The W mass and the t mass

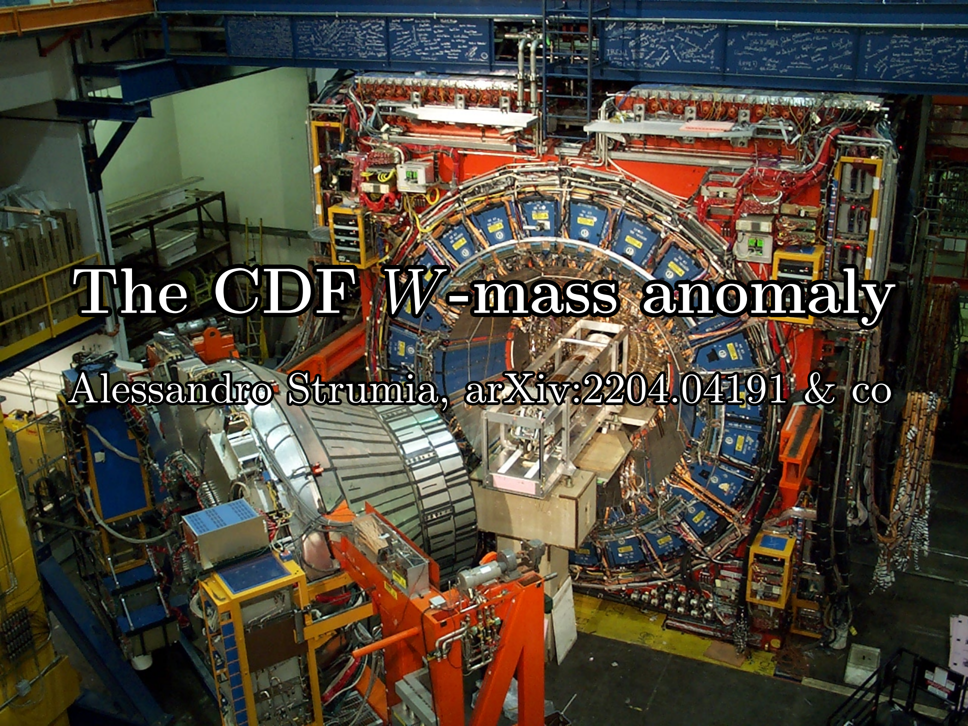
First part: the W-mass anomaly. Second part: future colliders

Alessandro Strumia, Lyon, 2022/6/20

"Fundamental forces from colliders to gravitational waves"

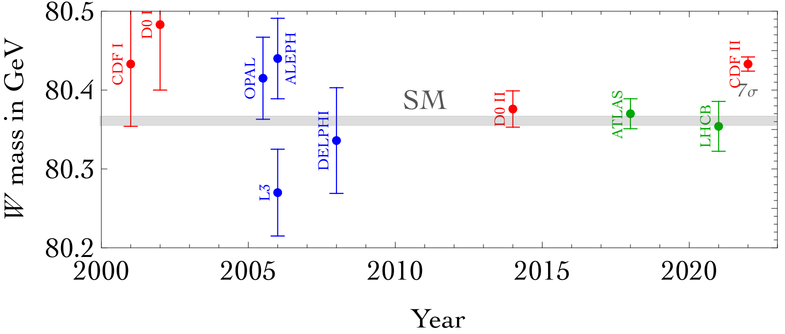
The CDF W-mass anomaly

Alessandro Strumia, arXiv:2204.04191 & co



The CDF W-mass anomaly

CDF claims a W boson mass 7σ or $0.7‰$ higher than the Standard Model



and $\sim 4\sigma$ above other experiments. Dangers of competitive precision physics? Waiting to see if CMS will confirm, we explore interpretations.

SM? It predicts $M_W = M_Z \cos\theta_W + \text{loops}$. M_Z and θ_W are precisely known from other measurements. Loops are perturbative and depend on known M_h, M_t. Changing M_t? The M_W anomaly needs a $\delta M_t \approx +11\,\text{GeV}$ shift: no way.

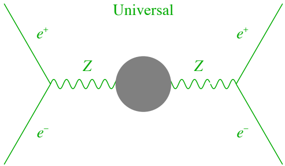
New physics beyond the SM is needed. Can it exist? What can it be?

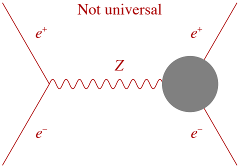
Make M_W heavier or M_Z lighter or distort couplings, compatibly with global fit.

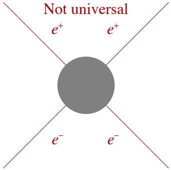
Theory of precision data

But precision tests of the SM were important before LHC... can new physics explain the M_W anomaly without being excluded by LHC? Yes, CDF precision can beat LHC energy, and the simplest 'universal' new physics is enough.

'Universal' or 'oblique' new physics $\equiv$ coupled to W, Z, γ only, writable as $\Pi_{ij}(q^2)$:







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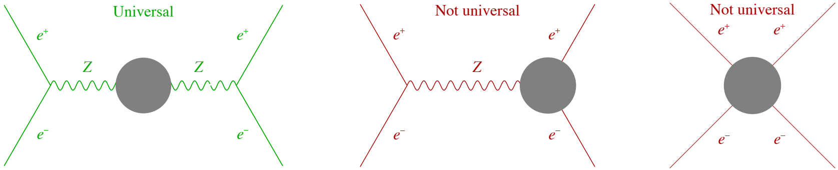

Archeological introduction. Around 1990 precision data were available at $\sqrt{s} = M_Z$ (e.g. g_L, g_R from the LEP1 and SLD colliders) and at $\sqrt{s} = 0$ (e.g. $G_{\rm F}$, $\alpha_{\rm em}$). Physicists noticed that this data tested 3 combinations of vector $\Pi_{ij}(q^2)$, dubbed S, T, U or $\varepsilon_1, \varepsilon_2, \varepsilon_3$. For example $T \sim \Pi_{W_3 W_3}(0) - \Pi_{W^+W^-}(0)$.

This was state of the art when e-mail started, and some physicists still use Pine.

Next LEP2 and LHC tested a wider $\Pi_{ij}(q^2)$ range: **more parameters** needed. Furthermore, no new physics was found around M_Z. The focus shifted on **heavy** new physics, allowing an EFT approach: the decoupling theorem allows to expand $\Pi_{ij}(q^2)$ in Taylor series as $\Pi(q^2) = \Pi(0) + q^2\Pi'(0) + \cdots$, so **less parameters**.

Theory of precision data

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Universal heavy new physics is described, at leading order, by 4 parameters

Dimension-less form factors			operators		
$(g'/g)\widehat{S}$	$=$	$\Pi'_{W_3B}(0)$	$\mathcal{O}_{WB}$	$=$	$(H^\dagger\tau^a H)W^a_{\mu\nu}B_{\mu\nu}$
$M_W^2\widehat{T}$	$=$	$\Pi_{W_3W_3}(0)-\Pi_{W^+W^-}(0)$	$\mathcal{O}_H$	$=$	$\lvert H^\dagger D_\mu H\rvert^2$
$2M_W^{-2}Y$	$=$	$\Pi''_{BB}(0)$	$\mathcal{O}_{BB}$	$=$	$(\partial_\rho B_{\mu\nu})^2/2$
$2M_W^{-2}W$	$=$	$\Pi''_{W_3W_3}(0)$	$\mathcal{O}_{WW}$	$=$	$(D_\rho W^a_{\mu\nu})^2/2$

that are the coefficients of the 4 universal dimension-6 operators

$$\mathscr{L}=\mathscr{L}_{\rm SM}+\frac{1}{v^2}\Big[c_{WB}\mathcal{O}_{WB}+c_H\mathcal{O}_H+c_{WW}\mathcal{O}_{WW}+c_{BB}\mathcal{O}_{BB}\Big].$$

$$\widehat{S}=2\frac{c_{\rm W}}{s_{\rm W}}c_{WB}\ ,\qquad \widehat{T}=-c_H\ ,\qquad W=-g^2c_{WW}\ ,\qquad Y=-g^2c_{BB}.$$

$\mathcal{O}_H=|H^\dagger D_\mu H|^2$ becomes $\widehat{T}$ picking $H\to(0,v)$ and $D_\mu\to A_\mu$.

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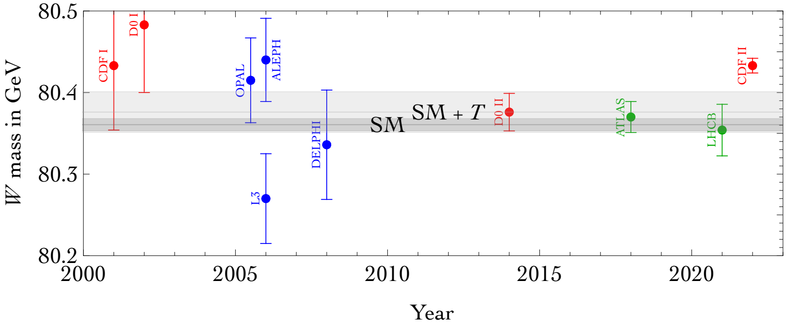
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{v^2}\left[c_{WB}\mathcal{O}_{WB} + c_H\mathcal{O}_H + c_{WW}\mathcal{O}_{WW} + c_{BB}\mathcal{O}_{BB}\right].$$

$$\widehat{S} = 2\frac{c_{\rm W}}{s_{\rm W}}c_{WB}\ , \qquad \widehat{T} = -c_H\ , \qquad W = -g^2 c_{WW}\ , \qquad Y = -g^2 c_{BB}.$$

Rosetta stone: $S = 4s_{\rm W}^2\widehat{S}/\alpha \approx 119\,\widehat{S}$, $T = \widehat{T}/\alpha \approx 129\,\widehat{T}$, U is dimension 8. The full SM-EFT contains 3631 at dimension 6, 44807 at dimension 8: not effective.

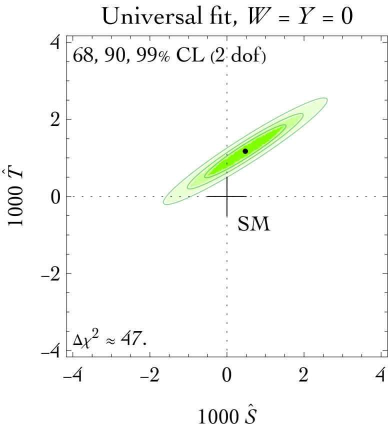
SM + $\widehat{T}$

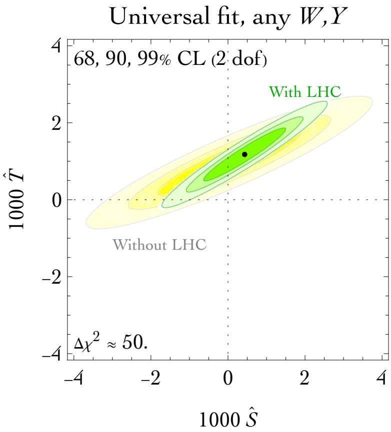
Adding $\widehat{T}$ widens the SM prediction for M_W, but only partially because $\widehat{T}$ modifies other precision data like $G_{\rm F}$. The result is enough to fit the CDF anomaly:



U would affect M_W only, but it's not needed and sub-leading in ~all models.

Universal fit for $\widehat{S}, \widehat{T}$

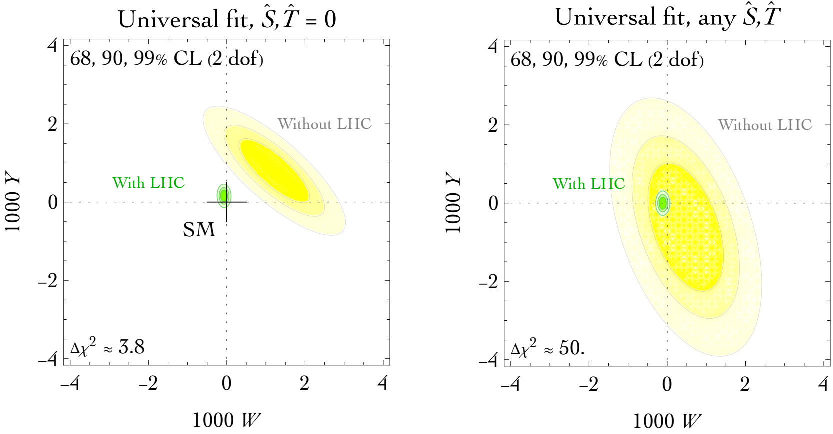




7σ allows qualitative fit: $\delta M_W/M_W \simeq (c_{\rm W}^2 \widehat{T}/2 - s_{\rm W}^2 \widehat{S})/(c_{\rm W}^2 - s_{\rm W}^2) + \cdots$ so:

- good fit for $\widehat{T} \approx 10^{-3}$ i.e. $-|H^\dagger D_\mu H|^2/(6\,\mathrm{TeV})^2$;
- strong correlation with $\widehat{S}$: $\widehat{S} \sim \widehat{T}$ allowed but not needed;
- $\widehat{S}$ with $\widehat{T} = 0$ can also fit, but poorly.

Universal fit for W, Y

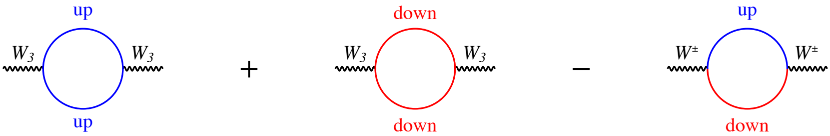


W, Y alone cannot fit. These effective operators recently got much strongly constrained by LHC $q\bar{q} \to \ell\ell$ than by LEP $e^+e^- \to \ell^+\ell^-$: energy won over precision. This does not happen for $\widehat{T}$ because it gives energy-enhanced $hh \to hh$, but not

$$\frac{\Gamma(h \to ZZ)/\Gamma(h \to WW)}{\Gamma(h \to ZZ)_{\rm SM}/\Gamma(h \to WW)_{\rm SM}} = 1 - 4\widehat{T}, \qquad \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} \approx 1 + 0.084\ 10^3 \widehat{S}$$

New physics: at loop level?

$\widehat{T}$ generated by loop of $\mathrm{SU}(2)_L$ multiplet with splitted components: $m, m+\Delta m$



$$\widehat{T} = \frac{\Pi_{W_3 W_3}(0) - \Pi_{W^+W^-}(0)}{M_W^2} \sim \frac{g_2^2 \Delta m^2}{(4\pi M_W)^2}$$

E.g. the SM top/bottom loop is like $\widehat{T} = \frac{3}{4}\frac{g_2^2 M_t^2}{(4\pi M_W)^2}$ showing $\delta M_t \sim 11\,\mathrm{GeV}$.

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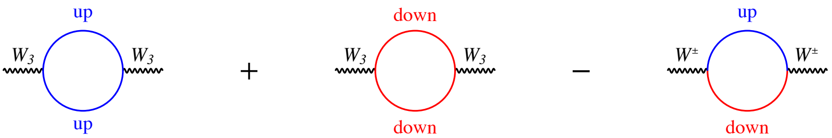

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Warning: heavier particles give bigger $\widehat{T}$? No! Cannot put Δm by hand.
The mass splitting must come from couplings g to the Higgs, as $\Delta m \sim y^2 v^2/m$.
So new physics decouples, $\widehat{T} \sim y^4 v^2/(4\pi m)^2$ as for any dimension-6 operator.

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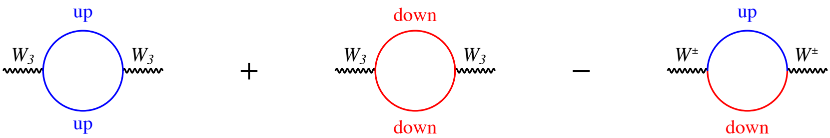

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Warning: splitting among different multiplets does not contribute to $\widehat{T}$.

New physics: at loop level?

Loop level

Generic coupling y gives $\widehat{S}, \widehat{T}, W, Y \approx \frac{y^4 v^2}{(4\pi m)^2} \qquad \Rightarrow \qquad \frac{m}{y^2} \sim 400\,\text{GeV}$.

Mostly excluded by LHC, unless hidden (e.g. quasi-degenerate decay in DM) or irrelevant (papers leave the collider issue in limbo). Examples, $f(1) = 1$:

- Gaugino+higgsino gives $\widehat{T} \simeq \frac{3}{16} \frac{g_2^4 v^2}{(4\pi M_2)^2} f(\frac{\mu}{M_2})$ so $M_2, \mu \lesssim 150\,\text{GeV}$.
- Stop gives $\widehat{T}_{\text{stop}} \simeq \frac{1}{6} \frac{y_t^4 v^2}{(4\pi M_{\tilde{Q}})^2}$ so $M_{\tilde{Q}} \sim M_t$.
- Inert Higgs $m^2|H'|^2 + \lambda_4 |H^* H'|^2 + \lambda_5[(H^* H')^2 + \text{h.c.}]/2 + \cdots$ gives $\widehat{T}_{\text{inert}} \simeq \frac{(\lambda_4^2 - \lambda_5^2) v^2}{6(4\pi m)^2}$, so $m \sim M_t$ if $\lambda_{4,5} \sim 1$. $H' \to -H'$ allows DM.
- Generic 2 Higgs doublets: same, without the DM benefit.
- Vector-like leptons $L' + N'$: $M_L \bar{L}' L' + \frac{1}{2} M_N N'^2 + \frac{1}{\sqrt{2}} y(HL' + H^* \bar{L}') N'$ give $\widehat{T} \simeq \frac{9}{5} \frac{y^4 v^2}{(4\pi M_L)^2} f(\frac{M_L^2}{M_R^2})$ so $M_{L,R}/y^2 \sim 500\,\text{GeV}$.
  Can be DM if $y \gtrsim 2$; fit the $g-2$ anomaly (?); models link with m_ν...

New physics: at tree level?

Tree level

- Scalar triplet T with $Y = 0$ and $A\,HH^\dagger T$ gives $\widehat{T} = 2v_T^2/v^2 > 0$, so $v_T \approx 3\,\text{GeV}$ and $M_T \approx \sqrt{Av^2/v_T}$ above LHC bounds $M_T \gtrsim 250\,\text{GeV}$. ($2T$ allow unification, but at $10^{14}\,\text{GeV}$).
- Triplet with $Y = 1$ and HHT^* (type II see-saw) gives $\widehat{T} = -2v_T^2/v^2$.
- Quadruplet Q with $Y = 1/2$ and $\lambda\,HH^\dagger HQ^*$ gives dimension-8 $\widehat{T} = 6v_Q^2/v^2 > 0$ so $v_Q \approx 2\,\text{GeV}$ and $M_Q \approx (\lambda v^3/v_Q)^{1/2}$ (ok?).
- Q with $Y = 3/2$ and $HHHQ^*$ gives $\widehat{T} = -6v_Q^2/v^2 < 0$.
- Extra Z' vector coupled to the Higgs as $Z'_\mu(H^\dagger D_\mu H)$. Intuitively: Z' gives correct sign because Z and Z' mix, reducing M_Z.
- Vector triplet with $Y = 1$, or vector doublet with $Y = 1/2$. Gauge?

Full theories: anything that mostly messes with the Higgs can give $|H^\dagger D_\mu H|^2$. E.g. technicolor, composite H, extra dimensions, little Higgs...

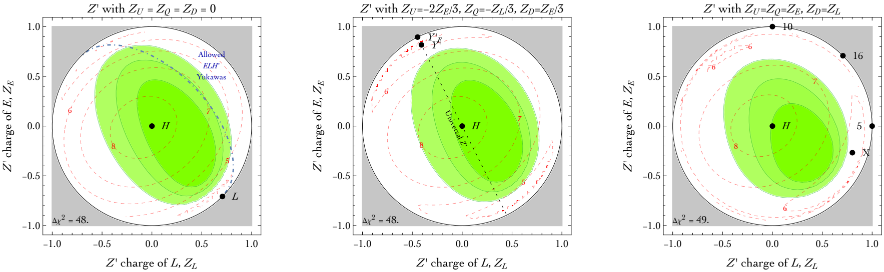
New physics: extra Z'

Generic Z' characterized by $M_{Z'}$, $g_{Z'}$ and charges Z_H, Z_L, Z_E, Z_Q, Z_U, Z_D.

Not universal. Rough universal-like approximation neglecting less precise quarks:

$$\widehat{T} = \frac{4M_W^2 g_{Z'}^2}{g^2 M_{Z'}^2}(Z_E - Z_H + Z_L)^2 \geq 0, \qquad \frac{M_{Z'}}{g_{Z'}} \approx 8\,\mathrm{TeV}|Z_E - Z_H + Z_L|.$$

Non-universal fits for $M_{Z'}/g_{Z'}$, can set $Z_H = \sqrt{1 - Z_L^2 - Z_E}$. Best is Z_H alone.



LHC bounds strongly depend on $Z_{Q,U,D}$. If they are order one: Z' lighter than $\sim 4\,\mathrm{TeV}$ excluded; heavier constrained by $(\bar{q}\gamma_\mu q)(\bar{\ell}\gamma_\mu \ell)/\Lambda^2$ as $\Lambda \gtrsim 10\,\mathrm{TeV}$.

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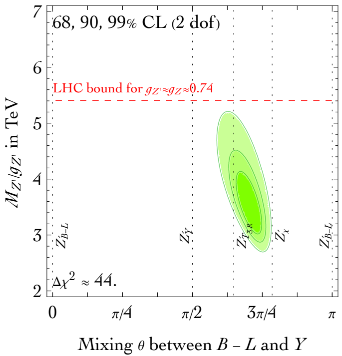
The most reasonable Z' with $Z_i = (B-L)_i \cos\theta + Y_i \sin\theta$ fits not too well

U(1)	Z_H	Z_L	Z_D	Z_U	Z_Q	Z_E
H	1	0	0	0	0	0
Y'	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{3}$	$-\frac{2}{3}$	$\frac{1}{6}$	1
Y'_F	0	$-\frac{1}{2}$	$\frac{1}{3}$	$-\frac{2}{3}$	$\frac{1}{6}$	1
$B-L$	0	-1	$-\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	1
L	0	1	0	0	0	-1
10	0	0	0	1	1	1
5	0	1	1	0	0	0
X	$\frac{2}{3}$	1	1	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
16	0	1	1	1	1	1
T_{3R}	$-\frac{1}{2}$	0	$-\frac{1}{2}$	$\frac{1}{2}$	0	$-\frac{1}{2}$
χ	2	3	3	-1	-1	-1



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New physics: little Higgs models

Tried achieving Higgs naturalness as pseudo-Goldstone. But bounds from precision data prevented naturalness. Good now. Contain Z' and more.

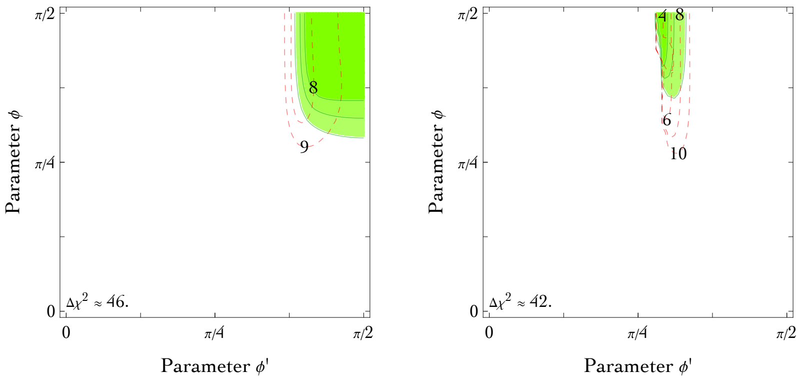
'Littlest' assumes global $\mathrm{SU}(5) \stackrel{v}{\to} \mathrm{SO}(5)$; gauged $\mathrm{SU}(2)_1 \otimes \mathrm{SU}(2)_2 \otimes \mathrm{U}(1)_1 \otimes \mathrm{U}(1)_2$.

$$M_{W'}^2 = \left(g_1^2 + g_2^2\right) \frac{f^2}{4} \qquad M_{Y'}^2 = \left(g_1'^2 + g_2'^2\right) \frac{f^2}{20} \qquad \widehat{T} = \frac{5 M_W^2}{g^2 f^2}$$

can fit the anomaly for big couplings $g_1' \equiv g'/\cos\phi'$ and possibly big $g_1 = g/\cos\phi$.

SU(5) "littlest" Higgs model

SU(5) "littlest" Higgs with R=3/5



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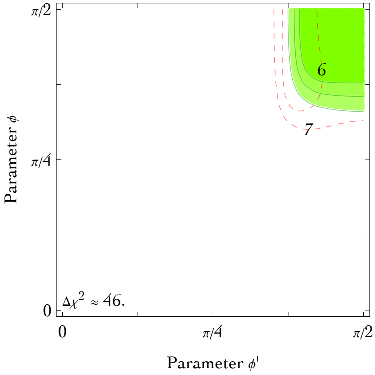
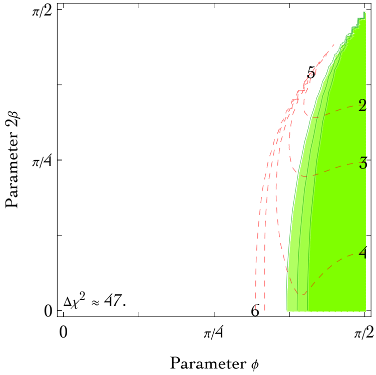
Related model with $\mathrm{SU}(6) \xrightarrow{v} \mathrm{Sp}(6)$ can also fit (no triplet, two doublets, no Y'):

SU(6) little Higgs model



Incomplete SU(6) little Higgs model



New physics: extra dimensions

Like little Higgs, with the two copies of SM vectors replaced by infinite towers.

Non-renormalizable (excluded by colliders?), but adds geometric flavour.

Recipe to get mostly $\widehat{T}$ and fit M_W: mess up sending H in extra dimensions. Keep SM fermions in 4d. Vectors can have a big localized kinetic term $c, c' \ll 1$.

Example: flat 5d with length $1/f$ (can be warped etc):

$$\widehat{S} = \frac{2}{3}\frac{M_W^2}{f^2}\ , \qquad \widehat{T} = \frac{M_W^2}{3c' f^2}, \qquad W = \frac{cM_W^2}{3f^2}\ , \qquad Y = \frac{c' M_W^2}{3f^2}.$$

Conclusions part I

Specific new physics can fit the CDF M_W anomaly compatibly with precision data and with bounds from LHC and other colliders:

- The effective operator $\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} - |H^\dagger D_\mu H|^2/(6\,{\rm TeV})^2$.
- It can be mediated at tree level by specific multi-TeV particles:
  - a scalar triplet with $Y = 0$;
  - a vector Z' coupled to the Higgs;
  - a few more less plausible candidates.
- It can be mediated at one loop level in many ways, by particles with

  $$m/y^2 \sim 400\,{\rm GeV}$$

  LHC bounds can be avoided assuming a large coupling $y \sim 2$, or particles with poor signals, such as DM.
- Hopefully the M_W anomaly will be soon clarified by CMS.

- If confirmed, a lepton collider could measure M_W from $\sigma(\ell^-\ell^+ \to W^-W^+)$ at $\sqrt{s} \approx 2M_W$ with accuracy helped by physics

  $$\frac{\delta M_W}{M_W} \sim \frac{\Gamma_W}{M_W}\frac{\delta\sigma}{\sigma} \sim \frac{1}{40}\frac{\delta\sigma}{\sigma}.$$

  This introduces the 2nd part.

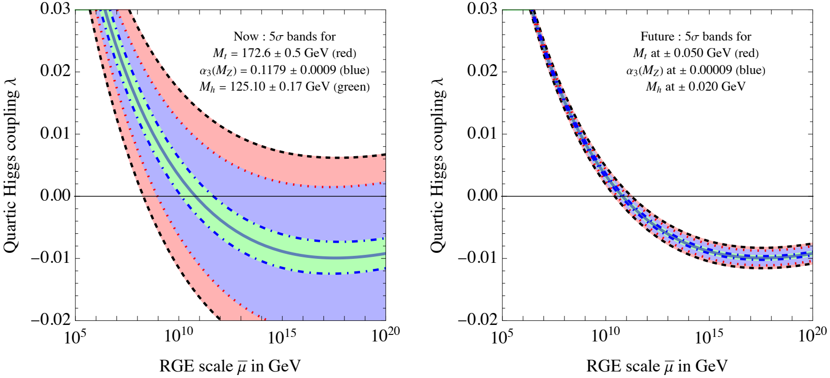
The collider landscape

Which collider for establishing the SM instability?

Alessandro Strumia, from arXiv:2203.17197 with Franceschini and Wulzer

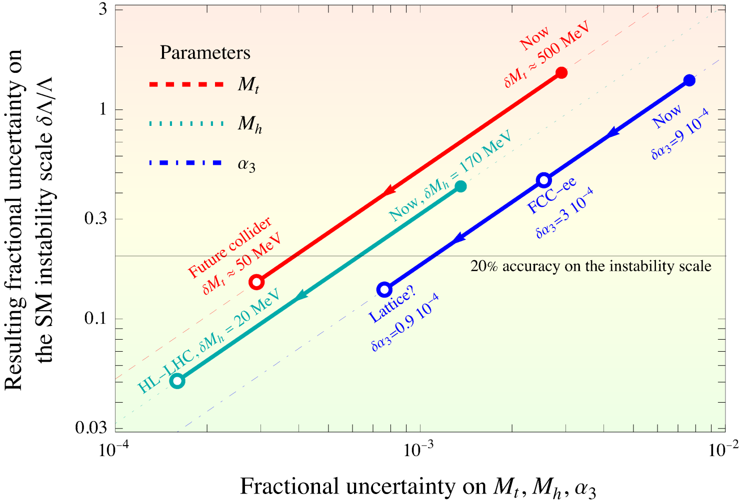
The SM vacuum (in)stability

Current data suggest that $\lambda(M_{\rm Pl})$ is near 0: the SM Higgs potential could have one or two minima. To measure, we need to improve on M_t, α_3, M_h.



The SM vacuum (in)stability scale

Measuring the possible instability scale Λ restricts cosmology $H_{\text{infl}}, T_{\text{RH}}$.

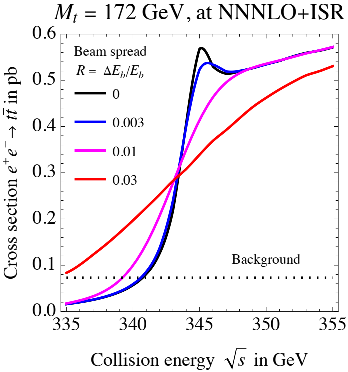


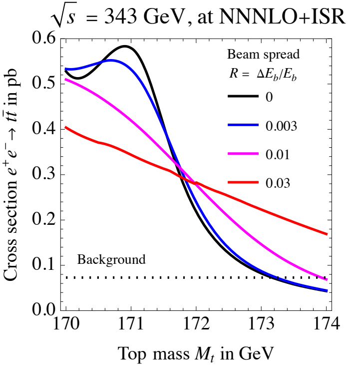
Which collider?

M_t at needed precision can only be done via top threshold scan at $\ell^-\ell^+$ collider

$$\frac{d\ln\sigma}{d\ln M_t} \sim \frac{M_t}{\Gamma_t} \approx 200\,,$$

with energy beam spread $R \equiv \Delta E_b/E_b$ better than Γ_t/M_t:





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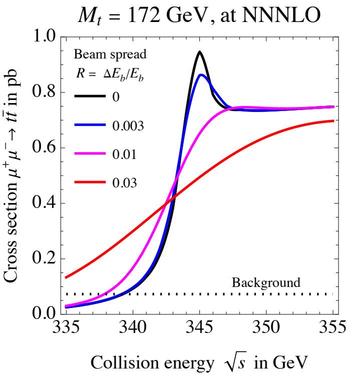
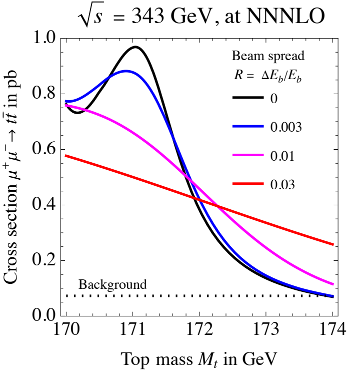
M_t at needed precision can only be done via top threshold scan at $\ell^-\ell^+$ collider

$$\frac{d\ln\sigma}{d\ln M_t} \sim \frac{M_t}{\Gamma_t} \approx 200\,,$$

with energy beam spread $R \equiv \Delta E_b/E_b$ better than Γ_t/M_t:

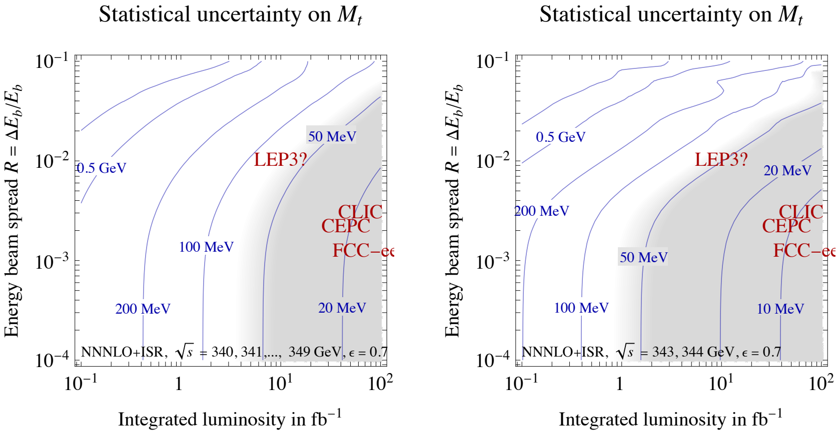




Luminosity needed for $\delta M_t|_{\rm stat} \sim 100\,$MeV: little

$$\delta M_t|_{\rm stat} \sim \frac{\Gamma_t}{\sqrt{N_t}} \max\left[1, \frac{M_t R}{\Gamma_t}\right] \qquad \delta M_t|_{\rm syst} \approx (40 - 70)\,\text{MeV}.$$

Precise estimate, with $\delta M_t|_{\rm syst} > \delta M_t|_{\rm stat}$ in the gray area:



Scan at two $\sqrt{s}$ needs lower luminosity than 10-point for measuring just M_t:

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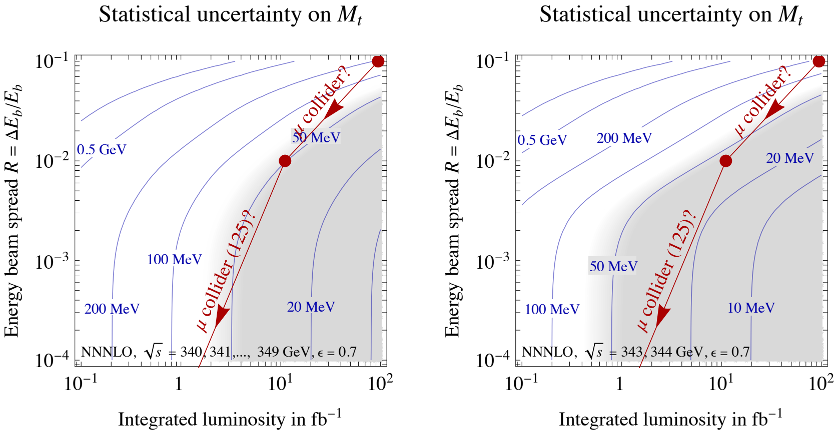


Scan at two $\sqrt{s}$ needs lower luminosity than 10-point scan for measuring just M_t.

Unconventional colliders

100 km e^-e^+ collider can over-reach $\delta M_t|_{\rm stat} \ll \delta M_t|_{\rm syst}$.

A LEP3 collider at the $t\bar t$ threshold radiates 28 GeV/turn: acceleration gradients can now be good enough, and new collision ideas allow much higher luminosities:

$$\mathscr{L}_{t\bar t}^{\rm LEP3} \approx \left\{ \begin{array}{ll} \mathscr{L}_{t\bar t}^{\rm FCC\text{-}ee}(26.6/100)^3 & \approx 0.075 \\ \mathscr{L}_{Zh}^{\rm LEP3}(240/350)^7 & \approx 0.088 \end{array} \right. 10^{34}{\rm cm}^{-2}{\rm s}^{-1}, \text{ power-limited.}$$

Estimated achievable luminosities in $10^{34}{\rm cm}^{-2}{\rm s}^{-1}$:

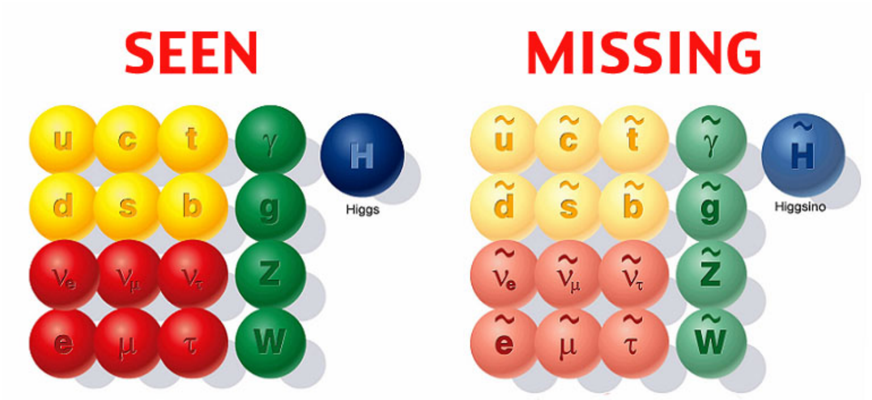
Collider		LEP	LEP3	FCC-ee	CEPC
Total length L		26.6 km	26.6 km	100 km	100 km
Z	$E_{\rm cm} = 91\,{\rm GeV}$	~ 0.004	7^*	460	115
W^+W^-	$E_{\rm cm} = 160\,{\rm GeV}$	~ 0.01	2^*	56	16
Zh	$E_{\rm cm} = 240\,{\rm GeV}$	0	1	17	5
$t\bar t$	$E_{\rm cm} = 350\,{\rm GeV}$	0	0.1^*	3.8	0.5

Study needed: many parameters mildly beyond state-of-the-art, nothing crazy.

Other possibility: a relatively small 'muon demonstrator' with $L \sim 0.7\,{\rm km}$.

Unconventional motivation for unconventional collider

SM completed



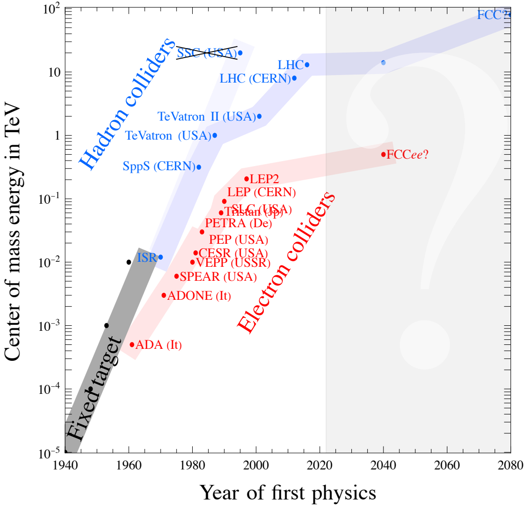
Unconventional motivation for unconventional collider

SM completed, no beyond SM was found

(Credits: Lucky Luke)

Unconventional motivation for unconventional collider

SM completed, no beyond SM, while colliders got too big



Unconventional motivation for unconventional collider

SM completed, no beyond SM, while colliders got too big and too slow.

Unconventional motivation for unconventional collider

SM completed, no beyond SM, while colliders got too big and too slow.

A plausible theory understanding of the apparent unnaturalness of M_h and Λ emerged: anthropic selection in a landscape of many vacua.

Seems realized in super-strings: in this context the observation that our vacuum has unnatural M_h, rater than weak-scale SUSY, presumably means that the landscape is statistically dominated by SUSY-breaking at the string scale. Such vacua could predict low-energy physics, rather than leaving it to flat SUSY directions.

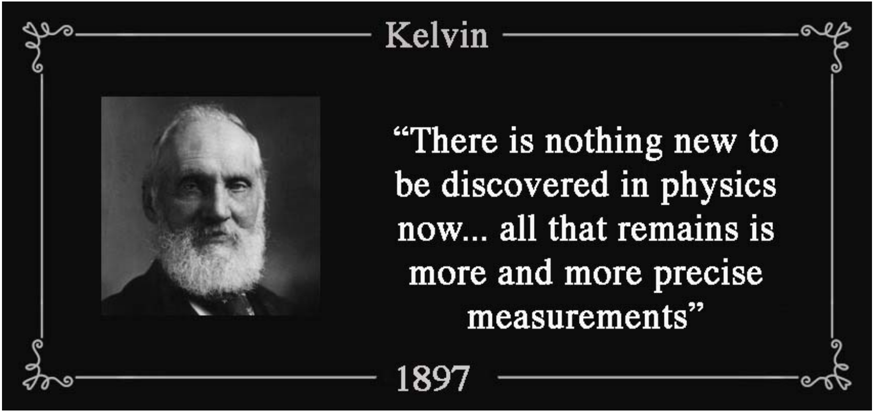
In this context, the sign of $\lambda(M_{\rm Pl})$ is a key observable. Measuring heavy SM particles is needed, so colliders need to reach the top, not above.

This is part of a wider future. Let's attempt discussing landscape implication for colliders: unconventional but more plausible than usual BSM-motivated plans.

Collider physics without new physics and without new colliders at higher energy?

Unconventional motivation for unconventional collider

SM completed, no beyond SM, while colliders got too big and too slow.



The Kelvin endeavour can have fundamental significance in the multiverse: localizing if the SM is in the landscape by *measuring more precisely the SM fundamental constants* that act as SM ‘coordinates’ in the landscape.

Not the Higgs couplings (since better known from masses), nor $g-2$ (SM), $c, \hbar, k_B$.

The Shannon entropy of the multiverse

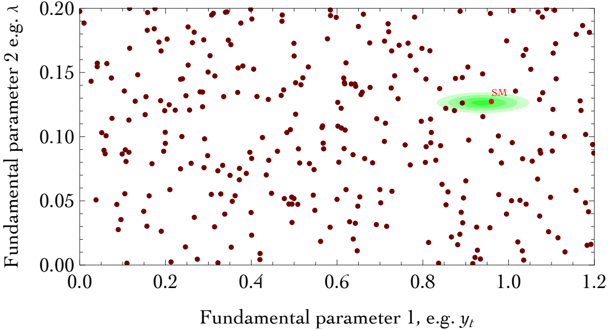
Brief: if $N = 10^{500}$ vacua we need something like 500 digits in base 10.

Long erudite: the Shannon information entropy quantifies our knowledge about SM localization in the landscape. Needs to be reduced to ≈ 0 starting from

$$H(\text{landscape}) = -\sum_{v=1}^{N} \wp(v) \ln \wp(v) = \ln N, \qquad \wp(v) = \frac{1}{N} \text{ maximal uncertainty}$$

i.e. $e^H = N$ vacua allowed. So we need $\ln N$ e-digits of relevant information.

To do this, we measure the n parameters y_i $(i = \{1, \ldots, n\})$ of the effective QFT: $y_i = \mu_i \pm \sigma_i$, for simplicity Gaussian uncorrelated. Vacuum v predicts y_{vi}.



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To do this, we measure the n parameters y_i ($i = \{1, \ldots, n\}$) of the effective QFT: $y_i = \mu_i \pm \sigma_i$, for simplicity Gaussian uncorrelated. Vacuum v predicts y_{vi}. Measurements reduce the entropy down to

$$H(\text{landscape}|\text{data } \mu_i \pm \sigma_i) = -\sum_{v=1}^{n} \wp(v|y) \ln \wp(v|y).$$

Without knowing measured values: *conditional entropy* average over expectations

$$H(\text{landscape}|\text{data}) = -\int d^n y \sum_{v=1}^{N} \wp(y) \wp(v|y) \ln \wp(v|y).$$

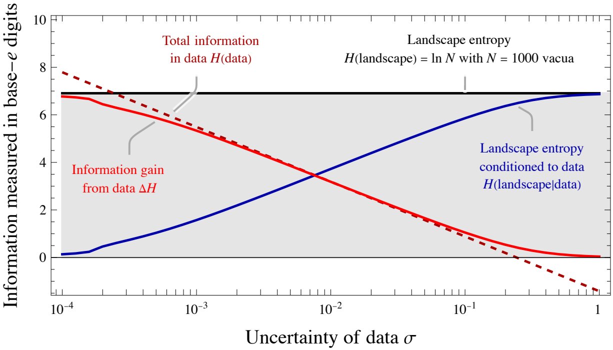
How much information we measured?

The information gained depends on detailed landscape predictions y_{vi}:

$$\Delta H = H(\text{landscape}) - H(\text{landscape}|\text{data}).$$

Without knowing them, we estimate assuming a dense feature-less $\wp(y) \approx 1$ so

$$\Delta H \simeq -\sum_{i=1}^{n} \ln(\sqrt{2\pi e}\sigma_i) \equiv H(\text{data}).$$



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Symbol	Model description	Number of parameters	Measured bits in base-e including 0	without 0
$g_{1,2,3}$	SM gauge couplings	3	37	36
λ_H	SM Higgs quartic	1	6	6
y_q	SM diagonal Yukawas of quarks	6	50	12
y_ℓ	SM diagonal Yukawas of leptons	3	72	47
$V_{\rm CKM}$	SM off-diagonal Yukawas of quarks	4	21	11
m_ν	Mass matrix of neutrinos	5	46	9
$v^2/M_{\rm Pl}^2, V/M_{\rm Pl}^4$	SM/ΛCDM mass scales	2	371	10
$\Omega_{m,b,r}, A_s, n_s$	ΛCDM cosmological parameters	5	51	19
	All physics	29	655	150

How many digits in $y_\mu \approx 0.00060687$: 9 or 5 or less?

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If Yukawas or masses are naturally small, 0s carry no information so $\wp(y) \approx 1/\wp$

$$H'(\text{data}) \simeq -\sum_{i=1}^{n} \ln(\sqrt{2\pi e}\sigma_i/\mu_i)\,.$$

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Furthermore, theory uncertainties in landscape predictions y_{iv} will add $\sigma_i^{\rm th}$, so we gain no information from too precise measurements.

Conclusions part II

- **If** no new physics is found, the landscape becomes the most plausible theory. Strategies for possible future colliders should take it into account.

- Hope that non-SUSY string vacua dominate and will give QFT prediction. Then more digits of fundamental SM parameters as the only future game?

  'Kelvin' pessimism aka 'Shannon entropy of the multiverse' crackpottism.

- Clarifying the possible Higgs instability seems the main concrete issue. Doable via lepton colliders at the top threshold: $e^- e^+$ LEP3 or $\mu^- \mu^+$ demo?