http://www.lal.in2p3.fr/

Colloque

Le mécanisme de Brout-Englert-Higgs et son boson scalaire

mardi 17 septembre 2013
de 16h à 17h30

à l'Auditorium Pierre Lehmann
LAL bât. 200, Université Paris-Sud, Orsay

F. Englert
ULB Bruxelles
Les fondements théoriques

rafraichissements servis à 15h30

Louis Fayard
LAL Orsay

La découverte et les premières propriétés

- ♥ **Historical introduction of the boson and of the LHC**
- ♥ **Rapid overview of the detectors**
- ♥ **The discovery**
- ♥ **The first measurements of the properties**

- ♥ **Historical introduction of the boson and of the LHC**
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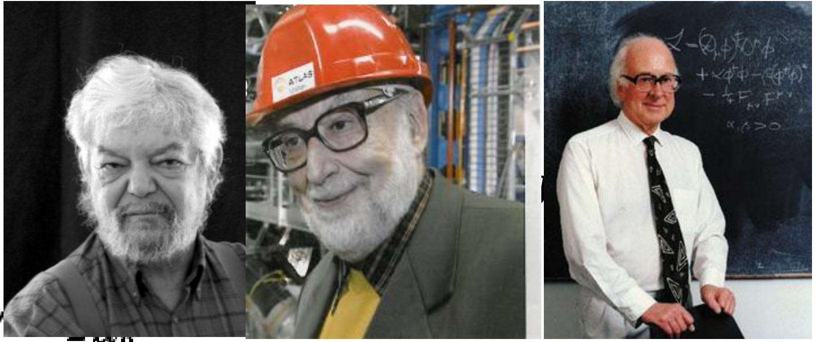
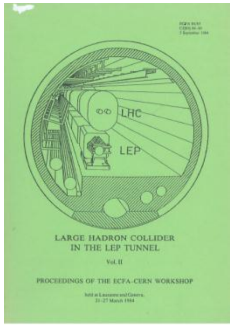
1950 Ginzburg-Landau *(Meissner-Ochsenfeld effect → London penetration length ~ W mass*
1959 Nambu *→ Pippard coherence length ~ H mass)*
1960 Goldstone
1961 Schwinger
1962 Anderson
1964 Brout, Englert, Higgs, Guralnik,Hagen,Kibble
1967 Weinberg, Salam Faddeev,Popov
1970 Glashow, Iliopoulos,
Maiani, ‘t Hooft, Ve particles of mass √

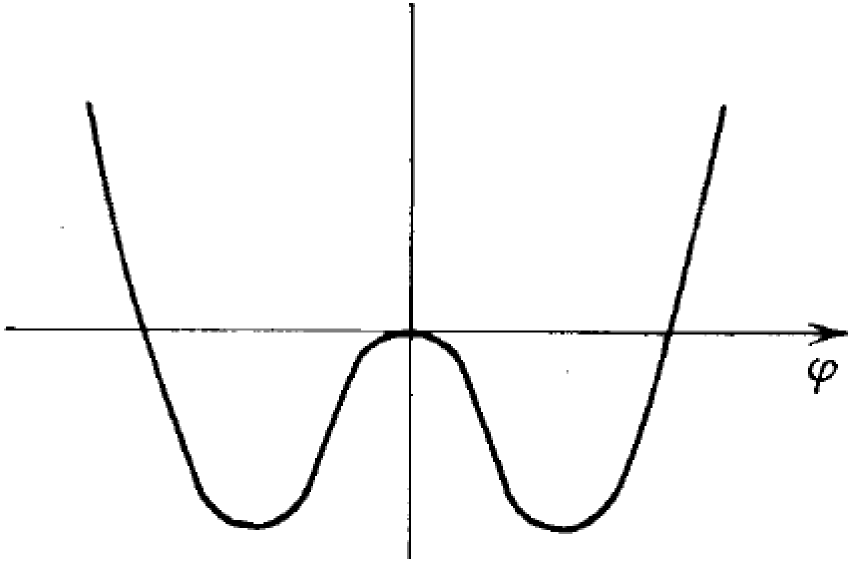


1983 Rubbia, van der Meer, Spiro, Banner, *discovery of W and Z at CERN*
1984 **Lausanne**


LARGE HADRON COLLIDER
IN THE LEP TUNNEL
Vol. II
PROCEEDINGS OF THE ECFA-CERN WORKSHOP
held at Lausanne and Geneva
21-27 March 1984

1989 **constructi**
beginning

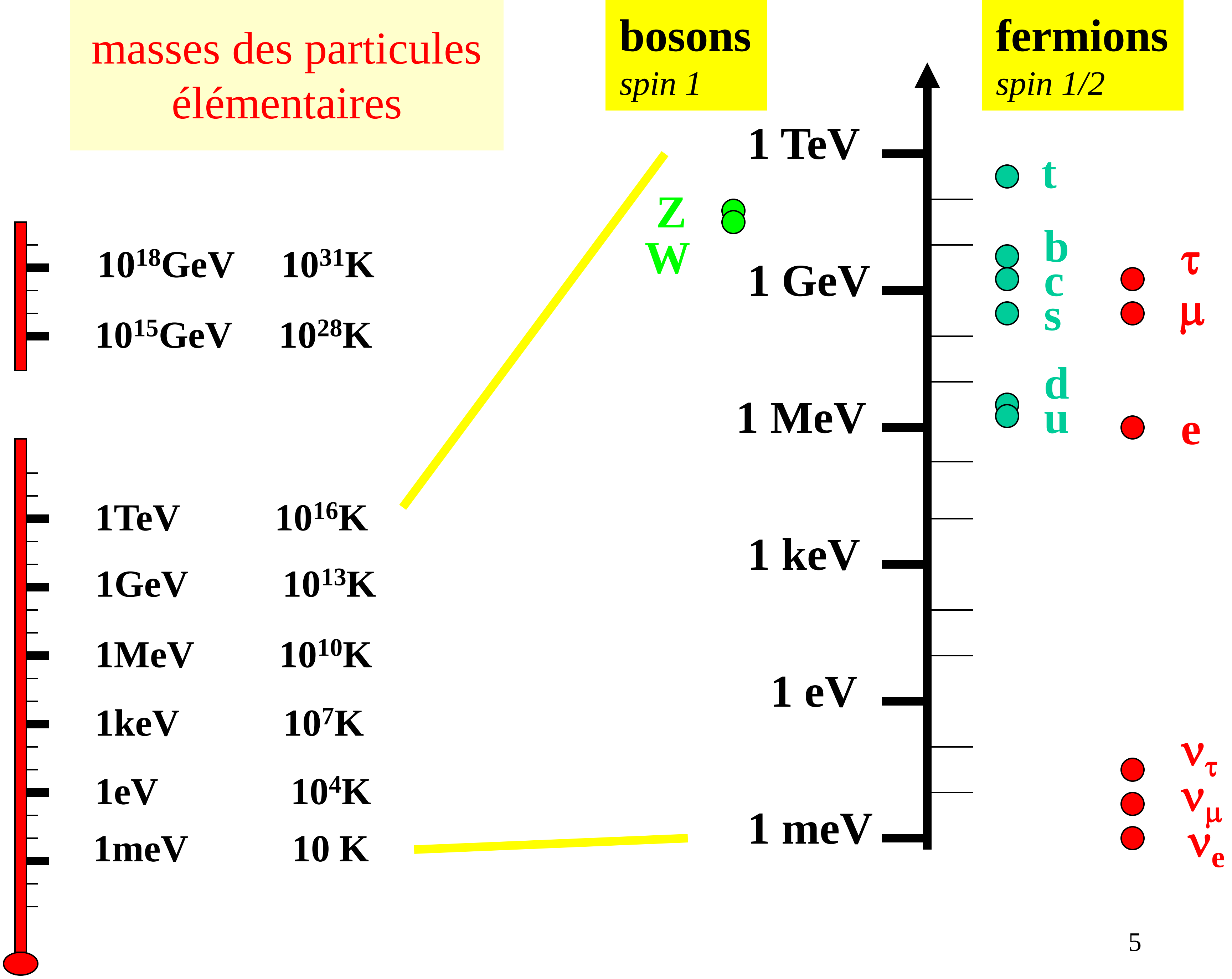
1992 ← LOI of ‘l
1994 ← TP of AT
1995 ***discovery***)
1996 ← approval
1998 ←
1999 ← **approval** **ALICE)**
ATLAS I



$$\frac{\mu_0^2}{2}\varphi^2+\frac{\lambda_0}{24}\varphi^4$$

2006 ← CMS Phy **79**
2008 ← ATLAS
2010 ← start-up
2012 ← 4th July discovery of boson
2013 ← boson like properties

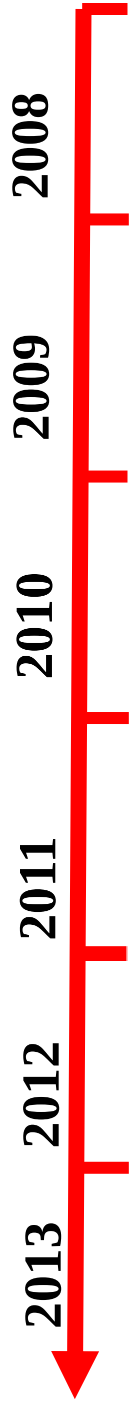
masses des particules élémentaires



bosons
spin 1

fermions
spin 1/2

10^{18}GeV	10^{31}K
10^{15}GeV	10^{28}K
1TeV	10^{16}K
1GeV	10^{13}K
1MeV	10^{10}K
1keV	10^{7}K
1eV	10^{4}K
1meV	10 K



10th september 2008 : first beams around
19th september 2008 : incident

14 months of major repairs and consolidation
New Quench Protection system

20th november 2009 : first beams around (*again*)
december 2009 : collisions at 2.36 TeV cms

January 2010 : decided scenario 2010-11 7 TeV cms
instead of 14 TeV

30th march 2010 : first collisions at 7 TeV cms
august 2010 : luminosity of 10^{31} cm^{-2} s^{-1}

may 2011 : luminosity > 10^{33} cm^{-2} s^{-1}
november 2011 : integrated luminosity ~ 5 fb^{-1}
13th december 2011 : first ‘signal’ around 126 GeV

march 2012 : start again at 8 TeV
4th July 2012 : evidence for a new boson
(*integrated luminosity ~ 6 fb^{-1}*)

(Standard-Model) boson-like properties

LHC =   Large Hadron Collider

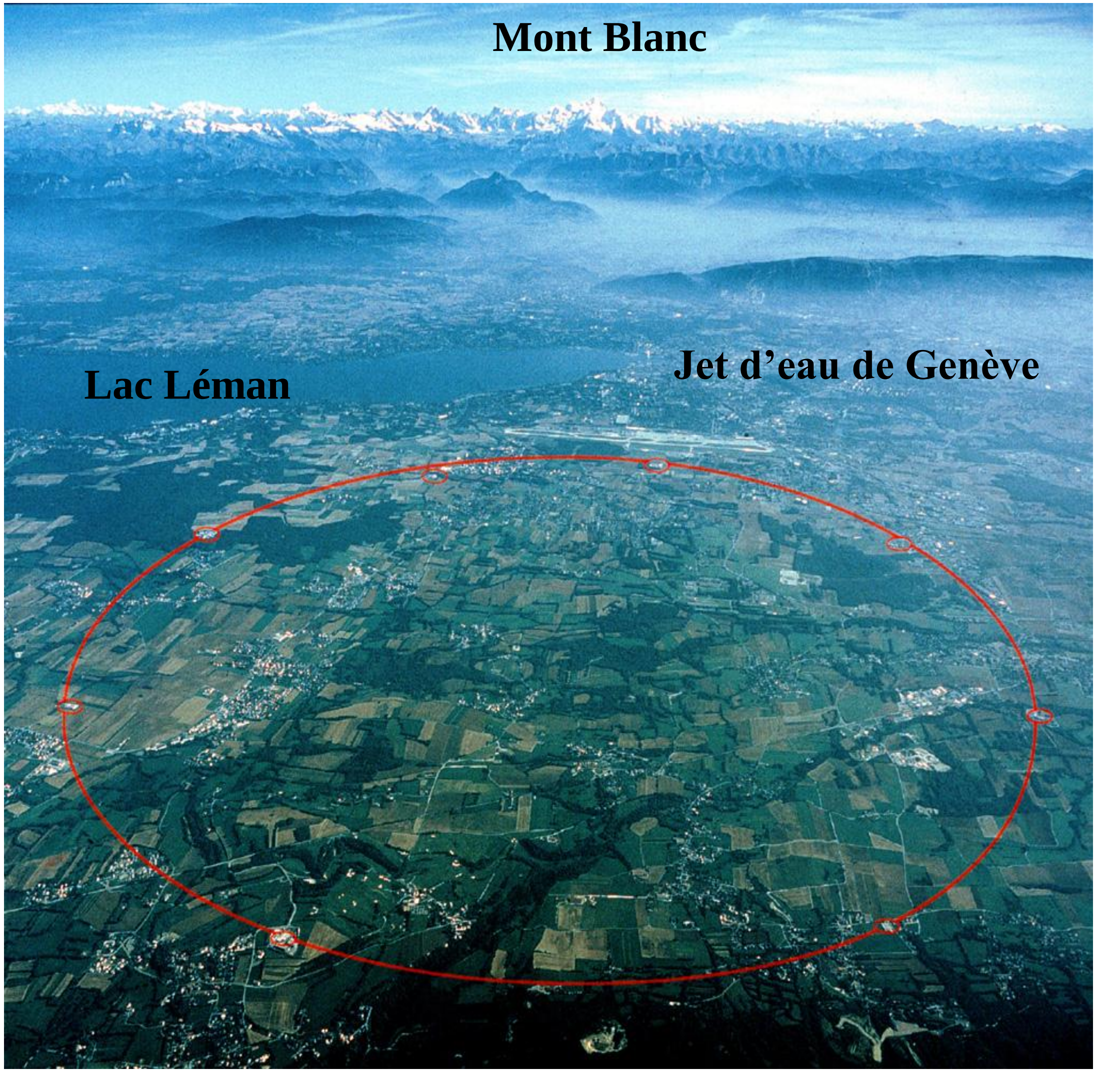
αδρός, hadrós   =   rugueux , fort
désigne les particules sensibles à l’ interaction forte

les hadrons s’opposent aux leptons
λεπτós = fin , mince

En fait il accélère principalement des protons mais aussi des ions

► Le LHC

Le LHC est un anneau de collision de 27 km de long dans un tunnel ~ 100 m sous terre près de Genève (tunnel déjà utilisé par LEP) devant fonctionner à terme à une énergie de 14 TeV (2 fois des protons de 7 TeV)



Le CERN
(Centre
Europeen
de
Recherche
(sub)Nucleaire)

en fait centre mondial

- ♥ **Historical introduction of the boson and of the LHC**
- ♥ **Rapid overview of the detectors**
- ♥ **The discovery**
- ♥ **The first measurements of the properties**

Il faut produire le boson de Brout-Englert-Higgs

Le taux de production est faible !

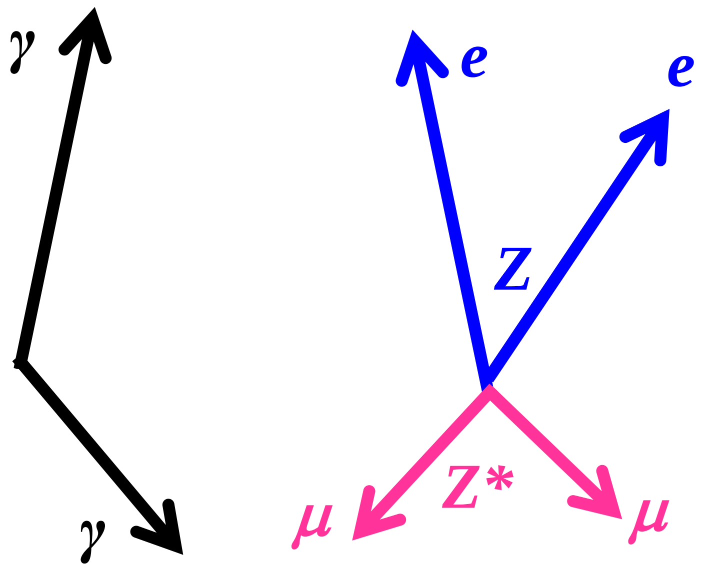
1 boson de BEH produit pour 10^9 collisions !

Mais le LHC est quand même le seul endroit ou on peut le découvrir (il y a cependant des indications au Tevatron)

Le LHC a produit 10^6 bosons de BEH !

Le taux de production de BEH est prédit avec une très bonne précision(~ 10%) par le Modèle Standard (interactions fortes entre quarks et gluons + couplages du boson BEH) ….. s'il est correct

On ne peut le mesurer qu’a travers ses produits de désintégration !



On peut reconstruire sa masse m_H ***en mesurant la somme des énergies (*** *dans le centre de masse* ***) des particules de désintégration***

E

puis $E = m_H c^2$

Le boson de Brout-Englert-Higgs est une particule qui se désintègre très vite !

en $\sim 10^{-22}$ ***s***

(correspondant à ***~100 fm*** $\sim 10^{-3}$ ***Å)***

On peut reconstruire sa masse m_H en mesurant la somme des énergies (** *dans le centre de masse* ***) des particules de désintégration

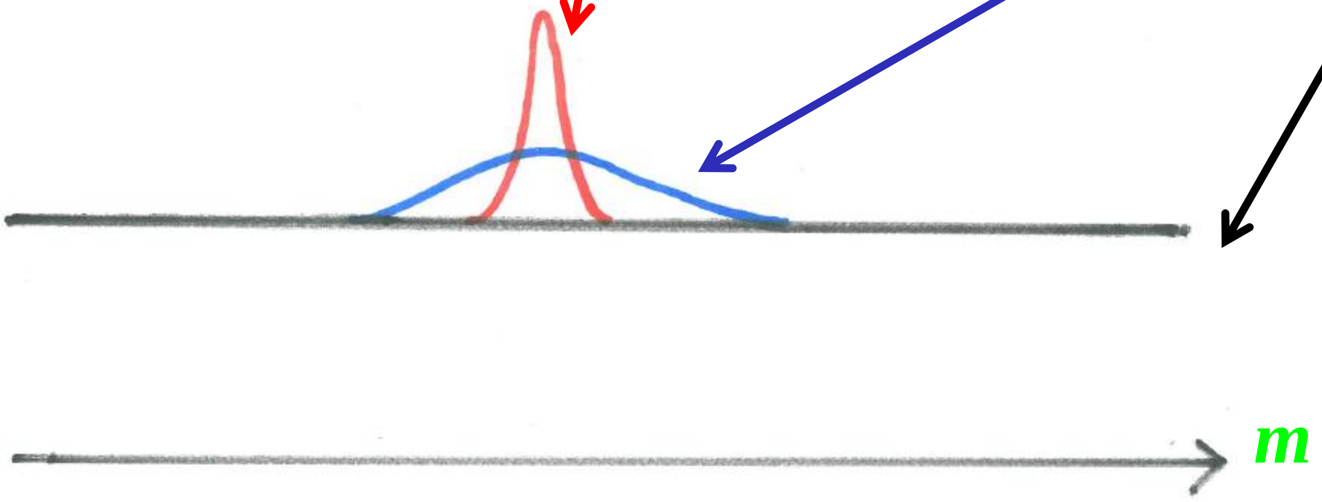
$$E$$

puis $E = m_H c^2$

Considerons la distribution en masse m d'evenements 'candidats BEH'

On a des evenements de bruit de fond

Un signal avec une bonne résolution sera mieux vu qu'un signal avec une mauvaise résolution



Il faut des detecteurs avec une bonne resolution

Nombre d'événements dans une expérience produits/détectés pour 5 fb^{-1} (7 TeV)

et S /B

(Signal /Bruit de fond)

700 / 50

S/B ~.3

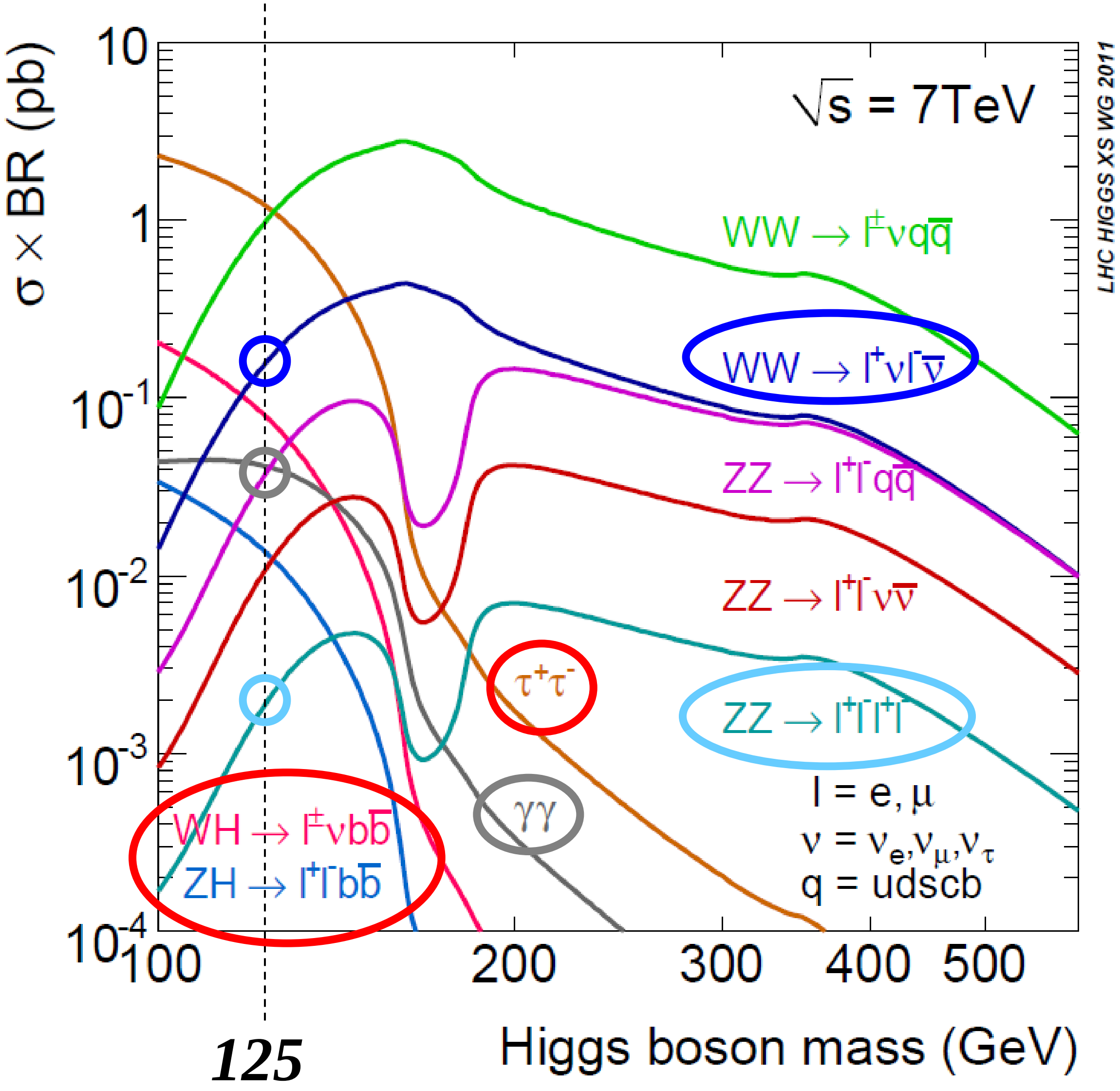
200 / 70

S/B ~ .02

10 / 2

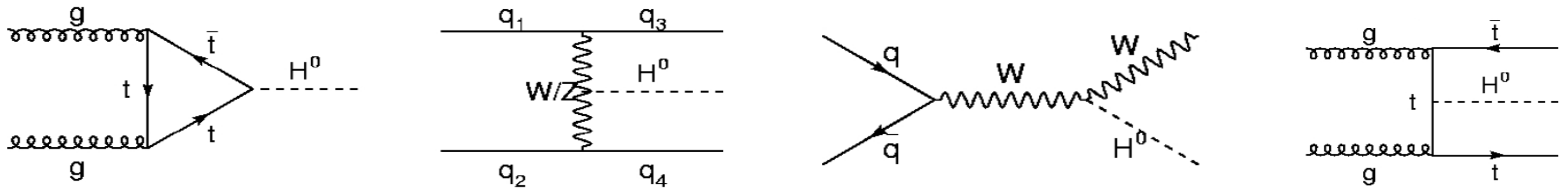
S/B ~ 1.5

d'autres modes de desintegration sont accessibles



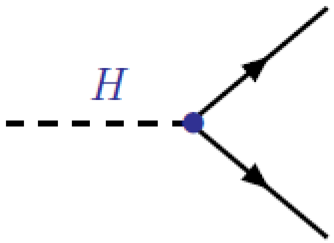
Au total 5 modes de desintegration accessibles

⇒ permet des tests des modeles

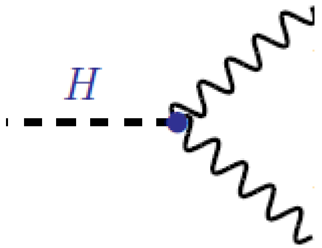


Plusieurs modes de production , couplages du boson à W , Z , t

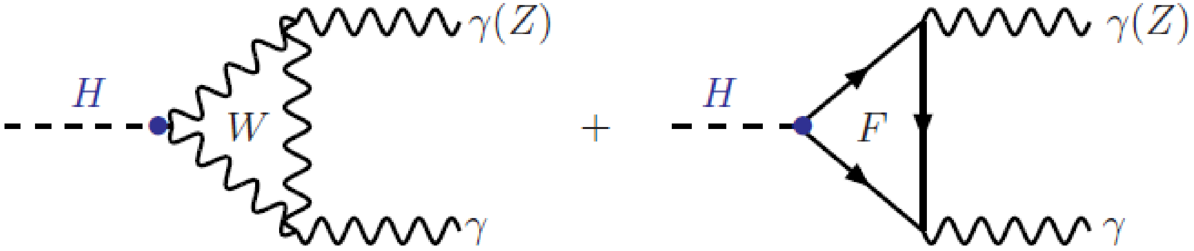
Plusieurs modes de désintégration observables



ττ , bb

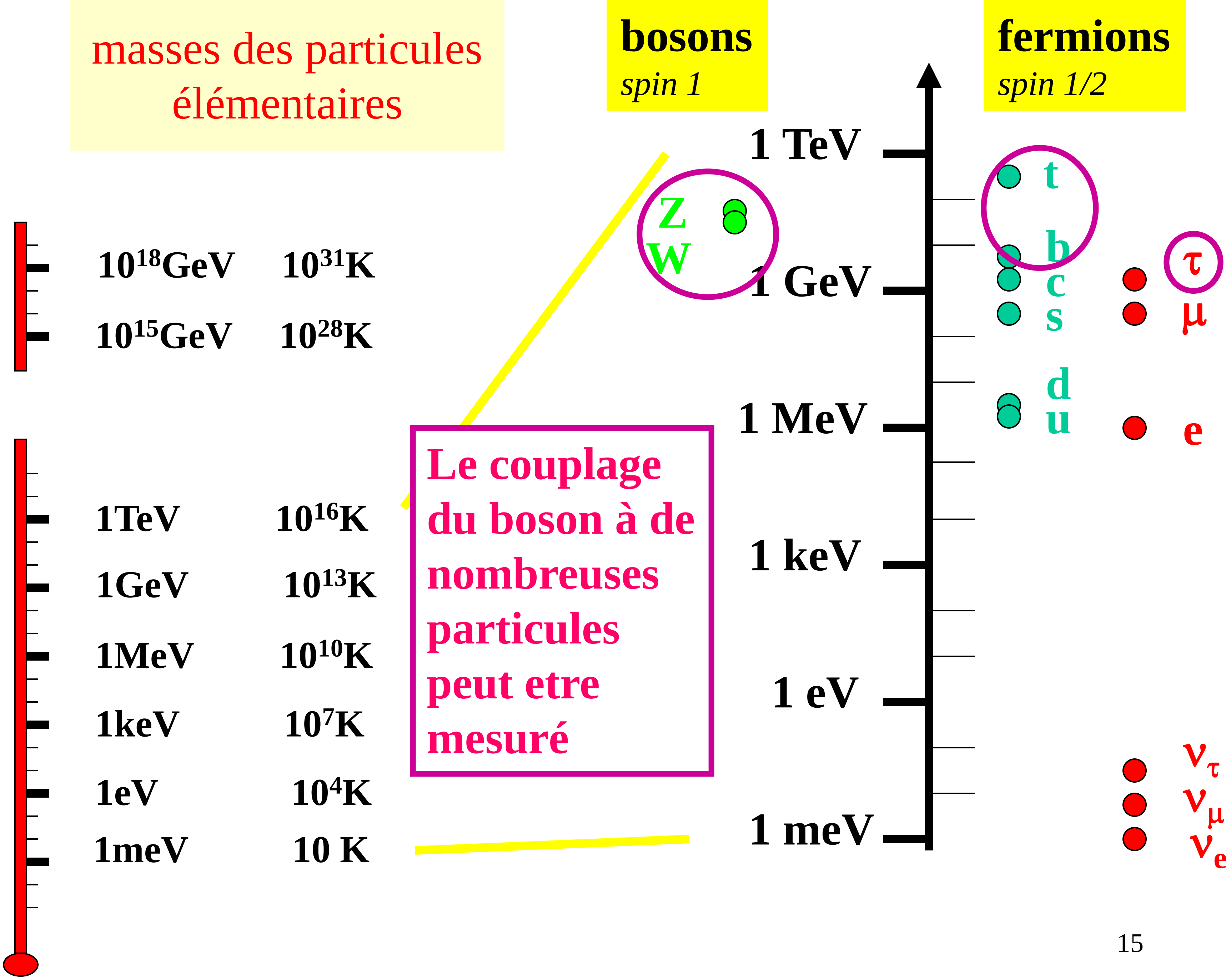


WW, ZZ



ĭnterference entre W et t

masses des particules élémentaires



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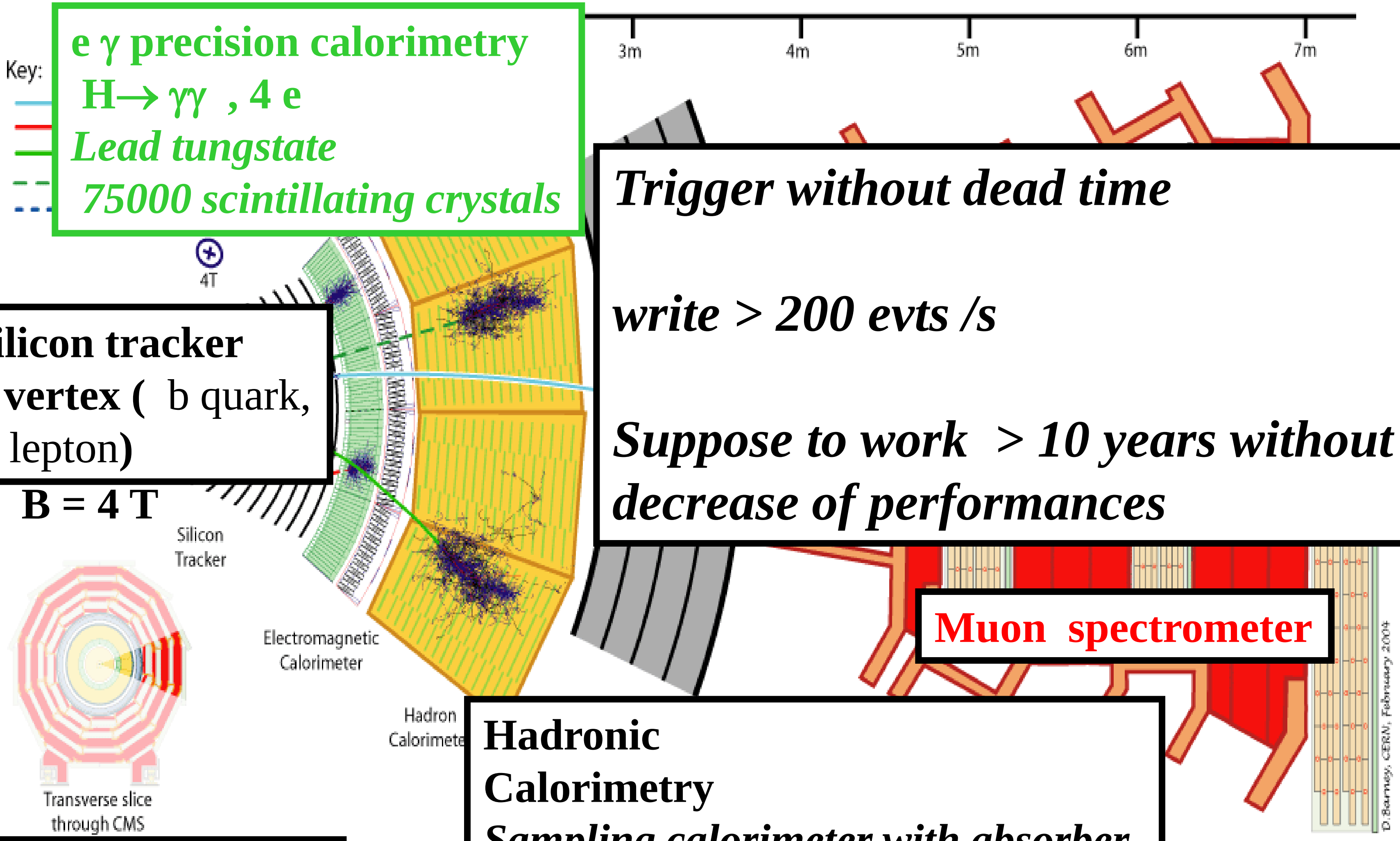
1meV	10 K

bosons
spin 1

fermions
spin 1/2

Le couplage du boson à de nombreuses particules peut etre mesuré

Exemple of CMS = (Compact Muon Solenoid)



e γ precision calorimetry
H→ γγ , 4 e
Lead tungstate
75000 scintillating crystals

Silicon tracker
+ vertex (b quark,
τ lepton)

B = 4 T

Trigger without dead time

write > 200 evts /s

Suppose to work > 10 years without decrease of performances

Muon spectrometer

Hadronic
Calorimetry
Sampling calorimeter with absorber (brass) and plastic scintillators
Jets and $E_T$miss

« 4 π » detector
up to η=5
(from θ = 1.35°)

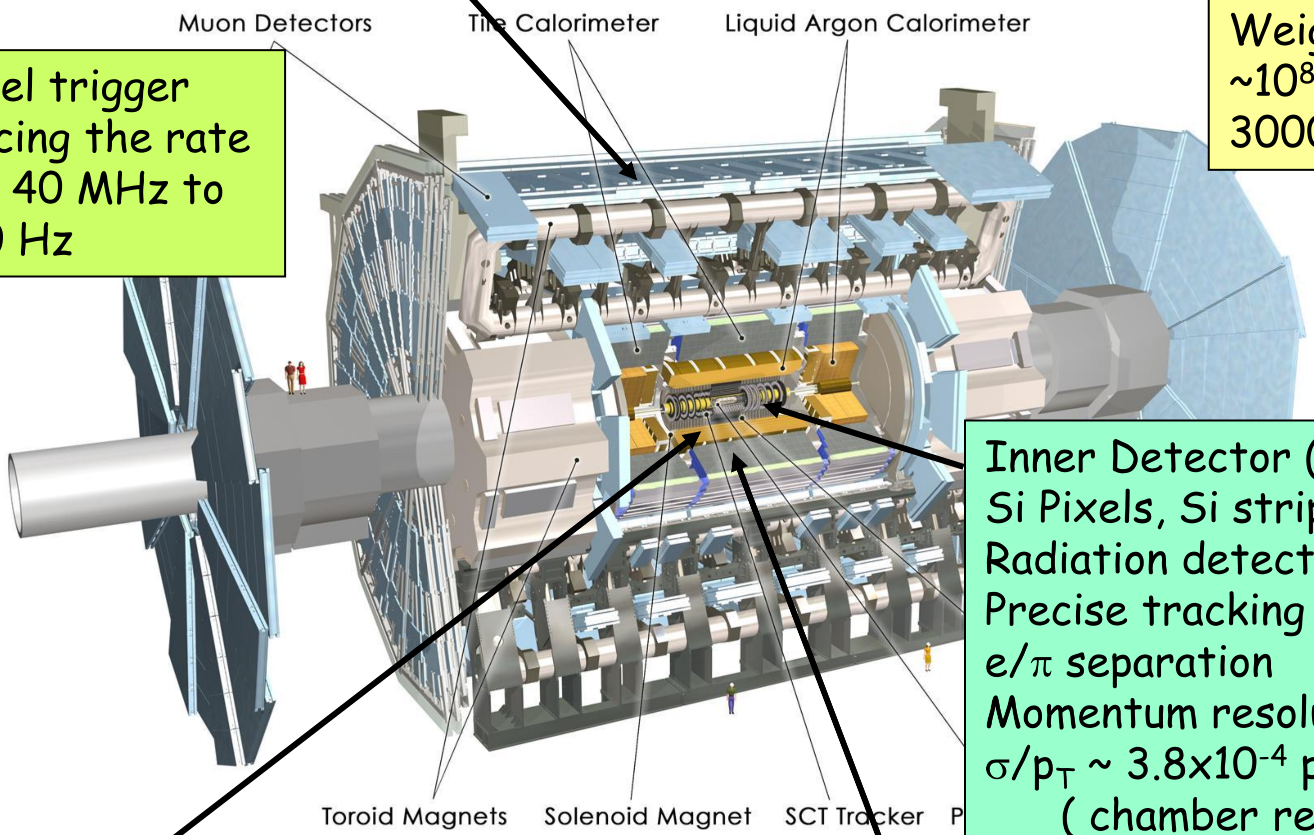
Contrôle qualité de très haut niveau !

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids (B ~ 0.5 / 1T in barrel/ end-cap) with gas-based muon chambers Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

ATLAS detector

3-level trigger reducing the rate from 40 MHz to ~200 Hz

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables



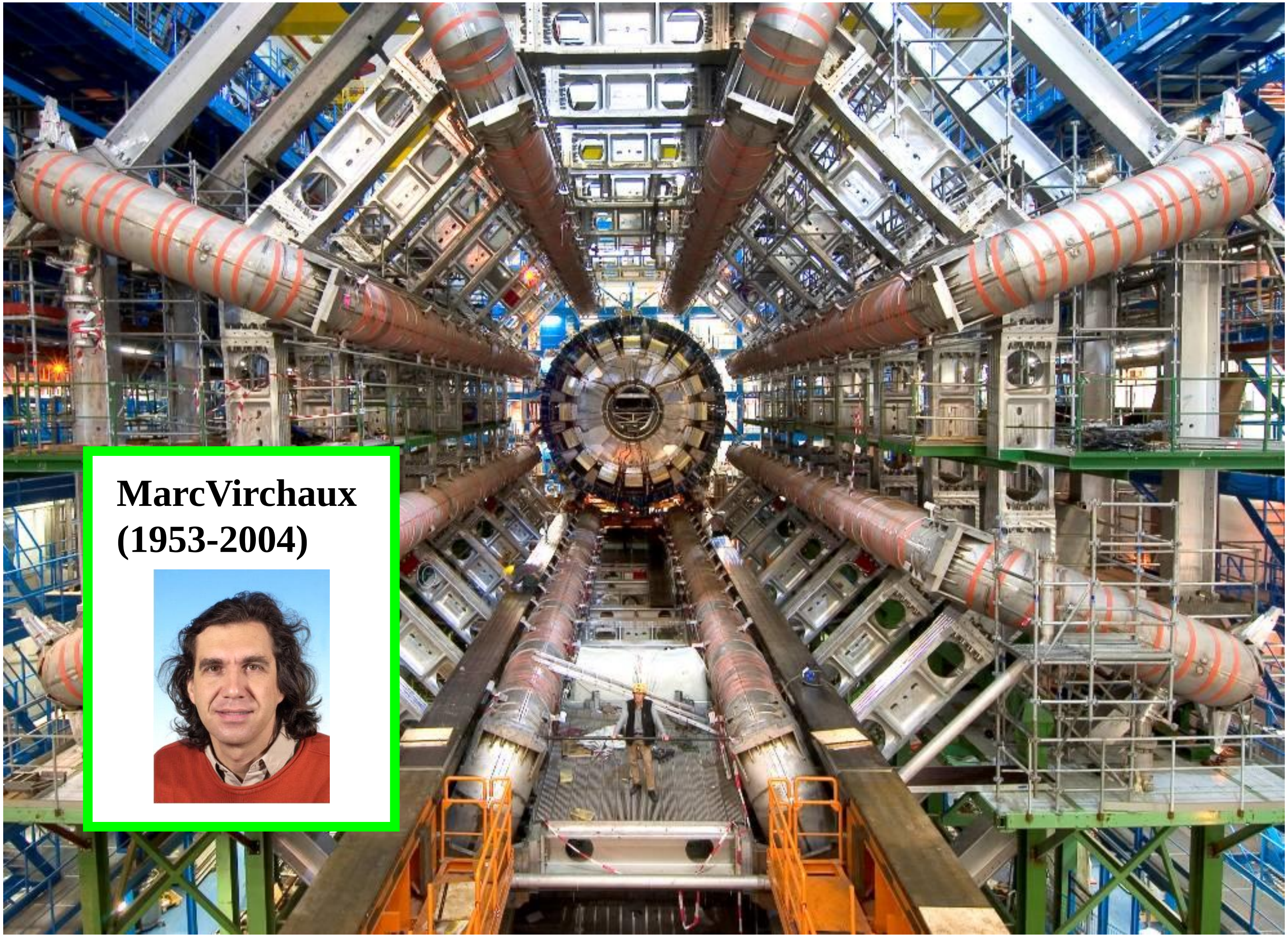
Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\text{GeV}) \oplus 0.015$
(chamber resolution ⊕ MS)

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

Daniel Fournier

Le toroide supraconducteur d’ATLAS (A Toroidal LHC ApparatuS)



MarcVirchaux
(1953-2004)

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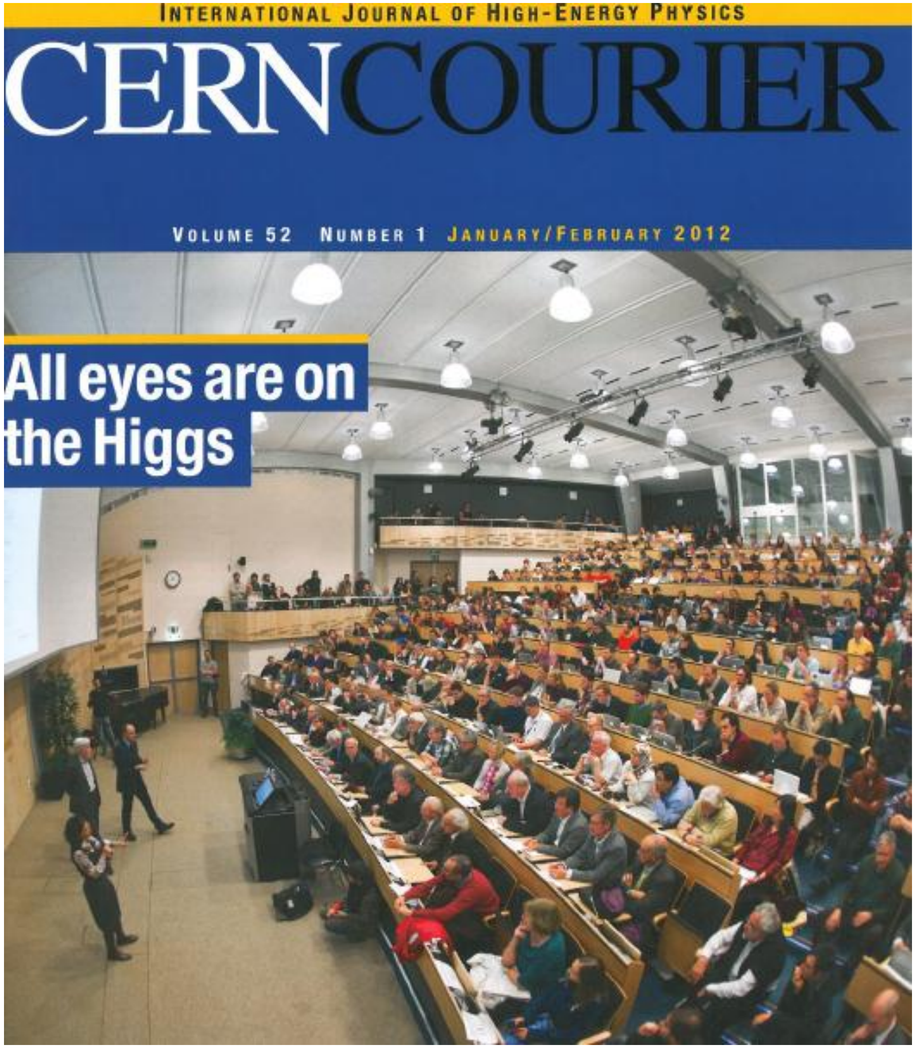
Hints of signal were already there in 13th december 2011



INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERNCOURIER

VOLUME 52 NUMBER 1 JANUARY/FEBRUARY 2012

All eyes are on the Higgs

The 4th July (2012) seminar

before

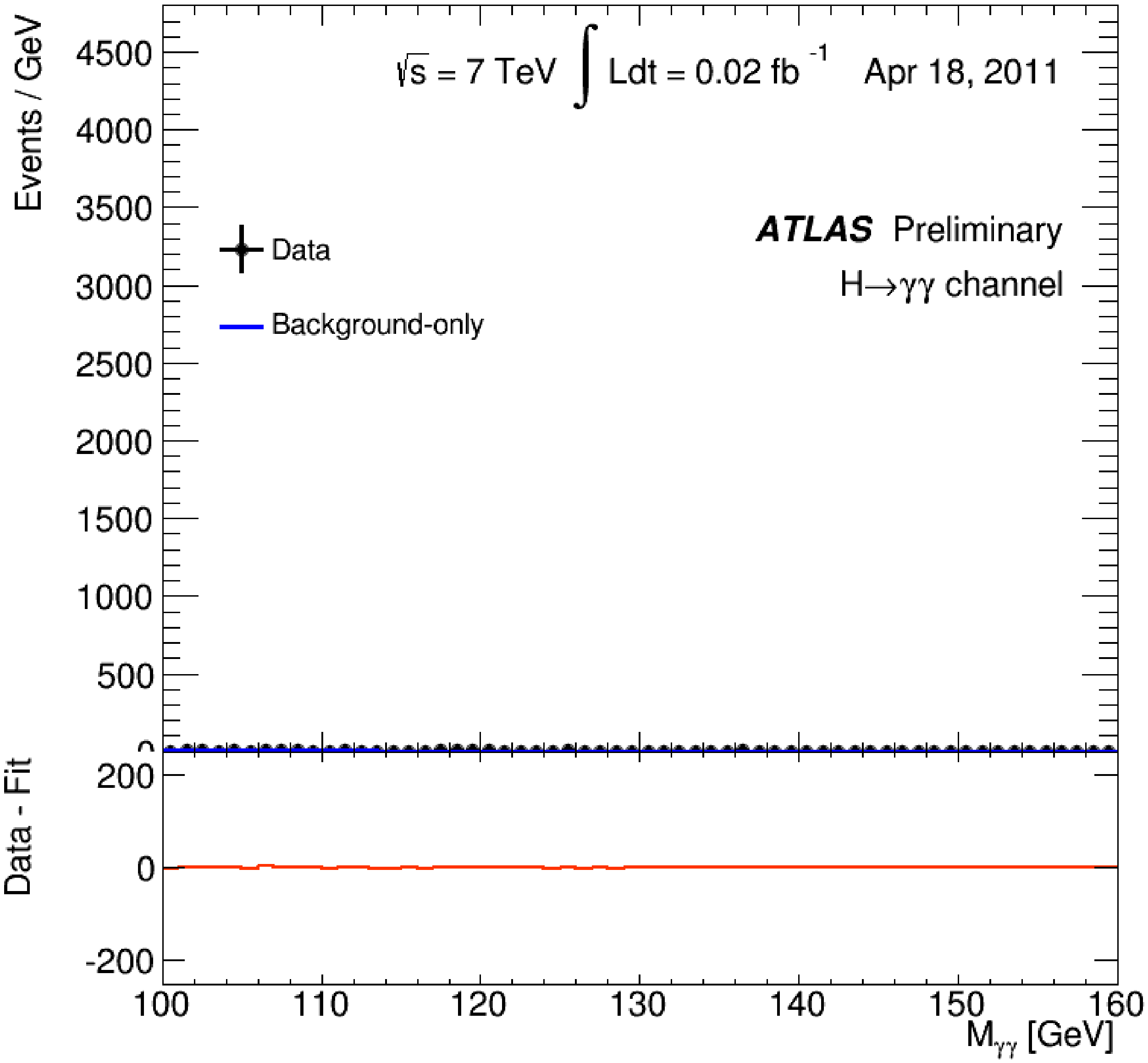
Francois Englert **Peter Higgs**

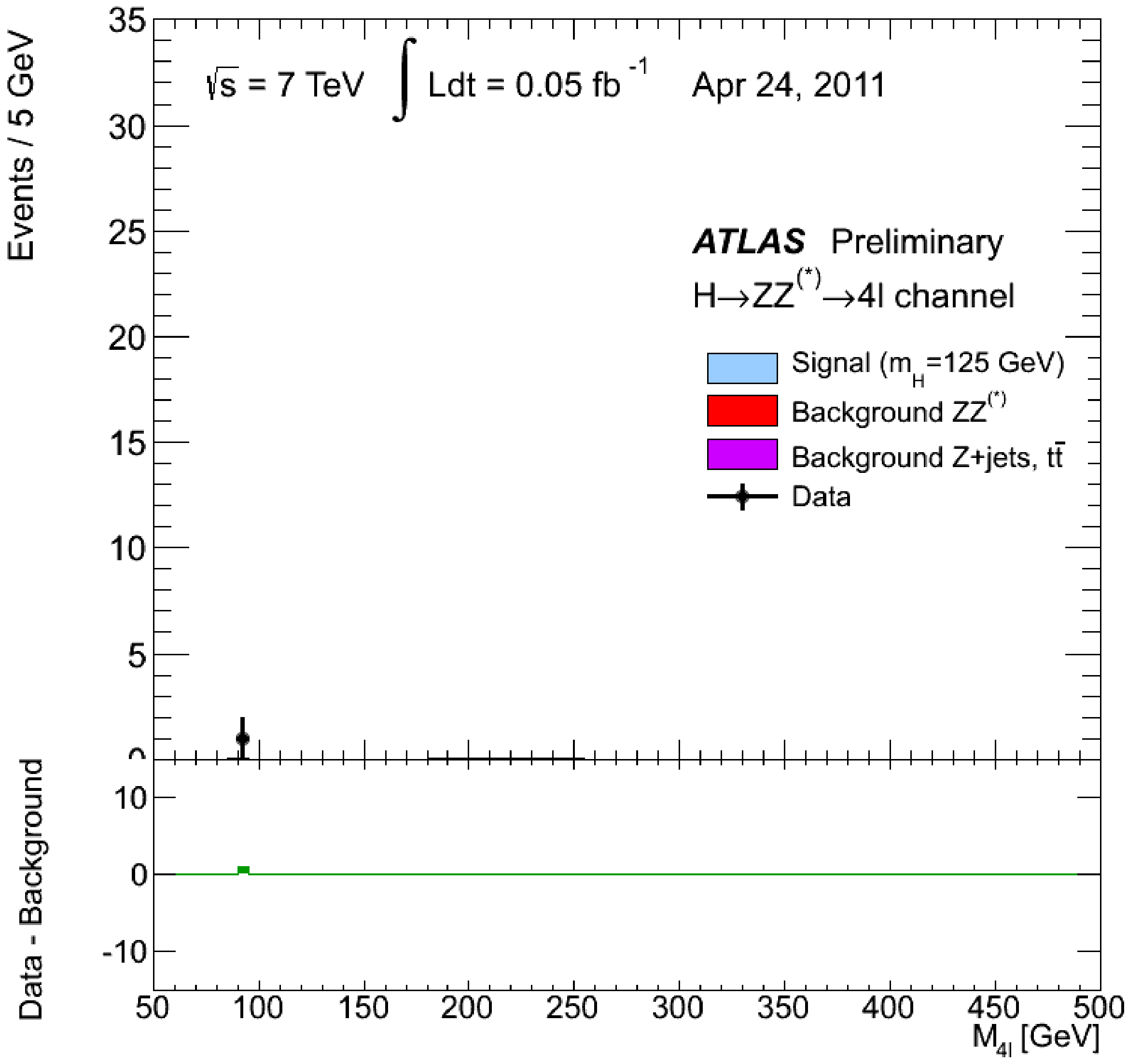
after

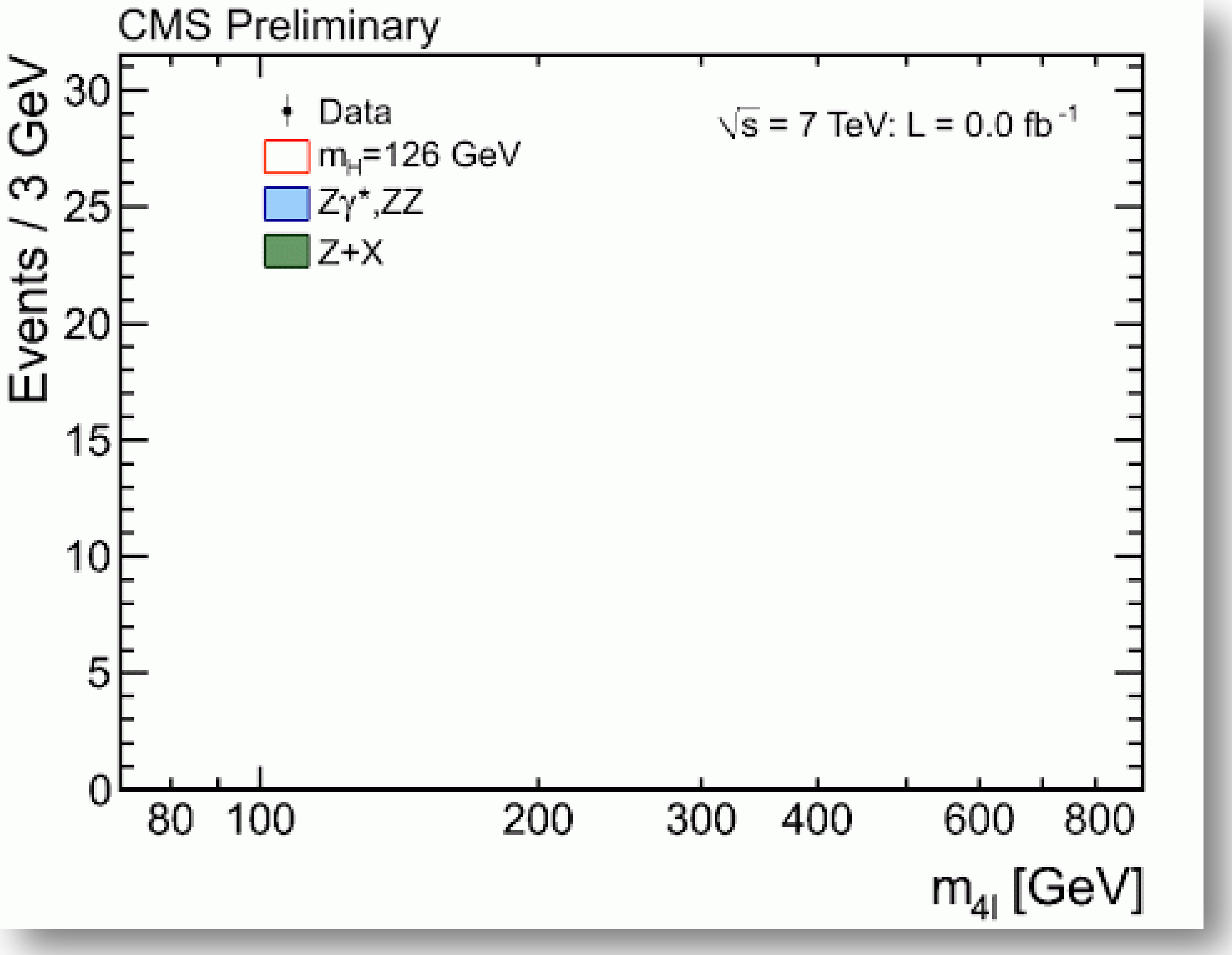

Joe Incandela

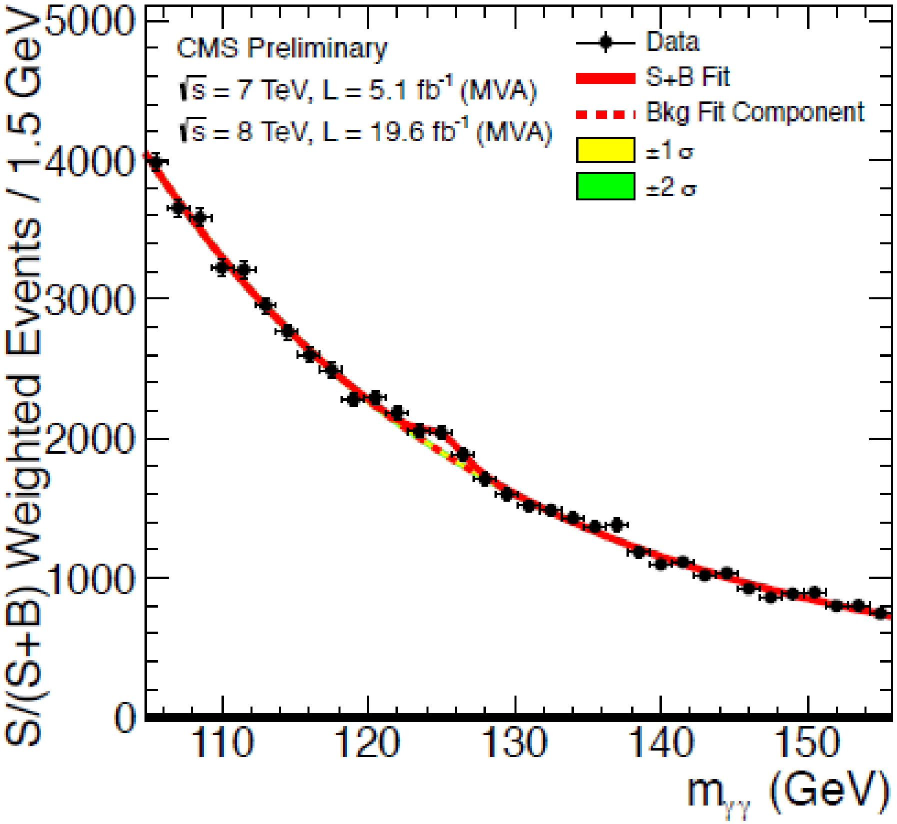
during

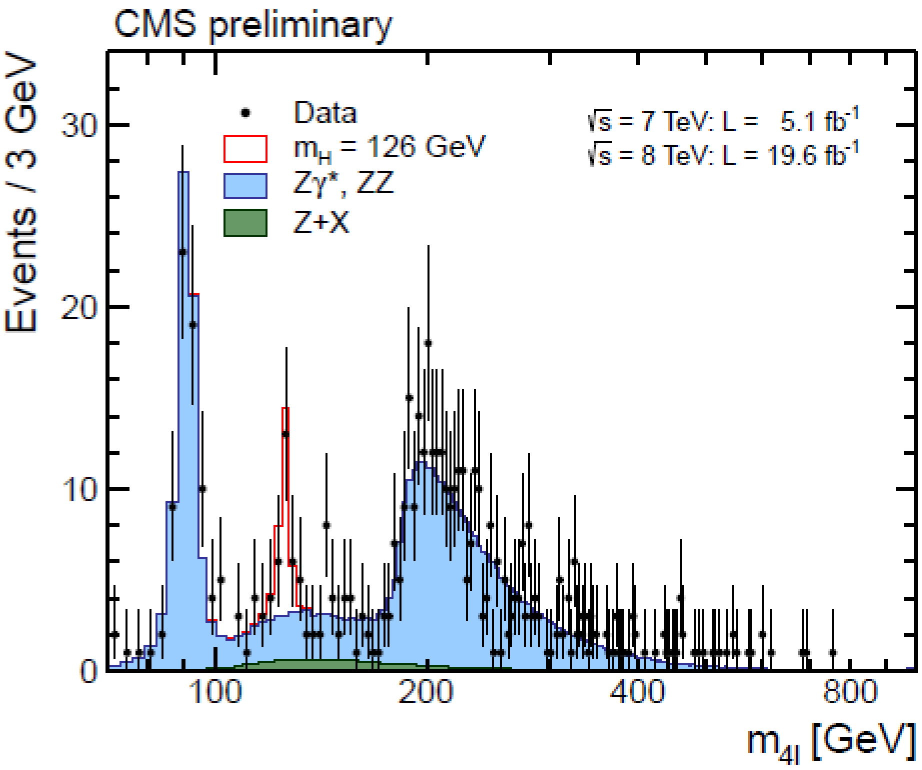

Fabiola Gianotti

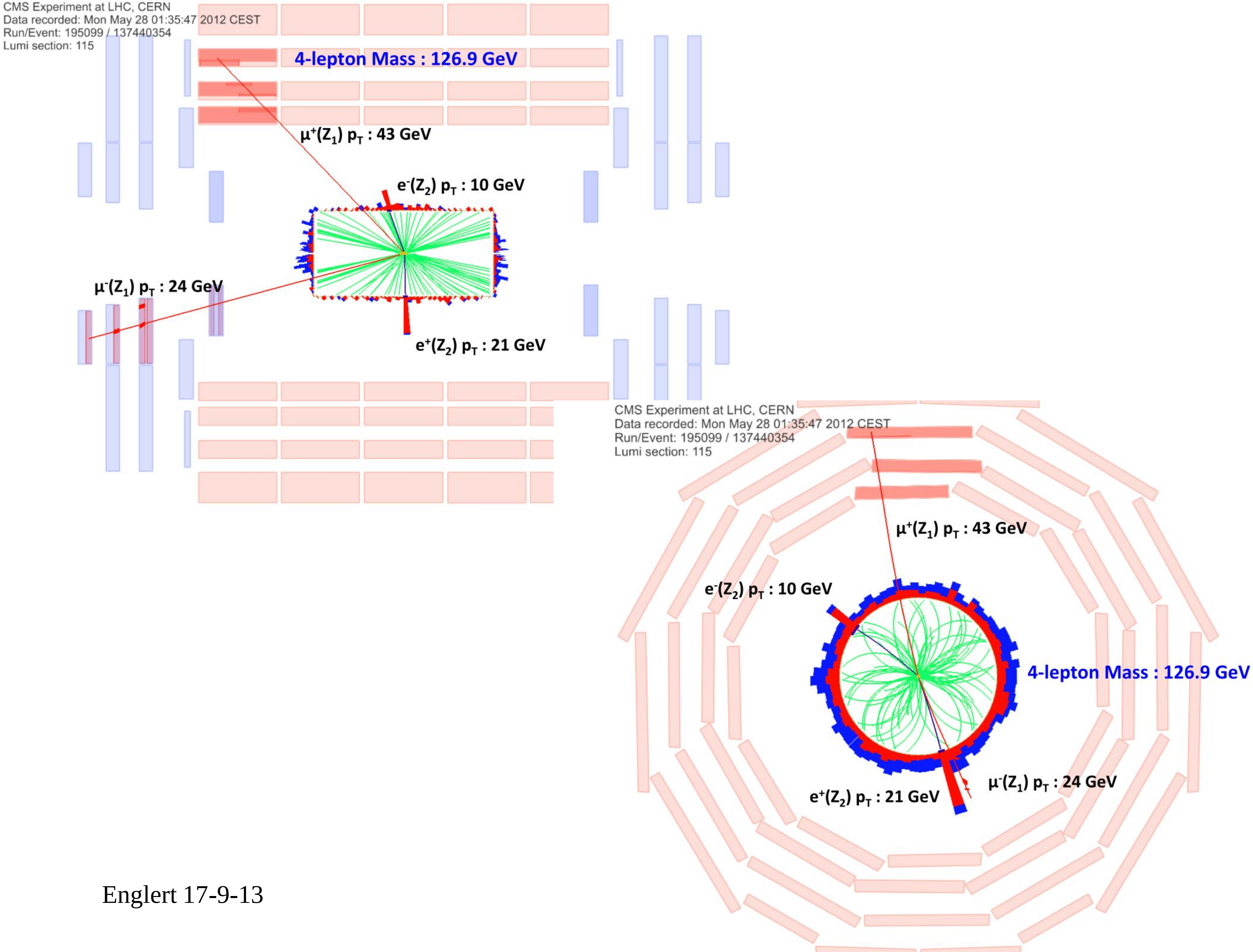

$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.02 fb^{-1} Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Data - Fit
200
0
-200
100
110
120
130
140
150
160
$M_{\gamma\gamma}$ [GeV]

Events / 5 GeV
35
30
25
20
15
10
5
0
$\sqrt{s}$ = 7 TeV
$\int Ldt$ = 0.05 fb^{-1}
Apr 24, 2011
ATLAS Preliminary
$H\to ZZ^{(*)}\to 4l$ channel
Signal (m_H=125 GeV)
Background $ZZ^{(*)}$
Background Z+jets, $t\bar{t}$
Data
Data - Background
10
0
-10
50
100
150
200
250
300
350
400
450
500
M_{4l} [GeV]


CMS Preliminary
Events / 3 GeV
30
25
20
15
10
5
0
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
$\sqrt{s}$ = 7 TeV: L = 0.0 fb^{-1}
80
100
200
300
400
600
800
m_{4l} [GeV]


CMS Preliminary
$\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1} (MVA)
$\sqrt{s}$ = 8 TeV, L = 19.6 fb^{-1} (MVA)
Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
S/(S+B) Weighted Events / 1.5 GeV
0
1000
2000
3000
4000
5000
110
120
130
140
150
$m_{\gamma\gamma}$ (GeV)


CMS preliminary
Data
m_H = 126 GeV
Zγ*, ZZ
Z+X
$\sqrt{s}$ = 7 TeV: L = 5.1 fb^{-1}
$\sqrt{s}$ = 8 TeV: L = 19.6 fb^{-1}
Events / 3 GeV
0
10
20
30
100
200
400
800
m_{4l} [GeV]



Englert 17-9-13

- ♥ **Historical introduction of the boson and of the LHC**
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Masse du boson

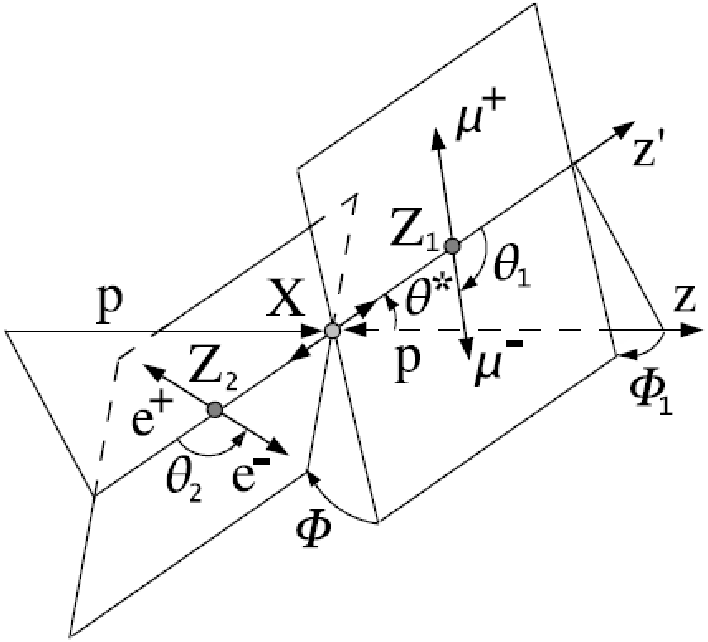
Les deux canaux de ‘haute precision’ (ZZ , γγ) donnent la masse

ATLAS : m = 125.5 ± .2 (stat) $^{+.5}_{-.6}$ (syst) GeV

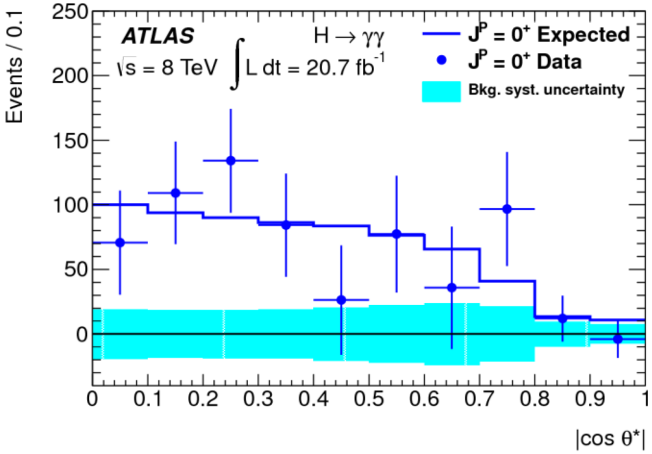
CMS : m = 125.7 ± .3 (stat) ± .3 (syst) GeV

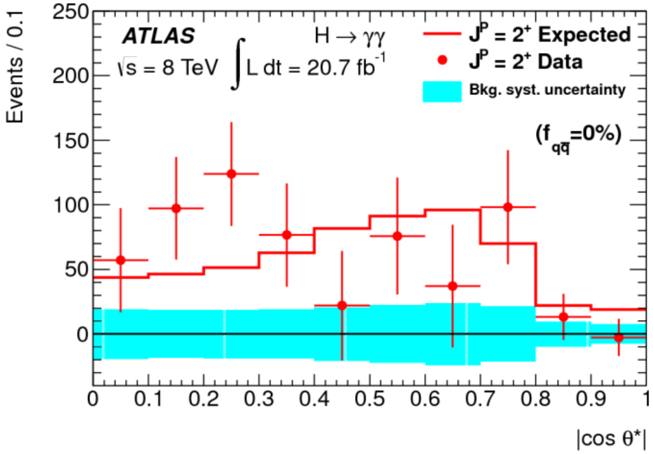
Spin (et parité)

Tout le monde s’attendait à un spin 0 et à une parité (*principalement*) +



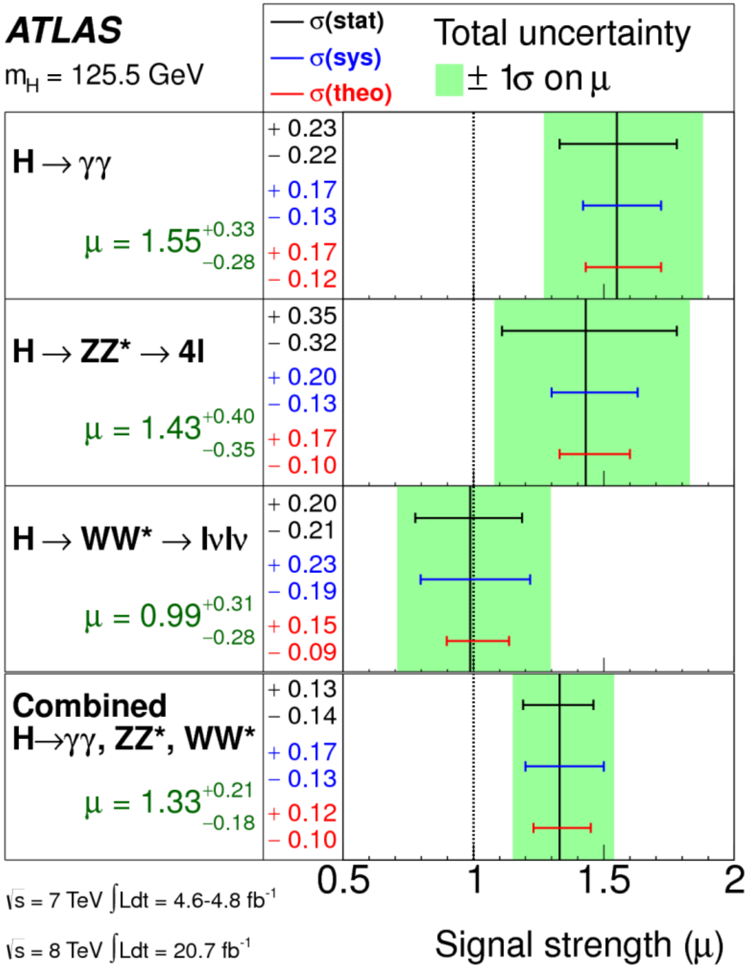
Etude des distributions angulaires

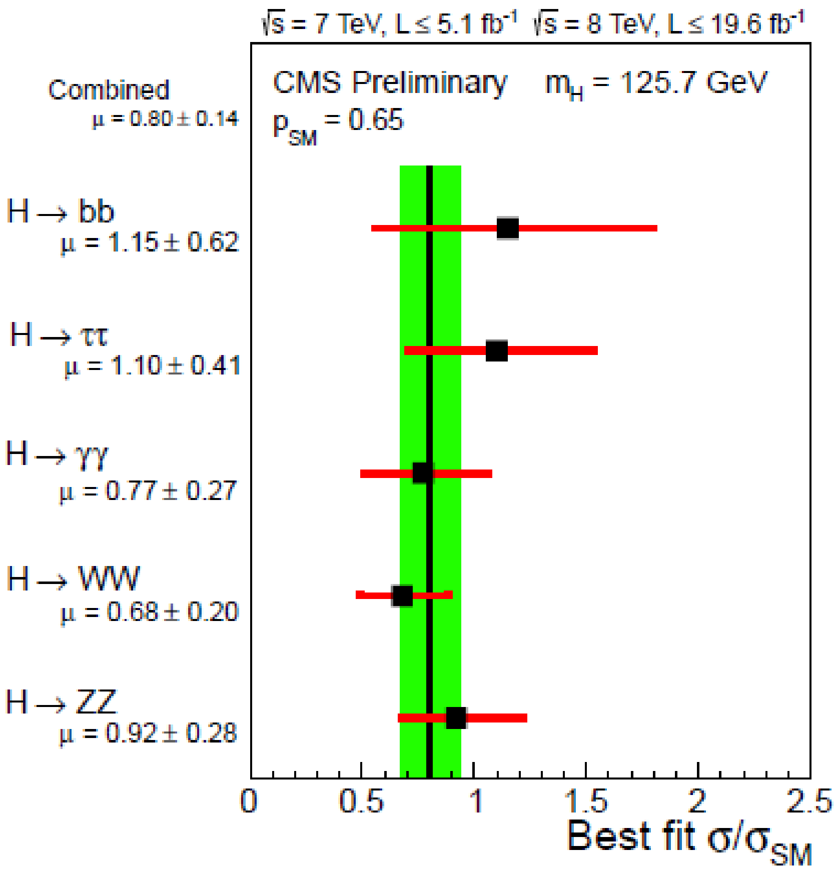




0+ très favorisé par rapport à 0- et 2+

(1 exclu : théorème de Landau-Yang)

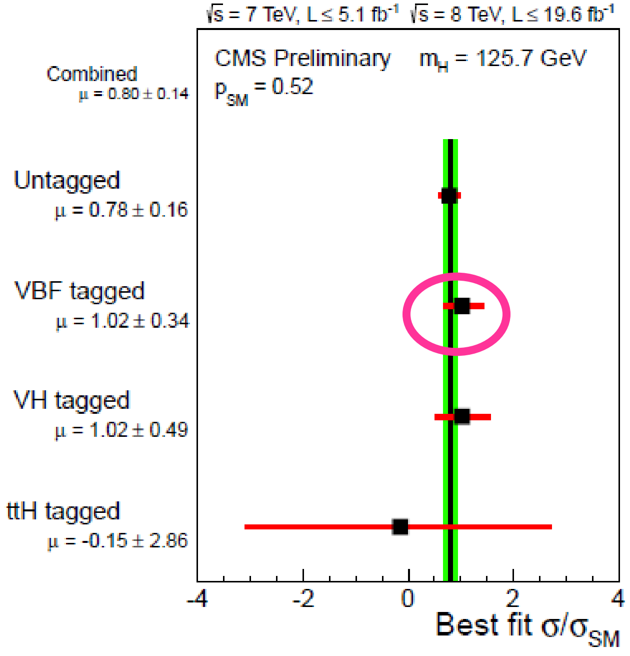




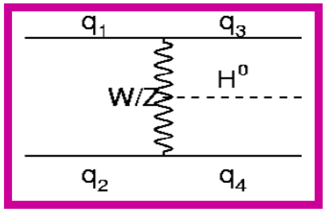
$\mu = \sigma / \sigma_{SM}$ **SM = SM boson**

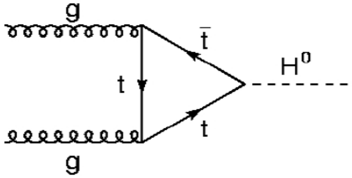
Les sections efficaces sont en bon accord avec le Modèle Standard

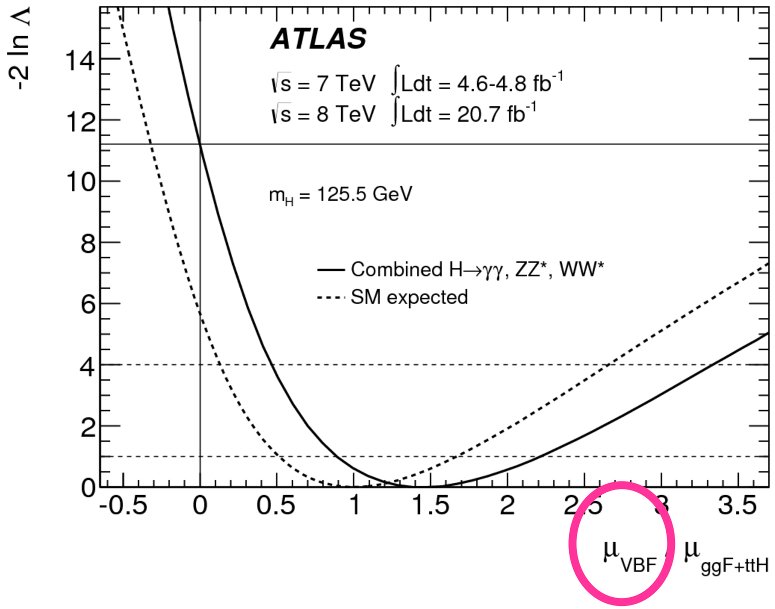
Mesure des rapports μ de sections efficaces par rapport au Modèle Standard pour les differents modes de production du boson



bon accord avec le Modèle Standard







Englert 17-9-13

Decouverte en 2012 du boson scalaire de Brout-Englert-Higgs au CERN

***Aboutissement** de plus de 20 ans de travail au LHC*

- ***conception des detecteurs***
- ***recherche et developpement***
- ***construction***
- ***analyse***

Très important travail des théoriciens

Il a l'air bien standard

Debut d'une autre ère !

étude détaillée du boson scalaire a faire ..

Arret de 2 ans du LHC puis redémarrage a plus forte énergie . On espère multiplier par 10 , voire 100 le nombre de bosons produits

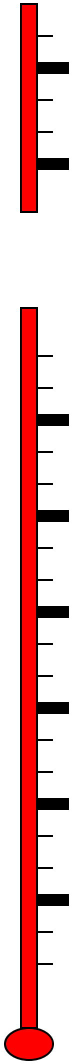
questions (1)

- ***Le boson est il 'standard' et jusqu'a quel point ?***
- ***Y en a-t-il plusieurs ?***

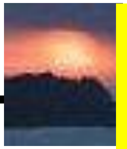
questions (2)

- **Pourquoi n'y a-t-il pas d'antimatiere dans l'Univers**
- **Comprendre la masse des neutrinos**
- **Comprendre la matière noire**
- **Comprendre l'unification des 3/4 forces ?**

Merci de votre attention



E,T			t
10^{18}GeV	10^{31}K	← *Unification avec la gravitation*	10^{-43} s
10^{15}GeV	10^{28}K	← *Unification avec l’intéraction forte*	10^{-35} s
1TeV	10^{16}K	← *Densité d’énergie obtenue au CERN* *Unification électrofaible*	10^{-10} s
1GeV	10^{13}K		
1MeV	10^{10}K		
1keV	10^{7}K	← *Température au centre du Soleil*	
1eV	10^{4}K	← *Physique atomique*	3 10^{5} ans
1meV	10 K	← *Rayonnement fossile*	10^{10} ans

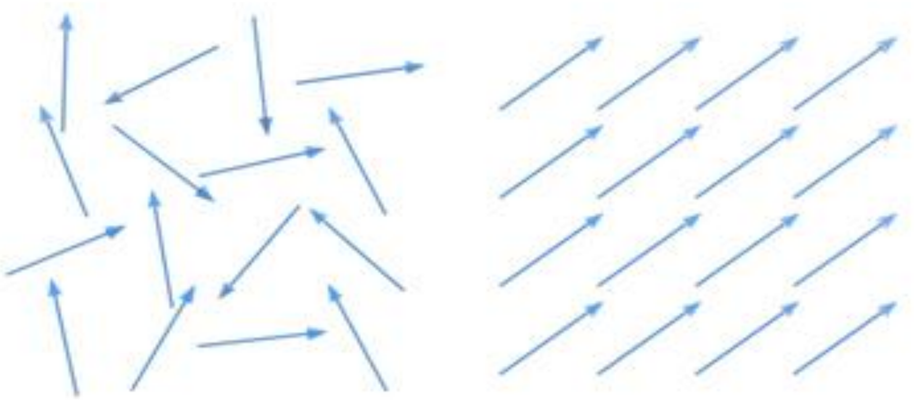


BACKUP

Brisure spontanée de symétrie = mot clef !

exemple : ferromagnétisme

pout $T < T_C$ les dipoles sont alignés dans une direction (arbitraire)



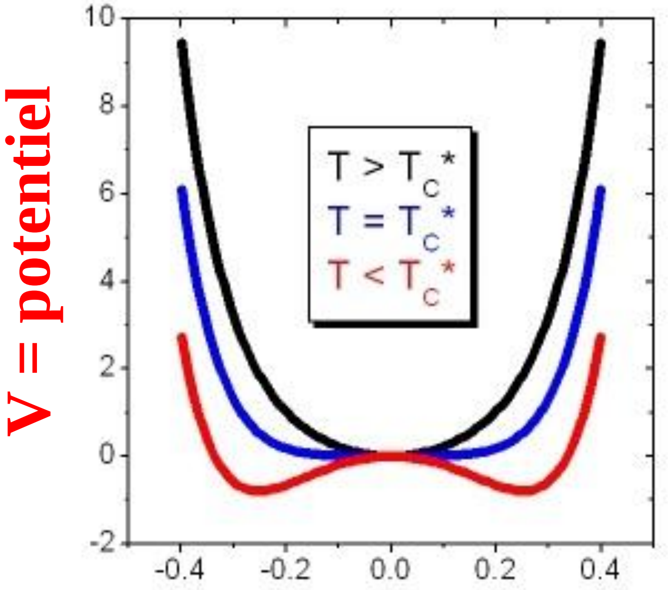
Température > température critique **Température < température critique**

L'etat fondamental brise la symétrie des lois physiques

(Superfluidité et) supraconductivité : transition de phase vers une condensation de Bose-Einstein

Pour $T < T_C$ le champ magnetique ne rentre pas a l'interieur d'un materiau supraconducteur (effet Meissner – Ochsenfeld)

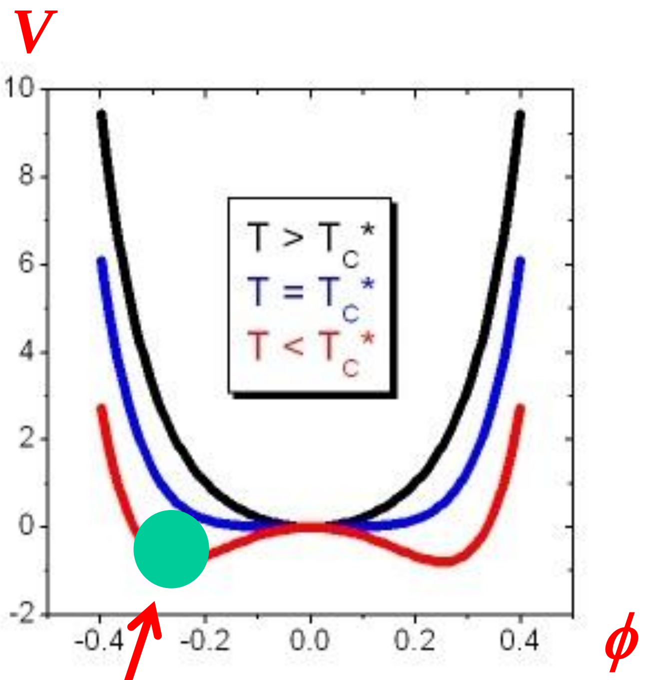
$\Rightarrow$ Le photon acquiert une masse (dans le supraconducteur)



**paramètre d'ordre
(lié au condensat de Bose Einstein)**

© N.Andari

De facon analogue a la supraconductivité mais de facon plus profonde on suppose que l'Univers est rempli du champ de BEH ϕ



Le potentiel (aux énergies nous intéressant) a une forme de chapeau mexicain et le vide ● correspond à une valeur non nulle de ϕ

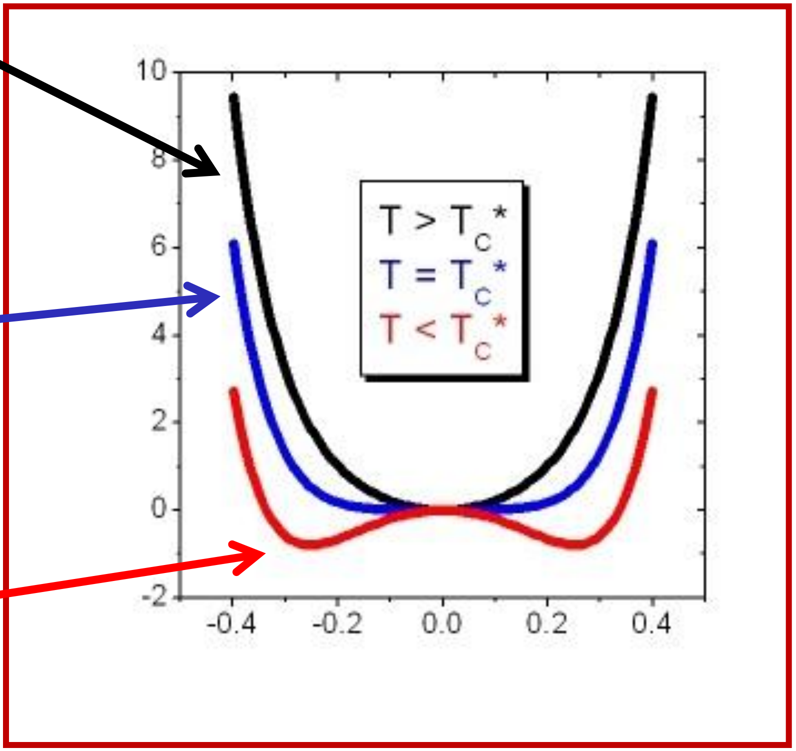
A ce moment les bosons faibles (W et Z) prennent une masse

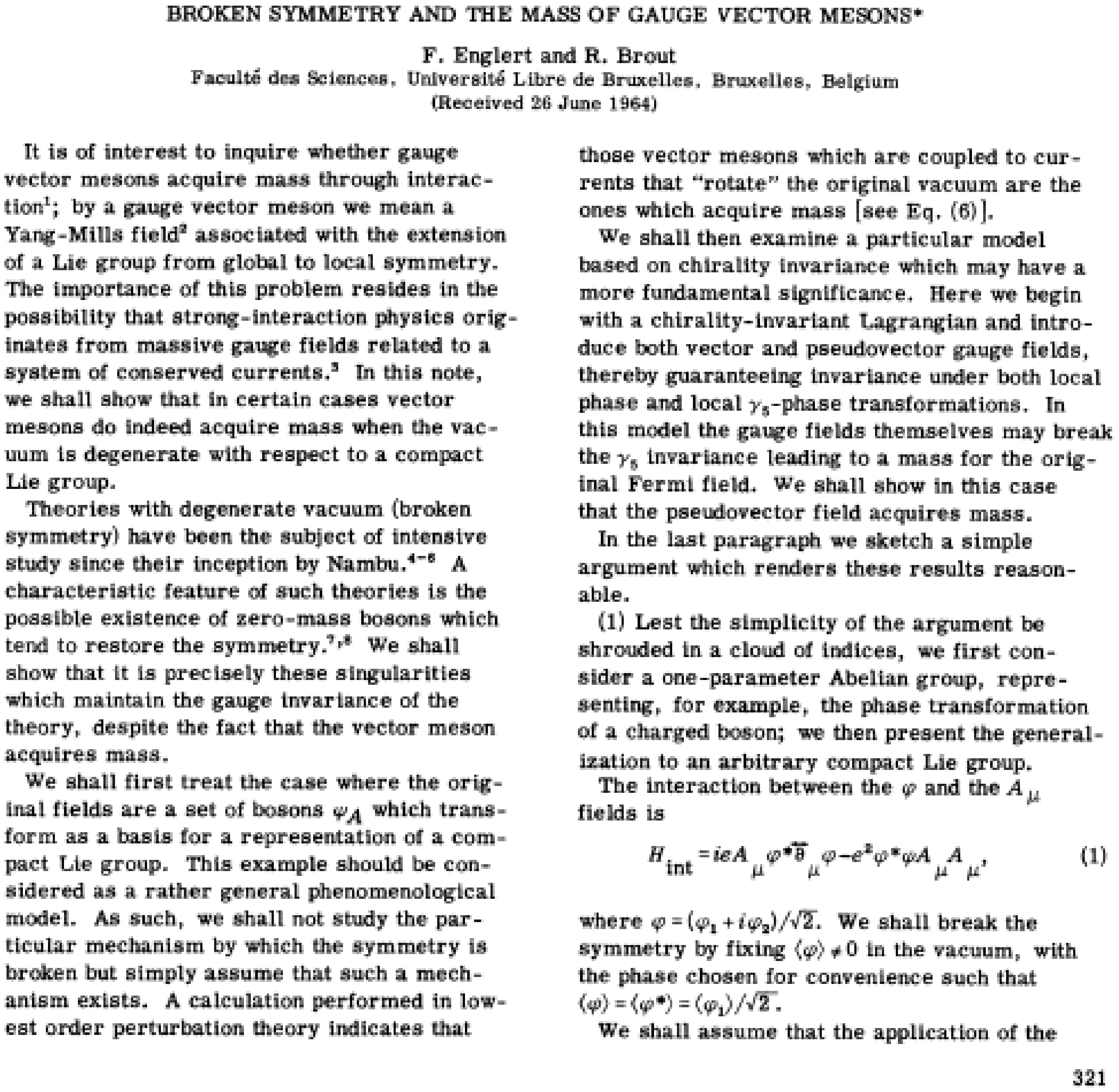
La masse du boson de BEH est liée aux oscillations de ϕ dans le vide (au minimum)

Mass of the 4 scalar bosons positive
W and Z mass = 0
fermion masses =0

10^{-10} s

Mass of one scalar (BEH) boson positive
W and Z mass positive
fermion have their masses





BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
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(Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction[1]; by a gauge vector meson we mean a Yang-Mills field[2] associated with the extension of a Lie group from global to local symmetry. The importance of this problem resides in the possibility that strong-interaction physics originates from massive gauge fields related to a system of conserved currents.[3] In this note, we shall show that in certain cases vector mesons do indeed acquire mass when the vacuum is degenerate with respect to a compact Lie group.

Theories with degenerate vacuum (broken symmetry) have been the subject of intensive study since their inception by Nambu.[4-6] A characteristic feature of such theories is the possible existence of zero-mass bosons which tend to restore the symmetry.[7,8] We shall show that it is precisely these singularities which maintain the gauge invariance of the theory, despite the fact that the vector meson acquires mass.

We shall first treat the case where the original fields are a set of bosons φ_A which transform as a basis for a representation of a compact Lie group. This example should be considered as a rather general phenomenological model. As such, we shall not study the particular mechanism by which the symmetry is broken but simply assume that such a mechanism exists. A calculation performed in lowest order perturbation theory indicates that those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)].

We shall then examine a particular model based on chirality invariance which may have a more fundamental significance. Here we begin with a chirality-invariant Lagrangian and introduce both vector and pseudovector gauge fields, thereby guaranteeing invariance under both local phase and local γ_5-phase transformations. In this model the gauge fields themselves may break the γ_5 invariance leading to a mass for the original Fermi field. We shall show in this case that the pseudovector field acquires mass.

In the last paragraph we sketch a simple argument which renders these results reasonable.

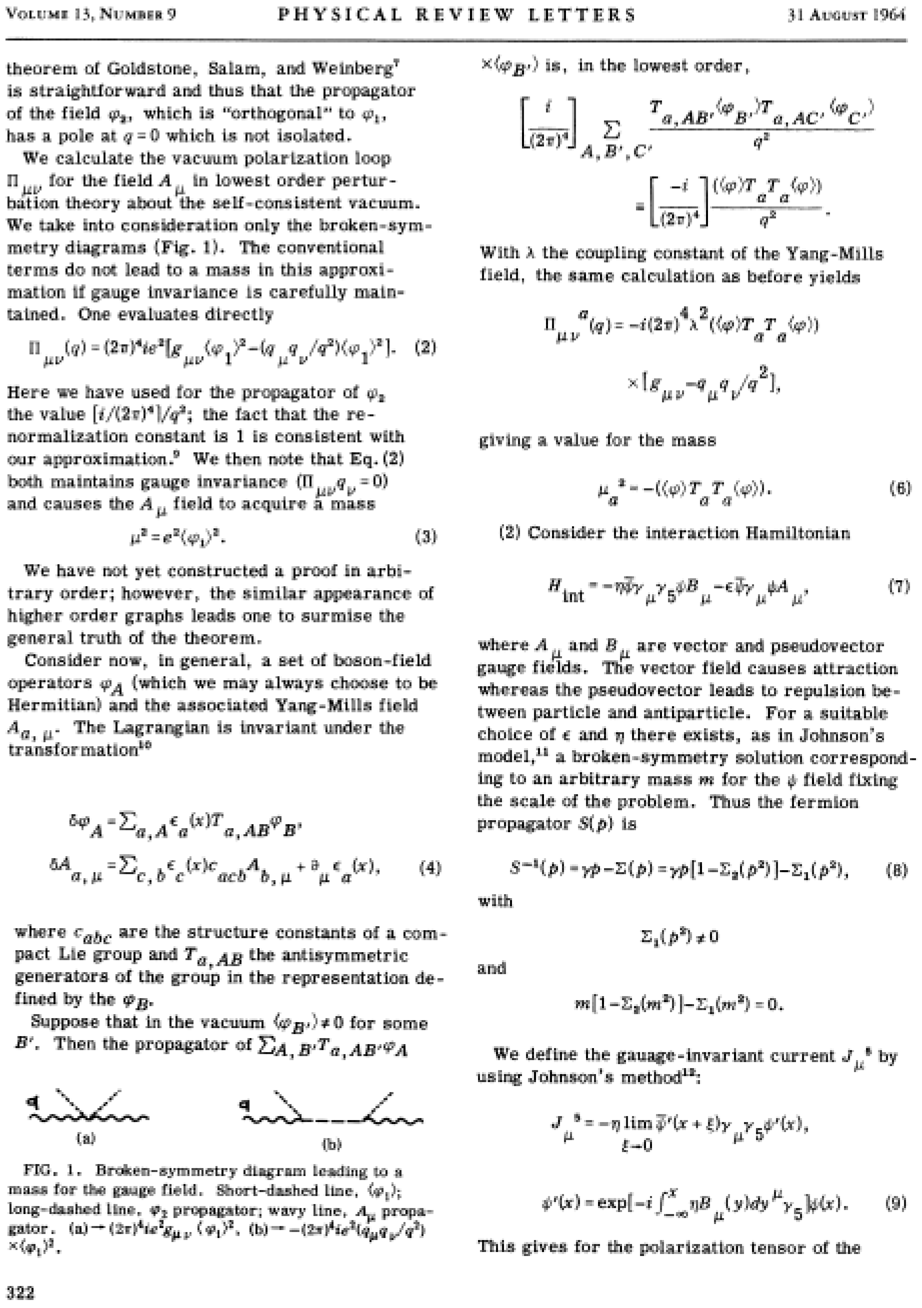
(1) Lest the simplicity of the argument be shrouded in a cloud of indices, we first consider a one-parameter Abelian group, representing, for example, the phase transformation of a charged boson; we then present the generalization to an arbitrary compact Lie group.

The interaction between the φ and the A_μ fields is

$$H_{\text{int}} = ieA_\mu \varphi^* \overleftrightarrow{\partial}_\mu \varphi - e^2 \varphi^* \varphi A_\mu A_\mu, \qquad (1)$$

where $\varphi = (\varphi_1 + i\varphi_2)/\sqrt{2}$. We shall break the symmetry by fixing $\langle\varphi\rangle \neq 0$ in the vacuum, with the phase chosen for convenience such that $\langle\varphi\rangle = \langle\varphi^*\rangle = \langle\varphi_1\rangle/\sqrt{2}$.

We shall assume that the application of the



theorem of Goldstone, Salam, and Weinberg[7] is straightforward and thus that the propagator of the field φ_2, which is "orthogonal" to φ_1, has a pole at $q=0$ which is not isolated.

We calculate the vacuum polarization loop $\Pi_{\mu\nu}$ for the field A_μ in lowest order perturbation theory about the self-consistent vacuum. We take into consideration only the broken-symmetry diagrams (Fig. 1). The conventional terms do not lead to a mass in this approximation if gauge invariance is carefully maintained. One evaluates directly

$$\Pi_{\mu\nu}(q) = (2\pi)^4 ie^2[g_{\mu\nu}\langle\varphi_1\rangle^2 - (q_\mu q_\nu/q^2)\langle\varphi_1\rangle^2]. \qquad (2)$$

Here we have used for the propagator of φ_2 the value $[i/(2\pi)^4]/q^2$; the fact that the renormalization constant is 1 is consistent with our approximation.[9] We then note that Eq. (2) both maintains gauge invariance ($\Pi_{\mu\nu}q_\nu = 0$) and causes the A_μ field to acquire a mass

$$\mu^2 = e^2\langle\varphi_1\rangle^2. \qquad (3)$$

We have not yet constructed a proof in arbitrary order; however, the similar appearance of higher order graphs leads one to surmise the general truth of the theorem.

Consider now, in general, a set of boson-field operators φ_A (which we may always choose to be Hermitian) and the associated Yang-Mills field $A_{a,\mu}$. The Lagrangian is invariant under the transformation[10]

$$\delta\varphi_A = \textstyle\sum_{a,A}\epsilon_a(x)T_{a,AB}\varphi_{B'}$$

$$\delta A_{a,\mu} = \textstyle\sum_{c,b}\epsilon_c(x)c_{acb}A_{b,\mu} + \partial_\mu\epsilon_a(x), \qquad (4)$$

where c_{abc} are the structure constants of a compact Lie group and $T_{a,AB}$ the antisymmetric generators of the group in the representation defined by the φ_B.

Suppose that in the vacuum $\langle\varphi_{B'}\rangle \neq 0$ for some B'. Then the propagator of $\sum_{A,B'}T_{a,AB'}\varphi_A$

(a) (b)

FIG. 1. Broken-symmetry diagram leading to a mass for the gauge field. Short-dashed line, $\langle\varphi_1\rangle$; long-dashed line, φ_2 propagator; wavy line, A_μ propagator. (a) → $(2\pi)^4 ie^2 g_{\mu\nu}\langle\varphi_1\rangle^2$, (b) → $-(2\pi)^4 ie^2(q_\mu q_\nu/q^2)\langle\varphi_1\rangle^2$.

$\times\langle\varphi_{B'}\rangle$ is, in the lowest order,

$$\left[\frac{i}{(2\pi)^4}\right]\sum_{A,B',C'}\frac{T_{a,AB'}\langle\varphi_{B'}\rangle T_{a,AC'}\langle\varphi_{C'}\rangle}{q^2}$$

$$= \left[\frac{-i}{(2\pi)^4}\right]\frac{(\langle\varphi\rangle T_a T_a\langle\varphi\rangle)}{q^2}.$$

With λ the coupling constant of the Yang-Mills field, the same calculation as before yields

$$\Pi_{\mu\nu}{}^a(q) = -i(2\pi)^4\lambda^2(\langle\varphi\rangle T_a T_a\langle\varphi\rangle)$$

$$\times[g_{\mu\nu} - q_\mu q_\nu/q^2],$$

giving a value for the mass

$$\mu_a{}^2 = -(\langle\varphi\rangle T_a T_a\langle\varphi\rangle). \qquad (6)$$

(2) Consider the interaction Hamiltonian

$$H_{\text{int}} = -\eta\bar{\psi}\gamma_\mu\gamma_5\psi B_\mu - \epsilon\bar{\psi}\gamma_\mu\psi A_\mu, \qquad (7)$$

where A_μ and B_μ are vector and pseudovector gauge fields. The vector field causes attraction whereas the pseudovector leads to repulsion between particle and antiparticle. For a suitable choice of ϵ and η there exists, as in Johnson's model,[11] a broken-symmetry solution corresponding to an arbitrary mass m for the ψ field fixing the scale of the problem. Thus the fermion propagator $S(p)$ is

$$S^{-1}(p) = \gamma p - \Sigma(p) = \gamma p[1-\Sigma_2(p^2)] - \Sigma_1(p^2), \qquad (8)$$

with

$$\Sigma_1(p^2) \neq 0$$

and

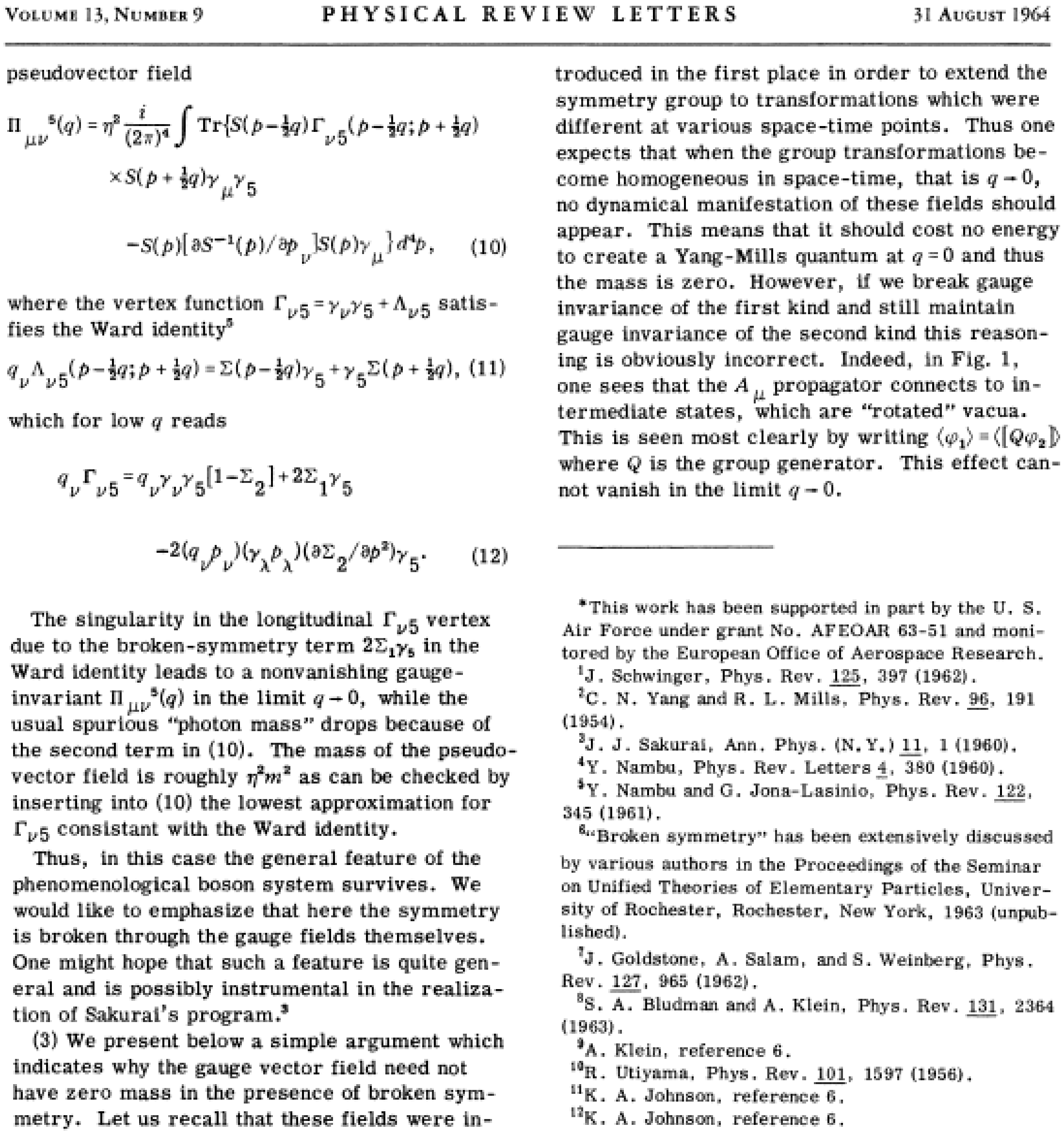
$$m[1-\Sigma_2(m^2)] - \Sigma_1(m^2) = 0.$$

We define the gauage-invariant current $J_\mu{}^5$ by using Johnson's method[12]:

$$J_\mu{}^5 = -\eta\lim_{\xi\to 0}\bar{\psi}'(x+\xi)\gamma_\mu\gamma_5\psi'(x),$$

$$\psi'(x) = \exp\left[-i\int_{-\infty}^{x}\eta B_\mu(y)dy^\mu\gamma_5\right]\psi(x). \qquad (9)$$

This gives for the polarization tensor of the



pseudovector field

$$\Pi_{\mu\nu}{}^{5}(q)=\eta^2\frac{i}{(2\pi)^4}\int \mathrm{Tr}\{S(p-\tfrac{1}{2}q)\Gamma_{\nu 5}(p-\tfrac{1}{2}q;p+\tfrac{1}{2}q)$$

$$\times S(p+\tfrac{1}{2}q)\gamma_{\mu}\gamma_5$$

$$-S(p)[\partial S^{-1}(p)/\partial p_{\nu}]S(p)\gamma_{\mu}\}d^4p, \qquad (10)$$

where the vertex function $\Gamma_{\nu 5}=\gamma_\nu\gamma_5+\Lambda_{\nu 5}$ satisfies the Ward identity[5]

$$q_\nu\Lambda_{\nu 5}(p-\tfrac{1}{2}q;p+\tfrac{1}{2}q)=\Sigma(p-\tfrac{1}{2}q)\gamma_5+\gamma_5\Sigma(p+\tfrac{1}{2}q), \quad (11)$$

which for low q reads

$$q_\nu\Gamma_{\nu 5}=q_\nu\gamma_\nu\gamma_5[1-\Sigma_2]+2\Sigma_1\gamma_5$$

$$-2(q_\nu p_\nu)(\gamma_\lambda p_\lambda)(\partial\Sigma_2/\partial p^2)\gamma_5. \qquad (12)$$

The singularity in the longitudinal $\Gamma_{\nu 5}$ vertex due to the broken-symmetry term $2\Sigma_1\gamma_5$ in the Ward identity leads to a nonvanishing gauge-invariant $\Pi_{\mu\nu}{}^{5}(q)$ in the limit $q\to 0$, while the usual spurious "photon mass" drops because of the second term in (10). The mass of the pseudovector field is roughly $\eta^2 m^2$ as can be checked by inserting into (10) the lowest approximation for $\Gamma_{\nu 5}$ consistant with the Ward identity.

Thus, in this case the general feature of the phenomenological boson system survives. We would like to emphasize that here the symmetry is broken through the gauge fields themselves. One might hope that such a feature is quite general and is possibly instrumental in the realization of Sakurai's program.[3]

(3) We present below a simple argument which indicates why the gauge vector field need not have zero mass in the presence of broken symmetry. Let us recall that these fields were introduced in the first place in order to extend the symmetry group to transformations which were different at various space-time points. Thus one expects that when the group transformations become homogeneous in space-time, that is $q\to 0$, no dynamical manifestation of these fields should appear. This means that it should cost no energy to create a Yang-Mills quantum at $q=0$ and thus the mass is zero. However, if we break gauge invariance of the first kind and still maintain gauge invariance of the second kind this reasoning is obviously incorrect. Indeed, in Fig. 1, one sees that the A_μ propagator connects to intermediate states, which are "rotated" vacua. This is seen most clearly by writing $\langle\varphi_1\rangle=\langle[Q\varphi_2]\rangle$ where Q is the group generator. This effect cannot vanish in the limit $q\to 0$.

---

[*] This work has been supported in part by the U. S. Air Force under grant No. AFEOAR 63-51 and monitored by the European Office of Aerospace Research.

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[7] J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).

[8] S. A. Bludman and A. Klein, Phys. Rev. 131, 2364 (1963).

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[10] R. Utiyama, Phys. Rev. 101, 1597 (1956).

[11] K. A. Johnson, reference 6.

[12] K. A. Johnson, reference 6.

Field Theories with «Superconductor» Solutions.

J. Goldstone
CERN - Geneva

(ricevuto l'8 Settembre 1960)

Plasmons, Gauge Invariance, and Mass

P. W. Anderson
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received 8 November 1962)

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

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(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

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Received 27 July 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

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Department of Physics, Imperial College, London, England

(Received 12 October 1964)

Spontaneous Symmetry Breakdown without Massless Bosons*

Peter W. Higgs†
Department of Physics, University of North Carolina, Chapel Hill, North Carolina

(Received 27 December 1965)

Symmetry Breaking in Non-Abelian Gauge Theories*

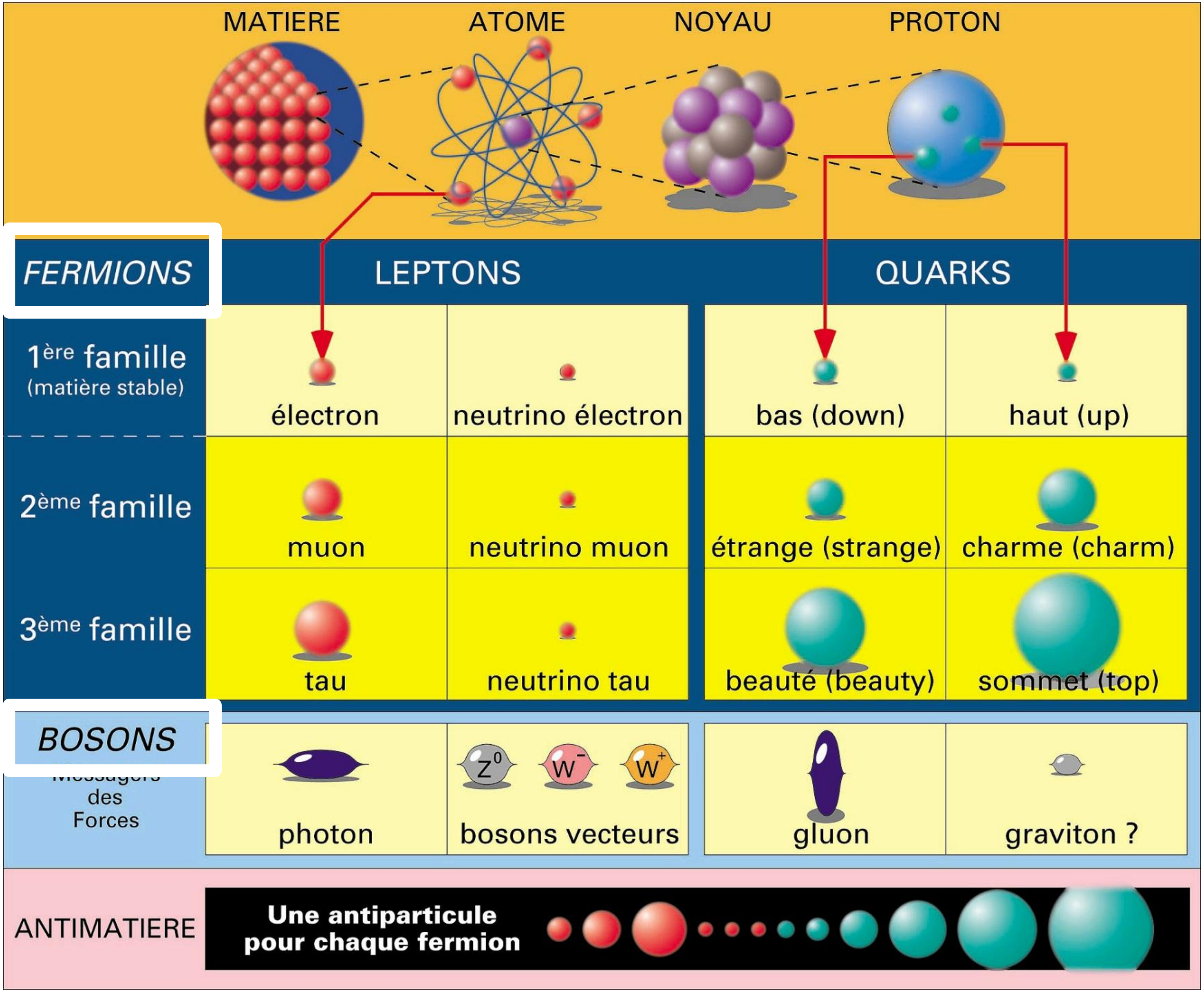
T. W. B. Kibble
Department of Physics, Imperial College, London, England

(Received 24 October 1966)

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 17 October 1967)



FERMIONS	LEPTONS		QUARKS	
1ère famille (matière stable)	électron	neutrino électron	bas (down)	haut (up)
2ème famille	muon	neutrino muon	étrange (strange)	charme (charm)
3ème famille	tau	neutrino tau	beauté (beauty)	sommet (top)
BOSONS Messagers des Forces	photon	bosons vecteurs	gluon	graviton ?
ANTIMATIERE	**Une antiparticule pour chaque fermion**			

Fermions et Bosons

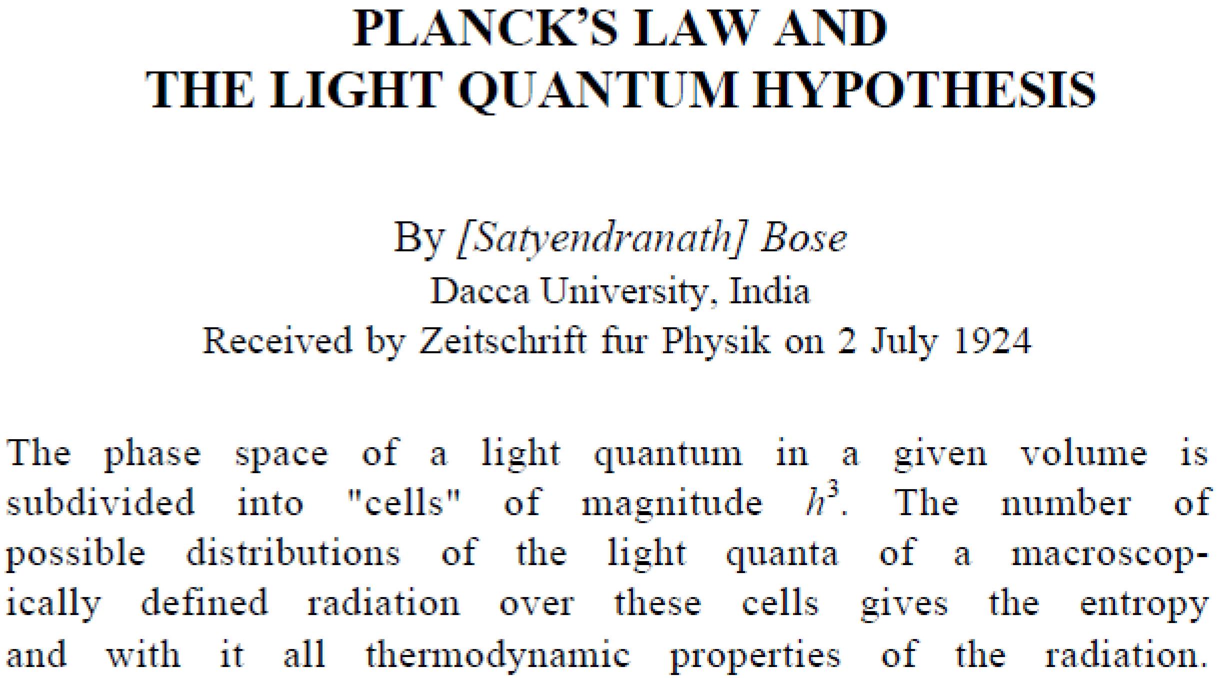
Propriété quantique des particules (liée au ‘spin’)

Deux fermions ne peuvent occuper le même état quantique en même temps Cela aboutit à la rigidité des états qui incluent des fermions (des noyaux atomiques, des atomes, des molécules, etc.) ⇒ les fermions sont les constituants de la matière

Les bosons peuvent occuper le même état : ils ont tendance à s'agréger ⇒ il peut y avoir une transition de phase à basse température, responsable notamment de la superfluidité de l'hélium ou de la supraconductivité de certains matériaux (condensation de Bose-Einstein **) Les messagers des forces sont des bosons ainsi que le BEH**

On comprend les liens entre les fondateurs du mécanisme de BEH et les théoriciens de la supraconductivité

j'y reviendrai plus tard



PLANCK'S LAW AND
THE LIGHT QUANTUM HYPOTHESIS

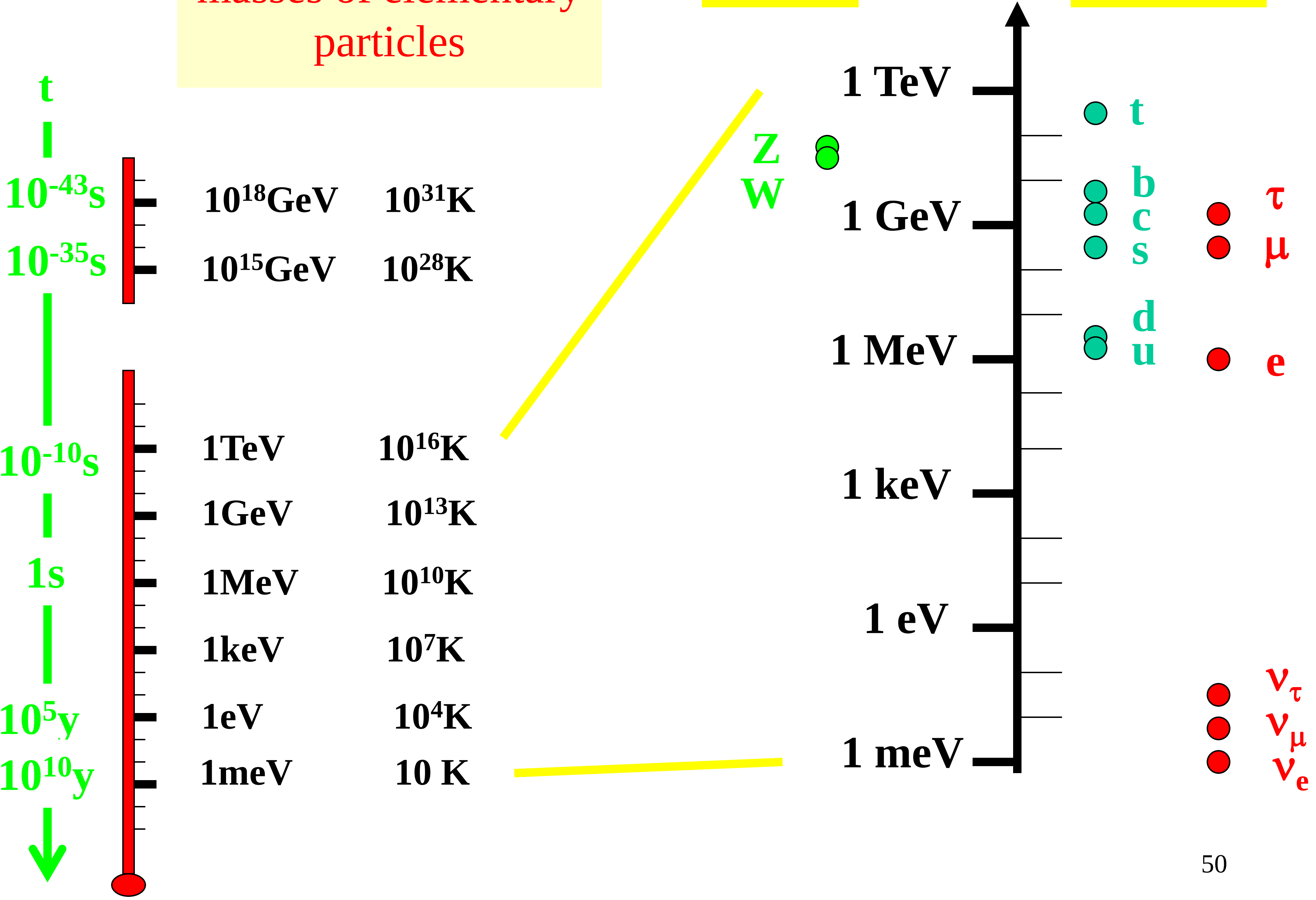
By *[Satyendranath] Bose*
Dacca University, India
Received by Zeitschrift fur Physik on 2 July 1924

The phase space of a light quantum in a given volume is subdivided into "cells" of magnitude h^3. The number of possible distributions of the light quanta of a macroscopically defined radiation over these cells gives the entropy and with it all thermodynamic properties of the radiation.

masses of elementary particles

bosons

fermions



t

10^{-43}s	10^{18}GeV	10^{31}K
10^{-35}s	10^{15}GeV	10^{28}K
10^{-10}s	1TeV	10^{16}K
	1GeV	10^{13}K
1s	1MeV	10^{10}K
	1keV	10^{7}K
10^{5}y	1eV	10^{4}K
10^{10}y	1meV	10 K

1 TeV

1 GeV

1 MeV

1 keV

1 eV

1 meV

Z

W

t

b

c

s

d

u

τ

μ

e

ν_τ

ν_μ

ν_e

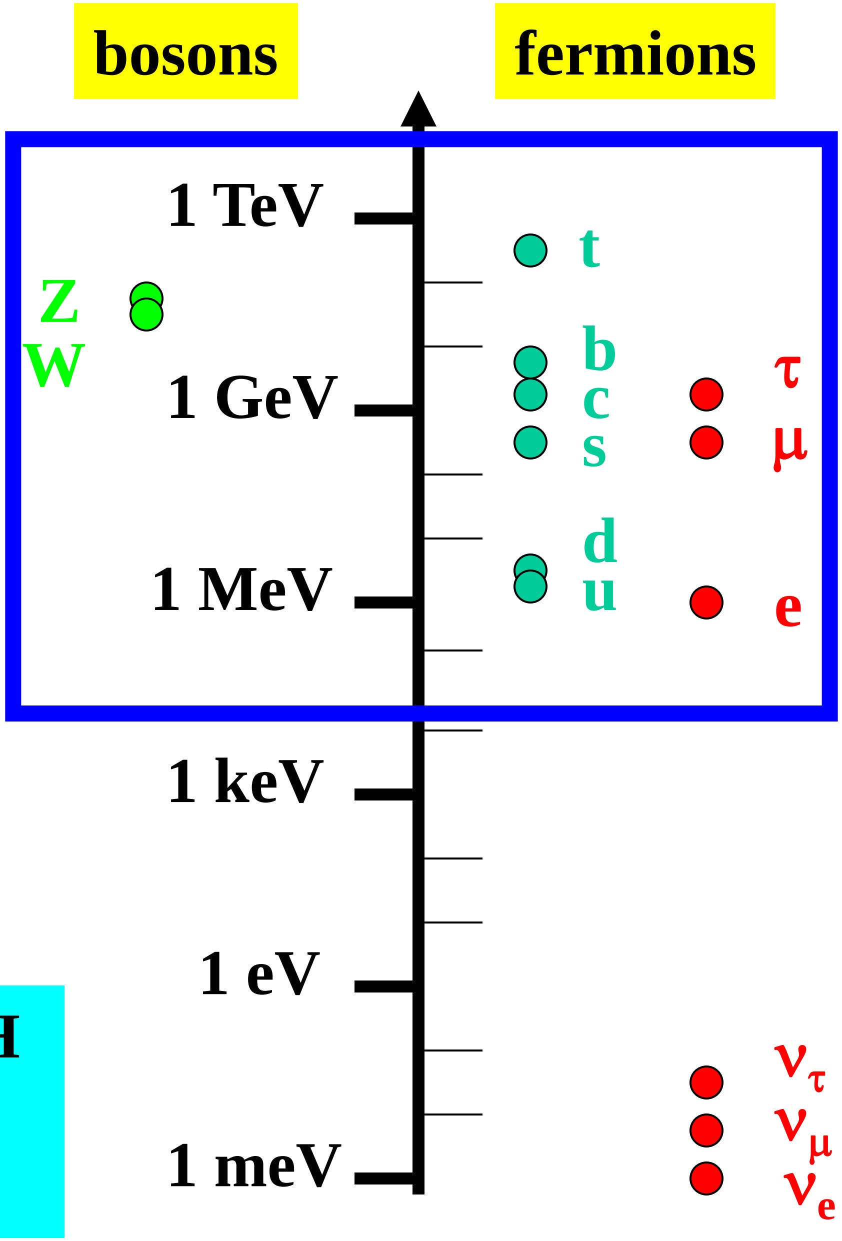
On pense que le vide est rempli par le champ de Brout-Englert-Higgs qui interagit avec les particules qui acquièrent alors une masse

Ce champ de Higgs fait partie du Modèle Standard électrofaible

Le mecanisme de Brout-Englert-Higgs est une forme de *supraconductivité dans le vide*

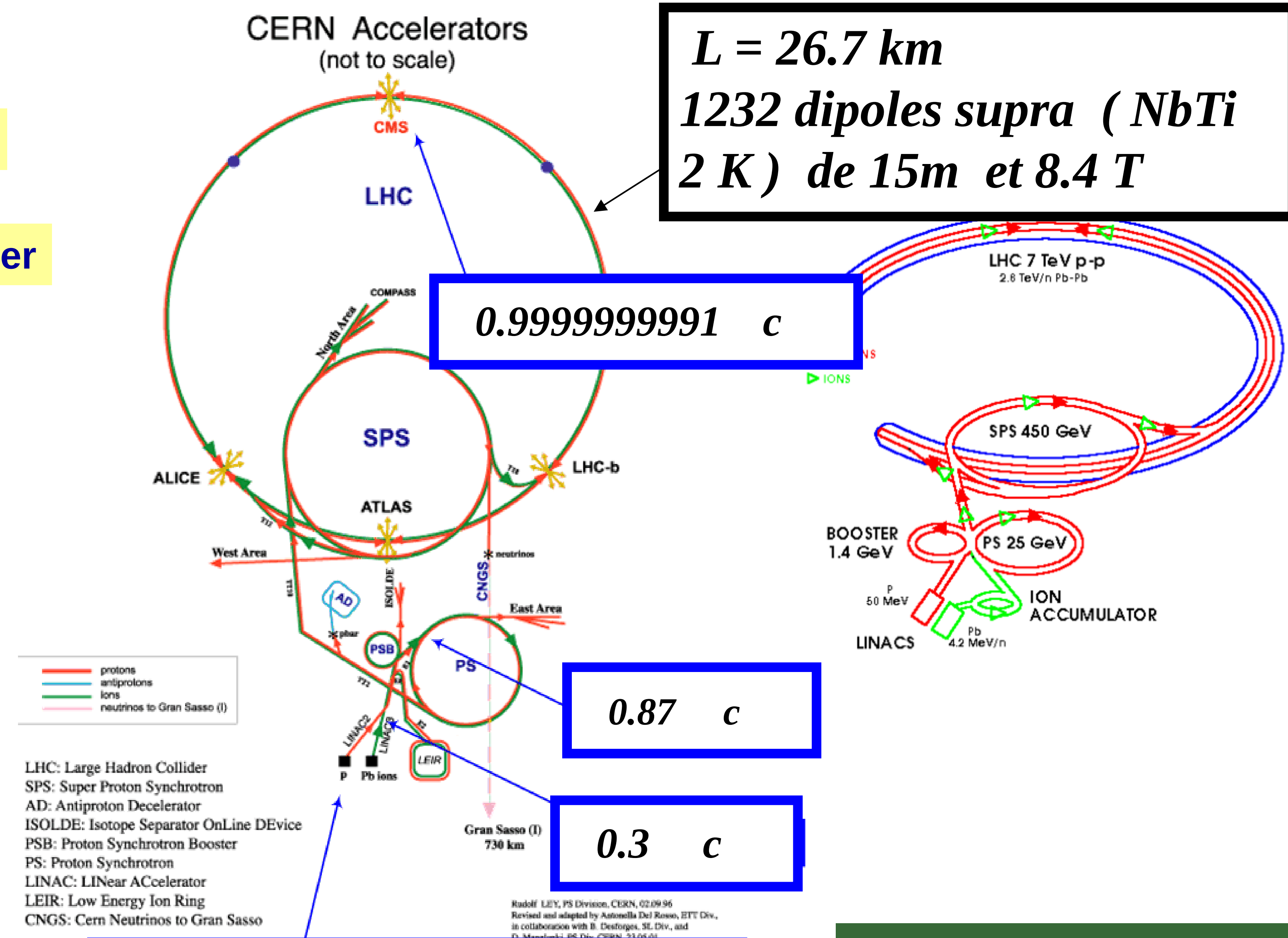
⇒ champ (particule) de BEH à trouver

masse de l'ordre de 100 GeV



L’ensemble des accelerateurs du CERN

Linac
↓
Booster
↓
PS
↓
SPS
↓
LHC



- protons
- antiprotons
- ions
- neutrinos to Gran Sasso (I)

LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Rudolf LEY, PS Division, CERN, 02.09.96
Revised and adapted by Antonella Del Rosso, ETT Div.,
in collaboration with B. Desforges, SL Div., and

L = 26.7 km
1232 dipoles supra (NbTi 2 K) de 15m et 8.4 T

0.9999999991 c

0.87 c

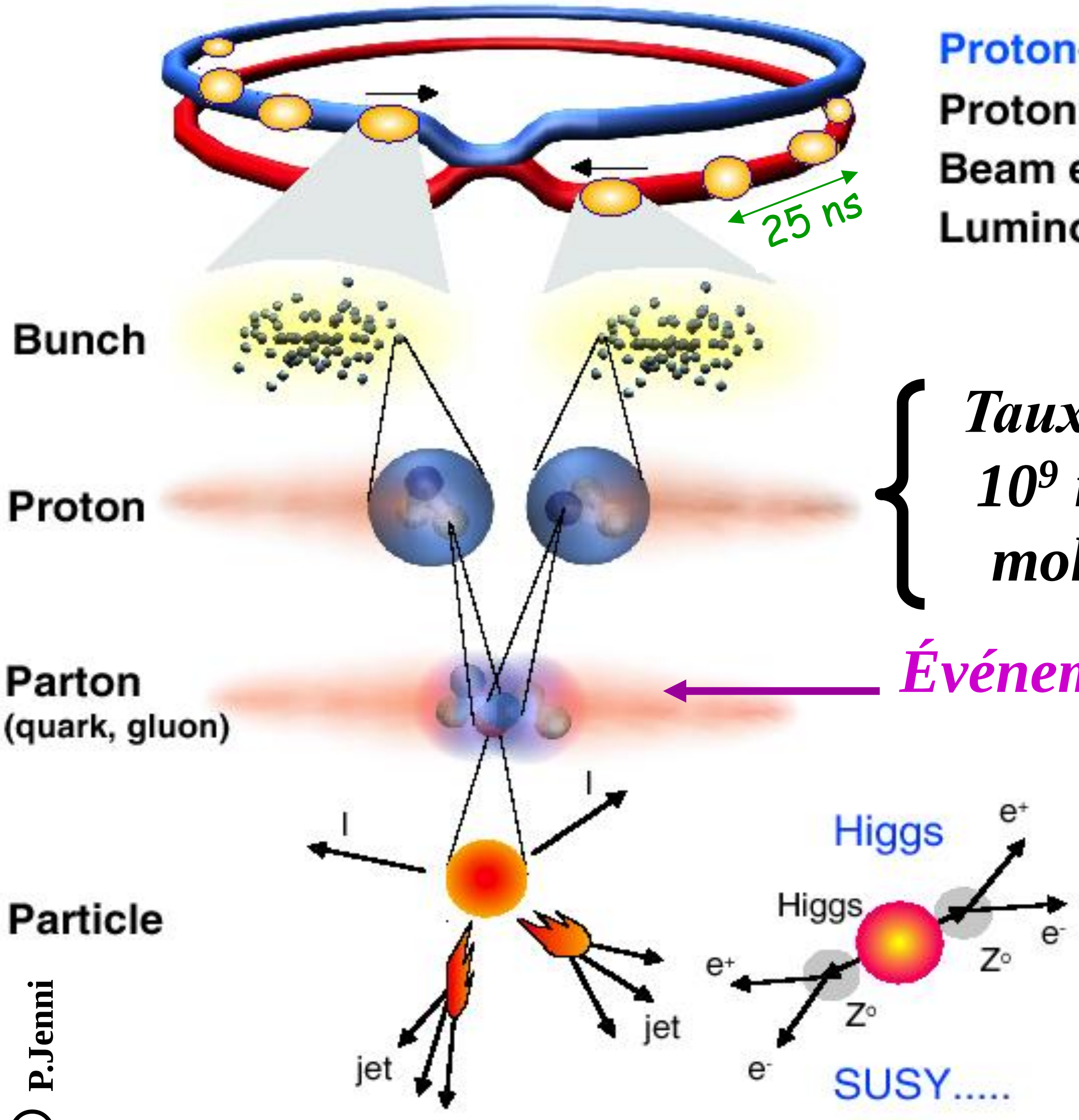
0.3 c

Les protons sont produits ici

© P.Jenni

> 50 ans du CERN operationnel

COLLISIONS AU LHC



Proton-Proton	
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

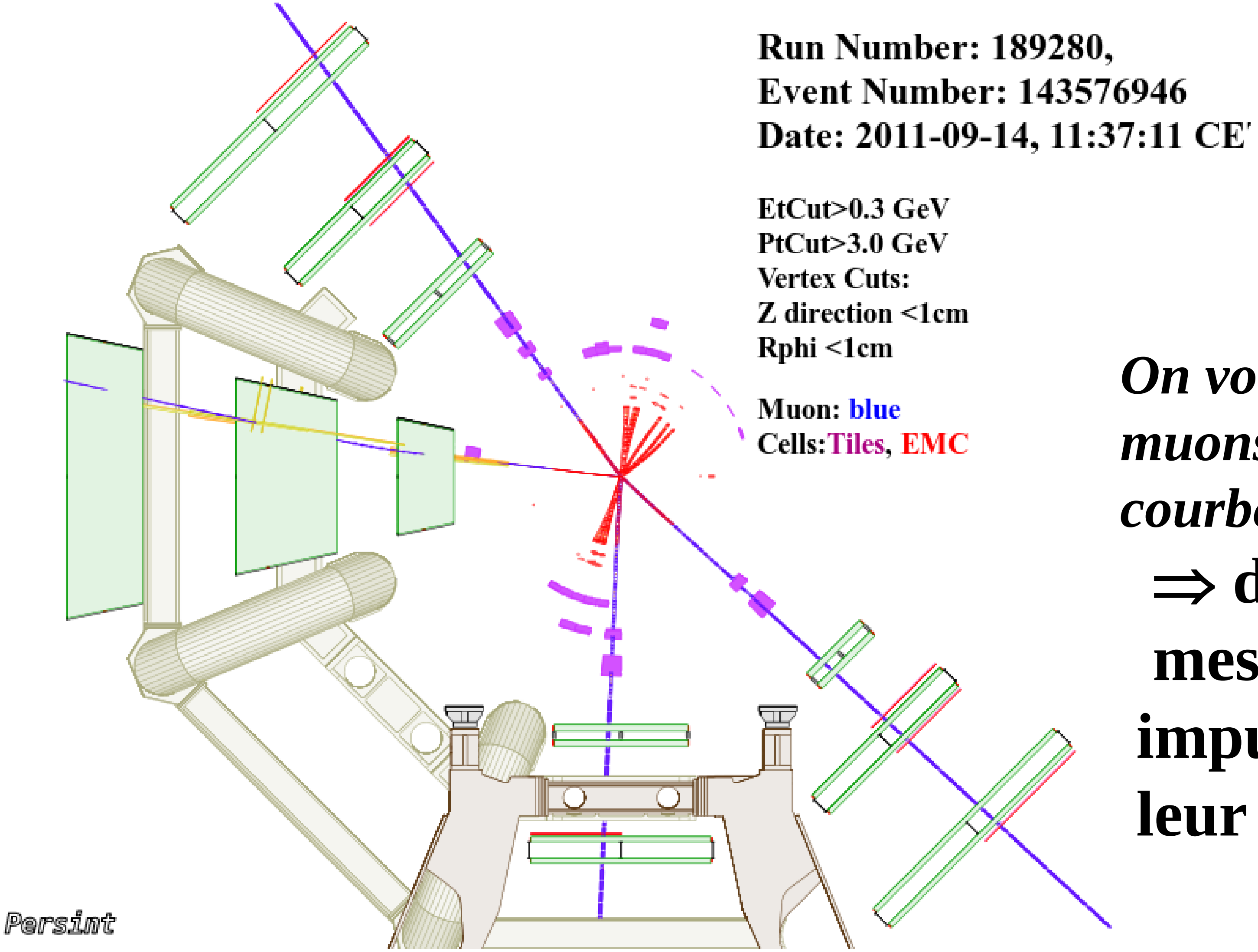
Taux d'événements
10^9 interactions (surtout molles) par seconde

Événements intéressants très rares

Sélection d' 1 événement
Sur 10 000 000 000 000
→ détecteurs très performants

© P.Jenni

evenement 4μ m = 124.6 GeV



On voit que les muons sont peu courbés

⇒ difficile de mesurer leur impulsion (ou leur energie)

In(acc)cident le 19 septembre 2008

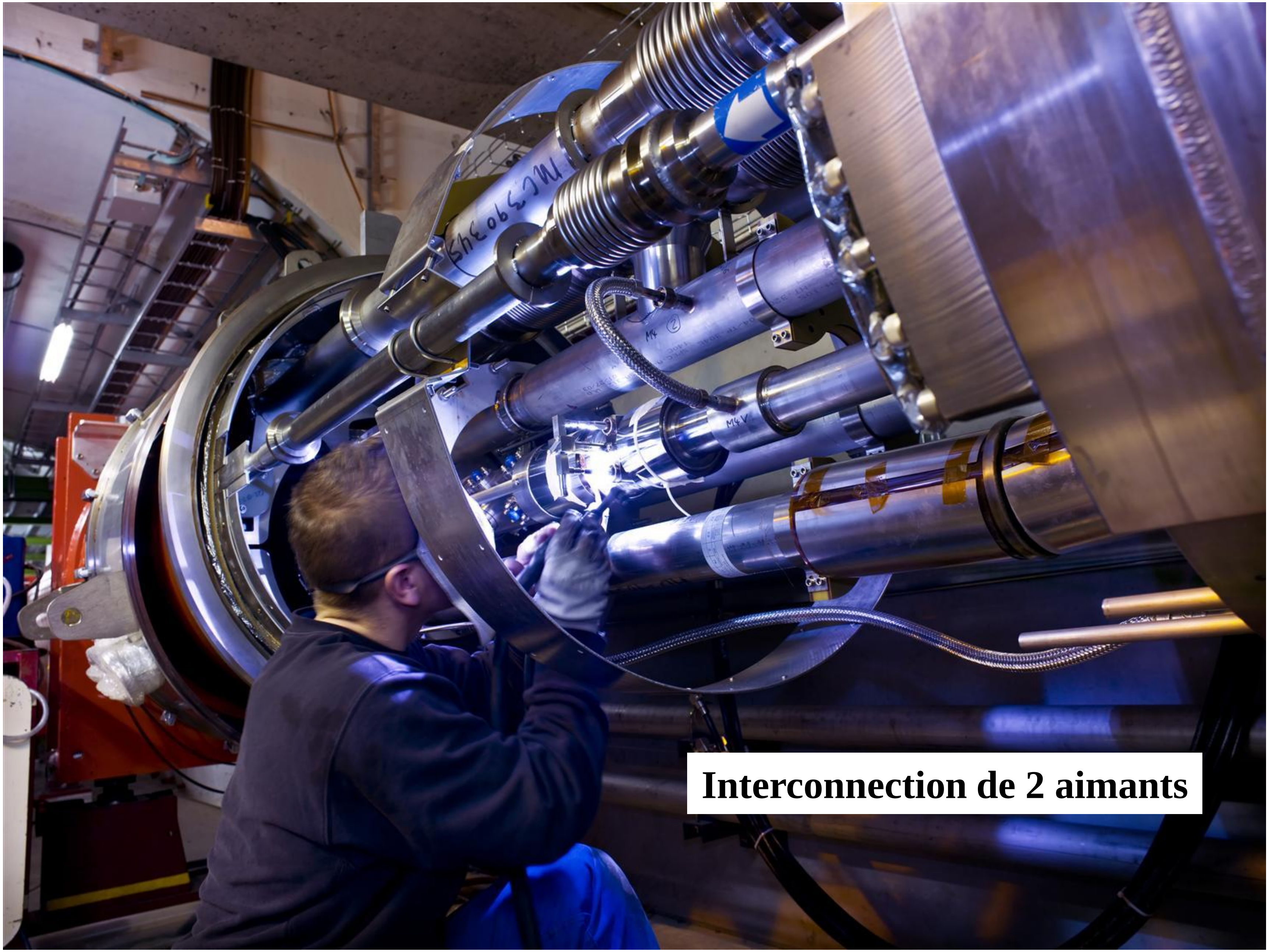
A 5.1 TeV une zone resistive est apparue dans la liaison entre un quadrupole et un dipole (mauvaise connection ..)

Vraisemblablement un arc électrique s’est developpé, perforant l’enceinte d’Helium, qui s’est deversé dans le vide d’isolation du cryostat . Les soupapes de sécurite on laché 6 t d’Helium dans le tunnel

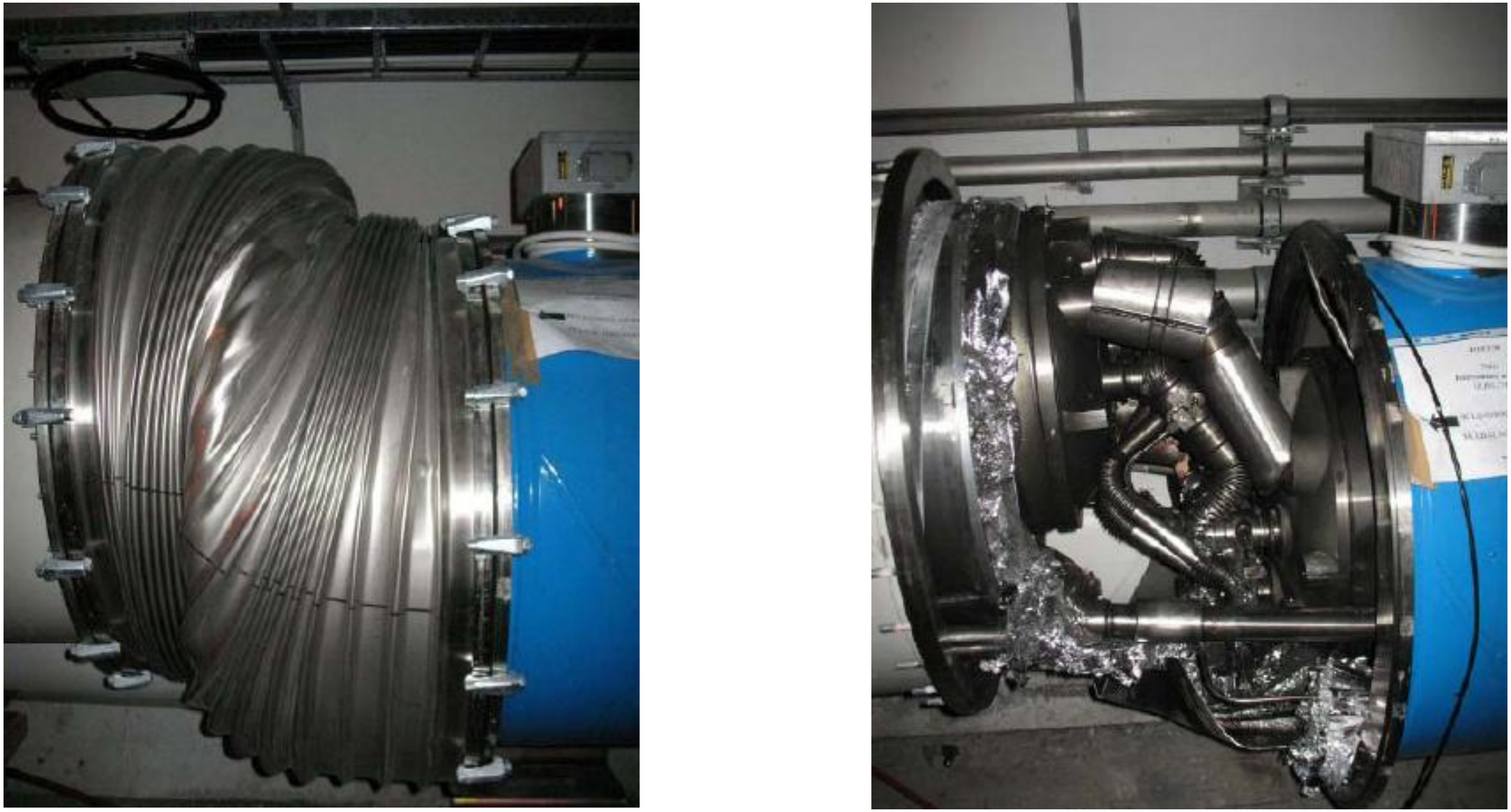
De grandes forces ont deplacé les aimants jusqu’a 50 cm

Plus de 50 aimants à changer , 2km de chambre à vide à nettoyer

Incident majeur → plus d’un an de retard

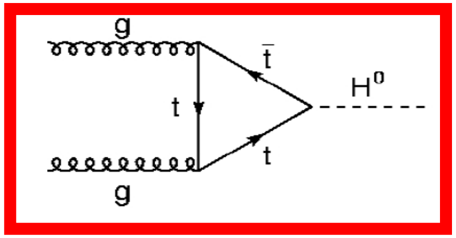


Interconnection de 2 aimants

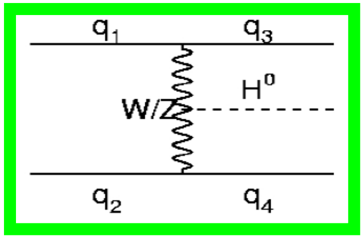


Dégâts collatéraux : déplacements d’aimants

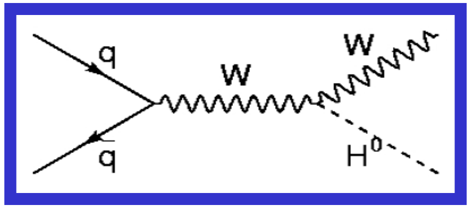
A.Djouadi Phys.Rept.457:1-216



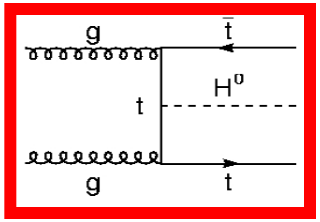
GF **H → WW , ZZ , γγ , bb,ττ**



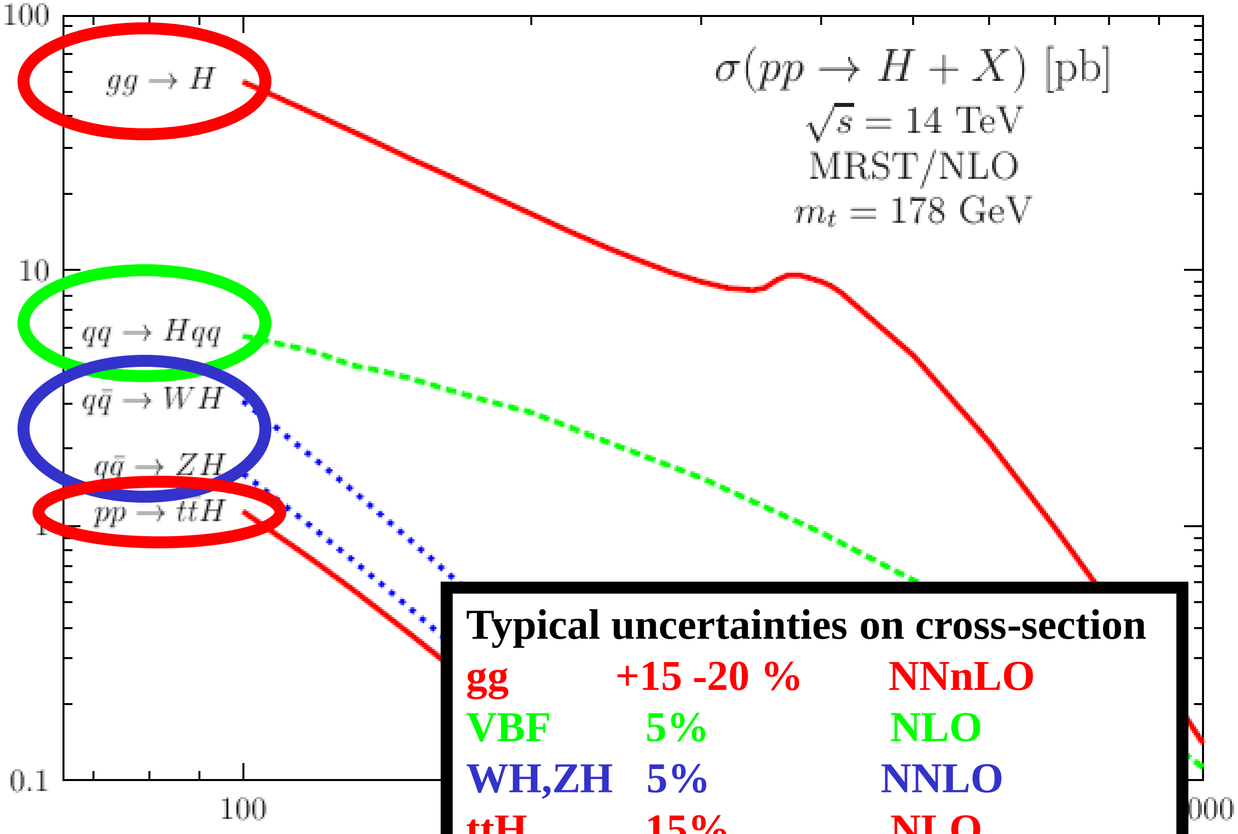
VBF **H → WW, ZZ , γγ , ττ**



H → WW, γγ, bb



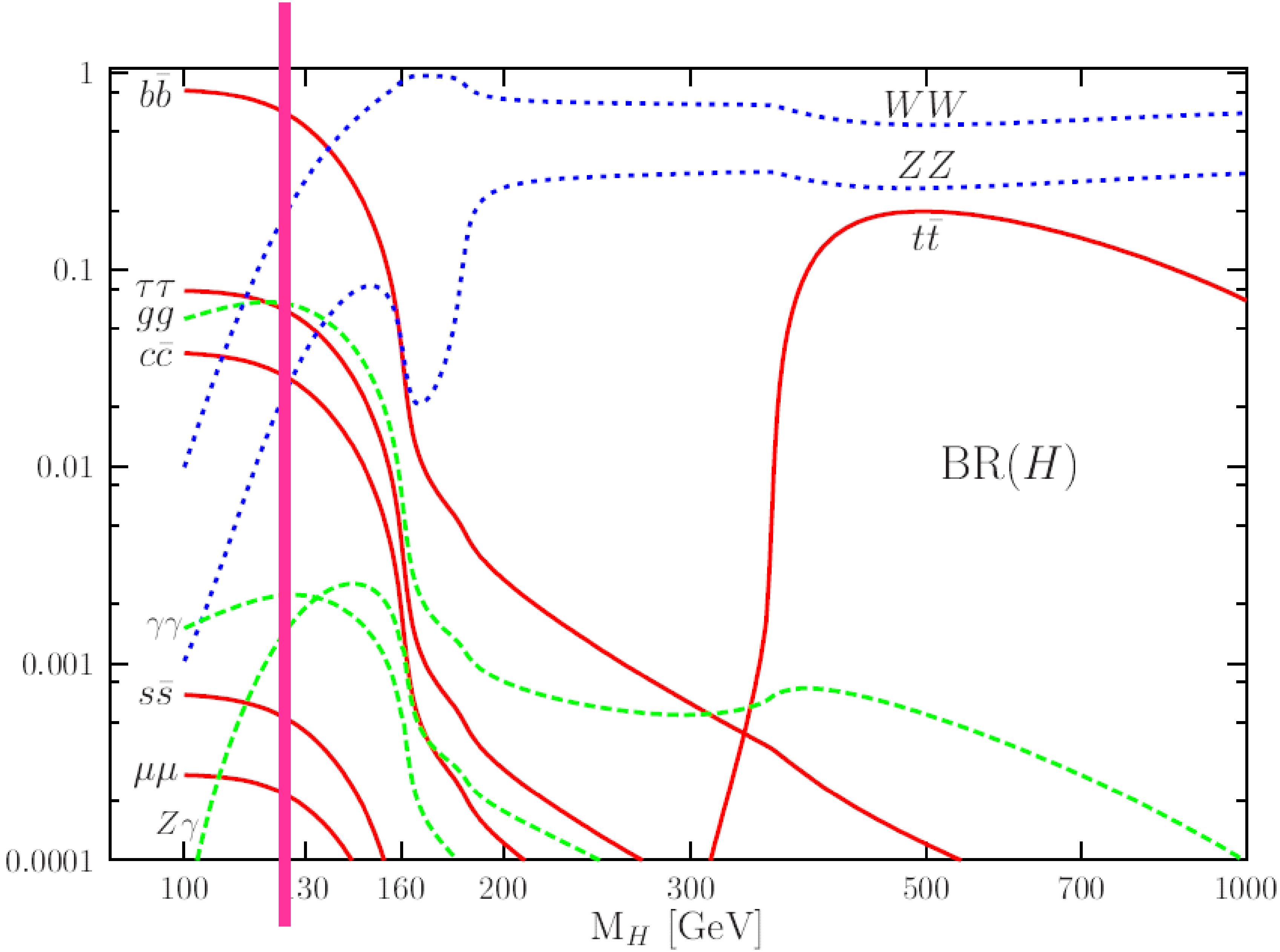
H → WW, γγ, bb



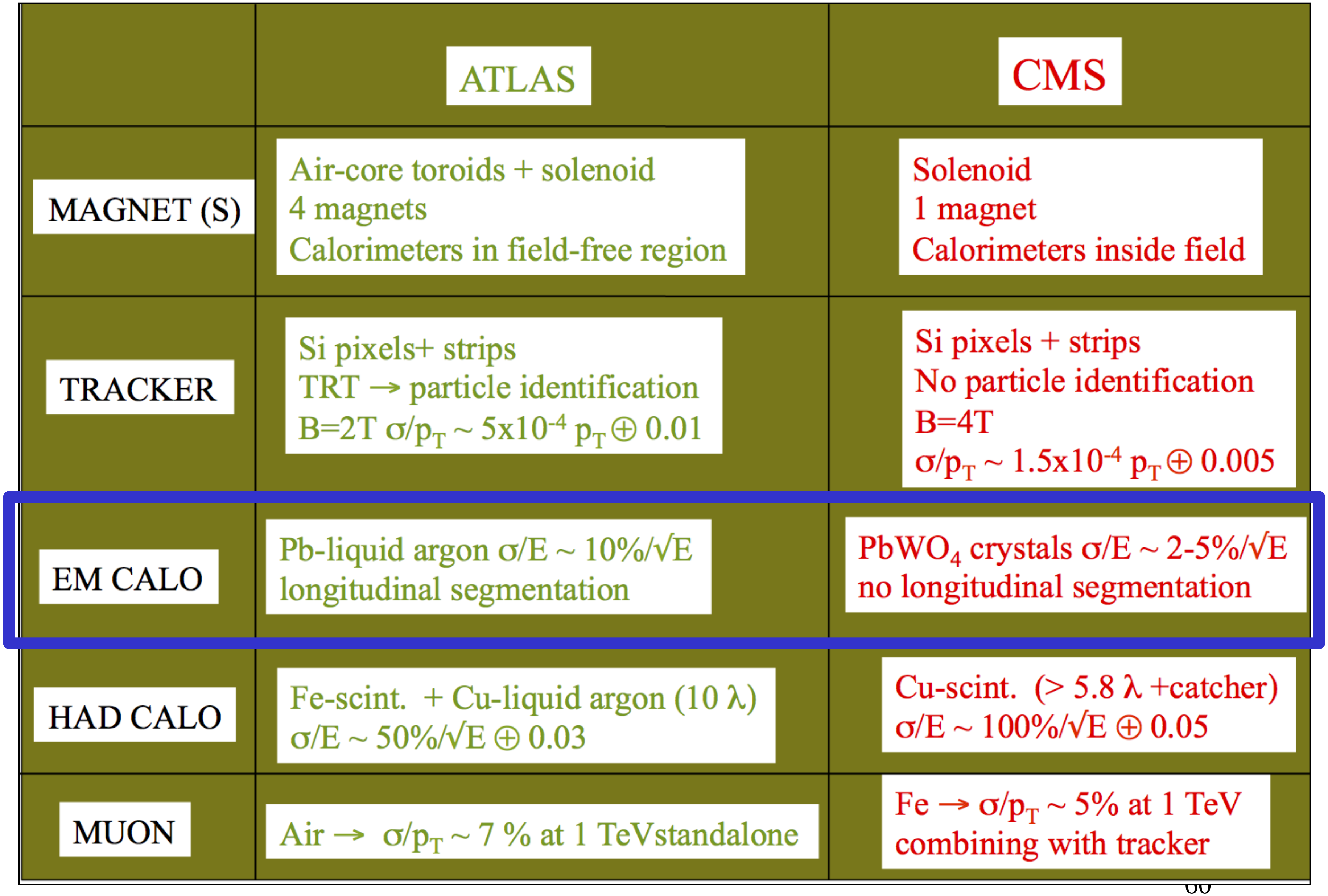
Typical uncertainties on cross-section

gg	**+15 -20 %**	**NNnLO**
VBF	**5%**	**NLO**
WH,ZH	**5%**	**NNLO**
ttH	**15%**	**NLO**

These production cross sections have to be used with the decays **bb , ττ , WW , ZZ , γγ**

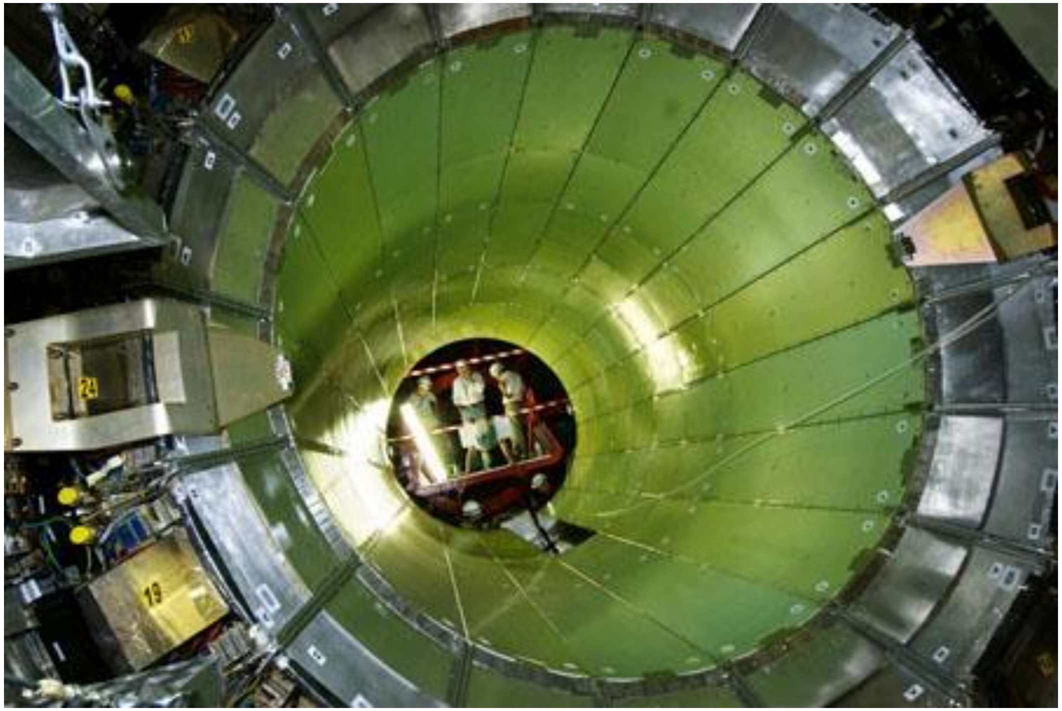


1
0.1
0.01
0.001
0.0001
$b\bar{b}$
$\tau\tau$
gg
$c\bar{c}$
$\gamma\gamma$
$s\bar{s}$
$\mu\mu$
$Z\gamma$
WW
ZZ
$t\bar{t}$
BR(H)
100
130
160
200
300
500
700
1000
M_H [GeV]



	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid 4 magnets Calorimeters in field-free region	Solenoid 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5x10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5x10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeVstandalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

Calorimètre électromagnétique de CMS : cristaux de PbW0$_4$



$$\sigma(E)/E = 3\%/\sqrt{E_{GeV}} \oplus 0.7\ \%$$

Plus de 75000 cristaux (scintillation) excellente résolution en énergie (surtout pour les photons , les électrons étant détériorés par la radiation dans le trajectographe)

Descente du calorimetre hadronique avant de CMS

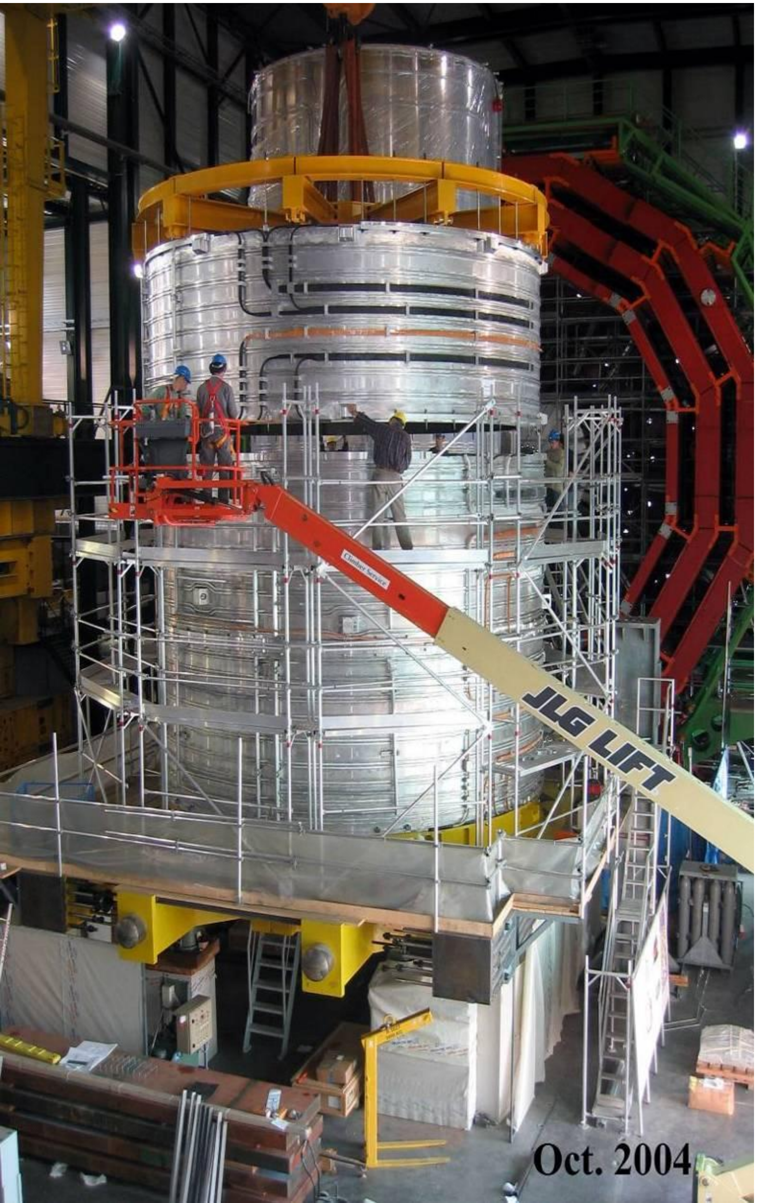
Jim Virdee (porte parole de CMS) avec Peter Higgs

Solénoïde de CMS

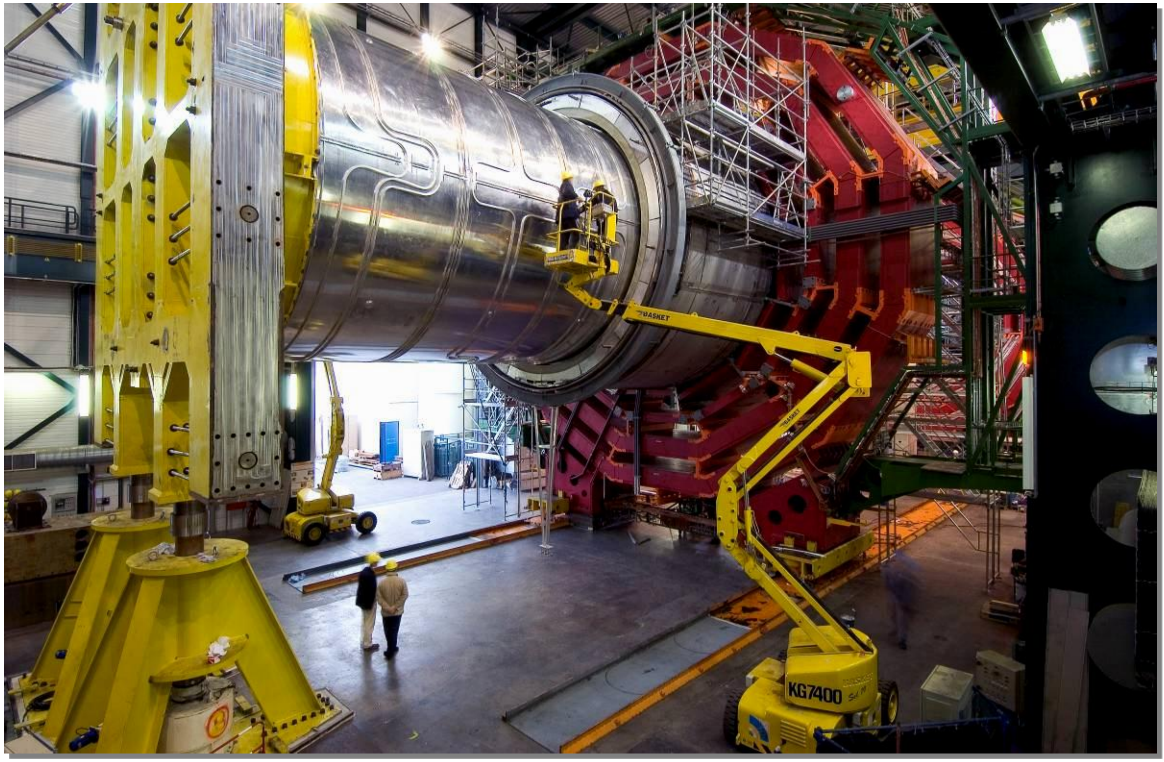
Solénoïde de CMS :

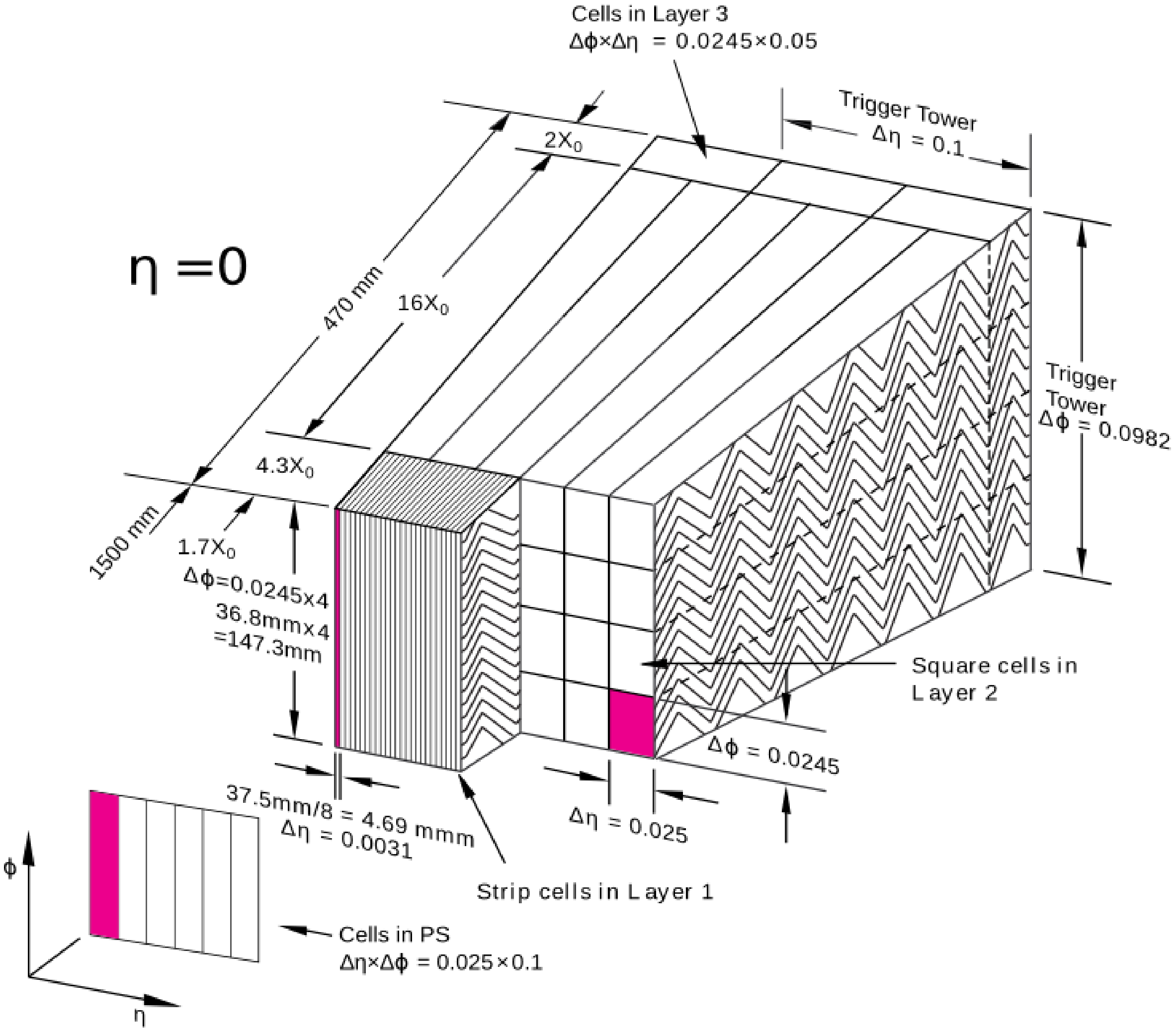
Longueur magnétique	**12.5 m**
Diametre	**6 m**
Champ magnétique	**4 T**
Courant nominal	**20 kA**
Energie stockée	**2.7 GJ**

Testé au courant nominal en été 2006



Oct. 2004

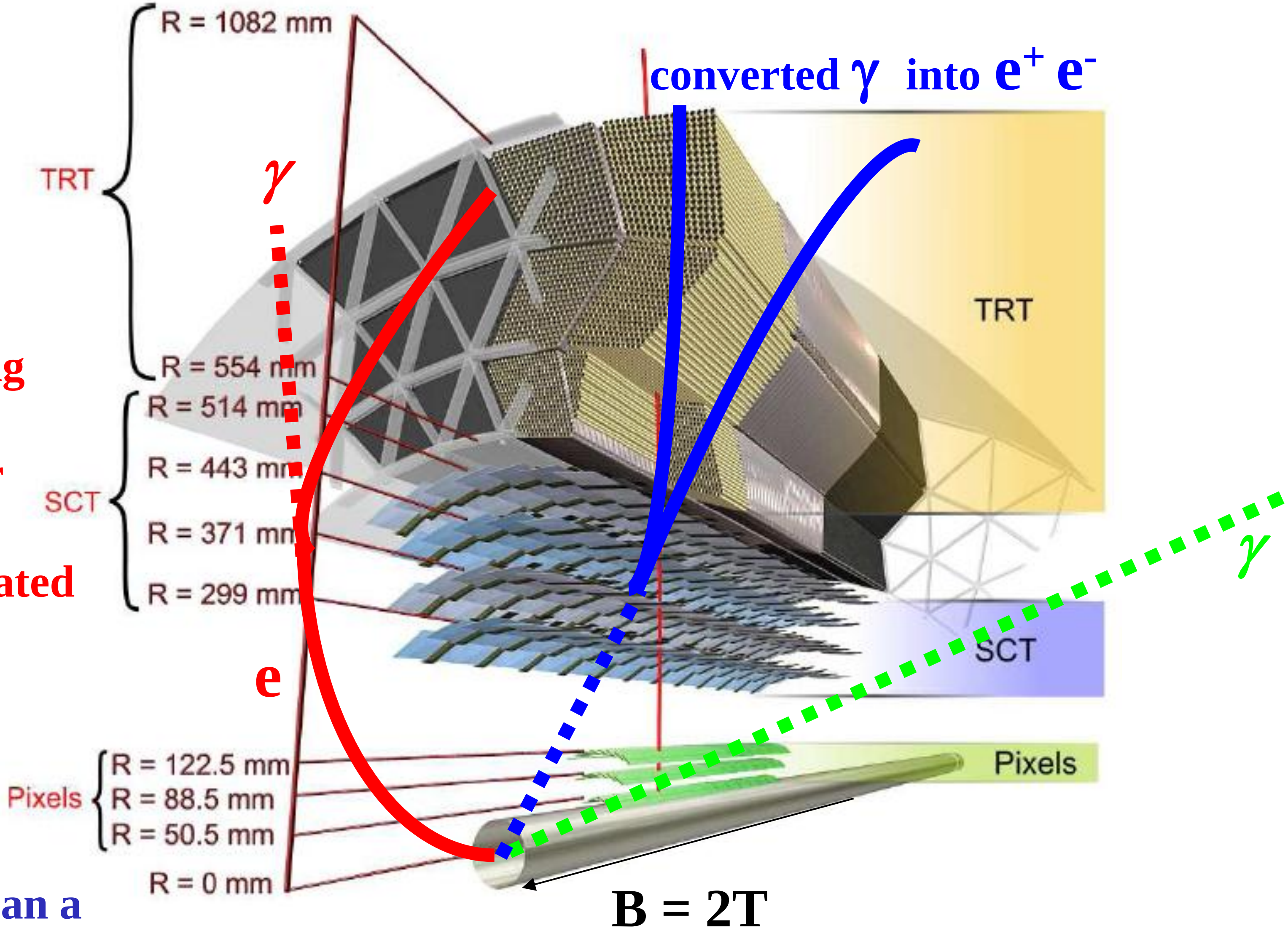




presampler and longitudinal segmentation of the EM (*Liquid Argon*) accordion calorimeter

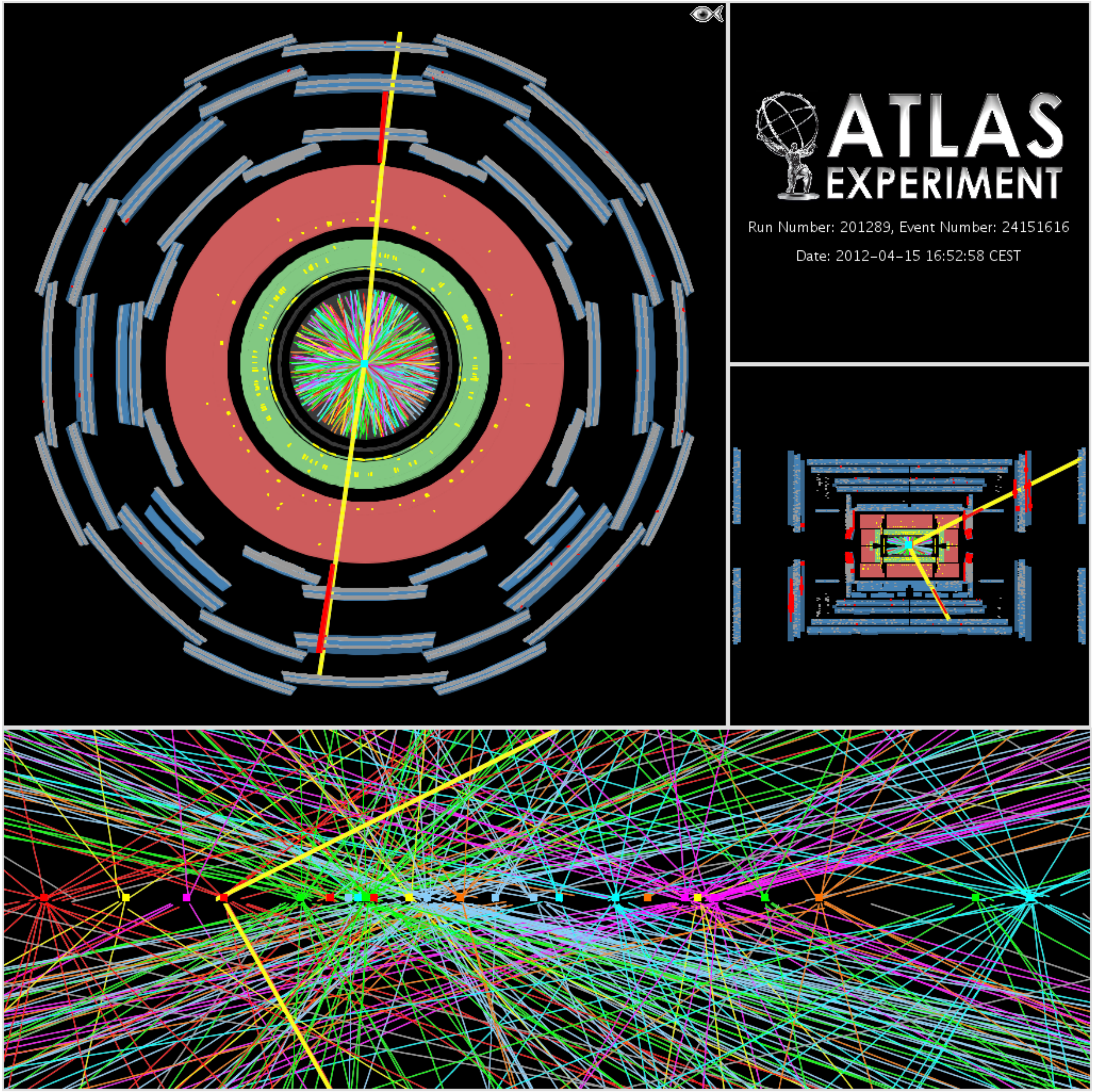
ATLAS inner detector

Outside you have the calorimeters and the muon detector

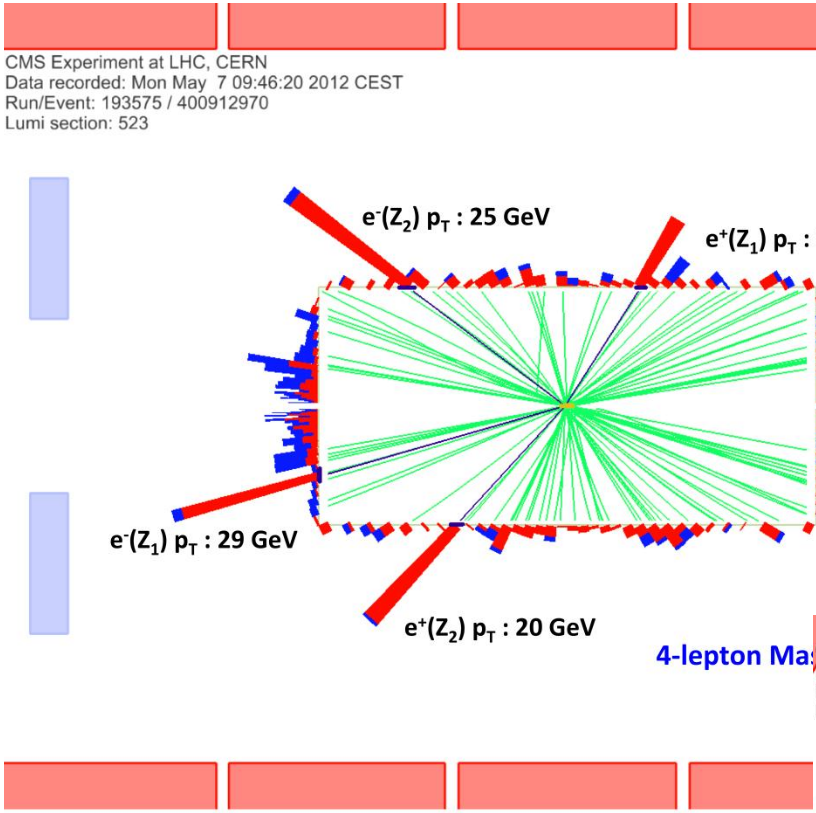


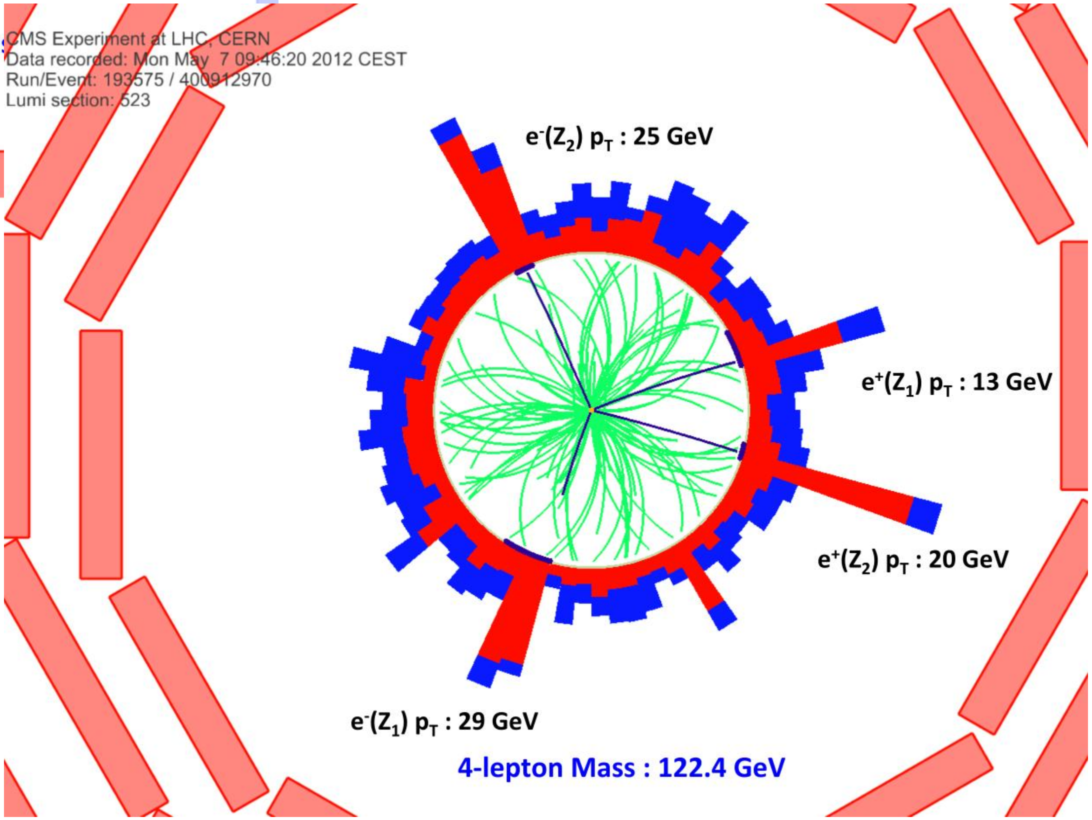
electrons can do some bremsstrahlung in the Inner Detector ⇒ response more complicated

photons can convert ⇒ more complicated than a non converted photon

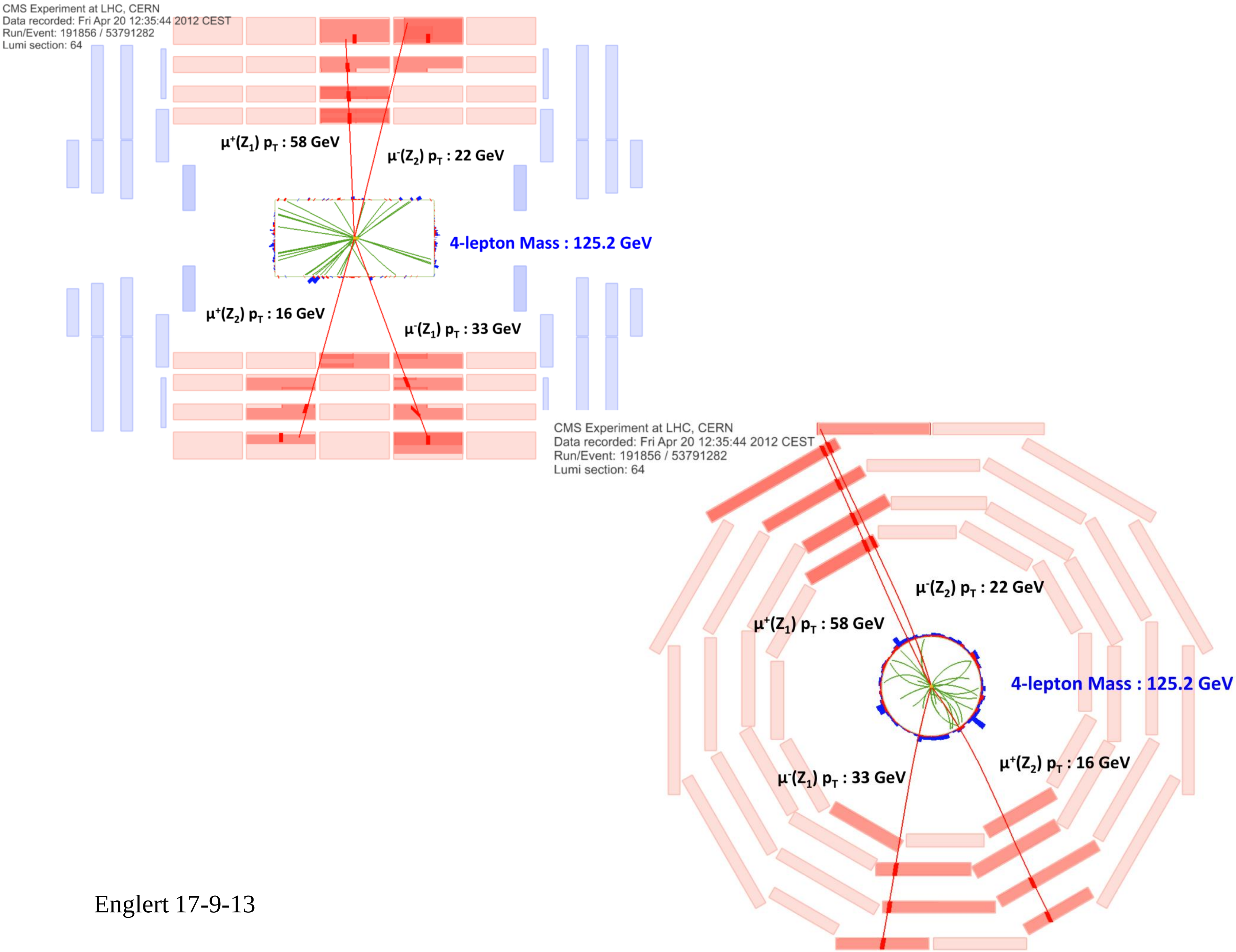


Event display with a Z→ $\mu^+\mu^-$ with 25 reconstructed vertices recorded April 15th 2012



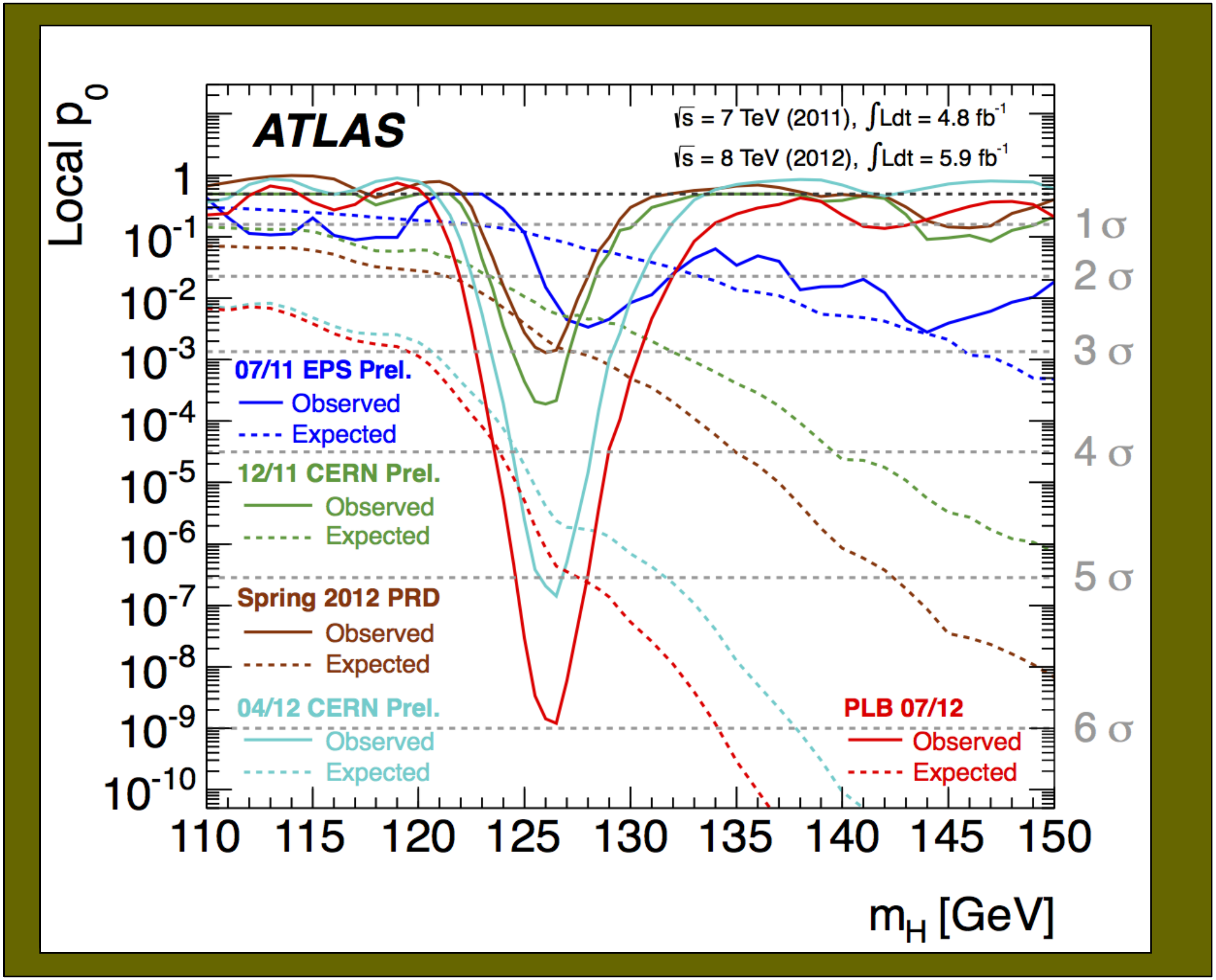


Englert 17-9-13

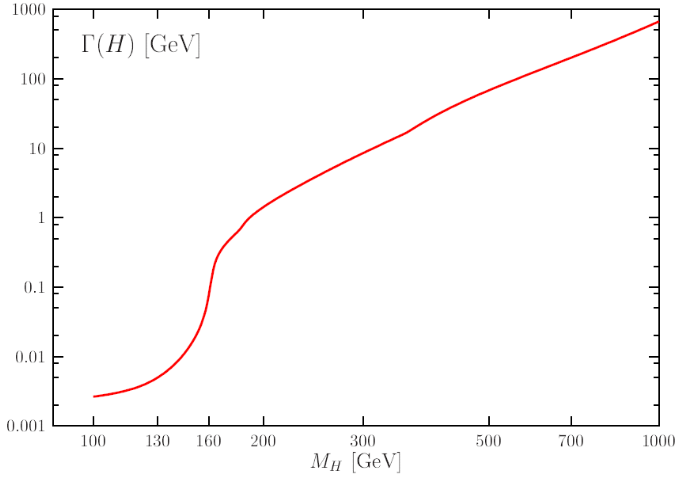


Englert 17-9-13

Evolution of the excess (all channels) with time



scalar boson width



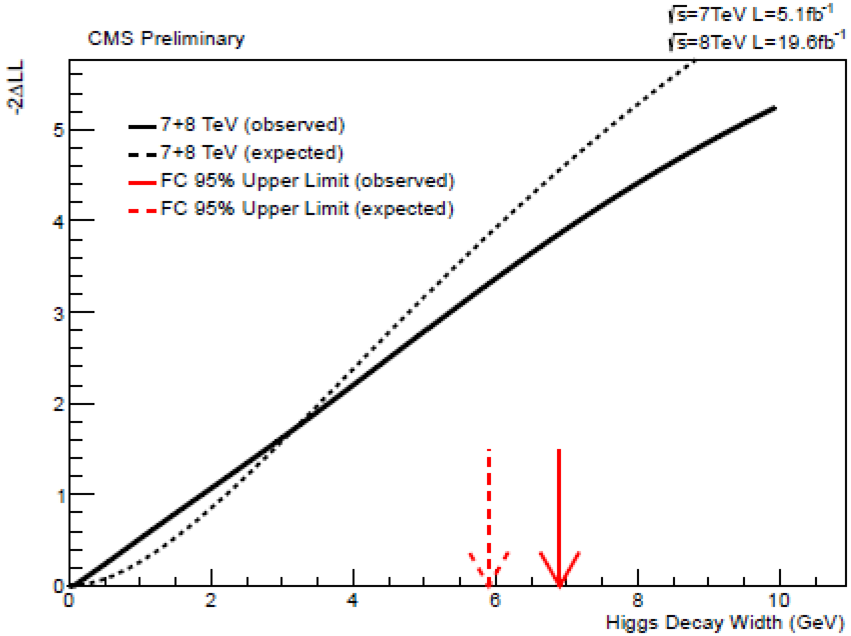
A.Djouadi Phys.Rept.457:1-216

the width of the SM scalar is small ($\Gamma = 4.2$ MeV)

compared to the experimental resolution FWHM ~ 4 GeV

and it is very difficult to obtain

$$\Gamma \sim \sqrt{(\,\mathrm{FWHM}_{(\mathrm{meas})}^{2} - \mathrm{FWHM}_{(\mathrm{pred})}^{2})}$$



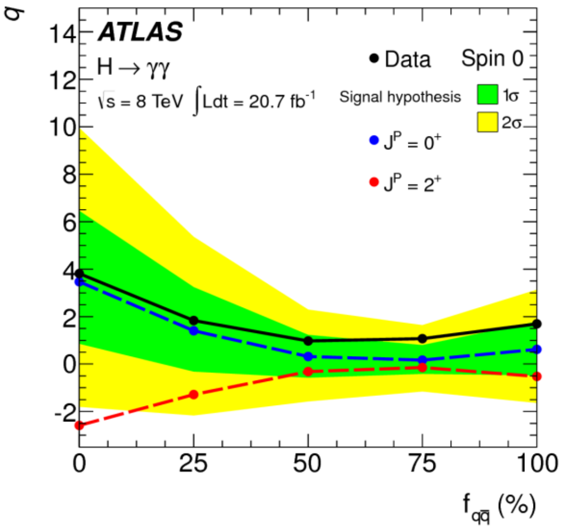
CMS PAS HIG-13-006

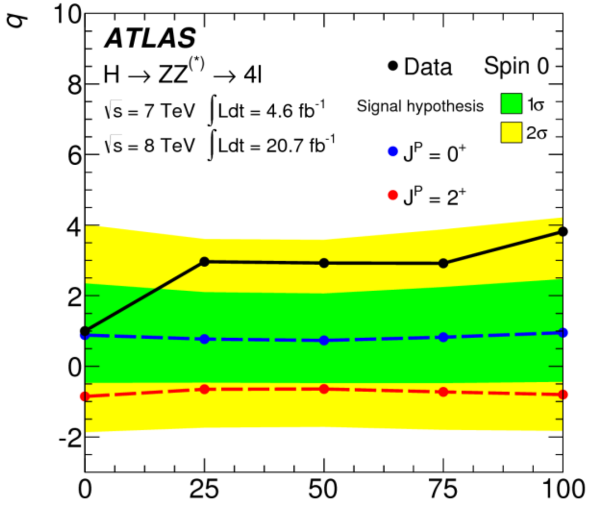
still a limit is set for Γ at 6.9 GeV 95%CL

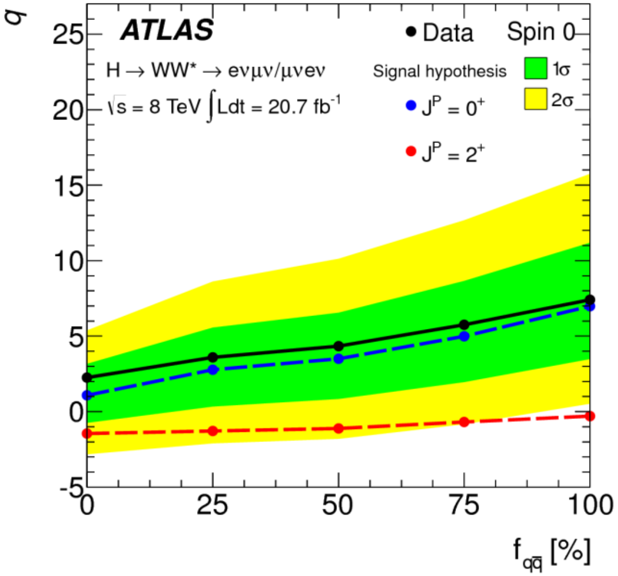
There are other (indirect) ways of putting limits (with few hypothesis) on invisible width or invisible branching ratio

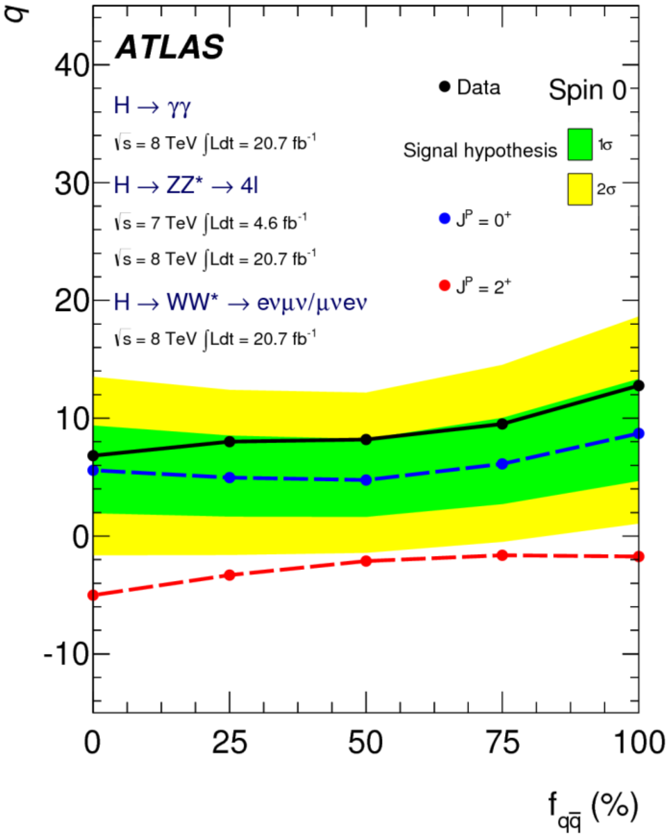
♥ ZH , H → inv

♥ couplings analysis

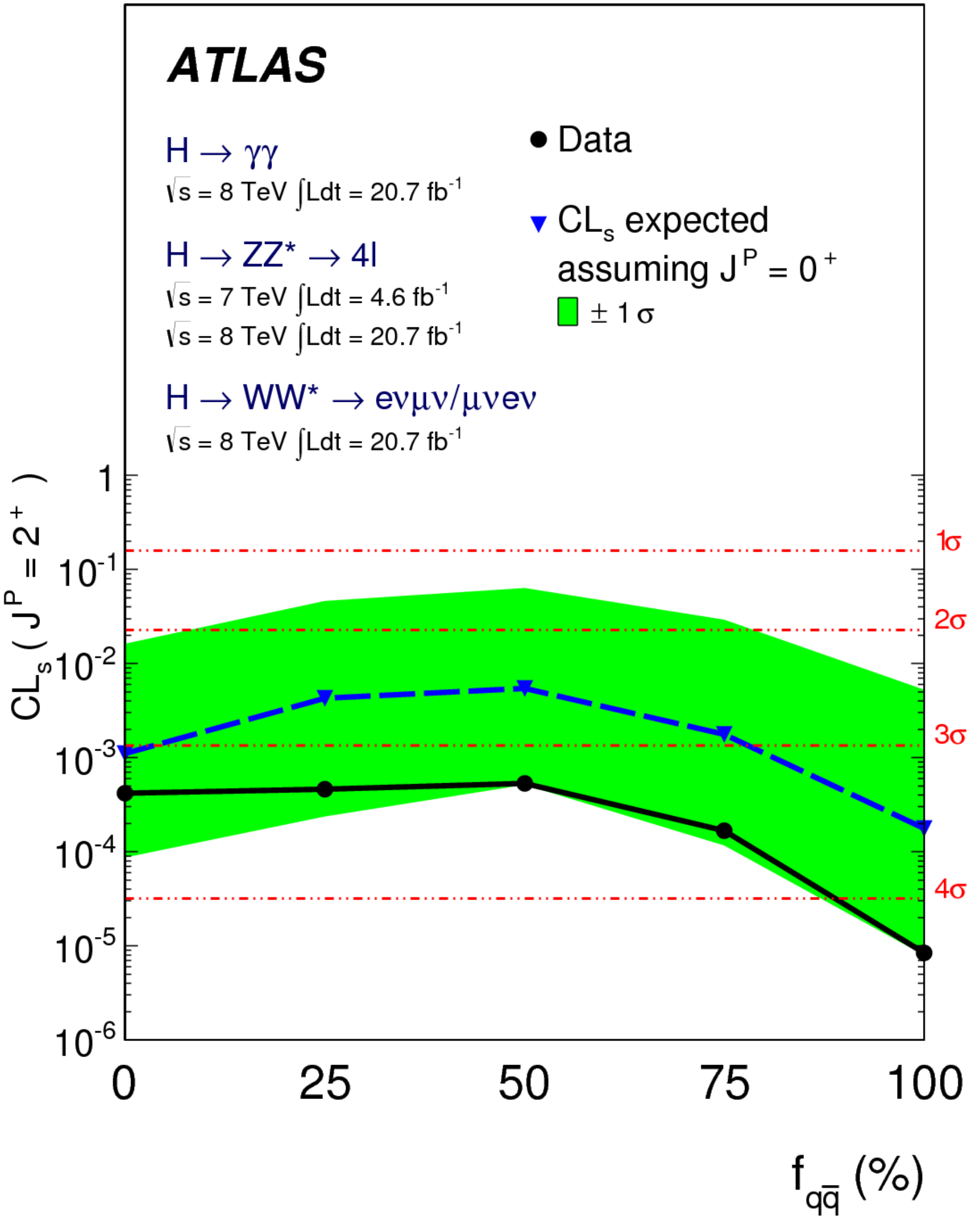








large sensitivity for all qq/gg


ATLAS
$H \rightarrow \gamma\gamma$
$\sqrt{s}$ = 8 TeV $\int Ldt$ = 20.7 fb^{-1}
$H \rightarrow ZZ^* \rightarrow 4l$
$\sqrt{s}$ = 7 TeV $\int Ldt$ = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV $\int Ldt$ = 20.7 fb^{-1}
$H \rightarrow WW^* \rightarrow e\nu\mu\nu/\mu\nu e\nu$
$\sqrt{s}$ = 8 TeV $\int Ldt$ = 20.7 fb^{-1}
● Data
▼ CL_s expected assuming $J^P = 0^+$
🟩 ± 1 σ
CL_s ($J^P = 2^+$)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1σ
2σ
3σ
4σ
0
25
50
75
100
$f_{q\bar{q}}$ (%)