fundamental interactions

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FUNDAMENTAL FORCES

force	range	strength	acts on
gravity	∞	$G_{Newton} \approx 6 \times 10^{-39}$	all [massive] particles
weak [nuclear]	$< 10^{-18}$ m	$G_{Fermi} \approx 1 \times 10^{-5}$	leptons, hadrons
electromagnetism	∞	$\alpha = 1/137$	all charged particles
strong [nuclear]	$\approx 1 \times 10^{-15}$ m	$g^2 \approx 1$	hadrons

- all natural phenomena result from the effect of just four fundamental forces [the unifying power of Physics]
- all phenomena experienced in everyday life are explained by just two: gravity and electromagnetism [those with infinite range]

[DISCLAIMER] I WILL NOT TALK ABOUT GRAVITY

- gravity will be conspicuously absent from my discussion
  - I will only discuss physics at scales [small yet sufficiently large] and for masses [small] for which gravity effects are negligible
  - I will focus on quantum descriptions of fundamental interactions
    - a consistent quantum theory of gravity remains elusive

[José Sande Lemos, Thu & Fri & Sat]

ELECTROMAGNETISM

- in the classical regime all electromagnetic phenomena are described by Maxwell's equations
  - can calculate, for example, electric field due to a given configuration of charges; the wave equation for propagation of electric and magnetic fields through space; ...
  - the concept of field appears naturally
- the extension of electromagnetism to the quantum level requires that we describe the interactions of charged particles via the electromagnetic field as exchanges of quanta of the field [photons] between the particles involved [we will get to this]

A NOTE ON NATURAL UNITS

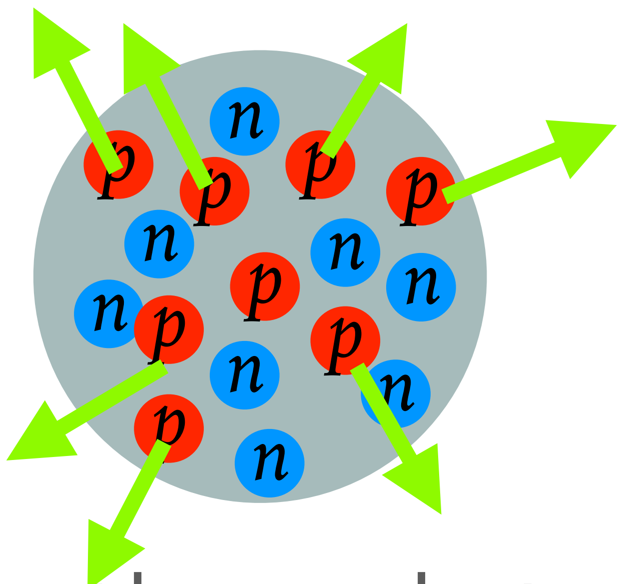
- particle physics [study of elementary particles and their interactions] uses a fit-for-purpose system of units, so-called natural, where $\hbar = c = k_B = 1$
- the fundamental unit is chosen to be the electron-volt, defined as the energy of an electron that has been accelerated through a potential difference of one volt [$1\text{eV} = 1.602 \times 10^{-19}$ J]
- Then:
  - momenta, energy, mass and temperature expressed in the same units [eV]
  - time and spatial coordinates expressed in the same units [1/eV]
  - ...

THE STRONG [NUCLEAR] FORCE

- the discovery of the neutron [Chadwick 1932] and thus that atomic nuclei are made of protons and neutrons, implies that:
  - a new force must exist to compensate the electric repulsion of protons and render atomic nuclei stable

THE STRONG [NUCLEAR] FORCE

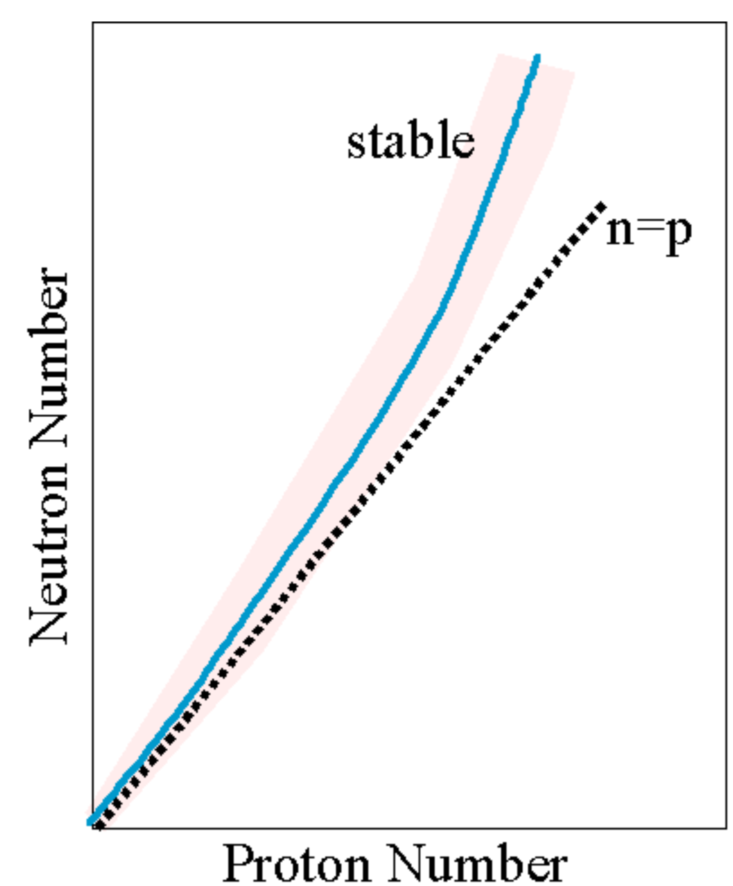
- must be strongly attractive



- must be very short range
  - Rutherford's early scattering experiments [low energy] of α-particles [He nuclei] on atomic nuclei could be explained by EM alone
  - only at higher energies [when α-particles can approach the nuclei more closely] the effects of the strong force are felt
  - strong force only 'active' when nucleons 'touch' :: range of the order of nuclear diameter [10^{-15} m = 1 fm] :: timescale of the order 10^{-23} s [10 ys]
  - must be independent of electric charge [act equally on protons and neutrons]

THE STRONG [NUCLEAR] FORCE

- in general heavier nuclei are more unstable [they decay]
  - supports picture of binding force having short range
    - if long range, the more nucleons the more stable
    - if just nearest neighbours than strong force on extra nucleon does not compensate electric repulsion amongst protons



THE STRONG [NUCLEAR] FORCE

- what is still missing from the discussion?
  - we want to describe strong interactions between elementary particles [which are not the protons and neutrons]
  - we will see later that the strong interaction can, in fact, be described [almost] analogously to the electromagnetic case

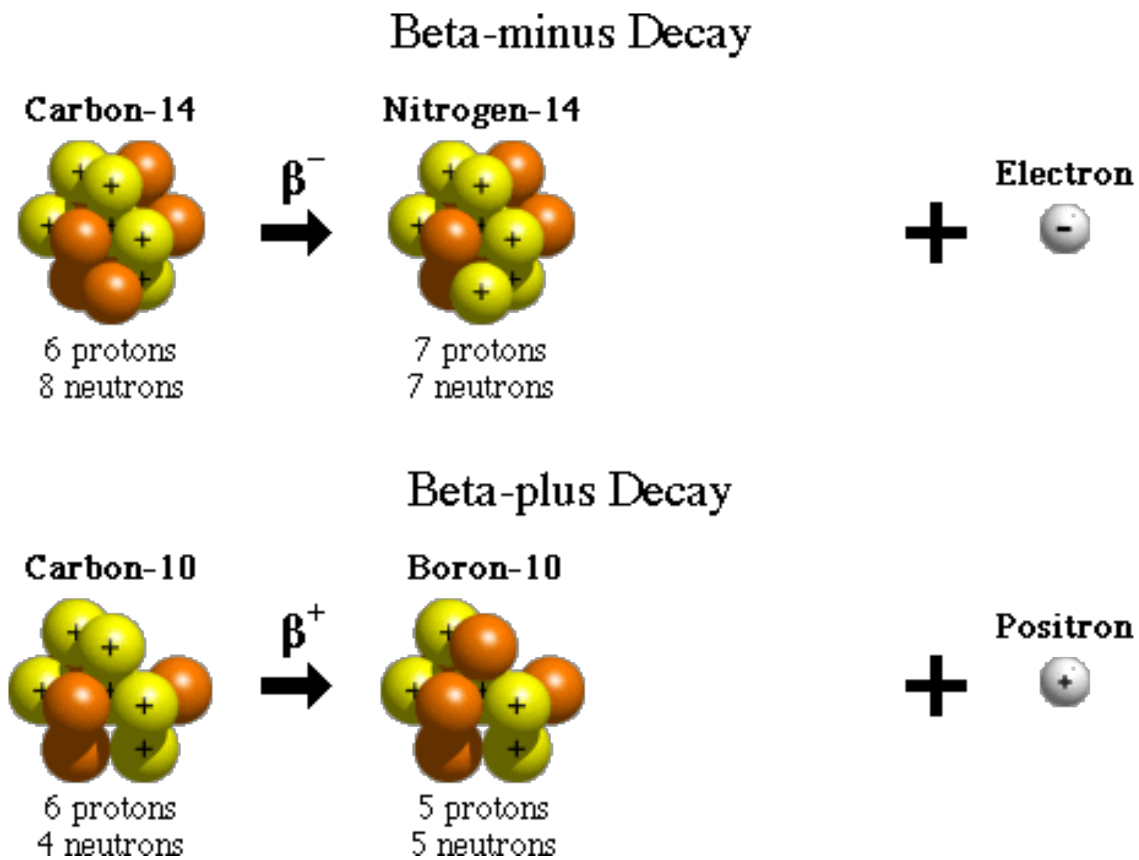
THE WEAK [NUCLEAR] FORCE

- the neutron decays spontaneously to a proton and an electron with a half-life [average time it takes for half of a sample to decay] of about 10 minutes
  - as this is much longer than the time-scales associated with the strong interaction [$\sim 10^{-23}$ s] and it is difficult to conceive how EM interactions could contribute to this process
    - neutron decay must be due to some new force :: weak force
    - half-life of 10 min results from weakness of the interaction and small mass difference between neutron and proton

THE WEAK [NUCLEAR] FORCE

THE WEAK [NUCLEAR] FORCE

- the weak force underlies the radioactive β decay of nuclei



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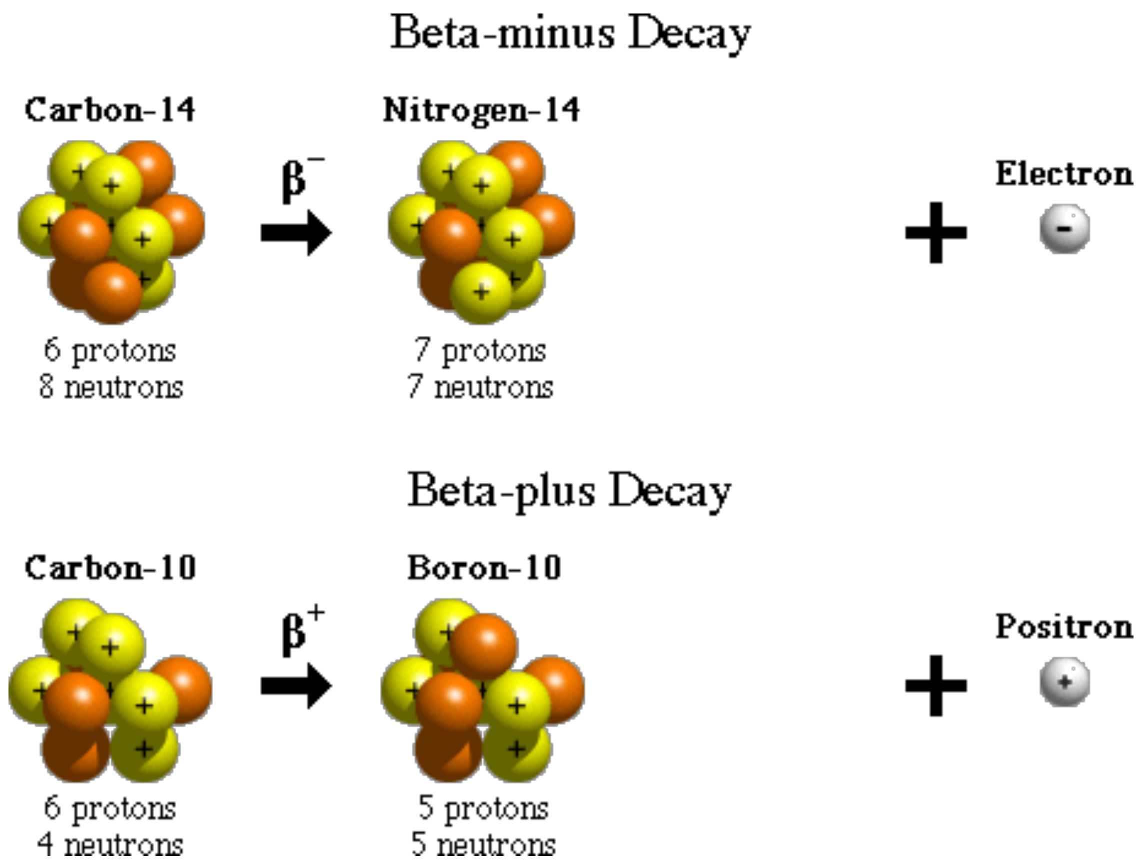
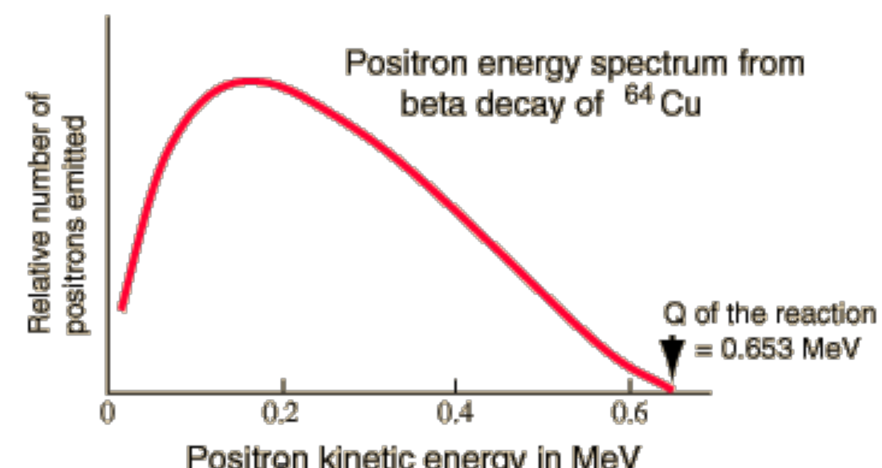
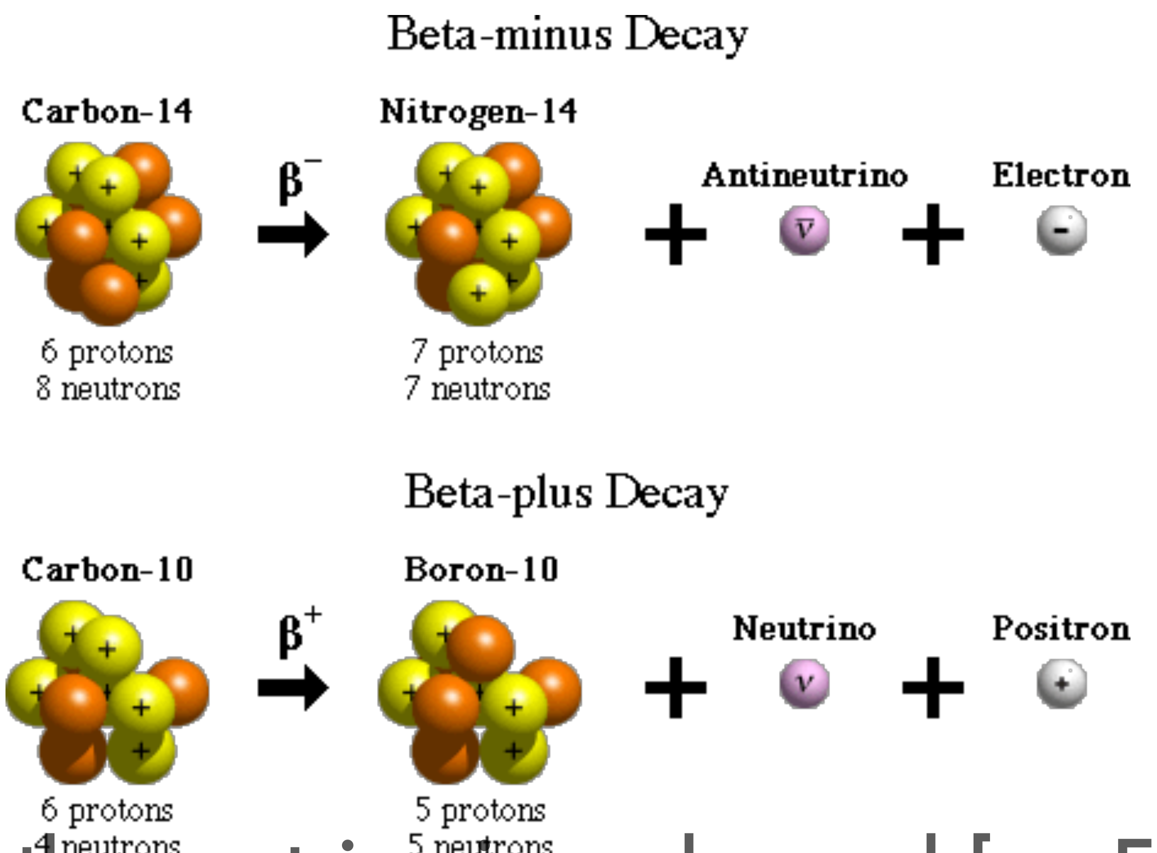




- however, the electron [or positron] emerges with energy up to [but not always equal to the mass difference of the initial and final nuclei] :: apparent violation of energy conservation [also angular momentum]

THE WEAK [NUCLEAR] FORCE

- Pauli [1930] postulated that a new invisible particle was also emitted in the decay and carried the missing energy [and angular momentum] :: the neutrino [named by Fermi]



- the neutrino is uncharged [no EM interactions]
- the neutrino 'invisibility' follows from the weakness of the weak interaction

THE PROGRAMME

- describe the [3] interactions experienced by the fundamental constituents of matter [elementary particles] in a unified theoretical framework
  - need to identify elementary particles
- theoretical description should/must:
  - respect relativistic invariance [as to make sense for speeds close to that of light]
  - respect quantum mechanics [as to make sense for small scales]
  - reflect fundamental symmetries
  - be consistent with experimental observations

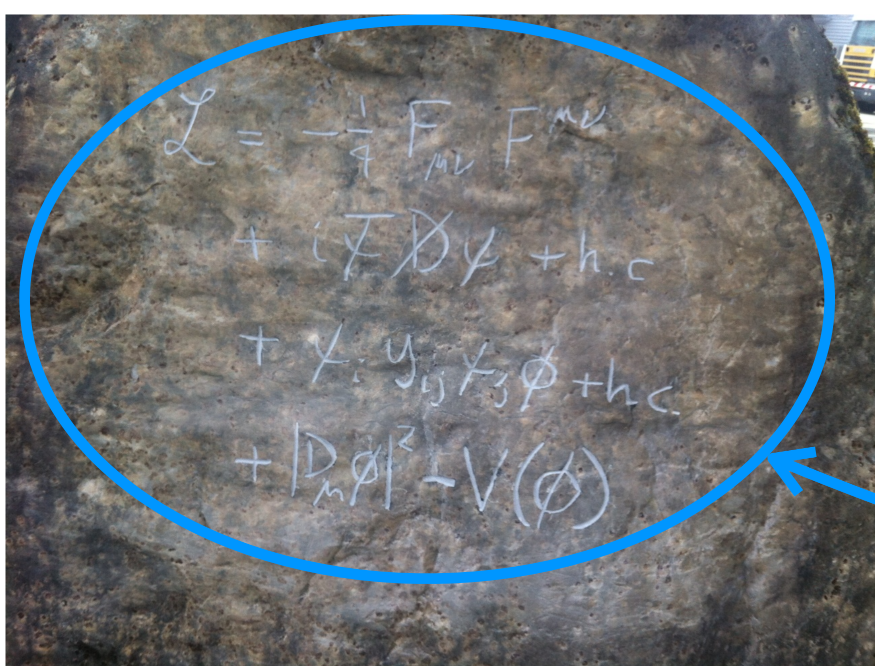
A NOTE ON UNIFICATION

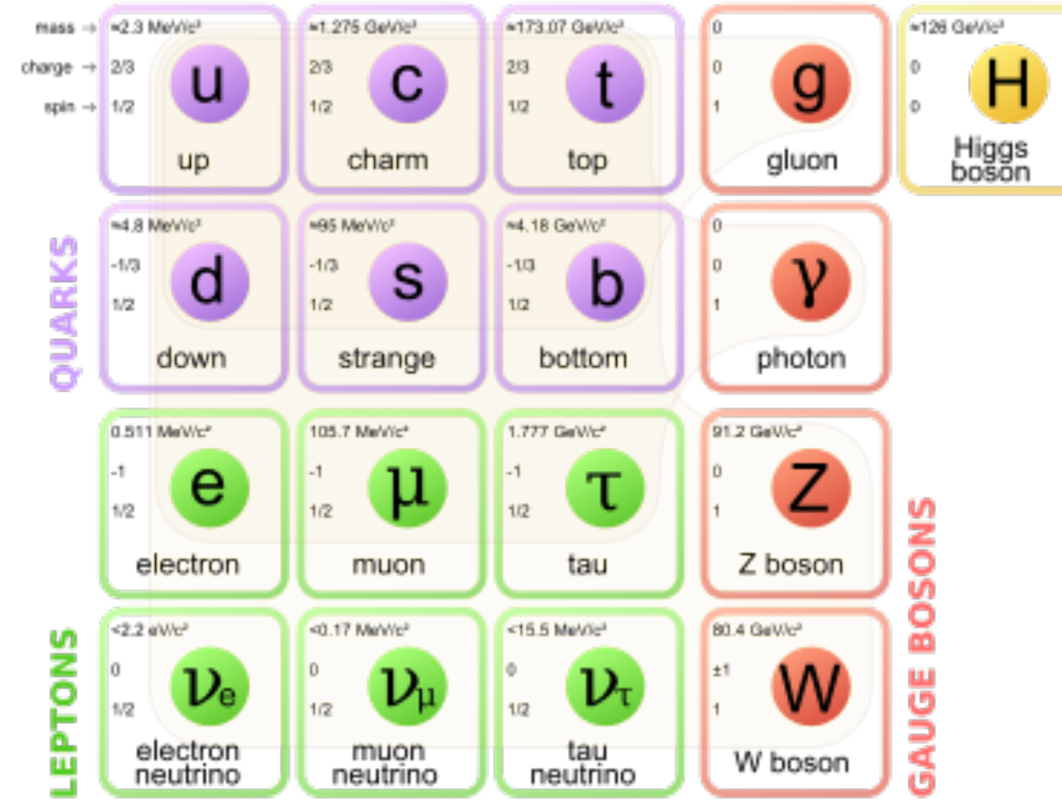
- distinguish two varieties of unification
  - physical unification :: understanding of distinct forces as manifestations of a common underlying interaction
    - electromagnetism = electricity + magnetism
    - [a further important example will come later]
  - formal :: description of distinct fundamental interactions within an unified theoretical formalism [common language fulfilling generic fundamental principles]
    - the focus of these lectures

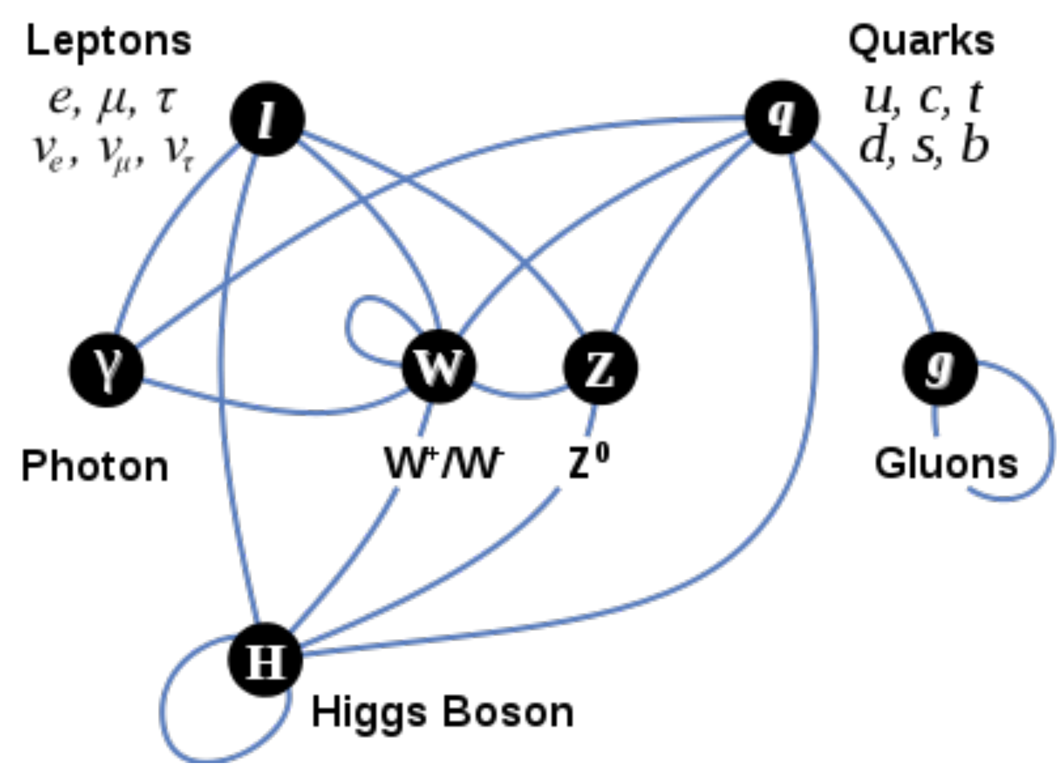
THEORETICAL FRAMEWORK

- fundamental interactions [electromagetic, weak and strong OR as we will see later electro-weak and strong] are described by Renormalizable Relativistic Quantum Gauge Field theories
  - relativistic: the theories are Lorentz invariant
  - quantum: degrees of freedom are quantized
  - gauge: symmetry [we will get there]
  - field: the fundamental degrees of freedom are fields [objects that have a value – number, vector, higher tensor – in each space-time points]
  - renormalizable: no physical infinities

[PREVIEW] THE STANDARD MODEL







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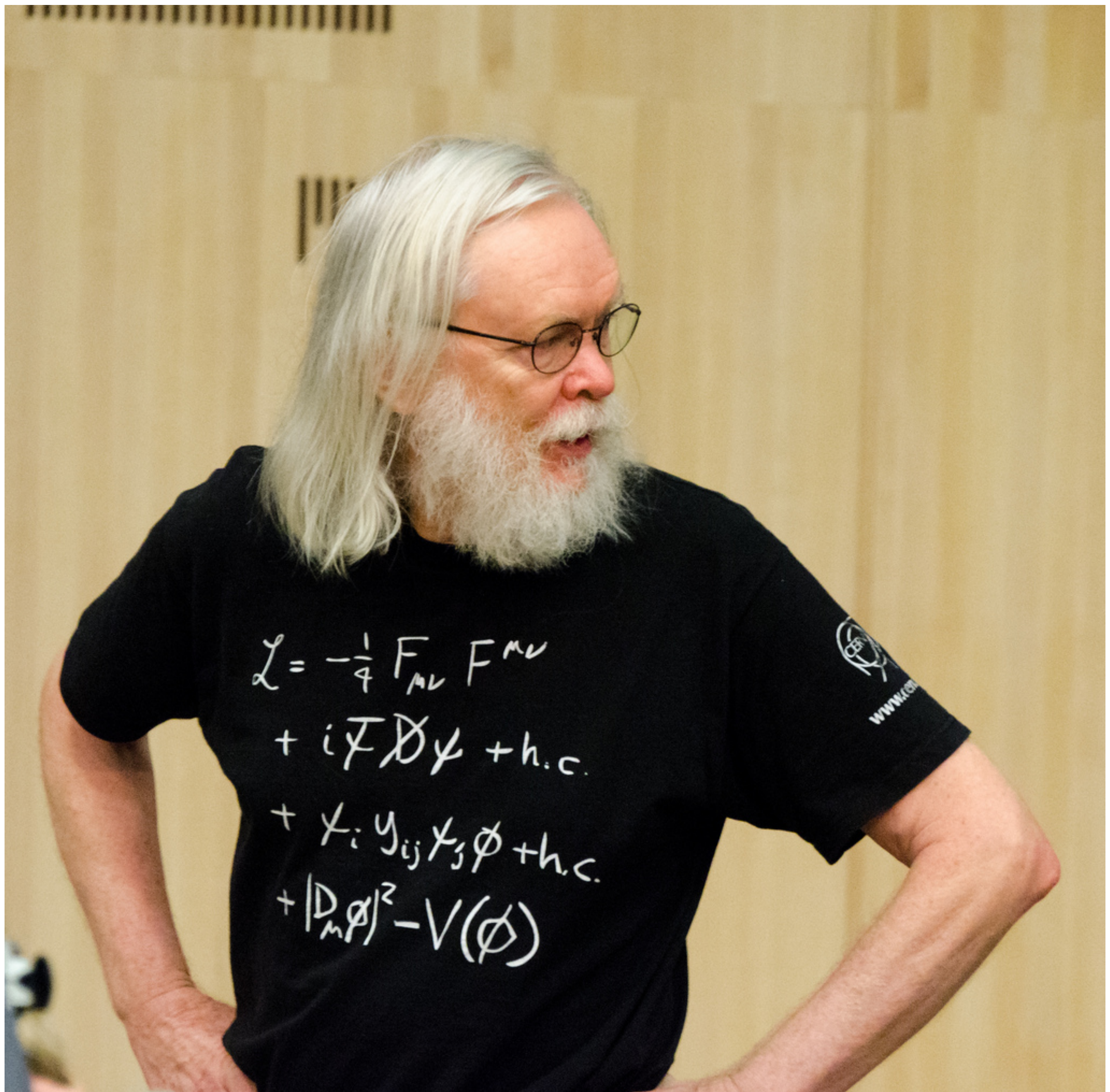

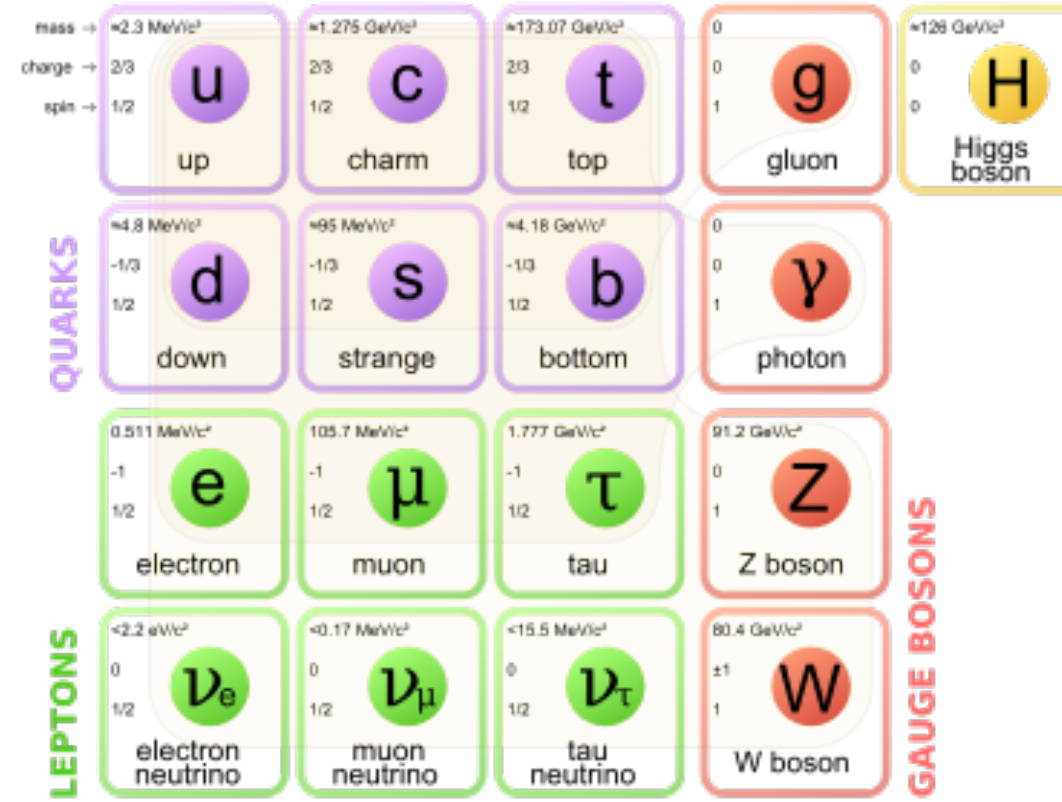

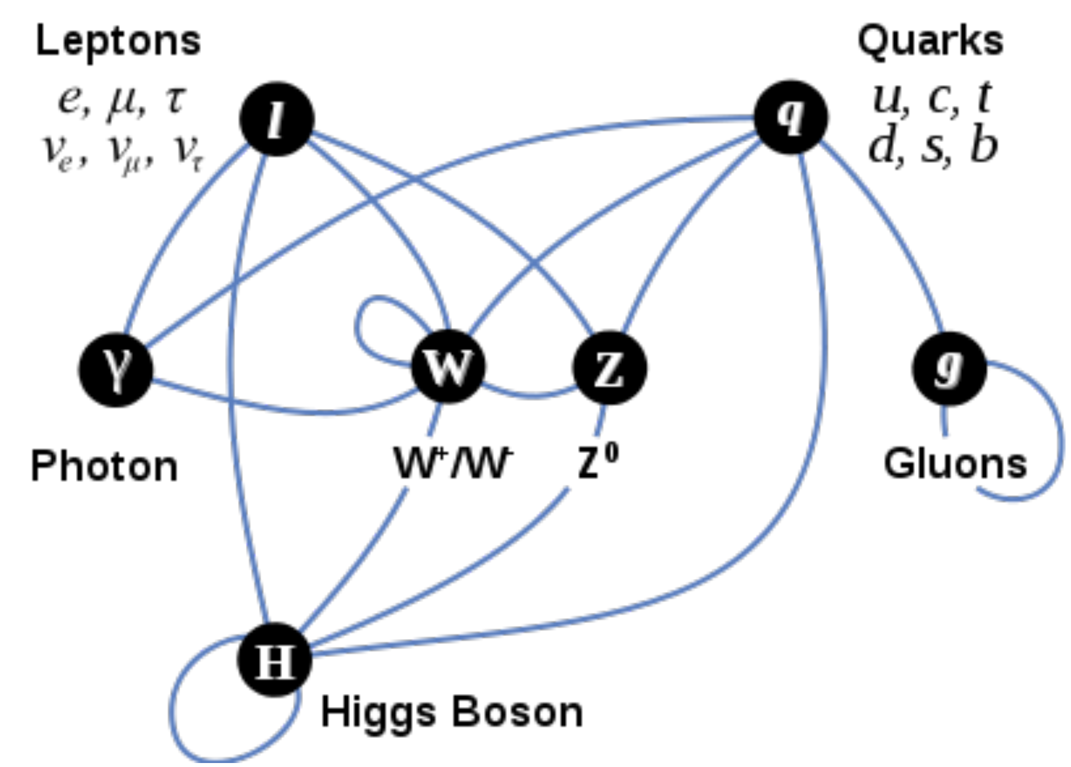

RELATIVISTIC INVARIANT QUANTUM MECHANICS

- The Schrodinger equation, which describes the time evolution of a wave function [a quantum system]

$$i\frac{\partial}{\partial t}\psi(\mathbf{x},t) = -\frac{1}{2m}\nabla^2\psi(\mathbf{x},t)$$

- is incompatible with special relativity
  - it relates energy momentum in the classical way ($E=p^2/m$)
  - it treats time and space differently

RELATIVISTIC INVARIANT QUANTUM MECHANICS

- relativistically we should have $E^2=\mathbf{p}^2+m^2$ [recall c=1]
  - implies existence of 'negative energy' states

$$E = \pm\sqrt{\mathbf{p}^2 + m^2}$$

  - to be [correctly] reinterpreted as anti-particles of positive energy

- insist that the correct equation is first order in time derivative [like the Schrodinger equation] and find Hamiltonian [operator on the rhs] that is local, linear in momentum [spatial derivatives] and gives the relativistic energy-momentum relation

RELATIVISTIC INVARIANT QUANTUM MECHANICS

- insist that the correct equation is first order in time derivative [like the Schrodinger equation] and find Hamiltonian [operator on the rhs] that is local, linear in momentum [spatial derivatives] and gives the relativistic energy-momentum relation [Dirac]

$$i\frac{\partial}{\partial t}\psi = H_d\psi$$

  - only works [you can try it out] if wave-function is multi-component [which implies spin] and

$$H_d = \alpha \cdot \mathbf{p} + \beta m$$

  - where α and **β** are four matrices that fulfil

$$\alpha_i\alpha_j + \alpha_j\alpha_i = 2\delta_{ij}$$

$$\beta\alpha_i + \alpha_i\beta = 0 \qquad\qquad \beta^2 = 1$$

WHY FIELDS AS DEGREES OF FREEDOM?

- single-particle equations [like the Dirac equation] are limited in the sense that they do not allow for particle creation/destruction [they preserve particle number]
  - note that relativistic theories cannot have fixed particle number: relativistic effects are relevant for $E \geq mc^2$ and at such energies particle production is possible [e.g., $p+p \to p+p+\pi^0$]
  - Lorentz invariance and variable particle number go hand-in-hand
- a multi-[and variable-] particle scenario is accommodated naturally in the concept of quantum field
  - think of a quantum field as an infinite collection of harmonic oscillators [a series of springs with masses attached]
  - when some of the oscillators become excited [they vibrate] at particular frequencies which correspond to excitations of the quantum field, that is to say to particles [field quanta]

WHY FIELDS AS DEGREES OF FREEDOM?

- the electron field is the [Fourier] sum of individual wavefunctions, with coefficients of each wavefunction representing the probability of creation/destruction of a quantum with a given wavelength (momentum)
  - this is what is often referred to as 2nd quantization

GAUGE SYMMETRY

- the conservation of electric charge implies [Noether's theorem] a global symmetry [a phase rotation for the fermion field]

$$\psi \to e^{i\alpha}\psi$$

- a gauge symmetry amounts to promoting the symmetry to local [realized for each and all spacetime locations]

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

QUANTUM ELECTRODYNAMICS [QED]

FEYNMAN, TOMONAGA, SCHWINGER [1946–50 :: NOBEL 1965]

- describe interactions of charged fundamental particles [eg, electron]

- ingredients:
  - fermion fields [electron/positron are the quanta]
  - U(1) gauge symmetry : local charge conservation
  - theory [=Lagrangian] fully specified by requiring that only terms that respect gauge invariance and are renormalizable are allowed

QED :: BUILDING THE LAGRANGIAN

- start with kinetic term for fermion field [essentially the Lagrangian for which the Dirac equation is the Euler-Lagrange equation] :: [μ=0,1,2,3 :: all are 4-vectors]

$$\bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi$$

- which is invariant for the global symmetry [charge conservation]

$$\psi \to e^{i\alpha}\psi$$

- but not for its gauge 'version'

$$\psi \to e^{i\alpha(x)}\psi \quad : \quad \bar{\psi}(\cdots)\psi \to \bar{\psi}\Big(i\gamma^\mu(\partial_\mu + i\partial_\mu\alpha(x)) - m\Big)\psi$$

- invariance under the local [gauge] transformations can be restored by introducing a new [bosonic] field :: the photon :: that transforms as

$$A_\mu(x) \to A_\mu(x) + \frac{1}{e}\partial_\mu\alpha(x)$$

- then we build a covariant derivative

$$D_\mu = \partial_\mu - ieA_\mu(x)$$

- such that $\psi(i\gamma^\mu D_\mu - m)\bar{\psi}$ is gauge invariant

QED :: BUILDING THE LAGRANGIAN

- once we introduced a new field, should check what new gauge invariant terms we can write. the only possibility is [a kinetic term for the photon]

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad : \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

- then the full QED Lagrangian is given by

$$\mathcal{L}_{QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \psi(i\gamma^\mu D_\mu - m)\bar{\psi}$$

$$D_\mu = \partial_\mu - ieA_\mu(x)$$

$$e\psi\gamma^\mu A_\mu(x)\bar{\psi}$$

fermion-photon coupling
[interaction]

fundamental interactions

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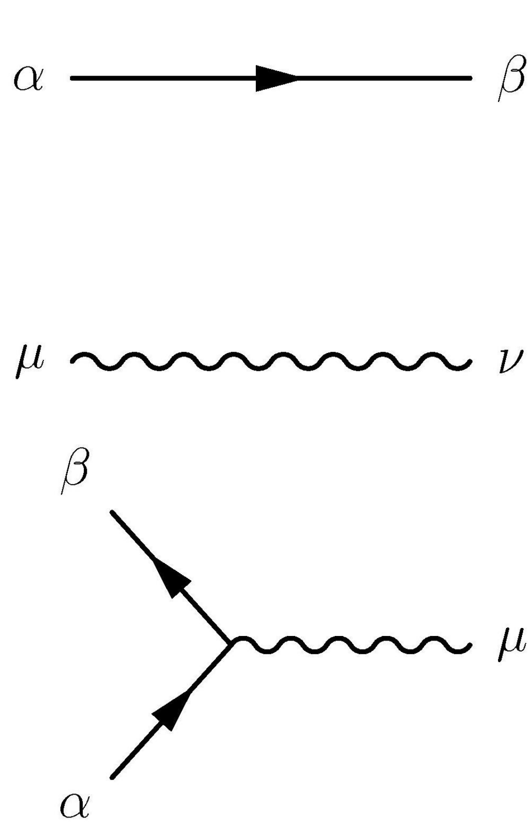
QED BUILDING BLOCKS :: FEYNMAN RULES



$$\rightarrow \left(\frac{i}{\not{p} - m + i\varepsilon}\right)_{\beta\alpha}$$

$$\rightarrow \frac{-i\eta_{\mu\nu}}{p^2 + i\varepsilon}$$

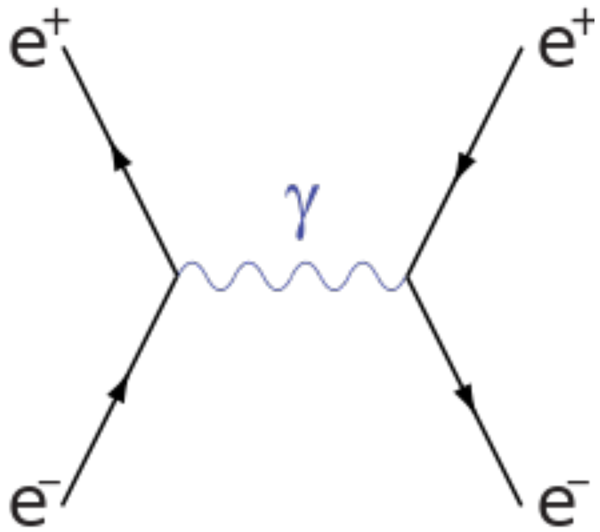
$$\rightarrow -ie\gamma^{\mu}_{\beta\alpha}(2\pi)^4\delta^{(4)}(p_1 + p_2 + p_3).$$

Incoming fermion:	α	$\rightarrow$	$u_\alpha(\vec{p}, s)$
Incoming antifermion:	α	$\rightarrow$	$\overline{v}_\alpha(\vec{p}, s)$
Outgoing fermion:	α	$\rightarrow$	$\overline{u}_\alpha(\vec{p}, s)$
Outgoing antifermion:	α	$\rightarrow$	$v_\alpha(p, s)$
Incoming photon:	μ	$\rightarrow$	$\epsilon_\mu(\vec{k}, \lambda)$
Outgoing photon:	μ	$\rightarrow$	$\epsilon_\mu(\vec{k}, \lambda)^*$

- rules follow straightforwardly from Lagrangian
- any QED process can be ‘assembled’ from these building blocks

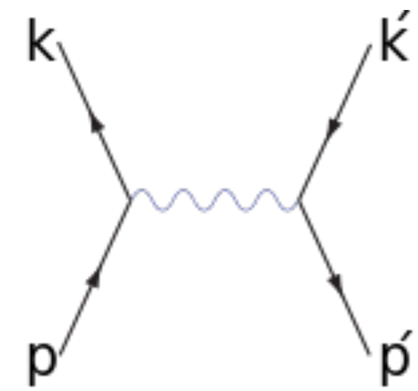
AN EXAMPLE :: [BHABBA SCATTERING]

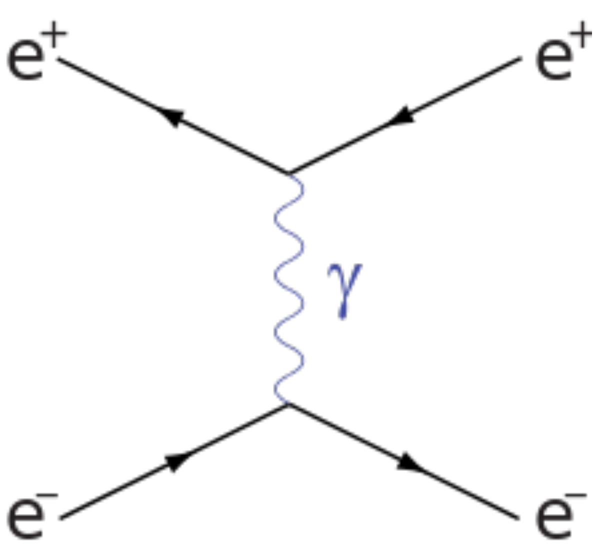
$$e^+e^- \longrightarrow e^+e^-$$



annihilation

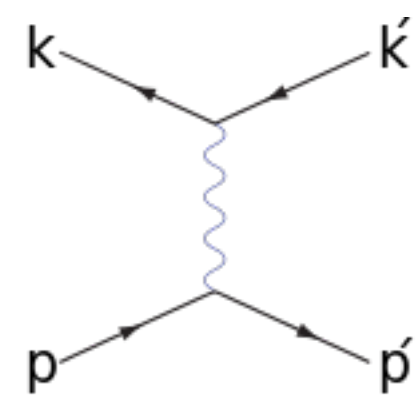
$$e^2\,(\bar{v}_k\gamma^\nu u_p)\,\frac{1}{(k+p)^2}\,(\bar{u}_{p'}\gamma_\nu v_{k'})$$





scattering

$$-e^2\,(\bar{v}_k\gamma^\mu v_{k'})\,\frac{1}{(k-k')^2}\,(\bar{u}_{p'}\gamma_\mu u_p)$$



AN EXAMPLE :: [BHABBA SCATTERING]

$$e^+e^- \longrightarrow e^+e^-$$

- the cross section [what is observable] is obtained from the square of the total amplitude [the sum of the two possible processes]

$$\mathcal{M} = \quad -e^2\,(\bar{v}_k\gamma^\mu v_{k'})\,\frac{1}{(k-k')^2}\,(\bar{u}_{p'}\gamma_\mu u_p) \;\; +e^2\,(\bar{v}_k\gamma^\nu u_p)\,\frac{1}{(k+p)^2}\,(\bar{u}_{p'}\gamma_\nu v_{k'})$$

- averaged over spin
them] and summed over spins of final particles [because we do not distinguish]

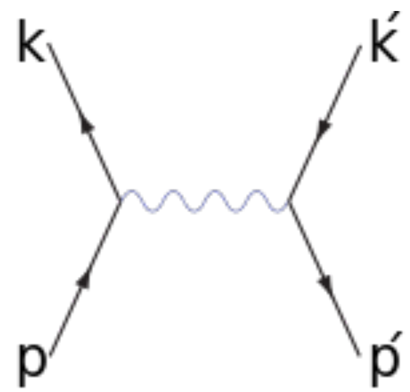
$$\overline{|\mathcal{M}|^2} = \frac{1}{(2s_{e-}+1)(2s_{e+}+1)}\sum_{\text{spins}}|\mathcal{M}|^2$$
$$= \frac{1}{4}\sum_{s=1}^{2}\sum_{s'=1}^{2}\sum_{r=1}^{2}\sum_{r'=1}^{2}|\mathcal{M}|^2$$

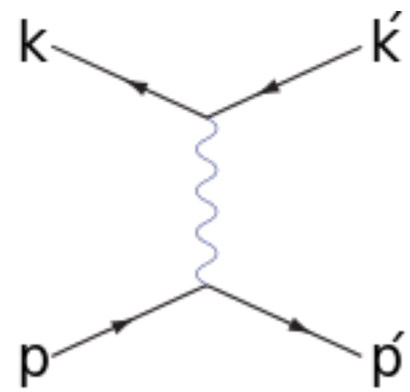
$$\begin{aligned}
|\mathcal{M}|^2 = \;& e^4\left|\frac{(\bar{v}_k\gamma^\mu v_{k'})(\bar{u}_{p'}\gamma_\mu u_p)}{(k-k')^2}\right|^2 && \text{(scattering)}\\
&- e^4\left(\frac{(\bar{v}_k\gamma^\mu v_{k'})(\bar{u}_{p'}\gamma_\mu u_p)}{(k-k')^2}\right)^*\left(\frac{(\bar{v}_k\gamma^\nu u_p)(\bar{u}_{p'}\gamma_\nu v_{k'})}{(k+p)^2}\right) && \text{(interference)}\\
&- e^4\left(\frac{(\bar{v}_k\gamma^\mu v_{k'})(\bar{u}_{p'}\gamma_\mu u_p)}{(k-k')^2}\right)\left(\frac{(\bar{v}_k\gamma^\nu u_p)(\bar{u}_{p'}\gamma_\nu v_{k'})}{(k+p)^2}\right)^* && \text{(interference)}\\
&+ e^4\left|\frac{(\bar{v}_k\gamma^\nu u_p)(\bar{u}_{p'}\gamma_\nu v_{k'})}{(k+p)^2}\right|^2 && \text{(annihilation)}
\end{aligned}$$

AN EXAMPLE :: [BHABBA SCATTERING]

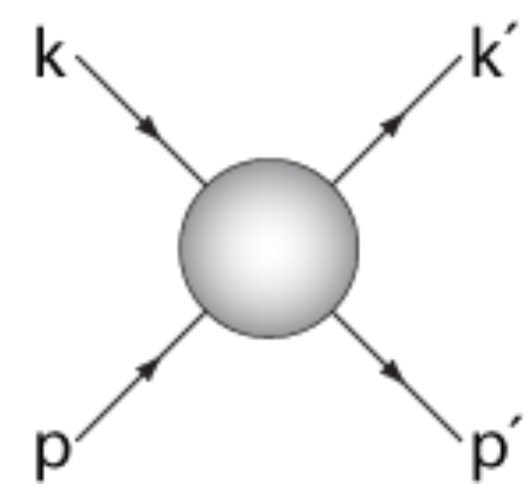
- the result is very simple

$$\frac{\overline{|\mathcal{M}|^2}}{2e^4} = \frac{u^2+s^2}{t^2} + \frac{2u^2}{st} + \frac{u^2+t^2}{s^2}$$





$$s = (k+p)^2 = (k'+p')^2 \approx 2k\cdot p \approx 2k'\cdot p'$$
$$t = (k-k')^2 = (p-p')^2 \approx -2k\cdot k' \approx -2p\cdot p'$$
$$u = (k-p')^2 = (p-k')^2 \approx -2k\cdot p' \approx -2k'\cdot p$$



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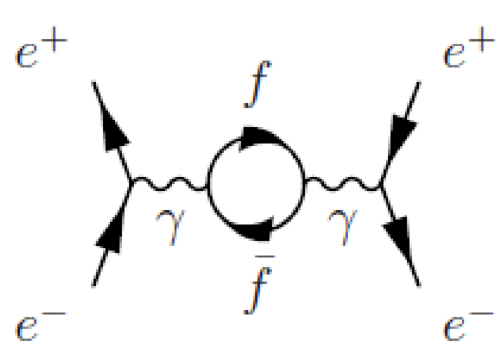
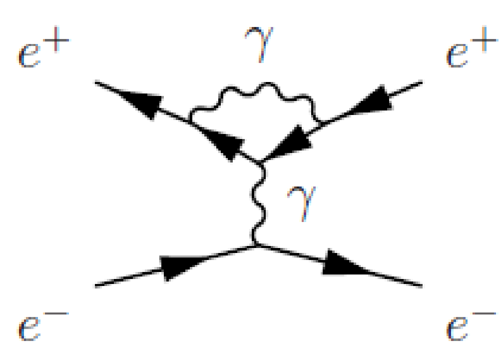
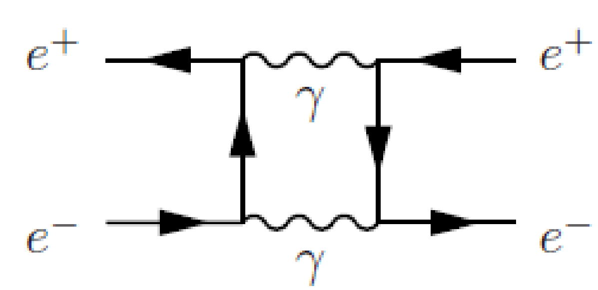
note that all contribution are of the same order in the coupling [the charge]

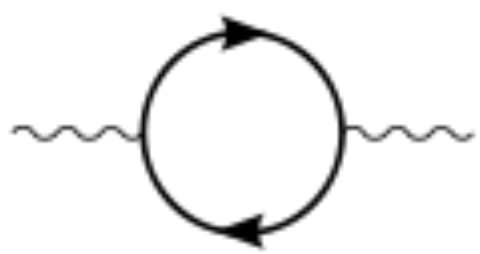
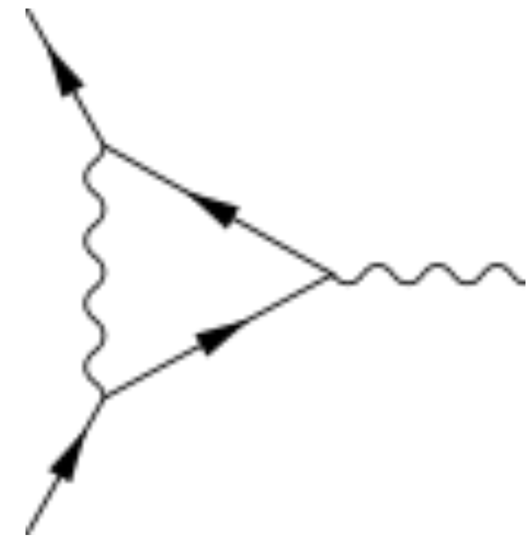
because the coupling is small, we know that contributions with more couplings will be small corrections [perturbation theory] :: importantly they are calculable





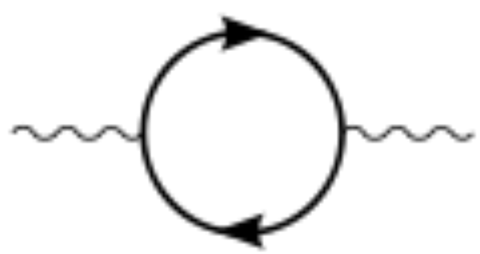


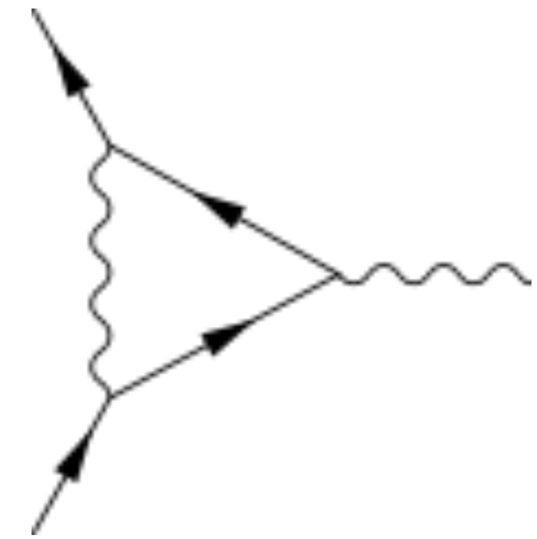
THE LOOP CORRECTIONS :: RENORMALIZATION

- this type of correction leads to undistinguishable final states from the leading order diagrams [the initial and final states are the same]
- the momenta that 'run' in the loops is UNCONSTRAINED [it can be anything] and has to be integrated over as it is not an observable quantity
  - all these integrals lead to INFINITIES [which is not good]

THE LOOP CORRECTIONS :: RENORMALIZATION





- many methods to solve this infinity problem
  - all amount to reabsorbing the 'infinite' contributions into the constants in the Lagrangian [the mass, the coupling]
  - this is what is called renormalization
    - when it is possible to do it for a theory up to all orders [all loops] we say the theory is renormalizable
    - all physical theories must be renormalizable

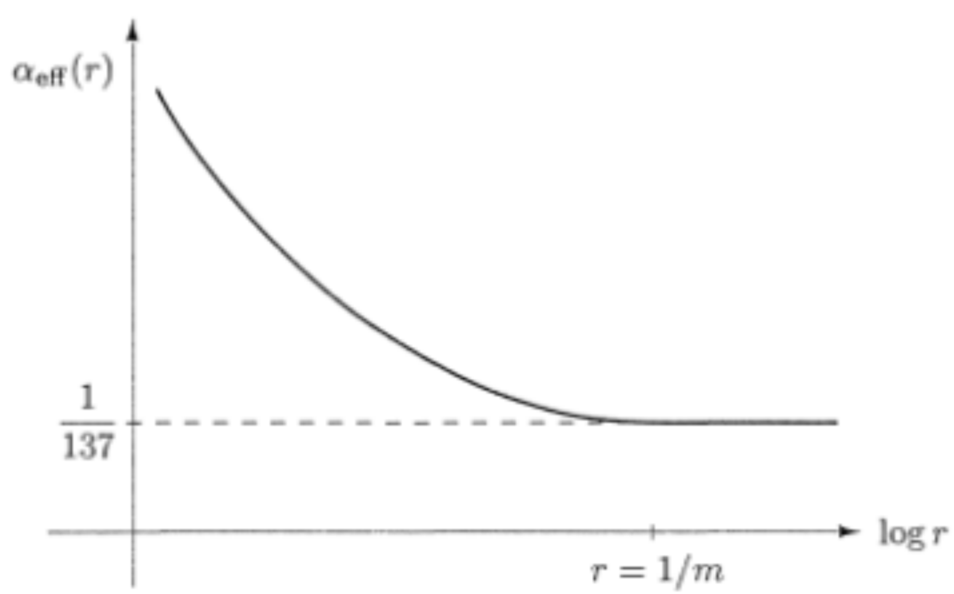
THE RUNNING OF THE COUPLING

- an immediate consequence of renormalization [of the vertex] is that the coupling 'constant' runs [changes] with energy :: the strength of the interaction changes with the energy/momentum [the inverse of the probing distance] of at which the interaction takes place

$$\alpha(Q^2) = \alpha(0)\left\{1 + \frac{\alpha(0)}{3\pi} f\left(\frac{Q^2}{m_e^2}\right) + O(\alpha^2)\right\}$$

$$\alpha = g_e^2/4\pi$$

α=1/137



HOW WELL DOES QED WORK?

- the electron magnetic dipole moment is the magnetic moment of the electron due to its intrinsic properties [charge and spin]

- at leading order [if you wish from the Dirac equation] is g=2
  - loop-contributions give small corrections :: it has been calculated up to very high order [5th] in the coupling [which is a lot of work] and measured with matching precision

a= (g-2)/2

a[TH] = 0.001 159 652 181 643 (764)

a[EXP] = 0.001 159 652 180 73 (28)

  - the theoretical prediction verified to highest accuracy in the history of Physics [and a very sensitive place to look for new physics (muon g-2) as with loops non-EM interactions also become relevant :: at present there is a mismatch of about 4σ between theory and experiment]

STRONG INTERACTIONS :: FUNDAMENTAL PARTICLES

- over the 40-60s [of last century], as particle colliders became available, a large number of particles was discovered [many as resonances] experiencing the strong interaction
  - a seriously explored possibility was that ALL of them were fundamental [this went well with 60s political views]

AT A RECENT COUNT

Meson Summary Table

See also the table of suggested $q\overline{q}$ quark-model assignments in the Quark Model section.

• Indicates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^{\pm}$	$1^-(0^-)$	• $\phi(1680)$	$0^-(1^{--})$
• π^0	$1^-(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• η	$0^+(0^{-+})$	• $\rho(1700)$	$1^+(1^{--})$
• $f_0(500)$	$0^+(0^{++})$	• $a_2(1700)$	$1^-(2^{++})$
• $\rho(770)$	$1^+(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\omega(782)$	$0^-(1^{--})$	$\eta(1760)$	$0^+(0^{-+})$
• $\eta'(958)$	$0^+(0^{-+})$	• $\pi(1800)$	$1^-(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $a_0(980)$	$1^-(0^{++})$	$X(1835)$	$?^?(0^{-+})$
• $\phi(1020)$	$0^-(1^{--})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\eta_2(1870)$	$0^+(2^{-+})$
• $b_1(1235)$	$1^+(1^{+-})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_2(1270)$	$0^+(2^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$	$a_0(1950)$	$1^-(0^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(1950)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	• $a_4(1970)$	$1^-(4^{++})$
• $a_2(1320)$	$1^-(2^{++})$	$\rho_3(1990)$	$1^+(3^{--})$
• $f_0(1370)$	$0^+(0^{++})$	$\pi_2(2005)$	$1^-(2^{-+})$
• $\pi_1(1400)$	$1^-(1^{-+})$	• $f_2(2010)$	$0^+(2^{++})$
• $\eta(1405)$	$0^+(0^{-+})$	$f_0(2020)$	$0^+(0^{++})$
• $h_1(1415)$	$0^-(1^{+-})$	• $f_4(2050)$	$0^+(4^{++})$
• $f_1(1420)$	$0^+(1^{++})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $\omega(1420)$	$0^-(1^{--})$	$f_0(2100)$	$0^+(0^{++})$
$f_2(1430)$	$0^+(2^{++})$	$f_2(2150)$	$0^+(2^{++})$
• $a_0(1450)$	$1^-(0^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $\rho(1450)$	$1^+(1^{--})$	• $\phi(2170)$	$0^-(1^{--})$
• $\eta(1475)$	$0^+(0^{-+})$	$f_0(2200)$	$0^+(0^{++})$
• $f_0(1500)$	$0^+(0^{++})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
$f_1(1510)$	$0^+(1^{++})$	$\eta(2225)$	$0^+(0^{-+})$
• $f_2'(1525)$	$0^+(2^{++})$	$\rho_3(2250)$	$1^+(3^{--})$
$f_2(1565)$	$0^+(2^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$\rho(1570)$	$1^+(1^{--})$	$f_4(2300)$	$0^+(4^{++})$
$h_1(1595)$	$0^-(1^{+-})$	$f_0(2330)$	$0^+(0^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	• $f_2(2340)$	$0^+(2^{++})$
• $a_1(1640)$	$1^-(1^{++})$	$\rho_5(2350)$	$1^+(5^{--})$
$f_2(1640)$	$0^+(2^{++})$	$X(2370)$	$?^?(?^{??})$
• $\eta_2(1645)$	$0^+(2^{-+})$	$f_6(2510)$	$0^+(6^{++})$
• $\omega(1650)$	$0^-(1^{--})$		
• $\omega_3(1670)$	$0^-(3^{--})$		
• $\pi_2(1670)$	$1^-(2^{-+})$		

OTHER LIGHT

Further States

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^{\pm}$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
• $K_0^*(700)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
• $K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
• $K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
• $K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

	$I(J^P)$
• $D^{\pm}$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^{\pm}$	$1/2(1^-)$
• $D_0^*(2300)$	$1/2(0^+)$
• $D_1(2420)$	$1/2(1^+)$
• $D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)$	$1/2(2^+)$
$D_0(2550)^0$	$1/2(0^-)$
$D_J^*(2600)^0$	$1/2(1^-)$
$D^*(2640)^{\pm}$	$1/2(?^?)$
$D_2(2740)^0$	$1/2(2^-)$
• $D_3^*(2750)$	$1/2(3^-)$
$D_1^*(2760)^0$	$1/2(1^-)$
$D(3000)^0$	$1/2(?^?)$

CHARMED, STRANGE ($C = S = \pm1$) (+ possibly non-$q\overline{q}$ states)

	$I(J^P)$
• $D_s^{\pm}$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^{\pm}$	$0(0^+)$
• $D_{s1}(2460)^{\pm}$	$0(1^+)$
• $D_{s1}(2536)^{\pm}$	$0(1^+)$
• $D_{s2}^*(2573)$	$0(2^+)$
• $D_{s1}^*(2700)^{\pm}$	$0(1^-)$
$D_{s1}^*(2860)^{\pm}$	$0(1^-)$
$D_{s3}^*(2860)^{\pm}$	$0(3^-)$
$X_0(2900)$	$?(0^+)$
$X_1(2900)$	$?(1^-)$
$D_{sJ}(3040)^{\pm}$	$0(?^?)$

BOTTOM ($B = \pm1$)

	$I(J^P)$
• $B^{\pm}$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^{\pm}/B^0$ ADMIXTURE	
• $B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
• $B_1(5721)$	$1/2(1^+)$
$B_J^*(5732)$	$?(?^?)$
• $B_2^*(5747)$	$1/2(2^+)$
$B_J(5840)$	$1/2(?^?)$
• $B_J(5970)$	$1/2(?^?)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

	$I(J^P)$
• B^0_s	$0(0^-)$
• B^*_s	$0(1^-)$
$X(5568)^{\pm}$	$?(?^?)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B_{s2}^*(5840)^0$	$0(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

	$I(J^P)$
• B_c^+	$0(0^-)$
• $B_c(2S)^{\pm}$	$0(0^-)$

$c\overline{c}$ (+ possibly non-$q\overline{q}$ states)

	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$0^-(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $\psi_2(3823)$	$0^-(2^{--})$

$c\overline{c}$ continued

	$I^G(J^{PC})$
• $\psi_3(3842)$	$0^-(3^{--})$
$\chi_{c0}(3860)$	$0^+(0^{++})$
• $\chi_{c1}(3872)$	$0^+(1^{++})$
• $Z_c(3900)$	$1^+(1^{+-})$
• $X(3915)$	$0^+(0/2^{++})$
• $\chi_{c2}(3930)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $X(4020)^{\pm}$	$1^+(?^{?-})$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^{\pm}$	$1^-(?^{?+})$
$X(4055)^{\pm}$	$1^+(?^{?-})$
$X(4100)^{\pm}$	$1^-(?^{??})$
• $\chi_{c1}(4140)$	$0^+(1^{++})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$Z_c(4200)$	$1^+(1^{+-})$
• $\psi(4230)$	$0^-(1^{--})$
$R_{c0}(4240)$	$1^+(0^{--})$
$X(4250)^{\pm}$	$1^-(?^{?+})$
$\psi(4260)$	$0^-(1^{--})$
• $\chi_{c1}(4274)$	$0^+(1^{++})$
$X(4350)$	$0^+(?^{?+})$
• $\psi(4360)$	$0^-(1^{--})$
$\psi(4390)$	$0^-(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
• $Z_c(4430)$	$1^+(1^{+-})$
$\chi_{c0}(4500)$	$0^+(0^{++})$
• $\psi(4660)$	$0^-(1^{--})$
$\chi_{c0}(4700)$	$0^+(0^{++})$

$b\overline{b}$ (+ possibly non-$q\overline{q}$ states)

	$I^G(J^{PC})$
• $\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$0^-(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon_2(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $h_b(2P)$	$0^-(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_{b1}(3P)$	$0^+(1^{++})$
• $\chi_{b2}(3P)$	$0^+(2^{++})$
• $\Upsilon(4S)$	$0^-(1^{--})$
• $Z_b(10610)$	$1^+(1^{+-})$
• $Z_b(10650)$	$1^+(1^{+-})$
$\Upsilon(10753)$	$?^?(1^{--})$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

Baryon Summary Table

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the table are not established baryons. The names with masses are of baryons that decay strongly. The spin-parity J^P (when known) is given with each particle. For the strongly decaying particles, the J^P values are considered to be part of the names.

p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	****
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	***
$N(1895)$	$1/2^-$	****
$N(1900)$	$3/2^+$	****
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	***
$N(2100)$	$1/2^+$	***
$N(2120)$	$3/2^-$	***
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2300)$	$1/2^+$	**
$N(2570)$	$5/2^-$	**
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	****
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	***
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	***
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**
Λ	$1/2^+$	****
Λ	$1/2^-$	**
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	****
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1710)$	$1/2^+$	*
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$	$1/2^-$	*
$\Lambda(2050)$	$3/2^-$	*
$\Lambda(2070)$	$3/2^+$	*
$\Lambda(2080)$	$5/2^-$	*
$\Lambda(2085)$	$7/2^+$	**
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	*
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(1780)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(1900)$	$1/2^-$	**
$\Sigma(1910)$	$3/2^-$	***
$\Sigma(1915)$	$5/2^+$	****
$\Sigma(1940)$	$3/2^+$	*
$\Sigma(2010)$	$3/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	*
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2160)$	$1/2^-$	*
$\Sigma(2230)$	$3/2^+$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}^?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	****
$\Omega(2012)^-$	$?^-$	***
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**
Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2860)^+$	$3/2^+$	***
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$	$3/2^-$	***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	****
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2923)$		**
$\Xi_c(2930)$		**
$\Xi_c(2970)$		***
$\Xi_c(3055)$		***
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
$\Omega_c(3000)^0$		***
$\Omega_c(3050)^0$		***
$\Omega_c(3065)^0$		***
$\Omega_c(3090)^0$		***
$\Omega_c(3120)^0$		***

Ξ_{cc}^{++}		***
Λ_b^0	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
$\Lambda_b(6146)^0$	$3/2^+$	***
$\Lambda_b(6152)^0$	$5/2^+$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
$\Sigma_b(6097)^+$		***
$\Sigma_b(6097)^-$		***
Ξ_b^-	$1/2^+$	***
Ξ_b^0	$1/2^+$	***
$\Xi_b'(5935)^-$	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
$\Xi_b(5955)^-$	$3/2^+$	***
$\Xi_b(6227)^-$		***
$\Xi_b(6227)^0$		***
Ω_b^-	$1/2^+$	***
$\Omega_b(6316)^-$		*
$\Omega_b(6330)^-$		*
$\Omega_b(6340)^-$		*
$\Omega_b(6350)^-$		*
$P_c(4312)^+$		*
$P_c(4380)^+$		*
$P_c(4440)^+$		*
$P_c(4457)^+$		*

**** Existence is certain, and properties are at least fairly well explored.

*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

** Evidence of existence is only fair.

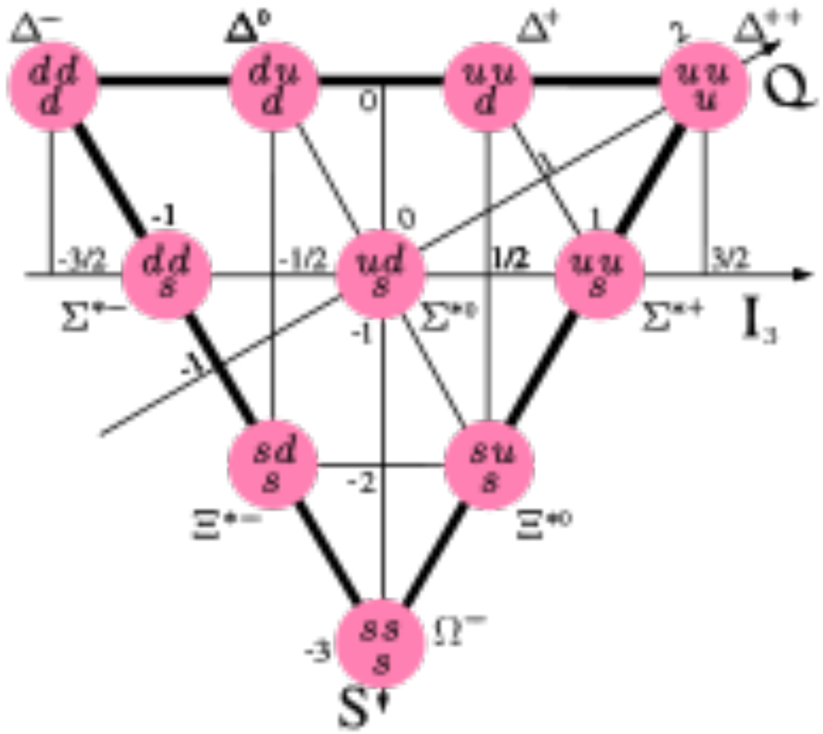
* Evidence of existence is poor.

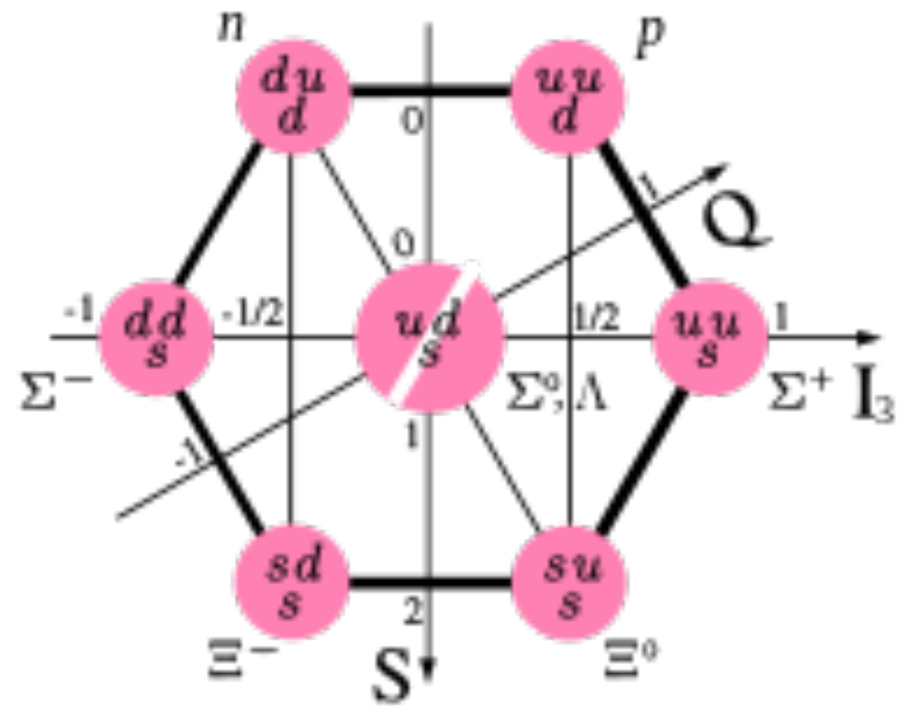
STRONG INTERACTIONS :: FUNDAMENTAL PARTICLES

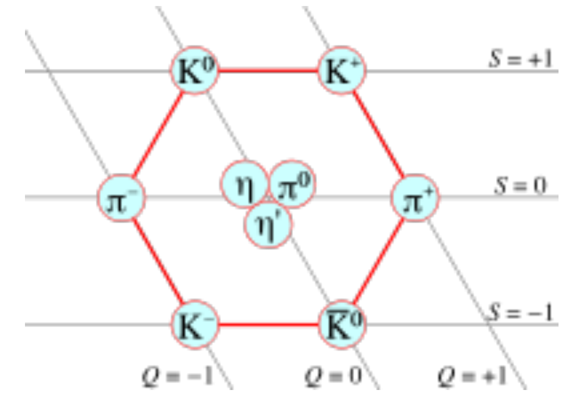
- over the 40-60s [of last century], as particle colliders became available, a large number of particles was discovered [many as resonances] experiencing the strong interaction
  - a seriously explored possibility was that ALL of them were fundamental [this went well with 60s political views]
    - clearly not a very elegant solution

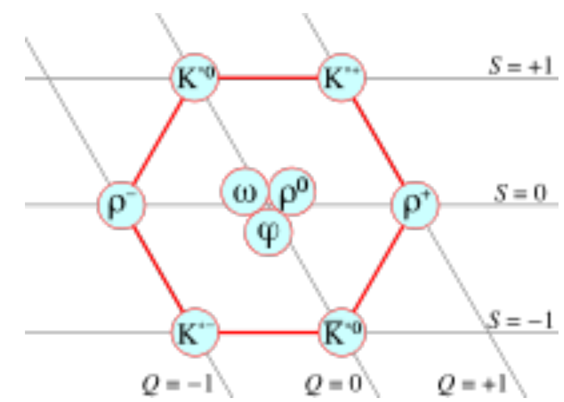
- Gell-Mann and Zweig [1964] proposed that all hadrons known by then were composed of more elementary constituents [named quarks after the obscure line '-Three quarks for Muster Mark!' in James Joyce's obscure book Finnegans Wake]
  - these 'hypothetical' quarks would come in 3 flavours [u(p),d(own),s(trange)] with the respective anti-particles [as they were fermions]

THE EIGHTFOLD WAY



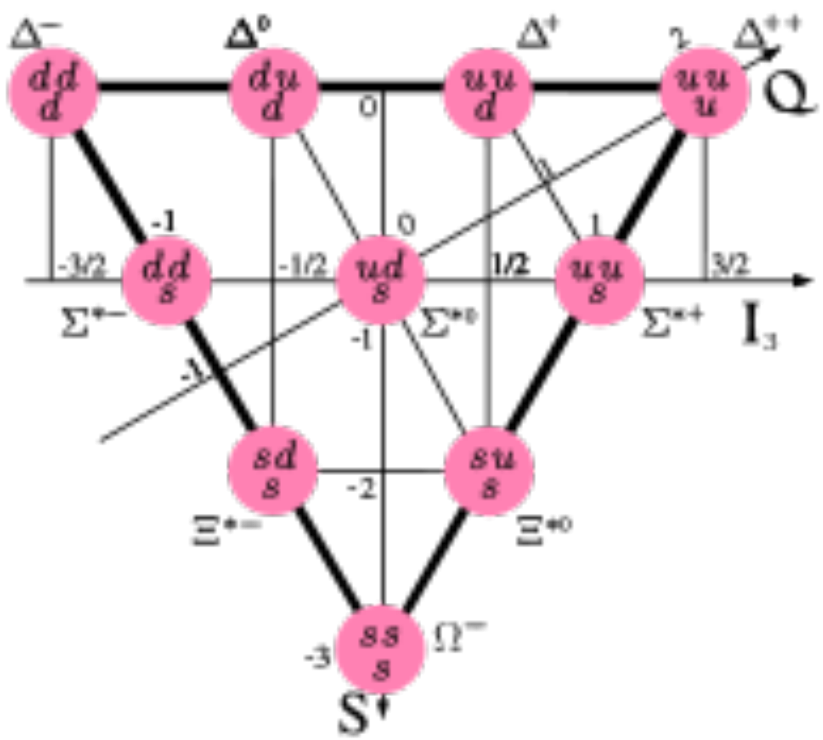






- by combining the quarks and anti-quarks in all possible ways it was possible to accommodate all known baryons and mesons known at the time and PREDICT the existence of a few others [later observed]

THE EIGHTFOLD WAY :: A CLEAR PROBLEM



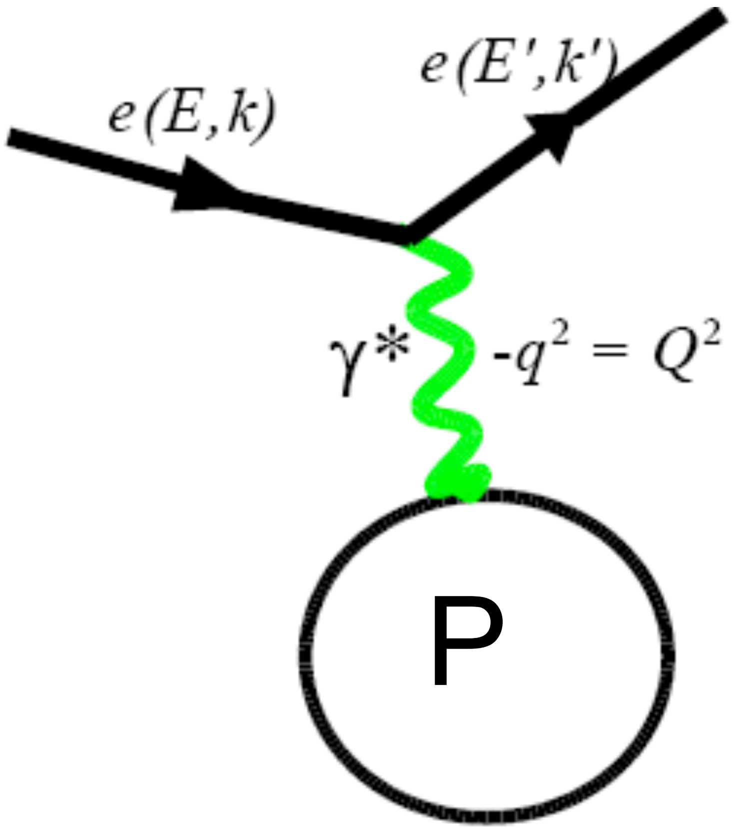
- states [particles] predicted and observed have 3 quarks of same flavour [uuu, ddd, sss]
- 3 spin-1/2 fermions in the same quantum state is problematic to say the least [Pauli exclusion principle]
  - solved by introducing a new quantum number [a charge] called colour [r,g,b]
  - all observed particles must be white
  - colour is the conserved charge of the strong interactions
  - 3 charges :: SU(3) gauge symmetry

WHERE ARE THE QUARKS

- although the model with 3 quarks [now we know there are 6] each in one of three possible colour states worked well to describe hadron zoology
  - free quarks had not [and have not] been observed
  - do they exist or are simply a convenient mathematical construction?

DEEP INELASTIC SCATTERING

FRIEDMAN, KENDALL, TAYLOR [SLAC-MIT EXPERIMENTS 1968- :: NOBEL 1990]



- in electron-proton scattering experiments the exchanged [virtual] photon acts as a microscope resolving structures with size $\sim 1/Q^2$
  - for low Q^2 the proton is seen as a whole
  - increasing Q^2 probes the proton internal structure [if any]
  - experimental results at sufficiently high Q^2 consistent with the existence of 3 quarks in the proton

WHY ARE QUARKS NEVER FREE ?

- look at the QCD Lagrangian [built like we did for QED but now imposing a SU(3) gauge symmetry]

QCD IN ONE SLIDE

:: each quark flavour [u,d,c,s,b,t] exists in 3 colours [r,g,b]

:: quark carries one colour index :: fundamental representation of SU(3) [triplet]

$$\mathcal{L}_{QCD} = \sum_{\text{flavours}} \bar{\psi}_a \big(i\gamma^\mu \partial_\mu - m\big)\psi_a$$

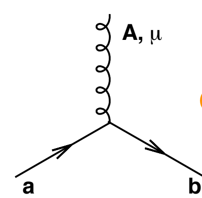
kinetic term :: quark propagation

not gauge invariant

:: need to introduce gauge field [gluon] to fulfil gauge invariance

:: gluon carries two colour indices :: adjoint representation of SU(3) [octet]

$$\mathcal{L}_{QCD} = \sum_{\text{flavours}} \Big(\bar{\psi}_a \big(i\gamma^\mu \partial_\mu - m\big)\psi_a - g_s \bar{\psi}_a \gamma^\mu t^C_{ab} A^C_\mu \psi_b\Big)$$



interaction term quark-gluon vertex

gauge field

:: once new field available, include all further gauge invariant terms

$$\mathcal{L}_{QCD} = \sum_{\text{flavours}} \bar{\psi}_a \Big(\big(i\gamma^\mu \partial_\mu - m\big)\delta_{ab} - g_s \gamma^\mu t^C_{ab} A^C_\mu\Big)\psi_b - \frac{1}{4} F^A_{\mu\nu} F^{\mu\nu, A}$$

$$F^A_{\mu\nu} = \partial_\mu \mathcal{A}^A_\nu - \partial_\nu \mathcal{A}^A_\nu - g_s\, f_{ABC} \mathcal{A}^B_\mu \mathcal{A}^C_\nu \qquad [t^A, t^B] = i f_{ABC} t^C$$

Lagrangian structure fixed by requirement of $\mathrm{SU}(3)_{\text{colour}}$ gauge symmetry

WELL, TWO…

$$\mathcal{L}_{QCD} = -\frac{1}{4}F^A_{\mu\nu}F^{\mu\nu,A} + \sum_{\text{flavours}} \bar{\psi}_a\Big(\big(i\gamma^\mu\partial_\mu - m\big)\delta_{ab} - g_s\gamma^\mu t^C_{ab}A^C_\mu\Big)\psi_b$$

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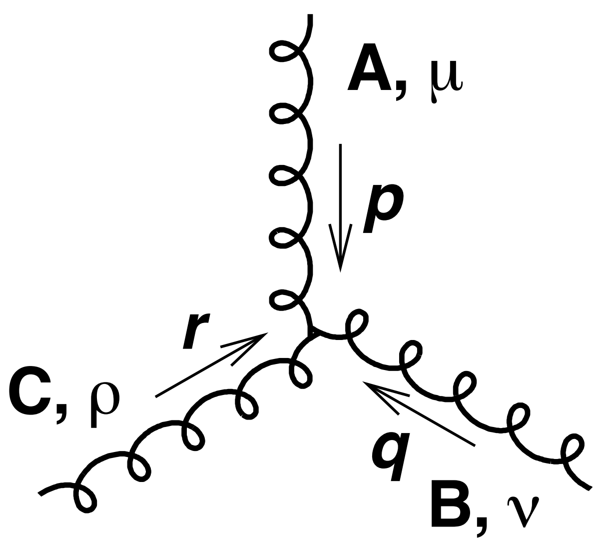
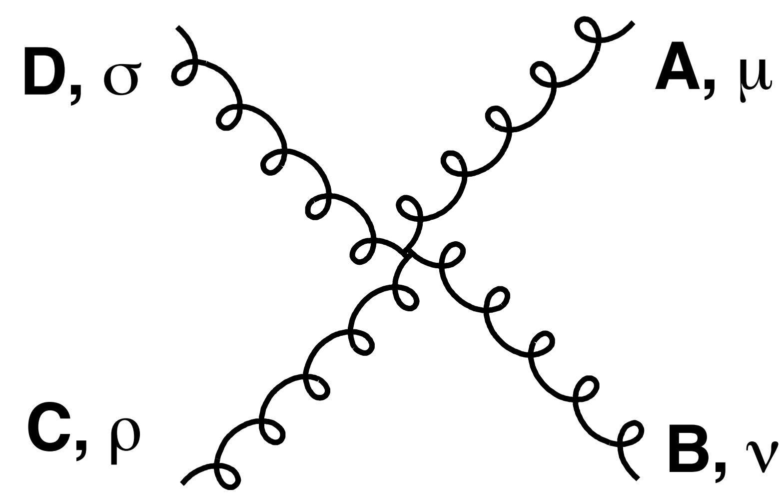
gluon propagator + gluon self-interactions





Quark masses

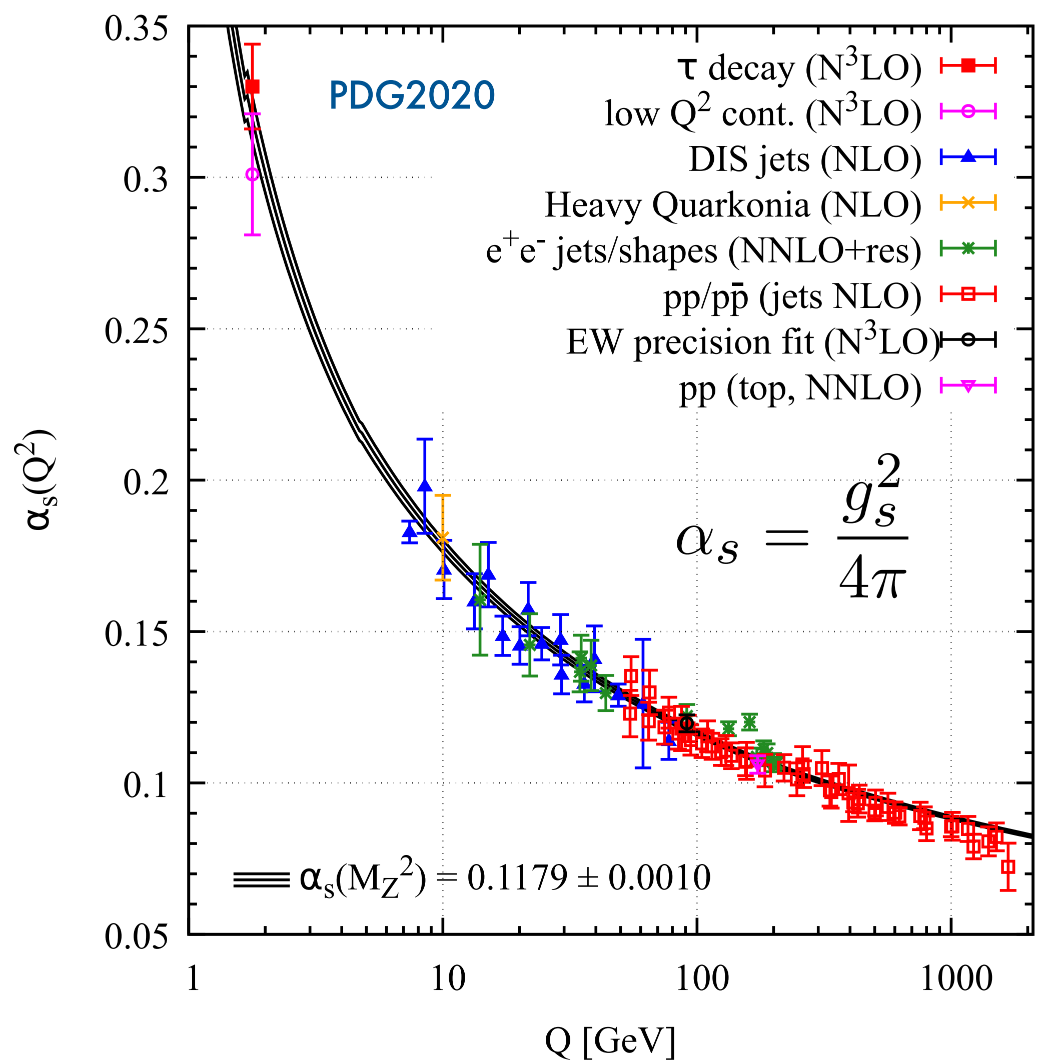
Up	2.3 MeV	Charm	1275 MeV	Top	173 GeV
Down	4.8 MeV	Strange	95 MeV	Bottom	4180 MeV

ASYMPTOTIC FREEDOM AND CONFINEMENT

$$\mathcal{L}_{QCD} = -\frac{1}{4} F^A_{\mu\nu} F^{\mu\nu,A} + \sum_{\text{flavours}} \bar{\psi}_a \Big((i\gamma^\mu \partial_\mu - m)\delta_{ab} - g_s \gamma^\mu t^C_{ab} A^C_\mu \Big) \psi_b$$

- ✓ renormalization [cancellation of divergences in higher order corrections] makes the coupling scale dependant
- ✓ self-interacting gauge fields lead to asymptotic freedom

:: quarks and gluon can only behave freely at high momentum scales [small distances] thus always observed confined within hadrons



WHY ARE QUARKS NEVER FREE ?

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$$\mathcal{L}_{QCD} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a + \bar{\psi}_i \left(i\gamma^\mu D_\mu - m \right)_{ij} \psi_j$$

$$F^a_\mu = \partial_\mu A^a - \partial \; A^a_\mu - \boxed{g f^{abc} A^b_\mu A^c}$$

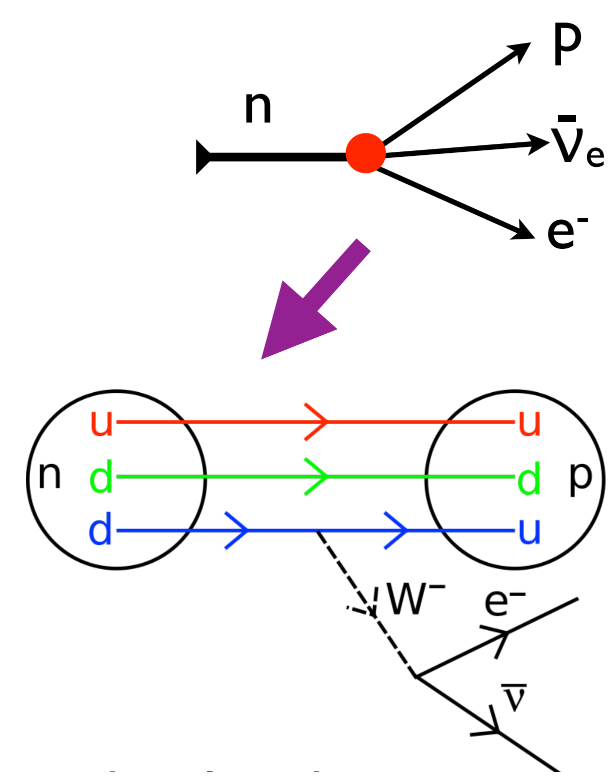
$$D_\mu = \partial_\mu + igA^a_\mu T^a$$

gauge bosons [gluons] self-interact
unlike photons in electrodynamics

- self-coupling of gluons leads makes [renormalized] coupling grow with increasing distance [confinement and asymptotic freedom]

Gross, Politzer, Wilczec [1973 :: Nobel 2004]

UNIFICATION OF FUNDAMENTAL INTERACTIONS

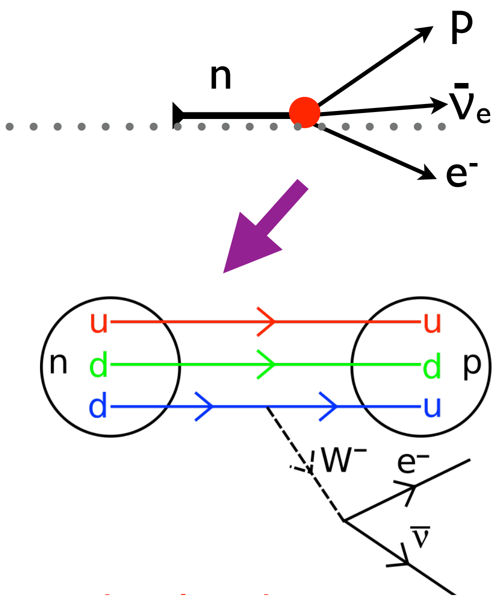


- Electricity and Magnetism [Maxwell 1873]
- weak interaction [Fermi 1934]
  - non-renormalizable [divergent at high energies]
- gauge invariance [Yang & Mills 1954]
  - 1930-60 :: search for gauge theories that unify EM and weak interaction (at this point it was not clear at all that strong interactions would fit in the QFT language)
  - SU(2)⊗U(1) symmetry [Glashow 1961]
    - spontaneous symmetry breaking [Weinberg & Salam 1967]

massless [Goldstone] gauge bosons which would lead to infinite range forces acquire mass through a simple mechanism

Englert-Brout-Higgs-Guralnik-Hagen-Kibble [1964] mechanism

UNIFICATION OF FUNDAMENTAL INTERACTIONS



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    - quebra espontânea [Weinberg & Salam 1967]

bosões de gauge [mediadores da interacção]
com massa nula [Goldstone] :: forças de alcance infinito

forma [a mais simples] de atribuir massa aos bosões de gauge [1964]

1964

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

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Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

the only mentioning that the spontaneous symmetry breaking mechanism implies the existence of a scalar boson

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

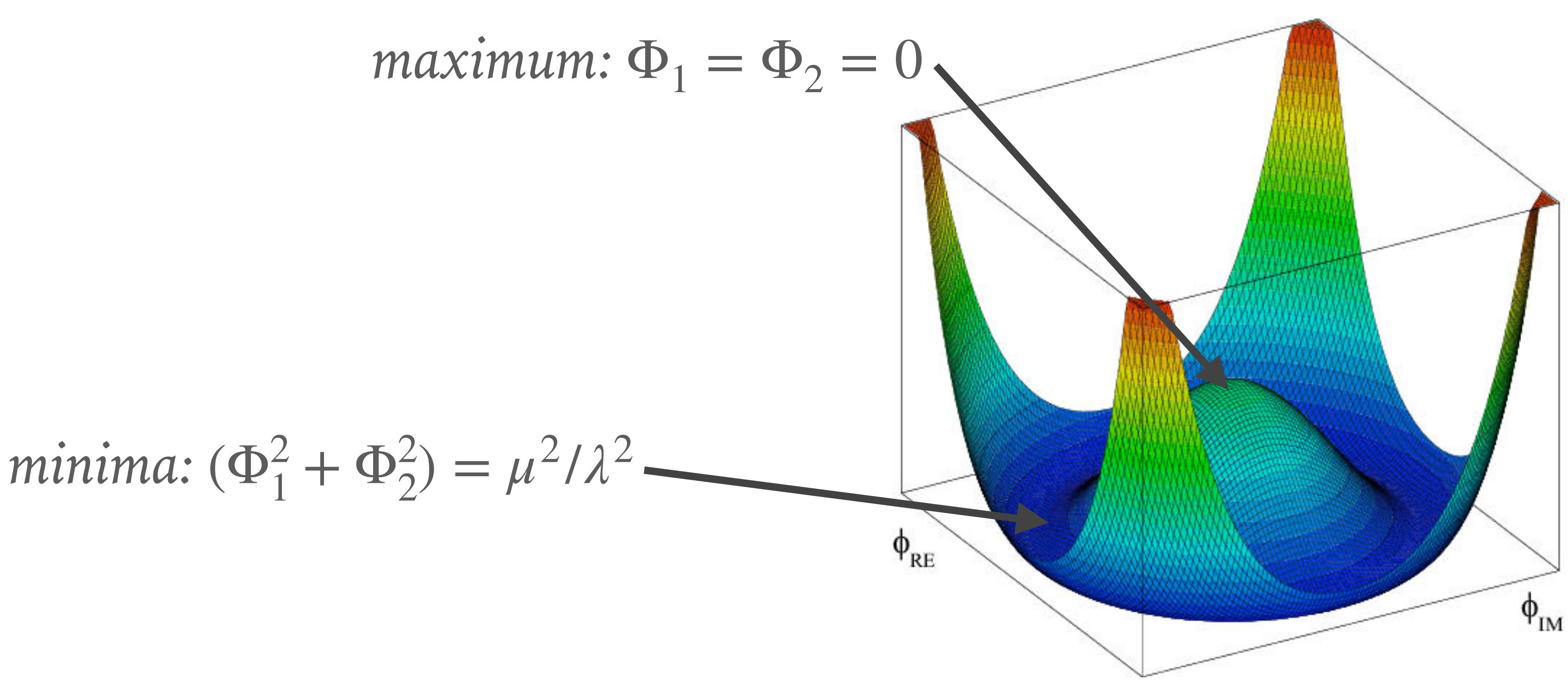
SPONTANEOUS SYMMETRY BREAKING

- simple example with two real scalar fields ϕ_1, ϕ_2 [or a complex valued scalar field]

$$\mathcal{L} = \mathcal{T}[\phi_1] + \mathcal{T}[\phi_2] - \mathcal{U}[\phi_1, \phi_2]$$

$$\mathcal{U}[\phi_1, \phi_2] = -\frac{1}{2}\mu^2(\phi_1^2 + \phi_2^2) + \frac{1}{4}\lambda^2(\phi_1^2 + \phi_2^2)^2$$

- select a minimum (e.g., $\Phi_1 = \mu/\lambda;\ \Phi_2 = 0$)
    - symmetry is spontaneously broken :: vacuum is not invariant for symmetries of the lagrangian



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- select a minimum (e.g., $\Phi_1 = \mu/\lambda;\ \Phi_2 = 0$)
    - symmetry is spontaneously broken :: vacuum is not invariant for symmetries of the lagrangian
    - expand around the minimum

$$\eta \equiv \phi_1 - \frac{\mu}{\lambda} \qquad \xi \equiv \phi_2$$

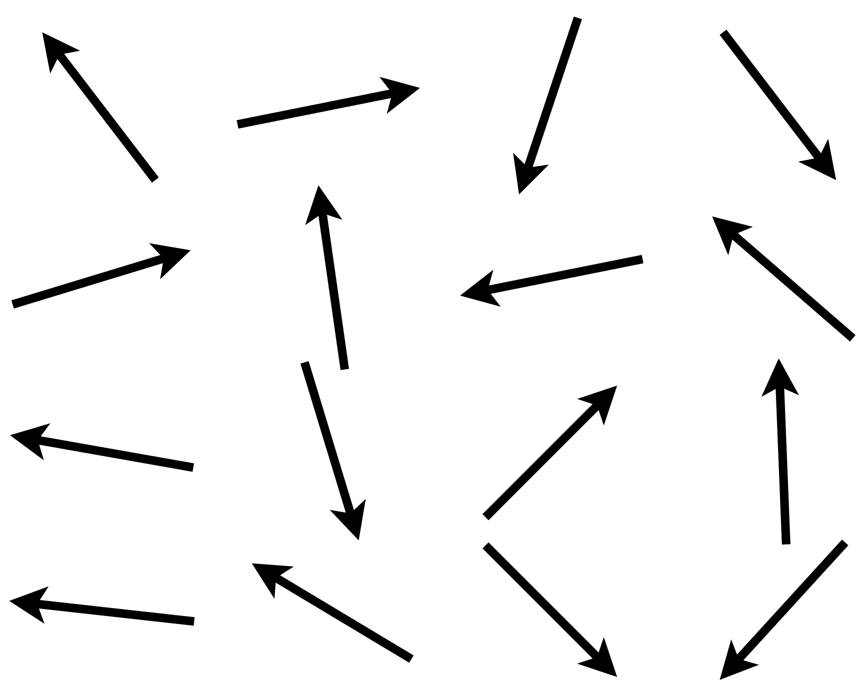
$$\mathcal{L} = \mathcal{T}[\eta] - \mu^2\eta^2 + \mathcal{T}[\xi] - 0 - \mu\lambda(\eta^3 + \eta\xi^2) - \frac{\lambda^2}{4}(\eta^4 + \xi^4 + 2\eta^2\xi^2) + \frac{\mu^4}{4\lambda^2}$$

massive η field

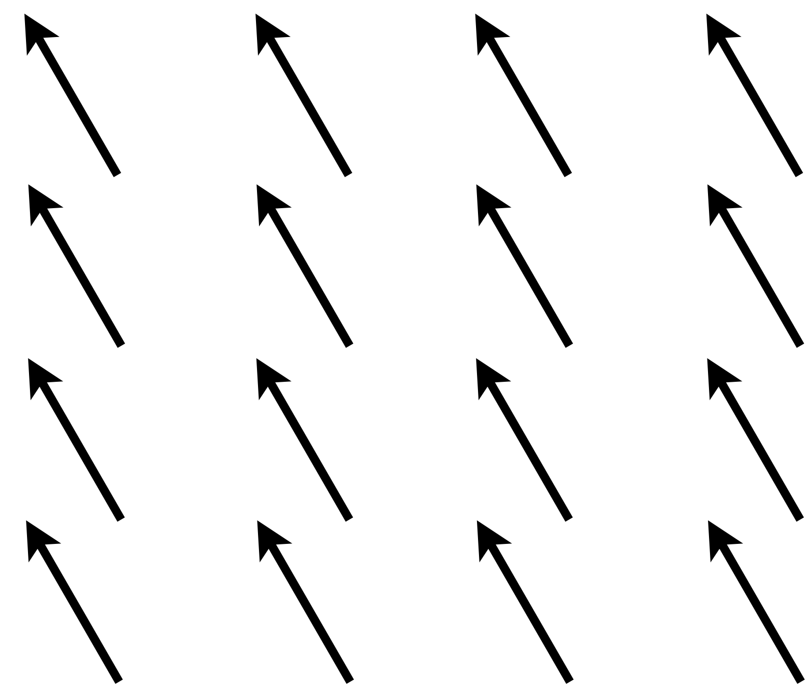
massless ξ field

SPONTANEOUS SYMMETRY BREAKING

- spontaneous symmetry breaking is an universal phenomenon
  - occurs, for example, in a system of magnetic dipoles



$T>T_c$



$T<T_c$

THE [. . .]– HIGGS – [. . .] MECHANISM

- gauge theory (i.e., with a local symmetry) for a complex scalar field $\Phi = \Phi_1 + i\Phi_2$
- [transverse] massless gauge field A_μ
- gauge symmetry $\Phi \longrightarrow e^{-i\theta(x)}\,\Phi$
  - $A_\mu \to A_\mu + \partial_\mu \theta(x)$; $D_\mu \to \partial_\mu + iqA_\mu$; $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

$$\mathcal{L} = \frac{1}{2}(D_\mu\phi)^*(D^\mu\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\mu^2\phi^*\phi - \frac{1}{4}\lambda^2(\phi^*\phi)^2$$

  - expand around minimum

$$\eta \equiv \phi_1 - \frac{\mu}{\lambda} \qquad \xi \equiv \phi_2 \to 0 \quad \left(\theta = \arctan(\phi_2/\phi_1)\right)$$

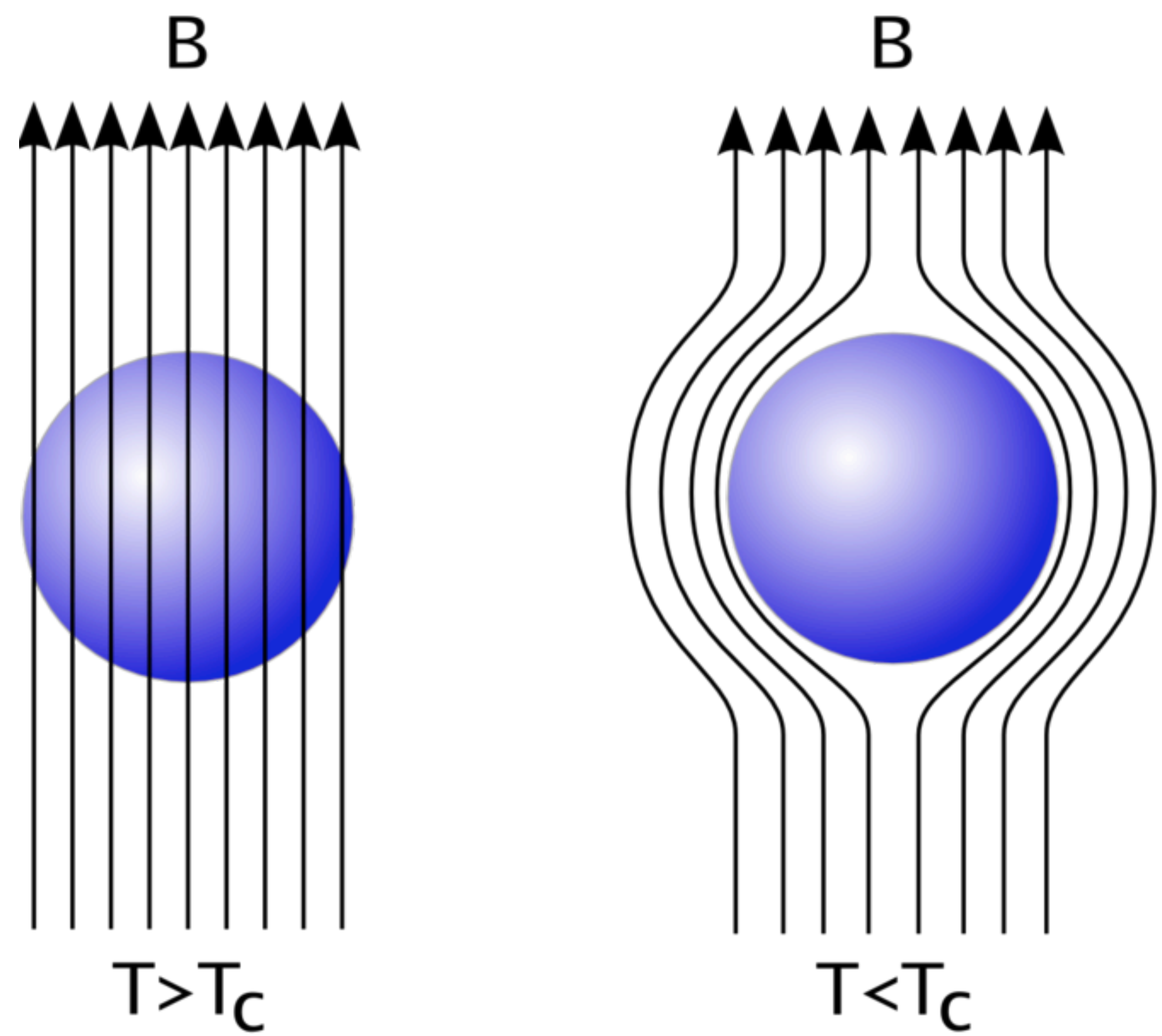
$$\mathcal{L} = \frac{1}{2}(\partial_\mu\eta)^*(\partial^\mu\eta) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \mu^2\eta^2 + \frac{q^2\mu^2}{2\lambda^2}A_\mu A^\mu + \mathcal{O}(3)$$

massive Higgs boson

mass for gauge boson
[adds longitudinal polarization dof]

IN SUPERCONDUCTORS

- Ginzburg-Landau explanation of the Meissner effect
  - photon acquires effective mass and penetration in the superconductor field has a range 1/m



fundamental interactions

Guilherme Milhano [LIP & IST, Lisbon]
gmilhano@lip.pt

EW SECTOR [BEFORE SSB]

The Lagrangian for the electroweak interactions is divided into four parts before electroweak symmetry breaking

$$\mathcal{L}_{EW} = \mathcal{L}_g + \mathcal{L}_f + \mathcal{L}_h + \mathcal{L}_y.$$

The $\mathcal{L}_g$ term describes the interaction between the three W particles and the B particle.

$$\mathcal{L}_g = -\frac{1}{4}W_a^{\mu\nu}W_{\mu\nu}^a - \frac{1}{4}B^{\mu\nu}B_{\mu\nu},$$

where $W^{a\mu\nu}$ $(a = 1, 2, 3)$ and $B^{\mu\nu}$ are the field strength tensors for the weak isospin and weak hypercharge fields.

$\mathcal{L}_f$ is the kinetic term for the Standard Model fermions. The interaction of the gauge bosons and the fermions are through the gauge covariant derivative.

$$\mathcal{L}_f = \overline{Q}_i i \not{D} Q_i + \overline{u}_i i \not{D} u_i + \overline{d}_i i \not{D} d_i + \overline{L}_i i \not{D} L_i + \overline{e}_i i \not{D} e_i,$$

where the subscript i runs over the three generations of fermions, Q, u, and d are the left-handed doublet, right-handed singlet up, and right handed singlet down quark fields, and L and e are the left-handed doublet and right-handed singlet electron fields.

The *h* term describes the Higgs field F.

$$\mathcal{L}_h = |D_\mu h|^2 - \lambda\left(|h|^2 - \frac{v^2}{2}\right)^2$$

The *y* term gives the Yukawa interaction that generates the fermion masses after the Higgs acquires a vacuum expectation value.

$$\mathcal{L}_y = -y_{u\,ij}\epsilon^{ab}\,h_b^\dagger\,\overline{Q}_{ia}u_j^c - y_{d\,ij}\,h\,\overline{Q}_i d_j^c - y_{e\,ij}\,h\,\overline{L}_i e_j^c + h.c.$$

EW SECTOR [AFTER SSB]

The Lagrangian reorganizes itself after the Higgs boson acquires a vacuum expectation value. Due to its complexity, this Lagrangian is best described by breaking it up into several parts as follows.

$$\mathcal{L}_{EW} = \mathcal{L}_K + \mathcal{L}_N + \mathcal{L}_C + \mathcal{L}_H + \mathcal{L}_{HV} + \mathcal{L}_{WWV} + \mathcal{L}_{WWVV} + \mathcal{L}_Y$$

The kinetic term $\mathcal{L}_K$ contains all the quadratic terms of the Lagrangian, which include the dynamic terms (the partial derivatives) and the mass terms (conspicuously absent from the Lagrangian before symmetry breaking)

$$\mathcal{L}_K = \sum_f \overline{f}(i\partial\!\!\!/ - m_f)f - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu} + m_W^2 W^+_\mu W^{-\mu}$$
$$-\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu + \frac{1}{2}(\partial^\mu H)(\partial_\mu H) - \frac{1}{2}m_H^2 H^2$$

where the sum runs over all the fermions of the theory (quarks and leptons), and the fields $A_{\mu\nu}$, $Z_{\mu\nu}$, $W^-_{\mu\nu}$, and $W^+_{\mu\nu} \equiv (W^-_{\mu\nu})^\dagger$ are given as

$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu + g f^{abc} X^b_\mu X^c_\nu$, (replace X by the relevant field, and f^{abc} with the structure constants for the gauge group).

The neutral current $\mathcal{L}_N$ and charged current $\mathcal{L}_C$ components of the Lagrangian contain the interactions between the fermions and gauge bosons.

$$\mathcal{L}_N = e J^{em}_\mu A^\mu + \frac{g}{\cos\theta_W}(J^3_\mu - \sin^2\theta_W J^{em}_\mu)Z^\mu,$$

where the electromagnetic current J^{em}_μ and the neutral weak current J^3_μ are

$$J^{em}_\mu = \sum_f q_f \overline{f}\gamma_\mu f,$$

and

$$J^3_\mu = \sum_f I^3_f \overline{f}\gamma_\mu \frac{1-\gamma^5}{2} f$$

q_f and I^3_f are the fermions' electric charges and weak isospin.

The charged current part of the Lagrangian is given by

$$\mathcal{L}_C = -\frac{g}{\sqrt{2}}\left[\overline{u}_i\gamma^\mu\frac{1-\gamma^5}{2}M^{CKM}_{ij}d_j + \overline{\nu}_i\gamma^\mu\frac{1-\gamma^5}{2}e_i\right]W^+_\mu + h.c.$$

EW SECTOR [AFTER SSB]

$\mathcal{L}_H$ contains the Higgs three-point and four-point self interaction terms.

$$\mathcal{L}_H = -\frac{gm_H^2}{4m_W}H^3 - \frac{g^2m_H^2}{32m_W^2}H^4$$

$\mathcal{L}_{HV}$ contains the Higgs interactions with gauge vector bosons.

$$\mathcal{L}_{HV} = \left(gm_W H + \frac{g^2}{4}H^2\right)\left(W_\mu^+ W^{-\mu} + \frac{1}{2\cos^2\theta_W}Z_\mu Z^\mu\right)$$

$\mathcal{L}_{WWV}$ contains the gauge three-point self interactions.

$$\mathcal{L}_{WWV} = -ig[(W_{\mu\nu}^+ W^{-\mu} - W^{+\mu}W_{\mu\nu}^-)(A^\nu \sin\theta_W - Z^\nu \cos\theta_W) + W_\nu^- W_\mu^+ (A^{\mu\nu}\sin\theta_W - Z^{\mu\nu}\cos\theta_W)]$$

$\mathcal{L}_{WWVV}$ contains the gauge four-point self interactions

$$\mathcal{L}_{WWVV} = -\frac{g^2}{4}\Big\{[2W_\mu^+ W^{-\mu} + (A_\mu \sin\theta_W - Z_\mu \cos\theta_W)^2]^2 - [W_\mu^+ W_\nu^- + W_\nu^+ W_\mu^- + (A_\mu \sin\theta_W - Z_\mu\cos\theta_W)(A_\nu \sin\theta_W - Z_\nu \cos\theta_W)]^2\Big\}$$

and $\mathcal{L}_Y$ contains the Yukawa interactions between the fermions and the Higgs field.

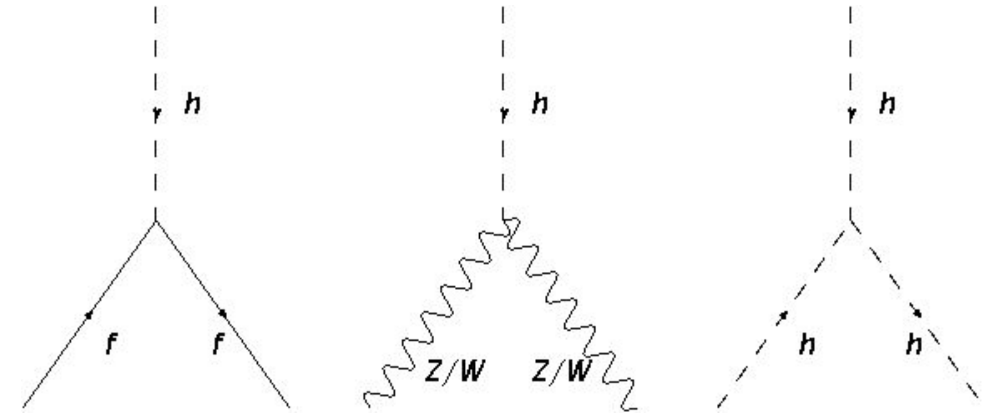
$$\mathcal{L}_Y = -\sum_f \frac{gm_f}{2m_W}\bar{f}fH$$

Note the $\dfrac{1-\gamma^5}{2}$ factors in the weak couplings: these factors project out the left handed components of the spinor fields. This is why electroweak theory (after symmetry breaking) is commonly said to be a chiral theory.

IN THE STANDARD MODEL

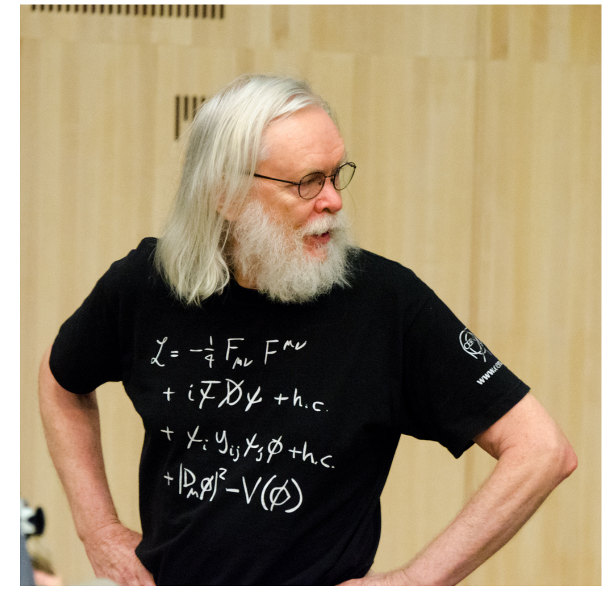
- in the SM the Higgs mechanism [SSB of the gauge symmetry $SU(2)\otimes U(1) \rightarrow U(1)$] with a quartic [renormalizable] potencial
  - gives mass to the carriers of the weak force [Z^0, $W^\pm$]
  - leaves the carrier of EM force [γ] massless
  - adds
    - a scalar massive particle [Higgs boson]
    - 2 parameters [μ/λ : vacuum expectation value; μ : Higgs mass]
  - allows for fermion [leptons and quarks] mass terms [without gauge simmetry violation] as couplings to the Higgs field

$$\mathcal{L}_{int} = -\alpha_f \bar{\psi}_f \psi_f \phi \Longrightarrow m_f = \alpha_f (\mu/\lambda)$$

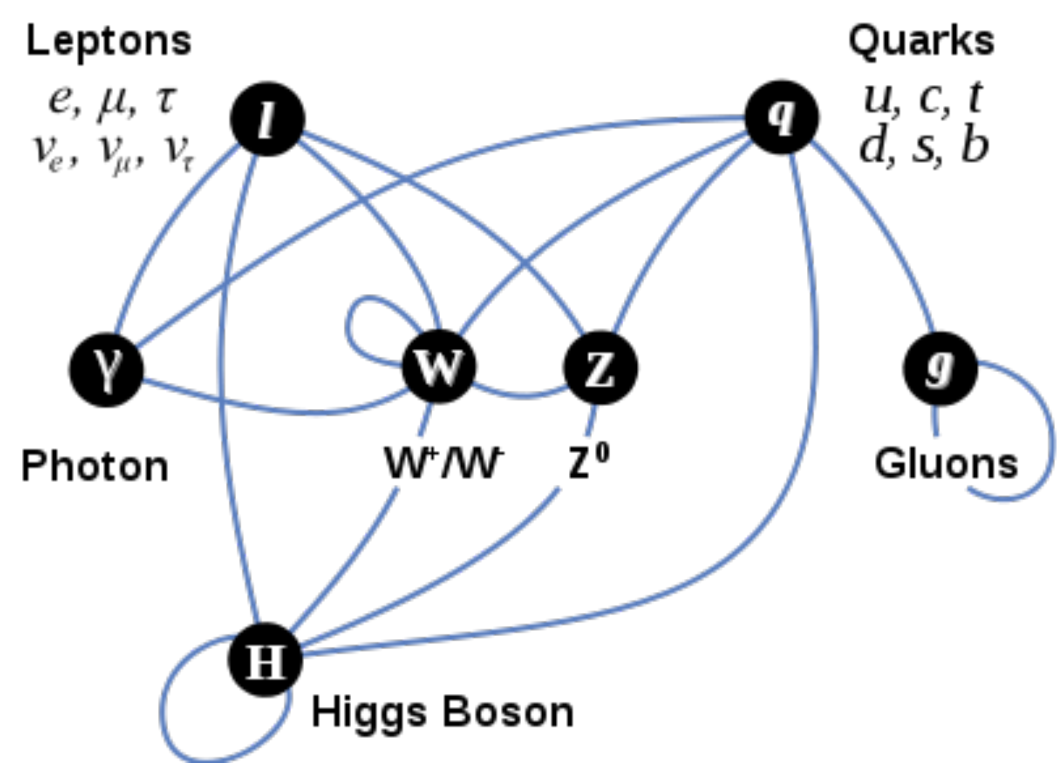


MODELO STANDARD [EW+STRONG]

$$
\begin{aligned}
\mathcal{L}_{GWS} = \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) + \\
+\frac{g}{\sqrt{2}}\sum_i (\bar{a}^i_L \gamma^\mu b^i_L W^+_\mu + \bar{b}^i_L \gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w}\sum_f \bar{\Psi}_f \gamma^\mu (I^3_f - 2s^2_w Q_f - I^3_f \gamma_5)\Psi_f Z_\mu + \\
-\frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2}|\partial_\mu W^+_\nu - \partial_\nu W^+_\mu + \\
-ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 + \\
-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 + \\
-\frac{1}{2}M^2_\eta \eta^2 - \frac{g M^2_\eta}{8M_W}\eta^3 - \frac{g'^2 M^2_\eta}{32 M_W}\eta^4 + |M_W W^+_\mu + \frac{g}{2}\eta W^+_\mu|^2 + \\
+\frac{1}{2}|\partial_\mu \eta + iM_Z Z_\mu + \frac{ig}{2c_w}\eta Z_\mu|^2 - \sum_f \frac{g}{2}\frac{m_f}{M_W}\bar{\Psi}_f \Psi_f \eta
\end{aligned}
$$



$$
\begin{aligned}
\mathcal{L}_{\mathrm{QCD}} &= \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a \\
&= \bar{\psi}_i (i\gamma^\mu \partial_\mu - m)\psi_i - g G^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a \,,
\end{aligned}
$$



⥁L(arge) H(adron) C(ollider)

- ***Large***

  ~ 27km perimeter

  :: re-uses LEP tunnel

  :: maximum energy depends on accelerator radius and magnitude of dipolar magnetic field that keeps particles in orbit

- ***Hadron***

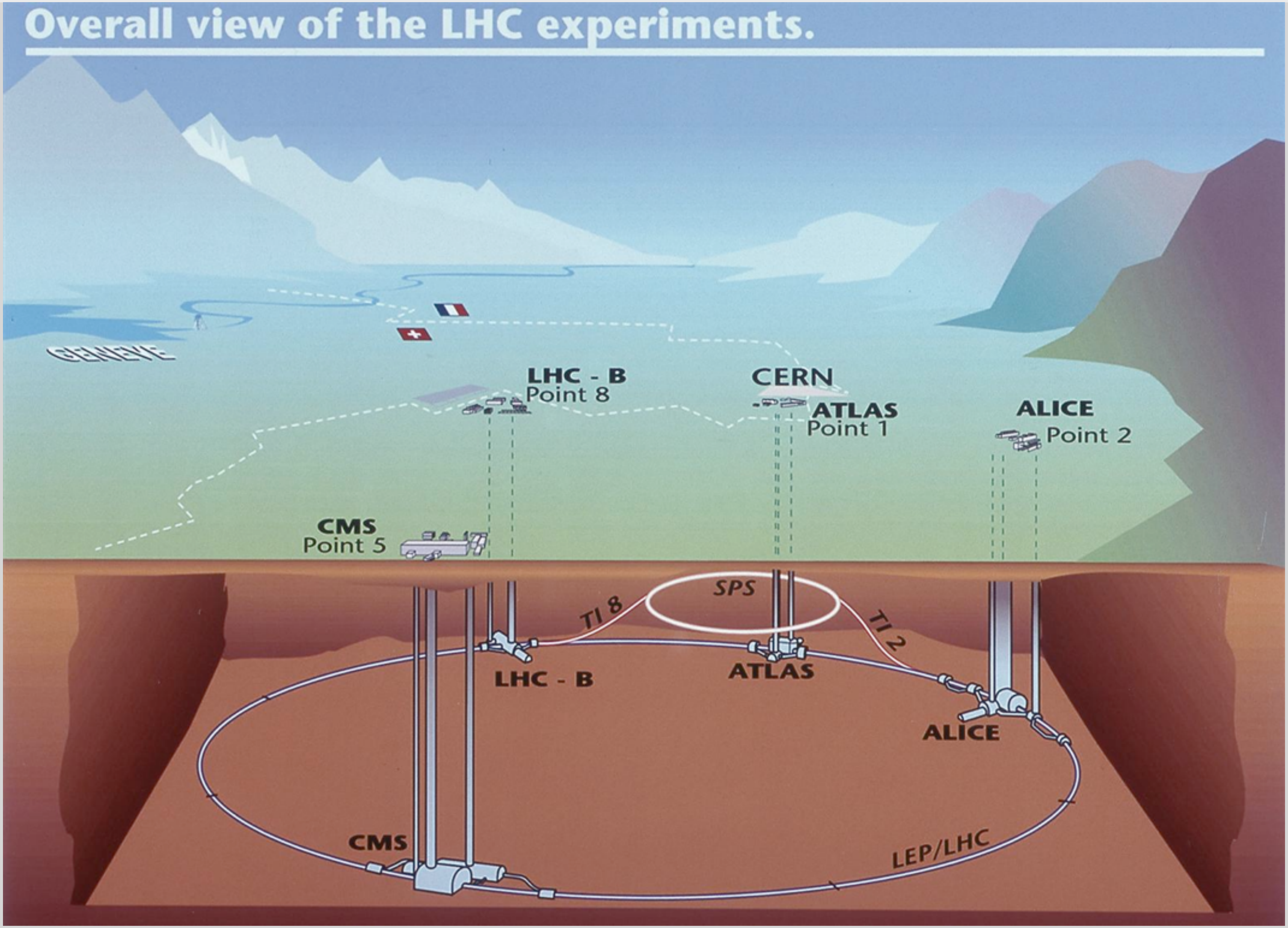
  protons e ions (Pb, Xe, soon O) [hadrons]

- ***Collider***

  CM energy is the sum of the two beams [circulating in opposite directions]

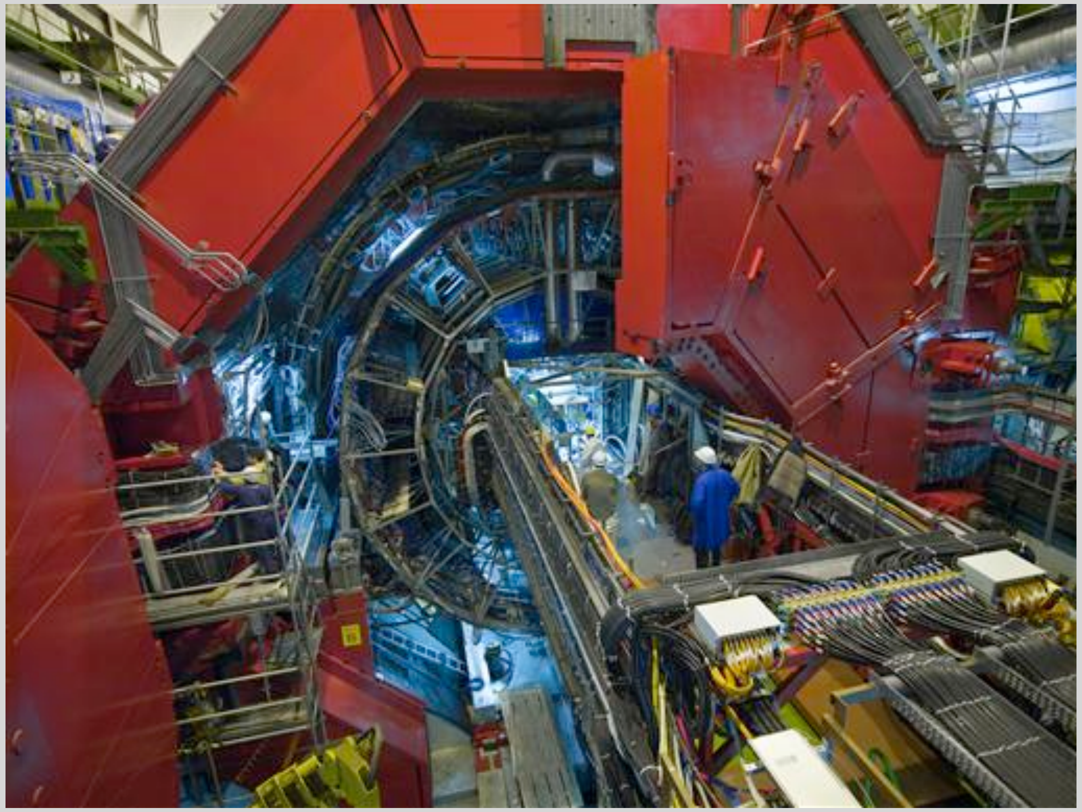
  :: advantageous wrt to fixed target and linear colliders

⥁ detectors [the experiments]



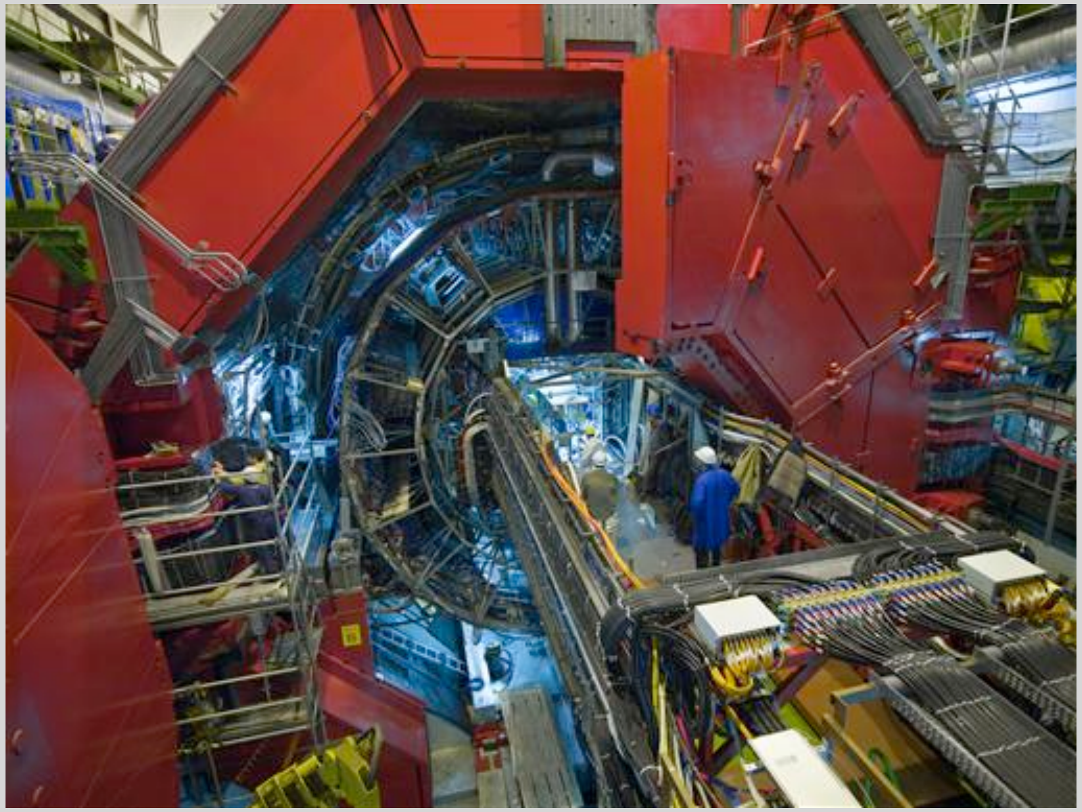
Detectors

Detectors



ALICE
1987 people [556 authors] 41 countries

Detectors



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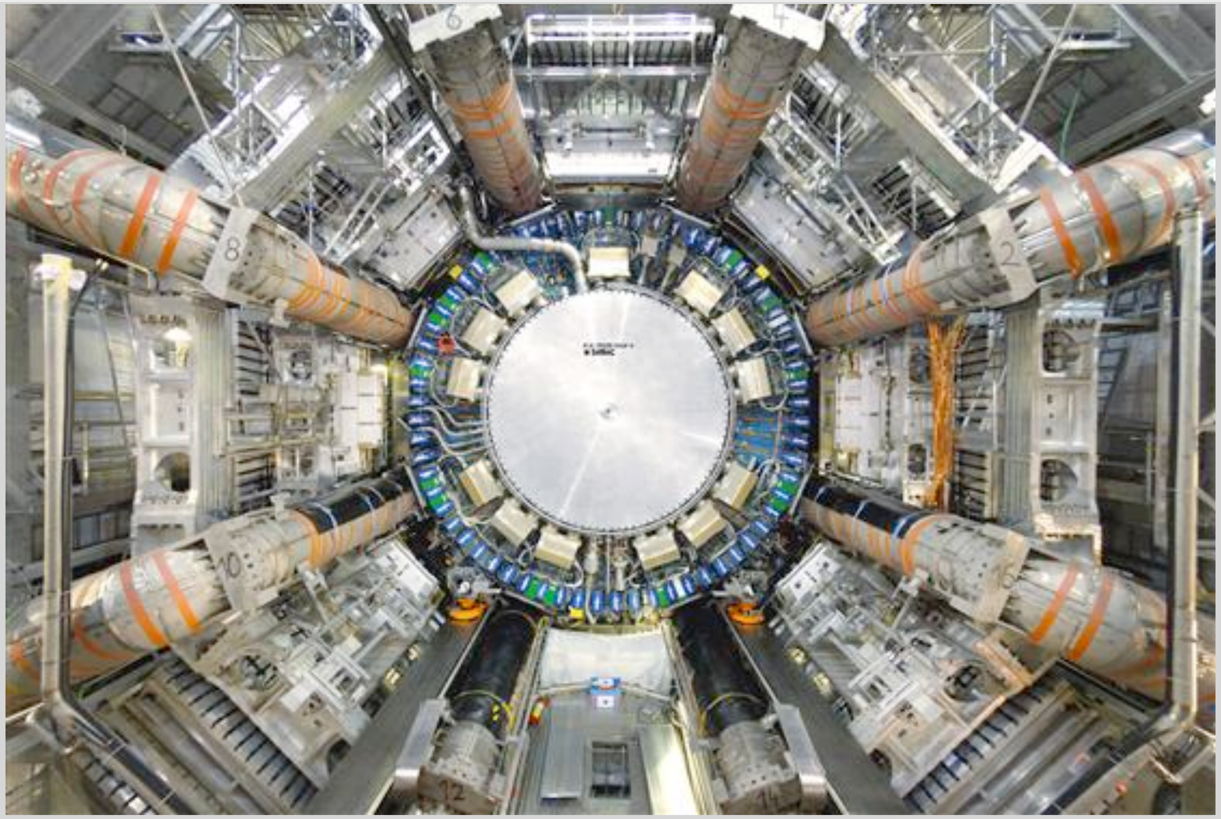
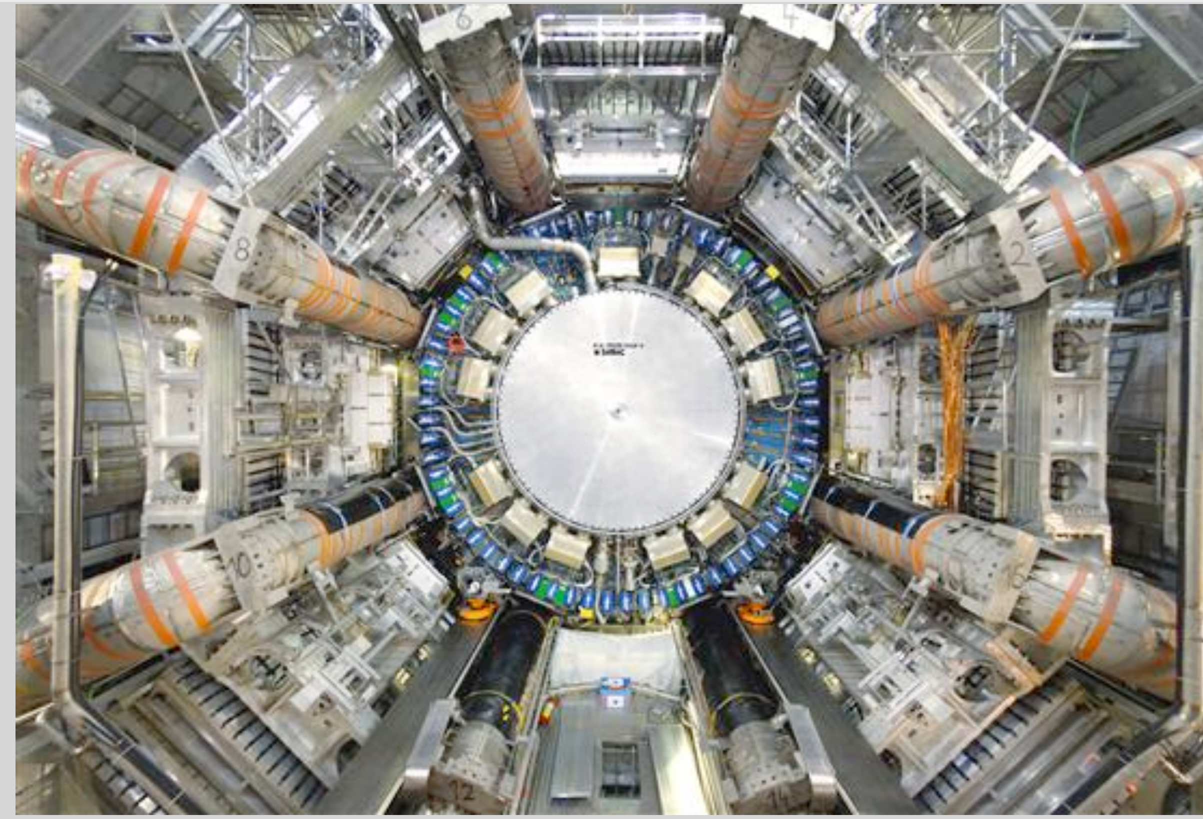


ATLAS
6530 people [1550 authors] 45 countries

Detectors

ALI
198

CMS
5665 people [2131 authors] 57 countries



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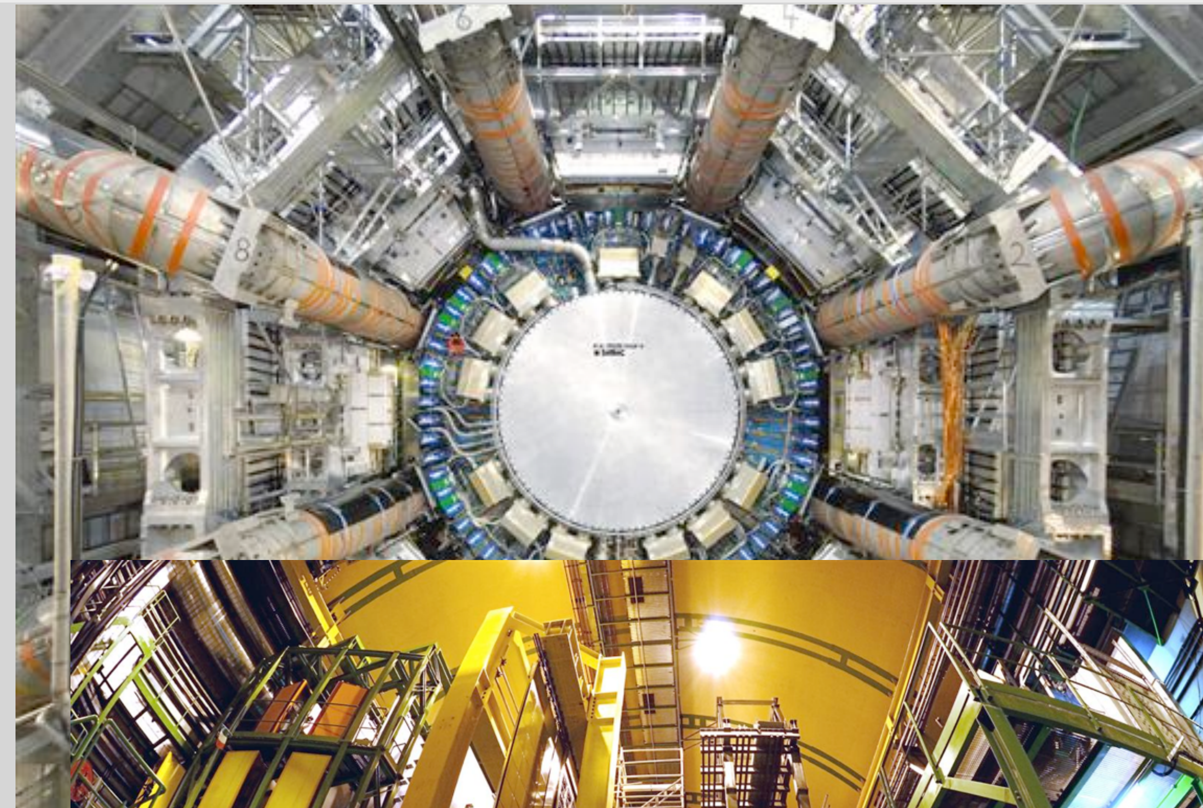


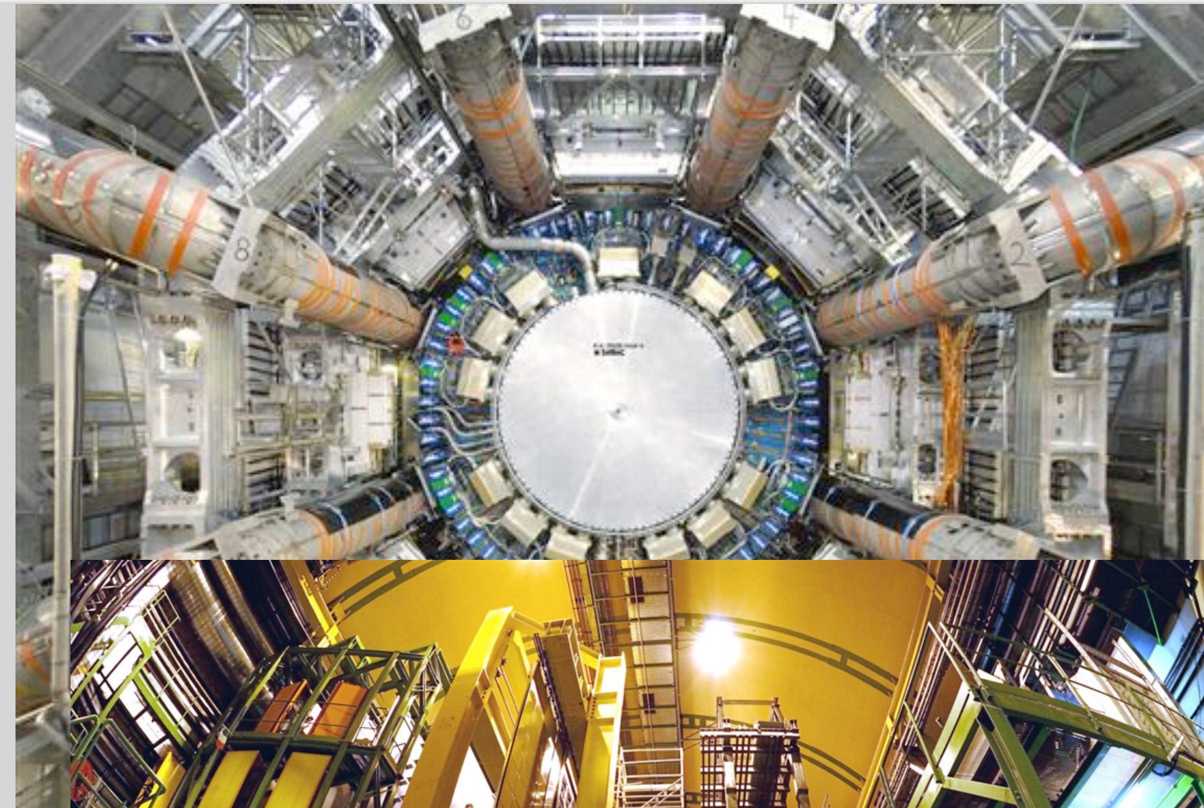
ALI
198

A
6.

CMS
5665 people [2131 authors] 57 countries

LHCb
1499 people [947 authors] 21 countries

Detectors



ALI
198

A
6.

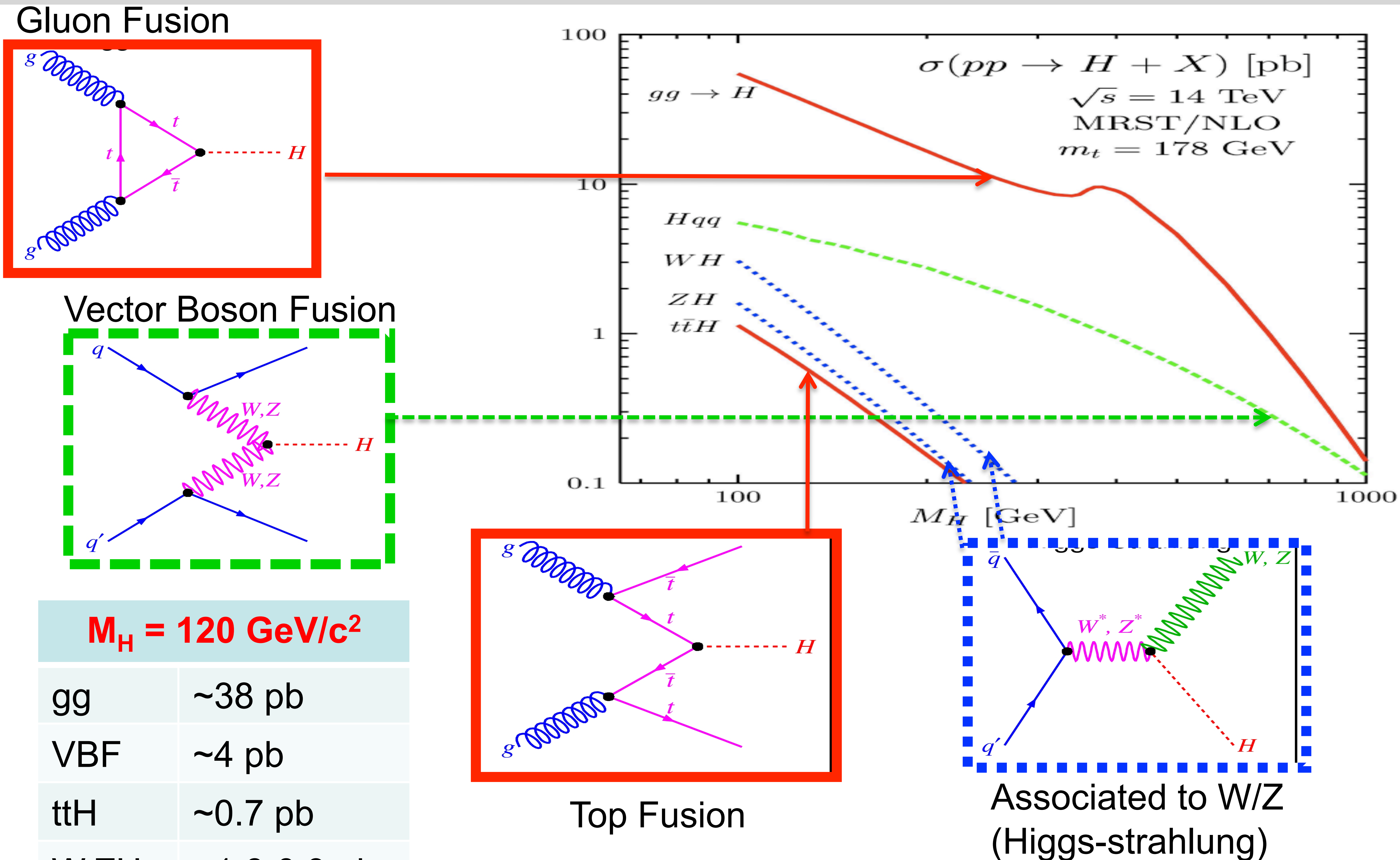
CMS
5665 people [2131 authors] 57 countries

LHCb
1499 people [947 authors] 21 countries

smaller experiments: FASER; TOTEM; LHCf; MoEDAL; SND@LHC

HIGGS DISCOVERY

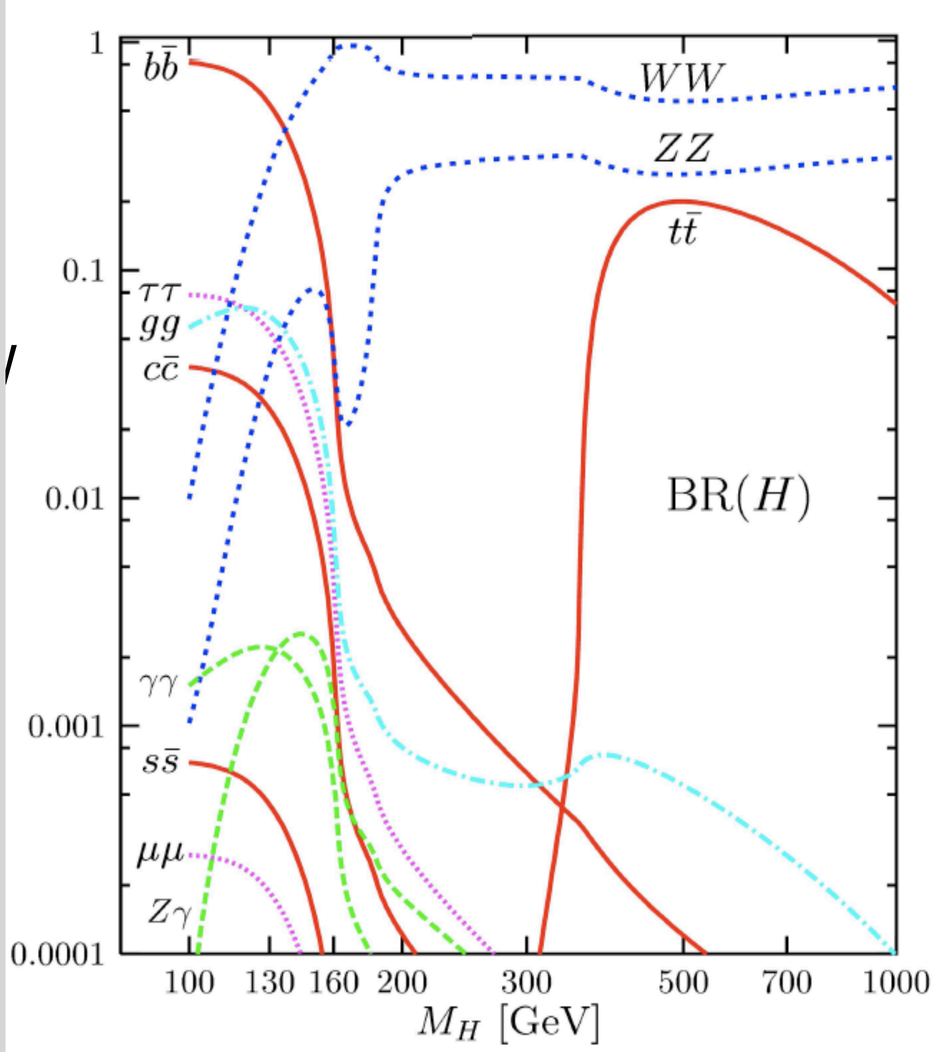
Higgs production



M_H = 120 GeV/c^2	
gg	~38 pb
VBF	~4 pb
ttH	~0.7 pb
W,ZH	~1.6-0.9 pb

Higgs final states

- Higgs decays [almost] instantaneously
  - for a light Higgs the highest decay probability
    - H → b bbar [belong to jets]
    - H → WW
    - H → ZZ
  - other important channels
    - H → **γγ** [excelent calorimetry]
    - **H** → **ττ**



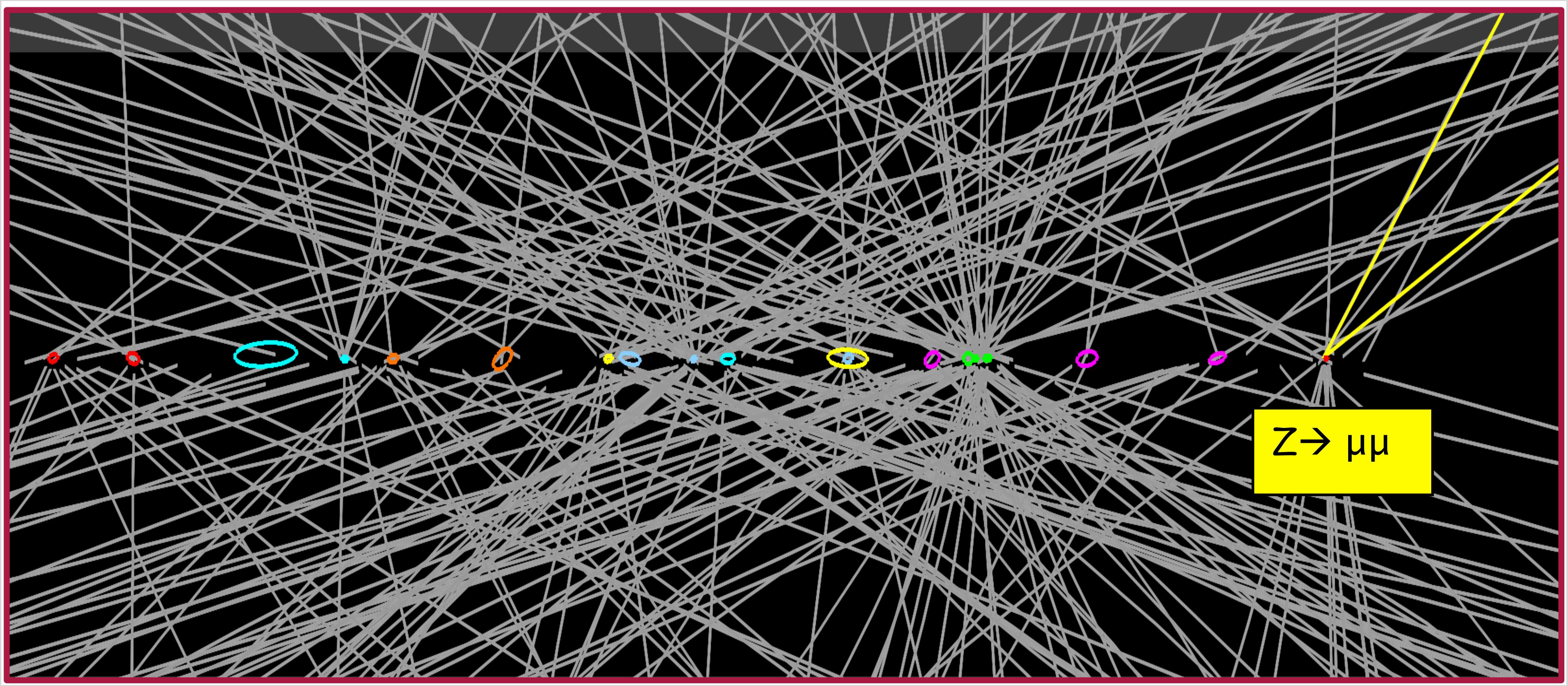
$$H \to \gamma\gamma$$

$$H \to WW \to e^{\mp}\nu_e\mu^{\pm}\nu_\mu$$
$$H \to WW \to e^{-}\bar{\nu}_e e^{+}\nu_e$$
$$H \to WW \to \mu^{-}\bar{\nu}_\mu\mu^{+}\nu_\mu$$

$$H \to ZZ \to e^{+}e^{-}e^{+}e^{-}$$
$$H \to ZZ \to \mu^{+}\mu^{-}\mu^{+}\mu^{-}$$
$$H \to ZZ \to \mu^{+}\mu^{-}e^{+}e^{-}$$

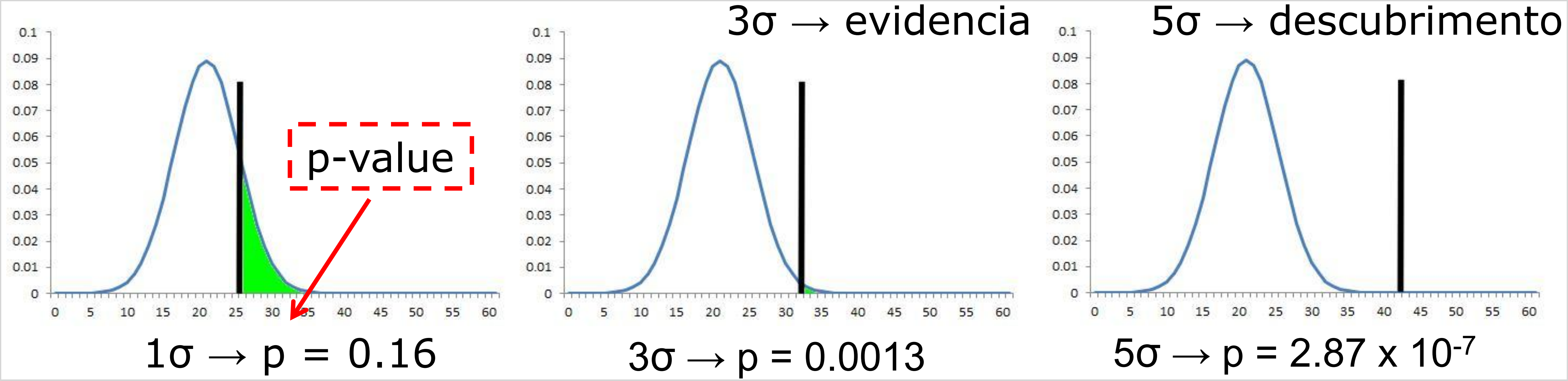
pile-up

- a major experimental challenge is how to deal with overlapping collisions
  - to increase luminosity
    - 10^{15} protons colliding every 50 ns (it will be 25ns soon)
      - each ‘event’ is the overlap of approximately 40 inelastic pp collisons



statistical significance

- all Higgs final states can occur as result of other SM processes [background]
  - ⟶ a discovery is not made on the basis of the observation of one event, but rather as a deviation [excess] wrt to background
  - ⟶ statistical fluctuations of background result in local deviationsr
  - ⟶ probability of a given deviation being the result of a fluctuation [for gaussian background]



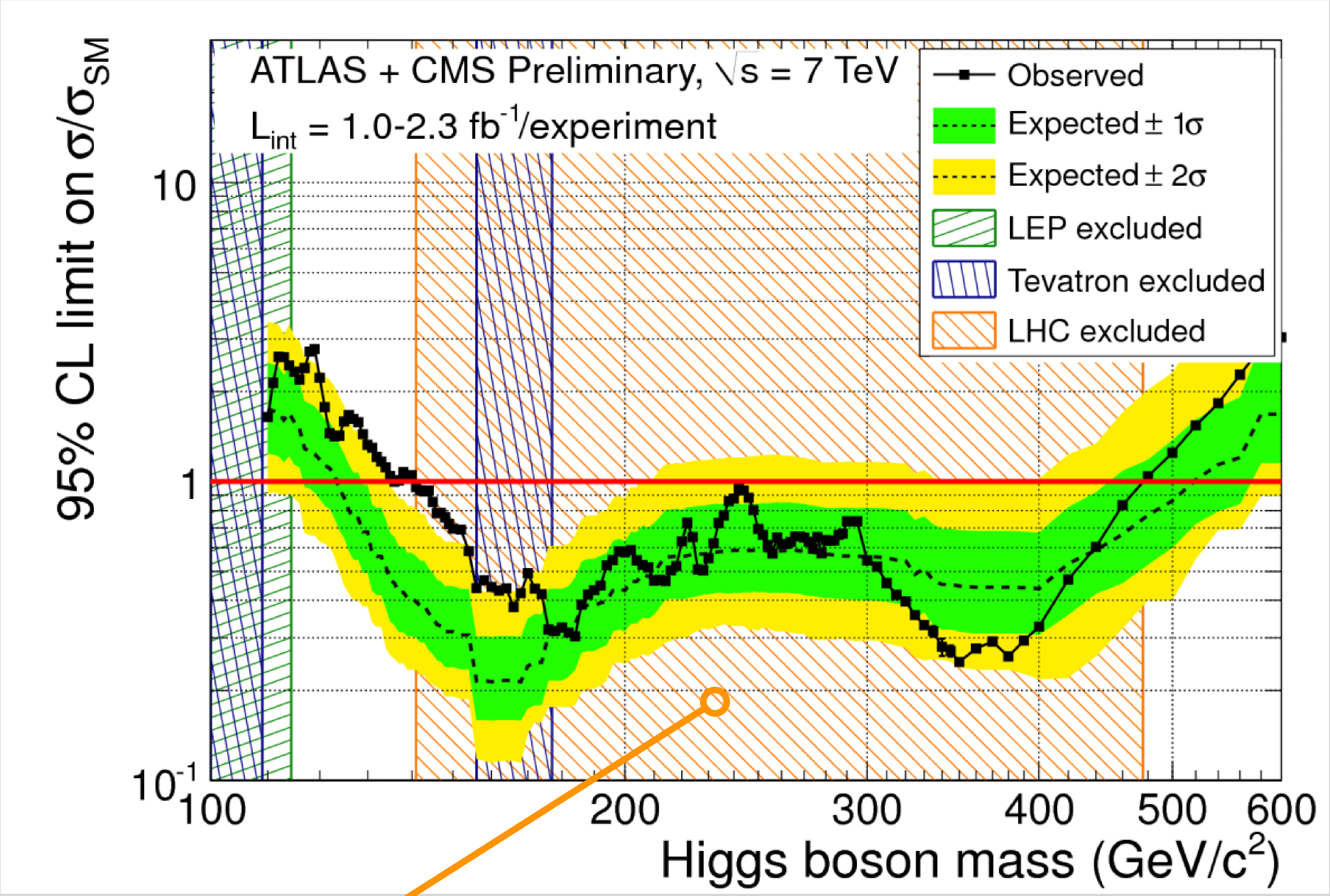
exclusion e look-elsewhere-effect

- to discover one has first to exclude
  - the first signal for a possible discovery is the inability to exclude
  - the ability to exclude depends on the available statistics [number of events]

- the larger the region [in this case of masses] you look at, the larger the probability of observing a deviation somewhere [look-elsewhere effect]
  - in ‘delocalized’ searches this has to be accounted for
  - this reduces the statistical significance of a local excess [magnitude of excess/ width of search region]

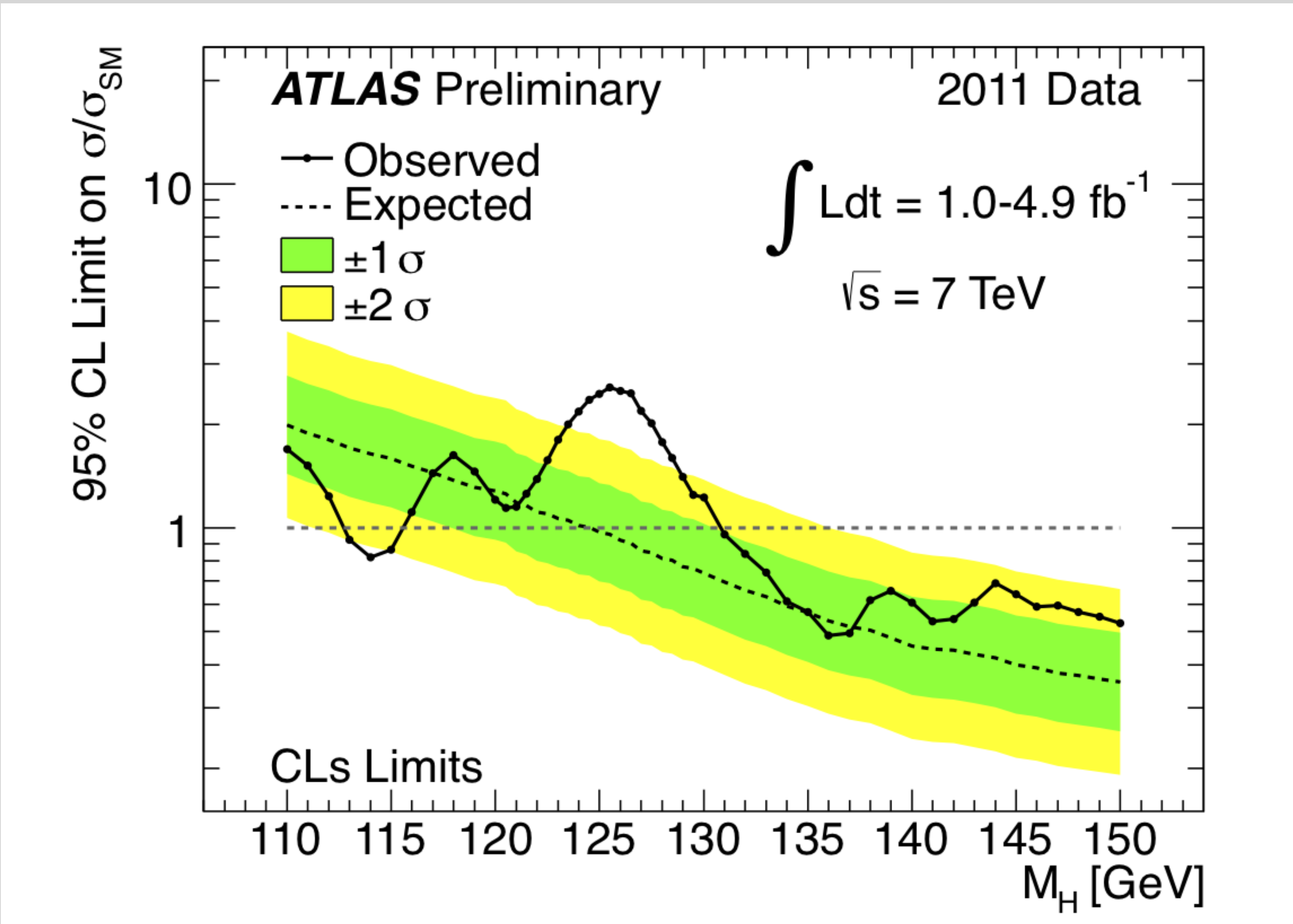
13 Dec 2011

13 Dec 2011



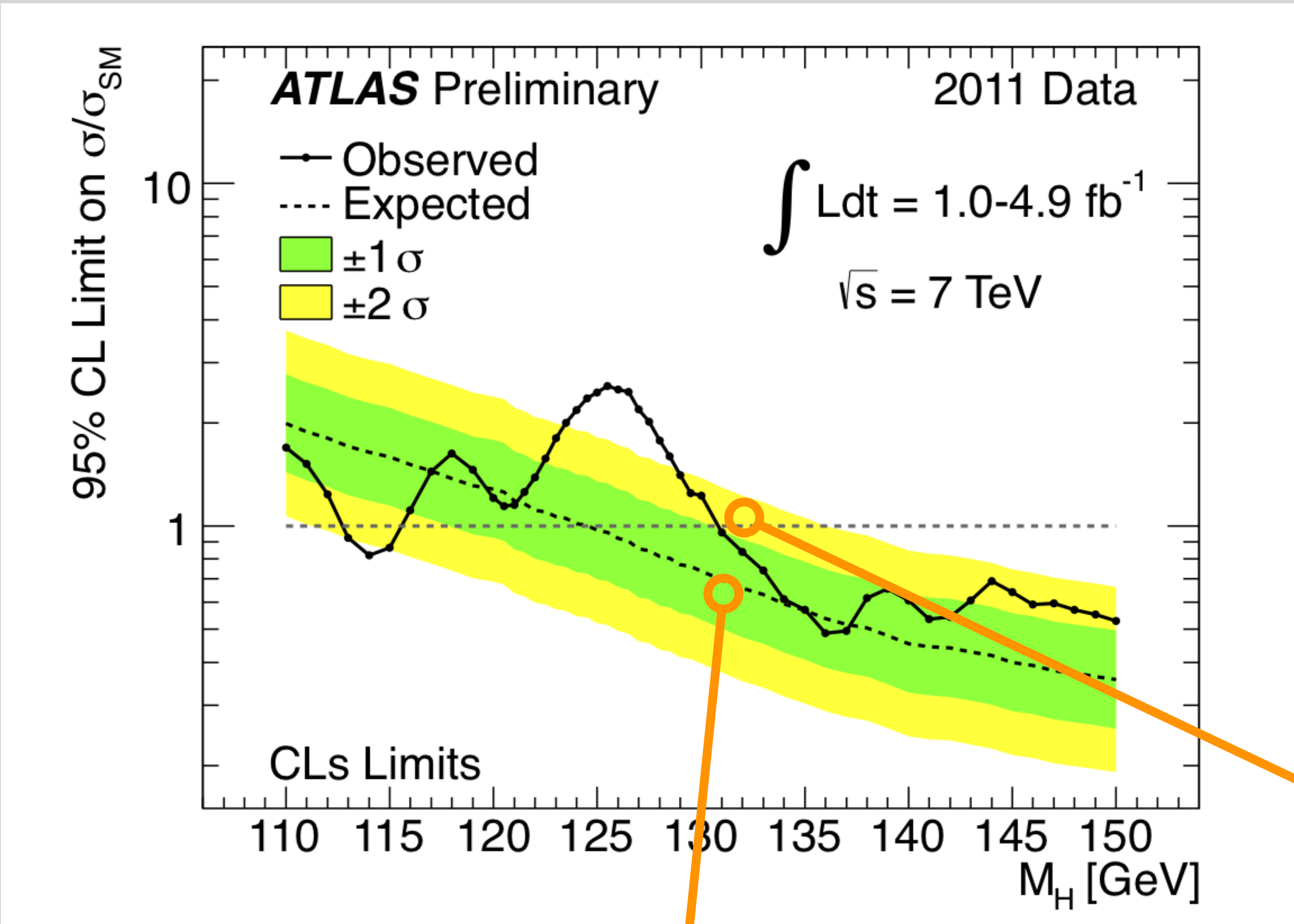
two years of LHC

exclusion plots



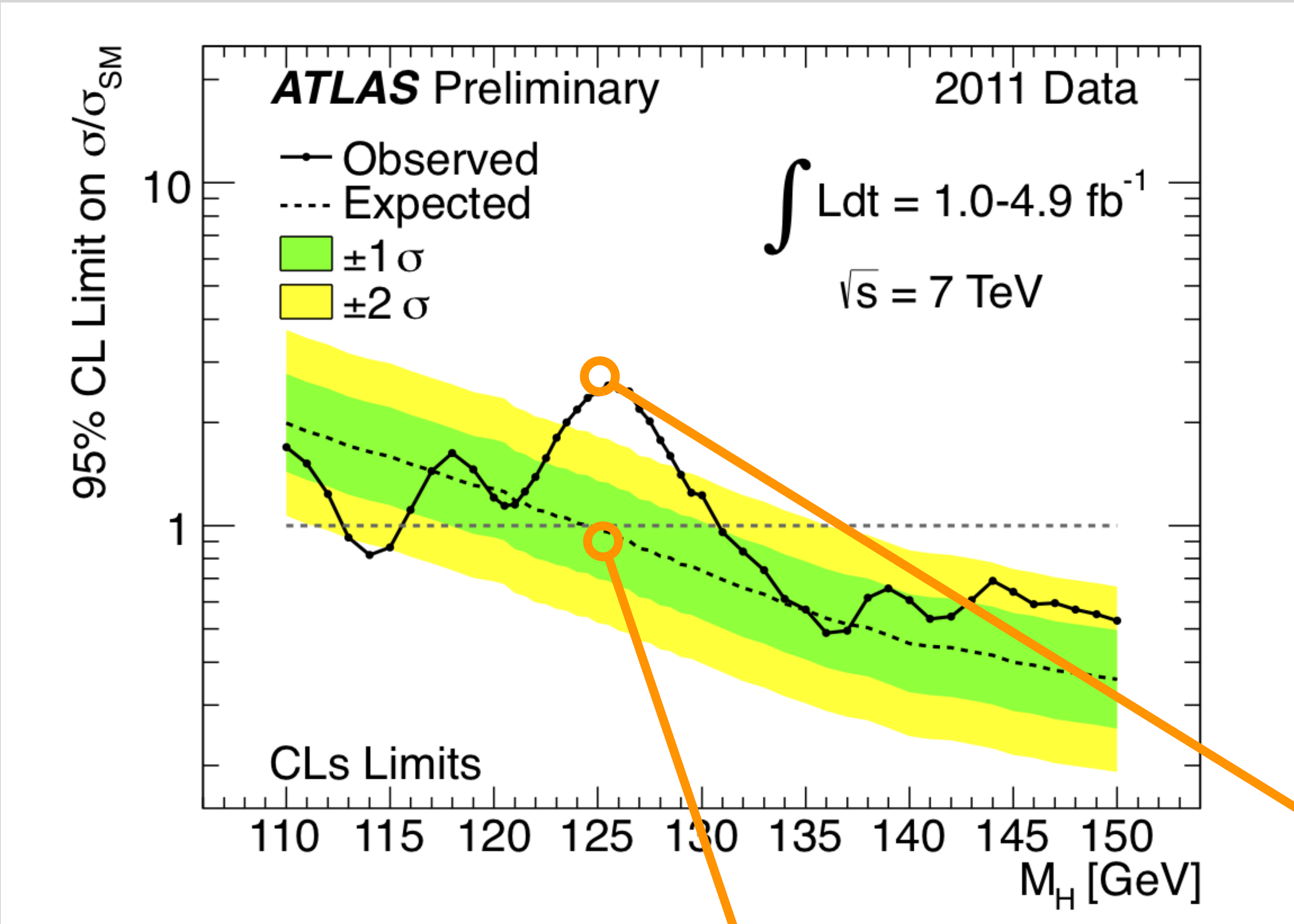
- vertical axis: 95% CL exclusion
- dashed line : without Higgs [bands of 68% and 95% CL]
- full line : ratio between cross section that is being excluded and expected SM cross section for a Higgs with a given mass

exclusion plots



- for m_H = 130 GeV
  - ↪ expected to exclude 0.7 of cross section BUT only excluded full cross section

exclusion plots



- for m_H = 125 GeV
  - expected to exclude 0.7 of cross section BUT only excluded 3x cross section
  - the inability to exclude signals a possible physical effect
    - local significance 3.6σ :: [LEE] 2.3σ :: p-value 1% [prob of being a fluctuation]

2012

$\sqrt{s}$ = 7 TeV → $\sqrt{s}$ = 8 TeV

:: increased production cross sections

increase of instantaneous luminosity

:: sucess in analyzing pile-up events

all particle physics analysis are ‘blind’ until the very end

4 Jul 2012 [dawn]

they got into the room

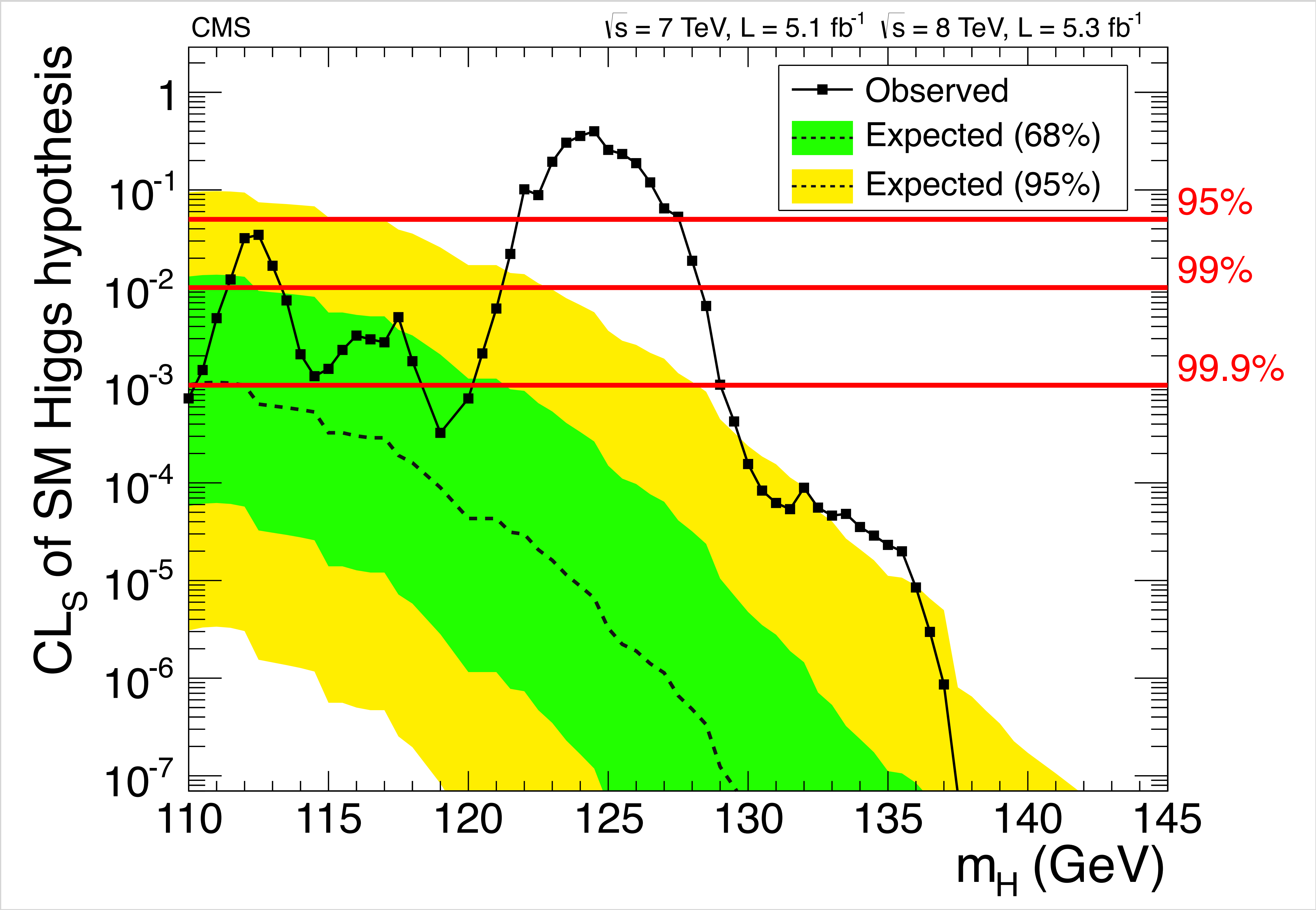
4 Jul 2012 [dawn]

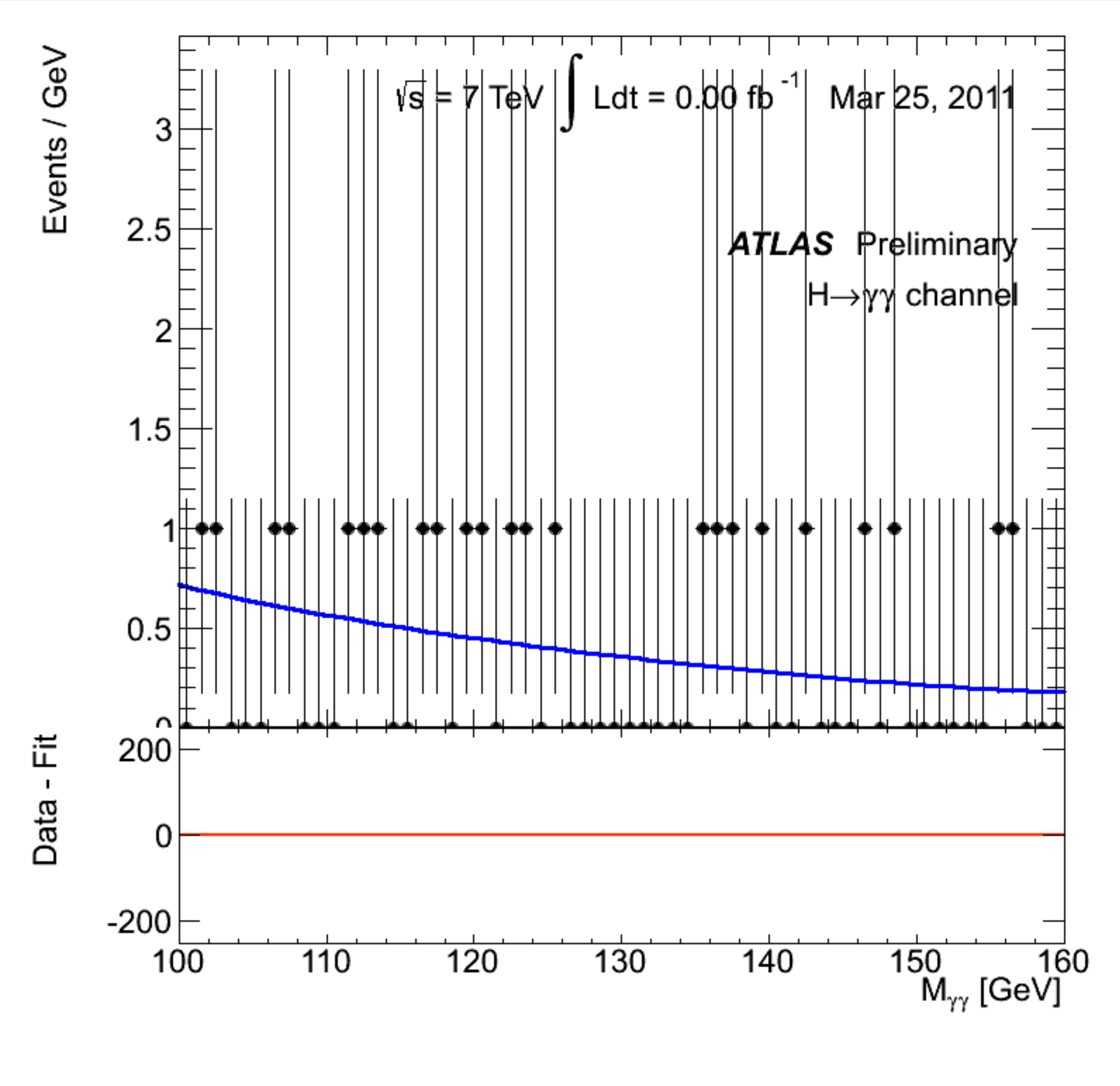
they got into the room

they DID NOT

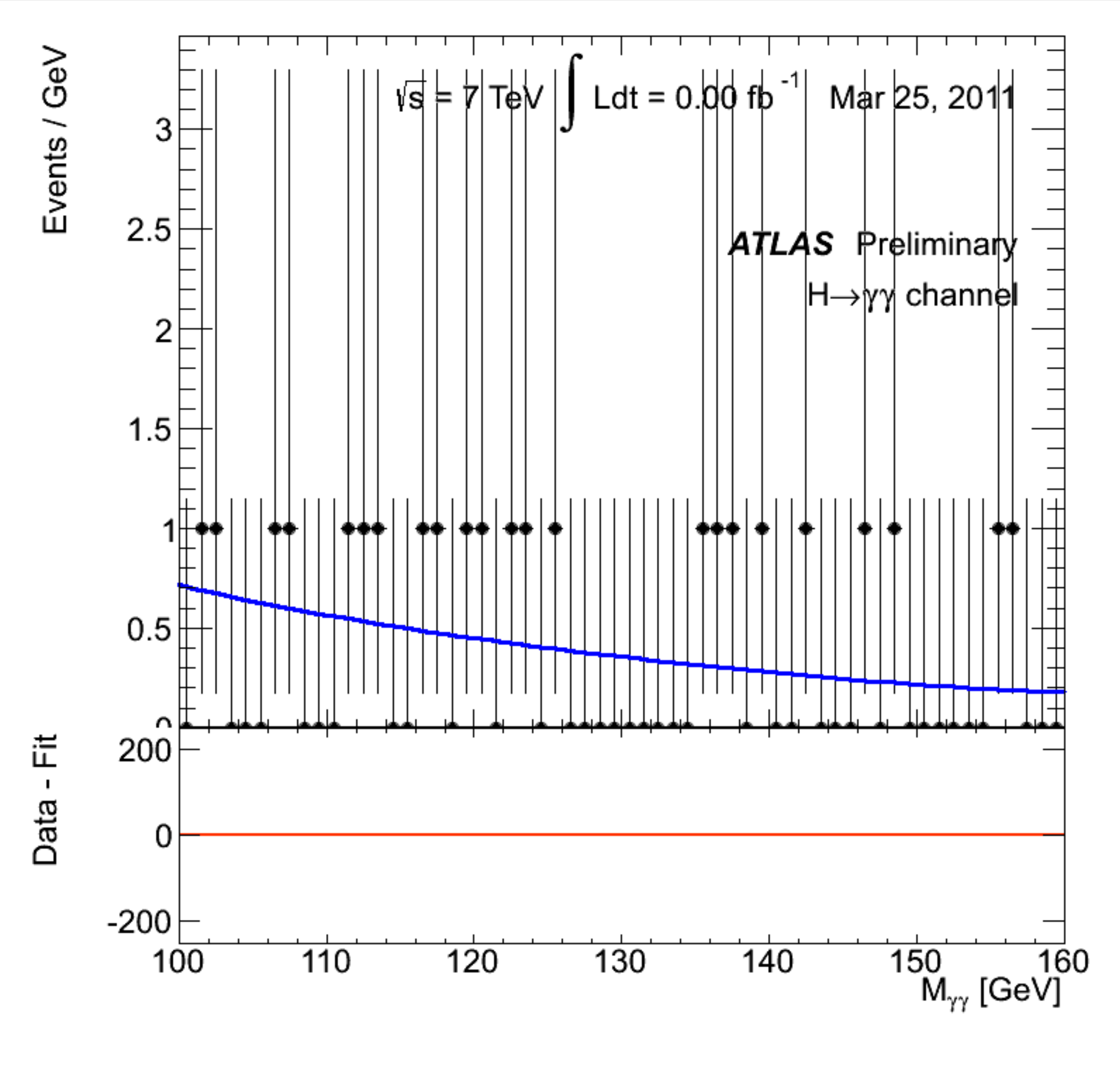
4 Jul 2012 [8h00]

exclusion plot

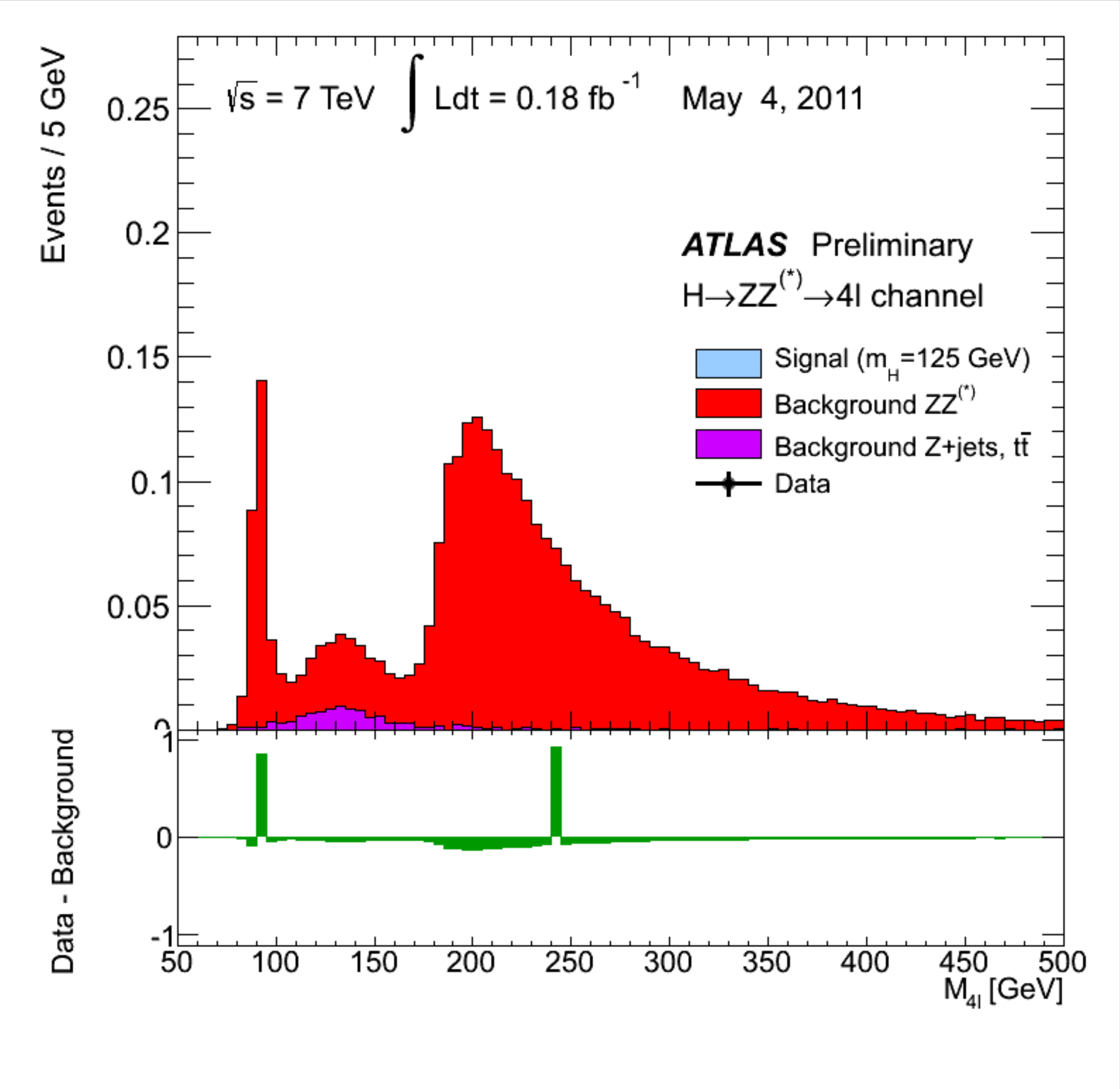




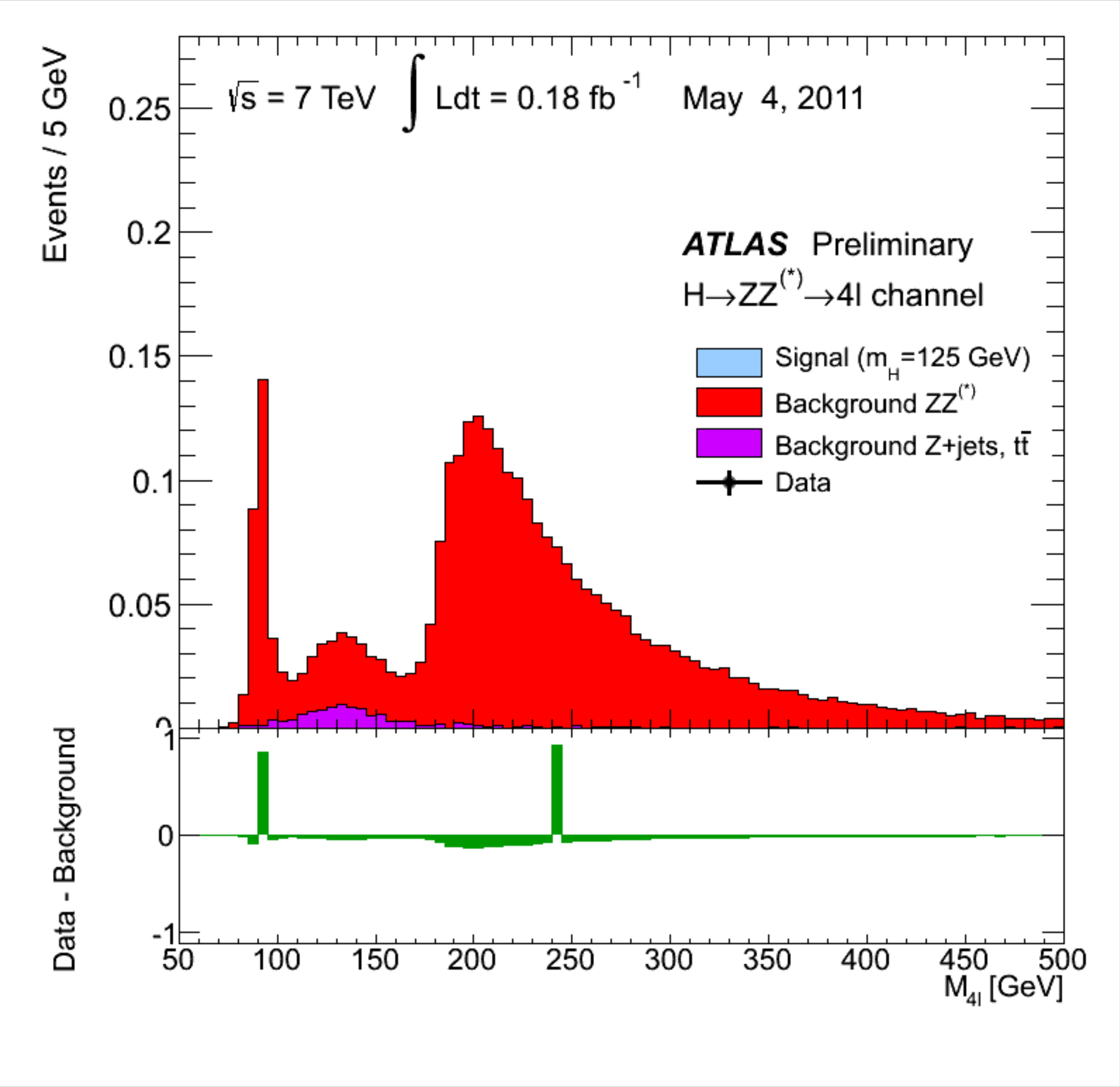
Higgs discovery in the γγ channel



Higgs discovery in the **γγ** channel



Higgs discovery in the 4l channel



Higgs discovery in the 4l channel

what has become history

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

12 469 citations

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

A R T I C L E   I N F O

Article history:
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Editor: W.-D. Schlatter

A B S T R A C T

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

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Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

12 162 citations

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

A R T I C L E   I N F O

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A B S T R A C T

Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $\text{b}\bar{\text{b}}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of $125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

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Higgs theoretical paper has ‘only’ 6593 citations

o que vai ficar para a História

PRESSMEDDELANDE
Press release

8 October 2013

The Nobel Prize in Physics 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert
Université Libre de Bruxelles, Brussels, Belgium

Peter W. Higgs
University of Edinburgh, UK

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

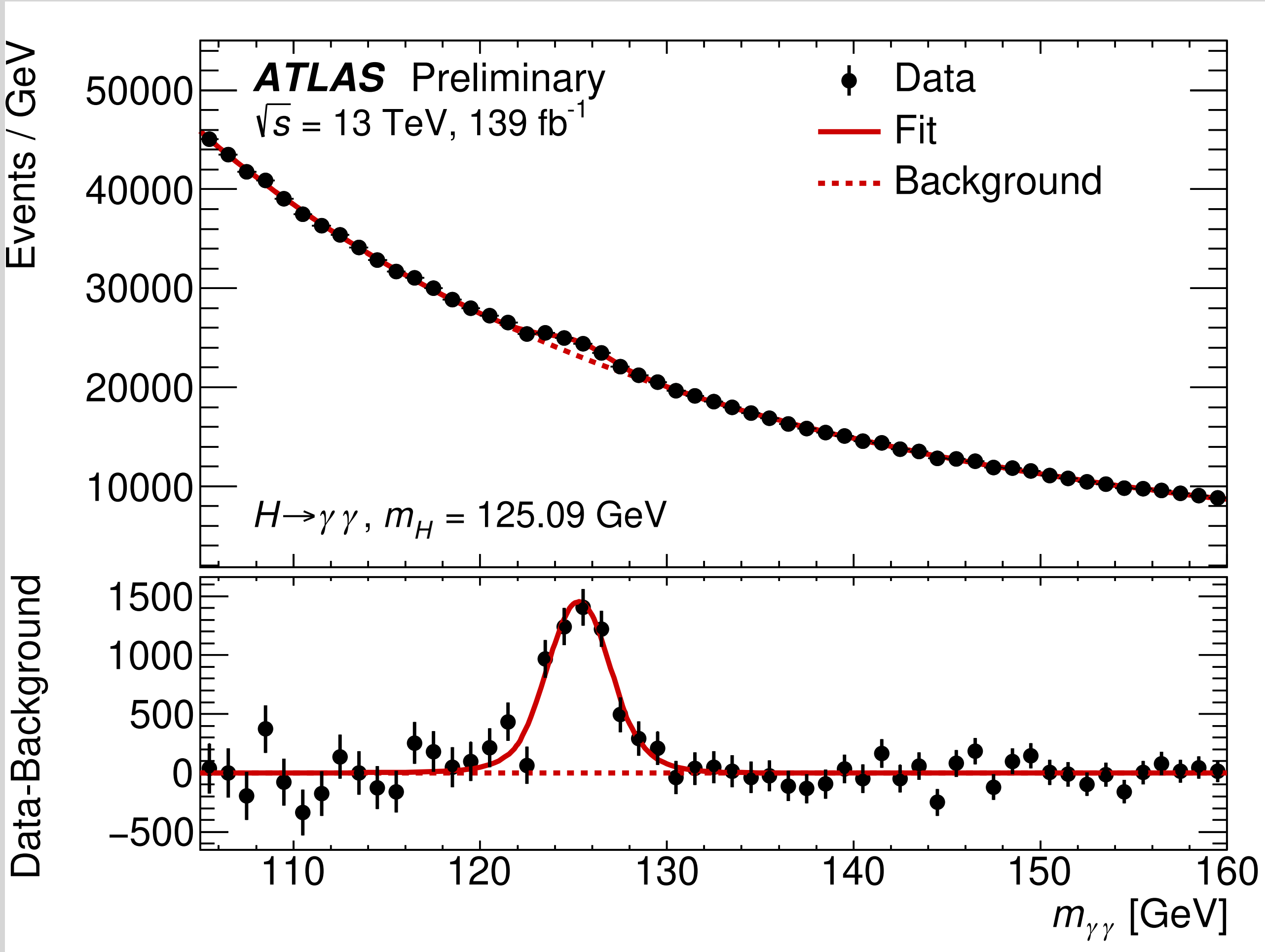
Here, at last!

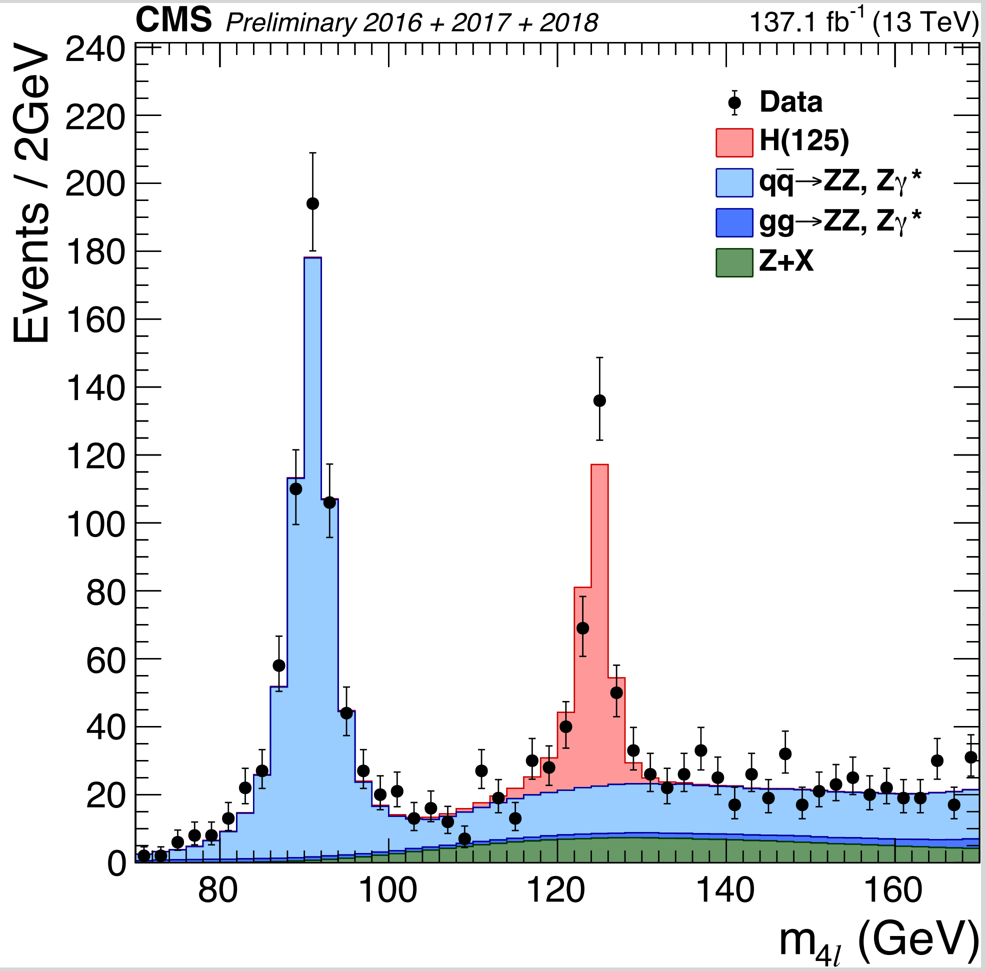
François Englert and Peter W. Higgs are jointly awarded the Nobel Prize in Physics 2013 for the theory of how particles acquire mass. In 1964, they proposed the theory independently of each other (Englert together with his now deceased colleague Robert Brout). In 2012, their ideas were confirmed by the discovery of a so called *Higgs particle* at the CERN laboratory outside Geneva in Switzerland.

The awarded theory is a central part of the Standard Model of particle physics that describes how the world is constructed. According to the Standard Model, everything, from flowers and people to stars and planets, consists of just a few building blocks: *matter particles*. These particles are governed by forces mediated by *force*

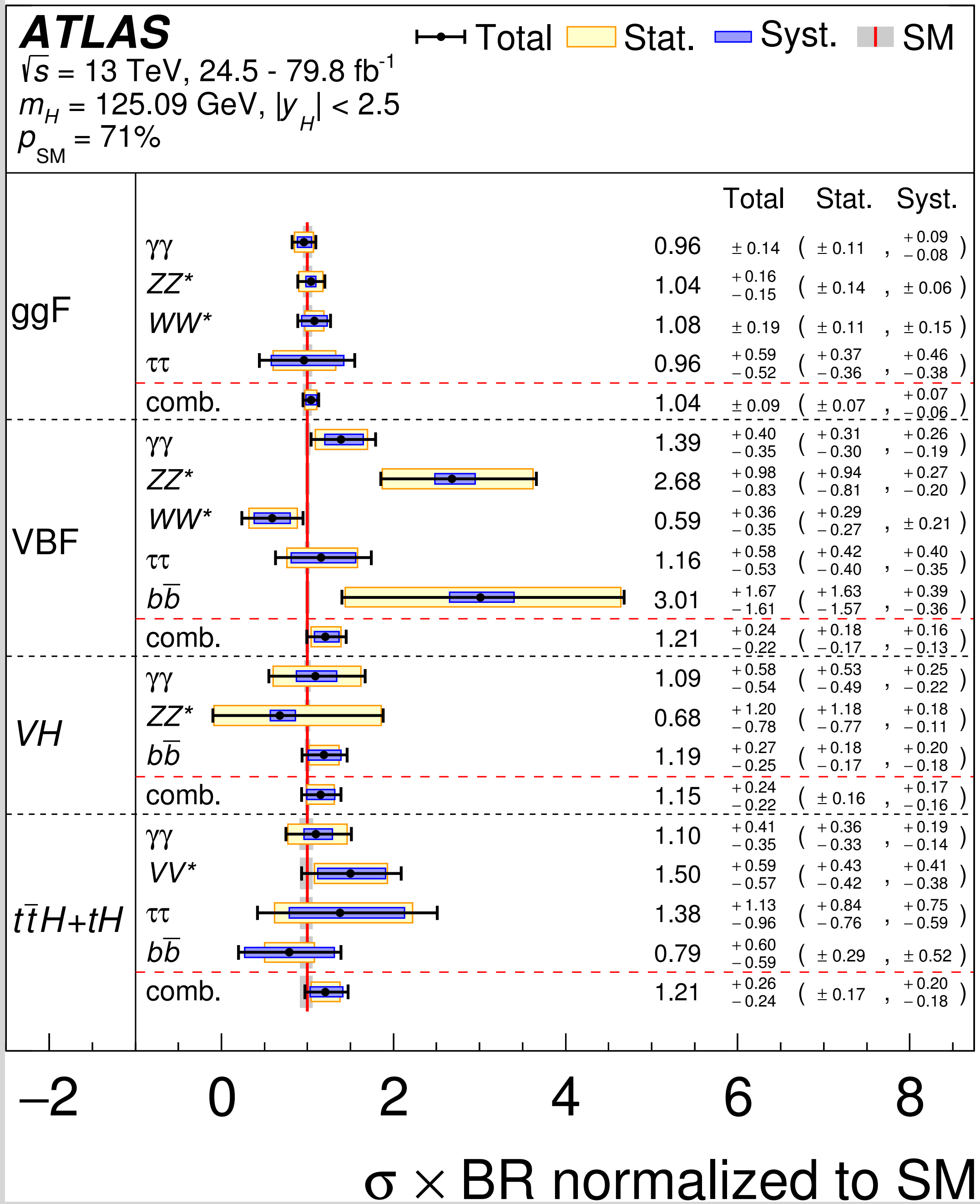
Hadron Collider), is probably the largest and the most complex machine ever constructed by humans. Two research groups of some 3,000 scientists each, ATLAS and CMS, managed to extract the Higgs particle from billions of particle collisions in the LHC.

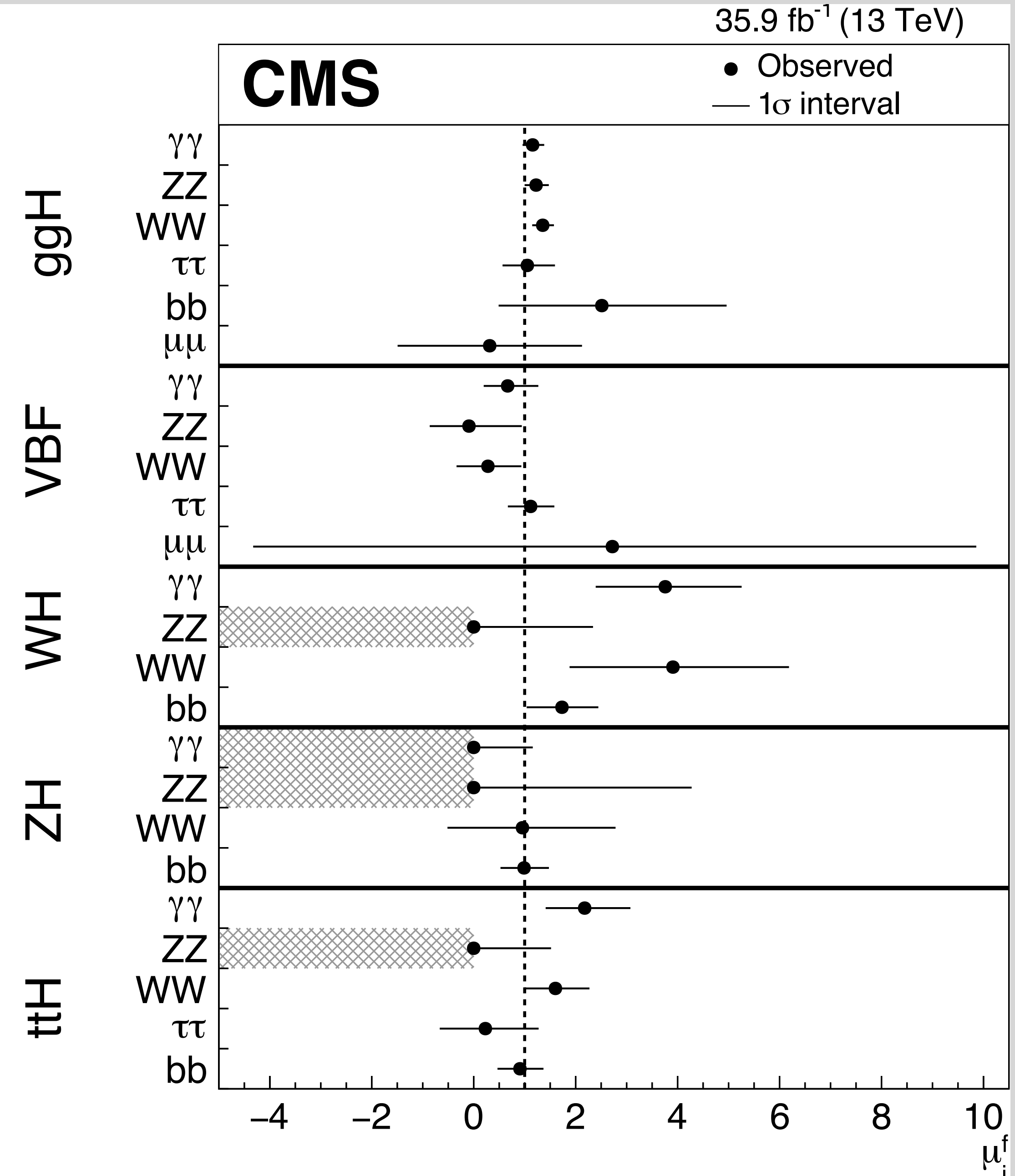
Even though it is a great achievement to have found the Higgs particle – the missing piece in the Standard Model puzzle – the Standard Model is not the final piece in the cosmic puzzle. One of the reasons for this is that the Standard Model treats certain particles, neutrinos, as being virtually massless, whereas recent studies show that they actually do have mass. Another reason is that the model only describes visible matter, which only accounts for one fifth of all matter in the





data has since become much better





the Higgs has since been discovered in multiple channels and ALL IS CONSISTENT WITH THE SM

VERY importantly we now have direct evidence for the Yukawa sector [fermion masses arising from the Higgs mechanism] :: recall that the Higgs mechanism was introduced to give masses to gauge bosons

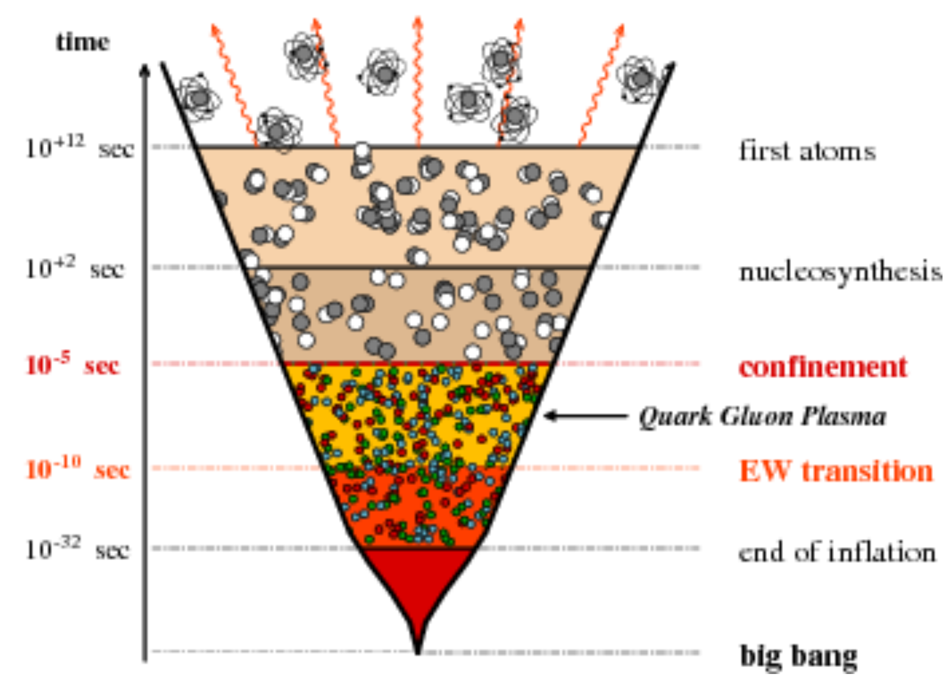
SO WHAT?

- the Standard Model
  - unifies the electromagnetic and weak interactions [physically] and [at the formal level] the strong interaction
  - accounts for ALL experimental observations with possible hints of discrepancies [mainly in the form of violation of lepton universality :: different leptons behaving differently]

- the Standard Model does not answer many questions
  - why 3 families?
  - why are the masses what they are?
  - can electro-weak and strong forces be physically unified?
  - what is the remaining 95% of the Universe?
  - is there a higher level theory from which the SM follows? Physics beyond the SM?
  - do very appealing, and thoroughly explored, Supersymmetric theories play a role?
  - how does gravity fit in?
  - ...

OTHER ELEPHANTS IN THE ROOM

- what is the dynamics responsible for confinement ?
    - we know how to deconfine [free quarks and gluons beyond nucleon scales] by colliding heavy nuclei
    - what is formed [quark gluon plasma] is the most perfect liquid ever observed and leads to a variety of collective behaviour patterns [emergent complexity from the simple fundamental rules of the QCD lagrangian]
    - how does the increased knowledge about the quark gluon plasma [the state of the Universe early on] affect our understanding of Cosmology?



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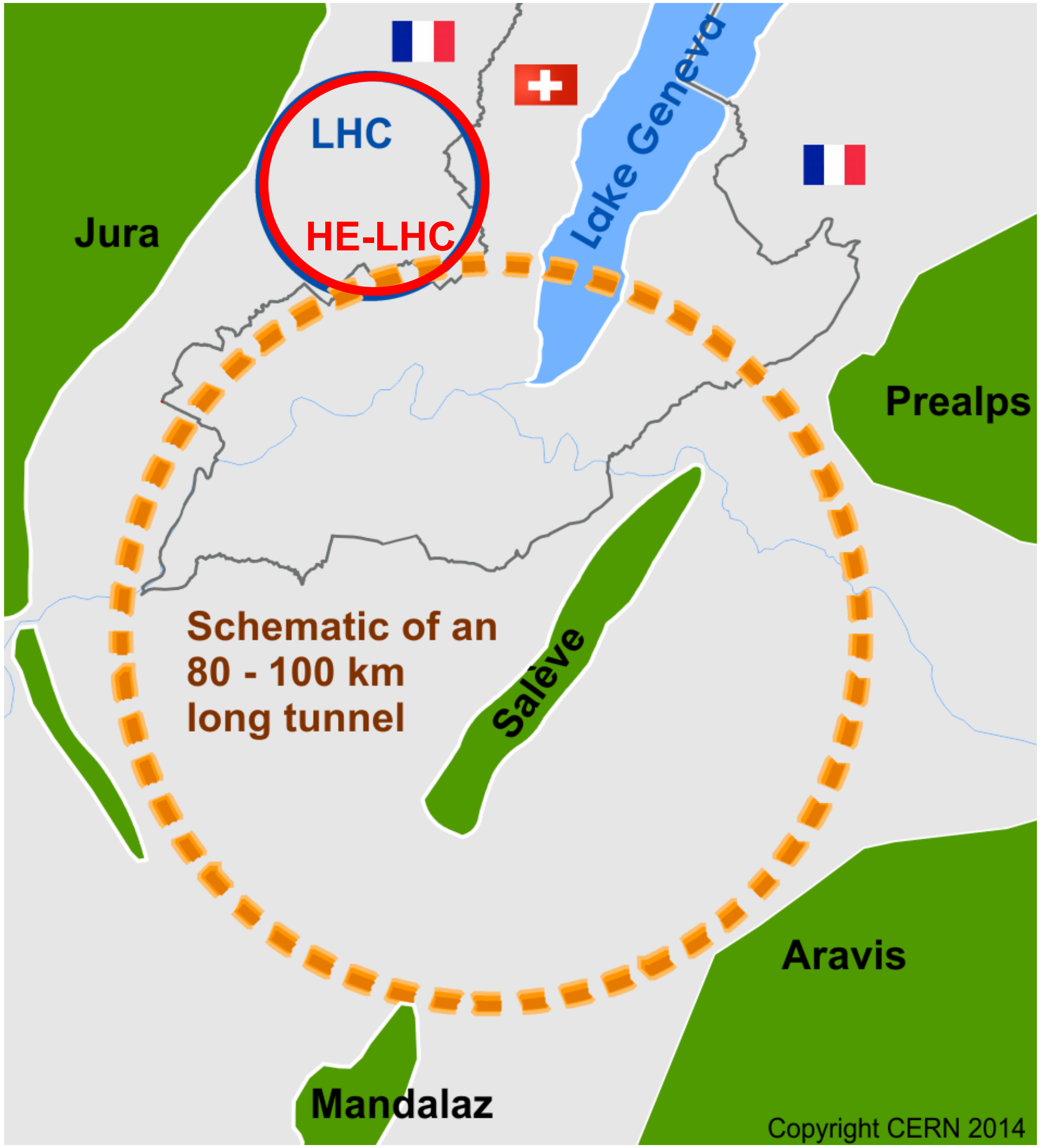
  - how does the increased knowledge about the quark gluon plasma [the state of the Universe early on] affect our understanding of Cosmology?
- [possibly the most intriguing thing I really care about] collective many-particle behaviour also observed in proton-proton collisions and for a small number of particles
  - is there a threshold at which collective descriptions make sense

HOW WILL WE FIND OUT [BEYOND THE LHC]

http://fcc-cdr.web.cern.ch

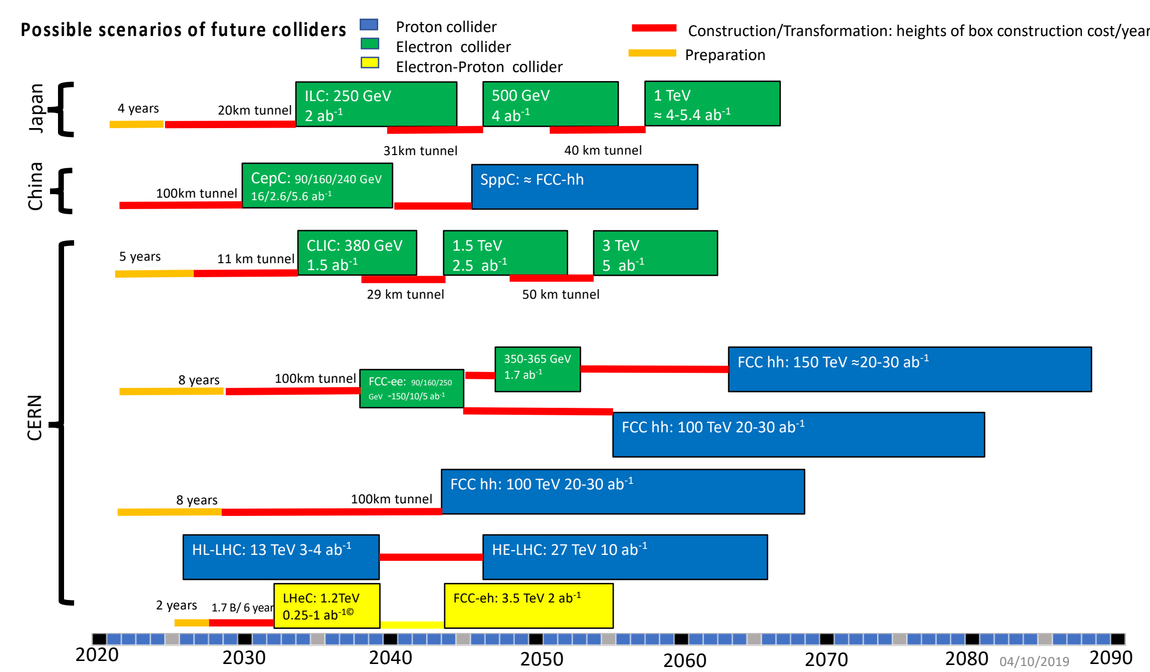


- ~100 km tunnel infrastructure in Geneva area, linked to CERN
- a broad study including:
  - FCC-ee
  - FCC-hh (pp and ions)
  - HE-LHC
  - ep/eA colliding modes
- 16 T magnets for pp@100 TeV :: PbPb@39TeV

FUTURE CIRCULAR COLLIDER [FCC] STUDY

http://fcc-cdr.web.cern.ch

- Concept Design Report [4 volumes] published
  - 1350 contributors from 350 institutes



a timeline...