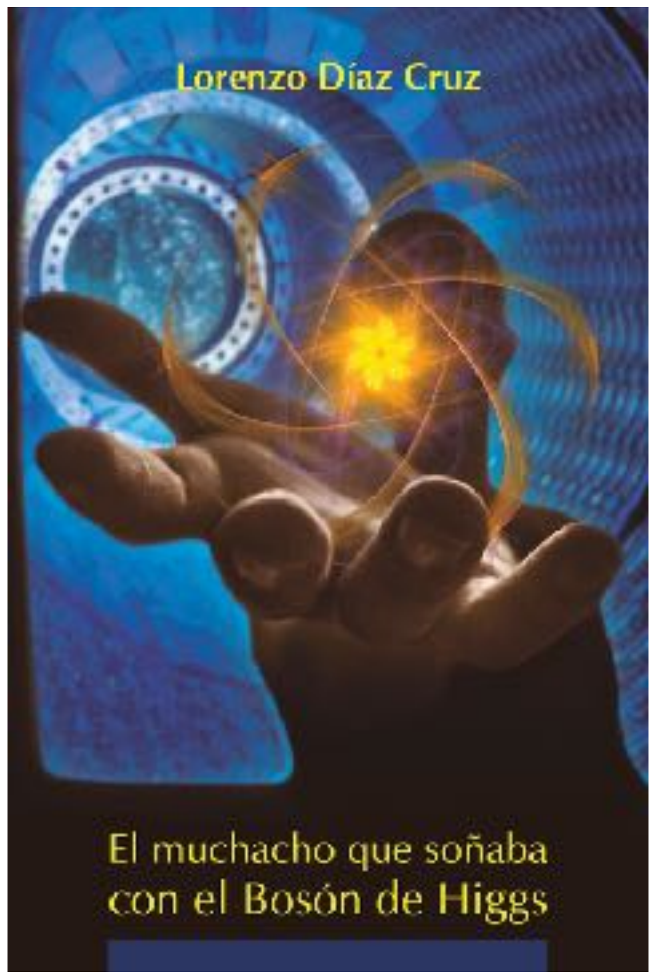
Light Higgs,
Hierarchy problem and
still no new physics



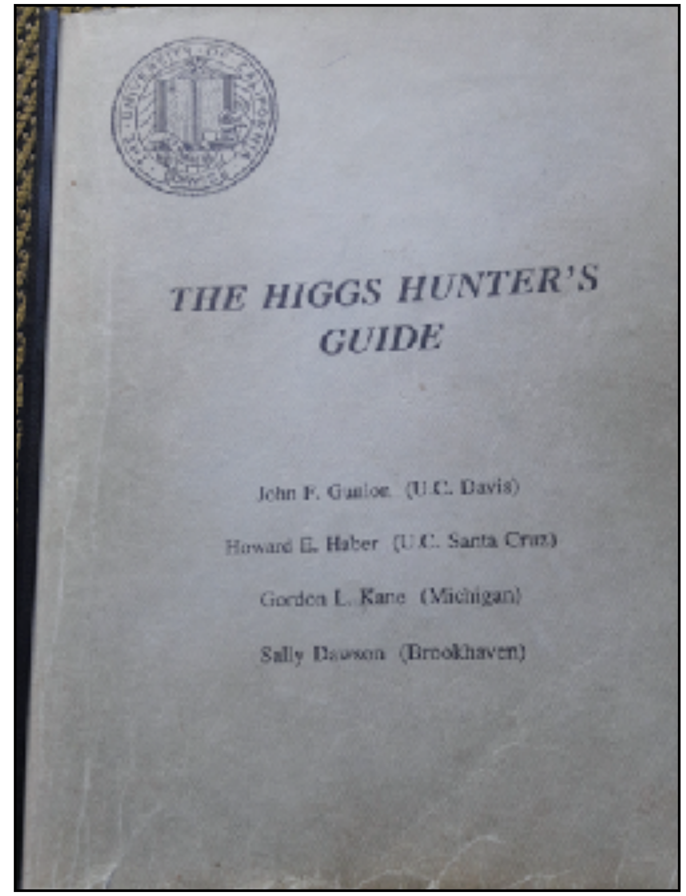
J. Lorenzo Diaz Cruz, CIIEC & CIFFU & FCFM-BUAP

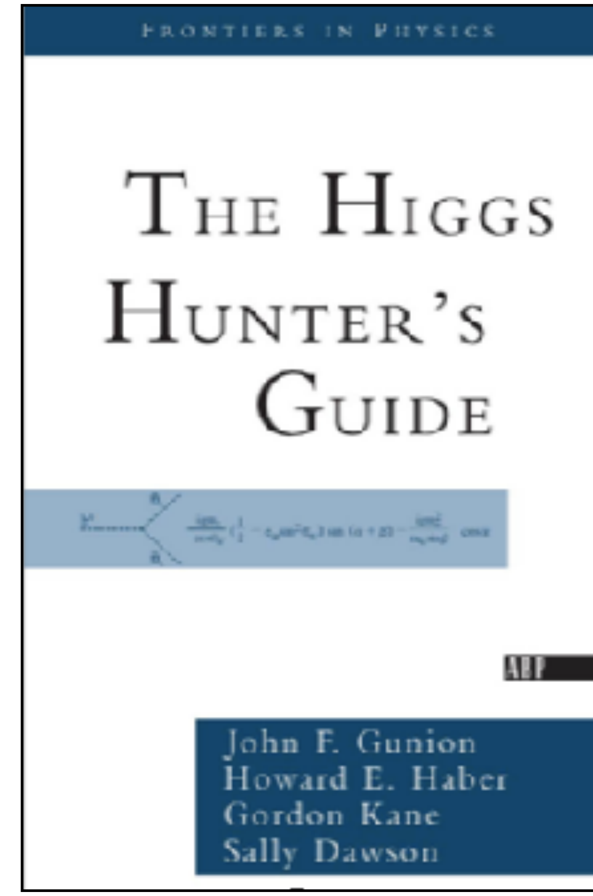
Annual meeting of DPyC-SMF, CDMX, June, 2024

A Particle Physics Riddle: Why the SM got more and more robust?

When I was younger, so much younger than today:

- The top quark mass was not known,
- The Higgs mass was allowed to be from a few GeV to many TeV´s (but many doubted it existed!),
- The SM was considered ugly and just a provisional step,
- There was confidence that a great theory was waiting just around the corner …
- Then Nature spoke! … A light Higgs was found at LHC; no BSM physics showed up (no DM wimps neither!),
- So, what went wrong? HELP or Let it be?

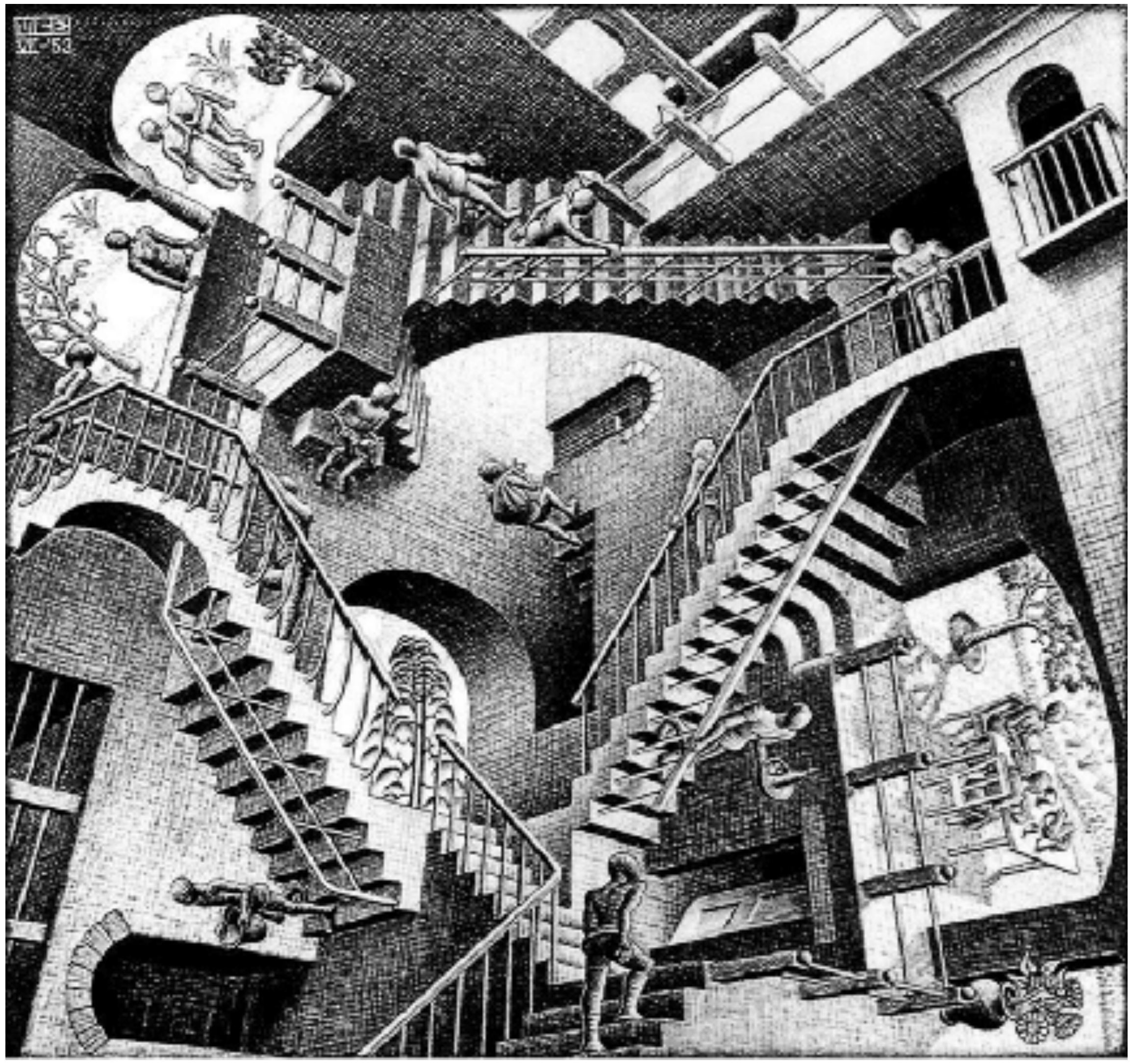




we gratefully acknowledge fruitful discussions with T. Banks, W. Buchmüller L. Bergstrom, C. Bernard, P. Burchat, M. Chanowitz, S. Chivukula, A. Cohen, J.L. Diaz-Cruz, J. Donoghue, M. Einhorn, H. Georgi, M. Golterman, B. Grinstein, B. Holdom, G. Hou, D. Kaplan, A. Khare, S. Komamiya, J. Kuti, A. Manohar, W. Marciano, P. Nason, A. Nelson, M. Peskin, E. Rabinovici, S. Raby, L. Randall, S. Rindani, M. Shifman, G. Valencia, M. Voloshin, G. West, and R. Willey. We are particularly grateful to Paula Franzini for her numerous comments on the manuscript. Other helpful comments have been provided by S. Bertolini, A. Buras, M. Duncan, M. Golden, P. Langacker, A. Linde, R. Petronzio, P. Roy, S. Sharpe, and P. Taxil. We would like to thank the following experimentalists who assisted us in ascertaining limits on light Higgs bosons: J. Lee-Franzini, Paulo Franzini, L. Littenberg, P. Meyers, H. Nelson, T. Shinkawa, B. Winstein, and M. Zeller.

Content:

1. Introduction-
2. Higgs hunting (From the early days to LHC),
3. The Higgs problems (& BSM Physics)
4. The SM structure and the Higgs sector,
5. Dark Matter & FIMPS
6. Conclusions.



1. The SM and the Higgs boson

- The SM is not a theory of everything, but still it is a great theory …

- The SM includes plenty of beautiful physics concepts: cancelation of anomalies, Spontaneous Symmetry Breaking & Renormalization, asymptotic freedom, confinement, chiral symmetry breaking, etc.

- It was born and evolved as:

SU(2)xU(1) model of leptons (Glashow) ->
Model of leptons+Higgs (SSB) (Weinberg) ->
2-family of quarks and leptons (GIM) ->.
3 family with mixing and CPV (KM) -> QCD,

S.L. Glashow, Nuclear Physics B (1961)

Abstract

Weak and electromagnetic interactions of the leptons are examined under the hypothesis that the weak interactions are mediated by vector bosons. With only an isotopic triplet of leptons coupled to a triplet of vector bosons (two charged decay-intermediaries and the photon) the theory possesses no partial-symmetries. Such symmetries may be established if additional vector bosons or additional leptons are

A Model of Leptons

Steven Weinberg (MIT, LNS)
Nov, 1967

3 pages
Published in: *Phys.Rev.Lett.* 19 (1967) 1264-1266,

Weak Interactions with Lepton-Hadron Symmetry

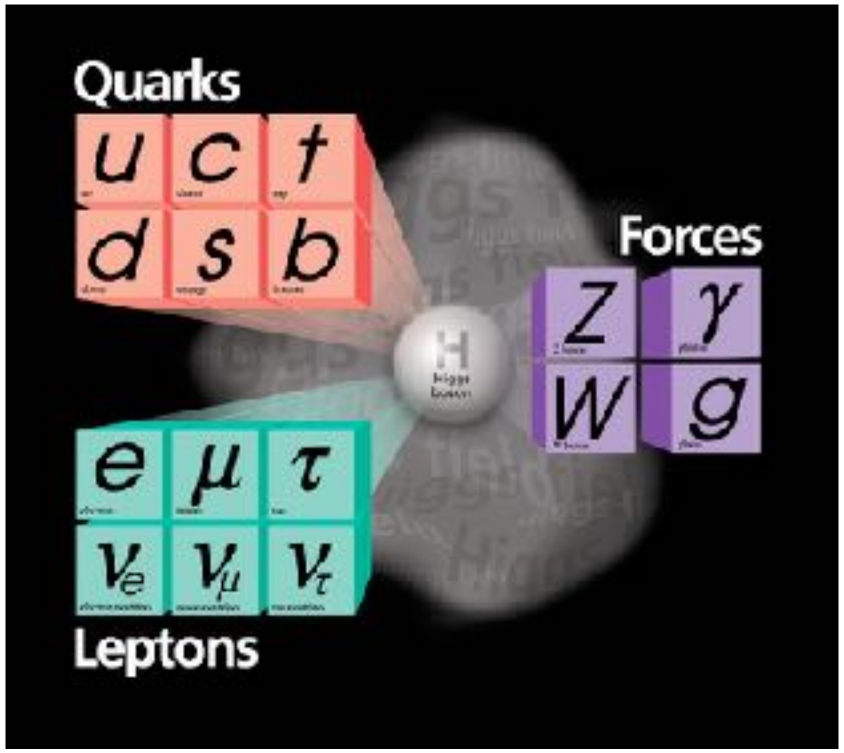
S. L. Glashow, J. Iliopoulos, and L. Maiani
Phys. Rev. D 2, 1285 – Published 1 October 1970

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

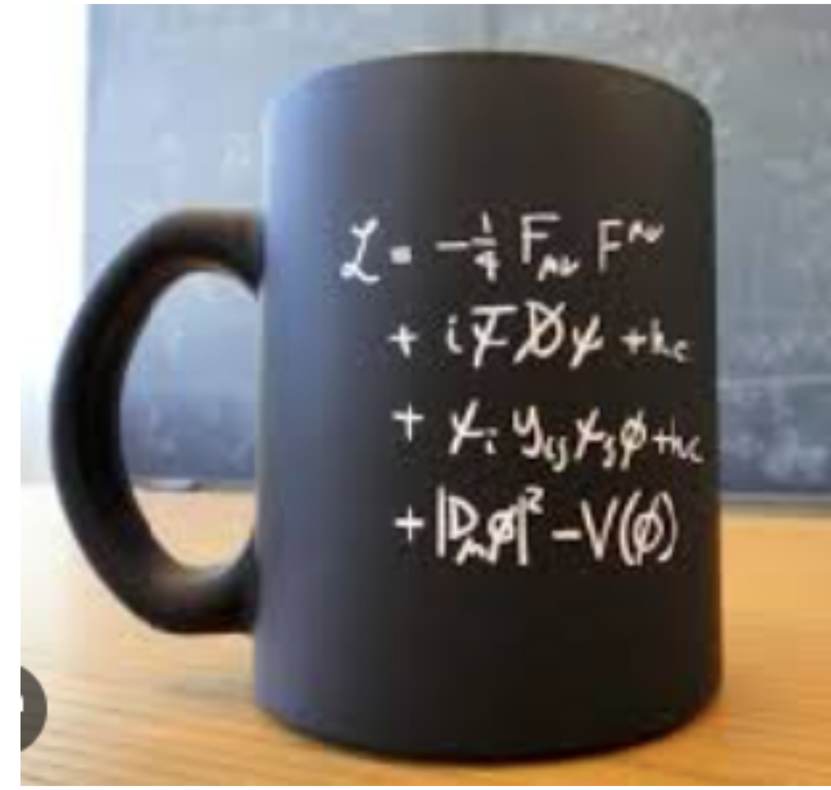
The Standard Model is a great Theory

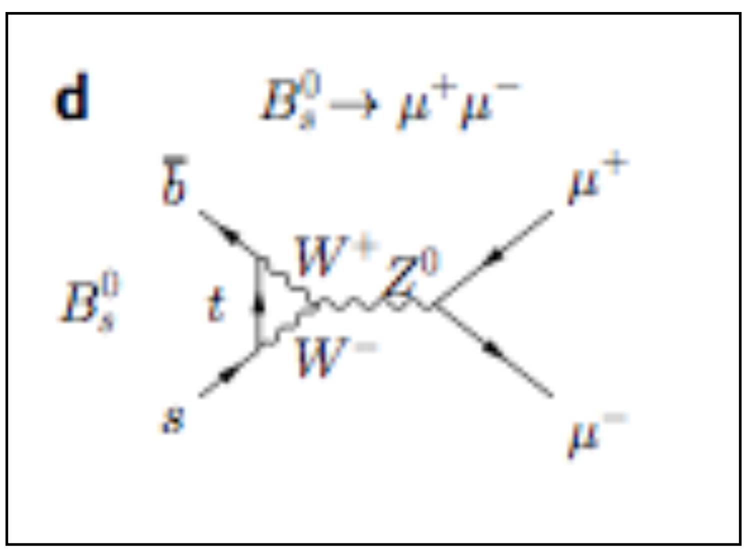


- It started as a "model for leptons", now it is a Superb theory,

- Success includes predictions/discovery of:

 - Neutral Currents, Charm, W,Z, 3rd family, Higgs, etc.





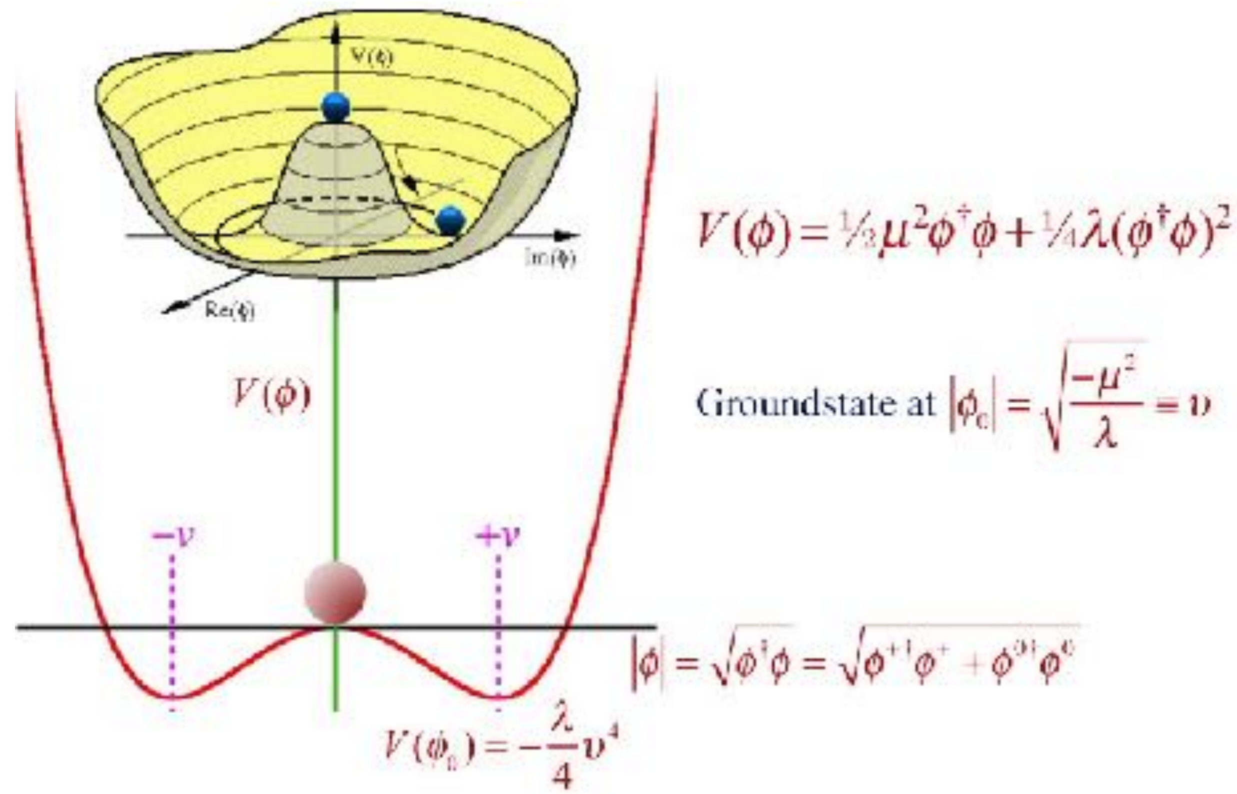
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.65 \pm 0.23) \times 10^{-9}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm exp} = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

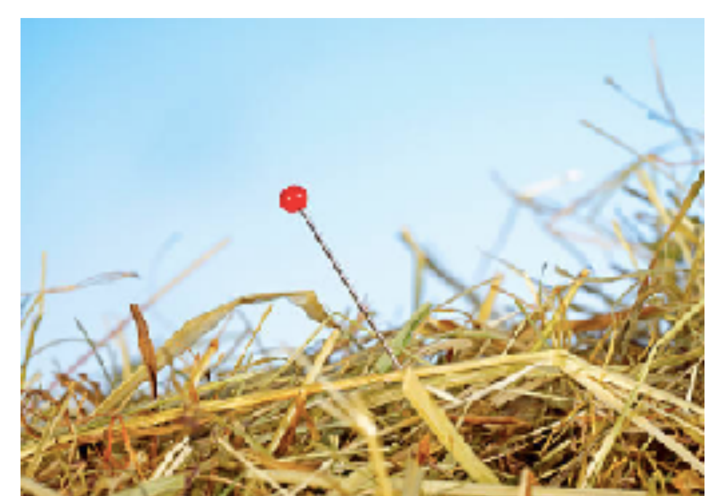
Quarks, Leptons & Gauge bosons were detected in XX century, only missing element: Higgs boson

SM Higgs Physics

- The SM contains one Higgs doublet, after SSB a physical scalar remains (=The Higgs boson aka God´s Particle),
- The essential feature of the SM Higgs is that it couples to the mass, which determines its decay modes and production mechanisms,
- Within the SM, the Higgs mass is not predicted, i.e. mh = lambda*v/sqrt(2),
- So, despite some early doubts, HEP community started the Higgs Hunting .. But where? how? when?



$$
\begin{aligned}
L &= Y_f\bar{\psi}\psi\phi + ... \\
&= Y_f\bar{\psi}\psi(v+h) + ... \\
&= (Y_f v)\bar{\psi}\psi + Y_f\bar{\psi}\psi h + ... \\
&= m_f\bar{\psi}\psi + \frac{m_f}{v}\bar{\psi}\psi h + ...
\end{aligned}
$$



2. Higgs hunting: from early days to LHC

- Key params. for Higgs search: m_higgs & m_top
- In the early 80´s: mt > 60-75 GeV,
- Unitarity and Pert. -> mh < O(1) TeV,
- Thus, Higgs mass range was divided into:

- light: mh<mZ,
- intermediate: mZ < mh < 2mt,
- Heavy/Obese: 2mt < mh < 600 GeV- O(1) TeV

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

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Decays of heavy charged Higgs bosons

J. L. Díaz-Cruz and M. A. Pérez
Phys. Rev. D 33, 273 – Published 1 January 1986

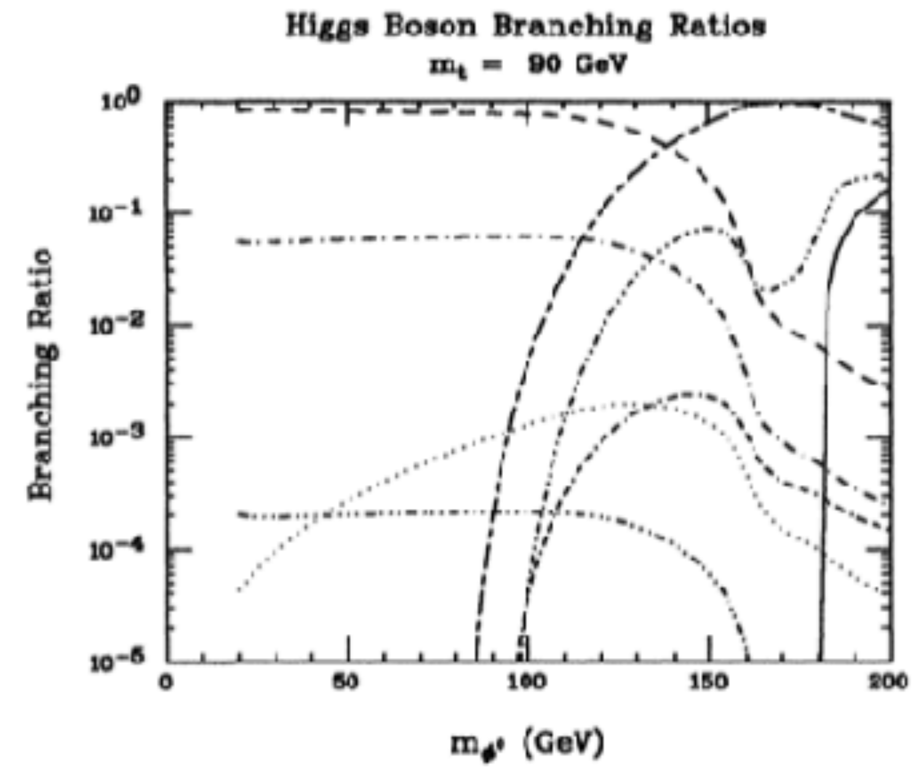


Figure 2.6 The branching ratios for ϕ^0 decay to a variety of channels, for $m_t = 90$ GeV. The curves for the various channels are: solid = $t\bar{t}$; dashes = $b\bar{b}$; dashdot = $\tau^+\tau^-$; longdash-shortdash = WW or WW^* (with no W, W^* branching ratios included); dash-doubledot = ZZ^* (no Z, Z^* branching ratios included); dots = $\gamma\gamma$; doubledash-dot = $Z\gamma$; dash-tripledot = $\mu^+\mu^-$. Since the gg decays are not experimentally useful, they are not plotted. Radiative corrections to $\Gamma(\phi^0 \to b\bar{b})$ [see fig. 2.2] have been included.

Rapid Communication

Higgs-scalar decays: $H \to W^{\pm} + X$

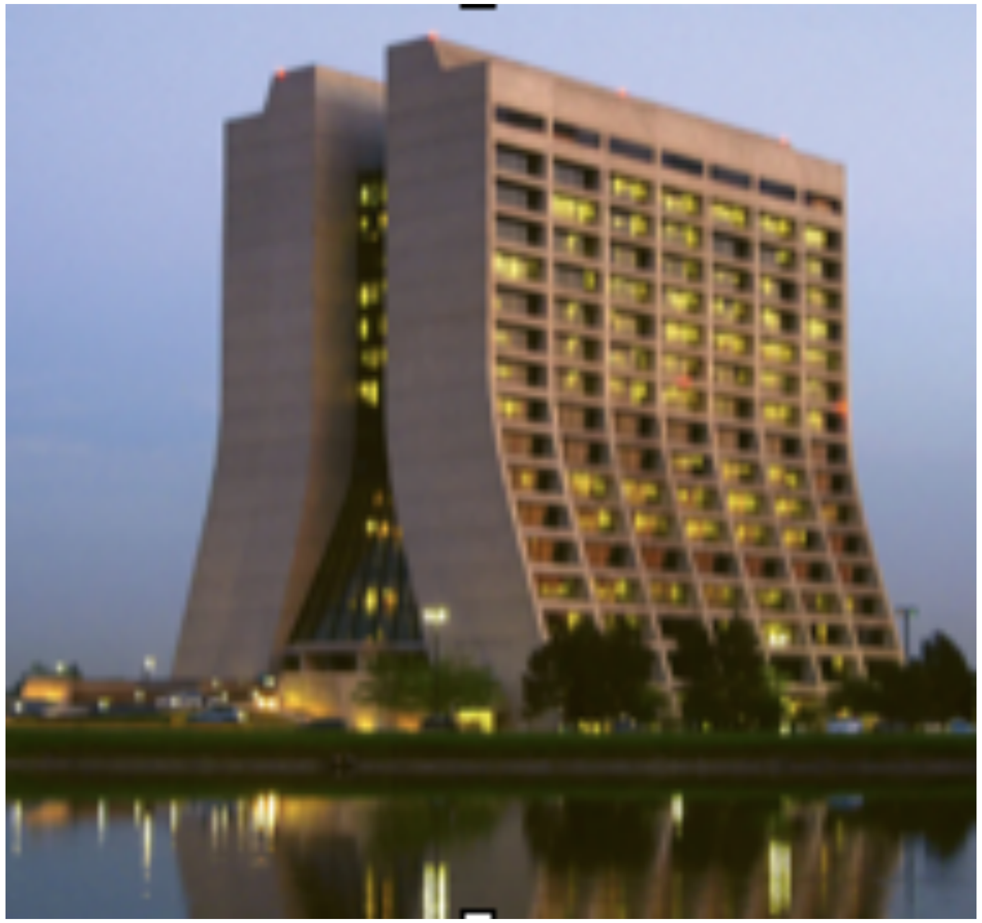
Wai-Yee Keung and William J. Marciano
Phys. Rev. D 30, 248(R) – Published 1 July 1984

Article | References | Citing Articles (86) | PDF | Export Citation

ABSTRACT

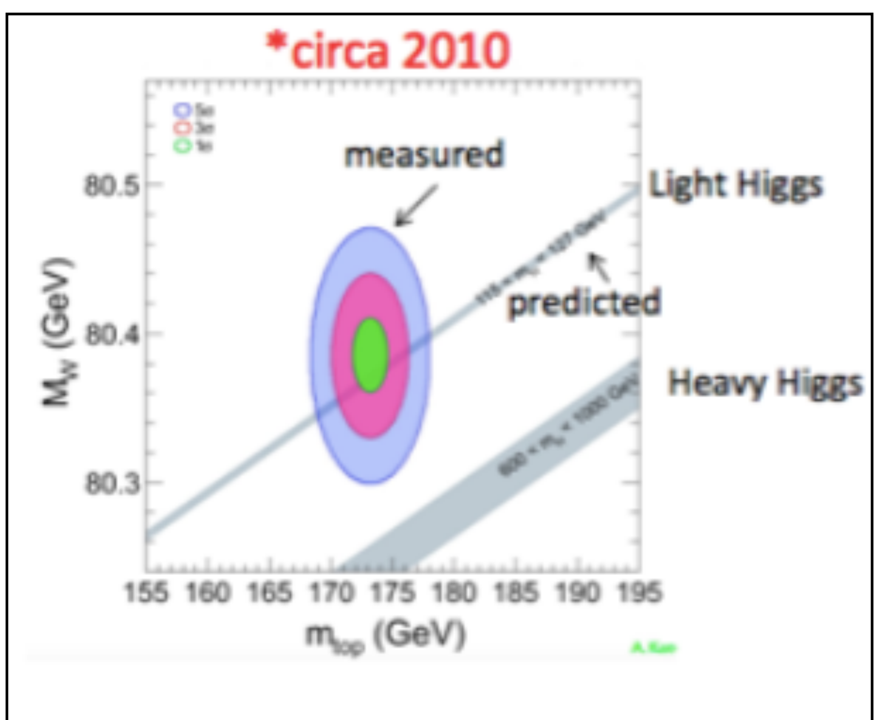
Decays of a Higgs scalar in the mass range $m_W \lesssim m_H \lesssim 2m_W$ (m_W = $W^{\pm}$ mass ~ 83 GeV) are examined. For $m_H \gtrsim 125$ GeV, the branching ratio for $H \to W^{\pm} + X$ is found to be substantial, provided the top quark is heavy, $m_t > \frac{m_H}{2}$. Implications of our results for hadron-hadron-collider experiments are briefly discussed.

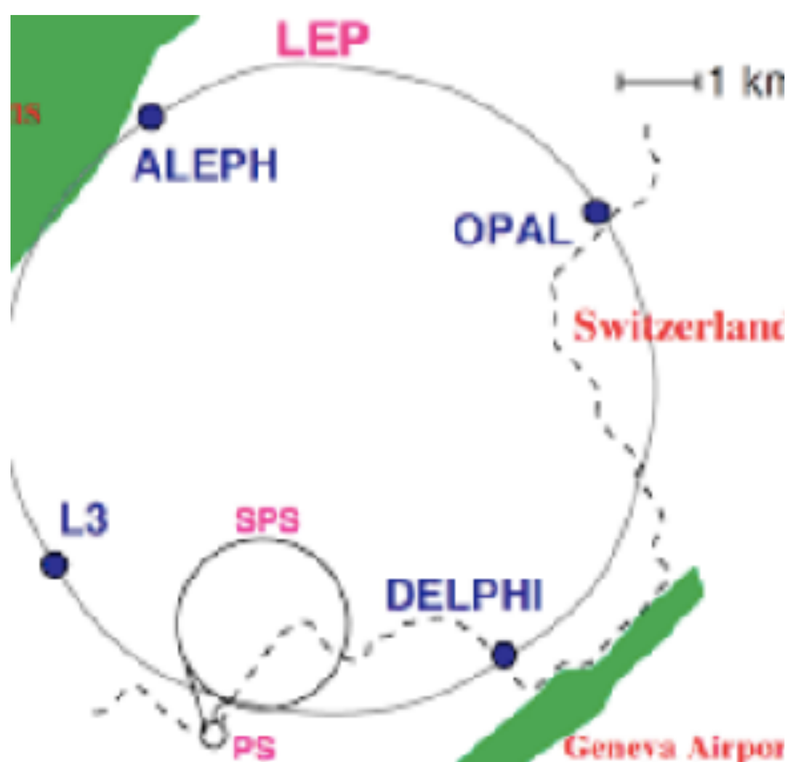
Received 28 March 1984

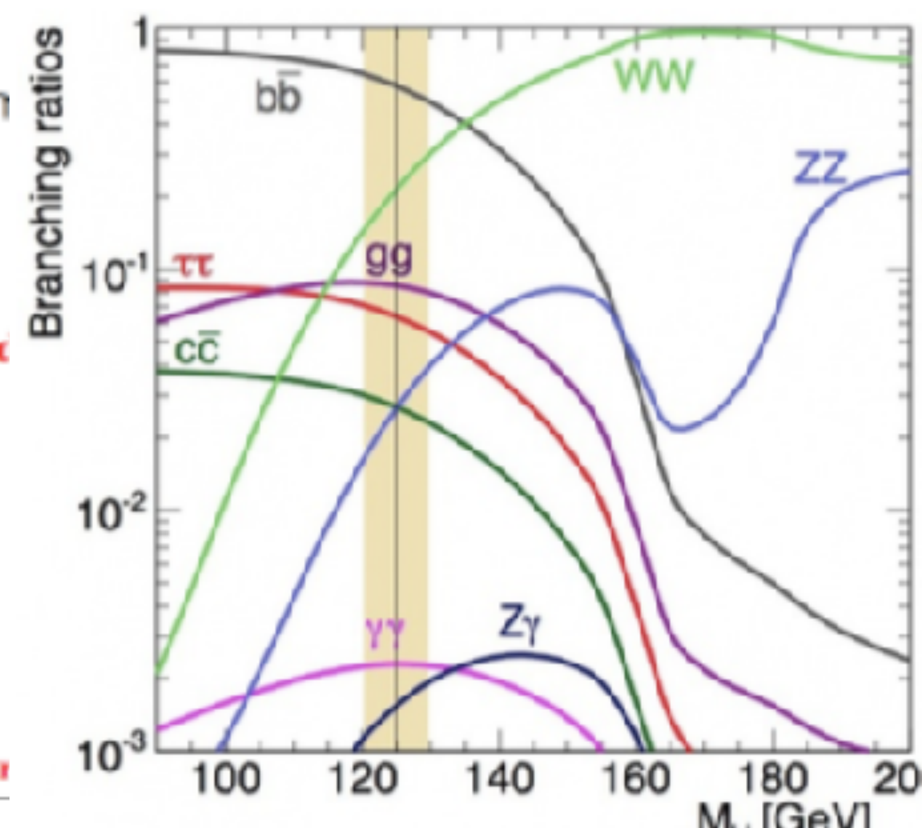


- Tevatron found top quark, with mt= 173 GeV,
- Then, IM Higgs region faded away,
- LEPII provided limit: mh > 105 GeV,
- Tevatron excluded the range around 160-170 GeV,
- EWPT improved limits, such that Higgs mass was restricted to the range: 105-130 GeV,

(This was Higgs mass range left for LHC),

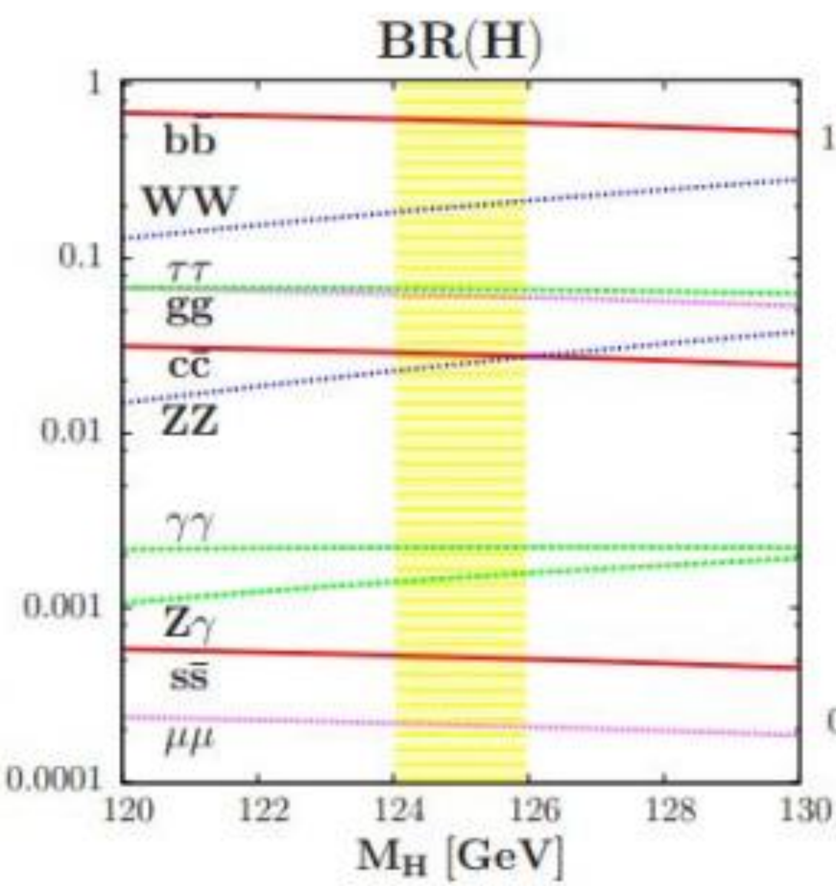


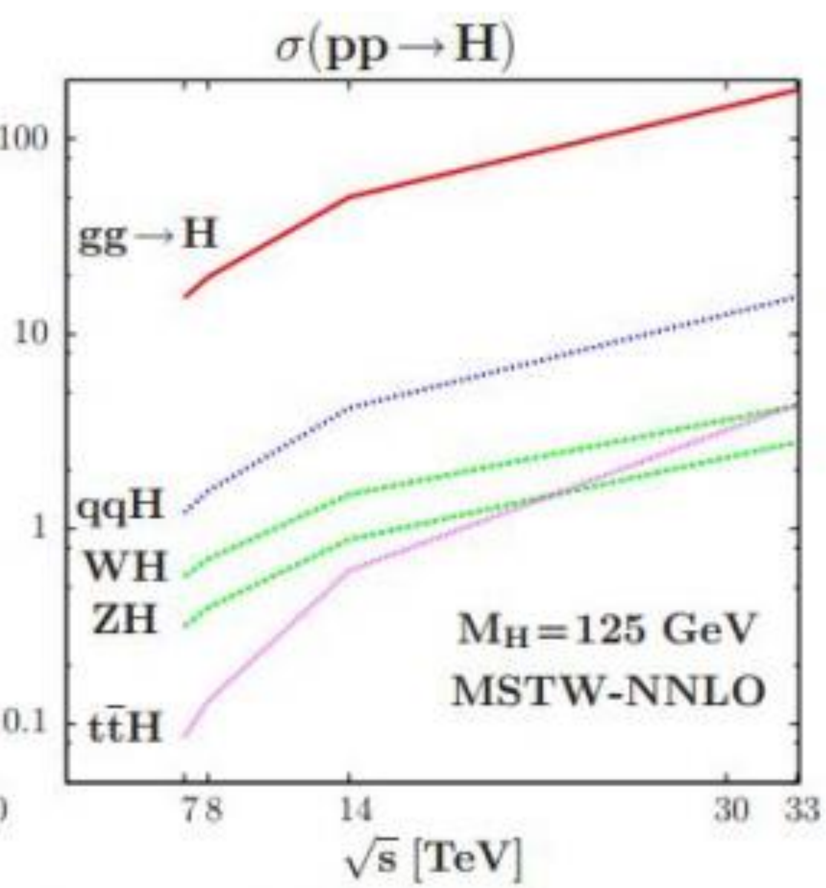


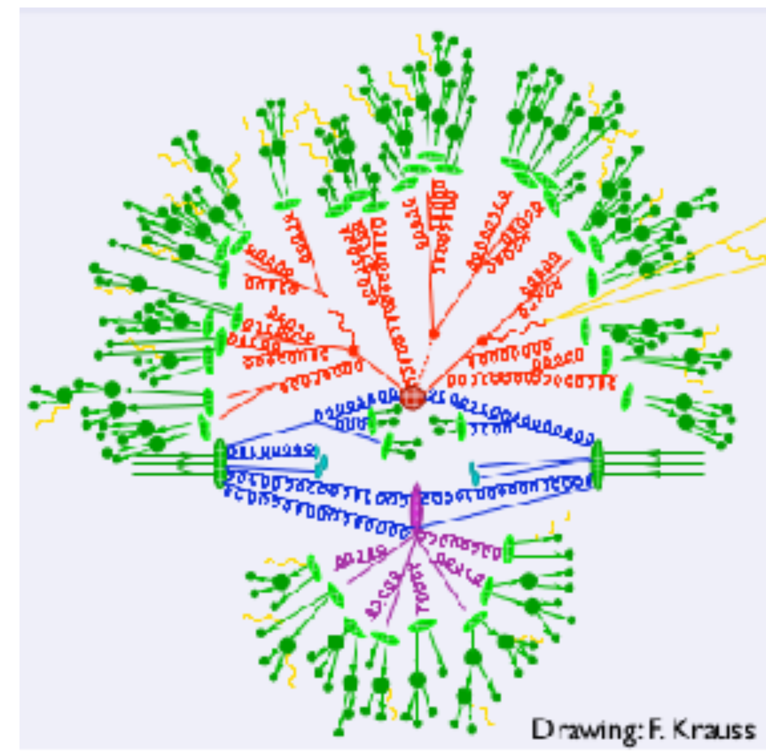


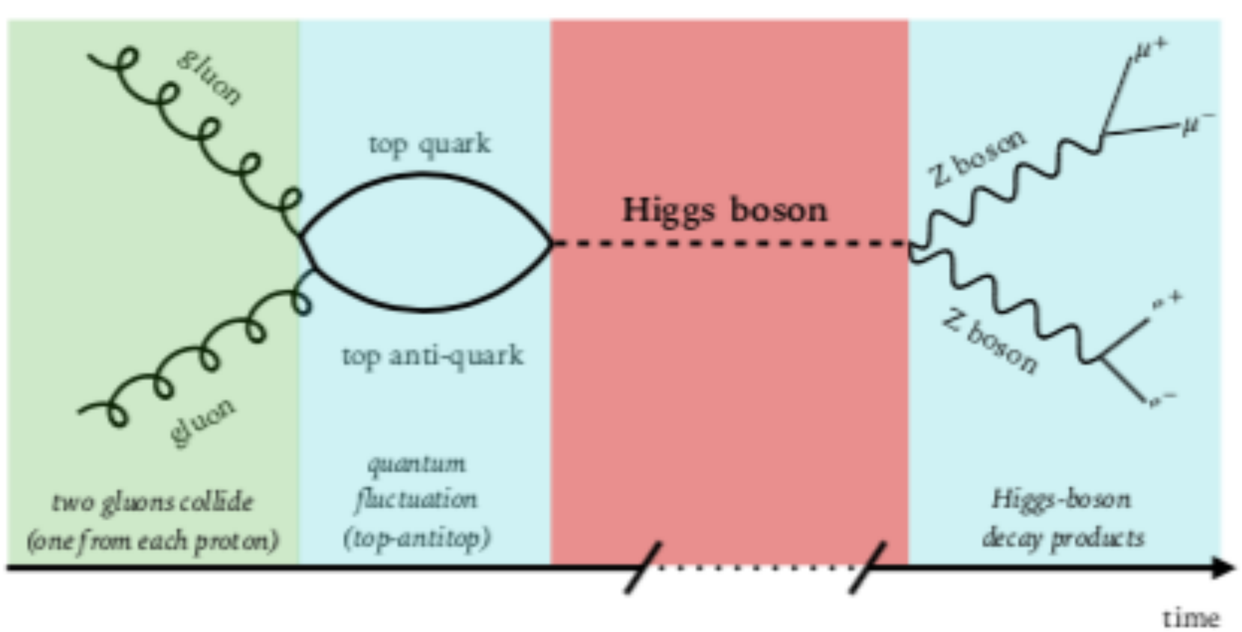
SM Higgs & LHC

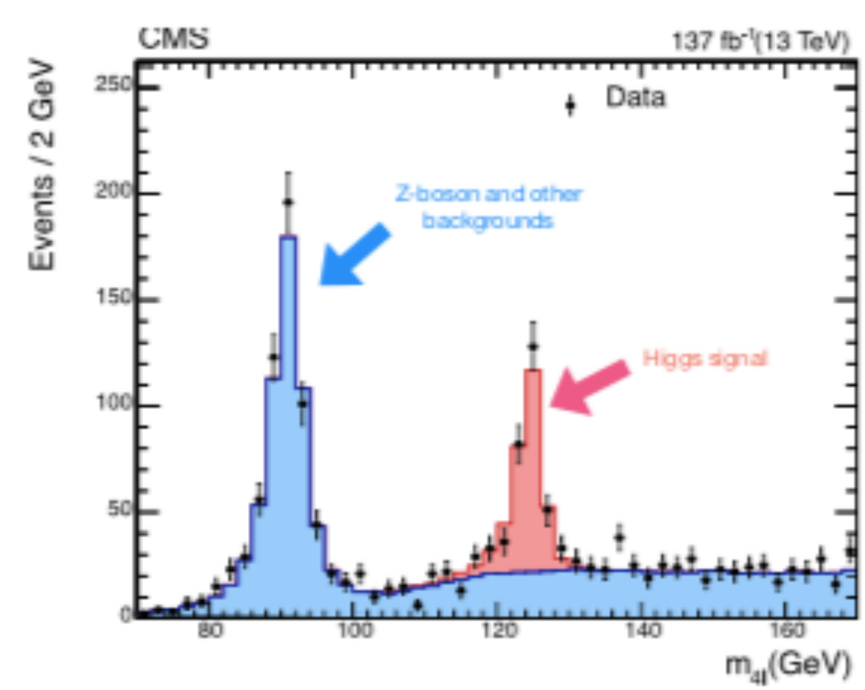
- Relevant couplings (Tree-level): htt, hbb, hll, hWW, hZZ,
- Relevant couplings (Loop-level): hAA, hgg, hAZ, …



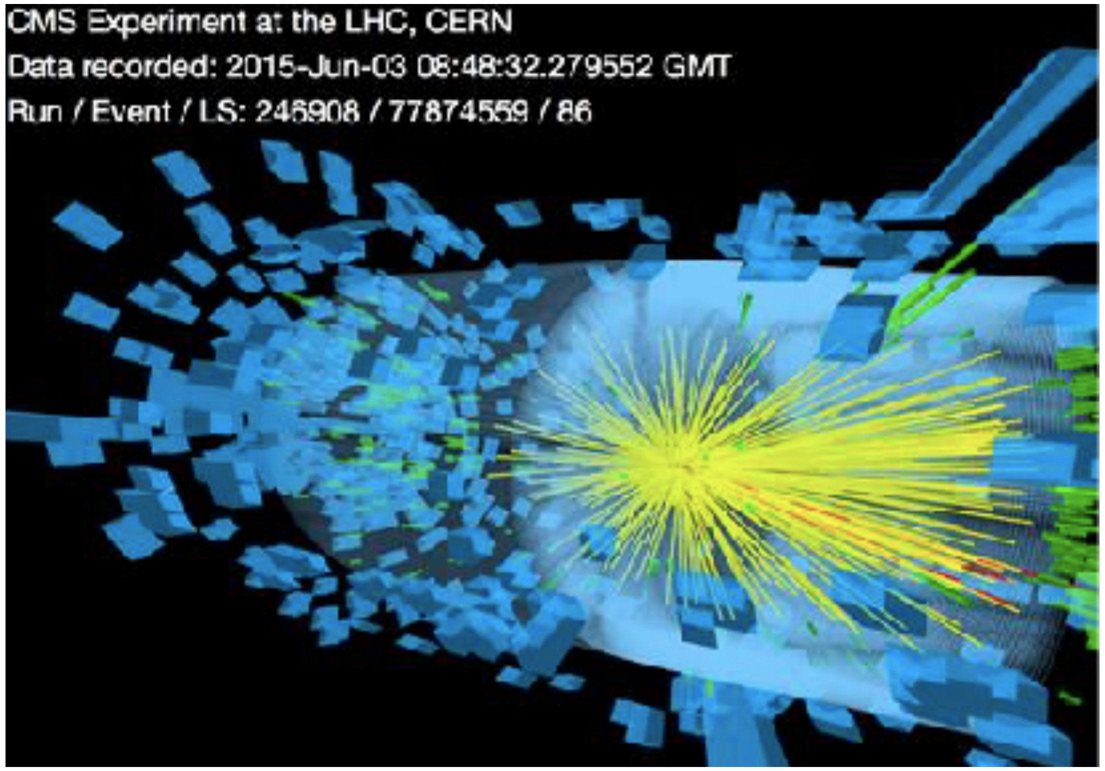


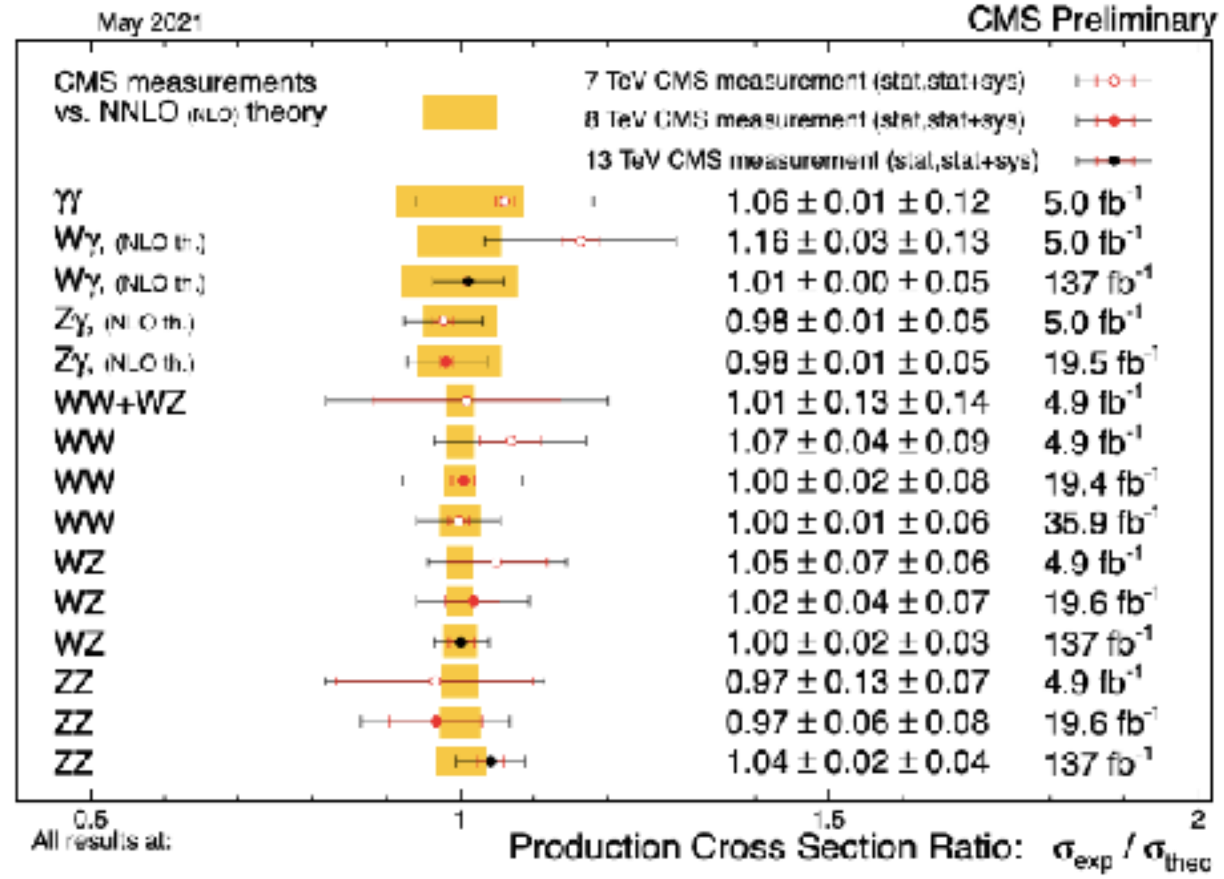


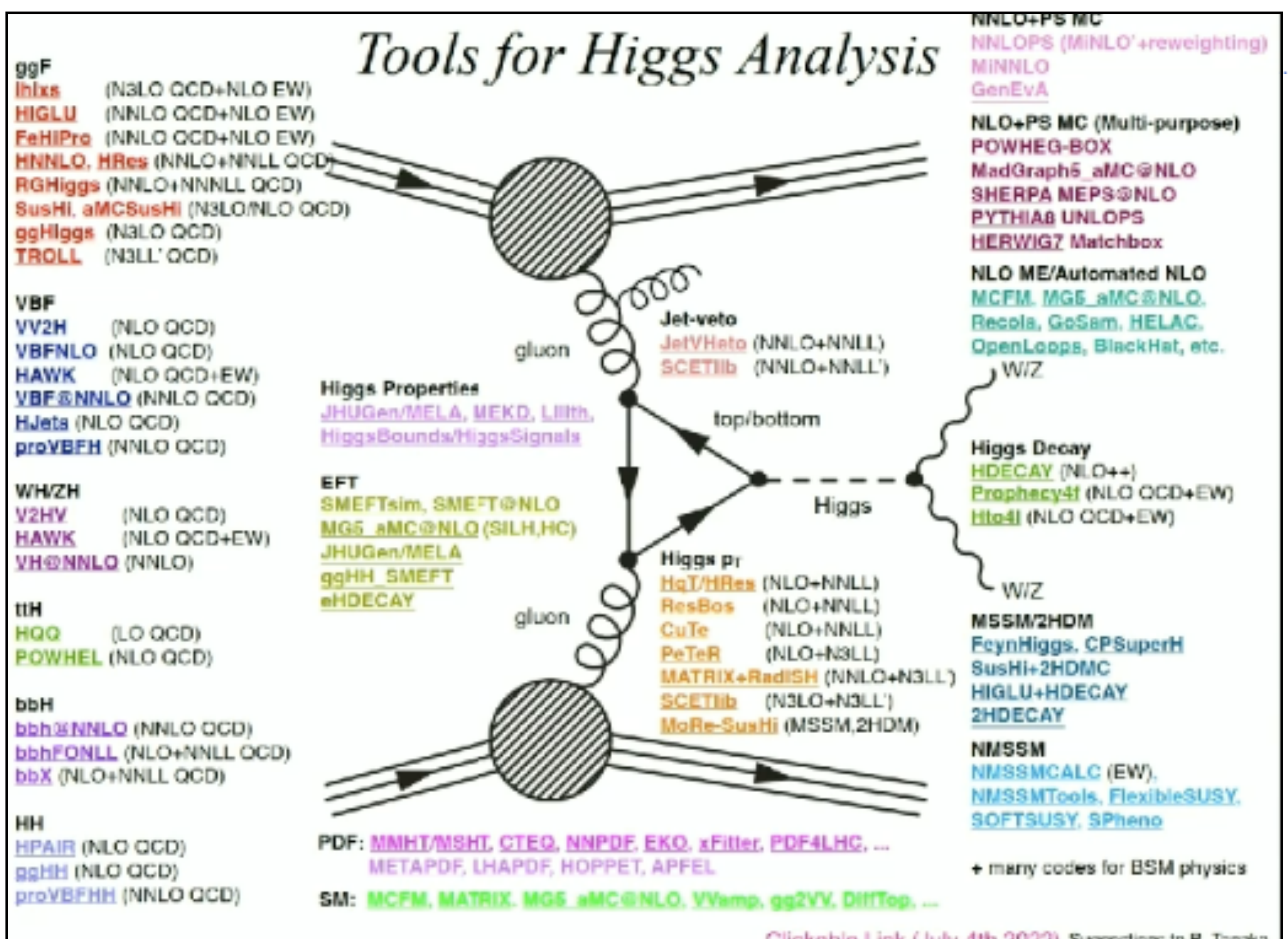




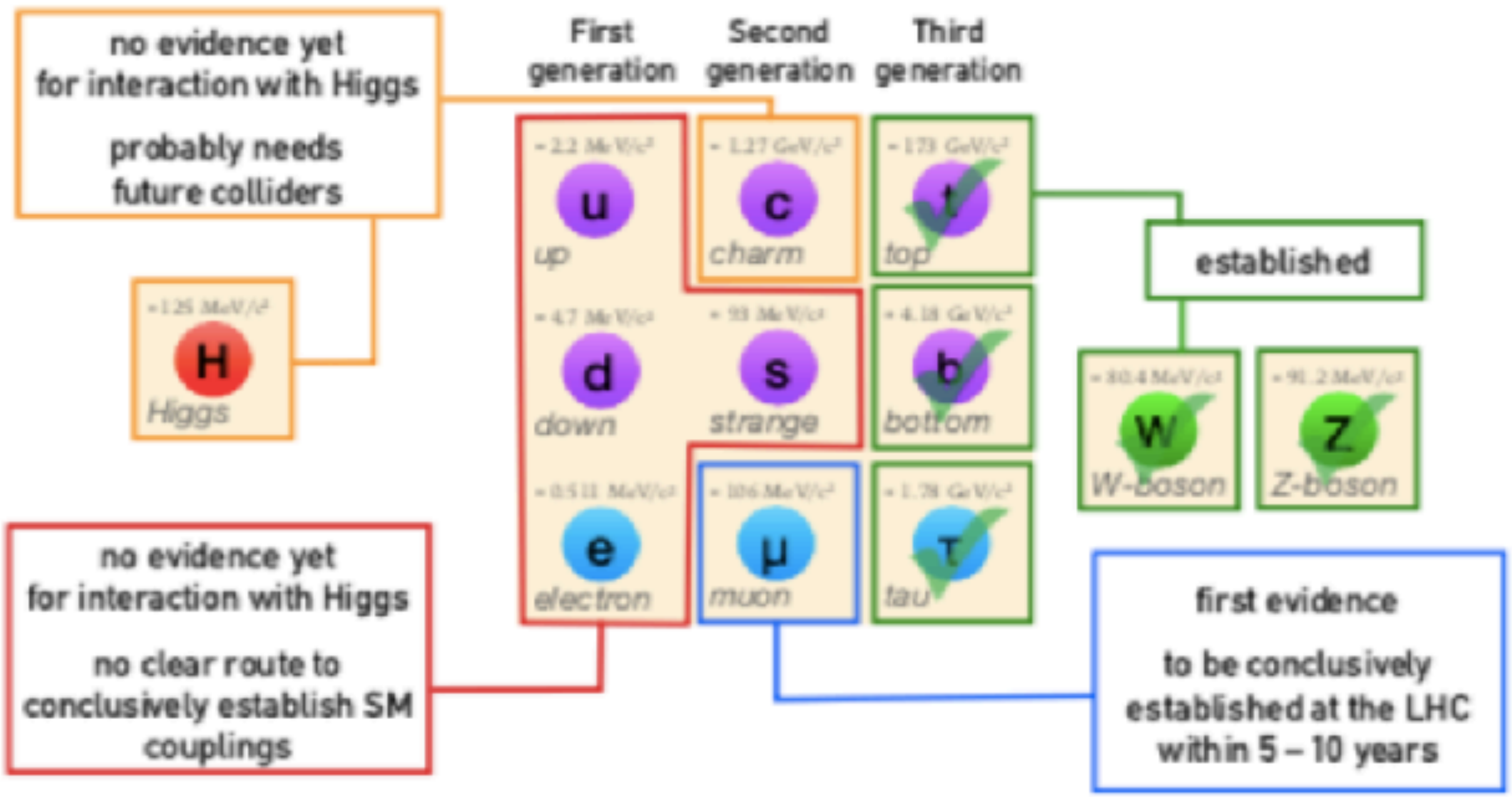
Lessons from LHC: Confirmation of the SM (& The Higgs)



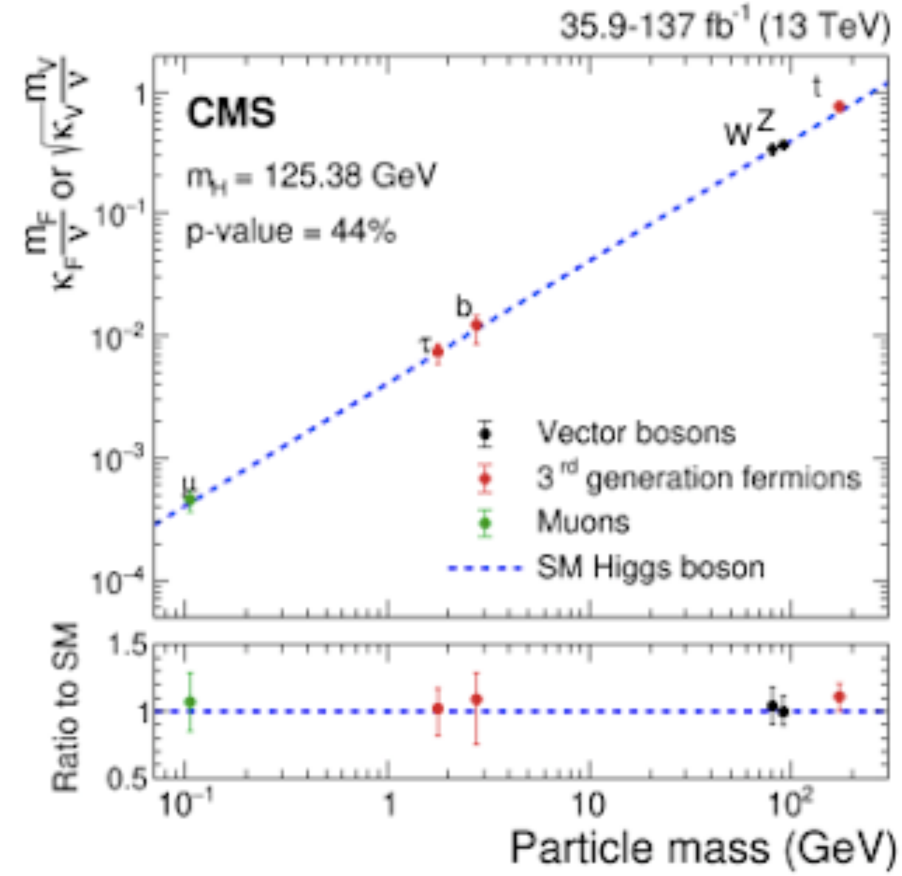




The Higgs profile after LHC: mh=125 GeV & SM-like



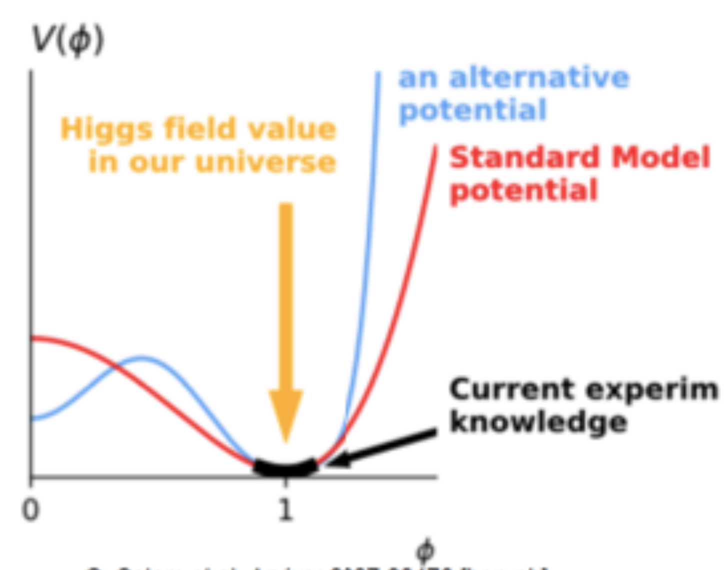
G. Salam et al, Arxive: 2207.00478 [hep-ph]



- Other properties needed to confirm the Higgs profile:

 - Higgs self-coupling (hhh): Higgs pair production,

 - Four-point interactions (hhVV, hhhh)



G. Salam et al, Arxive: 2207.00478 [hep-ph]

3.0 Beyond the SM - New Physics

- The SM is great, but there are open issues:

  - Why19 SM parameters?, why 3 families?,

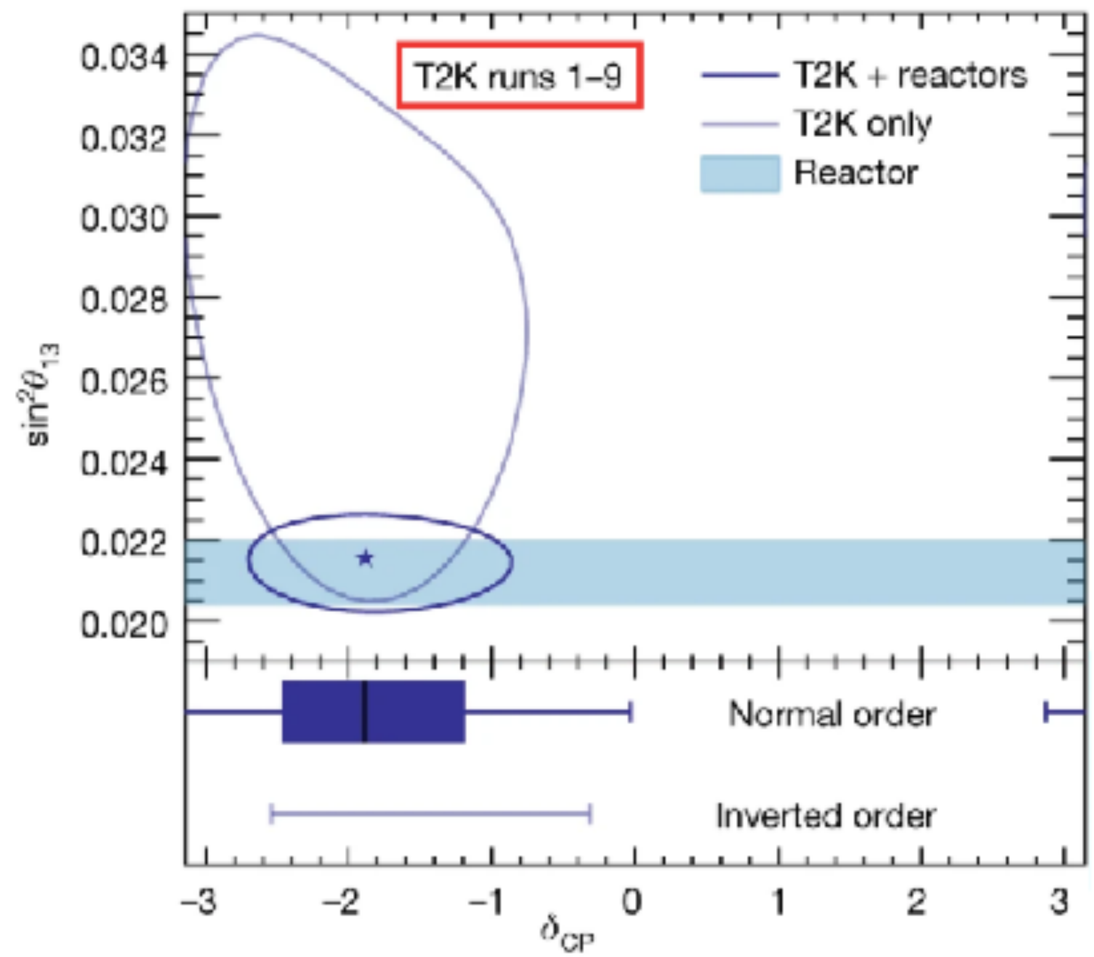
  - Strong CPV? How to include gravity?

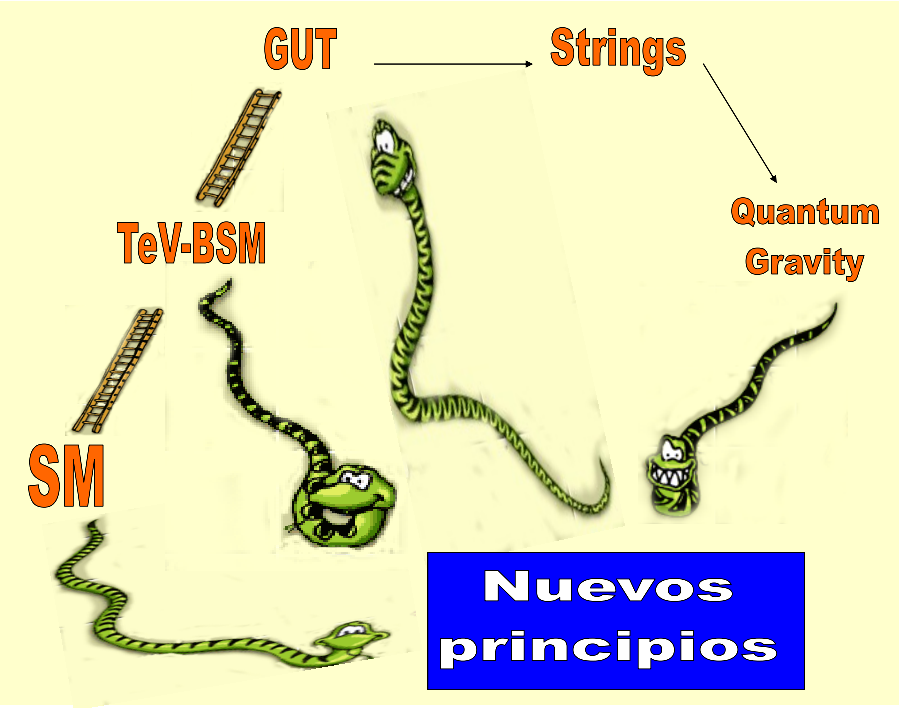
- Higgs mass & ierarchy Problem

- Hints of New Physics: Neutrino masses and mixing, DM, DE, BAU, Bigbang,

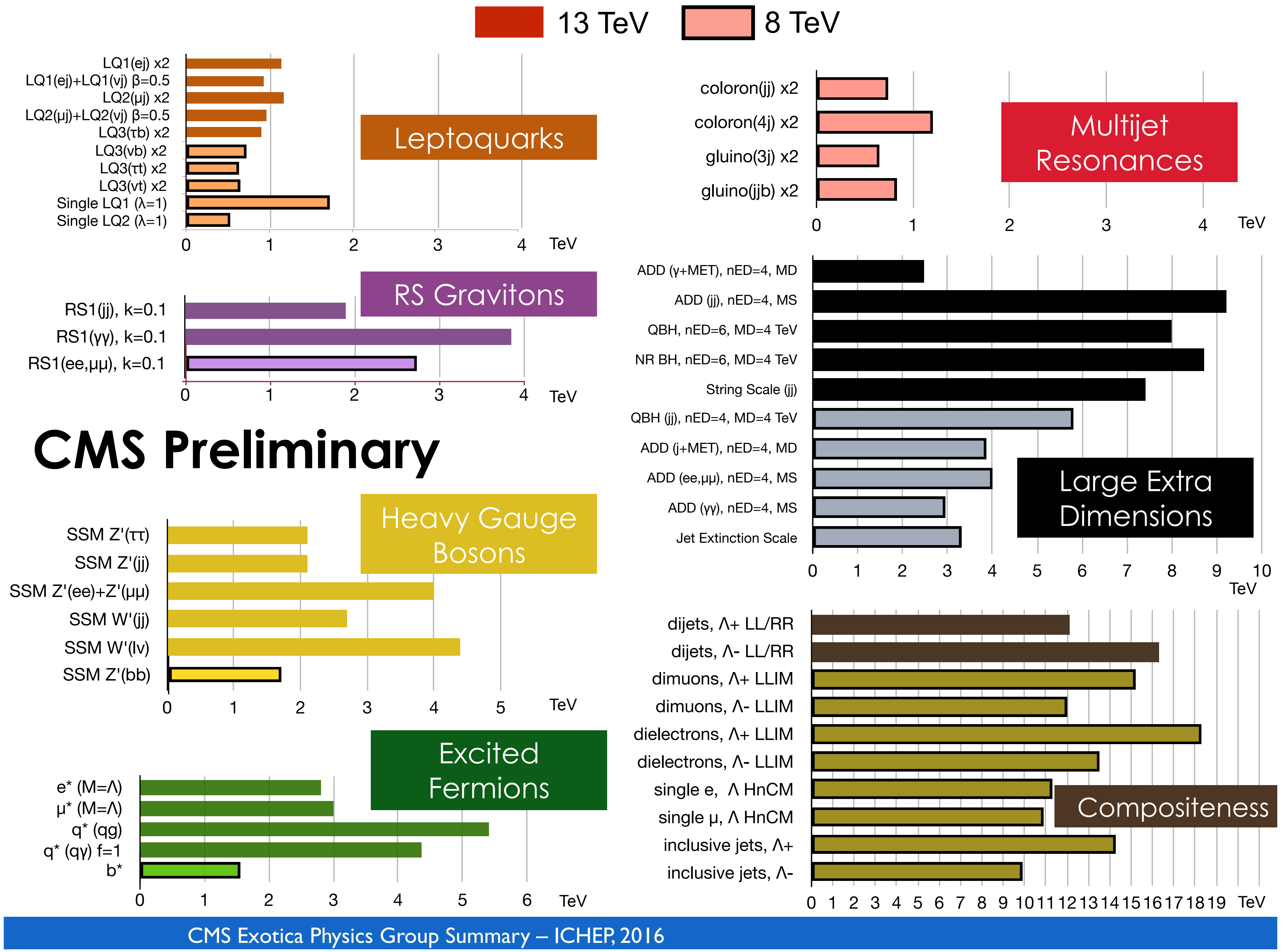
- Many BSM extensions: NHDM, extra forces, more fermions, extra dims (RS, XL,Q), etc

- SUSY, GUT´s and String theory,





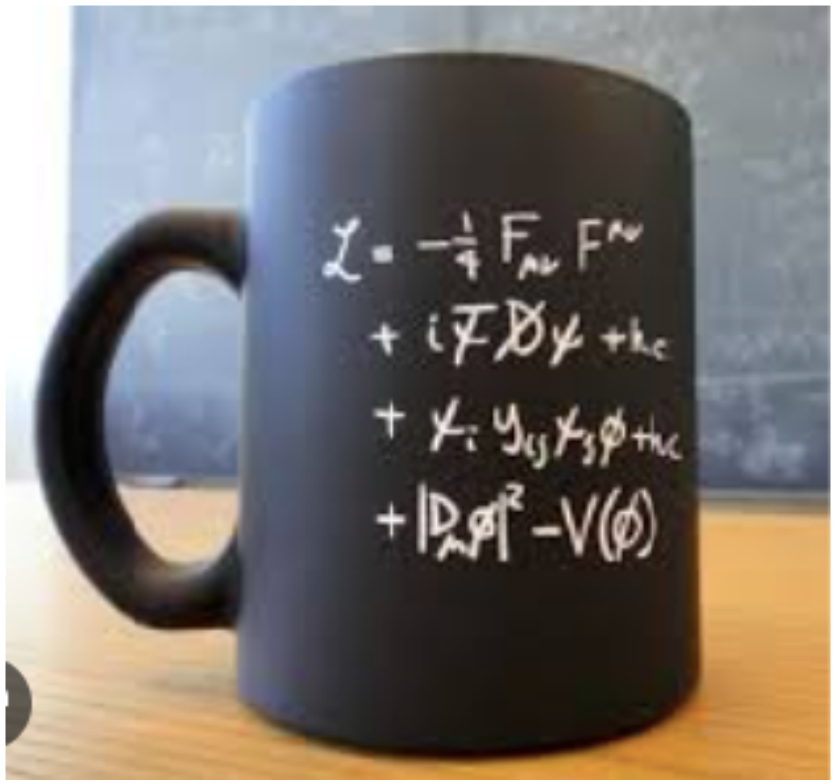
LHC SEARCH FOR NEW PHSICS: None



- But so much agreement between the SM with data is also intriguing. Where is BSM Physics?

3.1 The Higgs problems

- Naturalness/Hierarchy problem: Higgs mass is light (i.e. mh=125 GeV), large corrections somehow disappear, despite having M_NP > O(3-4) TeV).



- Why there is something rather than nothing? (Leibnitz)

$$S_{EH} = \int d^4x \sqrt{-g} \left(-\frac{2}{\kappa^2} R \right) ,$$

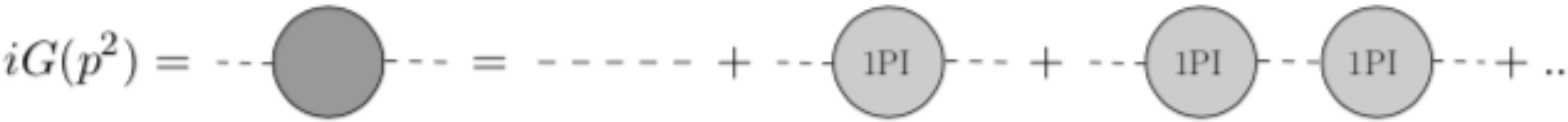
$$\kappa^2 = 32\pi G$$

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

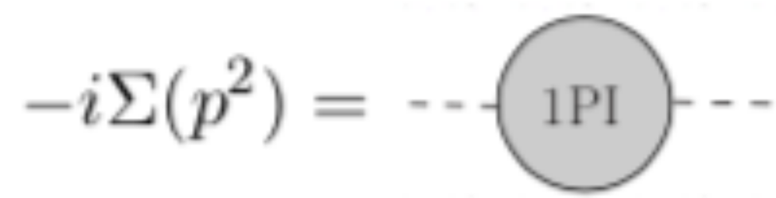
- Why are there two scales in the SM & GR that break the conformal symmetry?

Corrections to the Higgs mass

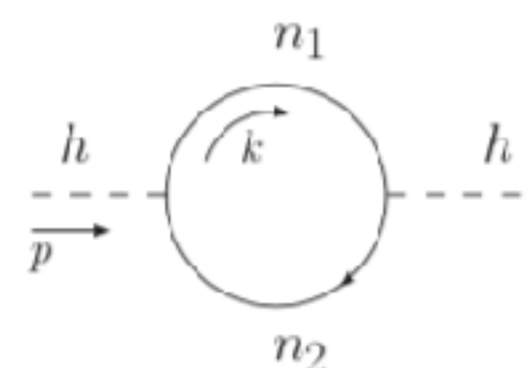
- The effect of heavy particles on the Higgs mass can be calculated, ex. One-loop diagrams,



$$= \frac{i}{p^2 - m^2 - \Sigma(p^2)} .$$



- To evaluate these diagrams, one needs first to regularize the loop-integrals (Dim. Reg.),
- One also has to identify the counter-terms,
- These counter-terms absorbe the infinities,
- Finally, one identifies the Ren. Scheeme (MS-bar),
- Integrals may have quadratic divergences,



$$\int d^4q \, \frac{i}{q^2 - m^2 + i\epsilon}$$

Historical remarks on Quad. Divs. & Naturalness (1)

- First paper on problems of Higgs mass & Quad. Divs. by L. Susskind,

PHYSICAL REVIEW D VOLUME 20, NUMBER 10 15 NOVEMBER 1979

Dynamics of spontaneous symmetry breaking in the Weinberg-Salam theory

Leonard Susskind*
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 5 July 1978)

We argue that the existence of fundamental scalar fields constitutes a serious flaw of the Weinberg-Salam theory. A possible scheme without such fields is described. The symmetry breaking is induced by a new strongly interacting sector whose natural scale is of the order of a few TeV.

- Veltman identified Quad. Divs in Dim. Reg. (poles in D=2), & a condition for its cancellation,

THE INFRARED-ULTRAVIOLET CONNECTION

Dedicated to Jacques Prentki on occasion of his sixtieth birthday.

BY M. VELTMAN*

Physics below 300 GeV is termed infrared, and physics above 1 TeV is called ultraviolet. Some aspects of the relation between these two regions are discussed. It is argued that the symmetries of the infrared must be symmetries in the ultraviolet. Furthermore, naturalness within the context of the standard model is considered. It is concluded that there is either a threshold in the TeV region, or alternatively a certain mass formula holds. This formula, when true, might be indicative for an underlying supersymmetry.

PACS numbers: 12.40.—y, 11.30.Ly

A suitable criterion, within the framework of dimensional regularization, is the occurrence of poles in the complex dimensional plane for n less than four. Thus naive quadratic divergencies at the one loop level correspond to poles for $n = 2$. We therefore inquire after the existence of poles for $n = 2$ in the standard model.

- Later on Veltman claimed that there are no quadratic divergences exist in the SM

Submitted for publication in
Acta Physica Polonica.

UM-TH-94-12

PERTURBATION THEORY AND RELATIVE SPACE †

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At this point we would like to distance ourselves from such an approach. Quadratic divergencies do not exist within the dimensional formulation. The concept of naturalness with respect to scalar particle masses needs revision. There are no large corrections related to quadratic divergencies as these divergencies do not exist in the dimensional method. Of course, corrections to scalar particle masses involving masses of heavier particles could still occur, but that is a quite different subject. Only within a well defined model can conclusions be drawn.

Corrections to scalar mass contains "Quadratic divergences" (old view),

$$m_h^2(\Lambda,\mu) = m_h^2(\Lambda) + \sum_{X=S,V,F} (-1)^{2J_x}(2J_x+1)\frac{g_x}{16\pi^2}[\Lambda^2 - m_h^2(\Lambda)\log\frac{\Lambda^2}{\mu^2}]$$

- When, Lambda is the UV cutoff, and it goes to infinity, it seems that a large correction to the Higgs mass is induced,

$$\Lambda \to \infty \qquad \delta m_h^2 = \frac{g_x^2}{16\pi^2}\Lambda^2$$

- Modern view: when Lambda goes to infinity, one just has to renormalize the Higgs mass, such that no large correction to the Higgs mass is induced, but ….

- Real problem: when Lambda represents the effect of a heavy particle, of mass M and coupling g_x; it leaves a correction to the Higgs mass of order:

$$\delta m_h^2 = \frac{g_x^2 M_x^2}{16\pi^2}$$

Known solutions assume:
g_x =O(1)=g_sm

$$\delta m_H^2 = \frac{\Lambda^2}{16\pi^2} C_n(\mu)$$

- SUSY: A relation among parameters, such that C_1= 0,

- Veltman Condition); A relation among masses, such that C_1=0 -> m_h=316 GeV

- Conformal symmetry: vanishes at tree level.

$$C_1 = C_b + C_f = 0 \qquad \lambda = C(g^2 + g'^2)$$

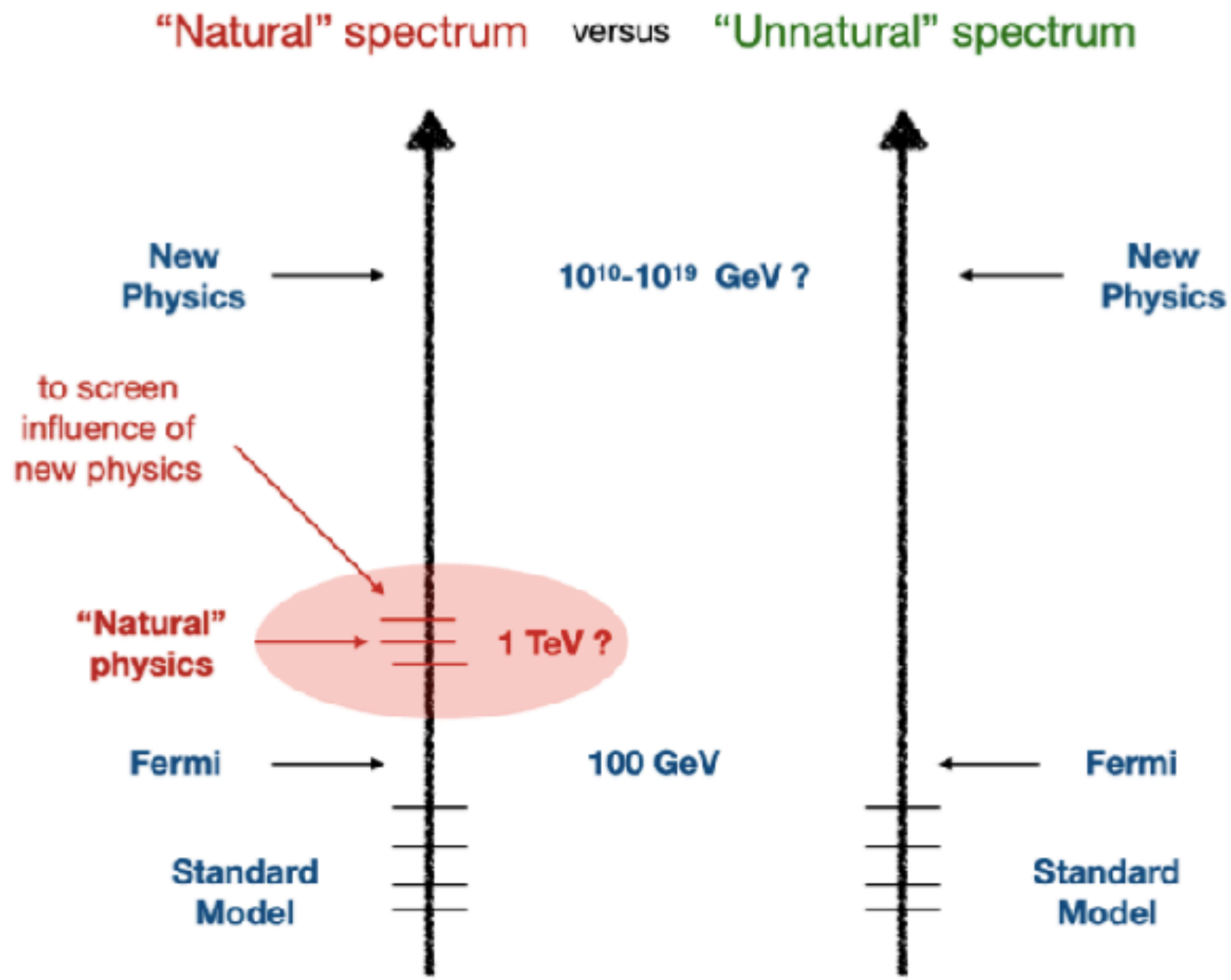
$$C_1 = 2\lambda + \frac{3}{2} g'^2 + \frac{9}{2} g^2 - 12\, y_t^2$$

$$m_h^2 = 4m_t^2 - 2m_W^2 - m_Z^2$$

$$\delta m_h^2 \simeq m^2 log M/m$$

Is the SM a Natural Theory?

- Previous thoughts on natural vs-unnatural physics:
- Since no PBSM showed up, with M=O(1) TeV, the SM could be valid up to: E >> O(1TeV),
- Is the SM still a Natural theory?



We understand better these questions, like what is QFT & renormalization, from a modern point of view -> Effective QFT (K. Wilson, 1970-80´s)

Integrating-out Heavy Particles & EFT

- Suppose a QFT has a heavy and a light fields:

  (With masses: M & m)

- For E> M, the theory is described by:

- For E<M, QFT only includes light fields, and it is described by:

- The parameters (H&L) are different in general,

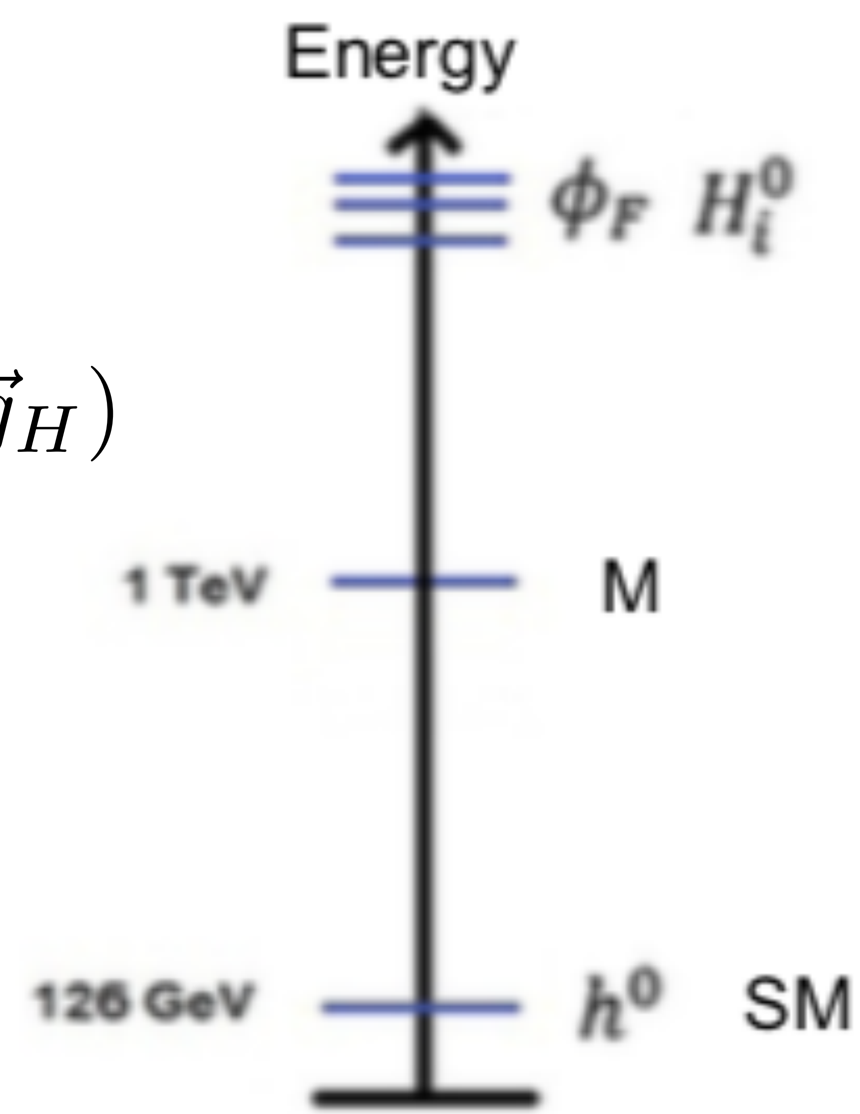
$$\Phi_H \text{ and } \phi_{\rm L}$$

$$\mathcal{L}_H = \mathcal{L}_H(\Phi_H, \phi_L; \vec{g}_H)$$

$$\downarrow$$

$$\mathcal{L}_L = \mathcal{L}_L(\phi_L; \vec{g}_L)$$

$$\vec{g}_H \neq \vec{g}_L$$



When the heavy field is integrated out & the parameters change with Energy (Scale, RGE):

$$g_i = g_i(M)$$

SM Naturalness & Fine-tuning (J.Wells)

- We can define the max. degree of fine-tuning, as follows:

$$\mathrm{FT}[g_{Li}\,|\,g_{Hj}] = \left|\frac{g_{Hj}}{g_{Li}}\frac{\partial g_{Li}}{\partial g_{Hj}}\right|_{\mu^2=M^2}$$

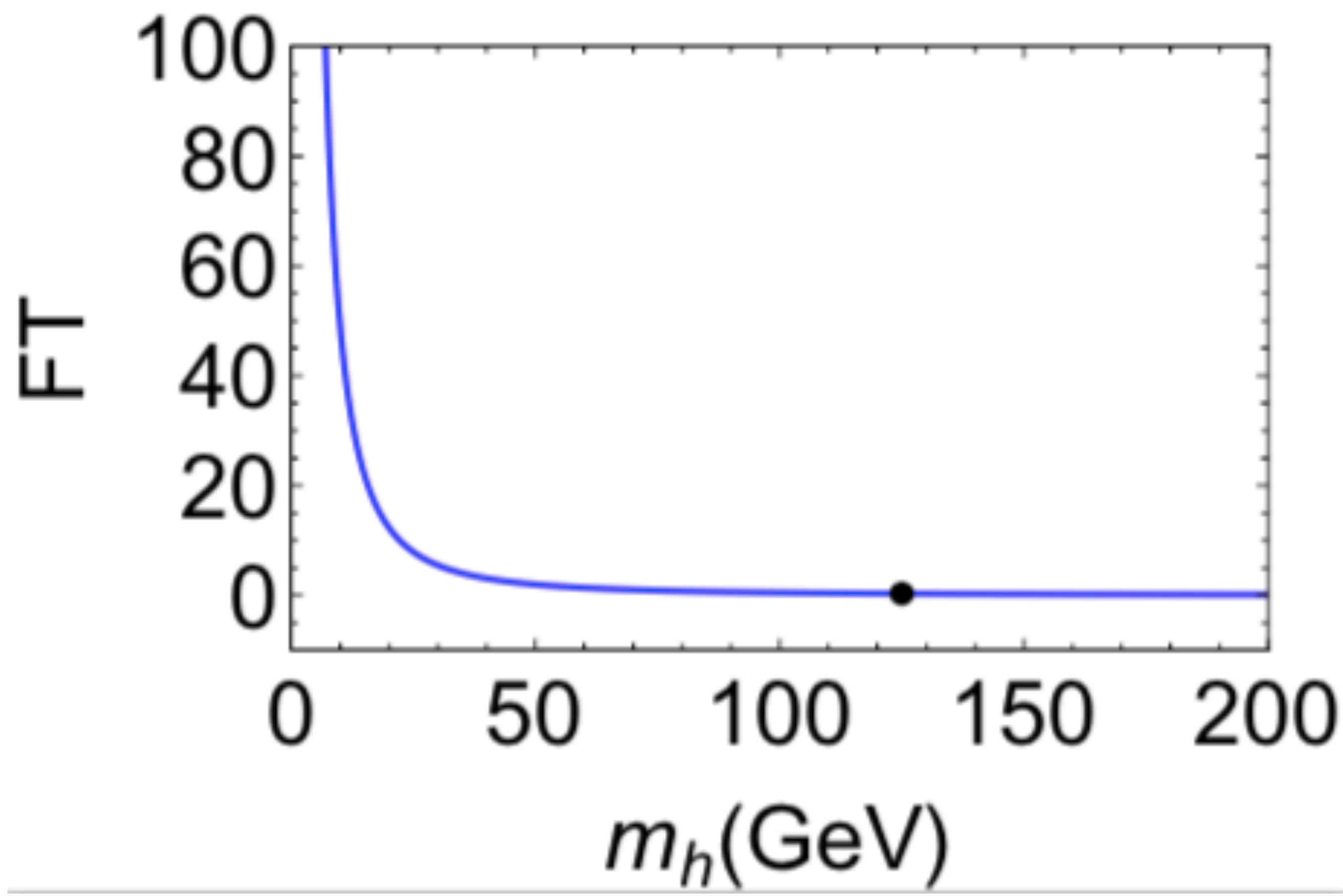
$$\mathrm{FT}[g_{Li}] = \max_k \ \mathrm{FT}[g_{Li}\,|\,g_{Hk}]$$

$$\mathrm{FT}[m^2] = 10^X \quad \longrightarrow \quad \text{Level-X finetuned theory.}$$

- Within the SM, the max. fine-tuning, appears in the Higgs mass, as function of the top mass:

$$\mathcal{L}_{\rm SM} = -m^2 H^\dagger H + \cdots .$$

$$\mathrm{FT}[m_h^2|m_t] \simeq \frac{3m_t^4}{\pi^2 v^2 m_h^2}$$



- But this fine-tuning is only of Level- 0.3,
- This is so because mh=125 GeV,
- Thus, there is no F.T. problem in the SM!

Are there still other solutions to the naturalness problem?

- What about the case g_x << 1?

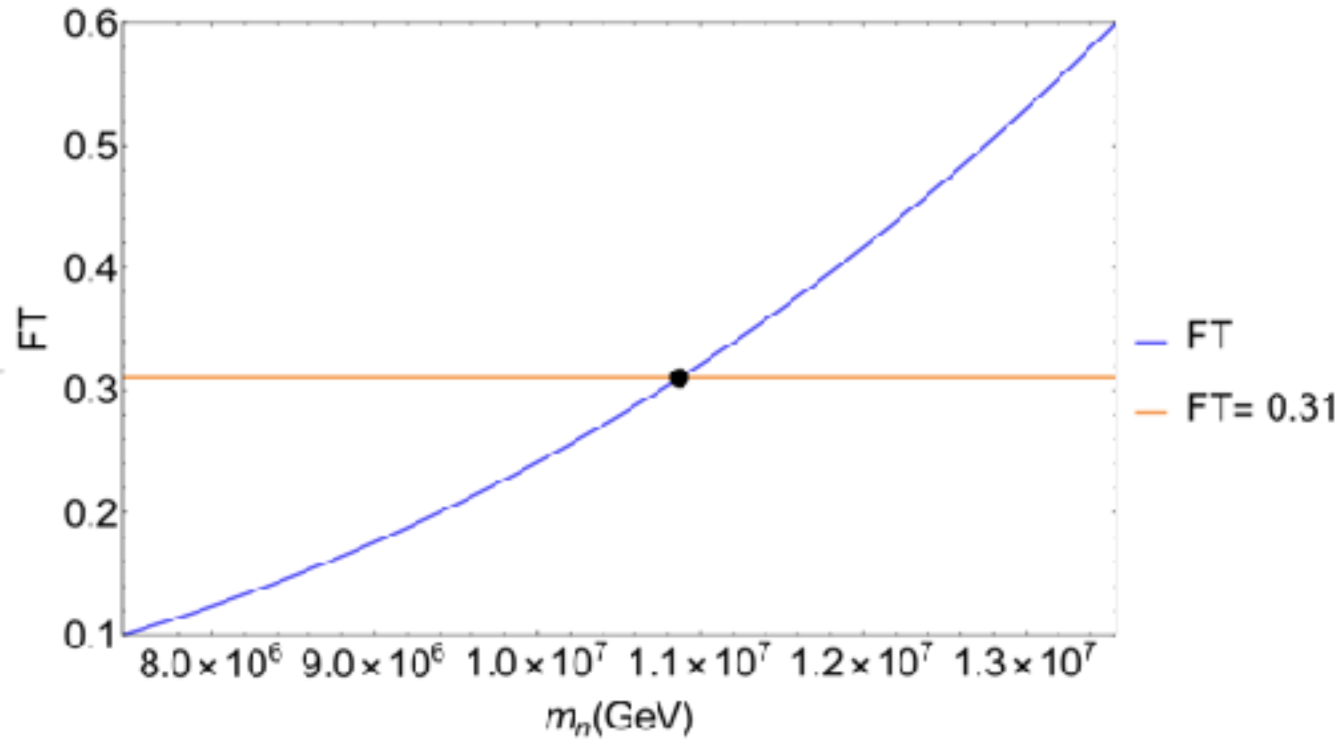
  (Feeble coupled sector = FECOS)

$$\delta m_h^2 = \frac{g_x^2 M_x^2}{16\pi^2}$$

J. Lorenzo Diaz-Cruz (Puebla U., Mexico)
e-Print: 2309.01378 [hep-ph]

- Actually the nuSM (See-saw) is one example of FECOS

$$\delta \mu_H^2(\mu) = \frac{4y^2}{(4\pi)^2} M_N^2 \left(1 - \log \frac{M_N^2}{\mu^2}\right) ,$$



- So, with FECOS it seems possible to keep Mh = O(EW) scale,
- But is it a valid solution? Yes!
- Is it useful for model building? Yes, as we will see next ..

4. The SM structure: what if the SM is the Fundamental Theory?

- Out of the largest possible symmetry group SU(16x3), only an small subgroup is "gauged": SU(3)xSU(2)xU(1)! … Why?

- Before the LHC, it was thought that the SM was a theory for the poor man, that would be substituted by something better …

- But after the LHC, without signals os new physics beyond the SM, may be we should consider the SM as something more fundamental …

What defines the SM?

- SM gauge group:

SU(3)_c x SU(2)_LxU(1)_Y

- Fermions Reprs.:

- Q (3, 2,Y_q)

- U (3, 1,Y_u), D (3, 1,Y_d)

- L (1, 2,Y_l), E (1, 1,Y_e)

- Higgs: H (1,2, Y_h)
- Renormalizability,

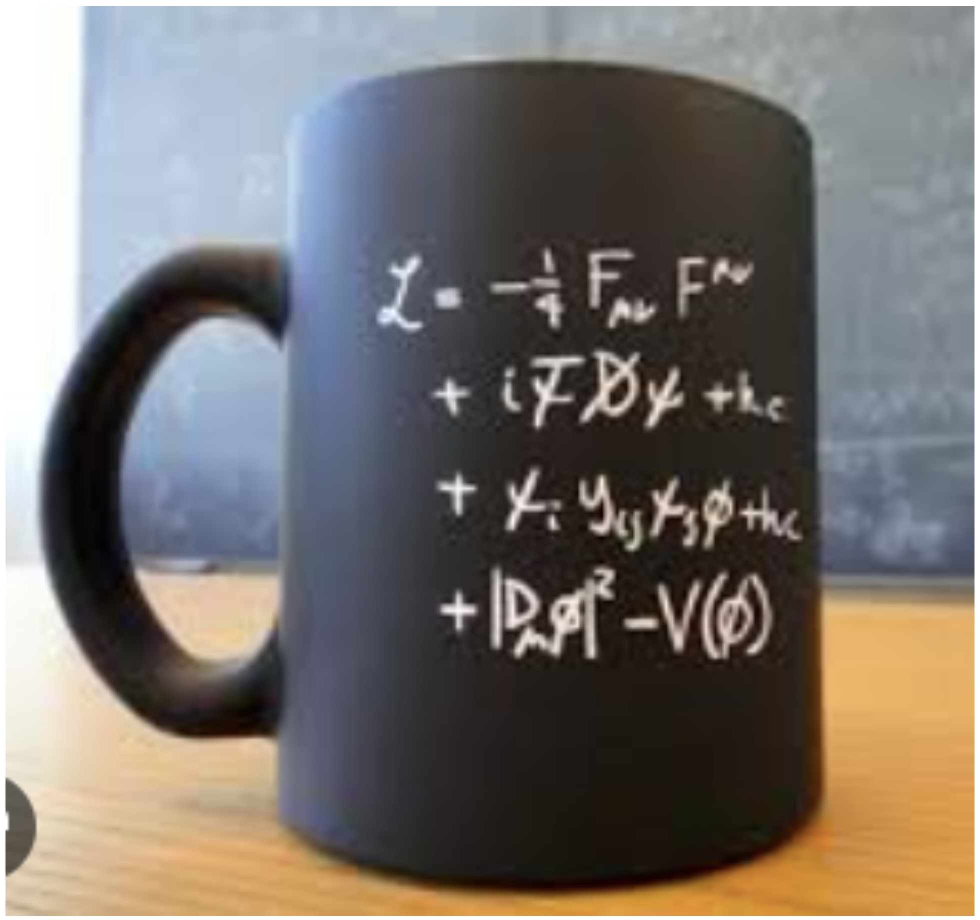
- Only small SM representations: singlets or doublets of SU(2), singlets or triplets of SU(3), such that SM is anomaly-free,
- Where have all the large reprs. Gone?
- SM particle content just enough to allow for CPV,
- SM includes a Higgs doublet, such that correct SSB is induced (rho=1),
- SM is a chiral theory, such that M_SM=0 & extra vector-like particles should have M=Planck,
- EWSB does not induce a photon mass, which only happens for the SM!

Vacuum alignment in multiscalar models

J.L. Diaz-Cruz (Barcelona, Autonoma U.), A. Mendez

Published in: *Nucl.Phys.B* 380 (1992) 39-50

The Standard Model Lagrangian



- SM Group:

SU(3)_c x SU(2)_LxU(1)_Y

- Fermions:

- Q (3, 2,Y_q)

- U (3, 1,Y_u), D (3, 1,Y_d)

- L (1, 2,Y_l), E (1, 1,Y_e)

- Higgs: H (1,2, Y_h)

$$Q_{em} = T_3 + \frac{Y}{2}$$

$$\Psi_a = (\nu, e)^T$$

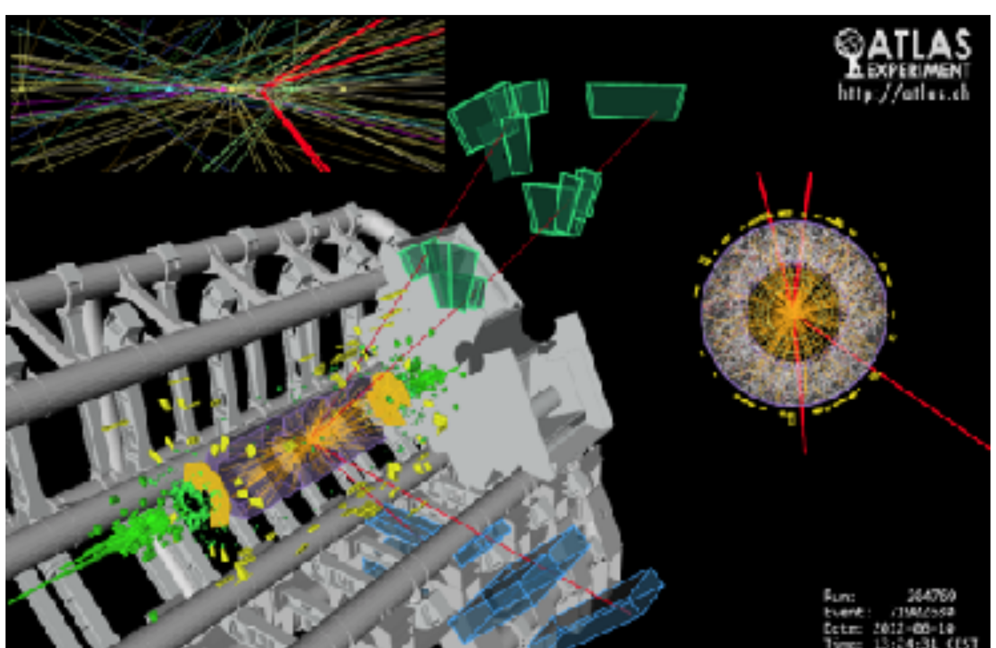
$$\mathcal{L}_{sm} = \mathcal{L}_{fg} + \mathcal{L}_V + \mathcal{L}_H + \mathcal{L}_Y + \mathcal{L}_{ghost}$$

• Why to expect some deviations from SM Fermion-Higgs Couplings?

- In the SM we do not know the origin of the Yukawa parameters,
- Are there patterns & relations between the fermion masses and CKM values?
- Is the hierarchical pattern of fermion masses & CKM due to some symmetry?
- Is the Higgs mechanism the only source of fermion masses?

Parameters of the Standard Model [hide]

Symbol	Description	Renormalization scheme (point)	Value
m_e	Electron mass		511 keV
m_μ	Muon mass		105.7 MeV
m_τ	Tau mass		1.78 GeV
m_u	Up quark mass	$\mu_{\overline{MS}}$ = 2 GeV	1.9 MeV
m_d	Down quark mass	$\mu_{\overline{MS}}$ = 2 GeV	4.4 MeV
m_s	Strange quark mass	$\mu_{\overline{MS}}$ = 2 GeV	87 MeV
m_c	Charm quark mass	$\mu_{\overline{MS}} = m_c$	1.32 GeV
m_b	Bottom quark mass	$\mu_{\overline{MS}} = m_b$	4.24 GeV
m_t	Top quark mass	On-shell scheme	172.7 GeV
θ_{12}	CKM 12-mixing angle		13.1°
θ_{23}	CKM 23-mixing angle		2.4°
θ_{13}	CKM 13-mixing angle		0.2°
δ	CKM CP-violating Phase		0.995
g_1 or g'	U(1) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.357
g_2 or g	SU(2) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.652
g_3 or g_s	SU(3) gauge coupling	$\mu_{\overline{MS}} = m_Z$	1.221
θ_{QCD}	QCD vacuum angle		~0
v	Higgs vacuum expectation value		246 GeV
m_H	Higgs mass		~ 125 GeV (tentative)



Probing LFV Higgs decays

- Muon number could be violated by scalar interactions first suggested by Bjorken and Weinberg (PRL38, 1977),
- Then, in 2HDM, Weinberg-Glashow theorem was used to avoid FCNC Higgs couplings,
- But it is possible to build 2HDMs with acceptable FCNC Higgs couplings, e.g. Cheng-Sher ansatz (PRD35,1987):
- Possibility of LFV Higgs decays at detectable levels found by us (DC & JJT, PRD62,2000)

A Mechanism for Nonconservation of Muon Number

J.D. Bjorken (SLAC), Steven Weinberg (Stanford U., Phys. Dept.) (Jan, 1977)

Published in: *Phys.Rev.Lett.* 38 (1977) 622

We consider the possibility that muon-number conservation is not a fundamental symmetry of nature. In simple SU(2) ⊗ U(1) gauge theories with several scalar boson doublets, muon number will still automatically be conserved by the intermediate-vector-boson interactions, but not by effects of virtual scalar bosons. The branching ratio for $\mu \to e + \gamma$ is estimated to be of order $(\frac{\alpha}{\pi})^3$. Other $\mu - e$ transition processes are also discussed.

Natural Conservation Laws for Neutral Currents

Sheldon L. Glashow (Harvard U.), Steven Weinberg (Harvard U.) (Aug, 1976)

Published in: *Phys.Rev.D* 15 (1977) 1958

Mass Matrix Ansatz and Flavor Nonconservation in Models with Multiple Higgs Doublets

T.P. Cheng (Missouri U., St. Louis), Marc Sher (Washington U., St. Louis) (Feb, 1987)

Published in: *Phys.Rev.D* 35 (1987) 3484

$$\eta_{ij} = \chi_{ij} \frac{\sqrt{m_i m_j}}{v} \quad B.R.(h \to \tau\mu) \simeq 10^{-1} - 10^{-2}$$

A More flavored Higgs boson in supersymmetric models

J. Lorenzo Diaz-Cruz (Puebla U., Inst. Fis.) (Jul, 2002)

Published in: *JHEP* 05 (2003) 036 • e-Print: hep-ph/0207030 [hep-ph]

Lepton flavor violating decays of Higgs bosons beyond the standard model #145

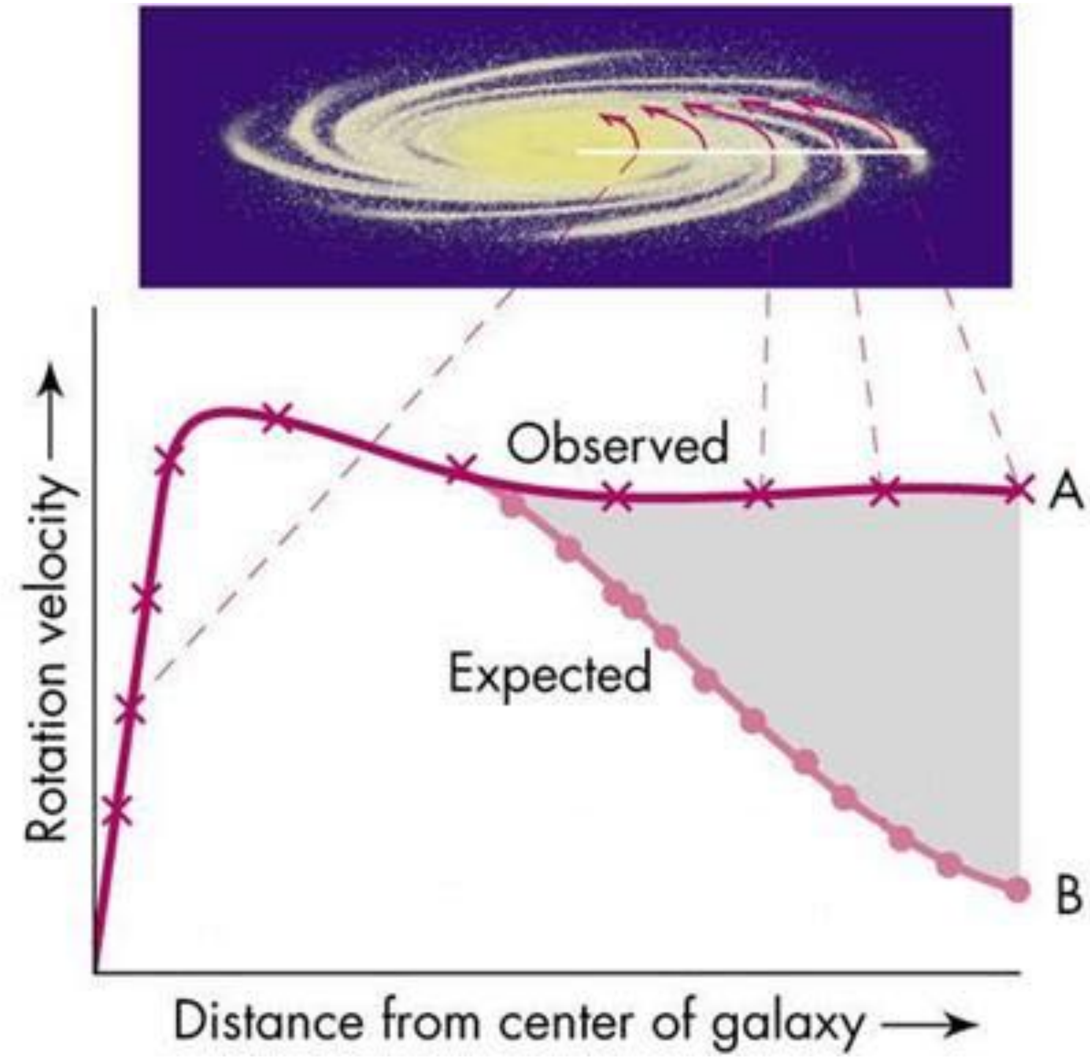
J.Lorenzo Diaz-Cruz (Puebla U., Mexico), J.J. Toscano (Puebla U., Mexico) (Oct, 1999)

Published in: *Phys.Rev.D* 62 (2000) 116005 • e-Print: hep-ph/9910233 [hep-ph]

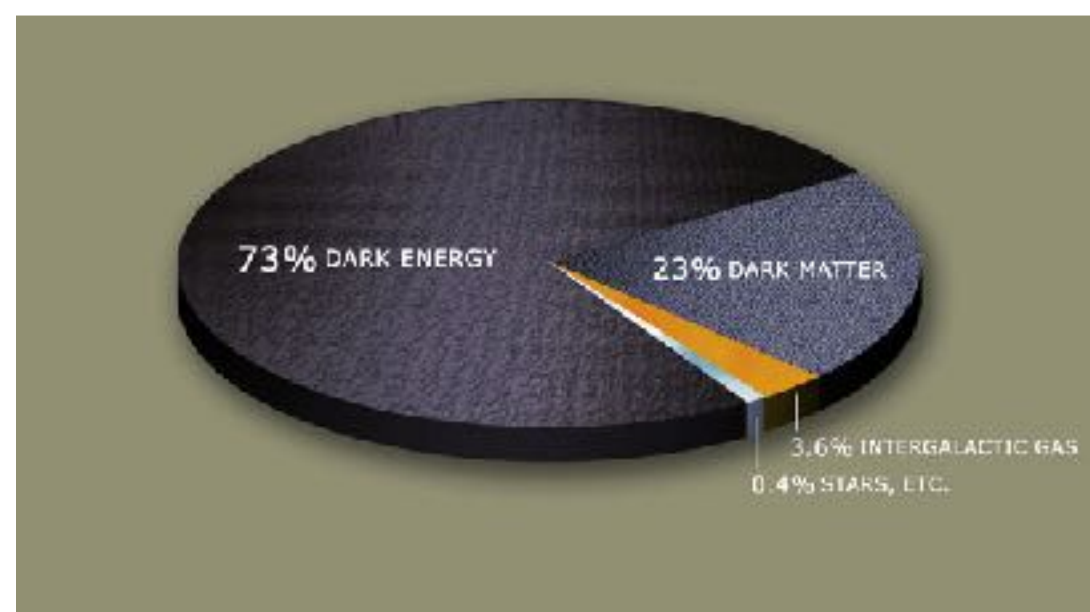
4. Dark matter: from WIMPS to FIMPS

- Dynamics of the galaxy (and galactic systems) indicate that some form of Dark matter should exists,

Galaxia de Andrómeda



- We do not know what is the nature of dark matter, it could be a particle (beyond the SM) or a modification of gravity, or …



It could be possible that physics BSM can explain DM

- WIMP (Weakly interacting massive Particle) miracle,
- WIMP candidates; scalars (IDM), Fermions (Leptons, RH Neutrinos), Vectors (Dark photons, forces), Composite states (strange cookies, DDM),
- WIMPS in Supergravity: neutralinos, gravitinos, exotics,
- New possibility: FIMPS (Feeble interacting massive particles)

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Holographic Dark Matter and Higgs Models

J. Lorenzo Diaz-Cruz

Phys. Rev. Lett. **100**, 221802 – Published 5 June 2008

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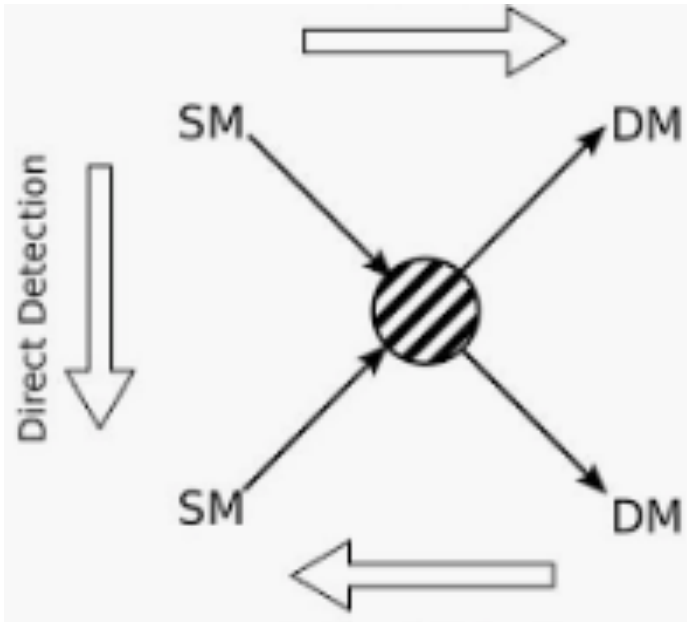
Physics Letters B

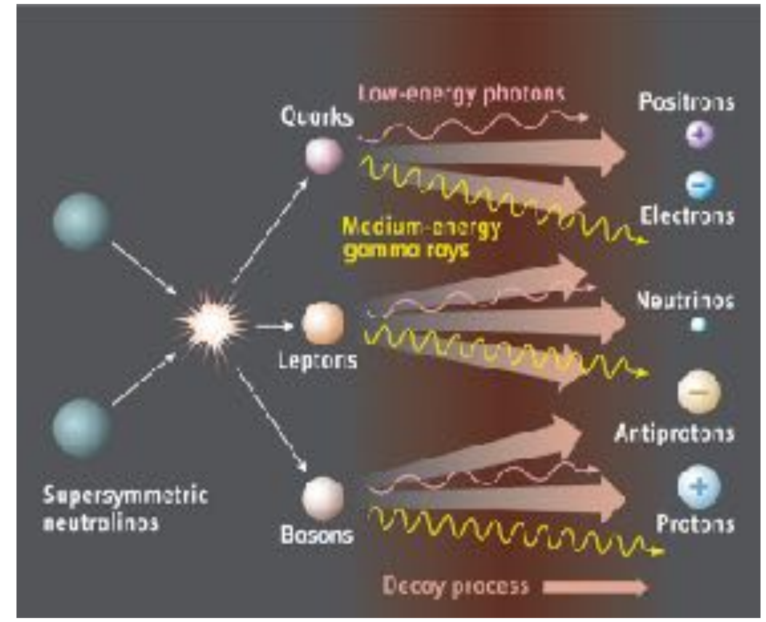
Volume 695, Issues 1–4, 10 January 2011, Pages 264-267

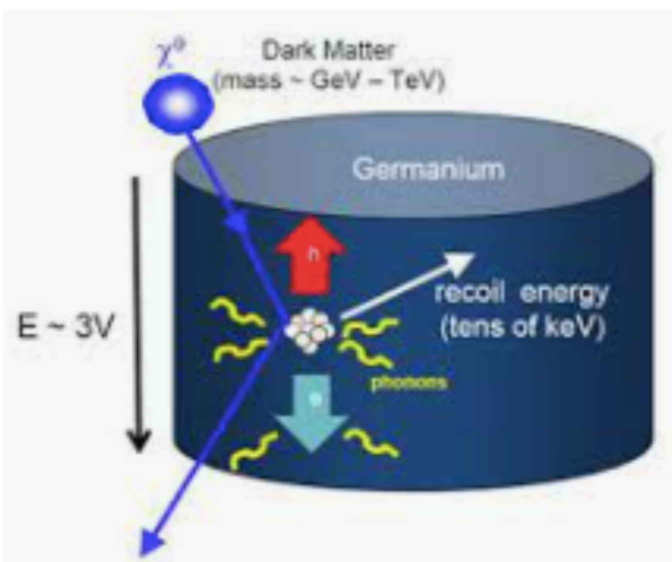
Neutral $SU(2)$ gauge extension of the standard model and a vector-boson dark-matter candidate

J. Lorenzo Diaz-Cruz [a], Ernest Ma [b]

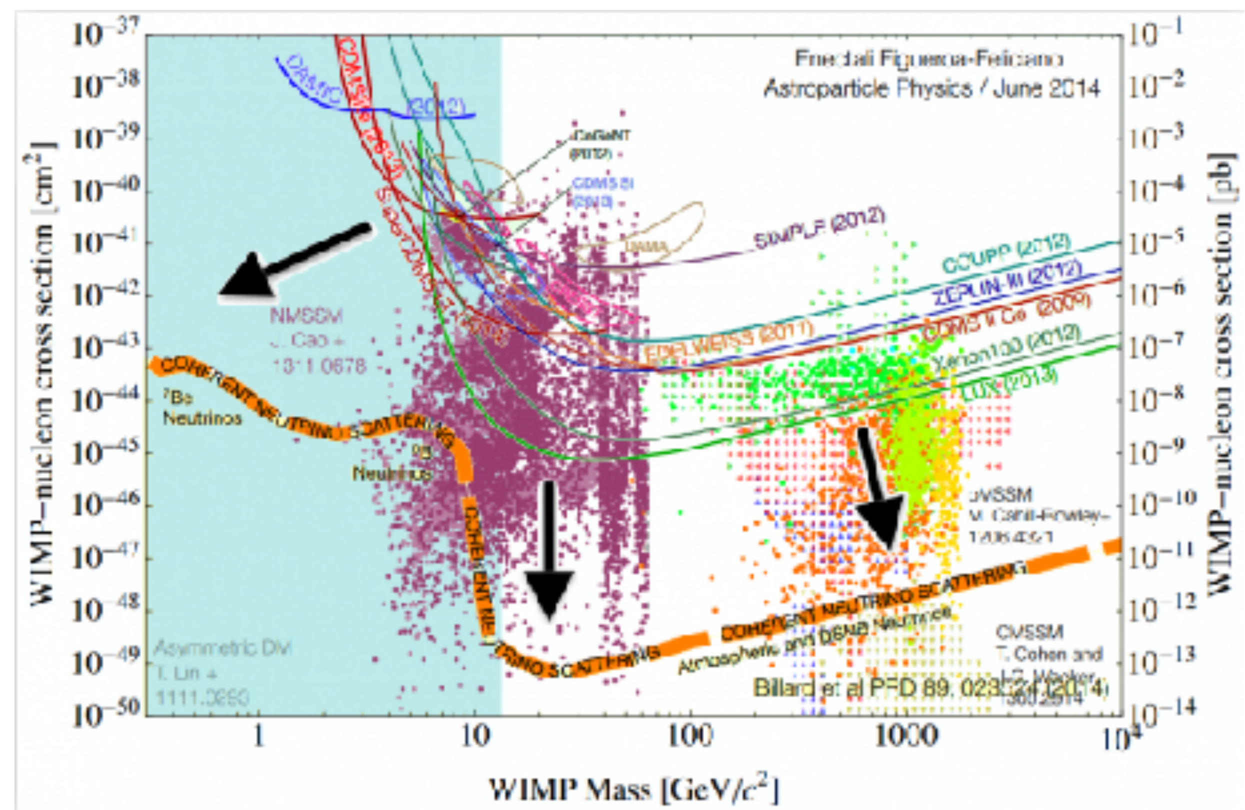
Search for DM- Direct & indirect







SLAC Cryogenic Dark Matter Search...
slac.stanford.edu



Results: No direct evidence of DM (WIMPS)

Could Higgs, Naturalness problems and DM be related?

Solving the Naturalness Problem with Feeble Coupled Sectors

J. Lorenzo Díaz-Cruz*[1,2]

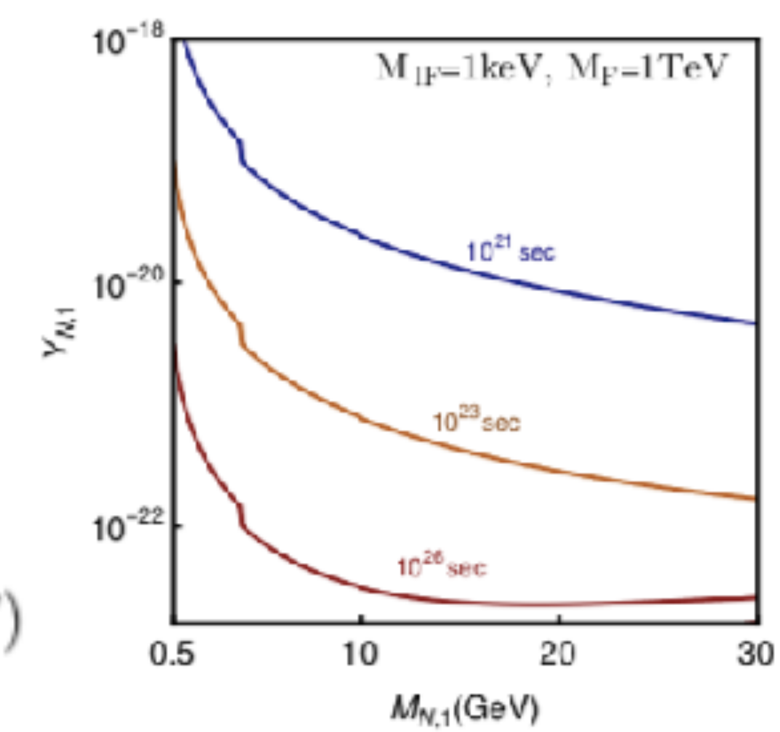
J. Lorenzo Diaz-Cruz (Puebla U., Mexico)

e-Print: 2309.01378 [hep-ph]

- Given that Higgs is light, no PBSM has been found, DM wimps have not been detected, it is possible that NP, if it exists, interacts very weakly with SM (FECOS!)
- So, within FECOS it seems possible to build natural models, i.e. to keep Mh = O(EW) scale after radiative corrections,
- In fact, a new class of DM models include precisely a FECOS dark sector,
- Other applications: Axions & Strong CP Problem

Models of decaying FIMP Dark Matter: potential links with the Neutrino Sector

Laura Covi,[a] Avirup Ghosh,[b] Tanmoy Mondal,[c] Biswarup Mukhopadhyaya[d]



$$\frac{dn_X}{dt} + 3Hn_X = \sum_X \langle\sigma v\rangle_{X\bar{X}\to\chi\bar{\chi}}\, \bar{n}_X^2(T) + \sum_{X'} \Gamma_{X'\to\chi\bar{\chi}}(T)\, \bar{n}_{X'}(T)$$

Dark Matter: From WIMPS to FIMPS

- Given the limits on WIMPS, its existence seems now less motivated,

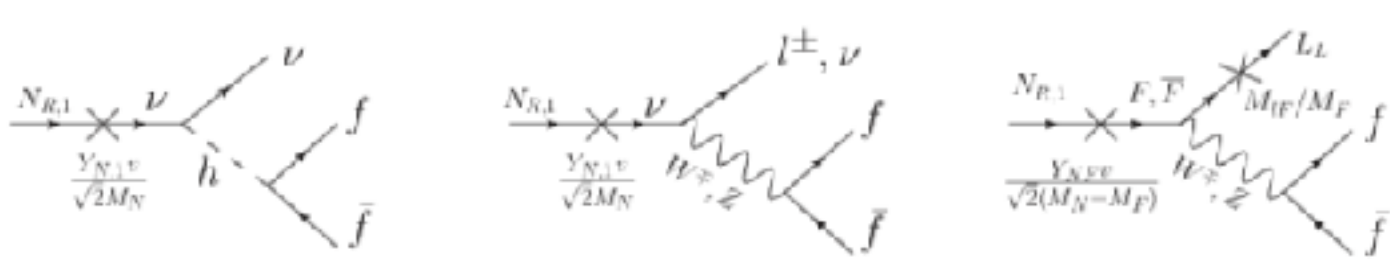
- Feeble Interacting Massive Particle (FIMPS) are another viable DM candidate,

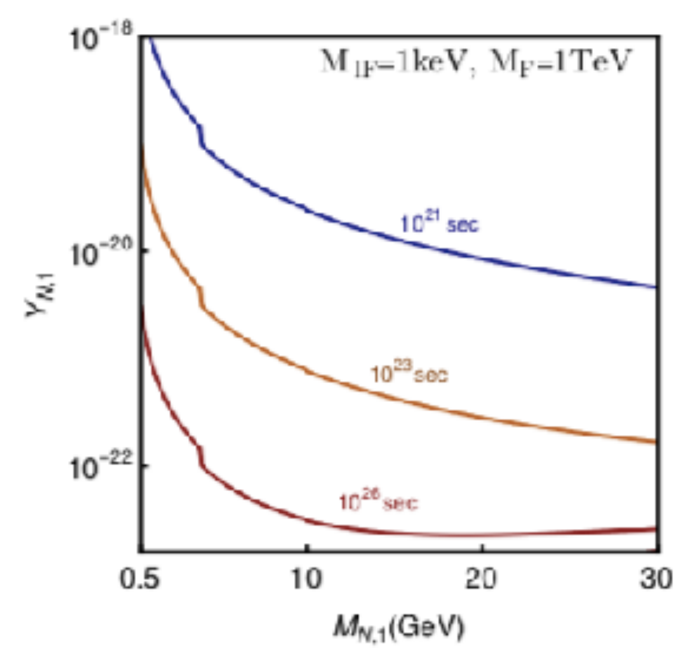
Models of decaying FIMP Dark Matter: potential links with the Neutrino Sector

Laura Covi,[a] Avirup Ghosh,[b] Tanmoy Mondal,[c] Biswarup Mukhopadhyaya[d]

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \sum_X \langle\sigma v\rangle_{X\bar{X}\to\chi\bar{\chi}}\bar{n}_X^2(T) + \sum_{X'} \Gamma_{X'\to\chi\bar{\chi}}(T)\bar{n}_{X'}(T)$$

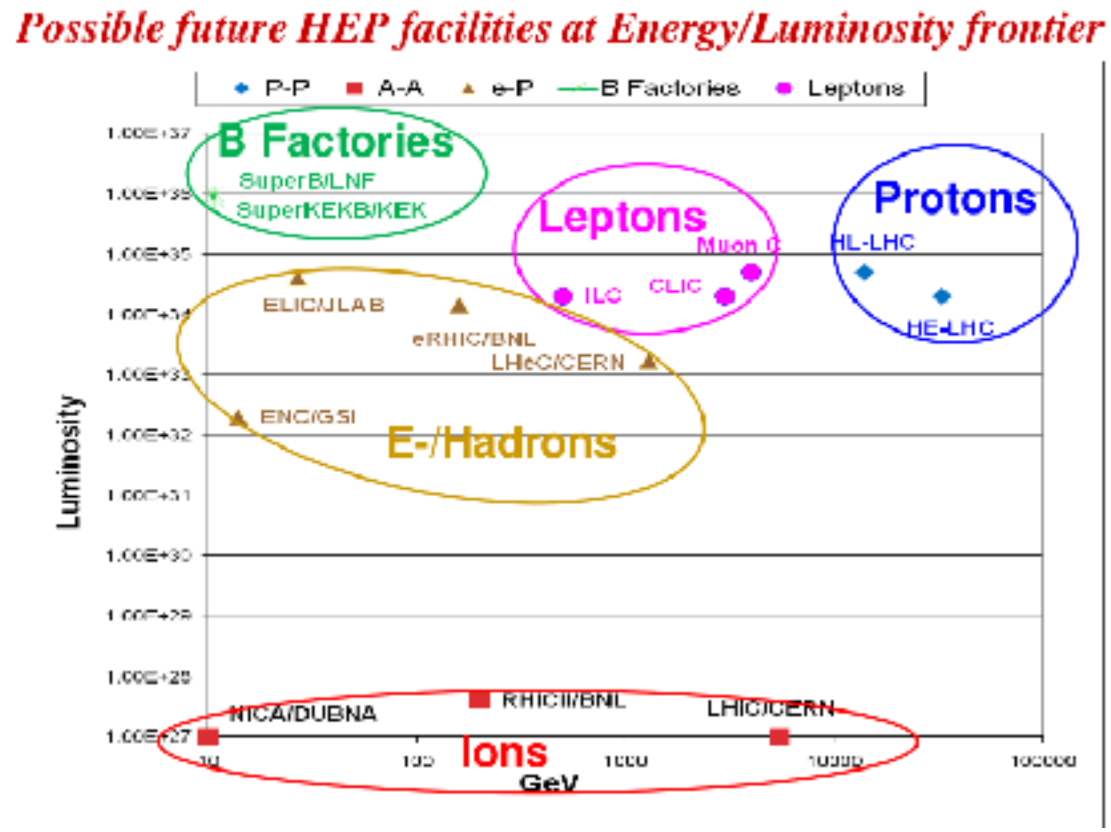
$$\begin{aligned}\mathcal{L} = \; & \overline{N}_{R,i} i\not{\partial} N_{R,i} + \overline{F} i\not{\partial} F - M_{N,i}\overline{N^c_{R,i}}N_{R,i} - M_F\overline{F}F - M_{l_iF}\left(\overline{L_{L,i}}F_R + \overline{F_R}L_{L,i}\right) \\ & - \left(Y_{N_i}\overline{L_L}H^c N_{R,i} + Y^\dagger_{N_i}\overline{N_{R,i}}H^\dagger L_L\right) - Y_{N_iF}\left(\overline{F_L}H^c N_{R,i} + \overline{N_{R,i}}H^\dagger F_L\right) \\ & - Y_{e_iF}\left(\overline{F_L}H\, l_{R,i} + \overline{l_{R,i}}H^\dagger F_L\right). \end{aligned} \quad (2.1)$$

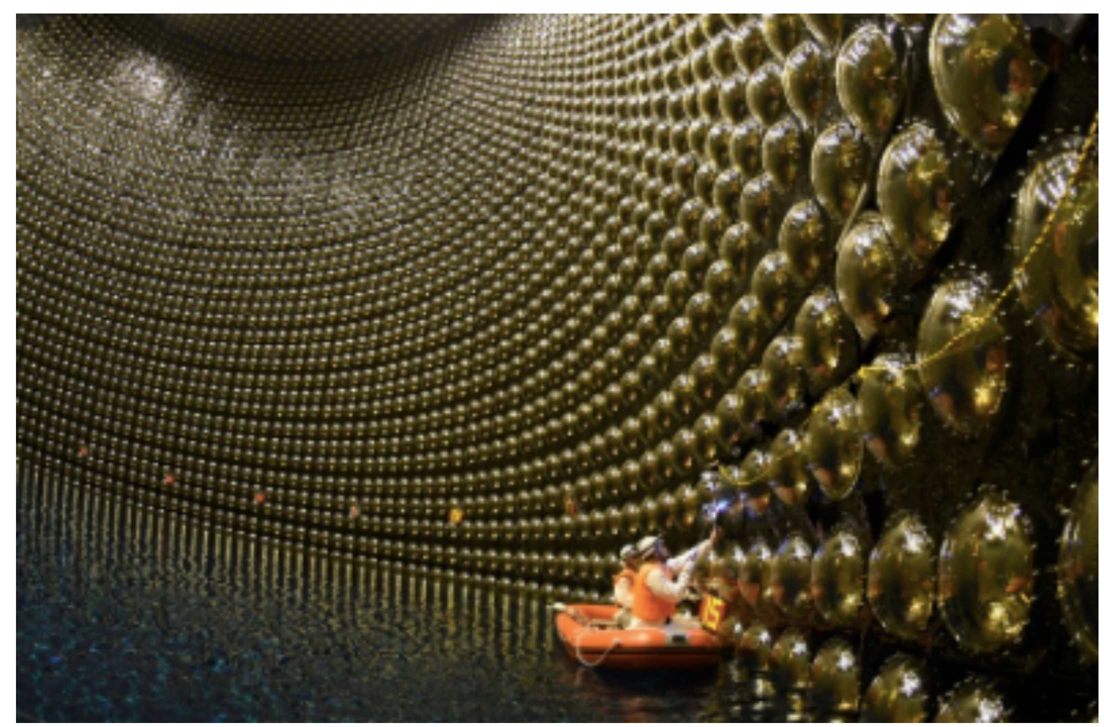




5) Conclusions

- The SM is not a theory of everything, but it could be more fundamental than we thought,
- Building SM extensions could be more subtle, we have to think more about naturalness …
- LHC has provided valuable data, in particular the existence of a Higgs with mh=125 GeV,
- So far, no signal of BSM at LHC, neither of direct DM …
- A new solution to naturalness is FECOS models, motivated by both of these facts,
- FECOS models include a FIMP DM candidate, with specific signatures …
- Keep searching … Energy, Precision, Cosmological frontiers





My life with the Higgs boson

PHYSICAL REVIEW D
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Decays of heavy charged Higgs bosons
J. L. Díaz-Cruz and M. A. Pérez
Phys. Rev. D **33**, 273 – Published 1 January 1986

Searching for supersymmetric Higgs bosons
Justiniano Lorenzo Diaz-Cruz (Merida, IPN) (1991)
Published in: *Nucl.Phys.B* 358 (1991) 1, 97-120

Associated production of the Higgs boson with t anti-b at hadron colliders
J.L. Diaz-Cruz (Barcelona, Autonoma U.), O.A. Sampayo (Barcelona, Autonoma U.)
Published in: *Phys.Lett.B* 276 (1992) 211-213

Vacuum alignment in multiscalar models
J.L. Diaz-Cruz (Barcelona, Autonoma U.), A. Mendez
Published in: *Nucl.Phys.B* 380 (1992) 39-50

Lepton flavor violating decays of Higgs bosons beyond the standard model #145
J.Lorenzo Diaz-Cruz (Puebla U., Mexico), J.J. Toscano (Puebla U., Mexico) (Oct, 1999)
Published in: *Phys.Rev.D* 62 (2000) 116005 • e-Print: hep-ph/9910233 [hep-ph]
pdf DOI cite claim reference search 179 citations

Mass matrix ansatz and lepton flavor violation in the THDM-III #123
J.L. Diaz-Cruz (Puebla U., Mexico), R. Noriega-Papaqui (Puebla U., Inst. Fis.), A. Rosado (Puebla U., Mexico and Puebla U., Inst. Fis.) (Jan, 2004)
Published in: *Phys.Rev.D* 69 (2004) 095002 • e-Print: hep-ph/0401194 [hep-ph]
pdf DOI cite claim reference search 83 citations

Gauge-Higgs unification with brane kinetic terms
Alfredo Aranda (Colima U.), J.Lorenzo Diaz-Cruz (Puebla U., Mexico)
Published in: *Phys.Lett.B* 633 (2006) 591-594 • e-Print: hep-ph/05

A More flavored Higgs boson in supersymmetric models
J. Lorenzo Diaz-Cruz (Puebla U., Inst. Fis.) (Jul, 2002)
Published in: *JHEP* 05 (2003) 036 • e-Print: hep-ph/0207030 [hep-ph]

Holographic dark matter and Higgs
J.Lorenzo Diaz-Cruz (Puebla U., Mexico) (Nov, 2007)
Published in: *Phys.Rev.Lett.* 100 (2008) 221802 • e-Print:

Solving the Naturalness Problem with Feeble Coupled Sectors
J. Lorenzo Diaz-Cruz (Puebla U., Mexico) (Sep 4, 2023)
e-Print: 2309.01378 [hep-ph]
pdf cite claim reference search

My life with the Higgs boson (Thanks to MAPA, Gordy Kane & Tiny Veltman, my collaborators and my students, we have had a great time!)

What could come after the SM? (DiazCruz)

- Is the New Physics still consistent with QM & Relativity
  - No → Holy ghost! We are in trouble …
  - Yes ↓

Is it a consistente QFT?
- No → Try String Theory or LQG or …
- Yes ↓

Is there a new gauge boson?
- Yes → Try extra U(1) or LR or GUTs …
- No ↓

Is the same Repr. as in the SM?
- No → Try extra U(1) or LR or SUSY or GUTs … (↓↑ Try extra U(1) or LR or GUTs …)
- Yes ↓

It is still Rock & Roll to me … keep calling it the SM-X

The DC extension of the SMEFT

J. Lorenzo Diaz-Cruz (Puebla U., Mexico)
e-Print: 2309.01378 [hep-ph]

- One assumes that naturalness problem is solved with heavy particles of FECOS type,
- FECOS particles are included to explain the dark cosmos (DC),
- The SM is treated as an effective lagrangian, which results from the interaction out of the FECOS particles,
- Many possibilities exist for the DC sector, which is also treated as an effective lagrangian; interesting case includes 3 RH neutrinos & an scalar singlet,

$$\mathcal{L}_{DC-SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{DC} + \sum_{i,d}[\frac{\alpha_{i,d}}{\Lambda^{d-4}} O^{sm}_{d,i} + \frac{\beta_{i,d}}{\Lambda^{d-4}} O^{sm}_{d,i}]$$

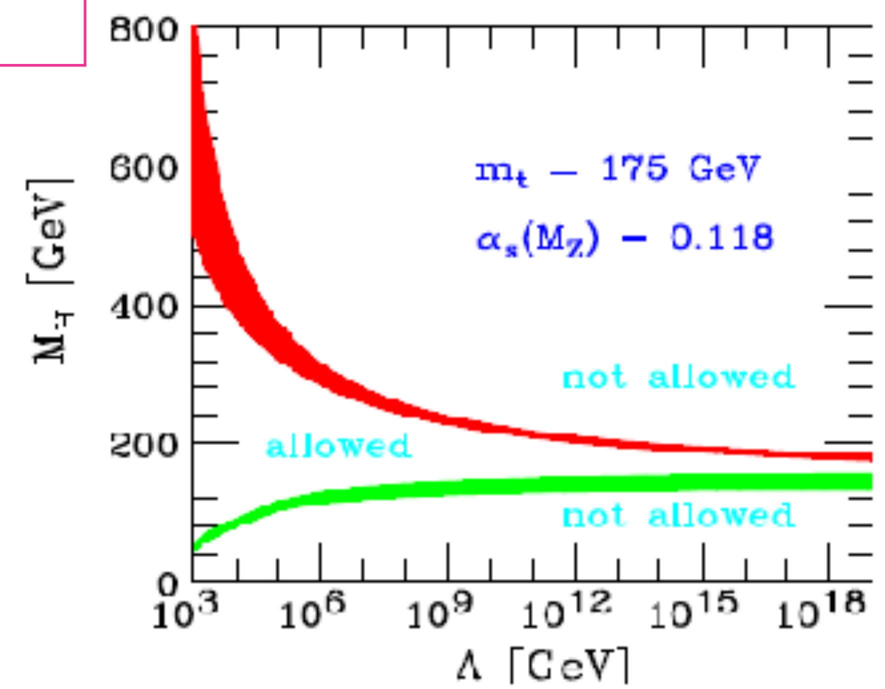
- Predictions: small corrections to Higgs observables (ex. Self-coupling), pattern of neutrino masses, decaying dark matter, etc.

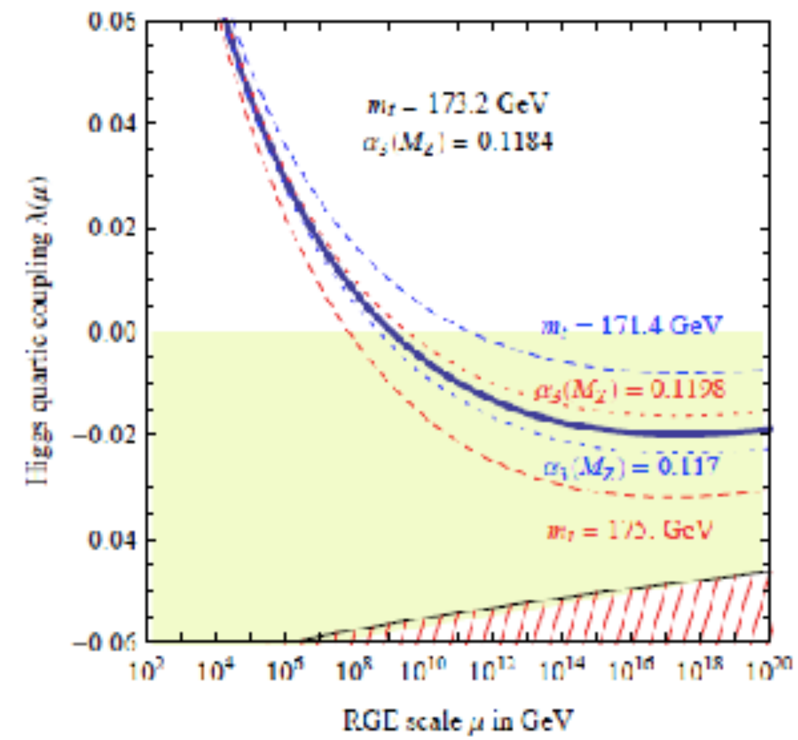
Is the Higgs Boson the Master of the Universe?

Fred Jegerlehner[1 2]

e-Print: 2305.01326 [hep-ph]

- Higgs boson discovery and absence of BSM physics at O(1) TeV -> new paradigm,
- SM masses & couplings show amazingly deep conspiracy -> SM vacuum stable up to the Planck scale,
- At higher energy (below Planck scale), there is a phase transition from Higgs phase (SSB) to symmetric one,
- In the disordered phase, four physical Higgs scalars are very heavy -> provide enormous Dark Energy (DE).





$$\delta m_H^2 = m_{H0}^2 - M_H^2 = C_1\,\Xi;\; C_1 = 2\lambda + 3/2\,g'^2 + 9/2\,g^2 - 12\,y_t^2$$

- C1 has a zero, at about E=10^(17) GeV, for mh=125 GeV.

Gracias!