Physics Beyond the Standard Model: theory perspective cédric delaunay

LAPTH | ANNECY-LE-VIEUX

ENIGMASS meeting | Grenoble | Dec. 7th 2017



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!) \blacktriangleright Valid up to very high scales $\Lambda \gg \text{TeV}$ (with $m_h \approx 125 \, {\rm GeV}$)

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: θ_{QCD} = θ + arg(detM_q) < 10⁻¹⁰
 * Higgs mass: μ² + Λ² ~ 10⁻³² (Λ/M_{Pl})²
 * vacuum energy: Λ_c + Λ⁴ ~ 10⁻¹²⁰ (Λ/M_{Pl})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: $\theta_{\rm QCD} \ll \theta_{\rm KM} \sim 70^{\circ}$

SM is not fundamental

EWSB is not dynamical (why μ² < 0?)
charge is not quantized
Why generations? Why only 3? (CP?)
Do gauge forces unify? g_{1,2,3}(10¹⁶ GeV) ~ 0.3
Why gravity is weak? g_{gravity} ~ (E/10¹⁹ GeV)²

Where is BSM physics?

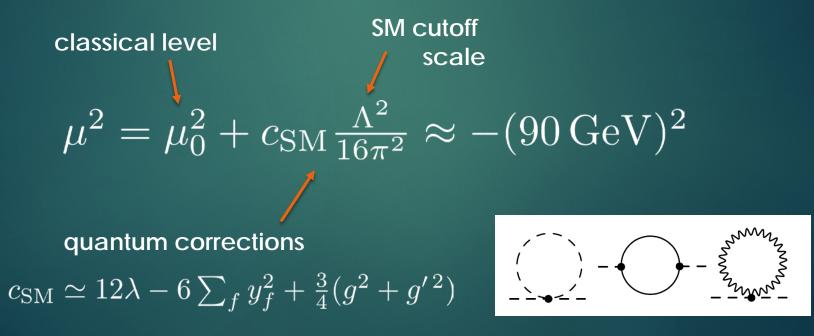
Unlike the Fermi theory, the SM is an effective description which does not itself reveal at what scale it breaks.

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: μ²H[†]H



Where is BSM physics?

• Either there is a miracle ($\Lambda \gg \text{TeV}$), or there is science.

► If $c_{\rm SM}\Lambda^2/16\pi^2$ is just a « correction » then new physics emerges below ~ TeV :

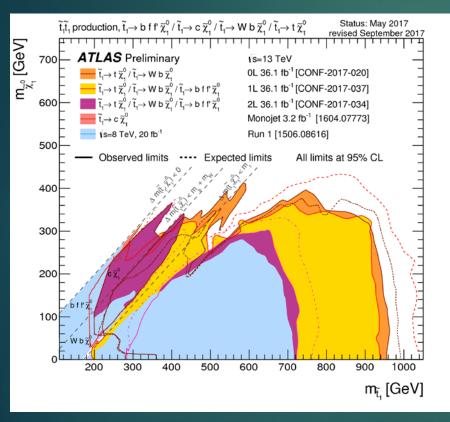
* the Higgs field is part of a strong dynamics ($\Lambda \sim \,{
m TeV}$)

* there are new states related to the SM fields by a symmetry: $c \equiv c_{BSM} + c_{SM} = 0$

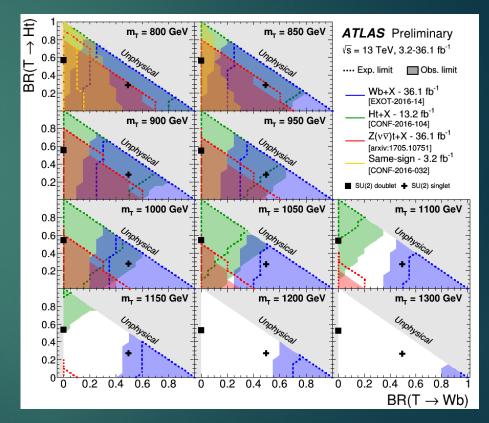
 $\mu^2 \sim \mu_0^2 + \frac{1}{16\pi^2} \log(\Lambda/m_{\rm SM})$

Top partners at LHC

scalars (supersymmetry)



fermions (composite Higgs)



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

Exotic searches at LHC

ATLAS Exotics Searches* - 95% CL Upper Exclusion LimitsATLASPreliminaryStatus: July 2017 $\int \mathcal{L} dt = (3.2 - 37.0) \text{ fb}^{-1}$ $\sqrt{s} = 8, 13 \text{ TeV}$									
010	Model	ί.γ	Jets† I	miss (r d+[0-	5	= (3.2 – 37.0) fb ⁻ *	$\sqrt{s} = 8, 13 \text{ TeV}$ Reference	
	Model	ι,γ	Jets	т Ј-	Curlin			Reference	
Extra dimensions	$\begin{array}{l} \text{ADD } G_{KK} + g/q \\ \text{ADD non-resonant } \gamma\gamma \\ \text{ADD oBH} \\ \text{ADD BH high } \sum p_T \\ \text{ADD BH multijet} \\ \text{RS1 } G_{KK} \rightarrow \gamma\gamma \\ \text{Bulk RS } G_{KK} \rightarrow WW \rightarrow qq\ell\nu \\ \text{2UED / RPP} \end{array}$		1 - 4j - 2j $\ge 2j$ $\ge 3j$ - 1J $\ge 2b, \ge 3j$	- - - - Yes	36.1 36.7 37.0 3.2 3.6 36.7 36.1 13.2	Mo. 775 TeV. Mr. 8.6 Te Ma. 8.0 Te Ma. 8.2 TeV. Ma. 0.55 T Gax mass 4.1 TeV. Kmass 1.75 TeV.	n = 6 $n = 6$, $M_D = 3$ TeV, rot BH	ATLAS-CONF-2017-060 CERN-EP-2017-132 1703.09217 1606.02265 1512.02586 CERN-EP-2017-152 ATLAS-CONF-2017-051 ATLAS-CONF-2016-104	
Gauge bosons	$\begin{array}{l} \mathrm{SSM} \ Z' \to \ell\ell \\ \mathrm{SSM} \ Z' \to \tau\tau \\ \mathrm{Leptophobic} \ Z' \to bb \\ \mathrm{Leptophobic} \ Z' \to tt \\ \mathrm{SSM} \ W' \to \ell\nu \\ \mathrm{HVT} \ V' \to WV \to qqq \ \mathrm{model} \ \mathrm{HVT} \ V' \to WH/ZH \ \mathrm{model} \ \mathrm{B} \\ \mathrm{LRSM} \ W_{R}^{\prime} \to tb \\ \mathrm{LRSM} \ W_{R}^{\prime} \to tb \end{array}$	1 e. µ	- 2 b ≥ 1 b, ≥ 1J/2j - 2 J 4 2 b, 0-1 j ≥ 1 b, 1 J	- Yes Yes - Yes	36.1 36.1 3.2 3.2 36.1 36.7 36.1 20.3 20.3	Z mass 4.3 TeV Z mass 2.4 TeV Z mass 1.5 TeV Z mass 2.0 TeV W mass 5.1 TeV V mass 3.5 TeV V mass 2.93 TeV W mass 1.92 TeV W mass 1.76 TeV	$\Gamma/m = 3\%$ $\delta_V = 3$ $\delta_V = 3$	ATLAS-CONF-2017-027 ATLAS-CONF-2017-050 1603.08791 ATLAS-CONF-2016-014 1706.04786 CERN-EP-2017-047 ATLAS-CONF-2017-055 1410.4103 1408.0886	
C	Cl qqqq Cl ℓℓqq Cl uutt	− 2 e,μ 2(SS)/≥3 e,μ	2 j 	-	37.0 36.1 20.3	Λ Λ Α 4.9 TeV	21.8 TeV η_{LL}^- 40.1 TeV η_{LL}^- $ C_{RR} = 1$	1703.09217 ATLAS-CONF-2017-027 1504.04605	
MQ	Axial-vector mediator (Dirac DM) Vector mediator (Dirac DM) $VV_{\chi\chi}$ EFT (Dirac DM)	1) 0 e, μ 0 e, μ, 1 γ 0 e, μ	$\begin{array}{c} 1-4j \\ \leq 1j \\ 1J, \leq 1j \end{array}$		36.1 36.1 3.2	mode 1.5 TeV mode 1.2 TeV M, 700 GeV	$\begin{array}{l} g_{\rm q}{=}0.25, g_{\chi}{=}1.0, m(\chi) < 400 \; {\rm GeV} \\ g_{\rm q}{=}0.25, g_{\chi}{=}1.0, m(\chi) < 480 \; {\rm GeV} \\ m(\chi) < 150 \; {\rm GeV} \end{array}$	ATLAS-CONF-2017-060 1704.03848 1608.02372	
10	Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen	2 e 2 μ 1 e,μ	≥ 2 j ≥ 2 j ≥1 b, ≥3 j	- - Yes	3.2 3.2 20.3	LO mass 1,1 TeV LO mass 1,05 TeV LO mass 640 GeV	$egin{array}{c} eta = 1 \ eta = 1 \ eta = 1 \ eta = 0 \end{array}$	1605.06035 1605.06035 1508.04735	
Heavy quarks	$ \begin{array}{l} VLQ\ TT \to Ht + X \\ VLQ\ TT \to Zt + X \\ VLQ\ TT \to Wb + X \\ VLQ\ BB \to Hb + X \\ VLQ\ BB \to Zb + X \\ VLQ\ BB \to Wt + X \\ VLQ\ QQ \to WqWq \end{array} $	1 e,μ 1 e,μ 2/≥3 e,μ	$\geq 2 b, \geq 3 j$ $\geq 1 b, \geq 3 j$ $\geq 1 b, \geq 1 J/2j$ $\geq 2 b, \geq 3 j$ $\geq 2/\geq 1 b$ $\geq 1/2 j$ $\geq 2 b, \geq 3 j$ $\geq 2/\geq 1 b$ $\geq 1 b, \geq 1 J/2 j$ $\geq 4 j$	Yes Yes - Yes	13.2 36.1 36.1 20.3 20.3 36.1 20.3	T mass 1.2 TeV T mass 1.16 TeV T mass 1.35 TeV B mass 700 GeV B mass 790 GeV B mass 690 GeV	$\begin{split} &\mathcal{B}(T \to Ht) = 1 \\ &\mathcal{B}(T \to Zt) = 1 \\ &\mathcal{B}(T \to Wb) = 1 \\ &\mathcal{B}(T \to Wb) = 1 \\ &\mathcal{B}(B \to Hb) = 1 \\ &\mathcal{B}(B \to Zb) = 1 \\ &\mathcal{B}(B \to Wt) = 1 \end{split}$	ATLAS-CONF-2016-104 1705.10751 CERN-EP-2017-094 1505.04306 1409.5500 CERN-EP-2017-094 1509.04261	
Excited fermions	Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited quark $b^* \rightarrow Wt$ Excited lepton t^* Excited lepton v^*	- 1 γ - 1 or 2 e,μ 3 e,μ 3 e,μ,τ	2j 1j 1b,1j 1b,20j - -	- Yes	37.0 36.7 13.3 20.3 20.3 20.3	q° mass 6.0 TeV q° mass 5.3 TeV b° mass 2.3 TeV b° mass 1.5 TeV 1' mass 3.0 TeV v° mass 1.6 TeV	only u^* and d^* , $A = m(q^*)$ only u^* and d^* , $A = m(q^*)$ $f_g = f_L = f_R = 1$ A = 3.0 TeV A = 1.6 TeV	1703.09127 CERN-EP-2017-148 ATLAS-CONF-2016-060 1510.02664 1411.2921 1411.2921	
Other	LRSM Majorana ν Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ Montop (non-res prod) Multi-charged particles Magnetic monopoles	$2 e, \mu$ $2,3,4 e, \mu$ (SS $3 e, \mu, \tau$ $1 e, \mu$ - - - - - - - -	2j - 1b - -	- Yes -	20.3 36.1 20.3 20.3 20.3 7.0	N ^e mass 2.0 TeV H ¹⁺⁴ mass 870 GeV H ¹⁺⁴ mass 400 GeV gen' simulable particle mass 657 GeV moltipic-hanged particle mass 785 GeV monopole mais 1.34 TeV	$\begin{split} m(W_R) &= 2.4 \text{ TeV}, \text{no mixing} \\ \text{DY production} \\ \text{DY production}, \mathcal{B}(H_L^{\pm\pm} \to \ell \tau) = 1 \\ a_{\text{non-res}} &= 0.2 \\ \text{DY production}, q &= 5e \\ \text{DY production}, g &= 1g_D, \text{ spin } 1/2 \end{split}$	1506.06020 ATLAS-CONF-2017-053 1411.2921 1410.5404 1504.04188 1509.08059	
	Ys = 0 leV Ys = 1 leV 10 ⁻¹ 1 10 Mass scale [TeV] *Only a selection of the available mass limits on new states or phenomena is shown. *Small-radius (large-radius) jets are denoted by the letter j (J). Mass scale [TeV]								

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

So what now?

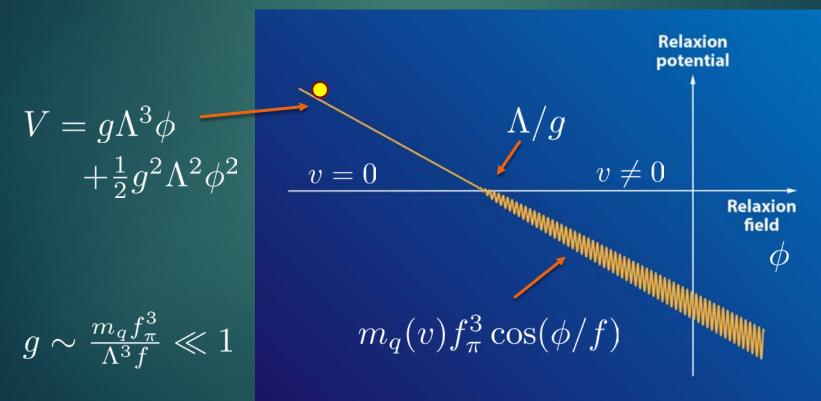
The Fermi scale could be accidentally mildly tuned: BSM is still right around the corner. Keep looking, including precision measurements: Higgs, top, flavor physics

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

Perhaps naturalness does not necessarily imply new physics near $\sim TeV$.

Relaxion

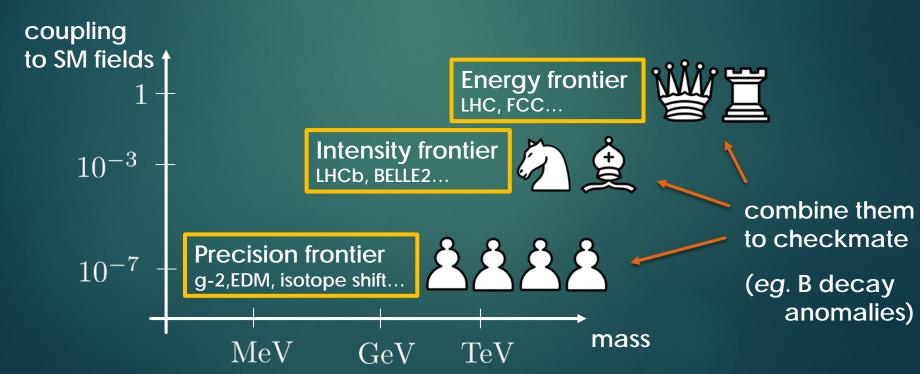
► The Fermi scale is set by a peculiar cosmological history of a light scalar field: $\mu^2 \rightarrow \mu^2(\phi) = -\Lambda^2 + g\Lambda\phi$



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