(Quantum) Top 2023

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Outline

- Intro., Y_{top} ? The quantum frontier:
  stability, flavor & naturalness

- Speculation beyond the conventional quantum top:
  (appetizer for the mini-workshop)

- Direct tests of QM in $t\bar{t}$ events?
- Non-linear QM & top-physics?
- New type of axion-DM, LHC as a big table*top*

Y_{top} ?

- Because we can (however there are many things we could study)
- Because the top is special:
  - The heaviest point-like particle known
  - The only quark that decays before hadronizing
  - Gives access to its spin through its decay product (lepton <=> perfect spin analyzer)

However:

Y_{top} ? (28th birthday is coming)

People pack Fermilab’s Ramsey Auditorium on March 2, 1995,
during the announcement of the discovery of the top quark. Photo: Reidar Hahn, Fermilab

The top quark, as it turned out, is by far the most massive of the elementary particles of the Standard Model — it is 40 times more massive than the bottom quark, the second heaviest of the quarks. It is as massive as an entire gold atom and 50% heavier than a Higgs boson. Fermilab’s original accelerator complex, which culminated in the Main Ring, could not provide sufficient energy to produce the top quark. Top quarks are thought to have existed only for a few brief moments right after the Big Bang: bringing them back into existence would require the lab’s scientists and users to replicate the intense energies of the early universe. (Fernebews)

Y_{top} ? (16th edition of top conf.)

Credit: Antonio Onofre

Y_{top} ? classical view

- Because we can (however there are many things we could study)
- Because the top is special:
    - The heaviest point-like particle known
    - The only hadron decay before hadronizing
    - Gives access to its spin through its decay product (lepton <=> perfect spin analyzer)

Several of these have been already established:

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG

without perspective it is hard to define targets/objectives …

Y_{top}? Quantum field theory (QFT) perspective

- The top-Higgs duo are the most interesting particles as in the quantum realm are the driving force of the blind spots of the standard model (SM):

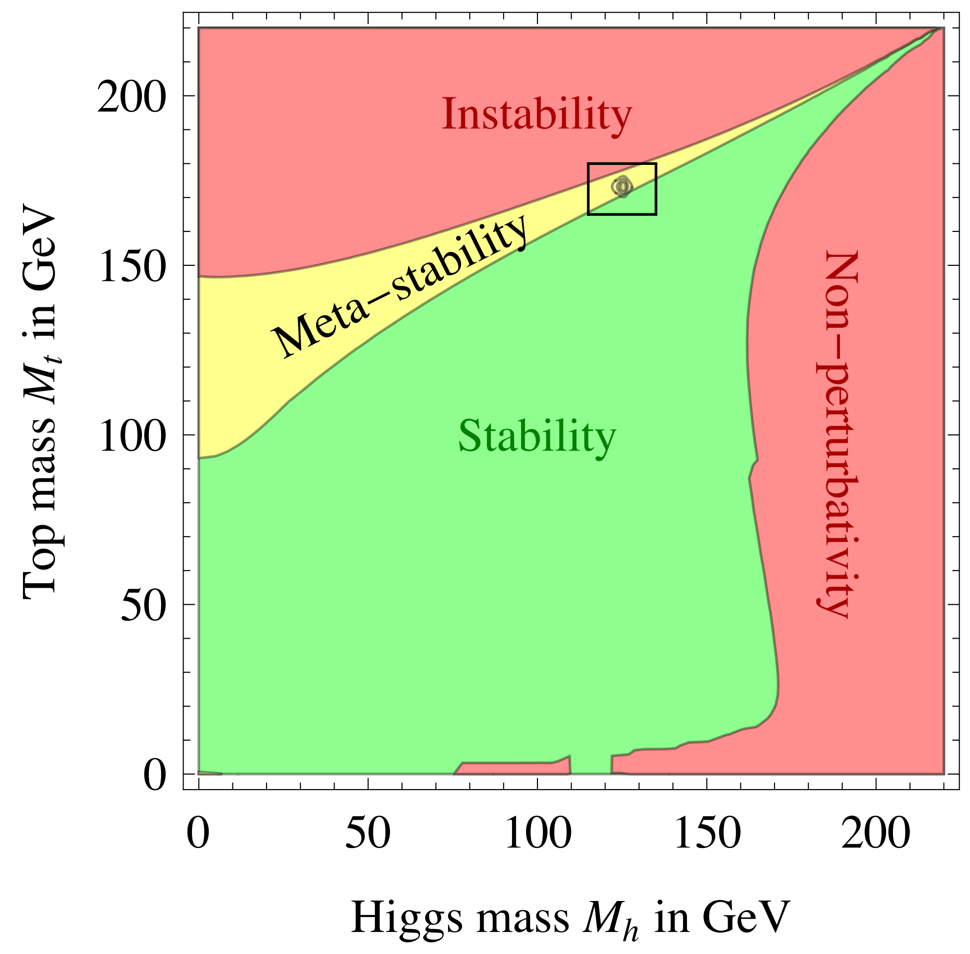
    - Lead to meta/instability of our vacuum => existential puzzle
    - Controls flavor violation
    - Induce the Higgs hierarchy problem

These are not new but one cannot talk about top physics without briefly discussing them

Living dangerously an existential puzzle

- The top Yukawa makes the Higgs quartic negative in the UV, $\beta_{\lambda_H} = -\frac{3}{8\pi^2} y_t^4 + \cdots$
- In the SM our universe is sufficiently long lived:

See for instance: Degrassi, Vita, Elias-Miro, Espinosa, Giudice, Isidori &



$$\tau_{\rm EW} \sim 10^{983^{+1410}_{-430}} \text{ years}$$

Khoury & Steingasser (22)

See more on Tue.: Myllymaki; Nellist; Kim

- Is it a coincidence that the top mass is close to its maximal value?

Should we be afraid of the weakless universe? Anthropics?

- Is the large top mass + small Higgs mass telling us something about what lies beyond our universe? After all, a raise of $< 3\%$ in top Yukawa => weakless universe

See for instance: Feldstein, Hall and Watari (06)

- It is hard to tell without addressing the light quark mass dependence. When they are allowed to be varied we find that a weakless universe is hospitable, possible favored

Harnik, Kribs & GP (06); Gedalia, Jankins & GP (10)

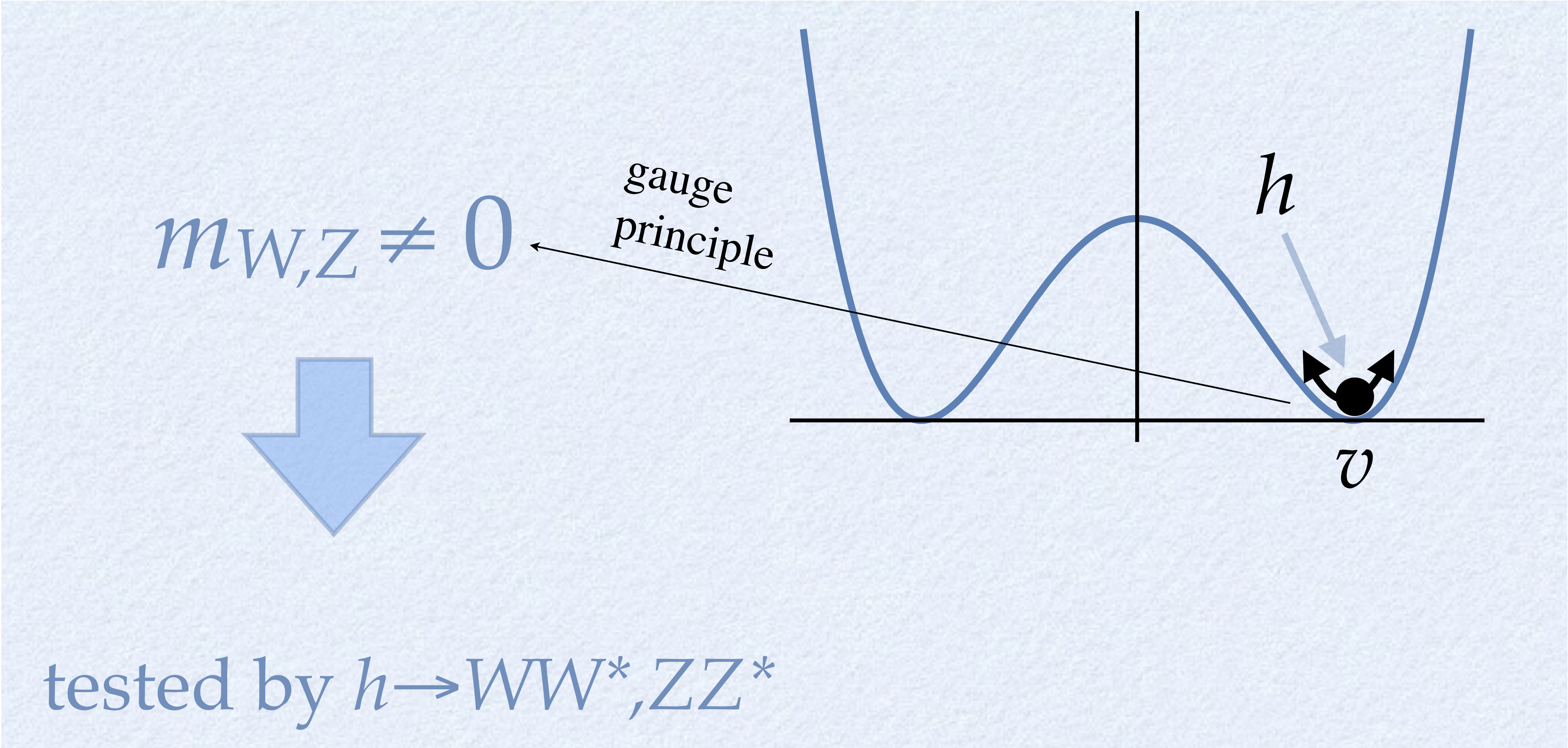
- It suggests that maybe we should maybe look for more mundane (natural) reasons for the lightness of the Higgs mass; but before that let's talk about the connection between Yukawa couplings and masses …

Minimality of Standard Model (SM) Higgs Mechanism

♦ Higgs in minimal SM plays 2 roles:

(i) induce electroweak (EW) gauge boson masses & unitarization (high-E consistency);

electroweak gauge boson masses tightly related to Higgs phys.

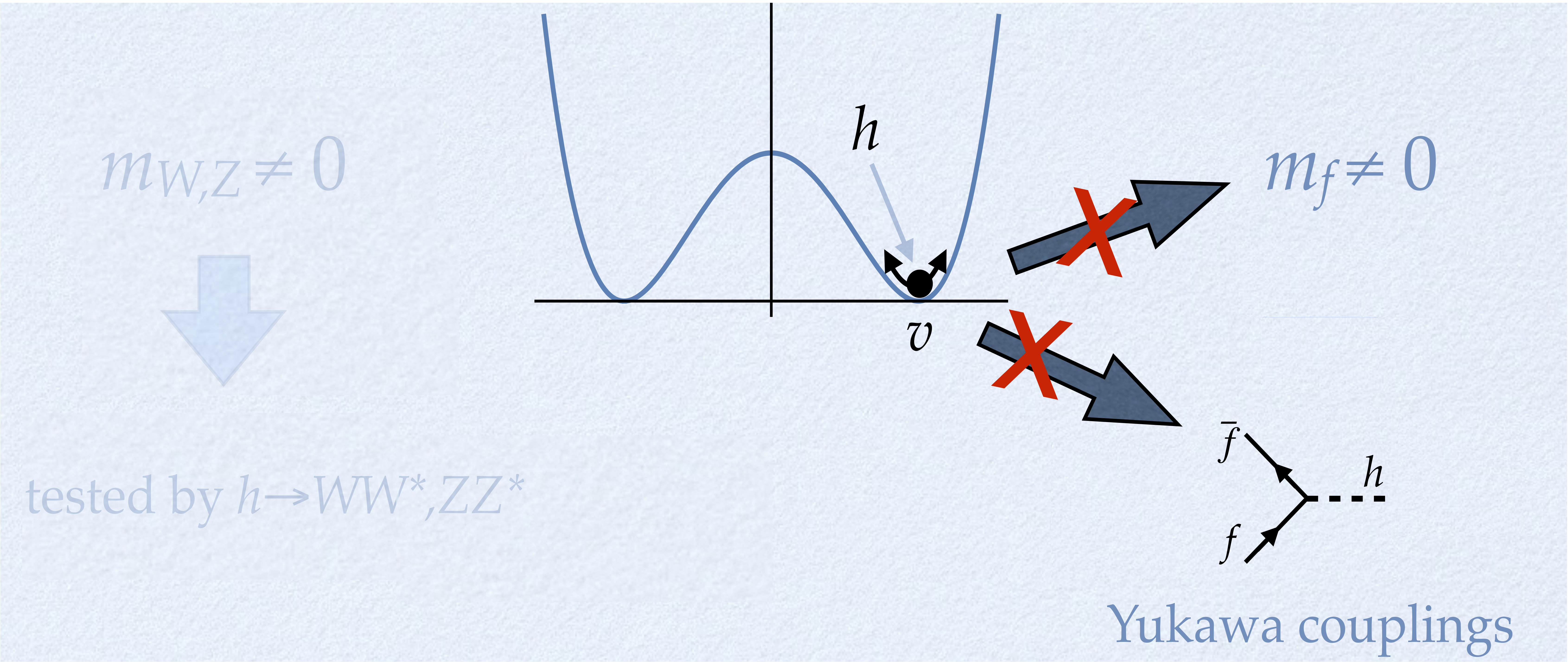


General: Higgs mechanism vs. fermion masses

◆ Higgs in minimal SM, 2 roles:

(i) induce electroweak (EW) gauge boson masses & unitarization (high-E consistency);

generically, no relation between Higgs coupling & (light) fermion masses



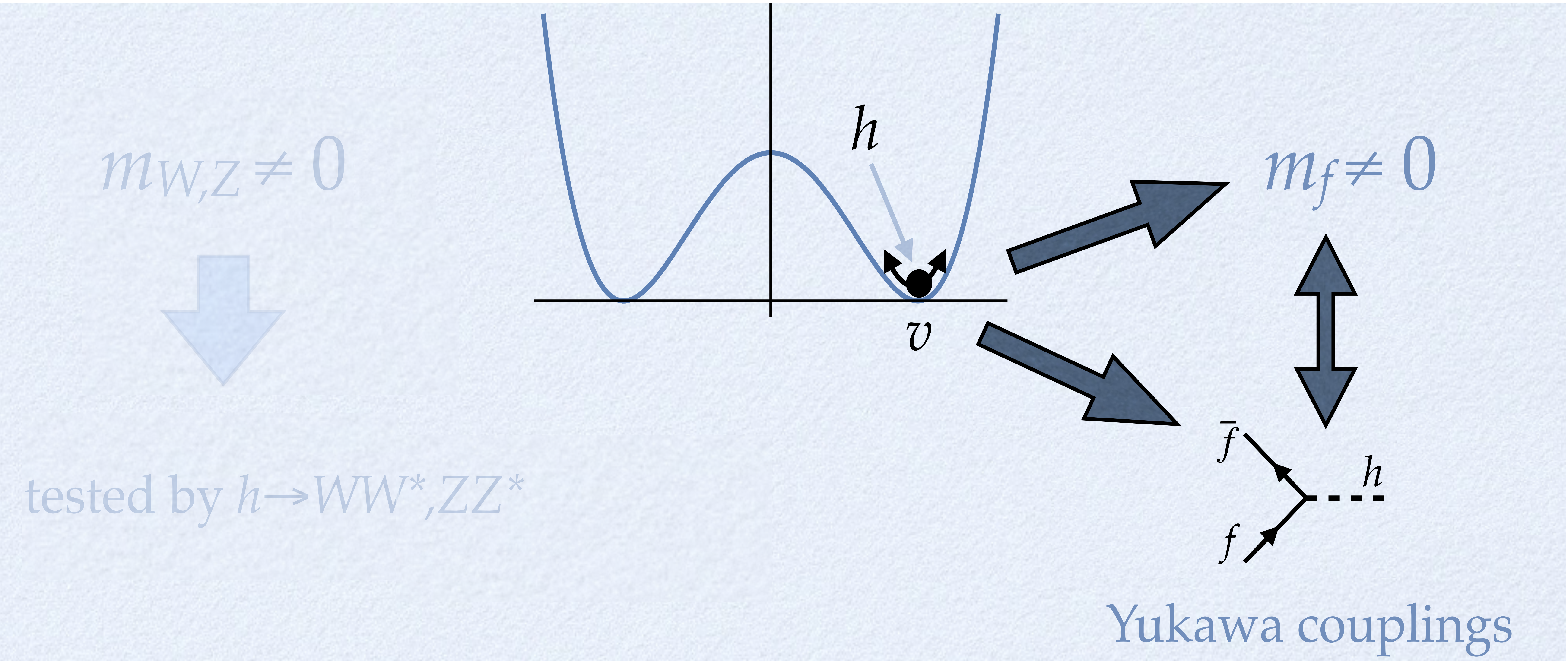
SM: Higgs mechanism vs. fermion masses

- Higgs in minimal SM, 2 roles:

(i) induce electroweak (EW) gauge boson masses & unitarization (high-E consistency);

(ii) induce fermion masses & unitarization (high-E consistency).

within the SM the two are one to one correlated



The Nobel prize that was not given to ATLAS+CMS

ATLAS+CMS confirmed that the Higgs mechanism is behind the 3rd generation charge fermions masses, and excluded most sensible theories by bracketing the charm and muon Yukawas.

For instance the top Yukawa ($\kappa_f \simeq y_f / y_f^{\rm SM}$):

$$\kappa_t \simeq 1.01 \pm 0.11 \quad 1\!-\!\sigma \text{ CL} \quad \text{CMS (20)}$$
$$\kappa_t \simeq 1.00 \pm 0.28 \quad 95\,\% \text{ CL} \quad \text{ATLAS (22)}$$

See more in Masetti's talk on Tue.
Mon.: Also 4-tops Van Den Bossche; Sharma

To appreciate it, if you're curious you can read the following afterwards (I won't have time to review):

Fermion mass generation in the SM vs. exp.

SM mass origin: $\mathcal{L}_{\rm mass} = y_f \bar{f} f H$ and $\langle H \rangle = v\,.$

⬇

$$m_f = y_f \times v \Leftrightarrow y_f = m_f/v\,.$$

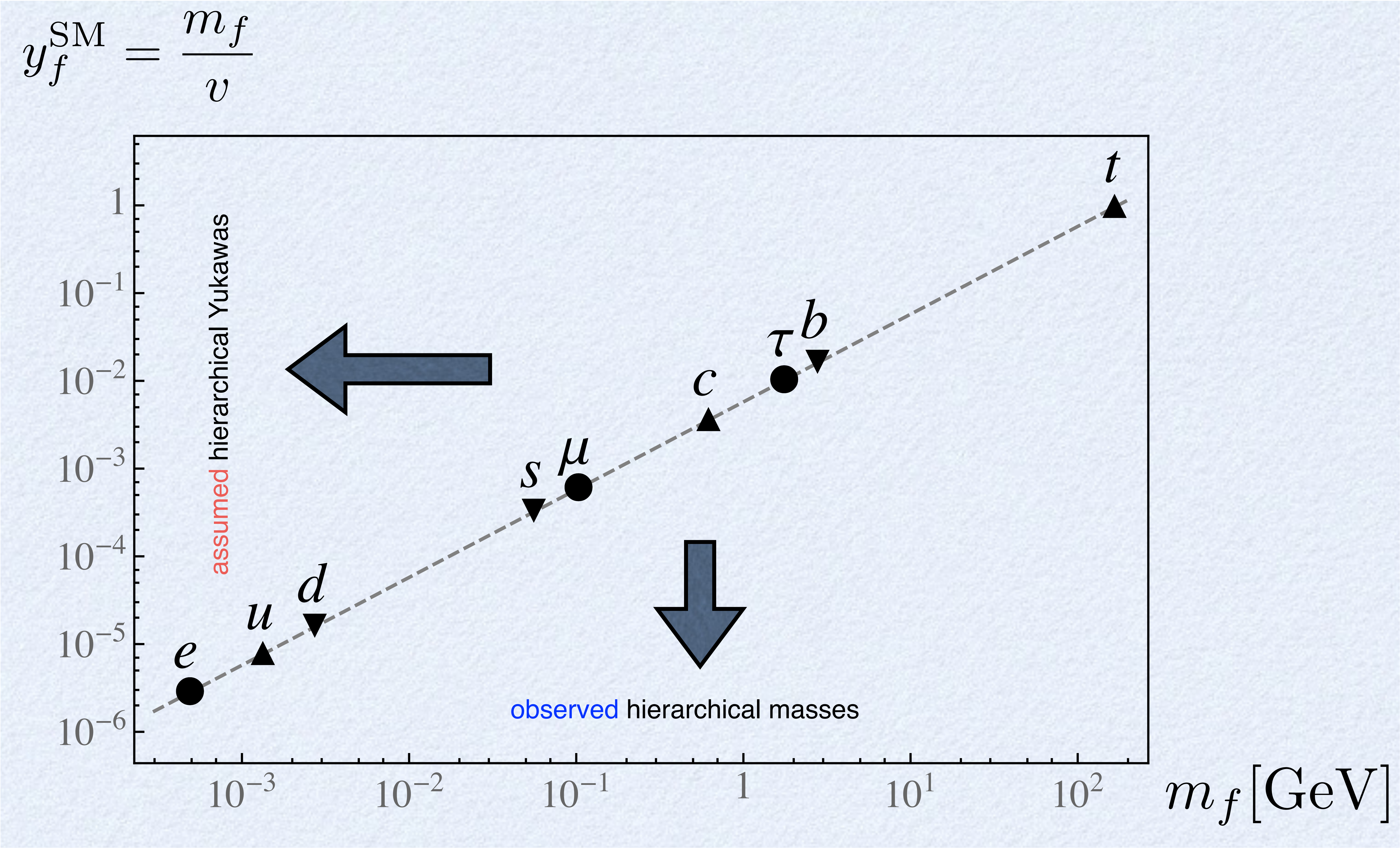
y_f = Higgs-fermion coupling, generically: $y_f = \left(\frac{\partial m_f}{\partial h}\right)_{\langle H\rangle = v}\,.$

⬇

In the SM: $\left(\frac{\partial m}{\partial h}\right)_{\langle H\rangle = v} = \frac{m}{v}\,.$

The (flavor) mass hierarchy puzzle

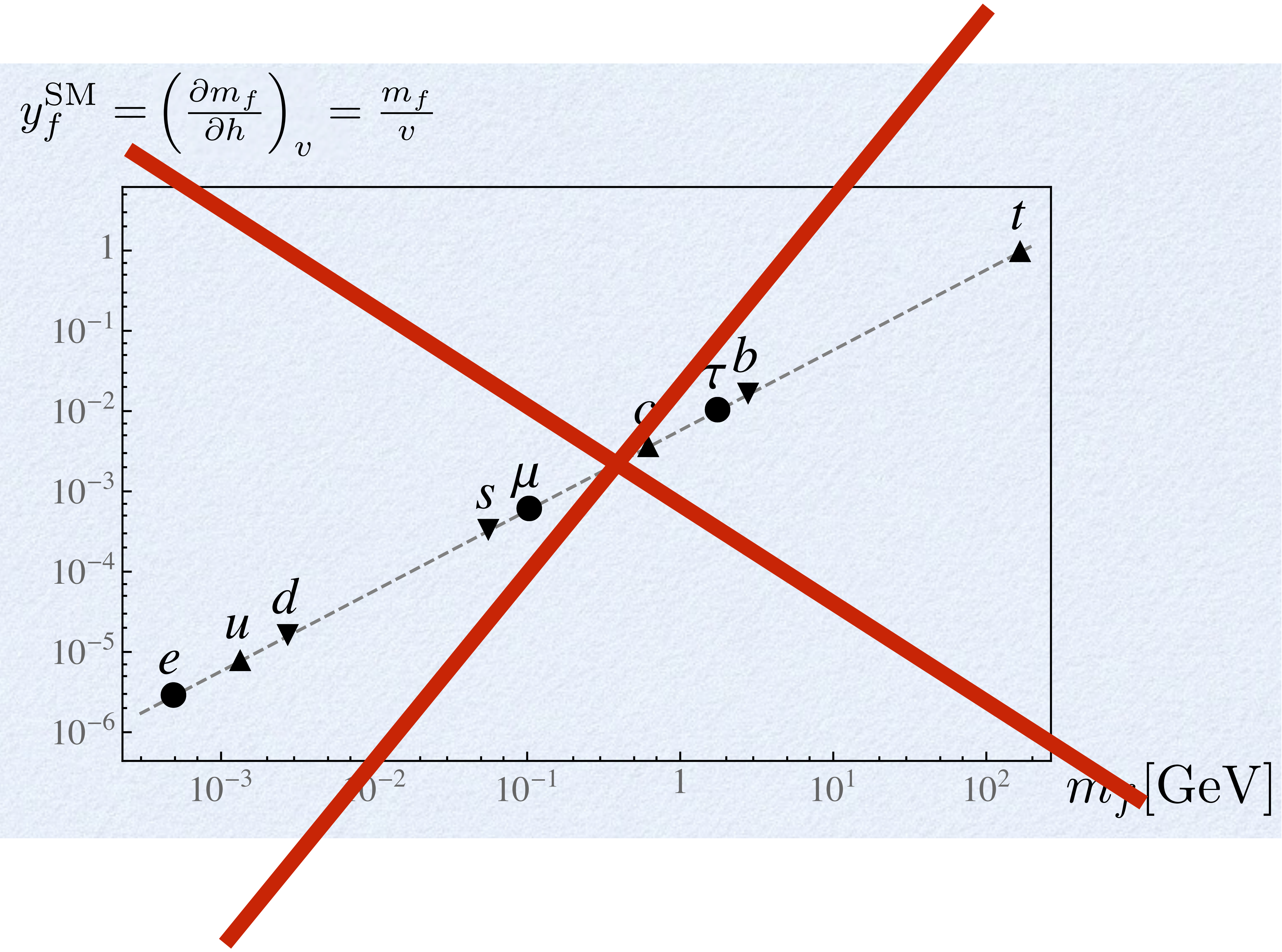
- SM: small/hierarchical masses because of small/hierarchical Yukawa couplings to Higgs.



Y. Soreq, Student Colloquium, 2015

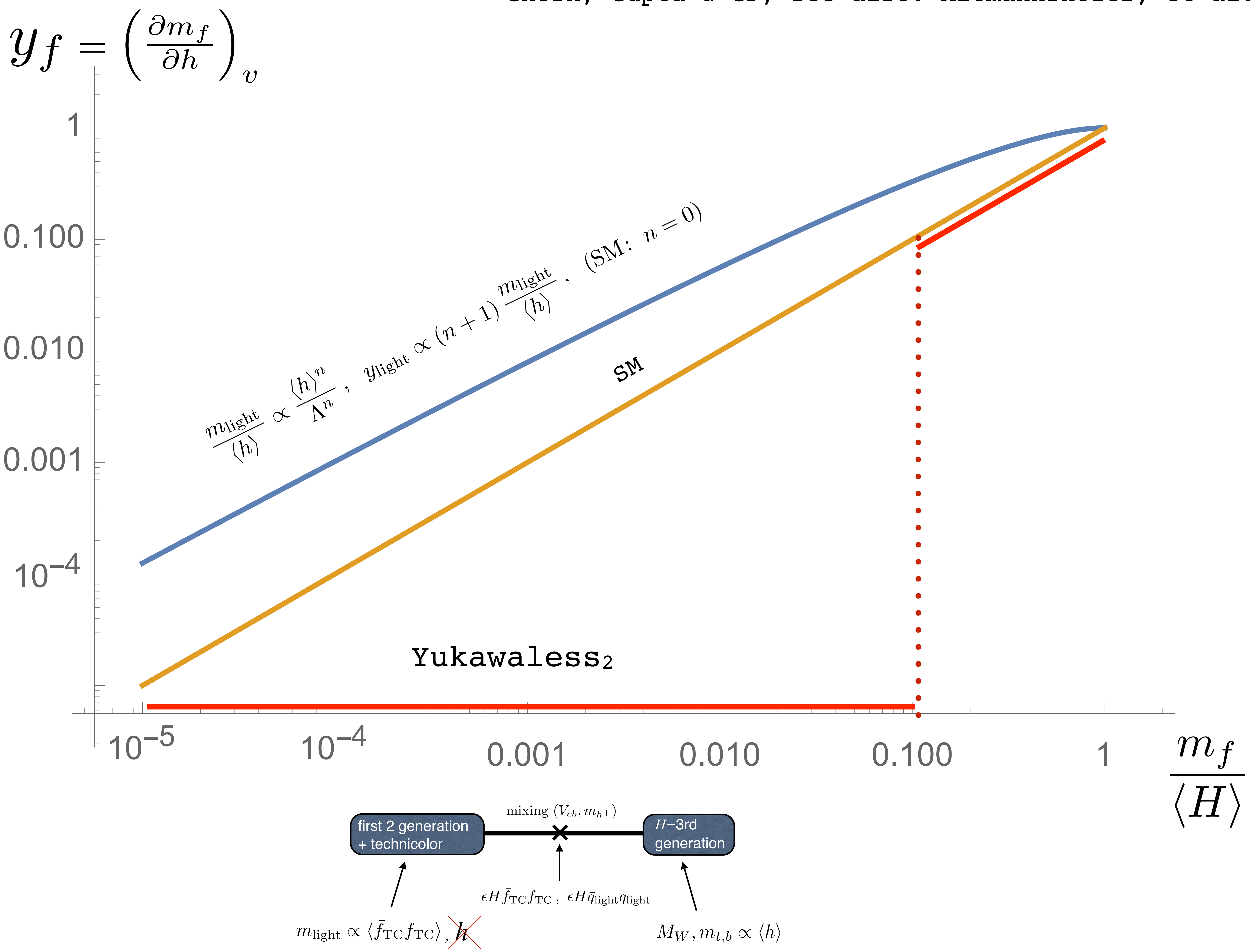
To appreciate it: Could the SM story of (light) fermion mass generation be wrong?

- Maybe we've looked at it the wrong way?



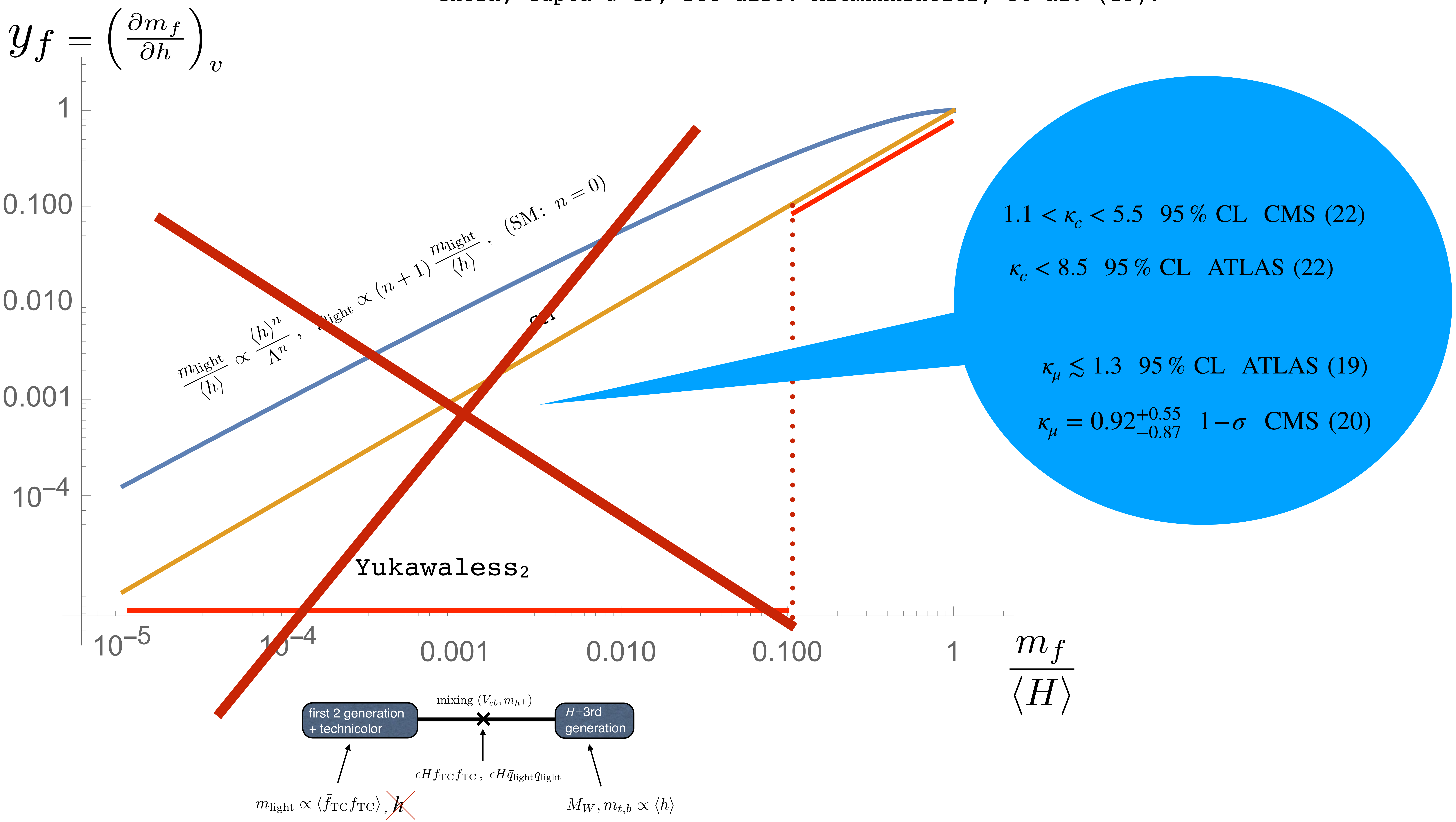
Two extremes: Yukawafull vs. Yukawaless

Giudice & Lebedev (08); see also Bauer, et al. (15).
Ghosh, Gupta & GP; see also: Altmannshofer, et al. (15).



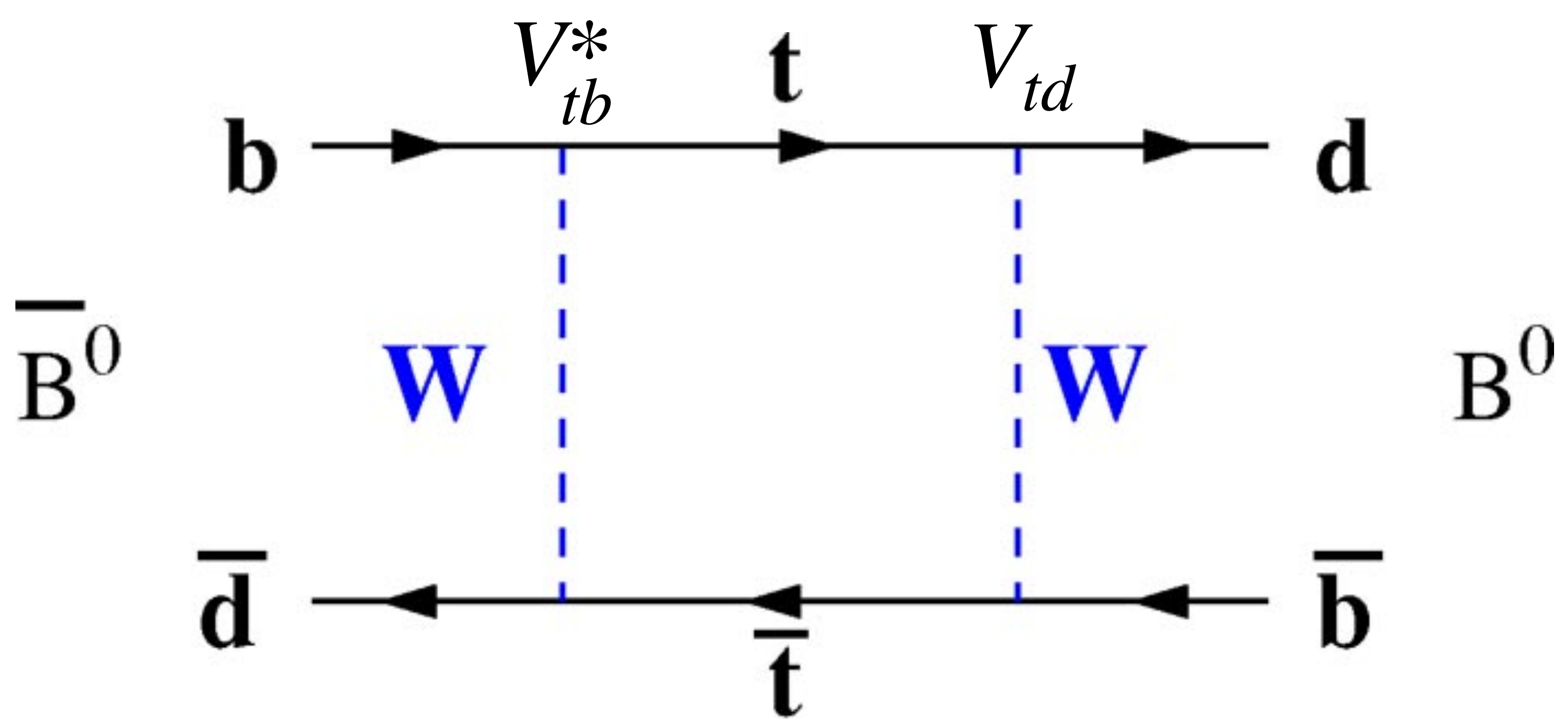
Possibility is excluded due to 2nd gen. measurements

Giudice & Lebedev (08); see also Bauer, et al. (15).
Ghosh, Gupta & GP; see also: Altmannshofer, et al. (15).



Top & quantum flavor violation

- We have now established directly that the SM minimal Higgs mechanism is behind the origin of flavor for the 3rd (and partially) 2nd generations
- To large extent one can understand most of the SM flavor violation through top Yukawa domination at the quantum level, which has been fully established:



- This has the important implication for beyond the SM physics, even if it only couple to the top => it needs to be heavy, for instance prediction for t-FCNC in composite Higgs:

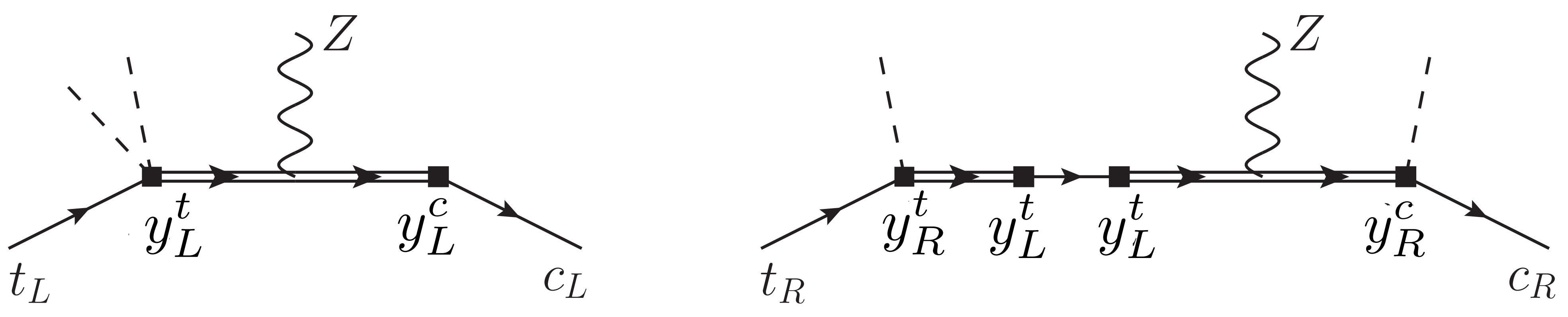
Composite natural pNGB-H vs $t\to cZ$

- However, pNGB structure + naturalness => $y_L \sim y_R \sim 1$.

- Thus, $t \to cZ$ in natural custodial composite models is large.

Azatov, Panico, GP & Soreq (14)

$$\mathrm{BR}(t \to cZ) \sim 10^{-5} \left(\frac{700}{M_*}\right)^4 .$$ <=>



Within the LHC reach! (Current bound is BR($t \to cZ$) ~ 10^{-4} ; ATLAS+CMS (23))

See more on Wed.: Bartos; Kim; Szewc

However it decouples quickly, $(NP\text{-}scale)^{-4}$

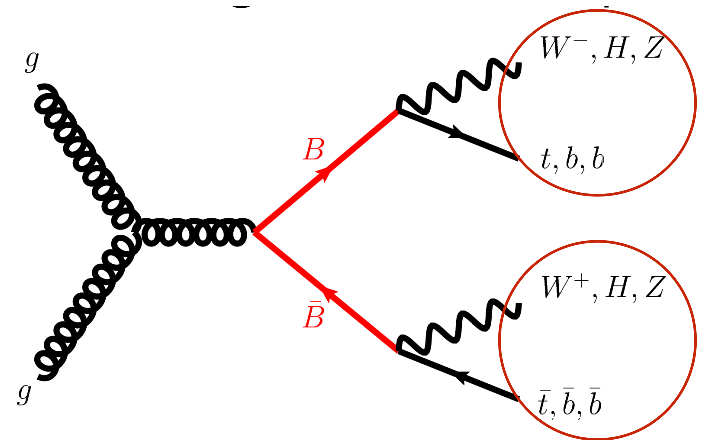
The Higgs hierarchy problem & the top

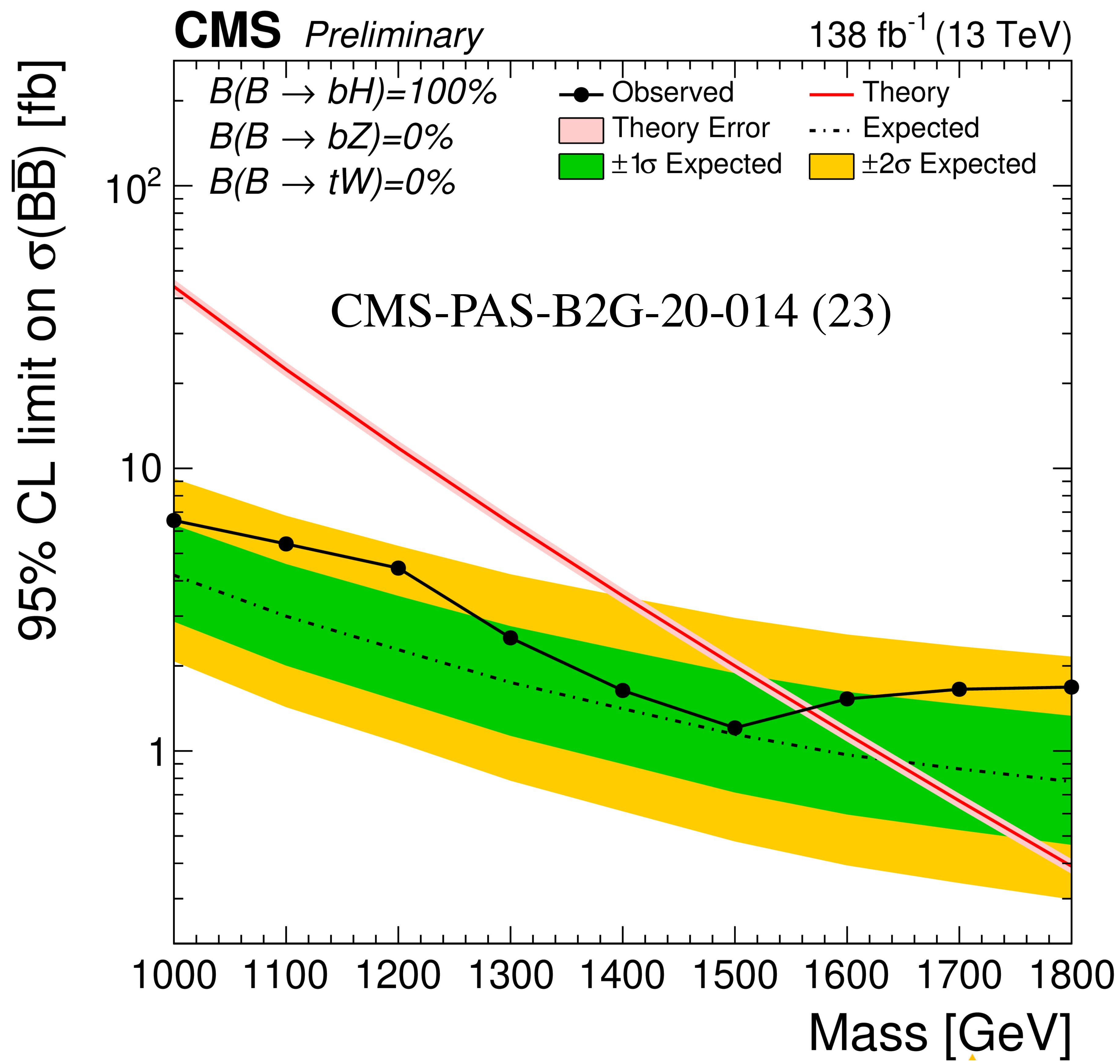
- As we established that we understand the role of the top in loops, using QFT, can’t ignore that it makes the Higgs mass sensitive to ultraviolet physics!
- This is probably the most important aspect of top BSM physics as it is the only principle that allows us associates it with a rough upper bound on the scale of new physics:

upper bound on the mass of top partners - in simplest models these would be the stops or vector-like-tops which would lead to top-rich final states.

Current status of top partner searches, $M_T \gtrsim$ TeV

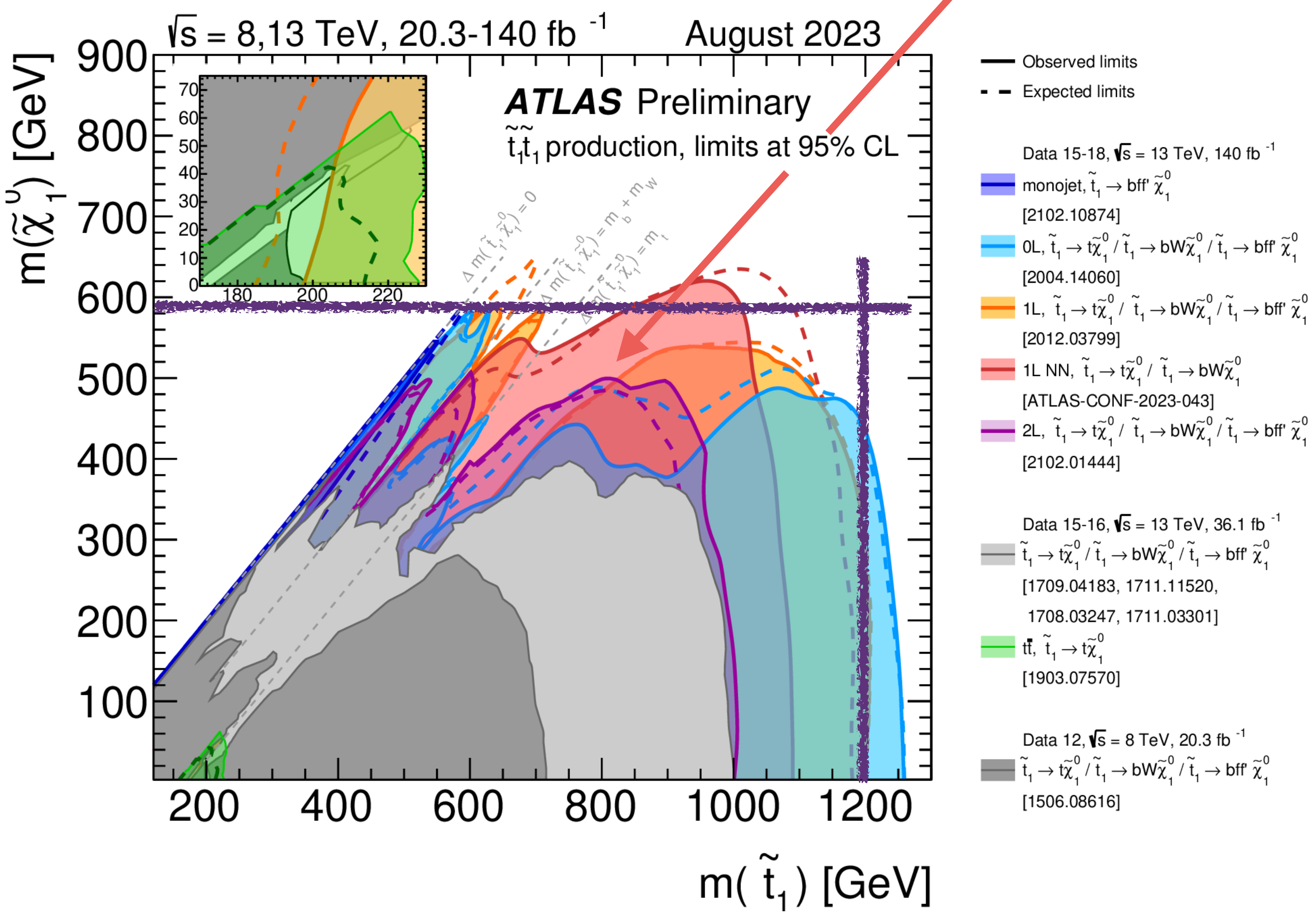
pair-production of VLQ B





ATLAS-CONF-2023-043

Sensitivity gains for $m_{\tilde{t}} \approx m_{\tilde{\chi}^0_1} + m_t$



We've seen that top-phys. yields a potential window to NP via quantum corrections

Could top-phys. teach us about new QM ?

Top-pair production & basic QM

- If we control t-pair production (per event) => isolate entanglement:

Near threshold $(t\bar{t})_{gg\to t\bar{t}} \Rightarrow$ J=L=0 state, hence spin of the 1st determines the 2nd (spin entanglement). It is testable for instance via spin-spin correlation

See for instance: Affik & Nova (21)

- We can in principle work harder and even perform Bell-inequality test

Tue.: Cheng; Thu.: Gonçalves; Severi; Baker; Negro; Afik

- This line of research raise however several questions:

(i) Been tested in multiple system - at low energies with photons/electrons to intermediate energies $B^0 - \bar{B}^0$; is it significant?

Nobel Prize (22)

(ii) Seems non-robust as "normal" BSM can modify

For instance: Aoude, Madge, Maltoni & Mantani (22)

(iii) Is there any sensible theory in which there's energy dependence ?

Non-linear QM

Kaplan & Rajendran (22)

- QM from the onset is constructed to be exactly linear: $i\partial_t \psi = \hat{H}\psi$
- In principle we could envision a non-linear version: $i\partial_t \psi = \hat{H}\psi + \hat{F}(|\psi|)\psi$

  (various works on it in the past)
- The challenge (Weinberg (89), Polchinski (90)) is how to make it causal
- Locality of QFT enabled Kaplan & Rajendran to argue that they can achieve it by incorporating *state-dependent* expectation value of fields into the action:

For ex. consider Yukawa theory: $\mathscr{L}_{\text{Yuk}}^{\text{NLQM}} = Y\phi\bar{f}f + \epsilon^{\text{NLQM}}\langle\phi\rangle_\psi \bar{f}f$

If you want to hear more come to the talk by Surjeet in the mini-workshop

Nelson-Barr solution to strong CP, new ultralight-DM pheno.

With: Dine, Nir, Ratzinger & Savoray in prep.

- The strong CP problem is how to explain: $\bar{\theta} \lesssim 10^{-10}$ & $\theta_{\rm KM} = \mathcal{O}(1)$
- Nelson-Barr models achieve it through spontaneously breaking CP in models with extra (very) heavy vector-like quark
- Naturally, the object that break-CP spontaneously would be axion-like field
- This axion field could be a dark matter candidate

Relaxion: Graham, Kaplan & Rajendran (15)

NB-relaxion - Davidi, Gupta, GP, Redigolo, & Shalit (17)

↓

New pheno': strong CP is zero, type of pheno: *time dep. CKM angles (3rd gen)*

Conclusions

- Broader perspective: if we to speculate what is the most robust argument for a concrete scale of new physics, it still is the one associate \w top-Higgs naturalness => in slight tension with direct searches & indirect searches (flavor)
- In both cases the QFT-top is playing a crucial role

- Recent theoretical & experimental progress suggest that 3rd-gen' physics might be sensitive to new type of questions/tests associated to mundane & crazy new versions of axion/QM