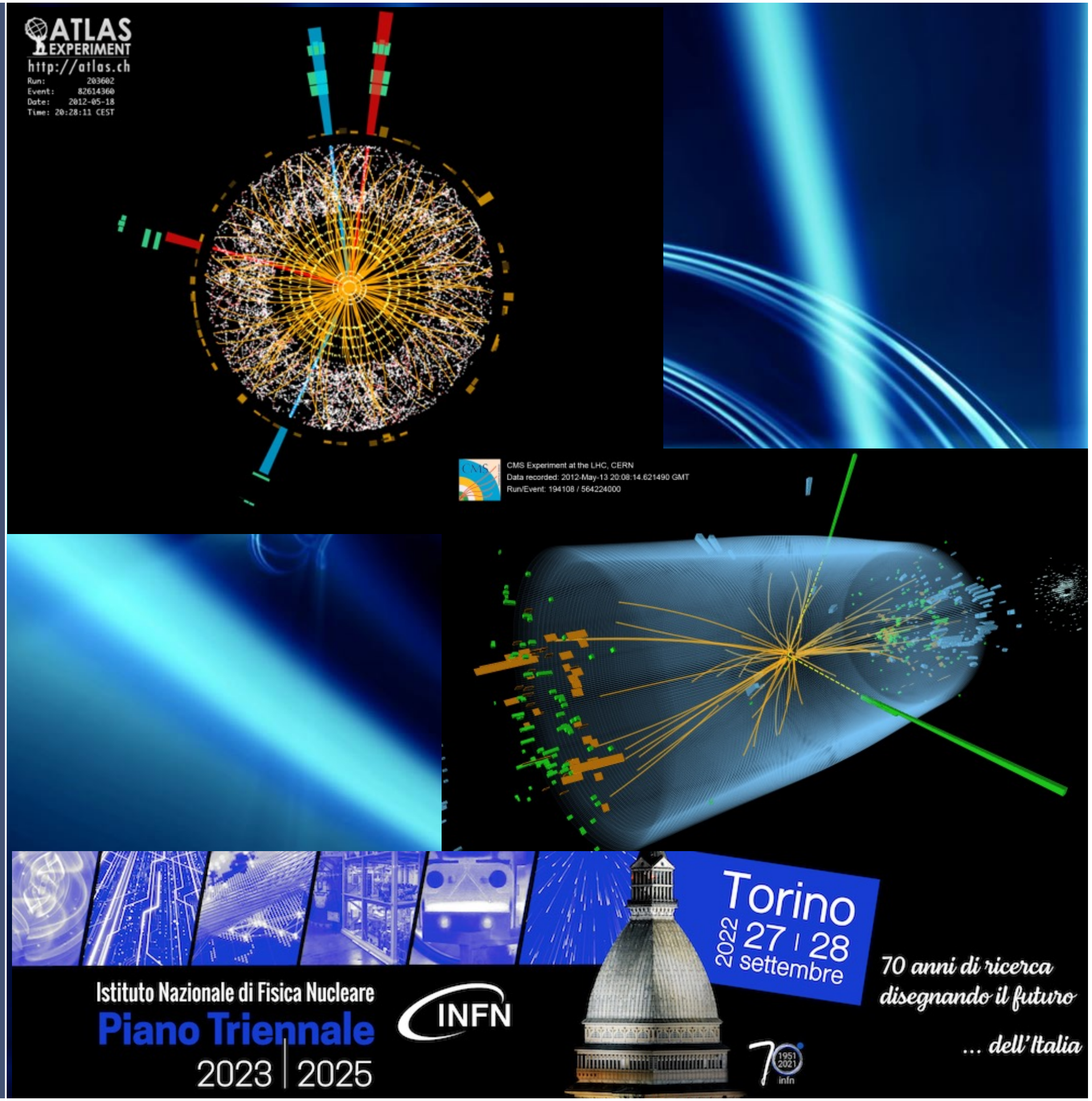
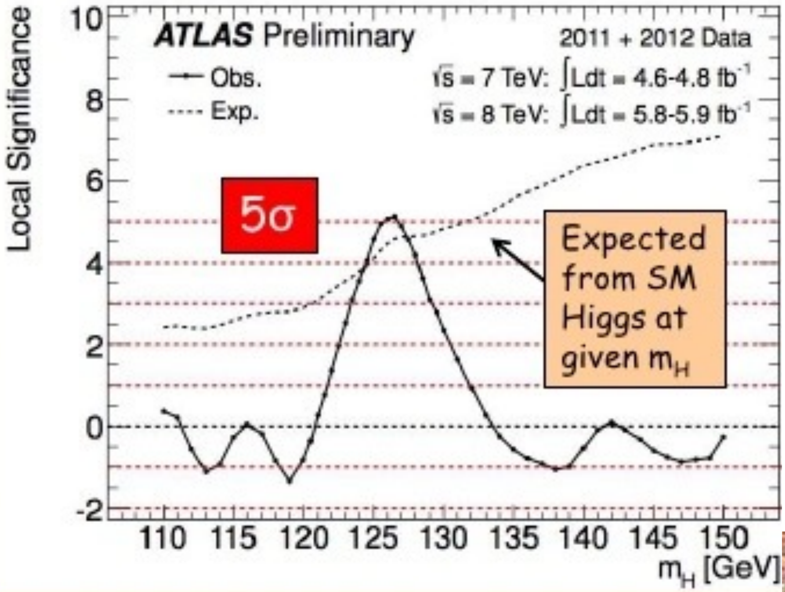
2012-2022
IL BOSONE DI HIGGS
10 ANNI DOPO

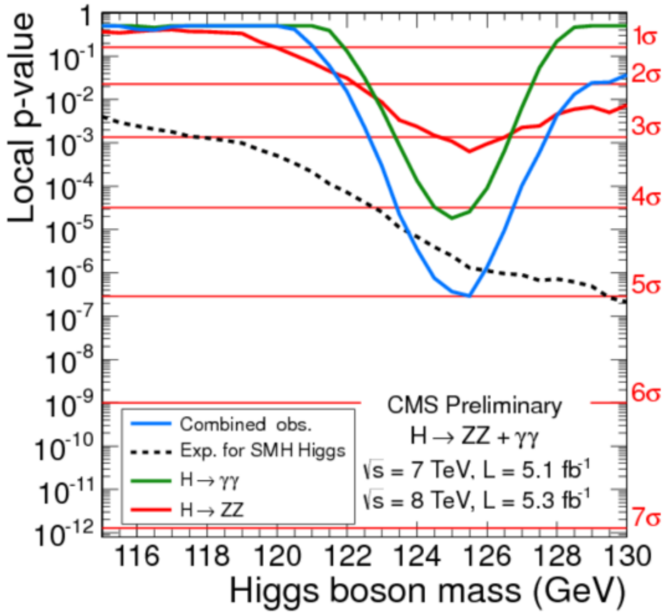
Marco Ciuchini

INFN



LA SCOPERTA





4 luglio 2012

1960- L'INIZIO DELLA STORIA...

I primi tentativi: le interazioni deboli e elettromagnetiche possono essere descritte da una teoria di gauge generalizzata (con 4 mediatori)

J. Schwinger; 1958; A.Salam and J. Ward; 1961; S. Glashow; 1961

È evidente che associare i bosoni vettori a una simmetria di gauge esatta non è una strada percorribile:

- le masse dei nuovi bosoni vettori sono nulle (come per il fotone), l'interazione mediata è a lungo raggio

Per le interazioni deboli la simmetria di gauge deve essere rotta

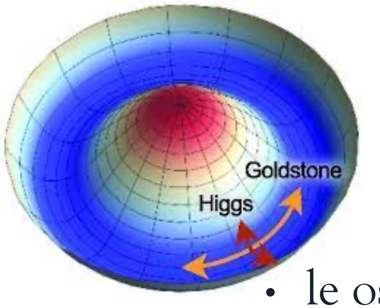
Tuttavia una rottura esplicita ottenuta introducendo nella teoria i termini di massa necessari (o la conservazione parziale) non è soddisfacente:

- la teoria risultante in generale non è rinormalizzabile ovvero la sua predittività è limitata

ROTTURA SPONTANEA DI SIMMETRIA

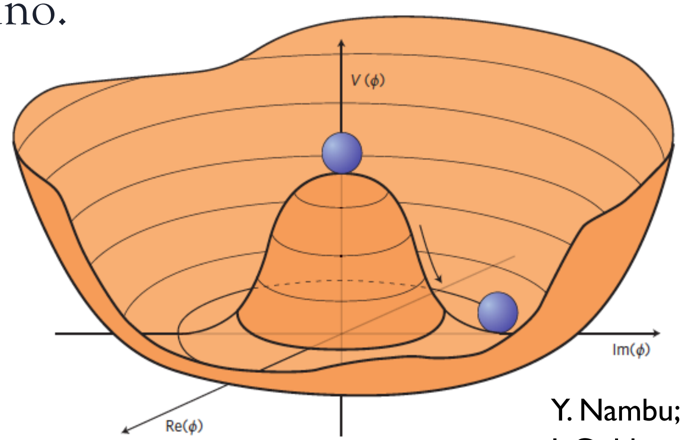
Negli stessi anni la rottura spontanea di simmetria viene introdotta nella teoria delle particelle elementari: una simmetria continua può essere rotta dinamicamente da un campo scalare complesso con un potenziale opportuno.

Il potenziale a sombrero è simmetrico per rotazioni



$$V(|\varphi|) = \lambda(|\varphi|^2 - v^2)^2$$

- c'è un continuo di minimi legati dalla trasformazione di simmetria
- il minimo selezionato rompe la simmetria



Y. Nambu; 1960
J. Goldstone; 1961

- le oscillazioni del campo intorno al minimo corrispondono a un modo massivo e uno a massa nulla, conseguenza del teorema di Goldstone: per ogni simmetria rotta appare un bosone a massa nulla

Si pensava che una teoria di gauge rotta spontaneamente fosse rinormalizzabile, ma che fare dei bosoni di Goldstone?

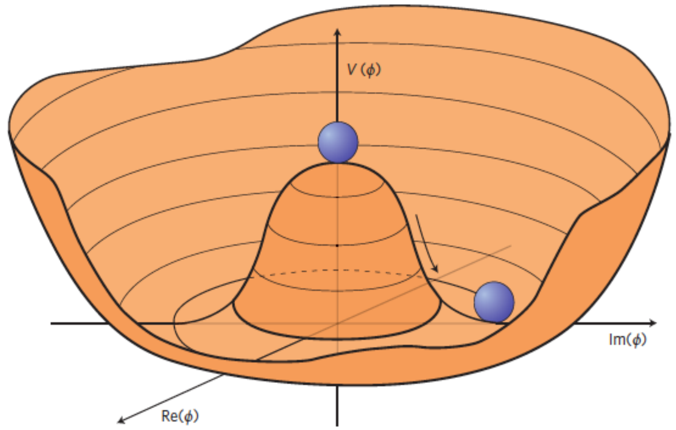
IL MECCANISMO DI HIGGS

P. Higgs; F. Englert and R. Brout; G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble; 1964

Nel caso di rottura spontanea di una simmetria di gauge le cose vanno diversamente…

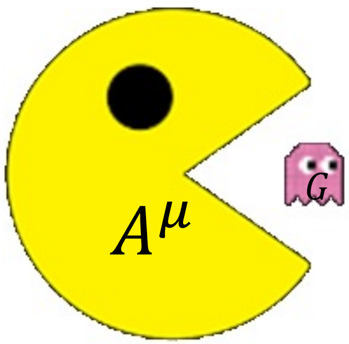
$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + |(\partial^\mu - iqA^\mu)\varphi|^2 - V(|\varphi|)$$

- il bosone di Goldstone non è fisico: può essere eliminato con una trasformazione di gauge
- il corrispondente grado di libertà scalare fornisce la polarizzazione longitudinale al bosone vettore A^μ che prende una massa $m = qv$



$$\varphi(x) = e^{i\theta(x)}(H(x) + v)$$

Grazie a questo meccanismo è possibile scrivere una teoria di gauge:



- spontaneamente rotta ovvero rinormalizzabile
- con bosoni vettori massivi e quindi con interazioni a corto raggio
- senza particelle scalari a massa nulla – i bosoni di Goldstone
- con un bosone scalare massivo fisico: il bosone di Higgs

A MODEL OF LEPTONS

S. Weinberg; 1967
A. Salam; 1968

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

We will restrict our attention to symmetry groups that connect the observed electron-type leptons only with each other, i.e., not with muon-type leptons or other unobserved leptons or hadrons. The symmetries then act on a left-handed doublet

$$L=[\tfrac{1}{2}(1+\gamma_5)]\binom{\nu_e}{e} \quad (1)$$

and on a right-handed singlet

$$R=[\tfrac{1}{2}(1-\gamma_5)]e. \quad (2)$$

The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu\partial_\mu L-\bar{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q=T_3-N_R-\frac{1}{2}N_L$, and the electron number $N=N_R+N_L$. But the gauge field corresponding to an unbroken symmetry will have zero mass,[4] and there is no massless particle coupled to N,[5] so we must form our gauge group out of the electronic isospin $\vec{T}$ and the electronic hyperchange $Y\equiv N_R+\frac{1}{2}N_L$.

Therefore, we shall construct our Lagrangian out of L and R, plus gauge fields $\vec{A}_\mu$ and B_μ coupled to $\vec{T}$ and Y, plus a spin-zero doublet

$$\varphi=\binom{\varphi^0}{\varphi^-} \quad (3)$$

whose vacuum expectation value will break $\vec{T}$ and Y and give the electron its mass. The only renormalizable Lagrangian which is invariant under $\vec{T}$ and Y gauge transformations is

$$\mathfrak{L}=-\tfrac{1}{4}(\partial_\mu\vec{A}_\nu-\partial_\nu\vec{A}_\mu+g\vec{A}_\mu\times\vec{A}_\nu)^2-\tfrac{1}{4}(\partial_\mu B_\nu-\partial_\nu B_\mu)^2-\bar{R}\gamma^\mu(\partial_\mu-ig'B_\mu)R-L\gamma^\mu(\partial_\mu ig\vec{t}\cdot\vec{A}_\mu-i\tfrac{1}{2}g'B_\mu)L$$
$$-\tfrac{1}{2}|\partial_\mu\varphi-ig\vec{A}_\mu\cdot\vec{t}\varphi+i\tfrac{1}{2}g'B_\mu\varphi|^2-G_e(\bar{L}\varphi R+\bar{R}\varphi^\dagger L)-M_1{}^2\varphi^\dagger\varphi+h(\varphi^\dagger\varphi)^2. \quad (4)$$

We have chosen the phase of the R field to make G_e real, and can also adjust the phase of the L and Q fields to make the vacuum expectation value $\lambda\equiv\langle\varphi^0\rangle$ real. The "physical" φ fields are then φ^-

and

$$\varphi_1=(\varphi^0+\varphi^{0\dagger}-2\lambda)/\sqrt{2} \quad \varphi_2=(\varphi^0-\varphi^{0\dagger})/i\sqrt{2}. \quad (5)$$

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$$-\tfrac{1}{8}\lambda^2g^2[(A_\mu{}^1)^2+(A_\mu{}^2)^2]$$
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$$W_\mu=2^{-1/2}(A_\mu{}^1+iA_\mu{}^2) \quad (8)$$

and has mass

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The neutral spin-1 fields of definite mass are

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Their masses are

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$$+\frac{i(g^2+g'^2)^{1/2}}{4}\left[\left(\frac{3g'^2-g^2}{g'^2+g^2}\right)\bar{e}\gamma^\mu e-\bar{e}\gamma^\mu\gamma_5e+\bar{\nu}\gamma^\mu(1+\gamma_5)\nu\right]Z_\mu. \quad (14)$$

We see that the rationalized electric charge is

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and, assuming that W_μ couples as usual to hadrons and muons, the usual coupling constant of weak interactions is given by

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Tutti gli ingredienti del Modello Standard:
- i campi di materia fermionici
  - il doppietto left-handed
  - il singoletto right-handed

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  - corrente debole neutra

A MODEL OF LEPTONS

S. Weinberg; 1967
A. Salam; 1968

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

We will restrict our attention to symmetry groups that connect the observed electron-type leptons only with each other, i.e., not with muon-type leptons or other unobserved leptons or hadrons. The symmetries then act on a left-handed doublet

$$L=[\tfrac{1}{2}(1+\gamma_5)]\binom{\nu_e}{e} \qquad (1)$$

and on a right-handed singlet

$$R=[\tfrac{1}{2}(1-\gamma_5)]e. \qquad (2)$$

The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu\partial_\mu L-\bar{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q=T_3-N_R-\frac{1}{2}N_L$, and the electron number $N=N_R+N_L$. But the gauge field corresponding to an unbroken symmetry will have zero mass,[4] and there is no massless particle coupled to N,[5] so we must form our gauge group out of the electronic isospin $\vec{T}$ and the electronic hyperchange $Y\equiv N_R+\frac{1}{2}N_L$.

Therefore, we shall construct our Lagrangian out of L and R, plus gauge fields $\vec{A}_\mu$ and B_μ coupled to $\vec{T}$ and Y, plus a spin-zero doublet

$$\varphi=\binom{\varphi^0}{\varphi^-} \qquad (3)$$

whose vacuum expectation value will break $\vec{T}$ and Y and give the electron its mass. The only renormalizable Lagrangian which is invariant under $\vec{T}$ and Y gauge transformations is

$$\mathcal{L}=-\tfrac{1}{4}(\partial_\mu\vec{A}_\nu-\partial_\nu\vec{A}_\mu+g\vec{A}_\mu\times\vec{A}_\nu)^2-\tfrac{1}{4}(\partial_\mu B_\nu-\partial_\nu B_\mu)^2-\bar{R}\gamma^\mu(\partial_\mu-ig'B_\mu)R-\bar{L}\gamma^\mu(\partial_\mu+ig\vec{t}\cdot\vec{A}_\mu-i\tfrac{1}{2}g'B_\mu)L$$
$$-\tfrac{1}{2}|\partial_\mu\varphi-ig\vec{A}_\mu\cdot\vec{t}\varphi+i\tfrac{1}{2}g'B_\mu\varphi|^2-G_e(\bar{L}\varphi R+\bar{R}\varphi^\dagger L)-M_1^2\varphi^\dagger\varphi+h(\varphi^\dagger\varphi)^2. \qquad (4)$$

We have chosen the phase of the R field to make G_e real, and can also adjust the phase of the L and Q fields to make the vacuum expectation value $\lambda\equiv\langle\varphi^0\rangle$ real. The "physical" φ fields are then φ^-

and

$$\varphi_1=(\varphi^0+\varphi^{0\dagger}-2\lambda)/\sqrt{2} \quad \varphi_2=(\varphi^0-\varphi^{0\dagger})/i\sqrt{2}. \qquad (5)$$

The condition that φ_1 have zero vacuum expectation value to all orders of perturbation theory tells us that $\lambda^2\cong M_1^2/2h$, and therefore the field φ_1 has mass M_1 while φ_2 and φ^- have mass zero. But we can easily see that the Goldstone bosons represented by φ_2 and φ^- have no physical coupling. The Lagrangian is gauge invariant, so we can perform a combined isospin and hypercharge gauge transformation which eliminates φ^- and φ_2 everywhere[6] without changing anything else. We will see that G_e is very small, and in any case M_1 might be very large,[7] so the φ_1 couplings will also be disregarded in the following.

The effect of all this is just to replace φ everywhere by its vacuum expectation value

$$\langle\varphi\rangle=\lambda\binom{1}{0}. \qquad (6)$$

The first four terms in $\mathcal{L}$ remain intact, while the rest of the Lagrangian becomes

$$-\tfrac{1}{8}\lambda^2g^2[(A_\mu^{\ 1})^2+(A_\mu^{\ 2})^2]-\tfrac{1}{8}\lambda^2(gA_\mu^{\ 3}+g'B_\mu)^2-\lambda G_e\bar{e}e. \qquad (7)$$

We see immediately that the electron mass is λG_e. The charged spin-1 field is

$$W_\mu=2^{-1/2}(A_\mu^{\ 1}+iA_\mu^{\ 2}) \qquad (8)$$

and has mass

$$M_W=\tfrac{1}{2}\lambda g. \qquad (9)$$

The neutral spin-1 fields of definite mass are

$$Z_\mu=(g^2+g'^2)^{-1/2}(gA_\mu^{\ 3}+g'B_\mu), \qquad (10)$$

$$A_\mu=(g^2+g'^2)^{-1/2}(-g'A_\mu^{\ 3}+gB_\mu). \qquad (11)$$

Their masses are

$$M_Z=\tfrac{1}{2}\lambda(g^2+g'^2)^{1/2}, \qquad (12)$$

$$M_A=0, \qquad (13)$$

so A_μ is to be identified as the photon field. The interaction between leptons and spin-1 mesons is

$$\frac{ig}{2\sqrt{2}}\bar{e}\gamma^\mu(1+\gamma_5)\nu W_\mu+\text{H.c.}+\frac{igg'}{(g^2+g'^2)^{1/2}}\bar{e}\gamma^\mu eA_\mu+\frac{i(g^2+g'^2)^{1/2}}{4}\left[\left(\frac{3g'^2-g^2}{g'^2+g^2}\right)\bar{e}\gamma^\mu e-\bar{e}\gamma^\mu\gamma_5e+\bar{\nu}\gamma^\mu(1+\gamma_5)\nu\right]Z_\mu. \qquad (14)$$

We see that the rationalized electric charge is

$$e=gg'/(g^2+g'^2)^{1/2} \qquad (15)$$

and, assuming that W_μ couples as usual to hadrons and muons, the usual coupling constant of weak interactions is given by

$$G_W/\sqrt{2}=g^2/8M_W^{\ 2}=1/2\lambda^2. \qquad (16)$$

Note that then the e-φ coupling constant is

$$G_e=M_e/\lambda=2^{1/4}M_eG_W^{\ 1/2}=2.07\times10^{-6}$$

The coupling of φ_1 to muons is stronger by a factor M_μ/M_e, but still very weak. Note also that (14) gives g and g' larger than e, so (16) tells us that $M_W>40$ BeV, while (12) gives $M_Z>M_W$ and $M_Z>80$ BeV.

The only unequivocal new predictions made by this model have to do with the couplings of the neutral intermediate meson Z_μ. If Z_μ does not couple to hadrons then the best place to look for effects of Z_μ is in electron-neutron scattering. Applying a Fierz transformation to the W-exchange terms, the total effective e-ν interaction is

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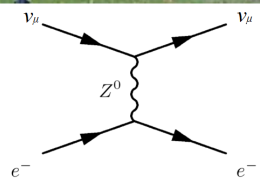
  - corrente debole neutra
- interazione di Yukawa
  - masse dei fermioni

30 ANNI DI SCOPERTE E VERIFICHE



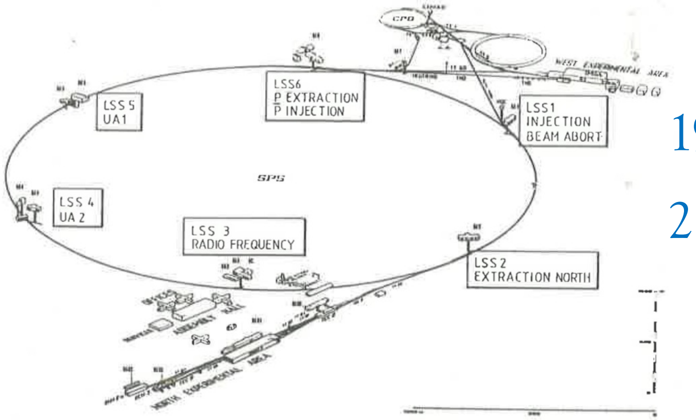
1973: correnti neutre a Gargamelle (CERN)

1974: quark charm a SLAC/BNL

1975: leptone tau a SLAC

1977: quark bottom a E288 (FNAL)

1983: bosoni W e Z al SPS (CERN)

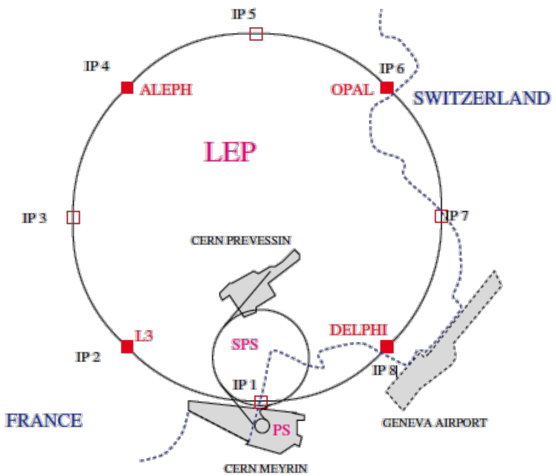


1995: quark top al Tevatron (FNAL)

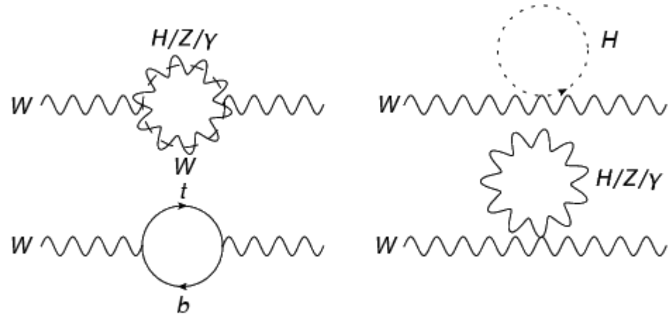
2000: neutrino tau a DONUT (FNAL)

1989-2000: EWPOs a LEP (CERN)

...manca solo il bosone di Higgs

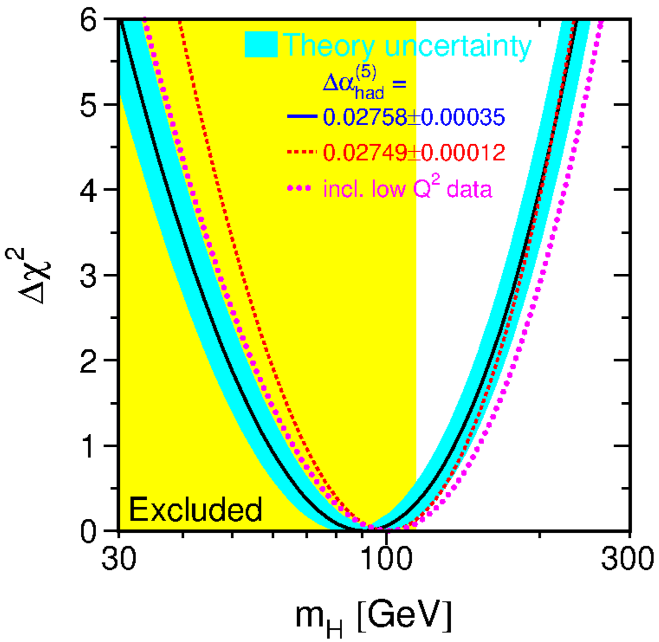


LA PARTICELLA MANCANTE

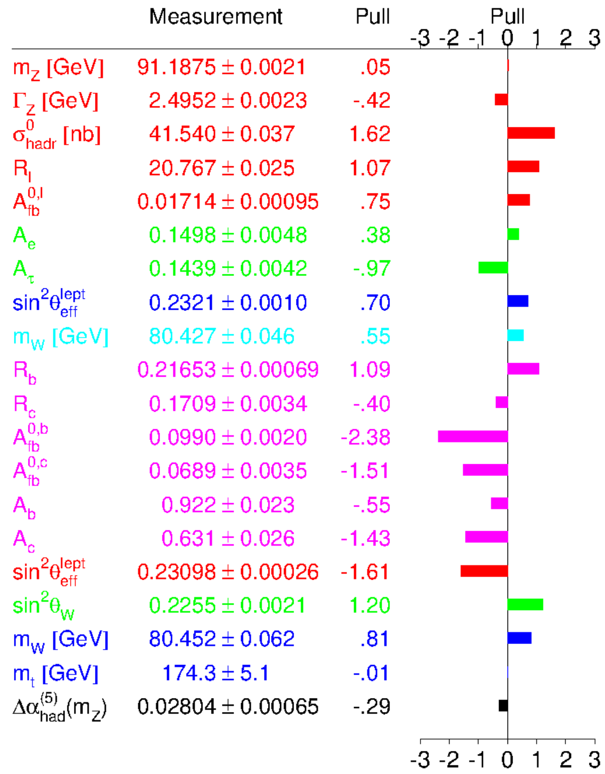


- Le osservabili di precisione a LEP verificano il Modello Standard a livello quantistico trovando un accordo eccellente

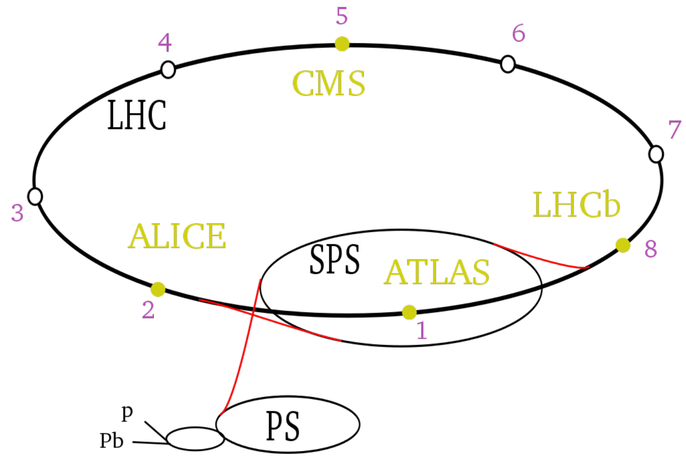
- Le correzioni radiative sono (poco) sensibili anche al bosone di Higgs: si trova una indicazione di Higgs leggero in tensione con la ricerca diretta

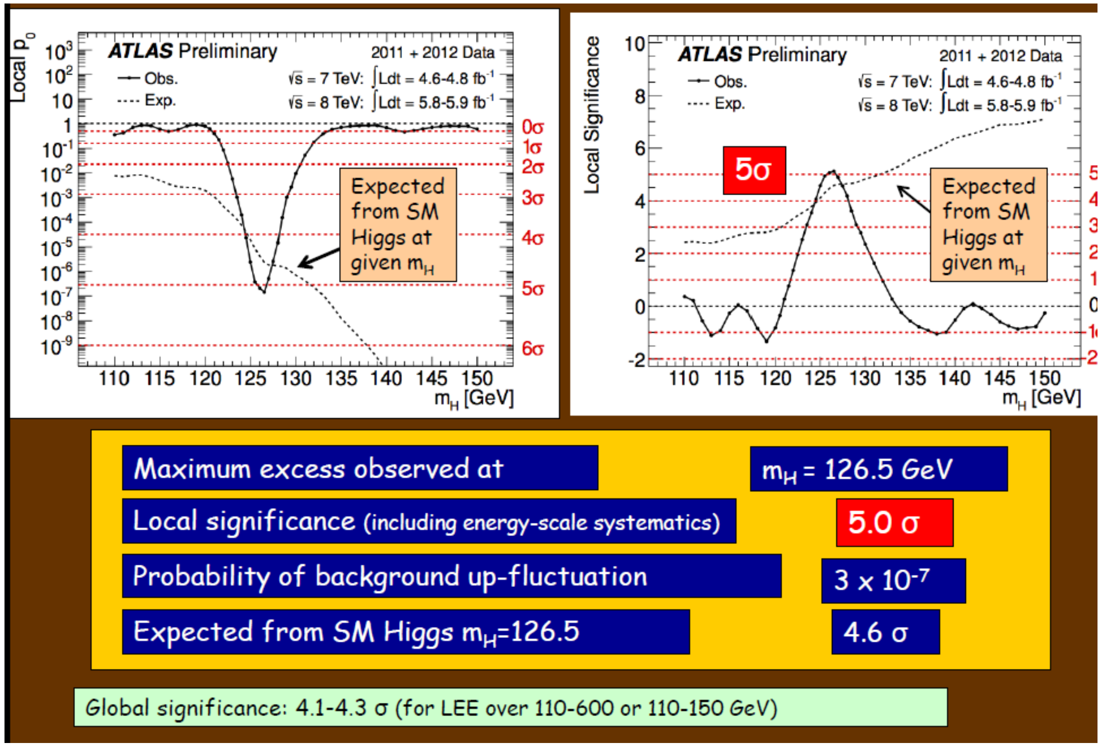


- LEP si conclude nel 2000 con un eccesso di eventi in 4 jets compatibile con un bosone di Higgs a circa 115 GeV...

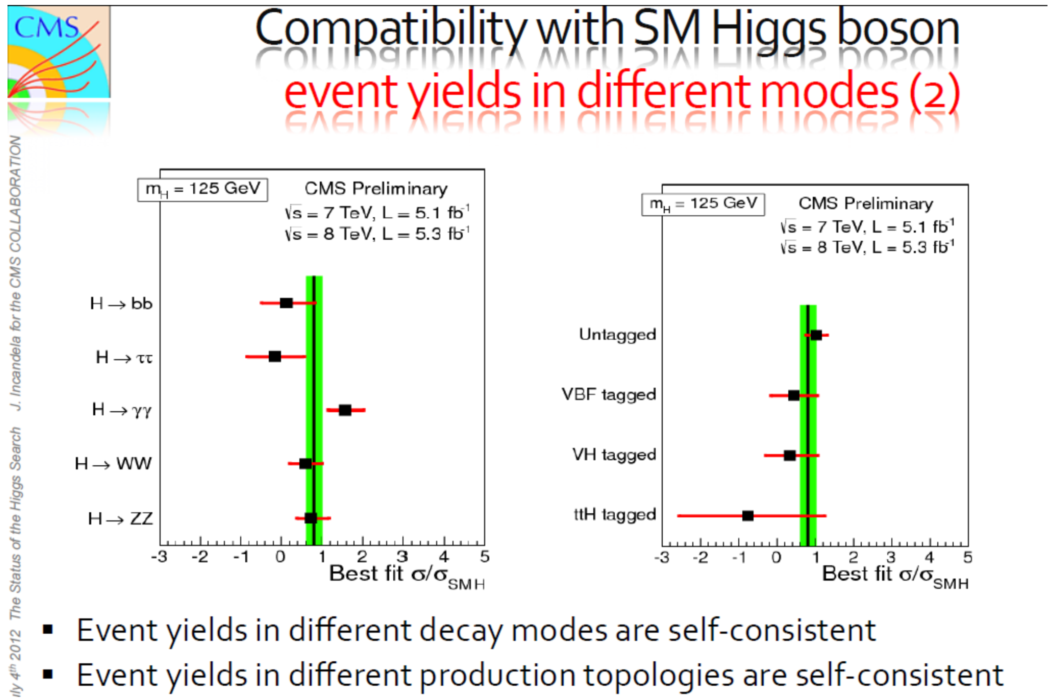


2012: LA SCOPERTA A LHC

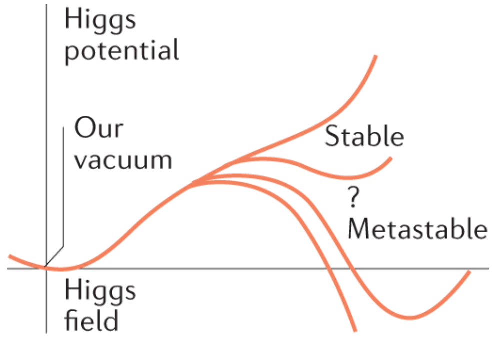




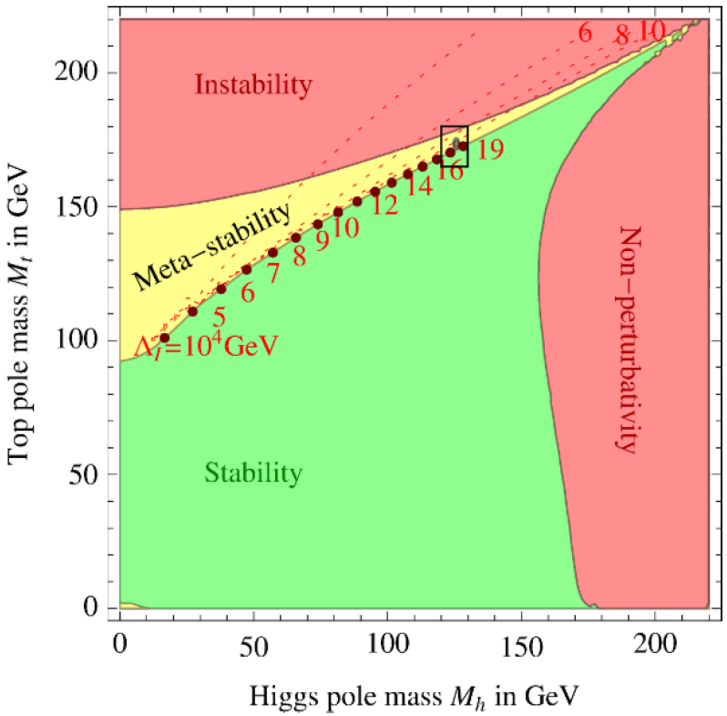
Osservato il decadimento di una particella compatibile con il bosone di Higgs del Modello Standard: si chiude con pieno successo un capitolo durato oltre 40 anni!

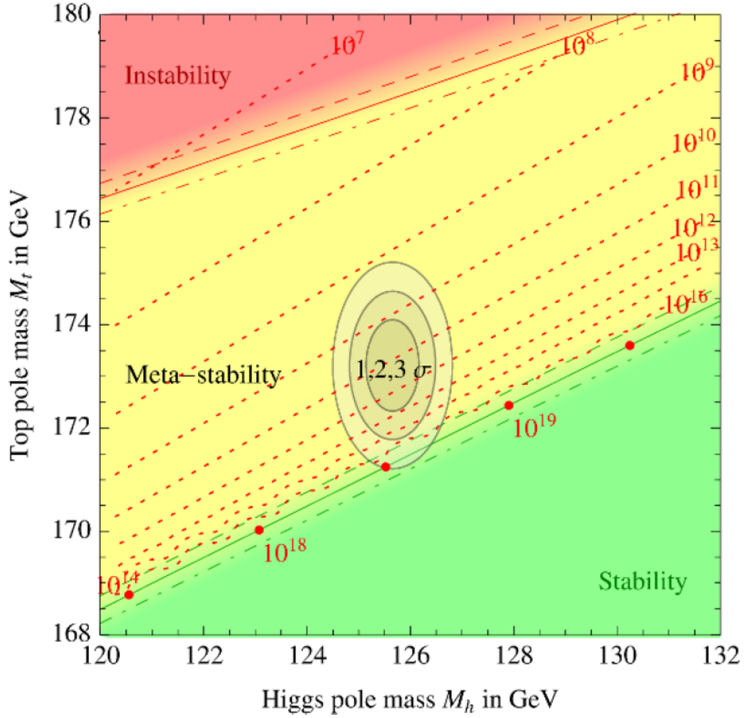


IL VUOTO È METASTABILE

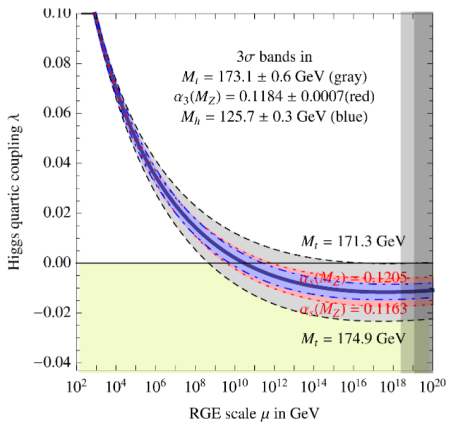


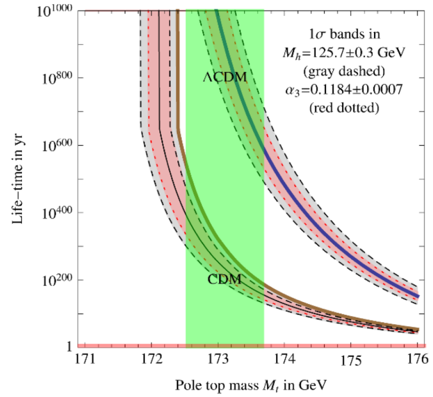
- <u>Assunzione</u>: Modello Standard valido fino alla scala di Plank



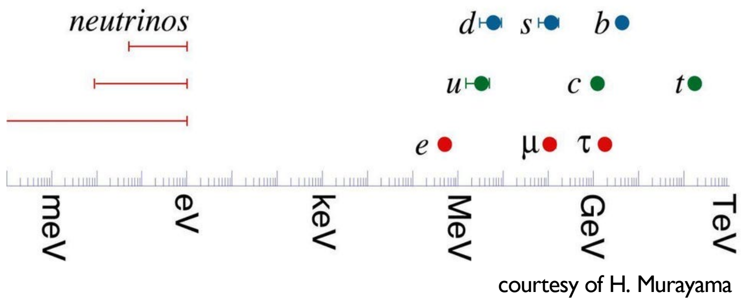


D. Buttazzo et al.; 2013

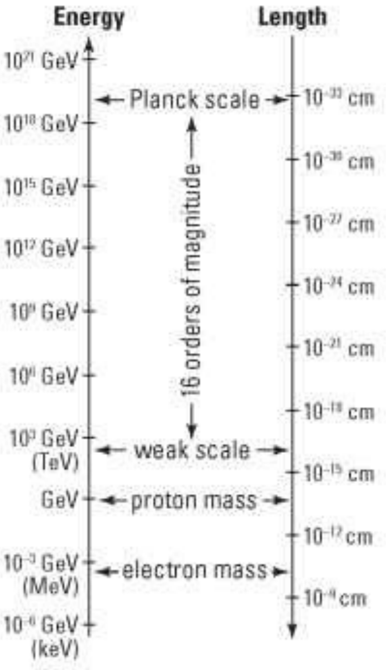




IL PROSSIMO CAPITOLO…



Il Modello Standard:



- **non** include l'interazione gravitazionale
- **non** ha una scala di massa naturale (problema della gerarchia)
- **non** spiega lo struttura di sapore dei fermioni (masse, mixing, CPV)
- **non** fornisce un candidato per la materia oscura
- **non** spiega l'asimmetria barionica nell'universo

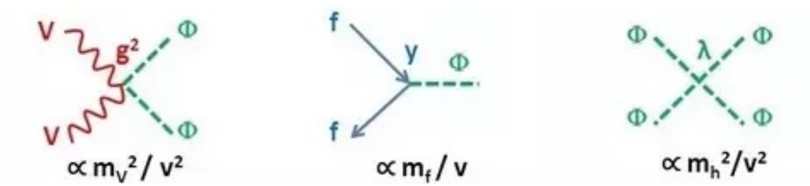
IL MODELLO STANDARD NON È TUTTA LA STORIA

qualche tensione già osservata? $(g\text{-}2)_\mu$, anomalie nel *B*, …

QUANTO È STANDARD IL BOSONE DI HIGGS?

Il bosone di Higgs del Modello Standard ha molte caratteristiche peculiari:

- è l'unico campo di materia bosonico
- è l'unico campo scalare
- introduce nuove interazioni non di gauge attraverso gli accoppiamenti di Yukawa ai fermioni
- tutti gli accoppiamenti sono proporzionali alle masse



- rompe la simmetria di sapore
- non introduce sorgenti addizionali di violazione di CP nei suoi accoppiamenti

È L'UNICO SCALARE? È ELEMENTARE? HA ACCOPPIAMENTI STANDARD?

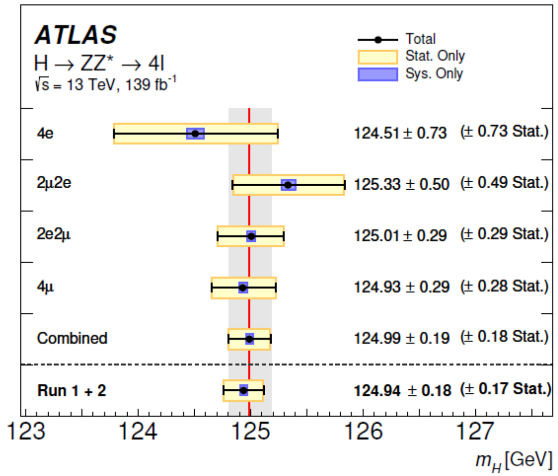
ATLAS Collaboration, *Nature* **607**, 52 (2022)
CMS Collaboration, *Nature* **607**, 60 (2022)

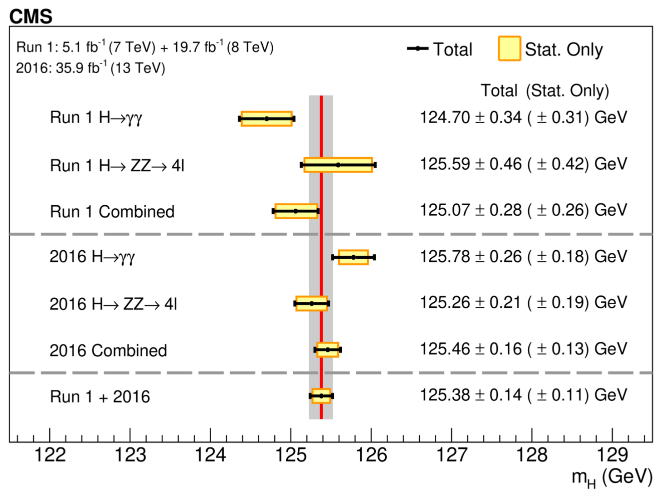
10 ANNI DOPO

- 30x eventi di Higgs rispetto al campione della scoperta
- incertezze teoriche e sperimentali quasi dimezzate rispetto al Run 1
- migliorate le tecniche di analisi

<u>Proprietà del bosone di Higgs</u>

- misura della massa al 1.4‰
- misura della larghezza
$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV} \quad (\Gamma_H^{SM} = 4.14 \pm 0.02\ \text{MeV})$$
- spin e parità
compatibile con uno stato 0^+, escluse le ipotesi di spin 1 e 2



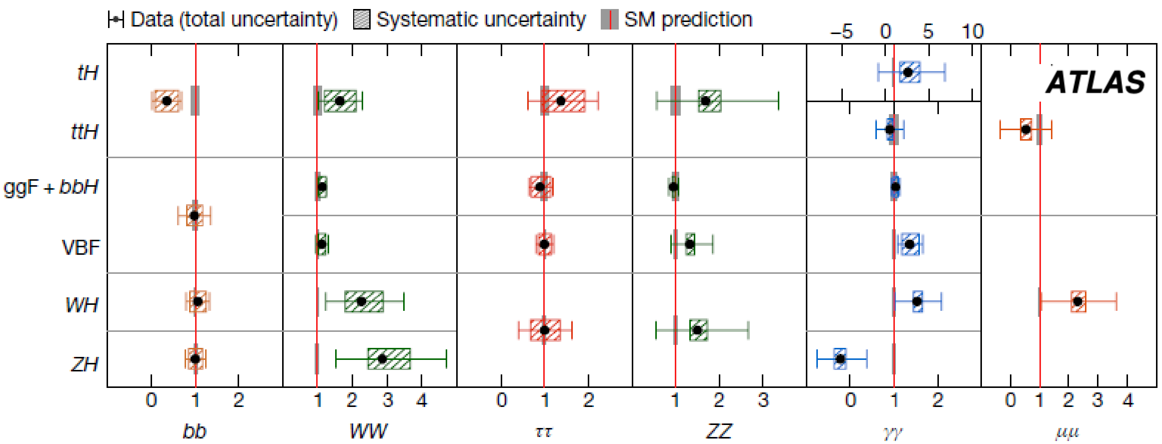


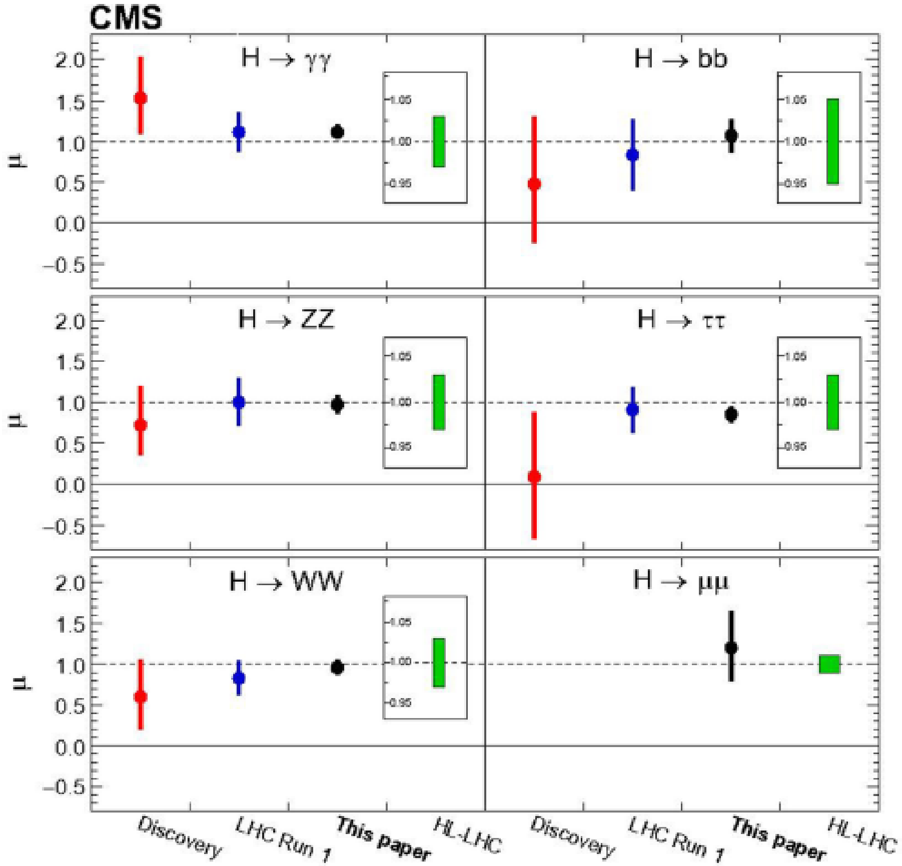
ATLAS Collaboration, *Nature* **607**, 52 (2022)
CMS Collaboration, *Nature* **607**, 60 (2022)

10 ANNI DOPO: SIGNAL STRENGTH

- approssimazione di risonanza stretta:
  rate ~ σ di produzione × BR del decadimento
- espressi in termini di signal strength $\mu_{if} = \frac{\sigma_i}{\sigma_i^{SM}} \frac{BR_f}{BR_f^{SM}}$
- consistente con il Modello Standard

$$\mu = \begin{cases} 1.05 \pm 0.06 \;\; ATLAS \\ 1.002 \pm 0.057 \; CMS \end{cases}$$





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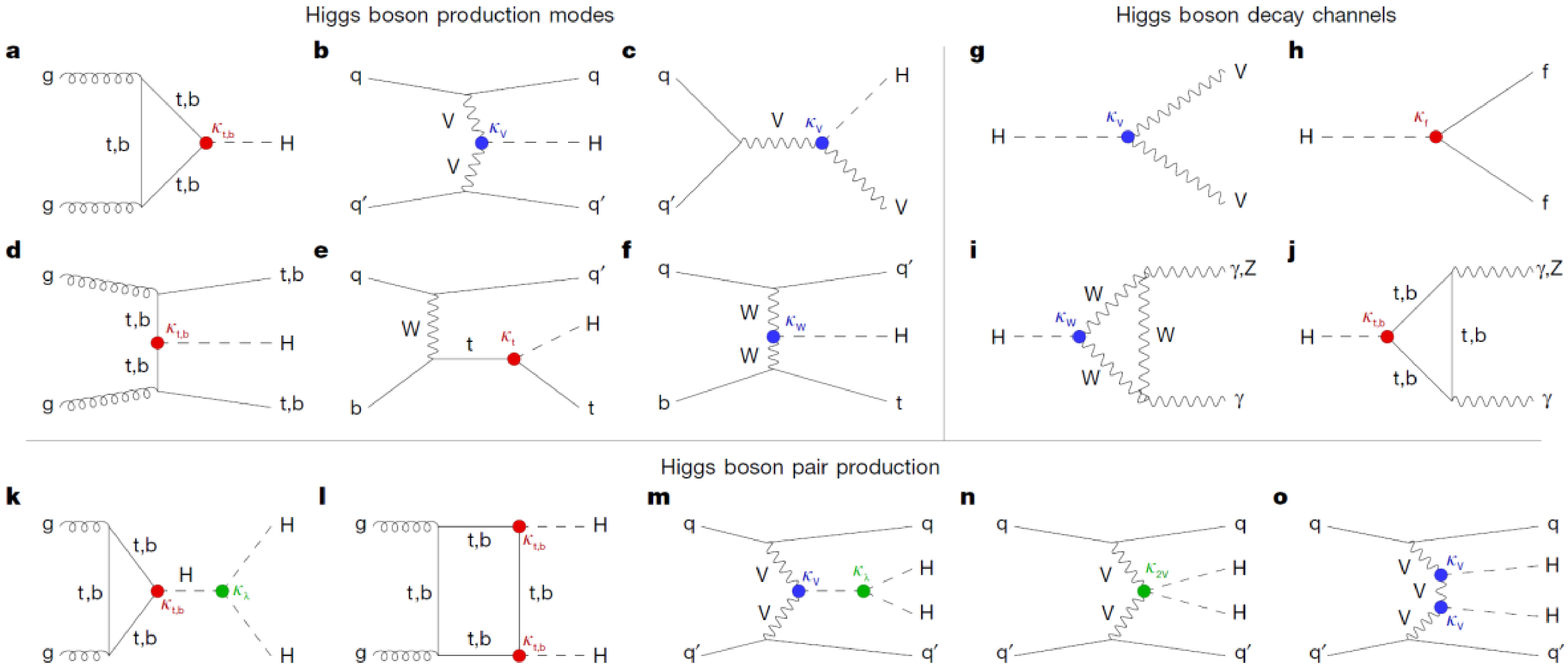
10 ANNI DOPO: ACCOPPIAMENTI



κ framework: $\kappa_{f,V} = g_{f,V}/g_{f,V}^{SM}$ + assunzioni sulla nuova fisica

ATLAS Collaboration, *Nature* **607**, 52 (2022)
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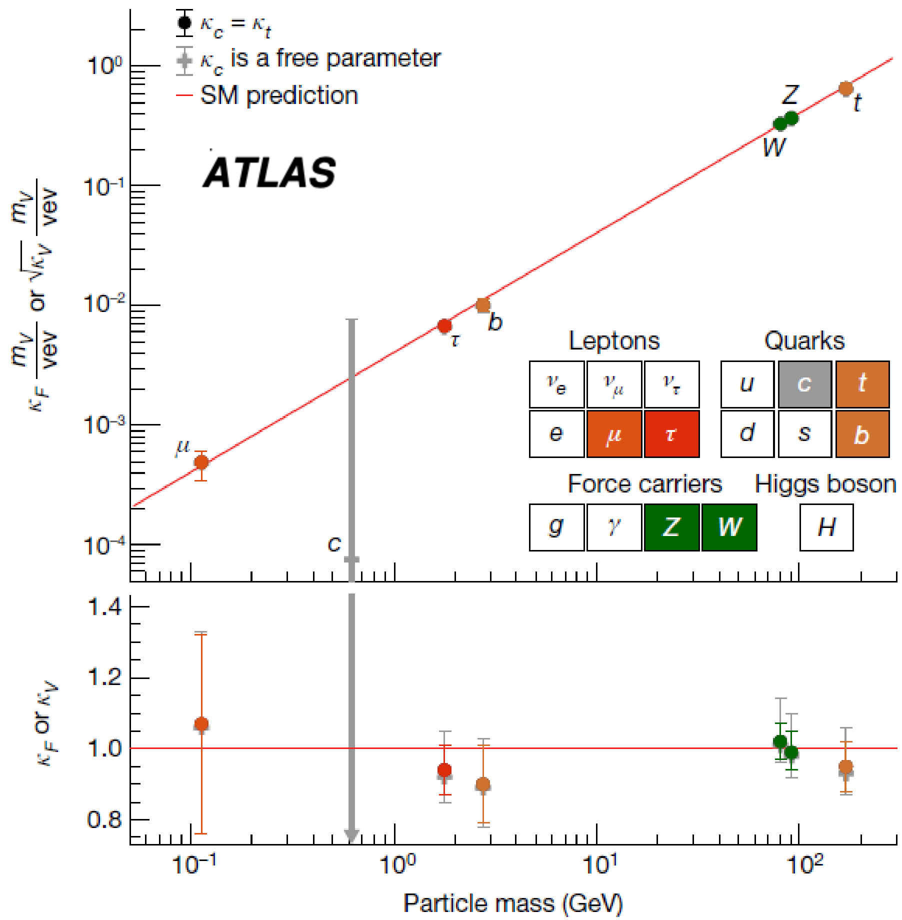
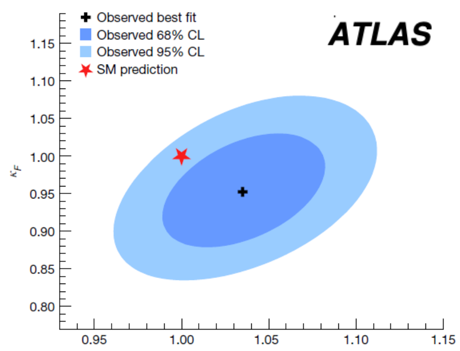
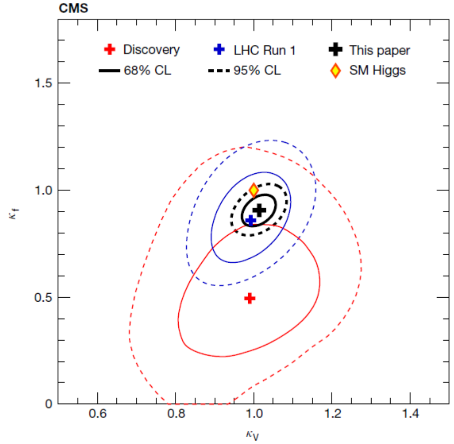
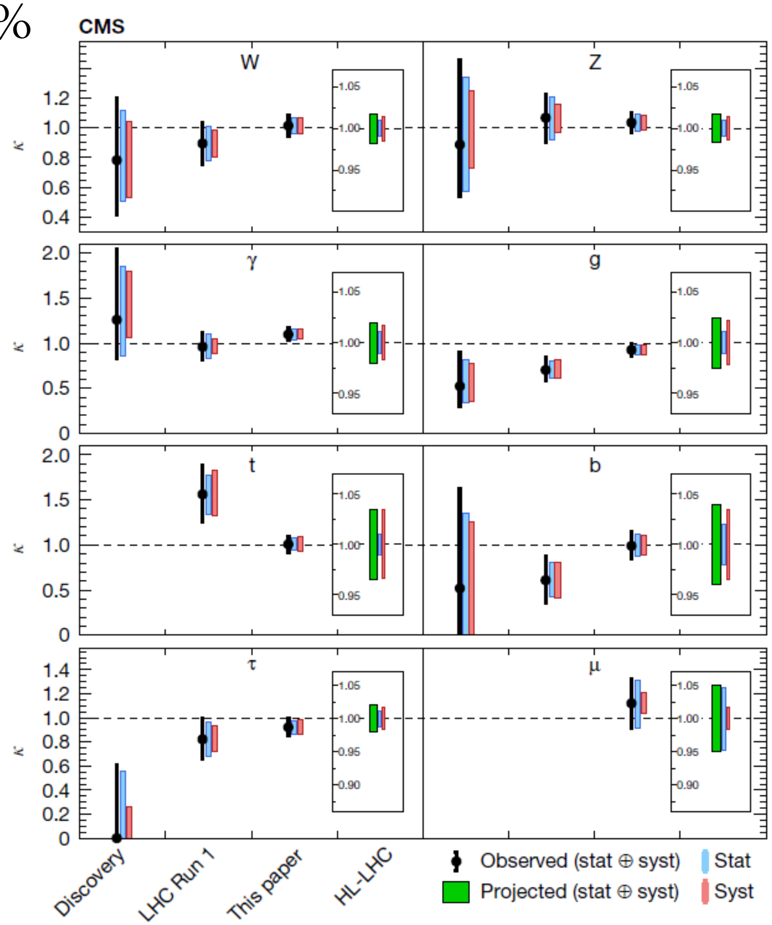
10 ANNI DOPO: ACCOPPIAMENTI

gli accoppiamenti sono in accordo con il Modello Standard entro ~5-30%



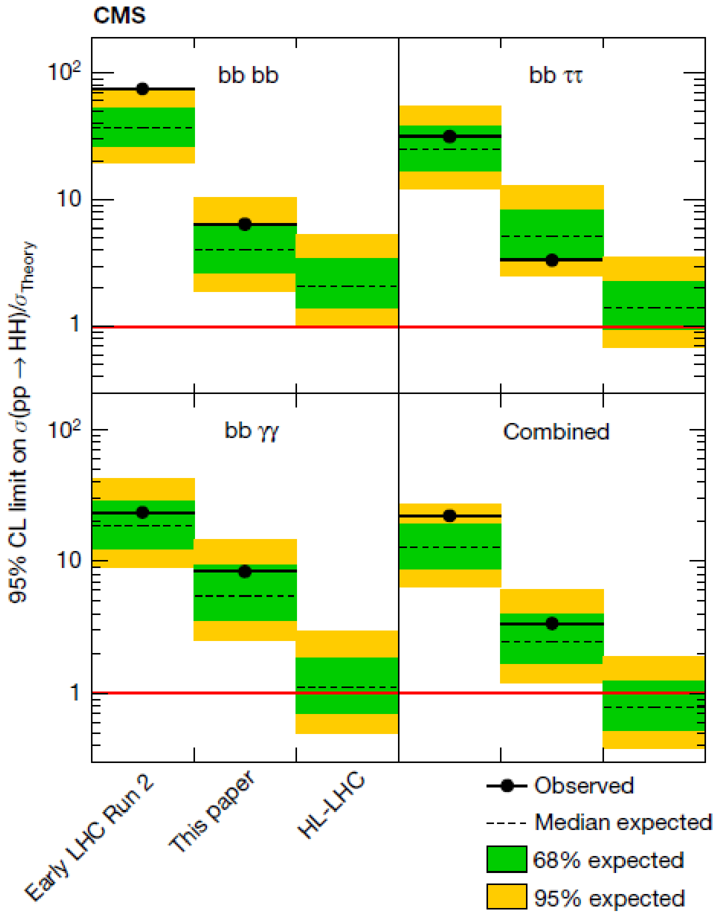




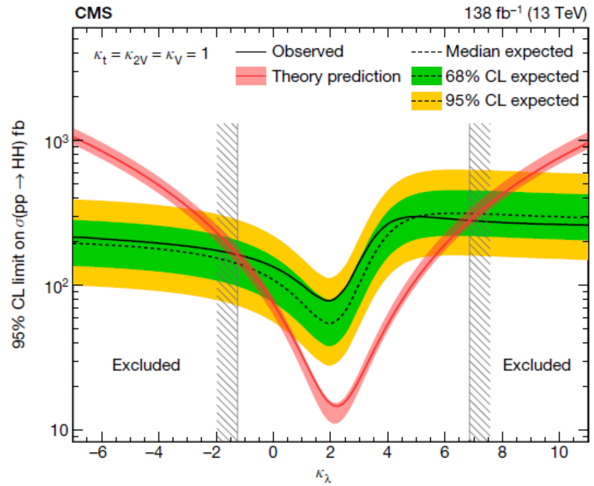


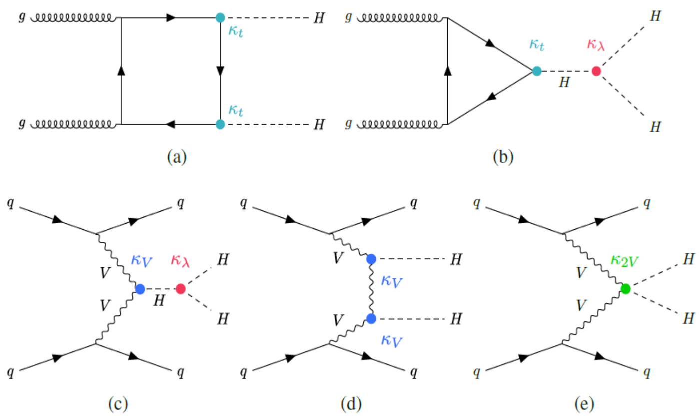
ATLAS Collaboration, *Nature* **607**, 52 (2022)
CMS Collaboration, *Nature* **607**, 60 (2022)

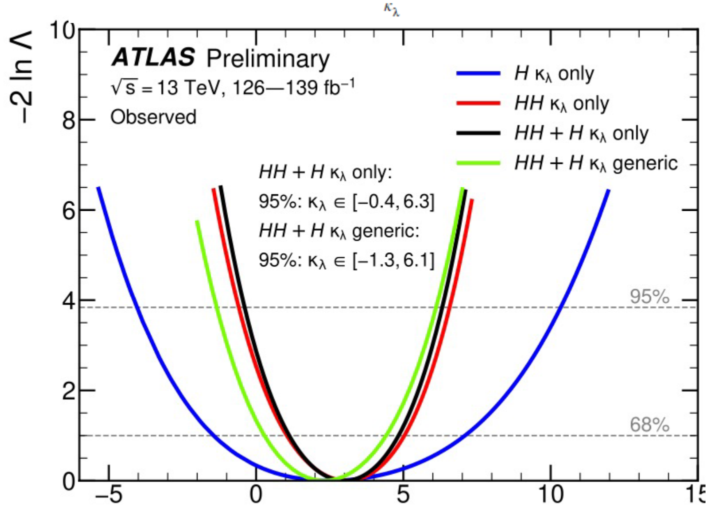
10 ANNI DOPO: IL TERMINE QUARTICO



- resta da misurare l'accoppiamento λ del termine H^4 del potenziale di Higgs
- posti limiti su superiori sui processi di produzione di 2 bosoni di Higgs
- limiti sul parametro $\kappa_\lambda = \lambda / \lambda_{SM}$





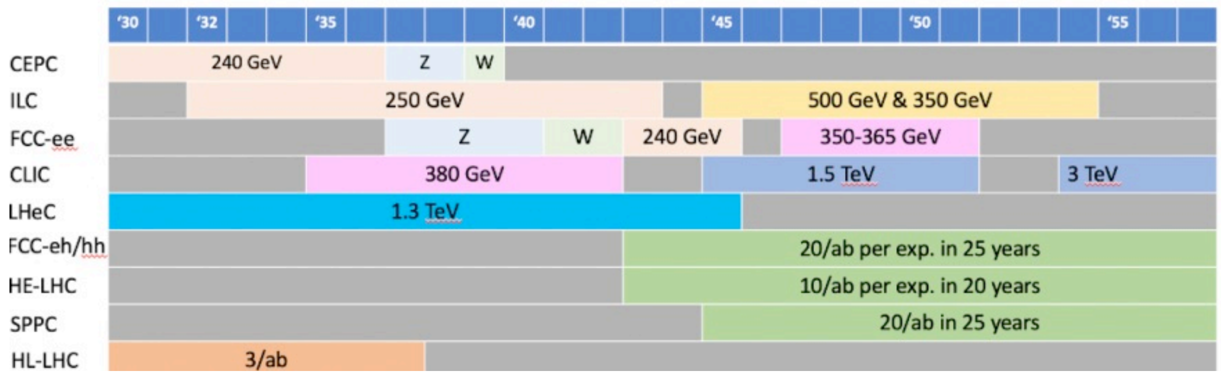


ATLAS-CONF-2022-050

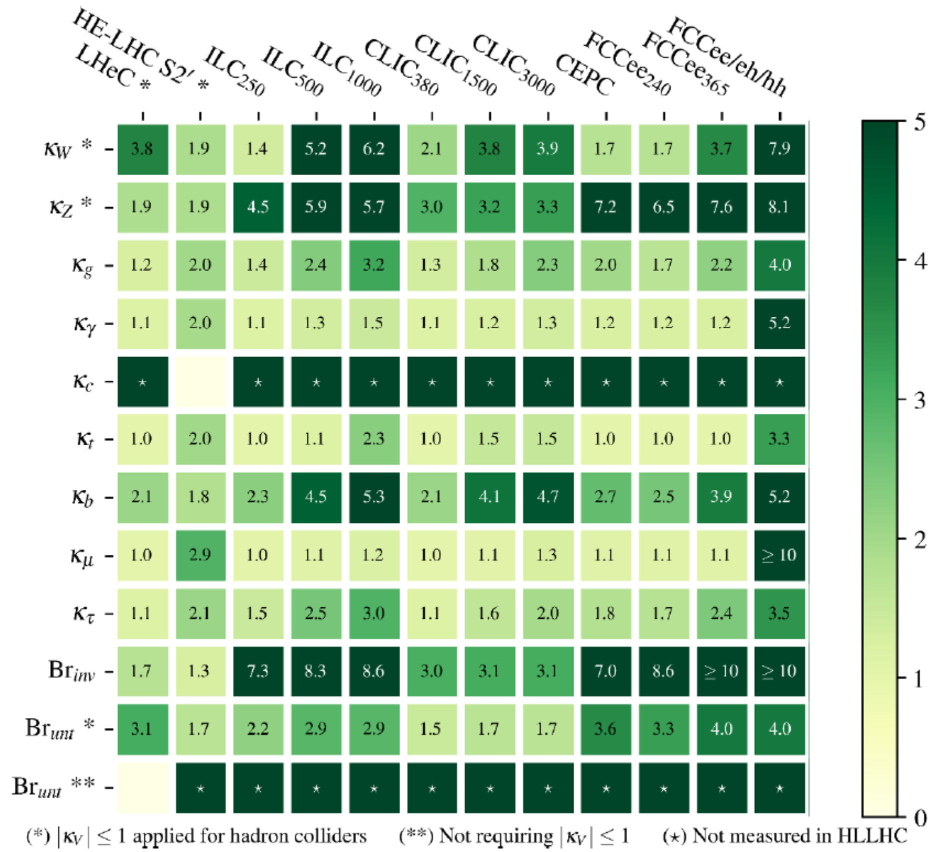
I PROSSIMI 40 ANNI

<u>2020 update of the European strategy for particle physics</u>

- completamento del progetto Hi-Lumi LHC
- studio di un futuro collider adronico al CERN con un energia di almeno100 TeV e con una factory e^+e^- di fisica del Higgs e elettrodebole come possible prima fase
- una Higgs factory e^+e^- è il prossimo collider a più alta priorità



de Blas et al., arXiv:1905.03764



Sensibilità nel κ framework ai collider futuri

IL BOSONE DI HIGGS A FCC

FUTURE CIRCULAR COLLIDER

$\sqrt{s}$	240 GeV		365 GeV	
Int. Luminosity	5 ab^{-1}		1.5 ab^{-1}	
Channel	ZH	WWH	ZH	WWH
$H\to$ any	±0.5		±0.9	
$H\to b\bar{b}$	±0.3	±3.1	±0.5	±0.9
$H\to c\bar{c}$	±2.2		±6.5	±10
$H\to gg$	±1.9		±3.5	±4.5
$H\to W^+W^-$	±1.2		±2.6	±3.0
$H\to ZZ$	±4.4		±12	±10
$H\to \tau^+\tau^-$	±0.9		±1.8	±8
$H\to \gamma\gamma$	±9.0		±18	±22
$H\to \mu^+\mu^-$	±19		±40	
$H\to$ invisible	< 0.3		< 0.6	

FCC-*ee* e FCC-*hh* sono complementari

G. Bernardi et al., arXiv:2203.06520

Collider	HL-LHC	$\text{FCC-ee}_{240\to365}$	FCC-ee + HL-LHC	FCC-INT	FCC-INT + HL-LHC
Int. Lumi (ab^{-1})	3	5 + 0.2 + 1.5	–	30	–
Years	10	3 + 1 + 4	–	25	–
g_{HZZ} (%)	1.5	0.18	0.17	0.17	0.16
g_{HWW} (%)	1.7	0.44	0.41	0.20	0.19
g_{Hbb} (%)	5.1	0.69	0.64	0.48	0.48
g_{Hcc} (%)	SM	1.3	1.3	0.96	0.96
g_{Hgg} (%)	2.5	1.0	0.89	0.52	0.5
$g_{H\tau\tau}$ (%)	1.9	0.74	0.66	0.49	0.46
$g_{H\mu\mu}$ (%)	4.4	8.9	3.9	0.43	0.43
$g_{H\gamma\gamma}$ (%)	1.8	3.9	1.3	0.32	0.32
$g_{HZ\gamma}$ (%)	11.	–	10.	0.71	0.7
g_{Htt} (%)	3.4	–	3.1	1.0	0.95
g_{HHH} (%)	50.	44.	33.	3–4	3–4
Γ_H (%)	SM	1.1	1.1	0.91	0.91

<u>Non solo kappa:</u>

- δM_H~few MeV , $\delta\Gamma_H/\Gamma_H$~few %
- accoppiamento di Y*e*
- decadimenti esotici

I PROSSIMI 40 ANNI

Oltre a partecipare attivamente ai gruppi di lavoro internazionali, abbiamo lanciato iniziative nazionali a supporto della fisica di FCC e alla ricerca e sviluppo per i nuovi acceleratori (magneti HTS, muon collider, …)

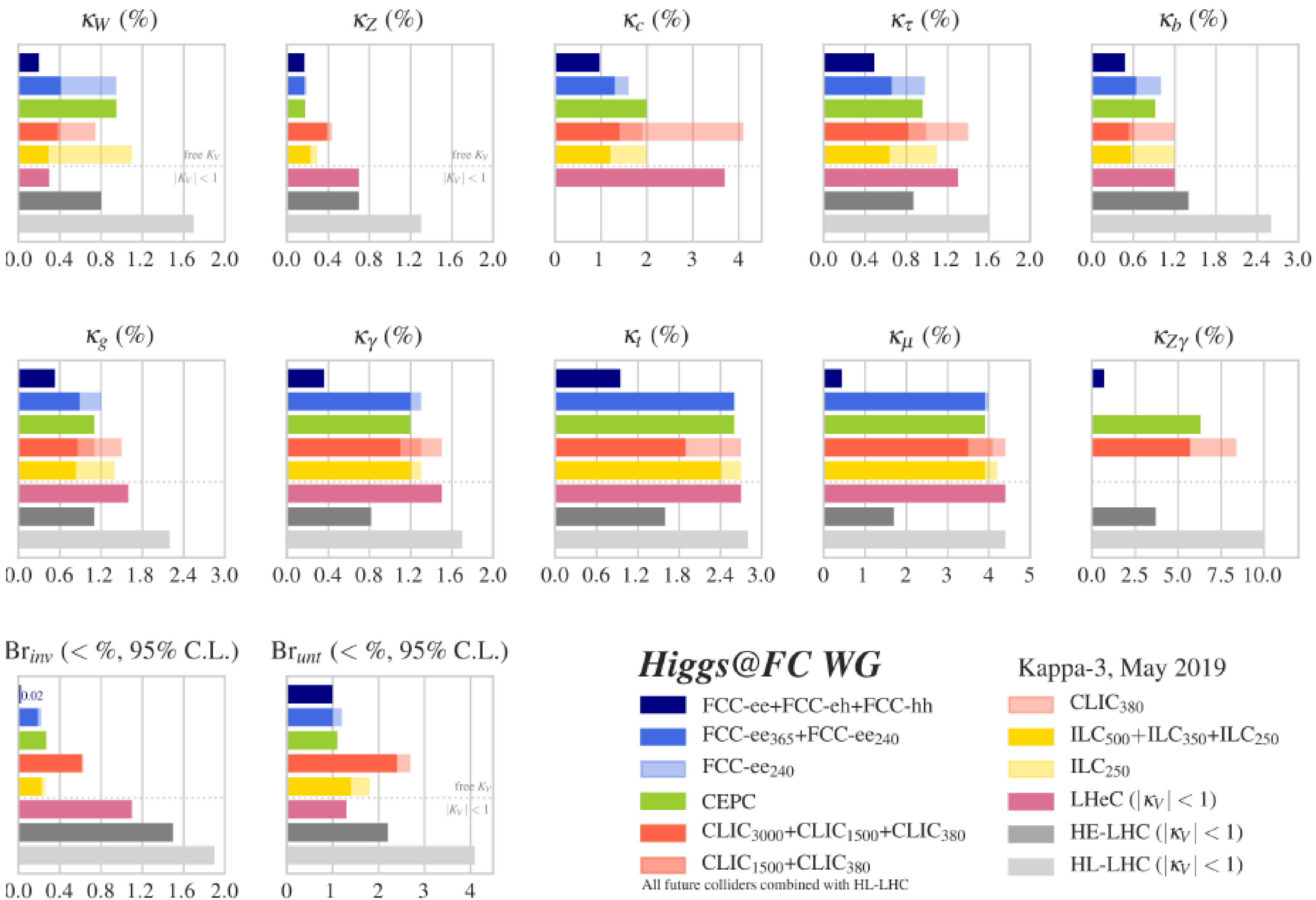
Innovative Research Infrastructure on applied Superconductivity IRIS

CI STIAMO ATTREZZANDO!

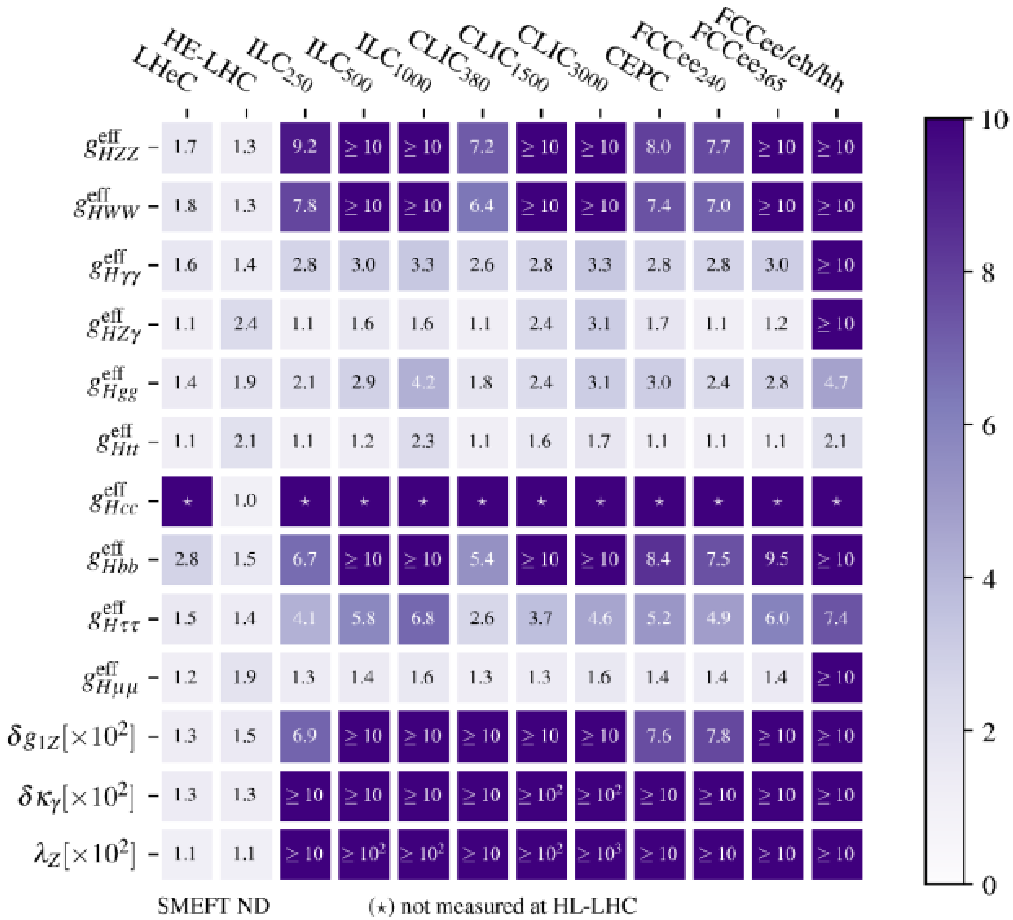
INFN ACCELERATORI

PER IL CAFFÈ SIAMO PRONTI

BACKUP



κ_W (%)
κ_Z (%)
κ_c (%)
κ_τ (%)
κ_b (%)
κ_g (%)
κ_γ (%)
κ_t (%)
κ_μ (%)
$\kappa_{Z\gamma}$ (%)
Br_{inv} (< %, 95% C.L.)
Br_{unt} (< %, 95% C.L.)
free K_V
$|K_V| < 1$
0.02
Higgs@FC WG
Kappa-3, May 2019
FCC-ee+FCC-eh+FCC-hh
$FCC\text{-}ee_{365}+FCC\text{-}ee_{240}$
$FCC\text{-}ee_{240}$
CEPC
$CLIC_{3000}+CLIC_{1500}+CLIC_{380}$
$CLIC_{1500}+CLIC_{380}$
$CLIC_{380}$
$ILC_{500}+ILC_{350}+ILC_{250}$
ILC_{250}
LHeC ($|\kappa_V| < 1$)
HE-LHC ($|\kappa_V| < 1$)
HL-LHC ($|\kappa_V| < 1$)
All future colliders combined with HL-LHC


LHeC
HE-LHC
ILC_{250}
ILC_{500}
ILC_{1000}
$CLIC_{380}$
$CLIC_{1500}$
$CLIC_{3000}$
CEPC
$FCCee_{240}$
$FCCee_{365}$
FCCee/eh/hh
g^{eff}_{HZZ} 1.7 1.3 9.2 ≥ 10 ≥ 10 7.2 ≥ 10 ≥ 10 8.0 7.7 ≥ 10 ≥ 10
g^{eff}_{HWW} 1.8 1.3 7.8 ≥ 10 ≥ 10 6.4 ≥ 10 ≥ 10 7.4 7.0 ≥ 10 ≥ 10
$g^{\mathrm{eff}}_{H\gamma\gamma}$ 1.6 1.4 2.8 3.0 3.3 2.6 2.8 3.3 2.8 2.8 3.0 ≥ 10
$g^{\mathrm{eff}}_{HZ\gamma}$ 1.1 2.4 1.1 1.6 1.6 1.1 2.4 3.1 1.7 1.1 1.2 ≥ 10
g^{eff}_{Hgg} 1.4 1.9 2.1 2.9 4.2 1.8 2.4 3.1 3.0 2.4 2.8 4.7
g^{eff}_{Htt} 1.1 2.1 1.1 1.2 2.3 1.1 1.6 1.7 1.1 1.1 1.1 2.1
g^{eff}_{Hcc} ⋆ 1.0 ⋆ ⋆ ⋆ ⋆ ⋆ ⋆ ⋆ ⋆ ⋆ ⋆
g^{eff}_{Hbb} 2.8 1.5 6.7 ≥ 10 ≥ 10 5.4 ≥ 10 ≥ 10 8.4 7.5 9.5 ≥ 10
$g^{\mathrm{eff}}_{H\tau\tau}$ 1.5 1.4 4.1 5.8 6.8 2.6 3.7 4.6 5.2 4.9 6.0 7.4
$g^{\mathrm{eff}}_{H\mu\mu}$ 1.2 1.9 1.3 1.4 1.6 1.3 1.3 1.6 1.4 1.4 1.4 ≥ 10
$\delta g_{1Z}[\times 10^2]$ 1.3 1.5 6.9 ≥ 10 ≥ 10 ≥ 10 ≥ 10 ≥ 10 7.6 7.8 ≥ 10 ≥ 10
$\delta \kappa_\gamma[\times 10^2]$ 1.3 1.3 ≥ 10 ≥ 10 ≥ 10 ≥ 10 $\geq 10^2$ $\geq 10^2$ ≥ 10 ≥ 10 ≥ 10 ≥ 10
$\lambda_Z[\times 10^2]$ 1.1 1.1 ≥ 10 $\geq 10^2$ $\geq 10^2$ ≥ 10 $\geq 10^2$ $\geq 10^3$ ≥ 10 ≥ 10 ≥ 10 ≥ 10
10
8
6
4
2
0
SMEFT ND
(⋆) not measured at HL-LHC