

HIGGS PARTICLE- THE END OF A CERTAIN STORY AND WHAT NEXT?

I WOULD LIKE TO BEGIN MY TALK ON A PERSONAL NOTE: MY FIRST VISITS TO THE CPhT HAPPENED IN THE PERIOD 1989-1991. I WAS INVITED FOR A COUPLE OF VISITS, A FEW MONTHS EACH, BY TRAN TRUONG, WHO WAS IN CHARGE OF THE PARTICLE THEORY GROUP.

I REMEMBER A LIVELY, EXCELLENT ATMOSPHERE AND PEOPLE AROUND: COSTAS BACHAS, AMITABHA CHAKRABARTI, GEORGE GRUNBERG, PHAM, CLAUDE ROIESNEL, BERNARD PIRE AND, OF COURSE, TRAN..

THERE WERE THERE ALSO A FEW SHORT TERM VISITORS, LIKE ME, EDUARDO DE RAFAEL, NIKOLAI KRASNIKOV, KYRIAKOS TAMVAKIS, JOHN RIZOS, PROBABLY MORE..

LATER ON, MY MAIN SCIENTIFIC CONTACTS IN CPhT
HAVE BEEN MOSTLY
WITH EMILIAN DUDAS AND IGNATIOS ANTONIADIS.
WITH EMILIAN, WE HAVE 13 JOINT PAPERS.

BUT TURNING NOW TO THE MAIN TOPICS OF THIS TALK

HIGGS PARTICLE - THE END OF A CERTAIN STORY

THE STORY BEGAN HERE, IN PARIS, WITH THE DISCOVERY OF RADIOACTIVITY

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XIX / XX; Henri Becquerel, Maria Curie, Pierre Curie, Ernest Rutherford. In particular, Rutherford discovered that the new radiation has two different components which he called α and β rays



Later understood as two new types of interactions

- strong interactions
- weak interactions

exist only at the quantum level

THE DISCOVERY OF RADIOACTIVITY BY HENRI
BECQUEREL: A „BY-PRODUCT”

OF A FEW MONTHS EARLIER DISCOVERY OF X-RAYS AND
BAD WEATHER IN PARIS IN FEBRUARY 1896

BOTH DISCOVERIES HAPPENED IN SPITE OF THE
COMMON OPINIONS OF THOSE TIMES LIKE

LE MONDE EST AUJOURD’HUI SANS MYSTERE-
M. BERTHELOT, *Les Origines de l’Alchimie* (1885)

ALL FUNDAMENTAL LAWS OF PHYSICS ARE ALREADY
KNOWN- A. MICHELSON, talk at Ryerson Lab, Univ. of
Chicago (1894)

WHAT A COMPLACENCE.....

AFTER MORE THAN 100 YEARS OF RESEARCH, THE ELECTROWEAK AND STRONG INTERACTIONS ARE (REASONABLY WELL) UNDERSTOOD IN THE FRAMEWORK OF A THEORY, MODESTLY CALLED, THE STANDARD MODEL OF ELEMENTARY INTERACTIONS.

THIS CHAPTER HAS BEEN CLOSED BY THE DISCOVERY OF THE HIGGS BOSON AT THE LHC IN 2012.

- VERY STRONG LINK BETWEEN EXPERIMENT AND THEORY, AND BETWEEN THE PROGRESS IN UNDERSTANDING ELECTROWEAK AND STRONG INTERACTIONS

MUTUAL STIMULATIONS ARE PARTICULARLY CLEAR AFTER PAULI AND FERMI

The Standard Model is a beautiful theory of strong and electroweak interactions

- AT LEAST AT THE ELECTROWEAK SCALE, THE SM IS THE CORRECT EFFECTIVE THEORY
- Particles and cosmology

EVERYTHING WHAT HAPPENED IN THE UNIVERSE
AFTER 10^{-9} sec
CAN BE UNDERSTOOD IN TERMS OF THE SM

IS THE SM A CONSISTENT THEORY UP TO THE PLANCK SCALE ?

YES!

RENORMALISABLE

NO LANDAU POLE UP TO M_p

(ALMOST) STABLE VACUUM UP TO M_p

THOSE CONCLUSIONS STRONGLY DEPEND ON

$$m_t = 173\text{GeV}, \quad m_h = 125\text{GeV}$$

IS THE SM A CONSISTENT THEORY UP TO THE PLANCK SCALE?

YES BUT....

ISNT IT INDEED JUST A „LOW ENERGY” EFFECTIVE THEORY, AN APPROXIMATION TO A DEEPER ONE (SIMILARLY AS QED, ALTHOUGH CONSITENT UP TO M_p , IS ONLY THE LOW ENERGY APPROXIMATION TO THE SM)?

*FOOTNOTE: STRICTLY SPEAKING THE SM IS FOR SURE AN EFFECTIVE FIELD THEORY BECAUSE IT CANNOT BE VALID UP TO ARBITRARILY HIGH ENERGIES EVEN IN THE ABSENCE OF GRAVITY (LANDAU POLE OF U(1))

A DIGRESSION:

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IS RENORMALISABILITY A VIRTUE EVEN IF THE THEORY IS AN EFFECTIVE THEORY:

RENORMALISABILITY=PREDICTIVITY, UP TO POSSIBLE CORRECTIONS E^2/M^2

(COMING FROM A DEEPER THEORY WITH THE CHARACTERISTIC SCALE M)

BLESSING:

ONE COULD FORMULATE QED ($E \sim 1 \text{ GeV}$)
WITHOUT UNDERSTANDING THE SM ($E \sim 100 \text{ GeV}$)

CURSE:

TO FIND LAWS OF PHYSICS BEYOND AN
EFFECTIVE RENORMALISABLE THEORY VALID
AT E ONE NEEDS ENERGY OF ORDER OF THE
NEW MASS SCALE M OR PRECISION OF ORDER
 E^2/M^2

**ISNT THE SM INDEED JUST AN EFFECTIVE THEORY,
AN APPROXIMATION TO A DEEPER ONE ?
MOST LIKELY!**

IMITATING OUR PREDECESSORS ONE SHOULD SAY:

**EN FAIT,
LE MONDE EST ENCORE PLEIN DE
MYSTERE AUJOURD'HUI**

BOTH ON THE EMPIRICAL AND THEORETICAL SIDE.....

A COUPLE OF PUZZLES OF THE SM:

THE HIGGS PARTICLE WOULD BE THE FIRST EXAMPLE OF AN ELEMENTARY SCALAR PARTICLE!

So far, Nature does not seem to like elementary scalars and the composite ones are never „unnaturally” light (much lighter than the compositeness scale) unless they are (pseudo) Nambu- Goldstone bosons, like pions in QCD

NATURALNESS PROBLEM OF THE SM: ONE EXPECTS

$$m_h^2 \sim \Lambda^2 \quad (\text{CUT-OFF SCALE TO THE VALIDITY OF THE SM})$$

BECAUSE THERE IS NO SYMMETRY REASON TO HAVE

$$m_h^2 \ll \Lambda^2$$

SM AND FLAVOR (= FERMION FAMILIES)

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IN A CERTAIN SENSE, FLAVOR IS A BEYOND
THE SM CONCEPT!

3 FAMILIES OF QUARKS AND LEPTONS WITH
IDENTICAL QUANTUM NUMBERS, AND IN
CONSEQUENCE IDENTICAL GAUGE INTERACTION.
WHICH DIFFER ONLY BY THEIR INTERACTIONS
WITH THE HIGGS FIELD

NEUTRINO PHYSICS

Also empirical evidence from cosmology for physics beyond SM:

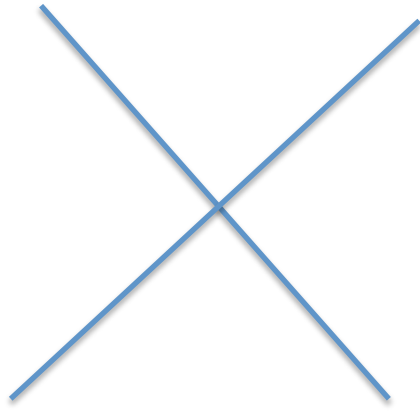
Dark matter, Matter-antimatter asymmetry, Dark energy..

**BUT WHERE IS THE NEW SCALE?
CONTRARY TO THE PAST, WE DO NOT
HAVE A STRONG HINT**

THE FERMI FOUR-FERMION THEORY FOR
 THE NEUTRON β -DECAY HAS
 INTRODUCED A NEW MASS SCALE INTO
 PARTICLE PHYSICS AND A GUARANTEE
 OF NEW DISCOVERIES

$$\mathcal{L}_F \approx G_F \bar{\Psi}_L^p \gamma_\mu \Psi_L^n \bar{\Psi}_L^e \gamma^\mu \Psi_L^\nu$$

$$G_F \approx 1/10^5 \text{ GeV}^2$$



$$G_F E^2 \approx \frac{E^2}{(300 \text{ GeV})^2}$$

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2+2 → 2+2 SCATTERING AMPLITUDE

(e.g. N+positron → P+antyneutrino)

EVENTUALLY VIOLATES UNITARITY AND
„SOMETHING NEW“ MUST HAPPEN TO RESTORE
IT!

BEFORE THE DISCOVERY OF THE HIGGS
BOSON THERE WAS AGAIN
THE GUARANTEE THAT „SOMETHING“
MUST HAPPEN TO UNITARIZE THE WW
SCATTERING AMPLITUDE.

NOTHING SIMILAR NOW.....

THEN, WHAT NEXT?

FIRST OF ALL, SYSTEMATIC EXPERIMENTAL EXPLORATION, PARTLY GUIDED BY THE THEORY (IN SPITE OF NO CLEAR HINT WHERE THE NEW SCALE IS)

LOOK FOR NEW MASS SCALES VIA E^2/M^2 (THE PRECISION FRONTIER)

AND SEARCHING FOR NEW PARTICLES (THE ENERGY FRONTIER)

THE THEORY (SM) GUIDE TO THE PRECISION FRONTIER:

- EXPLORE THE PROPERTIES OF THE HIGGS BOSON
- LOOK FOR FCNC EFFECTS
- LOOK FOR NONUNIVERSALITY OF GAUGE INTERACTIONS WITH FERMION FAMILIES
- LOOK FOR VIOLATION OF ACCIDENTAL SYMMETRIES OF THE SM, LIKE BARYON&LEPTON NUMBER CONSERVATION (GUTs AND PROTON DECAY),

NEUTRINO PHYSICS

RICH EXPERIMENTAL PROGRAMME IN FLAVOR PHYSICS

STRONG SUPPRESSION OF THE FCNC
PROCESSES IN THE SM

(GLASHOW-ILIOPOULOS-MAIANI MECHANISM)

MAKES THEM PARTICULARLY
SENSITIVE TO NEW
PHYSICS EFFECTS (GIVEN THE HIGH
PRECISION OF EXPERIMENTAL DATA)

THE THEORY GUIDE TO THE ENERGY FRONTIER:

- COMPLETE THE EXPLORATION OF THE WEAK SCALE:
LOOK FOR MORE SCALARS

STUDY THE ROLE OF THE HIGGS BOSON IN THE TAMING
OF THE HIGH ENERGY BEHAVIOUR OF THE
LONGITUDINAL GAUGE BOSON SCATTERING

- KEEP USING NATURALNESS AS A GUIDING PRINCIPLE
AND SEARCH FOR NEW MASS SCALES
- LOOK FOR THE DARK MATTER CANDIDATES

ON THE PURE THEORY SIDE:

A LESSON FROM THE SM: THE SYMMETRY IS A GOOD GUIDING PRINCIPLE TO UNDERSTAND ELEMENTARY INTERACTIONS AND THEIR DYNAMICS.

SO, EXPLORE NEW SYMMETRIES:
SUPERSYMMETRY, GAUGE SYMMETRIES IN EXTRA DIMENSIONS- AS THE RATIONALE FOR ELEMENTARY SCALARS;
CONFORMAL SYMMETRIES;

THE ROLE OF GRAVITY IN THE BSM, FATE OF GLOBAL SYMMETRIES.

A MESSAGE TO THOSE WHO ARE IMPATIENT:

TAKE PRIDE IN THE STUNNING SUCCESS OF
THE STANDARD MODEL AND ALSO THE
STANDARD COSMOLOGICAL MODEL.

THEY WILL REMAIN IN THE HISTORY OF
SCIENCE AS THE NEWTON EQUATIONS DO.

SURE, THERE IS STILL MUCH MORE TO BE LEARNED
BUT BE PATIENT!

BACKUP

THE HISTORY OF ESTABLISHING THE SM AS A SUCCESSFUL THEORY OF ELEMENTARY INTERACTIONS IS CHARACTERIZED BY SEVERAL GENERIC FOR A FRONT-LINE BASIC RESEARCH AND INDEED OBVIOUS (BUT PERHAPS STILL WORTH MENTIONING) FEATURES:

- **TOTALLY UNEXPECTED DISCOVERIES MAY HAPPEN**

THE DISCOVERY OF RADIOACTIVITY BY HENRI BECQUEREL: A „BY-PRODUCT” OF A FEW MONTHS EARLIER DISCOVERY OF X-RAYS AND BAD WEATHER IN PARIS IN FEBRUARY 1896

BOTH DISCOVERIES HAPPENED TO THE CONTRARY OF THE⁷
COMMON OPINIONS OF THOSE TIMES LIKE, FOR INSTANCE
THOSE EXPRESSED BY AUTHORITIES, LIKE MARCELIN
BERTHELOT AND ALBERT MICHELSON:

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ALL FUNDAMENTAL LAWS OF PHYSICS ARE ALREADY KNOWN-
A. MICHELSON (1894)

- MANY WRONG TRACKS, MISINTERPRETATIONS

PARTICULARLY VISIBLE IN THE EARLY DAYS OF RADIOACTIVITY (PRE-FERMI ERA). FASCINATING STORIES...

- WRONG MOTIVATIONS THAT TURNED OUT TO LEAD TO GREAT DISCOVERIES

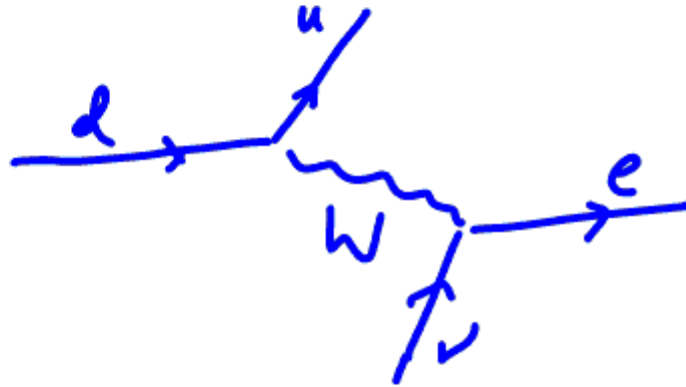
E.G. BROUT-ENGLERT-HIGGS MECHANISM

MY LIFE AS A BOSON (by PETER HIGGS):

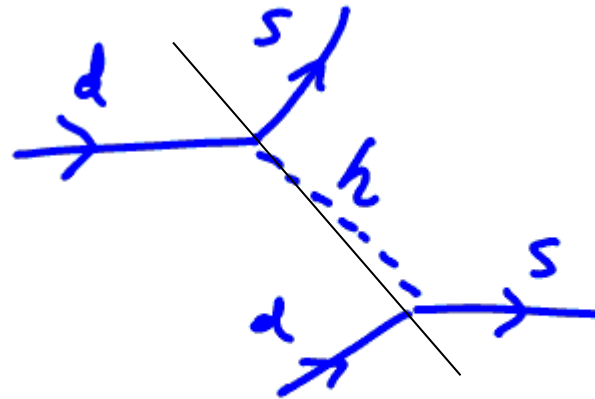
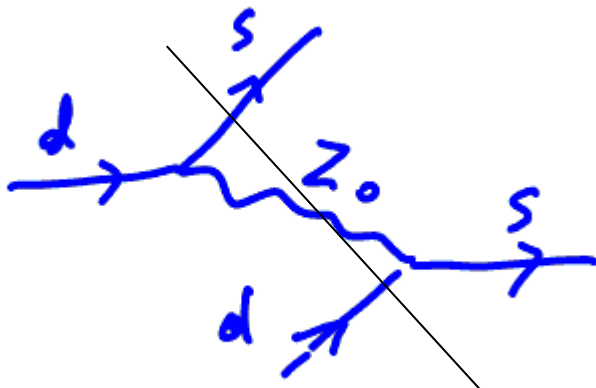
All of us, Brout, Englert and myself, had been going in the wrong direction, looking at hadron symmetries.

neutron decay

CHARGED AND NEUTRAL CURRENTS



$\bar{K}^0 - K^0$ mixing ?



The success of the SM in the FCNC and CP violating sectors relies on:

- **absence of tree-level effects**
- **GIM mechanism (unitarity of the quark mixing matrix)**
- **pattern of quark masses and mixing, taken from experiment**

RESULT: STRONG SUPPRESSION OF FCNC PROCESSES

SM:

VERY IMPORTANT CONCLUSION FOR CHARGED
LEPTONS (IN THE APPROXIMATION OF ZERO
NEUTRINO MASSES):

LEPTON FLAVOUR CONSERVATION

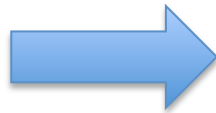
$$\mu \rightarrow e\gamma \quad \text{forbidden}$$

UNIVERSALITY OF LEPTON GAUGE
INTERACTIONS, BOTH IN CHARGED AND
NEUTRAL CURRENTS

IN SPITE OF NO HINT FOR NP AT THE LHC,
DONT RUSH TO A TOO QUICK CONCLUSION ON THE
VALIDITY OF THE SM TO PLANCK SCALE BECAUSE:

HIGGS COUPLINGS VERSUS NEW SCALES:

$$M = 1TeV$$



less than (3- 5) % deviations
from the SM couplings

**VERY CHALLENGING: DEVIATIONS MAY BE OF THE ORDER OF THE
PRESENT UNCERTAINTIES IN THE SM PREDICTIONS**

The essence of Brout-Englert-Higgs mechanism:

Gauge bosons are coupled to currents of a spontaneously broken global symmetry of some interactions

Goldstone bosons become longitudinal degrees of freedom of gauge bosons

For the weak gauge boson,
one needs a new dynamical sector with
at least $SU(2) \times U(1) \rightarrow SU(2)$ spontaneously
broken global symmetry

RENORMALISABILITY IS A VIRTUE EVEN IF THE THEORY IS AN EFFECTIVE THEORY:

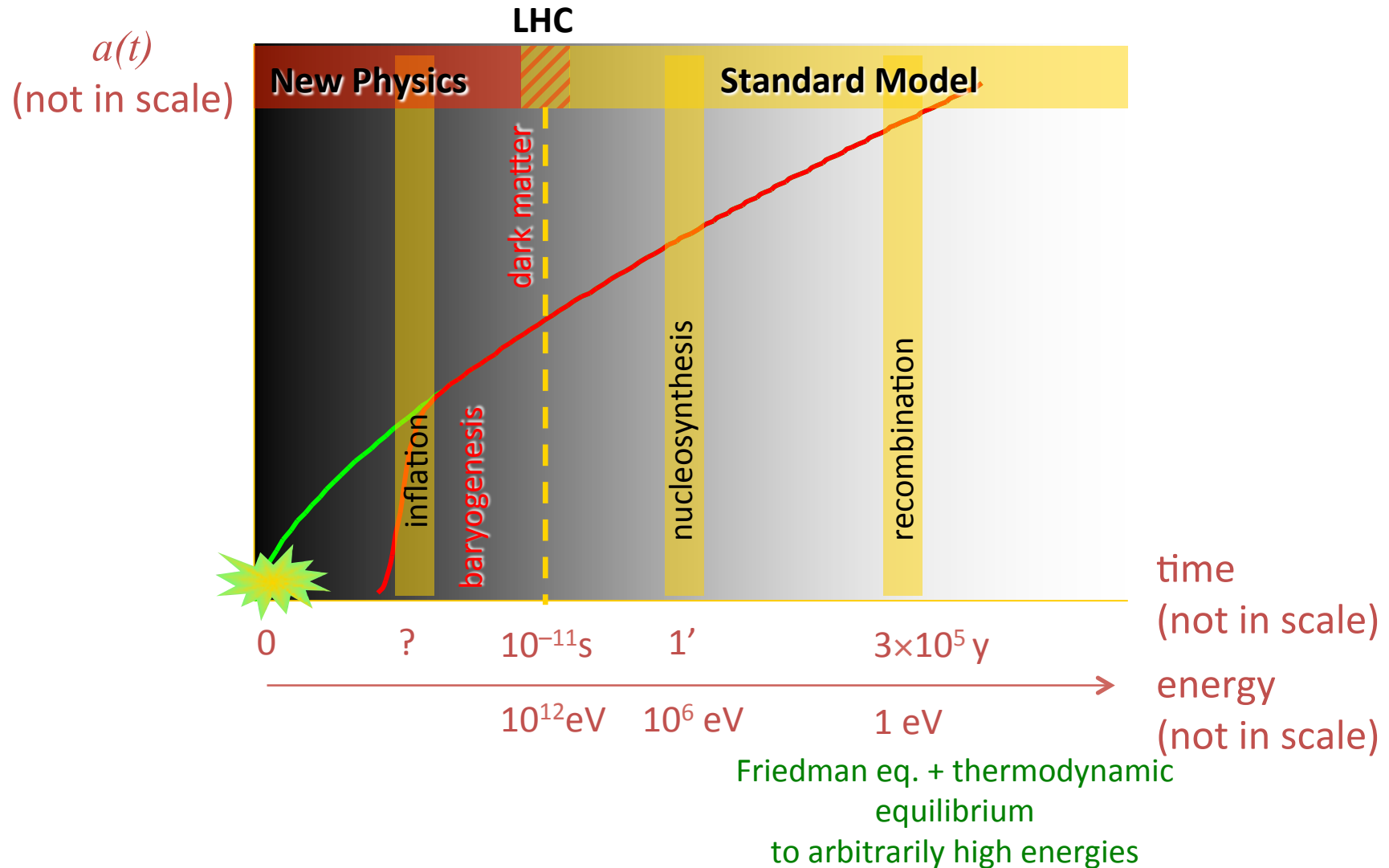
RENORMALISABILITY=PREDICTIVITY UP TO CORRECTIONS E^2/M^2

RENORMALIZABLE + HIGHER DIM OPERATORS= EFFECTIVE THEORY STEMING FROM A DEEPER ONE:

We can organise particle physics in terms of hierarchical energy scales, thanks to the Appelquist-Carazzone decoupling theorem:

If a gauge theory valid at energy scale M_1 is embedded into a larger theory with new particles of mass $M_2 \gg M_1$, the effects on observables probed at the scale M_1 are suppressed by powers of M_1/M_2 .

Particles and cosmology



SM AS AN EFFECTIVE THEORY

\mathcal{L}_{SM} + $SU(2) \times U(1)$ invariant higher dim operators

e.g. dim 6 four fermion operators contributing to

$M - \bar{M}$ mixing

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{C_{ijkl}}{\Lambda^2} (\bar{Q}_i Q_j \bar{Q}_k Q_l) + \dots$$

$l_j \rightarrow l_i \gamma$ decays

$$\mathcal{L}_{eff} = \frac{C_{ij}}{\Lambda^2} (\bar{L}_j \sigma^{\mu\nu} E_i) H B^{\mu\nu}$$

THE BEAUTY OF THE STANDARD MODEL (ITS ELECTROWEAK PART)

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- **GAUGE SYMMETRY AND ELECTROWEAK UNIFICATION**
- **CHIRAL FERMIONS (V-A STRUCTURE OF THE GAUGE CURRENTS)**
- **GAUGE ELECTROWEAK CURRENTS ARE IDENTIFIED WITH SOME GLOBAL SYMMETRY CURRENTS OF STRONG INTERACTIONS**
- **THE SCALAR SECTOR, ITS SPONTANEOUSLY BROKEN GLOBAL SYMMETRY AND THE BROUT-ENGLERT-HIGGS MECHANISM**
- **RENORMALISABILITY**

The essence of Brout-Englert-Higgs mechanism:

In a renormalisable theory, for the weak gauge boson masses,

one needs a new dynamical sector with at least $SU(2) \times U(1) \rightarrow SU(2)$ spontaneously broken global symmetry

Goldstone bosons become longitudinal degrees of freedom of gauge bosons

Simplest dynamical sector (considered by many as a toy model) with global chiral symmetry (to be spontaneously broken) – self interacting scalar field, a doublet of SU(2)- **IS NOW PROMOTED TO A REAL THING**

$$V = m_H^2 H H^\dagger + \frac{1}{2} \lambda (H H^\dagger)^2$$

$$v^2 = -m_H^2 / \lambda$$

$$m_h^2 = 2\lambda v^2$$

3 Goldstone bosons +
physical elementary scalar

The beauty and the puzzles of the Standard Model:

- THE SCALAR SECTOR, ITS SPONTANEOUSLY BROKEN GLOBAL SYMMETRY AND THE BROUT-ENGLERT-HIGGS MECHANISM
- RENORMALISABILITY
- Particles and cosmology

EVERYTHING WHAT HAPPENED IN THE UNIVERSE
AFTER 10^{-9} sec
CAN BE UNDERSTOOD IN TERMS OF THE SM