Physics Beyond the Standard Model: theory perspective

CÉDRIC DELAUNAY

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Outline

- The SM and what it is not
- LHC results and what they tell us
- Multiple frontier era of BSM searches

SM is a great theory

- Successful description of
  - strong and electroweak int. up to 1TeV
  - EWSB (Higgs boson ensures unitarity)
  - flavor and CPV physics (CKM rules!)
- Valid up to very high scales $\Lambda \gg \mathrm{TeV}$
  (with $m_h \approx 125\,\mathrm{GeV}$)
- It's tempting to believe that this is it…
  …but should we?

SM is not complete

- Basic observations unaccounted for:
  - neutrino oscillations
  - (cold) dark matter
  - baryon (+lepton) asymmetry

SM is not satisfactory

- (Hierarchy of) Hierarchy problems:
  - strong CP: $\theta_{\text{QCD}} = \theta + \arg(\det M_q) < 10^{-10}$
  - Higgs mass: $\mu^2 + \Lambda^2 \sim 10^{-32} \left(\Lambda / M_{\text{Pl}}\right)^2$
  - vacuum energy: $\Lambda_c + \Lambda^4 \sim 10^{-120} \left(\Lambda / M_{\text{Pl}}\right)^4$
- Flavor puzzles:
  - (charged) fermion masses: $m_e \sim 10^{-6} m_t$
  - mixing angles: $V_{ub} \sim 0.1 V_{cb} \sim 0.01 V_{us} \sim 0.004$
  - CP phases: $\theta_{\text{QCD}} \ll \theta_{\text{KM}} \sim 70°$

SM is not fundamental

- EWSB is not dynamical (why $\mu^2 < 0$?)
- charge is not quantized
- Why generations? Why only 3? (CP?)
- Do gauge forces unify? $g_{1,2,3}(10^{16}\,\mathrm{GeV}) \sim 0.3$
- Why gravity is weak? $g_{\mathrm{gravity}} \sim (E/10^{19}\,\mathrm{GeV})^2$

Where is BSM physics?

- Unlike the Fermi theory, the SM is an effective description which does not itself reveal **at what scale it breaks**.
- Neutrinos, dark matter, baryon asymmetry do not point to a definite scale either. (although we have clues.)
- One is then left to follow guidance from the principle of **naturalness**:
  long distance is not contingent to short distance

Where is BSM physics?

- **Stability of the Fermi scale**. In past decades we cherished a growing hope for the TeV scale: $\mu^2 H^\dagger H$

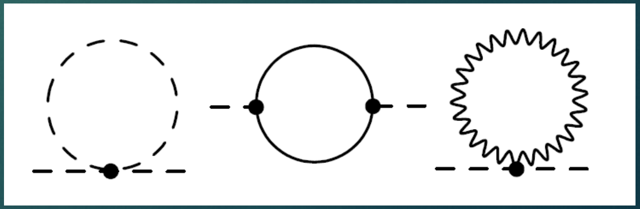
classical level

SM cutoff scale

$$\mu^2 = \mu_0^2 + c_{\rm SM}\frac{\Lambda^2}{16\pi^2} \approx -(90\,{\rm GeV})^2$$

quantum corrections

$$c_{\rm SM} \simeq 12\lambda - 6\sum_f y_f^2 + \tfrac{3}{4}(g^2 + g'^2)$$



Where is BSM physics?

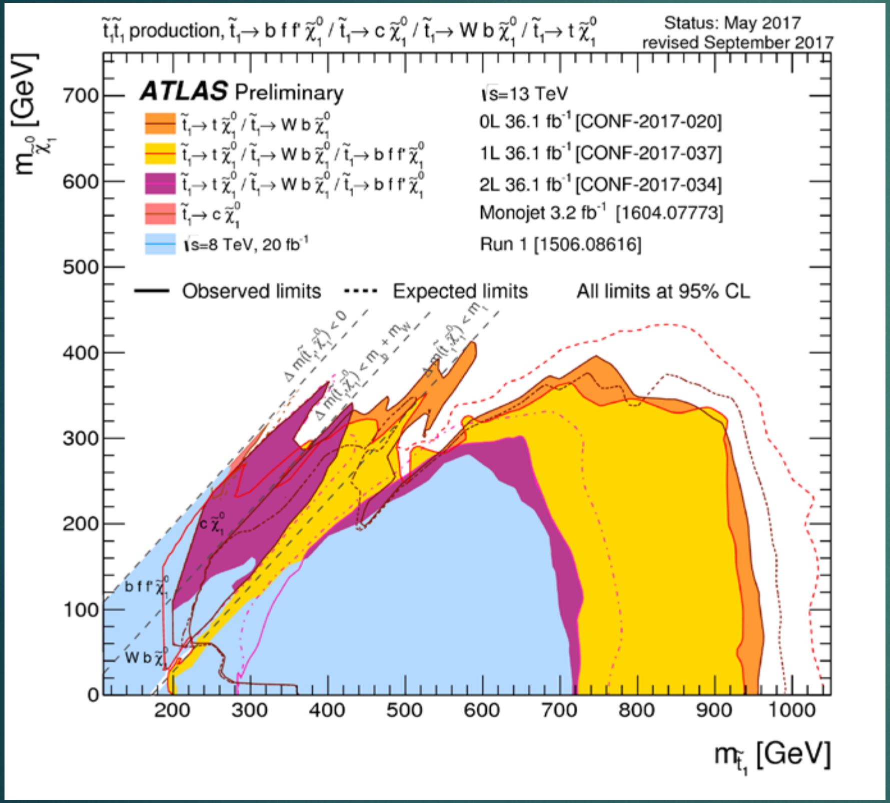
- Either ~~there is a miracle~~ ($\Lambda \gg \mathrm{TeV}$), or **there is science**.

- If $c_{\mathrm{SM}}\Lambda^2/16\pi^2$ is just a « correction » then new physics emerges below $\sim \mathrm{TeV}$:
  - the Higgs field is part of a **strong dynamics** ($\Lambda \sim \mathrm{TeV}$)
  - there are new states related to the SM fields by a **symmetry**: $c \equiv c_{\mathrm{BSM}} + c_{\mathrm{SM}} = 0$

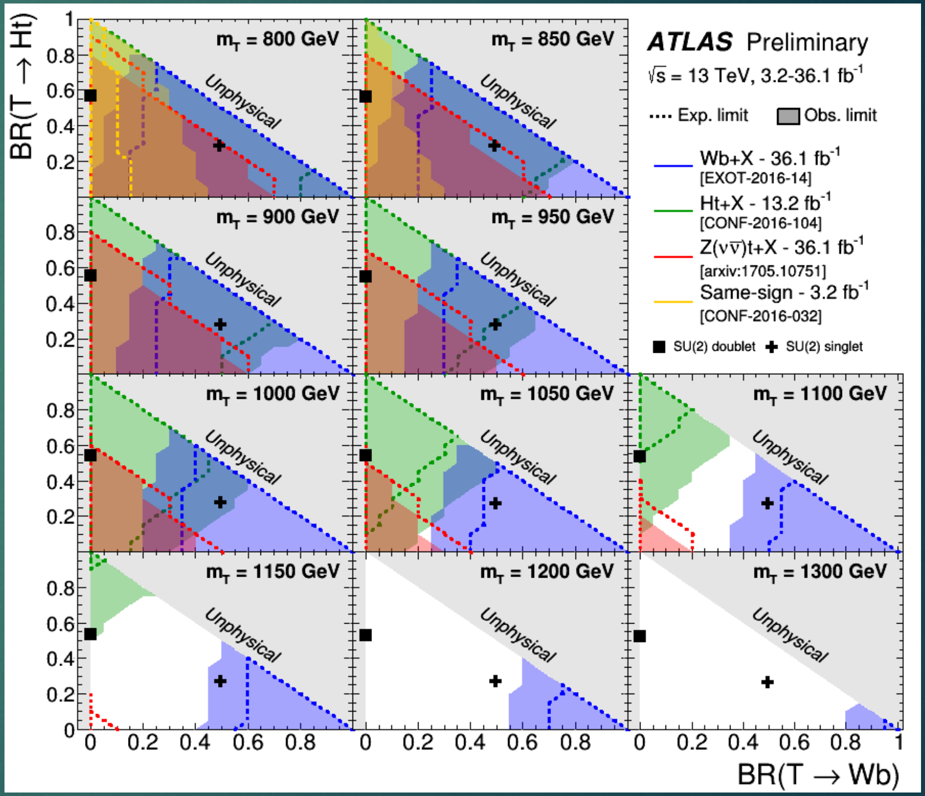
$$\mu^2 \sim \mu_0^2 + \frac{1}{16\pi^2}\log(\Lambda/m_{\mathrm{SM}})$$

Top partners at LHC

scalars (supersymmetry)

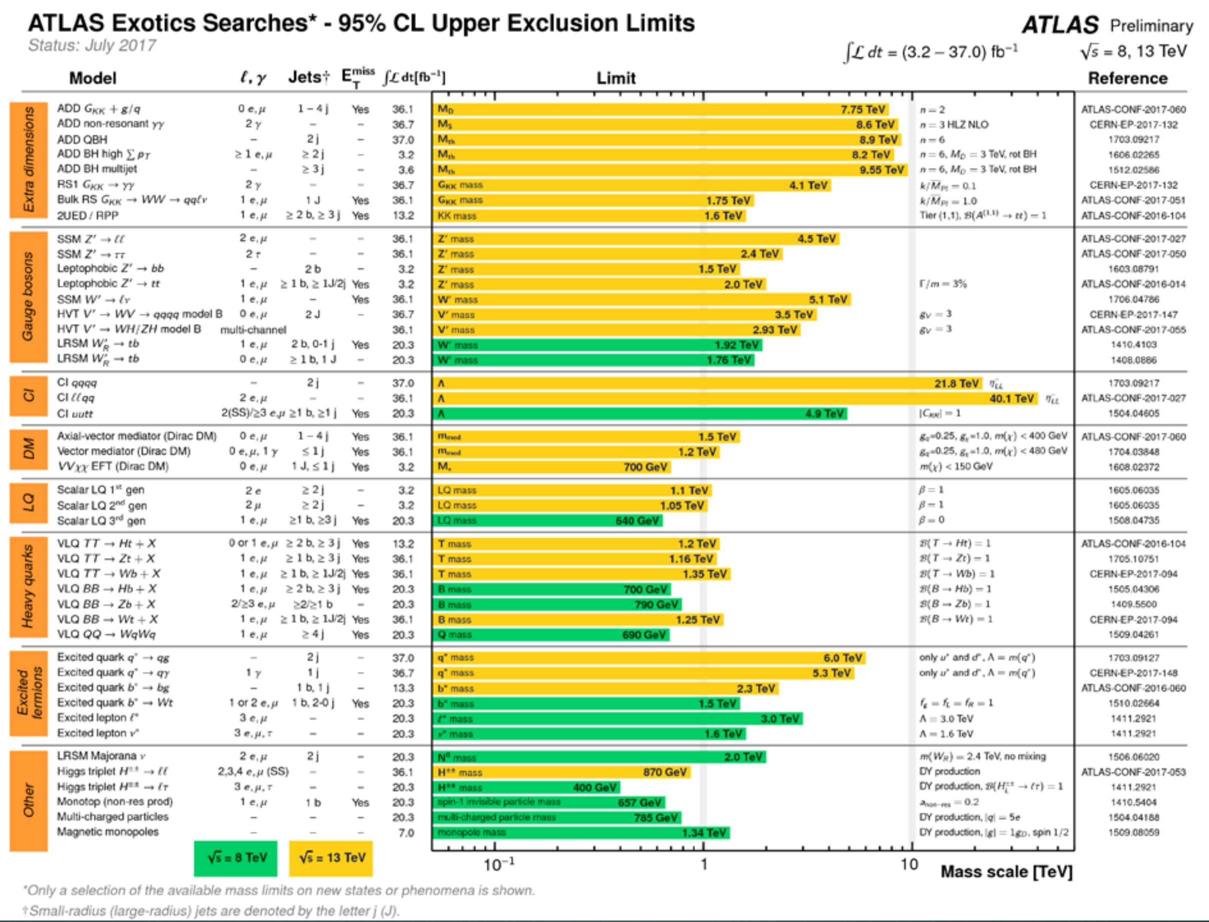


fermions (composite Higgs)



- **No colored partners found up to** $\sim 1\,\mathrm{TeV}$

Exotic searches at LHC



- no new states observed (including DM) up to $\sim 1 - 5\,\mathrm{TeV}$

So what now?

- The Fermi scale could be accidentally **mildly tuned**: BSM is still right around the corner. Keep looking, including **precision measurements**: Higgs, top, flavor physics

- Top partners are not colored: neutral naturalness, **Twin Higgs** and co.

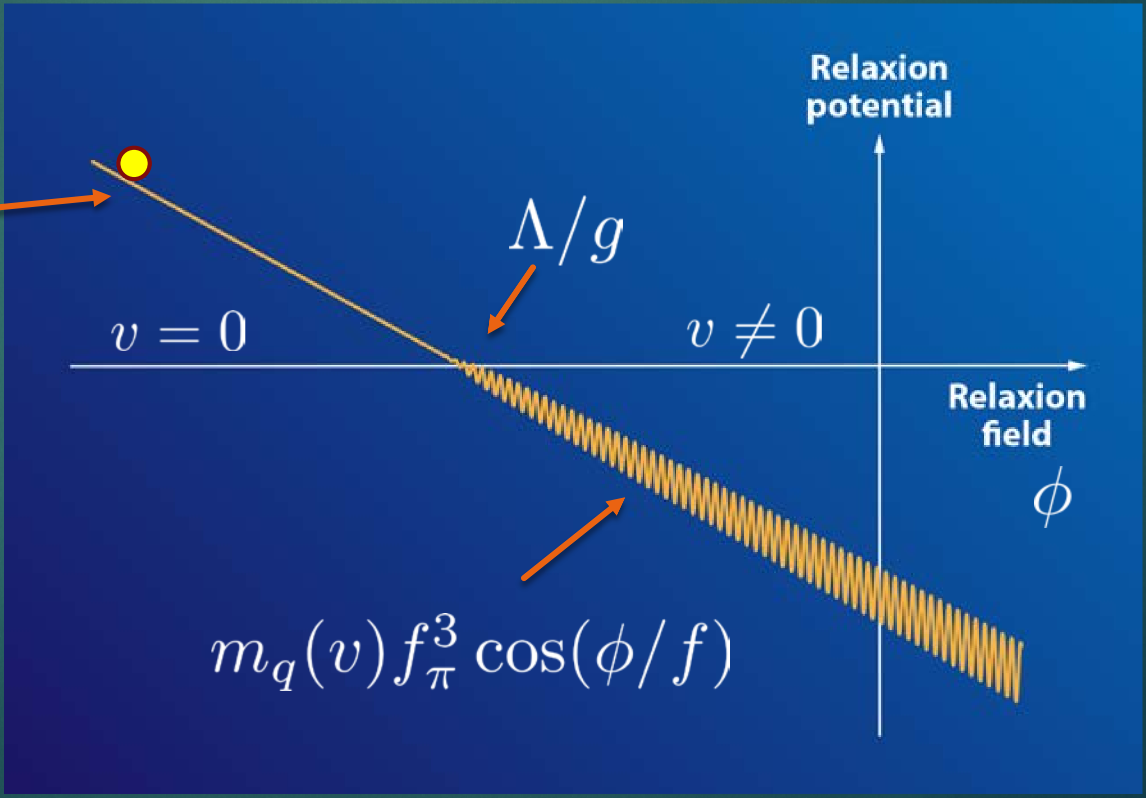
- Perhaps naturalness does not necessarily imply new physics near $\sim \mathrm{TeV}$.

Relaxion

- **The Fermi scale is set by a peculiar cosmological history of a light scalar field:** $\mu^2 \to \mu^2(\phi) = -\Lambda^2 + g\Lambda\phi$

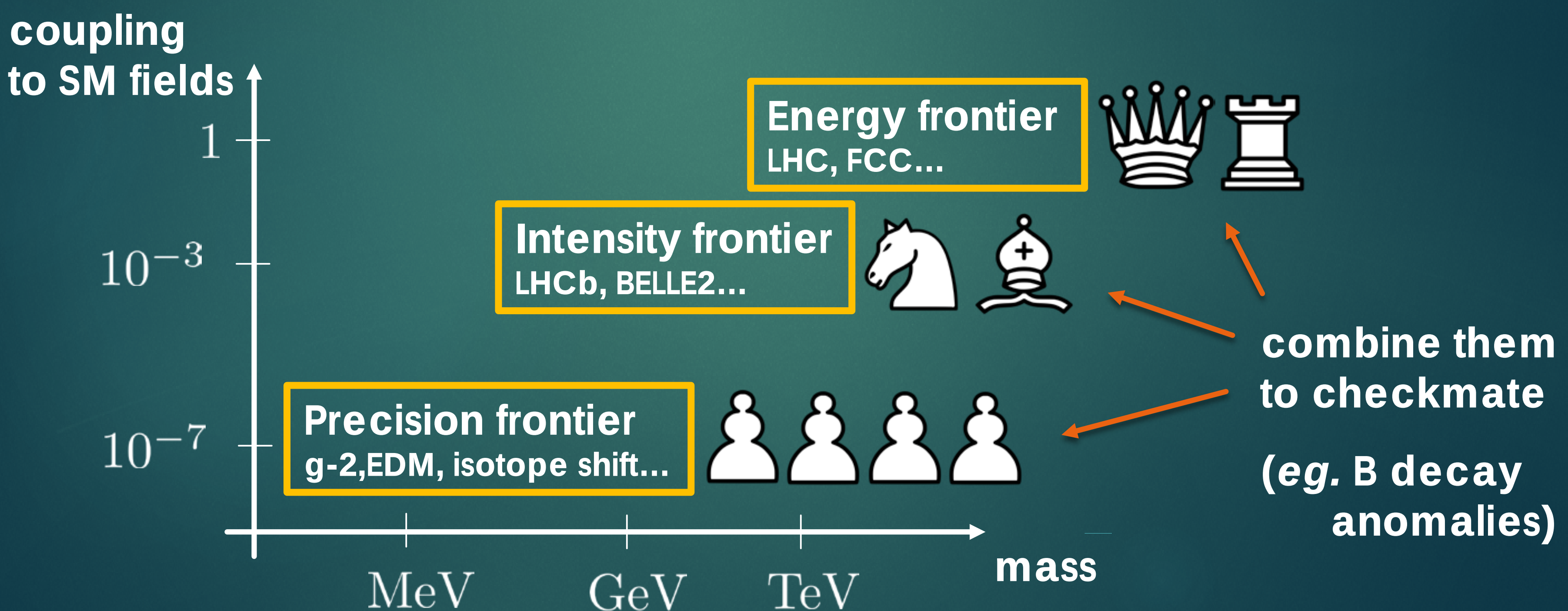
$$V = g\Lambda^3\phi + \frac{1}{2}g^2\Lambda^2\phi^2$$

$$g \sim \frac{m_q f_\pi^3}{\Lambda^3 f} \ll 1$$



A multi-frontier era begins

- New physics can be anywhere
- Need to join efforts from multiple frontiers to find new physics:



Conclusion

- With no BSM discovery at the LHC, we are not in a nightmare scenario.
- Our spectrum of expectations is broader than ever, beyond colliders.
- « *You can never cross the ocean unless you have the courage to lose sight of the shore.* » Christopher Columbus