Theory Vision

Nathaniel Craig
University of California, Santa Barbara

LHCP CONFERENCE 2019

Disclaimer

This conference has seen a dazzling array of results and perspectives, including outstanding plenaries by M. Krammer, G. Iadarola, L. Malgeri, K.F. Einsweiler, J. Klein, G. Passaleva, C. Nellist, E.N. Umaka, P. Gandini, N. Leonardo, A. Pich, Y.C. Pachmayer, P.A. Cartelle, J. Ngadiuba, R. Erbacher, M. Borsato, S-C Hsu, S. Forte, R. Bonciani, J.L. Merino, C. Pollard, C. Royon, D. Teaney, A.O. Velasquez, O. Evdokimov, C.L. da Silva, R. Lea, T. McCarthy, F. Yumiceva, D. Zanzi, K. Melnikov, A. Vicini, L. Reina, L. Cadamuro, J. Adelman, L. Finco, X. Sun, J. Erler, M.M. Llacer, P. Chang, D. Pagani, B.M. Dit Latour, S. Zambito, I. Suarez, K. Mei, C. Wagner, M.A. Winn, F. Polci, V. Rekovic, B. Nachman, A. Wulzer, A. Sandoval, and J. Konigsberg, and innumerable equally outstanding parallel talks & posters.

Whereas my theory vision has no basis more reliable than my own meandering experience. I will dispense this theory vision now.

LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva,
21–27 March 1984

Theory vision circa 1984

Satisfied with these successes, we have now to face deeper questions such as:

- what is the origin of mass?
- what kind of unification may exist beyond the standard model?
- what is the origin of flavour?
- is there a deeper reason for gauge symmetry?

We have simply too many a priori plausible hypotheses concerning the nature of symmetry breaking in the standard model. Experimentation in the TeV range at the constituent level is bound to provide most essential clues, and the present successes of the $p\bar{p}$ collider are a very strong encouragement to go to higher energies and to higher luminosities in hadron-hadron collisions.

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Theory vision circa 2019

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Theory vision circa 2019

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Theory vision circa 2019

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+ What is the nature of dark matter?
+ Why does the strong force ~conserve CP?

A Higgs! Yet:
Is it the only one?
Is it the SM Higgs?
Why is there EWSB?
What sets the scale?

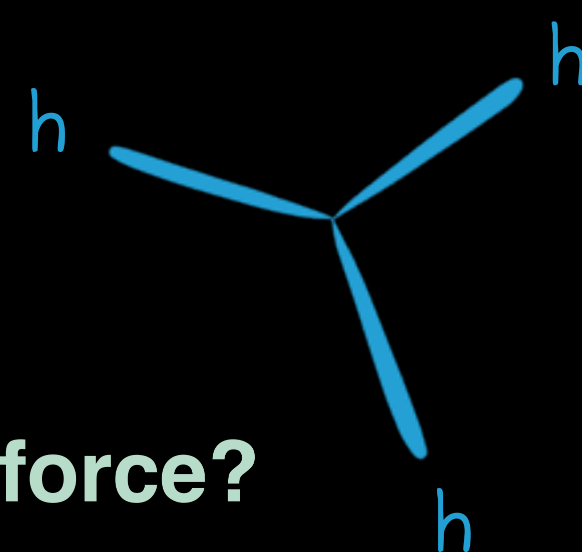
Building on discovery

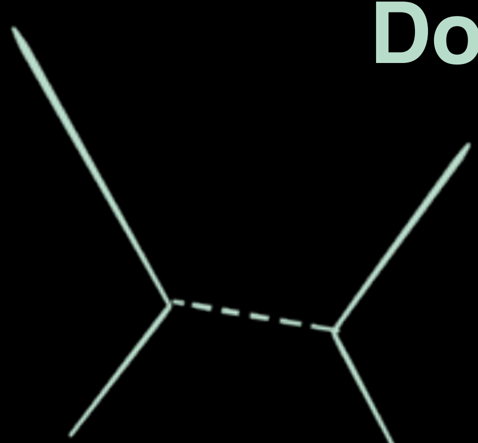
For all the excitement of its discovery, we still know *very little* about the Higgs.

Is it the SM Higgs? (What does that mean, practically?)
Perhaps more useful are **major conceptual questions**:

Is it elementary, or composite?

Does it interact with itself?

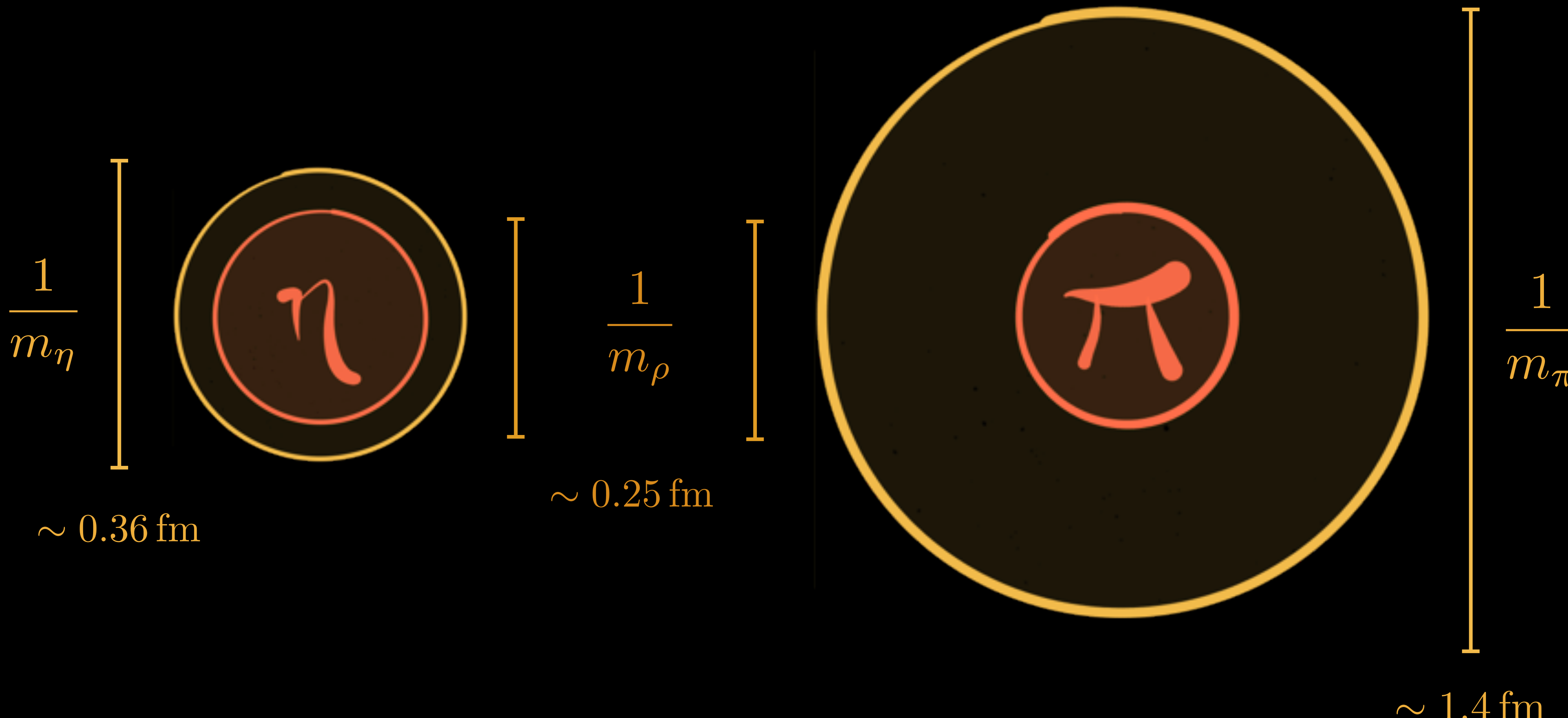




Does it mediate a Yukawa force?

A fundamental scalar?

Have seen scalars in nature already…



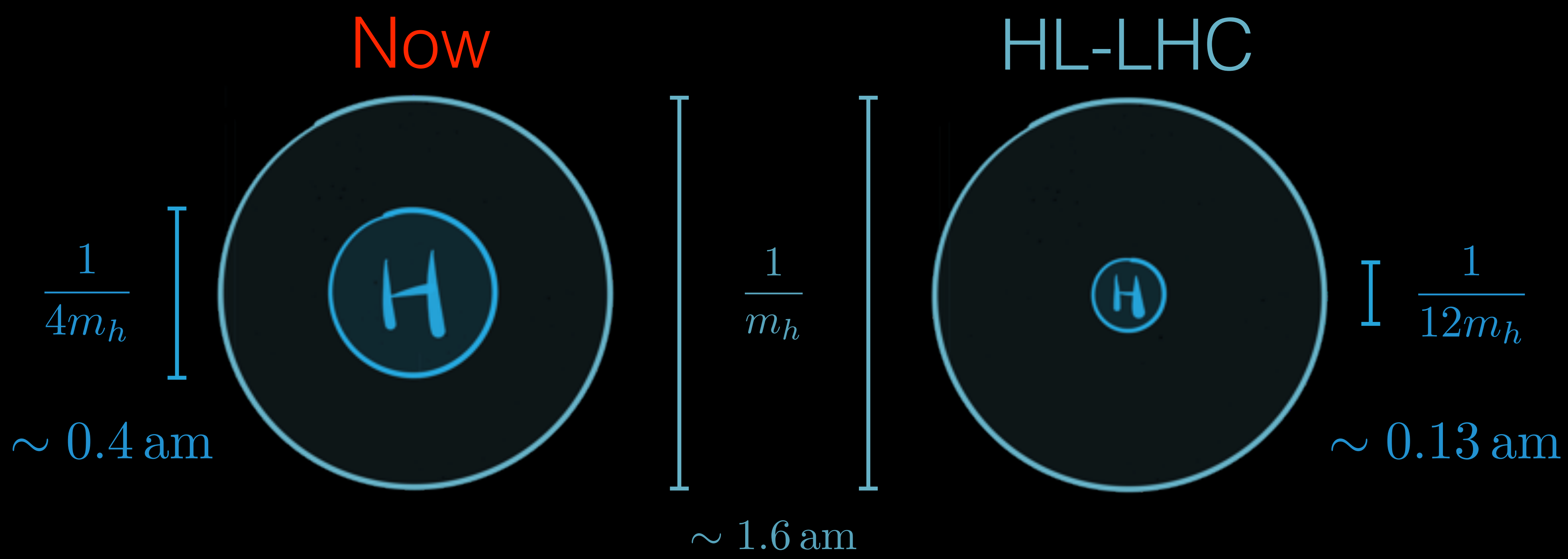
E.g. ***η*** (quite composite!) and ***π*** ("fairly composite") mesons

A fundamental scalar?

Is the Higgs elementary or composite?

Just beginning to probe the size of the Higgs at the LHC, not yet testing pion-like levels of compositeness

More precisely: bound "size" corrections such as $\frac{1}{2\Lambda^2}\left(\partial_\mu |H|^2\right)^2$

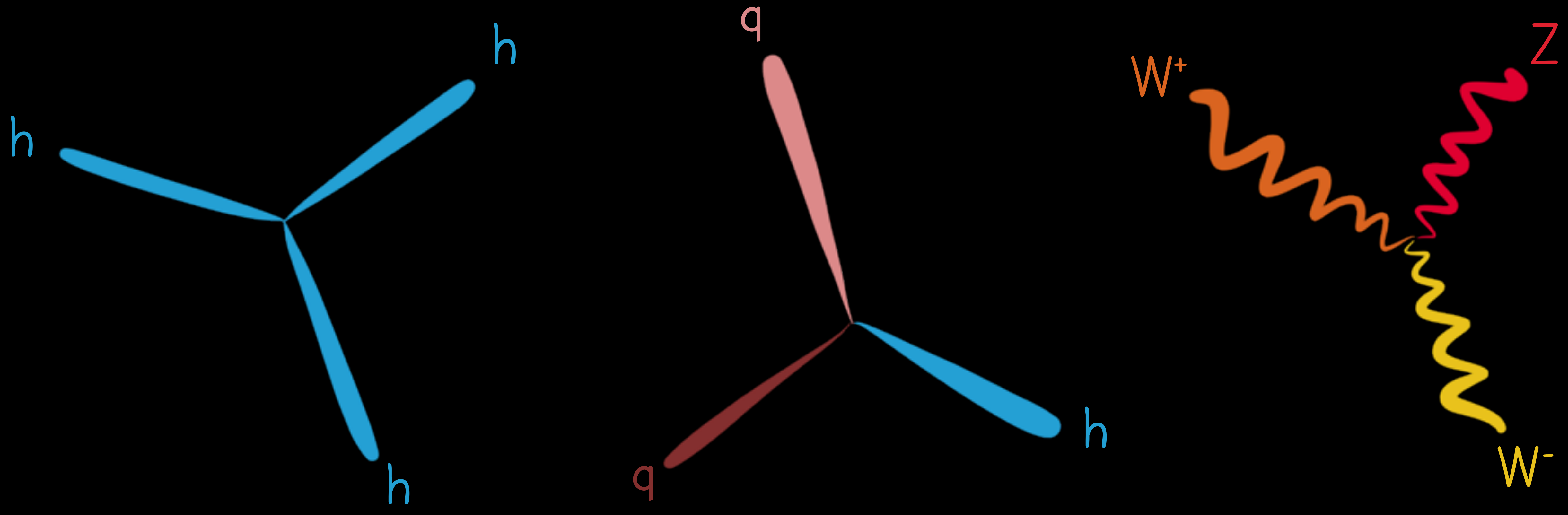


LHC will ultimately probe size of the Higgs well beyond this, providing strong evidence that the Higgs is elementary. *If not, abundant new physics awaits.*

A self-interacting particle?

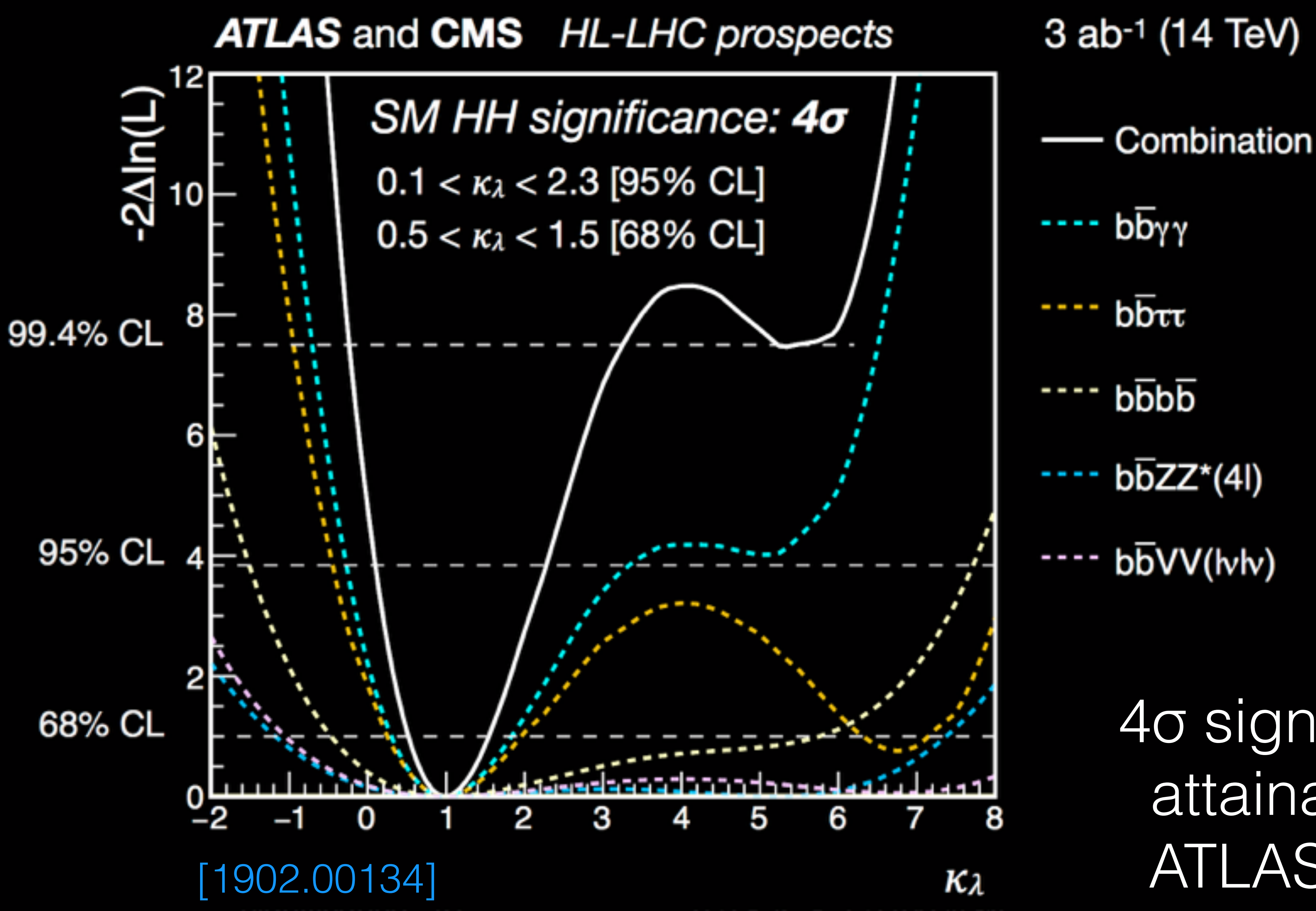
The Standard Model Higgs is predicted to interact with itself

If so, it would be unlike anything yet seen in nature
(all other interactions change particle identity)



Any deviations would point to a wealth of unforeseen new physics.

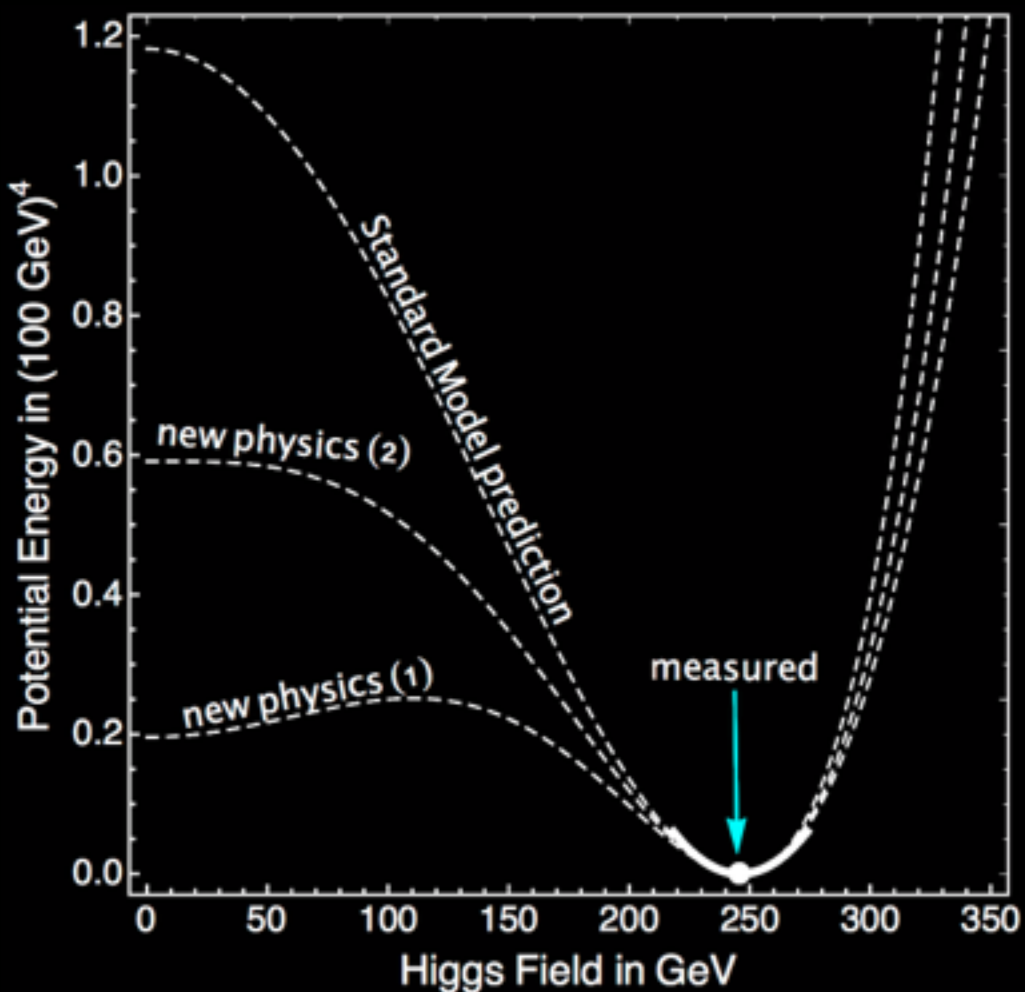
A self-interacting particle?



[1902.00134]

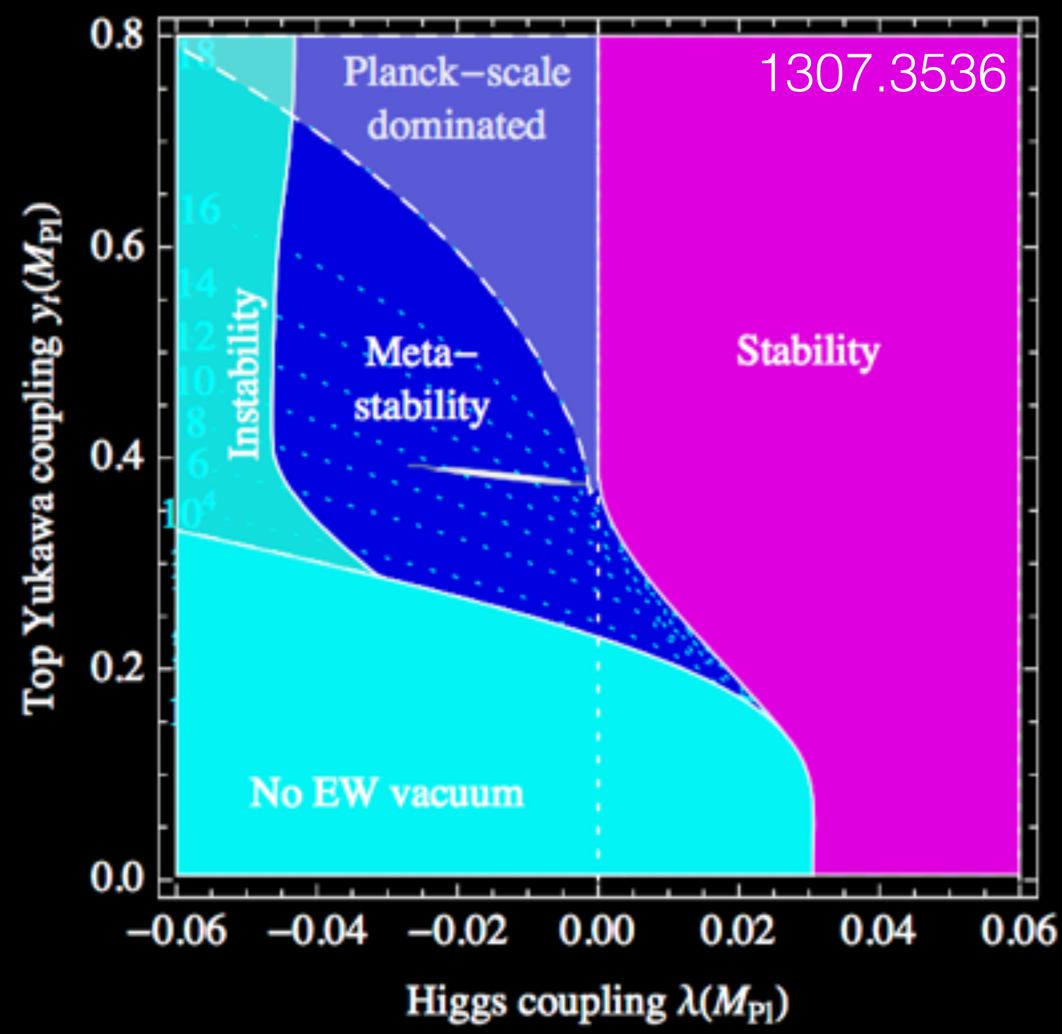
4σ significance attainable by ATLAS+CMS

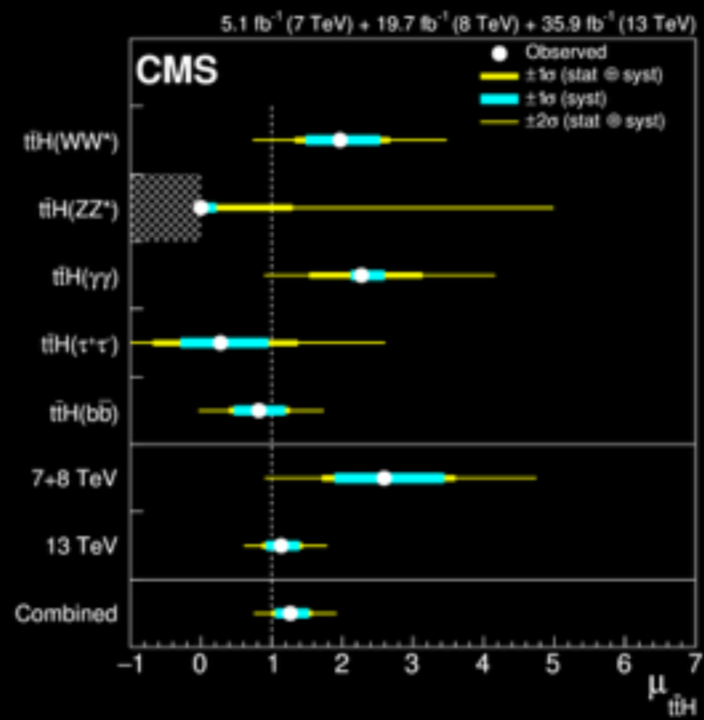
Deep implications



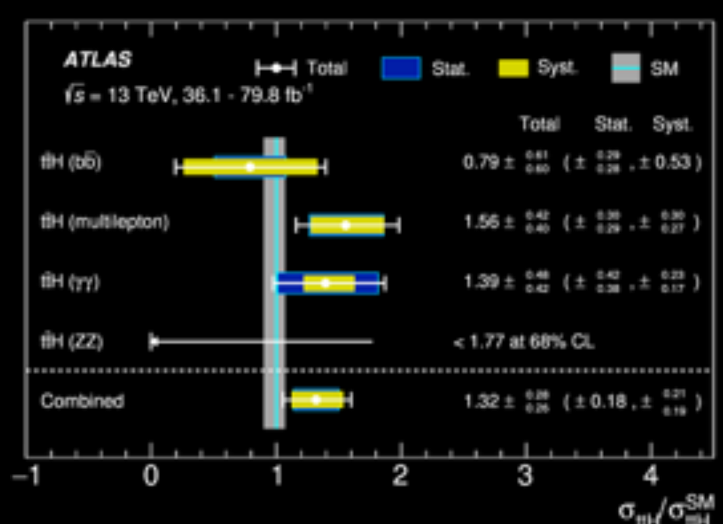
How is electroweak symmetry broken?

What is the fate of the universe?



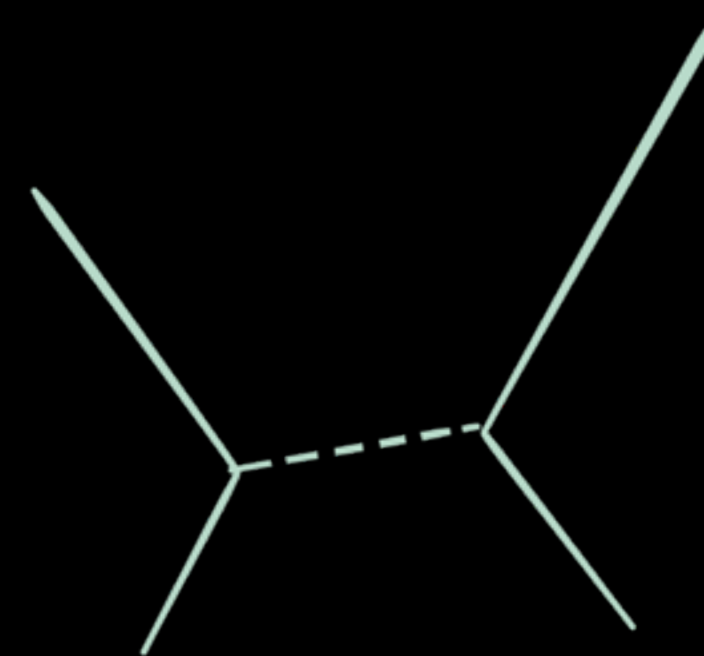


A Yukawa Force?



Yukawa force between fundamental particles: never seen until now

Established by >5σ observation of ttH, H→bb and H→ττ in LHC Run 2



$$\frac{V_{\mathrm{Higgs}}(r)}{V_{\mathrm{Weak}}(r)} \sim \frac{y^2}{g^2} e^{-(m_h - m_Z)r}$$

"Is this any less important than the discovery of the Higgs boson itself? My opinion: no, because fundamental interactions are as important as fundamental particles"

— G. Salam, LHCP 2018

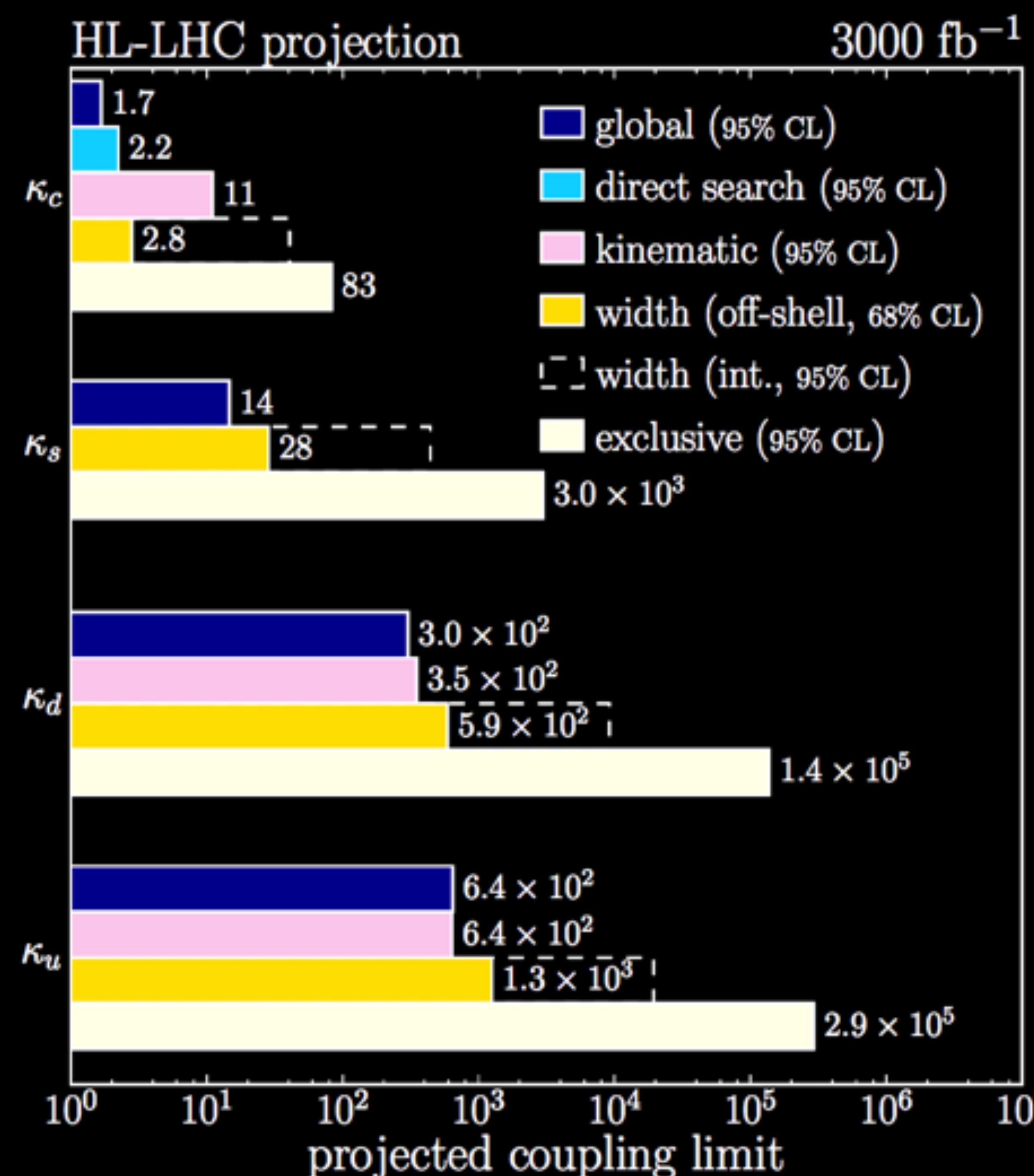
A Yukawa Force?

Situation no less interesting for 1st & 2nd generation. Relative lightness makes flavor puzzle compelling, measurements could hold key to flavor puzzle.

$H \to \mu^+\mu^-$ $3000 fb^{-1}$

Experiment	ATLAS		CMS	
Process	Combination		Combination	
Scenario	S1	S2	S1	S2
Total uncertainty	$^{+15\%}_{-14\%}$	$^{+13\%}_{-13\%}$	13%	10%
Statistical uncert.	$^{+12\%}_{-13\%}$	$^{+12\%}_{-13\%}$	9%	9%
Experimental uncert.	$^{+3\%}_{-3\%}$	$^{+2\%}_{-2\%}$	8%	2%
Theory uncer.	$^{+8\%}_{-5\%}$	$^{+5\%}_{-4\%}$	5%	3%

[1902.00134]

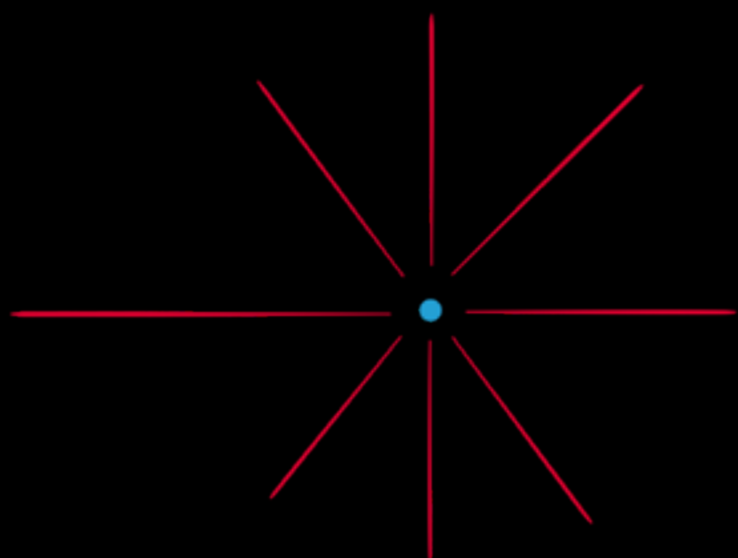


These are the central questions of the post-discovery era.

The answers are all profoundly interesting, whether or not they are in agreement with SM predictions.

Why EWSB? What scale?

The naturalness strategy: an analogy from E&M



$$\Delta E_C = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e}$$

$$(m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_C$$

Experimentally $r_e \lesssim 10^{-18}\,\mathrm{cm} \Rightarrow \Delta E_C \gtrsim 100\,\mathrm{GeV}$

If so, $0.511 = -99999.489 + 100000.000\,\mathrm{MeV}$

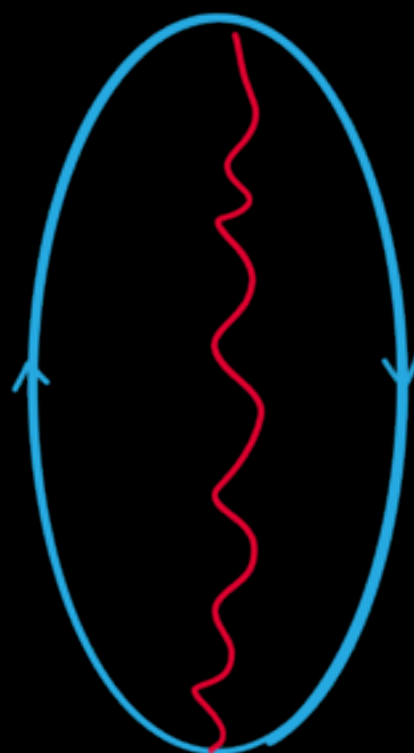
To avoid fine-tuning, i.e. for the theory to be “natural”, need picture to change on scales below 2.8×10^{-13} cm

The Naturalness Strategy

An analogy

Weisskopf (1939)

$$\Delta t \sim \hbar/\Delta E \sim \hbar/(2m_e c^2)$$



$$d \sim c\Delta t \sim 200 \times 10^{-13}\ \mathrm{cm}$$

$$\Delta E = \Delta E_C + \ldots$$

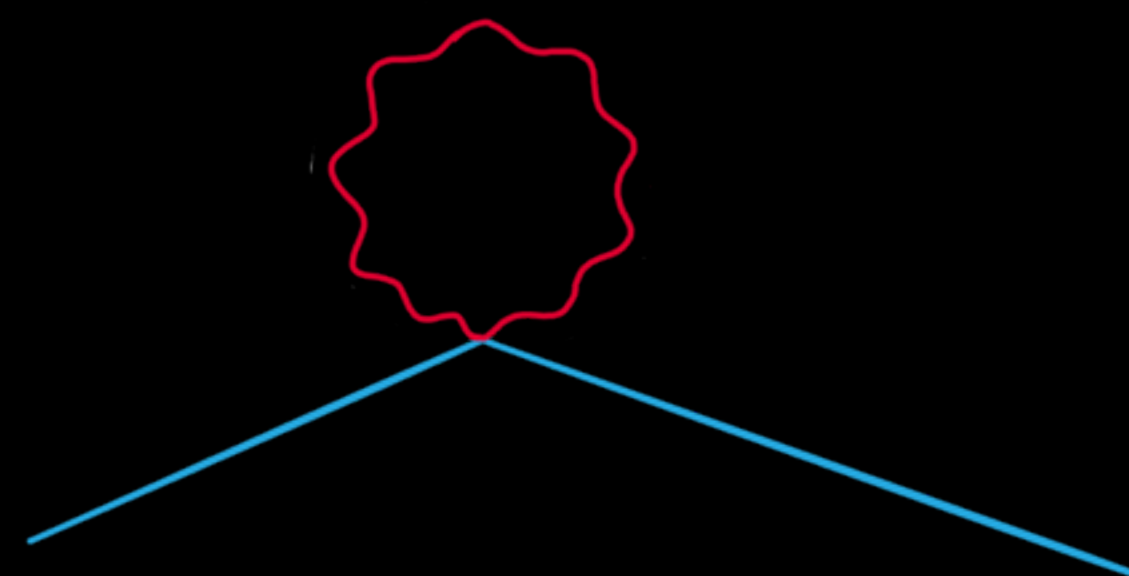
$$\Delta E = -\Delta E_C + \ldots$$

$$\Delta E = \Delta E_C - \Delta E_C + \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}$$

The Naturalness Strategy

What about scalars?

Consider the pion…



Another divergence…

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 = \frac{3\alpha}{4\pi}\Lambda^2$$

Given observed splitting, *predict* scale of new physics:

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 = (35.5\,\mathrm{MeV})^2 \Rightarrow \Lambda \lesssim 850\,\mathrm{MeV} \qquad \checkmark$$

Another (more predictive) example: K_L-K_S mass difference.

The "Hierarchy Problem"

The Higgs is an apparently elementary scalar

Assuming the Standard Model is valid down to some length scale $r_{\rm new} \equiv \frac{\hbar c}{\Lambda}$ then we have

$$\Delta m_H^2 = \frac{\Lambda^2}{16\pi^2}\left[-6y_t^2 + \frac{9}{4}g_2^2 + \frac{3}{4}g_Y^2 + 6\lambda + \ldots\right]$$

Expecting NP at Λ such that $\Delta m_H^2 \sim m_H^2$ is a *strategy*.
More ambitious: explain $m_H^2 < 0$, explain EWSB.

Related: Why not $m_H \sim \Lambda \sim M_{Pl}$? Neutrons no longer stabilized in nuclei for $\langle H \rangle \gtrsim 5\langle H \rangle_{SM}$!
[Agrawal, Barr, Donoghue, Seckel '97]

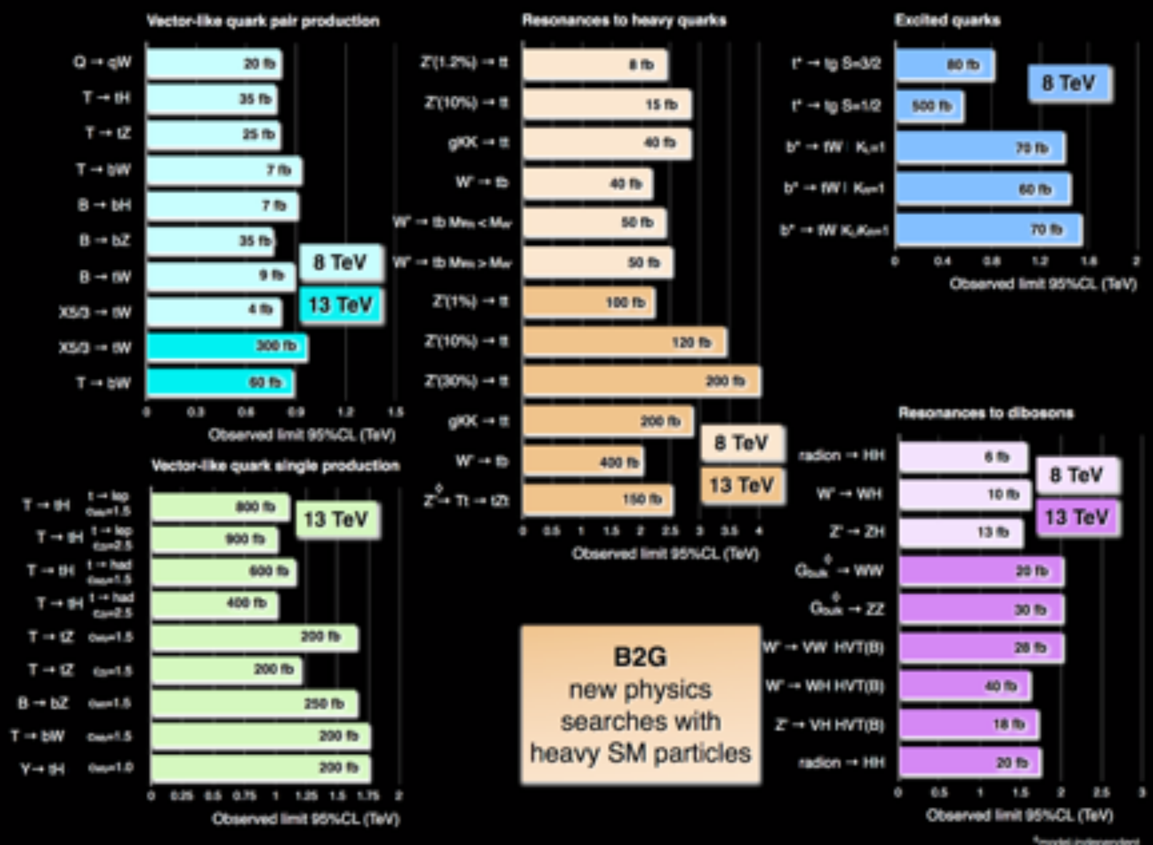
Why is there something, rather than nothing?

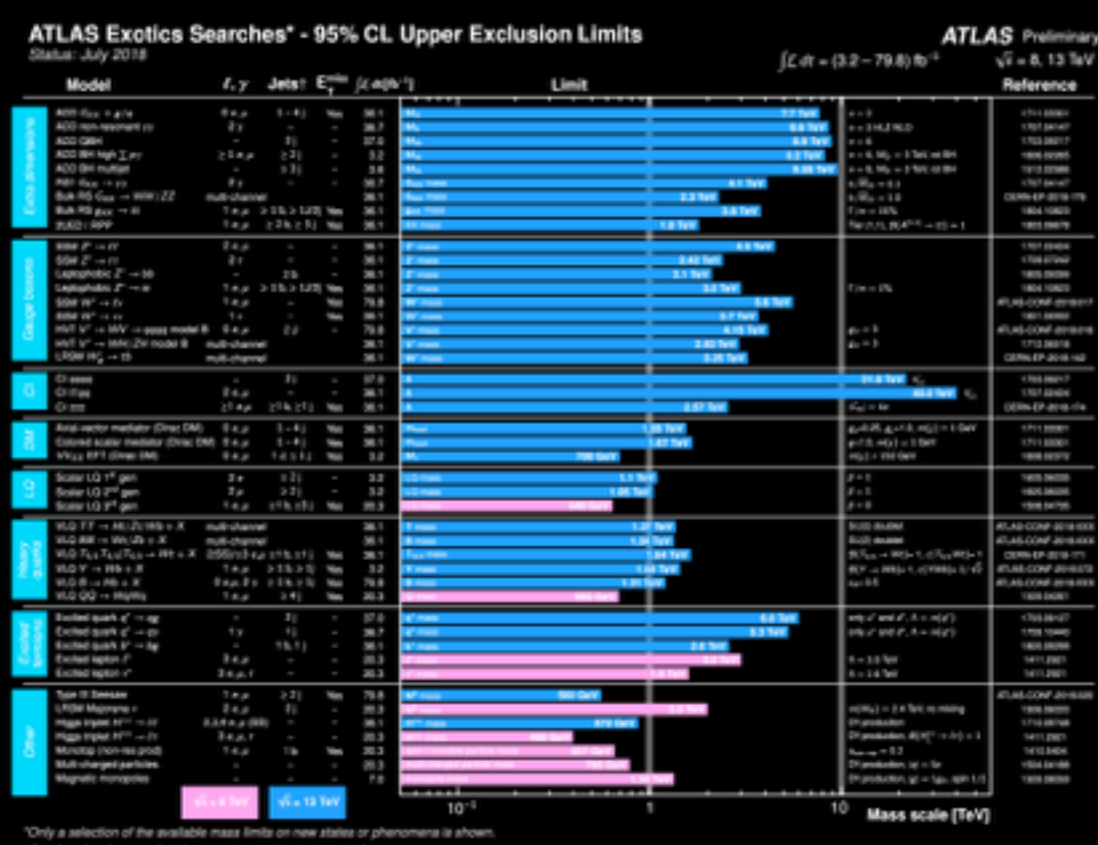
Realizations are up to us

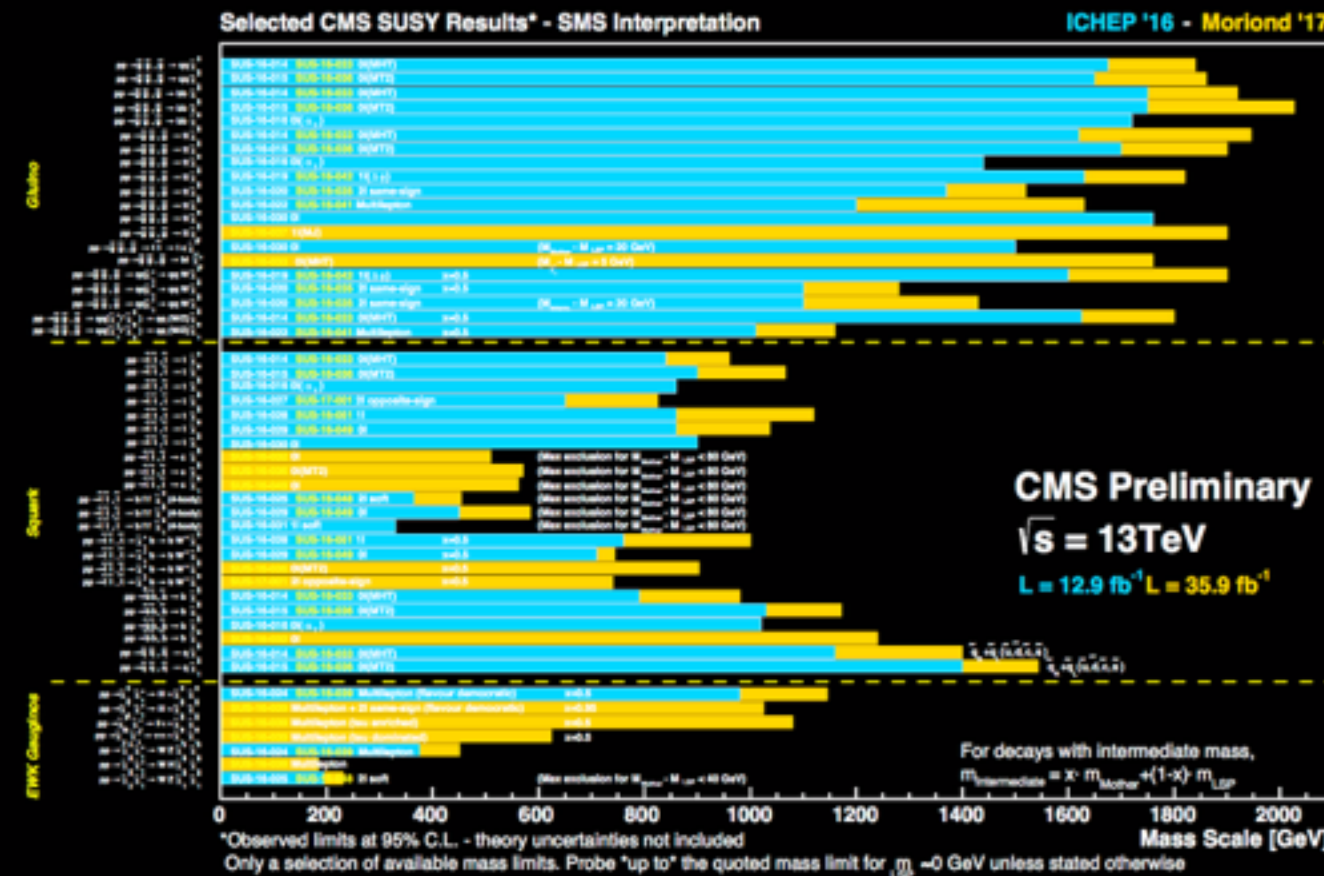
We've refined this strategy using some rules of thumb, *for example…*

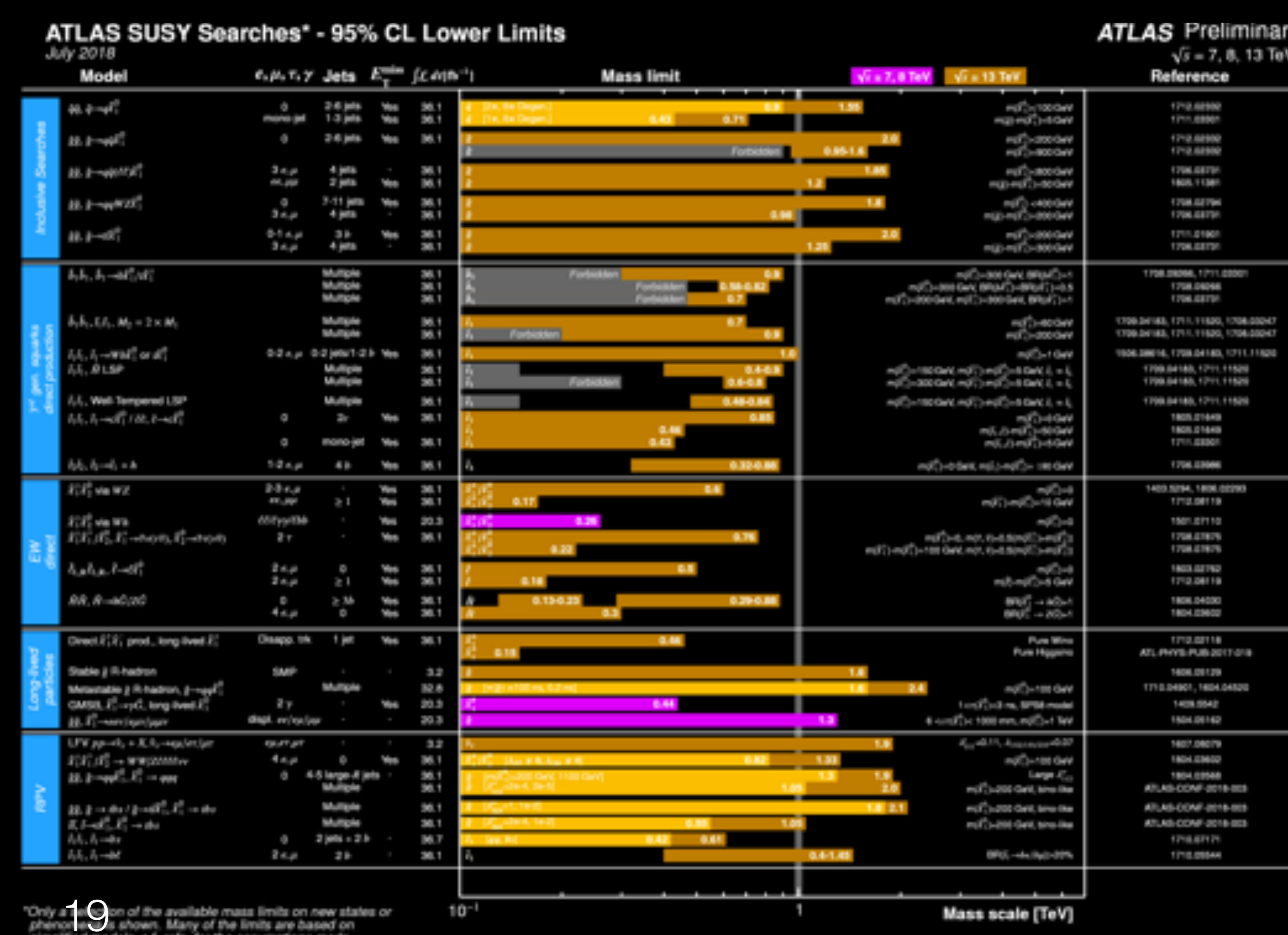
1. The Standard Model coupled to gravity is a generic EFT.
2. The solutions to the hierarchy problem involve symmetries, low cutoffs, or anthropics.
3. Symmetries imply new particles charged under the SM.

Thus far…


Vector-like quark pair production
Resonances to heavy quarks
Excited quarks
8 TeV
13 TeV
Vector-like quark single production
Resonances to dibosons
B2G
new physics
searches with
heavy SM particles
Observed limit 95%CL (TeV)


ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: July 2018
ATLAS Preliminary
Model
Limit
Reference
Mass scale [TeV]


Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
Gluino
Squark
EWK Gauginos
CMS Preliminary
√s = 13TeV
L = 12.9 fb⁻¹ L = 35.9 fb⁻¹
For decays with intermediate mass,
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Mass Scale [GeV]
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe *up to* the quoted mass limit for m_LSP ~0 GeV unless stated otherwise


ATLAS SUSY Searches* - 95% CL Lower Limits
July 2018
ATLAS Preliminary
√s = 7, 8, 13 TeV
Model
Jets
Mass limit
Reference
Inclusive Searches
EW direct
Long-lived particles
RPV
Mass scale [TeV]

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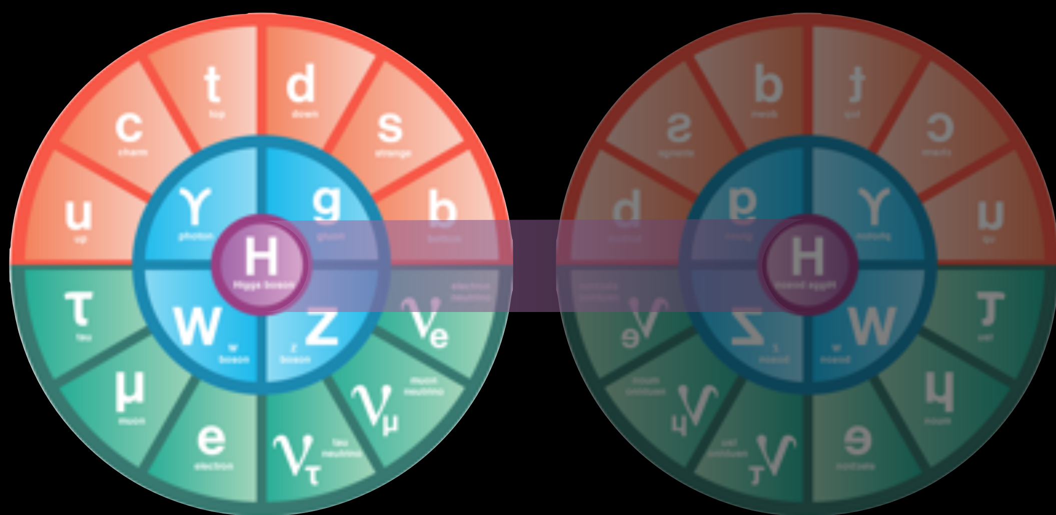
Discrete symmetries



E.g. "Twin Higgs"
[Chacko, Goh, Harnik '05, …]

Higgs is a pNGB of an accidental SU(4), but spectrum only respects a Z_2

$$\Delta V = -\frac{6y_t^2}{16\pi^2}\Lambda^2\left(|H_A|^2 + |H_B|^2\right) + \ldots$$

$$\Delta m_H^2 = -\frac{6y_t^2}{16\pi^2}\Lambda^2 + \frac{6y_t^2}{16\pi^2}\Lambda^2 - 6\frac{y_t^2}{16\pi^2}(m_T^2 - m_t^2)\log\frac{\Lambda^2}{m_T^2}$$

Still a plethora of new particles, not interacting via SM gauge forces but coupling to Higgs.

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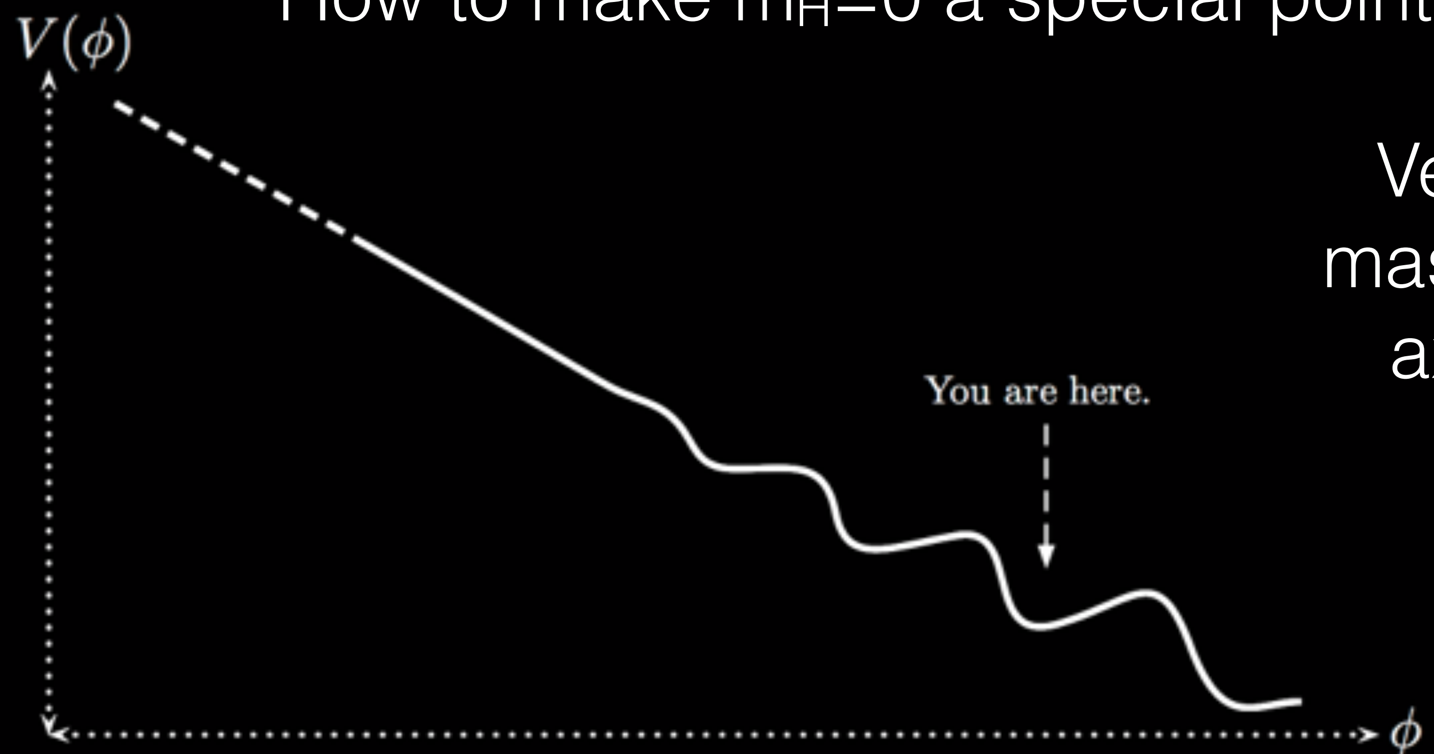
Relaxion

What if the weak scale is selected by scanning?

How to make m_H=0 a special point of potential?



Vev gives quark masses which give axion potential.

"Relaxion"

[Graham, Kaplan, Rajendran '15,…]

Signals? Higgs portals $g\phi|H|^2$ $\Lambda^4(H)\cos(\phi/f)$

$\Lambda^4(H)\cos(\phi/f)$ gives ϕ - H mixing* w/ $\sin\theta \approx \frac{\Lambda^4}{v f m_h^2}$

[Flacke, Friguele, Fuchs, Gupta, Perez '16]

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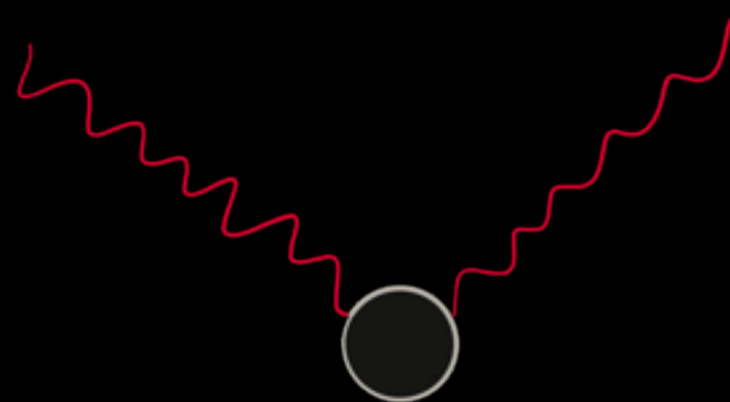
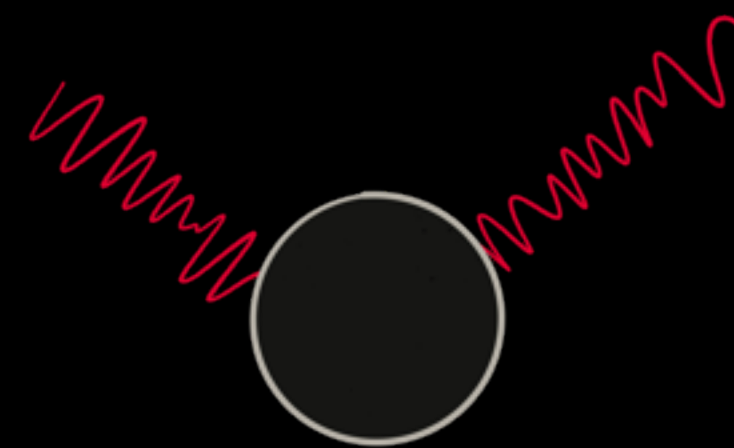
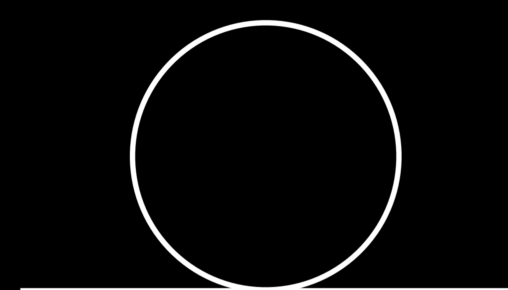
UV/IR Mixing

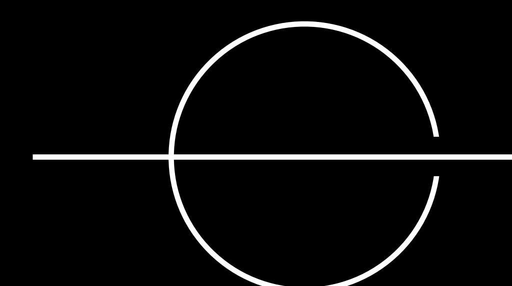
Two examples of UV/IR mixing: Quantum gravity….





…and non-commutative QFT. For example [Minwalla, Seiberg, Van Raamsdonk '99]





$$\sim \int \frac{d^4k}{k^2} \sim \Lambda^2$$

$$\sim \int \frac{d^4k}{k^2} e^{ip\Theta k} \sim \frac{1}{\Theta^2 p^2}$$

$$[x^\mu, x^\nu] = i\Theta^{\mu\nu}$$

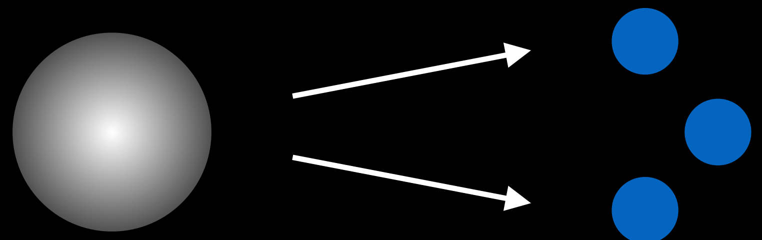
Weak Scale from Weak Gravity

(Electric) weak gravity conjecture: an abelian gauge theory must contain a state of charge *q* and mass *m* satisfying

[Arkani-Hamed, Motl, Nicolis, Vafa '07]

$$q > \frac{m}{M_{Pl}}$$

Motivate by e.g., decay of extremal black holes



Can bound the weak scale if a particle satisfying the WGC acquires some of its mass from EWSB [Cheung, Remmen '14]

Implies new particles at or below the weak scale with appreciable coupling to the Higgs [NC, Garcia Garcia, Koren '19]

See also: [Ibañez, Martin-Lozano, Valenzuela '17,…]

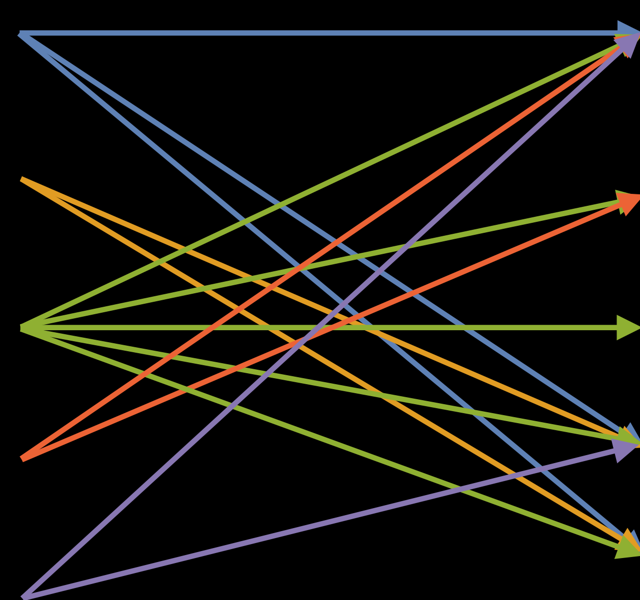
1. ~~The Standard Model coupled to gravity is a generic EFT.~~

2. ~~The solutions to the hierarchy problem involve symmetries, low cutoffs, or anthropics.~~

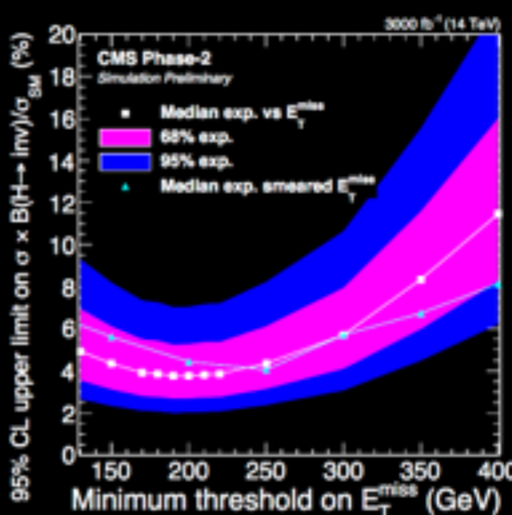
3. ~~Symmetries imply new particles charged under the SM.~~

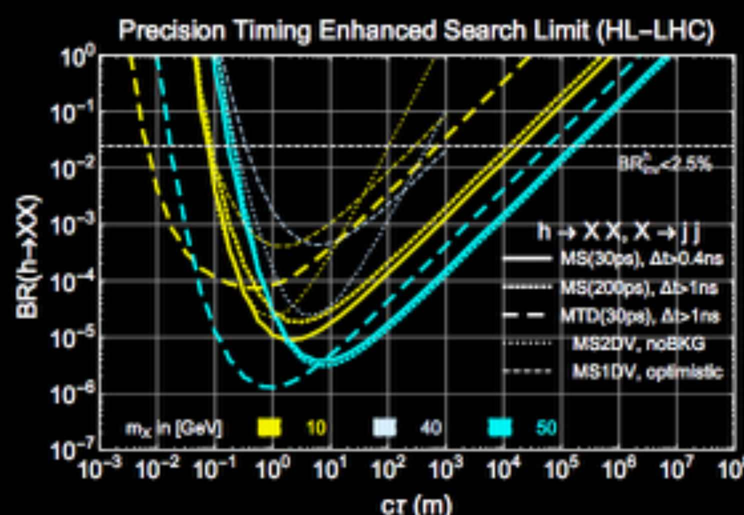
Look to the Higgs

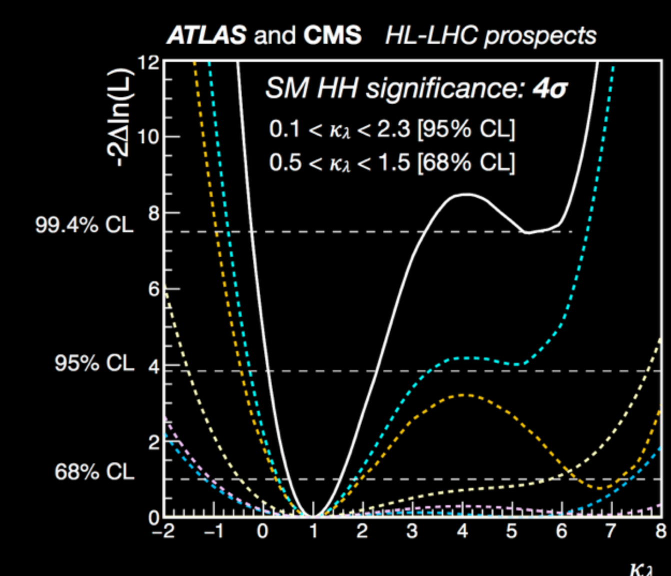
Supersymmetry
Global symmetry
Discrete symmetry
Relaxation
UV/IR mixing



Higgs → invisible
Higgs → exotic
Higgs → LLPs
Higgs couplings
Di-Higgs





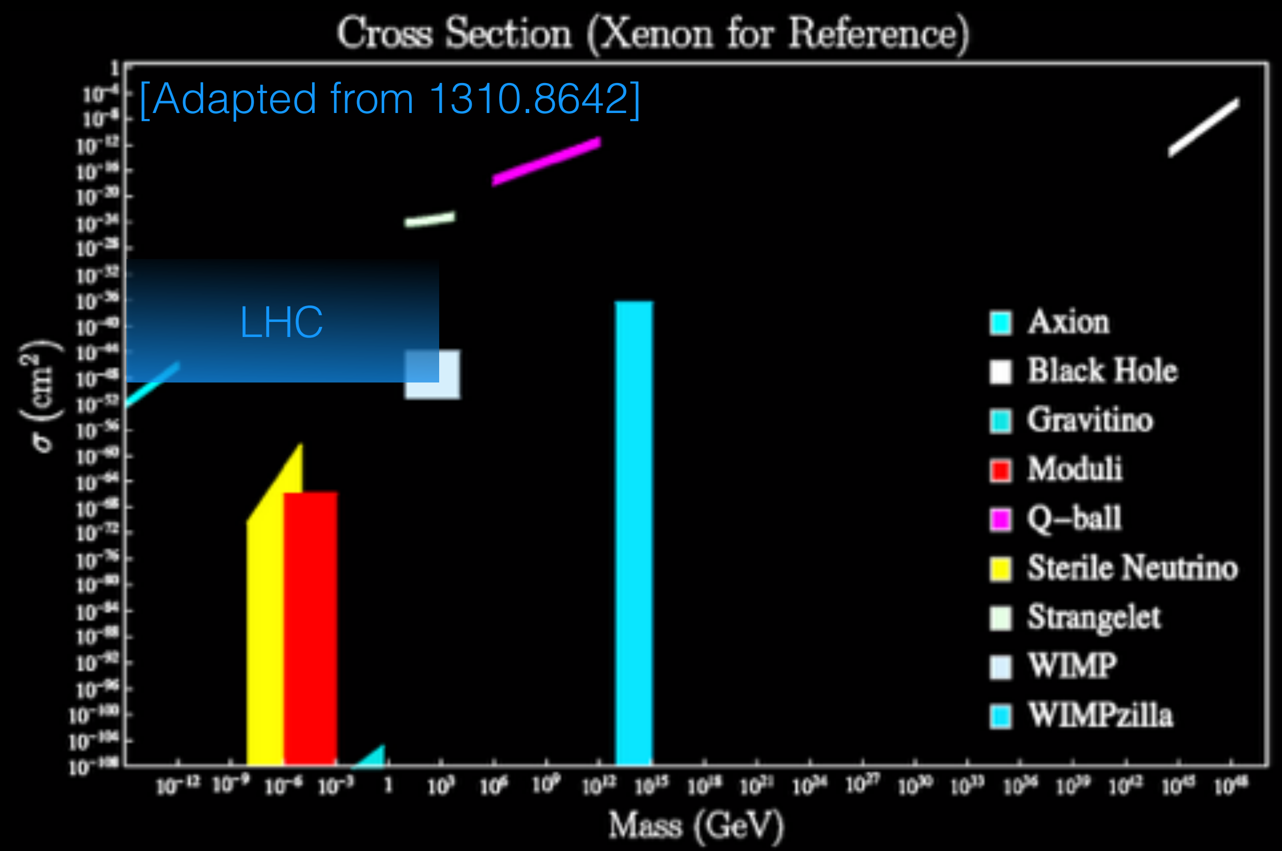


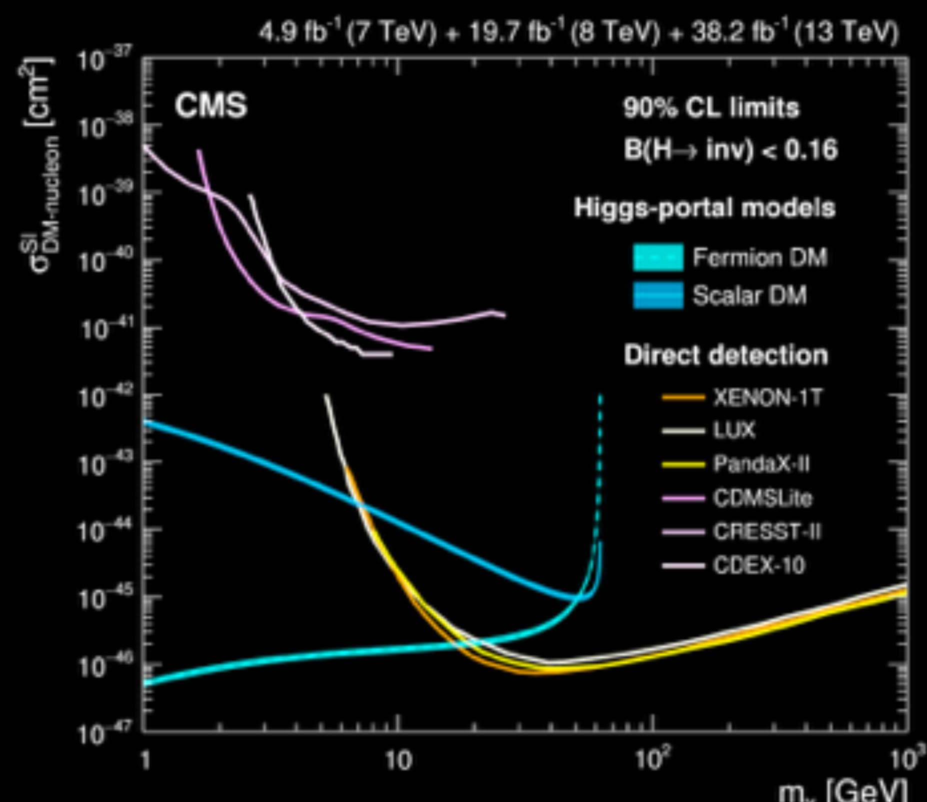
Dark matter

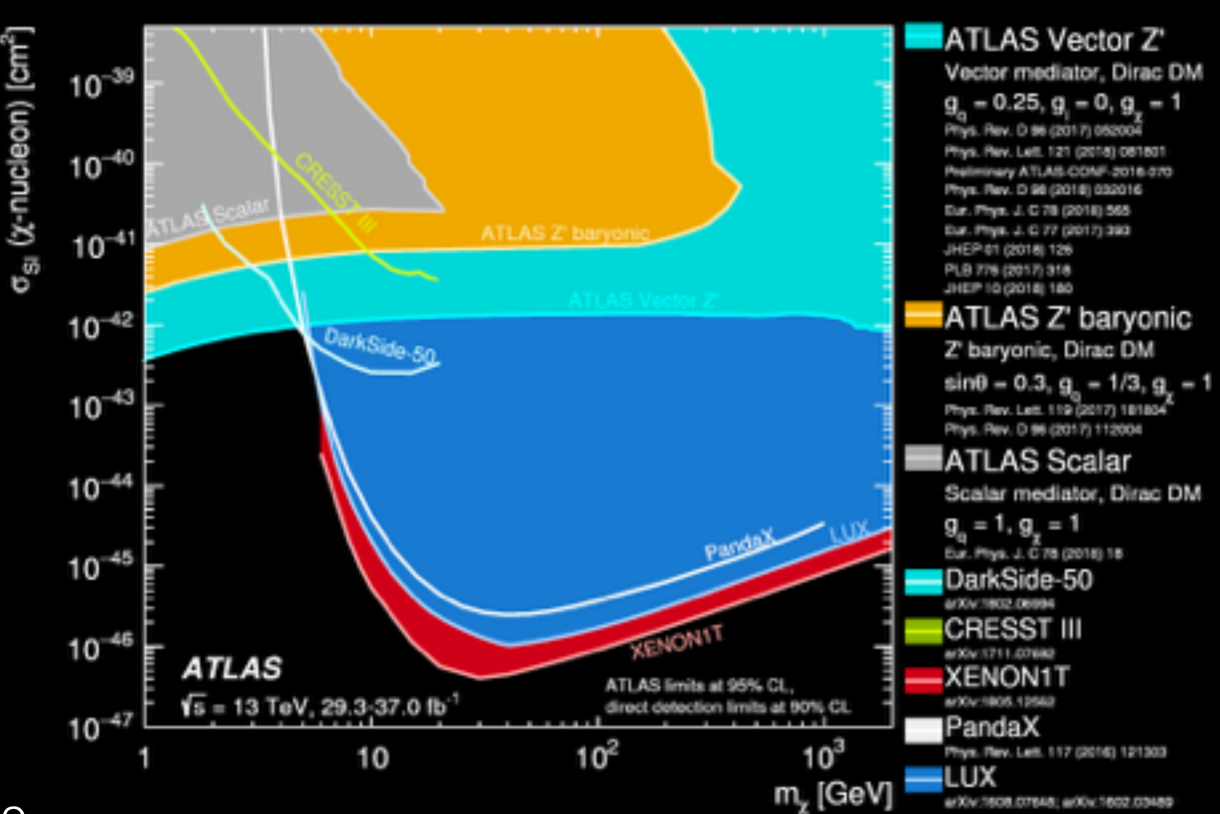
We know it's there;
coincidence of Ω_b, Ω_{dm} suggests interactions beyond gravitational

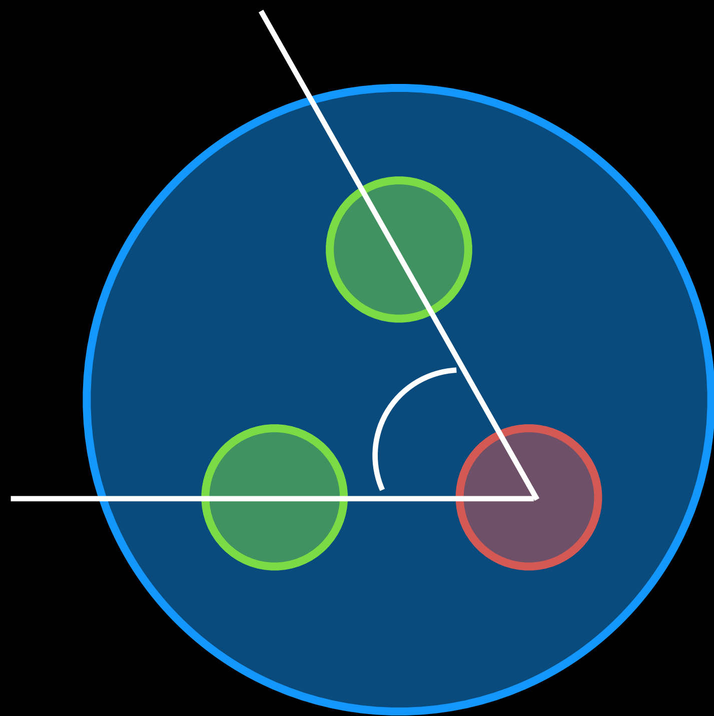
LHC *strongly* complementary, expect continuous improvement

Higgs a powerful handle









Strong CP

Classical version: bound on neutron EDM

$$|d_n| \lesssim 3 \times 10^{-26}\, e\,\mathrm{cm}$$

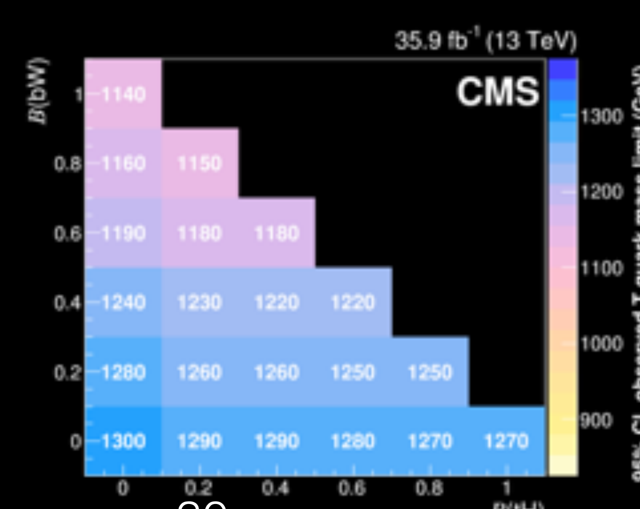
"implies" up, down quarks aligned to within 10^{-12}

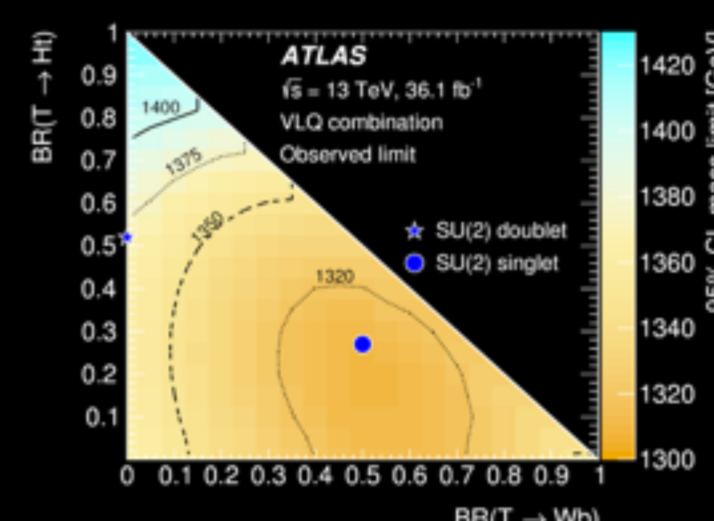
Quantum version: naively O(1) θ parameter is actually < 10^{-10}

Axions: popular solution, but not much for the LHC to say.
Equally interesting: parity solutions, e.g.

$$SU(3)c \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_c \times SU(2)_L \times SU(2)'_L \times U(1)_Y$$

New parity partners of all SM fermions. Likely LHC accessible, probed by (light flavor) VLQ searches





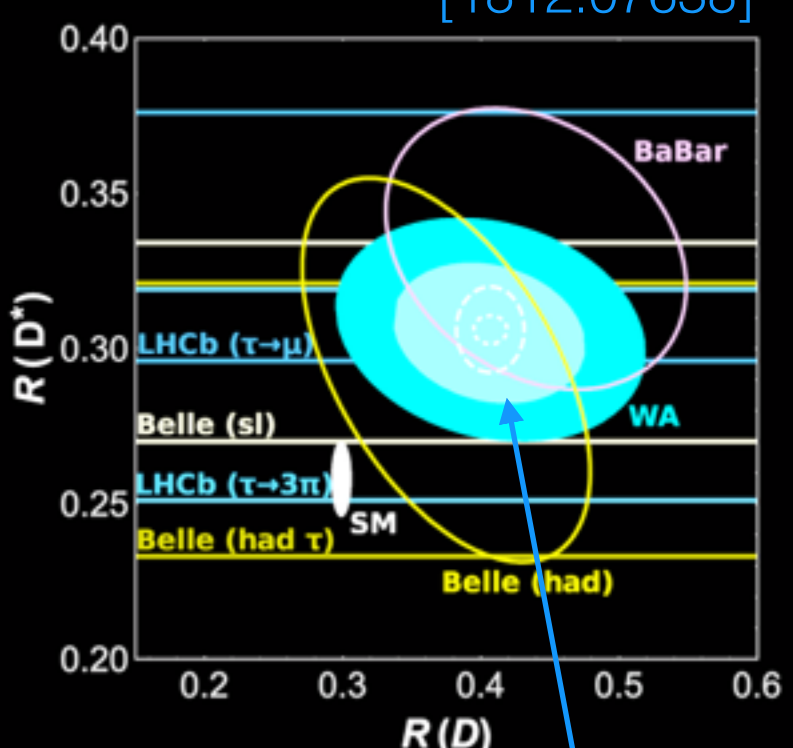
Flavor

Success of SM flavor structure long a source of discomfort for BSM physics.

Now in an era of numerous anomalies, particularly 3rd generation. Decisive input from HL-LHC, Belle II will point the way…

b → c τ ν

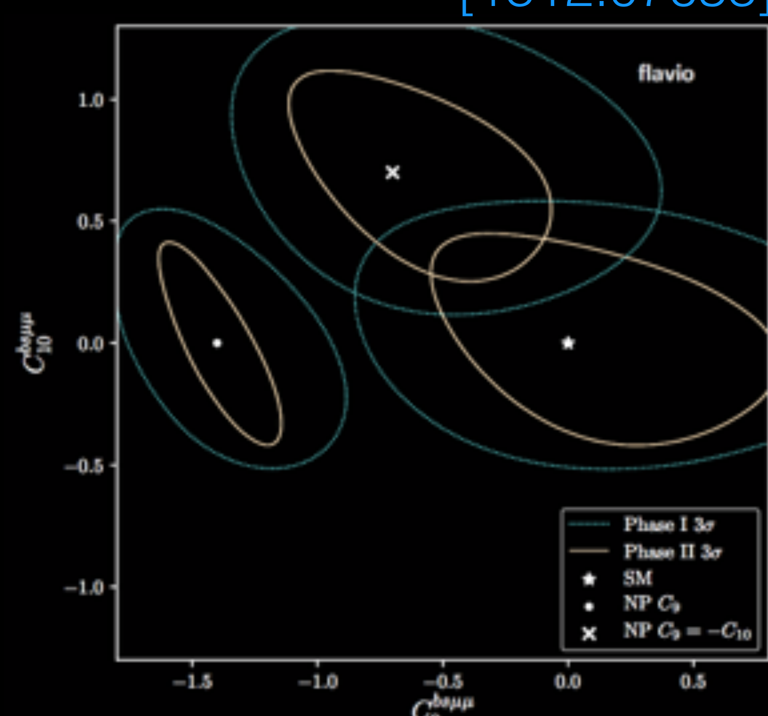
[1812.07638]



LHCb 2025 & Upgrade II

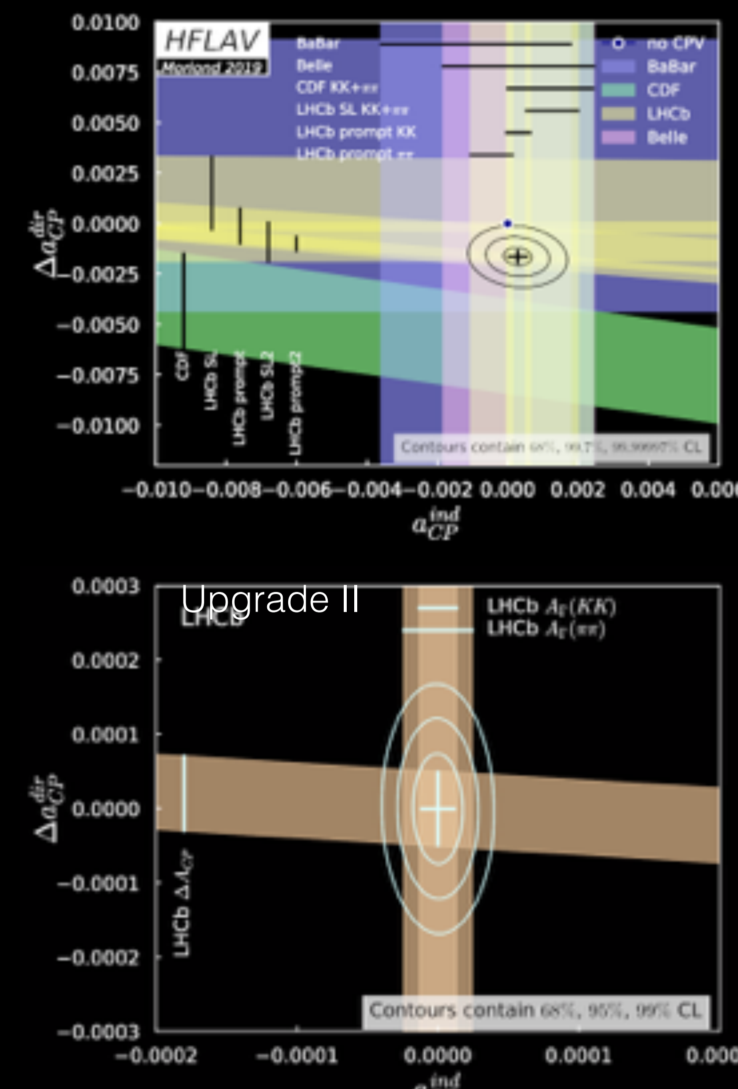
b → s μ μ

[1812.07638]

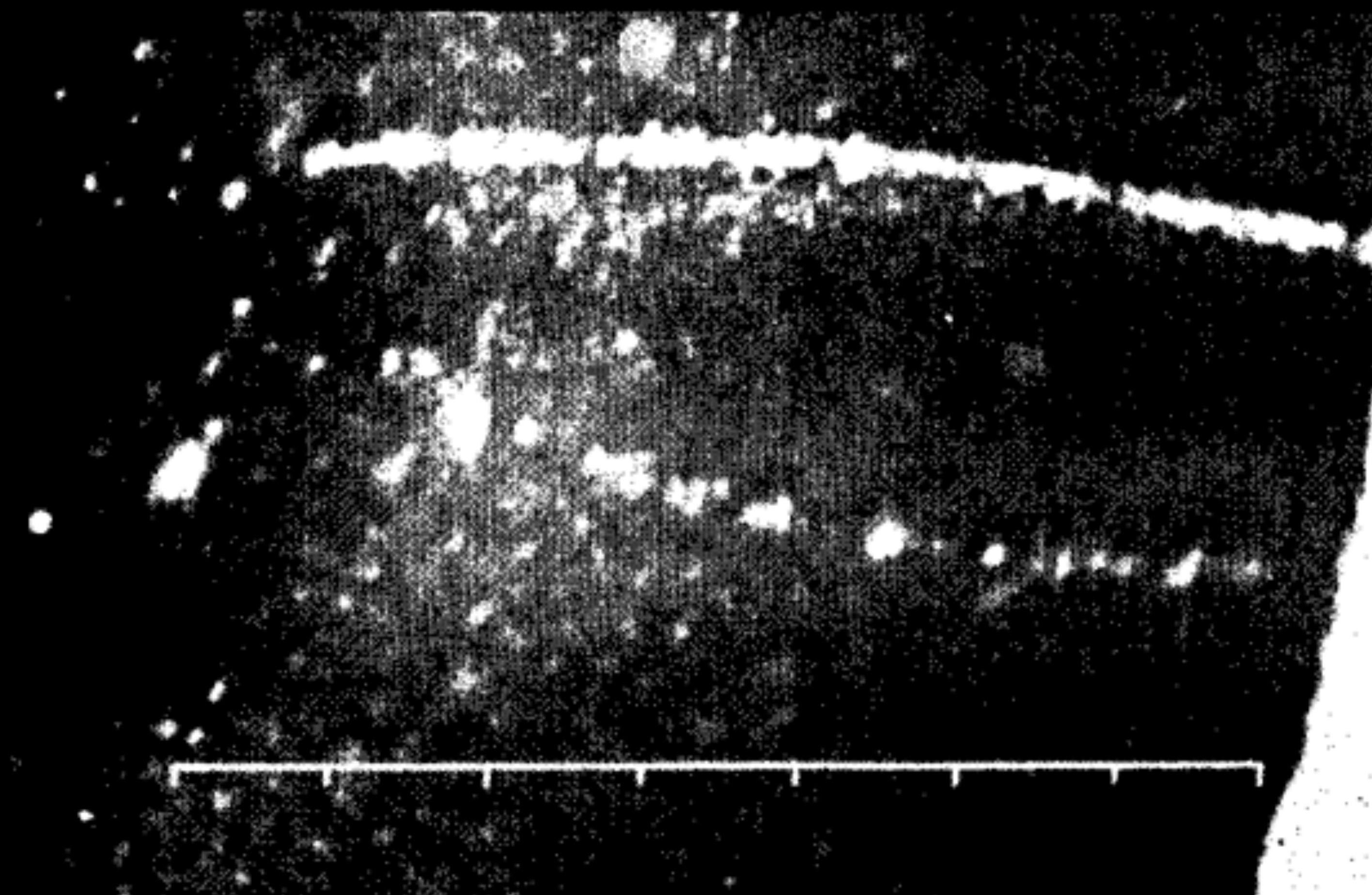


ATLAS, CMS, LHCb combination

Charm CPV



Who ordered that?

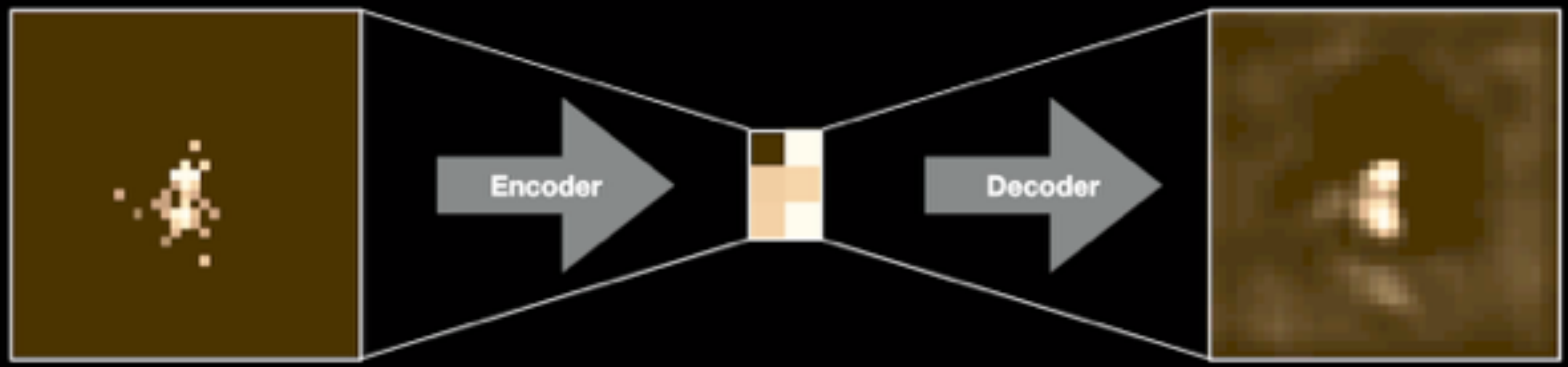


"The other double trace of the same type (figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle whith a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive electron the ionization is too strong. The present double trace is probably a segment from a "shower" of particles as they have been observed by Blackett and Occhialini, i.e. the result of a nuclear explosion".

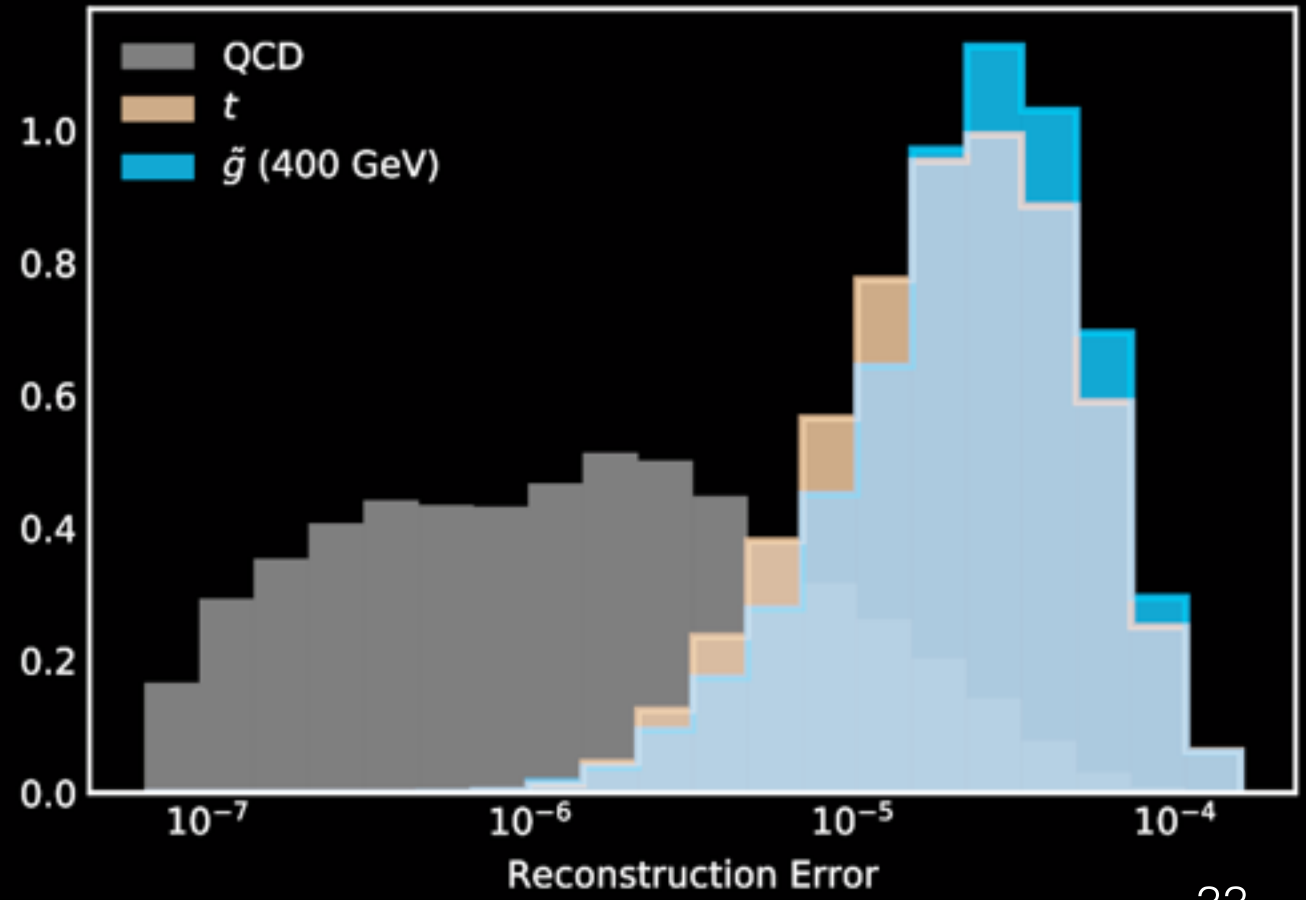
Kunze, P., Z. Phys. 83, (1933) 1

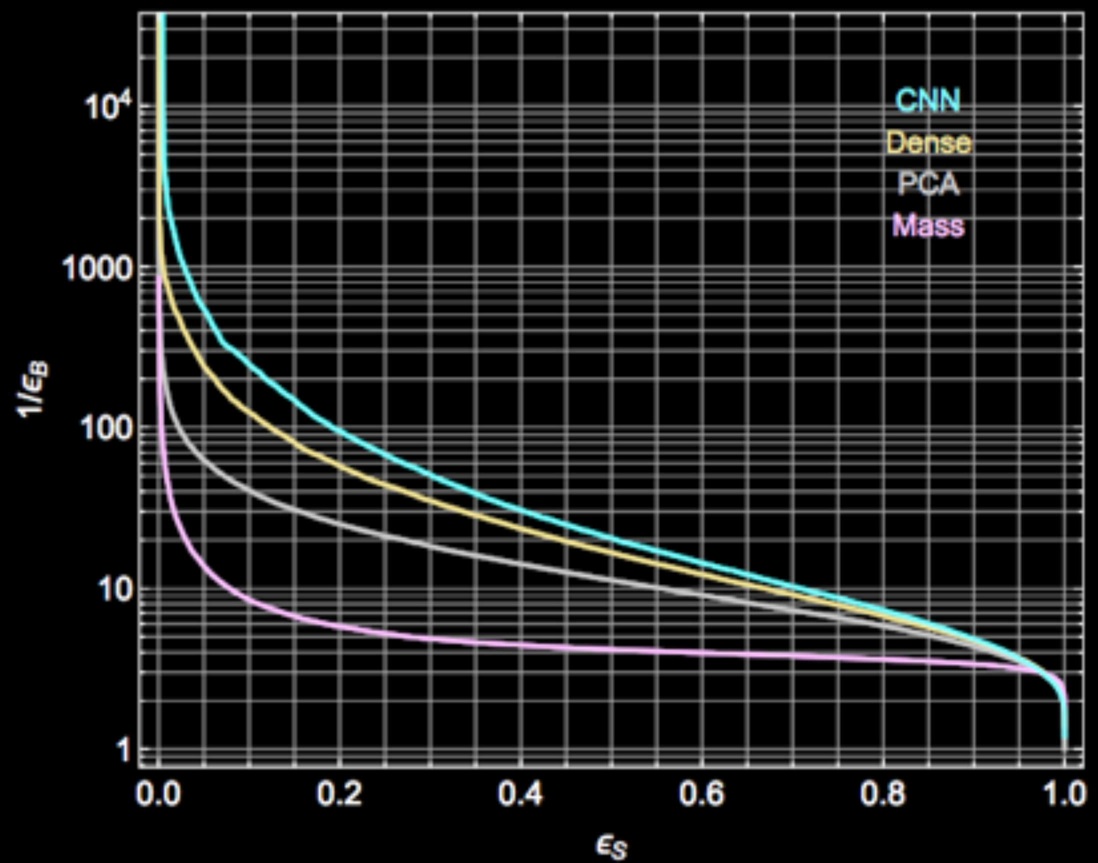
New (theorist-free) searches

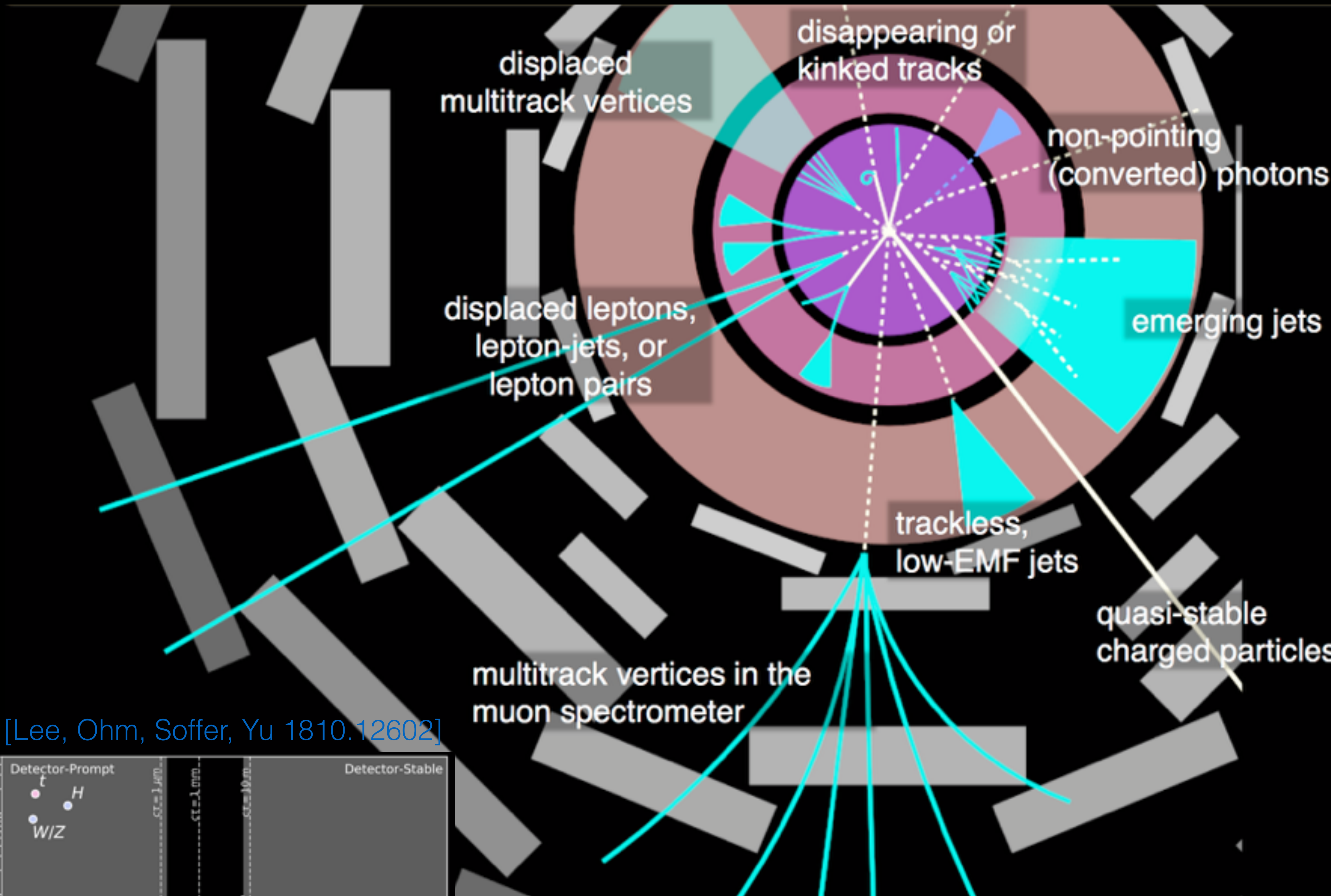
E.g. unsupervised learning for anomaly detection (autoencoders, …)



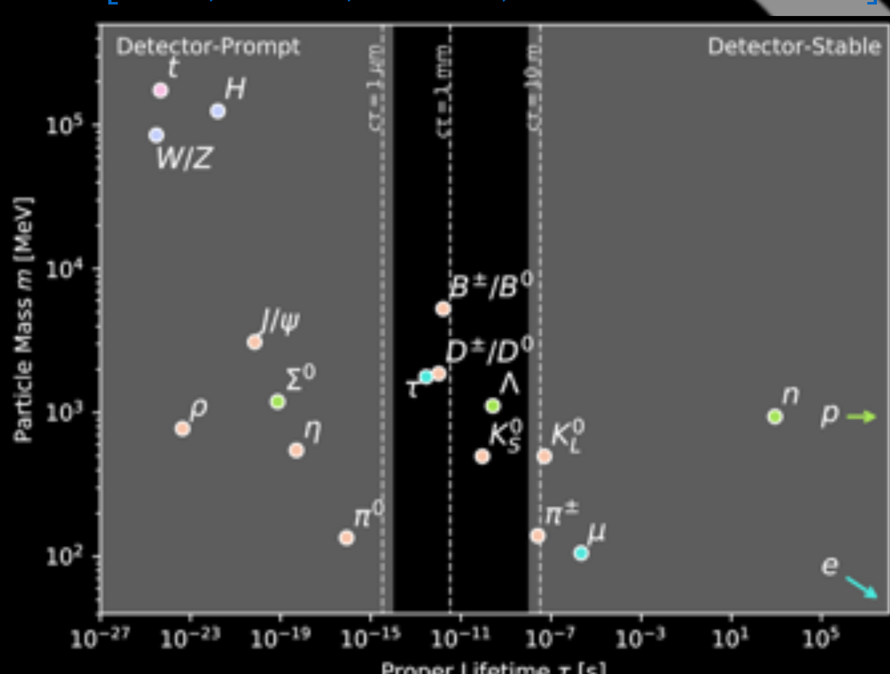
[Farina, Nakai, Shih 1808.08992]







[Lee, Ohm, Soffer, Yu 1810.12602]

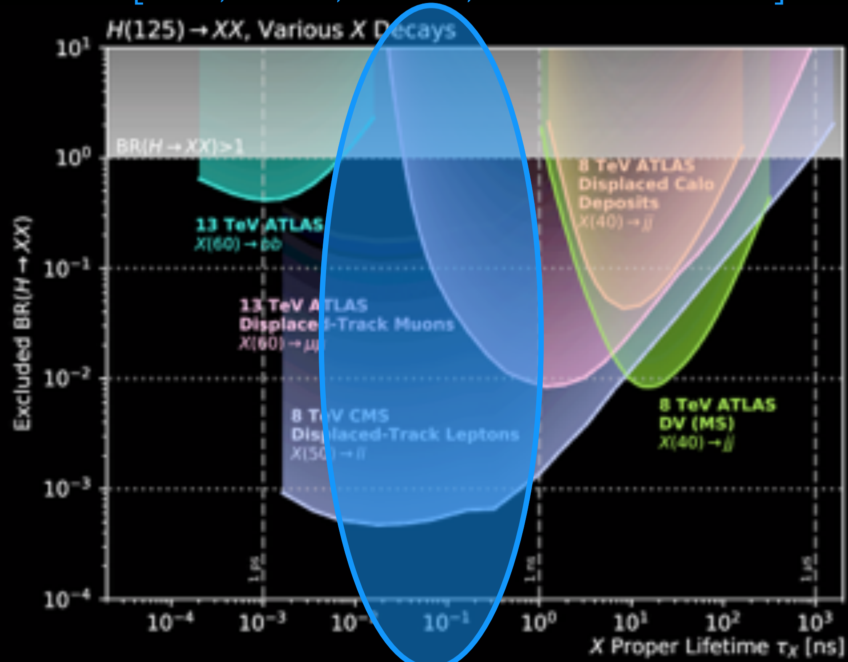


[Heather Russell '17]

New signatures

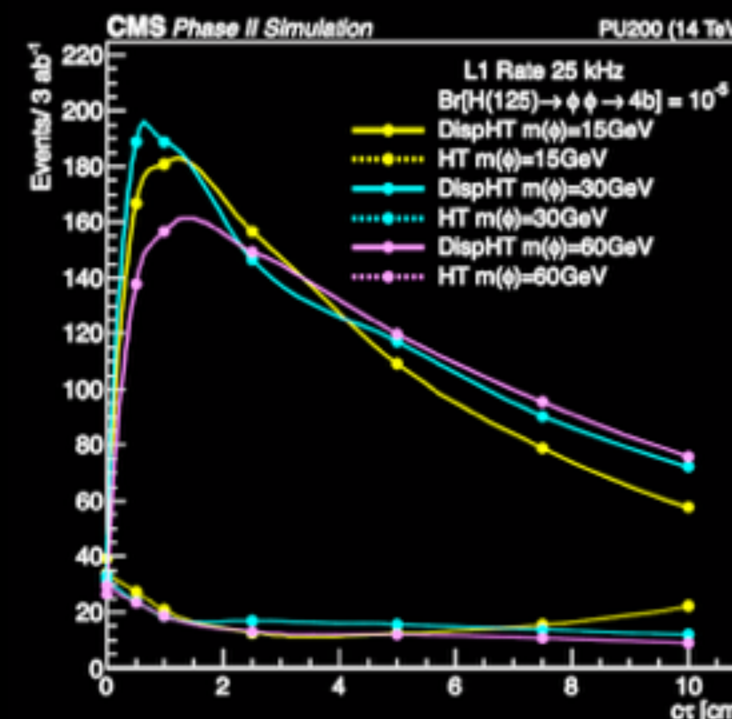
New opportunities

[Lee, Ohm, Soffer, Yu 1810.12602]

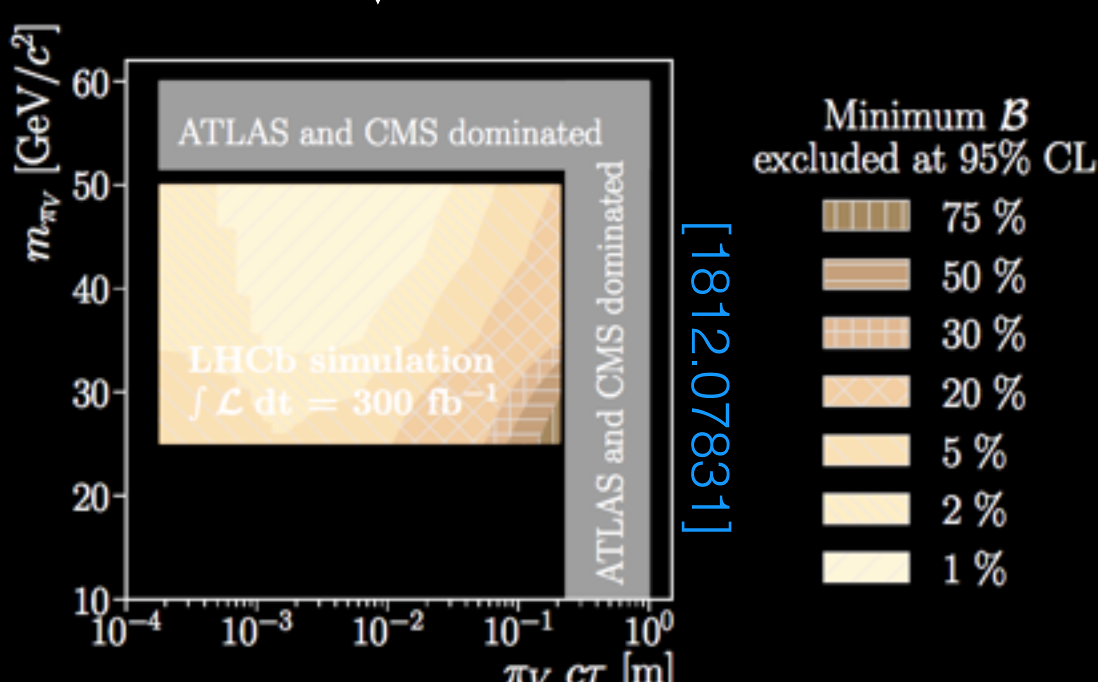


~Blind spot for Higgs decays to LLPs in hadronic final states between 1cm-1m

Track Trigger

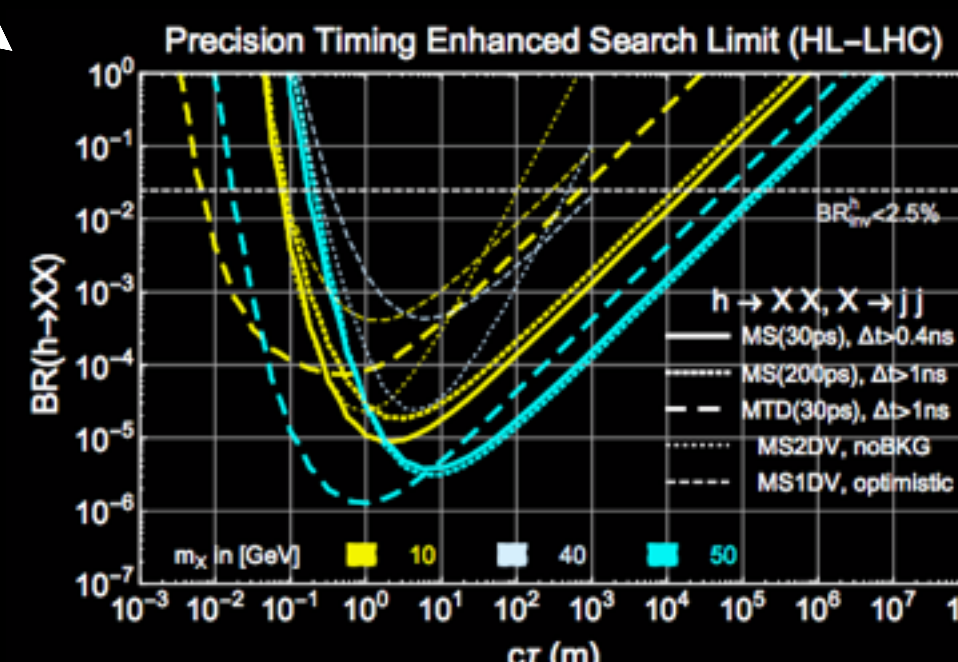


[1902.00134]



[1812.07831]

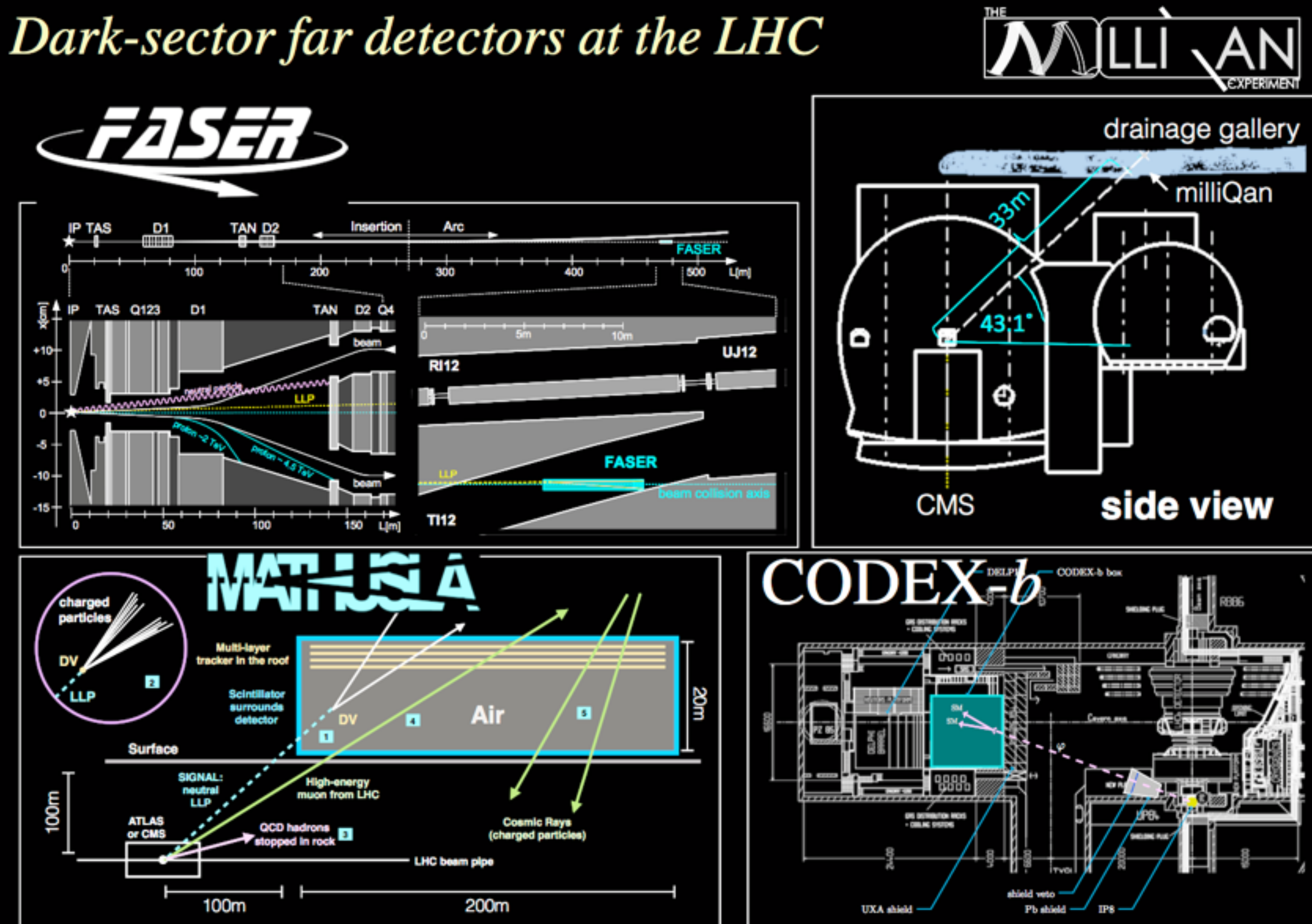
LHCb Upgrades



[1902.00134]

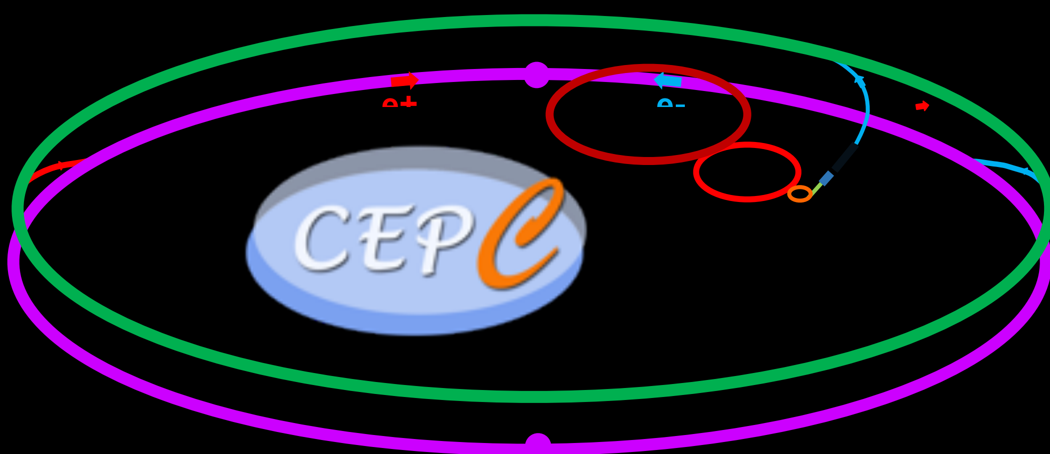
Precision Timing

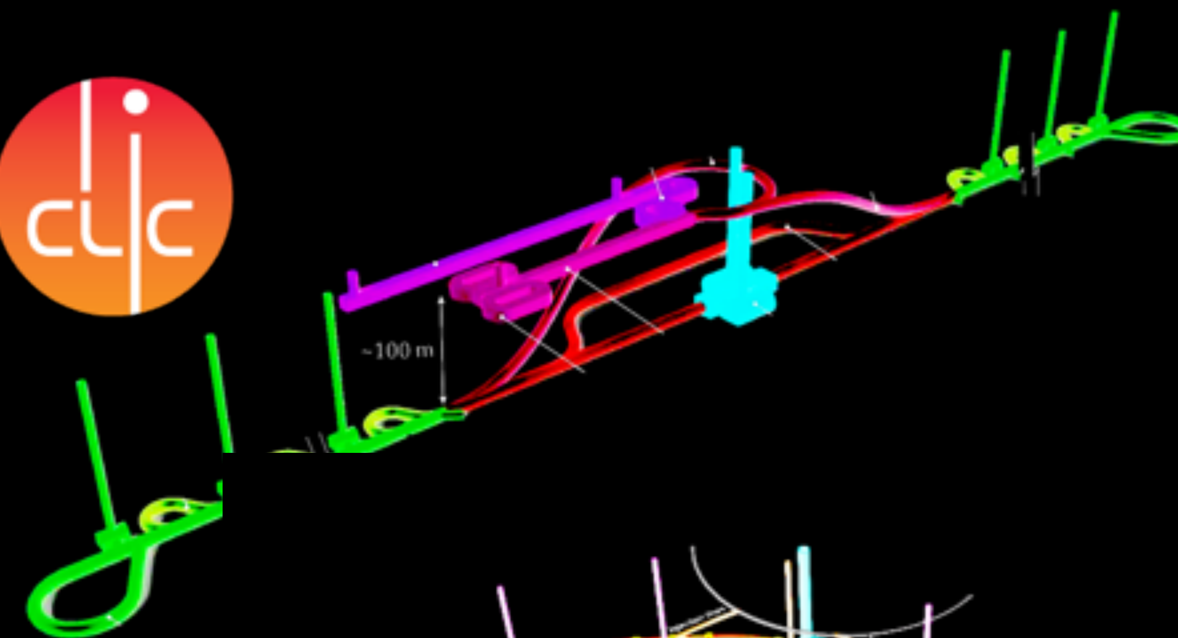
New force multipliers

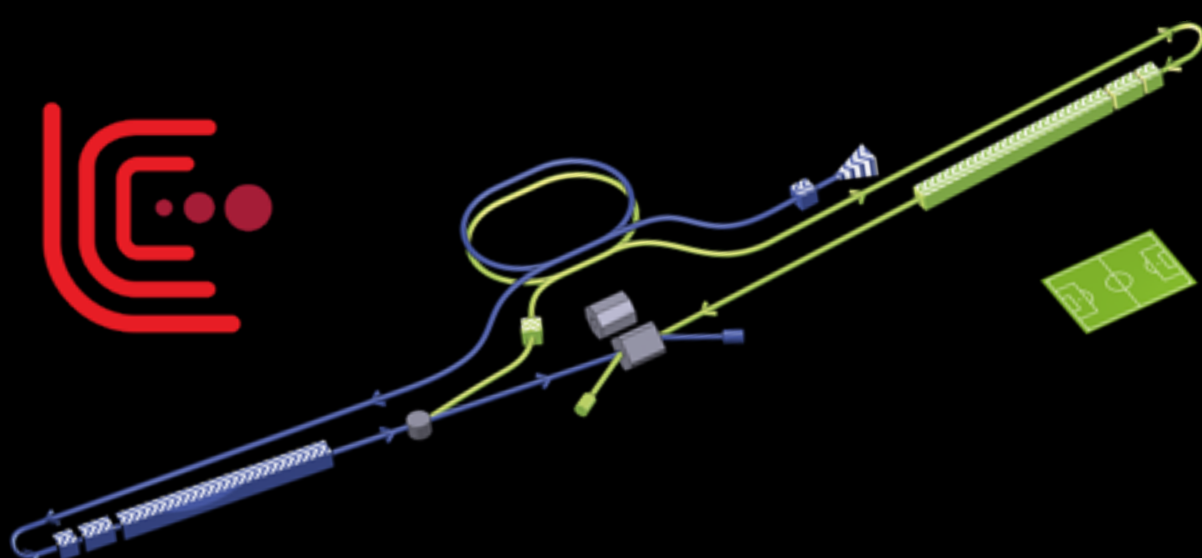


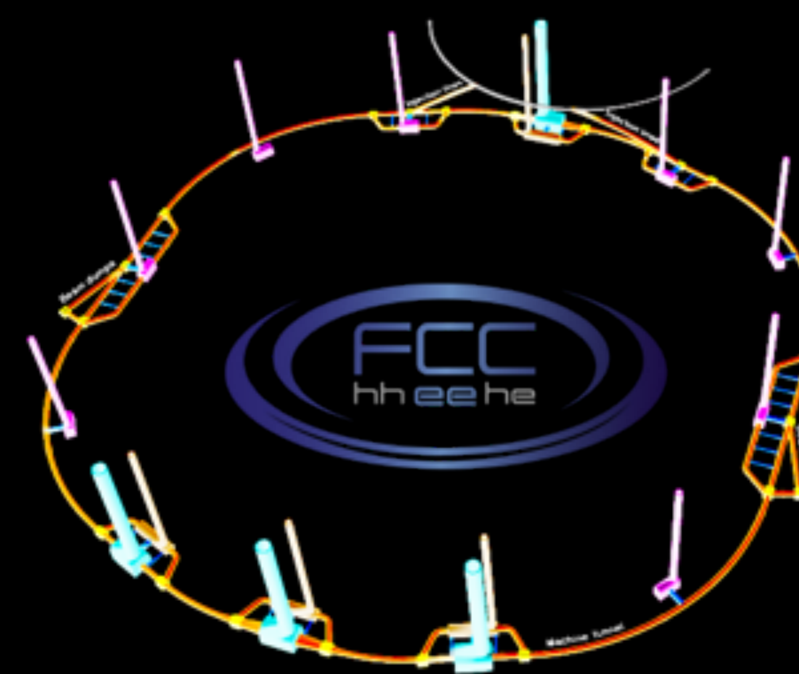
D.W. Miller LHCP2019

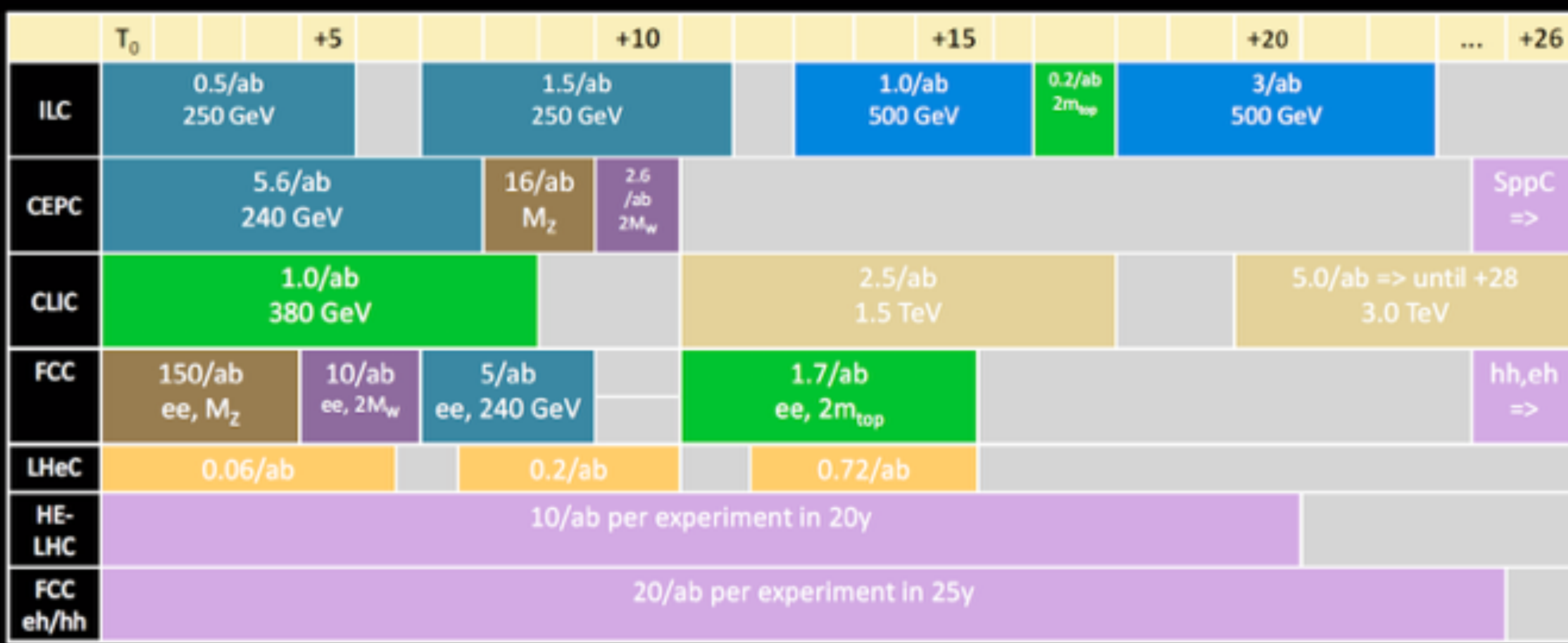
New Colliders





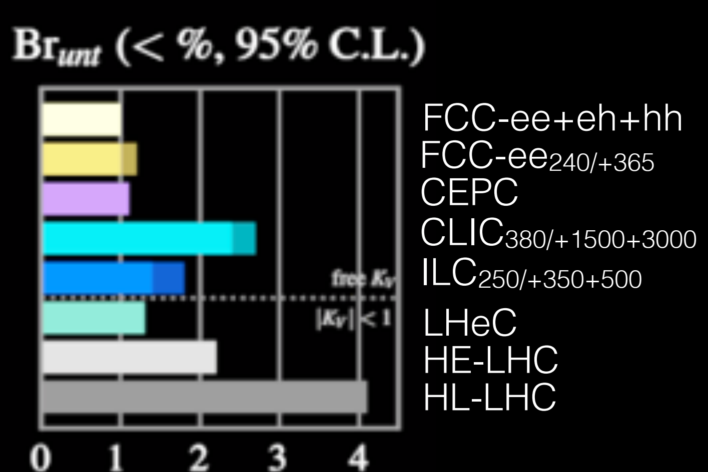


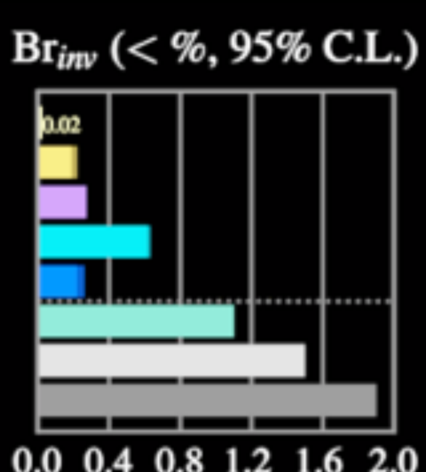


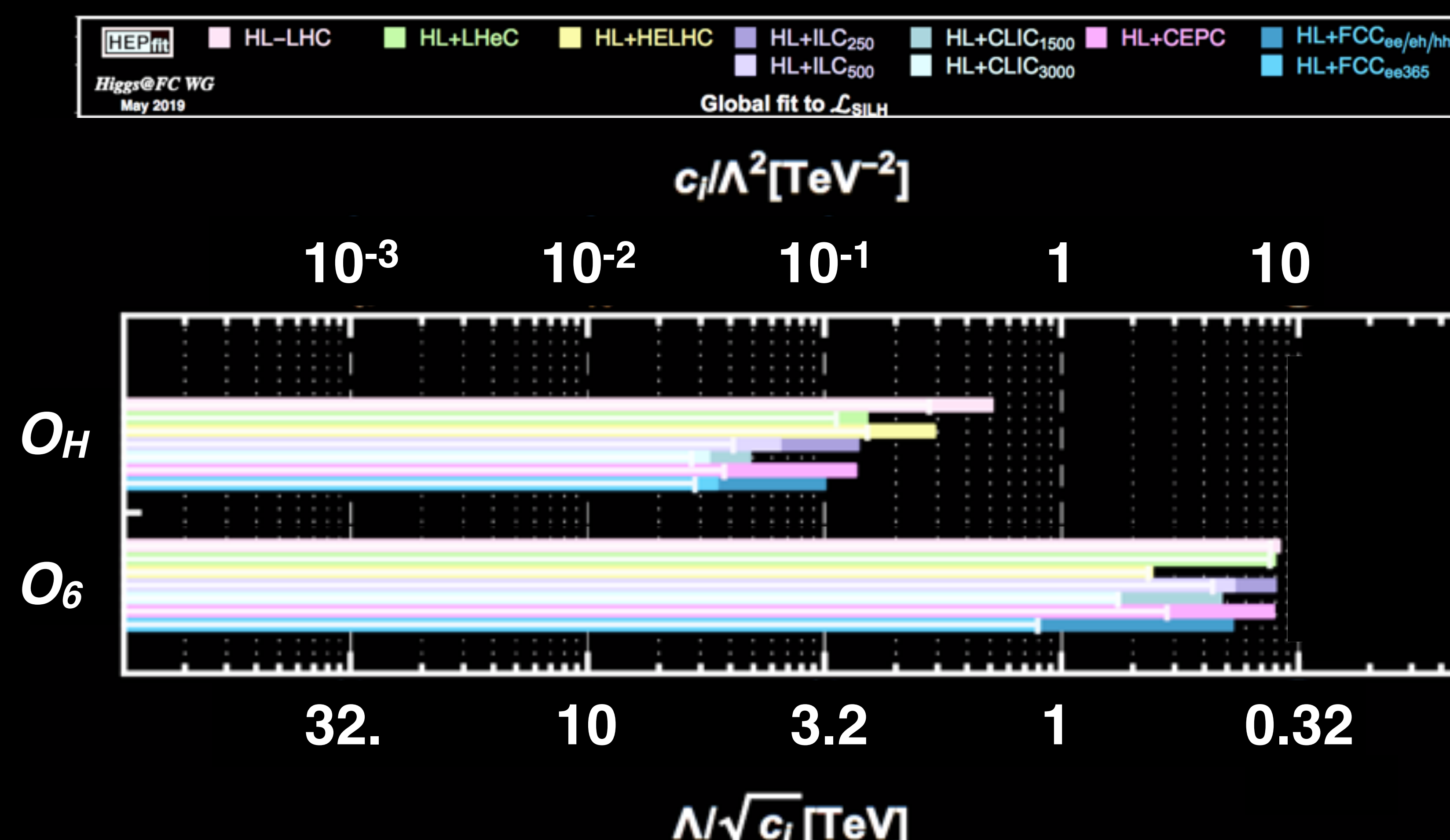


~Order of magnitude improvement achievable in Higgs properties most interesting for SM, BSM (over already-impressive HL-LHC sensitivity)

Ideal machines for the questions of our era







[1905.03764]

ECFA 84/85
CERN 84-10
5 September 1984

LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA–CERN WORKSHOP

held at Lausanne and Geneva,
21–27 March 1984

Does the physics case for future colliders require a guarantee of discovery?

PHYSICS WITH A MULTI-TeV HADRON COLLIDER

C.H. Llewellyn Smith,

7. HIGGS BOSONS

Extensive studies of Higgs boson production were reported at Lausanne[15,16] which lead to the conclusion that discovering a conventioanl heavy Higgs boson will be difficult even at 20 TeV., the energy we assume in the following discussion.

SUMMARY REPORT On the other hand, searching for the Higgs meson as it appears in the standard model looks difficult. Rates are low and background large.

Conclusions c. 1984

PHYSICS WITH A MULTI-TeV HADRON COLLIDER

C.H. Llewellyn Smith,

Looking at the wide variety of alternatives which have been proposed, it might appear that theorists are in disarray but it seems to me that the present situation is an inevitable consequence of the successes of the 1970's. The problems of the 1960's - the nature of hadrons, the nature of the strong force, the nature of the weak force - have been solved. We now confront deeper problems - the origin of mass, the choice of fundamental building blocks (the problem of flavour), the question of further unification of forces including gravity, the origin of charge and of gauge symmetry. It is only to be expected that many of the first attempts to grapple with these problems will be misguided. As ever, we must reply on experiment to reveal the truth.

Conclusions c. 2019

```
✓ What is the origin of mass?
What kind of unification may exist?
What is the origin of flavor?
Is there a deeper reason for gauge symmetry?
+ What is the nature of dark matter?
+ Why does the strong force ~conserve CP?
```

- Higgs discovery defines new conceptual questions: A fundamental scalar? A self-interacting particle? A Yukawa force-carrier?
- These are the questions of this era. We are poised to make substantial progress throughout the lifetime of the LHC and decisively answer them with a future collider program.
- Equally compelling opportunities to address the longer-standing questions of the weak scale, flavor, dark matter, strong CP. Theoretical “first attempts” being challenged, new directions under exploration.
- *As ever, we must rely on experiment to reveal the truth.*