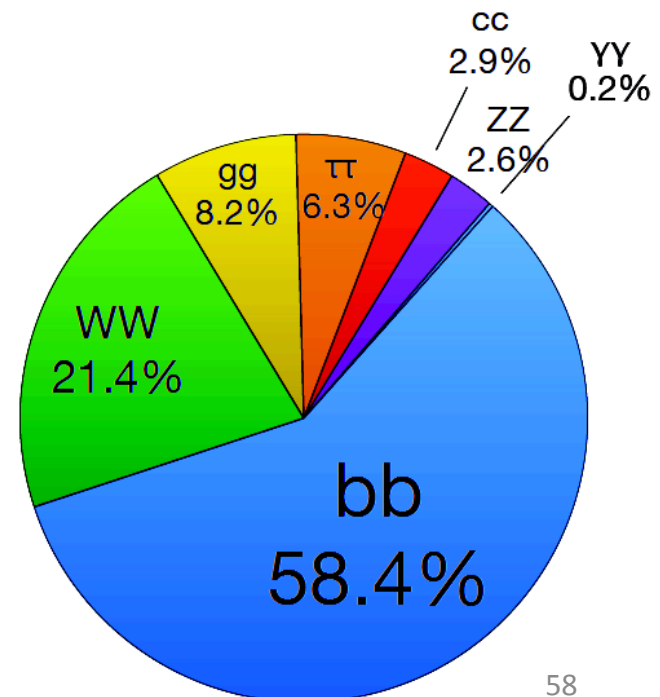
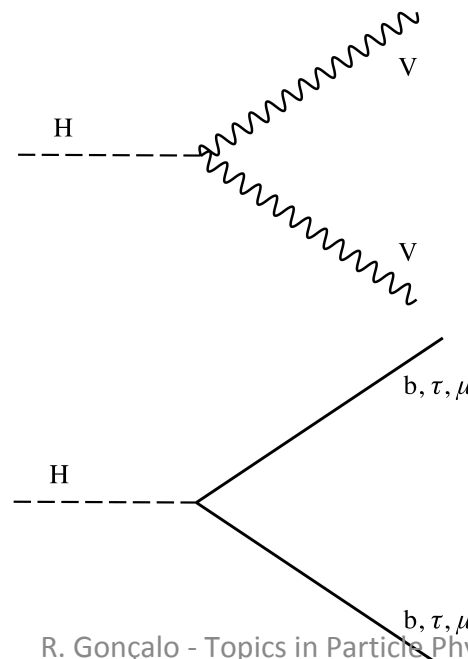
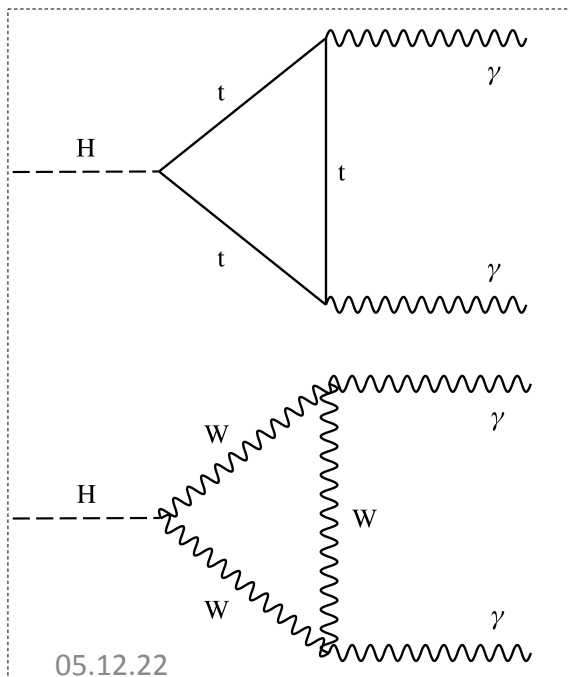
Higgs @ the LHC

- Many different production and decay mechanisms
 - Span 3 orders of magnitude in cross section and branching ratio
 - Some very clean decays with low BR ($\gamma\gamma$, $4l$)
 - Other very difficult with higher rates (bb , WW , $\tau\tau$,...)
- Access Higgs properties through combination of different channels



Higgs @ the LHC

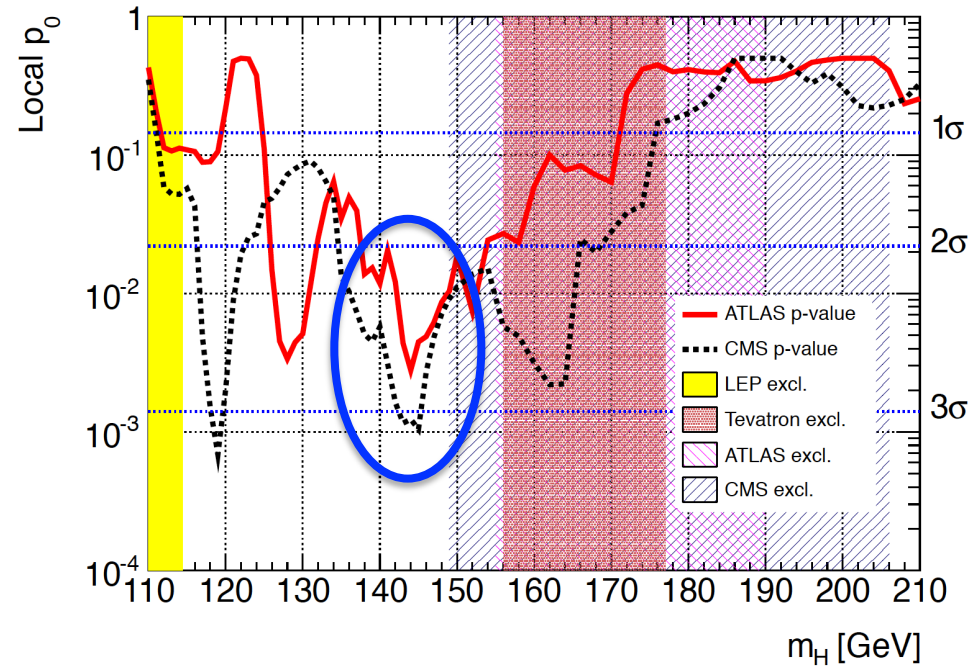
- Many different production and decay mechanisms
 - Span 3 orders of magnitude in cross section and branching ratio
 - Some very clean decays with low BR ($\gamma\gamma$, $4l$)
 - Other very difficult with higher rates (bb , WW , $\tau\tau$,...)
- Access Higgs properties through combination of different channels



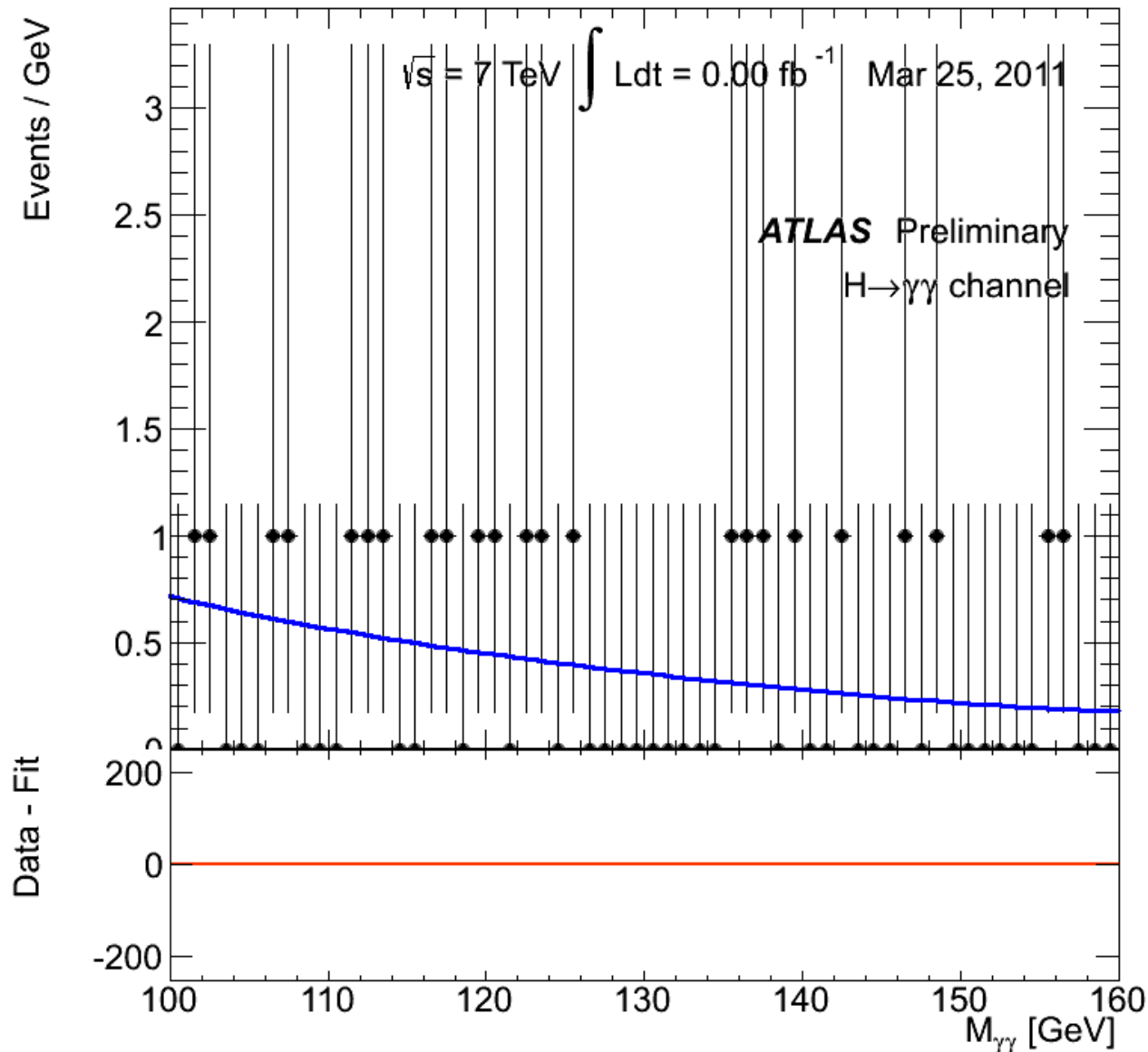
It takes time to get it right



EPS-HEP 2011 conference [6]



2012: Descoberta do bóson de Higgs: $H \rightarrow \gamma\gamma$

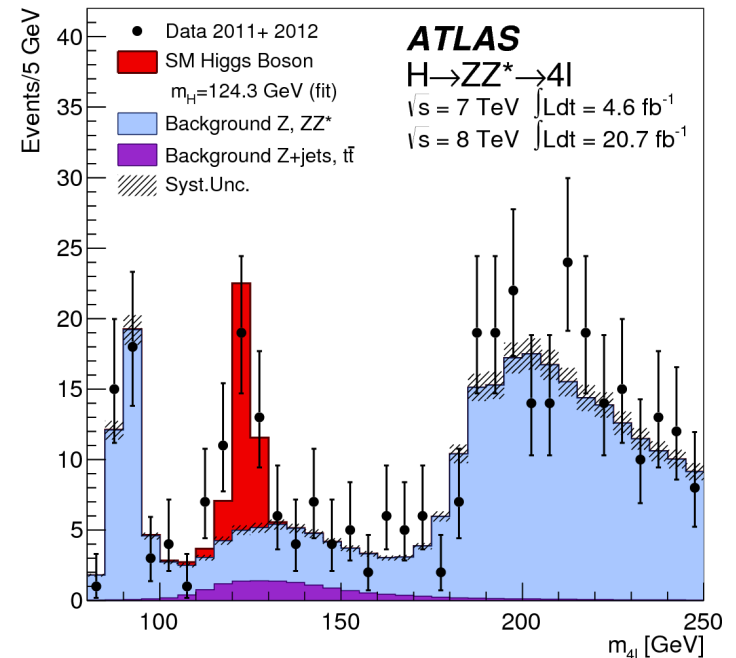
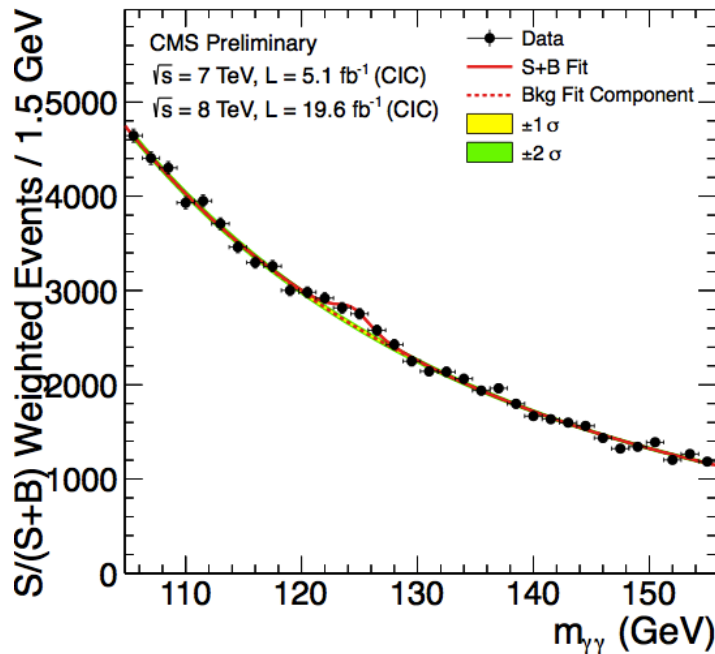


Discovery channels

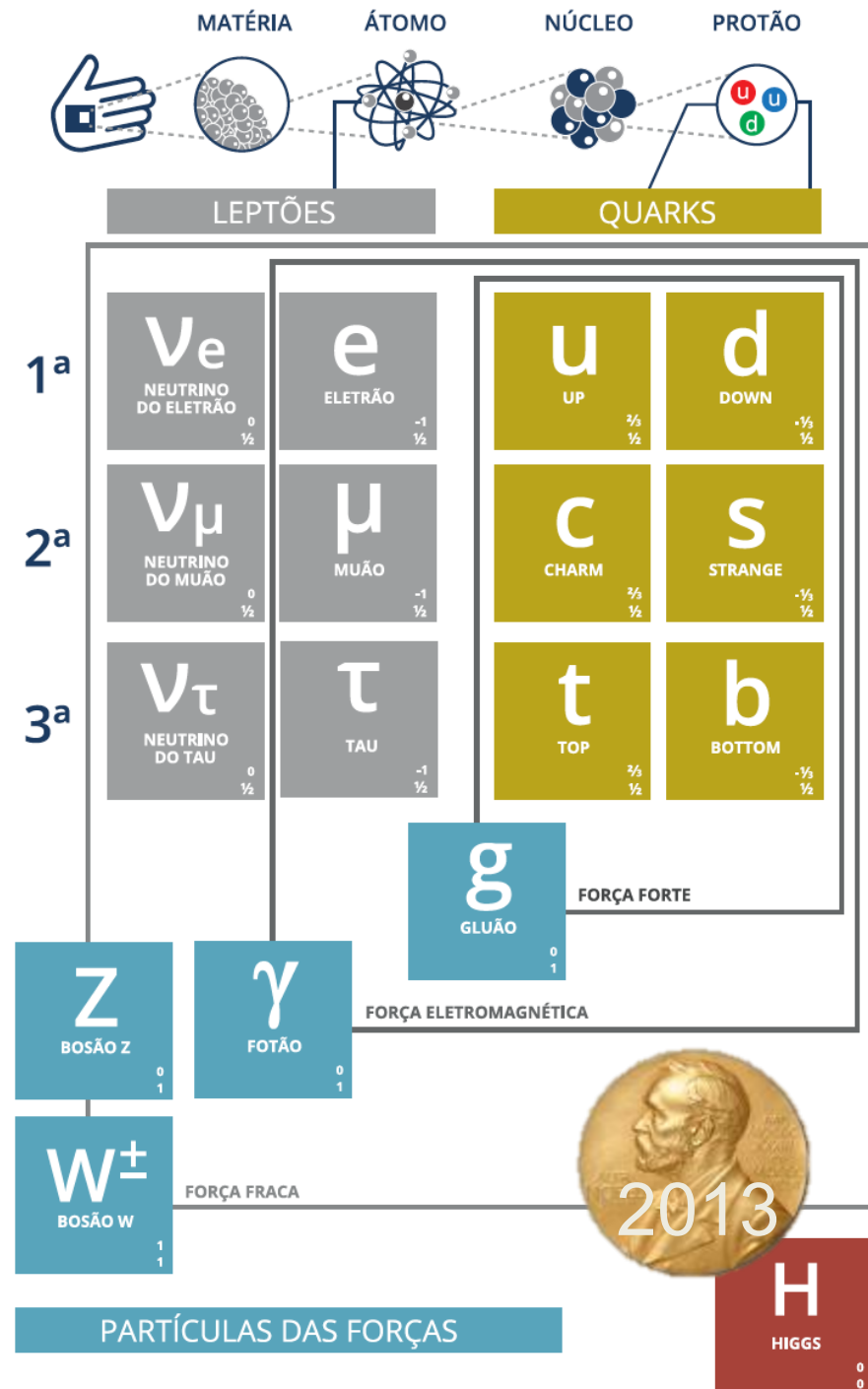
- Discovery was made in ATLAS and CMS with about 5 fb^{-1} of 7 TeV data and 20 fb^{-1} of 8 TeV data per experiment; several channels combined

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

- This means about 400 000 Higgs bosons produced in about 8 000 000 000 000 000 (8×10^{15}) proton collisions
 - Only about 4000 events with Higgs bosons contributed to the discovery



The Standard Model of particle physics completed

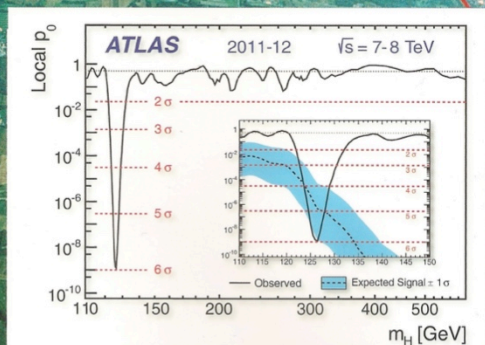
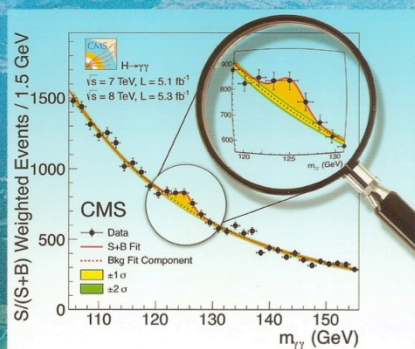


A Descoberta do bóson de Higgs





First observations of a new particle in the search for the Standard Model Higgs boson at the LHC



www.elsevier.com/locate/physletb

Two quotations from the experimental papers presented in this publication:

"... The search for the Higgs boson, the only elementary particle in the Standard Model that has not yet been observed, is one of the highlights of the Large Hadron Collider physics program."

- ATLAS Collaboration

"... The decay to two photons indicates that the new particle is a boson with spin different from one. The results presented here are consistent, ... with expectations for a standard model Higgs boson."

- CMS Collaboration

< Best wishes!
< Peter Higgs

What now?!

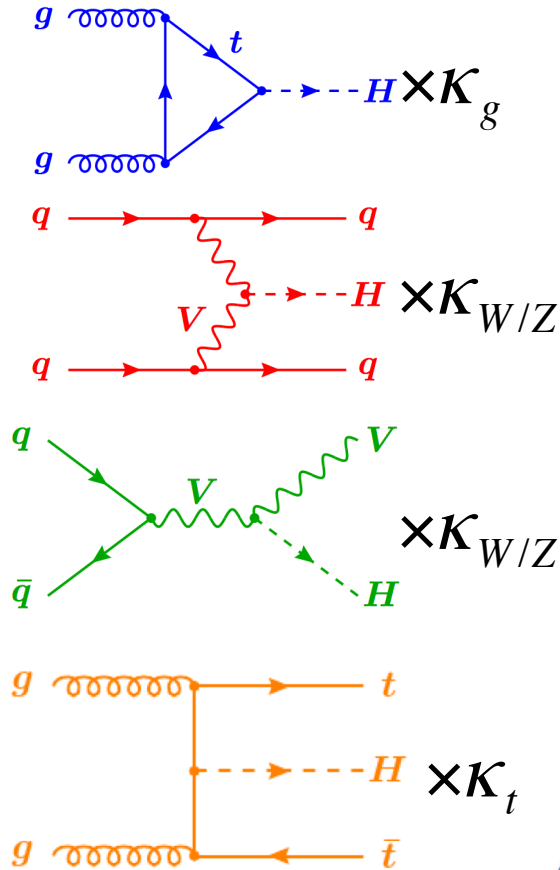


Probing the 125 GeV Higgs

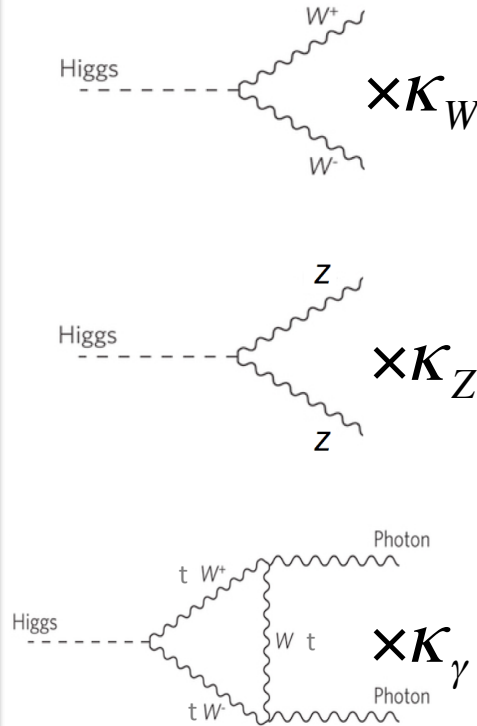


$$\kappa_i^2 = \sigma_i / \sigma_i^{SM} \quad \kappa_f^2 = \Gamma_f / \Gamma_f^{SM} \quad \mu = \frac{(\sigma \cdot BR)^{Obs.}}{(\sigma \cdot BR)^{SM}} = \kappa_i^2 \cdot \kappa_f^2$$

Production

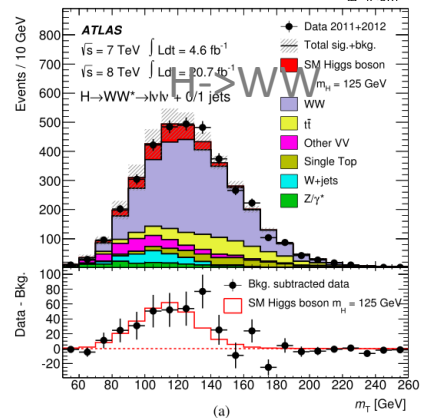
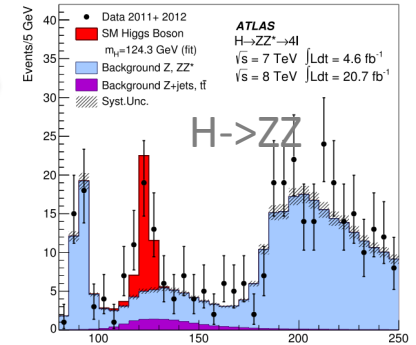
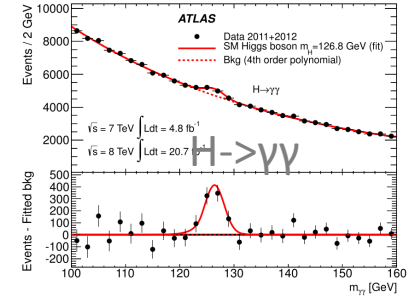


Decay

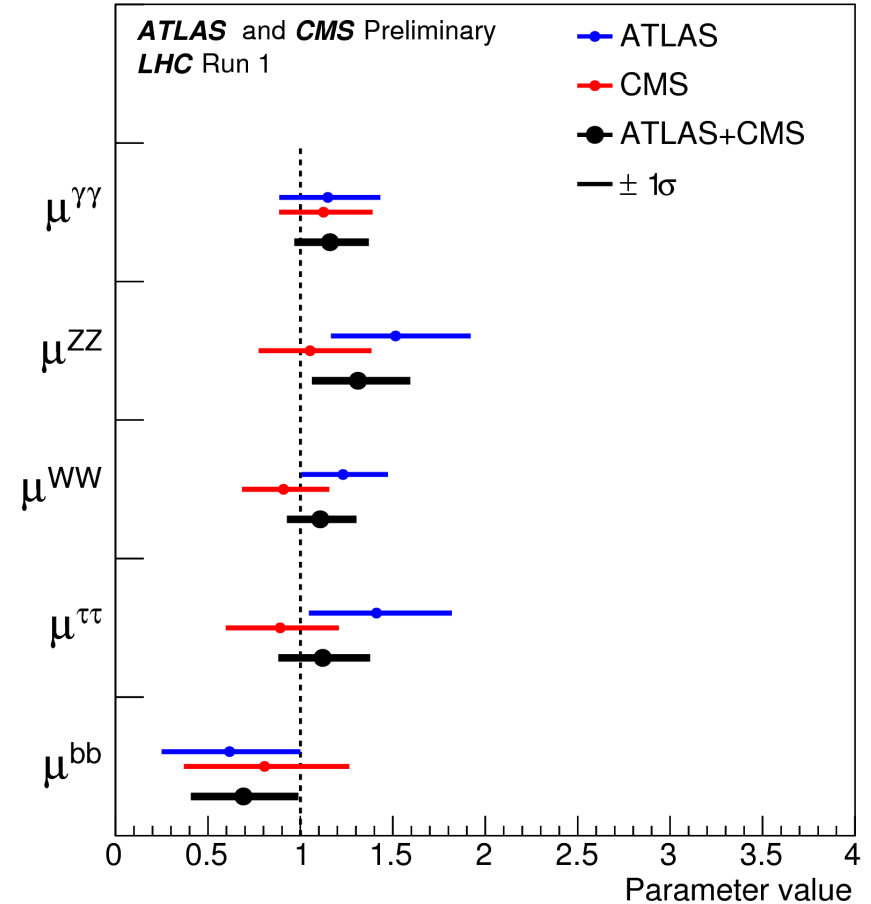
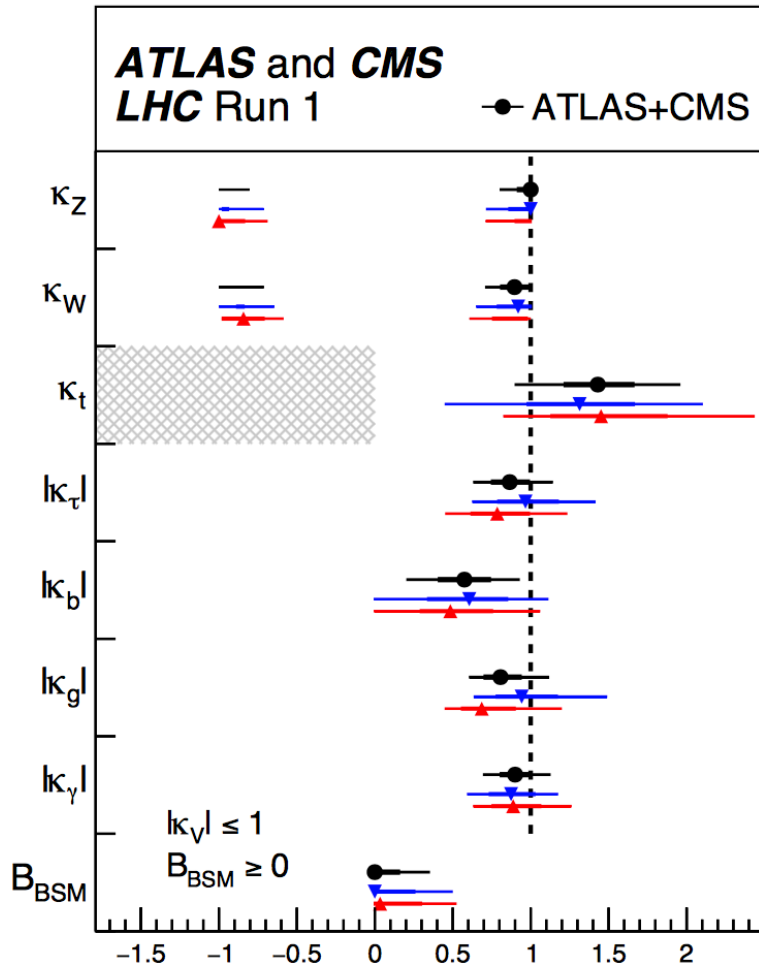


FIT

Backgrounds +

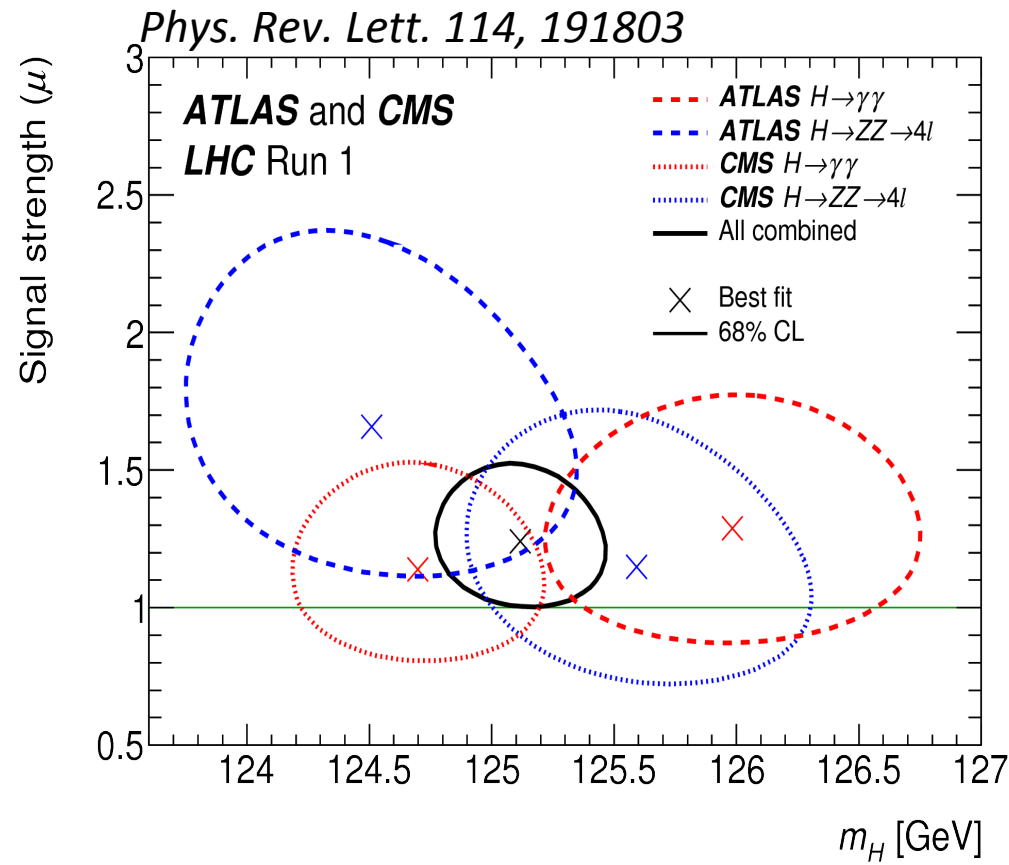


Signal strength measurements



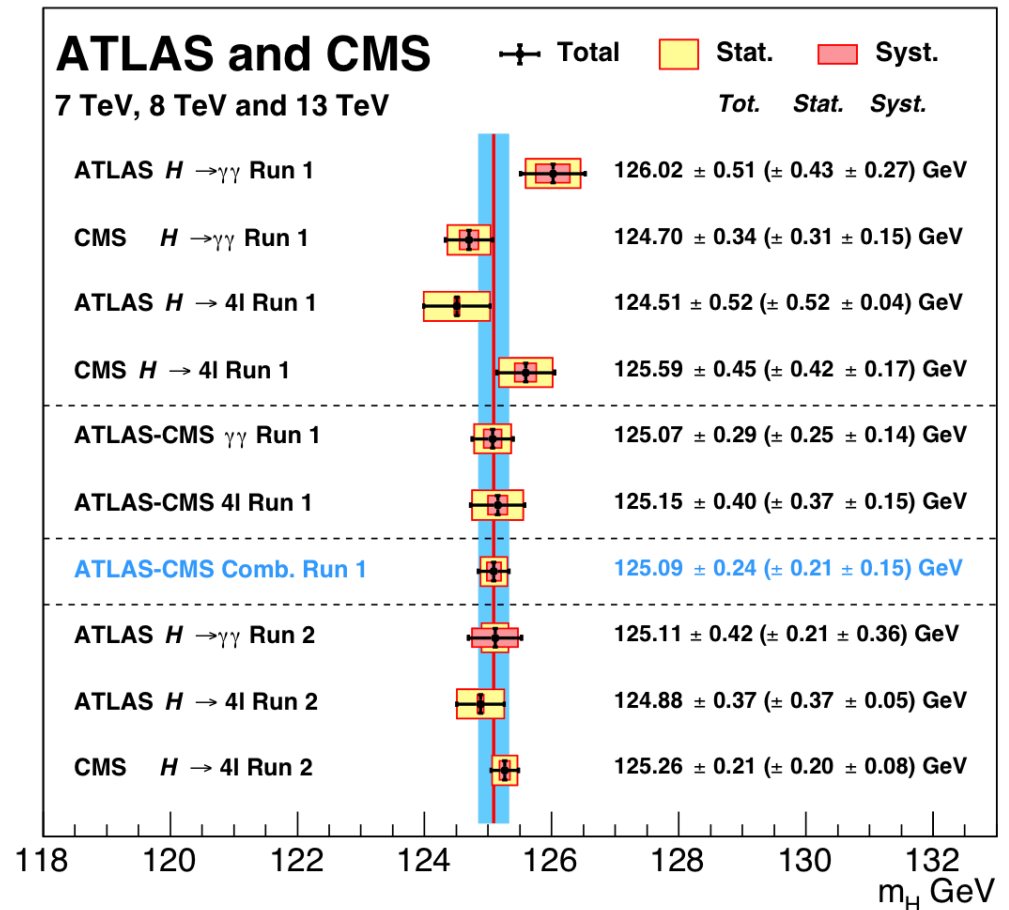
Higgs boson mass

- Mass: around 125GeV
Was the only unknown SM parameter ☺
- For a while, different mass values were being measured in ATLAS and CMS, and in different channels
- Numbers evolved with accumulated statistics



Higgs boson mass

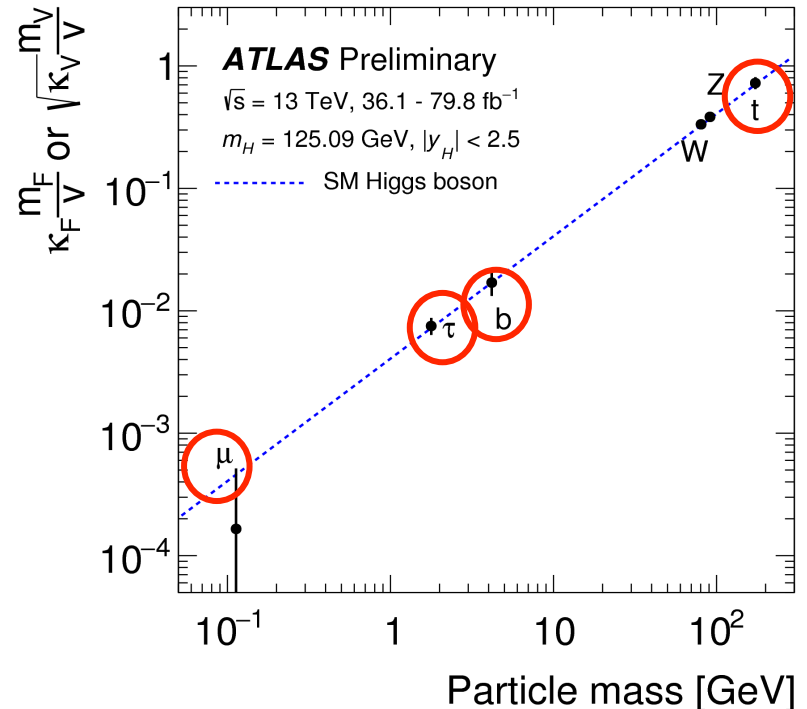
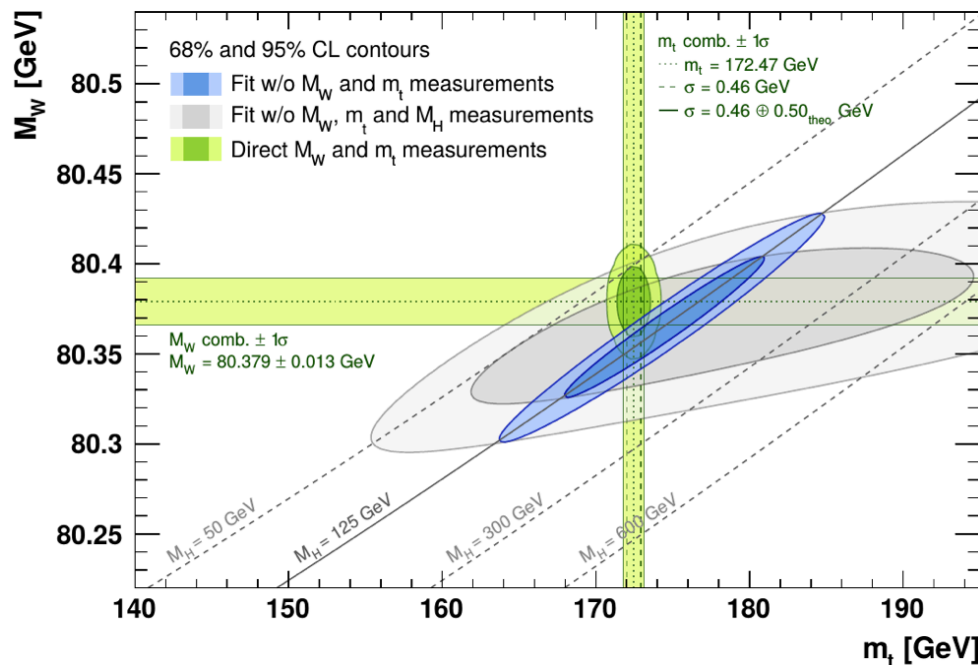
- Mass measurement from
 - $H \rightarrow ZZ^* \rightarrow 4l$
 - $H \rightarrow \gamma\gamma$
- Precision at the permille level achieved



Exploring the electroweak scale

- Precision measurements of m_W , m_t , m_H are stringent tests of the SM at the EW scale
 - E.g. excluding measured m_H , global EW fit gives $m_H = 90 \pm 21$ GeV (1.7σ tension) driven in part by m_{top}

arXiv:1803.01853



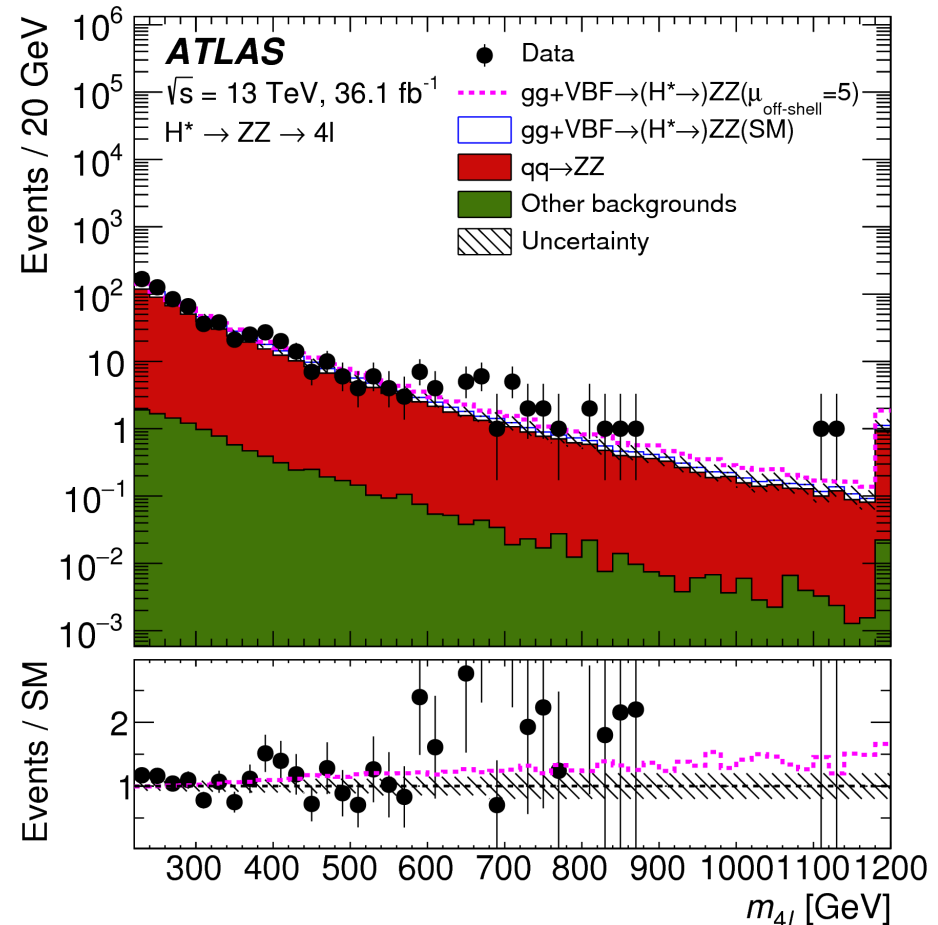
Higgs boson width

- SM Higgs width $\Gamma_H \sim 4.1$ MeV
 - Too small to be measured directly
 - Best direct limit from CMS:
 - $\Gamma_H < 1.1 \text{ GeV}$ @ 95% CL

- Off-shell Higgs production sensitive(*) to Γ_H

$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\kappa_{g,\text{off-shell}}^2 \cdot \kappa_{Z,\text{off-shell}}^2}{\kappa_{g,\text{on-shell}}^2 \cdot \kappa_{Z,\text{on-shell}}^2} \frac{\Gamma_H}{\Gamma_H^{SM}}$$

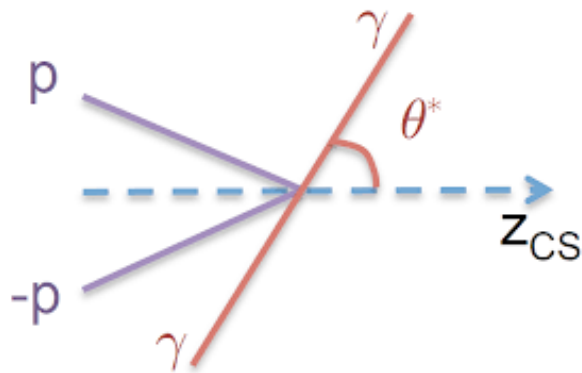
- ATLAS measurement:
 - $pp \rightarrow H \rightarrow ZZ \rightarrow 4l$ and $ZZ \rightarrow 2l2\nu$
 - $m(H) > 2 m(Z)$
 - 36.1 fb⁻¹ of 13 TeV data
 - Observed (expected) limit:
 - $\Gamma_H < 14.4$ (15.2) MeV



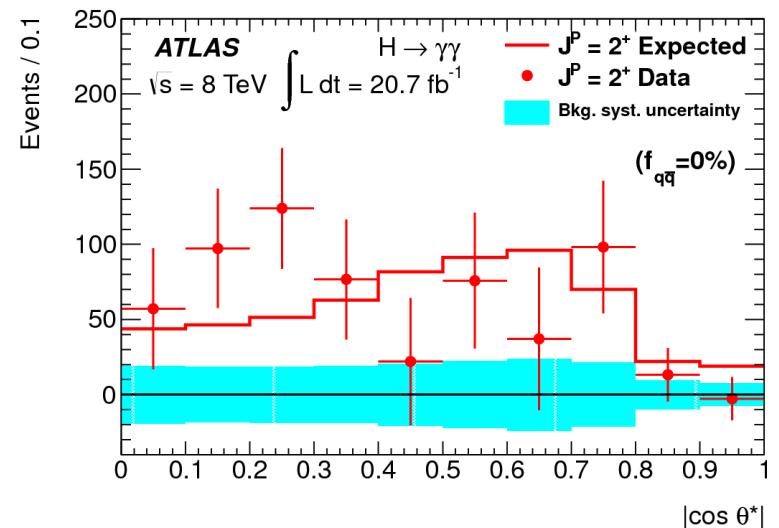
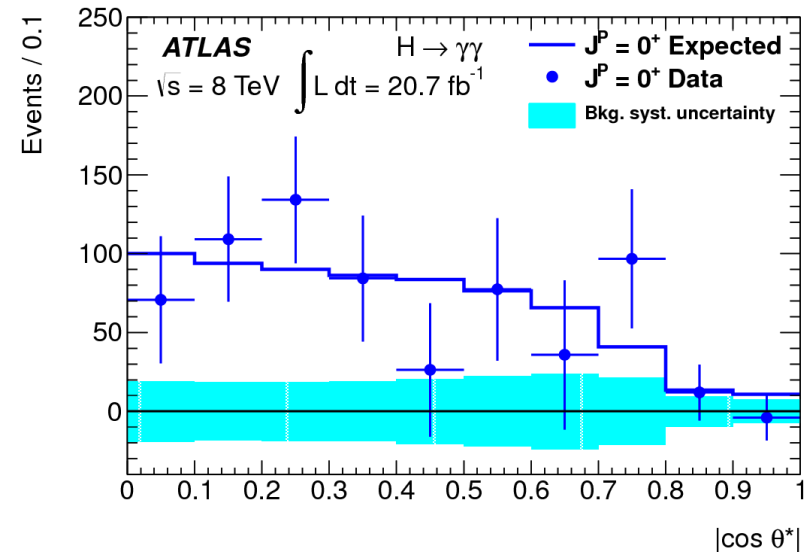
(*) Assume interference term with $gg \rightarrow ZZ$ proportional to $K_{g,\text{off-shell}} \cdot K_{Z,\text{off-shell}}$

Measuring the Higgs Spin

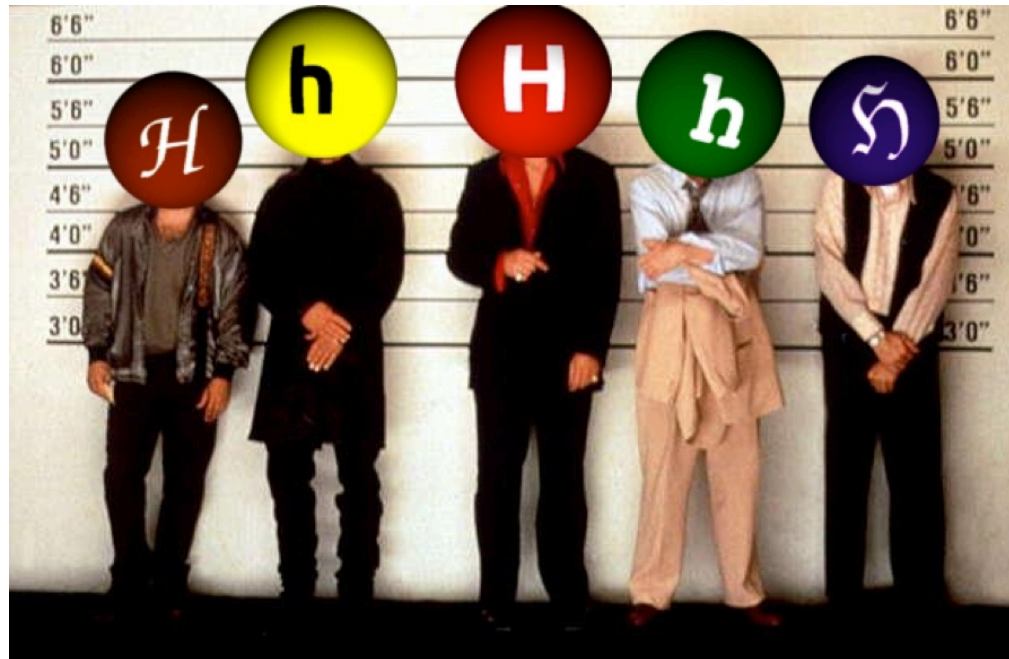
- Polar angle θ in the rest frame of the diphoton system (Collins-Soper frame)



$$|\cos \Theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1 + \frac{p_{T,\gamma\gamma}^2}{m_{\gamma\gamma}^2}}} \frac{2p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

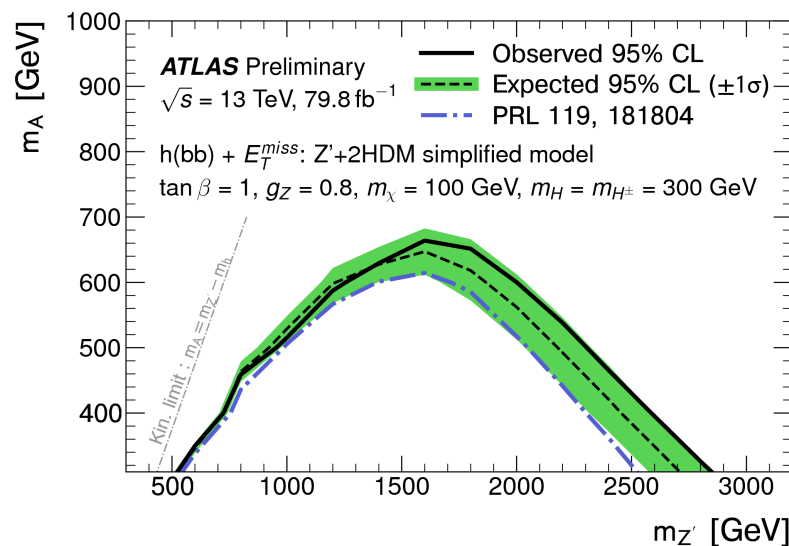
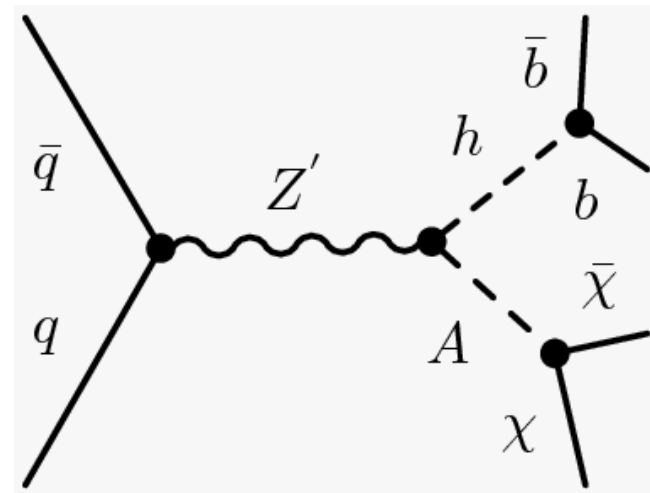


Casting a wider net



Higgs + Dark Matter

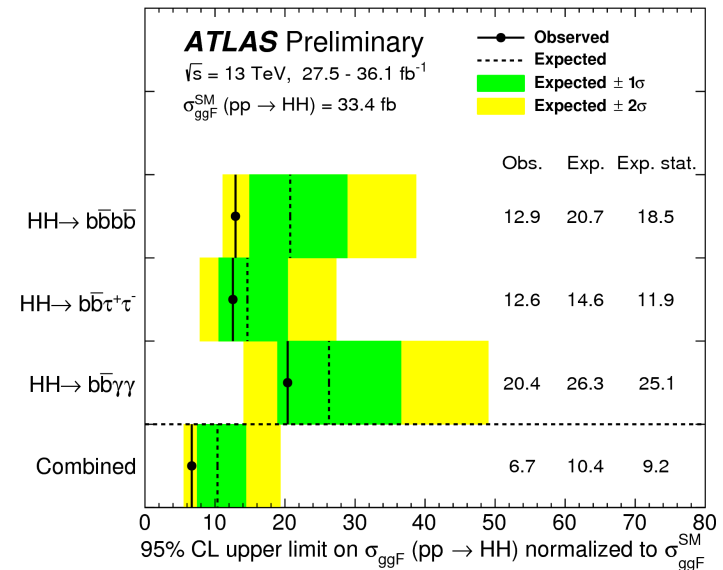
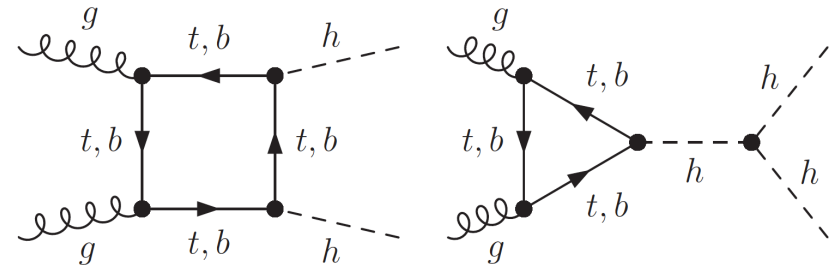
- Used 79.8 fb^{-1} of 13 TeV data
 - High E_T^{miss} ($>150 \text{ GeV}$) and b-tagging to suppress backgrounds
 - Reconstruct b-jets as 2 small jets or merged variable-radius (VR) track jets
- Signal benchmark: Type-II 2HDM + $U(1)_{Z'}$ symmetry (Z'-2HDM)
- Main backgrounds: $t\bar{t}$, W/Z+jets
- Excluded region in $m_A - m_{Z'}$ plane



Triple Higgs coupling

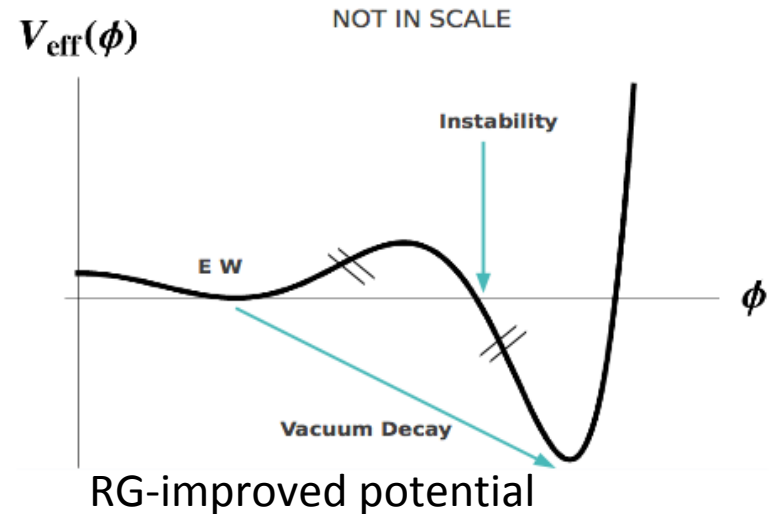
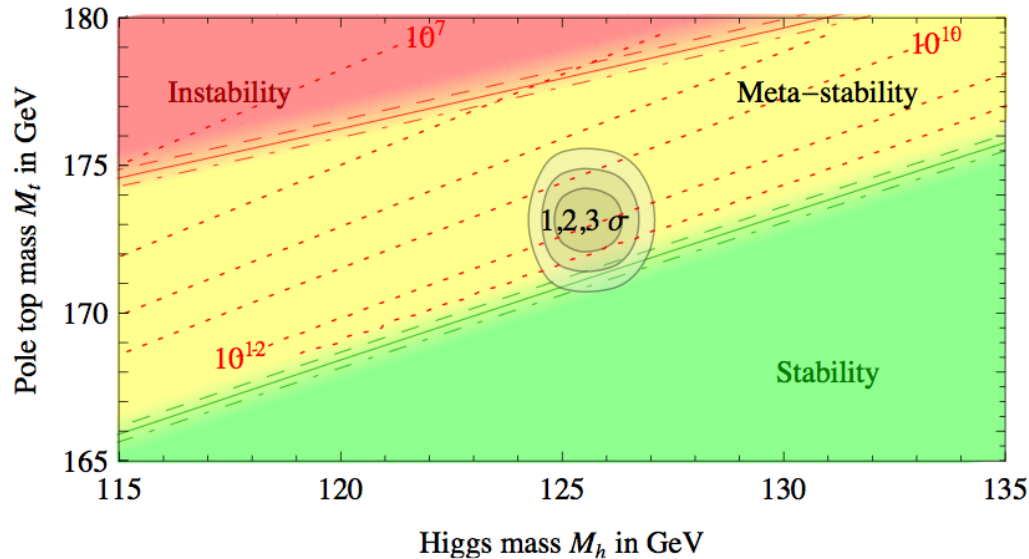
- The triple Higgs coupling λ_{HHH} can be probed through di-Higgs production
- Very suppressed in SM!
 - Negative interference between LO diagrams
 - Cross section 1500x less than ggF
- Wide range of decay BR and channel purity
- bb $\tau\tau$ analysis:
 - Used 36 fb⁻¹ of 13 TeV data
 - Final state BR(bb $\tau\tau$)=7%
 - Non-Resonant 95% CL limit:
 $\mu < 12.7$ observed (14.8 expected)
- Combination: at $\approx 10 \times$ SM sensitivity**
 - with 3% of the HL-LHC luminosity analyzed

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



Di-Higgs combination plot [here](#)

A bit of fun...



- 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 \Rightarrow 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. Degraassi et al, arXiv:1205.6497v2; R.Contino, Workshop sulla fisica p-p a LHC, 2013

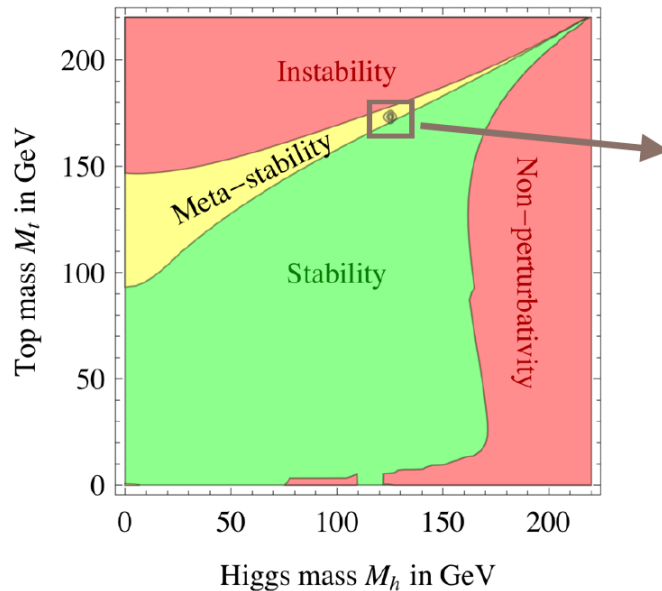
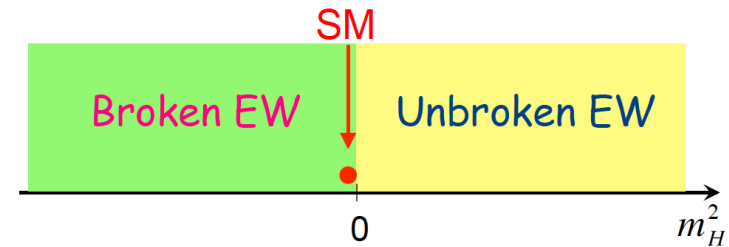
The universe seems to live near a critical condition

JHEP 1208 (2012) 098

Why?!

Explained by underlying theory?

Anthropic principle?



Higgs @ LIP ATLAS Group

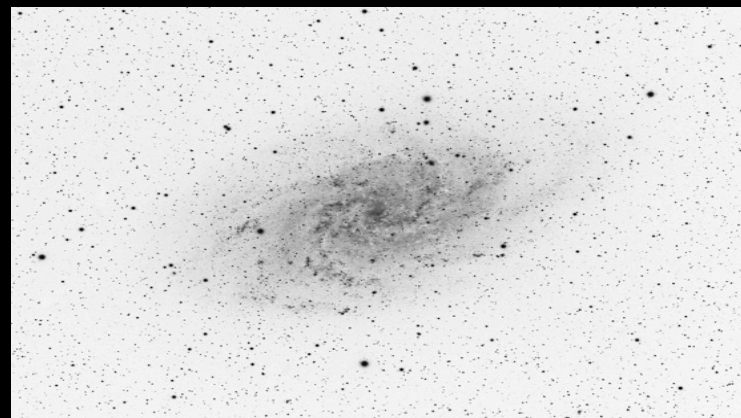
- Exploring Higgs couplings to heavy quarks
- Less well known... Much more space for surprises!
- New physics effects may show up already at leading order



2018: Hbb and Htt couplings demonstrated
2020: CP of ttH coupling in ttH, H- $\gamma\gamma$
2022: ttH, H- $\gamma\gamma$ fiducial cross section
2022: Preliminary results for CP of ttH coupling studied in ttH, H- $\gamma\gamma$

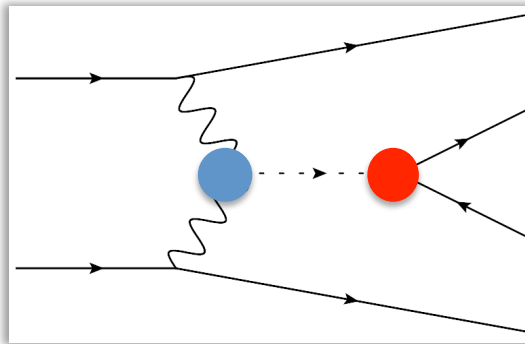
ttH CP measurement

- Sakharov conditions for a matter-dominated universe require CP violation
- Known CP-violating processes:
 - From complex phases in CKM-matrix - quark mixing
 - Maybe in PNMS-matrix as well - neutrino mixing
- BUT: insufficient, by orders of magnitude
- CP violation in Higgs sector?
 - Possible in some models with extended Higgs sector (e.g. some 2HDMs)
 - Need **mixing** of scalar (CP-even) and pseudo-scalar (CP-odd) Higgs states
- What do we know about Higgs CP properties?
 - In the SM, Higgs scalar is a CP eigenstate with $J^{CP} = 0^{++}$
 - Pure $J^P = 0^-$ hypothesis for observed Higgs boson was ruled out in Run 1
 - But a **large** CP-odd admixture is not ruled out



How to search for a CP-odd admixture?

- Effect of CP-odd components on **bosonic couplings** parametrized as expansion with higher order terms suppressed by powers of scale of new physics Λ
- Could explain why a CP-odd admixture has not been seen

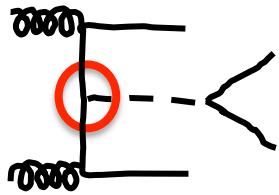


- **Fermionic couplings** are affected at tree level
- Mixing angle α between CP-even and CP-odd coupling components
- More notable for heavier fermions due to enhanced coupling

$$\mathcal{L}_{VVH} = \mathcal{L}_{VVH,SM} + \frac{1}{\Lambda^2} c \phi \tilde{V}_{\mu\nu} V^{\mu\nu} + \dots$$

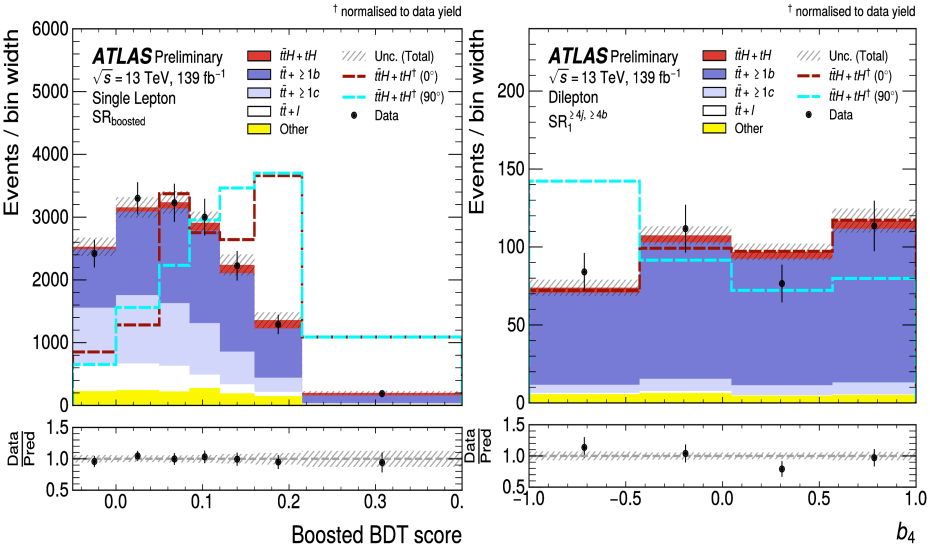
$$\mathcal{L}_{ffH} = \kappa'_f y_f \phi \bar{\psi}_f (\cos \alpha + i \gamma_5 \sin \alpha) \psi_f$$

H-top Coupling in ttH/tH production

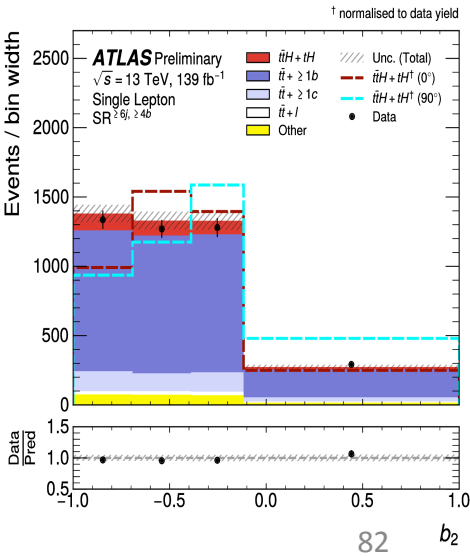


- Calculate CP-sensitive observables b_2 and b_4 from top-quark 3-momenta
- Use different observables in combined fit depending on region

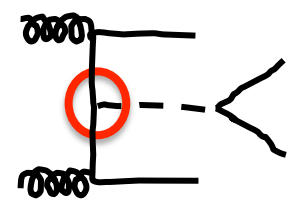
$$b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|} \quad b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|}$$



Channel (PSR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton (PSR $^{\geq 4j, \geq 4b}$)	CR $^{\geq 4j, \geq 4b}_{\text{no-reco}}$	–	$\Delta\eta_{\ell\ell}$
	CR $^{\geq 4j, \geq 4b}$	BDT $\in [-1, -0.086)$	b_4
	SR $^{\geq 4j, \geq 4b}_1$	BDT $\in [-0.086, 0.186)$	b_4
	SR $^{\geq 4j, \geq 4b}_2$	BDT $\in [0.186, 1]$	b_4
ℓ + jets (PSR $^{\geq 6j, \geq 4b}$)	CR $^{\geq 6j, \geq 4b}_1$	BDT $\in [-1, -0.128)$	b_2
	CR $^{\geq 6j, \geq 4b}_2$	BDT $\in [-0.128, 0.249)$	b_2
	SR $^{\geq 6j, \geq 4b}$	BDT $\in [0.249, 1]$	b_2
ℓ + jets (PSR $_{\text{boosted}}$)	SR $_{\text{boosted}}$	BDT $\in [-0.05, 1]$	Classification BDT score



H-top Coupling in ttH/tH production



Simultaneous fit in all regions

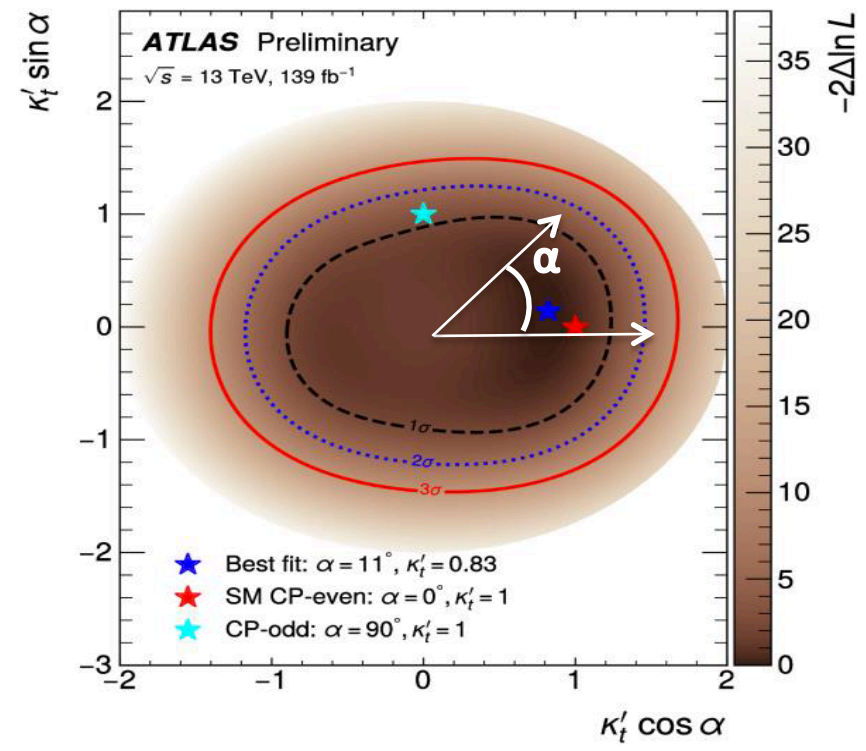
- $\mu = 0.83^{+0.30}_{-0.46}$
- $\alpha = 11^\circ \text{ }^{+55}_{-77}$

Expected:

- $\mu = 1.0^{+0.25}_{-0.27}$
- $\alpha = 0^\circ \text{ }^{+49}_{-50}$
- Pure CP-odd ($\alpha = 90^\circ$) disfavoured at **1.2 σ**

Complementary to previous ttH($H \rightarrow \gamma\gamma$) analysis:

- [Phys. Rev. Lett. 125 \(2020\) 061802](#)
- Pure CP-odd ($\alpha = 90^\circ$) excluded at **3.9 σ**
- Limit on **$|\alpha| < 43^\circ$** at 95% C.L.

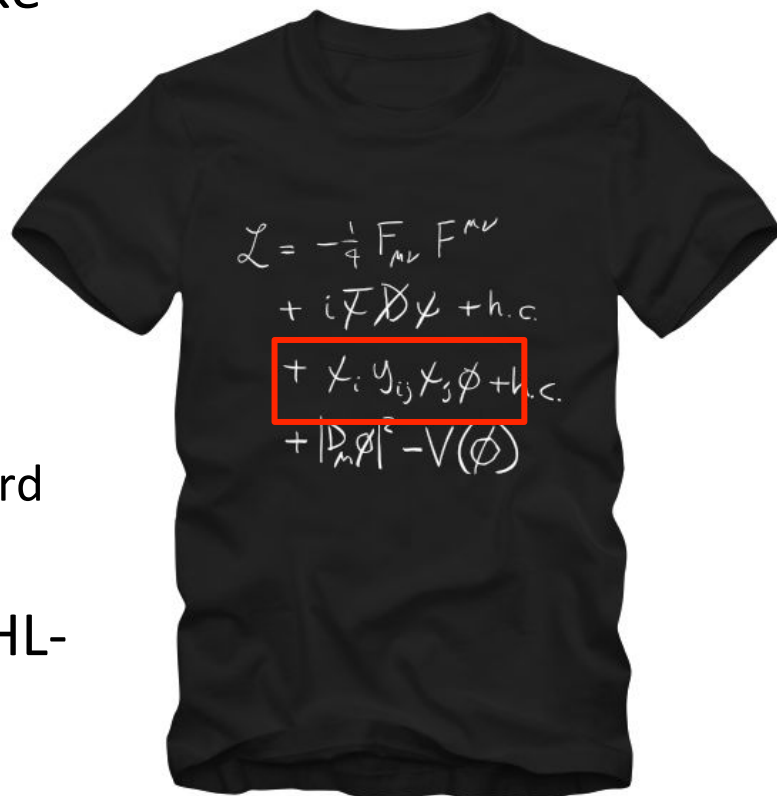


$$\mathcal{L}_{t\bar{t}H} = -\kappa'_t y_t \phi \bar{\psi}_t (\cos \alpha + i \gamma_5 \sin \alpha) \psi_t$$

Summary

- Higgs sector measurements look SM-like so far
- **But there is new physics out there!**
- The Higgs is:
 - The only fundamental scalar
 - Connected to EW symmetry breaking
 - A great window to look beyond the Standard Model
- And we have only collected $\approx 5\%$ of all HL-LHC data!

Watch this space!





Questions?

Thank you
for your
interest!

jgoncalo@lip.pt

05.12.22

R.

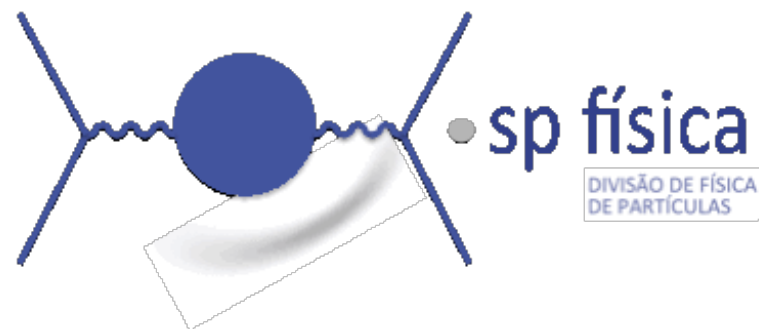
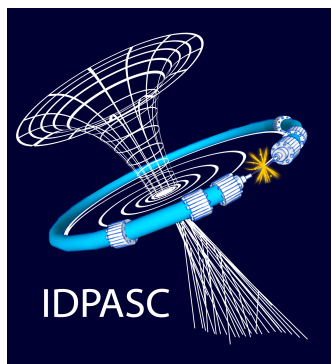
SAY GOD PARTICLE



**ONE MORE
GODDAMN TIME**



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