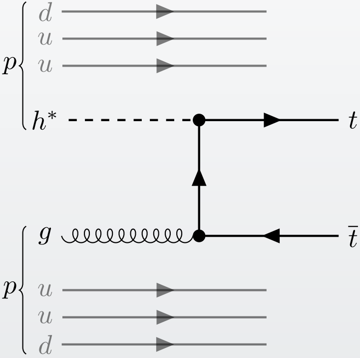
Implications of gauge symmetry for precision Higgs physics

Leonardo Pedro



LIP-Lisboa, May 18th 2017

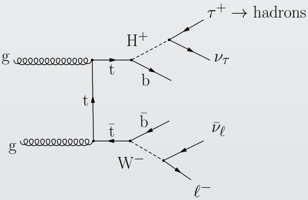
1601.02006 with Axel Maas

1605.01512

proposal

(also 1607.05860

1701.02881)



(2009-2011) H^+ searches in $t\bar{t}$ decays with CMS-LIP

Deviations from the Standard Model

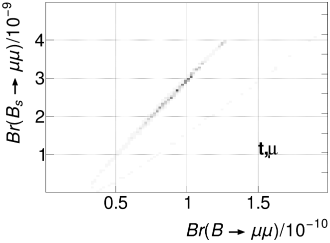
(CMS 2016) "Limits are set on scalar resonances produced through gluon-gluon fusion, and on Randall-Sundrum gravitons. A modest excess of events compatible with a narrow resonance with a mass of about 750 GeV is observed."

$\Rightarrow$ >500 Models of New Physics: parametrizations of deviations from SM.

Always a region of parameters where models compatible with SM.

Alternatives? Yes, within the SM

Botella et al. (2014) For BGL:



Summary

- No spontaneous breakdown of gauge symmetry
- Higgs field in the structure of leptons and hadrons
- Shortcomings of Mean-field approximation to the Higgs PDFs
- Higgs PDFs from lattice simulations
- Higgs PDFs from experimental data

After discussion:

- New Physics searches + Higgs PDFs studies

Spontaneous breakdown of global symmetry

Expectation value $<\phi>_{J,N}$

ϕ: observable

J: parameter affected by transformation g

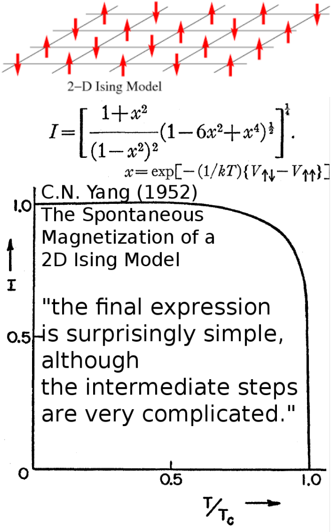
Finite size N:

$$\lim_{J\to 0} <(\phi - g(\phi))>_{J,N} = 0$$

Spontaneous symmetry breaking when:

$$\lim_{J\to 0}\{\lim_{N\to\infty} <(\phi - g(\phi))>_{J,N}\} \neq 0$$

Limits do not commute



Spontaneous breakdown of gauge symmetry?

Local gauge transformation affects
small region near each space-time point: $\cancel{\lim_{N\to\infty}}$

Mainstream view:
Anderson (1958) “longitudinal and transverse excitations are different in the superconductor... this difference allows a gauge-invariant explanation of the Meissner effect.”

Nambu (1960) “The Meissner effect calculation is thus rendered strictly gauge invariant, but essentially keeping the BCS result unaltered for transverse fields.”

Higgs (1966) “our result suggests that it must be possible to rewrite the theory in a form in which only gauge-invariant variables appear.”

Elitzur (1975) "a spontaneous breaking of local symmetry for a symmetrical gauge theory without gauge fixing is impossible."

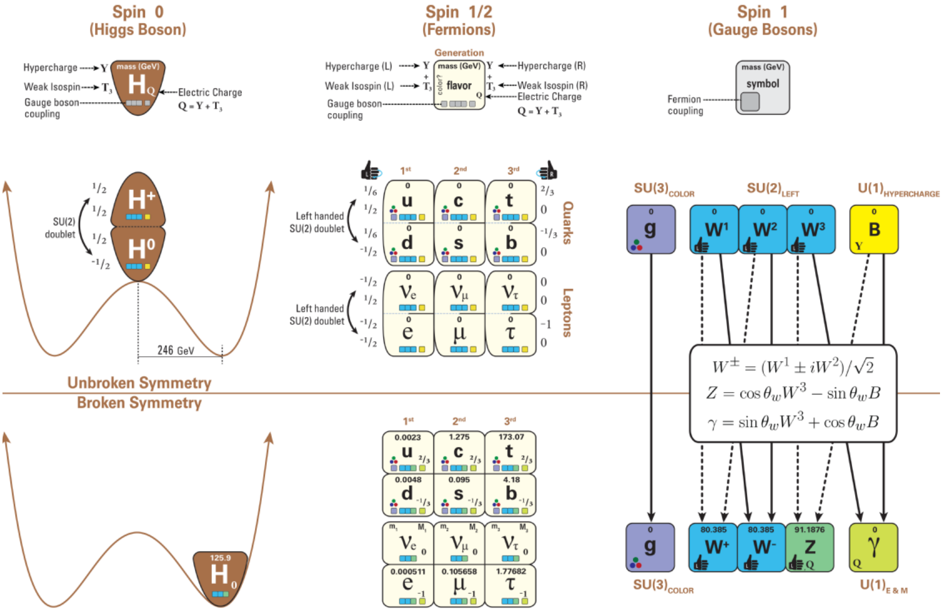
't Hooft (1980) "the words *spontaneous breakdown* are formally not correct for local gauge theories. The vacuum *never* breaks local gauge invariance. The neutral intermediate vector boson is the "meson"

$$\phi^\dagger D_\mu \phi = i\frac{gv^2}{4} W_\mu^3 + \text{total derivative} + \text{higher orders}$$

The $W_\mu^\pm$ are obtained from the "baryons" $\epsilon_{ij}\phi^i D_\mu \phi^j$, and the Higgs particle can also be obtained from $\phi^\dagger\phi$."

Englert (2014)"strictly speaking there is no spontaneous symmetry breaking of a local symmetry.

One uses perturbation theory to select at zero coupling a scalar field configuration from global SSB; but this preferred choice is only a convenient one."



Mean-field approximation $\Rightarrow$ Broken gauge symmetry.

Mean-field approximation

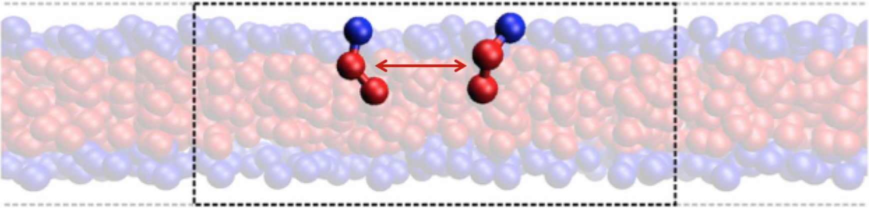
Kadanoff (2009) “the concept of mean field forms the basis of much of modern condensed matter physics and also of particle physics.

sometimes an infinite statistical system has a phase transition, and that transition involves a discontinuous jump in a quantity we call the order parameter.

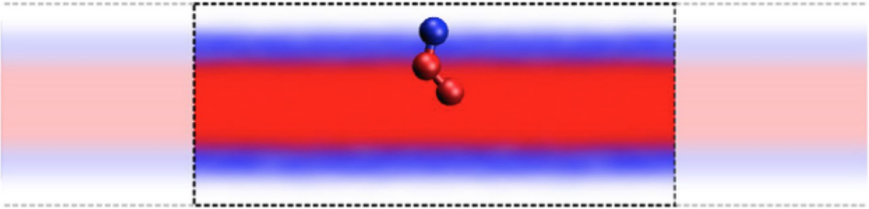
But we have given no indication of how big the jump might be, nor of how the system might produce it. Mean field theory provides a partial, and partially imprecise, answer to that question.”

Mean-field approximation

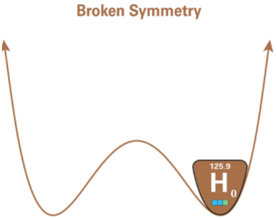
Every pair of molecules interact at a close distance.
To take into account all these interactions is computationally expensive

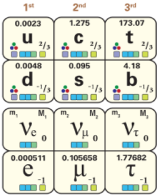


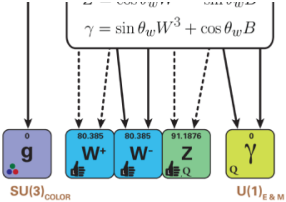
Mean-field approach: every molecule interacts only with the average distribution of other molecules



Strocchi (2013) “If the potential has a non-trivial minimum $\phi = \overline{\phi}$, one can consider a semiclassical approximation based on the expansion $\phi = \overline{\phi} + \varphi$, treating $\overline{\phi}$ as a classical constant field and φ as small.”







Strocchi (2013) “Thus, the expansion can be seen as an expansion around a (symmetry breaking) mean field ansatz, and it is very important that a renormalized perturbation theory based on it exists and yields a non vanishing symmetry breaking order parameter $< \phi > \neq 0$ at all orders. This is the standard (perturbative) analysis of the Higgs mechanism.”

Structure of leptons

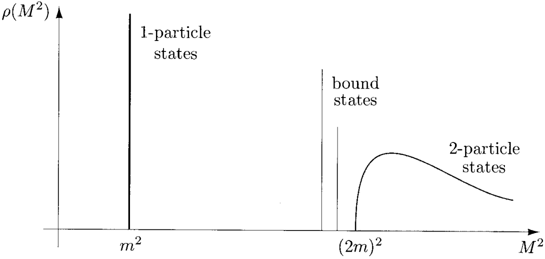
$U(1)_Y$ gauge is abelian, neglected here

$SU(2)_L$ gauge doublets:

ϕ: Higgs field

$\Psi_{e\nu}$: electron and neutrino

$\mathcal{O}^{\nu e} = \phi^\dagger \Psi_{e\nu}$ gauge-invariant



Propagator:

$$< \mathcal{O}^{\nu e}(x)\bar{\mathcal{O}}^{\nu e}(y) > = v^2 < e\bar{e} > +$$
$$+ v < (\varphi^*(x) + \varphi(y))e\bar{e} > + < \varphi^* \varphi e\bar{e} >$$

$\phi_0 = v + \varphi$ (neutral Higgs component in the unitary gauge)

('t Hooft (1980); Frohlich et al. (1981)) Mean-field $\sim$ 1-particle state

(Maas and Mufti (2015)) 2-particle states seen on lattice simulations

Higgs PDFs from Mean-Field

PDFs (parton density functions): composition of gauge-invariant bound states in terms of elementary fields (in fixed gauge)

Mean field approximation: physical electron $\Rightarrow ve$
(at the minimum of the Higgs potential $\phi_0 = v$)

$\Rightarrow$ Trivial Higgs PDFs are a good approximation

Support from: -Experimental data;

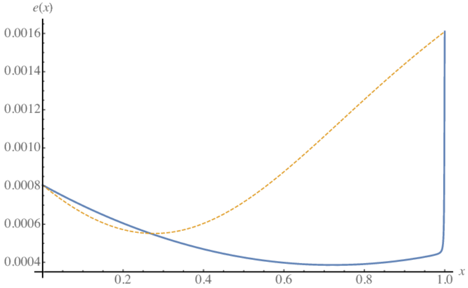
-Theory Elitzur (1975); De Angelis et al. (1978); Osterwalder and Seiler (1978); Frohlich et al. (1981);

-Lattice simulations Fradkin and Shenker (1979); Caudy and Greensite (2008); Bonati et al. (2010); Wurtz and Lewis (2013); Maas (2013); Maas and Mufti (2014, 2015).

Electron structure???

Relevant for:

- AC Stark Shift Kobe (1983).



Miller (2014) free electron distribution function (shaded)

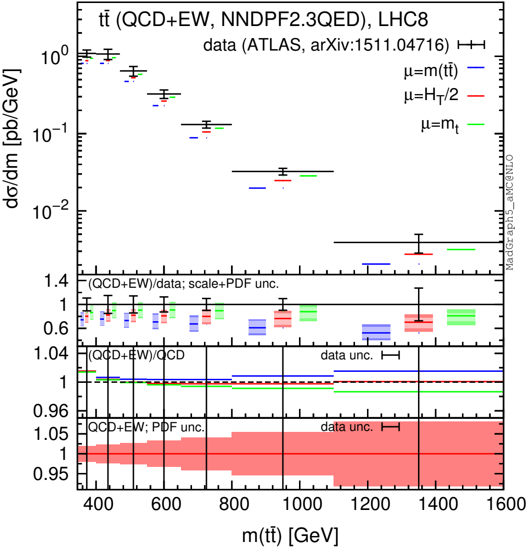
- initial-state radiation at LEP

(Schael et al. (2006); Yennie et al. (1961); Kuraev and Fadin (1985); Skrzypek and Jadach (1991); Abdallah et al. (2014); Slominski and Szwed (2001));

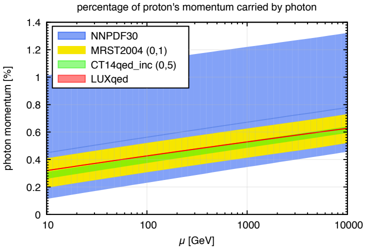
The contribution from pure QED to the electron structure functions is calculated using perturbation theory.

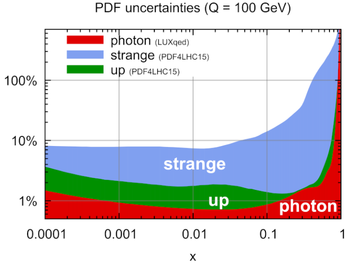
Example: photon PDF in the proton

Pagani et al. (2016)

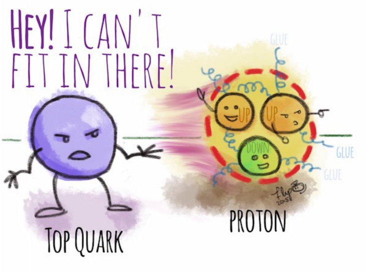


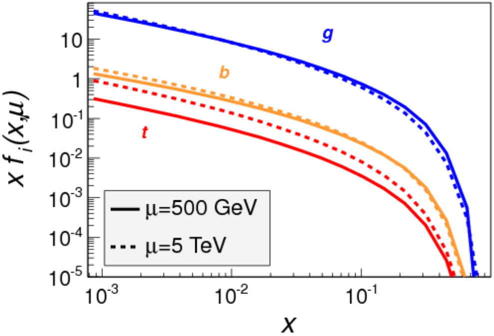
LUXqed.web.cern.ch

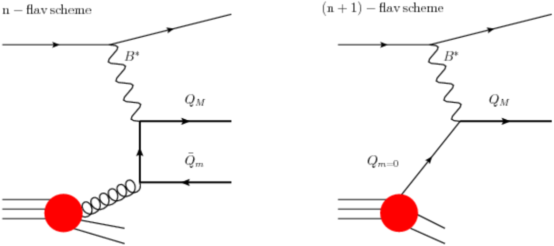




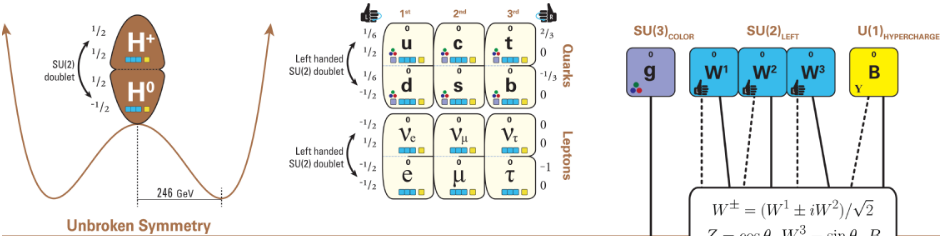
top quark PDF in the proton







Han et al. (2015)
Maltoni et al. (2012)
"simpler and allow the resummation of possibly large initial state logarithms"

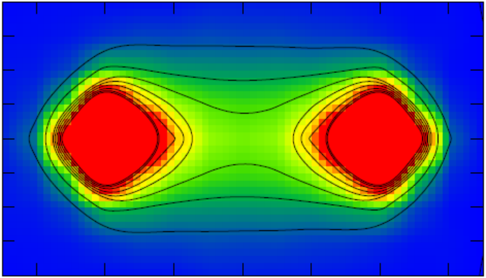


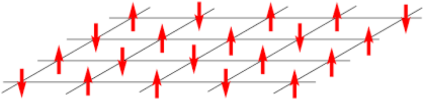
How does an experimentalist estimate
the systematic uncertainty of a mean field approximation?

Using an alternative approximation

(Analogy in QCD: Lund string model vs. Cluster model)

Cardoso et al. (2010) quark-antiquark

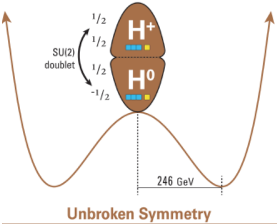


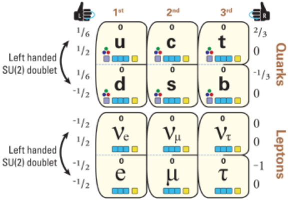


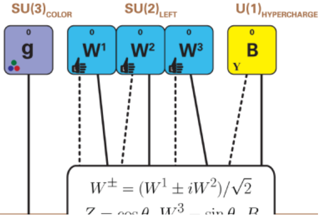
Lattice simulations: non-perturbative approximation

Gattringer and Lang (2010) “Replacing space-time by a Euclidean lattice has proven to be an efficient approach which allows for both theoretical understanding and computational analysis. Lattice QCD has become a standard tool in elementary particle physics.”

Monte-Carlo simulations, distribution of events is function of the Lagrangian







Strocchi (2013) "mean field expansions may yield misleading results about the occurrence of symmetry breaking and the energy spectrum.

the Euclidean functional integral approach [Lattice simulations] gives symmetric correlation functions and in particular $<\phi>=0$.

This means that the mean field ansatz is incompatible with the non-perturbative quantum effects and the approximation leading to the quadratic Lagrangian is not correct."

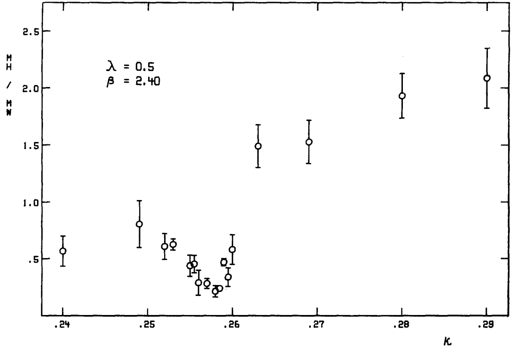
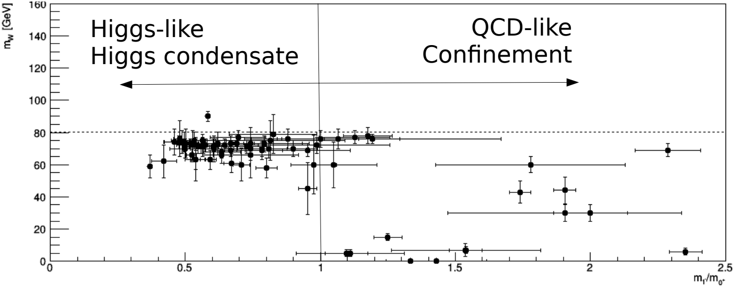


Fig. 3. Ratios m_H/m_W of the masses shown in fig. 2c.

when $m_H/m_W < 1$:
lattice $\neq$ perturbation theory
Not a weak $\rightarrow$ strong coupling transition
$(m_H/m_W \propto \sqrt{\lambda})$



Evertz et al. (1986); Langguth and Montvay (1985); Maas and Mufti (2014)

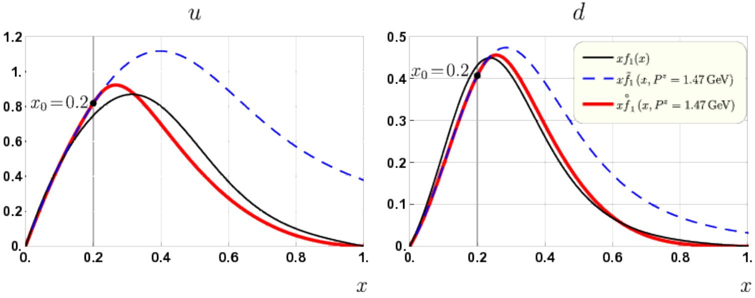
+ shortcomings of Mean-field approximation

- mean-field approximations in nuclear and solid-state physics can be improved in many ways, fake breaking of symmetries common (Grasso et al. (2016); Egido (2016));
- in a grand-unified theory at weak coupling the spectrum in the lattice $\neq$ mean-field Maas and Torek (2016);
- in a theory with abelian Higgs mechanism mean field fails Tada and Koma (2016);
- trivial PDFs require + assumptions (e.g. on the gravity sector) to sidestep a non-perturbative gauge dependence (Maas and Mufti (2014); Ilderton et al. (2010); Faddeev (2008));
- phase diagram is different for different gauge-fixings Caudy and Greensite (2008).

PDFs from Lattice simulations

PDFs calculable (in principle) $\neq$ model of new physics

Ji (2013) "studying a large momentum hadron on lattice is computationally still challenging, but at least this could be achieved when computational power continues improving."



Bacchetta et al. (2017) "In the future, the method can be used to produce PDFs entirely based on lattice QCD results."

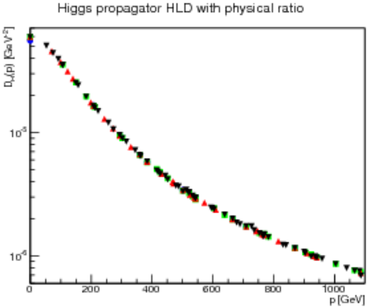
Higgs PDFs from Lattice simulations

Today, indications from the lattice.

Sufficient, if combined with experimental data.

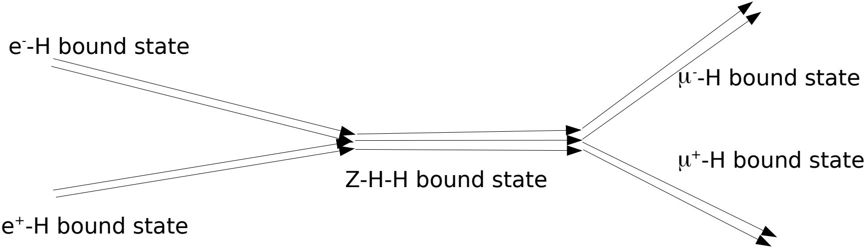
Experimental constraints also allow faster lattice simulations

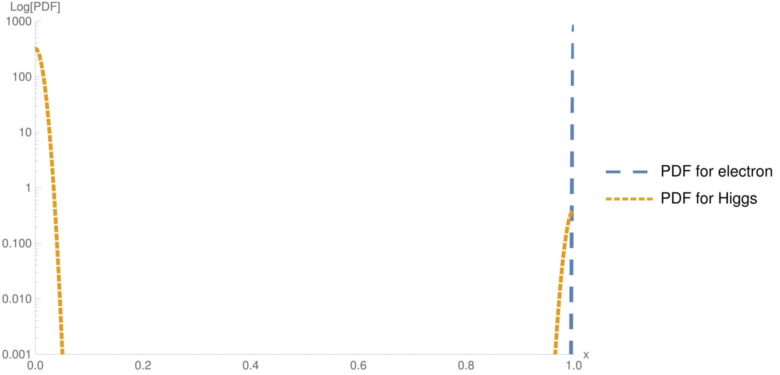
Maas and Mufti (2014)



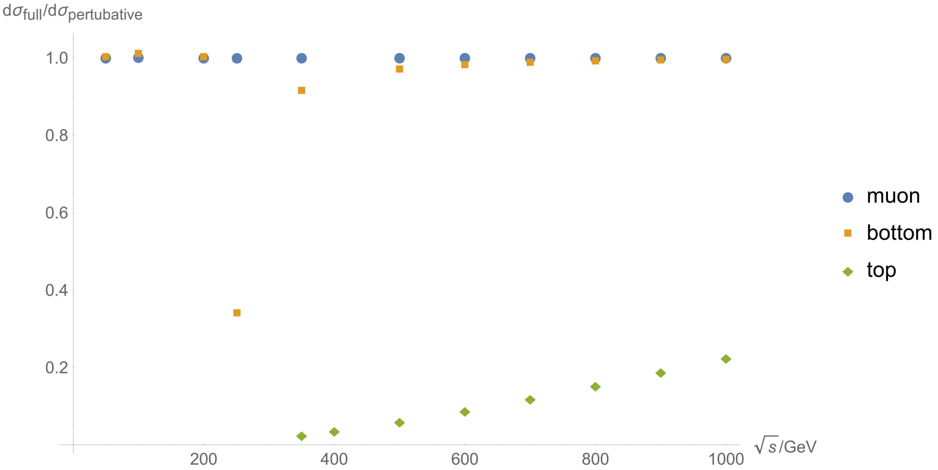
Alternatives: symmetry conserving mean-field (Grasso et al. (2016)), etc.

 Proof of concept (CEPC/ILC)





Egger et al. (2017) Proof of concept (CEPC/ILC)



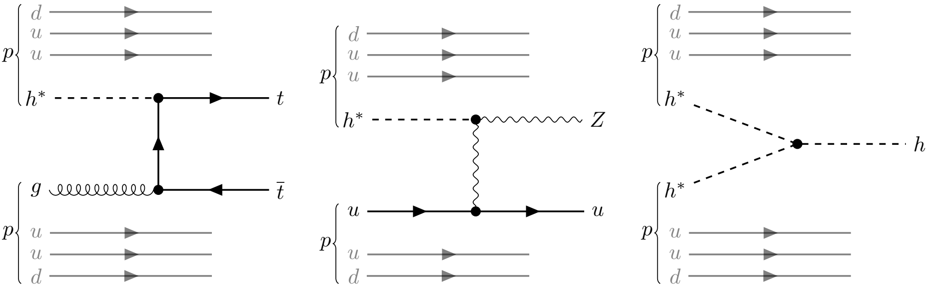
(plot at zero rapidity)

Higgs PDFs can be constrained at colliders.

Below $2M_H$ threshold: off-shell suppression

Higgs PDFs from LHC

h^*: valence higgs boson (on-shell or off-shell)



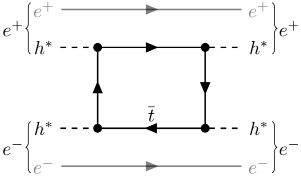
- constraining the photon and gluon PDF using $t\bar{t}$ events Pagani et al. (2016); Czakon et al. (2016)

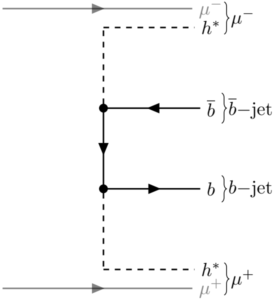
- constraining the underlying event using anomalous Z production Aad et al. (2014); Mucibello (2012)

- anomalous on-shell Higgs production due to an anomalous trilinear coupling

Degrassi et al. (2016); Englert and Spannowsky (2014); Logan (2015)

Higgs PDFs from LEP





- Anomalous Bhabha scattering at LEP Bourilkov (1999); Alcaraz et al. (2006); Schael et al. (2013)

- Fragmentation: Searches for the Higgs boson at LEP in the $HZ \to \mu^+\mu^- b\bar{b}$ final state

Dittmaier and Schumacher (2013)

Summary

- No spontaneous breakdown of gauge symmetry
- Higgs field in the structure of leptons and hadrons
- Shortcomings of Mean-field approximation to the Higgs PDFs
- Higgs PDFs from lattice simulations
- Higgs PDFs from experimental data

After discussion:

- New Physics searches + Higgs PDFs studies

New Physics+ Higgs PDFs

"Model independent" analysis $\Rightarrow$ Mean-field approximation independent?

Maybe not.

Extension of the software for PDFs from QCD, to Higgs PDFs (goal)

Adapt Hera PDF studies to the LHC Higgs PDF studies

New Physics+ Higgs PDFs

Many theories are motivated by problems of the perturbative approach to the Standard Model.

Problem may be in the mean-field approximation, not in the Standard Model.

Example (Supersymmetry): The (gauge-invariant) bound state masses are independent of the renormalization $\Rightarrow$ not affected as the gauge-dependent elementary fields by hierarchy problem Frohlich et al. (1981); Maas (2013)

Example (Flavour puzzle): In principle, the families (e, μ, τ) can be excited bound states of $e - H$. Impossible to know soon Egger et al. (2017).

Software

Decouple systematic uncertainties from the experimental results is possible Cranmer et al. (2015); Brehmer et al. (2016); Boudjema et al. (2013); Kraml et al. (2012).

After decoupling theoretical uncertainties, an experimental result is a numerical function (whose arguments are the parameters affected by the theoretical uncertainties).

Functional Package Management GNU's Guix and Guile Courtès (2013); Courtès and Wurmus (2015), would allow to publish, access and combine (many) experimental results and manage their dependencies.

Obrigado

References

F. J. Botella, G. C. Branco, A. Carmona, M. Nebot, L. Pedro, and M. N. Rebelo. Physical constraints on a class of two-Higgs doublet models with FCNC at tree level. *Journal of High Energy Physics*, 7:78, July 2014, 1401.6147. Software documentation `http://cftp.ist.utl.pt/~leonardo`.

Philip W. Anderson. COHERENT EXCITED STATES IN THE THEORY OF SUPERCONDUCTIVITY: GAUGE INVARIANCE AND THE MEISSNER EFFECT. *Phys. Rev.*, 110:827–835, 1958.

Yoichiro Nambu. Quasiparticles and Gauge Invariance in the Theory of Superconductivity. *Phys. Rev.*, 117:648–663, 1960.

Peter W. Higgs. Spontaneous symmetry breakdown without massless bosons. *Phys. Rev.*, 145: 1156–1163, May 1966.

S. Elitzur. Impossibility of Spontaneously Breaking Local Symmetries. *Phys. Rev.*, D12:3978–3982, 1975.

Gerard 't Hooft. Which Topological Features of a Gauge Theory Can Be Responsible for Permanent Confinement? *NATO Sci. Ser. B*, 59:117, 1980.

Fran çois Englert. Nobel lecture: The beh mechanism and its scalar boson*. *Rev. Mod. Phys.*, 86: 843–850, Jul 2014. Non-perturbative picture in p847.

Leo P. Kadanoff. More is the Same: Phase Transitions and Mean Field Theories. *J. Statist. Phys.*, 137: 777, 2009, 0906.0653.

F. Strocchi. *An Introduction to Non-Perturbative Foundations of Quantum Field Theory*. International Series of Monographs on Physics. OUP Oxford, 2013. ISBN 9780191651335. electric charge localization on sec.7.2.

J. Frohlich, G. Morchio, and F. Strocchi. HIGGS PHENOMENON WITHOUT SYMMETRY BREAKING ORDER PARAMETER. *Nucl.Phys.*, B190:553–582, 1981. standard perturbation expansion on sec.8.2.

Axel Maas and Tajdar Mufti. Spectroscopic analysis of the phase diagram of Yang-Mills-Higgs theory. *Phys. Rev.*, D91(11):113011, 2015, 1412.6440.

Gian Fabrizio De Angelis, Diego de Falco, and Francesco Guerra. A Note on the Abelian Higgs-Kibble Model on a Lattice: Absence of Spontaneous Magnetization. *Phys. Rev.*, D17:1624, 1978.

K. Osterwalder and E. Seiler. Gauge Field Theories on the Lattice. *Annals Phys.*, 110:440, 1978. Higgs Lattice Phase diagram.

Eduardo H. Fradkin and Stephen H. Shenker. Phase Diagrams of Lattice Gauge Theories with Higgs Fields. *Phys. Rev.*, D19:3682–3697, 1979.

W. Caudy and J. Greensite. On the Ambiguity of Spontaneously Broken Gauge Symmetry. *Phys. Rev.*, D78:025018, 2008, 0712.0999.

C. Bonati, G. Cossu, M. D'Elia, and A. Di Giacomo. Phase diagram of the lattice SU(2) Higgs model. *Nucl. Phys.*, B828:390–403, 2010, 0911.1721.

Mark Wurtz and Randy Lewis. Higgs and W boson spectrum from lattice simulations. *Phys.Rev.*, D88: 054510, 2013, 1307.1492.

Axel Maas. Bound-state/elementary-particle duality in the Higgs sector and the case for an excited 'Higgs' within the standard model. *Mod.Phys.Lett.*, A28:1350103, 2013, 1205.6625.

Axel Maas and Tajdar Mufti. Two- and three-point functions in Landau gauge Yang-Mills-Higgs theory. *JHEP*, 1404:006, 2014, 1312.4873.

Donald H. Kobe. Gauge invariant derivation of the AC Stark shift. *Journal of Physics B: Atomic and Molecular Physics*, 16(7):1159–1169, 1983. ISSN 0022-3700.

Gerald A. Miller. Electron structure: Shape, size, and generalized parton distributions in QED. *Phys. Rev.*, D90(11):113001, 2014, 1409.7412.

S. Schael et al. Precision electroweak measurements on the Z resonance. *Phys. Rept.*, 427:257–454, 2006, hep-ex/0509008.

D. R. Yennie, Steven C. Frautschi, and H. Suura. The infrared divergence phenomena and high-energy processes. *Annals Phys.*, 13:379–452, 1961.

E. A. Kuraev and Victor S. Fadin. On Radiative Corrections to e+ e- Single Photon Annihilation at High-Energy. *Sov. J. Nucl. Phys.*, 41:466–472, 1985. [Yad. Fiz.41,733(1985)].

Maciej Skrzypek and Stanislaw Jadach. Exact and approximate solutions for the electron nonsinglet structure function in QED. *Z. Phys.*, C49:577–584, 1991.

J. Abdallah et al. Measurement of the electron structure function $F_{\frac{e}{2}}$ at LEP energies. *Phys. Lett.*, B737:39–47, 2014.

Wojciech Slominski and Jerzy Szwed. Phenomenology of the electron structure function. *Eur. Phys. J.*, C22:123–127, 2001, hep-ph/0008259.

Davide Pagani, Ioannis Tsinikos, and Marco Zaro. The impact of the photon PDF and electroweak corrections on $t\bar{t}$ distributions. *Eur. Phys. J.*, C76(9):479, 2016, 1606.01915.

Tao Han, Joshua Sayre, and Susanne Westhoff. Top-Quark Initiated Processes at High-Energy Hadron Colliders. *JHEP*, 04:145, 2015, 1411.2588.

Fabio Maltoni, Giovanni Ridolfi, and Maria Ubiali. b-initiated processes at the LHC: a reappraisal. *JHEP*, 07:022, 2012, 1203.6393. [Erratum: JHEP04,095(2013)].

M. Cardoso, N. Cardoso, and P. Bicudo. Lattice QCD computation of the colour fields for the static hybrid quark-gluon-antiquark system, and microscopic study of the Casimir scaling. *Phys. Rev.*, D81:034504, 2010, 0912.3181.

Christof Gattringer and Christian B. Lang. *Quantum chromodynamics on the lattice*. Lect. Notes Phys., 2010.

H. G. Evertz, J. Jersak, C. B. Lang, and T. Neuhaus. SU(2) HIGGS BOSON AND VECTOR BOSON MASSES ON THE LATTICE. *Phys. Lett.*, B171:271, 1986.

W. Langguth and I. Montvay. TWO STATE SIGNAL AT THE CONFINEMENT HIGGS PHASE TRANSITION IN THE STANDARD SU(2) HIGGS MODEL. *Phys. Lett.*, B165:135, 1985.

M. Grasso, D. Lacroix, and U. van Kolck. From effective field theories to effective density functionals in and beyond the mean field. *Phys. Scripta*, 91(6):063005, 2016.

J. Luis Egido. State-of-the-art of beyond mean field theories with nuclear density functionals. *Phys. Scripta*, 91(7):073003, 2016, 1606.00407.

A. Maas and P. Torek. Predicting the singlet vector channel in a partially Higgsed gauge theory. 2016, 1607.05860.

Yasuhiro Tada and Tohru Koma. Decay of Superconducting Correlations for Gauged Electrons in Dimensions $D \leq 4$. 2016, 1612.00619.

Anton Ilderton, Martin Lavelle, and David McMullan. Symmetry Breaking, Conformal Geometry and Gauge Invariance. *J.Phys.*, A43:312002, 2010, 1002.1170.

L. D. Faddeev. An Alternative interpretation of the Weinberg-Salam model. In *Progress in High Energy Physics and Nuclear Safety: Proceedings, NATO Advanced Research Workshop on Safe Nuclear Energy, Yalta, Crimea, Ukraine, Sep 29 - Oct 2, 2008*, pages 3–8, 2008, 0811.3311.

Xiangdong Ji. Parton Physics on a Euclidean Lattice. *Phys. Rev. Lett.*, 110:262002, 2013, 1305.1539.

Alessandro Bacchetta, Marco Radici, Barbara Pasquini, and Xiaonu Xiong. Reconstructing parton densities at large fractional momenta. *Phys. Rev.*, D95(1):014036, 2017, 1608.07638.

Larissa Egger, Axel Maas, and RenÃ© Sondenheimer. Pair production processes and flavor in gauge-invariant perturbation theory. 2017, 1701.02881.

Michal Czakon, Nathan P. Hartland, Alexander Mitov, Emanuele R. Nocera, and Juan Rojo. Pinning down the large-x gluon with NNLO top-quark pair differential distributions. 2016, 1611.08609.

Georges Aad et al. Measurement of distributions sensitive to the underlying event in inclusive Z-boson production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. *Eur. Phys. J.*, C74(12):3195, 2014, 1409.3433.

Luca Mucibello. *Measurement of the Underlying Event activity with the CMS detector at the LHC*. PhD thesis, Antwerp U., WISINF, 2012. URL `https://inspirehep.net/record/1231288/files/TS2012_037.pdf`.

Giuseppe Degrassi, Pier Paolo Giardino, Fabio Maltoni, and Davide Pagani. Probing the Higgs self coupling via single Higgs production at the LHC. *JHEP*, 12:080, 2016, 1607.04251.

Christoph Englert and Michael Spannowsky. Limitations and Opportunities of Off-Shell Coupling Measurements. *Phys. Rev.*, D90:053003, 2014, 1405.0285.

Heather E. Logan. Hiding a Higgs width enhancement from off-shell gg(->h*)->ZZ measurements. *Phys. Rev.*, D92(7):075038, 2015, 1412.7577.

Dimitri Bourilkov. Global analysis of Bhabha scattering at LEP-2 and limits on low scale gravity models. *JHEP*, 08:006, 1999, hep-ph/9907380.

J. Alcaraz et al. A Combination of preliminary electroweak measurements and constraints on the standard model. 2006, hep-ex/0612034.

S. Schael et al. Electroweak Measurements in Electron-Positron Collisions at W-Boson-Pair Energies at LEP. *Phys. Rept.*, 532:119–244, 2013, 1302.3415.

S. Dittmaier and M. Schumacher. The Higgs Boson in the Standard Model - From LEP to LHC: Expectations, Searches, and Discovery of a Candidate. *Prog. Part. Nucl. Phys.*, 70:1–54, 2013, 1211.4828.

Kyle Cranmer, Sven Kreiss, David Lopez-Val, and Tilman Plehn. Decoupling Theoretical Uncertainties from Measurements of the Higgs Boson. *Phys. Rev.*, D91(5):054032, 2015, 1401.0080.

Johann Brehmer, Kyle Cranmer, Felix Kling, and Tilman Plehn. Better Higgs Measurements Through Information Geometry. 2016, 1612.05261.

F. Boudjema et al. On the presentation of the LHC Higgs Results. 2013, 1307.5865. URL https://inspirehep.net/record/1244142/files/arXiv:1307.5865.pdf.

S. Kraml et al. Searches for New Physics: Les Houches Recommendations for the Presentation of LHC Results. *Eur. Phys. J.*, C72:1976, 2012, 1203.2489.

L. Courtès. Functional Package Management with Guix. *European Lisp Symposium*, May 2013, 1305.4584.

L. Courtès and R. Wurmus. Reproducible and User-Controlled Software Environments in HPC with Guix. *2nd International Workshop on Reproducibility in Parallel Computing (RepPar)*, June 2015, 1506.02822.

Astrid Eichhorn, Holger Gies, Joerg Jaeckel, Tilman Plehn, Michael M. Scherer, and RenÃ© Sondenheimer. The Higgs Mass and the Scale of New Physics. *JHEP*, 04:022, 2015, 1501.02812.

G. C. Branco and I. P. Ivanov. Group-theoretic restrictions on generation of CP-violation in multi-Higgs-doublet models. *JHEP*, 01:116, 2016, 1511.02764.

V. N. Gribov. Quantization of non-Abelian gauge theories. *Nucl. Phys.*, B139:1, 1978.

I. M. Singer. Some Remarks on the Gribov Ambiguity. *Commun. Math. Phys.*, 60:7–12, 1978.

R. Haag. *Local quantum physics: Fields, particles, algebras*. Springer, Berlin, 1992. Berlin, Germany: Springer (1992) 356 p. (Texts and monographs in physics).

J. Fröhlich, G. Morchio, and F. Strocchi. HIGGS PHENOMENON WITHOUT SYMMETRY BREAKING ORDER PARAMETER. *Nucl.Phys.*, B190:553–582, 1981. Gauge-invariant Higgs.

Erhard Seiler. On the Higgs-Confinement Complementarity. 2015, 1506.00862.

FranÃ§ois Englert. Broken symmetry and Yang-Mills theory. In G. 't Hooft, editor, *50 years of Yang-Mills theory*, pages 65–95. 2005, hep-th/0406162.

V P Karassiov. Algebras of the su(n) invariants: structure, representations and applications. *Journal of Physics A: Mathematical and General*, 25(2):393, 1992.

A.S. Wineman and A.C. Pipkin. Material symmetry restrictions on constitutive equations. *Archive for Rational Mechanics and Analysis*, 17(3):184–214, 1964. ISSN 0003-9527.

R. Giles. The Reconstruction of Gauge Potentials From Wilson Loops. *Phys.Rev.*, D24:2160, 1981.

D. S. Shirokov. Calculation of Elements of Spin Groups Using Generalized Pauli's Theorem. *Advances in Applied Clifford Algebras*, 25(1):227–244, 2015, 1409.2449.

Apostolos Pilaftsis. On the Classification of Accidental Symmetries of the Two Higgs Doublet Model Potential. *Phys.Lett.*, B706:465–469, 2012, 1109.3787.

Deva O'Neil. Phenomenology of the Basis-Independent CP-Violating Two-Higgs Doublet Model [Dissertation]. 2009, 0908.1363.

I.P. Ivanov. Two-Higgs-doublet model from the group-theoretic perspective. *Phys.Lett.*, B632:360–365, 2006, hep-ph/0507132.

F.J. Botella, G.C. Branco, and M.N. Rebelo. Invariants and Flavour in the General Two-Higgs Doublet Model. *Phys.Lett.*, B722:76–82, 2013, 1210.8163.

Randy Lewis and R.M. Woloshyn. Spontaneous symmetry breaking in a two-doublet lattice Higgs model. *Phys.Rev.*, D82:034513, 2010, 1005.5420. 2HDM.

P. S. Bhupal Dev and Apostolos Pilaftsis. Maximally Symmetric Two Higgs Doublet Model with Natural Standard Model Alignment. *JHEP*, 12:024, 2014, 1408.3405.

Steven Weinberg. Quantum Mechanics Without State Vectors. *Phys.Rev.*, A90(4):042102, 2014, 1405.3483.

Leonardo Pedro. On the real representations of the Poincare group. 2013, 1309.5280.

C. N. Yang. The Spontaneous Magnetization of a Two-Dimensional Ising Model. *Phys. Rev.*, 85: 808–816, 1952.

Holger Gies and René Sondenheimer. Higgs Mass Bounds from Renormalization Flow for a Higgs-top-bottom model. *Eur.Phys.J.*, C75(2):68, 2015, 1407.8124.

Howard E. Haber and Ze'ev Surujon. A Group-theoretic Condition for Spontaneous CP Violation. *Phys.Rev.*, D86:075007, 2012, 1201.1730.

H. Georgi. *Weak Interactions and Modern Particle Theory*. Dover Books on Physics Series. Dover Publications, 2009. ISBN 9780486469041. source fields in sec.5.3.

G. C Branco and D. Emmanuel-Costa. Flavour Physics and CP Violation in the Standard Model and Beyond. *Third IDPASC School 2013, 2013, Santiago de Compostela, Spain*, February 2014, 1402.4068.

J. Ellis. Summary of the Nobel symposium on Large Hadron Collider results. *Physica Scripta Volume T*, 158(1):014020, December 2013, 1309.3549.

Guido Altarelli. The Higgs and the Excessive Success of the Standard Model. *Frascati Phys. Ser.*, 58: 102, 2014, 1407.2122.

Rainer Wanke. *How to Deal with Systematic Uncertainties*, pages 263–296. Wiley, 2013. ISBN 9783527653416.

Ariana Borrelli. A philosophical experiment: empirical study of knowledge production at the LHC. *CERN Colloquium*, Feb 2013. URL `http://ph-news.web.cern.ch/content/philosophical-experiment-empirical-study-knowledge-production-lhc-1`.

A. J. Buras and J. Girrbach. Towards the identification of new physics through quark flavour violating processes. *Reports on Progress in Physics*, 77(8):086201, August 2014, 1306.3775.

“The federal government recommended flossing in 1979-2015.

In 2016 the government acknowledged the effectiveness of flossing had never been researched, as required.” (Associated Press)

(Feynman 1973)

All the people are doing the same ritual brush, brush, brush—for no good reason? Think about it.

Prelude

Spontaneous symmetry breaking (SSB) $\rightarrow$ disjoint phases in a system (local interactions, e.g. the Ising model or gauge theories)

Expectation value $\omega_{J,N} : \mathcal{A} \rightarrow \mathbb{R}$ (positive linear functional)

J: intensity of external source breaking a group of symmetries G.
$\mathcal{A}$: set of observables.

Finite size N: continuous expectation values

$$\begin{cases} \omega_{J,N}(A - g(A)) = 0 & \text{if } J = 0 \\ \lim_{J \rightarrow 0} \omega_{J,N}(A - g(A)) = 0 & \end{cases}$$

any observable $A \in \mathcal{A}$ and any transformation $g \in G$.

Definition 1. Spontaneous symmetry breaking when:

$$\lim_{J\to 0}\{\lim_{N\to\infty}\omega_{J,N}(A-g(A))\}\neq 0$$

for some $A\in\mathcal{A}$ and some $g\in G$.

Limit of a convergent sequence of continuous functions is not necessarily continuous.

Other definitions in statistical mechanics are not based on explicit symmetry breaking.

SSB possible for a global symmetry in a system with infinite size.

Elitzur (1975) “a spontaneous breaking of local symmetry for a symmetrical gauge theory without gauge fixing is impossible.”

local gauge transformation affects
only a small sized system near each space-time point.

Outline

1 Higgs potential

Holomorphic functions $\frac{\partial f(z,z^*)}{\partial z^*} = 0$
central objects of study in complex analysis

The Higgs potential is not an holomorphic function
$\frac{\partial V(\phi_j,\phi_j^*)}{\partial \phi^*} \neq 0.$

No advantage in the Higgs field being a complex vector space
$V(\phi_j, \phi_j^*) = V(Re(\phi_j), Im(\phi_j))$

Complex irreducible representations of $G \times H$ are a direct product of complex irreducible representations of G and of H.
Not the case for real irreducible representations.
(wiki/Representation_theory_of_finite_groups,arXiv:1309.5280)

Standard Higgs field (4 real components) $V(\phi, \phi^*) = V(\phi^\dagger \phi)$

$SO(4) \simeq (SU(2)_R \times SU(2)_L)/Z_2$ (generators τ^j and σ^j)

$SU(2)_L$ gauge symmetry
Global symmetry $SO(4)/SU(2)_L \simeq SO(3)$ (E.g. $\phi^\dagger D_\mu \tau^j \phi$)

N-Higgs-doublets (4N real components):

- different global symmetry $G/SU(2)_L$
- charged scalars;
- mixing between neutral scalar particles;
- Spontaneous/explicit global symmetry violation in the Higgs potential;
- Rich flavour phenomenology (e.g. meson decays, oscillations)

Definition 2. (Electroweak symmetry breaking)

After perturbative gauge-fixing,
the Higgs vev minimizes the Higgs potential.

The symmetries broken by the Higgs vev
are the spontaneously broken symmetries.

Perturbation theory can only deal with small perturbations of the Higgs field $\rightarrow$ non-null Higgs vev.

Challenge: spontaneous breaking of global symmetries
in the presence of the Higgs mechanism

- Find an absolute minimum of the potential $\phi = \frac{v}{\sqrt{2}}\phi_0$;
- Projector P_0 on the $SU(2)_L$-orbit of ϕ_0 such that $P_0\phi_0 = \phi_0$;
- Modify the Higgs potential $W = V + \epsilon U$,
  $\epsilon > 0$ is arbitrarily small and $U = -v^2\phi^\dagger P_0\phi + (\phi^\dagger\phi)^2$;
- The absolute minima of $W = V + \epsilon U$ is the $SU(2)_L$-orbit of ϕ_0;

The perturbation theory then implies that in the limit $\epsilon \to 0$, there are finite vevs breaking the global symmetries $\Rightarrow$ SSB by Def. 1

Evaluating vevs of $SU(2)_L$-invariant observables,
we make no assumptions about SSB of gauge symmetry.

Classical minimization: no limit on the order of the potential $\Rightarrow$ effective field theory, no assumptions on the ultra-violet completion (appropriate for experimental data Eichhorn et al. (2015))

Consistency: Let $p(\phi)$ be a G_f-invariant polynomial in the Higgs field ϕ.

If any G_f-invariant Higgs potential is necessarily G-invariant,
the observable $p(\phi)$ must also be invariant under G,
since $p(\phi)$ can appear in a G_f-invariant Higgs potential.
If G_f is a classical$\times$finite group $\Rightarrow$ No spontaneous symmetry breaking of G/G_f since all G_f-invariant observables are also G-invariant.

Example: Global symmetry $G/SU(2)_L$ for one-Higgs-doublet cannot be explicitly broken $\Rightarrow$ no spontaneous symmetry breaking of $G/SU(2)_L$

More examples with CP Branco and Ivanov (2016)

2 Confinement

Options for Electroweak Theory:

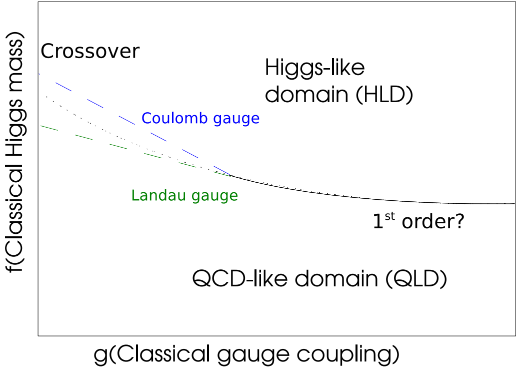
1) Define the theory with gauge fixing (standard in perturbation theory), Gribov (1978); Singer (1978) non-perturbative ambiguity, the local non-abelian gauge-fixing condition is insufficient

2) gauge-invariant gauge charge, e.g. dressed elementary operators (photons are neutral), non-abelian (global) gauge charges cannot be (locally) gauge-invariant Haag (1992).

3) Fröhlich, Morchio, and Strocchi (1981): FMS mechanism inspired in the confinement mechanism, effectively matches gauge fixing+perturbation theory under some assumptions

4) Technicolor 5) ? (next) ...

Maas and Mufti (2015) SU(2) Yang-Mills-Higgs on the lattice phase diagram



$\frac{1}{g} \propto$ gauge coupling

$f \propto m_h^2 v^2$ dashed lines: break global subgroup remaining after incomplete gauge-fixing.

Osterwalder and Seiler (1978)

Fradkin and Shenker (1979)

Caudy and Greensite (2008)

Seiler (2015)

Bonati et al. (2010) “hints that the above transitions are not related to confinement”

Englert (2005) “Electric-magnetic dualities suggest that, at some fundamental level, confinement is a condensation of magnetic monopoles and constitutes the magnetic dual of the BEH mechanism”

However Englert does not cite FMS mechanism

3 Gauge-invariant operators in 2HDM (no $U(1)_Y$)

$SU(2)_L$ Higgs doublets ϕ_1, ϕ_2

gauge field W_μ^j with $j, k, l = 1, 2, 3$

Higgs Potential $V(\phi_1, \phi_2)$,

coupling constant g,

$$\mathcal{L} \equiv ((D^\mu \phi_1)^\dagger (D_\mu \phi_1) + ((D^\mu \phi_2)^\dagger (D_\mu \phi_2) - V(\phi_1, \phi_2) - \frac{1}{4} W_{\mu\nu}^j W^{j\mu\nu}$$

$$D_\mu \equiv \partial_\mu + igW_\mu^j \frac{\sigma^j}{2}$$

$$W_{\mu\nu}^j \equiv -\frac{i}{g} \mathrm{tr}([D_\mu, D_\nu]\sigma^j) = \partial_\mu W_\nu^j - \partial_\nu W_\mu^j - g\epsilon^{jkl} W_\mu^k W_\nu^l$$

Levi-Civita ϵ^{jkl}, Pauli matrices in gauge space σ^j

Karassiov (1992) (+ general Wineman and Pipkin (1964))

Any polynomial of ϕ_1, ϕ_2 which is gauge invariant is a polynomial on

$\phi^*_{1a}\phi_1{}^a$, $\phi^*_{2a}\phi_2{}^a$, $\phi^*_{2a}\phi_1{}^a$; $\epsilon_{ab}\phi_1{}^a\phi_2{}^b$; $\epsilon_{ab}\phi_1{}^{a*}\phi_2{}^{b*}$

$\phi^*_{jb} \equiv (\phi_j{}^b)^*$ $a, b = 1, 2$ are gauge indices.

Also parallel transport $U(x, y, C)$ from y to x along line C.

for infinitesimal line elements

$$U(x, y, C) \approx (1 + D_\mu(x)dl_1^\mu)(1 + D_\nu(x)dl_2^\nu)...(1 + D_\alpha(x)dl_n^\alpha)$$

$dl_1, dl_2, ..., dl_n$ (n finite) are infinitesimal Lorentz vectors forming C by concatenation.

Set of primitive (algebraically ind.) gauge-invariant operators for 2HDM:

- $tr(U(x,x,C'))$ Giles (1981)
- $\phi_j^\dagger(x)U(x,y,C)\phi_k(y)$
- $\phi_j^\dagger(x)U(x,y,C)\overline{\phi}_k(y)$
- $\overline{\phi}_j^\dagger(x)U(x,y,C)\phi_k(y)$
- $\overline{\phi}_j^\dagger(x)U(x,y,C)\overline{\phi}_k(y)$

$\overline{\phi}_j{}^a(x) \equiv \epsilon^{ab}\phi_{jb}^*(x)$,

indices $j,k=1,2$ are Higgs flavor indices,

4 Majorana construction

Shirokov (2015): A^a, B^a are $2^n \times 2^n$ complex unitary matrices

$$A^a A^b + A^b A^a = 2g^{ab}1$$
$$B^a B^b + B^b B^a = 2g^{ab}1$$

$a \in \{1, ..., 2n\}$, $n < 4$, $g \equiv \mathrm{diag}(-1, ..., +1, ...)$ (n entries -1 and n $+1$)
Generalized Pauli's theorem:

1. $B^a = SA^aS^{-1}$. S is unitary and unique up to a phase;
2. there is a basis where all A^a are real;
3. Clifford algebra generated by A^a is isomorphic to the algebra of $2^n \times 2^n$ matrices.

Majorana spinors: 2^n complex vectors u satisfying $\Theta u = u$.
Θ: anti-linear involution commuting with A^a, unique up to a phase.

$n = 3$: 8-dimensional Majorana spinor ϕ (Pilaftsis (2012)).

Generators of $SU(2)_L$: $i\sigma^j \equiv \epsilon^{jkl} A_k A_l$ $(j, k, l = 1, 2, 3)$

$\Sigma_j \equiv A^{j+3}$ $(j = 1, 2, 3)$, $\Sigma_4 \equiv A^1 A^2 A^3$ and $\Sigma_5 \equiv \Sigma_1 \Sigma_2 \Sigma_3 \Sigma_4 = -A^7$.

$1, \Sigma_a$ $(a, b = 1, ..., 5)$: basis of hermitian matrices conserved by $SU(2)_L$. Σ_a anti-commute with each other.

$[\Sigma_a, \Sigma_b]$: basis of skew-hermitian matrices conserved by $SU(2)_L$, generators of $Spin(5)$ (double cover of $SO(5)$).

Rewrite set of primitive gauge-invariant operators:

- $\phi^\dagger(x) U(x, y, C) \phi(y)$ (singlet under $SO(5)$);
- $\phi^\dagger(x) U(x, y, C) \Sigma_a \phi(y)$ (**5** representation of $SO(5)$);
- $\phi^\dagger(x) U(x, y, C) [\Sigma_a, \Sigma_b] \phi(y)$ (**10** representation of $SO(5)$);

5 Observable states of 2HDM

Higgs potential (basis-invariant formalism O'Neil (2009)):

$$V(\phi) = \mu_a \phi^\dagger \Sigma_a \phi + \frac{1}{2}\lambda_{ab}(\phi^\dagger \Sigma_a \phi)(\phi^\dagger \Sigma_b \phi)$$

parameters of the potential $\Rightarrow$ background fields (spurions)

Ivanov (2006); Botella et al. (2013)

μ_0, λ_{00} singlets,
μ_a, λ_{0a} are 5-dim representations of $SO(5)$
λ_{ab} is a tensor of $SO(5)$

Lagrangian invariant under gauge $SU(2)_L$ and background $Spin(5)$.

Let $V(\phi = \frac{v}{\sqrt{2}}\phi_0)$ be absolute minimum, ($v \equiv$ vev, $\phi_0^\dagger \phi_0 = 1$).

by reparametrization $\Sigma_5 \phi_0 = \phi_0$ ($Spin(5) \to Spin(4)$)

$H_1 \equiv \frac{1+\Sigma_5}{2}\phi$ $H_2 \equiv \Sigma_4 \frac{1-\Sigma_5}{2}\phi$, at the minimum $H_2 = 0$.

isomorphism $Spin(4) \simeq (SU(2)_{R1} \times SU(2)_{R2})$

$SU(2)_{R1}$ generators $\Sigma_j \Sigma_4 (1+\Sigma_5)/2$

$SU(2)_{R2}$ generators $\Sigma_j \Sigma_4 (1-\Sigma_5)/2$

after (suitable) gauge fixing, constant $\frac{v}{\sqrt{2}}\phi_0$ minimizing the potential $i\sigma_j\phi_0 = \Sigma_4\Sigma_j\phi_0$ $(j = 1, 2, 3)$,

ϕ^0 conserves $SO(3) \times Spin(3) \simeq (SU(2)_{R1} \times SU(2)_{R2})/Z_2$,

generators $(\Sigma_4\Sigma_j(1 + \Sigma_5)/2 - i\sigma_j)$ and $\Sigma_4\Sigma_j(1 - \Sigma_5)$, respectively.

ϕ_0 fixes a system of gauge coordinates.

4 projections $\phi_0\phi_0^\dagger$ and $-\Sigma_4\Sigma_j\phi_0\phi_0^\dagger\Sigma_4\Sigma_j$ (fixed $j = 1, 2, 3$) sum to 1 and decompose the 4 dim real spinor space of $SU(2)_L$

subspace $\propto \phi_0$: $\phi_0^\dagger H_1$, $\phi_0^\dagger H_2$.

subspace $\propto \Sigma_4\Sigma_j\phi_0$: would-be Goldstone bosons $\phi_0^\dagger\Sigma_4\Sigma_j H_1$ and $\phi_0^\dagger\Sigma_4\Sigma_j H_2$.

3 projections for the triplet of $SU(2)_L$,

subspace $\propto (\phi_0 \otimes \Sigma_4\Sigma_j\phi_0 - \Sigma_4\Sigma_j\phi_0 \otimes \phi_0)$: $\phi_0^\dagger D_\mu\Sigma_4\Sigma_j\phi_0 = \frac{g}{2}W_\mu^j$.

expand $\sqrt{2}\phi = v\phi_0 + \varphi$

Assuming the fluctuations φ small in average compared to v

$J(SU(2)_{R1})$	$J(SU(2)_{R2})$	Operator	Expansion
0	0	$H_1^\dagger H_1$	$\frac{v^2}{2} + v\phi_0^\dagger \varphi$
1/2	1/2	$H_1^\dagger \Sigma_a \Sigma_4 H_2$	$\frac{v}{2}\phi_0^\dagger \Sigma_a \varphi$
1	0	$H_1^\dagger D_\mu \Sigma_j \Sigma_4 H_1$	$\frac{gv^2}{4} W_\mu^j$

($j = 1, 2, 3$ and $a = 1, 2, 3, 4$, first terms in expansion only)

other primitive invariants involving ≤ 1 covariant derivative expand to ≥ 2 elementary fields at leading order, since the vev contribution to H_2 is null.

Possible to use further covariant derivatives, but cannot expand to 1 elementary field, as there are none with other Lorentz quantum numbers.

6 Spontaneous symmetry breaking in 2HDMs

If absolute minimum not unique (up to gauge transformations),
fixing $\Sigma_5\phi_0 = \phi_0$ is in conflict with a global symmetry.

If the symmetry is spontaneously broken, then such a would-be global symmetry of the model is explicitly broken by an infinitesimal parameter.

It may occur in 2HDMs (lattice Lewis and Woloshyn (2010))
depending on the Higgs potential.

Finite lattice , no spontaneous symmetry breaking:
estimate the results for the infinite-volume limit and then extrapolate the estimates to $J \to 0$

Lewis and Woloshyn (2010): Done for continuous symmetry breaking in a 2HDM.

7 The FMS mechanism

Frohlich, Morchio, and Strocchi (1981) (group-theory) correspondence:

$$H_1 \Leftrightarrow \frac{v}{\sqrt{2}}\phi_0 (\text{fixes gauge coordinate system})$$
$$\text{gauge} - \text{invariant states} \Leftrightarrow \text{elementary gauge} - \text{dependent fields}$$

one-to-one (set of primitive states), except for would-be Goldstone bosons

$\phi_0^\dagger \Sigma_4 \Sigma_j H_1$ disappear from the spectrum,

$\Sigma_4 \Sigma_j$ is skew-adjoint so $H_1^\dagger \Sigma_4 \Sigma_j H_1 = 0$.

Complete expansion:

$$2H_1^\dagger H_1 = v^2 + 2v\phi_0^\dagger\varphi + \varphi^\dagger\varphi$$

$v\phi_0^\dagger\varphi$, $\varphi^\dagger\varphi$ same quantum numbers, to distinguish:

- approximately by the energy spectrum
- or in perturbation theory.

recall KLN theorem sum all initial and final states (incl. soft photons) with same quantum number in a energy window $\Rightarrow$ infrared finite.

Assuming $\varphi^\dagger\varphi \approx$ scattering state, energy spectrum $\gtrsim 2m_H \neq m_H$.

In perturbation theory, for asymptotic state the mass is on-shell m_H, so contribution from $\varphi^\dagger\varphi$ negligible.

For intermediate states, since the (gauge-invariant) Lagrangian is the same no deviations expected.

Calculating the spectrum and testing the FMS mechanism in the lattice is an extension of Maas (2013); Wurtz and Lewis (2013); Maas and Mufti (2014, 2015)

We must still account for precision electroweak observables
In any case, Frohlich et al. (1981)
"standard perturbation expansion cannot be asymptotic to gauge-dependent correlation functions."

8 $Spin(4)$ symmetric 2HDM for the lattice

$$V(\phi) = \mu_0\phi^\dagger\phi + \mu_5\phi^\dagger\Sigma_5\phi$$
$$+ \frac{1}{2}\lambda_{00}(\phi^\dagger\phi)^2 + \lambda_{05}(\phi^\dagger\phi)(\phi^\dagger\Sigma_5\phi) + \frac{1}{2}\lambda_{55}(\phi^\dagger\Sigma_5\phi)^2$$

To avoid breaking the $Spin(4)$ group, $\pm\Sigma_5\phi_0 = \phi_0$. For $\lambda_{05} = 0$:

1. ("control sample") $\mu_5 > 0$, $\lambda_{55} = 0$, realistic Bhupal Dev and Pilaftsis (2014) Maximally-Symmetric 2HDM.
2. $\mu_5 \to 0$ with $\mu_5 > 0$ and $\lambda_{55} \neq 0$, spontaneous symmetry breaking of the discrete Z_4.
3. $\mu_5 \to 0$ with $\mu_5 > 0$ and $\lambda_{55} = 0$, spontaneous symmetry breaking of the continuous $Spin(5) \to Spin(4)$. 4 massless Goldstone bosons.

$< H_1^\dagger(y) H_1(y) H_1^\dagger(x) H_1(x) >$ and $< H_2^\dagger(y) H_2(y) H_2^\dagger(x) H_2(x) >$

After gauge fixing, we can expand them as:

$$< H_1^\dagger(y) H_1(y) H_1^\dagger(x) H_1(x) > \approx \frac{v^4}{4} + \frac{v^2}{2} < \varphi^\dagger(y) \phi_0 \phi_0^\dagger \varphi(x) > + ...$$
$$< H_2^\dagger(y) H_2(y) H_2^\dagger(x) H_2(x) > = < \varphi_2^\dagger(y) \varphi_2(y) \varphi_2^\dagger(x) \varphi_2(x) >$$

where $\varphi_2 \equiv \phi_0^\dagger \Sigma_4 \varphi$.
Neglecting interactions, energy spectrum $\gtrsim m_h$ and $\gtrsim 2m_H$.

$\mu_5 \to 0$, check if Z_4 symmetry is recovered.
If $\mu_5 = 0$ by definition the correlations are Z_4 symmetric.

9 Summary

Assuming gauge symmetry breaking or using only complex representations of groups is not enough to study the phenomenology of multi-Higgs-doublet models

For multi-Higgs-doublets, the FMS mechanism justifies that the spectrum is well described by the gauge-dependent elementary states.

If not, the physical states would, as in QCD, require non-perturbative methods, even at weak coupling.

The assumptions:
the field fluctuations around the vacuum are small in average
and there is spontaneous symmetry breaking of the global symmetry when the gauge orbit minimizing the Higgs potential is not unique.

To confirm the FMS mechanism and assumptions requires non-perturbative calculations, next step.

(Addition of photons and fermions in 1601.02006)

Next?

Classical electrodynamics: gauge-invariant local states

Quantum U(1) gauge: either
gauge-invariant non-local states or gauge-dependent local states

Quantum SU(2) gauge: gauge-invariant local states (Higgs mechanism)
Quantum SU(3) gauge: gauge-invariant local states (confinement)

To me, we need to look for gauge-invariant local states in U(1).
Implies probabilities instead of amplitudes Weinberg (2014), in-in formalism
And to work with phaseless (real) operators Pedro (2013)

In the mean time, gauge-dependent local states in U(1)

option 1) ok for abelian Higgs mechanism
(Ginzburg-Landau Superconductivity),

the Higgs mechanism is based in the fact:

breaking local gauge symmetries $\neq$ global symmetries

the Goldsone theorem does not apply
the Nambu-Goldstone bosons may be absent.

Englert (2014) "The vacuum is no more degenerate and strictly speaking there is no spontaneous symmetry breaking of a local symmetry.[...]

The disappearance of the NG boson is thus an immediate consequence of local symmetry. The above argument (Englert, 2005) was formalized much later (Elitzur, 1975)"

10 Introducing Photons

$U(1)_Y$ gauge symmetry with generator $\Sigma_1\Sigma_2$:

background symmetry: $(U(1)_Y \times Spin(3)) \rtimes Z_4$
custodial $Spin(3)$ generators $\Sigma_3\Sigma_4$, $\Sigma_3\Sigma_5$, $\Sigma_4\Sigma_5$
Z_4 generated by the charge reversal transformation $\phi \to \Sigma_2\Sigma_3\phi$.

The $U(1)_Y \times Spin(3)$ is a normal subgroup.
Any transformation is the product of:
element of $U(1)_Y \times Spin(3)$ and element of Z_4.

Parity and charge reversal are conserved separately in the absence of fermions
under charge reversal $B_\mu \to -B_\mu$.

Neutral vacuum condition: ϕ_0 aligned along linear combination of $\Sigma_{3,4,5}$.

11 Introducing Fermions

Quark field Q_L, $\Sigma_1\Sigma_2 Q_L = iQ_L$, $\Sigma_5 Q_L = Q_L$ and transforming under $SU(2)_L$ as ϕ.

Most general Yukawa couplings with the quarks:

$$-\mathcal{L}_{Y_Q} = \overline{Q_L}\ \Gamma_d \phi\ d_R + \overline{Q_L}\ \Sigma_3\Sigma_1\Gamma_u\phi\ u_R + \text{h.c.}$$
$$\Gamma_w \equiv \Gamma_{w\,0} + \Gamma_{w\,1}\Sigma_3\Sigma_4 + \Gamma_{w\,2}\Sigma_4\Sigma_5 + \Gamma_{w\,3}\Sigma_5\Sigma_3)$$

Γ_{wa} self-conjugate and acting as real scalars on ϕ
$w = u, d$ and $a = 0, 1, 2, 3$.

The custodial $Spin(3)$ group acts on ϕ and $\Gamma_w^\dagger$ in the same way, the product $\Gamma_w\phi$ is $Spin(3)$ invariant.

By reparametrization of Γ_w, $\Sigma_5\phi_0 = \phi_0$. In this basis
$H_1 \equiv \frac{1-i\Sigma_1\Sigma_2}{2}\frac{1+\Sigma_5}{2}\phi$,
$H_2 \equiv \Sigma_4\Sigma_5\frac{1-i\Sigma_1\Sigma_2}{2}\frac{1-\Sigma_5}{2}\phi$,
$\widetilde{H}_j \equiv \Sigma_3\Sigma_1 H_j^*$.

$$
\begin{aligned}
-\frac{v}{\sqrt{2}}\mathcal{L}_{Y_Q} \qquad &= \overline{Q_L}\ H_1 M_d d_R + \overline{Q_L}\ H_2 N_d^0 d_R \\
&+\overline{Q_L}\ \widetilde{H}_1 M_u u_R + \overline{Q_L}\ \widetilde{H}_2 N_u^0 u_R + \text{h.c.},
\end{aligned}
$$

where $M_w \equiv \Gamma_{w0} + i\Gamma_{w1}$, $N_w^0 \equiv \Gamma_{w3} + i\Gamma_{w4}$.

Majorana masses in seesaw I (νMSM) gauge singlets $\Rightarrow$ nonperturbative $\checkmark$

- $H_1^\dagger i D_\mu \Sigma_1 \Sigma_3 H_1$ (W_μ^+)
- $\cos\theta_W H_1^\dagger i D_\mu H_1 - \sin\theta_W \frac{gv^2}{4} B_\mu$ (Z_μ)
- $\mathcal{A}_\mu \equiv \sin\theta_W H_1^\dagger i D_\mu H_1 + \cos\theta_W \frac{gv^2}{4} B_\mu$ (A_μ)
- $H_1^\dagger H_1$ (h)
- $H_1^\dagger \Sigma_4 H_2$ (R)
- $H_1^\dagger \Sigma_3 H_2$ (I)
- $H_1^\dagger \Sigma_1 H_2$ (H^+)

$H_1^\dagger Q$ (d_L)

$\tilde{H}_1^\dagger Q$ (u_L)

$H_1^\dagger L$ (e_L)

$\tilde{H}_1^\dagger L$ (ν_L)

$$\Sigma_5 \phi_0 = \phi_0$$
$$H_1 \equiv \frac{1-i\Sigma_1\Sigma_2}{2}\frac{1+\Sigma_5}{2}\phi$$
$$H_2 \equiv \Sigma_4\Sigma_5\frac{1-i\Sigma_1\Sigma_2}{2}\frac{1-\Sigma_5}{2}\phi$$

Yang (1952) “It is the purpose of the present paper to calculate the spontaneous magnetization (i.e. , the intensity of magnetization at zero external field) of a two-dimensional Ising model of a ferromagnet.”

Spontaneous as particular case of Explicit symmetry breaking.
Other *equivalent* (for the Ising model) definitions:

“The spontaneous magnetization I per atom is exactly the usual long-range order parameter s which may be defined as the average of the absolute value of the total spin of the lattice divided by the number of atoms.

That I is equal to s is easily seen-from the fact that the introduction of a vanishingly weak positive magnetic field merely cuts out all states of the lattice for which the total spin is negative.”

't Hooft (1980) "the words "spontaneous breakdown" are formally not correct for local gauge theories. The vacuum *never* breaks local gauge invariance because it itself is gauge invariant.

The neutral intermediate vector boson is the "meson"

$$\phi^\dagger D_\mu \phi = i\frac{gv^2}{4} W^3_\mu + \text{total derivative} + \text{higher orders}$$

The $W^\pm_\mu$ are obtained from the "baryons" $\epsilon_{ij}\phi^i D_\mu \phi^j$, and the Higgs particle can also be obtained from $\phi^\dagger \phi$.

Is there no fundamental difference then between a theory with spontaneous breakdown and a theory with confinement? Sometimes there is. In the above example the Higgs was a faithful representation of $SU(2)$. This is why the above procedure worked."

Fröhlich et al. (1981) "the relevant feature is the structure of the residual group." (defined by the minimizing orbit of the Higgs potential)

Implications for one Higgs doublet from lattice sim.:

Maas and Mufti (2015) $m_h < m_W \Rightarrow$ non-perturbative effects rule

Gies and Sondenheimer (2015) (top-bottom-Higgs system)
non-perturbative effects affect (in)stability of the Higgs potential

...and a big unknown
mostly unexplored, due to technology and mathematical limitations

Careful, non-perturbative effects for small couplings are common
e.g. Hydrogen energy levels

despite that for larger couplings, larger non-perturbative effects expected

Background symmetries

background field or spurion:

- fixed when minimizing the action
- non-trivial representation of background symmetries

when calculating observables, spurions $\Rightarrow$ numerical values.

observables invariant under group of background symmetries

Ivanov (2006) reparametrization

Haber and Surujon (2012) basis transformation that do not change the Lagrangian's functional form or spurion analysis

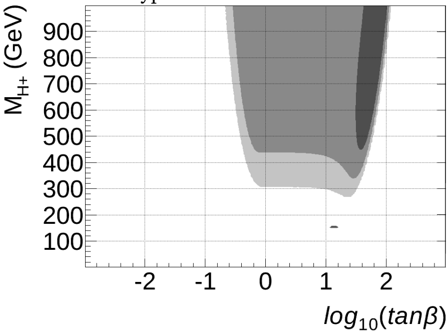
Botella et al. (2013) weak-basis transformations

Georgi (2009) spurions as source fields

11.1 A contribution for a systematic search for FCNCs

BGL analysis code: cftp.ist.utl.pt/∼ leonardo

Test on 2HDM type II:



Giac and Ginac (C++ algebra systems) available (also Flavour Kit, etc.);

Using LLVM the code generation of GiNaC can be improved;

Library containing many known formulas for decays important for FCNC;(contribution)

Library making global fits, from models, from formulas, from experimental data (contribution)

Library containing the experimental data distributions.

(CERN-based ROOSTATS-like package for FCNCs?)

Beyond the Standard Model

Branco and Emmanuel-Costa (2014) the simplest scheme to break spontaneously:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{em}$$

$\Rightarrow$ One Higgs Doublet

Ellis (2013) QCD, ElectroWeak, Flavour $\Rightarrow$ Experiments ✓

ν masses and mixing, baryon asymmetry,
dark matter, CMB fluctuations

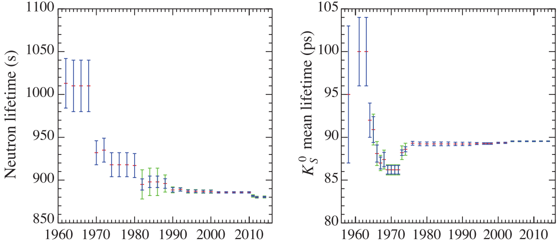
$\Rightarrow$ New Physics

Altarelli (2014) νMSM(3 ν_R, Seesaw I)+inflaton field $\Rightarrow$ Experiments ✓

gravity;cosmological const.(dark energy);hierarchy;strong CP;
arbitrariness;meta-stability;non-perturbative definition;
accidental suppression of FCNCs,EDMs,p^+ decay

Contributions from Social Sciences

PDG (2014)



Wanke (2013) *"significant jumps, pointing either to a common systematic shift or to the effect of biased analyses."*

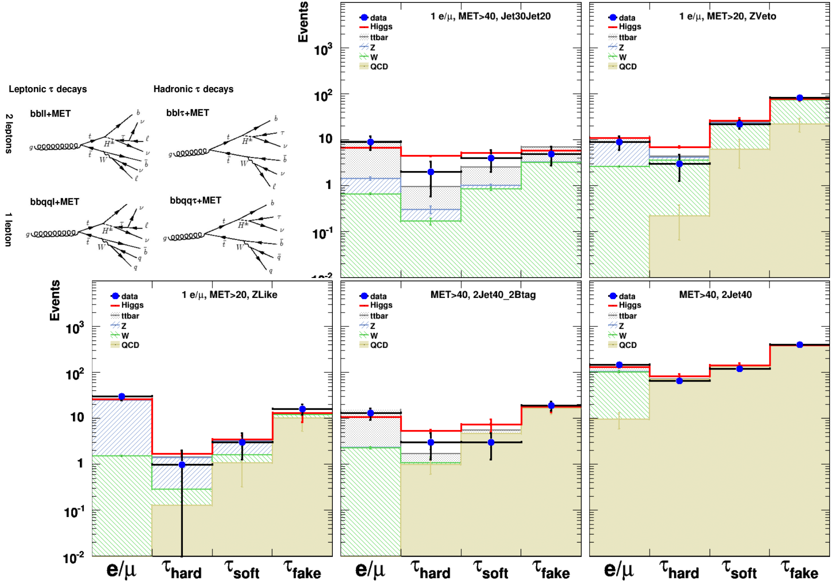
Borrelli (2013) presented at CERN *"As far as theorists are concerned, the role of personal skills seems to be a major factor in the choice of models to work on."*

Kahnemann(2002)

Nobel in Economics Lecture

"people rely on a limited number of heuristic principles which reduce the complex tasks of assessing probabilities and predicting values to simpler judgmental operations. In general, these heuristics are quite useful, but sometimes they lead to severe and systematic errors."

Correlations are important in data analysis



to attribute to new physics a deviation in data

Top-down and Bottom-up approaches

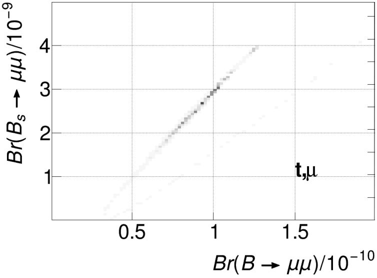
Buras and Girrbach (2014)

models (e.g. BGL) vs. effective field theory (e.g. MFV)

- correlations between observables

  low/high energy, all flavours, hadronic/leptonic
- less sensitive to free parameters
- patterns of flavour violation
- may differ from the SM and MFV

For BGL:



Extend the scalar sector to study Higgs mechanism and SM problems.
But constrain FCNCs, Flavour and CP violation pattern accounted by SM.