Standard Model of Particle Physics, or Beyond?

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Outline

The outline of this colloquium is

- Standard Model: reminder
  - Electroweak interactions
  - Strong interactions
  - The Higgs sector
  - Experimental successes
  - Theoretical and observational drawbacks
- Beyond the Standard Model
  - Supersymmetry
  - Large extra dimensions
  - Warped extra dimensions/composite Higgs
- Concluding remarks

Disclaimer: I will not discuss any technical details. With my apologies to my theorist (and experimental) colleagues

The Standard Model: reminder

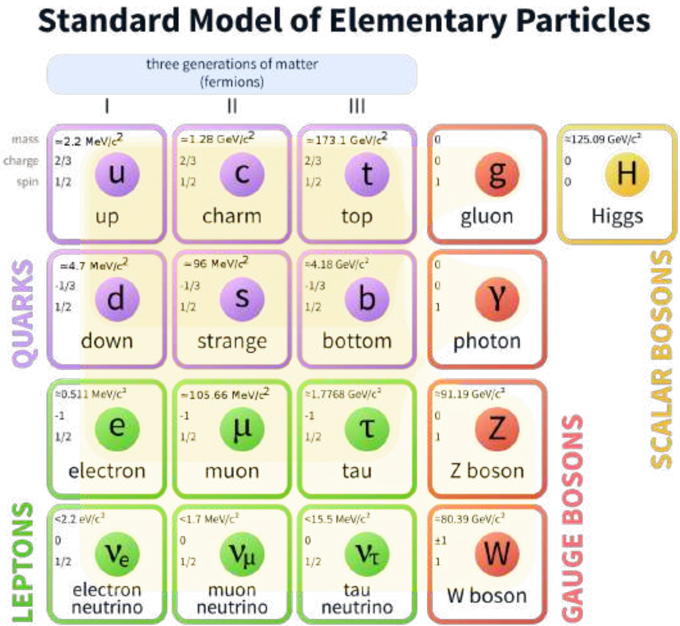
- The knowledge of the Standard Model of strong and electroweak interactions requires (as any other physical theory) the knowledge of
  - The elementary particles or fields (the characters of the play)
  - How particles interact (their behavior)

The characters of the play

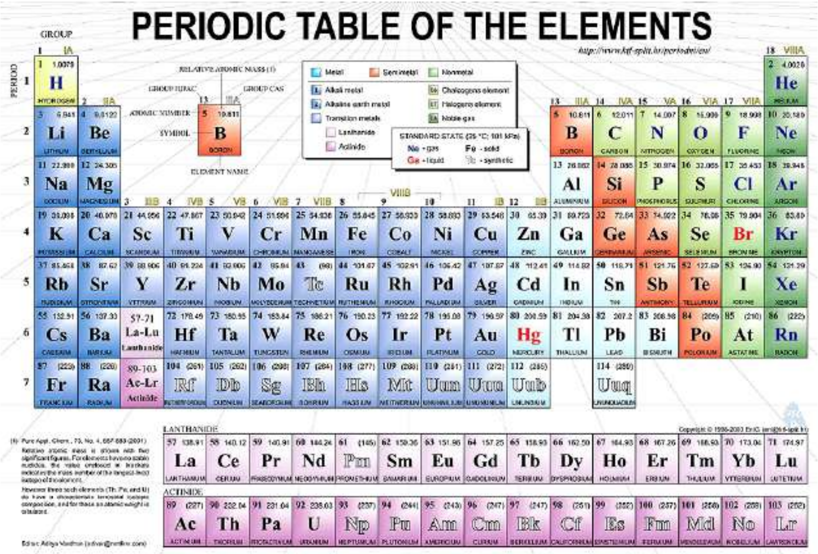
- Quarks: spin-1/2 fermions
- Leptons: spin-1/2 fermions
- Higgs boson: spin-0 boson
- Carriers of the interactions: spin-1 (gauge) bosons

- All these particles have already been discovered and their mass, spin, and charge measured

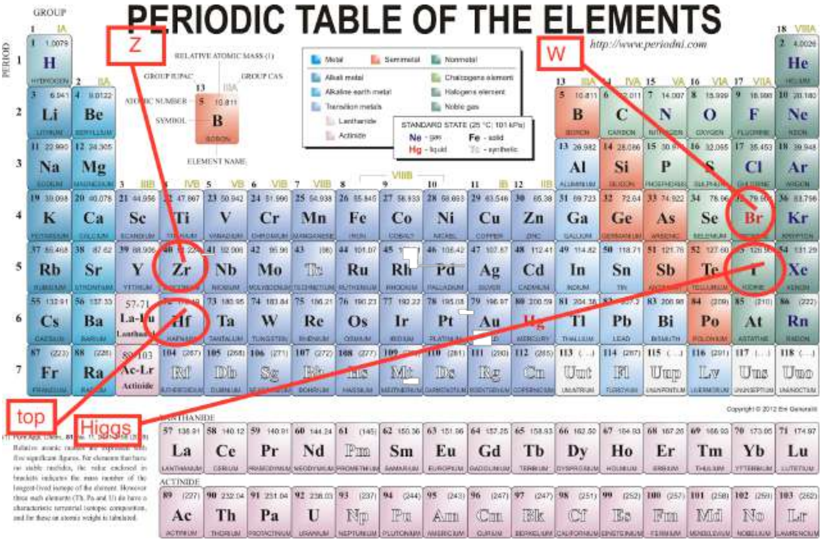
"More in detail the characters of the play"



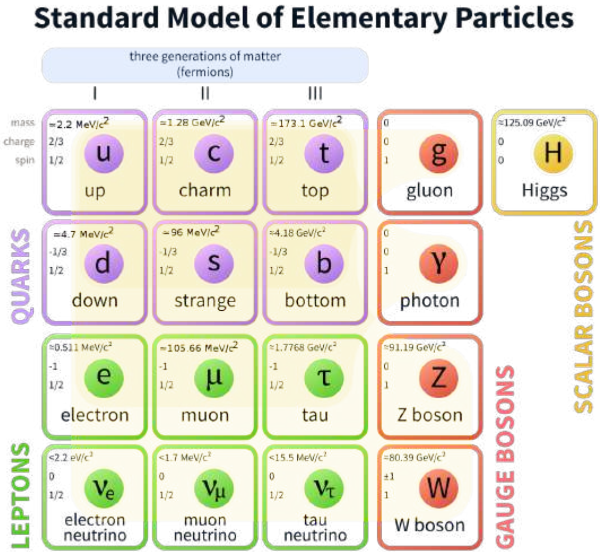
- Everybody knows the Periodic Table of the Elements



- Compare elementary particles with some (of course composite) very heavy nuclei



What are the interactions between the elementary building blocks of the Standard Model?



- Interactions are governed by a symmetry principle
- The more symmetric the theory the more couplings are related (the less of them they are) and the more predictive it is

Strong interactions: symmetry=$SU(3)_c$ or QCD

- Carried by gluons [8=$dim\ SU(3)$]
- Felt by quarks (in 3 colors)

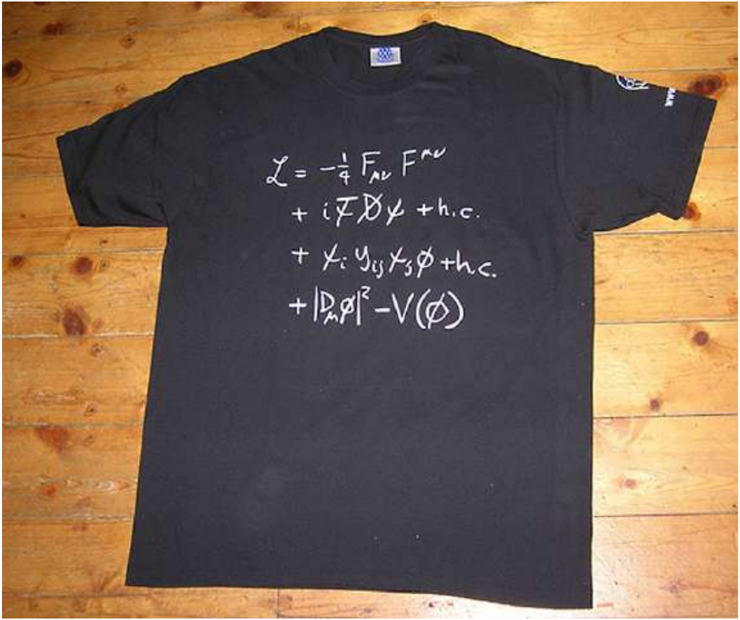
Electroweak interactions: symmetry=$SU(2)_L \otimes U(1)_Y$

- Carried by $W^{\pm}$, Z, γ [4=$dim\ SU(2) \times U(1)$]
- Felt by quarks and leptons

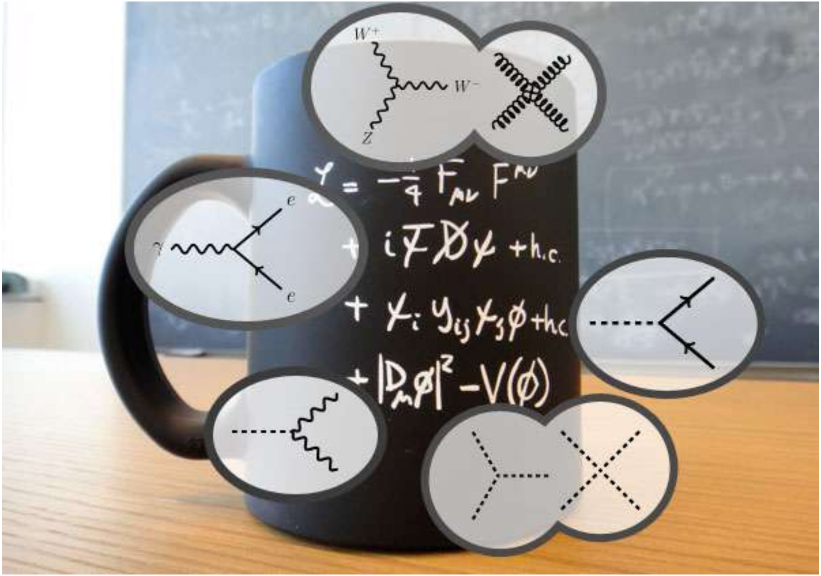
Yukawa interactions: no known associated symmetry

- Carried by the Higgs and felt by quarks and leptons

Interactions (Lagrangian) fit in a T-shirt



and even in a coffee mug



Electroweak interactions

Nobel prize for electroweak interactions (th)

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including the prediction of the weak neutral current"

Nobel prize for electroweak interactions (exp)

The Nobel Prize in Physics 1984 was awarded jointly to Carlo Rubbia and Simon van der Meer "for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

QCD

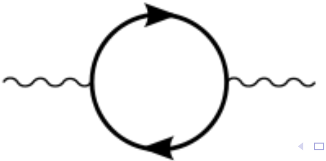
QCD enjoys two peculiar properties

Confinement

The force between quarks increases as they are separated. Because of this, it would take a huge amount of energy to separate two quarks; they are forever bound into hadrons such as the proton and the neutron

Asymptotic freedom

In very high-energy reactions, quarks and gluons interact very weakly. This prediction of QCD was first discovered in the early 1970s by David Politzer, Frank Wilczek and David Gross.

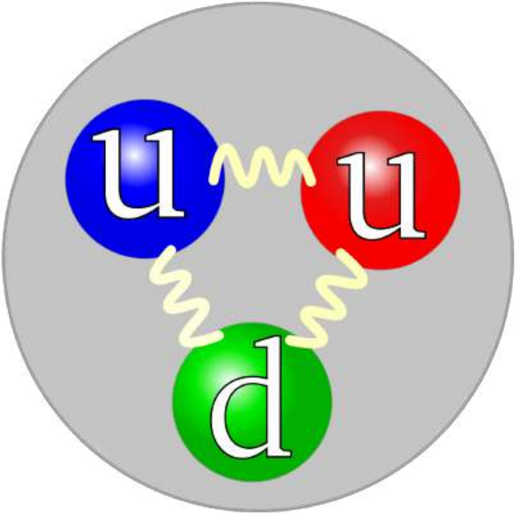


Nobel prize for QCD

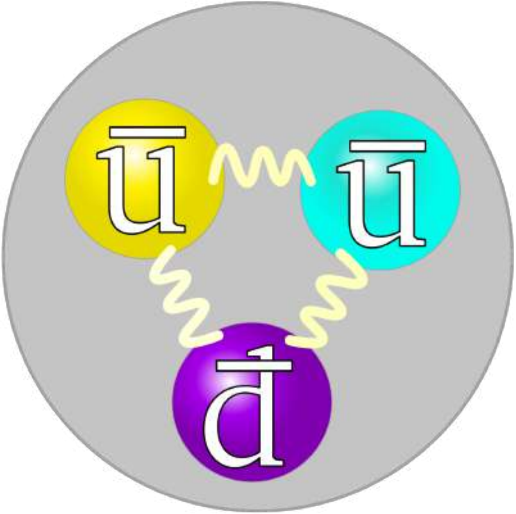
The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek "for the discovery of asymptotic freedom in the theory of the strong interaction". The Nobel Prize in Physics 1990 was awarded jointly to Jerome I. Friedman, Henry W. Kendall and Richard E. Taylor "for their pioneering investigations concerning deep inelastic scattering (...) of essential importance for the development of the quark model "



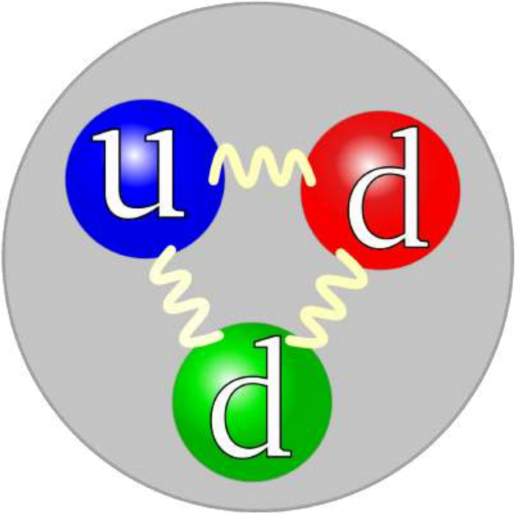
- The confining IR behavior of QCD is on the basis of the hadronic spectrum we observe today (π's, K's, p,...)
- QCD behaves as a weakly coupled theory for scales larger than $\Lambda_{QCD} \simeq 200$ MeV. The degrees of freedom are quarks and gluons. It behaves similarly to the electroweak theory
- QCD becomes strongly coupled for scales smaller than Λ_{QCD}. Below this scale the degrees of freedom are hadrons: mesons and baryons. Strictly speaking the theory of quarks and gluons is no longer valid for low scales.
- Only in high-energy collider we can excite quarks and/or gluons for short times which immediately "hadronize" into mesons or baryons.



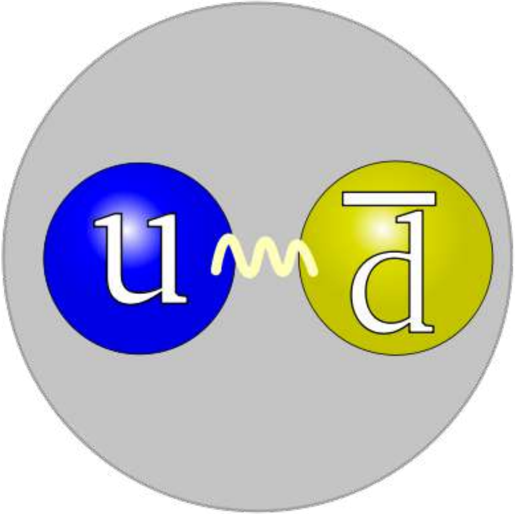
PROTON



ANTI-PROTON



NEUTRON



π^+

This is the way all mesons (s =integer) are built

Mesons $q\bar{q}$					
Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	**Name**	**Quark content**	**Electric charge**	**Mass GeV/c²**	**Spin**
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

... and the baryons (s =half-integer)

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

The Higgs sector

- We understand everything in the Standard Model....

including the origin of the masses of W, Z and those of elementary fermions

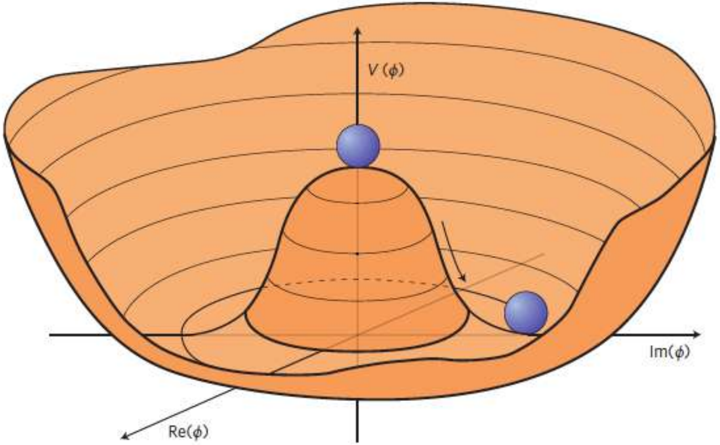
- The simplest consistent solution is

Spontaneous symmetry breaking

It happens when the vacuum has less symmetry than the interactions of the theory (Lagrangian)

Cartoon of spontaneous symmetry breaking $U(1)$

ϕ complex field



Spontaneous symmetry breaking in the Standard Model

- The symmetry of the interactions is
$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$
- The symmetry of the vacuum is
$$SU(3)_c \otimes U(1)_{em}$$

- To achieve Spontaneous Symmetry Breaking one needs a scalar field: the Higgs with four degrees of freedom

The Higgs

- Three degrees of freedoms (Goldstone bosons) will be absorbed by $W^{\pm}$ and Z to become massive
- The forth degree of freedom acquires a background value and is a physical (detectable) particle
- Yukawa interactions of the Higgs with fermions will give them a mass

The Standard Model with spontaneous symmetry breaking is a consistent theory: proved by 't Hooft and Veltman

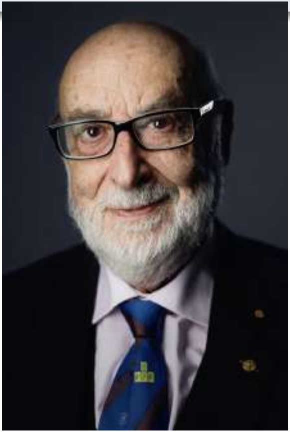
The Nobel Prize in Physics 1999 was awarded jointly to Gerardus 't Hooft and Martinus J.G. Veltman "for elucidating the quantum structure of electroweak interactions in physics"

The fact that W and Z become massive by absorbing Goldstone Bosons $\Rightarrow$ Nobel prize for spontaneous breaking

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu "for the discovery of the mechanism of spontaneously broken symmetry in subatomic physics", the other half jointly to Makoto Kobayashi and Toshihide Maskawa "for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Finally the Higgs boson found experimentally 2012

The Nobel Prize in Physics 2013 was awarded jointly to Francois Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, confirmed by the ATLAS and CMS experiments at CERN's Large Hadron Collider."



Experimental successes: gauge sector

- The Standard Model has faced from the very beginning lots of experimental predictions very successfully
- In the gauge sector the electroweak theory has three free parameters: the coupling constants of $SU(2) \otimes U(1)$ and the background Higgs value
- They are traded by well measured quantities:

  - Electric charge of the electron at zero momentum
  - The Z mass measured at LEP
  - The Fermi constant measured in β decay of the μ

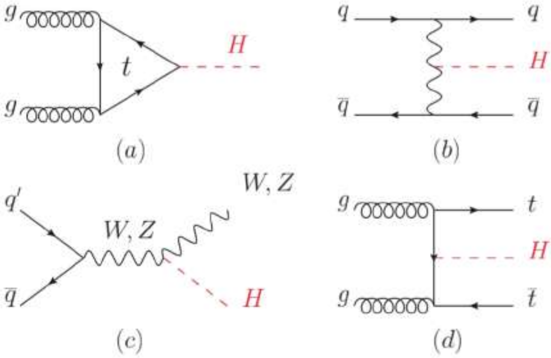
- After fixing them there are a "bunch of observables" that are predictions of the theory
- The scrutiny is very positive in particular after the discovery of the Higgs with a mass 125 GeV.

EW pull

Quantity	Value	Standard Model	Pull
M_Z [GeV]	91.1876 ± 0.0021	91.1884 ± 0.0020	-0.4
Γ_Z [GeV]	2.4952 ± 0.0023	2.4942 ± 0.0008	0.4
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7411 ± 0.0008	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.44 ± 0.04	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.959 ± 0.008	—
σ_{had}[nb]	41.541 ± 0.037	41.481 ± 0.008	1.6
R_e	20.804 ± 0.050	20.737 ± 0.010	1.3
R_μ	20.785 ± 0.033	20.737 ± 0.010	1.4
R_τ	20.764 ± 0.045	20.782 ± 0.010	-0.4
R_b	0.21629 ± 0.00066	0.21582 ± 0.00002	0.7
R_c	0.1721 ± 0.0030	0.17221 ± 0.00003	0.0
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01618 ± 0.00006	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1030 ± 0.0002	-2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0735 ± 0.0001	-0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1031 ± 0.0002	-0.5
$\bar{s}_\ell^2$	0.2324 ± 0.0012	0.23154 ± 0.00003	0.7
	0.23148 ± 0.00033		-0.2
	0.23104 ± 0.00049		-1.0
A_e	0.15138 ± 0.00216	0.1469 ± 0.0003	2.1
	0.1544 ± 0.0060		1.3
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		-0.3
A_τ	0.136 ± 0.015		-0.7
	0.1439 ± 0.0043		-0.7
A_b	0.923 ± 0.020	0.9347	-0.6
A_c	0.670 ± 0.027	0.6677 ± 0.0001	0.1
A_s	0.895 ± 0.091	0.9356	-0.4

Experimental successes: Higgs sector

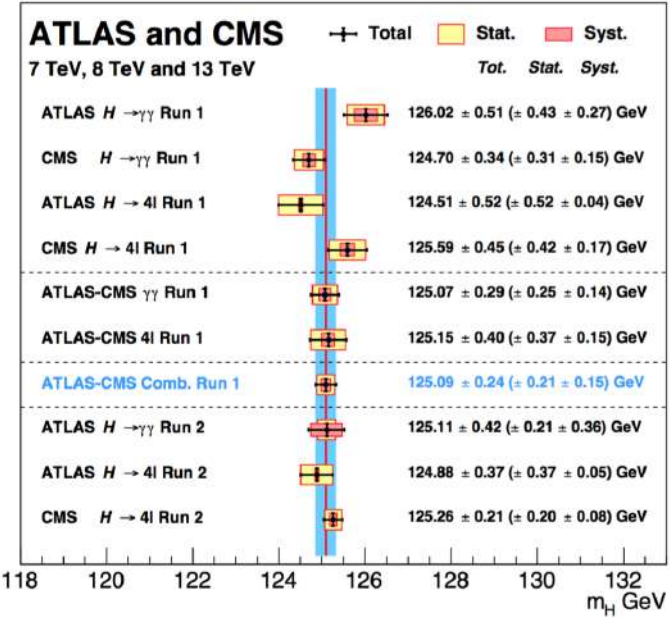
The Higgs boson is produced at the LHC by various mechanisms



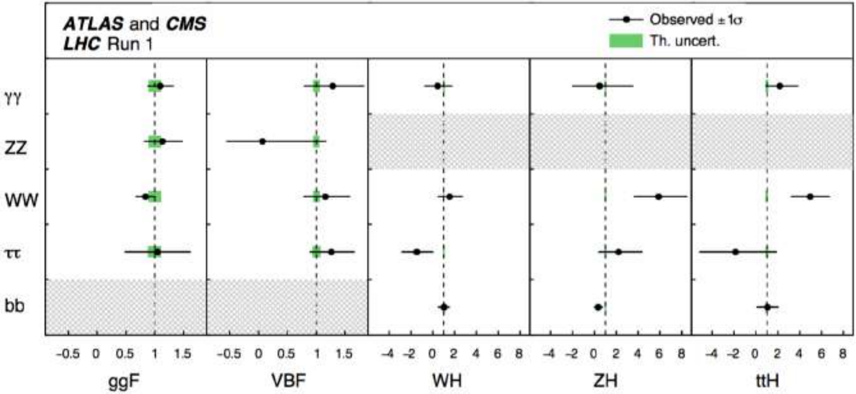
The decay modes of the (125 GeV) Higgs are:

Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.62×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.14×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.84×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.53×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.18×10^{-4}	$^{+6.0\%}_{-5.9\%}$

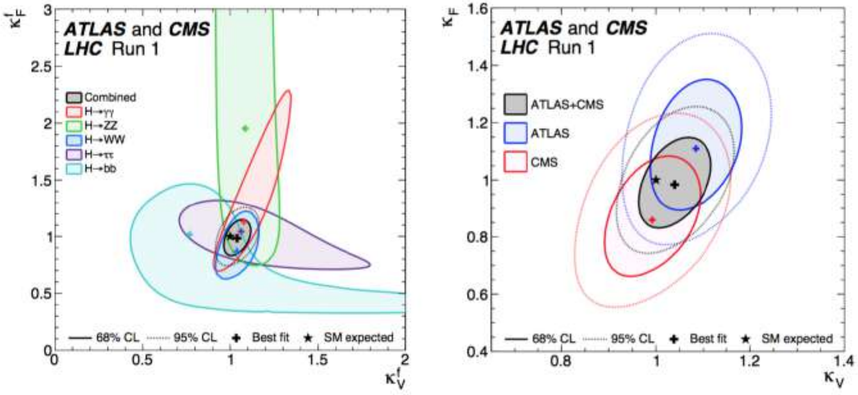
The Higgs production rate and decay depends on its mass



The Higgs couplings are in good agreement with the SM prediction



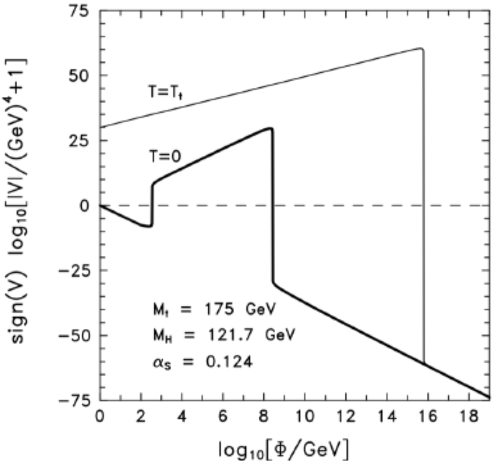
Likelihood contours for different channels (left) and combined (right)



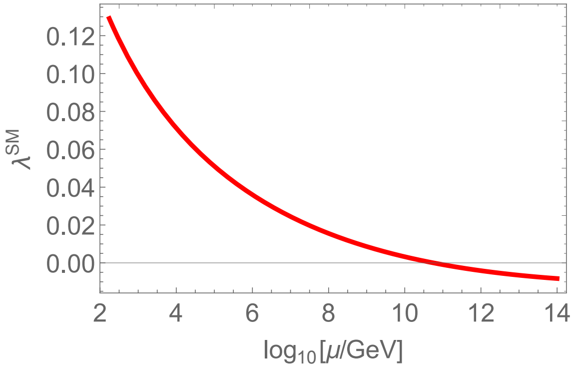
Theoretical and observational drawbacks

1.- Vacuum instability at high values of the field

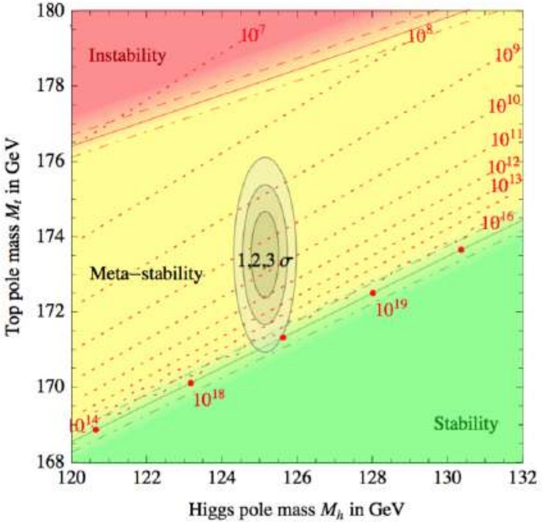
- If we look at the Higgs potential for values of the field less than a few hundred GeV, the potential looks stable
- However if we look at "larger values" it is unstable



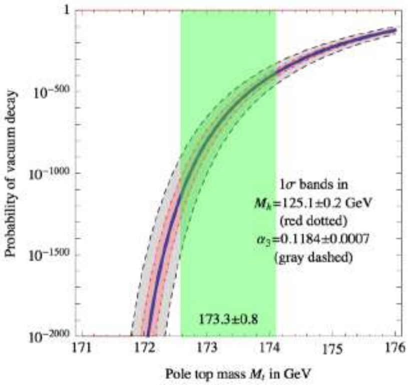
The technical reason for the instability is that evolving the quartic coupling $\lambda^{SM}|H|^4$ to higher values of the scale (field value) with the renormalization group equation it gets negative

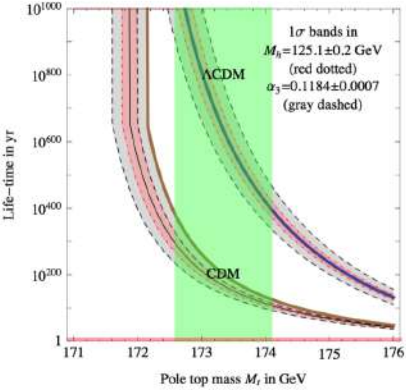


If the potential is unstable, the SM vacuum can decay into the wrong vacuum, located for ϕ at a scale which depends on (m_h, m_t), by quantum tunneling. Depending on the decay life-time the vacuum will be unstable or meta-stable



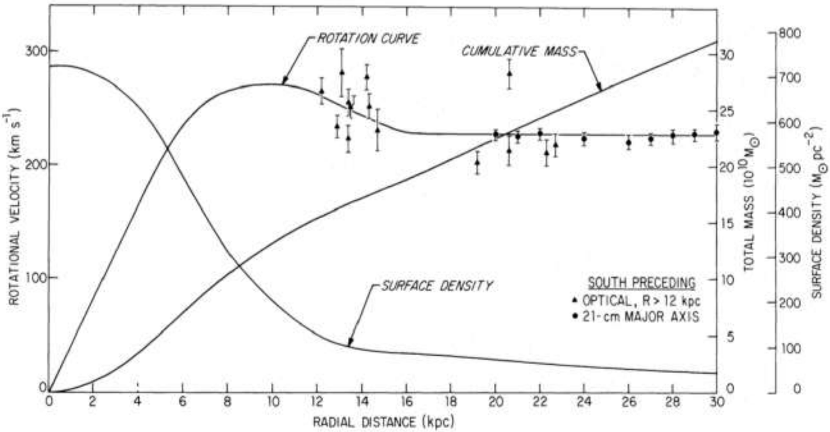
However metastability is not a real concern (not now...)





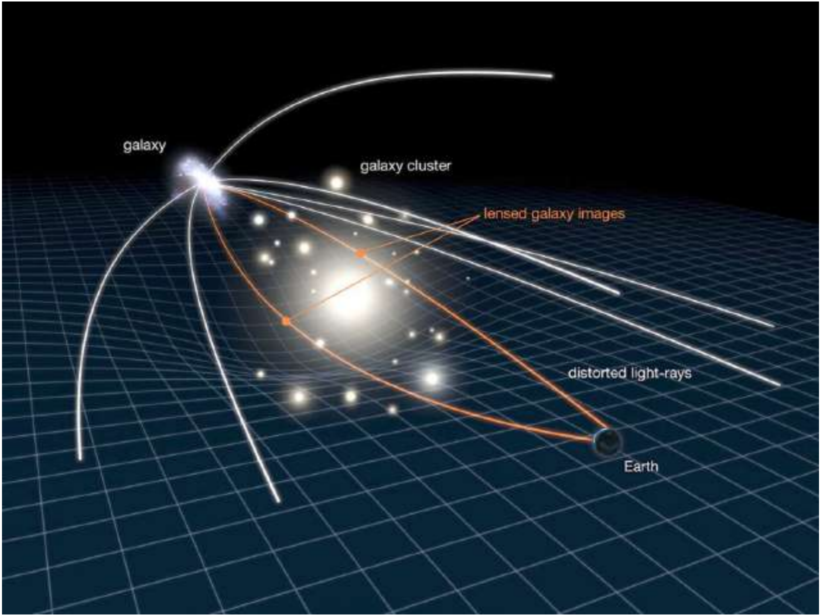
2.-Absence of a candidate to describe the dark matter

Rotation curves for Galaxies

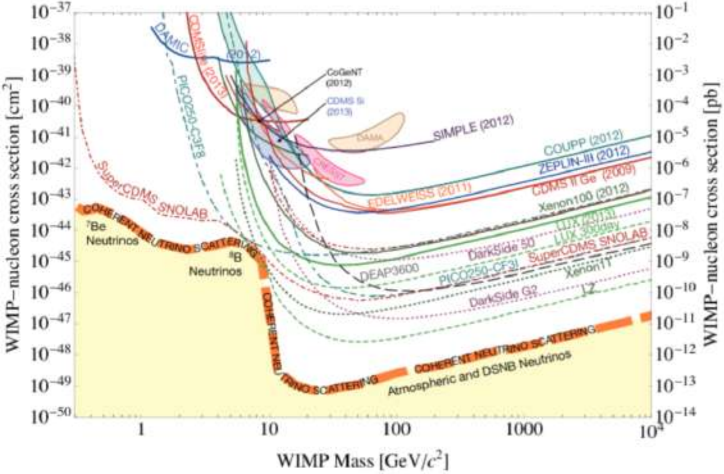


Rotation curves for M31 (Andromeda) galaxy

Dark matter bends light rays: gravitational lensing

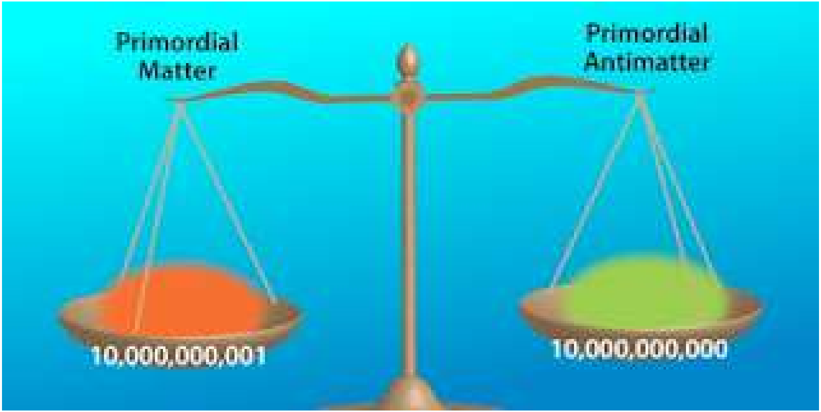


Experimental (direct) searches of dark matter negative up to now



3.-Baryogenesis

Baryogenesis is the mechanism to understand the baryon asymmetry of the Universe. For $T > 1$ GeV there should be an asymmetry between baryons and antibaryons



There is no solution in the Standard Model!! $\Rightarrow$ BSM

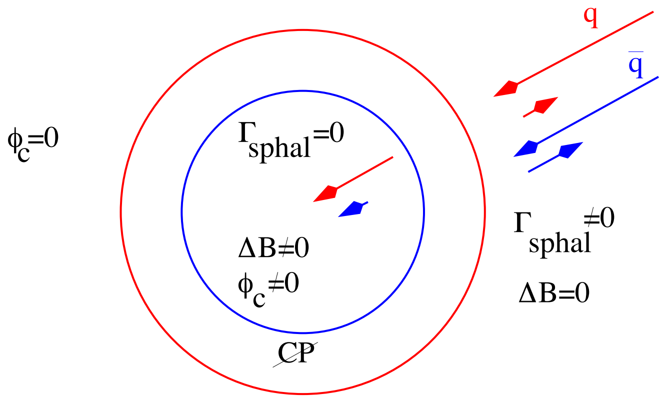
In 1967 Andrei Sakharov proposed three necessary conditions that a baryon-generating interaction must satisfy to produce matter and antimatter

1. Baryon number violation
2. C and CP violation
3. Out of equilibrium conditions

The Standard Model could satisfy them

1. B violation by non-perturbative effects (sphalerons)
2. CP violation by CKM phase δ
3. Out of equilibrium conditions if first order phase transition

Mail stamp issued



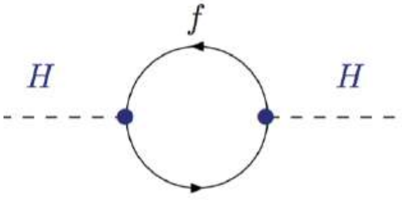
Unfortunately the SM fails in condition 2 (enough CP violation) and 3 (first order phase transition)

⇓

NEW PHYSICS

4.-The naturalness (a.k.a. hierarchy) problem

- The Standard Model has a sensitivity to UV physics
- In the SM this translates into the appearance of quadratic divergences at one-loop (cutoff sensitivity)



Paradigm

New Physics is required to cancel the UV sensitivity

- This paradigm has triggered a huge experimental effort to discover New Physics (Beyond the Standard Model) at different colliders: LEP (CERN), Tevatron (FermiLab), LHC (CERN), BaBar (SLAC), Belle (KEK),...

Of course there are other theoretical problems in the pure SM:

The strong CP problem: Implies an anomalous $U(1)$ axial symmetry, usually called Peccei-Quinn (PQ) symmetry, under which a complex scalar field is charged. This symmetry is spontaneously broken by the vacuum expectation value obtained by this scalar field, and the axion is the pseudo-Goldstone boson of this broken symmetry.

The flavor problem: The problem of understanding the mass spectrum and mixing angles of quarks and leptons. Why 3G? It usually needs some extra symmetry, as in the Frogatt-Nielsen mechanism.

The Dark Energy nature: The actual universe is accelerated. Perhaps it is just a constant term in Lagrangian.

Problems of the SCM: Horizon, Flatness Usually requires a period of cosmological inflation led by inflaton

Quantization of Gravity: It is essentially out of question in QFT: the best solution is by string theory

Beyond the Standard Model

- There are several ways out to the hierarchy problem
- All of them require some kind of new physics: BSM

BSM solutions to the hierarchy problem

- Supersymmetry: to enlarge the global/local space-time symmetry such that the new fields cancel the quadratic sensitivity to NP
- Large extra dimensions: in the higher-dimensional theories the 4D Planck scale is not a fundamental scale. The higher-dimensional Planck scale can be at the TeV if there are very large (submillimeter) extra dimensions (with just gravity in the bulk)
- Warped extra dimensions: The Planck scale is red-shifted to the TeV by a non-trivial (warped) geometry in the extra dimension(s). The Higgs is composite and in the limit of very heavy mass it is technicolor

Supersymmetry

- Is a generalization of the Standard Model (MSSM) where there are "partners" of every SM particle with a different spin

Supersymmetric Spectrum$_{\text{spin}}$

$$(u, d, \ell, \nu)_{1/2} \bigoplus (\tilde{u}, \tilde{d}, \tilde{\ell}, \tilde{\nu})_0 \text{ (sfermions)}$$

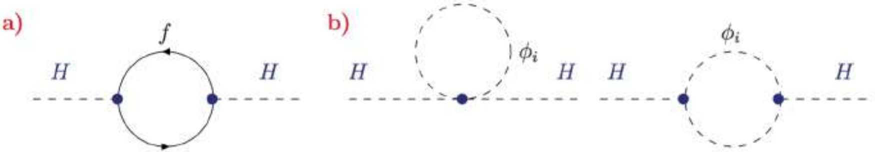
$$(W, Z, \gamma)_1 \bigoplus (\tilde{W}, \tilde{Z}, \tilde{\gamma})_{1/2} \text{ (gauginos)}$$

$$(H)_0 \Rightarrow (H_1, H_2)_0 \text{ (2HDM)} \bigoplus (\tilde{H}_1, \tilde{H}_2)_{1/2} \text{ (Higgsinos)}$$

- The couplings are fixed by supersymmetry such that the quadratic divergences cancel

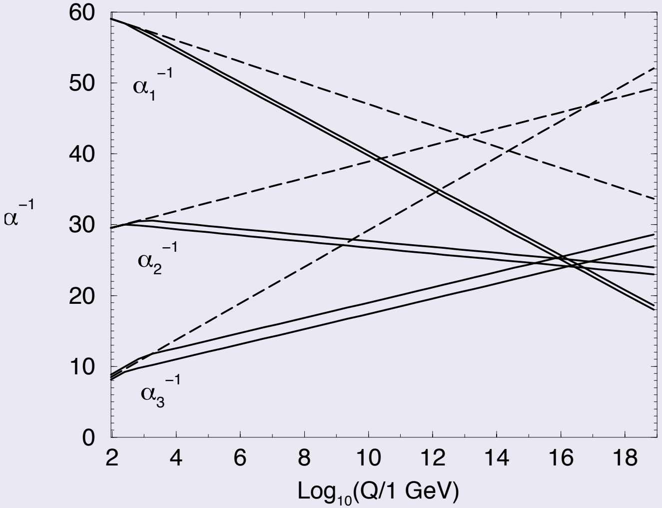
- The cancellation happens between SM particles and their supersymmetric partners due to the couplings which are fixed by supersymmetry

Top (quark) / stop (squark) cancellation

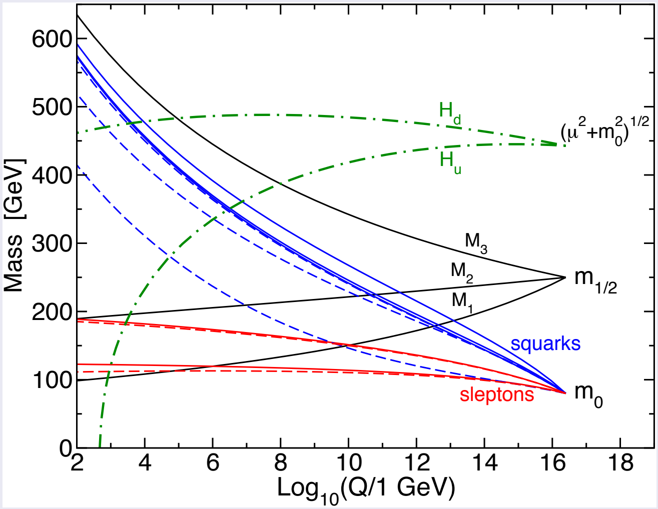


- Apart from cancellation of quadratic divergences supersymmetry presents two appealing features (not shared by the SM)
  - Gauge coupling unification at $M_G = 2 \times 10^{16}$ GeV (exp. hint?)
  - Radiative electroweak breaking

Gauge coupling unification



Radiative EWSB



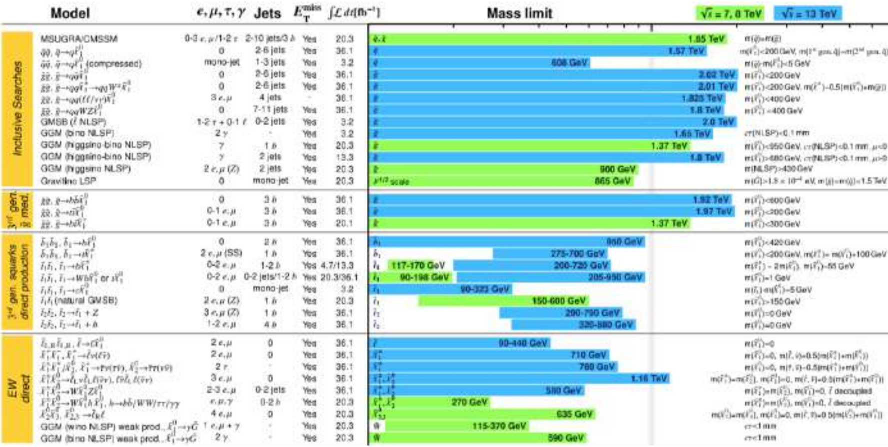
- The MSSM has normally built in a discrete symmetry (*R*-parity) by which only pairs of supersymmetric particles are produced. As a consequence

R-parity implication: Dark Matter

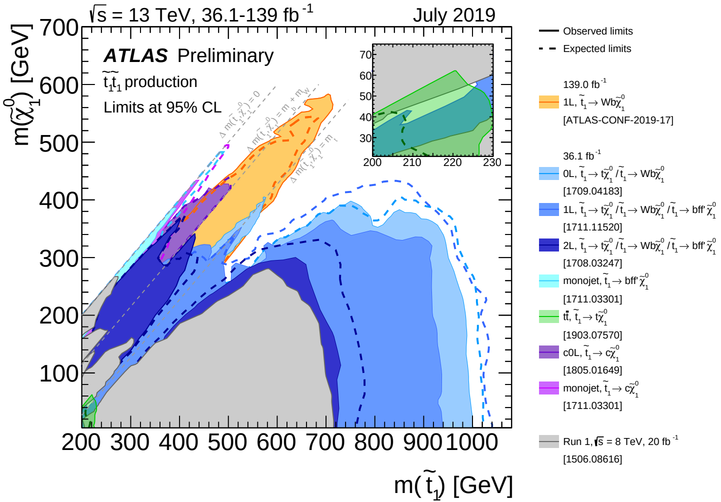
- The LSP (normally a neutral admixture of gauginos and Higgsinos: neutralino) is a candidate to the Dark Matter, so called Weakly Interacting Massive Particle (WIMP)
- The experimental signature at colliders is missing energy (carried by the undetectable LSP)

- R-parity also guarantees proton stability
- Models without R-parity have constraints in the R-breaking couplings: explored at the LHC

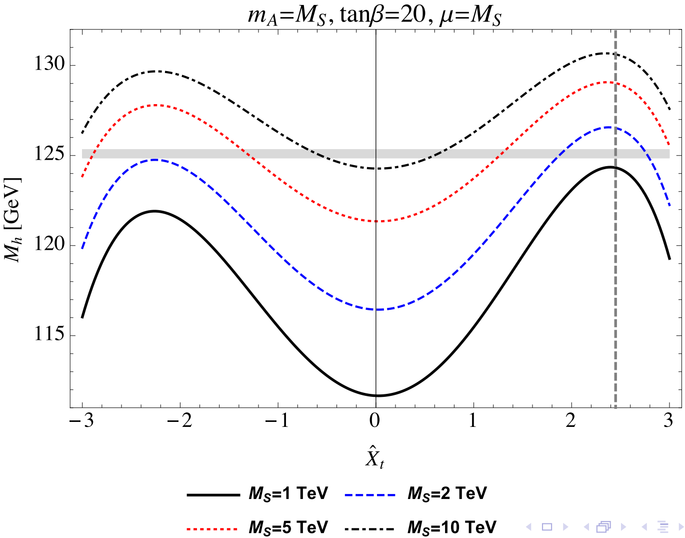
For the moment experimental results yield bounds



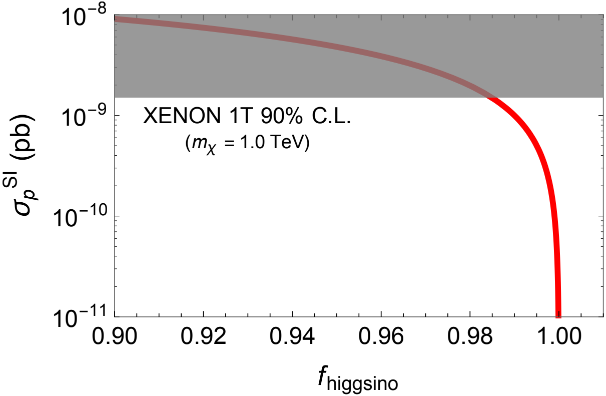
- However: some windows to optimism
- First: the third generation squarks should be lighter that the first and second generation squarks
- It happens so: stops bounds are weaker



- Second: the Higgs has been discovered with a mass $m_H = 125$ GeV (heavish)
- The Higgs mass is a prediction in the MSSM (unlike in the SM) and its mass leads to a heavy SUSY spectrum

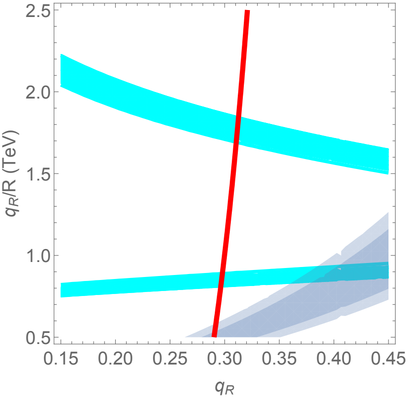


- Third: the lightest neutralino can be Dark Matter
- Although direct detection experiments are excluding part of the MSSM parameter space, there are blind spots
- One of those is an almost pure Higgsino with a mass $m_{\widetilde{H}} = 1.1$ TeV [1]



[1] K. Kowalska and E. M. Sessolo, arXiv:1802.04097 [hep-ph]

- This scenario was realized in a 5D model with SUSY breaking by Scherk-Schwarz [2]
- The model predicts a correct Higgs mass, electroweak symmetry breaking and correct dark matter abundance



[2] A. Delgado, A. Martin and M.Q., arXiv:1812.08019 [hep-ph]

Large extra dimensions

- This solution was proposed by Nima Arkani-Hamed (Princeton, IAS), Savas Dimopoulos (Stanford) and Gia Dvali (Munich & NYU) in 1998
- It is inspired in string theories
- If there is a number (n) of very large extra dimensions (at most at the submillimeter size) the Planck scale (or string scale) in the higher dimensional theory (M_*) can be at the TeV while the 4D Planck scale (not a fundamental scale any longer) can be at the value fixed by the Newton constant $M_p = 2.4 \times 10^{18}$ GeV

ADD relation

$$M_P^2 = M_*^{2+n} R^n$$

- Only gravity sector can live in the bulk of the extra dimensions
- It solves the hierarchy problem by a natural TeV cutoff

- Two main kind of experimental signatures for the large extra dimensions

Modifications of Newtons law: Table-Top experiments

$$V(r) = \begin{cases} -\frac{G_N}{r}\left(1+\alpha e^{-r/\lambda}+\cdots\right), & r \geq \lambda \\ -\frac{G_N^{(4+n)}}{r^{1+n}}, & r \ll \lambda \end{cases}$$

Present bounds: $\lambda \lesssim 0.1$ mm

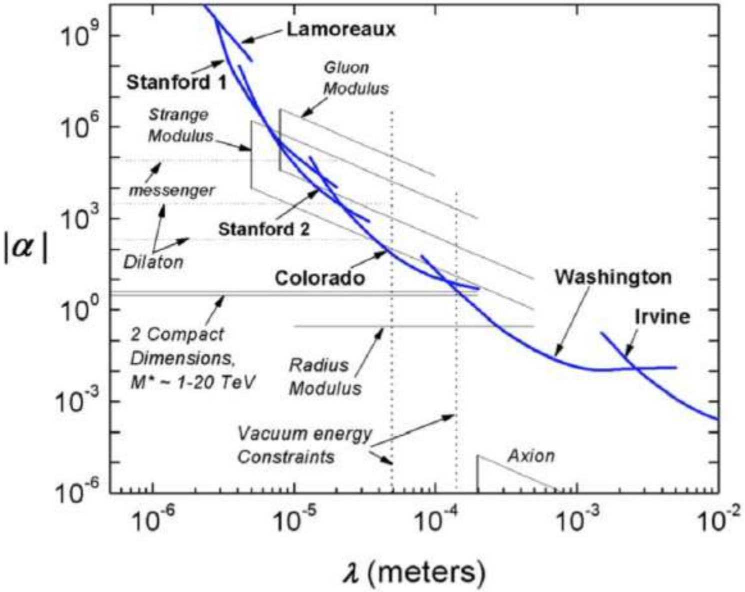
Colliders signatures

Based on missing energy in reactions corresponding to the production of (massive)-gravitons in the bulk

$$q\bar{q} \longrightarrow \gamma \sum_n G^{(n)}$$

Present bounds: $M_* \gtrsim 3.6$ TeV (for n=2)

Table-top experiments for gravity:

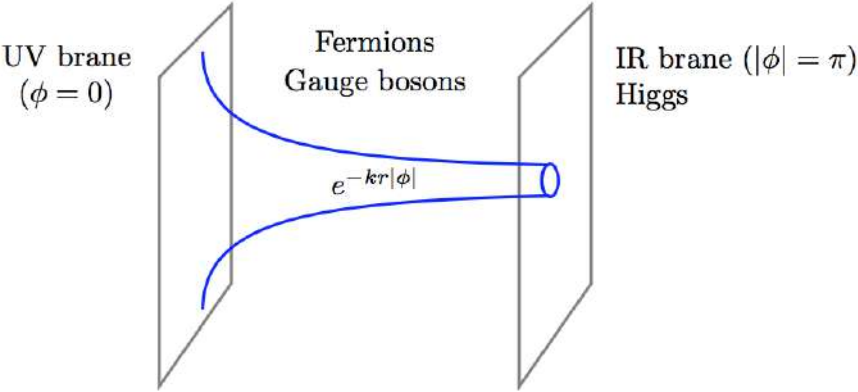


Warped extra dimensions/Composite Higgs

- This solution was proposed by Lisa Randall (Harvard) and Raman Sundrum (Maryland) in 1999 and it is based on a 5D space-time with a non-trivial AdS geometry and two flat branes on the UV and IR regions.
- The 4D theory is Minkowski
- It solves the hierarchy problem because

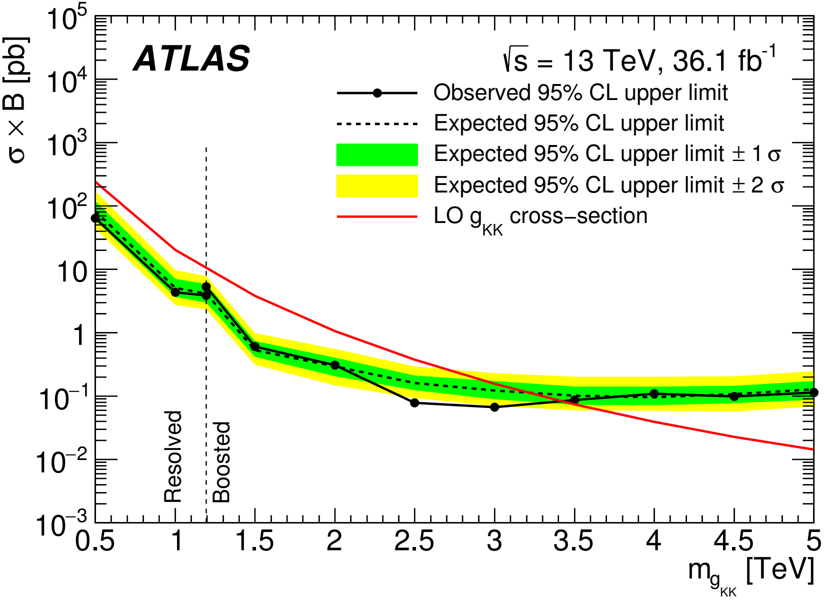
The Planck scale is red-shifted by the warp factor to the TeV

- The 4D theory becomes strongly coupled at a few (tens) of TeV
- The AdS gravitational theory in 5D is dual (AdS/CFT) to a 4D strongly coupled conformal field theory (CFT) which makes all fields localized towards the IR brane composite [connection with Composite Higgs theories]

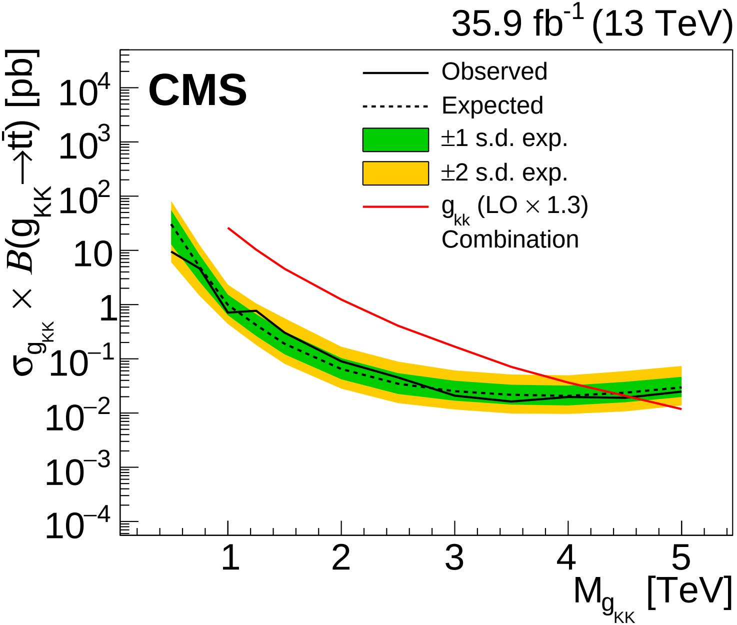

UV brane
$(\phi = 0)$
Fermions
Gauge bosons
$e^{-kr|\phi|}$
IR brane $(|\phi| = \pi)$
Higgs

Experimental signatures

- All SM particles in the bulk
- There is a tower of massive modes (almost) equally spaced in mass corresponding to any SM particle: tower of gravitons, Z, W, g, γ, q,...
- The lightest massive mode has a mass in the TeV range
- The heavy modes are coupled with large couplings to heavy quarks, which makes the difference with e.g. Z' vectors coming from grand unification
- Different localization of fermions in the bulk of the fifth dimension can eventually "explain" the flavor problem (modulo bounds from FCNC)
- Present bounds are very model dependent, but generically $m_{KK} \gtrsim 3$ TeV

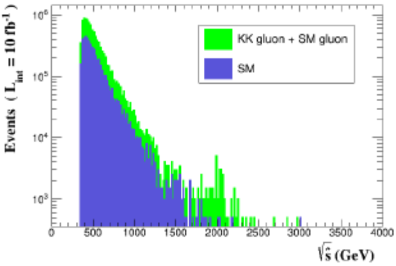


ATLAS
√s = 13 TeV, 36.1 fb⁻¹
Observed 95% CL upper limit
Expected 95% CL upper limit
Expected 95% CL upper limit ± 1 σ
Expected 95% CL upper limit ± 2 σ
LO g_KK cross-section
Resolved
Boosted
σ × B [pb]
m_gKK [TeV]

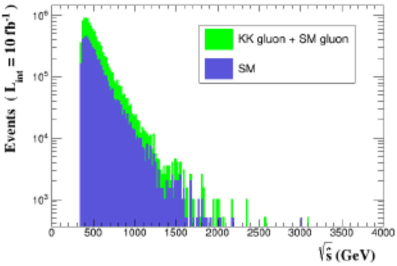


35.9 fb^{-1} (13 TeV)
CMS
Observed
Expected
±1 s.d. exp.
±2 s.d. exp.
g_{kk} (LO × 1.3)
Combination
$\sigma_{g_{KK}} \times \mathcal{B}(g_{KK} \to t\bar{t})$ [pb]
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
2
3
4
5
$M_{g_{KK}}$ [TeV]

- Present experimental searches are based on finding bumps in the invariant mass of the produced (narrow) resonances
- Perhaps this is not the way Nature has chosen
- Alternative solutions have to be found
- For instance, if resonances are very broad present bounds should evanesce. In particular for $pp \to tt$ [3]



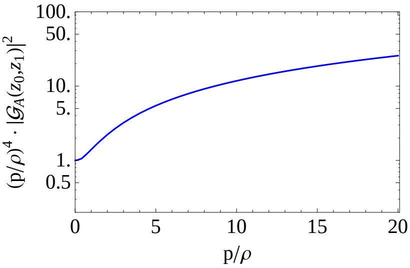
$\Gamma = 0.1M$



$\Gamma = 0.5M$

[3] R. Escribano, M. Mendizabal, M.Q., in preparation

- Another option is if instead of a discretum we have a continuum of KK modes with a TeV gap [4]
- This solution is the continuum limit of clockwork models
- It is also similar to unparticles proposed by H. Georgi [5]



DY process $\sigma/\sigma_{SM}(q\bar{q} \to t\bar{t})$, $p = \sqrt{\hat{s}}$, $\rho = 2$ TeV (partonic level)

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[4] E. Megias, M.Q., arXiv:1905.07364 [hep-ph]

[5] H. Georgi, 0703260 [hep-ph]

Concluding remarks

- Two main avenues for searches of new physics

Direct discoveries: main searches are

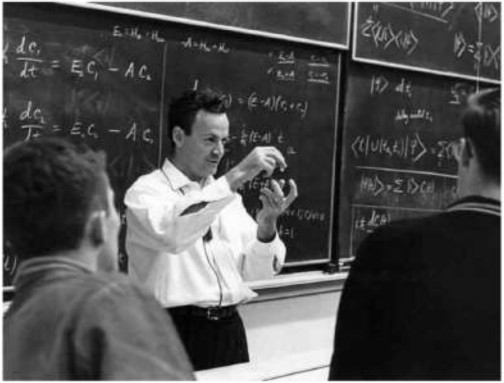
- Supersymmetric partners: missing energy (as for ν's)
- Extra gauge bosons or KK resonances : bump in the invariant mass
- Excess in production (e.g. by fields disappearing in the bulk or a continuum)

Indirect discoveries: anomalies

Some anomalies already exist but need to be confirmed

- μ anomalous magnetic moment: $g_\mu - 2$, $g_e - 2$,...
- In B-physics for neutral and charged correntss:
  - $b \to s\ell\ell$: $R_{K^{(*)}}$
  - $b \to c\ell\nu_\ell$: $R_{D^{(*)}}$

Even if (some of us) are theorists, the final word is for experiments...



"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." [Feynman]

- For the moment experimental data for New Physics searches have been elusive, but when they will show up we will be ready....
- This is as Picasso's inspiration...

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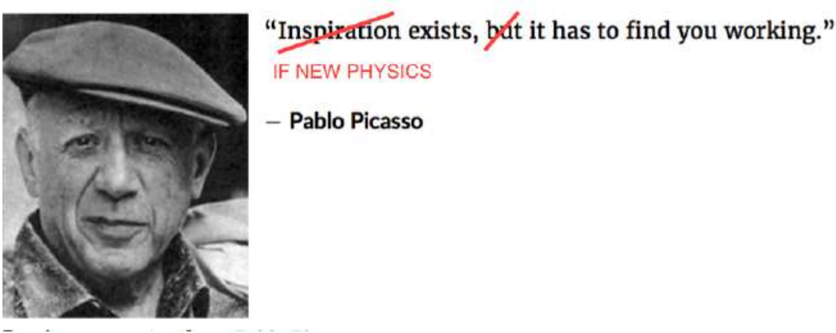

THANK YOU!