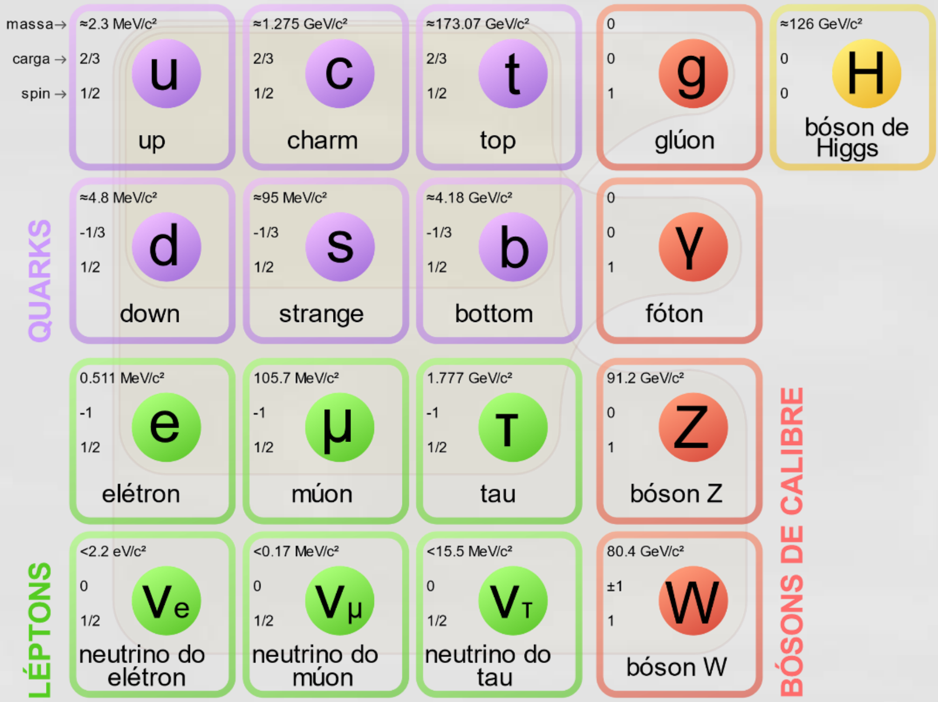
The precision frontier: higher order corrections to observables and predictions of the 2HDM; development of new regularization techniques.

Adriano Lana Cherchiglia - UFABC

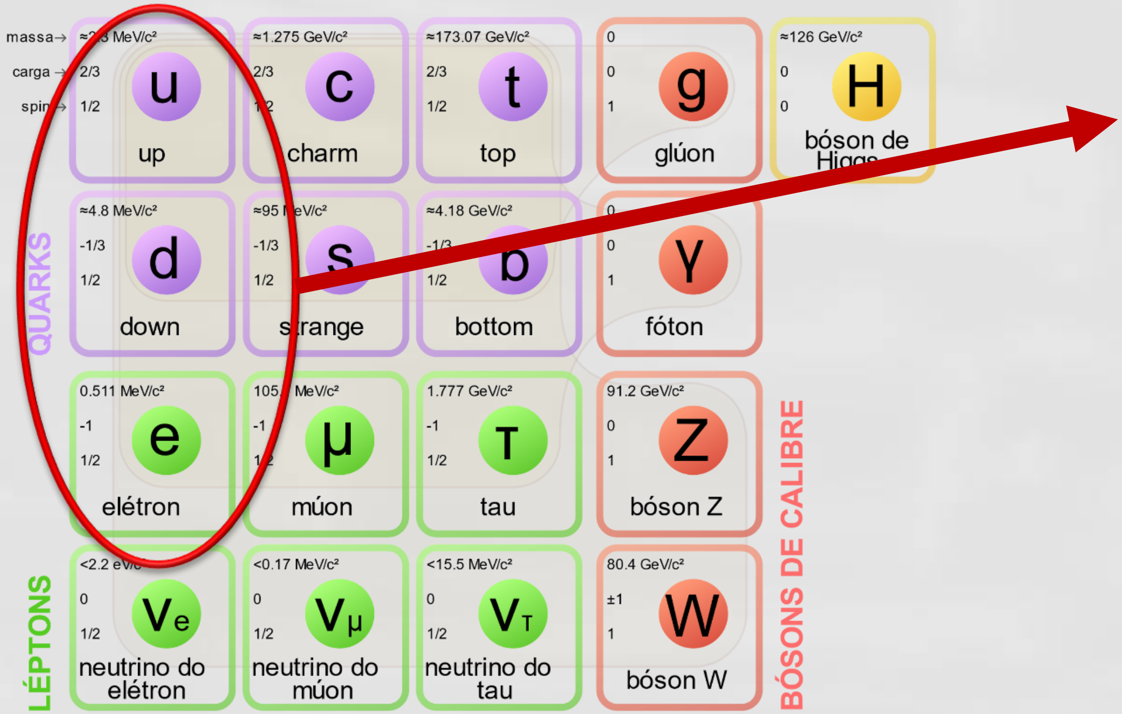
Valencia, 1st March 2018

Standard Model



https://commons.wikimedia.org/w/index.php?curid=49632920

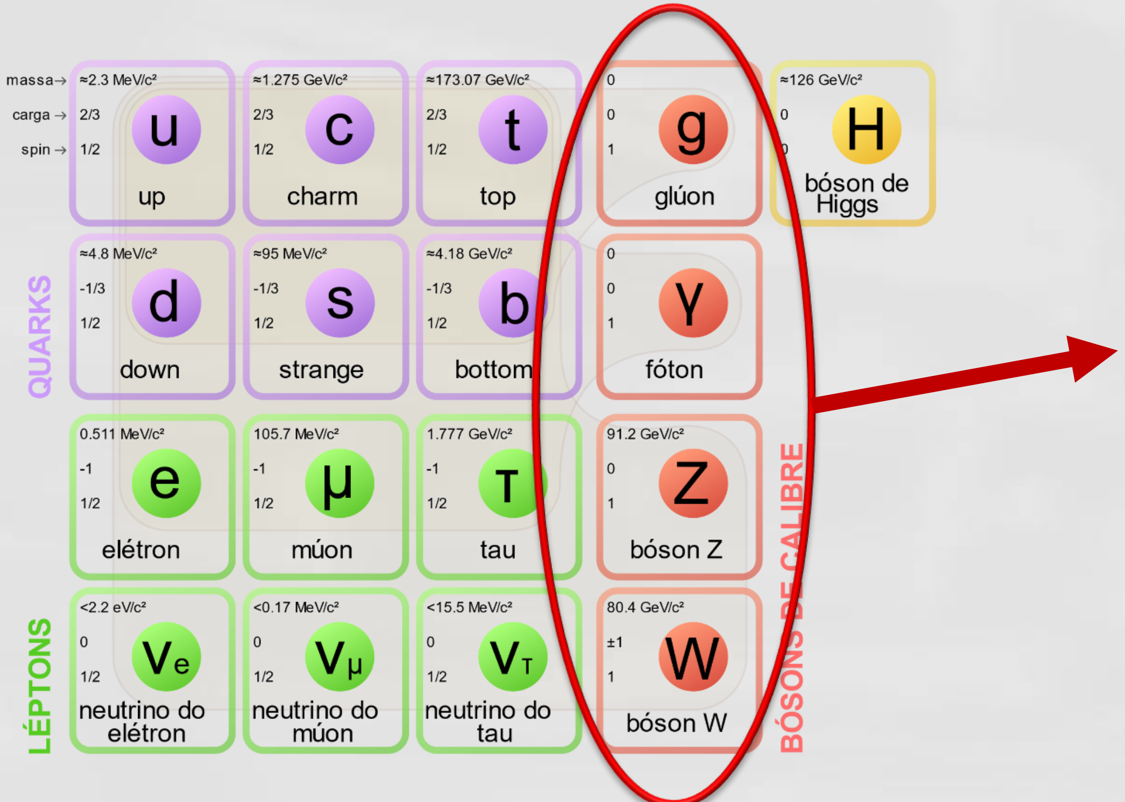
Standard Model



Structures of our Universe

https://commons.wikimedia.org/w/index.php?curid=49632920

Standard Model

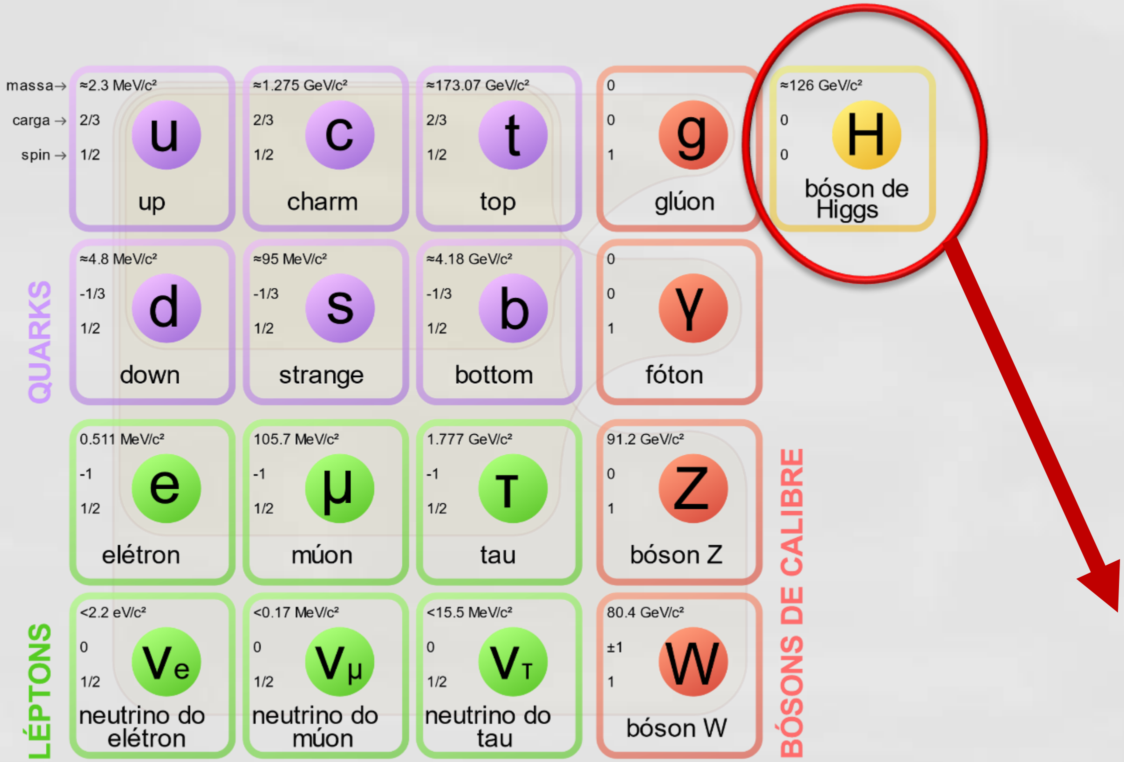


https://commons.wikimedia.org/w/index.php?curid=49632920

Structures of our Universe

Mediators of strong, weak, and electromagnetic forces

Standard Model



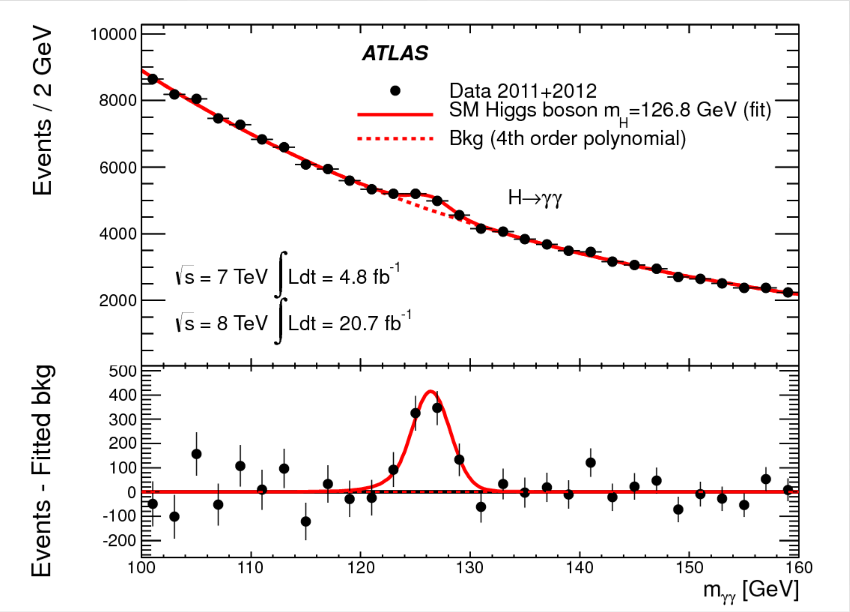
https://commons.wikimedia.org/w/index.php?curid=49632920

Structures of our Universe

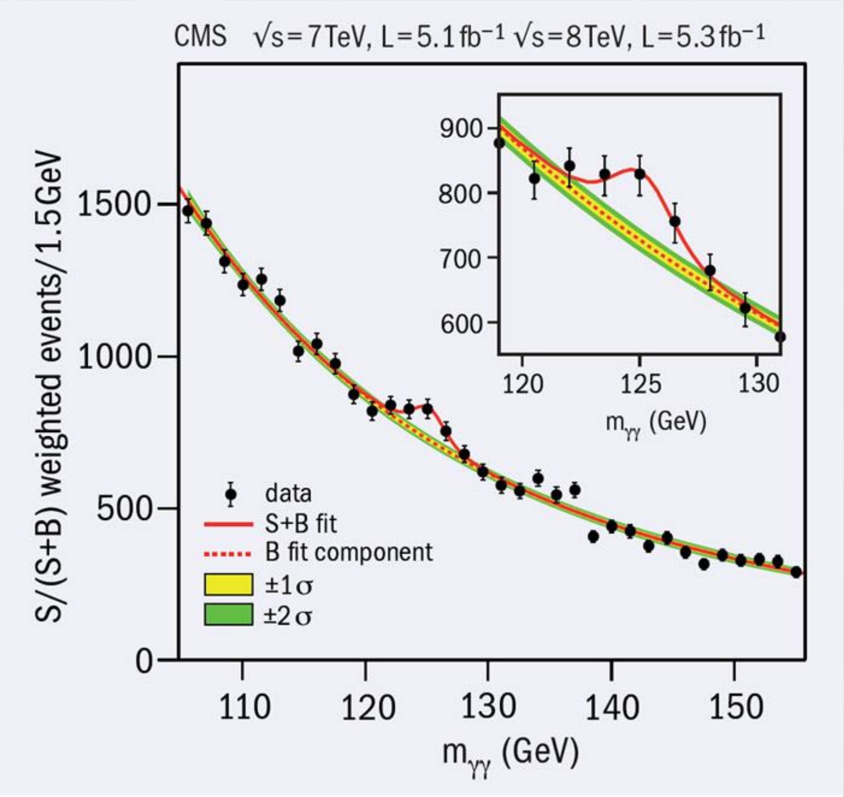
Mediators of strong, weak, and electromagnetic forces

Gives masses to all particles

Standard Model (2012)



Phys.Lett. B716 (2012) 1-29

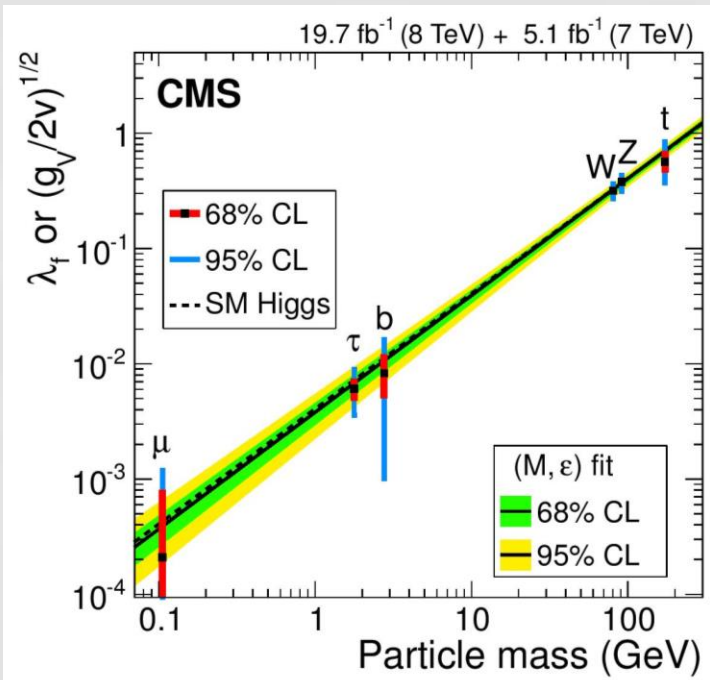


Phys.Lett. B716 (2012) 30-61

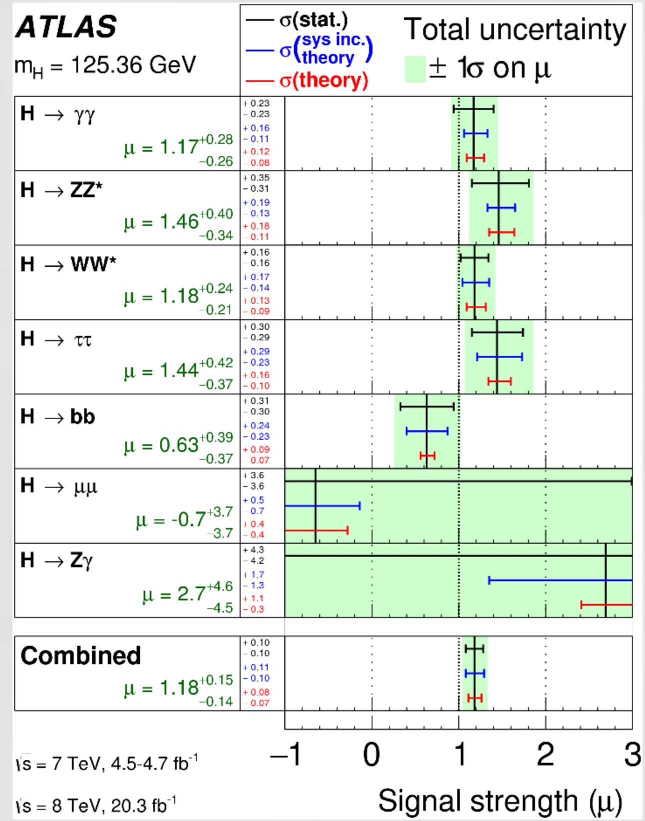
Higgs boson discovered!

Standard Model (pos-2012)

- Scalar sector scrutinized
  - Is the scalar found the one of the SM?
  - Are there other scalars?



Eur. Phys. J. C 75 (2015) 212



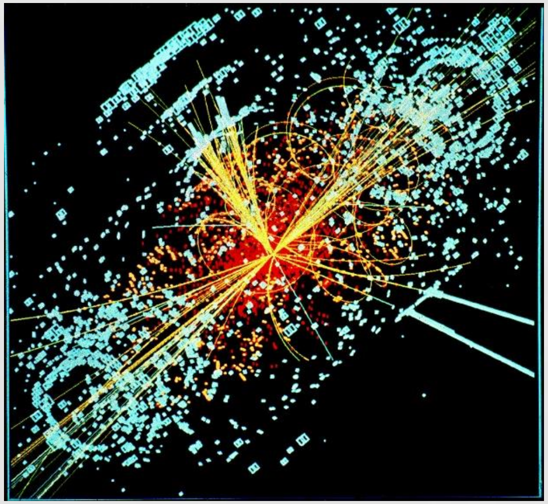
Eur. Phys. J. C76 (2016) 6

Standard Model (pos-2012)

- High Energy Physics (colliders)
  - Small deviations

BSM predictions   Increase precision

- Open questions:
  - No gravitational interactions included;
  - No candidates for Dark Matter;
  - Matter-antimatter assymetry;
  - ......



http://cds.cern.ch/record/628469

Beyond Standard Model

- Two-Higgs-Doublet-Model (2HDM)
  - Minimal extension to scalar sector → Some variants (inert model) have dark matter candidate
  - Four more scalars

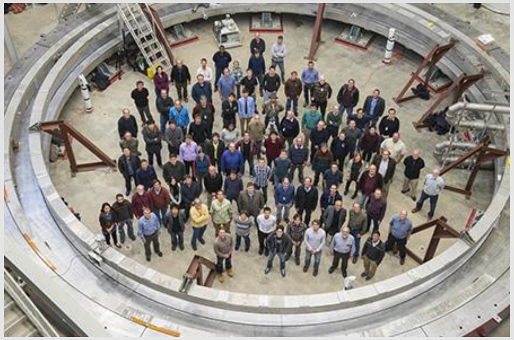
- Supersymmetry (SUSY)
  - Correlates bosons and fermions;
  - Has a non-minimal scalar sector (2HDM);
  - Predicts a partner to each particle of SM.
    - Dark matter candidate;
    - Solves naturalness problem.

In the search for New Physics

- High Energy Physics (colliders)
  - Still no sign of New Physics.

https://cds.cern.ch/record/1295244

- Low-energy observables
  - Muon magnetic moment.



http://muon-g-2.fnal.gov/

$(g-2)_\mu$

- Basic idea

http://muon-g-2.fnal.gov/

$$H_B = -\overrightarrow{\mu}.\overrightarrow{B}$$

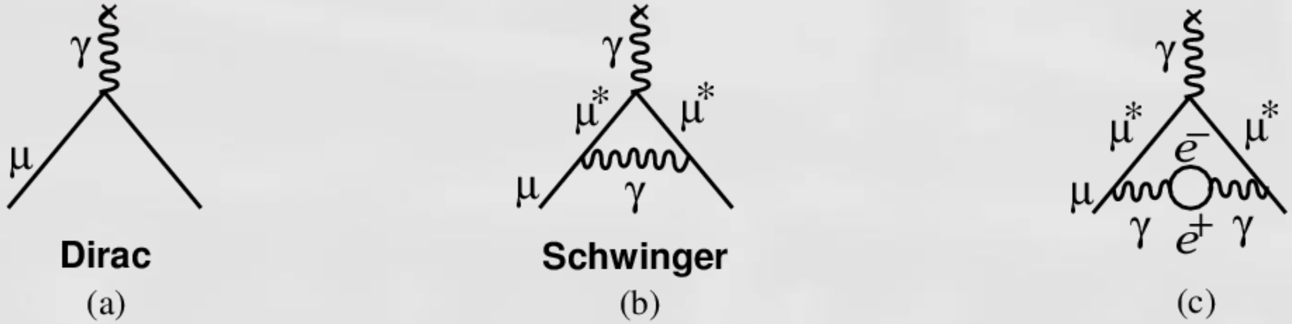
$$\overrightarrow{\mu_s} = g\left(\frac{q}{2m}\right)\vec{s}$$

- Dirac: $g = 2$
- Quantum Field Theory: $g = 2 + \cdots$

$$\longrightarrow \boxed{a_\mu = \frac{(g-2)}{2}}$$

$(g-2)_\mu$

- Theory (Standard Model)



Rept.Prog.Phys.70:795,2007

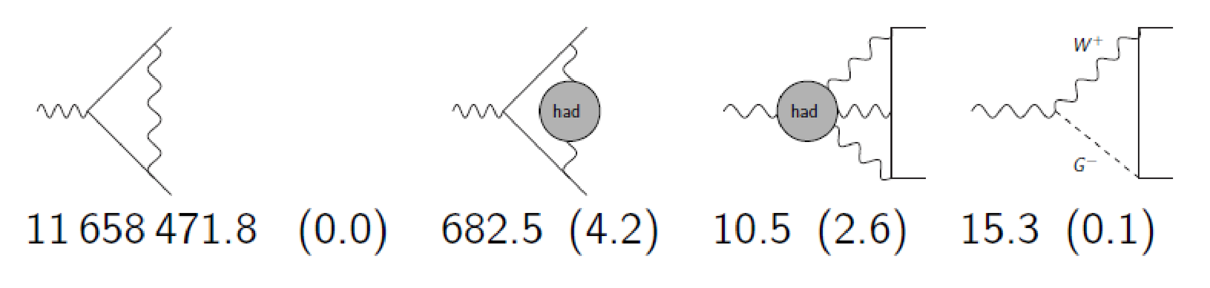
$a_\mu = 0$

$a_\mu = \frac{\alpha}{2\pi} \approx 0.0011623...$

$a_\mu = c_2 \left(\frac{\alpha}{\pi}\right)^2 \approx -0.0000176...$

$(g-2)_\mu$

- Theory (Standard Model)



Thanks to D. Stöckinger

$$a_\mu^{th} = (11\,659\,180.8 \pm 3.6) \times 10^{-10}$$

"Muon g-2 Theory Initiative"

$(g-2)_\mu$

- Experiment
  - E821 BNL
  - Final result in 2004

http://www.g-2.bnl.gov/

$$a_\mu^{exp} = (11\,659\,208.9 \pm 6.3) \times 10^{-10}$$

Phys. Rev. Lett. 92, 161802 (2004)

$(g-2)_\mu$

- Theory X Experiment

$$a_\mu^{th} = (11\,659\,180\,.\,8 \pm 3\,.6) \times 10^{-10}$$

$$a_\mu^{exp} = (11\,659\,208\,.\,9 \pm 6.3\,) \times 10^{-10}$$

$(g-2)_\mu$

- Theory X Experiment

$$a_\mu^{exp} - a_\mu^{th} = (28.1 \pm 7.3) \times 10^{-10}$$

3.8 σ !

$(g-2)_\mu$

- Theory X Experiment

$$a_\mu^{exp} - a_\mu^{th} = (28.1 \pm 7.3) \times 10^{-10}$$

BSM

Increase precision

http://muon-g-2.fnal.gov/

$(g-2)_\mu$

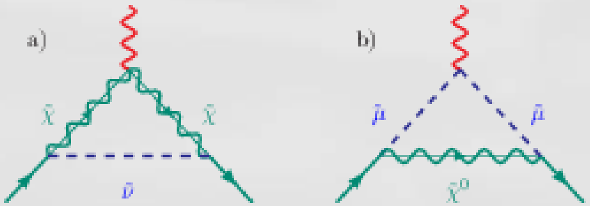
- Beyond Standard Model:
  - Radiative corrections

Phys.Rept. 477 (2009) 1-110

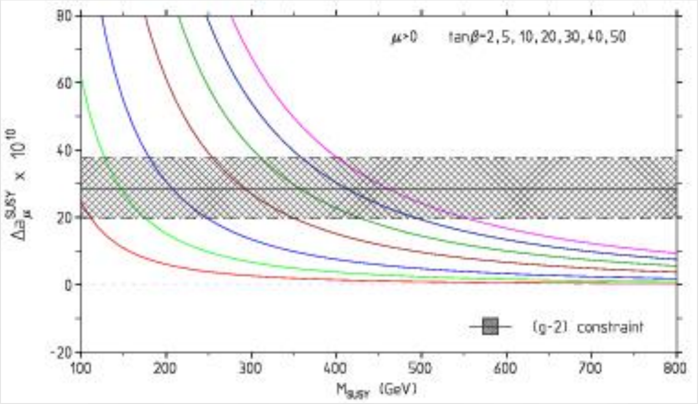
  - Complementary information to direct searches (LHC)

$(g-2)_\mu$

- Beyond Standard Model:
  - SUSY



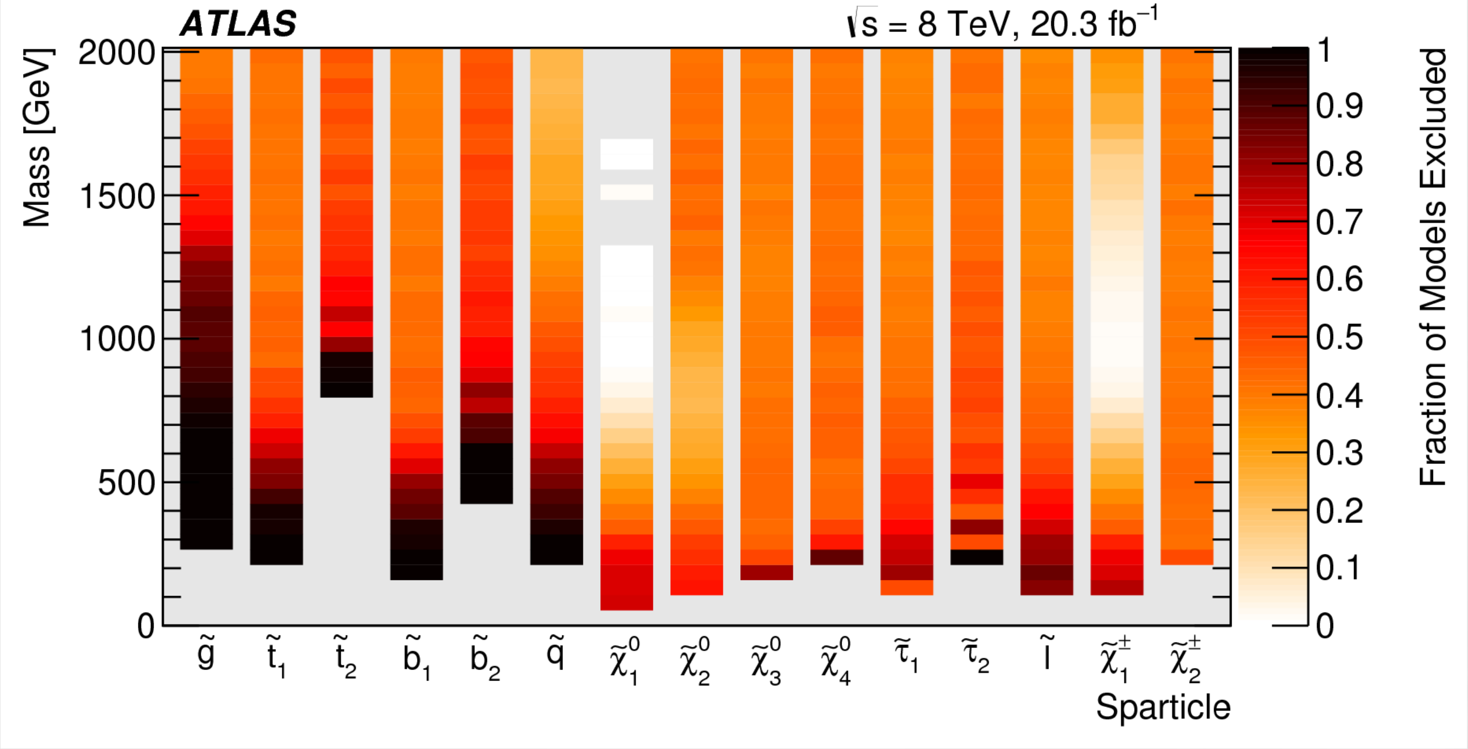
$$a_\mu(SUSY) \cong 123\times 10^{-11}\left(\frac{100\ GeV}{M_{SUSY}}\right)^2 \tan\beta$$



Phys.Rept. 477 (2009) 1-110

$(g-2)_\mu$

- Beyond Standard Model:
  - SUSY



https://atlas.web.cern.ch

$(g-2)_\mu$

- Beyond Standard Model:
  - SUSY

Other scenarios → Ex: extensions to the scalar sector

$$\mathcal{L}_S = (D_\mu \phi_1)^\dagger (D^\mu \phi_1) + (D_\mu \phi_2)^\dagger (D^\mu \phi_2) - V(\phi_1, \phi_2)$$

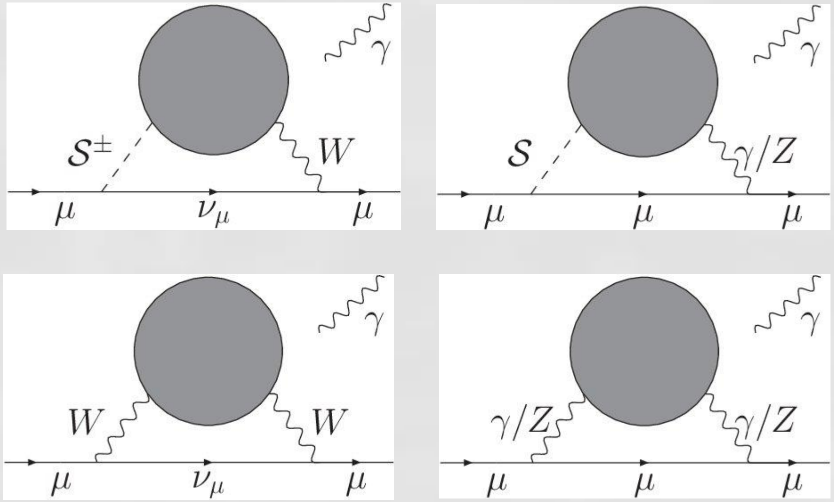
2HDM

Invariant under CP

$(g-2)_\mu$

- Beyond Standard Model : 2HDM
  - More loops

Higher Precision



Complete two-loop prediction

Leading order (one-loop suppressed by m_μ^2/m_H^2)

Cherchiglia et al, JHEP 1701 (2017) 007

$(g-2)_\mu$

- Beyond Standard Model : 2HDM

$$Y_f^h = s_{\beta\alpha} + c_{\beta\alpha}\varepsilon_f$$

$$Y_f^H = c_{\beta\alpha} - s_{\beta\alpha}\varepsilon_f$$

$$Y_{d,l}^A = -\varepsilon_{d,l}\ Y_u^A = \varepsilon_u$$

S: *h, H, A, H*$^\pm$

$$tan\beta = \frac{v_2}{v_1}$$

Flavour-aligned: $\varepsilon_l, \varepsilon_u, \varepsilon_d$

Cherchiglia et al, [hep-ph] 1711.11567

$(g-2)_\mu$

- Beyond Standard Model : 2HDM

Constraints

- B-physics;
- Tau decay;
- $Z \to \tau\tau$;
- Collider;
- Theoretical;
- S, T, U parameters.

S: *h, H, A, H*$^{\pm}$

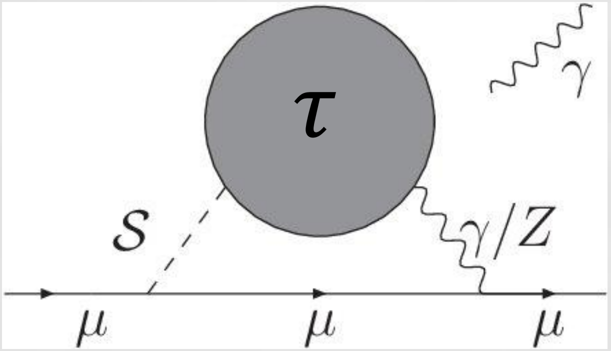
$$tan\beta = \frac{v_2}{v_1}$$

Flavour-aligned: $\varepsilon_l, \varepsilon_u, \varepsilon_d$

Cherchiglia et al, [hep-ph] 1711.11567

$(g-2)_\mu$

- Beyond Standard Model : 2HDM
  - Tau loop



Constraints

- B-physics;
- Tau decay;
- $Z \to \tau\tau$;
- Collider;
- Theoretical;
- S, T, U parameters.

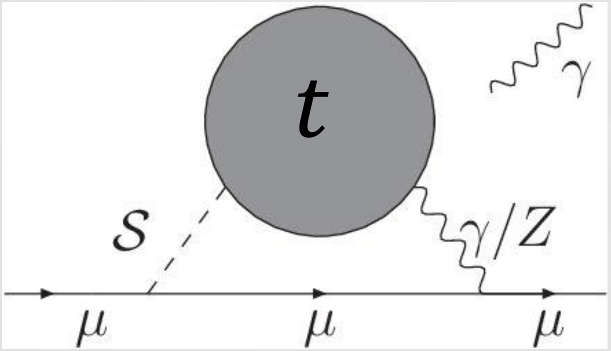
S: *h*, *H*, *A*, *H*$^{\pm}$

Flavour-aligned: ε_l, ε_u, ε_d

Cherchiglia et al, [hep-ph] 1711.11567

$(g-2)_\mu$

- Beyond Standard Model : 2HDM
  - Top loop



Constraints

- B-physics;
- Tau decay;
- $Z \to \tau\tau$;
- Collider;
- Theoretical;
- S, T, U parameters.

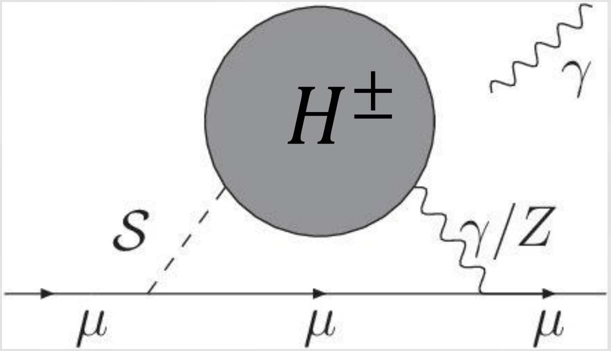
S: *h, H, A, H*$^{\pm}$

Flavour-aligned: $\varepsilon_l, \varepsilon_u, \varepsilon_d$

Cherchiglia et al, [hep-ph] 1711.11567

$(g-2)_\mu$

- Beyond Standard Model : 2HDM
  - Bosonic



Constraints

- B-physics;
- Tau decay;
- $Z \to \tau\tau$;
- Collider;
- Theoretical;
- S, T, U parameters.

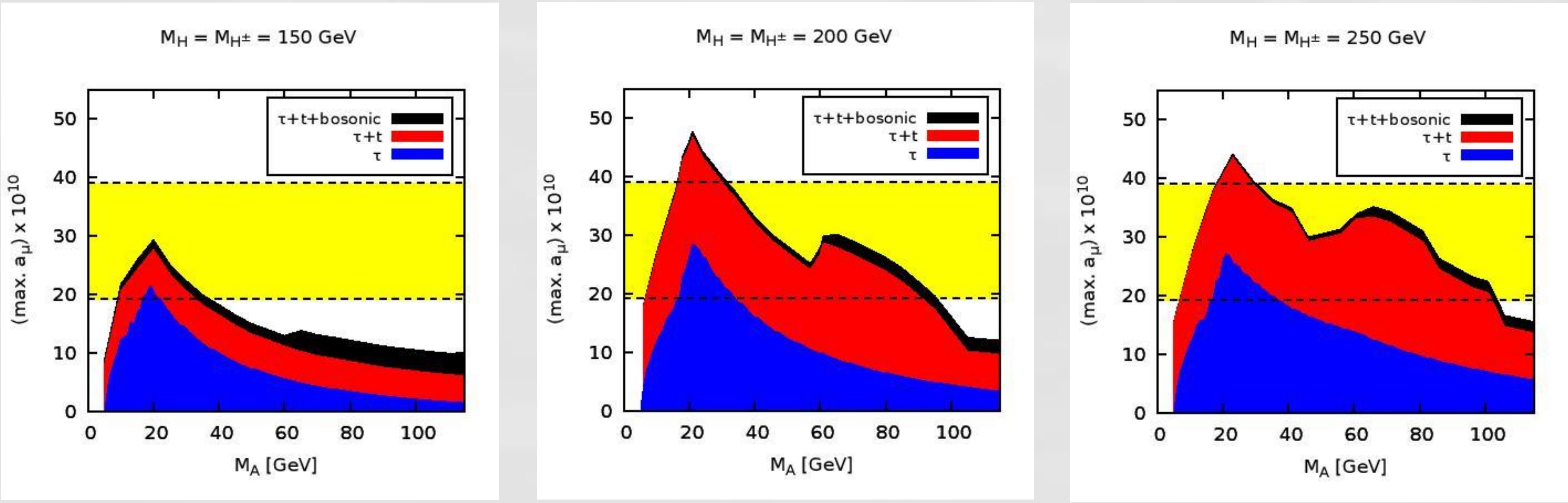
S: *h*, *H*, *A*, $H^\pm$

Flavour-aligned: ε_l, ε_u, ε_d

Cherchiglia et al, [hep-ph] 1711.11567

$(g-2)_\mu$

- Beyond Standard Model : 2HDM



Cherchiglia et al, [hep-ph] 1711.11567

Precision Frontier

- One-loop (and Beyond?): example in the 2HDM

At tree level

$$V_0 = m_{11}^2|\phi_1|^2 + m_{22}^2|\phi_2|^2 - [m_{12}^2\phi_1^\dagger\phi_2 + \text{h.c.}] + \frac{1}{2}\lambda_1|\phi_1|^4 + \frac{1}{2}\lambda_2|\phi_2|^4$$
$$+ \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2 + \left\{\frac{1}{2}\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{ h.c.}\right\}$$

Cherchiglia et al, JHEP 1711 (2017) 106

Precision Frontier

- One-loop (and Beyond?): example in the 2HDM

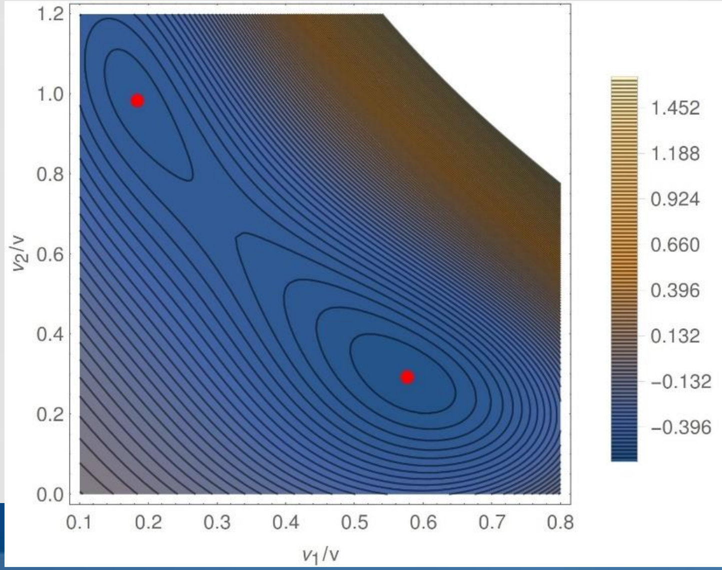
At tree level → Richer vaccum possibilities → Two coexisting minima

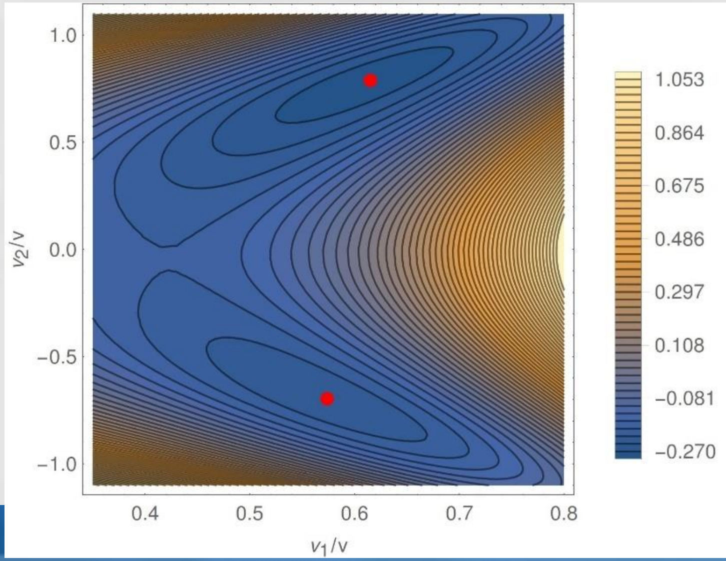
$$\langle \varphi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \langle \varphi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

Precision Frontier

- One-loop (and Beyond?): example in the 2HDM

At tree level → Richer vaccum possibilities → Two coexisting minima





Cherchiglia et al, JHEP 1711 (2017) 106

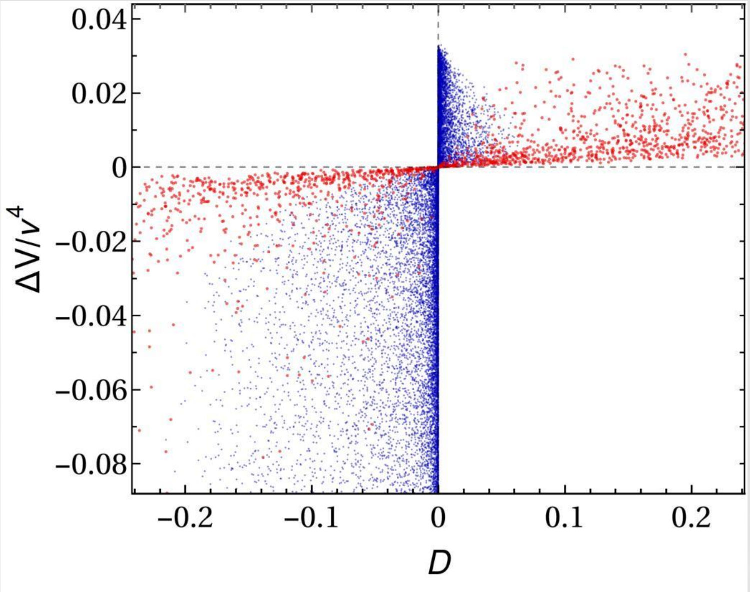
Precision Frontier

- One-loop (and Beyond?): example in the 2HDM

At tree level → Straightforward to find global minimun

$$D = \frac{1}{v^4} m_{12}^2 (m_{11}^2 - k^2 m_{22}^2) s_{2\beta} (t_\beta^2 - k^2)$$

$$k \equiv (\lambda_1/\lambda_2)^{1/4}$$



Cherchiglia et al, JHEP 1711 (2017) 106

Precision Frontier

- One-loop (and Beyond?): example in the 2HDM

Adding one-loop

$$V = V_0 + V_{1l}$$

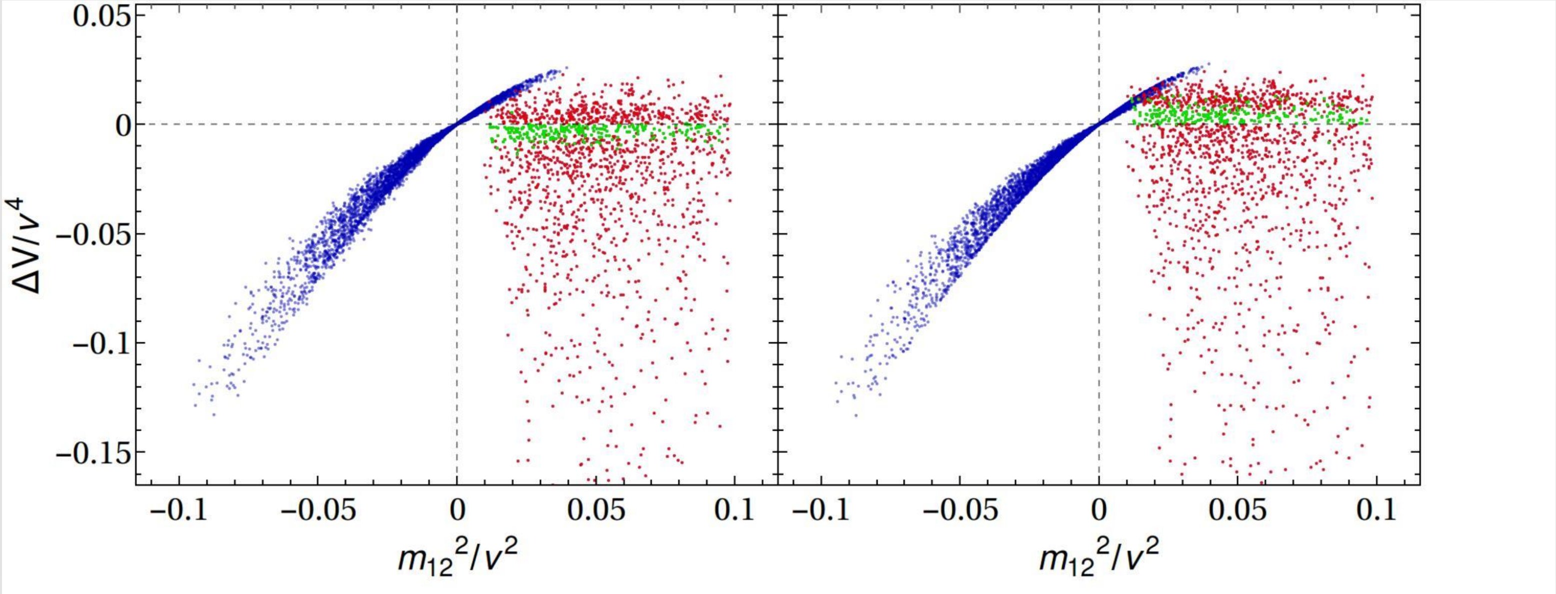
$$V_{1l} = \frac{1}{64\pi^2} \sum_k c_k M_k^4(\varphi_i) \left(\ln \frac{M_k^2(\varphi_i)}{\mu^2} - \frac{3}{2} \right)$$

Cherchiglia et al, JHEP 1711 (2017) 106

Precision Frontier

- One-loop (and Beyond?): example in the 2HDM

$V = V_0$ $\qquad\qquad$ $V = V_0 + V_{1l}$

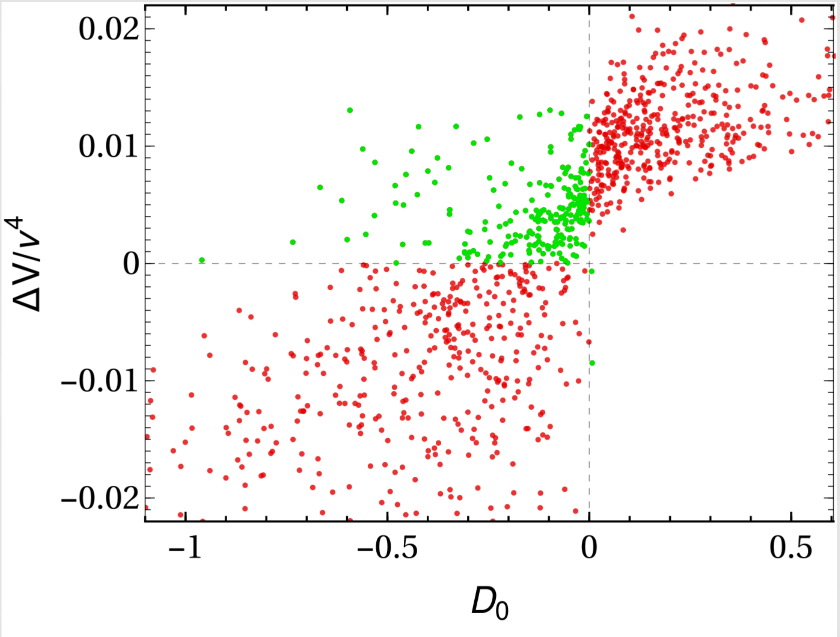


Cherchiglia et al, JHEP 1711 (2017) 106

Precision Frontier

- One-loop (and Beyond?): example in the 2HDM

Adding one-loop → NO straightforward way to find global minimun



Cherchiglia et al, JHEP 1711 (2017) 106

Precision Frontier

- High Energy Physics

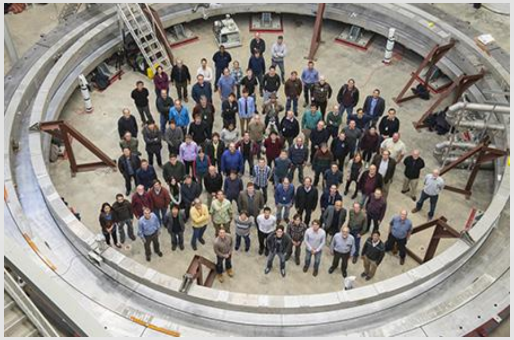
↓

Precision calculations

↑

- Low-energy observables

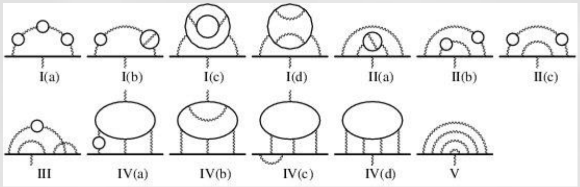
https://cds.cern.ch/record/1295244



http://muon-g-2.fnal.gov/

Precision Frontier

- More loops



Phys.Rev.Lett. 109 (2012) 111808

More efficient algorithms

New regularization techniques

Precision Frontier

- New regularization techniques:

Eur. Phys. J. C (2014) 74:3197
DOI 10.1140/epjc/s10052-014-3197-4
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Theoretical Physics

On the four-dimensional formulation of dimensionally regulated amplitudes

A. R. Fazio[1,a], P. Mastrolia[2,3,b], E. Mirabella[3,c], W. J. Torres Bobadilla[1,2,d]
[1] Departamento de Física, Universidad Nacional de Colombia, Ciudad Universitaria, Bogotá, D.C., Colombia
[2] Dipartimento di Fisica e Astronomia, Università di Padova, and INFN, Sezione di Padova, via Marzolo 8, 35131 Padua, Italy
[3] Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 Munich, Germany

Received: 16 September 2014 / Accepted: 24 November 2014 / Published online: 18 December 2014

JHEP
Published for SISSA by Springer
Received: September 19, 2016
Accepted: October 18, 2016
Published: October 28, 2016

Four-dimensional unsubtraction with massive particles

Germán F.R. Sborlini, Félix Driencourt-Mangin and Germán Rodrigo
Instituto de Física Corpuscular, Universitat de València,
Consejo Superior de Investigaciones Científicas,
Parc Científic, Paterna, Valencia, E-46980 Spain
E-mail: german.sborlini@ific.uv.es, felix.dm@ific.uv.es, german.rodrigo@csic.es

Journal of High Energy Physics
November 2012, 2012:151

A four-dimensional approach to quantum field theories

Authors Authors and affiliations
R. Pittau

Article
First Online: 27 November 2012
DOI: 10.1007/JHEP11(2012)151
Cite this article as:
Pittau, R. J. High Energ. Phys. (2012) 2012: 151. doi:10.1007/JHEP11(2012)151

- ......

Precision Frontier

Eur. Phys. J. C (2017) 77:471
DOI 10.1140/epjc/s10052-017-5023-2

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Theoretical Physics

To *d*, or not to *d*: recent developments and comparisons of regularization schemes

C. Gnendiger[1,a], A. Signer[1,2], D. Stöckinger[3], A. Broggio[4], A. L. Cherchiglia[5], F. Driencourt-Mangin[6], A. R. Fazio[7], B. Hiller[8], P. Mastrolia[9,10], T. Peraro[11], R. Pittau[12], G. M. Pruna[1], G. Rodrigo[6], M. Sampaio[13], G. Sborlini[6,14,15], W. J. Torres Bobadilla[6,9,10], F. Tramontano[16,17], Y. Ulrich[1,2], A. Visconti[1,2]

[1] Paul Scherrer Institut, 5232 Villigen, PSI, Switzerland
[2] Physik-Institut, Universität Zürich, 8057 Zürich, Switzerland
[3] Institut für Kern- und Teilchenphysik, TU Dresden, 01062 Dresden, Germany
[4] Physik Department T31, Technische Universität München, 85748 Garching, Germany
[5] Centro de Ciências Naturais e Humanas, UFABC, 09210-170 Santo André, Brazil
[6] Insituto de Física Corpuscular, UVEG–CSIC, Universitat de València, 46980 Paterna, Spain
[7] Departamento de Física, Universidad Nacional de Colombia, Bogotá D.C., Colombia
[8] CFisUC, Department of Physics, University of Coimbra, 3004-516 Coimbra, Portugal
[9] Dipartimento di Fisica ed Astronomia, Università di Padova, 35131 Padua, Italy
[10] INFN, Sezione di Padova, 35131 Padua, Italy
[11] Higgs Centre for Theoretical Physics, The University of Edinburgh, Edinburgh EH9 3FD, UK
[12] Dep. de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, 18071 Granada, Spain
[13] Departamento de Física, ICEX, UFMG, 30161-970 Belo Horizonte, Brazil
[14] Dipartimento di Fisica, Università di Milano, 20133 Milan, Italy
[15] INFN, Sezione di Milano, 20133 Milan, Italy
[16] Dipartimento di Fisica, Università di Napoli, 80126 Naples, Italy
[17] INFN, Sezione di Napoli, 80126 Naples, Italy

Precision Frontier

- New regularization techniques:
  - Implicit Regularization

O. A. BATTISTEL, A. L. MOTA, and M. C. NEMES, *Mod. Phys. Lett. A* **13**, 1597 (1998). DOI: http://dx.doi.org/10.1142/S0217732398001686

CONSISTENCY CONDITIONS FOR 4-D REGULARIZATIONS

Partially supported by CNPq-Brazil.

O. A. BATTISTEL

Departamento de Física, ICEx, Universidade Federal de Minas Gerais, Belo Horizonte, CEP 30161-970, C.P. 702, MG, Brazil

A. L. MOTA

Departamento de Física, ICEx, Universidade Federal de Minas Gerais, Belo Horizonte, CEP 30161-970, C.P. 702, MG, Brazil

M. C. NEMES

Departamento de Física, ICEx, Universidade Federal de Minas Gerais, Belo Horizonte, CEP 30161-970, C.P. 702, MG, Brazil

Received: 21 November 1997

From the study of well-known divergent amplitudes we deduce three consistency conditions which are necessary and sufficient to eliminate ambiguities and symmetry violations. The conditions relate divergent integrals of the same degree of divergence and are automatically satisfied within the context of dimensional regularization. We show how the deduced consistency conditions can be satisfied in four-dimensional regularizations. An important conclusion of the present study is the possibility of working with 4-D regularization schemes which preserve the virtues of dimensional regularization avoiding, however, its restrictions.

→ Sistematization of ambiguities

PHYSICAL REVIEW D **87**, 065011 (2013)

(Un)determined finite regularization-dependent quantum corrections: The Higgs boson decay into two photons and the two-photon scattering examples

A. L. Cherchiglia,[1,*] L. A. Cabral,[2,†] M. C. Nemes,[1,‡] and Marcos Sampaio[1,§]

[1]*Departamento de Física, ICEx, Universidade Federal de Minas Gerais, P.O. Box 702, Belo Horizonte, Minas Gerais 30.161-970, Brazil*

[2]*Departamento de Física, Universidade Federal do Tocantins, P.O. Box 132, Araguaina, Tocantins 77804-970, Brazil*

(Received 7 November 2012; published 15 March 2013)

We investigate the appearance of arbitrary, regularization-dependent parameters introduced by divergent integrals in two *a priori* finite but superficially divergent amplitudes: the Higgs decay into two photons and the two-photon scattering. We use a general parametrization of ultraviolet divergences which makes explicit such ambiguities. Thus we separate in a consistent way using implicit regularization the divergent, finite, and regularization-dependent parts of the amplitudes which in turn are written as surface terms. We find that, although finite, these amplitudes are ambiguous before the imposition of physical conditions, namely, momentum routing invariance in the loops of Feynman diagrams. In the examples we study, momentum routing invariance turns out to be equivalent to gauge invariance. We also discuss the results obtained by different regularizations and show how they can be reproduced within our framework allowing for a clear view on the origin of regularization ambiguities.

DOI: 10.1103/PhysRevD.87.065011 PACS numbers: 11.10.Gh, 13.40.Hq, 14.80.Bn

PHYSICAL REVIEW D **86**, 025016 (2012)

Momentum routing invariance in Feynman diagrams and quantum symmetry breakings

L. C. Ferreira,[1,*] A. L. Cherchiglia,[1,†] Brigitte Hiller,[2,‡] Marcos Sampaio,[1,§] and M. C. Nemes[1,‖]

[1]*Universidade Federal de Minas Gerais - Departamento de Física - ICEx, P. O. BOX 702, 30.161-970, Belo Horizonte MG - Brazil*

[2]*Departamento de Física, Faculdade de Ciências e Tecnologia, Universidade de Coimbra, Rua Larga, P-3004-516 Coimbra - Portugal*

(Received 4 November 2011; published 13 July 2012)

We illustrate with examples that quantum symmetry breakings in perturbation theory are connected to breakdown of momentum routing invariance (MRI) in the loops of a Feynman diagram. We show that MRI is a necessary and sufficient condition to preserve Abelian gauge symmetry at arbitrary loop order. We adopt the implicit regularization framework in which surface terms that are directly connected to momentum routing can be constructed to arbitrary loop order. The interplay between momentum routing invariance, surface terms and anomalies is discussed. We also illustrate that MRI is important to preserve supersymmetry. For theories with poor symmetry content, such as scalar field theories, MRI is shown to be important in the calculation of renormalization group functions.

DOI: 10.1103/PhysRevD.86.025016 PACS numbers: 11.10.Gh, 11.15.Bt, 11.30.Qc

- ......

Precision Frontier

- New regularization techniques:
  - Implicit Regularization

International Journal of Modern Physics A
Vol. 26, No. 15 (2011) 2591–2635

DOI: 10.1142/S0217751X11053419

SYSTEMATIC IMPLEMENTATION OF IMPLICIT REGULARIZATION FOR MULTILOOP FEYNMAN DIAGRAMS

A. L. CHERCHIGLIA,* MARCOS SAMPAIO† and M. C. NEMES‡

Federal University of Minas Gerais, Physics Department, ICEx, PO Box 702, 30.161-970, Belo Horizonte MG, Brazil
**adriano@fisica.ufmg.br*
†msampaio@fisica.ufmg.br
‡carolina@fisica.ufmg.br

Received 27 January 2011
Revised 22 March 2011

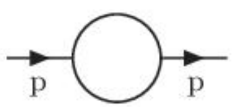
Implicit Regularization (IReg) is a candidate to become an invariant framework in momentum space to perform Feynman diagram calculations to arbitrary loop order. In this work we present a systematic implementation of our method that automatically displays the terms to be subtracted by Bogoliubov's recursion formula. Therefore, we achieve a twofold objective: we show that the IReg program respects unitarity, locality and Lorentz invariance and we show that our method is consistent since we are able to display the divergent content of a multiloop amplitude in a well-defined set of basic divergent integrals in one-loop momentum only which is the essence of IReg. Moreover, we conjecture that momentum routing invariance in the loops, which has been shown to be connected with gauge symmetry, is a fundamental symmetry of any Feynman diagram in a renormalizable quantum field theory.

→ Satisfies Lorentz invariance, locality and unitarity

Precision Frontier

- New regularization techniques :

Efficiency in the identification and removal of divergences.



$$\int \frac{d^6 k}{(2\pi)^6} \frac{1}{k^2} \frac{1}{(k-p)^2}$$

Divergent Part + Finite Part

$$\frac{1}{\varepsilon}$$

$$\int_k \frac{1}{(k^2-\mu^2)^3}$$

Precision Frontier

- New regularization techniques :

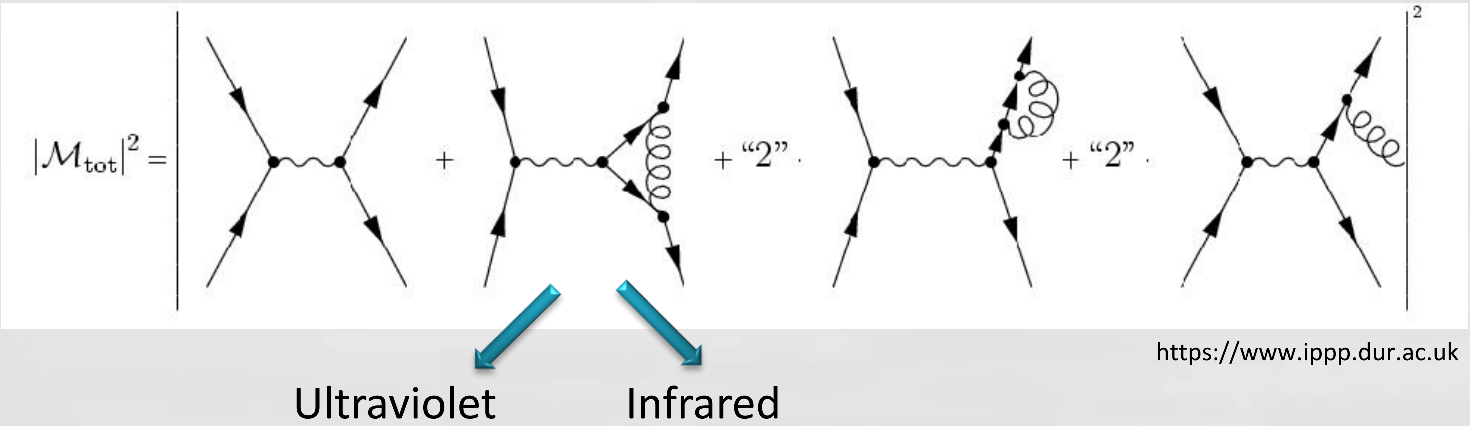
Efficiency in the identification and removal of divergences

Allows numerical implementation

Precision Frontier

- Example of NLO observable with IReg

$$e^+e^- \to q\bar{q}\ (g)$$



https://www.ippp.dur.ac.uk

Precision Frontier

- Example of NLO observable with IReg

Eur. Phys. J. C (2017) 77:471
DOI 10.1140/epjc/s10052-017-5023-2

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Theoretical Physics

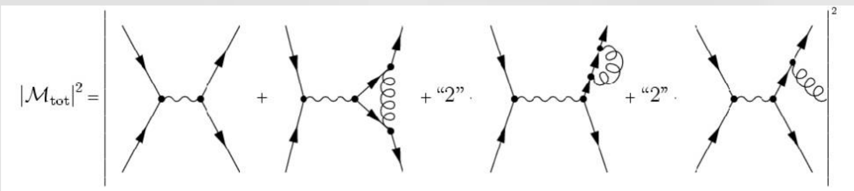
To *d*, or not to *d*: recent developments and comparisons of regularization schemes

C. Gnendiger[1,a], A. Signer[1,2], D. Stöckinger[3], A. Broggio[4], A. L. Cherchiglia[5], F. Driencourt-Mangin[6], A. R. Fazio[7], B. Hiller[8], P. Mastrolia[9,10], T. Peraro[11], R. Pittau[12], G. M. Pruna[1], G. Rodrigo[6], M. Sampaio[13], G. Sborlini[6,14,15], W. J. Torres Bobadilla[6,9,10], F. Tramontano[16,17], Y. Ulrich[1,2], A. Visconti[1,2]

[1] Paul Scherrer Institut, 5232 Villigen, PSI, Switzerland
[2] Physik-Institut, Universität Zürich, 8057 Zürich, Switzerland
[3] Institut für Kern- und Teilchenphysik, TU Dresden, 01062 Dresden, Germany
[4] Physik Department T31, Technische Universität München, 85748 Garching, Germany
[5] Centro de Ciências Naturais e Humanas, UFABC, 09210-170 Santo André, Brazil
[6] Insituto de Física Corpuscular, UVEG–CSIC, Universitat de València, 46980 Paterna, Spain
[7] Departamento de Física, Universidad Nacional de Colombia, Bogotá D.C., Colombia
[8] CFisUC, Department of Physics, University of Coimbra, 3004-516 Coimbra, Portugal
[9] Dipartimento di Fisica ed Astronomia, Università di Padova, 35131 Padua, Italy
[10] INFN, Sezione di Padova, 35131 Padua, Italy
[11] Higgs Centre for Theoretical Physics, The University of Edinburgh, Edinburgh EH9 3FD, UK
[12] Dep. de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, 18071 Granada, Spain
[13] Departamento de Física, ICEX, UFMG, 30161-970 Belo Horizonte, Brazil
[14] Dipartimento di Fisica, Università di Milano, 20133 Milan, Italy
[15] INFN, Sezione di Milano, 20133 Milan, Italy
[16] Dipartimento di Fisica, Università di Napoli, 80126 Naples, Italy
[17] INFN, Sezione di Napoli, 80126 Naples, Italy

Precision Frontier

- Example of NLO observable with IReg



https://www.ippp.dur.ac.uk

$$\int \frac{d^4k}{(2\pi)^4} \frac{\bar{u}(p_q)\gamma^{\nu}(\not{k}+\not{p}_q)\gamma_{\mu}(\not{k}-\not{p}_{\bar{q}})\gamma_{\nu}u(p_{\bar{q}})}{k^2(k+p_q)^2(k-p_{\bar{q}})^2}$$

Precision Frontier

- Example of NLO observable with IReg

$$\int \frac{d^4k}{(2\pi)^4} \frac{\bar{u}(p_q)\gamma^\nu(\not{k} + \not{p}_q)\gamma_\mu(\not{k} - \not{p}_{\bar{q}})\gamma_\nu u(p_{\bar{q}})}{k^2(k+p_q)^2(k-p_{\bar{q}})^2}$$

  - Perform Dirac algebra in 4D;
  - Add μ^2 in propagators;
  - Use

$$\frac{1}{(k-p)^2-\mu^2} = \frac{1}{(k^2-\mu^2)} + \frac{(-1)(p^2-2p\cdot k)}{(k^2-\mu^2)[(k-p)^2-\mu^2]}$$

Precision Frontier

- Example of NLO observable with IReg

$$\int \frac{d^4k}{(2\pi)^4} \frac{\bar{u}(p_q)\gamma^{\nu}(\not{k} + \not{p}_q)\gamma_{\mu}(\not{k} - \not{p}_{\bar{q}})\gamma_{\nu}u(p_{\bar{q}})}{k^2(k+p_q)^2(k-p_{\bar{q}})^2}$$

  - Perform Dirac algebra in 4D;
  - Add μ^2 in propagators;
  - Isolate UV divergences as $I_{\log}^{\nu_1\cdots\nu_{2N}}(\mu^2) \equiv \int \frac{d^4k}{(2\pi)^4} \frac{k^{\nu_1}\cdots k^{\nu_{2N}}}{(k^2-\mu^2)^{N+2}}$

  - Infrared divergences appear, after integration, as logarithms in μ^2.

Precision Frontier

- Example of NLO observable with IReg

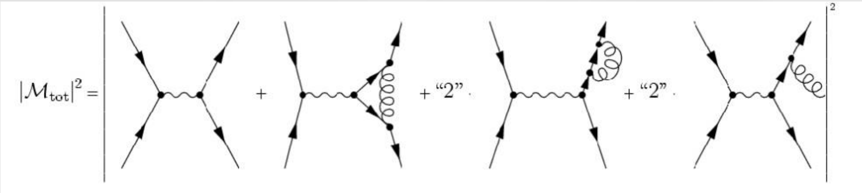
$$\int \frac{d^4k}{(2\pi)^4} \frac{\bar{u}(p_q)\gamma^{\nu}(\not{k} + \not{p}_q)\gamma_{\mu}(\not{k} - \not{p}_{\bar{q}})\gamma_{\nu}u(p_{\bar{q}})}{k^2(k+p_q)^2(k-p_{\bar{q}})^2}$$

$$\sigma^{(v)}_{\mathrm{IREG}} = \sigma^{(0)}\left(\frac{\alpha_s}{\pi}\right)C_F\left[-\frac{\ln^2(\mu_0)}{2} - \frac{3}{2}\ln(\mu_0) - \frac{7-\pi^2}{2} + \mathcal{O}(\mu_0)\right],$$

$$\mu_0 \equiv \mu^2/s \qquad s \equiv (p_q + p_{\bar{q}})^2 = 2p_q \cdot p_{\bar{q}}$$

Precision Frontier

- Example of NLO observable with IReg



https://www.ippp.dur.ac.uk

$$\sigma^{(r)}_{\text{IREG}} = \frac{1}{2s}\int \frac{d^3k_1}{(2\pi)^3 2\omega_1}\int \frac{d^3k_2}{(2\pi)^3 2\omega_2} \times \int \frac{d^3k_3}{(2\pi)^3 2\omega_3}(2\pi)^4\delta^{(4)}(q-k_1-k_2-k_3) \times M^{(0)}_{\text{IREG}}(q\bar{q}g),$$

Precision Frontier

- Example of NLO observable with IReg

$$\sigma^{(r)}_{\mathrm{IREG}} = \frac{1}{2s}\int \frac{d^3k_1}{(2\pi)^3 2\omega_1}\int \frac{d^3k_2}{(2\pi)^3 2\omega_2}$$
$$\times \int \frac{d^3k_3}{(2\pi)^3 2\omega_3}(2\pi)^4\delta^{(4)}(q-k_1-k_2-k_3)$$
$$\times M^{(0)}_{\mathrm{IREG}}(q\bar{q}g),$$

  - Add mass μ to quark and gluon;
  - Infrared divergences appear, after integration, as logarithms in μ^2.

Precision Frontier

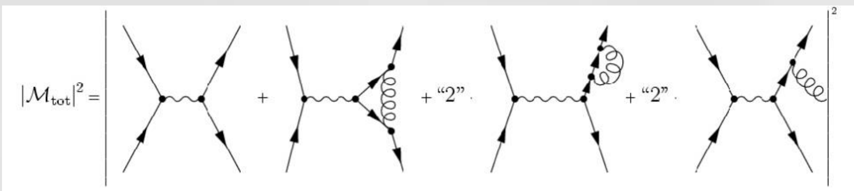
- Example of NLO observable with IReg

$$\sigma^{(r)}_{\text{IREG}} = \frac{1}{2s} \int \frac{d^3 k_1}{(2\pi)^3 2\omega_1} \int \frac{d^3 k_2}{(2\pi)^3 2\omega_2} \times \int \frac{d^3 k_3}{(2\pi)^3 2\omega_3} (2\pi)^4 \delta^{(4)}(q - k_1 - k_2 - k_3) \times M^{(0)}_{\text{IREG}}(q\bar{q}g),$$

$$\sigma^{(r)}_{\text{IREG}} = \sigma^{(0)} \left(\frac{\alpha_s}{\pi}\right) C_F \times \left[\frac{\ln^2(\mu_0)}{2} + \frac{3}{2}\ln(\mu_0) + \frac{17}{4} - \frac{\pi^2}{2} + \mathcal{O}(\mu_0)\right]$$

Precision Frontier

- Example of NLO observable with IReg

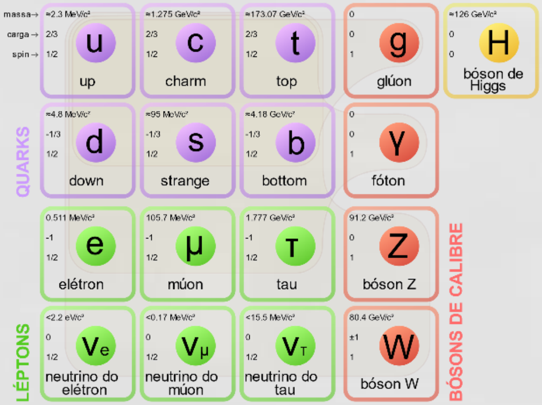


https://www.ippp.dur.ac.uk

$$\sigma^{(1)} = \sigma^{(0)} + \sigma^{(v)}_{\text{IREG}} + \sigma^{(r)}_{\text{IREG}}|_{\mu_0 \to 0} = \frac{Q_q^2 N_c}{3s}\left(\frac{e^4}{4\pi}\right) \times \left[1 + \left(\frac{\alpha_s}{4\pi}\right) 3C_F\right]$$

Conclusions

Standard Model



https://commons.wikimedia.org/

https://cds.cern.ch/record/1295244

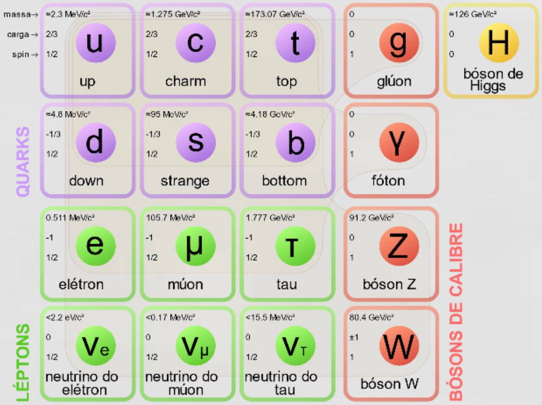
Small deviations

THEORY

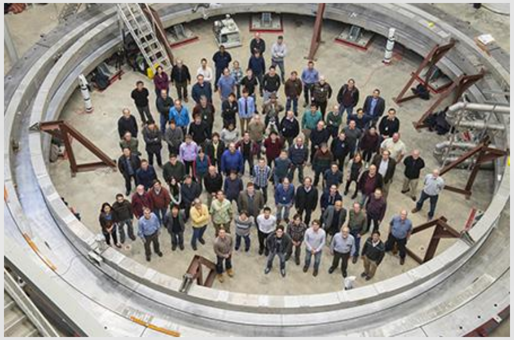
EXPERIMENT

Conclusions

Standard Model



https://commons.wikimedia.org/



http://muon-g-2.fnal.gov/

3.8σ deviation

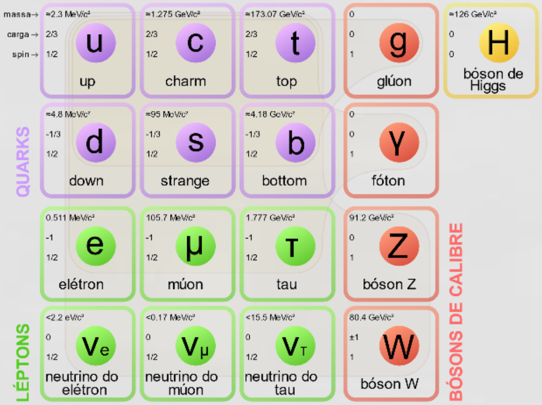
THEORY

EXPERIMENT

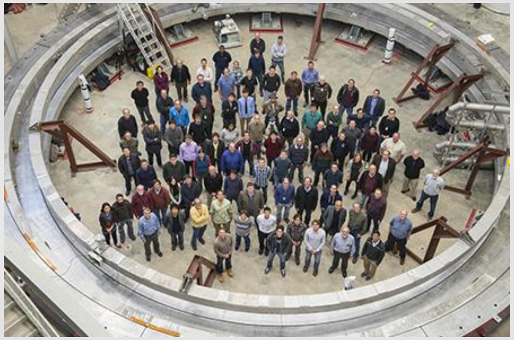
Conclusions

Standard Model

?



https://commons.wikimedia.org/



http://muon-g-2.fnal.gov/

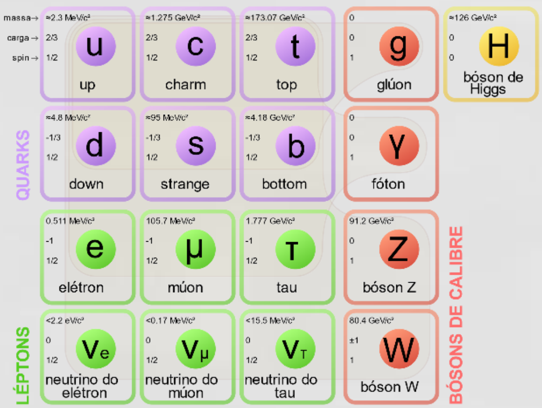
3.6σ deviation

THEORY

EXPERIMENT

Conclusions

Standard Model



https://commons.wikimedia.org/

Final Theory

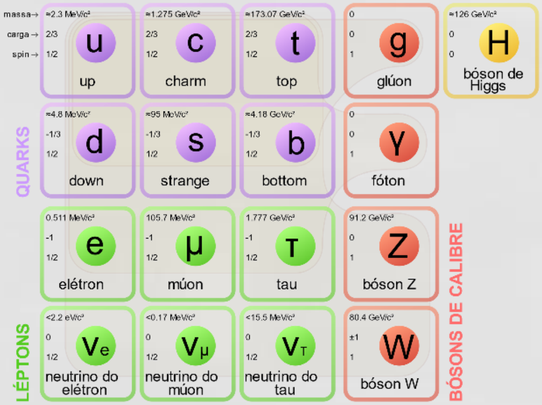
2HDM

SUSY

......

Conclusions

Standard Model



https://commons.wikimedia.org/

Final Theory

2HDM

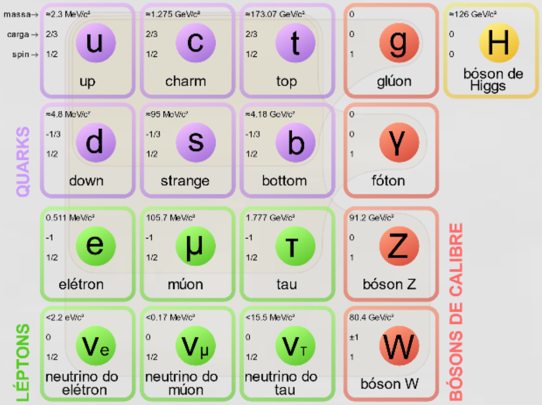
SUSY

......

Phenomenology
$(g-2)_\mu$

Conclusions

Standard Model



https://commons.wikimedia.org/

Final Theory

2HDM

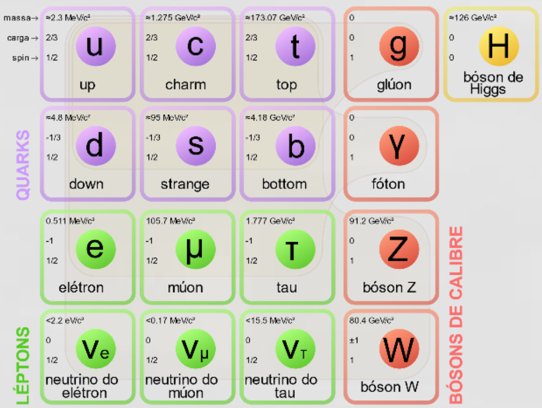
SUSY

......

Precision calculations

Conclusions

Standard Model



https://commons.wikimedia.org/

Final Theory

2HDM

SUSY

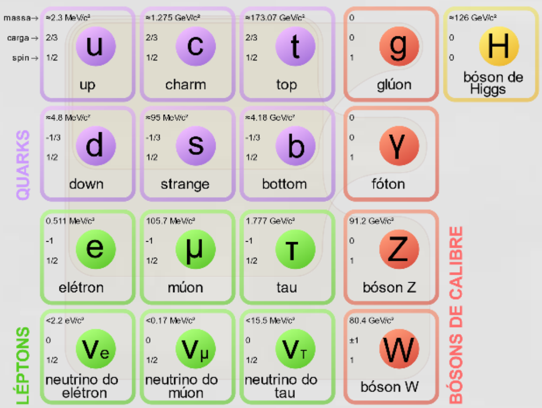
......

Precision calculations

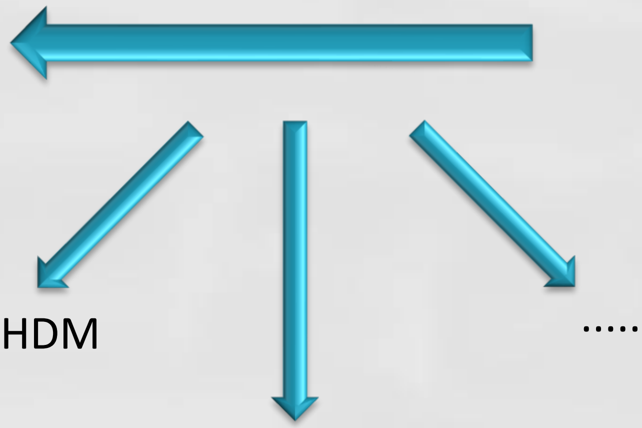
New regularization techniques

Conclusions

Standard Model



https://commons.wikimedia.org/



Final Theory

2HDM

SUSY

......

Precision calculations

Implicit Regularization

Thanks!