XXXVII ENFPC

Phenomenology of Physics Beyond the Standard Model

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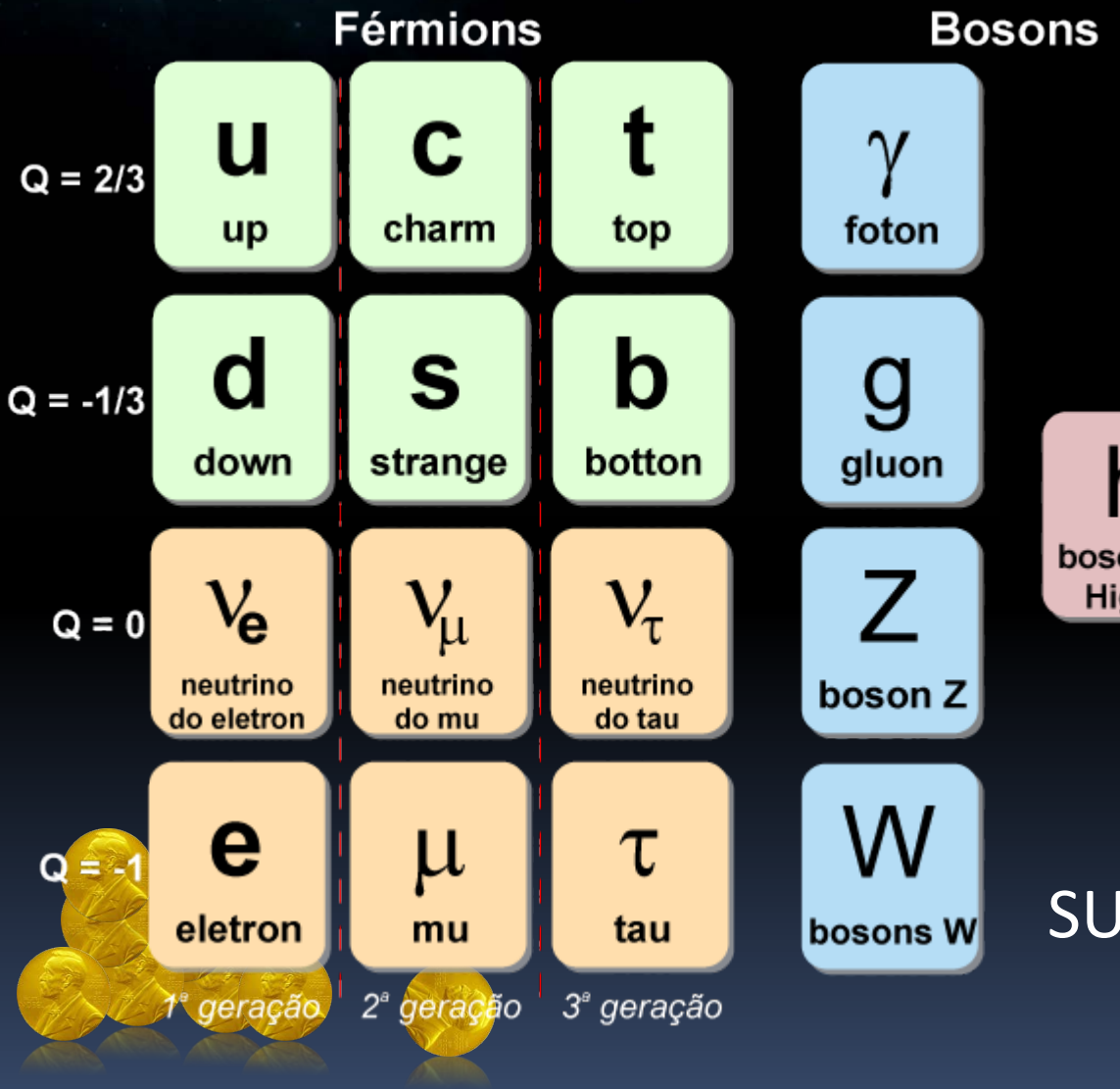
The Standard Model

A story of success



h
boson de Higgs

✓ July, 2012

$SU(3)_c \times SU(2)_L \times U(1)_y$

The Standard Model

A story of success

LEP Electroweak Working Group, http://lepewwg.web.cern.ch

The Standard Model

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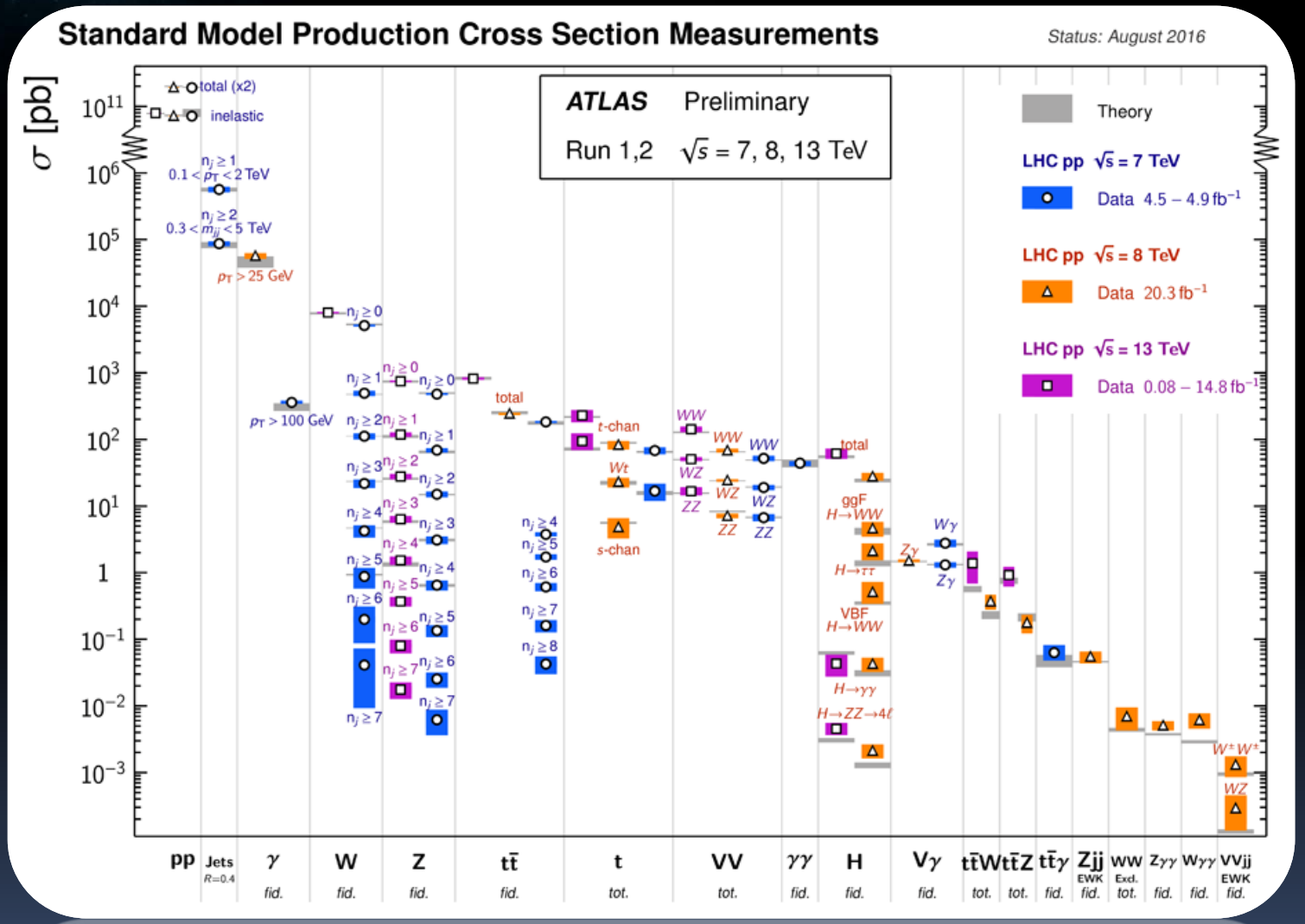

The Standard Model

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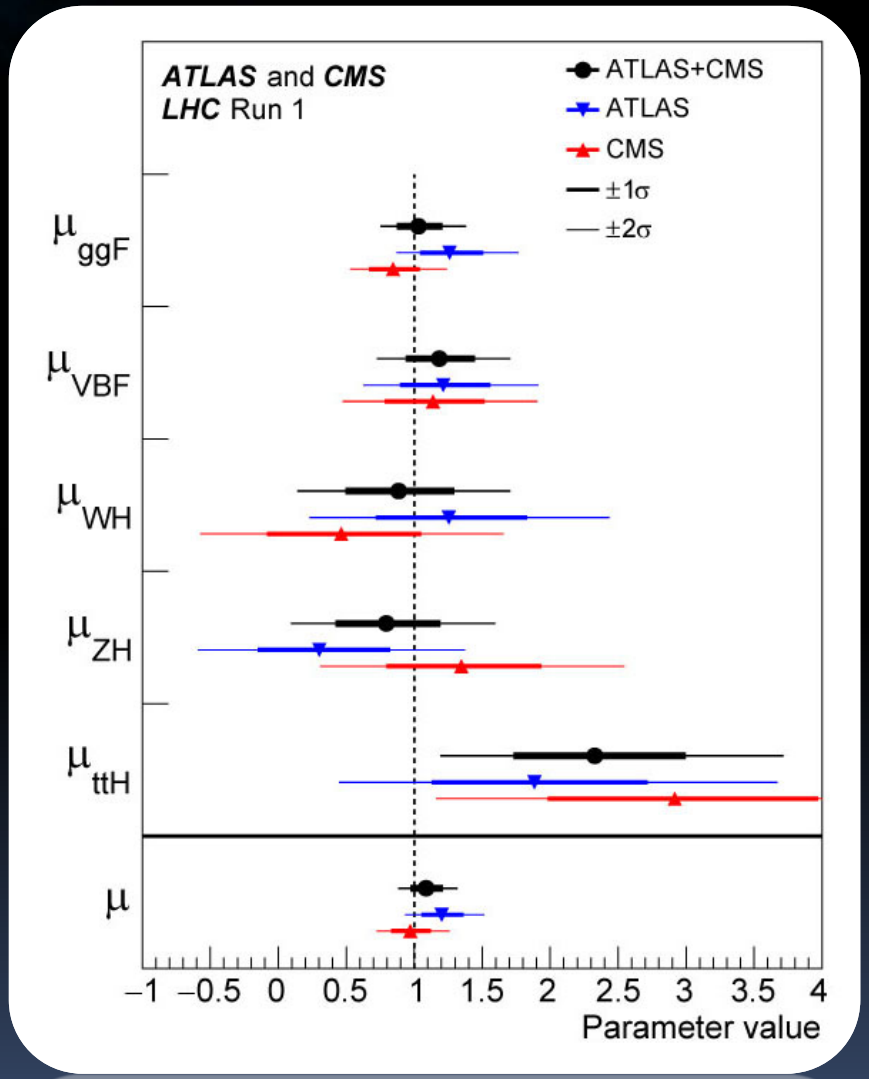


The Standard Model

Are we done?

What about…

- …fermion masses?

$$\mathcal{L}_H = m_d \bar{d}_L d_R + h.c.$$

$$m_d = \frac{Y_d v}{\sqrt{2}}$$

$$v \approx 246 \text{ GeV}$$

$$Y_e \sim 10^{-5}$$

$$Y_u \approx Y_d \sim 10^{-3}$$

$$Y_t \sim 1$$

No idea of how!

Are neutrinos also getting mass the same way?

- …dark matter?

- …CP violation? (big enough to deal with Bariogenesis)

The Standard Model

Are we done?

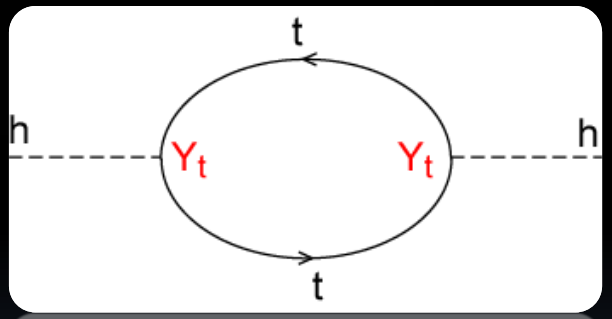
What about…

- …quantum corrections (to the Higgs mass)?

$$V\left(H^\dagger H\right) = \mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2$$

$$m_h^2 = -\mu^2 = 2\lambda v^2$$

quantum corrections:



$$\delta m_h^2 \propto \frac{\Lambda^2}{16\pi^2}$$

$$\Lambda \sim 10^{18}\ \text{GeV}\quad (M_p)$$

$$m_h \sim \sqrt{-\mu^2 + 10^{34}\ \text{GeV}}$$

= 125 GeV

The Standard Model

Are we done?

What about…

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$\Lambda \sim 10^{18}\ \mathrm{GeV}\ \ (M_p)$ $\qquad$ $m_h \sim \sqrt{-\mu^2 + 10^{34}\ \mathrm{GeV}}$ **= 125 GeV**

Set by quantum gravity $\qquad$ Set by EW scale physics

How can these two numbers be SO similar?

A more NATURAL situation would be having both to be set at the EW scale:

$\Lambda \sim 10^{3}\ \mathrm{GeV}$ $\qquad$ $m_h \sim \sqrt{-\mu^2 + 10^{4}\ \mathrm{GeV}}$

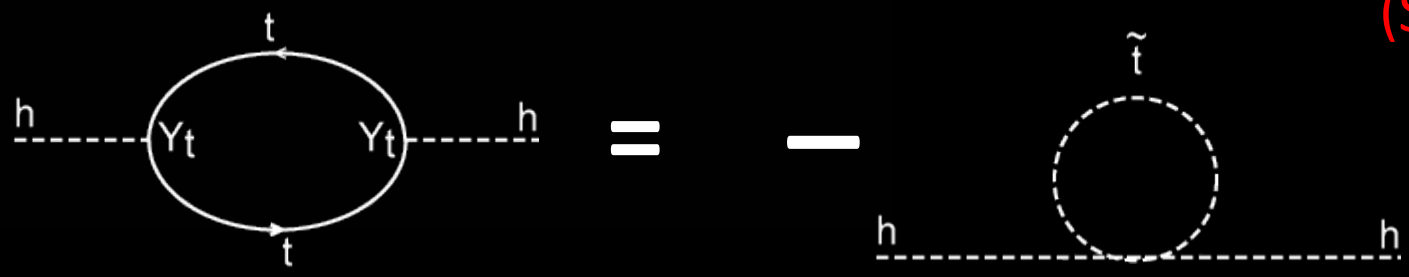
But that means NEW PHYSICS at the TeV scale

Physics Beyond the SM (BSM)

The traditional solutions to the hierarchy problem can be roughly divided in two classes:

- There is a light fundamental scalar & cancel quantum corrections

(SUSY)



- The light scalar is not fundamental & quantum corrections only make sense up to the compositeness scale

(Composite Higgs Models)

Physics Beyond the SM (BSM)

In most cases there is a DECOUPLING LIMIT where, by making the scale Λ associated with the new physics very big, one gets:

- A theory increasingly SIMILAR to the SM. New physics effects DECREASE with INCREASING Λ.

Precision measurements

Agreement with SM

→ Pushes Λ away!

The models are never really gone, just pushed away.

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Precision measurements

Agreement with SM

→ Pushes Λ away!

- A re-introduction of the hierarchy problem

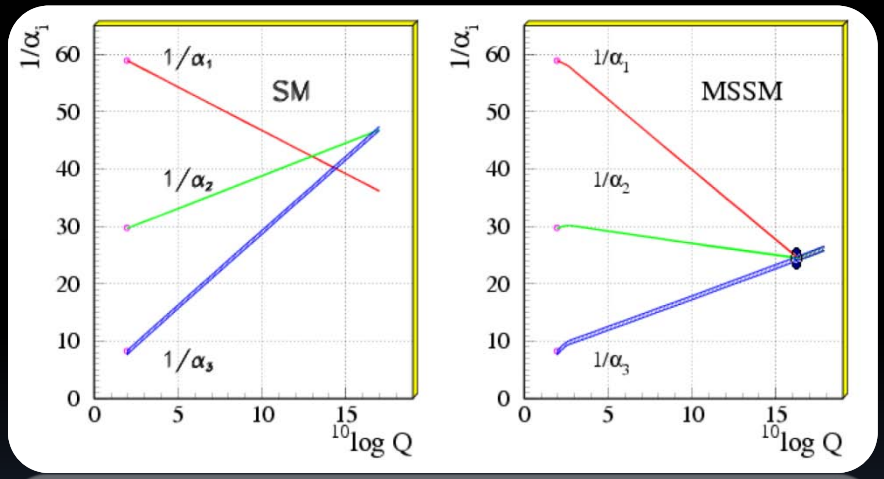
e.g.:

The cancelling is only good if $m_t \simeq m_{\tilde{t}}$

Physics Beyond the SM (BSM)

Supersymmetry - very attractive from a variety of theoretical reasons:

- Quantum corrections to Higgs mass are (partially) canceled
- Unification of Gauge Couplings



- Dark Matter candidates as a direct consequence of stabilizing the proton
- UV completion / Strings

Physics Beyond the SM (BSM)

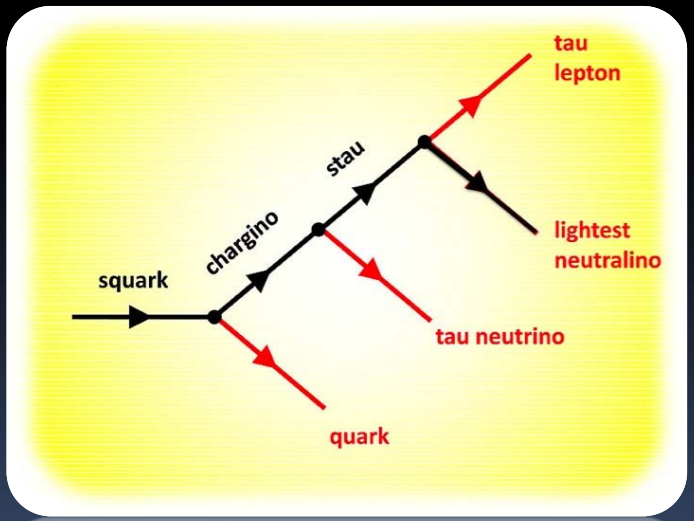
Supersymmetry signatures at the LHC are very much dependent on various details of the model.

What is the Lightest Supersymmetric Particle (LSP)? Is it colored or EW interacting?
R-Parity is conserved?
Compressed or split spectrum?

But some general features are expected:

Superpartners decaying through long decay chains, leading to multi-jets + MET;

Long-lived particles; Displaced vertices;



Physics Beyond the SM (BSM)

Composite Higgs Models – broad class that can refer to a lot of different models (including some extra dimensional models). Nowadays used more in connection with the Higgs being a pNGB of some broken global symmetry. The motivations are more empirical:

- No loop contributions from above the composition scale
- No other fundamental scalars ever detected
- Has been realized in nature time and again, at various scales (pions, Cooper pairs)
- Some models also implement unification

Physics Beyond the SM (BSM)

Composite Higgs Models signatures are connected with the presence of a whole new interaction, and also depend on details of that interaction, but generally speaking:

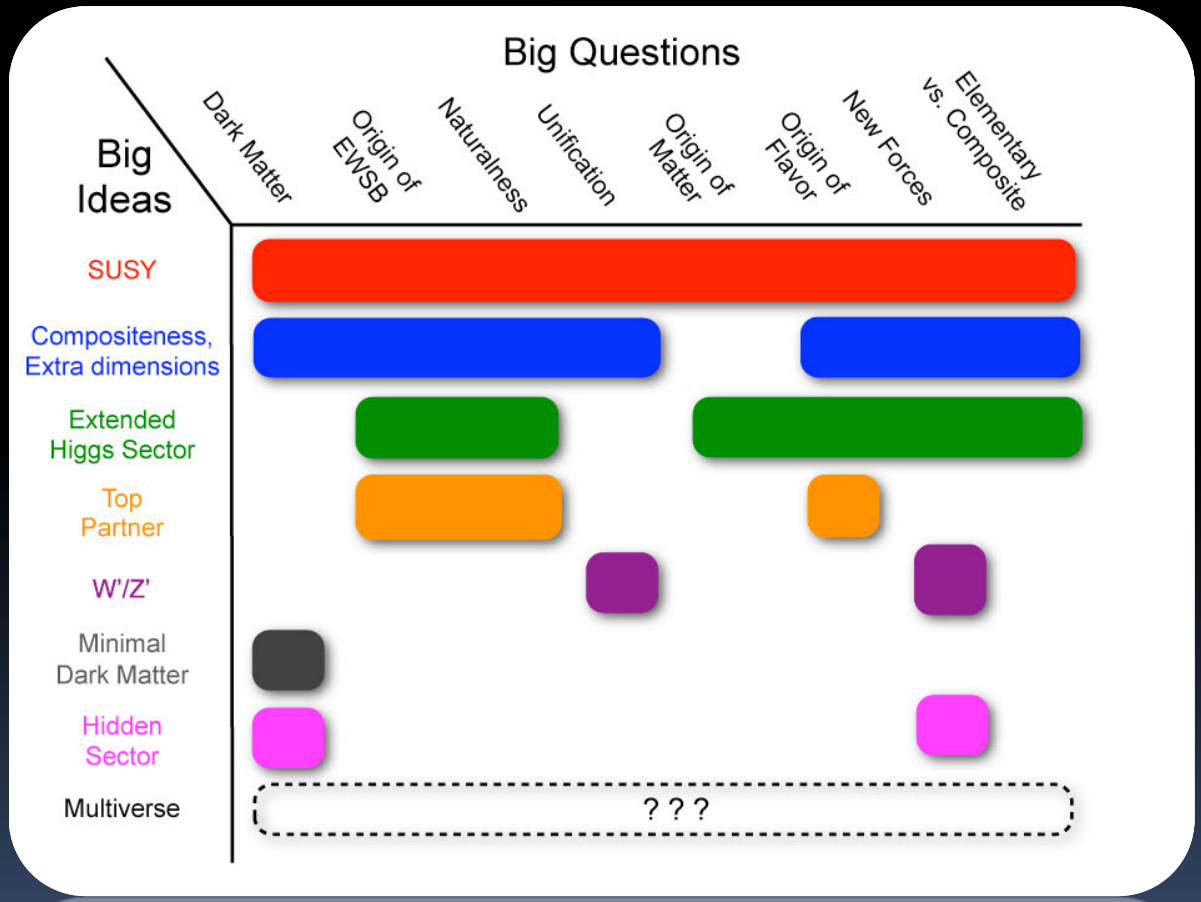
- Presence of bound states / resonances at the compositeness scale

- Being composite, the Higgs properties deviate from the SM (couplings become form factors)

- Heavier standard model particles (specially the Top) can mix with the resonances, leading to deviations in their couplings and (dangerous) flavor violating effects – increased recent interest in Partial Compositeness Scenarios (which suppress FV)

Physics Beyond the SM (BSM)

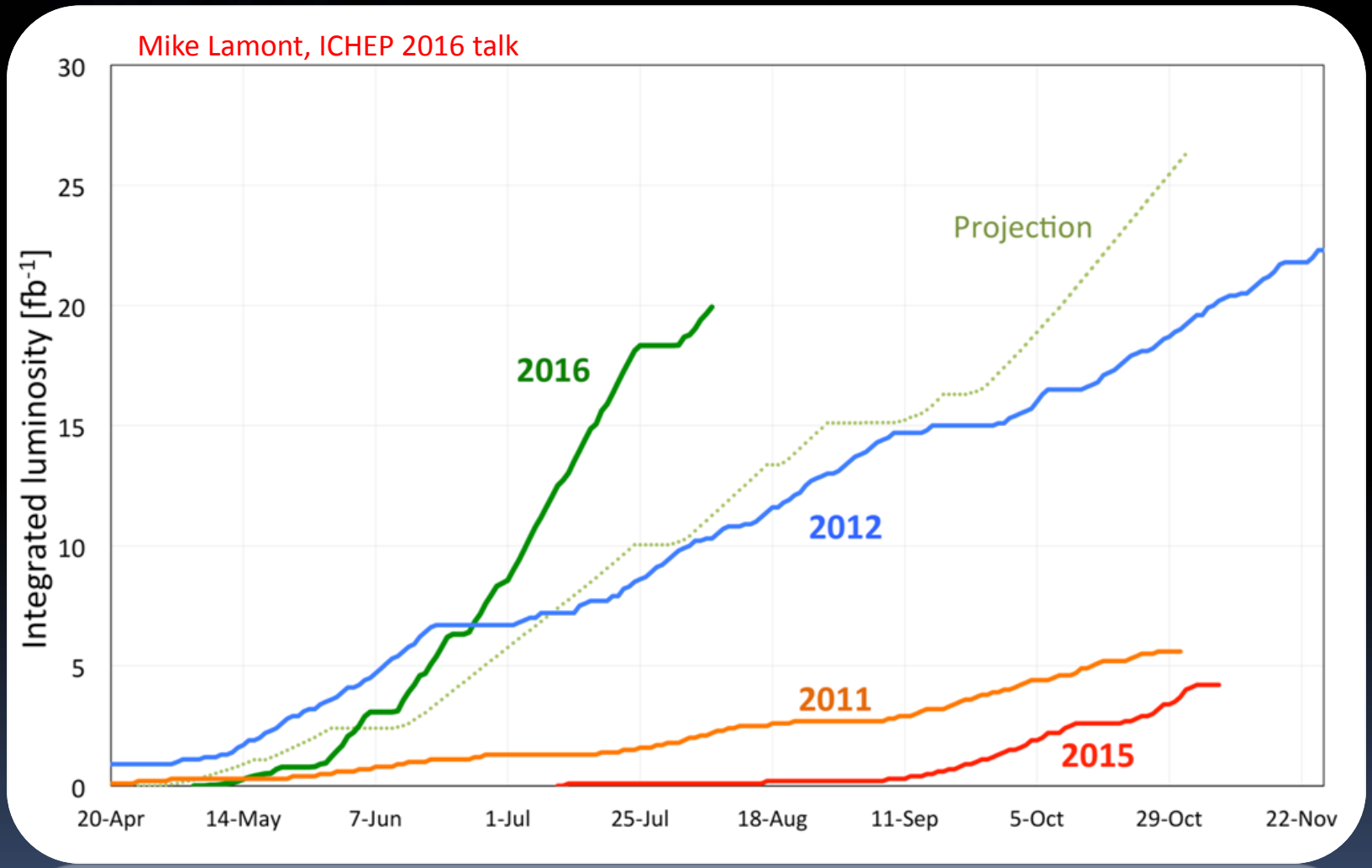
Many other extensions of the SM possible, not directly connected with the Hierarchy problem (therefore not necessary at the TeV scale):



New Particles Working Group Report of the Snowmass 2013 Community Summer Study, arXiv:1504.07551

The search for BSM signals

The LHC is rolling full-steam!



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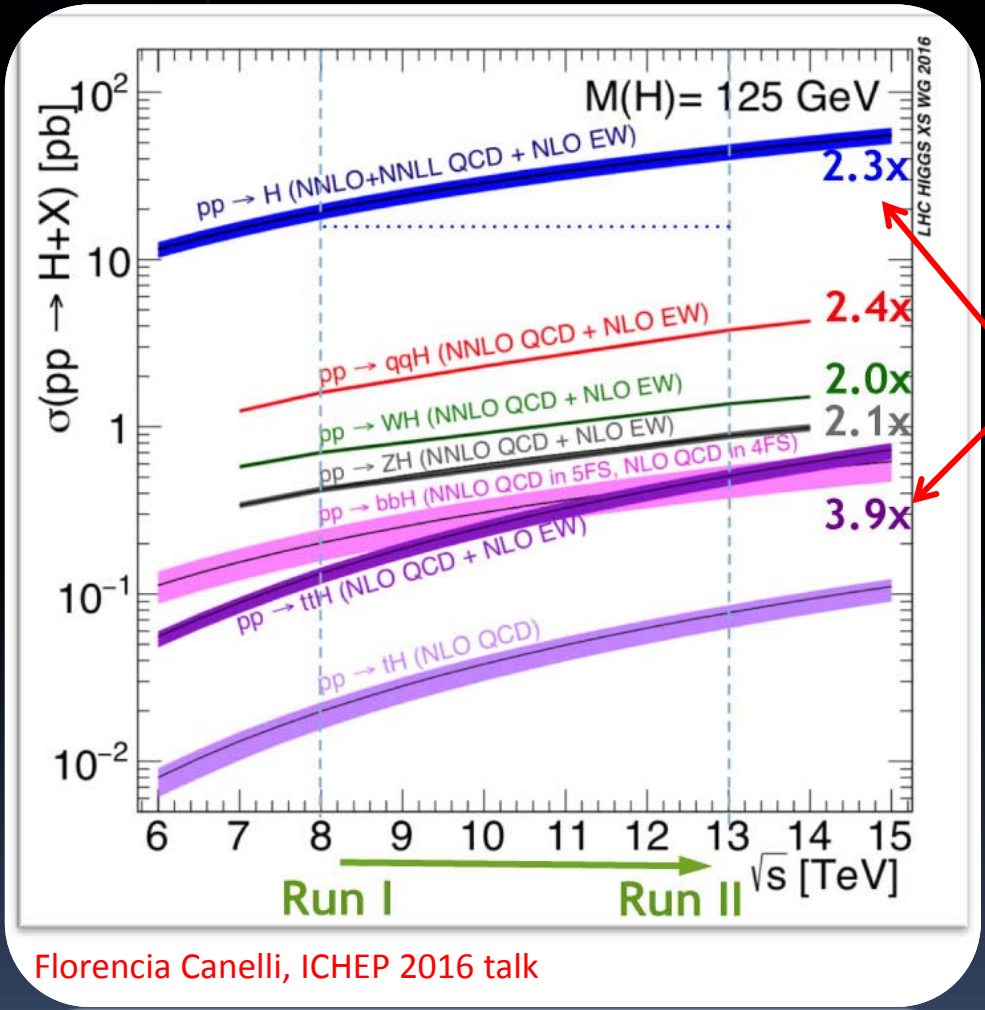


Florencia Canelli, ICHEP 2016 talk

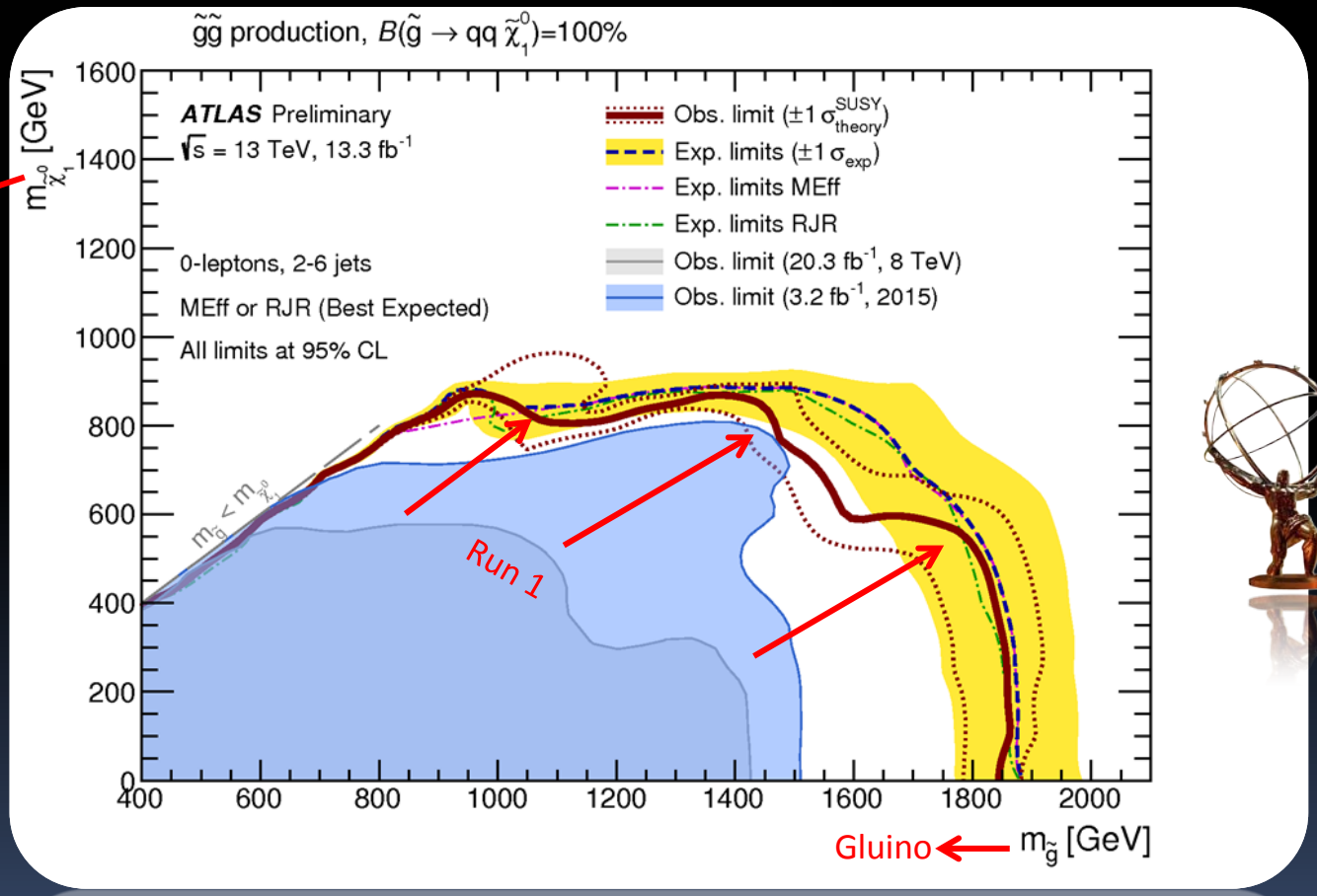
Many more interesting events being produced

The Higgs is already going into the "Intensity Frontier"!

The search for BSM signals

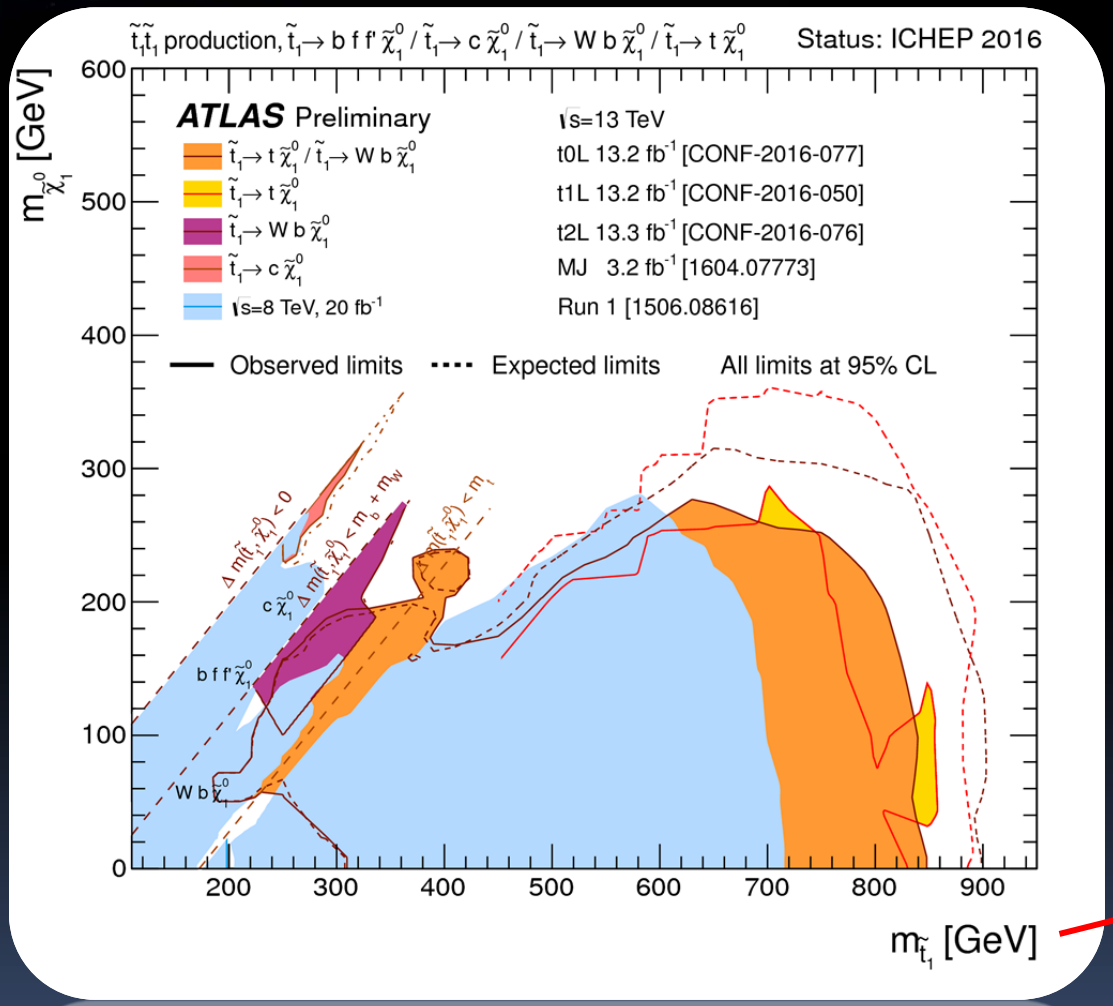
This is where models come to die (and we should not weep for them)

Jets + missing Et



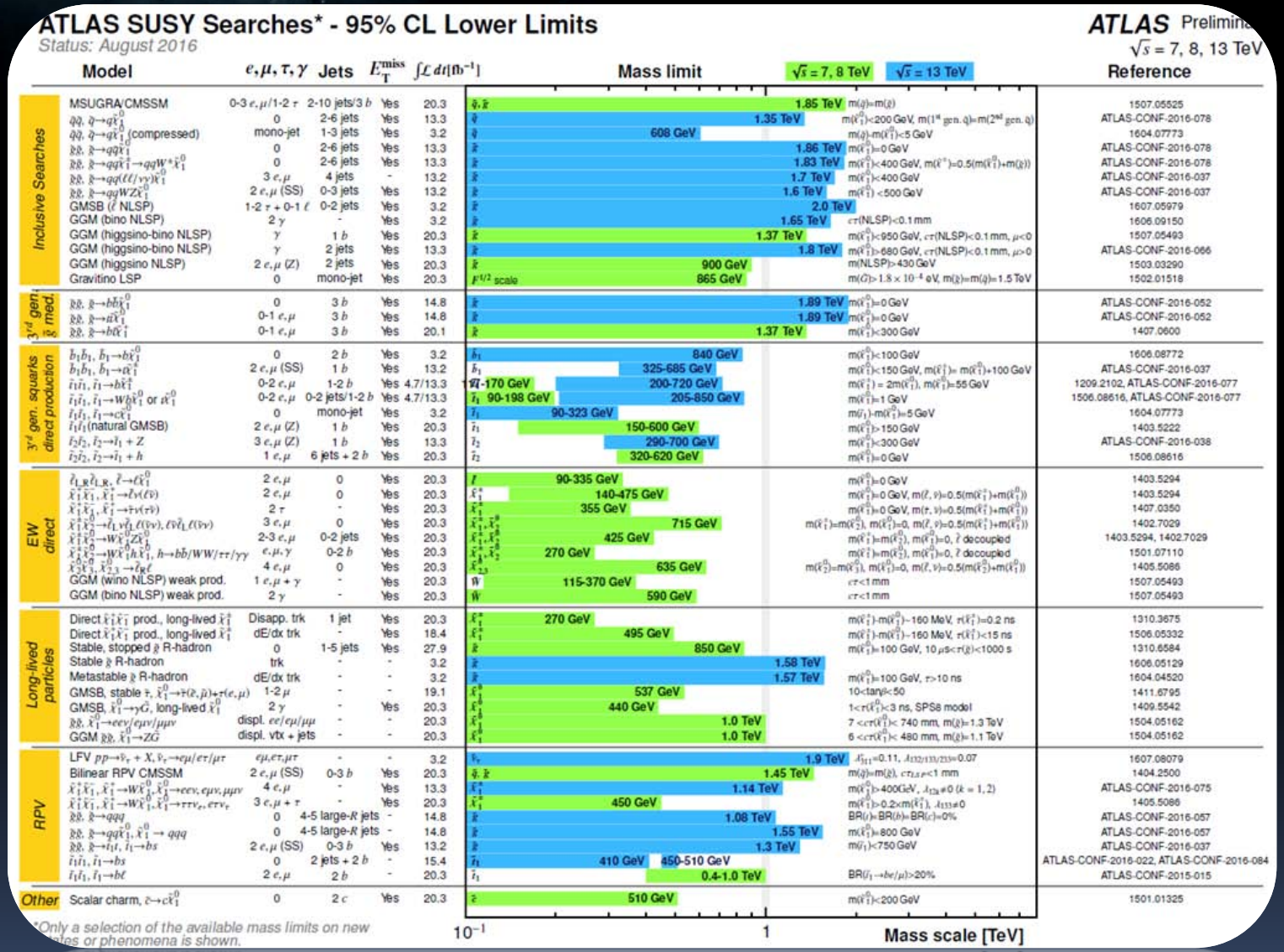
The search for BSM signals

Supersymmetric Top search:



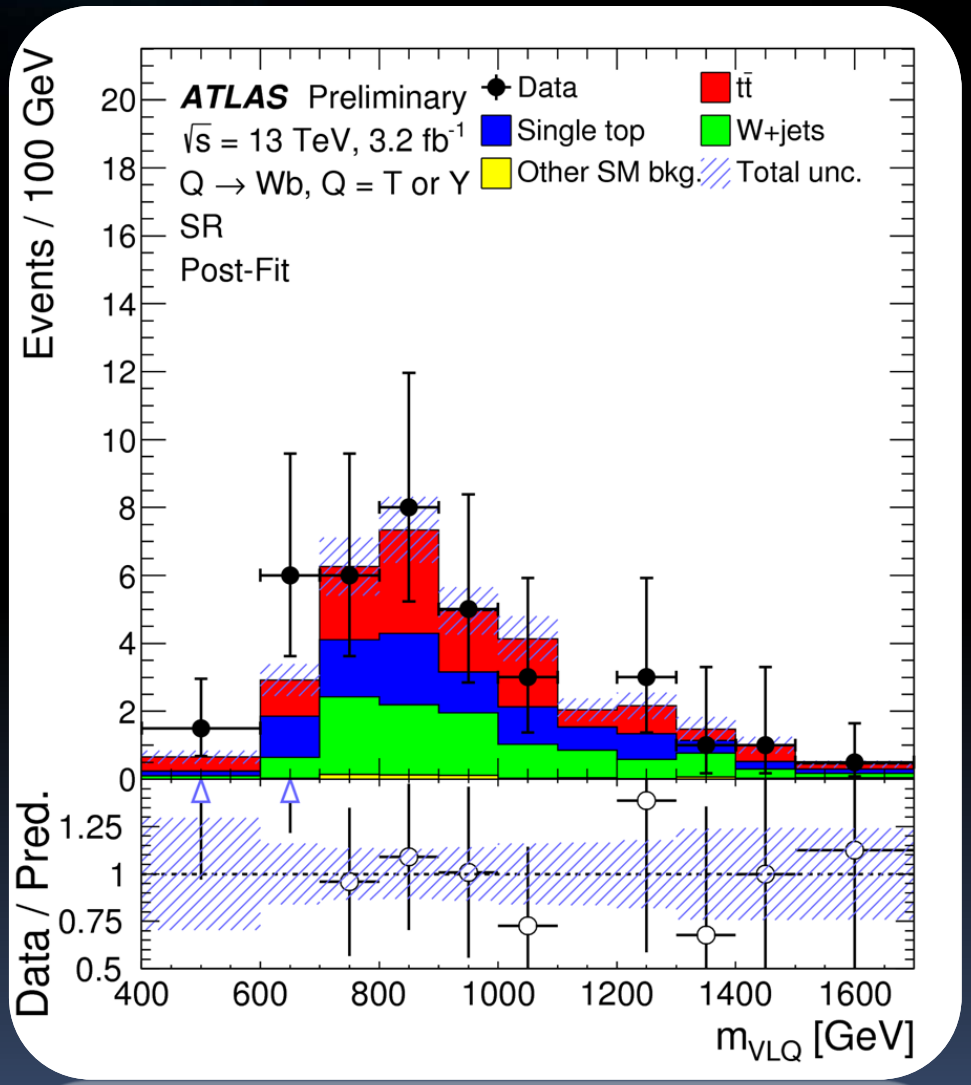
stop

The search for BSM signals



The search for BSM signals

Vector-like top partner search:

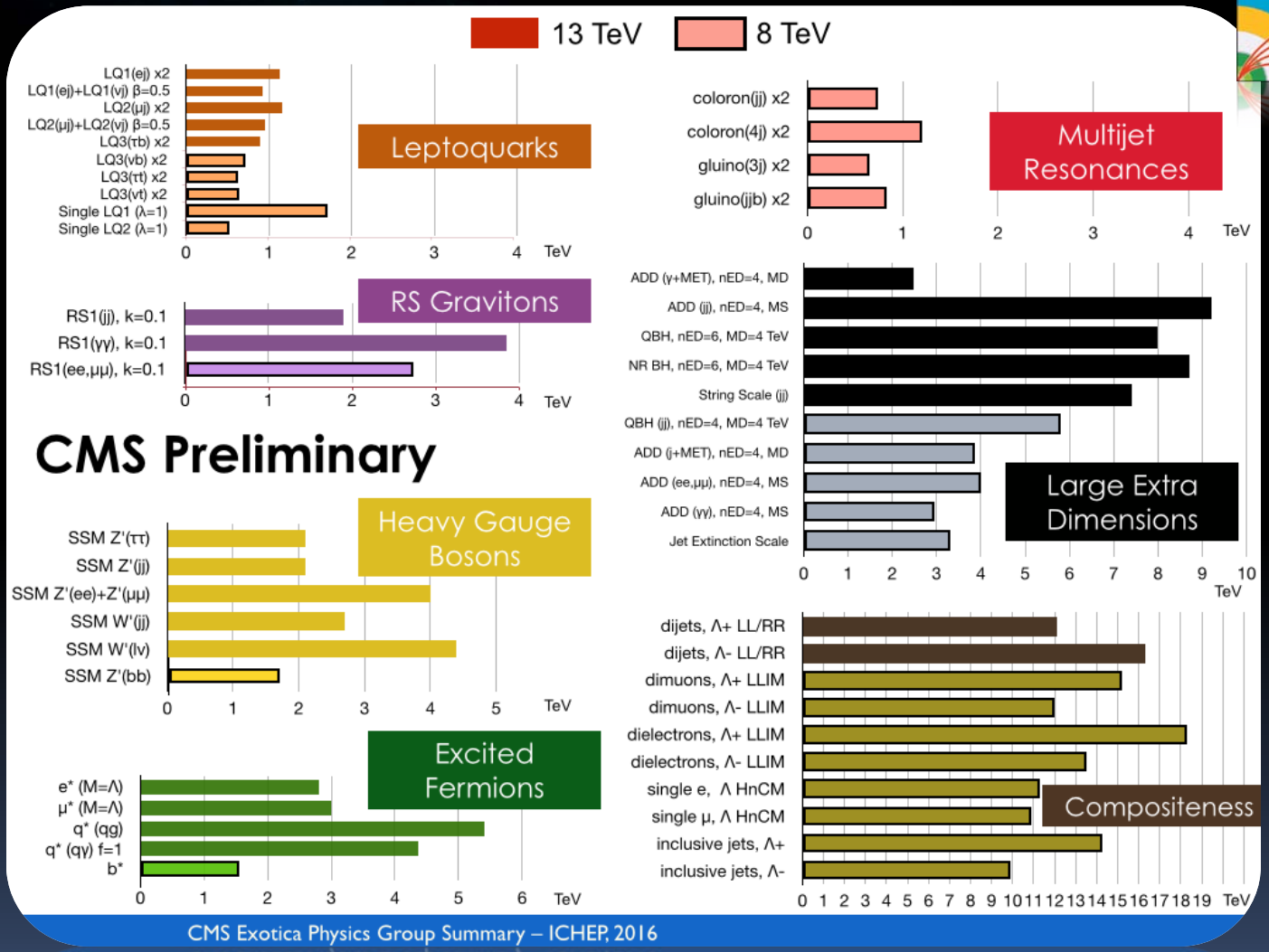


$m_T \gtrsim 1000$ GeV

ATLAS-CONF-2016-072

The search for BSM signals

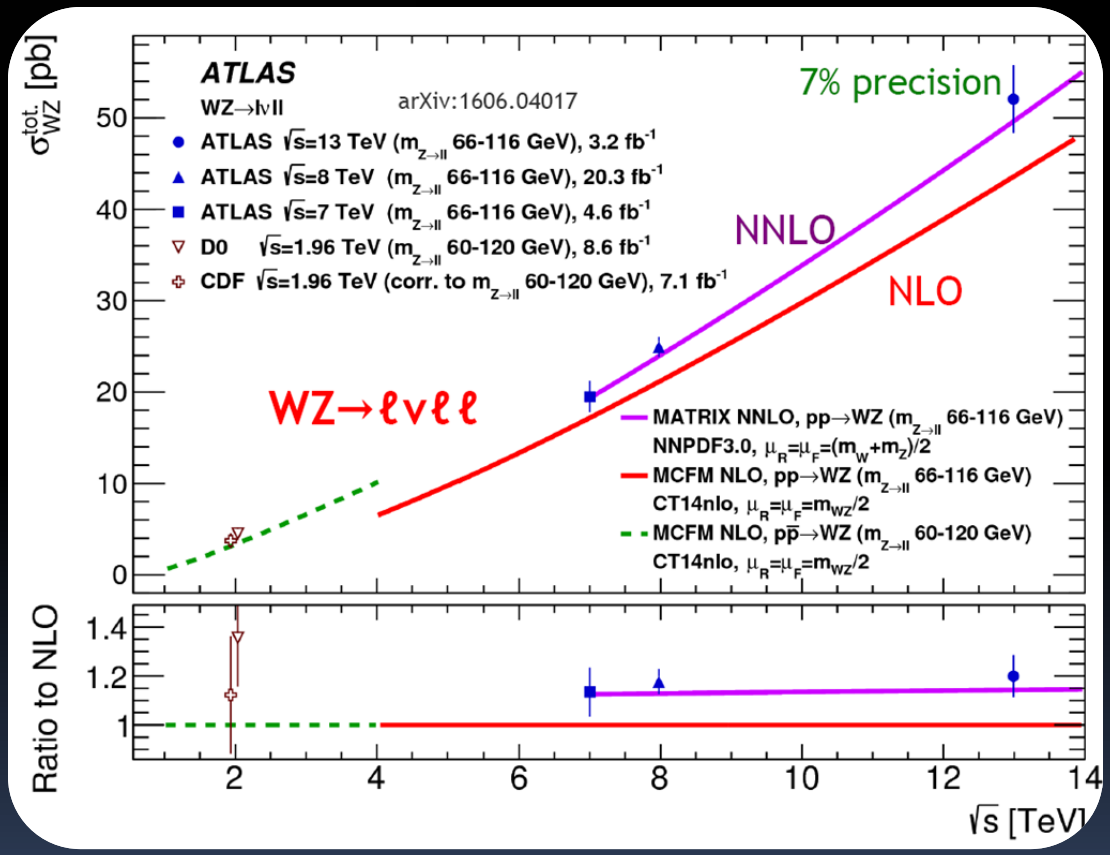
Other searches:



Theoretical Work

So, experimentalists are having all the fun right now, what is needed from theoreticians / phenomenologists?

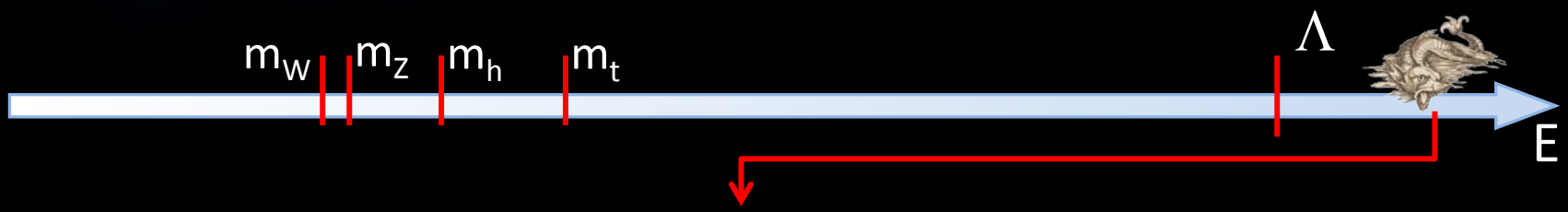
- Precision calculations: (NNLO and beyond)



- LHCb CP violating decays: true excess or uncontrolled QCD effects?

Theoretical Work

- Model independent approaches: simplified models and EFT



Unknown UV can generate all Higher Dimensional Operators that…

- Are built only of known fields (no new particles below Λ)
- Are invariant under $SU(3)_c \times SU(2)_L \times U(1)_y$
- Conserve barion and lepton numbers

$$\mathcal{L}_{\mathcal{EFT}} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i$$

59 dimension 6 operators (baring flavor and Hermitian conj.)
1 dimension 5 operator (Majorana Mass for neutrinos)

Theoretical Work

- New Ideas: can the hierarchy problem be solved in subtler ways?

Theoretical Work

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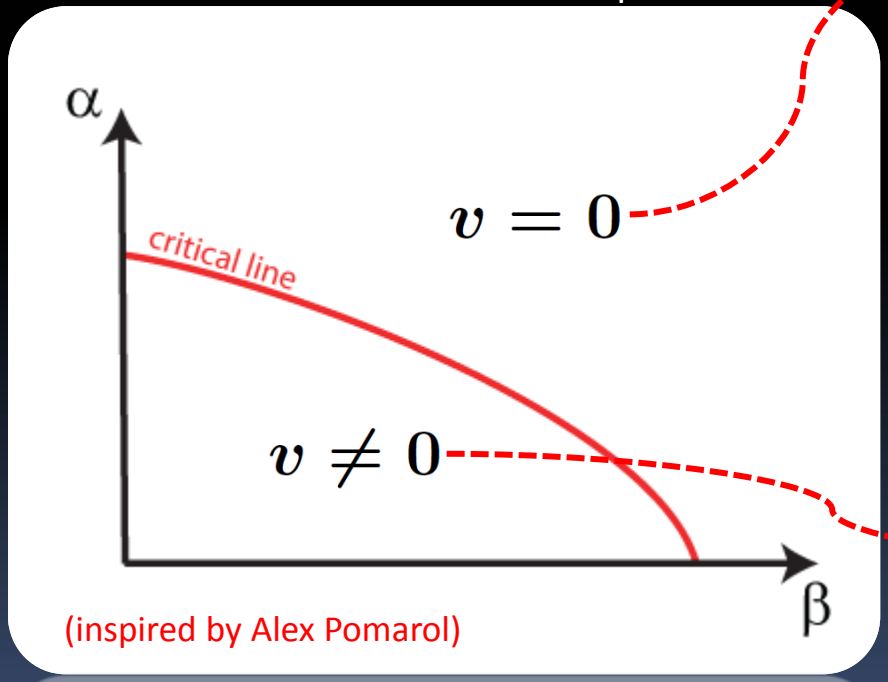
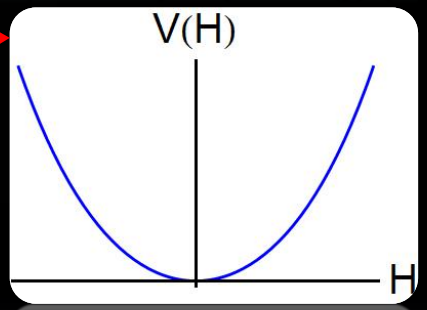
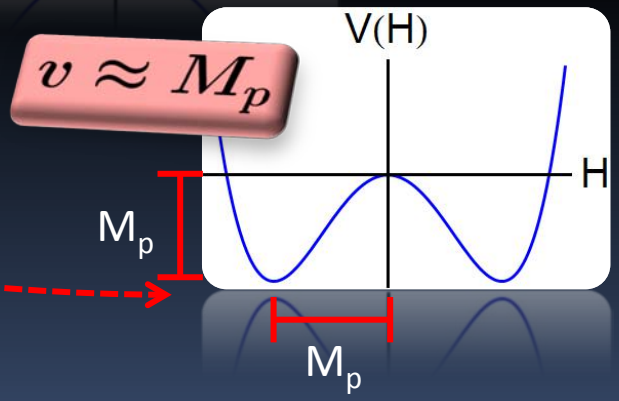
Think about the Standard Model (SM) as an EFT with a cut-off at M_p:

$$V(H) = m_H^2(\alpha, \beta)H^2 + \lambda h^4 + \mathcal{O}(1/M_p^2) \qquad \langle H \rangle = v$$

The only mass scale is M_p!







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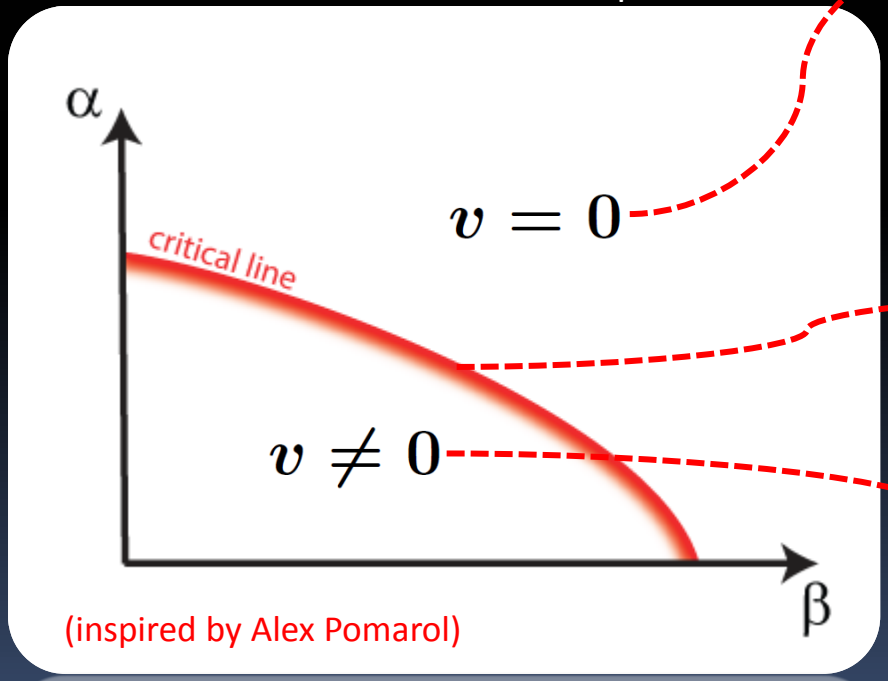
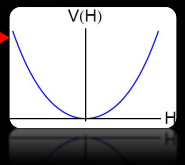
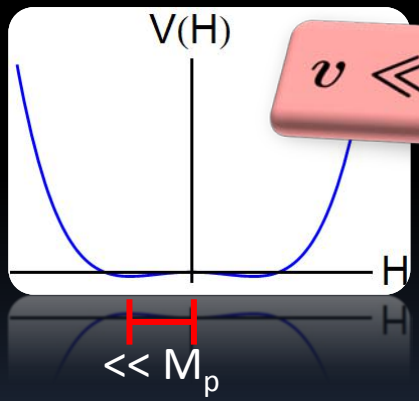
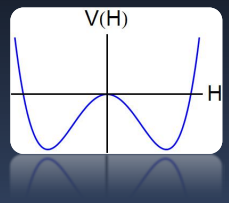








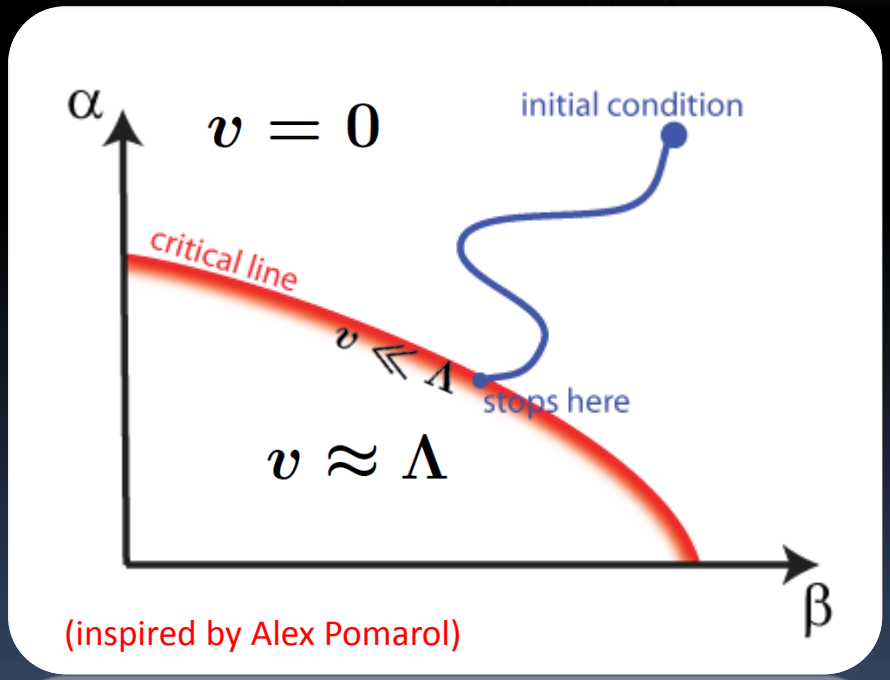
Cosmological Relaxation

Hierachy amounts to the question:

How come we live so close to the line?

"The Third Way": History! Make α and β dynamical (fields in fact)

(stupid) Example: $m_H^2(\alpha,\beta)H^2 \to \alpha\beta H^2$ $\quad m_H^2 = \langle\alpha\rangle\langle\beta\rangle$



But how does the evolution stop?

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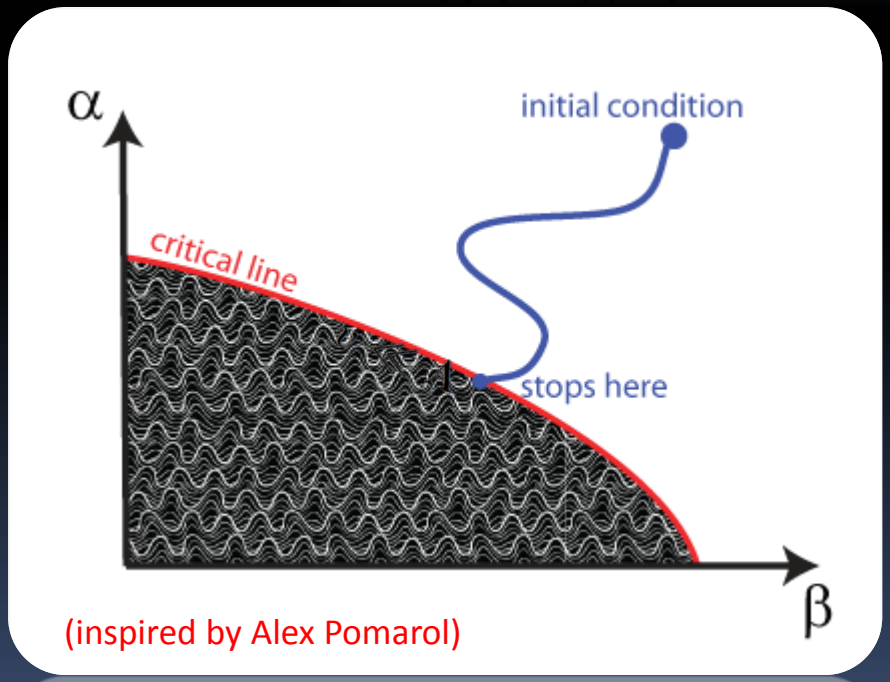


But how does the evolution stop?

Local Minima! A whole LOT OF local minima!

Can it be done in a (technically) natural way?

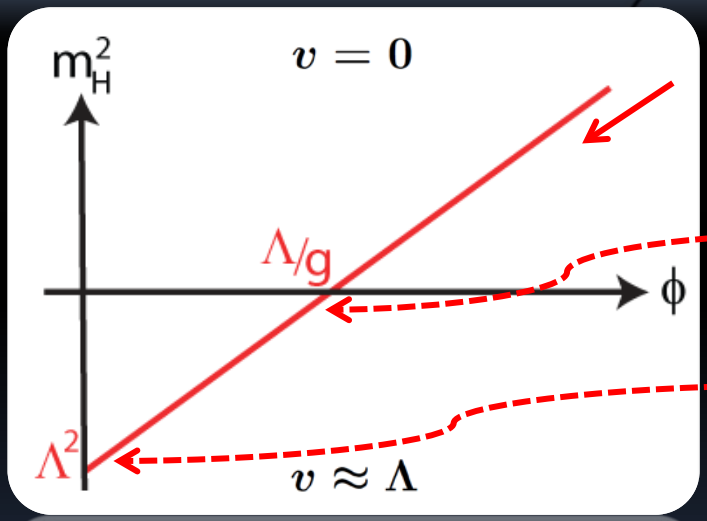
(spoiler: yes! But…)

Cosmological Relaxation

Introduce one scalar field ϕ, and:

Graham, Kaplan, Rajendran, arXiv:1504.07551

$$m_H^2 \to m_H^2(\phi) = -\Lambda^2\left(1 - \frac{g\phi}{\Lambda}\right)$$



"rolls" down

Must stop here…

… not here

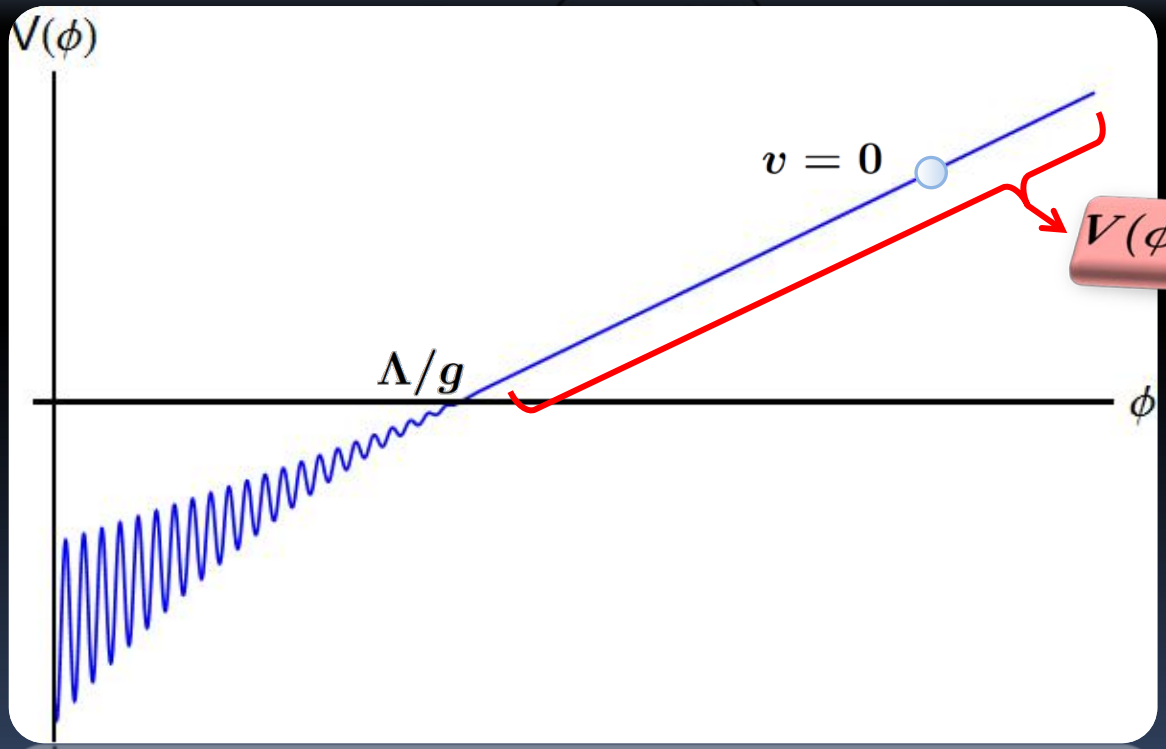
$\phi_c \equiv \Lambda/g$ If $g \ll 1$ $\longrightarrow$ $\phi \approx \Lambda/g \gg \Lambda$

Cosmological Relaxation

The minimal model:

Espinosa et al.
arXiv: 1506.09217

$$V(\phi, H) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2\left(1 - \frac{g\phi}{\Lambda}\right) H^2 + \epsilon\Lambda_c^2 H^2 \cos(\phi/f)$$



$V(\phi, H = 0) = \Lambda^3 g\phi$

Cosmological Relaxation

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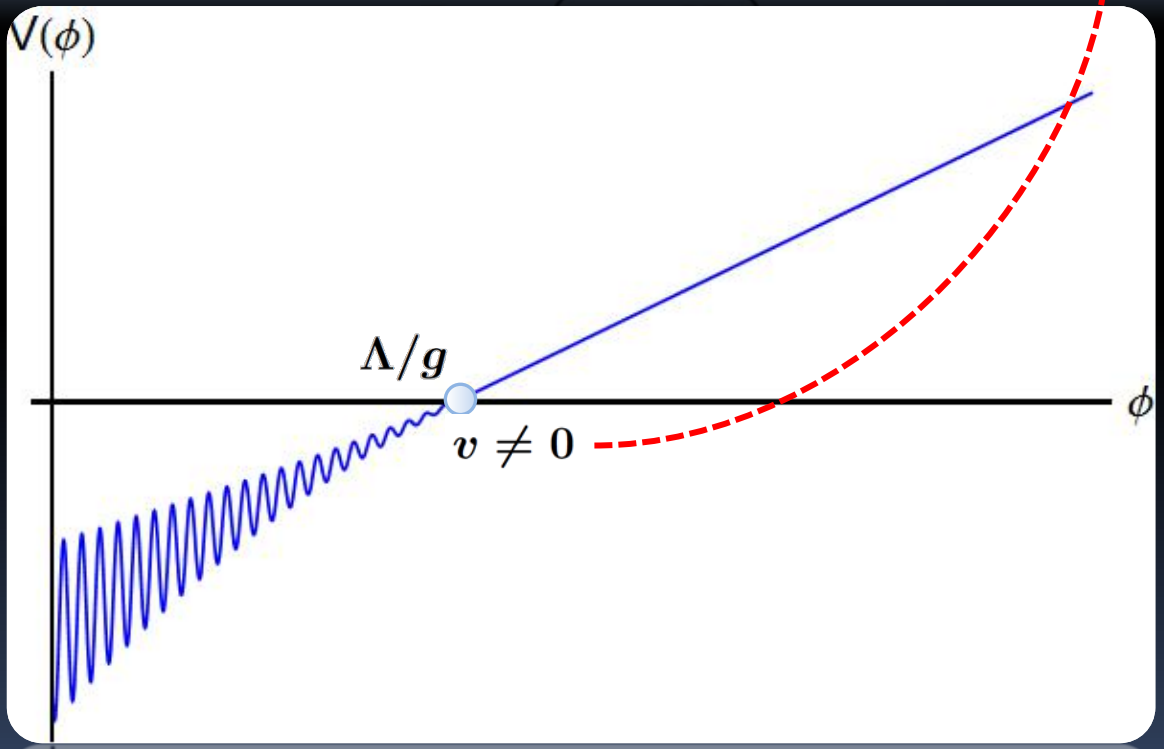

Becomes more important as *v* grows

Cosmological Relaxation

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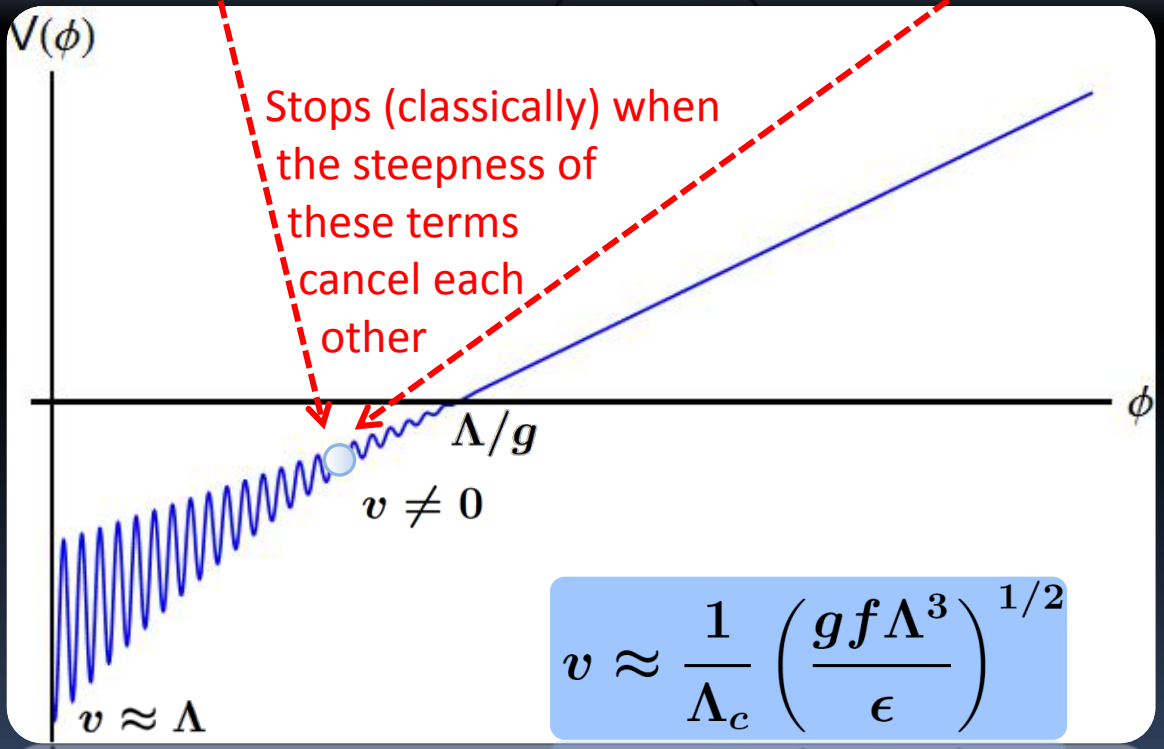


The overall slope is controlled by *g*.

$$v \ll \Lambda$$

$$\Updownarrow$$

$$g \ll 1$$

Technically Natural!

NO NEW PHYSICS close to *v*

Cosmological Relaxation

A lot of improvements over the last year and a half (incomplete sample):

- 4/15 – Graham, Kaplan, Rajendran – seminal paper
- 6/15 – Espinosa et al – double scanner scenario
- 7/15 – Hardy – finite temperature effects instead of inflation
- 9/15 – Gupta et al – potential must be periodic
- 11/15 – Choi, Im – multiple axions for generating potential
- 11/15 – Kaplan, Rattazzi – clockwork axion
- 1/16 – Fonseca, de Lima, Machado, Matheus – few site relaxion
- 2/16 – Evans, Gherghetta, Nagata, Thomas – application to Susy
- 6/16 – Hook, Marques-Tavares – relaxation from particle production

• • •

… but there are still theoretical issues that need to be solved

Cosmological Relaxation

Proof of concept: Technically natural model that solves the Hierachy problem WITH NO NEW PHYSICS AT THE TeV SCALE.

Is there any observable?

- Very light particle with weaker than gravity interaction.
- Classical Oscillations can affect gravitational potential: pulsar timing (astro-ph.CO/1309.5888) and structure formation (astro-ph.CO/1410.2896)
- Late decay of relaxions can show up in CMB and diffuse gamma ray background
- Fifth force (too weak for present day precision)

Mostly astrophysical / cosmological measurements!

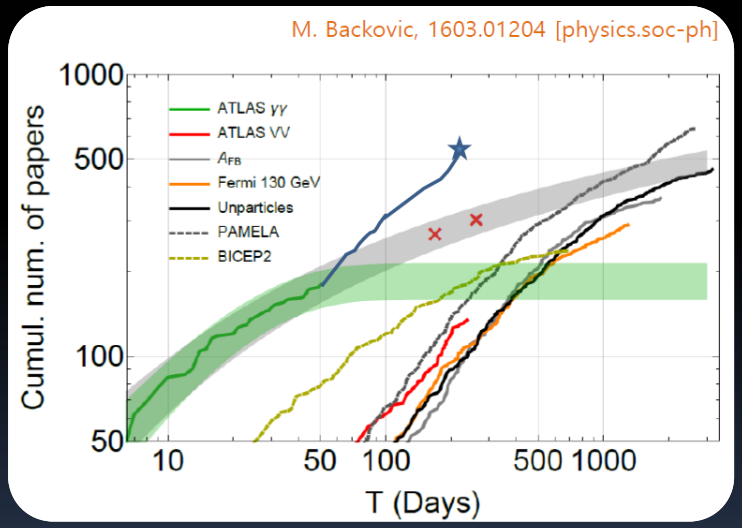
Messages

- The LHC is rocking it!

- It is the end of BSM as we know it, and we should feel fine

- Phenomenological studies should concentrate in N(N)LO effects and model independent constraints until concrete signs of NEW PHYSICS show up.

- If something shows up:

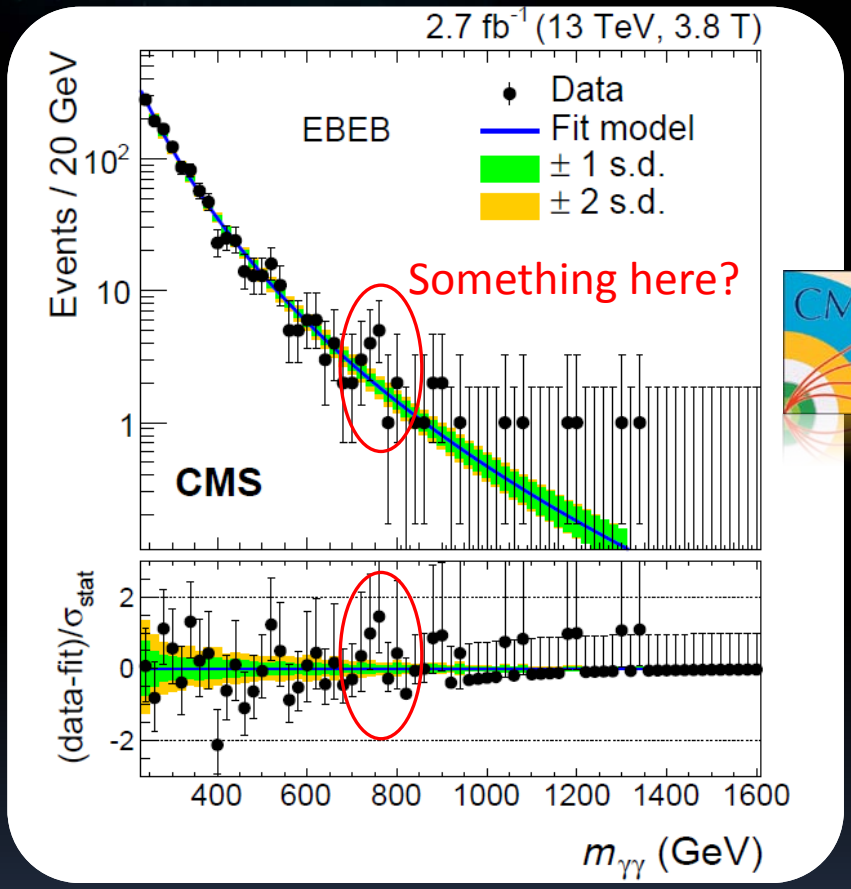


- If nothing shows up, new ideas will be needed to “explain away” or solve the hierarchy problem. Some hints already on the horizon

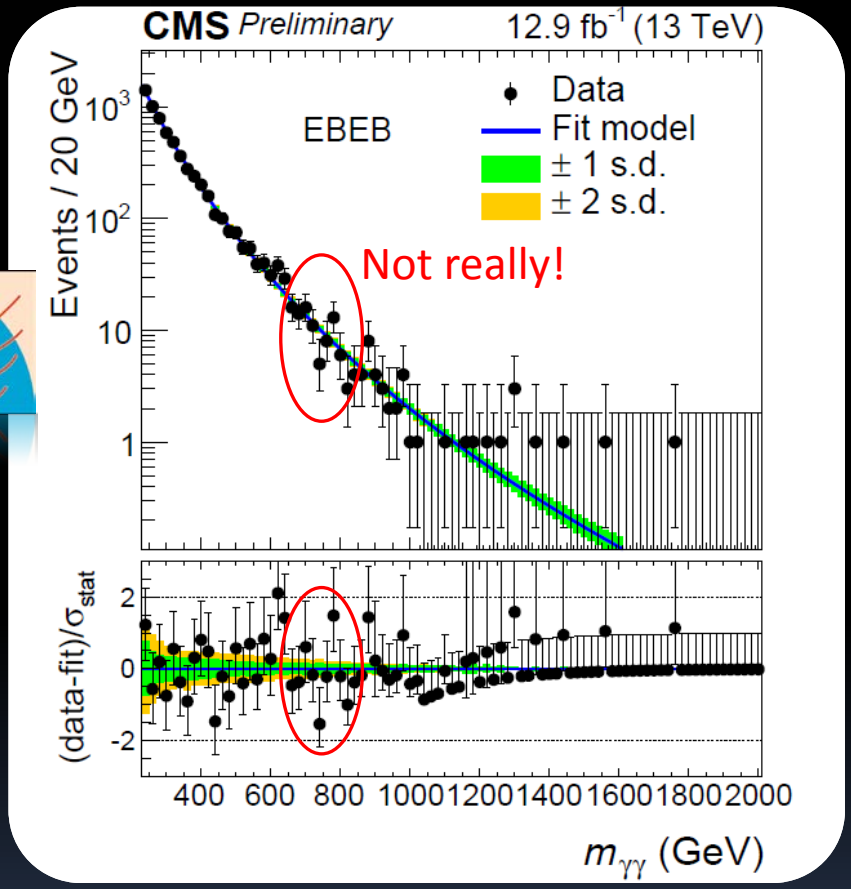
Thank You!

Also…

2015



2016



… no 750 GeV di-photon excess for you

(same situation in Atlas)