BSM Theory Overview

~~Susy~~

Alex Pomarol, UAB/IFAE (Barcelona)

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Interpreting *null* results… ~~and one hope!~~

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Interpreting *null* results… ~~and one hope!~~

Back to the SM?

Impressive number of searches for new phenomena at LHC,

giving us **plenty of negative results!**

"What's the opposite of Eureka?"

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But even *null* results
allow us to make progress!

If experiments are well-motivated!

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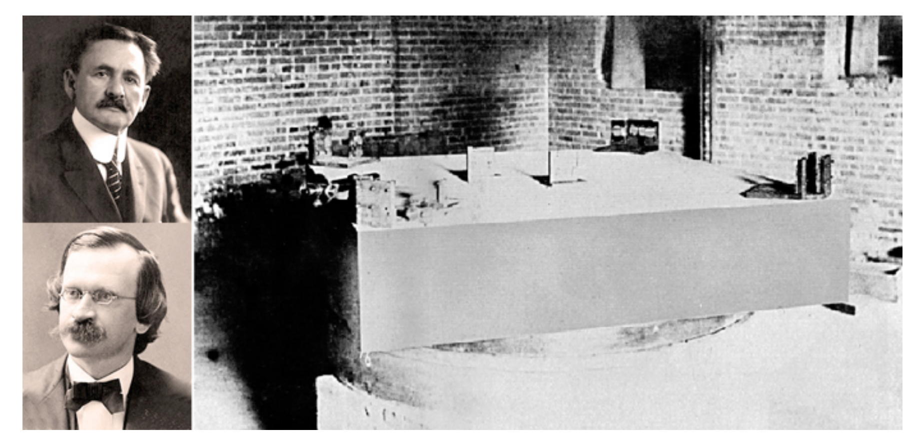

as Michelson-Morley experiment

Making progress from *null* results:

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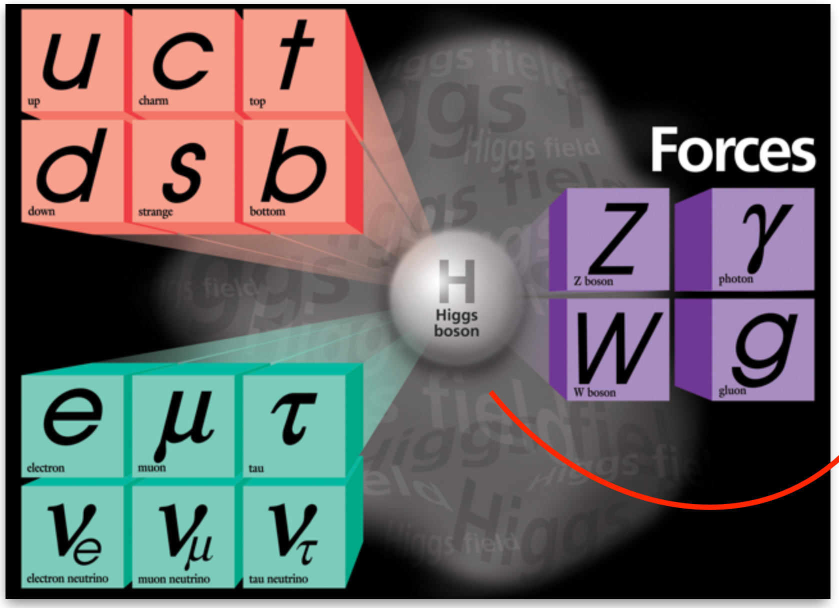
If we assume that **the only scale** is $\langle H \rangle \sim 246\ GeV$ **(as in the SM),**

we have excluded **experimentally** any new physics!



No extra fermions,
gauge bosons,…
getting their mass from H

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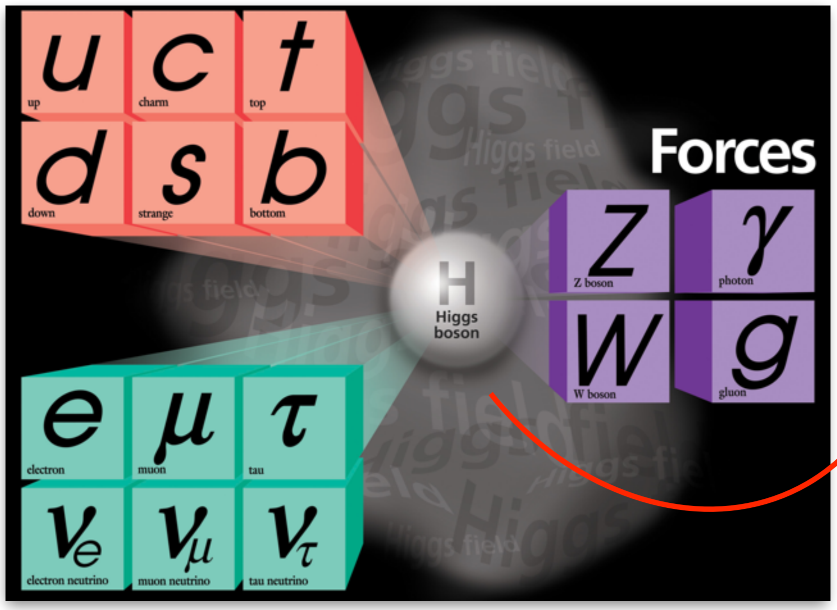
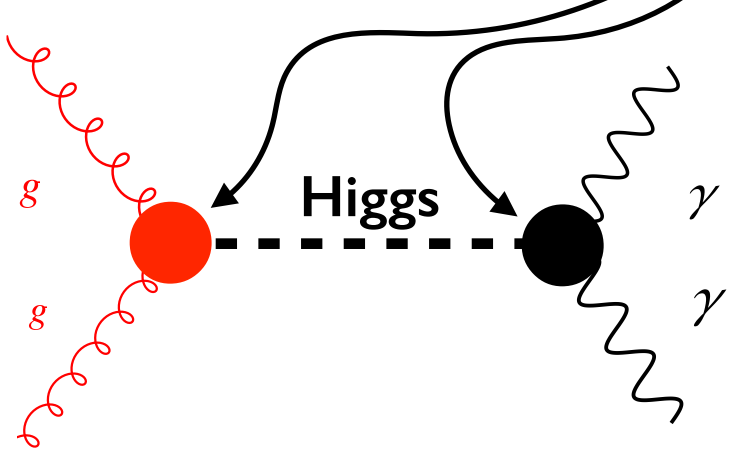


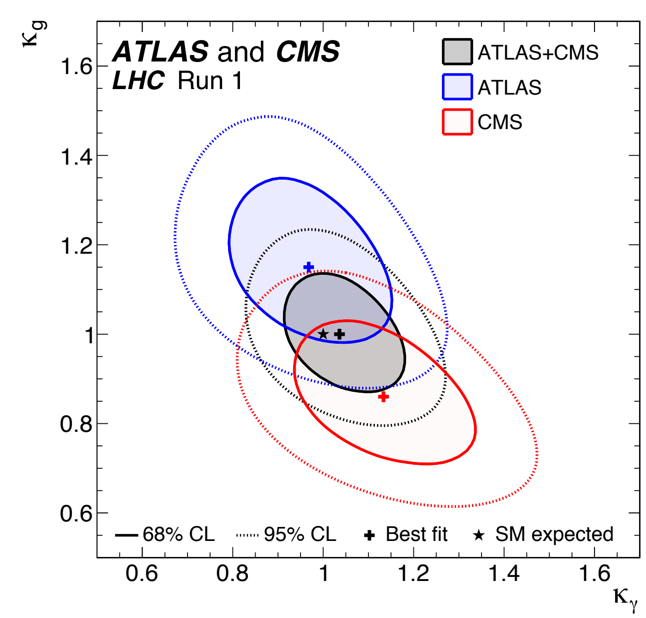
No extra fermions, gauge bosons,… getting their mass from H

We know this thanks to the interplay between direct & indirect searches:

- **If light:** they should have been seen in detectors
- **If heavy:** they should have been seen <u>indirectly</u>

AP, LHCP16 proceedings

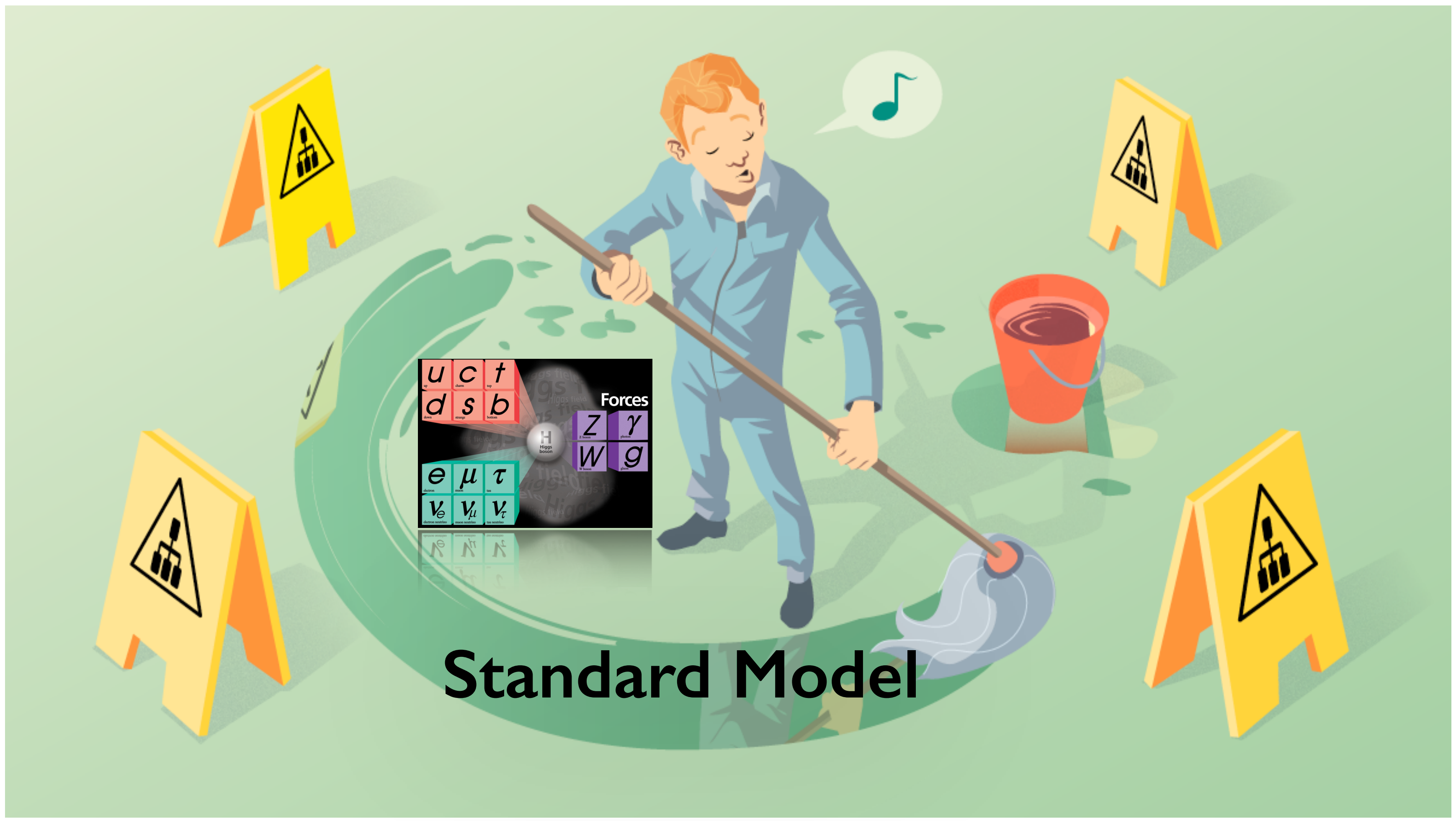




crucial piece of information!

Making progress from *null* results:

We have been able to **clean up** the electroweak sector, being now **confident in the SM**



No theory argument to have SU(3)xSU(2)xU(1) with 3 families (**the SM**), instead of something else

Consequences:

New states **should** bring their own mass-scale

e.g. $M\bar{\Psi}\Psi$

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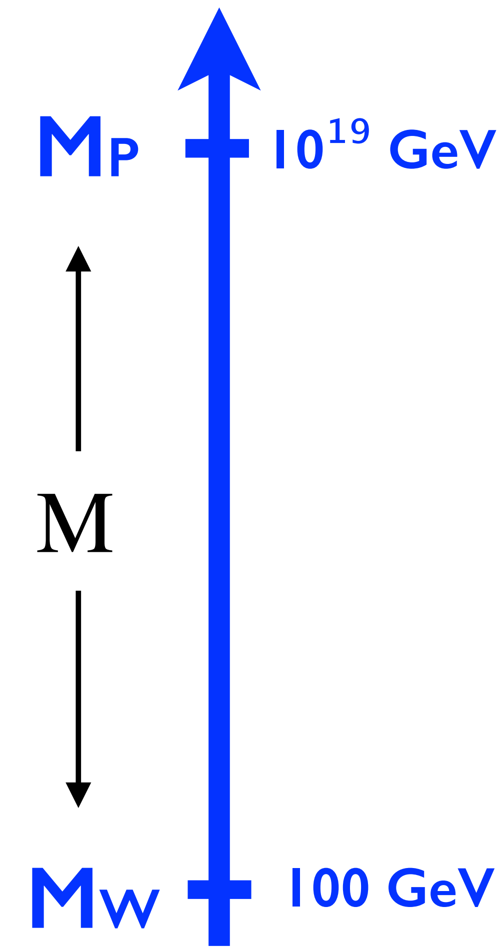

But… why M should be around the EW-scale ?

Consequences:

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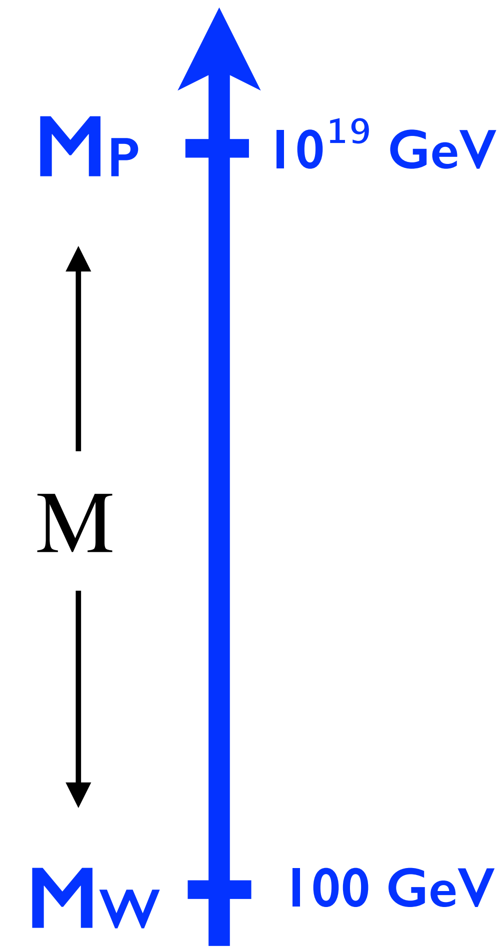

But… why M should be around the EW-scale ?

Crucial question to **address**
to know whether there is a **motivation**
to search for them at the LHC

How could new physics scales be connected to the EW scale?

Possible if we assume that $\langle H \rangle$ is **not** a fundamental parameter:

There is a more fundamental scale at ~TeV
from which m_H (or $\langle H \rangle$) arises, together with something else

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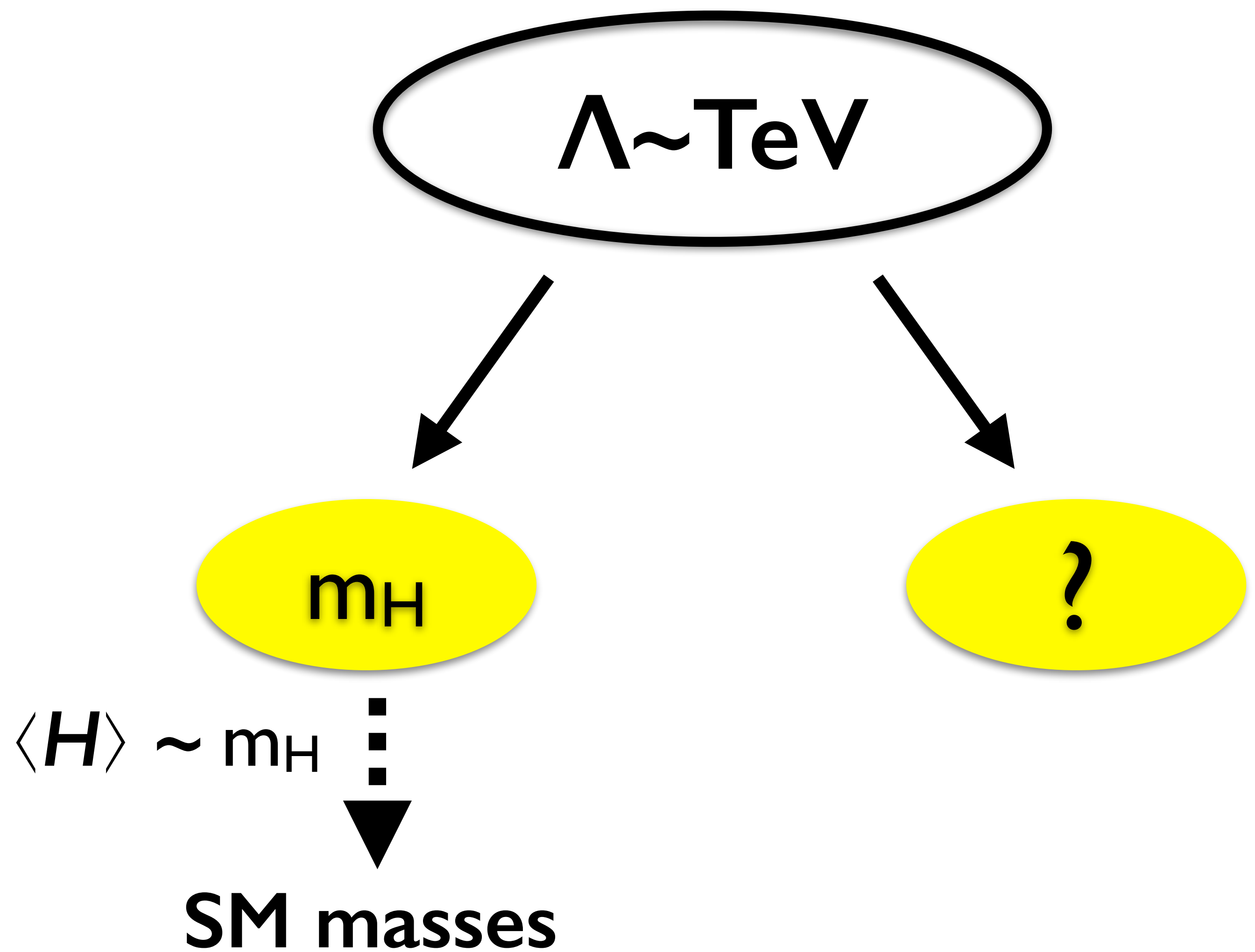

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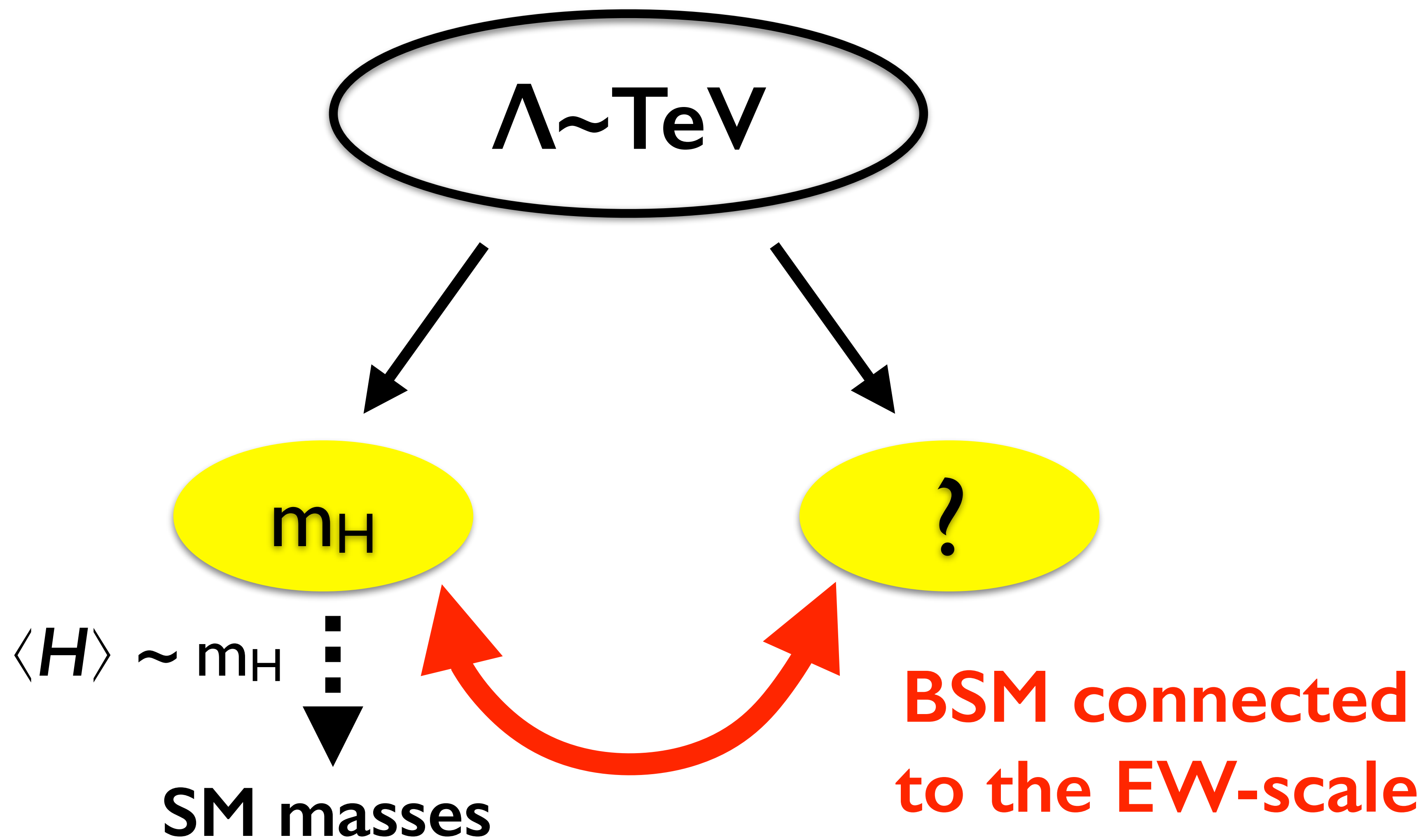

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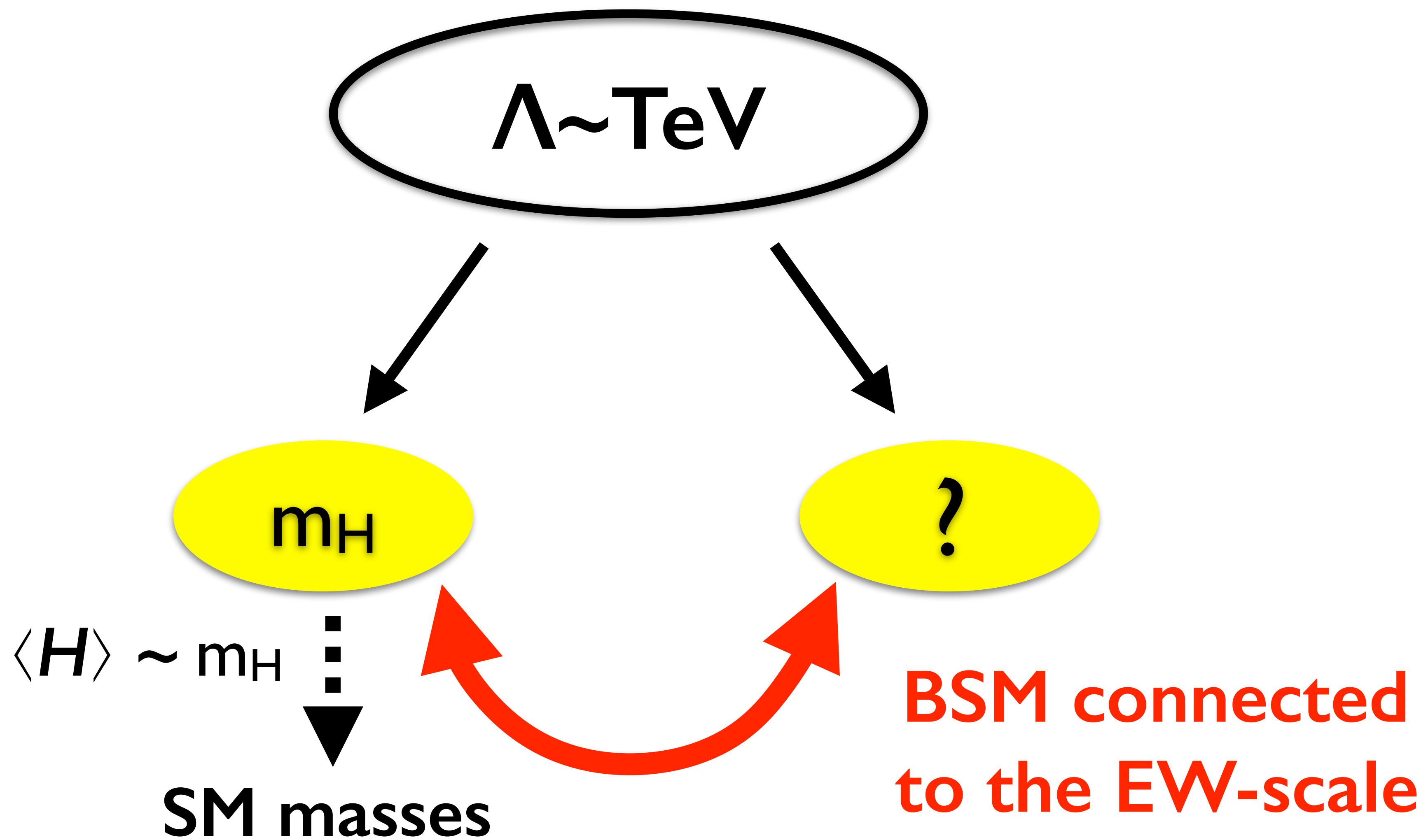

↳**Also <u>needed</u> if we want <u>to explain</u> why $m_H \ll M_P$!**

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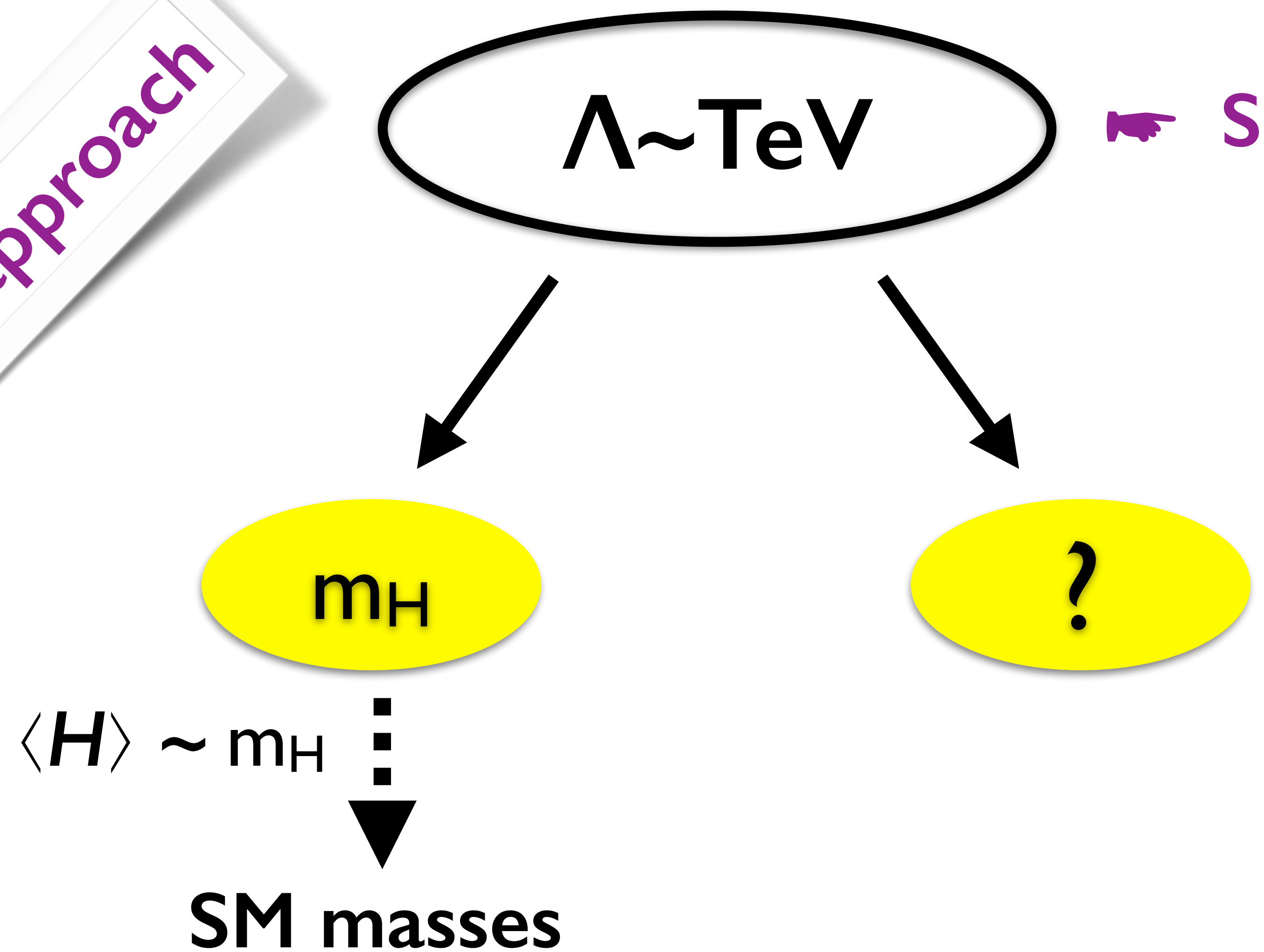
In the Susy approach



☛ Softly-broken MSSM

☛ Superpartners

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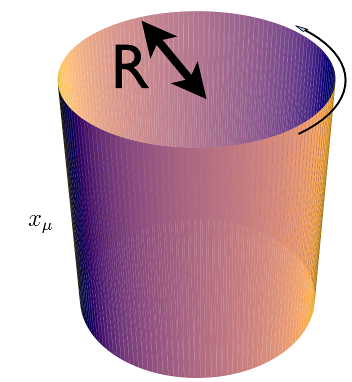
Extra-dimensional approach

Λ~TeV ☛ **Extra dimension**
Λ~1/R



m_H **?** ☛ **Kaluza-Klein states**

$\langle H \rangle \sim m_H$

SM masses

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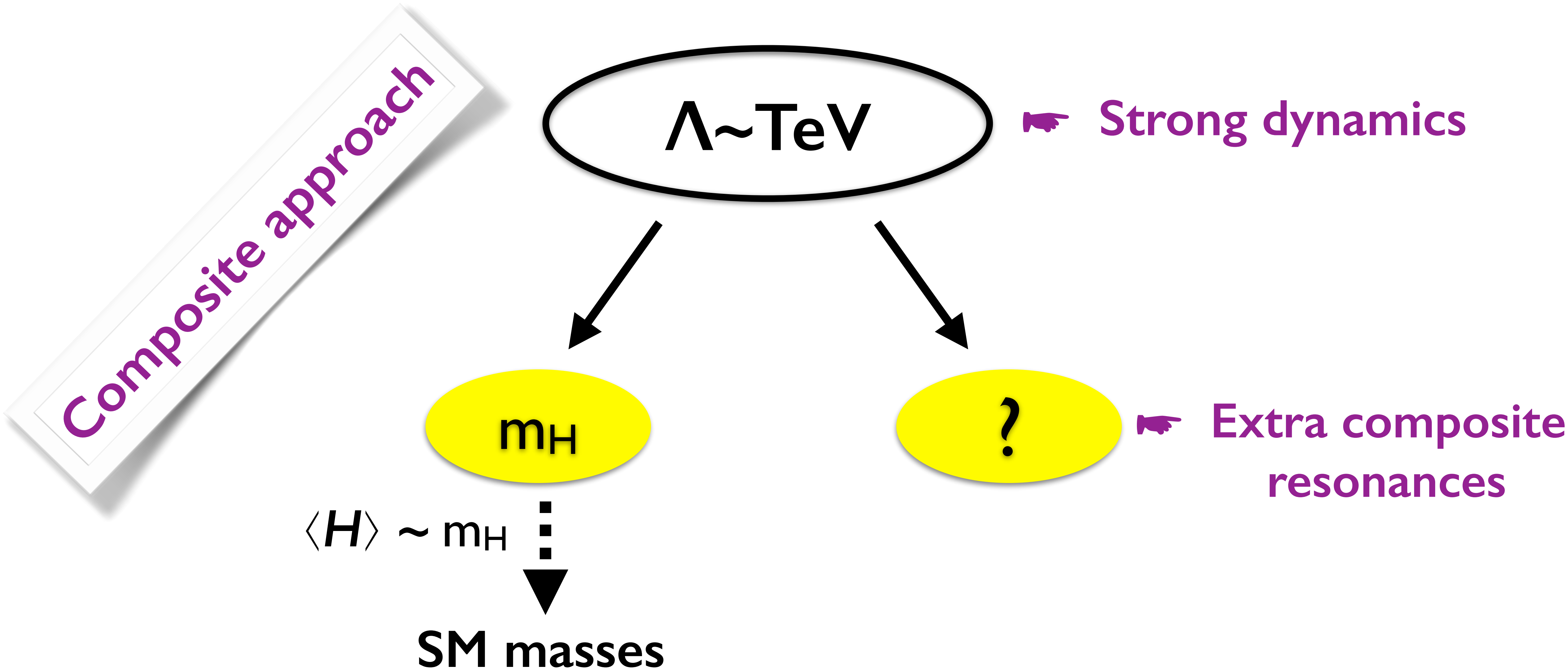

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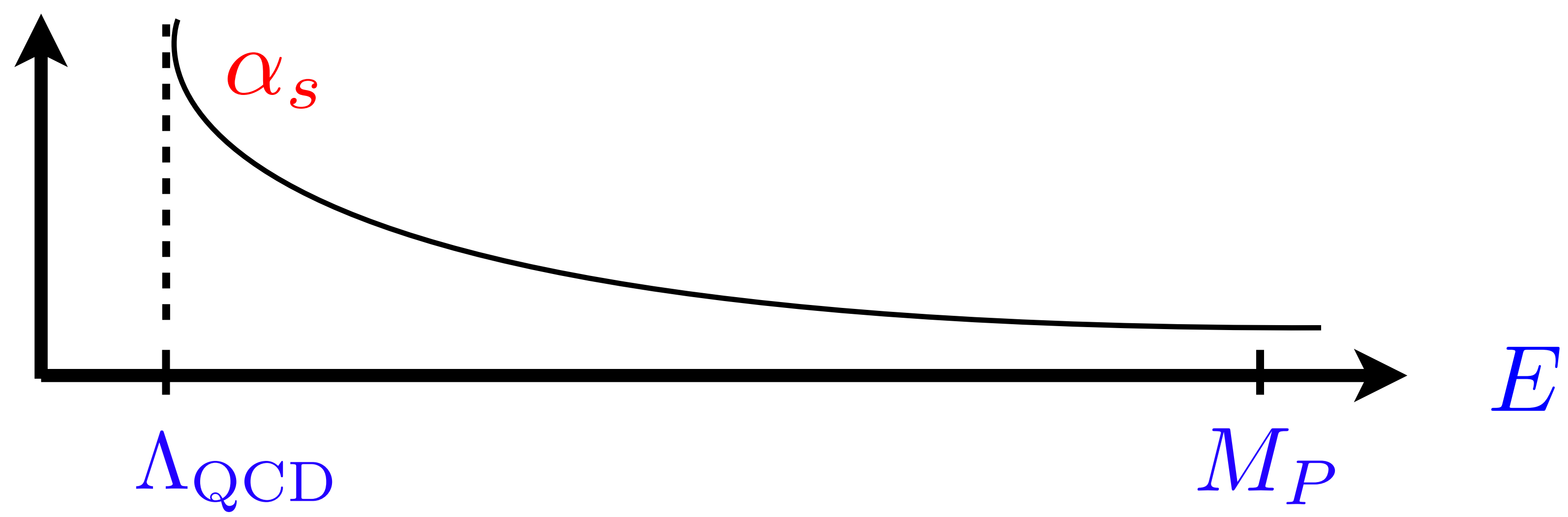
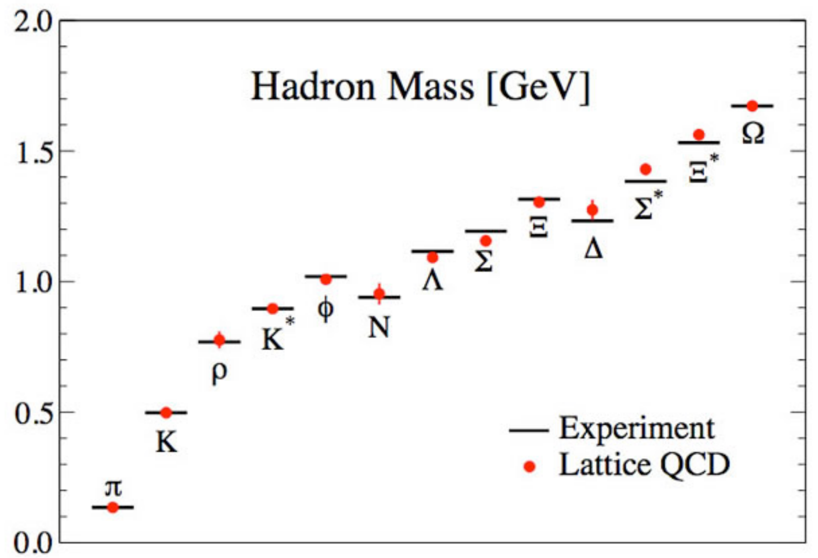
Strong dynamics at Λ~TeV

QCD as an inspiration:



Explains why $\Lambda_{\rm QCD} << M_P$ and the origin of most hadron masses



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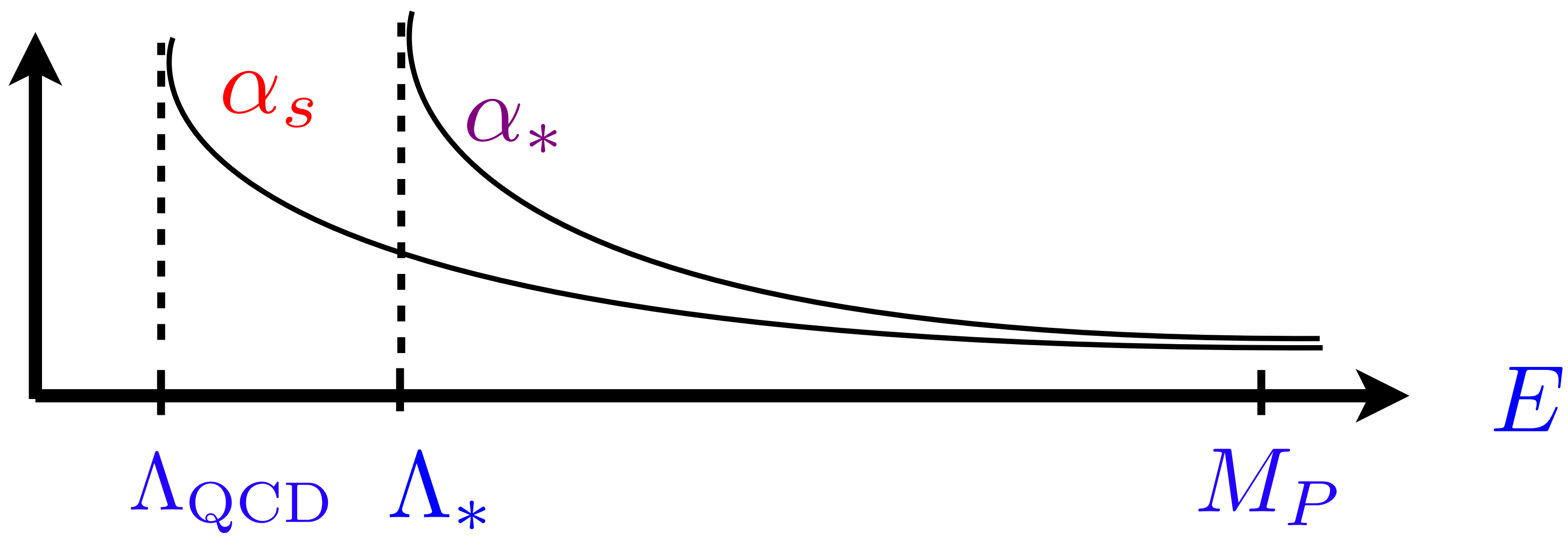
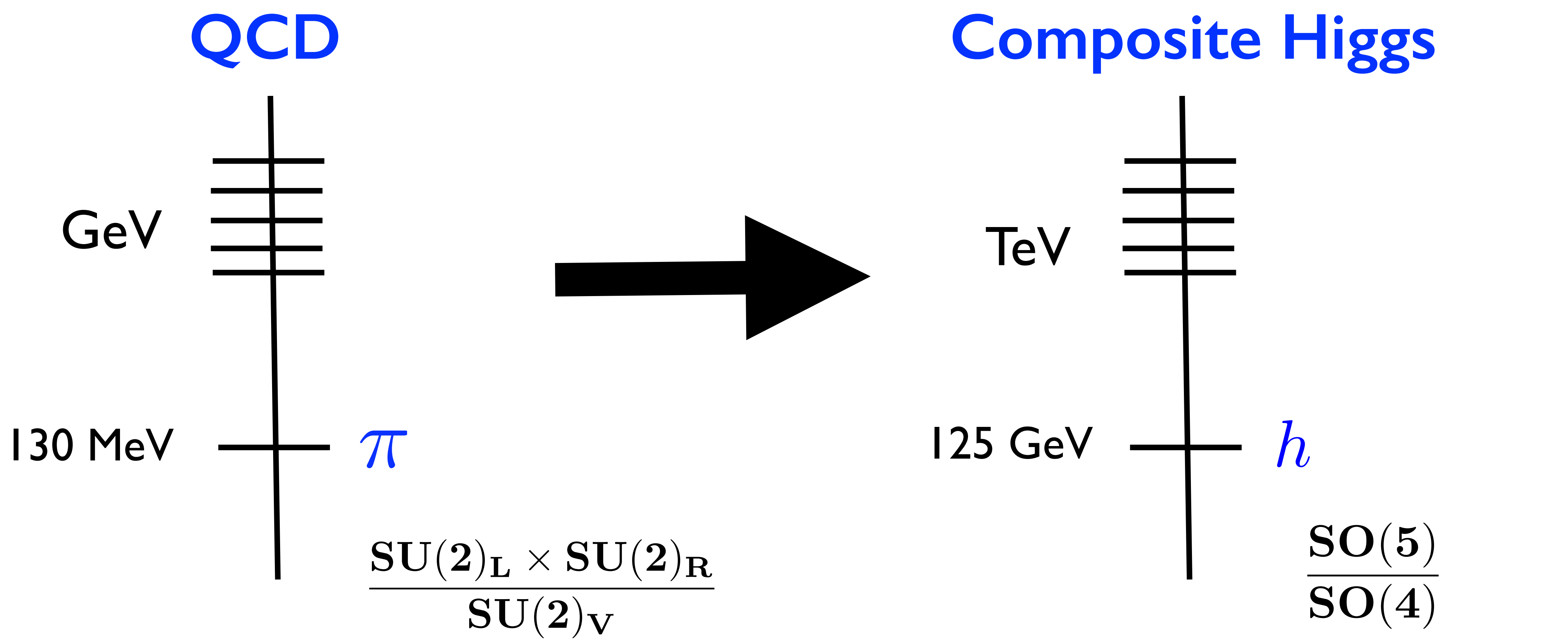


New strong dynamics at TeV

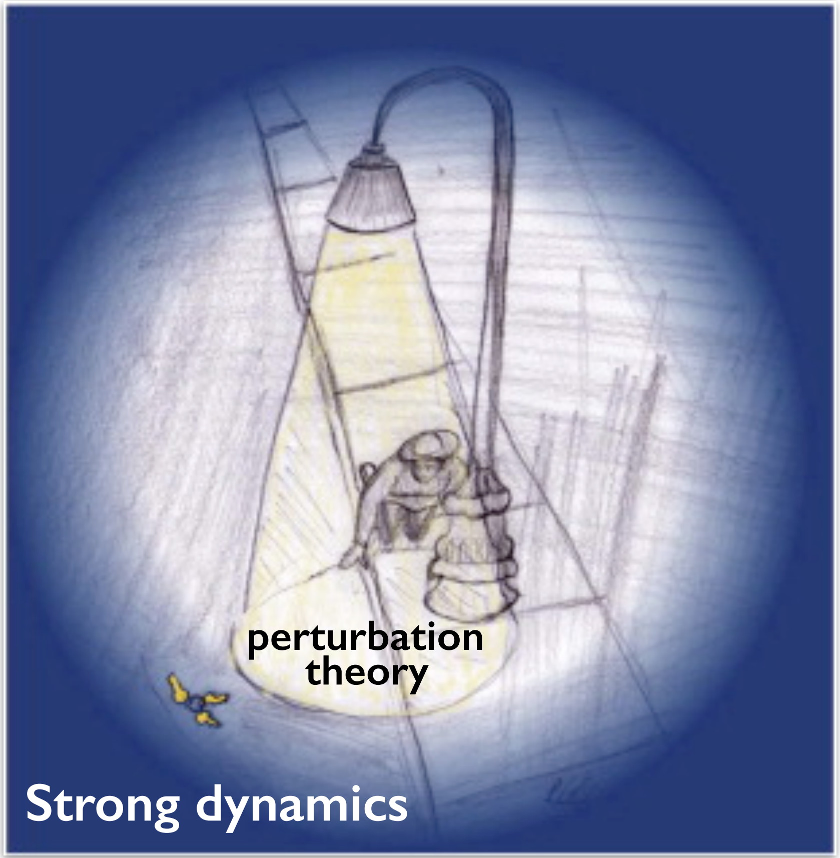
It could explain why $m_H \lesssim \Lambda_* \sim \mathrm{TeV} \ll M_P$

Composite Higgs



The **Higgs, the lightest** of the new strong resonances,
as pions in QCD: they are Pseudo-Goldstone Bosons (**PGB**)

Beyond the lamp-post:



Even though <u>no possibility to calculate</u>,

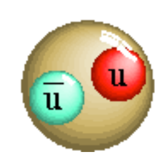
it's possible provide a <u>characterization</u> of the expected signals

(as in the 60', experiments will be driving the field)

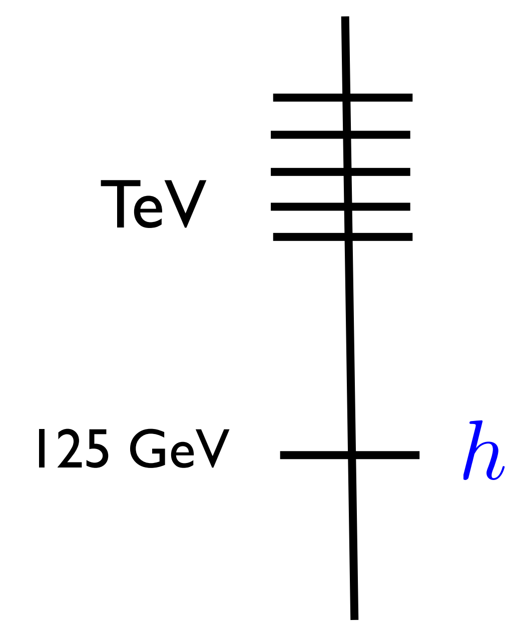
Physical implications of TeV strong-dynamics

New **flavor-violating & CP-violating** transitions

Signs of **compositeness** in the Higgs (and top)



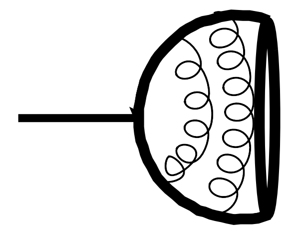
New **resonances**

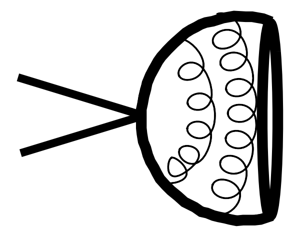


New flavor-violating & CP-violating transitions

New flavor-violating & CP-violating transitions

Yukawa origin depend on how the SM fermions couple to the strong sector:

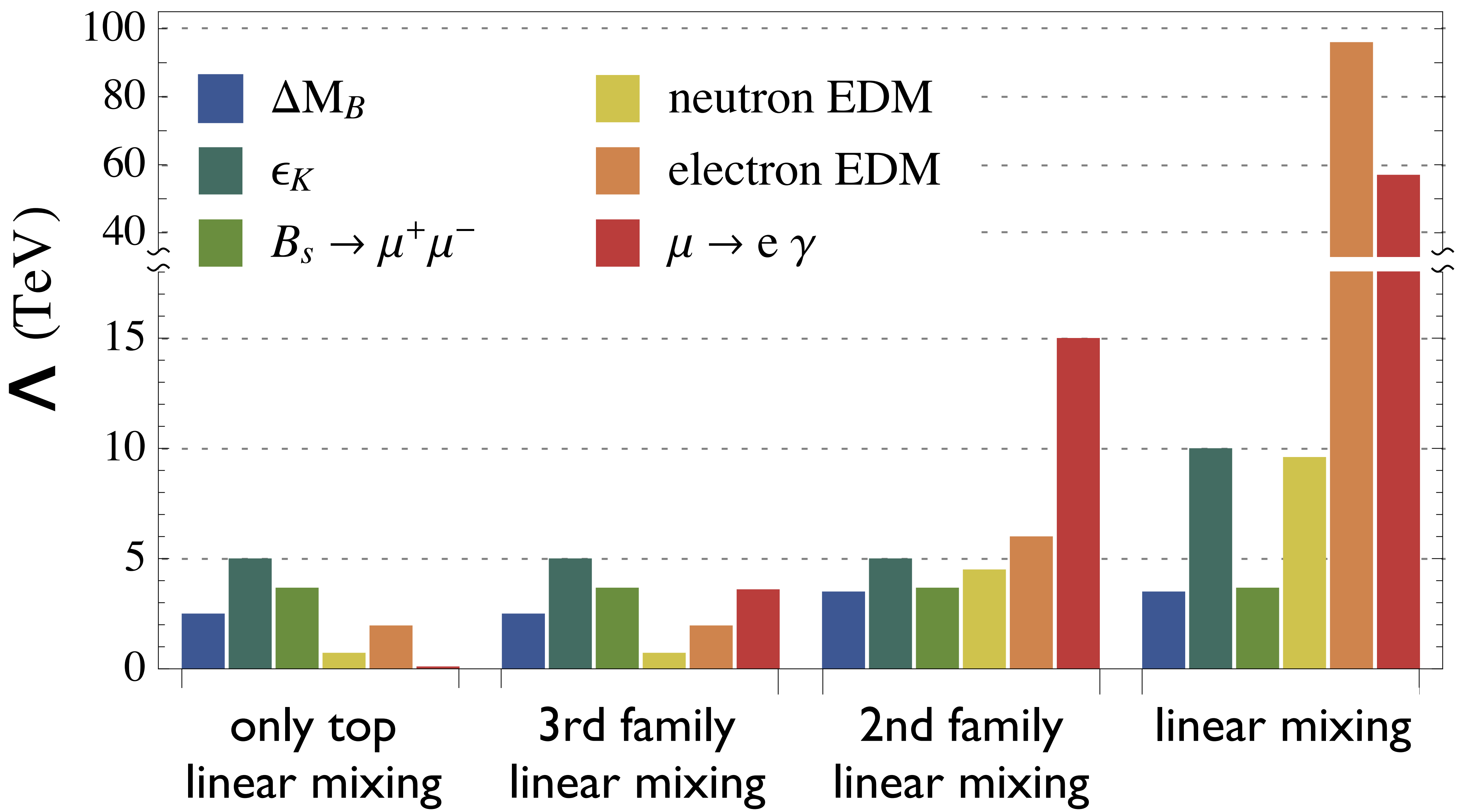
1) Linear mixing: f_{SM}  **Resonances**

2) Bilinear mixing: f_{SM} f'_{SM}  **Resonances**

flavor structure from mixings without flavor symmetries!

New flavor-violating & CP-violating transitions

Lower bounds on the scale of the strong dynamics Λ



G.Panico & AP: arXiv:1603.06609

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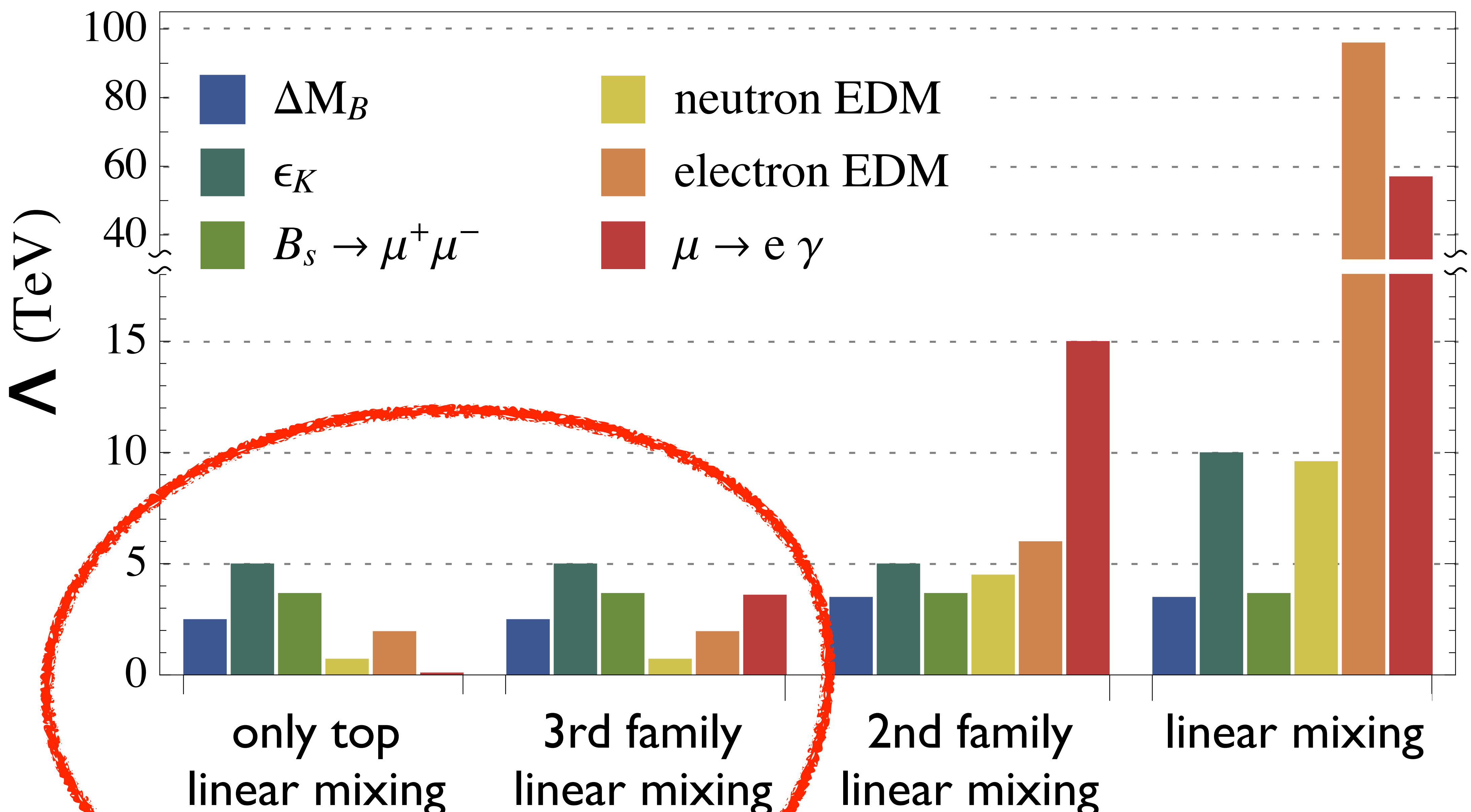

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Bounds of $\mathcal{O}$(TeV)! **Effects visible soon. Hopes for the future!**

Signs of compositeness of the Higgs

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Well-defined pattern of deviations in Higgs couplings:

Giudice,Grojean,AP,Rattazzi 07

$$\frac{g_{hWW}}{g_{hWW}^{\rm SM}} = \sqrt{1-\frac{v^2}{f^2}}$$

f = Decay-constant of the PGB Higgs related to the compositeness scale

(model dependent but expected f ~ v)

AP,Riva 12

$$\frac{g_{hff}}{g_{hff}^{\rm SM}} = \frac{1-(1+n)\frac{v^2}{f^2}}{\sqrt{1-\frac{v^2}{f^2}}}$$

$$n = 0, 1, 2, \ldots$$

MCHM4 MCHM5

small deviations on the h$\gamma\gamma$(gg)-coupling due to the Goldstone nature of the Higgs

Signs of compositeness of the Higgs

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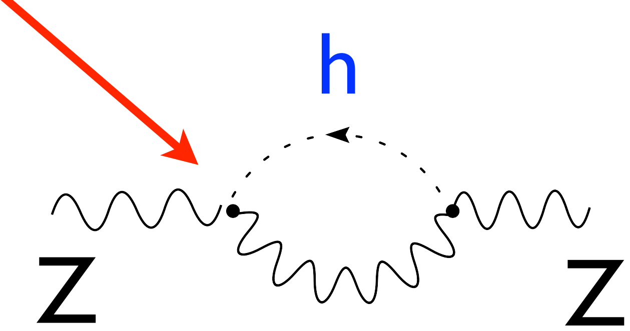
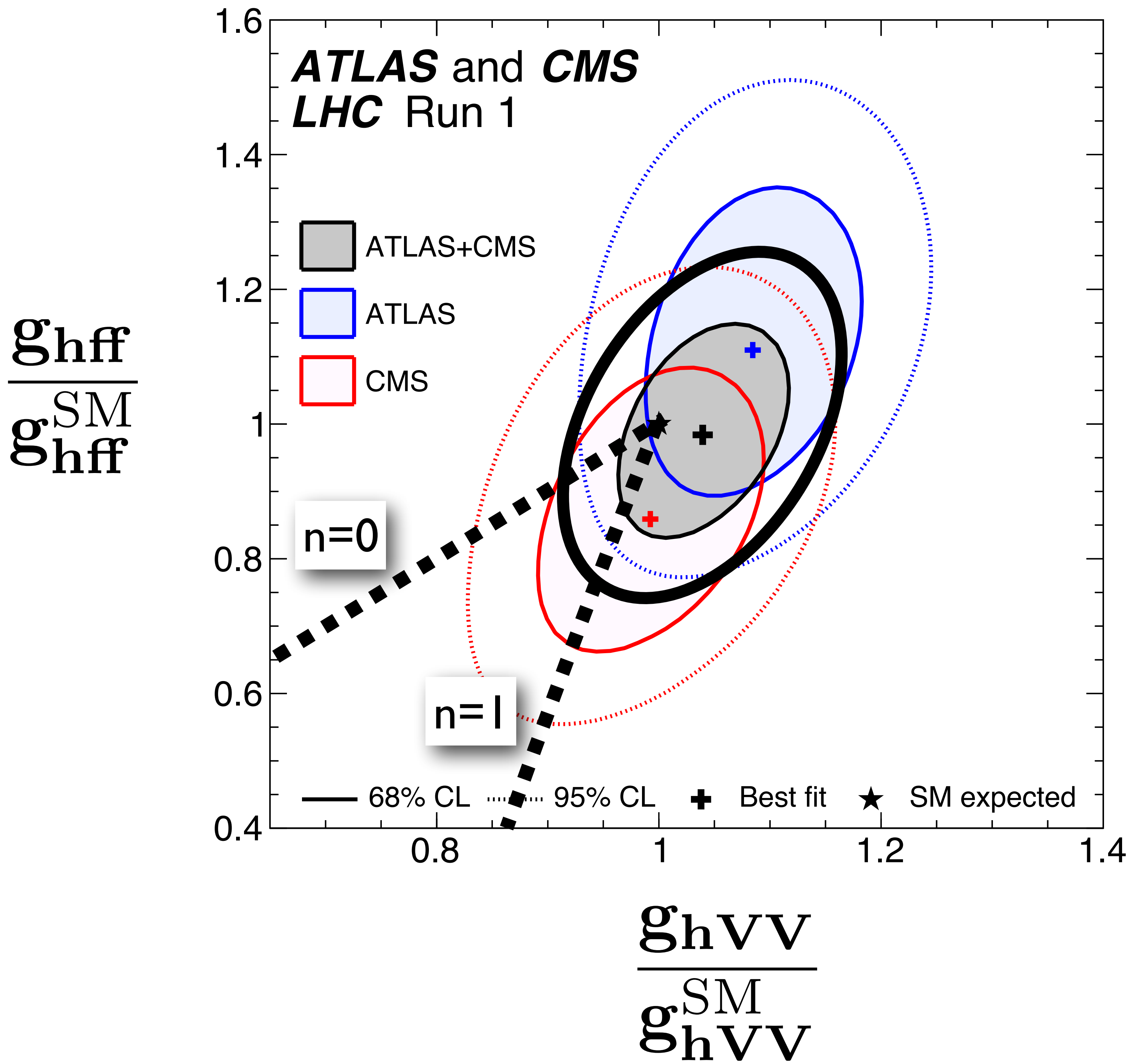
But already constrained at LEP



$$\frac{\delta g_{hWW}}{g_{hWW}} \lesssim 5\%$$

We could not expect large deviations in Higgs coupling measurements

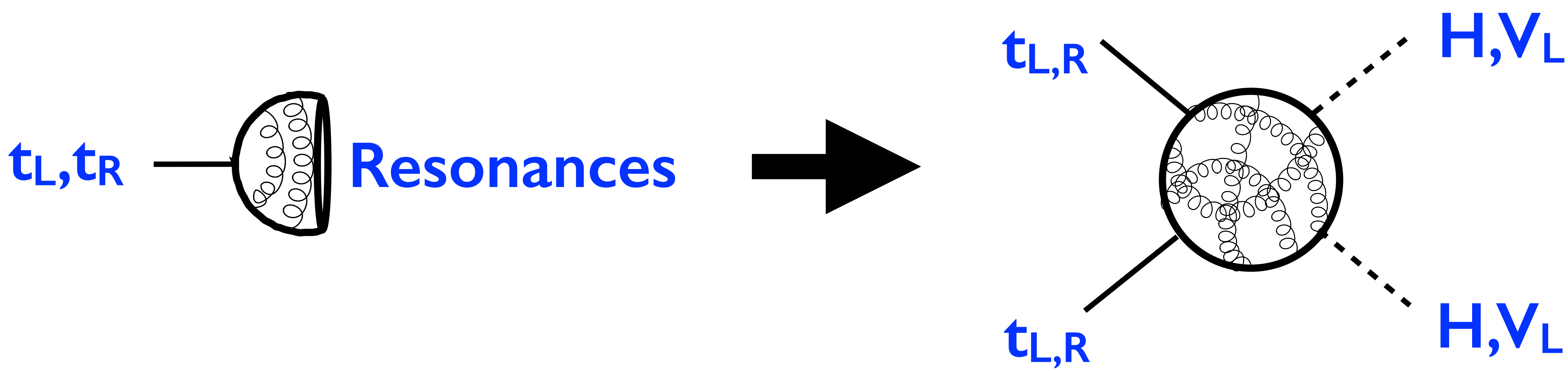
Signs of compositeness of the Higgs



Entering the interesting region: bounds getting below 10%!

Signs of compositeness of the top

Since its mass is large, its mixing with the strong sector must be large:



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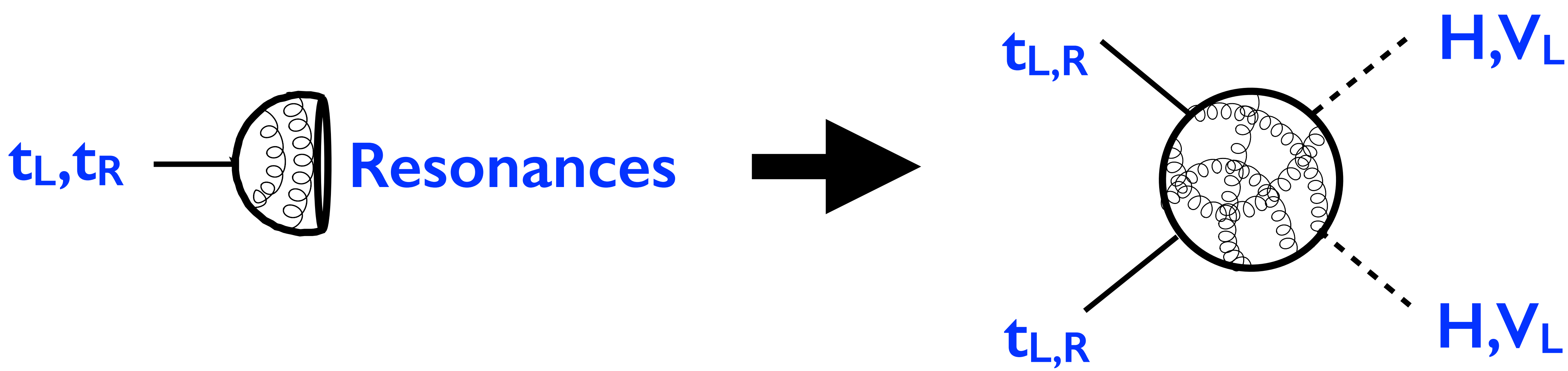
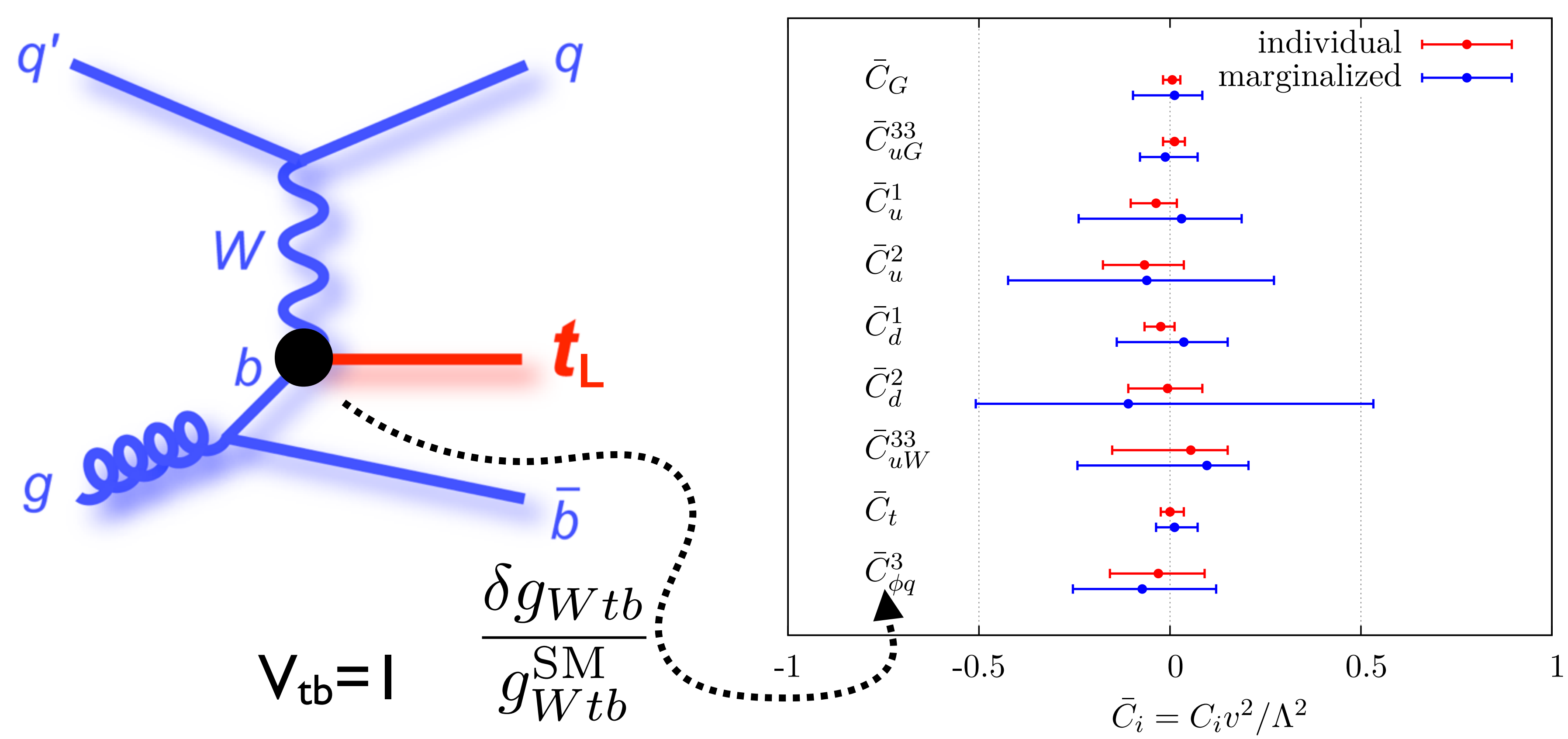


t_L couplings don't show much deviations from SM predictions:



see for example,

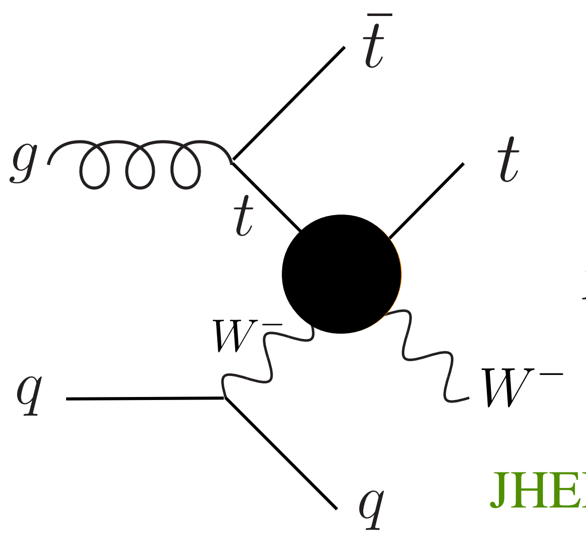
arXiv:1512.03360

arXiv:1504.03785

arXiv:1601.08193

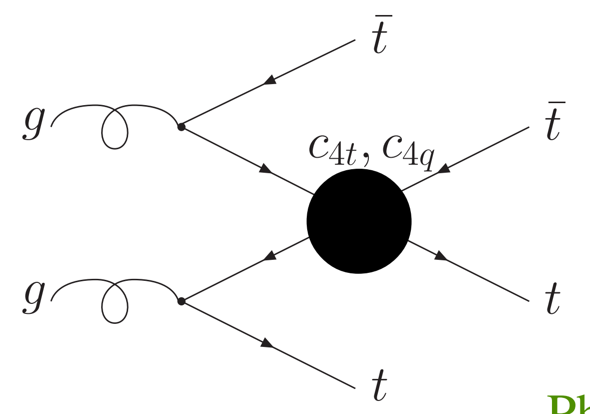
If t_R is highly composite, it will be a challenge to know it!

Best ways to see it in the future:



$pp \to t\bar{t}W^{\pm} + j$

JHEP 1601 (2016) 071



$pp \to t\bar{t}t\bar{t}$

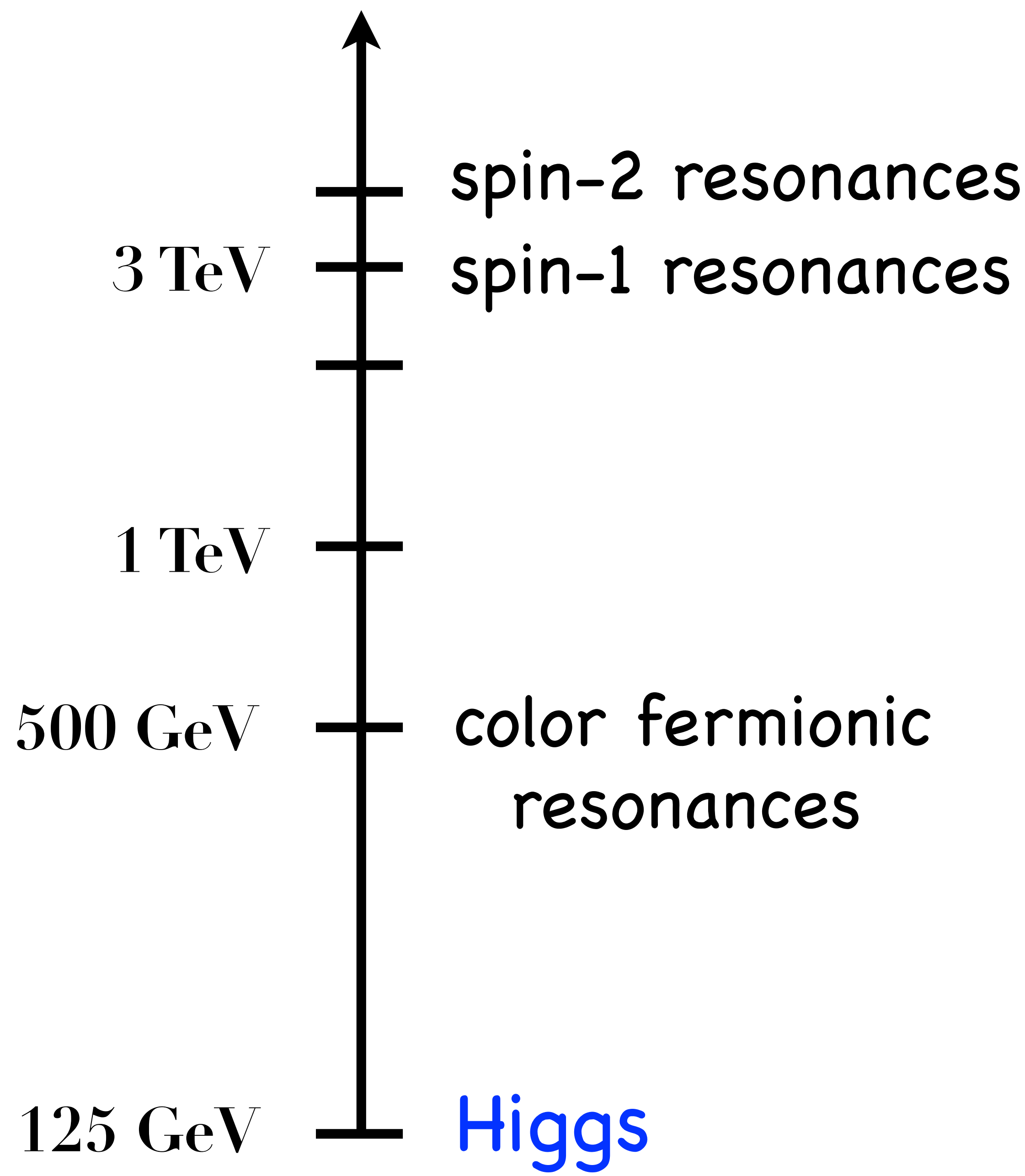
Phys.Rev. D78 (2008) 074026

for a recent analysis, see arXiv:1611.05032

Effects grow with the energy!

New resonances

Expected spectrum of the TeV Composite Sector



Good BSM prototype for many searches e.g Little Higgs

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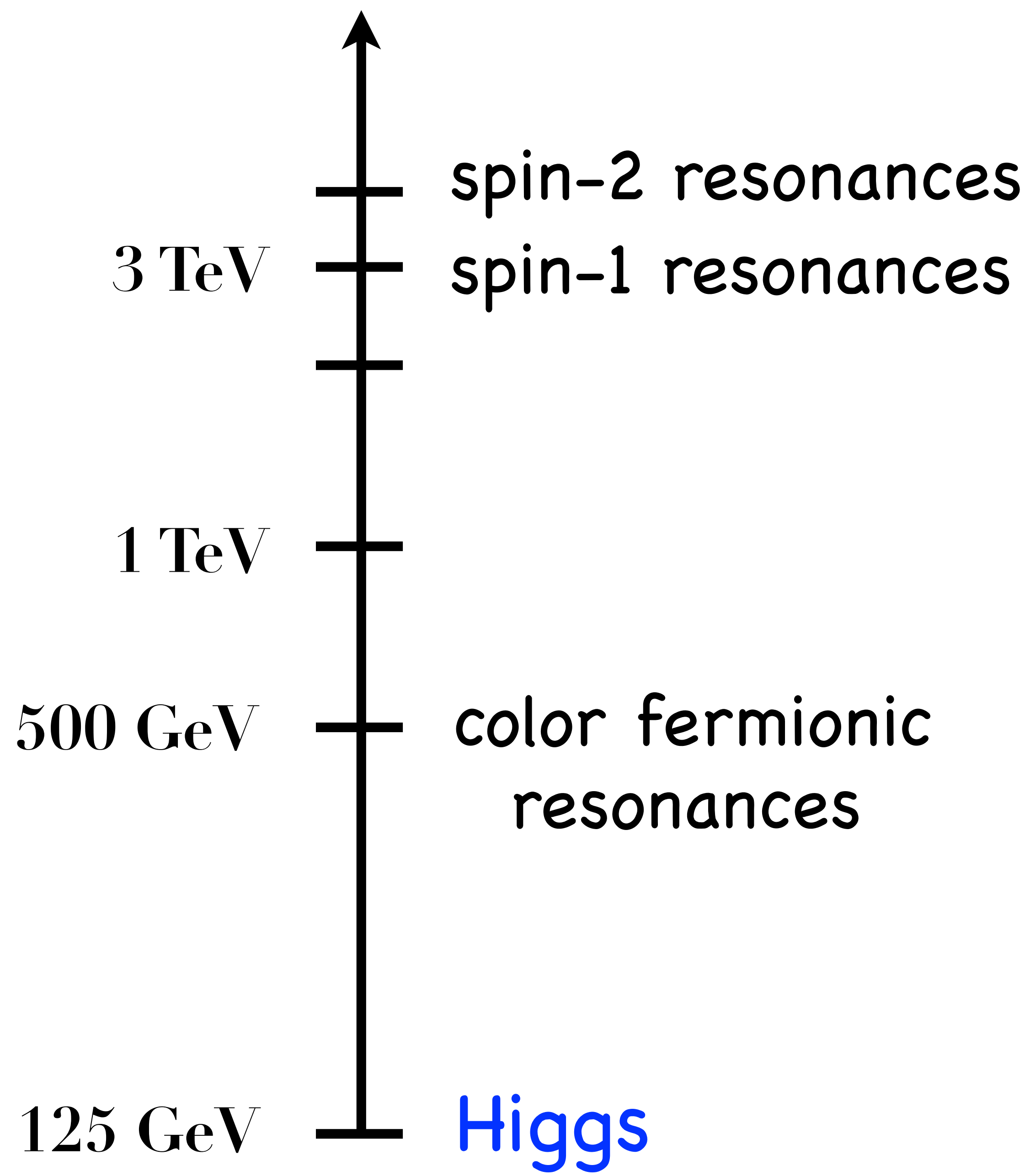

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By the AdS/CFT correspondence:

Physics of Composite Sector ↔ Physics of Extra dimension

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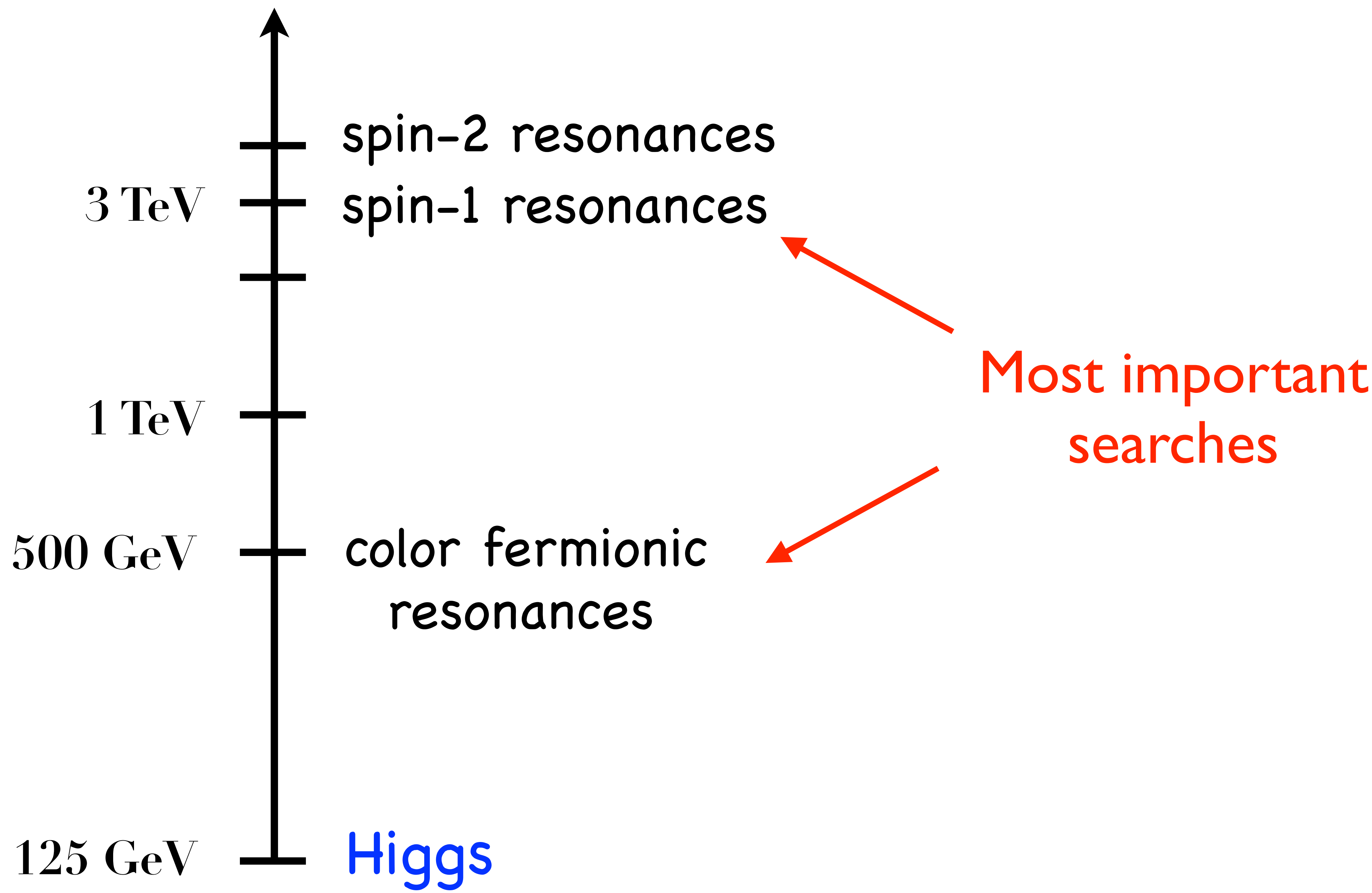

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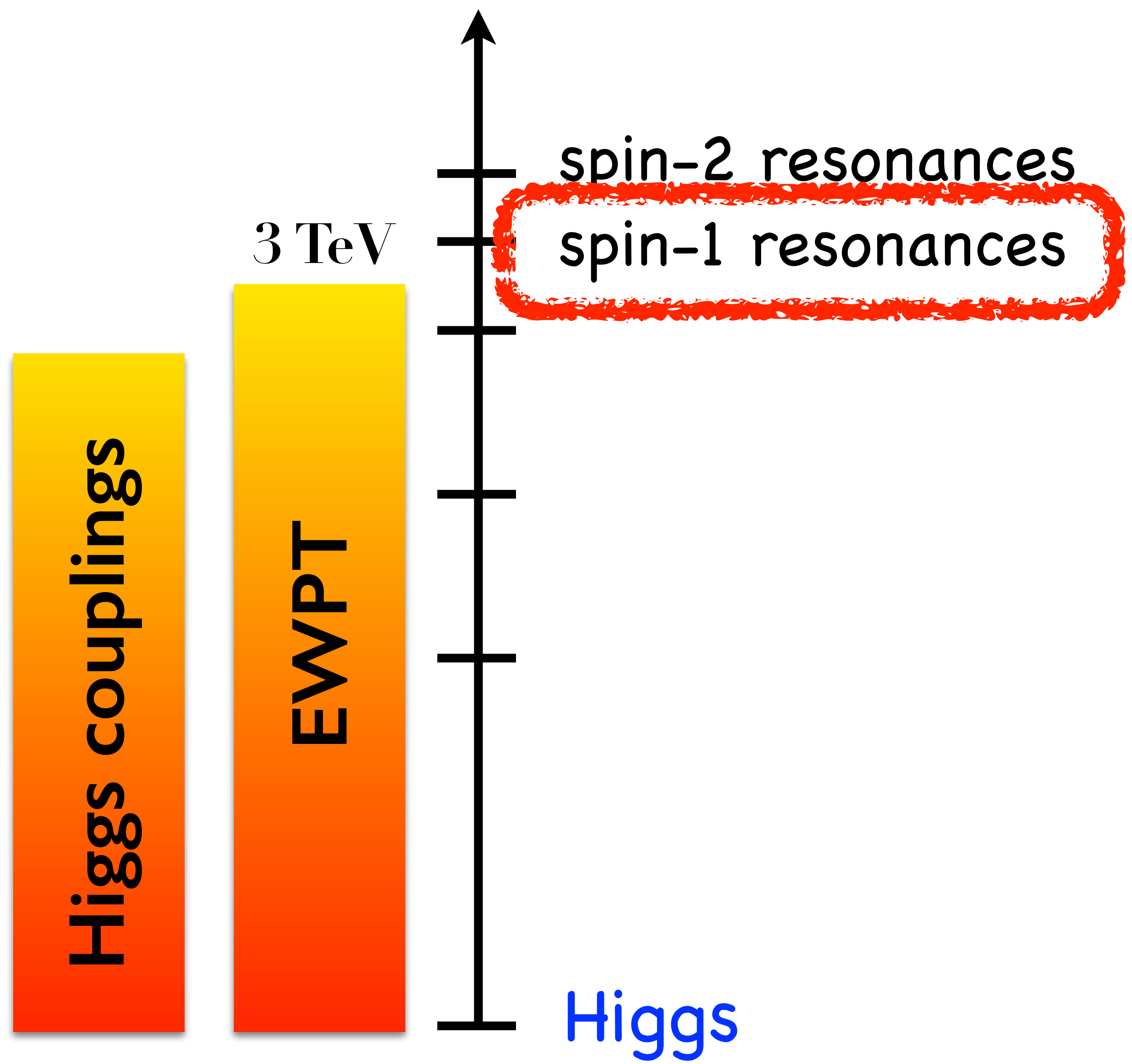

Before 13 TeV LHC bounds
dominated by indirect effects

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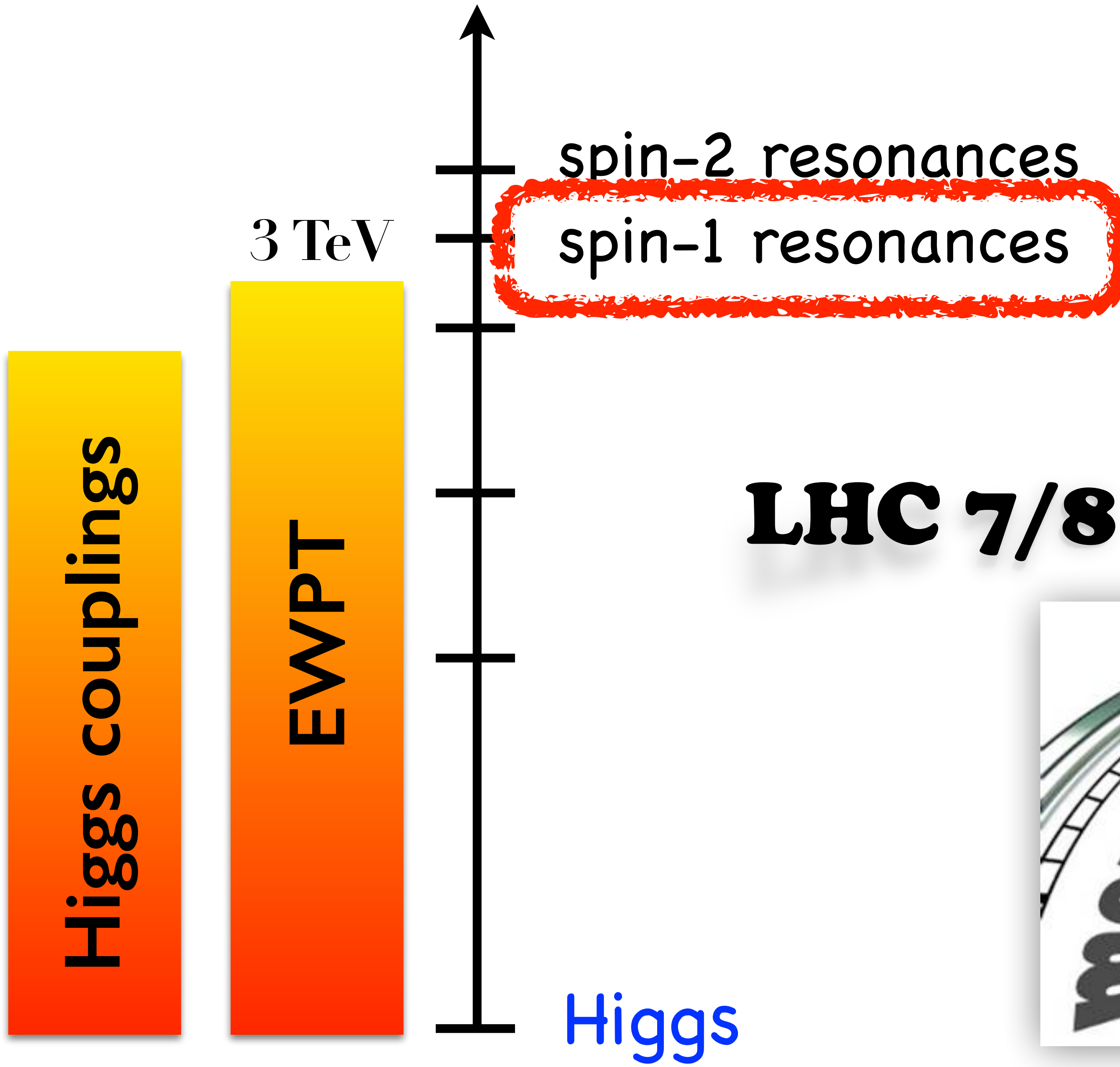
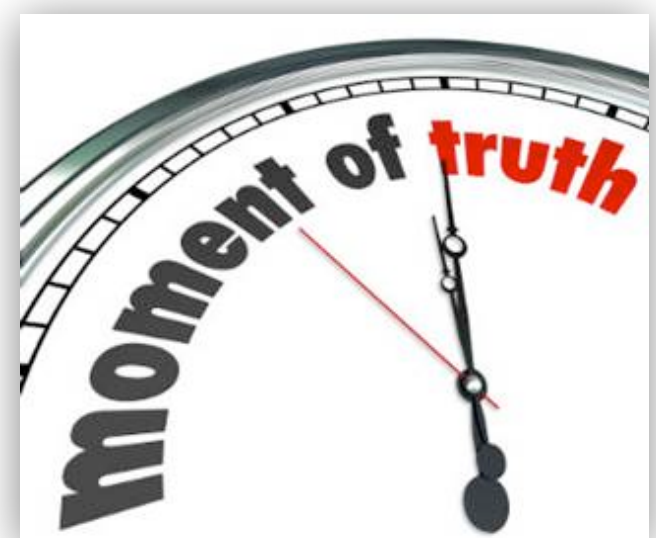


LHC 7/8 TeV → 13 TeV



Before 13 TeV LHC bounds
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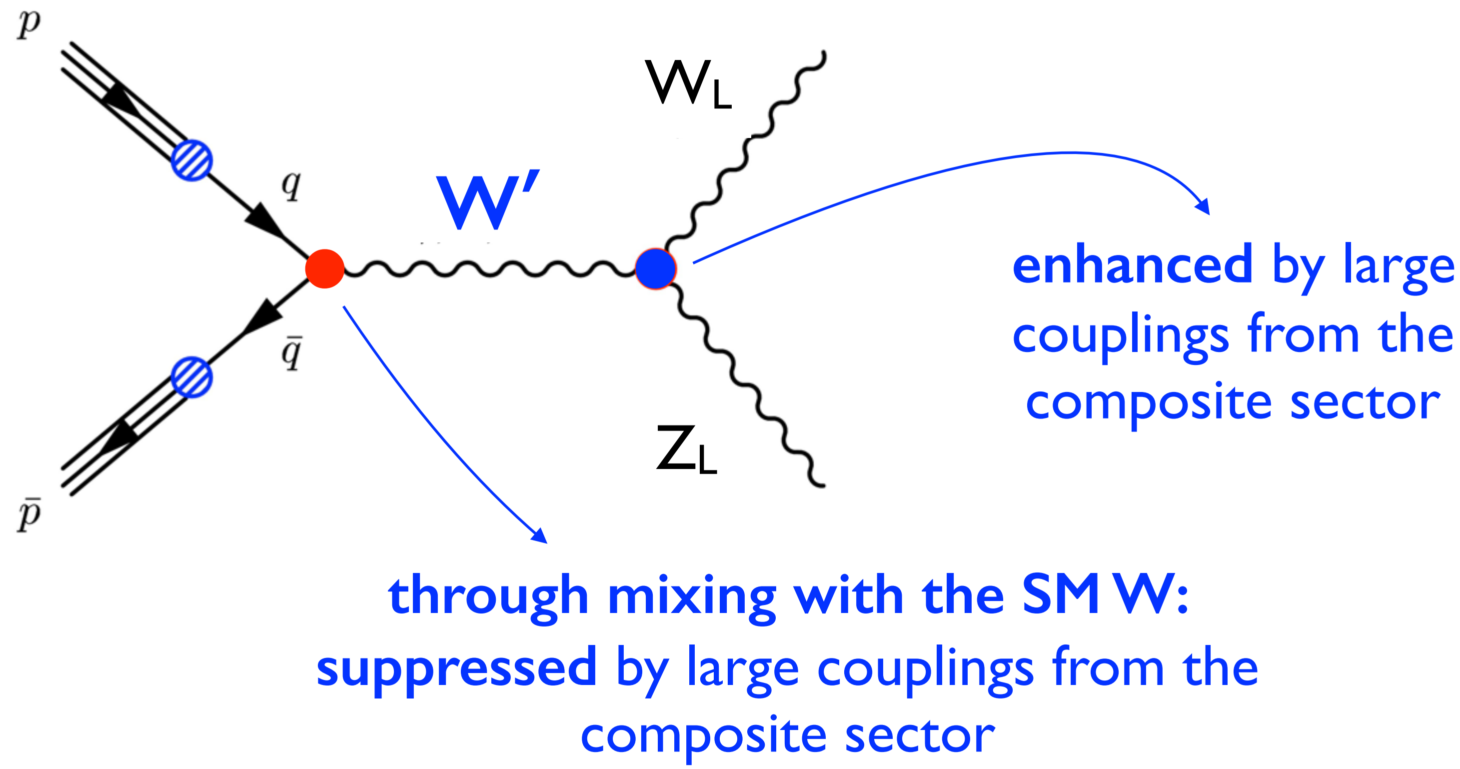
Spin-1 resonance searches:



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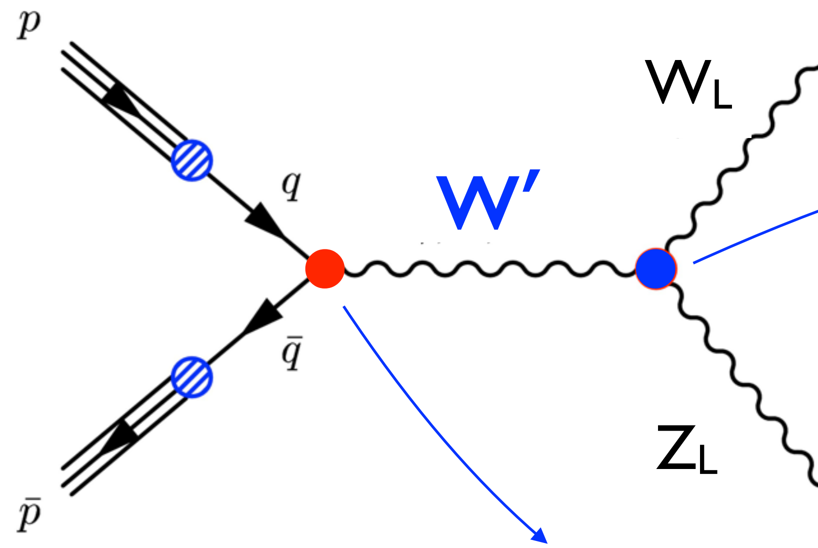
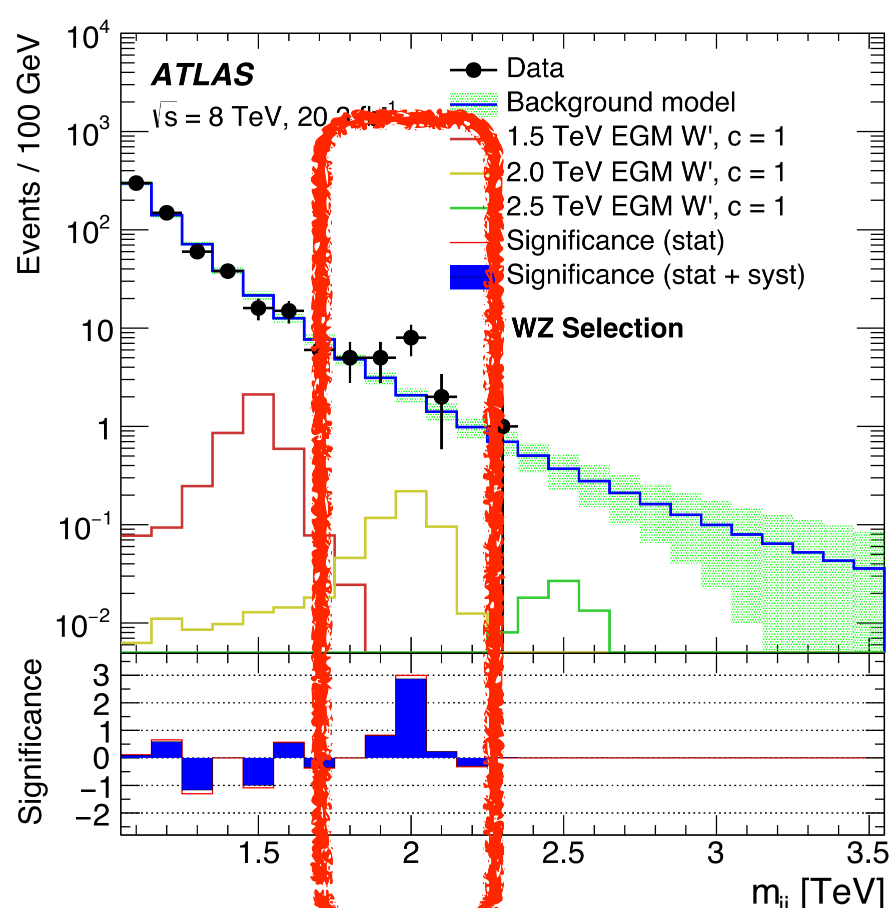


enhanced by large couplings from the composite sector

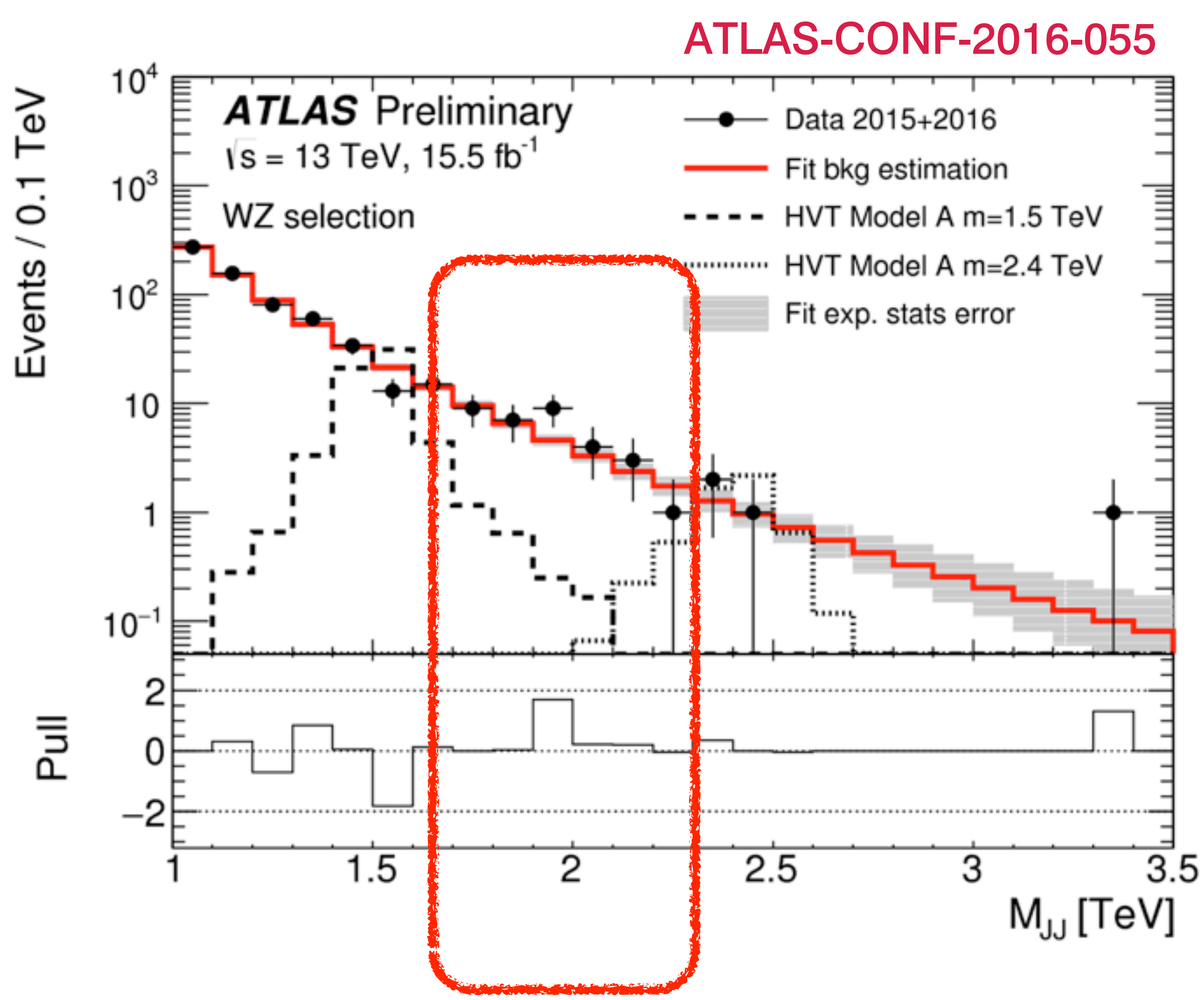
through mixing with the SM W:
suppressed by large couplings from the composite sector

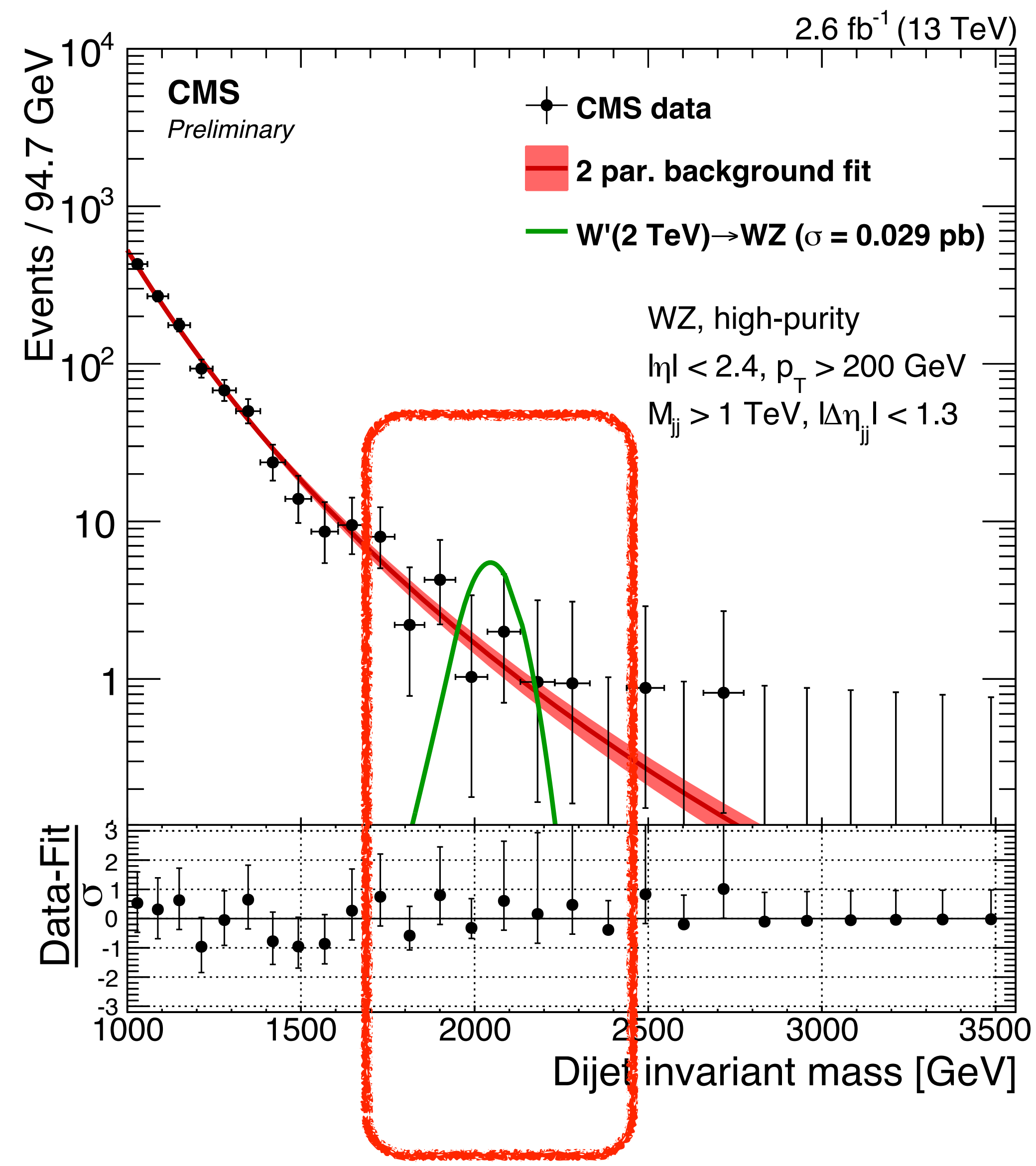
Glimpses at the LHC?

At 8 TeV, some <u>excess</u> in ZW decays (in jets) mostly in ATLAS:

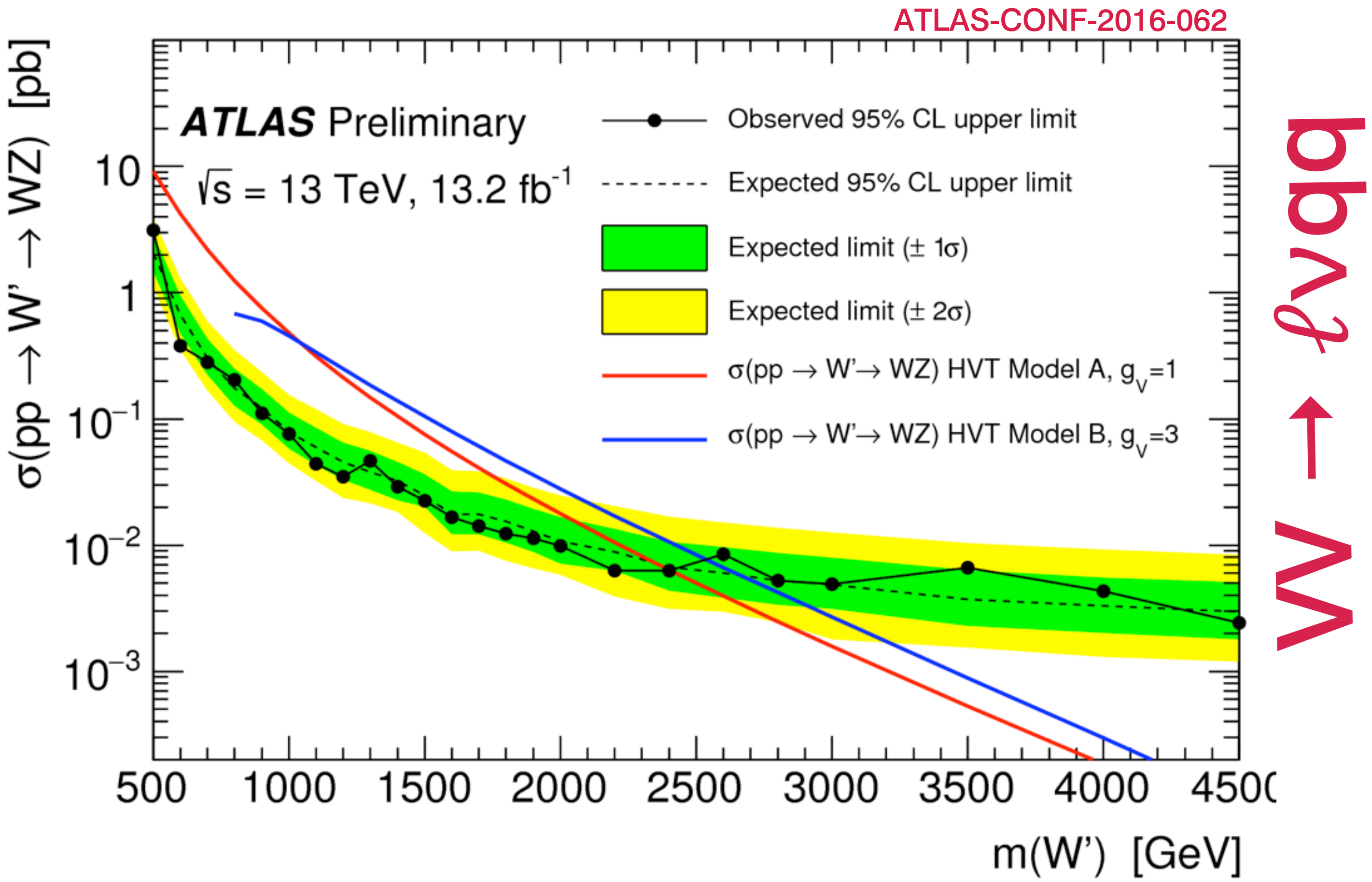


At the LHC 13 TeV…





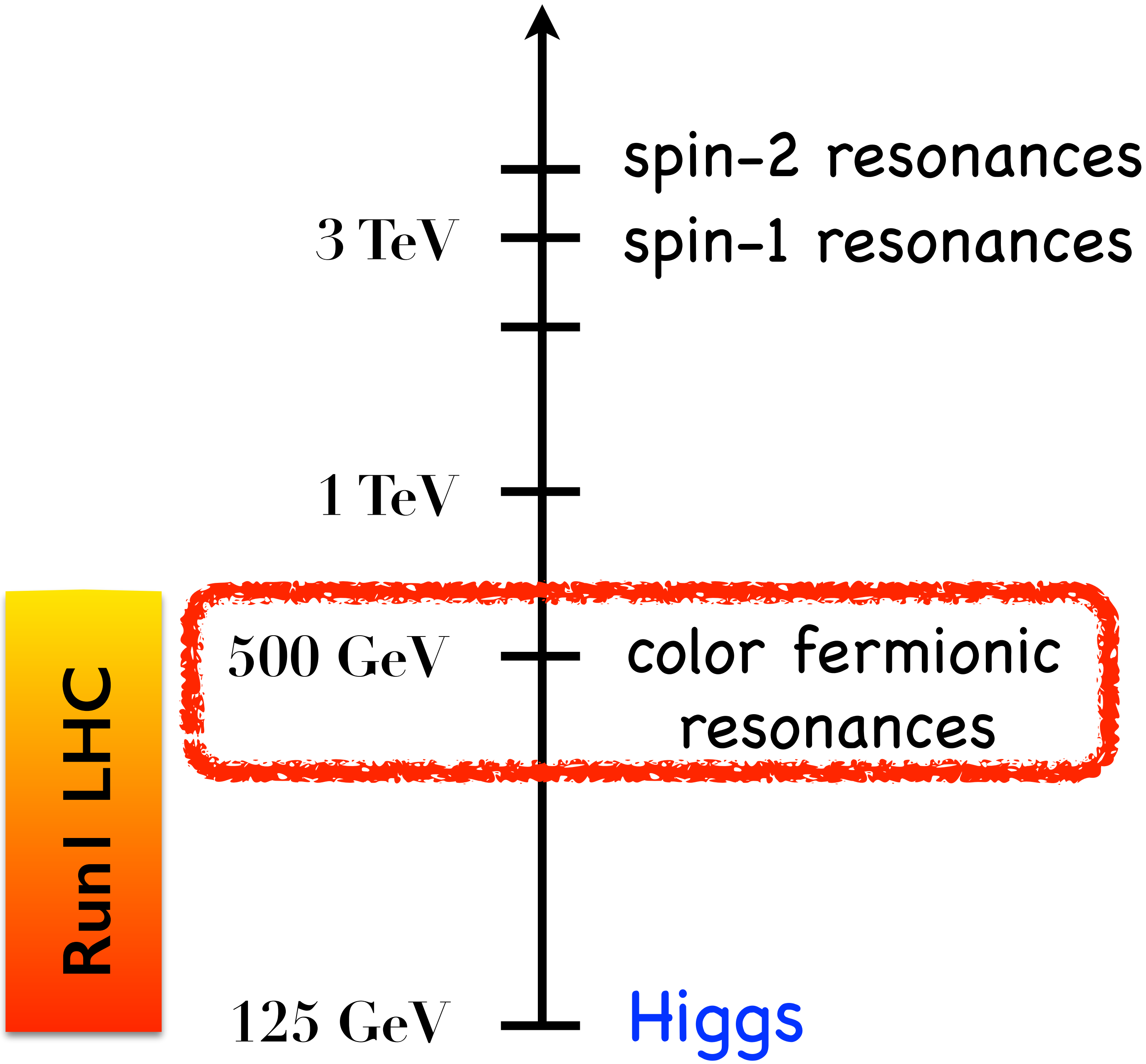
…not much of a di-Boson excess!



$$\mathbf{m(W') \gtrsim 2.5\ TeV}$$

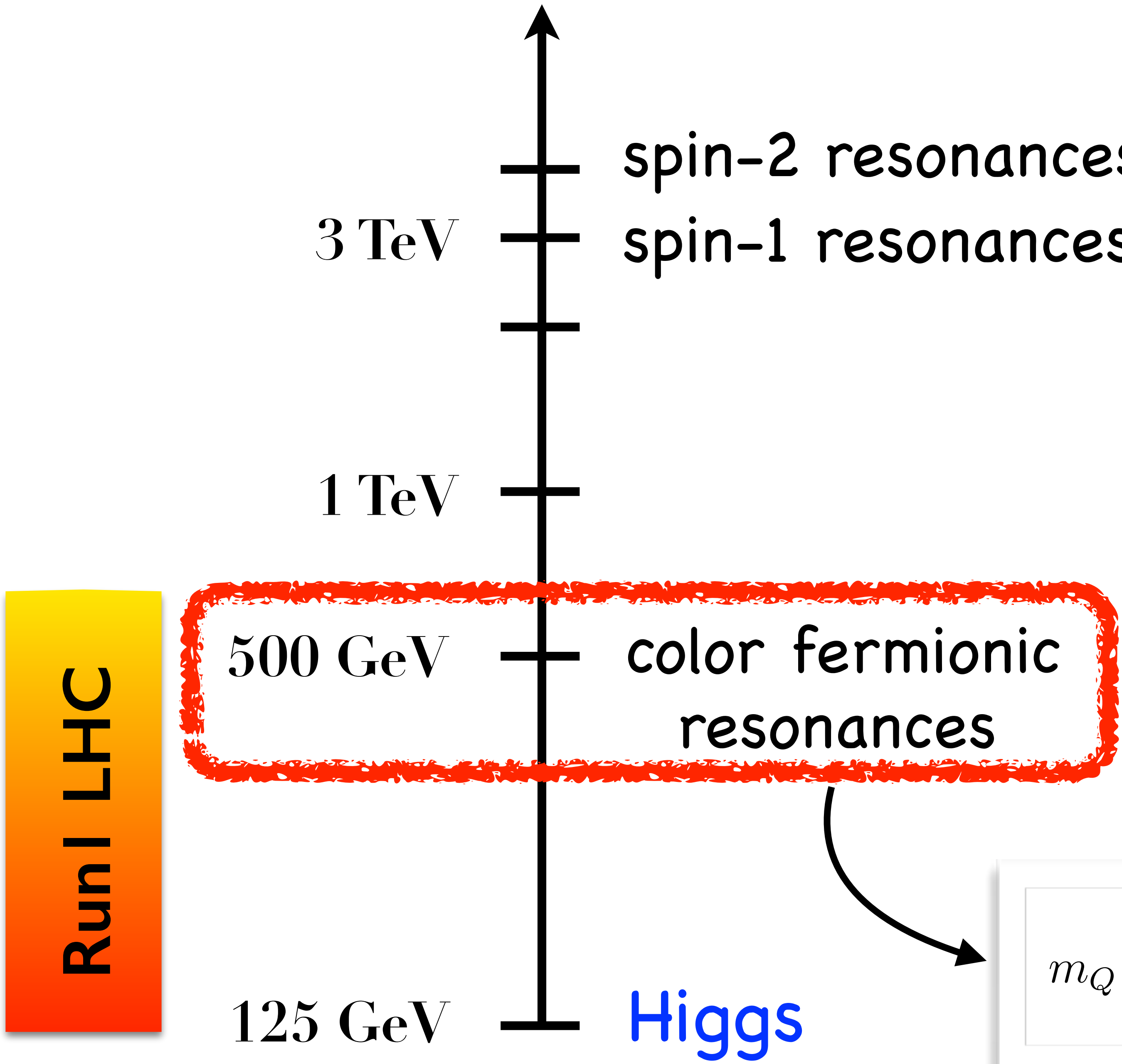
scratching the interesting regions!

Expected spectrum of the TeV Composite Sector



7/8 TeV LHC searches
"scratching the surface"

Expected spectrum of the TeV Composite Sector



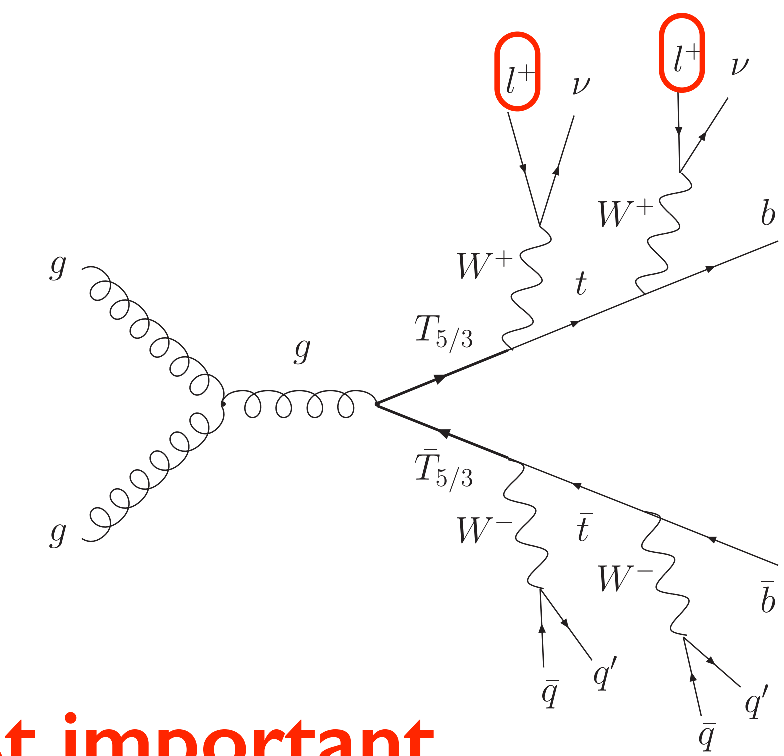
the lightest resonances
due to the
lightness of the Higgs

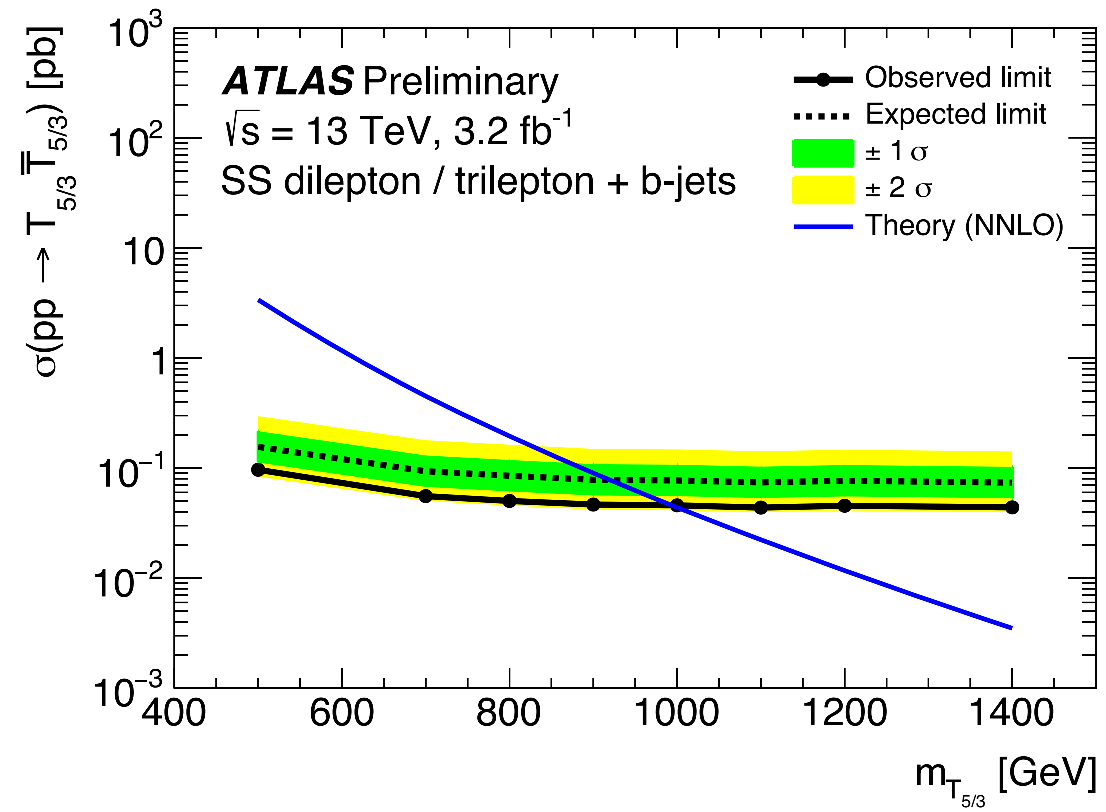
$$m_Q \lesssim 700 \text{ GeV} \left(\frac{m_h}{125 \text{ GeV}}\right) \left(\frac{160 \text{ GeV}}{m_t}\right) \left(\frac{f}{500 \text{ GeV}}\right)$$

AP, F.Riva JHEP 1208 (2012) 135

7/8 TeV LHC searches
“scratching the surface”

Colored fermion resonances at LHC 13 TeV

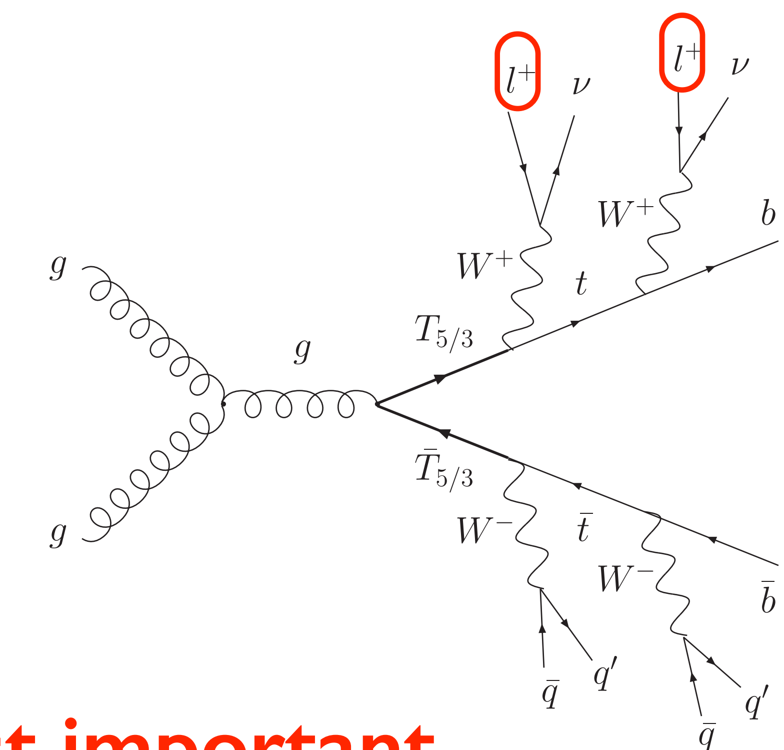


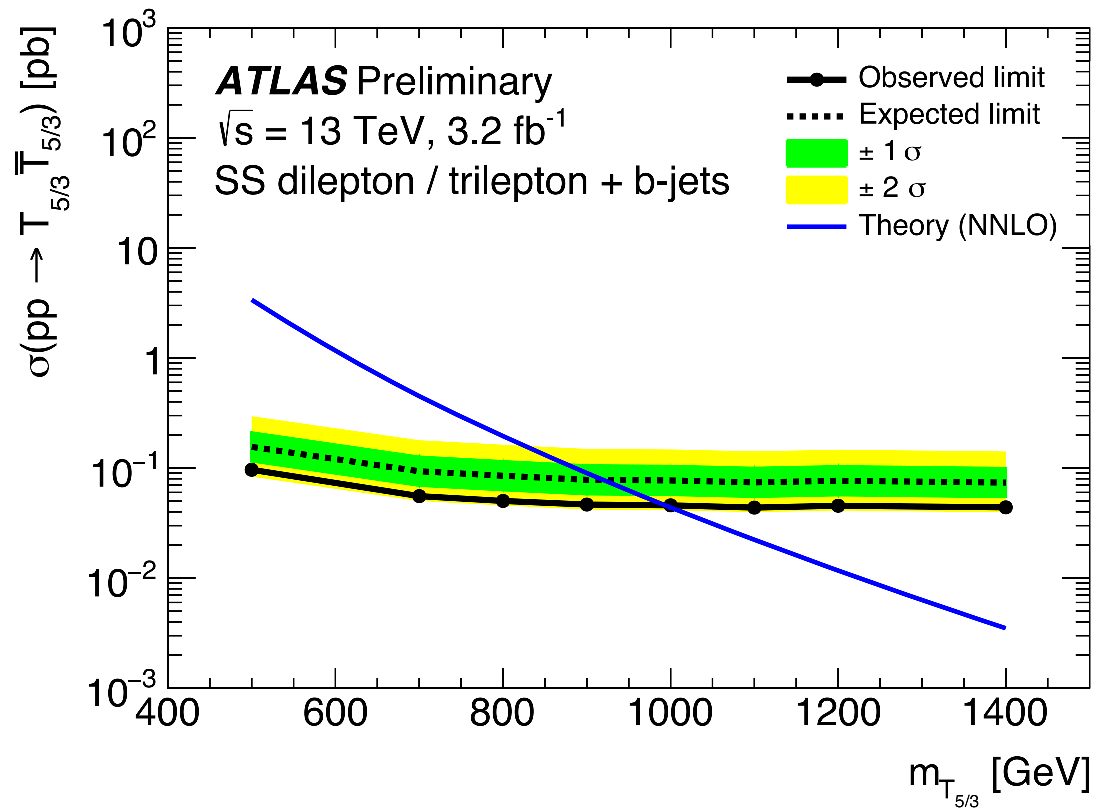


First important constraint from LHC:

$$\mathbf{m(X_{5/3}) \gtrsim 1\ TeV}$$

Colored fermion resonances at LHC 13 TeV





First important constraint from LHC:

$$\mathbf{m(X_{5/3}) \gtrsim 1\ TeV}$$

The situation starts being worrisome..

but not yet desperate

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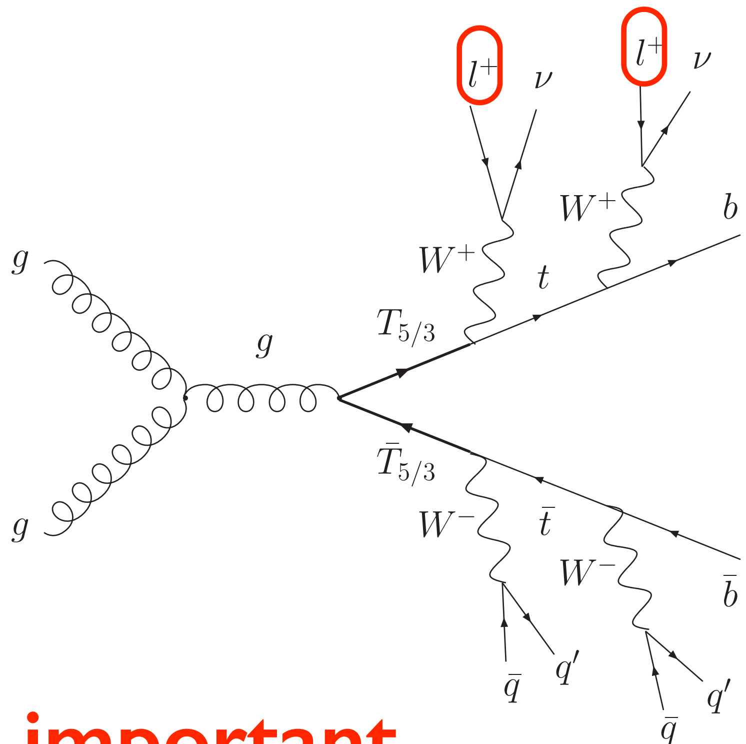

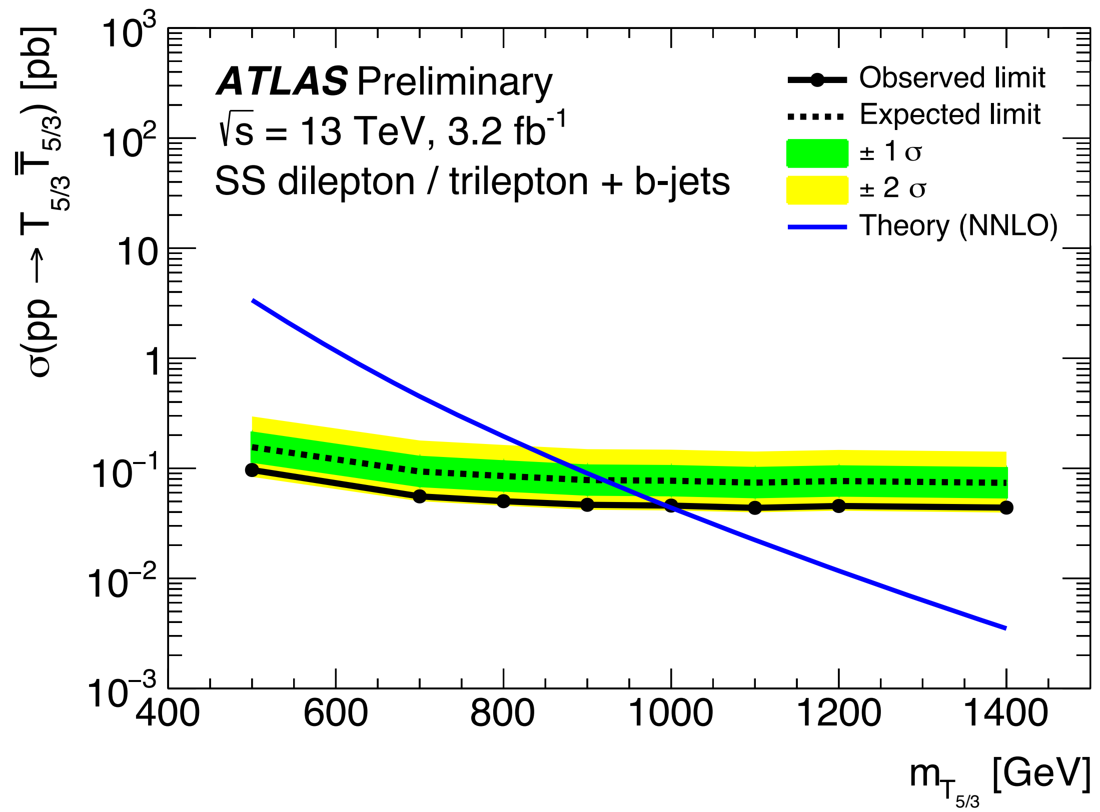

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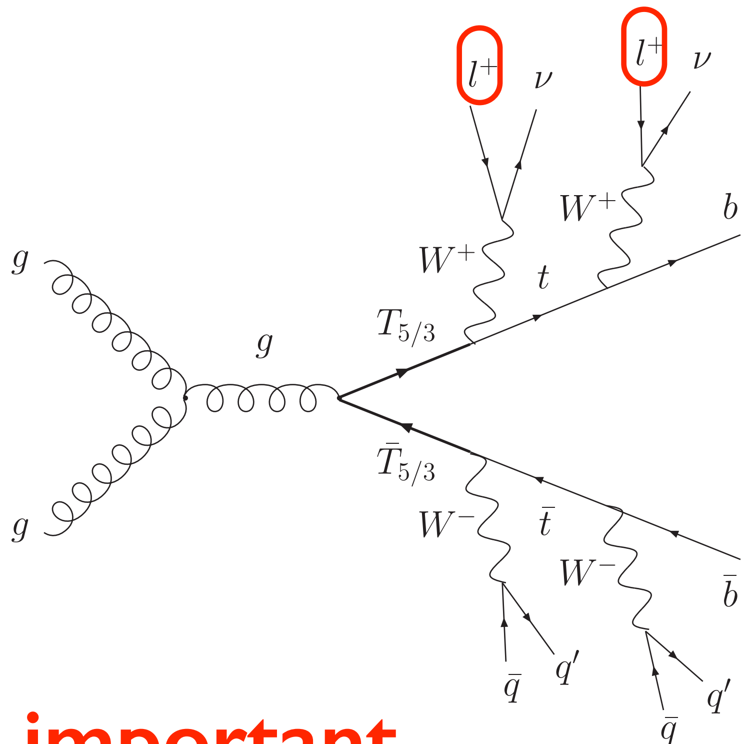

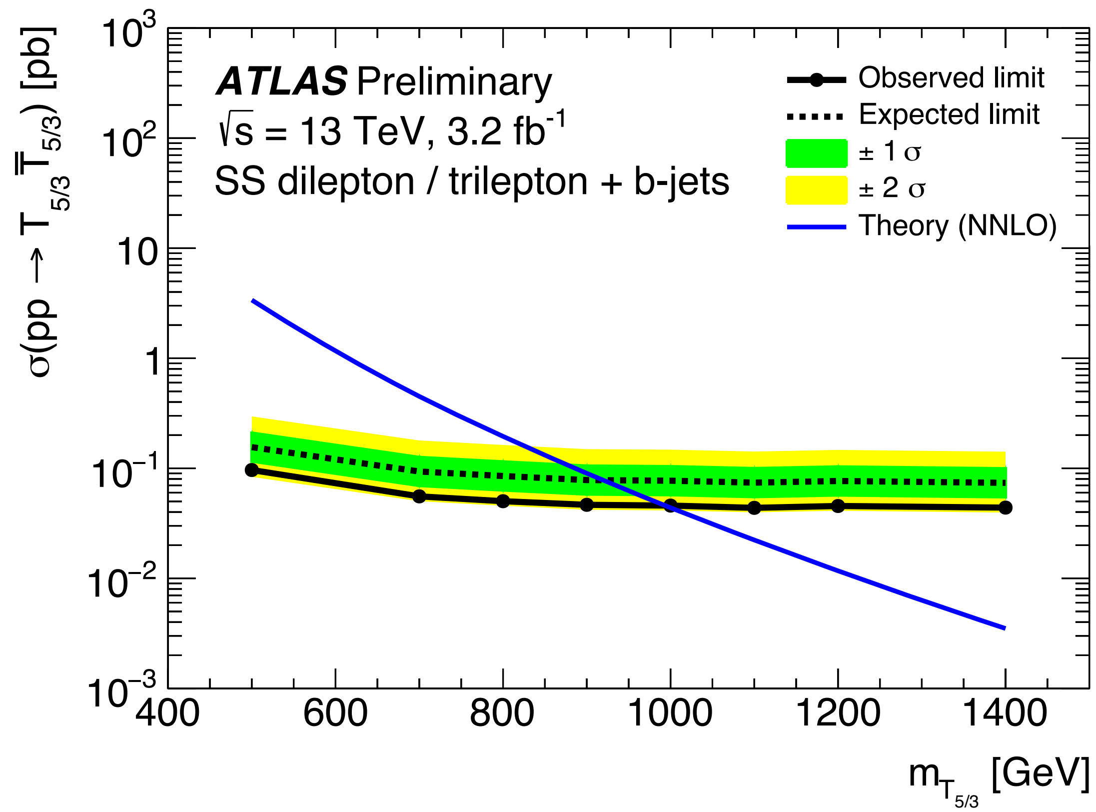

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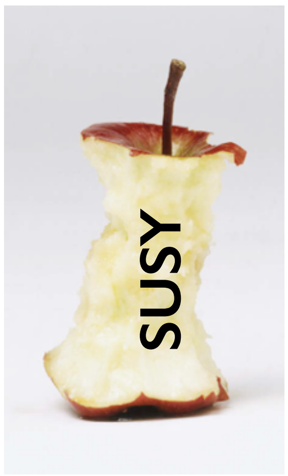

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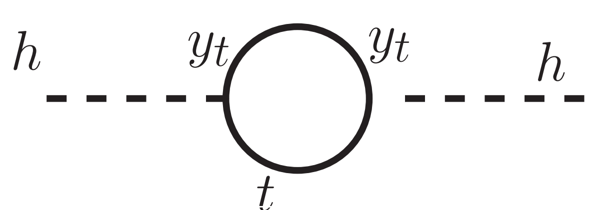
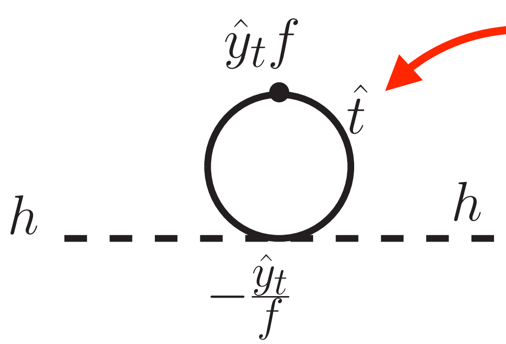
Who is keeping the Higgs light?





The missing top-partner problem!

Models without colored **top partners** are possible?

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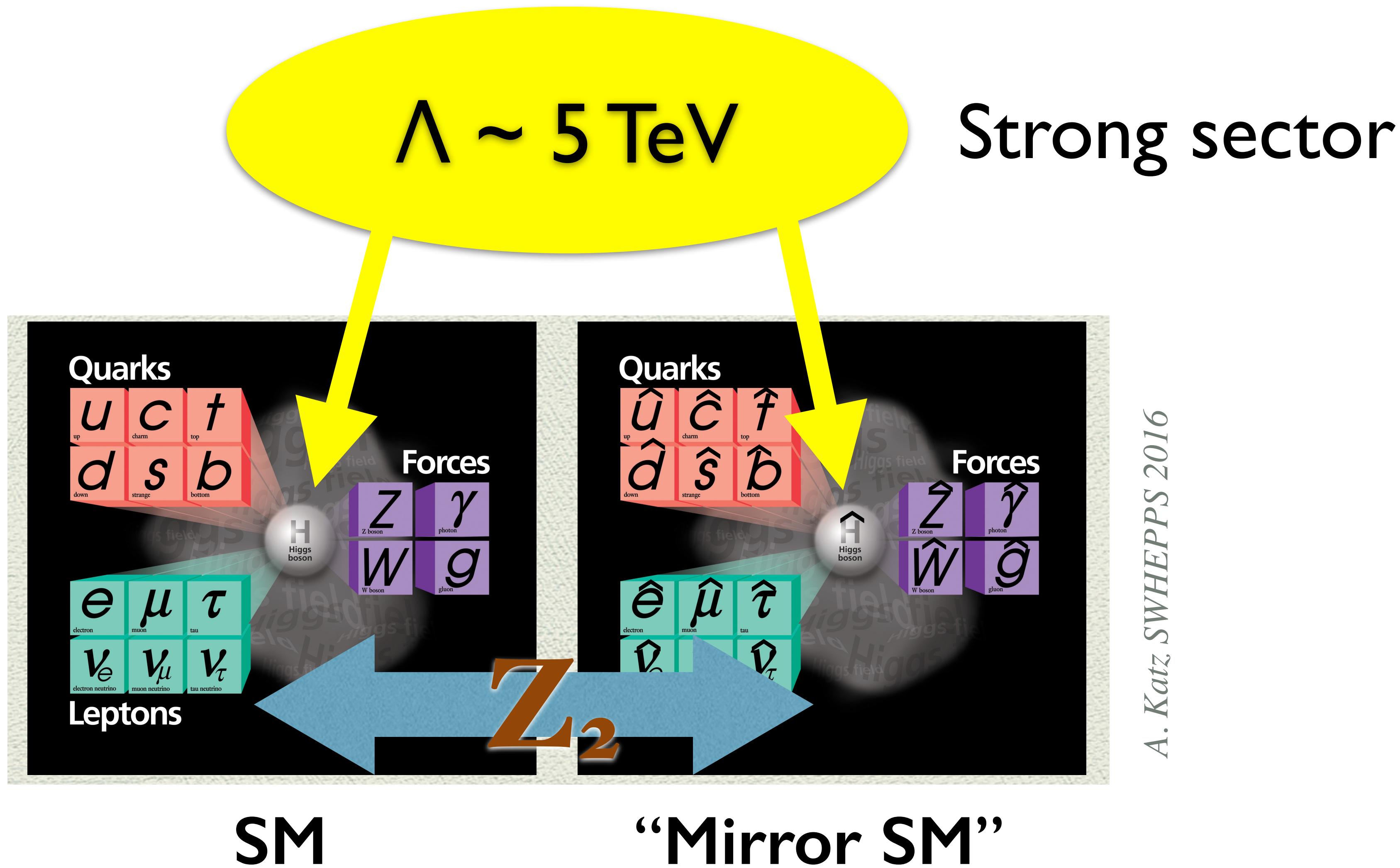
"Twin Higgs" Models:



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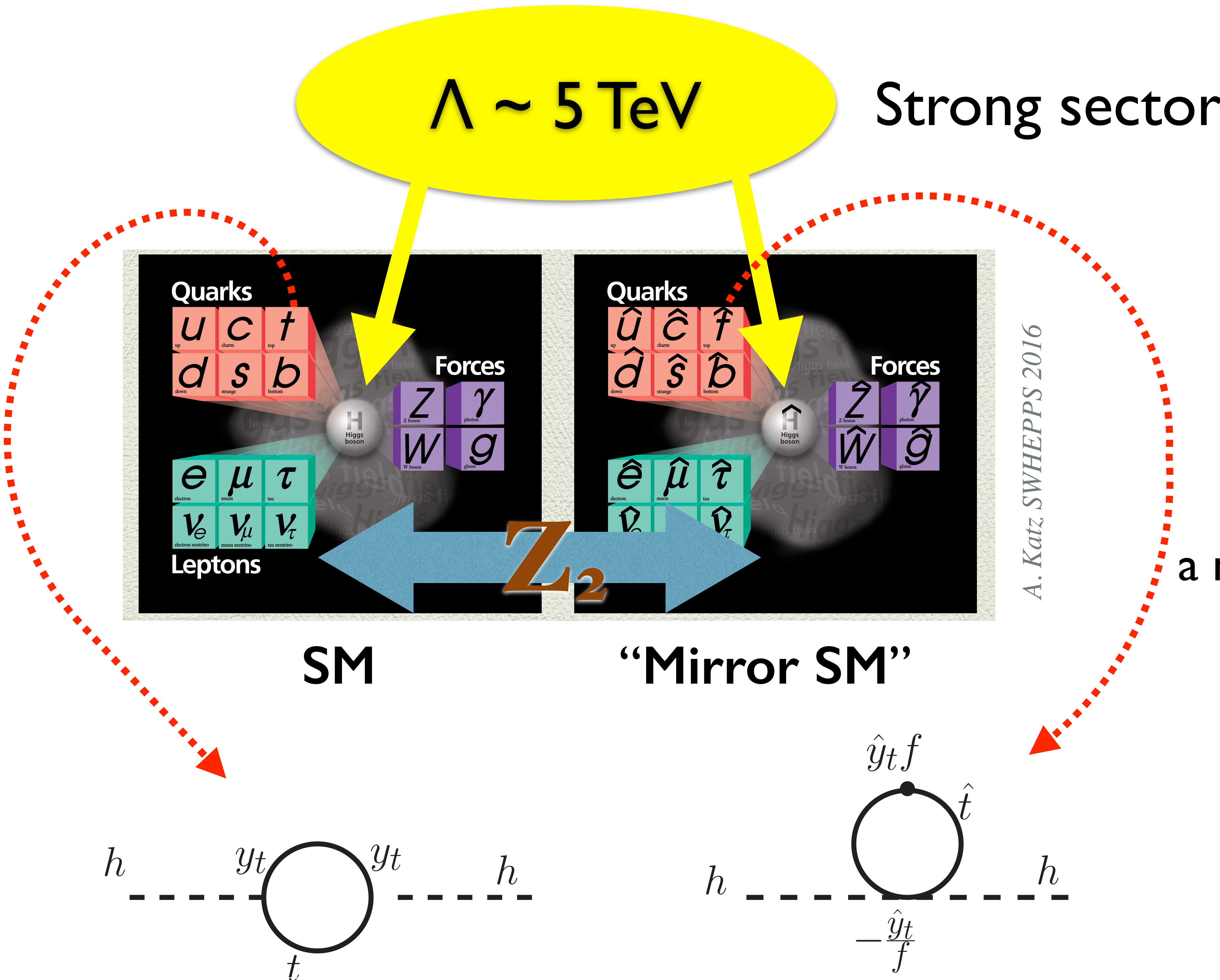
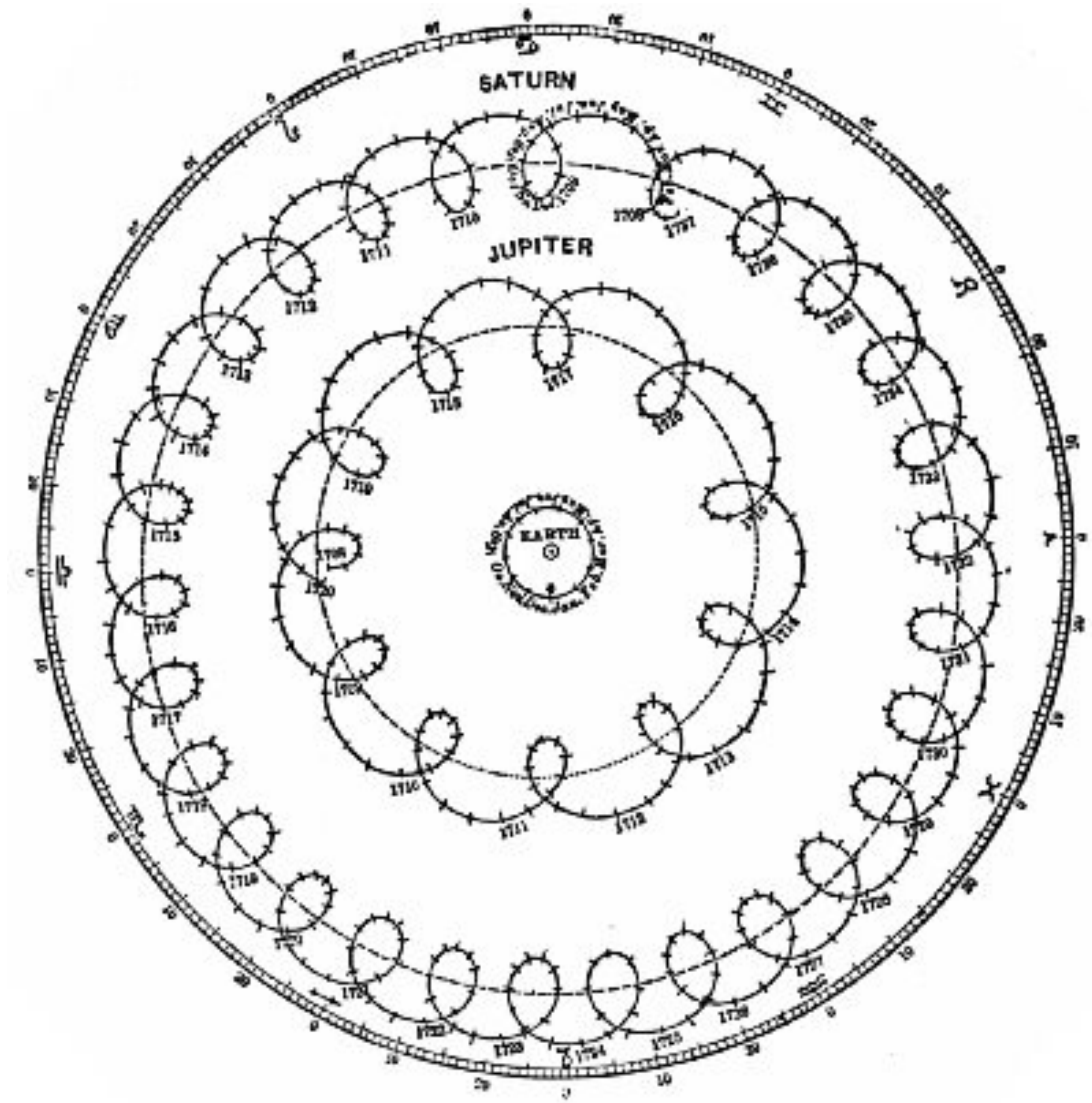


a neutral sector keeps the Higgs light!

Aren’t we adding too many epicycles?



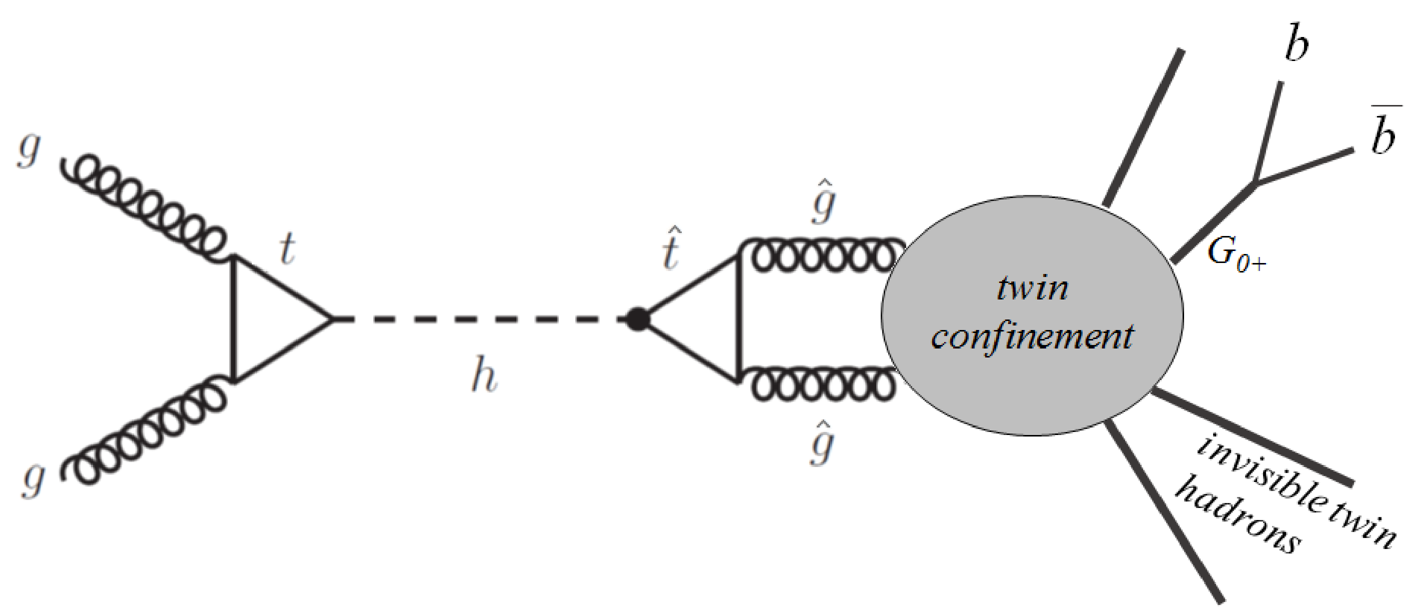
Implications of twin Higgs models:

Not possible to see these top-partners at the LHC
as they are **not charged under the SM**

Main LHC signature:

Higgs decays invisibly (to the "mirror" world)
that **could** decay back to us (giving displaced vertices)

arXiv:1501.05310



Higgs portal to the "Mirror SM"

Conclusions

- The long-awaited **13 TeV collider** is finally here!

  Main aim: learn on the origin of the SM electroweak scale

  First rounds: **Mostly Negative Results!**

- **Missing top-partner problem** becoming more severe

  but we must *dig* more to see how serious it is!

- Clearly, **BSM** had already too **many chances** to **show up**

  (in EDM, flavor, Z/H couplings, as a WIMP, new particles,…)

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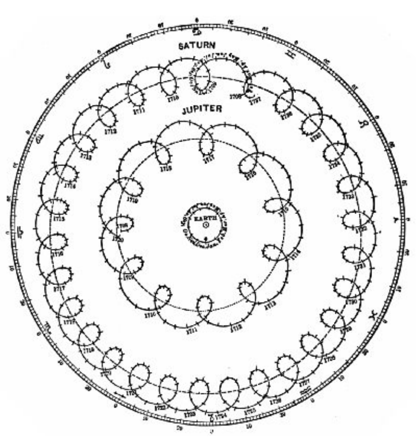

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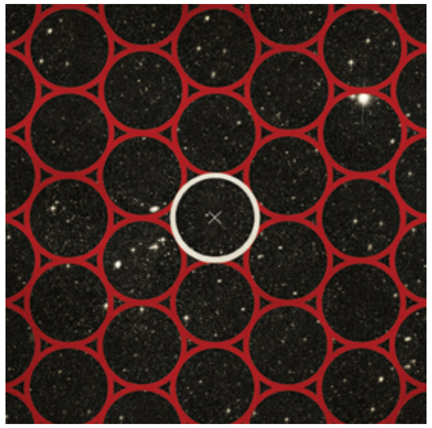

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paradigm shift? *Multiverse, relaxion*

EW scale from cosmological evolution

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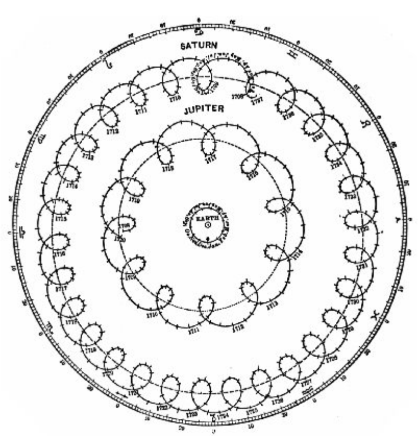

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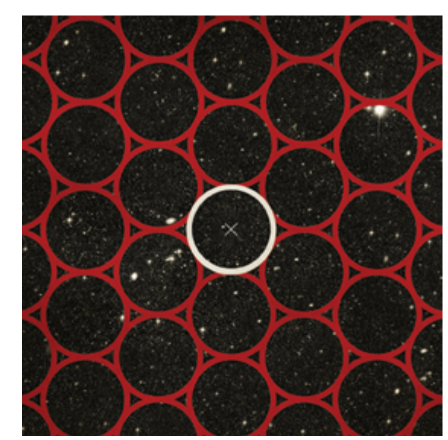

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EW scale from cosmological evolution

In any case, we will be making (*painful*) progress even with null results!

MORE IF NEEDED

All you need to know about *relaxion*

“Relaxation” mechanism:

P.W. Graham, D.E. Kaplan, S.Rajendran
arXiv:1504.07551

Higgs-mass parameter $\longrightarrow$ Field-dependent Higgs mass

$$m_H^2 |H|^2 \qquad\qquad m_H^2(\phi)|H|^2$$

minimum of $\boldsymbol{\phi}$ where

$$m_H^2(\phi) \ll M_P^2$$

Breakthrough:

An axion-like ϕ can have the following (natural) potential:

$$V(\phi,h)=\Lambda^3 g\phi-\frac{1}{2}\Lambda^2\left(1-\frac{g\phi}{\Lambda}\right)h^2+\epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n\cos(\phi/f)$$

P.W. Graham, D.E. Kaplan, S.Rajendran
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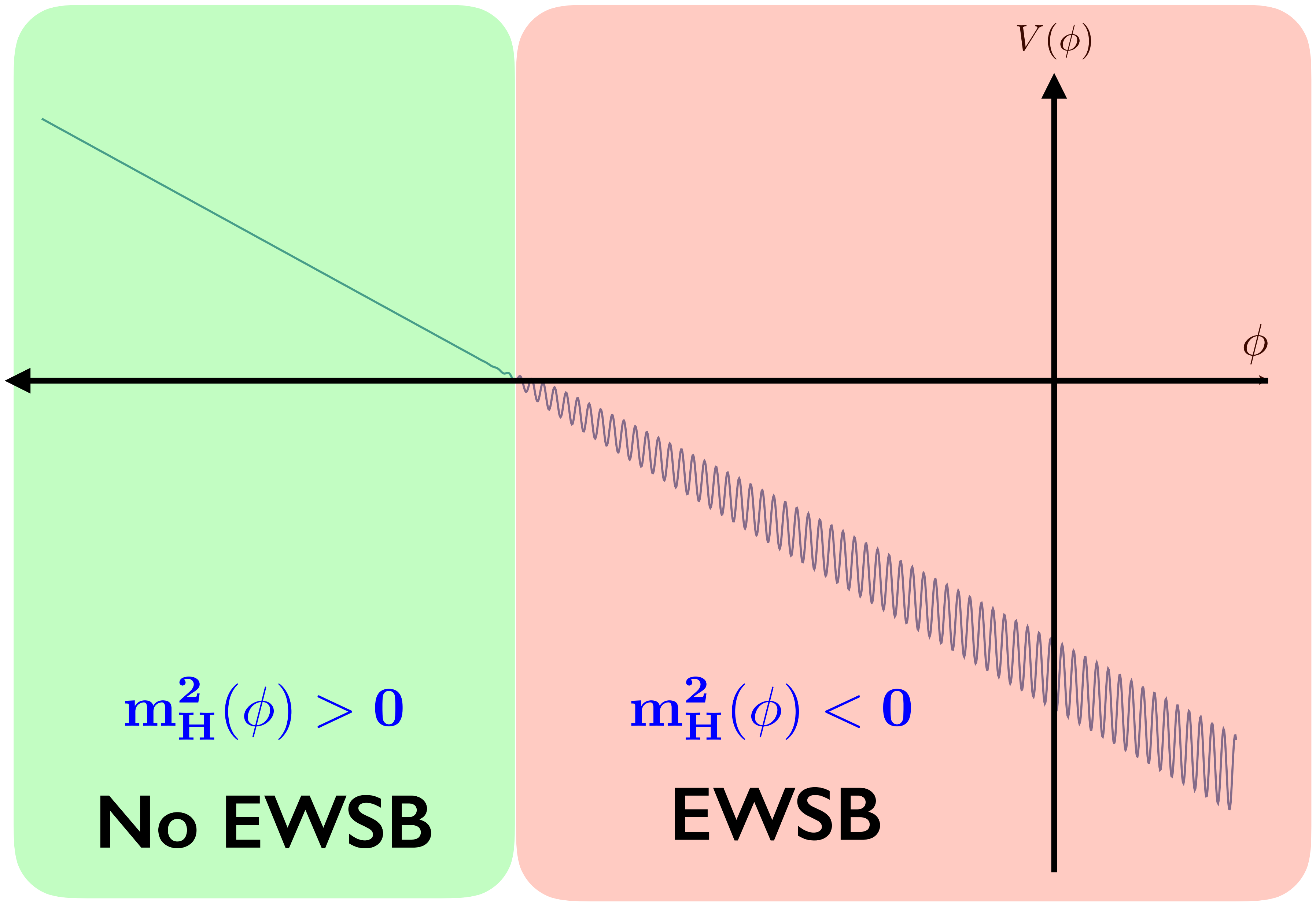

Cosmological evolution can lead to a small EW scale

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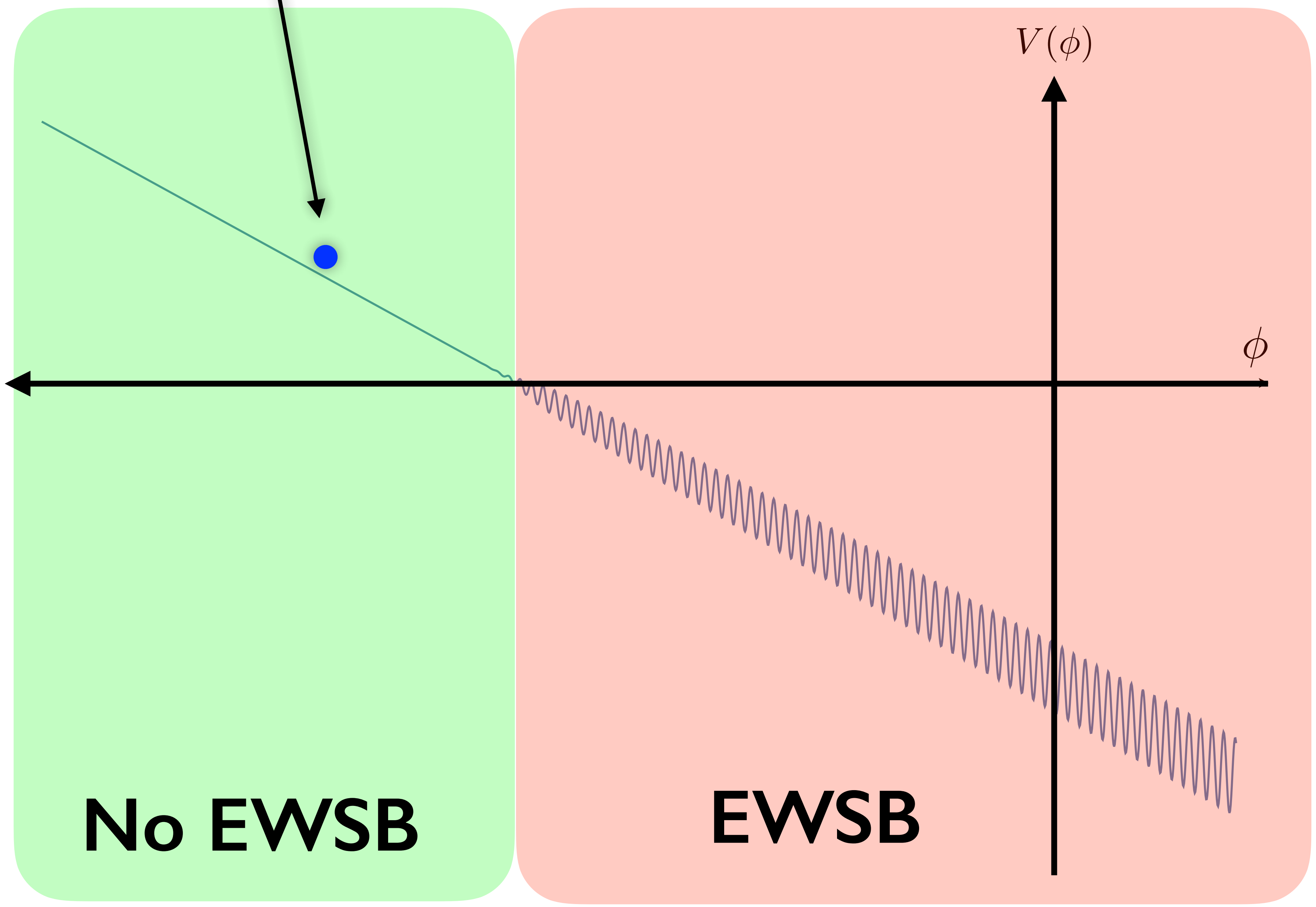

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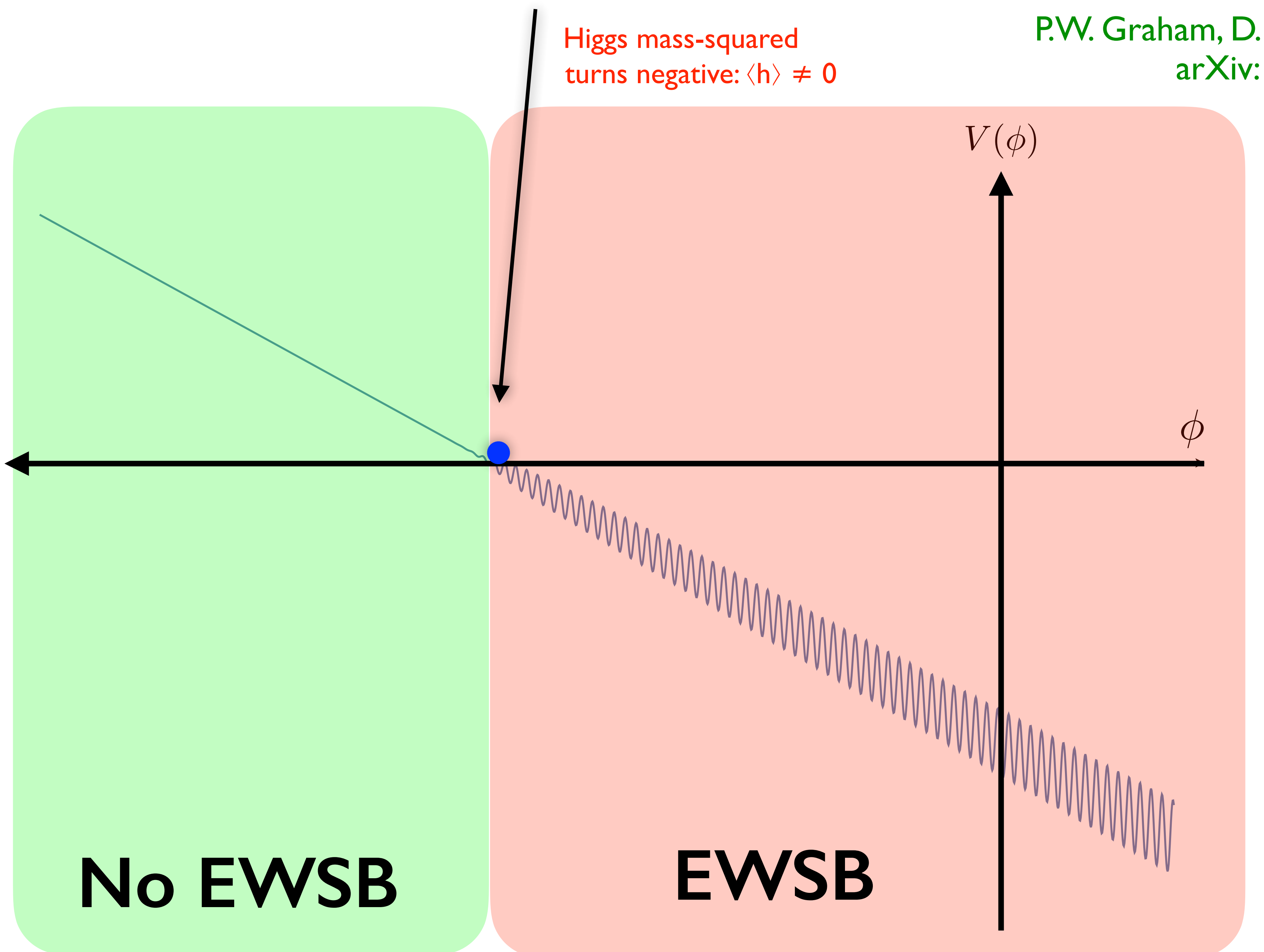

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becomes
more & more
important

P.W. Graham, D.E. Kaplan, S.Rajendran
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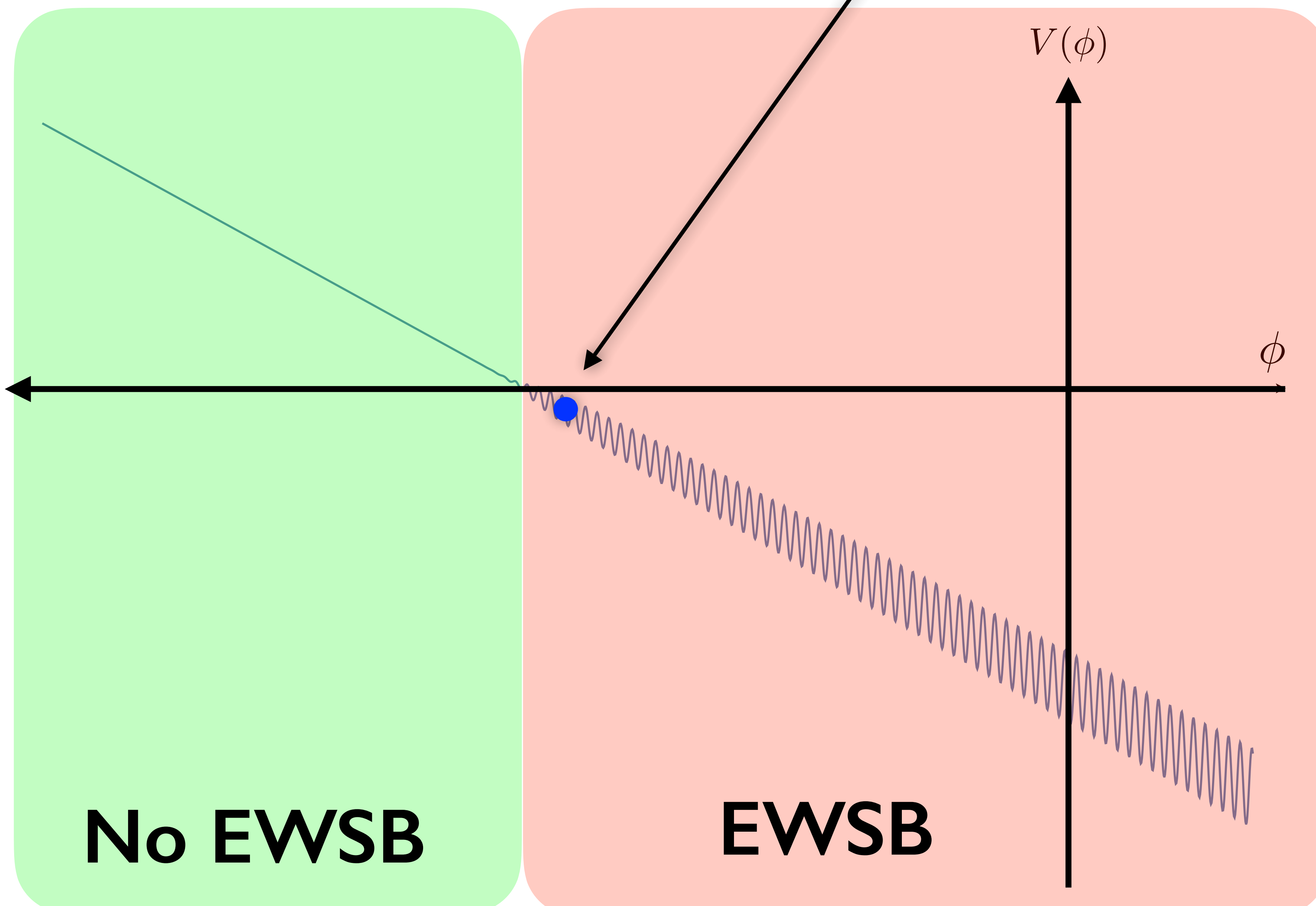

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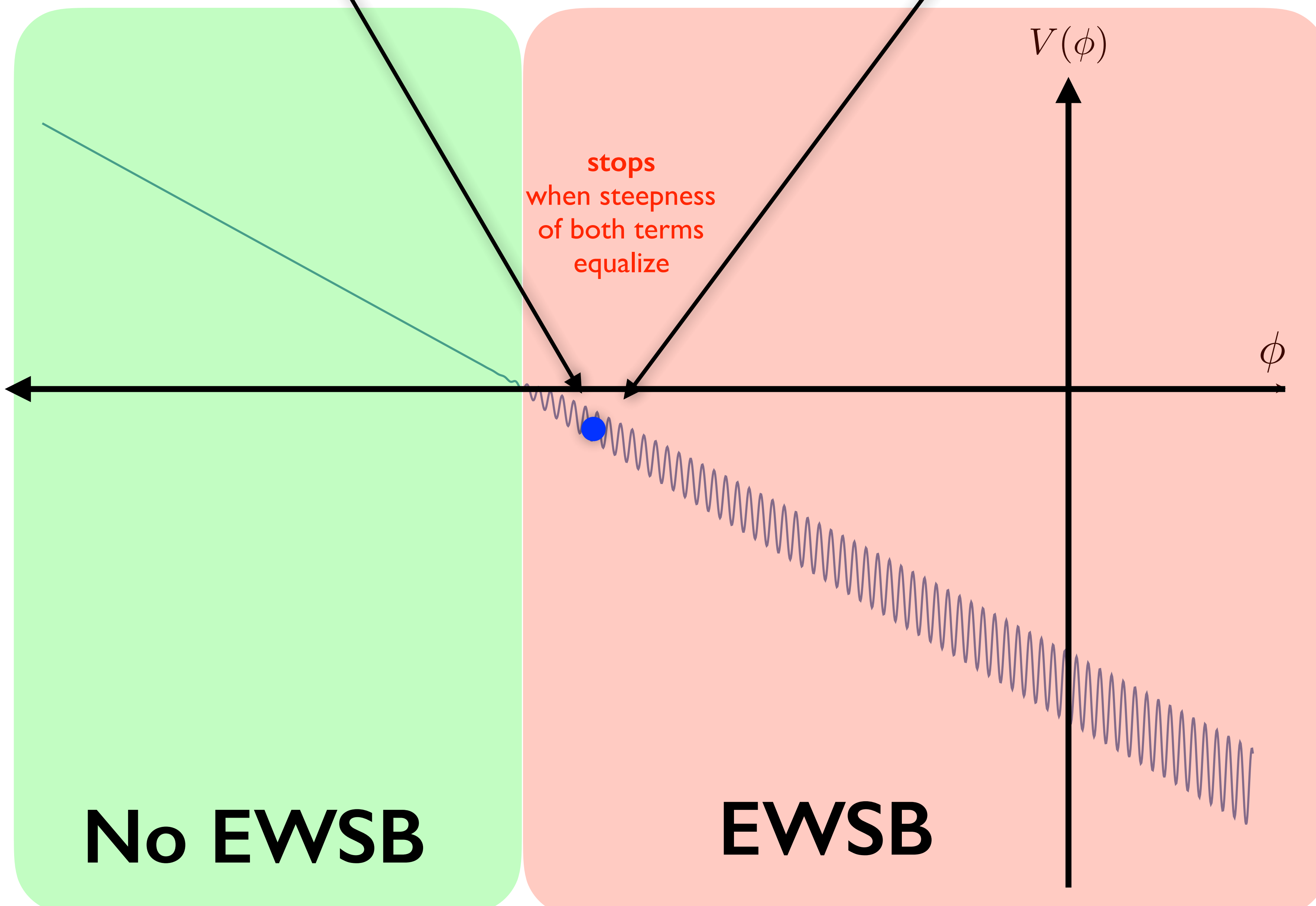

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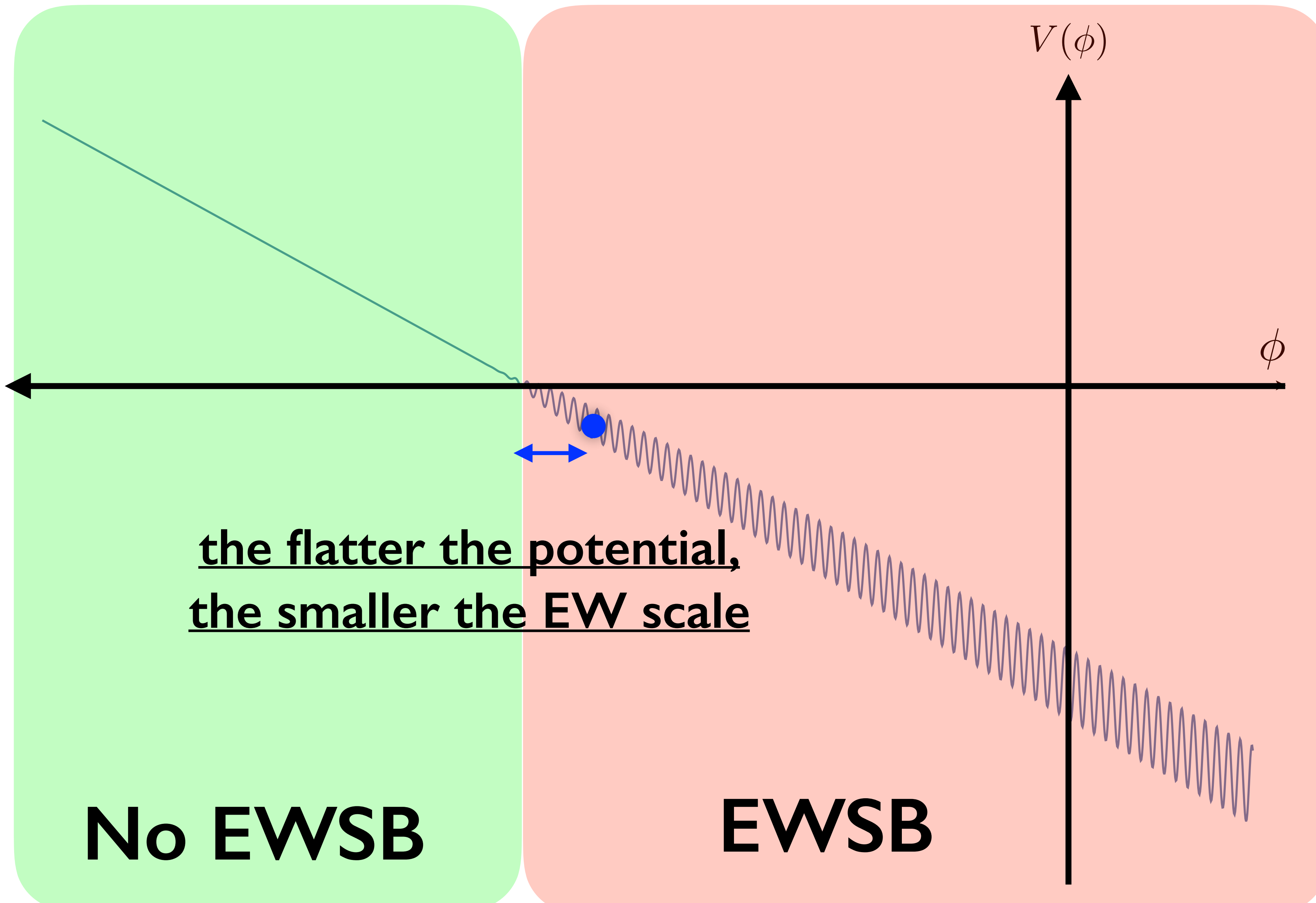

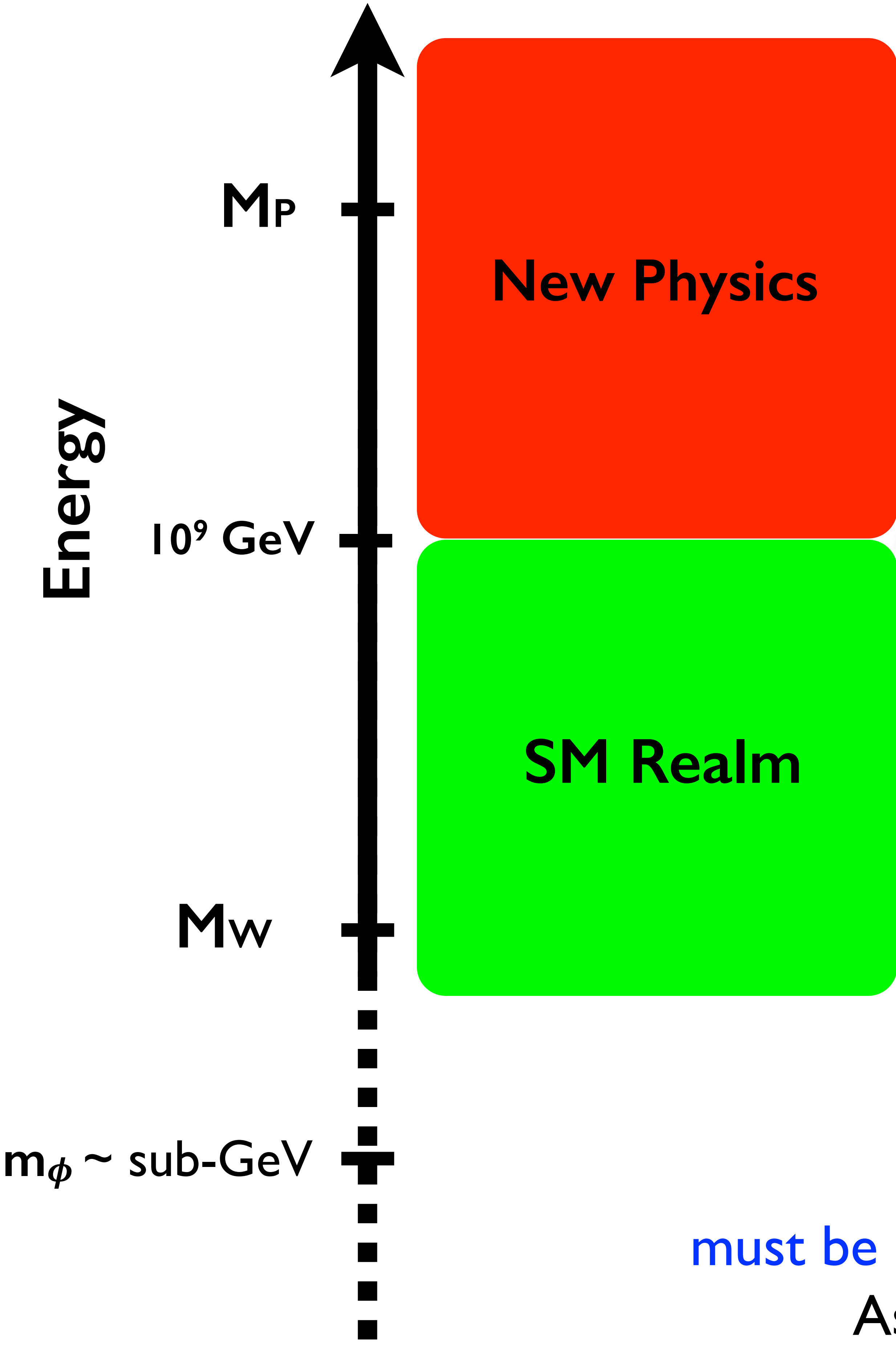

New physics scale can be pushed up naturally to at least 10^9 GeV

see for example, J.R.Espinosa, C.Grojean, G.Panico, A.P., O.Pujolàs, G.Servant 15

Main prediction:

ϕ's: very light & extremely weakly-coupled states (*axion-like*)

must be searched in different type of experiments:

Astro (γ-rays, pulsar timing, …), CMB, table-top (fifth-force searches, EPV), …