BSM theory review

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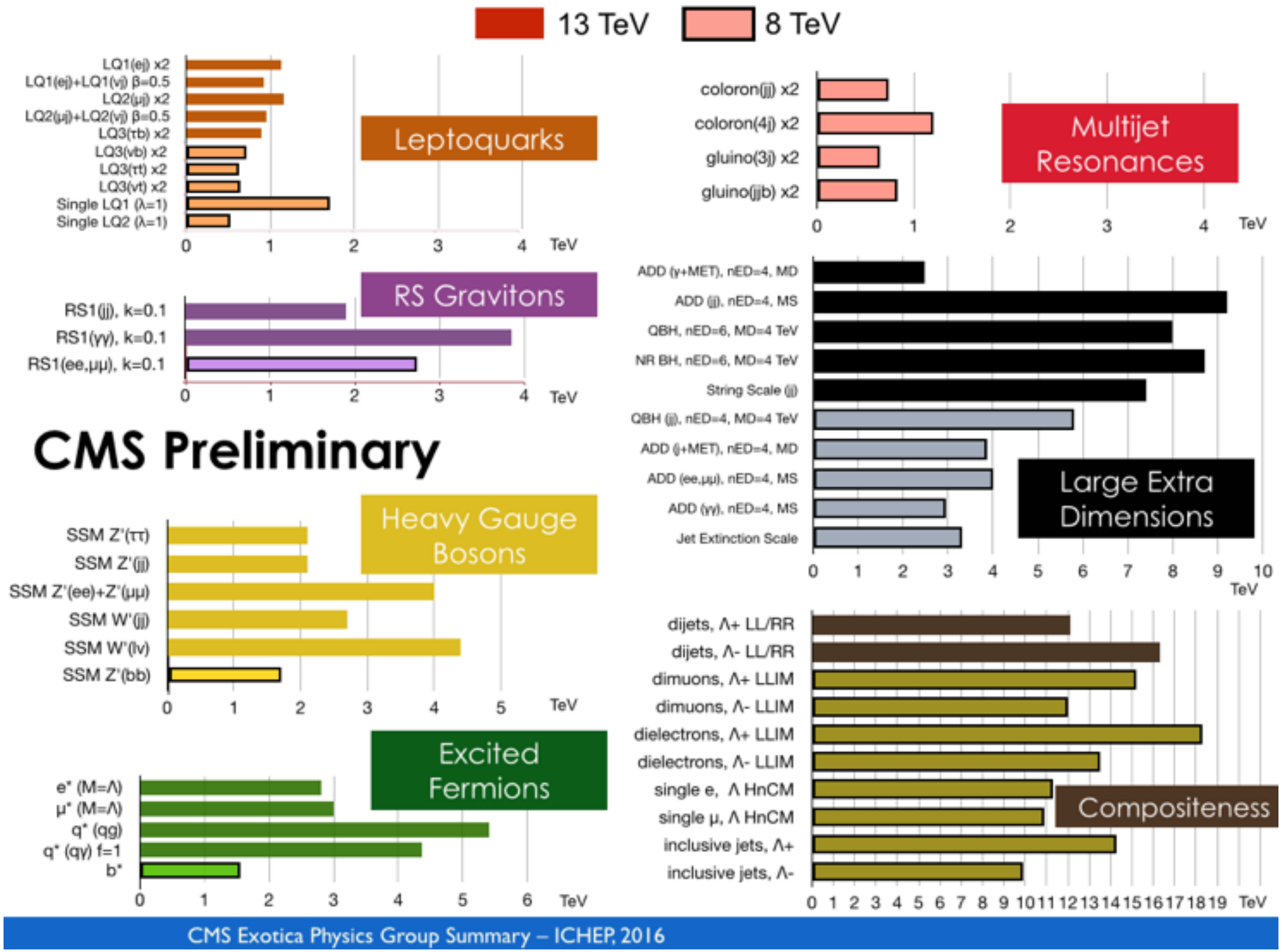
What is BSM?

+?

Nobody really knows…

Current status of BSM searches

Talk by P.Sphicas



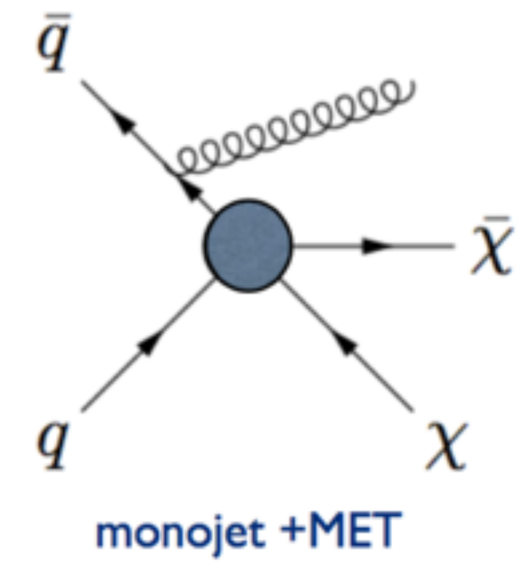
See, however Nikitenko's talk for an excess of events in a ~ 28 GeV dimuon mass region observed in the 8 TeV data

What is BSM?

+ Nothing ?

We can start by looking at experimental facts not addressed by SM…

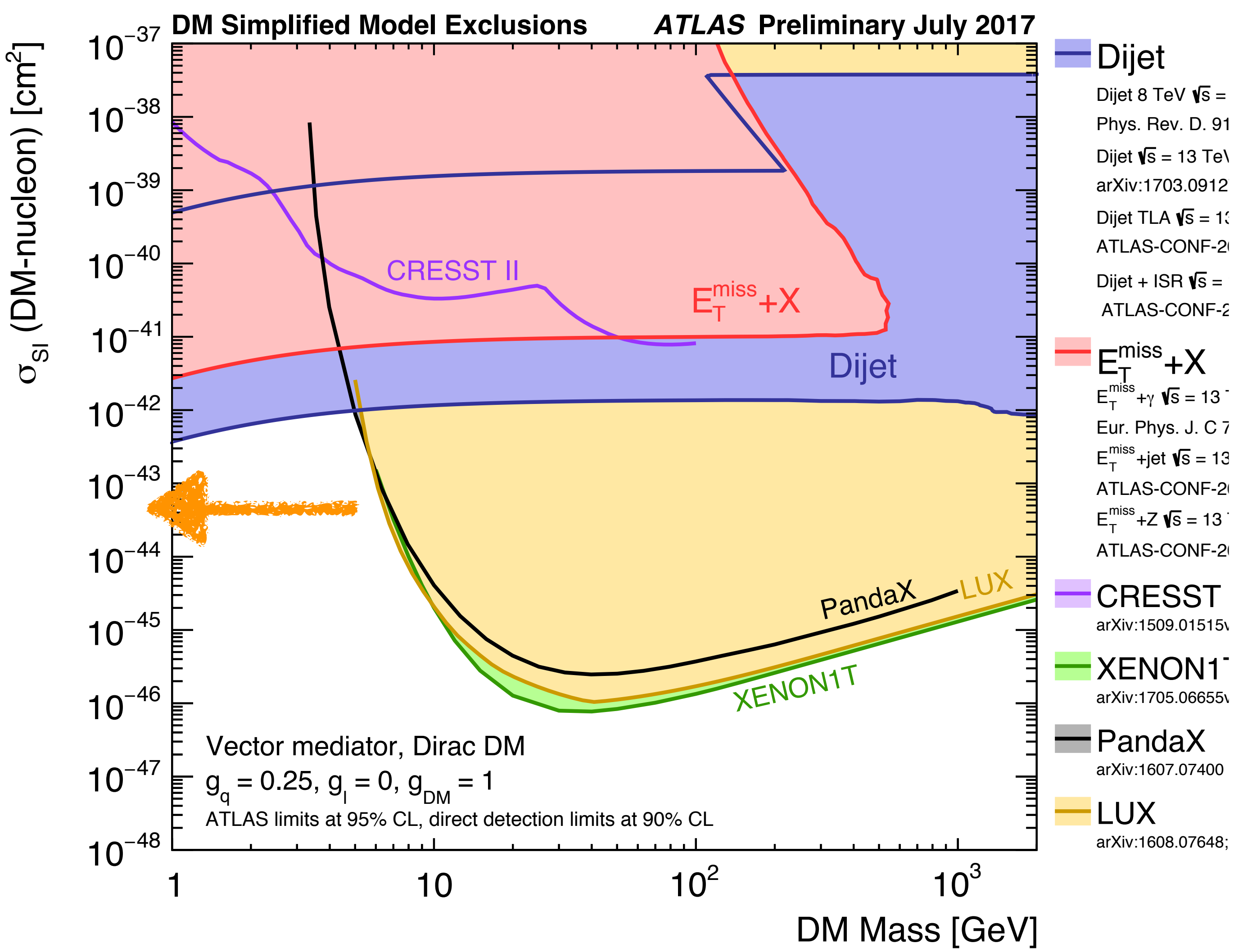
Need for BSM (experiment)



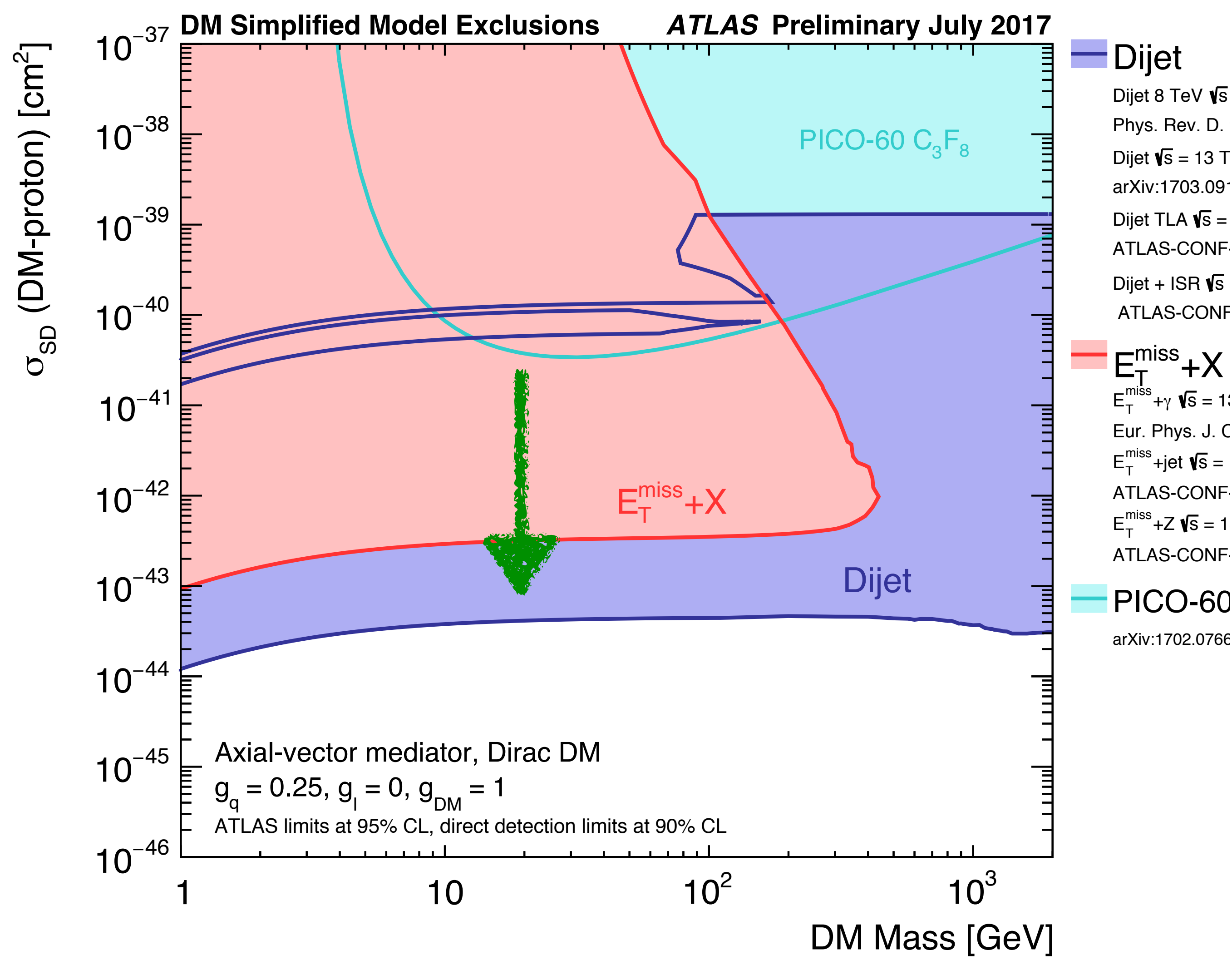
- Dark Matter

mono-X searches@ LHC

Spin-independent DM-nucleon cross section vs m_{DM}



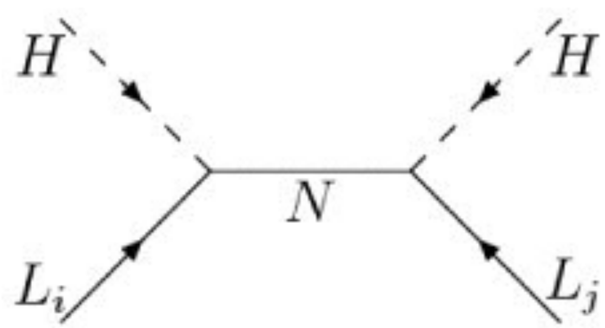
Spin-dependent DM-proton cross section vs m_{DM}



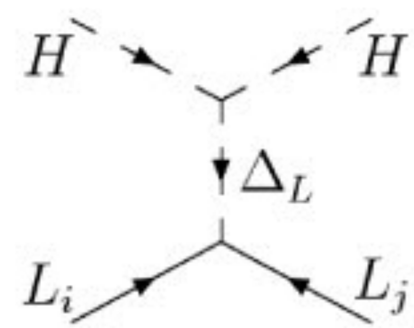
Need for BSM (experiment)

- Neutrino masses $\frac{(HL)^2}{\Lambda_L}$ $\Lambda_L \sim 10^{14}\ GeV$

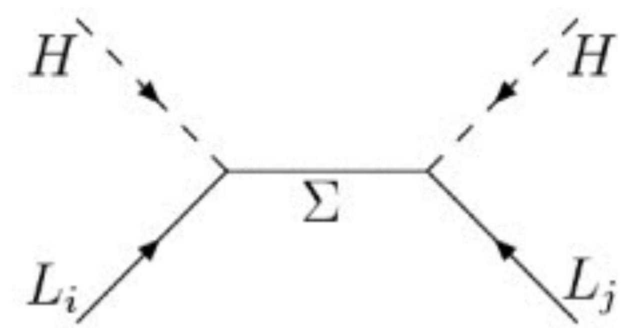
Seesaw



Type-I (RH neutrino)

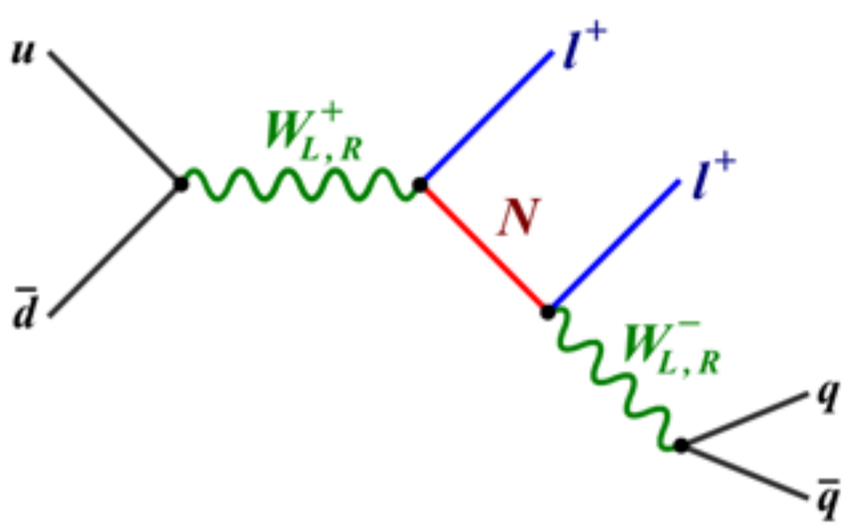


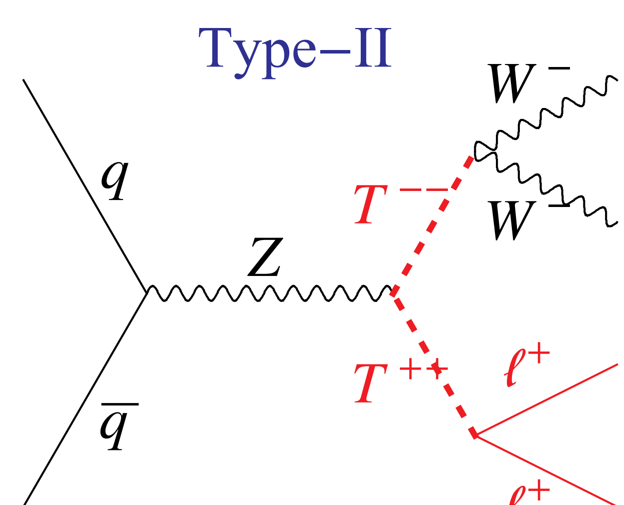
Type-II (scalar triplet)

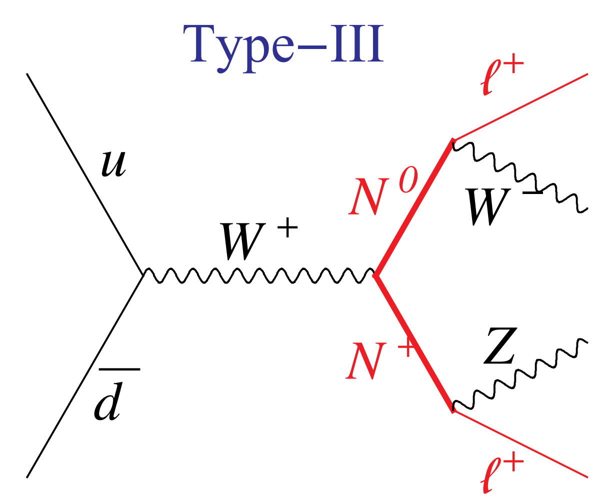


Type-III (fermion triplet)

LHC







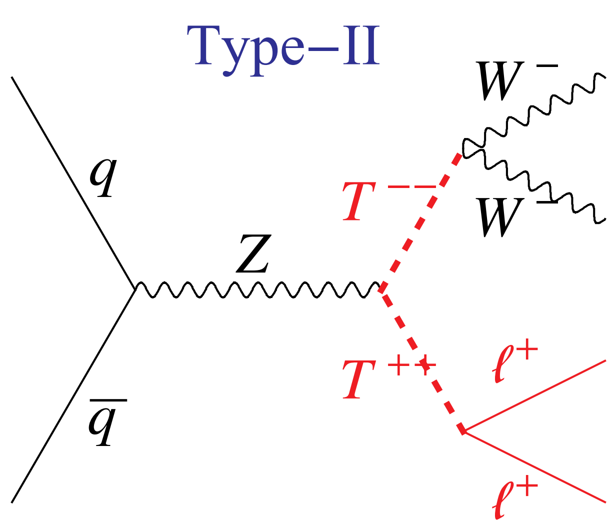
Lepton number violating signals at the LHC

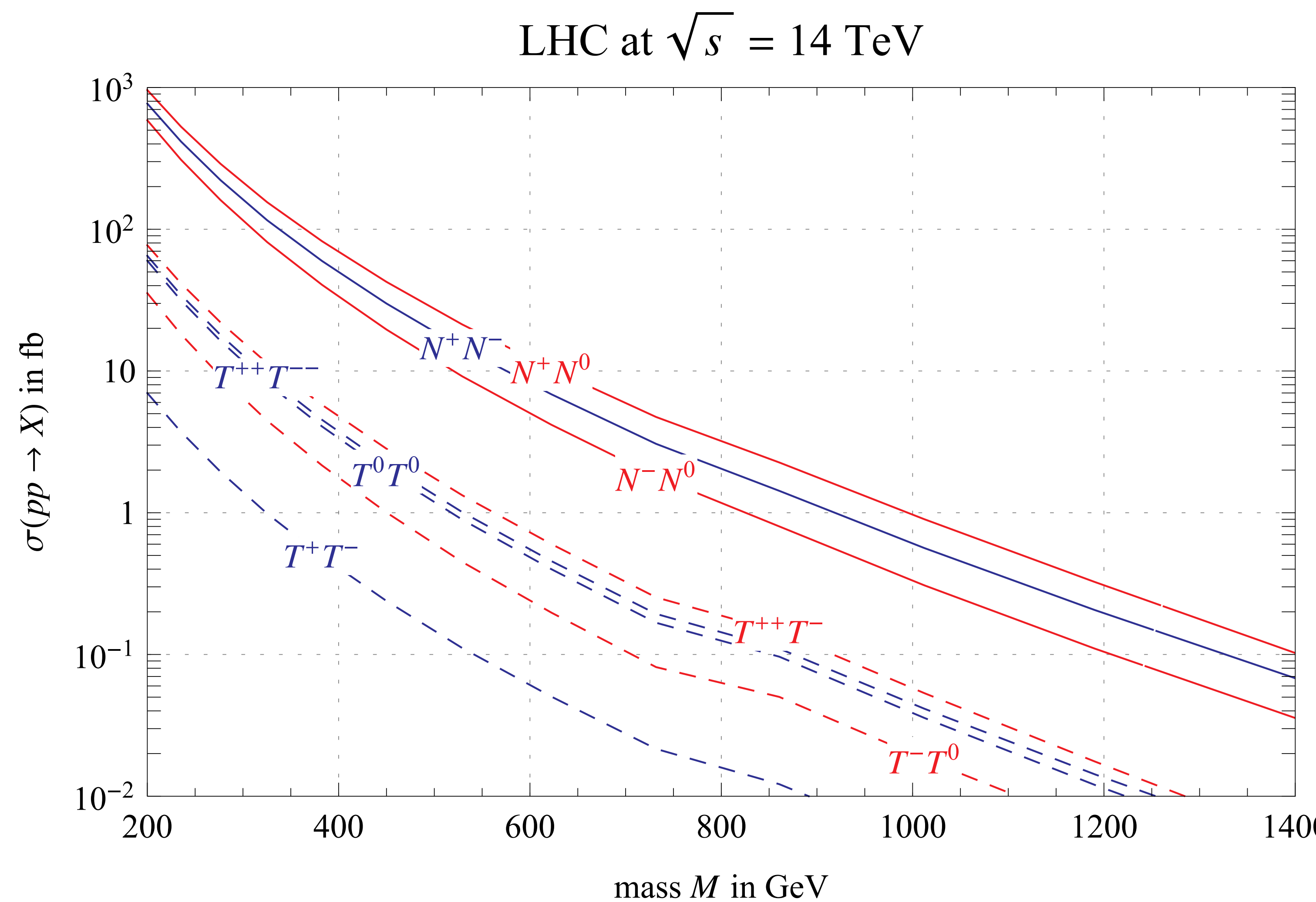
Need for BSM (experiment)

- Neutrino masses

$$\frac{(HL)^2}{\Lambda_L} \qquad \Lambda_L \sim 10^{14}\ GeV$$

$$\mathscr{L} = \mathscr{L}_{\rm SM} + |D_\mu T|^2 - M^2|T|^2 + \frac{1}{2}\Big(\lambda_L LLT + M\lambda_H\, HHT^* + \text{h.c.}\Big) \qquad m_\nu = \lambda_L \lambda_H v^2/M$$





$$pp \to T^{++}T^{--} \to \begin{cases} \ell_1\ell_2\bar\ell_1\bar\ell_2 & \propto \lambda_L^4 \\ W^+W^+W^-W^- & \propto \lambda_H^4 \\ \ell_1\ell_2 W^+W^+ & \propto \lambda_L^2\lambda_H^2 \end{cases}$$

Production controlled by electroweak couplings

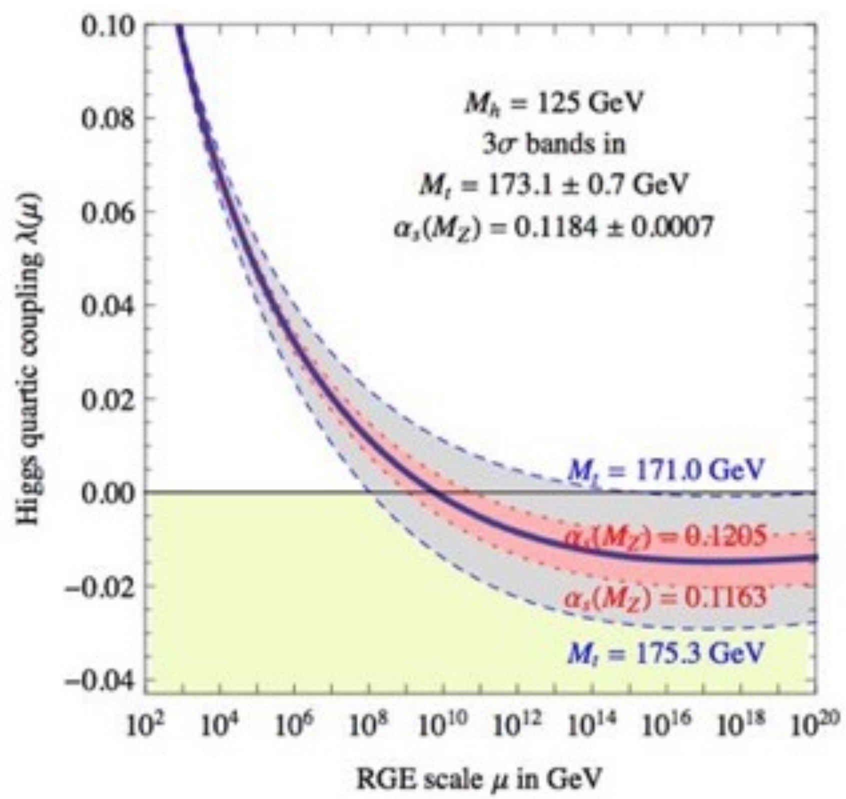
Need for BSM (experiment)

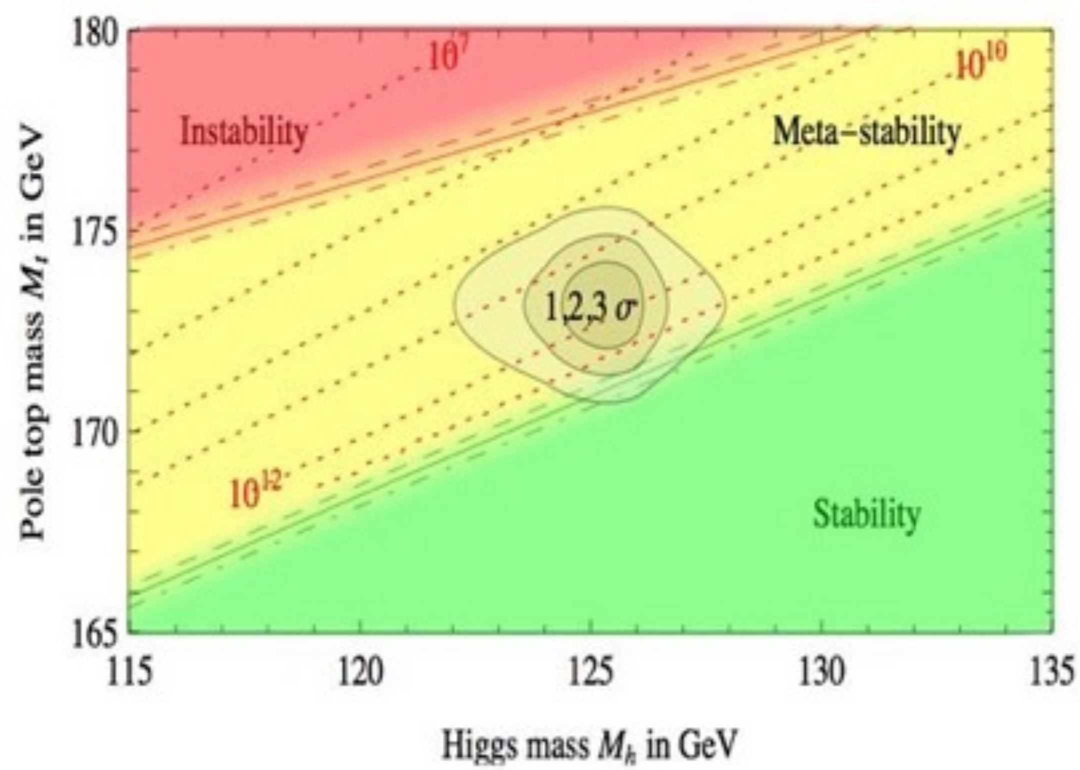
- Matter-antimatter asymmetry
- muon g-2
- ….

Need for BSM (theory)

- Higgs potential metastability

Running of the Quartic Coupling, Metastability





$\lambda \sim 0$
(at the high scale)

Large dependence on top mass and of course Higgs boson mass

Need to measure Higgs, top mass and quartic coupling

Could this be a guiding principle?

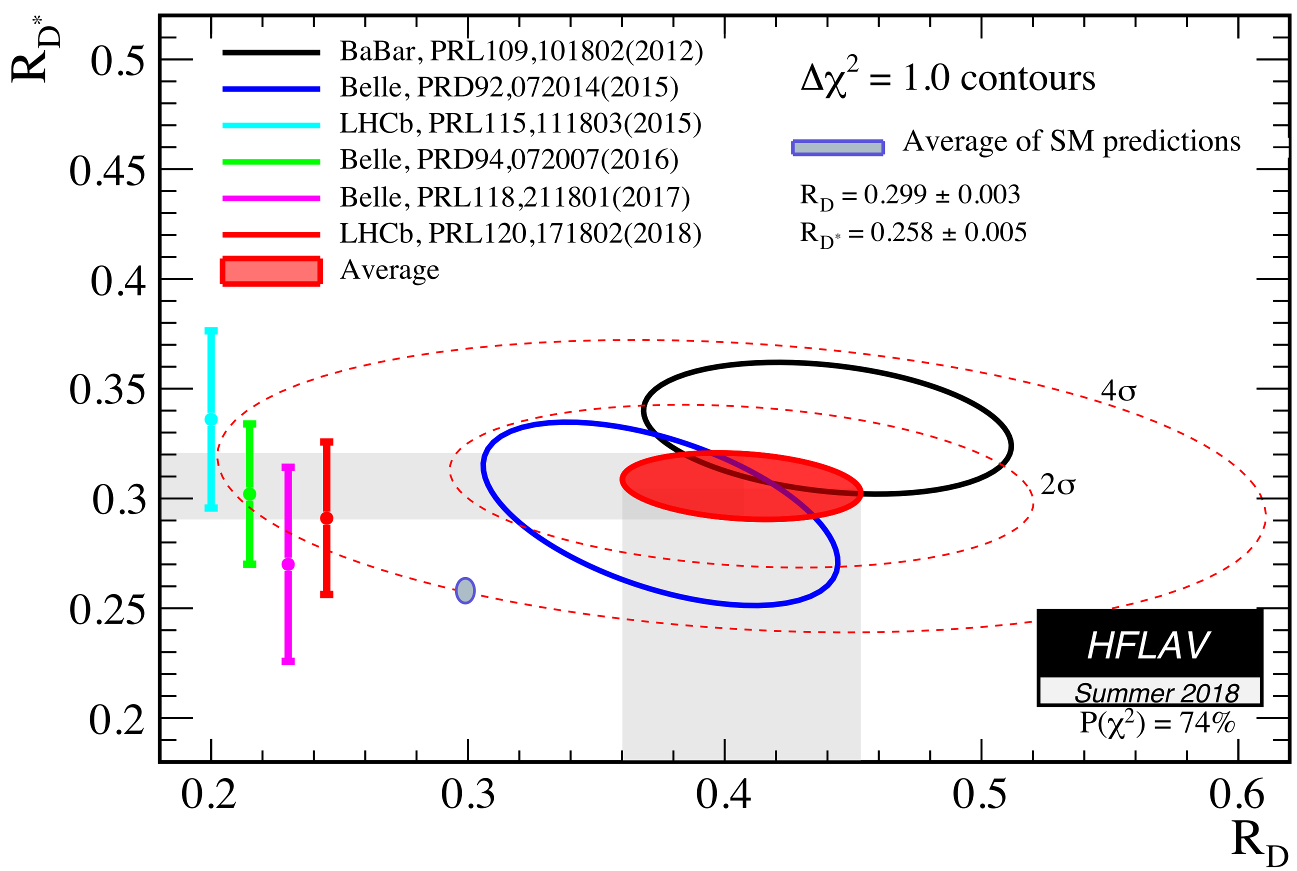
Need for BSM (theory)

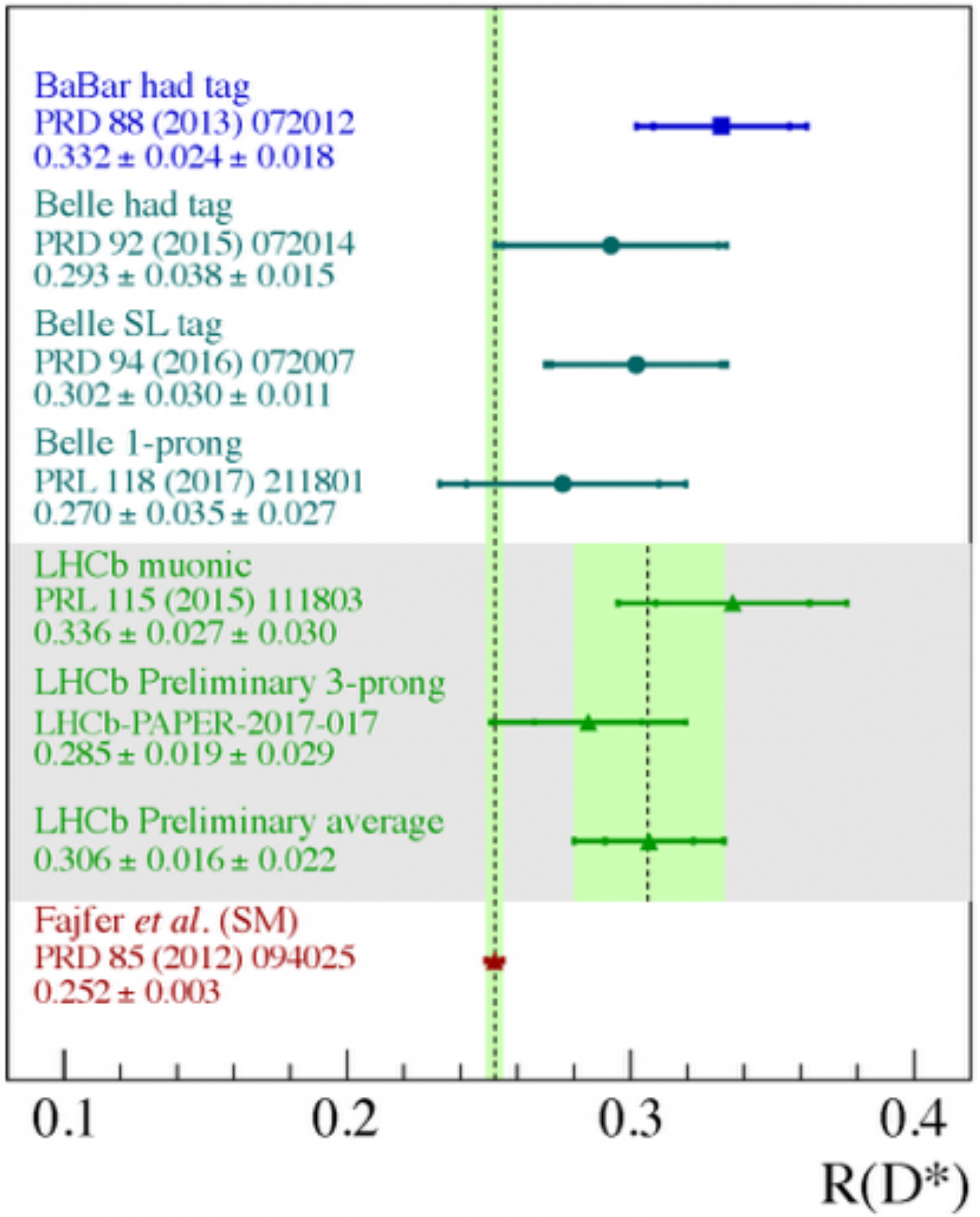
- Flavour problem

Talks later today by
Capriotti, Mihara, Kamenik

Intriguing results from LHCb and Belle experiment with anomalies in B and D meson systems

$$R(D^{(*)}) = \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}l\nu)}$$





Need for BSM (theory)

- Strong CP problem

$$L_{QCD} = \bar{q}(i\gamma_\mu D^\mu - m_q)q - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{\theta}{32\pi^2}\tilde{F}_{\mu\nu}F^{\mu\nu}$$

Experimentally (neutron EDM) : $\theta < 10^{-10}$

why is it so un-naturally small?

Most popular solution: AXION — Peccei Quinn 77

Axion can be also DM candidate !

$$\frac{\theta}{32\pi^2}\tilde{F}_{\mu\nu}F^{\mu\nu}$$

AXIONS

Promote the θ-term to a field "a":

$$L_{axion} = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{a}{32\pi^2 f_a}\tilde{F}_{\mu\nu}F^{\mu\nu}$$

$$\theta_{eff} \to \theta + \frac{< a >}{f_a}$$

The field "a" has a potential just like Higgs and it is minimised for

$$\theta_{eff} = 0$$

It is a dynamical solution independent of the value of the original value of the θ-term

Need for BSM (theory)

- Gauge hierarchy problem (naturalness). Dominant guiding principle for BSM model building

The only dimensionful (quadratically divergent) parameter in the SM :

$$m^2 H^2$$

Small value of this parameter in the SM (compared to, say, Planck scale) is un-natural due to huge fine-tuning

Need for BSM (theory)

- Cosmological constant problem
- Gravity (gravity waves) see talk by N. Leroy
- Proton decay
- …

Not the main LHC focus…

Scale of the new physics

High scale?

- Proton Decay $\frac{uude}{M_{NP}^2}$ $M_{NP} \sim 10^{16}\ GeV$
- Neutrino mass $\frac{(HL)^2}{\Lambda_L}$ $\Lambda_L \sim 10^{14}\ GeV$

Low scale?

- CC problem $M_{NP} \sim 10^{-3}\ eV$
- Naturalness $M_{NP} \sim 1\ TeV$

How do we actually build models?

Two approaches to BSM

- UV guides/predicts IR (strings, GUTs, naturalness)
- IR constraints UV (experiments drive theory)

Naturalness principle

't Hooft

Small value for the coupling is natural if it is associated to the symmetry

- the fermion mass parameters are protected by chiral symmetry

  - Un-naturalness (apparent fine-tuning of the parameter) may signal new physics

- the rho meson (QCD) to cutoff the EM contribution to the charged pion mass

$$M^2_{\pi^\pm} - M^2_{\pi^0} = \frac{3\alpha}{4\pi} M^2_\rho \frac{F^2_\rho}{f^2_\pi} \ln \frac{F^2_\rho}{F^2_\rho - f^2_\pi} \quad \Longrightarrow \quad \Lambda^2_{NP} < \frac{\delta M^2}{\alpha}$$

The only dimensionful (quadratically divergent) parameter in the SM :

$$m^2 H^2$$

Small value of this parameter in the SM (compared to, say, Planck scale) is un-natural due to huge fine-tuning

In a cutoff scheme, with cutoff Λ

$$m^2 = m_0^2 (1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2}) - f_2(\lambda, g_i) \Lambda^2$$

m_0 is bare mass parameter

m is renormalised (measured) mass parameter

- new physics at the TeV scale to cancel the UV sensitivity of the Higgs mass?

Approaches to Higgs naturalness

Single vacuum solutions

1. Symmetry (SUSY, conformality)
2. Form-factor (Composite Higgs/TC)
3. Low UV scale (extra-dimensions, RS,…)

Many vacua solutions (recent developments)

1. Antropic multiverse
2. NNnaturalness with many SM copies
3. Relaxion and cosmological scanning

Single vacuum solutions:

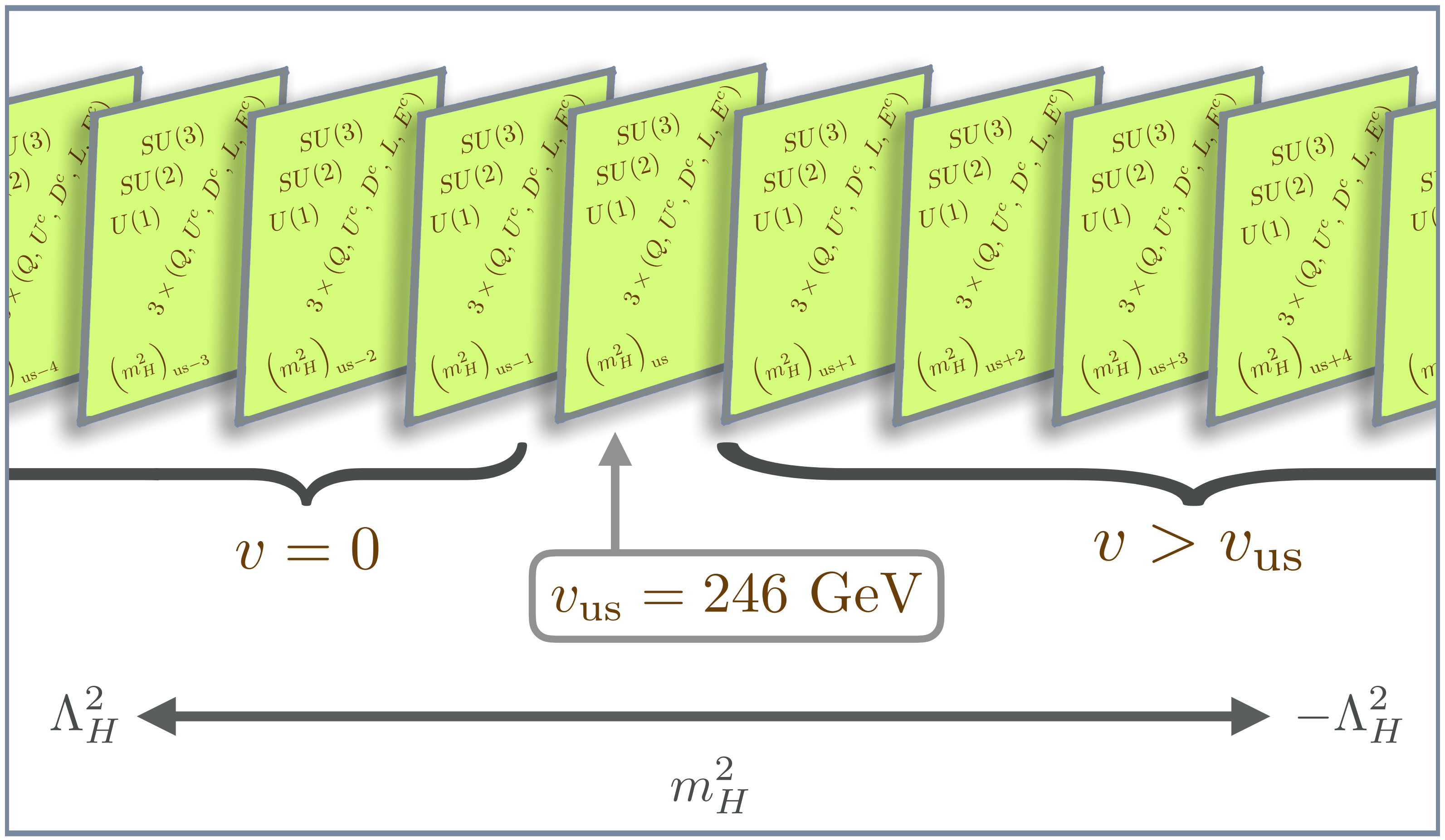
$$m^2 = m_0^2(1 + f_1(\lambda, g_i)\log\frac{\Lambda^2}{m_0^2}) - f_2(\lambda, g_i)\Lambda^2$$

- SM tuning : no predictions for the BSM physics
- SUSY: $f_2 = 0$ by supersymmetry
- Tuning via conformal symmetry: $m_0 = 0, \quad \Lambda$ is dropped
- Composite Higgs/TC : Higgs is not fundamental

Many vacua solutions:

nNaturalness

1607.06821



Some sectors are accidentally tuned at the 1/N level : $\left|m_H^2\right|_{\min} \sim \Lambda_H^2/N.$

Need to change dramatically the cosmological history and hierarchy problem is rephrased into question on how to reheat only sectors with fine-tuned Higgs mass. For this "reheaton" field is introduced which decays predominantly to small Higgs mass sector

Many vacua solutions:

relaxion mechanism in a nutshell

$$m^2 H^2$$

- Higgs mass-squared promoted to a field
- The field evolves in time in the early universe and scans a vast range of Higgs mass
- The Higgs mass-squared relaxes to a small negative value
- The electroweak symmetry breaking stops the time-evolution of the dynamical system

Example of **self-organised criticality** when the dynamical evolution of a system is stopped at a critical point due to back-reaction

Relaxion mechanism

1504.07551

Minimal model: SM + QCD axion + inflaton

$$(-M^2 + g\phi)|h|^2 + V(g\phi) + \frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Below QCD scale:

$$(-M^2 + g\phi)|h|^2 + \left(gM^2\phi + g^2\phi^2 + \cdots\right) + \Lambda^4\cos(\phi/f) \qquad \Lambda^4 \sim f_\pi^2 m_\pi^2$$

- During inflation axion slow-rolls and scans Higgs mass
- Once mass gets negative, Higgs obtains a vev
- Axion potential barriers (linear in the vev) grow and stop scanning

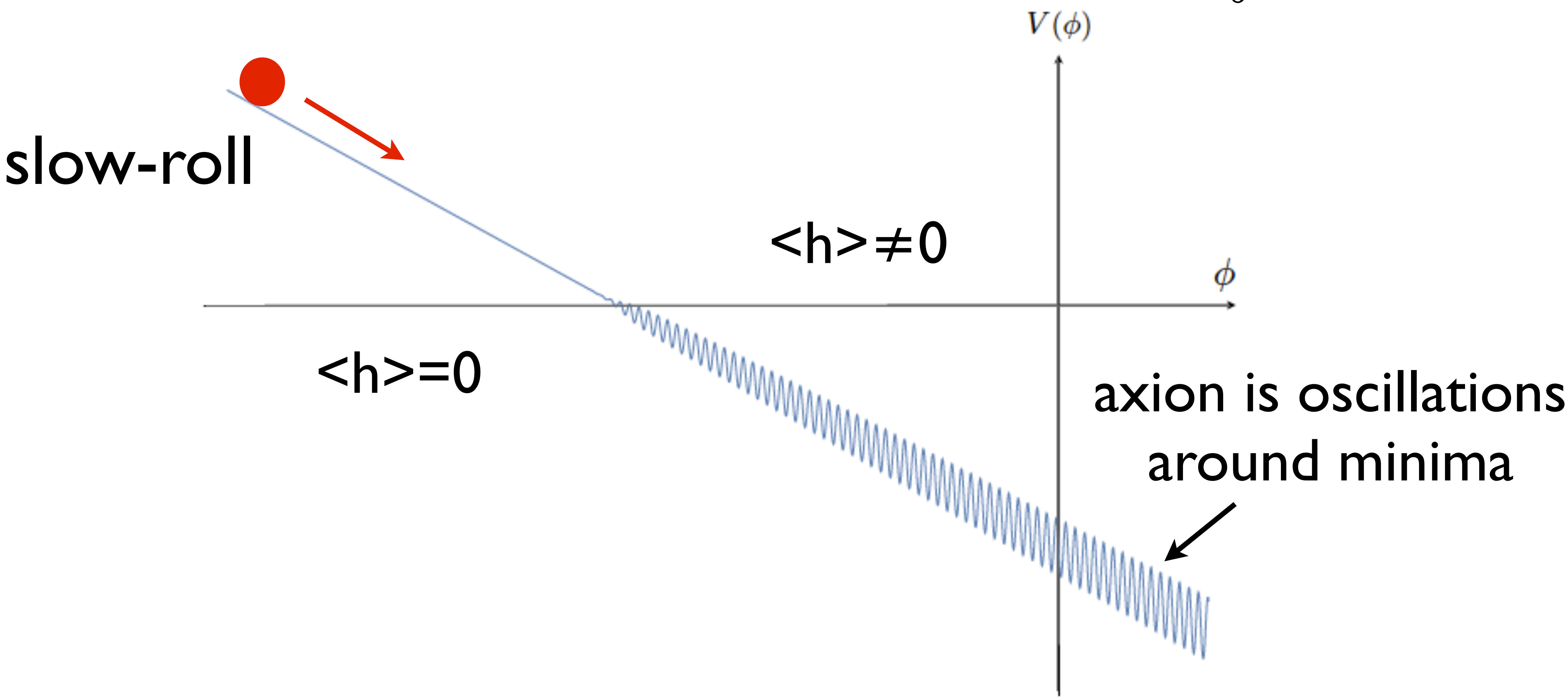
$$m_\pi^2 \sim m_q f_\pi \sim y_q < h > f_\pi \quad \Rightarrow \quad y_q f_\pi^3 < h > \cos\frac{\phi}{f}$$

Relaxion mechanism

$$(-M^2 + g\phi)|h|^2 + \left(gM^2\phi + g^2\phi^2 + \cdots\right) + \Lambda^4 \cos(\phi/f)$$

Rolling stops when slopes match :

$$gM^2 \sim \frac{m_\pi^2 f_\pi^2}{f}$$



Conclusions

- No NP from the LHC so far
- However, new ideas continue to emerge in theoretical community
- A lot of new physics is still to be tested !

The topics to be discussed include:

1 DM (Theory, Observations, Detection)
2 Structures in the Universe
3 New observational probes of the Universe
4 Multimessenger cosmology (Gravitational waves, Cosmic rays, Neutrinos)
5 Unknown physics in the Universe