Frontiers of the Standard Model and beyond

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Fermilab Users Meeting – June 12, 2013

> *"We struggle to understand nature, building a great chain of research institutes, from the Museum of Alexandria [...] to [...] Fermilab. But we know that we will never get to the bottom of things [...]"*
>
> *Steven Weinberg (2008)*

Particle Physics has established that all known natural phenomena can be described (in principle) by a local quantum field theory which is invariant under:

- **3+1 dimensional Lorentz transformations and translations**
- $SU(3)_C \times \underbrace{SU(2)_W \times U(1)_Y}$ **gauge transformations**

  broken by the VEV of the
  Higgs doublet ($H \supset W_L^{\pm}, Z_L, h^0$)

$\Longrightarrow$ *all elementary fields have certain spin, color, and electroweak charges.*

SM

Spin-1 fields:

$$\left\{ \begin{array}{ll} G^\mu & (8,1,\ \ 0) \\ W^\mu & (1,3,\ \ 0) \\ B^\mu & (1,1,\ \ 0) \end{array} \right.$$

Spin-0 field: $H\ (1,2,\ +1/2)$

Spin-1/2 fields:

$$3 \times \left\{ \begin{array}{ll} q_L & (3,2,\ \ +1/6) \\ u_R & (3,1,\ \ +2/3) \\ d_R & (3,1,\ \ -1/3) \\ l_L & (1,2,\ \ -1/2) \\ e_R & (1,1,\ \ -1) \end{array} \right.$$

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Spin-2 field: graviton with M_{Planck}-suppressed interactions

(effective theory breaks down near 10^{16} *TeV)*

ν masses require:

$\frac{C_5}{M} H H l_L l_L$ interactions, suppressed by $M/C_5 \approx 10^{14}$ GeV

or

additional spin-1/2 fields: $3 \times \nu_R\ (1,1,0)$ which together with the SM ν_L acquire Dirac masses.

SM

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SMνg

Spin-2 field: graviton with $M_{\rm Planck}$-suppressed interactions

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Dark matter requires particle(s) beyond the SM$\nu\mathcal{G}$

DM particle can be a fermion (Majorana or Dirac)
or a boson (spin 0 or 1).

DM particle may be part of a large hidden sector.

There can be several particles contributing to the DM density.

WIMP 'miracle': relic density $\propto m^2/g^4$ is correct for
$m = 0.1 - 1$ TeV and $g = O(1)$.

$\Rightarrow$ this suggests that DM may be produced at the LHC

(complementary to searches based on direct detection or indirect detection)

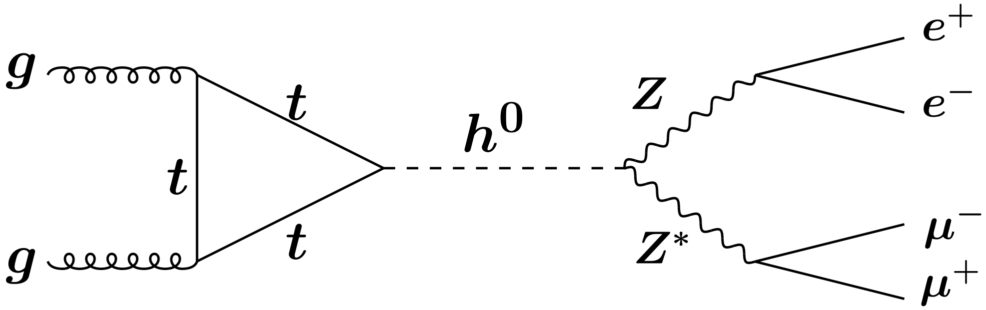
Dark Matter sector could be surprising (and complicated).

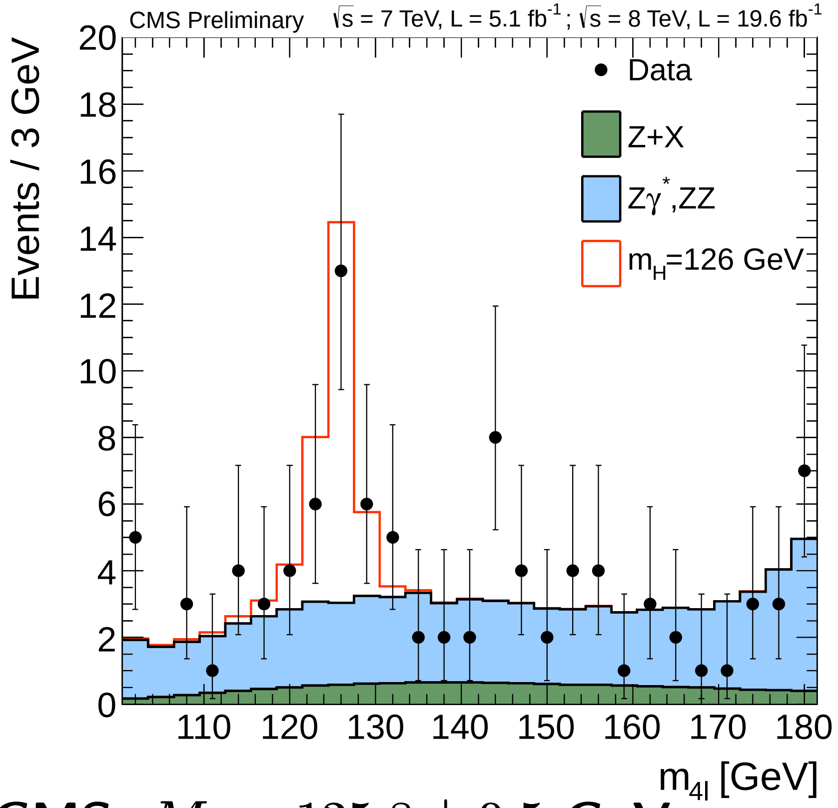
Experiments at the Intensity Frontier may probe it!

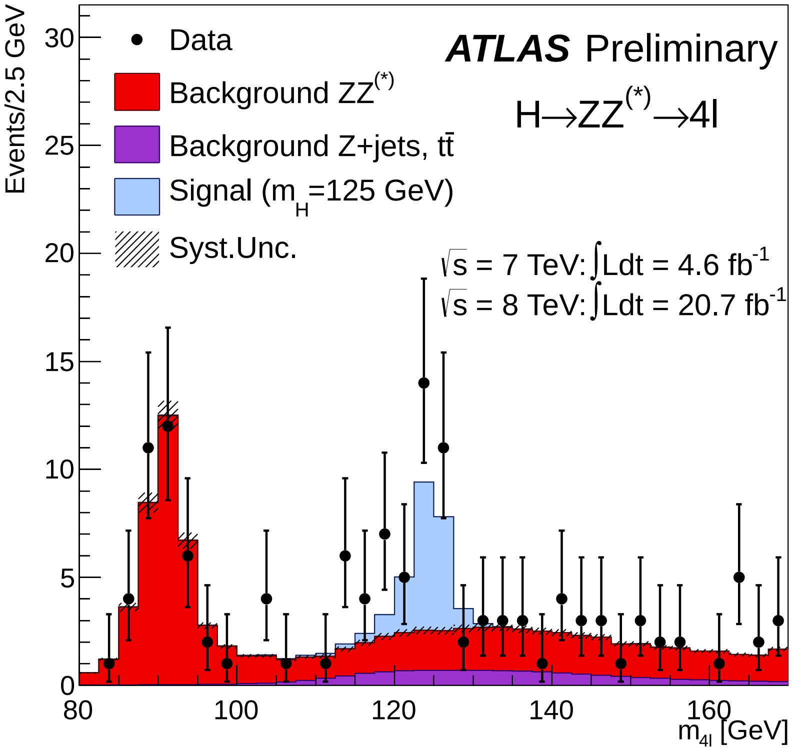
Novel ideas:

- **ν beam experiments can probe light DM:**
  produced in the target,
  elastic scattering in the detector.
  (deNiverville, McKeen, Ritz: 1205.3499)
- **Axion DM induces a (small) time-varying neutron Electric Dipole Moment** *(Graham, Rajendran: 1101.2691)*
- ...

Higgs particle







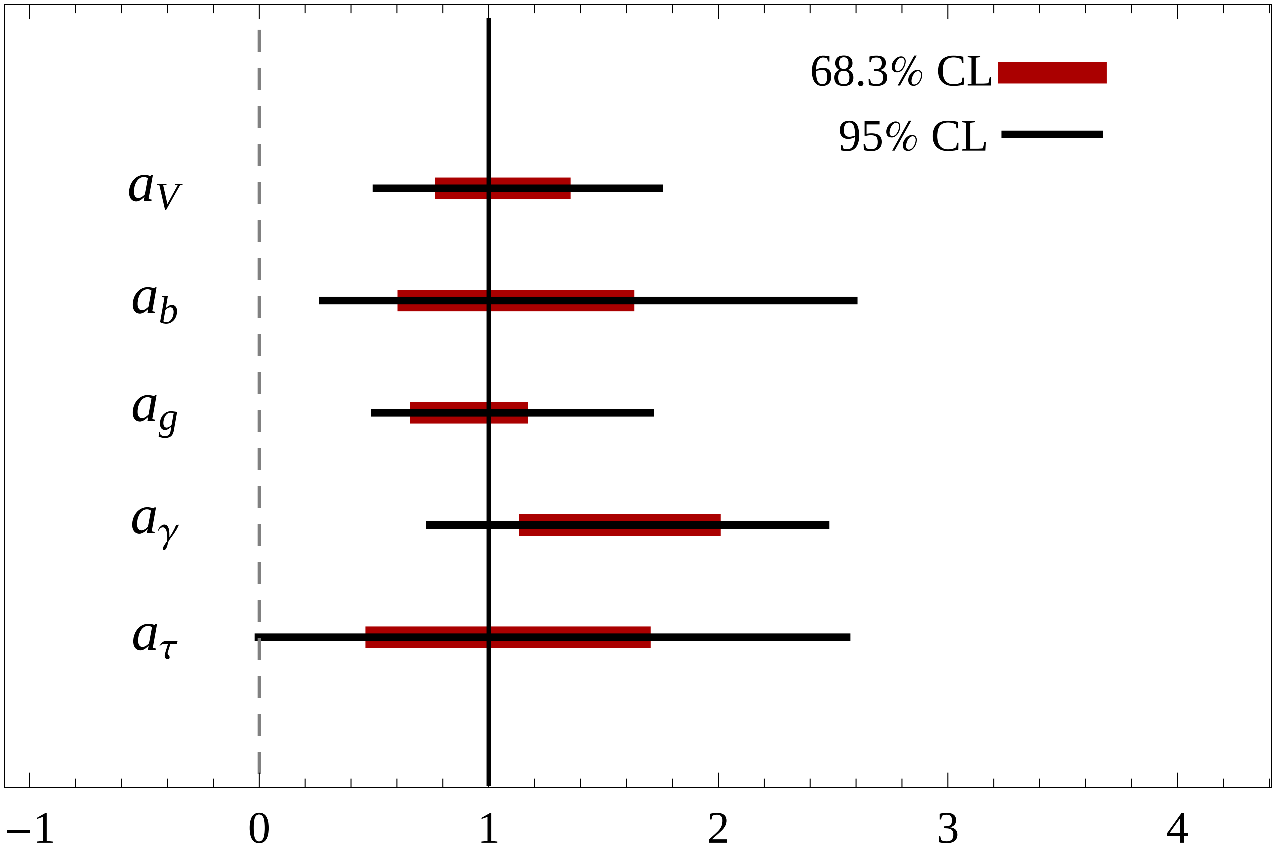
CMS: $M_h = 125.8 \pm 0.5$ **GeV**

ATLAS: $M_h = 124.3 \pm 0.7$ **GeV**

‘Couplings’ of Higgs particle to WW or ZZ (κ_V), $b\bar{b}$ (κ_b), gg (κ_g), $\gamma\gamma$ (κ_γ), $\tau^+\tau^-$ (κ_τ) equal to 1 in the SM.

‘Apparent squared-couplings’ can be extracted from the measured Higgs rates:

$$a_{\mathcal{P}} = \kappa_{\mathcal{P}}^2 \left(\frac{\Gamma_h^{\rm SM}}{\Gamma_h}\right)^{1/2}$$



Update of 1210.3342 (combines the ATLAS, CMS and Tevatron data in quadrature...)

The remarkable success of the SM (actually SM$\nu\mathcal{G}$) has lead some to question whether there is anything left to discover ...

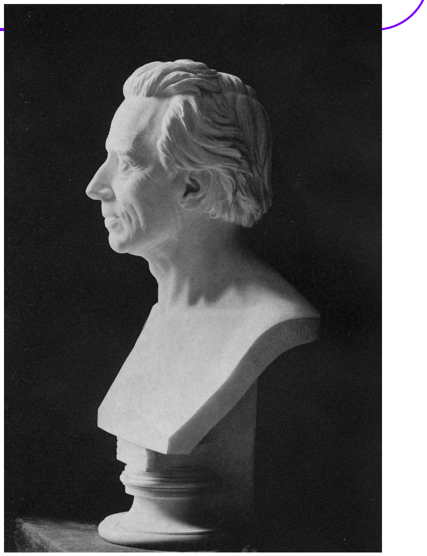
The Guardian (Jan 2013):

“Anthropic big desert up to the Planck scale, or ...”

There is only one way to find out:

perform more precise experiments and/or at higher energy, including channels not explored so far.

Don't go into physics, "in this field, almost everything is already discovered, and all that remains is to fill a few unimportant holes." (1878)



Philipp von Jolly
(professor of Planck)

Max Planck - 1878

Fortunately, Planck did not follow the advice:

in Dec. 1900 he ushered in the era of quantum physics,

while prominent physicists (Michelson, Kelvin, ...) were

still saying that there is not much left to be discovered.

SM$\nu\mathcal{G}$ + DM describes well a large array of data.

Same is true for any model with a decoupling limit

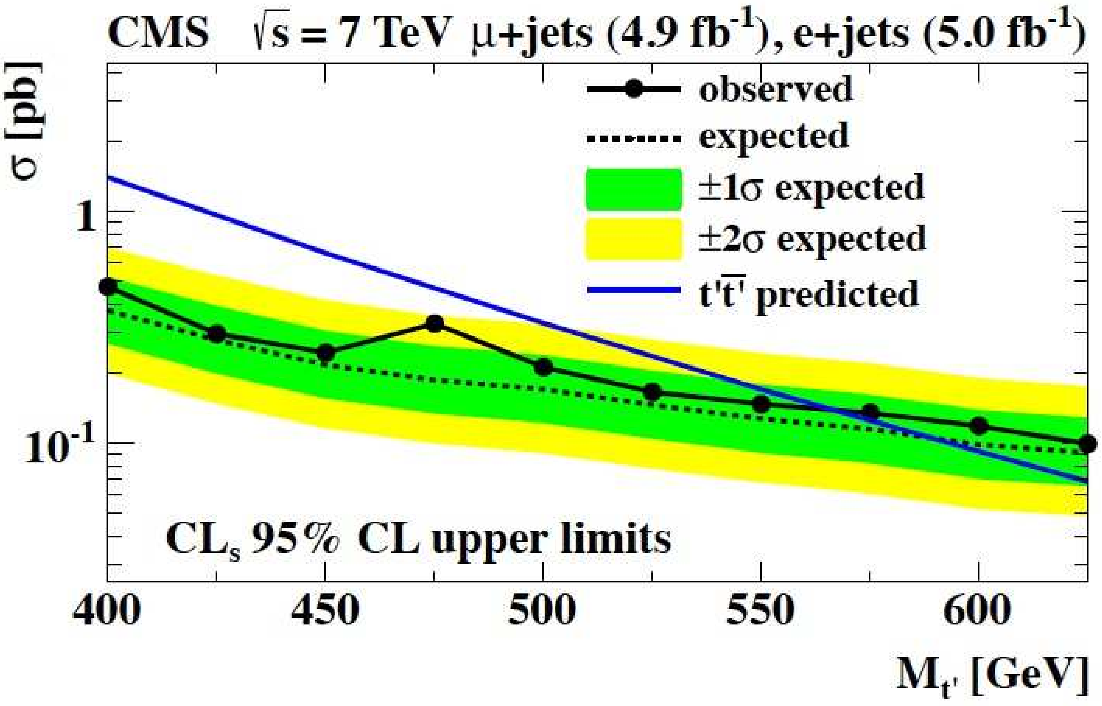
(*i.e.*, effects of new particles are suppressed by $1/M_{\rm new}$ or $g_{\rm new} \ll 1$),

including larger gauge symmetries, vectorlike quarks, new scalars ...

Models without a decoupling limit are ruled out:

- Higgsless models
- SM + 4th generation

Fermion coupling to Higgs is proportional to mass:
perturbative limit $m_f \lesssim 600$ GeV



The SM$\nu\mathcal{G}$ is valid up to the existence of things that the current experiments have not probed:

$\star$ new interactions that induce flavor processes

(*e.g.*, $K \to \pi\nu\bar{\nu}$ with $Br \approx 10^{-10}$.)

$\star$ new heavy particles (*e.g.*, W' of mass 3 TeV and coupling 0.3).

$\star$ very light, very weakly coupled particles (sterile ν's, axion, ...)

More exotic phenomena (strongly coupled sectors, deviations from field theory, etc.) may also have a decoupling limit.

Does Occam's razor suggest that the SM is preferred over the SM + new decoupling particles? Not really!

Occam's razor failed again and again during the construction of the SM.

Why are there 3 generations of quarks and leptons?

"Who ordered that?"

Why are there weak interactions? $SU(3) \times U(1)$ *would be enough!*

"Weakless Universe" (Harnik et al, hep-ph/0604027)

Connections between physics probed in high-energy collisions and in searches for rare processes

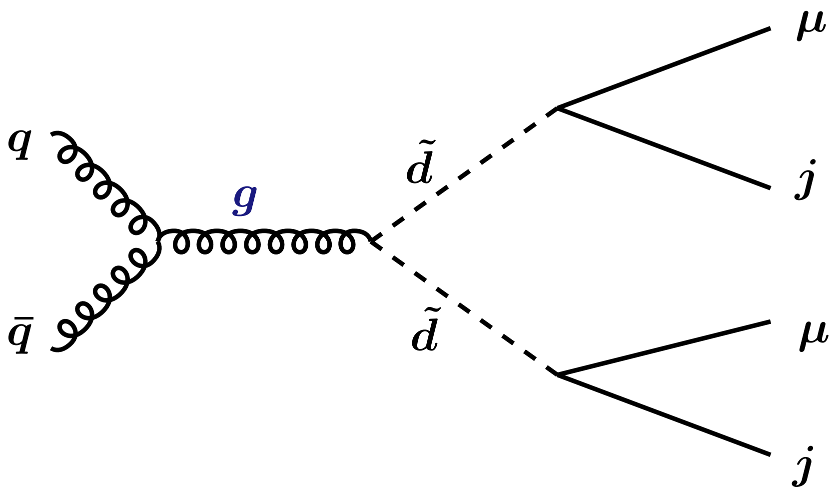
m_ν require the coupling of ν's to the Higgs doublet.

The origin of quark and lepton masses (arising from physics at some high scale) is likely to induce flavor processes involving mesons, muons, ...

Whether new very light particles exist is probably determined by the symmetries of the underlying theory at a high scale.

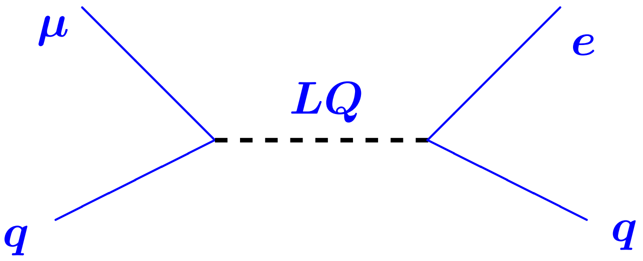
New particles may reveal themselves in one or another frontier depending on the values of some free parameters.
(E.g., leptoquarks, Z'_B, γ', H^0, ...)

Leptoquarks



CMS limit: $M > 1.1$ TeV.

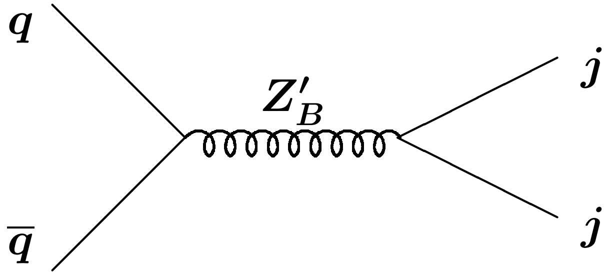
Leptoquarks which couple to both eq and μq induce $\mu\mathcal{N} \to e\mathcal{N}$ conversion:

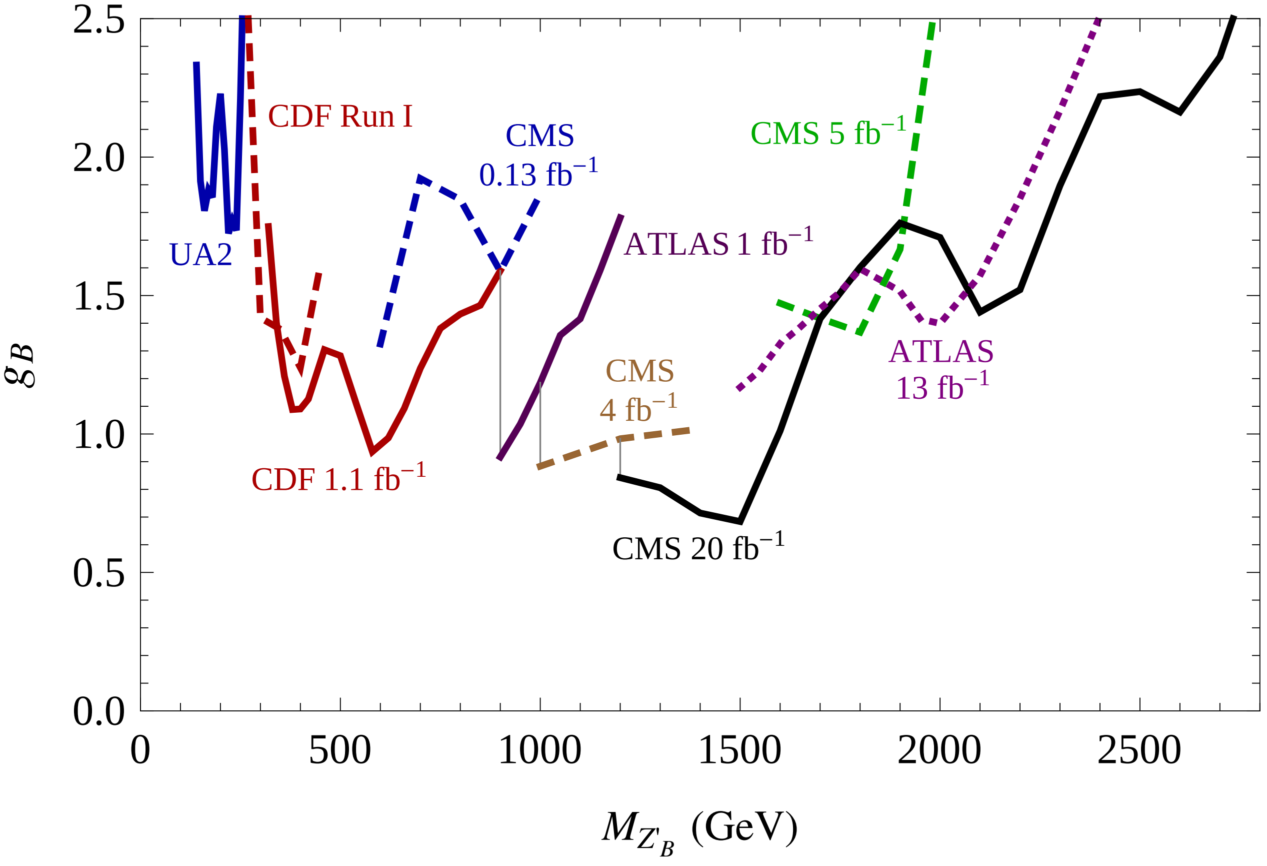


Current limit: $M_{LQ} > 1000$ TeV $\times \sqrt{g_\mu g_e}$

Vector boson coupled to baryon number

Dijet resonance at hadron colliders:





Felix Yu, 1306.2629

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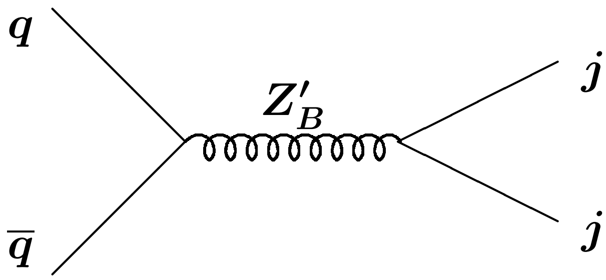
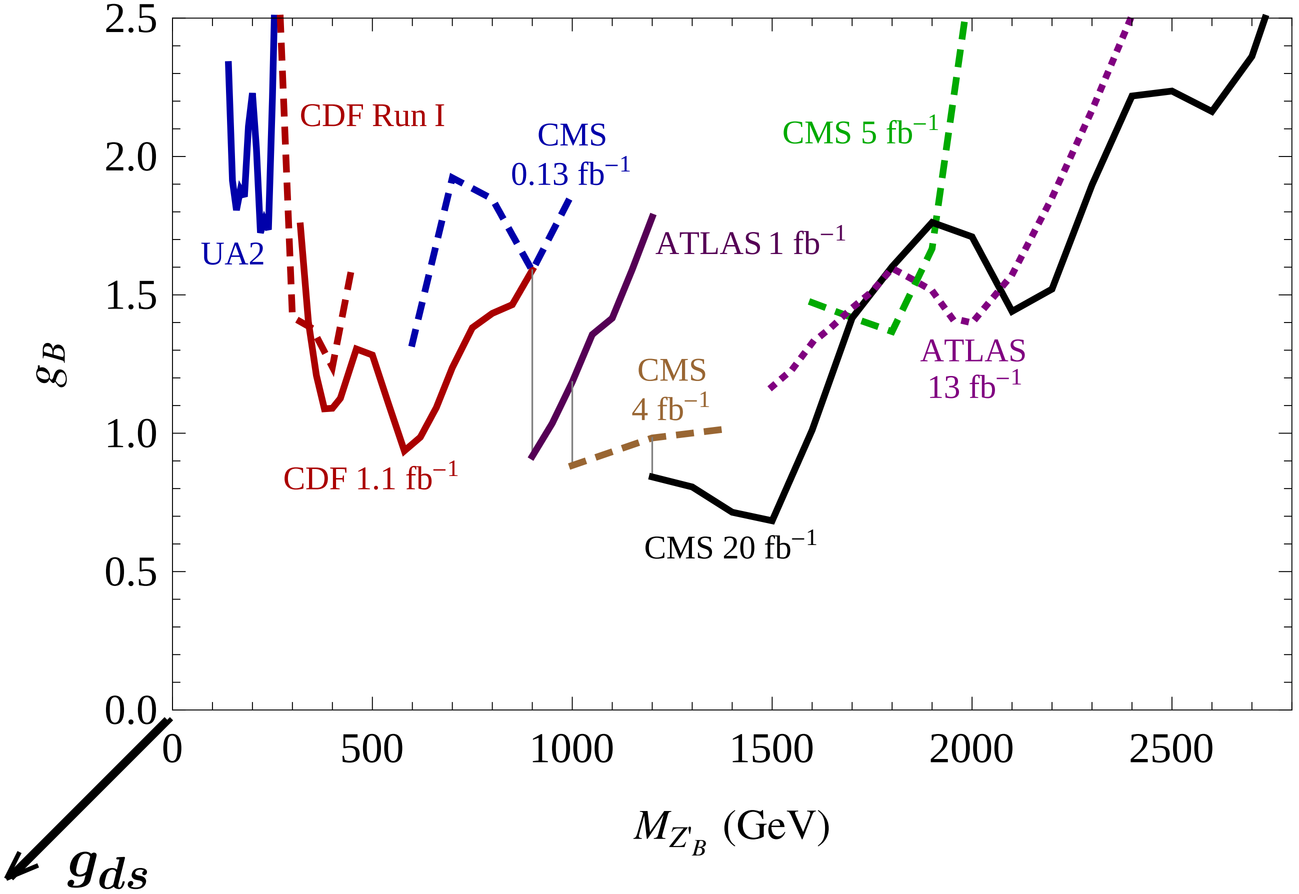




Felix Yu, 1306.2629

If, however, Z' has flavor-dependent couplings, then low-energy measurements with Kaons are sensitive to $M_{Z'} \sim 100$ TeV $\times (g_{ds}/0.1)$

Massless gauge bosons other than the photon

hep-ph/0411004

γ' couplings to quarks and leptons: $c_f \frac{m_f}{M^2} F'_{\mu\nu} \bar{f}_L \sigma^{\mu\nu} f_R$

c_f: 3×3 *matrices in flavor space, dimensionless parameters*

$\rightarrow$ magnetic-like and electric-like dipole moments.

Exotic flavor processes: $\mu \rightarrow e + \not{E}$, $\Gamma\left(\mu \rightarrow e\gamma'\right) = c_{e\mu}^2 \frac{m_\mu^5}{8\pi M^4}$

$$B\left(\mu \rightarrow e\gamma'\right) < 3 \times 10^{-5} \qquad \Rightarrow \qquad \frac{M}{\sqrt{c_{e\mu}}} \gtrsim 15 \text{ TeV}$$

γ' production at the LHC: $t\bar{t}$ *+ missing energy*

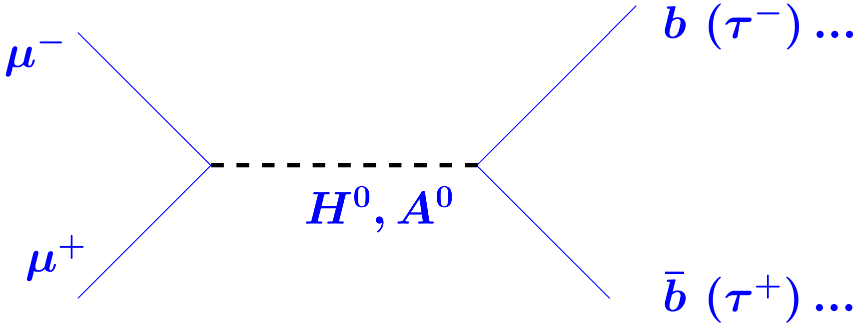
Coupling grows with momentum: $2\frac{m_t}{M^2}\left(\partial_\mu A'_\nu\right) \bar{t}\, \sigma^{\mu\nu} (\mathrm{Re}\, c_t + i\gamma^5 \mathrm{Im}\, c_t)\, t$

Extended Higgs sector

Multi-TeV $\mu^+\mu^-$ collider –"factory" of heavy Higgs particles

(Eichten, Martin, 1306.2609)

$M_{H^0} = 2$ **TeV** $\longrightarrow O(10^4)$ **events/year for** $\mathcal{L} = 10^{33}$ **cm**$^{-2}$ **s**$^{-1}$



Energy frontier with hadron collisions is different than energy frontier with $\mu^+\mu^-$ *collisions!*

Depending on the structure of the extended Higgs sector,
$H^0, A^0, H^\pm$ **can induce flavor processes at the intensity frontier.**
(nucleon EDMs, rare K decays, ...)

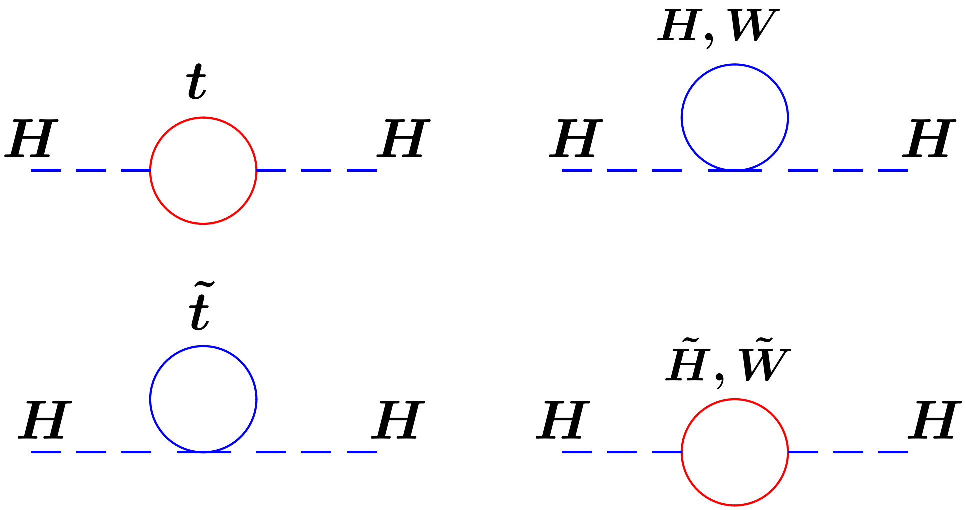
Hierarchy problem

Quantum fluctuations tend to increase the vacuum expectation value of the Higgs doublet.

Stability of the electroweak scale requires a modification of SM at scales not far above ~ 1 TeV, or fine-tuning.

Solution #1: Supersymmetry

No quadratic divergences because loops with superpartners cancel the SM loops:

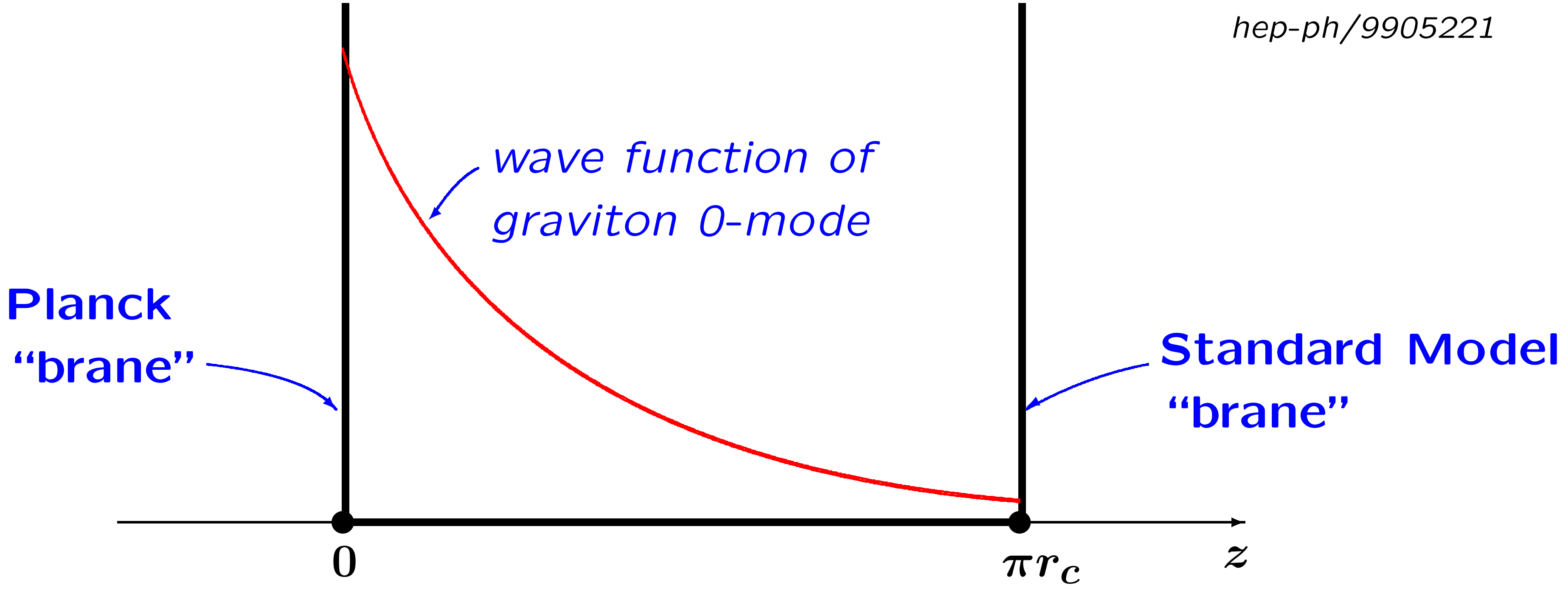


Additional structures required to explain why $\mu \sim \langle H \rangle$, and to break supersymmetry dynamically.

Prediction: $\tilde{H}^{\pm}$, $\tilde{H}^0$, $\tilde{t}_1$, $\tilde{t}_2$ have masses $\lesssim O(1)$ TeV.

Solution #2: A warped extra dimension

Randall, Sundrum,
hep-ph/9905221



Interaction of the graviton 0-mode (the massless 4D spin-2 field) with SM particles is suppressed by its exponentially small wave function at the SM brane $\longrightarrow \langle H \rangle \ll M_{\rm Planck}$.

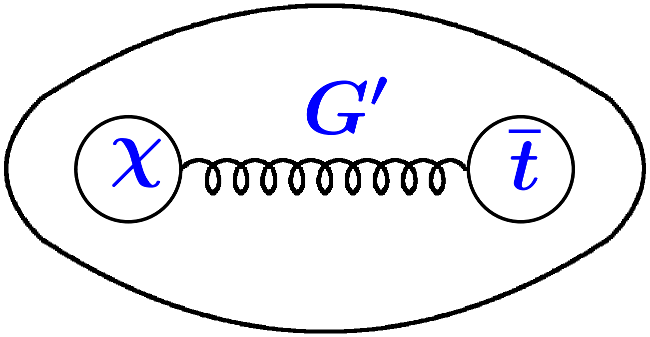
Prediction: **graviton KK modes $\Rightarrow$ s-channel spin-2 resonances.**

New limits from $\ell^+\ell^-$, $\gamma\gamma$ resonance searches at CMS & ATLAS

Solution #3: Composite Higgs models

Higgs boson may be a bound state of top quark with a new (vector-like) quark χ: "Top seesaw model" *(Chivukula et al, hep-ph/9809470,...)*

Binding may be due to some strongly interacting heavy gauge bosons:



Scale of Higgs compositeness $\gtrsim 5$ *TeV.*

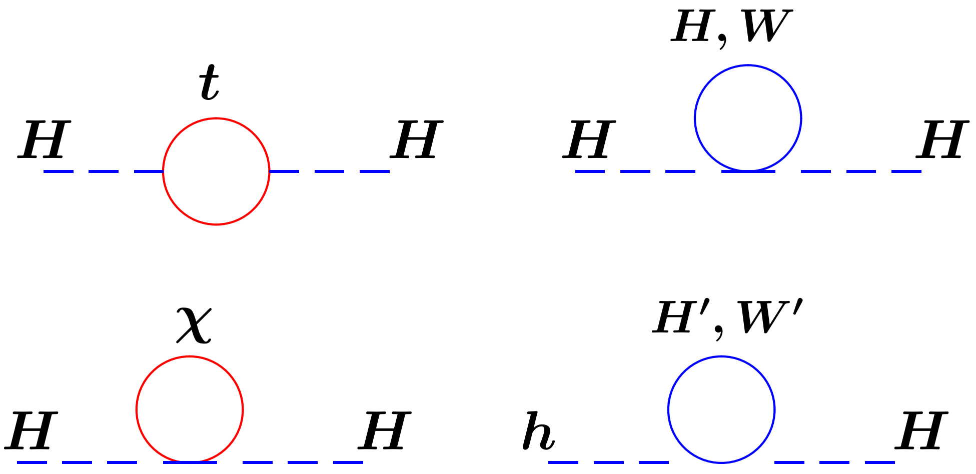
Solution #4: Higgs doublet as a (composite) pseudo Nambu-Goldstone boson

(Georgi, Kaplan, 1984, ... ; Agashe, Contino, Pomarol, hep-ph/0412089, ...)

(Partial) Solution #5: "Little Higgs"

1-loop quadratic divergences cancelled by same-spin partners

(Arkani-Hamed et al, hep-ph/020602, ...)



Effective theory valid up to scales of order ~ 5 TeV, where some unspecified new dynamics takes over.

(Partial) Solution #6: "Twin Higgs"

(Chacko, Goh, Harnik, hep-ph/0506256)

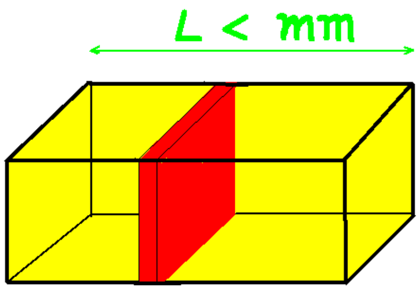
1-loop quadratic divergences are cancelled if a parity interchanges each SM particle with a particle transforming under a twin group.

Unlike other known solutions, where $\tilde{t}$ squarks or a χ quark or KK gravitons are at the TeV scale, Twin Higgs does not include colored or strongly coupled new particles.

(Potential) solution #7: Large extra dimensions (ADD)

Graviton only in flat extra dimensions

We may live on a wall in extra dimensions



Newton's law in extra dimensions: $F_N = \frac{m_1 m_2}{(M_s r)^{2+n}}$

New limits from monojet, mono-γ searches at CMS and ATLAS *(talks by ....)*, and from searches for new macroscopic forces.

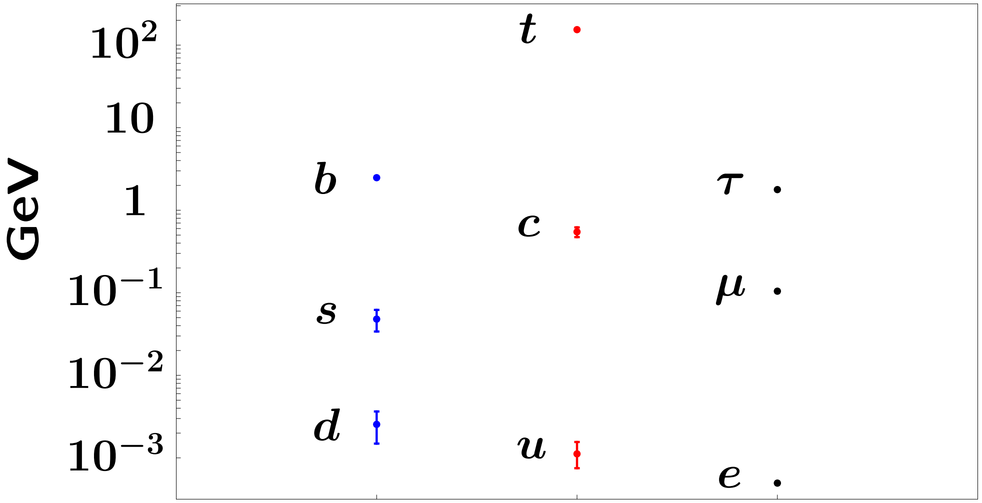
(Potential) Solution #8: approximate scale invariance

(Bardeen 1995; C. Hill, hep-th/0510177, ...)

Solution #9: ???

Hierarchy argument for new phenomena: **naturalness requires new physics at the TeV scale, but there are many possibilities.**

Quark and lepton masses:
(at 1 TeV)



Any explanation for the hierarchy of Higgs Yukawa couplings (proportional to fermion masses) requires physics beyond the SM:

- discrete symmetries → $(\langle\phi\rangle/M)^n$ suppressions
- loop suppressions
- grand unification
- wave function overlaps in extra dimensions
- ...

Scale of fermion-mass generation may be large: need to study rare K, D, B decays, LFV processes, ...

Other theoretical reasons to expect phenomena beyond the SM$\nu\mathcal{G}$:

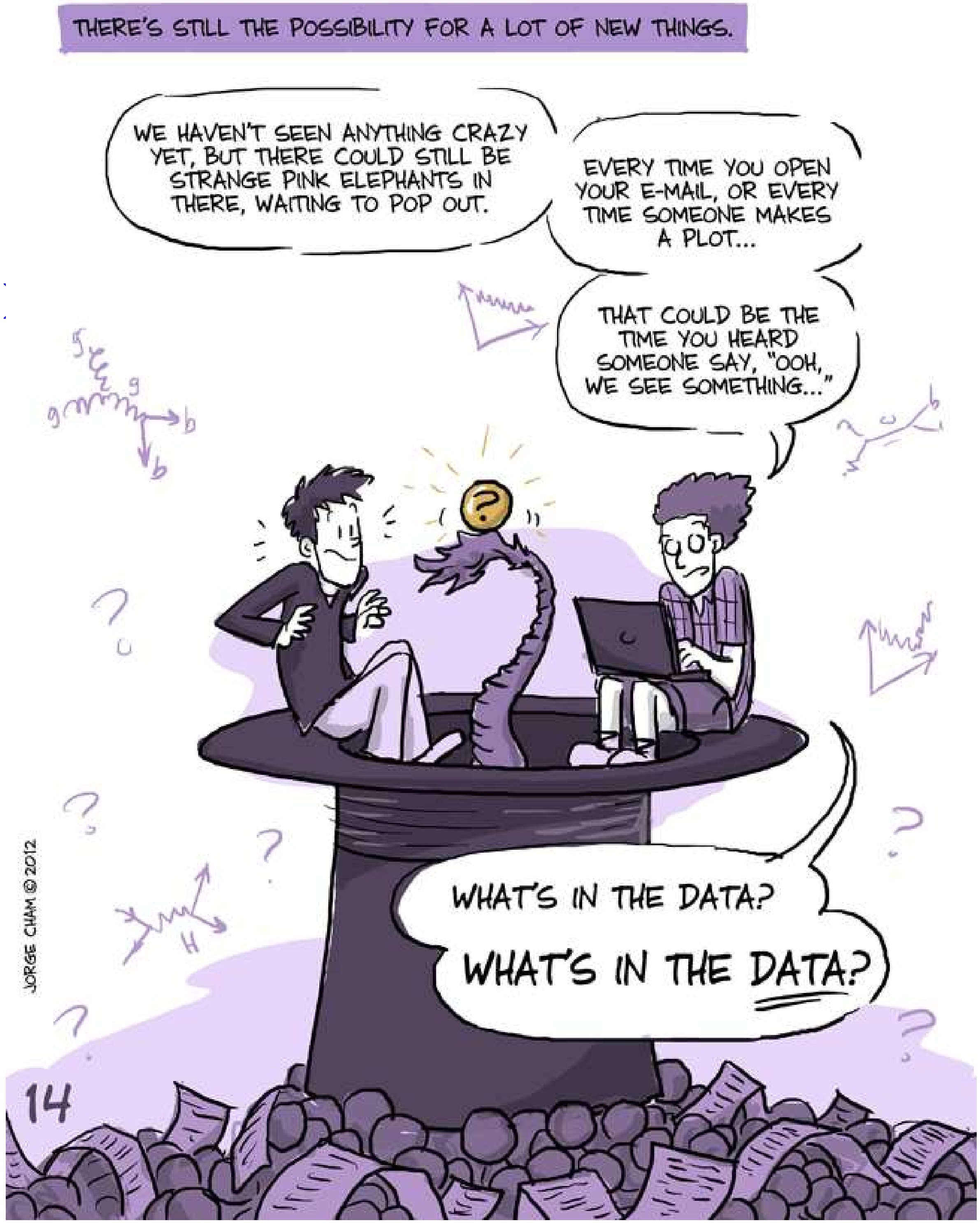
strong CP problem, baryogenesis, inflation,
successes of GUTs, why 3 generations, ...

Conclusions

Many possible new particles:

- **Gauge bosons: Z', W', G', γ', ...**
- **Vectorlike quarks and leptons**
- **Sterile ν's**
- **Various scalar particles**
- **...**

Discovering such particles at colliders, or observing their effects in rare processes at low-energies, would point to new symmetries or deeper organizing principles.



phdcomics.com/higgs