APS Global Physics Summit 2025
Anaheim, California
March 20, 2025

A Perspective on the future of Higgs physics

Gavin Salam
University of Oxford & All Souls College

THE ROYAL SOCIETY

UNIVERSITY OF OXFORD

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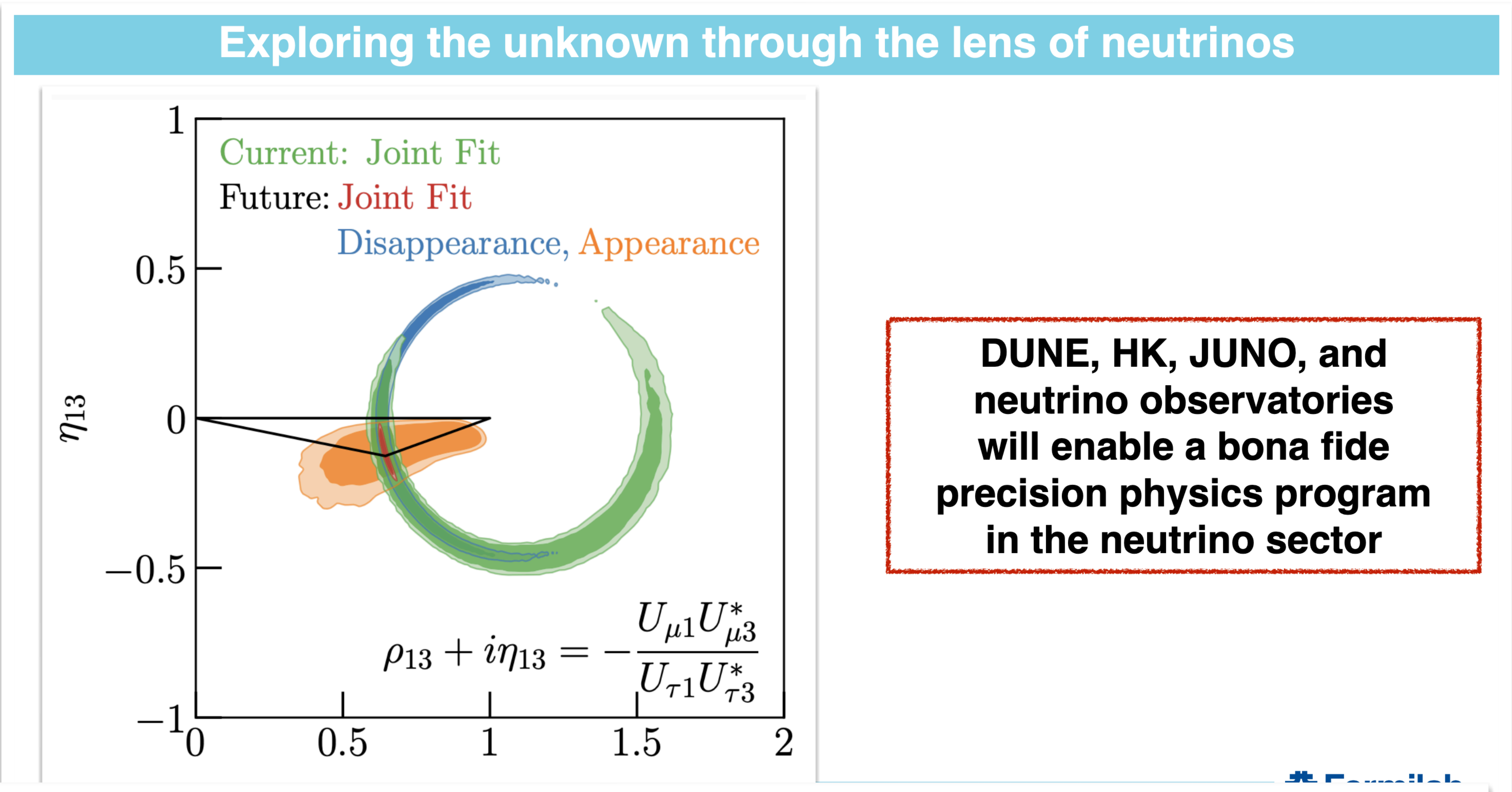
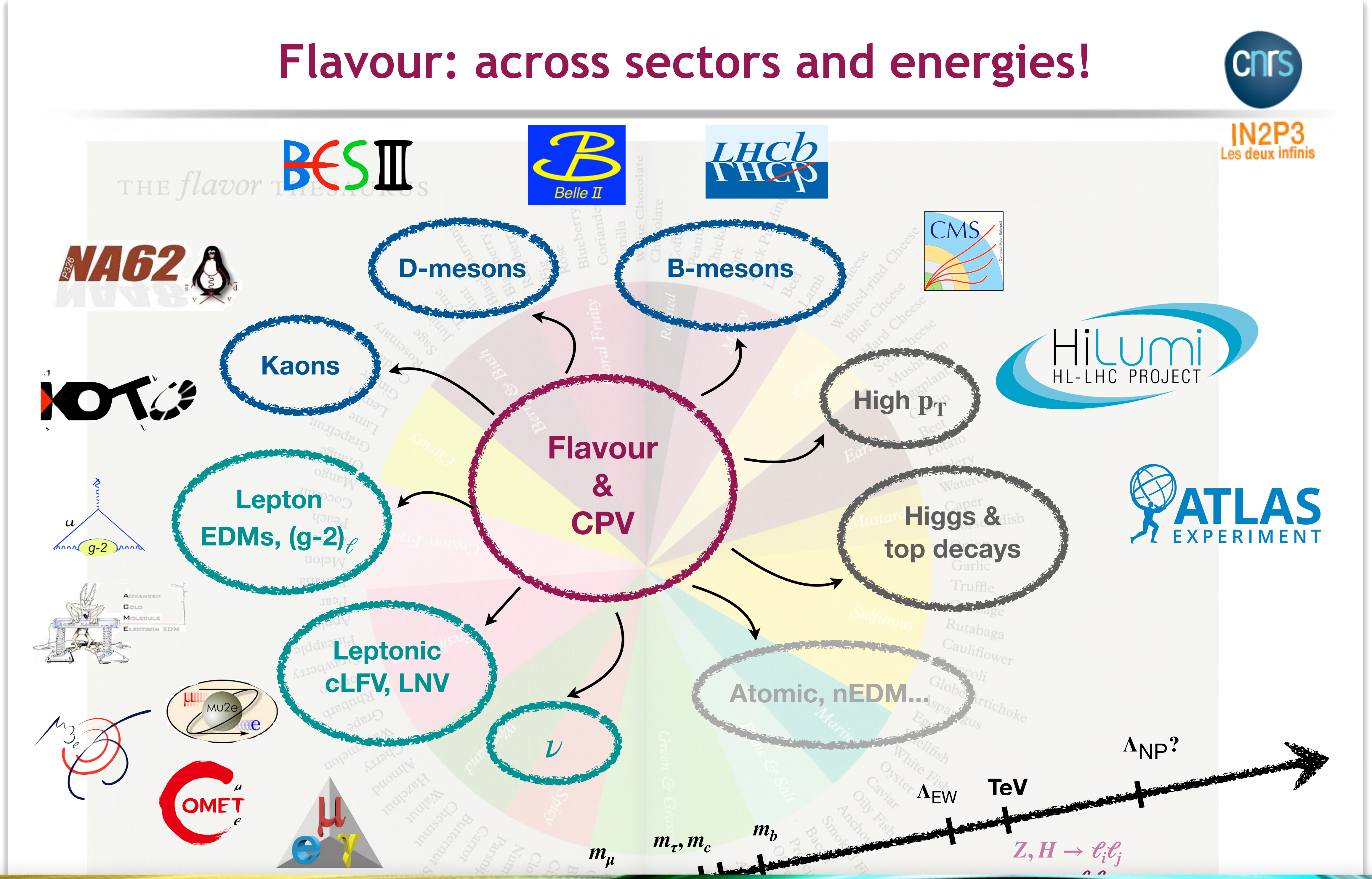
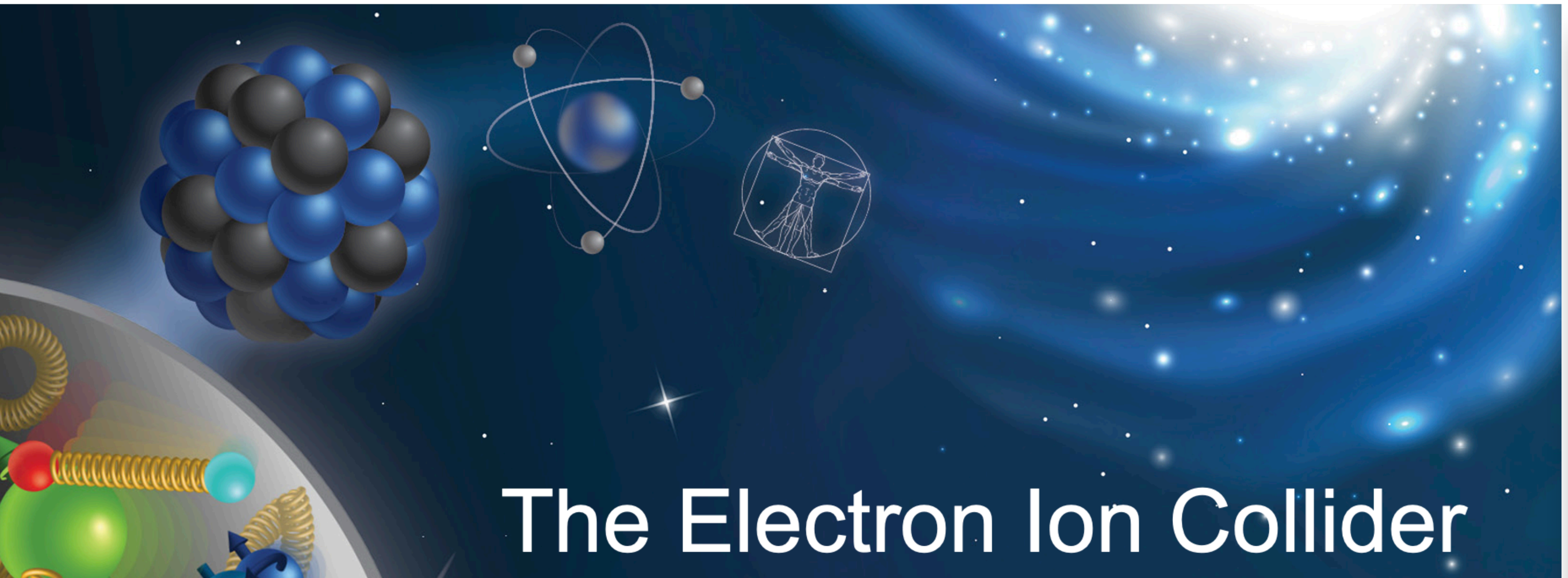
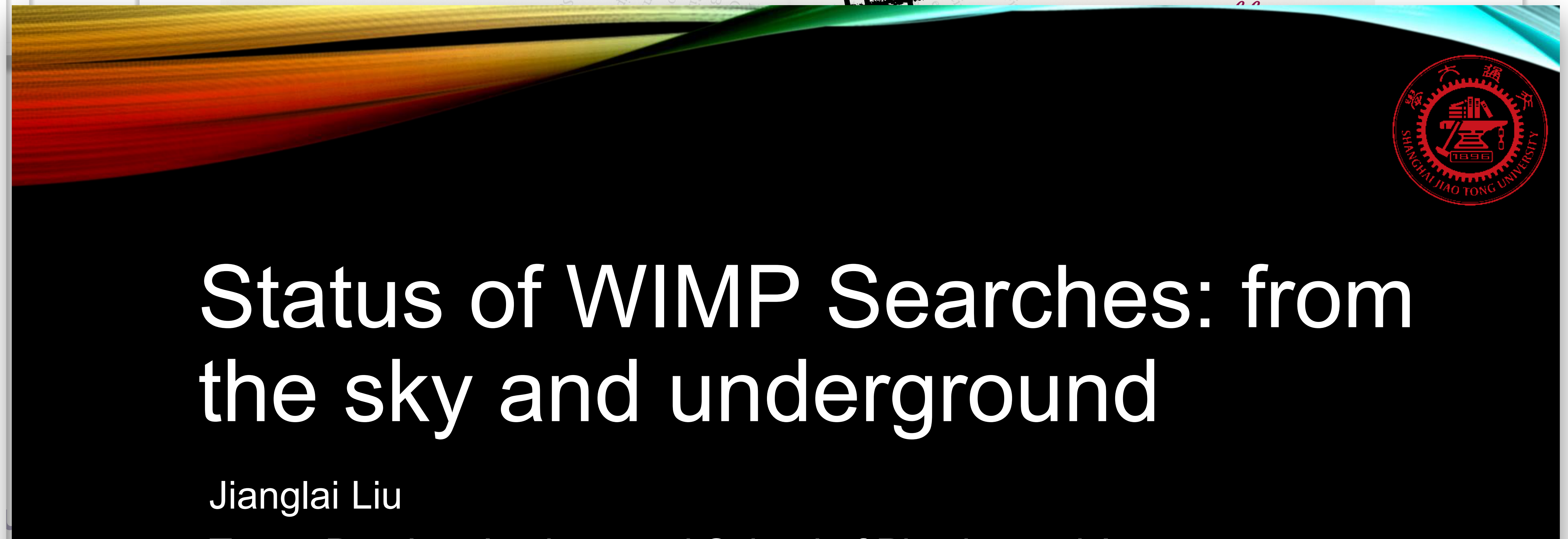
Medium/large projects: community knows how to motivate and get them funded









desirable features of the next major HEP project(s)?

an important target to be reached ~ guaranteed discovery

exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

likelihood of success, robustness (e.g. multiple experiments)

cost-effective construction & operation,
low carbon footprint, novel technologies

https://krea-prod-v1-generations.s3.us-east-1.amazonaws.com/images/665c051f-5540-4f33-b85e-da9ac2a81c36.webp

Dear Santa Claus,

We have been good these past decades. Please could you now bring us

- *a dark matter candidate*
- *an explanation for the fermion masses*
- *an explanation of matter-antimatter asymmetry*
- *an axion, to solve the strong CP problem*
- *a solution to fine tuning the EW scale*
- *a solution to fine tuning the cosmological constant*

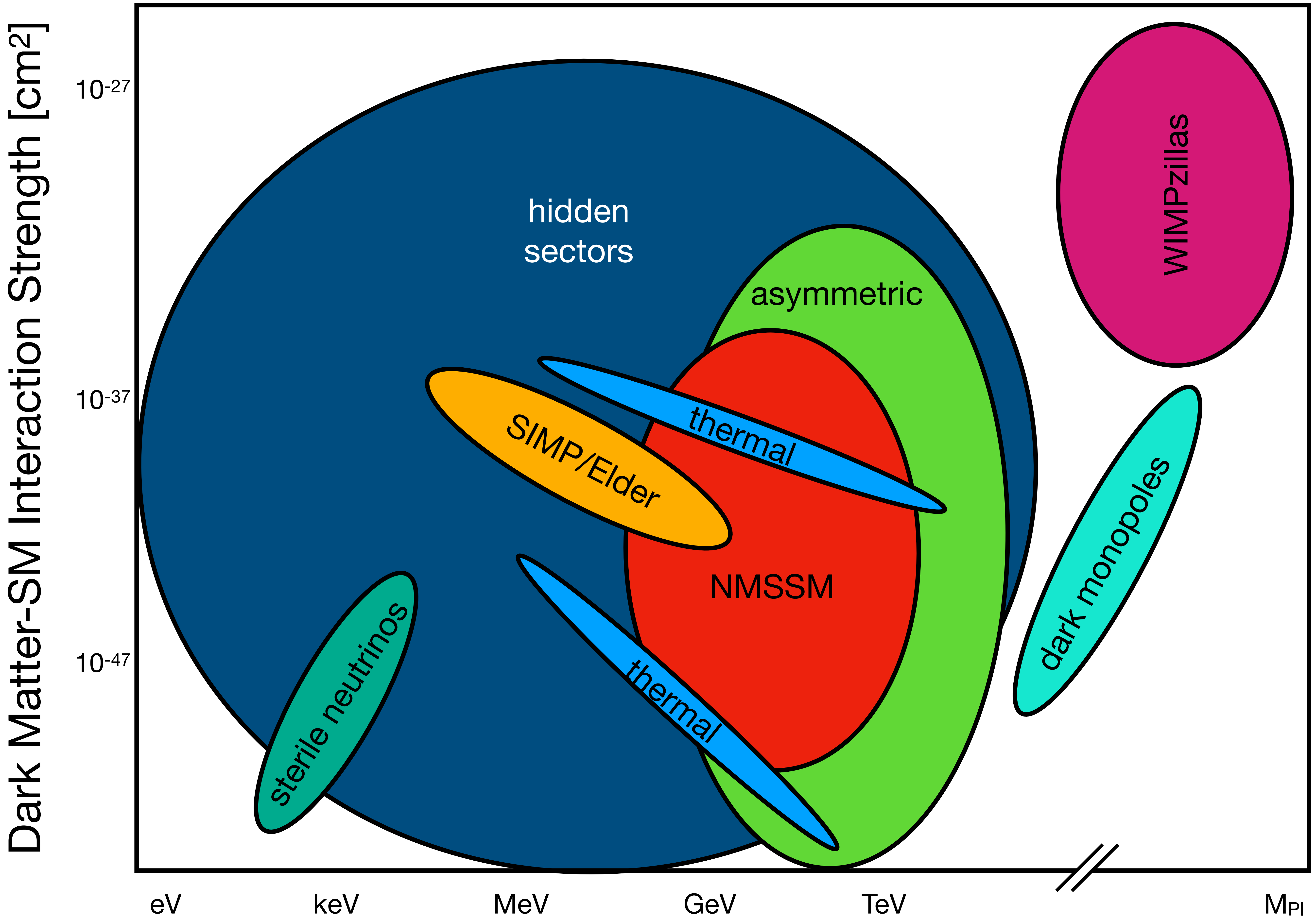
Thank you, Particle Physicists

ps: please, no anthropics

we have so far been unlucky in getting answers to these many questions

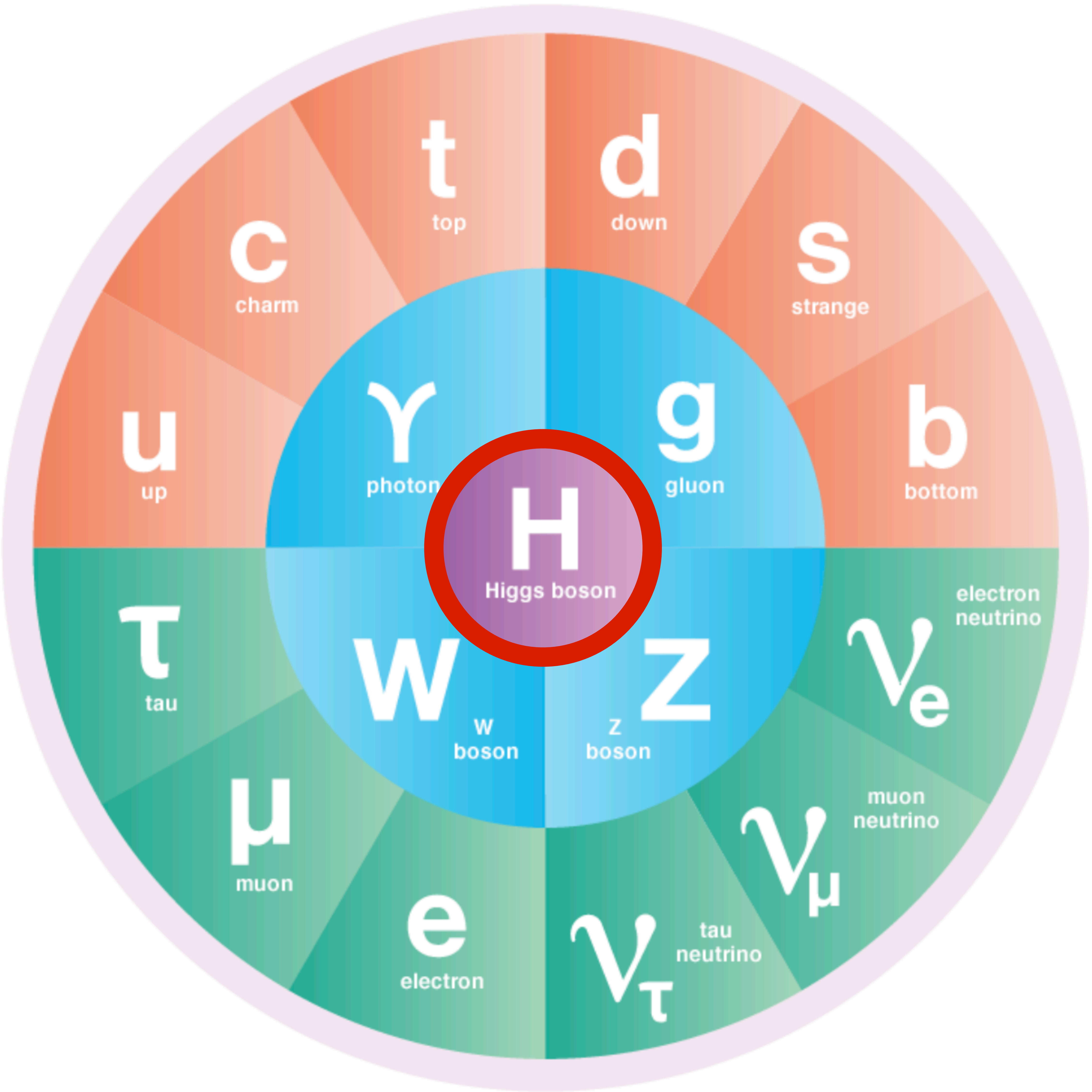
Snowmass Dark Matter report, 2209.07426

30 orders of magnitude in interaction strength

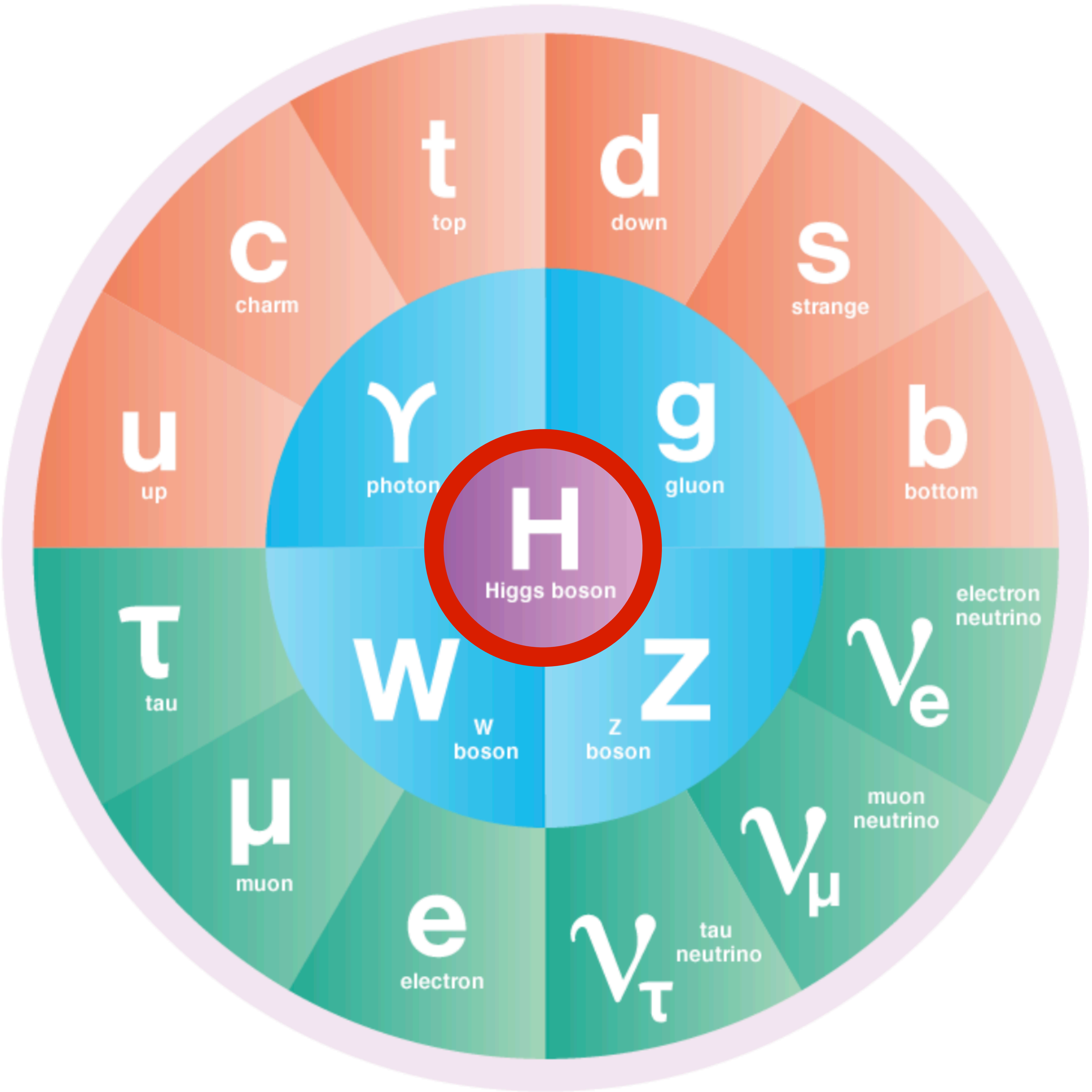


30 orders of magnitude in mass

the standard-model particle set is complete



https://www.symmetrymagazine.org/standard-model/



https://www.symmetrymagazine.org/standard-model/

the standard-model particle set is complete

but we have been lucky with the Higgs boson's 125 GeV mass

it opens a door to the most mysterious part of the Standard Model

desirable features of the next major HEP project(s)?

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Higgs physics

Higgs is the last particle of the SM.

So the SM is complete, right?

parts of this talk adapted from "The Higgs boson turns ten", GPS, Zanderighi and Wang
Nature 607 (2022) 7917, 41-47

The Lagrangian and Higgs interactions: two out of three qualitatively new!

$$\mathscr{L}_{\mathrm{SM}} = \cdots + |D_\mu \phi|^2 + \psi_i y_{ij} \psi_j \phi - V(\phi)$$

Gauge interactions, structurally like those in QED, QCD, EW, **studied for many decades** (but now with a scalar)

Yukawa interactions. Responsible for fermion masses, and induces “fifth force” between fermions. **Direct study started only in 2018!**

Higgs potential → self-interaction (“sixth?” force between scalars).

Holds the SM together.

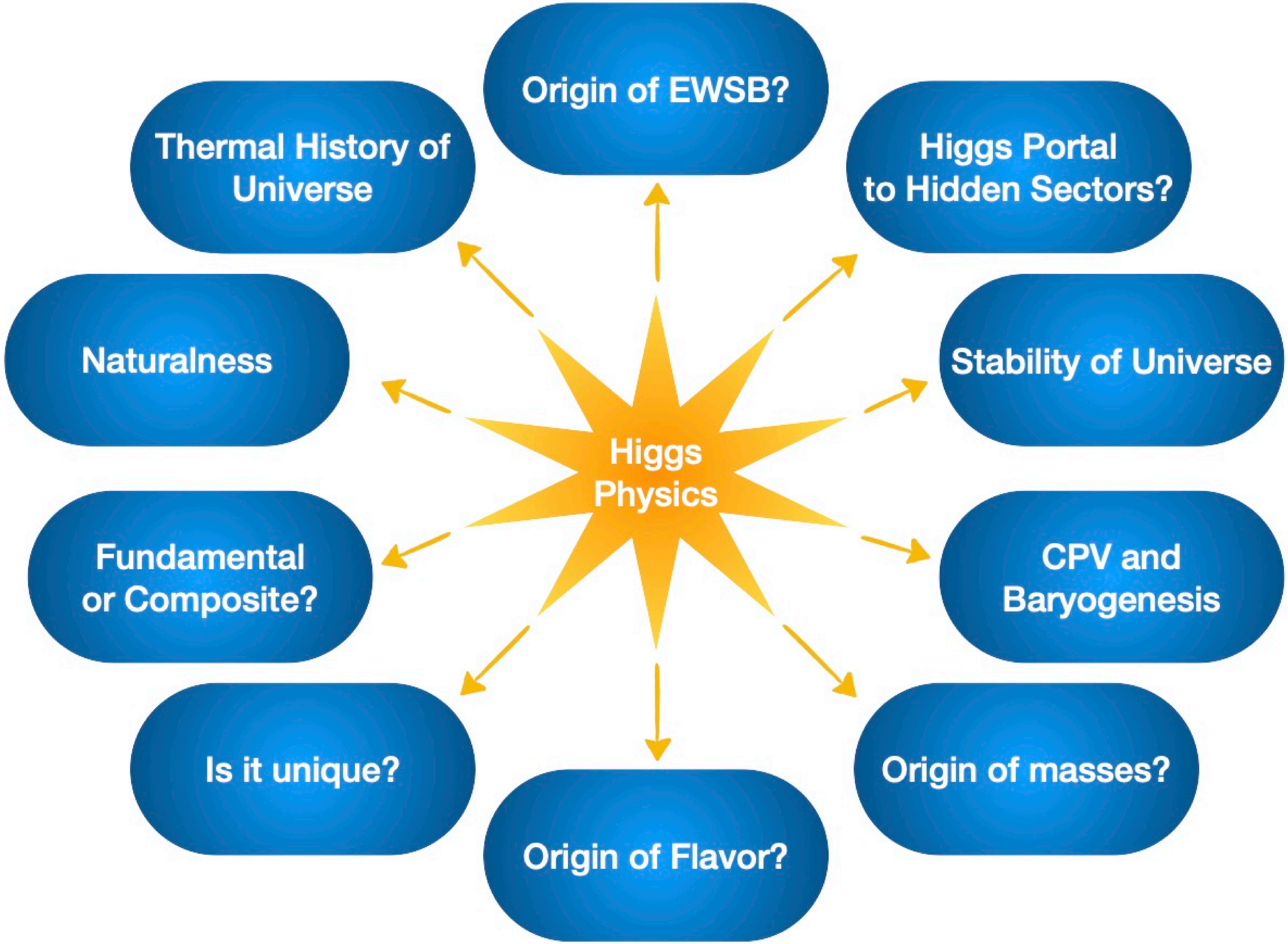
Unobserved

Almost every problem of the Standard Model originates from Higgs interactions

$$\mathscr{L} = y H \psi \bar{\psi} + \mu^2 |H|^2 - \lambda |H|^4 - V_0$$

flavour (y) *naturalness* (μ^2) *stability* (λ) *cosmological constant* (V_0)

https://arxiv.org/abs/2211.11084



Yukawa interaction hypothesis

Yukawa couplings ~ fermion mass

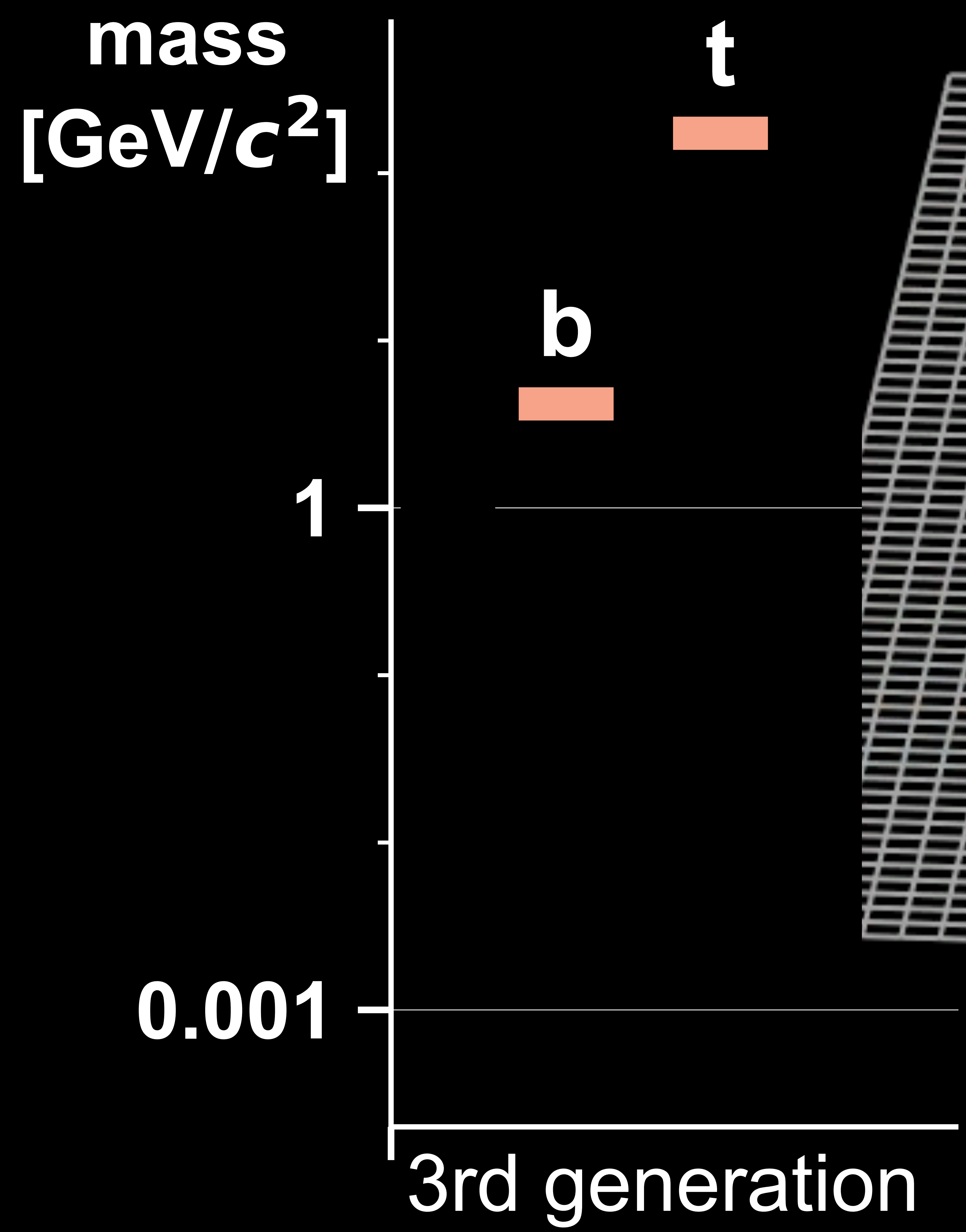
first fundamental interaction that we probe at the quantum level where interaction strength (y_{ij}) not quantised

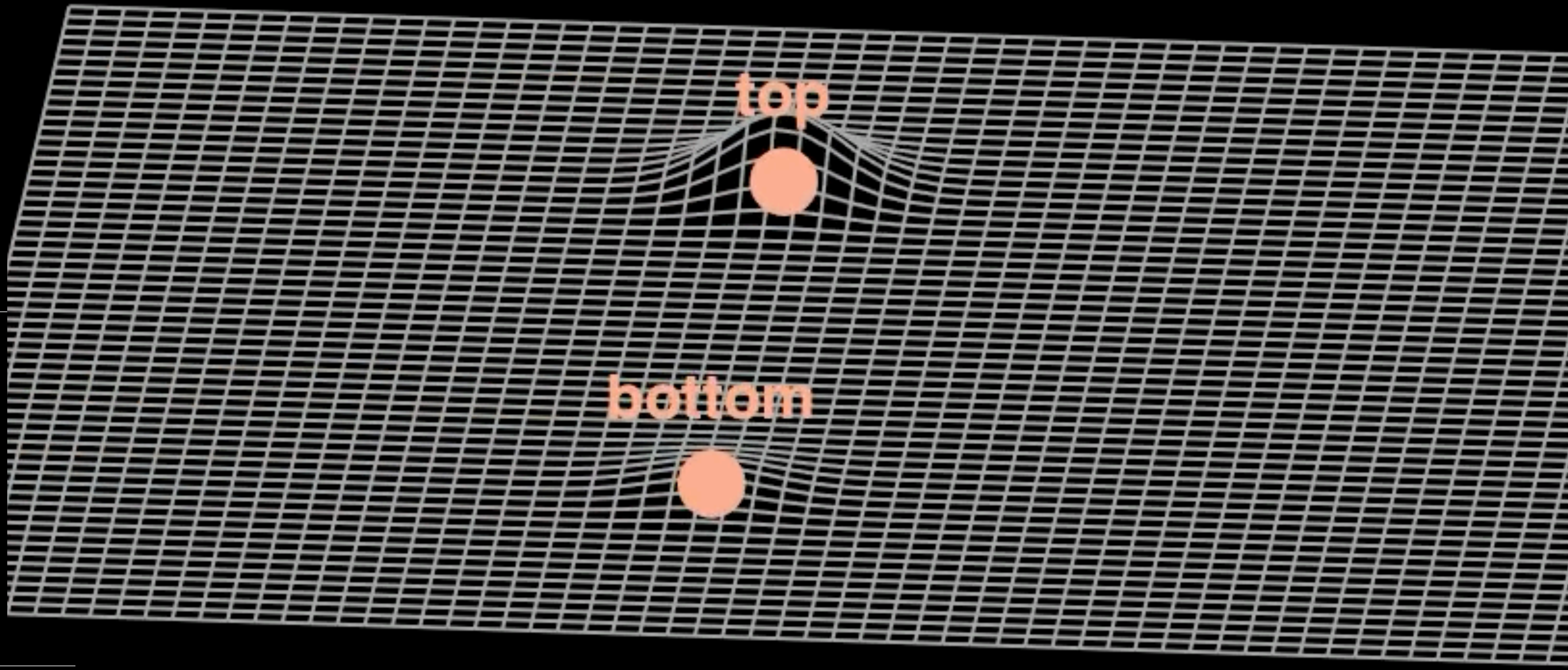
(i.e. no underlying unit of conserved charge across particles)

Higgs field

SM: larger mass of top comes from stronger interaction with Higgs field

Higgs field

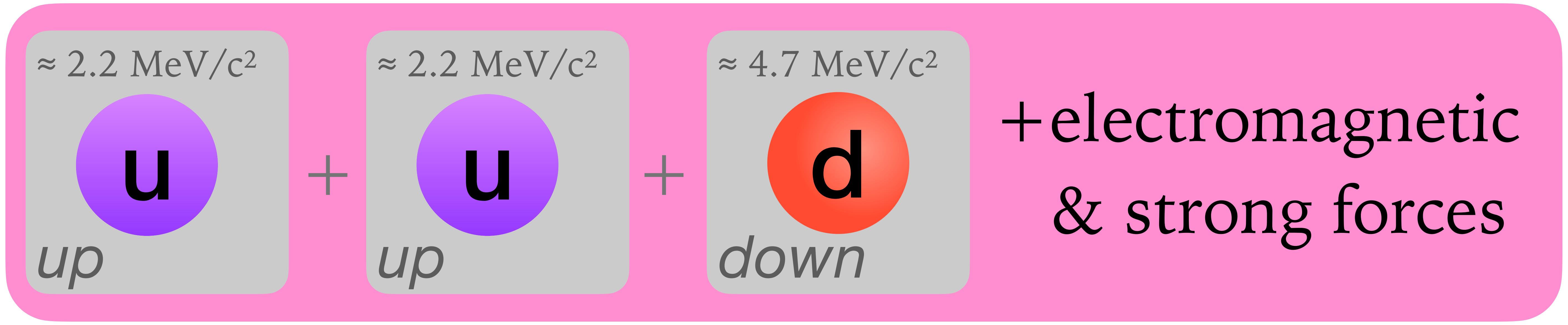




SM: larger mass of top comes from stronger interaction with Higgs field

2.2 MeV **2.2 MeV** 4.7 MeV

proton:



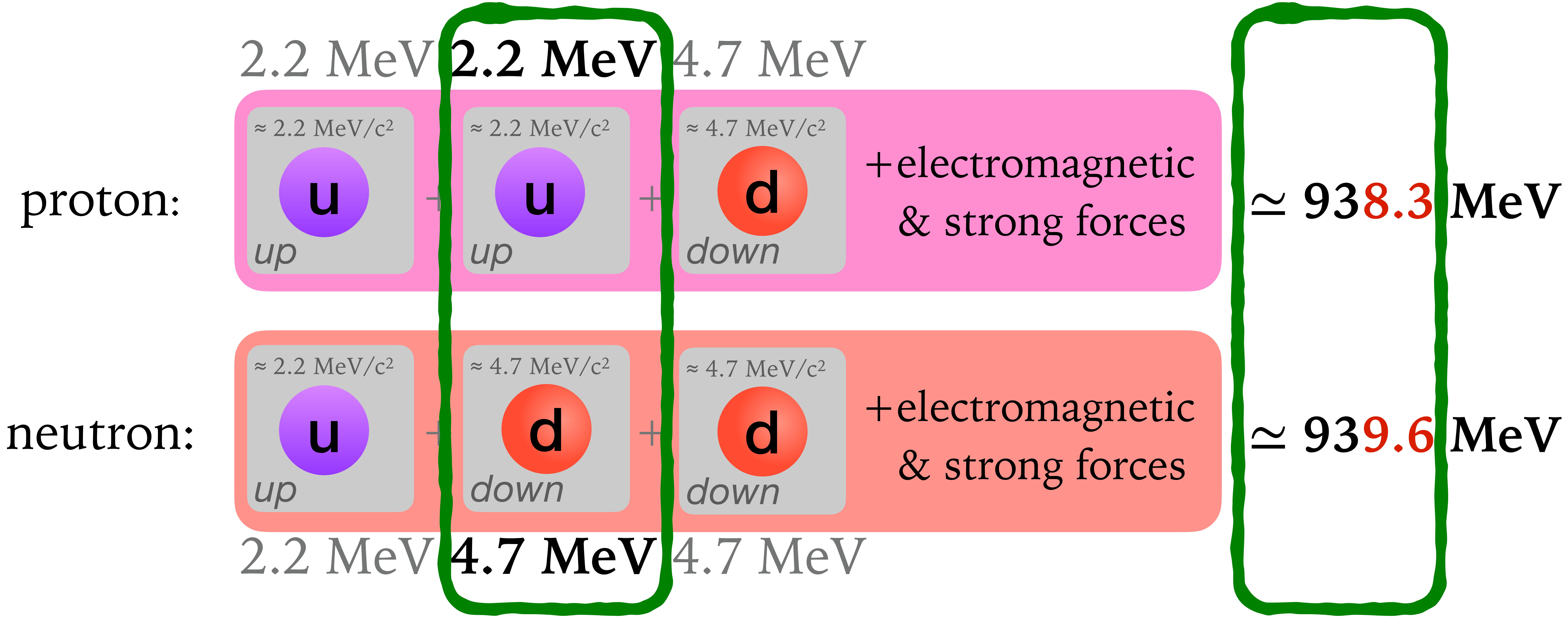
$\simeq$ **938.3 MeV**

2.2 MeV **2.2 MeV** 4.7 MeV

proton: | ≈ 2.2 MeV/c² u *up* + ≈ 2.2 MeV/c² u *up* + ≈ 4.7 MeV/c² d *down* +electromagnetic & strong forces | ≃ **938.3 MeV**

neutron: | ≈ 2.2 MeV/c² u *up* + ≈ 4.7 MeV/c² d *down* + ≈ 4.7 MeV/c² d *down* +electromagnetic & strong forces | ≃ **939.6 MeV**

2.2 MeV **4.7 MeV** 4.7 MeV


2.2 MeV 2.2 MeV 4.7 MeV
proton:
≈ 2.2 MeV/c²
u
up
+
≈ 2.2 MeV/c²
u
up
+
≈ 4.7 MeV/c²
d
down
+electromagnetic
& strong forces
≃ 938.3 MeV
neutron:
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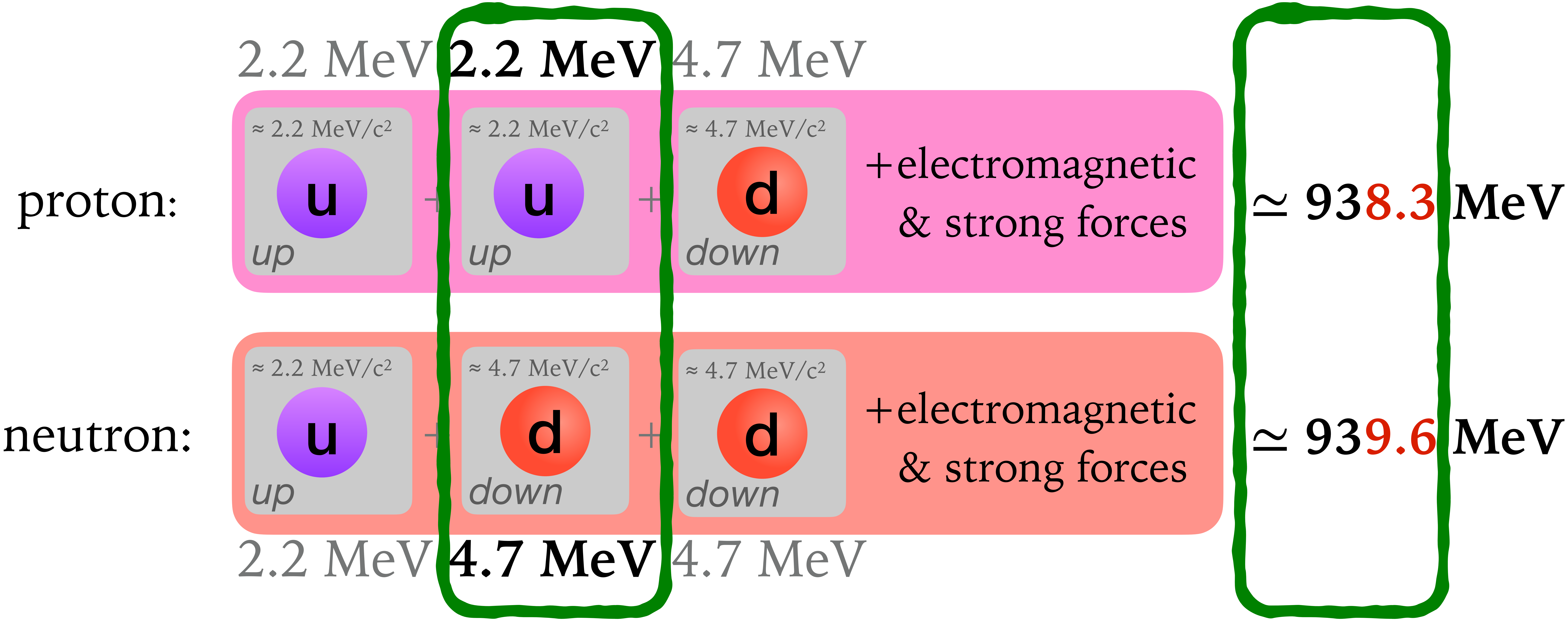
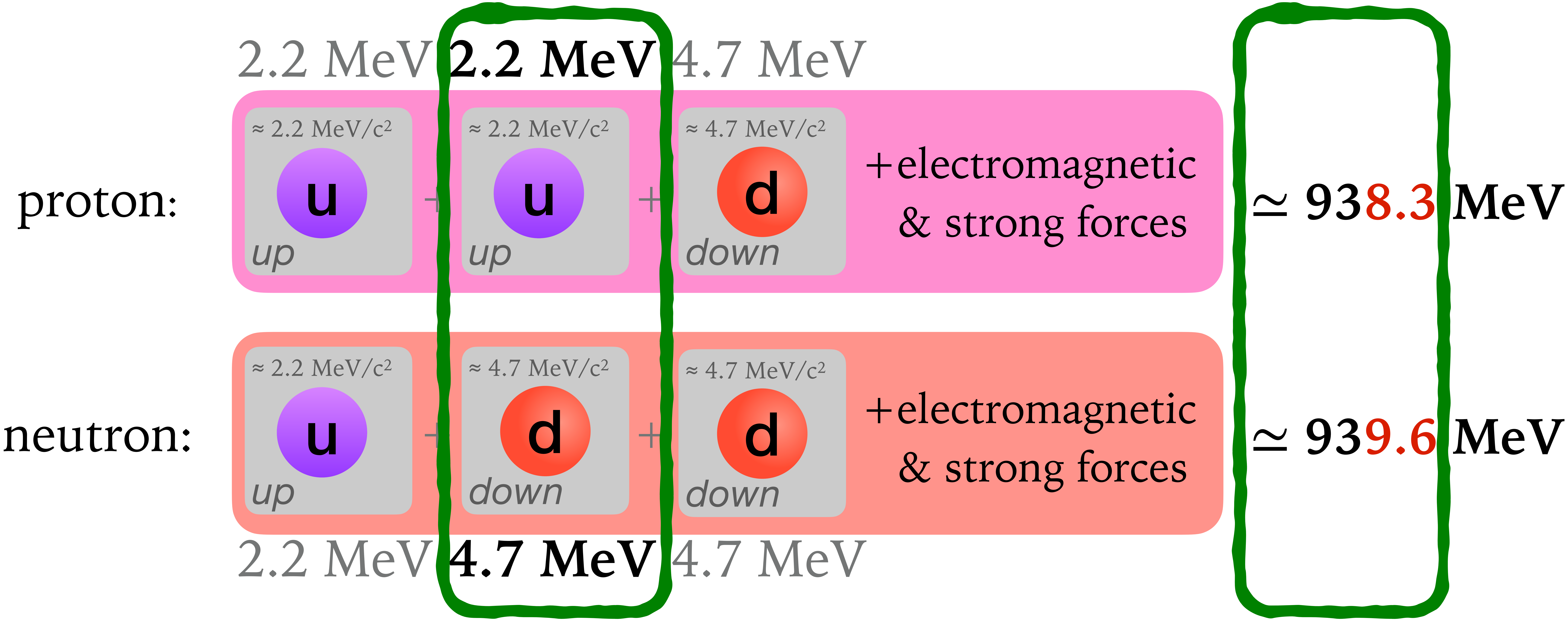


Protons are **lighter** than neutrons → protons are stable.
Giving us the hydrogen atom, & chemistry and biology as we know it



Protons are **lighter** than neutrons→ protons are stable.
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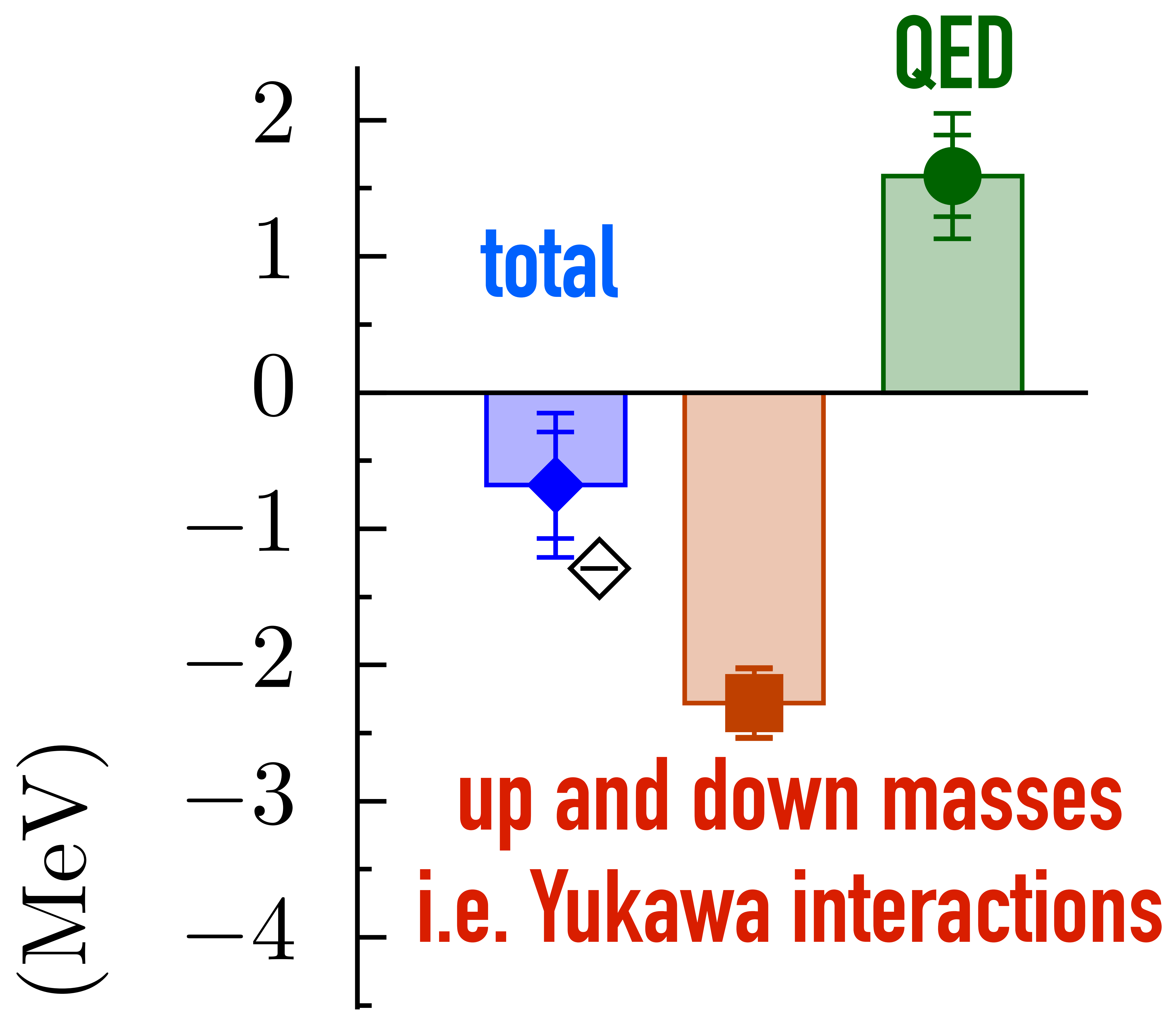
Supposedly because up quarks interact more weakly with the Higgs field than down quarks

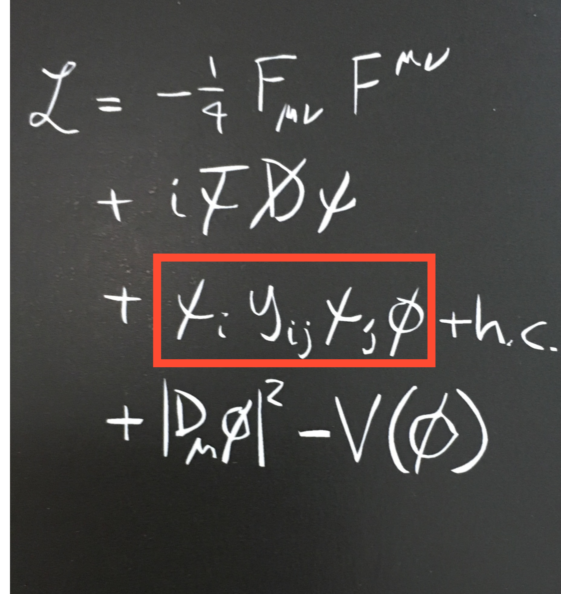
proton – neutron mass difference



Lattice calculation
(BMW collab.)
1306.2287
1406.4088

Why do Yukawa couplings matter?

(2) Because, within SM **conjecture**, they're what give masses to all **leptons**


This equation neatly sums up our current understanding of fundamental particles and forces.

Bohr radius

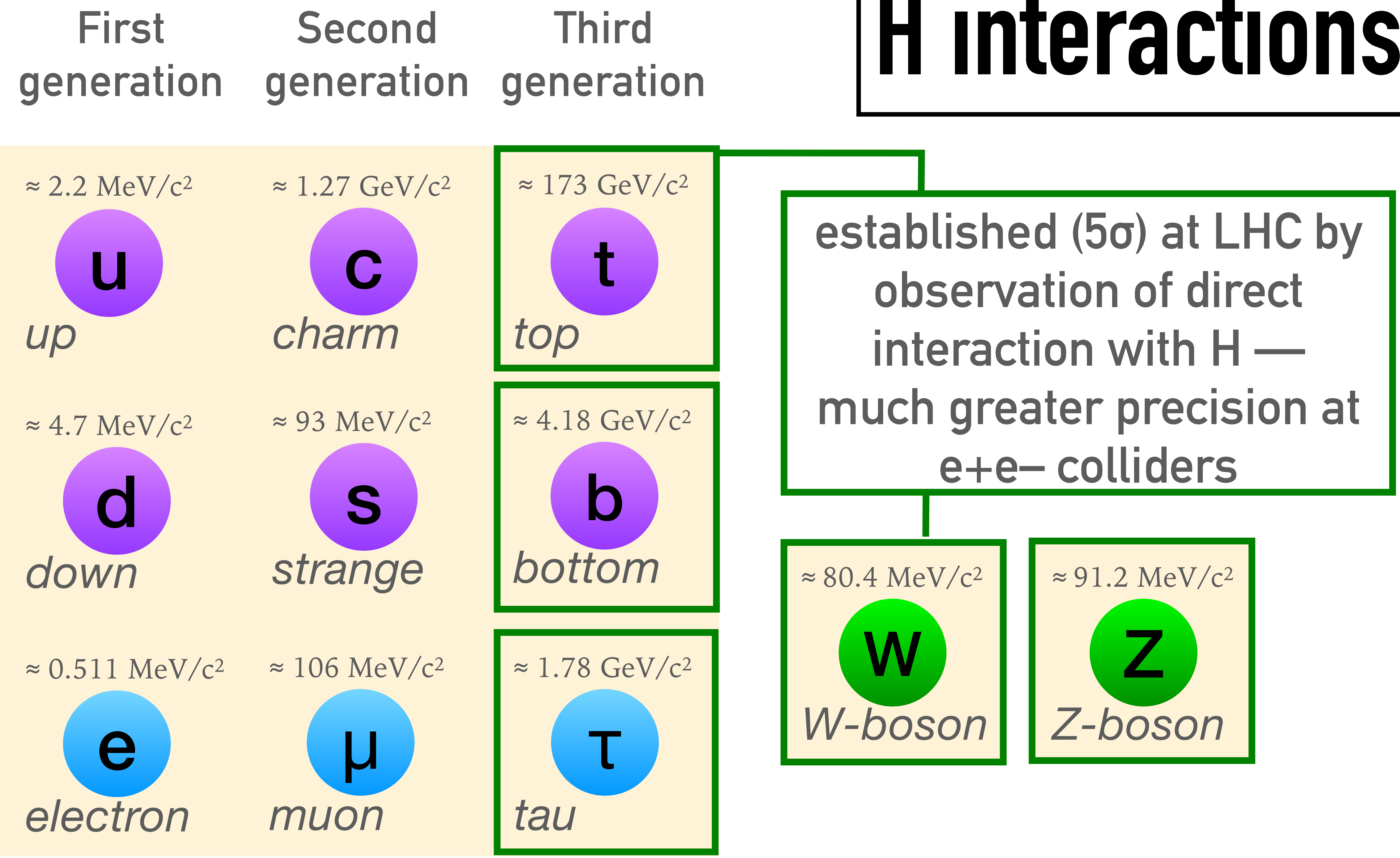
$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e c\alpha} \propto \frac{1}{y_e}$$

electron mass determines size of all atoms

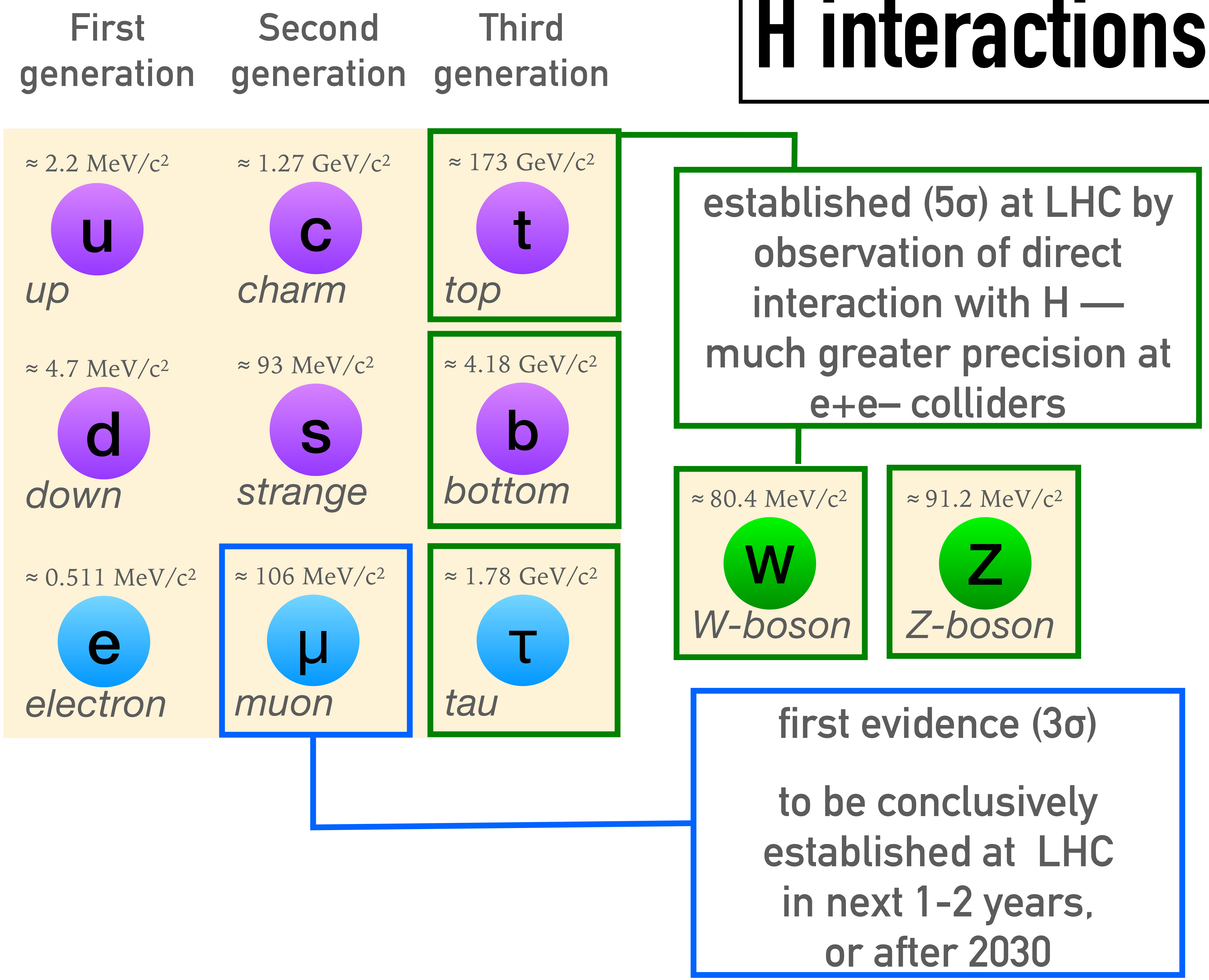
it sets energy levels of all chemical reactions

currently we have no evidence that up and down quarks and the electron get their masses from Yukawa interactions — it's in textbooks, but is it nature?

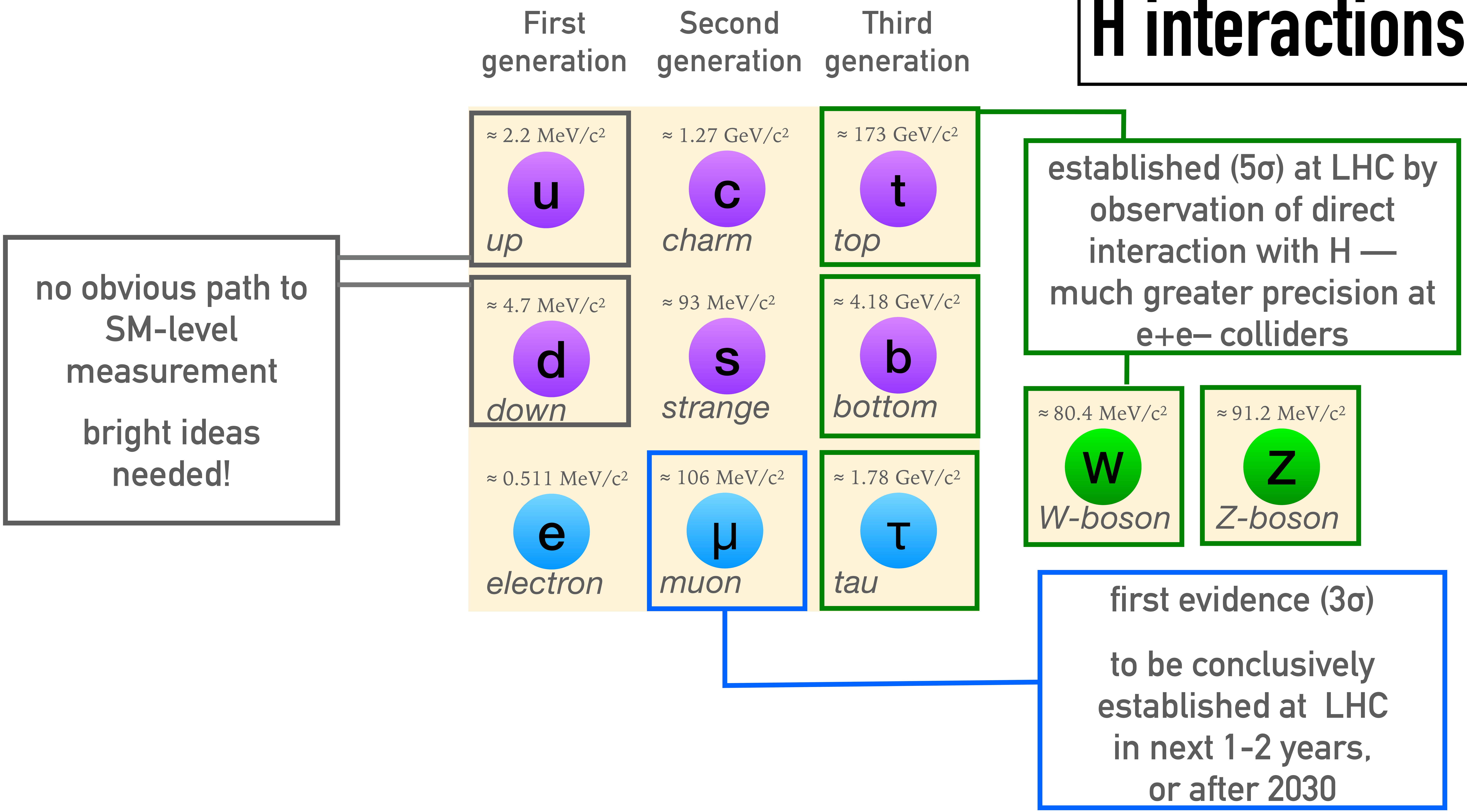
H interactions



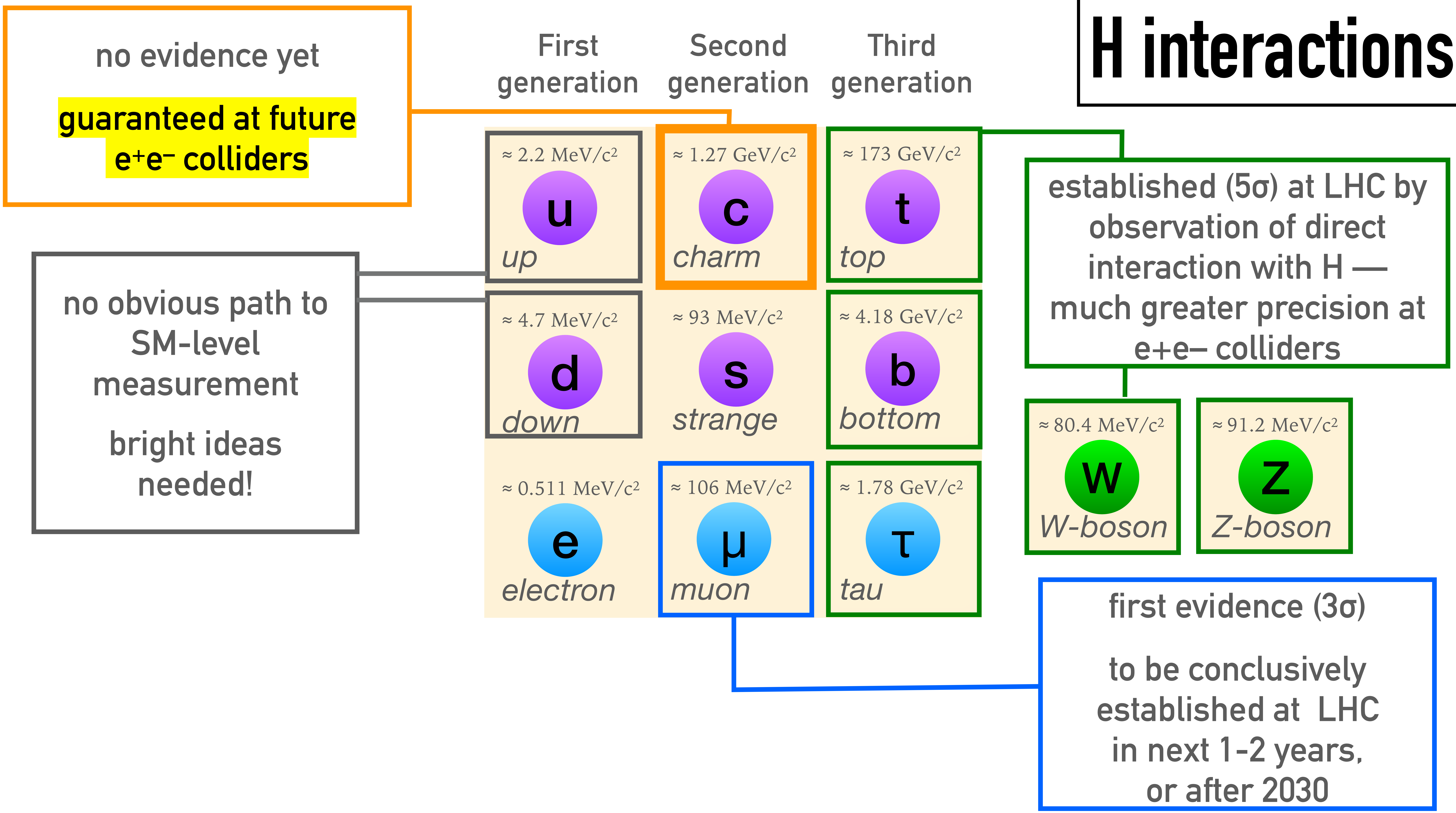
H interactions



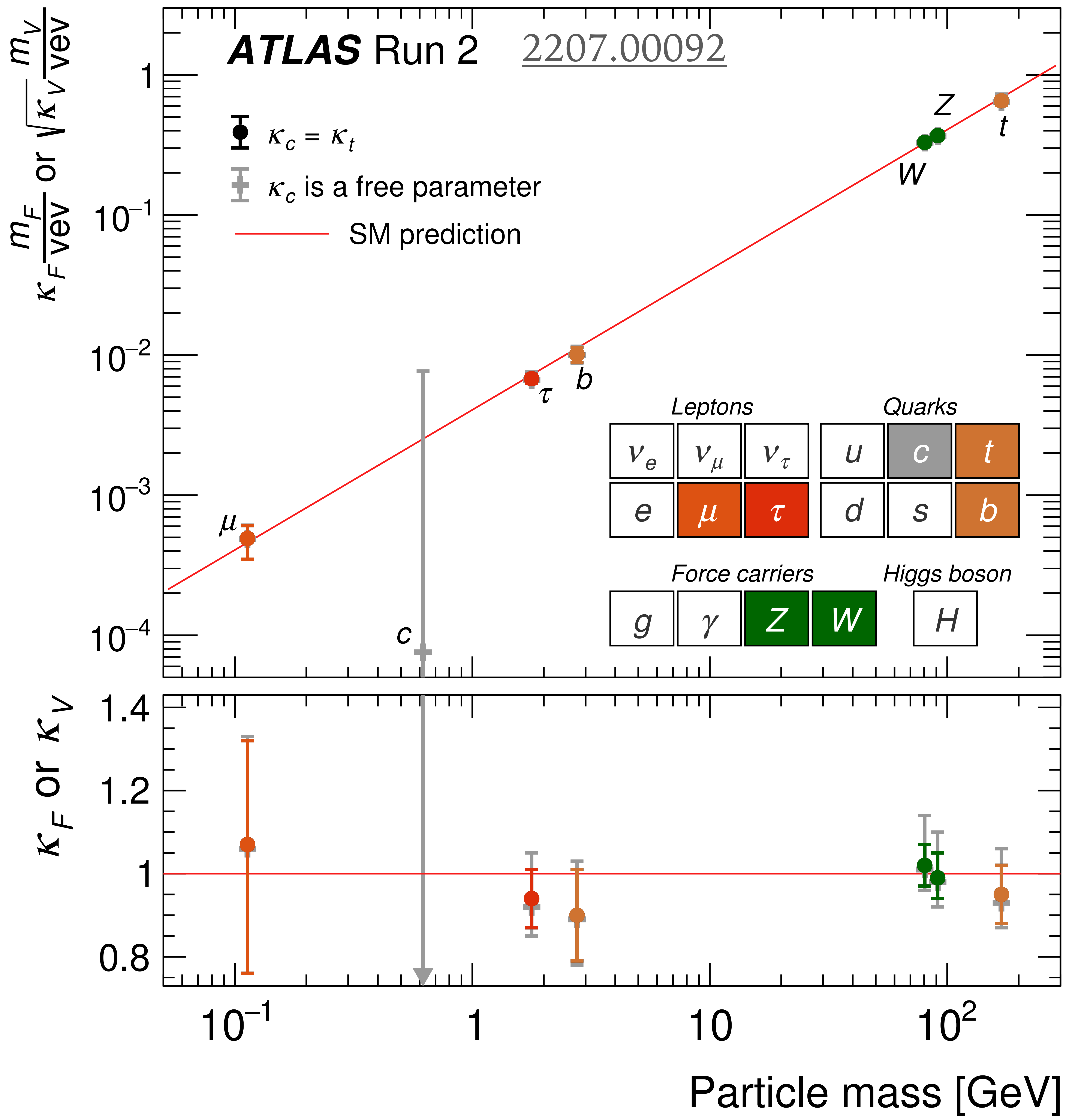
H interactions



H interactions




H interactions
First generation
Second generation
Third generation
≈ 2.2 MeV/c²
u
up
≈ 1.27 GeV/c²
c
charm
≈ 173 GeV/c²
t
top
≈ 4.7 MeV/c²
d
down
≈ 93 MeV/c²
s
strange
≈ 4.18 GeV/c²
b
bottom
≈ 0.511 MeV/c²
e
electron
≈ 106 MeV/c²
μ
muon
≈ 1.78 GeV/c²
τ
tau
≈ 80.4 MeV/c²
W
W-boson
≈ 91.2 MeV/c²
Z
Z-boson
no evidence yet
guaranteed at future e+e− colliders
no obvious path to SM-level measurement
bright ideas needed!
no evidence yet
tantalisingly close to reach of circular e+e− colliders?
established (5σ) at LHC by observation of direct interaction with H — much greater precision at e+e− colliders
first evidence (3σ)
to be conclusively established at LHC in next 1-2 years, or after 2030

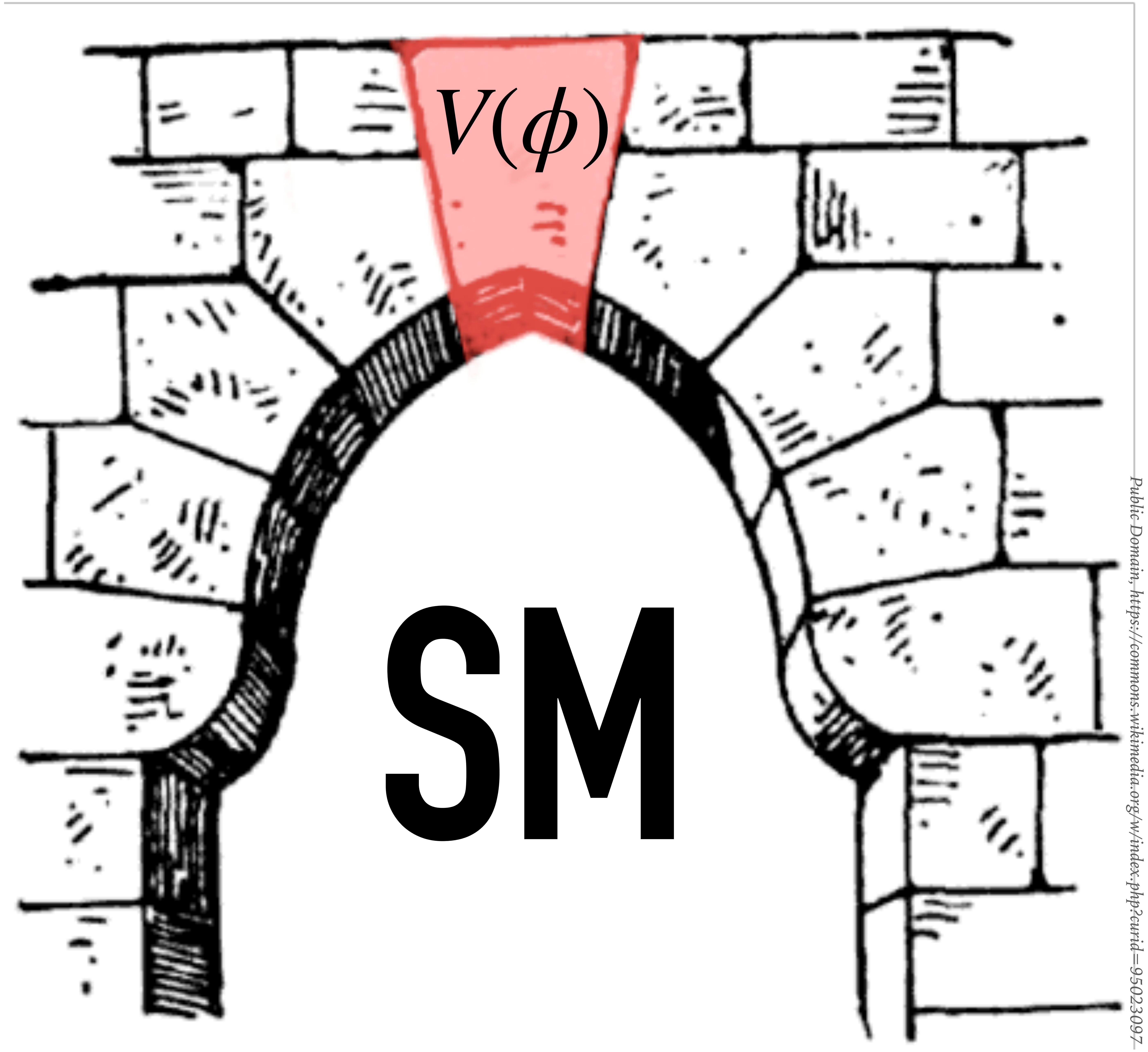


Strength of interaction with Higgs field versus particle mass

(and similar plot from CMS collaboration)

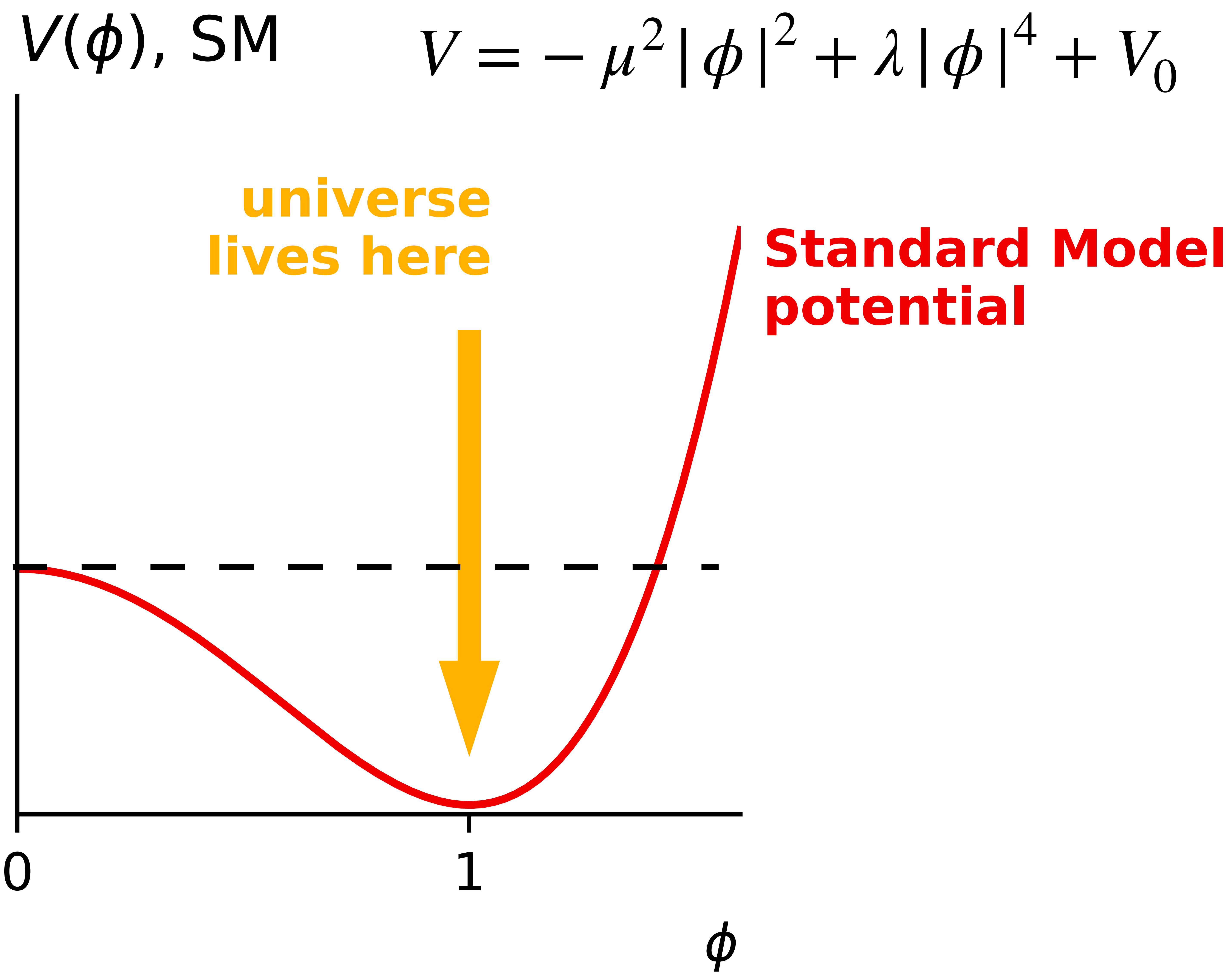
A side comment on the near future at LHC

- particle physics normally deals with esoteric particles that have [almost] no relation with the world as we experience it
- LHC will reach 5σ sensitivity for $H \to \mu\mu$ in the coming years (if it is SM-like), offering first proof that particles other than 3rd generation also get their mass from Yukawa mechanism
- that will be a crucial step on the way from 3rd generation Yukawas to 1st
- it deserves a big event with the world's press to announce it
- an opportunity to explain the quest for understanding the origin of the mass of the fundamental particles that **we are made of**



the Higgs potential

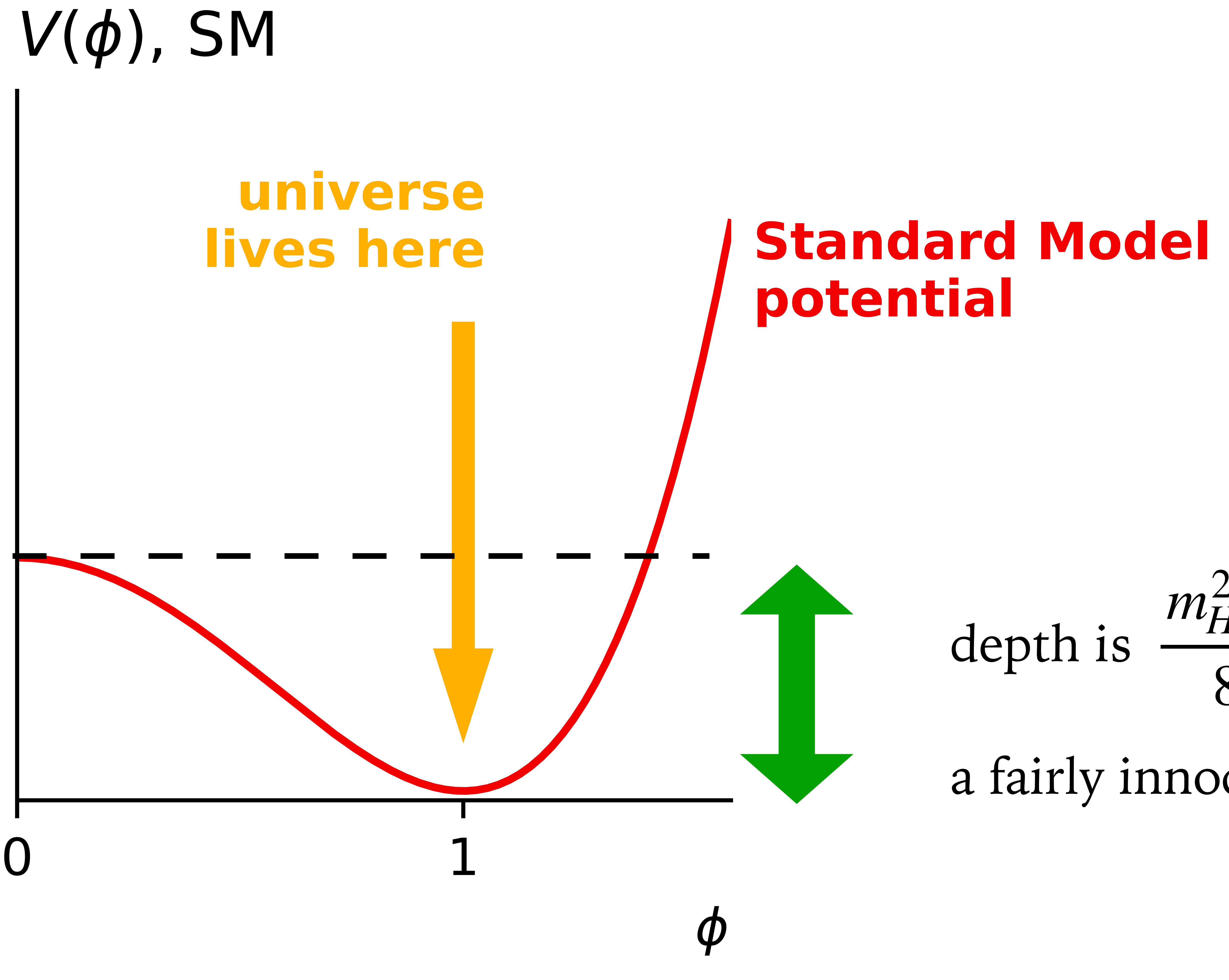
Higgs potential



the Higgs mechanism gives mass to particles because the Higgs field φ is non-zero

That happens because the minimum of the SM potential is at non-zero φ

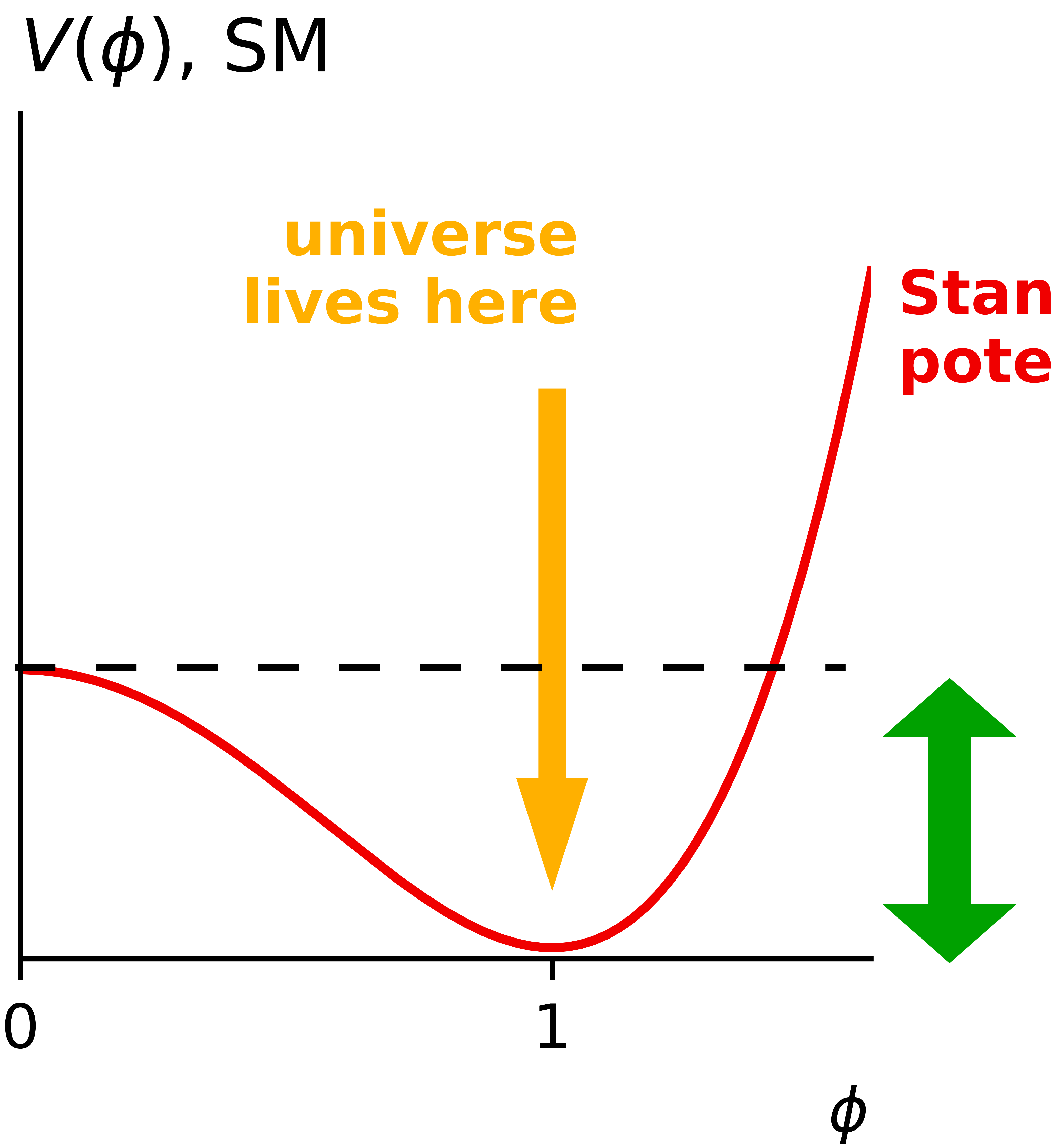
Higgs potential



depth is $\frac{m_H^2 v^2}{8}$ $(m_H \simeq 125\,\text{GeV},\ v \simeq 246\,\text{GeV})$

a fairly innocuous sounding $(104\,\text{GeV})^4$

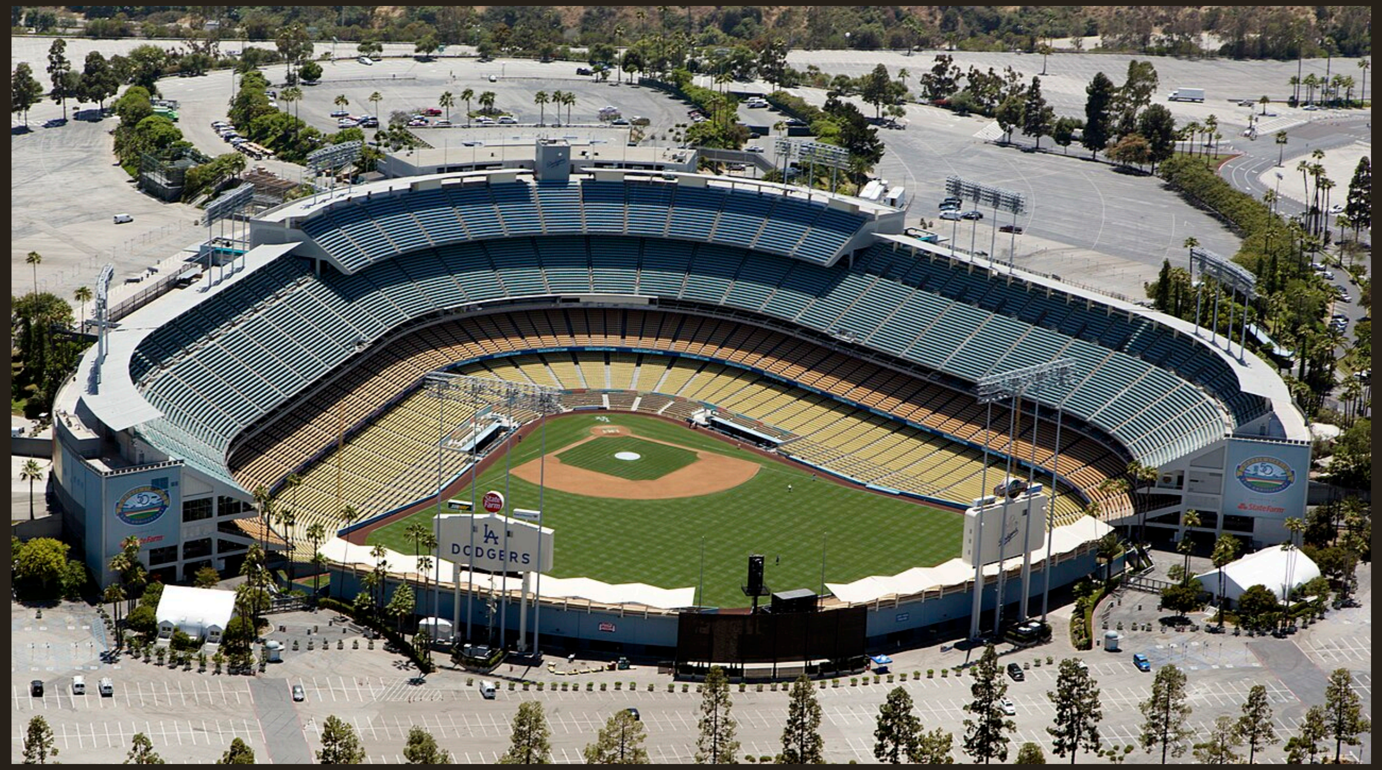
Higgs potential – remember: it's an energy density



Corresponds to an energy density of 1.5×10^{10} GeV/fm^3
i.e. >**10 billion times nuclear density**

Mass density of 2.6×10^{28} kg/m^3

https://en.wikipedia.org/wiki/Globe#/media/File:World_Globe_Map.jpg
https://en.wikipedia.org/wiki/Old_fashioned_glass#/media/File:Old_Fashioned_Glass.jpg
Stadium: By Carol M. Highsmith - Library of CongressCatalog: http://lccn.loc.gov/2013632695



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Earth at neutron star density

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Earth at neutron star density

Earth at Higgs potential density

cosmological constant & fine-tuning [classically]

$$V_{min} = \left[-\mu^2|\phi|^2 + \lambda|\phi|^4\right]_{\phi_0} + V_0$$

cosmological constant

$$= -2.6 \times 10^{28}\, kg/m^3 \;\; + \; V_0 = \boxed{5.96 \times 10^{-27}\, kg/m^3}$$

- V_0 needs to be fine tuned for cosmological constant to have today's size (also with respect to various sources of quantum correction)
- not the only fine-tuning problem in fundamental physics,
  –– arguably special in that it appears already classically
- collider physics cannot tell us anything about V_0
  — but it would seem negligent not to try and establish the rest of the potential

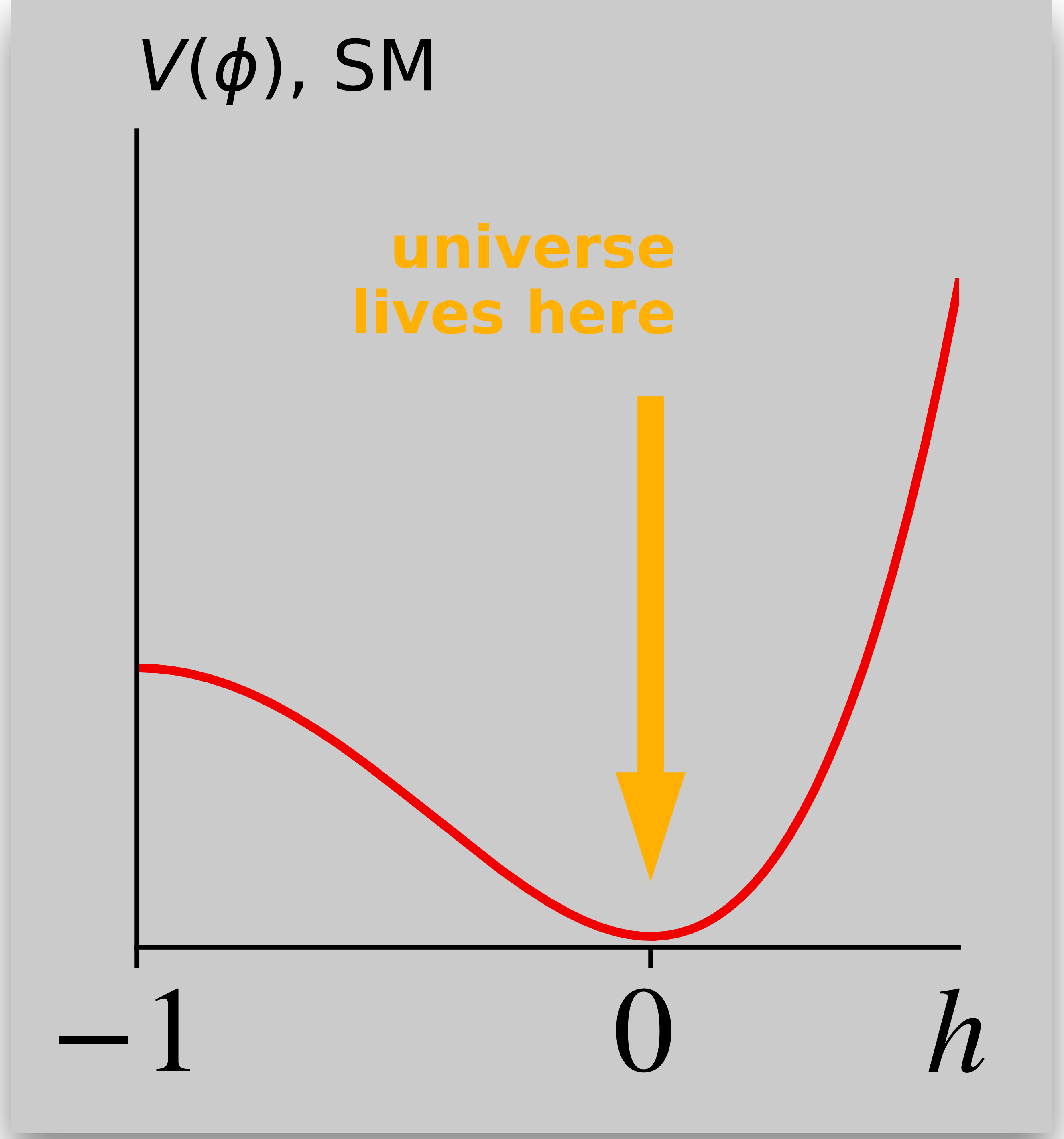
The potential expanded around the minimum

- take h as the Higgs field excitation in units of the field at minimum

$$V = \frac{m_H^2 v^2}{8}\left(-1 + 4h^2 + \color{red}{4h^3} + h^4\right)$$

the Higgs boson mass term

prediction of the strength of HHH interaction
[modifier may be called κ_λ or κ_3]



g
g
H
λ_3
H
H
luon
gluo
φ
y
x
Higgs field in space

g
g
H
λ_3
H
H
luon
gluo
Φ
y
x
Higgs field in space


g
g
H
λ_3
H
H
luon
gluo
Φ
y
x
Higgs field in space

Testing SM V(φ) by measuring HH production at FCC: ~3–5% accuracy

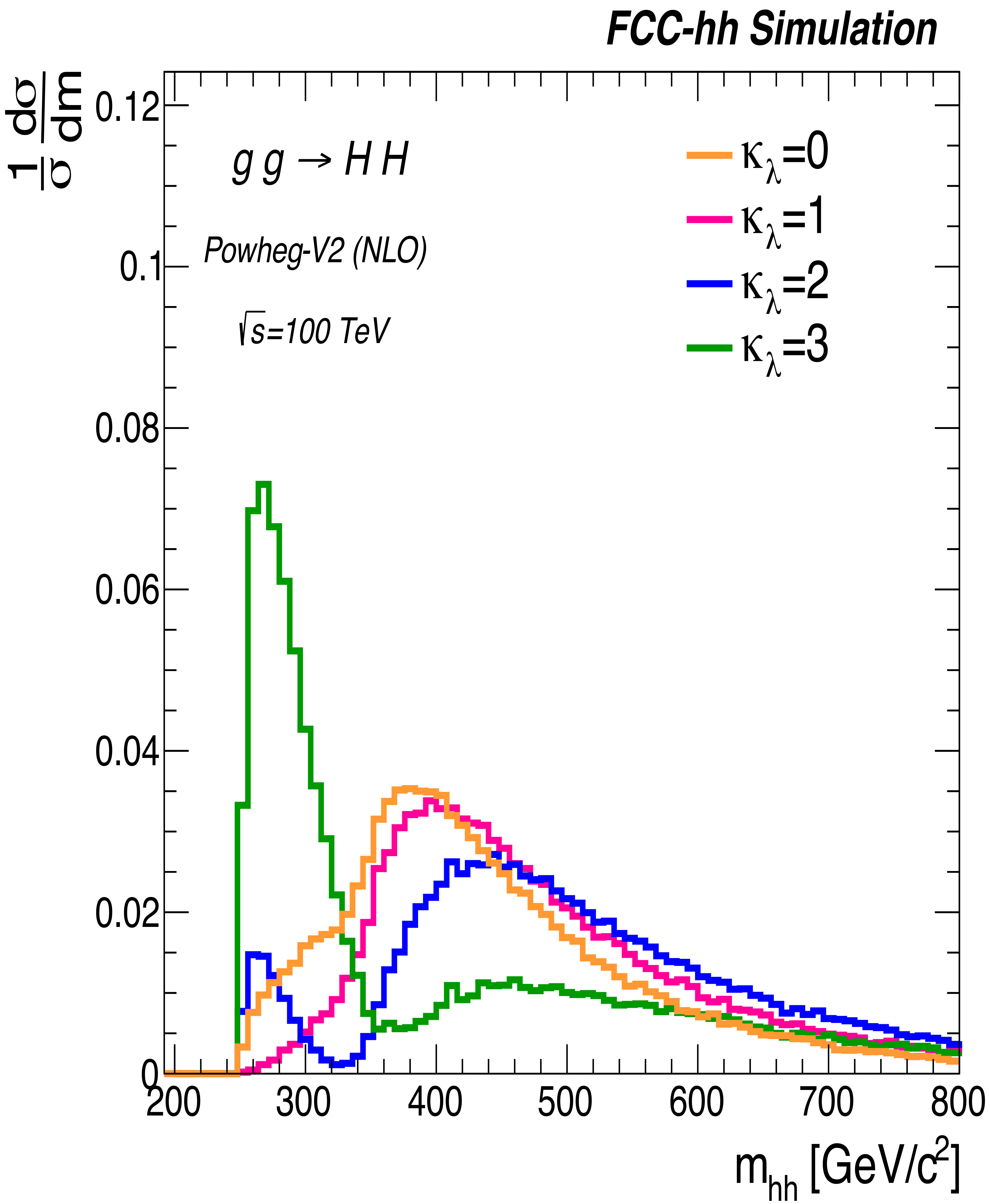
- ➤ kinematic shape of HH pair clearly distinguishes independent HH production from correlated HH
- ➤ FCC-hh → few % determination
  (needs accurate $t\bar{t}Z$ and Higgs couplings from FCC-ee)

FCC-hh 68%cl precision (%) on double-Higgs production

	@68% CL	scenario I	scenario II	scenario III
δ_μ	stat only	2.2	2.8	3.7
	stat + syst	2.4	3.5	5.1
δ_{κ_λ}	stat only	3.0	4.1	5.6
	stat + syst	3.4	5.1	7.8

(optimistic ~ LHC Run 2 perf)

($30 fb^{-1}$ @ 100 TeV, | Mangano, Ortona & Selvaggi, 2004.03505)



when would we claim discovery? [5σ in each of two independent experiments is our gold standard]

- equivalent for an interaction is a bit ambiguous — but better than ±20% determination is probably a reasonable target
- for something of this importance, we may be wary of relying on 20% only from a combination of N experiments — a result's robustness comes from confirmation by independent experiments
- indirect v. direct:
  - all measurements are indirect (we measure hadrons and leptons…)
  - single H is good to have
  - but HH & kinematic structure brings assurance that what we are seeing is indeed HHH coupling
- NB there exist different points of view on this

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- indirec…
  - all me… …ure hadrons and leptons…)
  - single … …ve
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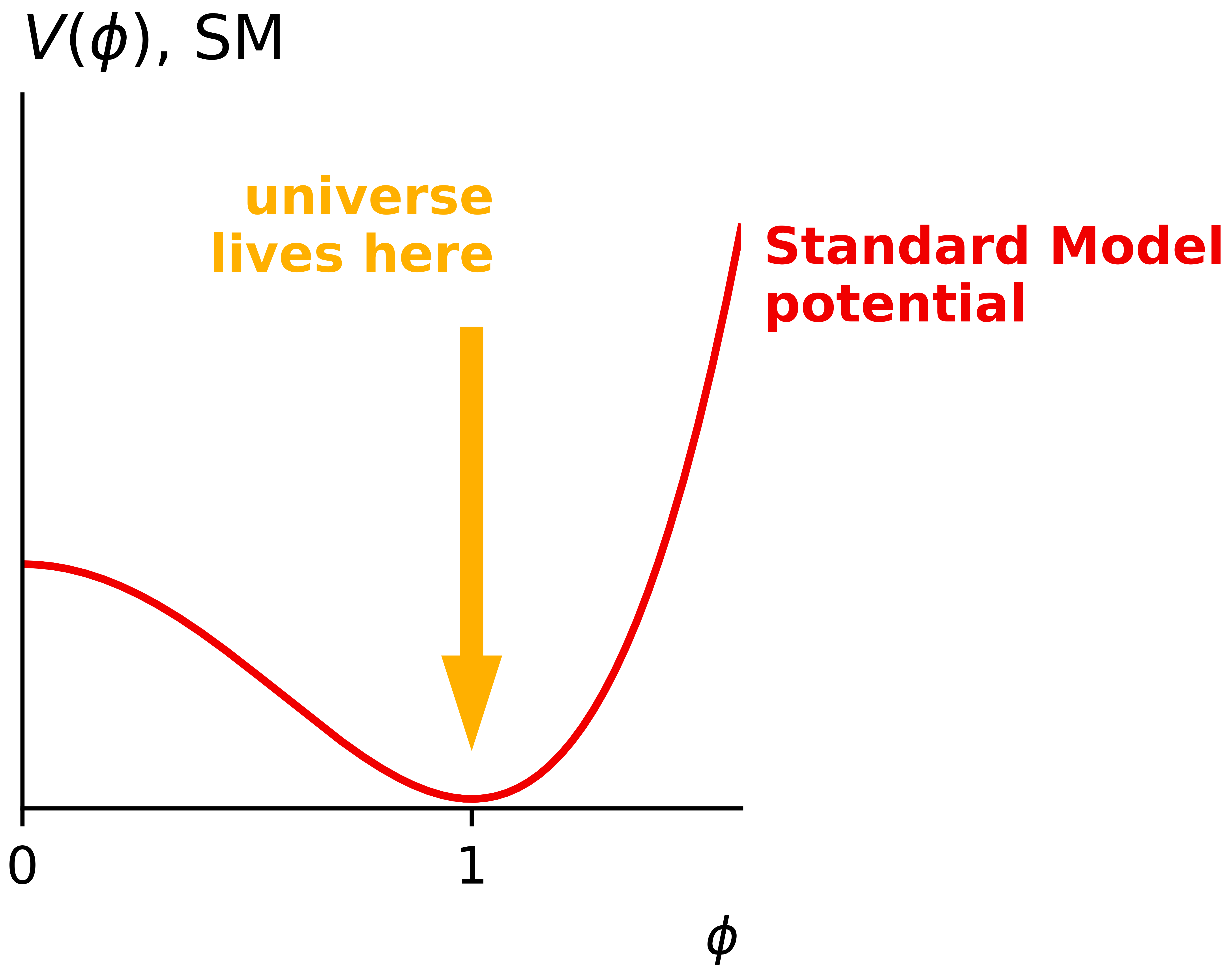
- NB there exist different points of view on this

observation of HHH interaction is a "guaranteed discovery" that HEP should be aiming for

Higgs potential

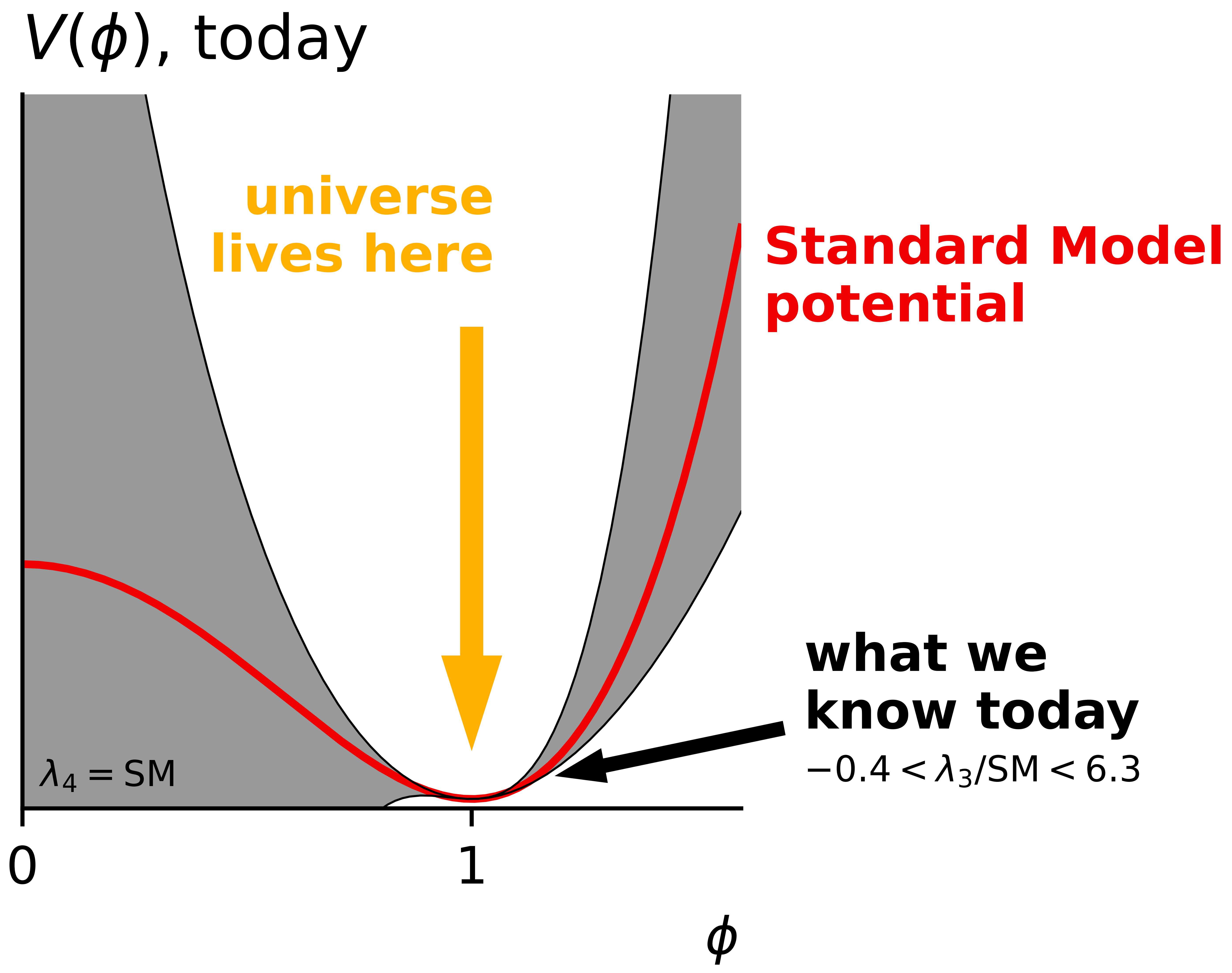


Studying H→HH probes specific mathematical property of the potential's shape:

its third derivative (λ_3), i.e. how asymmetric it is at the minimum

[reconstruction in plot assumes higher derivatives as in SM]

Higgs potential



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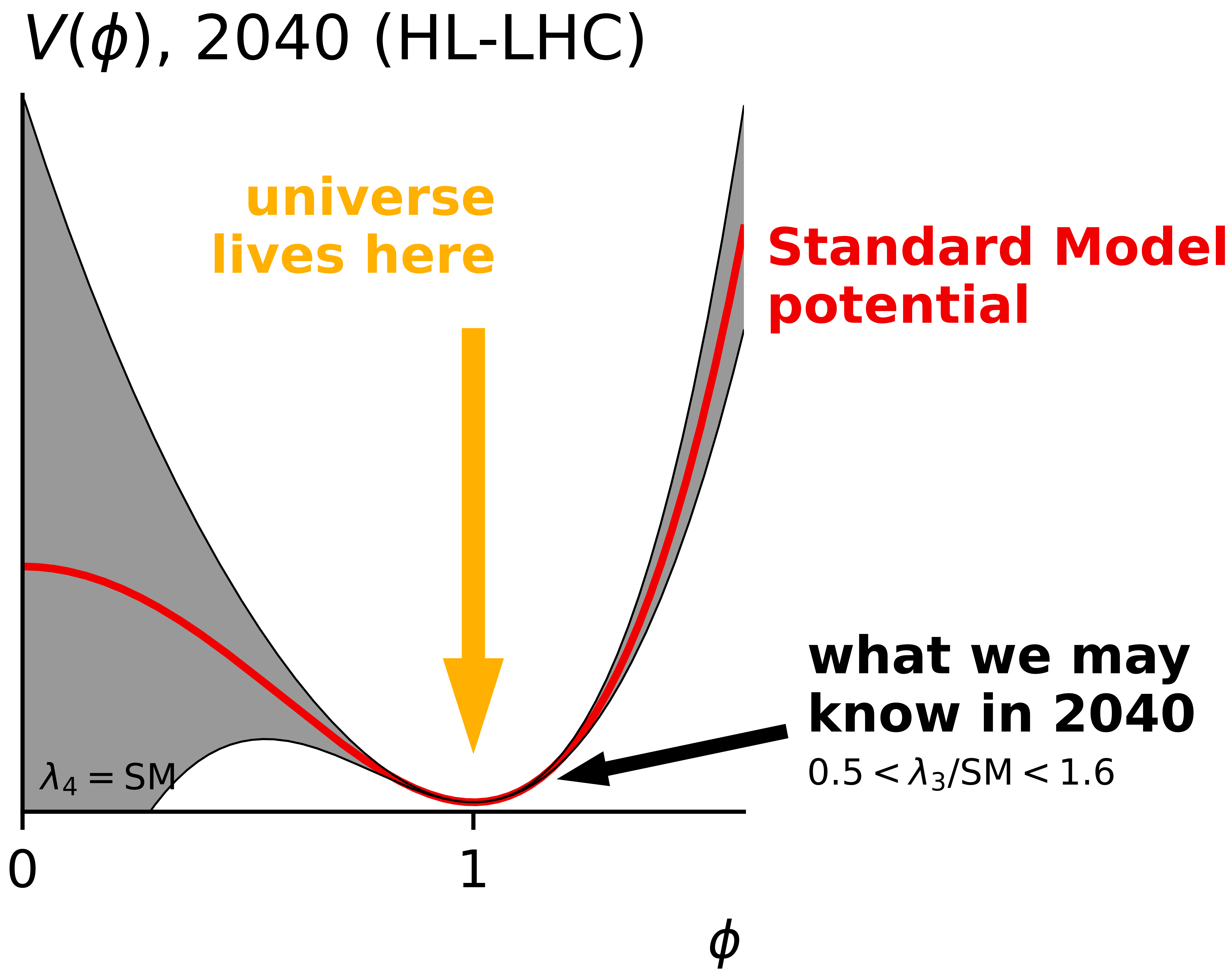

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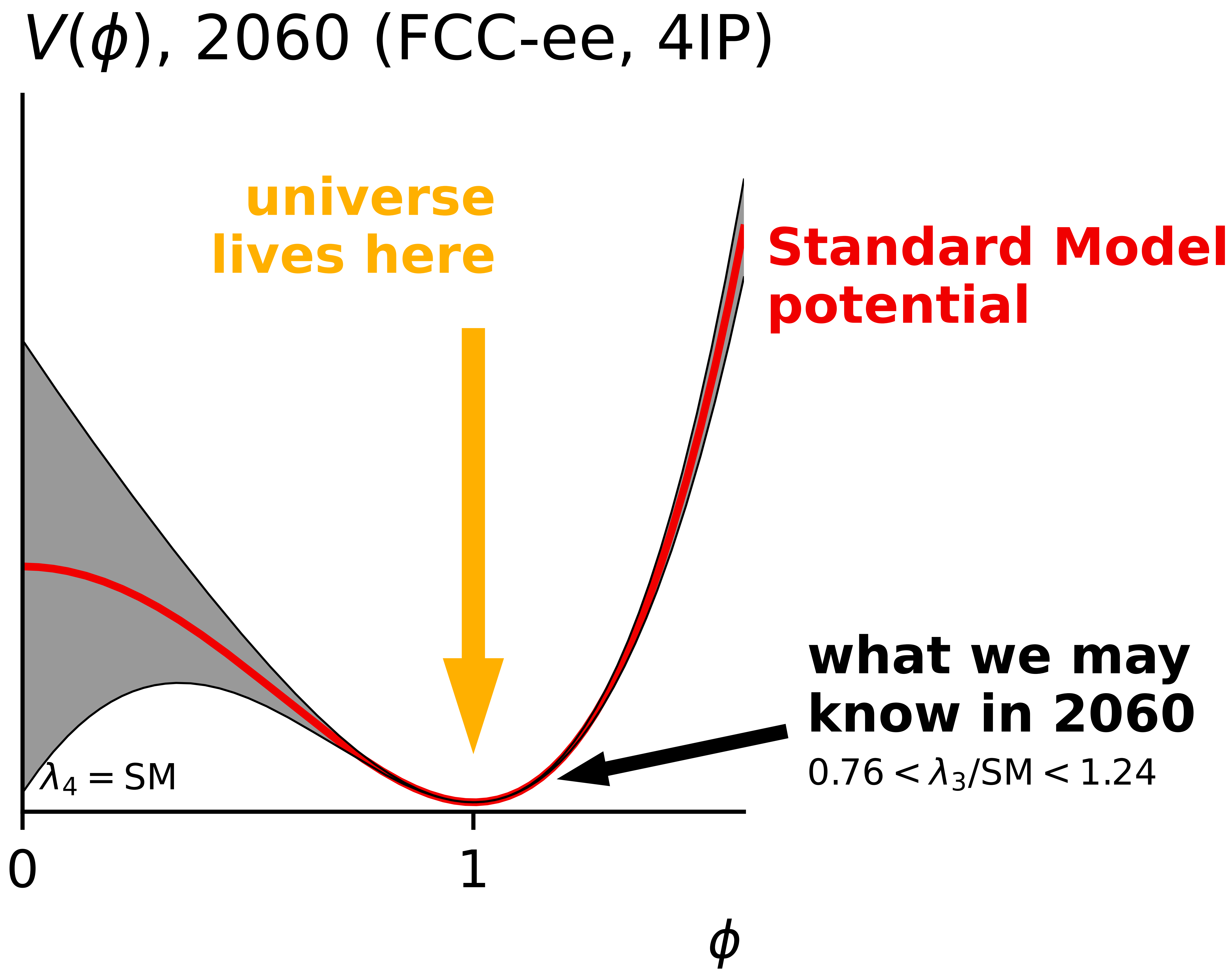

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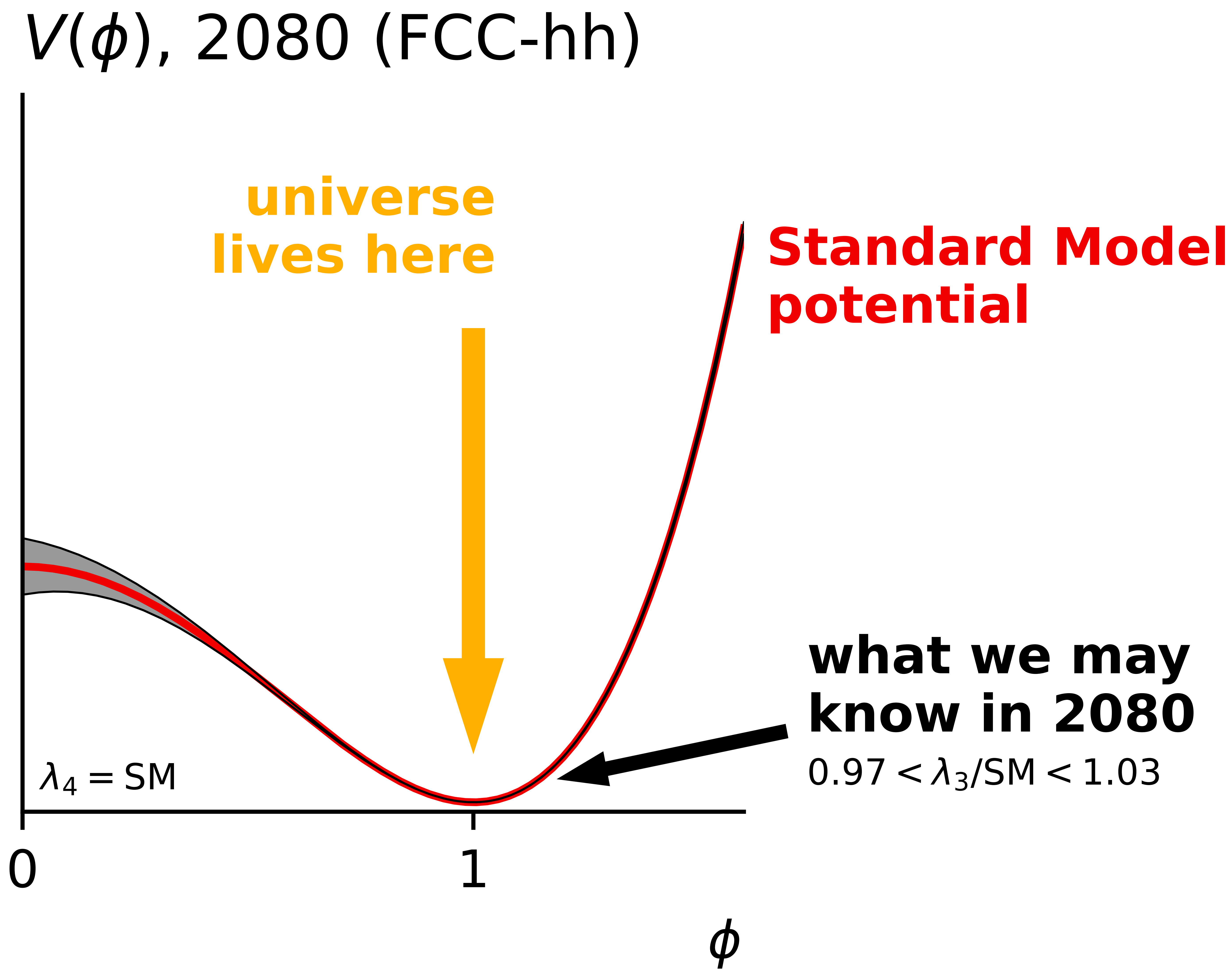


Studying H→HH probes specific mathematical property of the potential's shape:

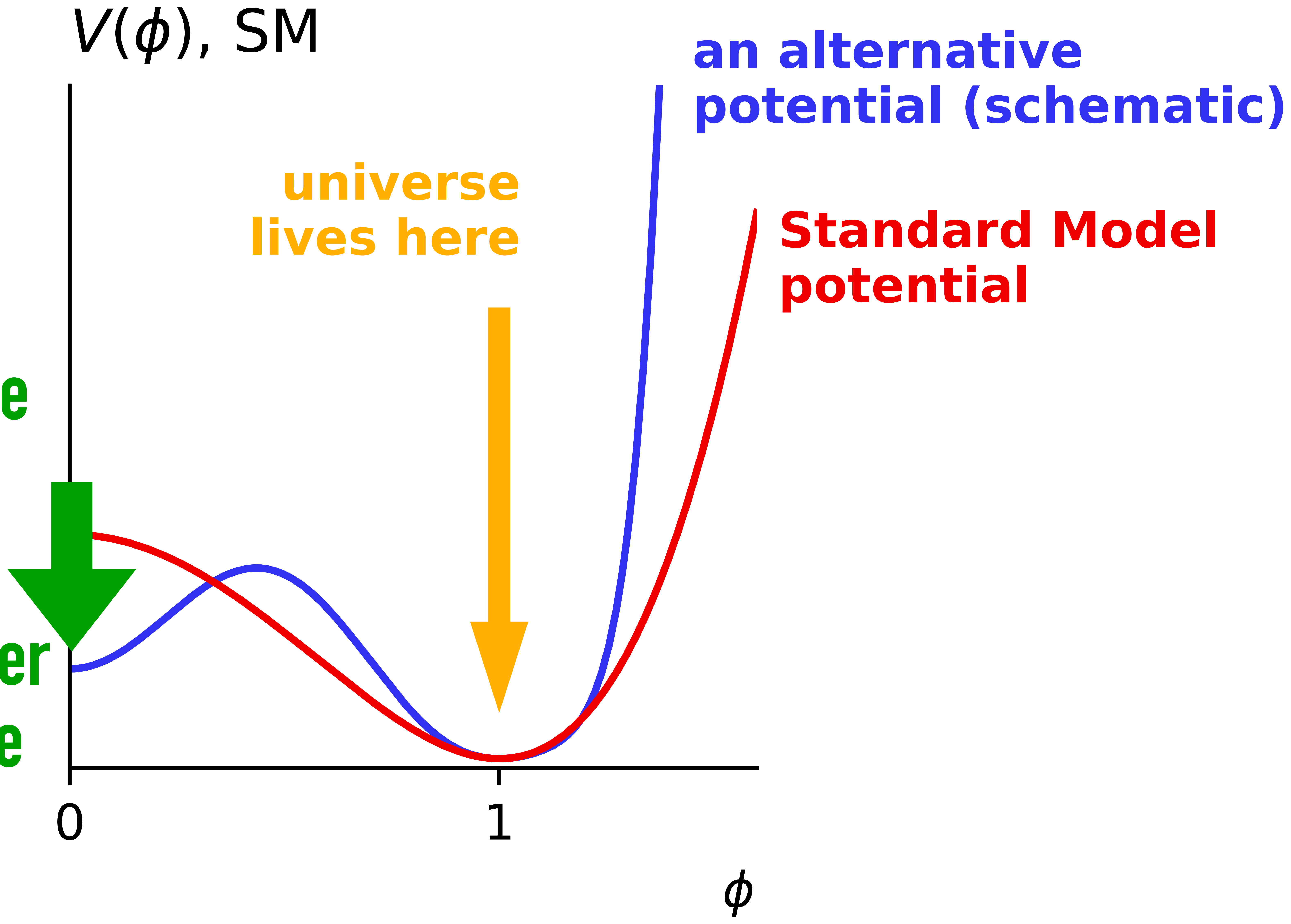
its third derivative (λ_3), i.e. how asymmetric it is at the minimum

[reconstruction in plot assumes higher derivatives as in SM]

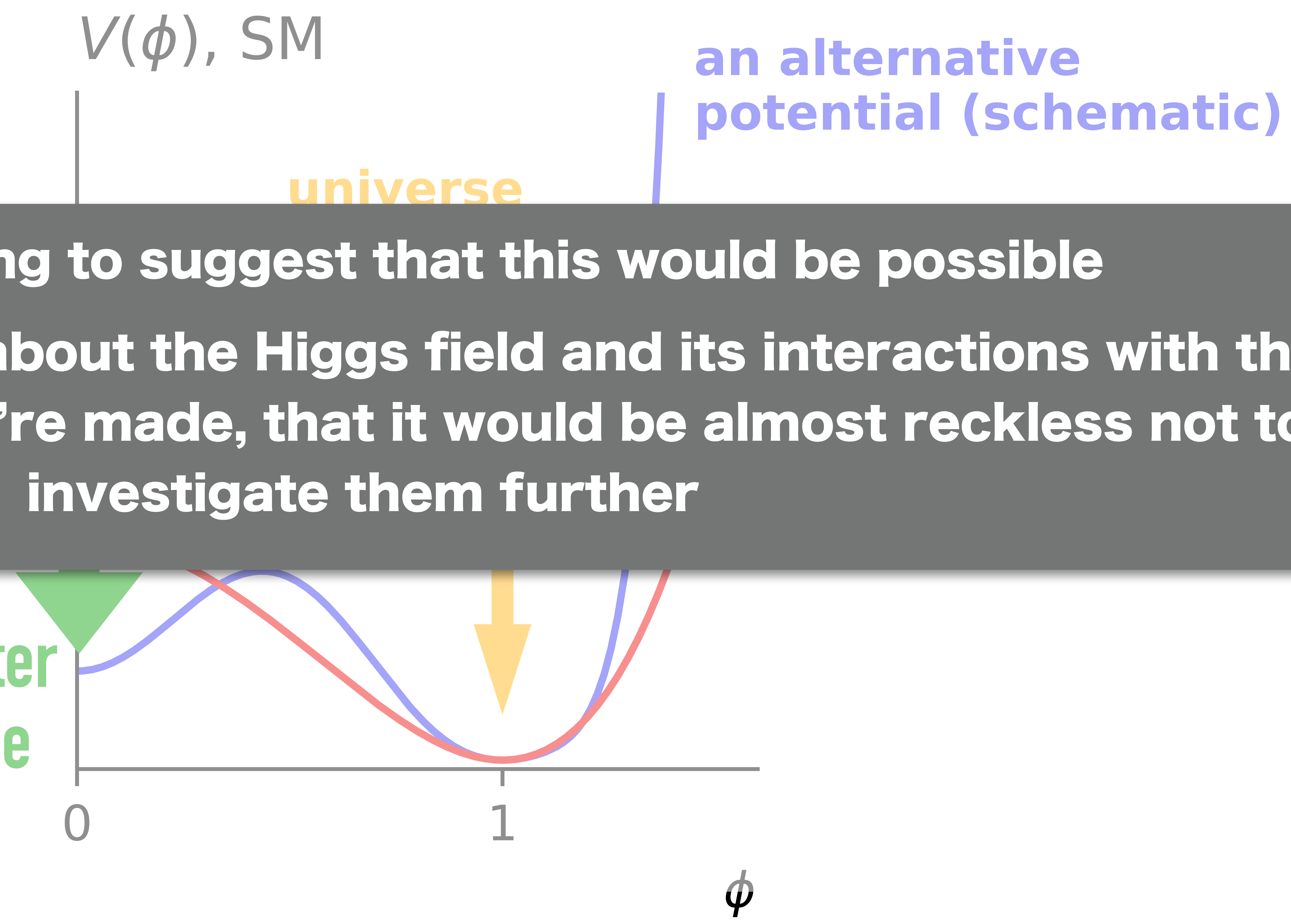
Science fiction

could we make a bubble with zero Higgs field?

if so, properties of matter in that bubble would be completely different



Science fiction



there is nothing to suggest that this would be possible

but we know so little about the Higgs field and its interactions with the particles of which we're made, that it would be almost reckless not to investigate them further

if so, properties of matter in that bubble would be completely different

desirable features of a worldwide HEP project?

an important target that is guaranteed to be reached
(no-lose theorem)

exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

likelihood of success, robustness (incl. multiple experiments)

cost-effective construction & operation, low carbon footprint

what should we expect as a step up in energy?

I like the $Z'_{\rm SSM}$ as a simple measure of progress
(simple and most experiments look for it)

Tevatron
$p\bar{p}$, 1.96 TeV, 10 fb^{-1}

Exclusion limit ~ 1.2 TeV

(if they had analysed all their data in electron and muon channels; actual CDF limit 1.071 TeV, 4.7fb^{-1}, μμ only)

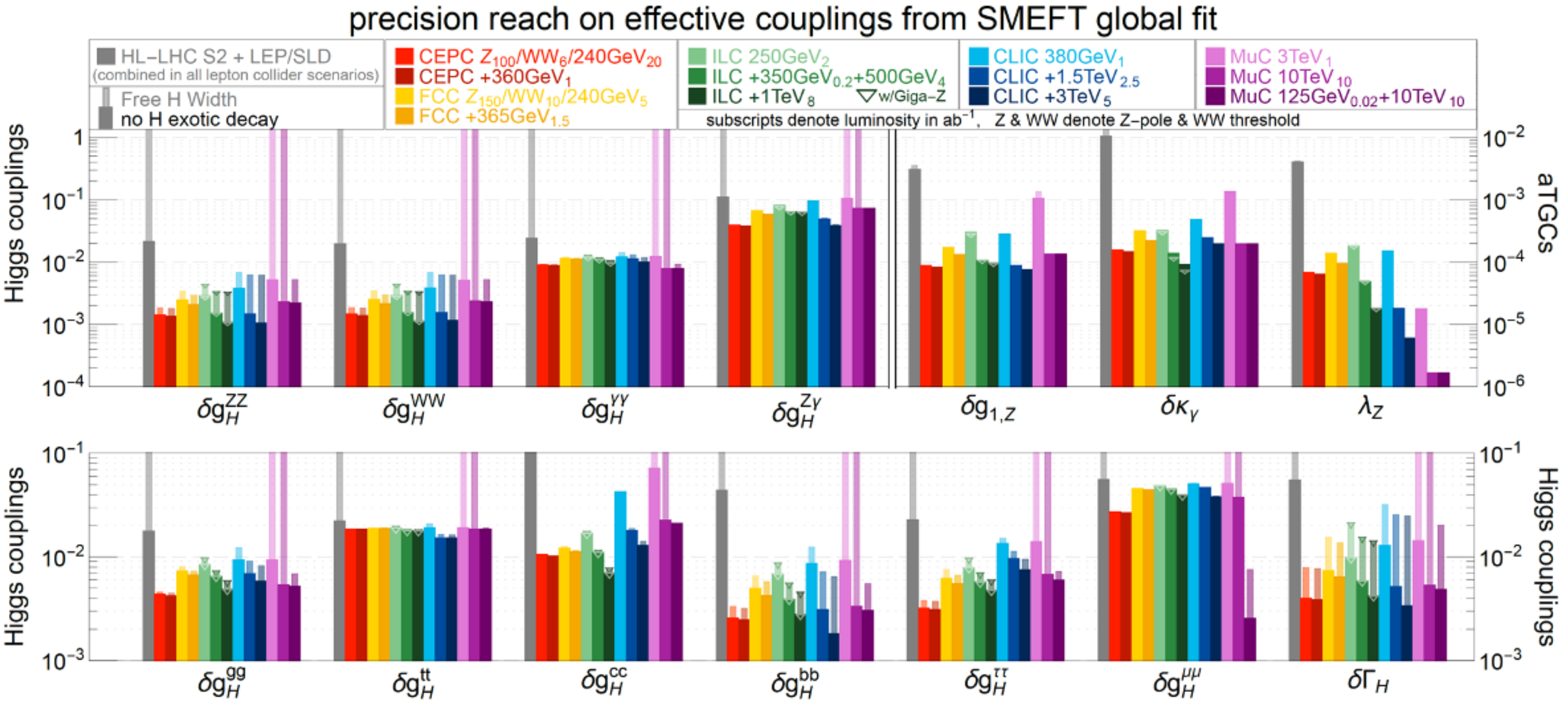
→ × 5.6 →

LHC
pp, 14 TeV, 3000 fb^{-1}

Exclusion limit ~ 6.7 TeV

(electron and muon channels, single experiment)

energy reach through increase in precision



https://arxiv.org/abs/2206.08326

increase in precision is like $\times\ 4-5$ increase in energy reach

J. de Blas et al, https://arxiv.org/abs/2206.08326

step up in energy for direct searches?

I like the Z'_{SSM} as a simple measure of progress
(simple and most experiments look for it)

LHC
pp, 13 TeV, 3000 fb^{-1}

Exclusion limit ~ 6.7 TeV

(electron and muon channels, single experiment)

× 6.1 →

FCC-hh
pp, 100 TeV, 20 ab^{-1}

Exclusion limit ~ 41 TeV

(based on PDF luminosity scaling, assuming detectors can handle muons and electrons at these energies)

step up in energy for direct searches?

I like the Z'_{SSM} as a simple measure of progress
(simple and most experiments look for it)

LHC
pp, 13 TeV, 3000 fb^{-1}

Exclusion limit ~ 6.7 TeV

(electron and muon channels, single experiment)

× 6.4 →

SppC
125 TeV, 5 ab^{-1}

Exclusion limit ~ 43 TeV

(based on PDF luminosity scaling, assuming detectors can handle muons and electrons at these energies)

desirable features of the next major HEP project(s)?

an important target to be reached ~ guaranteed discovery

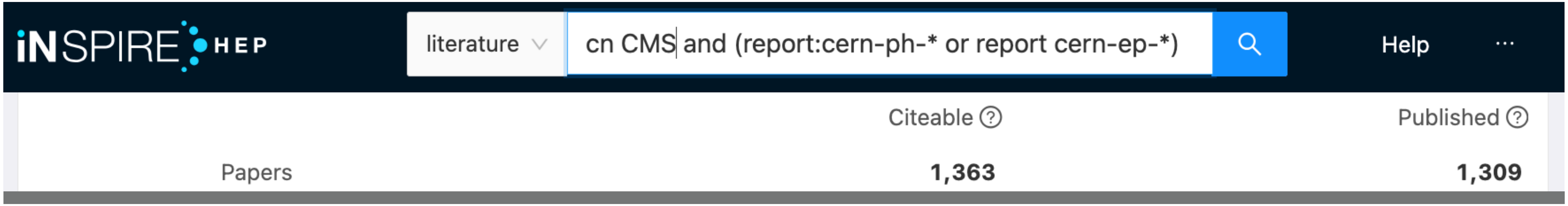
exploration into the unknown by a significant factor in energy

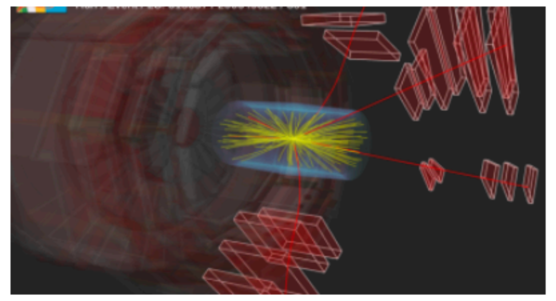
major progress on a broad array of particle physics topics

likelihood of success, robustness (e.g. multiple experiments)

cost-effective construction & operation,
low carbon footprint, novel technologies

Collider experiments bring incredible variety of physics

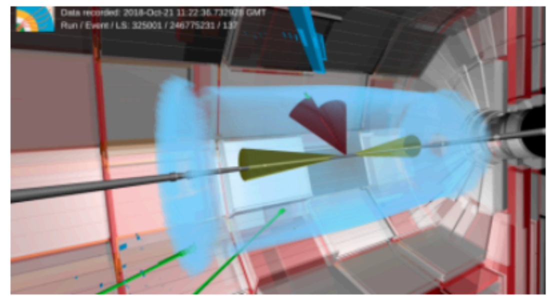




PEEKING INSIDE THE PROTON: THE STORY OF Z+Υ

19 MAR 2025 | MAIQBAL | PHYSICS

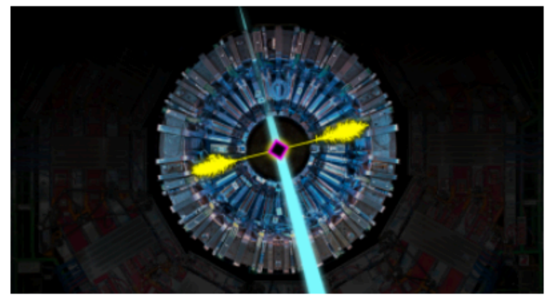
CMS discovers associated production of a Z boson and an Υ meson. At the CMS experiment, we have observed for the first time an exceptionally rare process: the associated production of a Z boson with an Υ(1S) meson, the lightest bound state of…



A TALE OF TWO HIGGS: THE QUEST FOR PRODUCTION OF HIGGS BOSON PAIRS AT CMS

02 DEC 2024 | MAIQBAL | PHYSICS

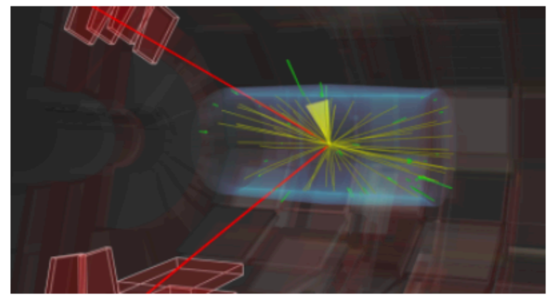
In a recent result, the CMS experiment has combined a comprehensive set of searches for the production of not one but two Higgs bosons – the result is a significant step towards observation of this elusive process, and constitutes a legacy of…



THE "LARGE PHOTON COLLIDER": CMS OBSERVES SCATTERING OF LIGHT BY LIGHT AT THE LHC

13 JAN 2025 | MAIQBAL | PHYSICS

CMS scientists discover some of the rarest collisions that the LHC can produce – such as the scattering of light by light – and learn more about the quantum nature of electromagnetism, search for new particles, and much more. In everyday life…



HIDDEN SIGNALS OF NEW PHYSICS IN EVENTS WITH A HIGH ENERGY LEPTON PAIR

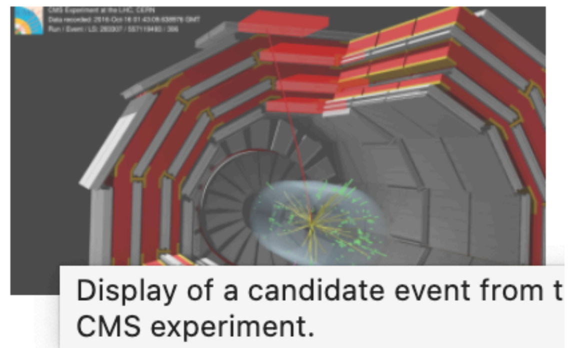
13 SEP 2024 | MAIQBAL | PHYSICS

A primary goal of the Large Hadron Collider (LHC) is to hunt for evidence of beyond the Standard Model (BSM) dynamics through deviations from the Standard Model (SM) predictions. If the mass of BSM particles exceeds the energy accessible in…

CLOCKING NATURE'S HEAVIEST ELEMENTARY PARTICLE: DO TOP QUARKS PLAY BY EINSTEIN'S RULES THE WHOLE DAY AND NIGHT?

27 NOV 2024 | MAIQBAL | PHYSICS

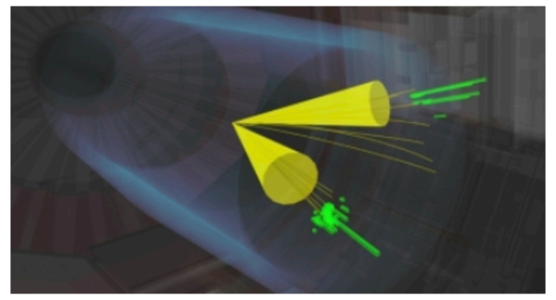
In a first measurement of its kind at the LHC, the CMS experiment tests whether top quarks adhere to Einstein's special theory of relativity, and improves the bounds on noncompliance by up to a factor of one hundred with respect to previous…



CMS DELIVERS THE BEST-PRECISION MEASUREMENT OF THE W BOSON MASS AT THE LHC

17 SEP 2024 | MAIQBAL | PHYSICS

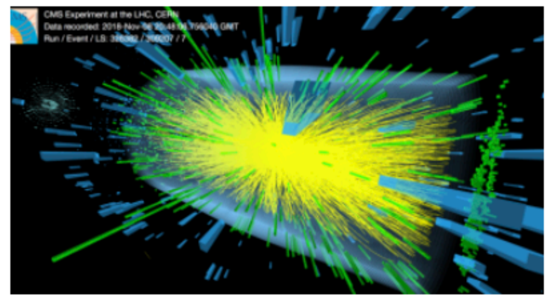
In an extraordinary feat of precision physics, CMS measures the mass of the W boson, and finds it to be in good agreement with the prediction by the Standard Model of particle physics. In the most precise measurement of its kind ever obtained at the…



A CHARMING LOOK INTO THE STRUCTURE OF NUCLEI USING COLLISIONS WITH PHOTON CLOUDS

02 OCT 2024 | MAIQBAL | PHYSICS

In a recent result, the CMS experiment measures the production of charmed D0 mesons in collisions of a photon with a heavy lead nucleus for the first time. Atomic nuclei are made up of protons and neutrons, which in turn are made up of more…

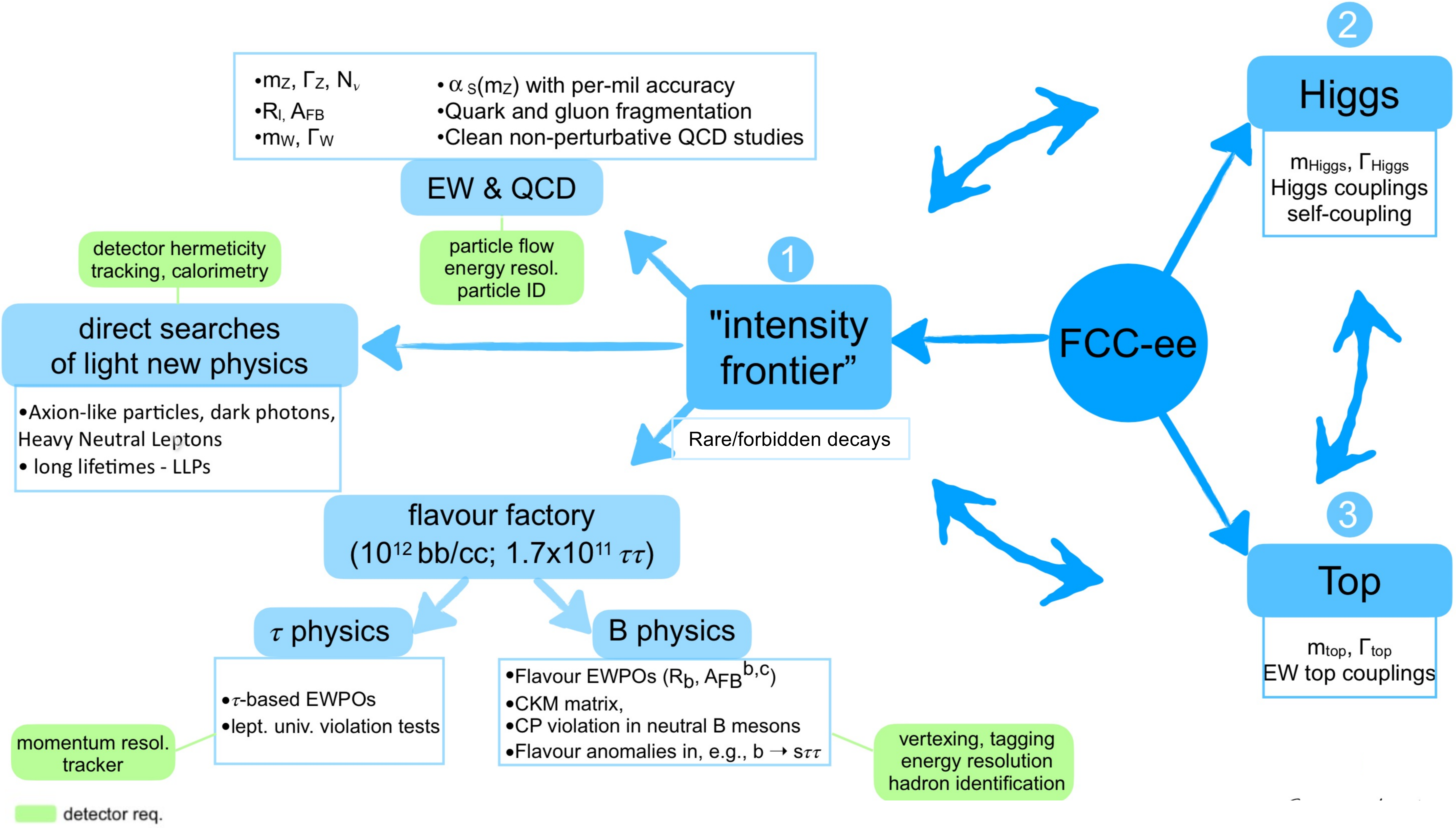


JOURNEY THROUGH THE QUARK GLUON PLASMA

19 AUG 2024 | MAIQBAL | PHYSICS

At the LHC, lead ions are smashed together at extremely high speeds to create a unique state of matter called the quark gluon plasma. Normally, quarks and gluons, such as those that make up lead ions, are confined within protons and neutrons…

illustration is for FCC-ee — but message is comparable for other colliders



Slide from C. Grojean @ FCC Week'22

conclusions

Conclusions

- There is a **guaranteed discovery:** directly establishing Higgs self-interaction, which holds the SM together, via robust precision of Higgs factory and direct measurement at higher-energy colliders
  - is there a chance of a second discovery in establishing (or disproving) SM origin of electron mass at circular e^+e^- colliders?
- The same colliders and experiments that probe major Higgs-physics questions also bring us **step up in energy reach $\sim \times 4 - 5$**, a step up similar to past colliders
  - e^+e^- colliders deliver that mostly in "indirect" sensitivity, through precision increase $\sim \times 18$
  - FCC-hh/SppS deliver that in direct search sensitivity (muon collider does for some scenarios)
- **Diversity and robustness of the programme** = essential part of their strength

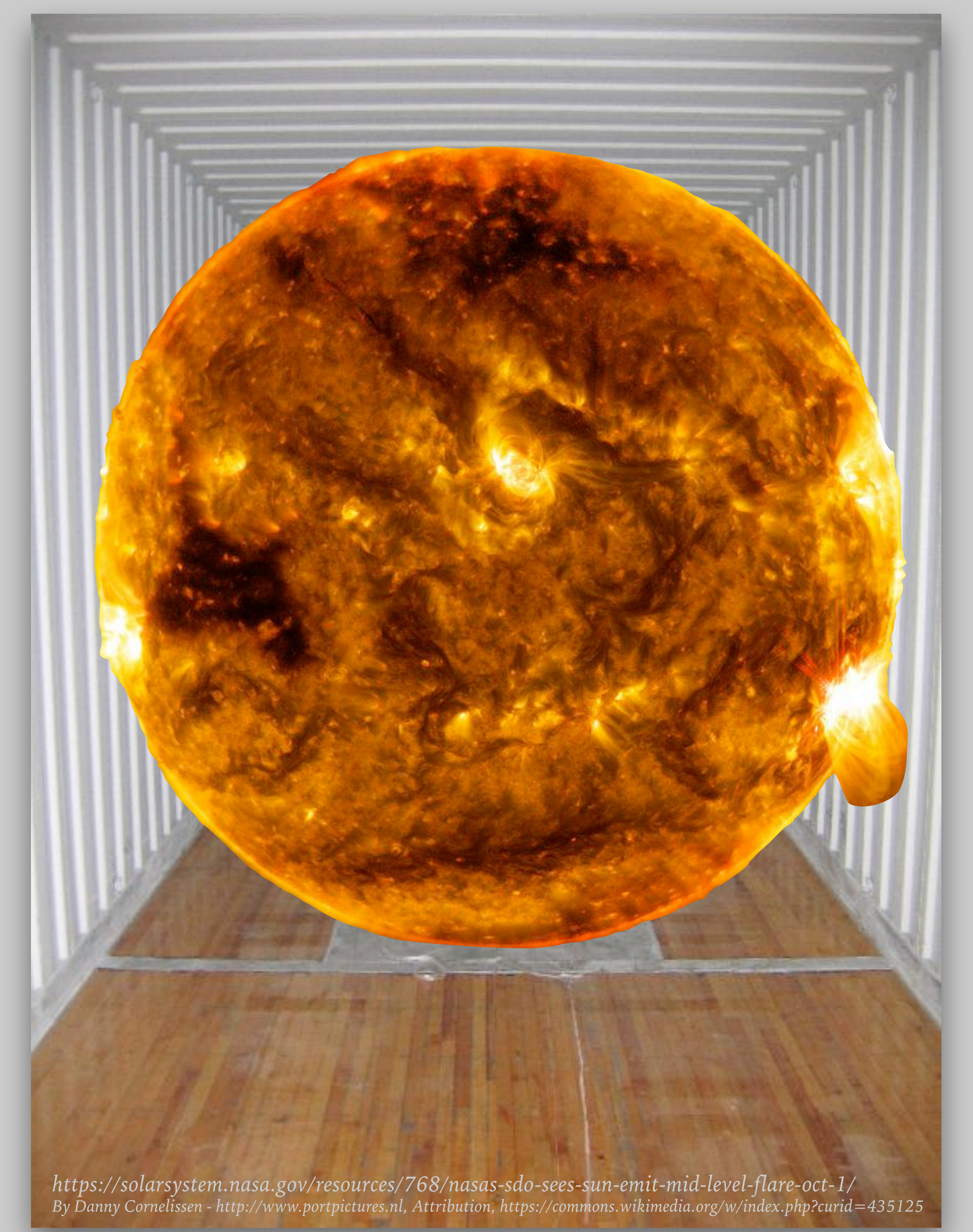
backup

What does 2.6×10^{28} kg/m^3 mean?

What does 2.6×10^{28} kg/m^3 mean?

What does 2.6×10^{28} kg/m^3 mean?

By KMJ, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1443327


https://solarsystem.nasa.gov/resources/768/nasas-sdo-sees-sun-emit-mid-level-flare-oct-1/
By Danny Cornelissen - http://www.portpictures.nl, Attribution, https://commons.wikimedia.org/w/index.php?curid=435125

fit the mass of the sun into a standard 40ft shipping container

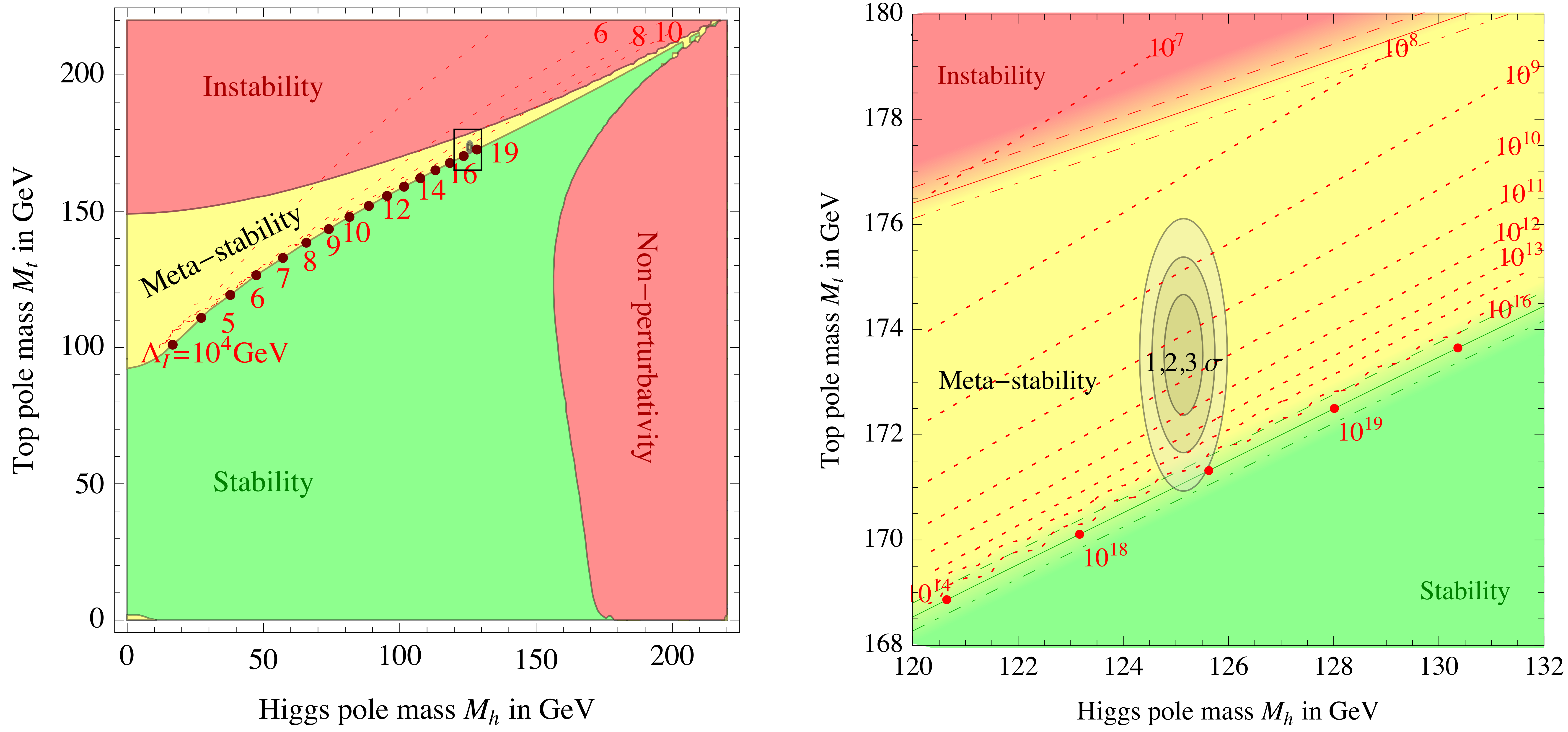
https://upload.wikimedia.org/wikipedia/commons/4/44/Mecanismo_de_Higgs_PH.png
https://en.wikipedia.org/wiki/Neutron_star#/media/File:Neutron_Star_X-ray_beaming_with_accretion_disk.jpg

Electroweak fits (1910.11775), e.g. S & T parameters (i.e. specific EFT operator combinations)

Table 3.3: Values for 1σ sensitivity on the S and T parameters. In all cases the value shown is after combination with HL-LHC. For ILC and CLIC the projections are shown with and without dedicated running at the Z-pole. All other oblique parameters are set to zero. The intrinsic theory uncertainty is also set to zero.

	Current	HL-LHC	ILC_{250}	(& ILC_{91})	CEPC	FCC-ee	$CLIC_{380}$	(& $CLIC_{91}$)
S	0.13	0.053	0.012	0.009	0.0068	0.0038	0.032	0.011
T	0.08	0.041	0.014	0.013	0.0072	0.0022	0.023	0.012

improvements of up to × 14–18



It's not inconceivable that the top mass could be sufficiently mis-measured at hadron colliders that the SM-universe is stable all the way to the Planck scale

condition in terms of the pole top mass. We can express the stability condition of eq. (64) as

$$M_t < (171.53 \pm 0.15 \pm 0.23_{\alpha_3} \pm 0.15_{M_h})\,\text{GeV} = (171.53 \pm 0.42)\,\text{GeV}. \qquad (66)$$

arXiv:1307.3536

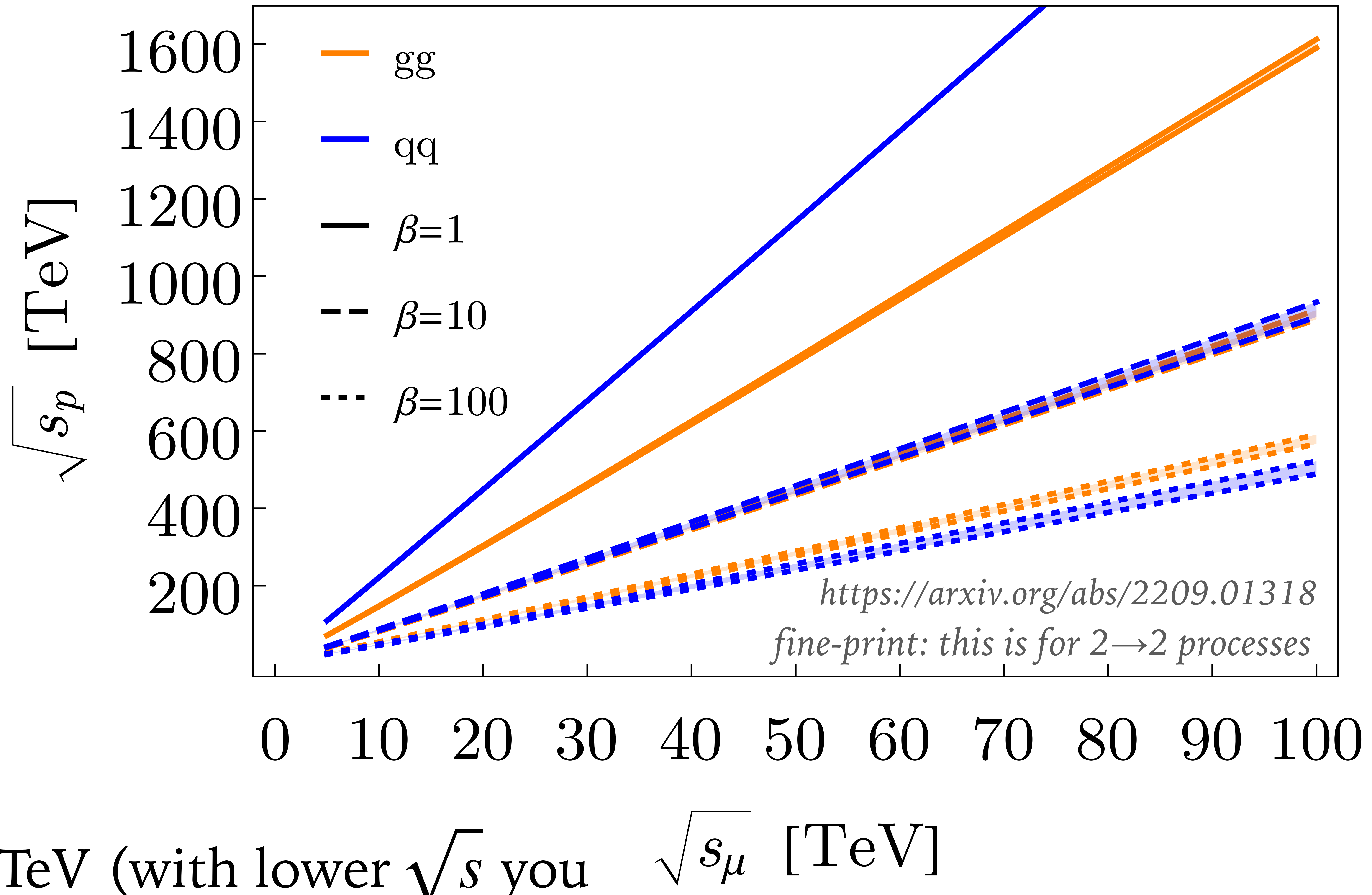
Searches at muon collider

Plots being shown suggest:
4 TeV muon collider beats a
100 TeV pp collider
in searches for new physics.

Useful to nuance the statement:

- 100 TeV pp, 20 ab^{-1} can discover Z' up to $m_{Z'} \sim 38$ TeV
- For $\mu\mu$ collider to discover Z' at $m_{Z'} \sim 38$ TeV, it needs $\sqrt{s} \sim 38$ TeV (with lower $\sqrt{s}$ you would see deviation from SM, but not know what it is)
- However a 38 TeV muon collider would be much better at studying the Z' than the 100 TeV pp machine

Fig. 3 of Snowmass Muon Collider Forum Report



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exploration into the unknown by a significant factor in energy

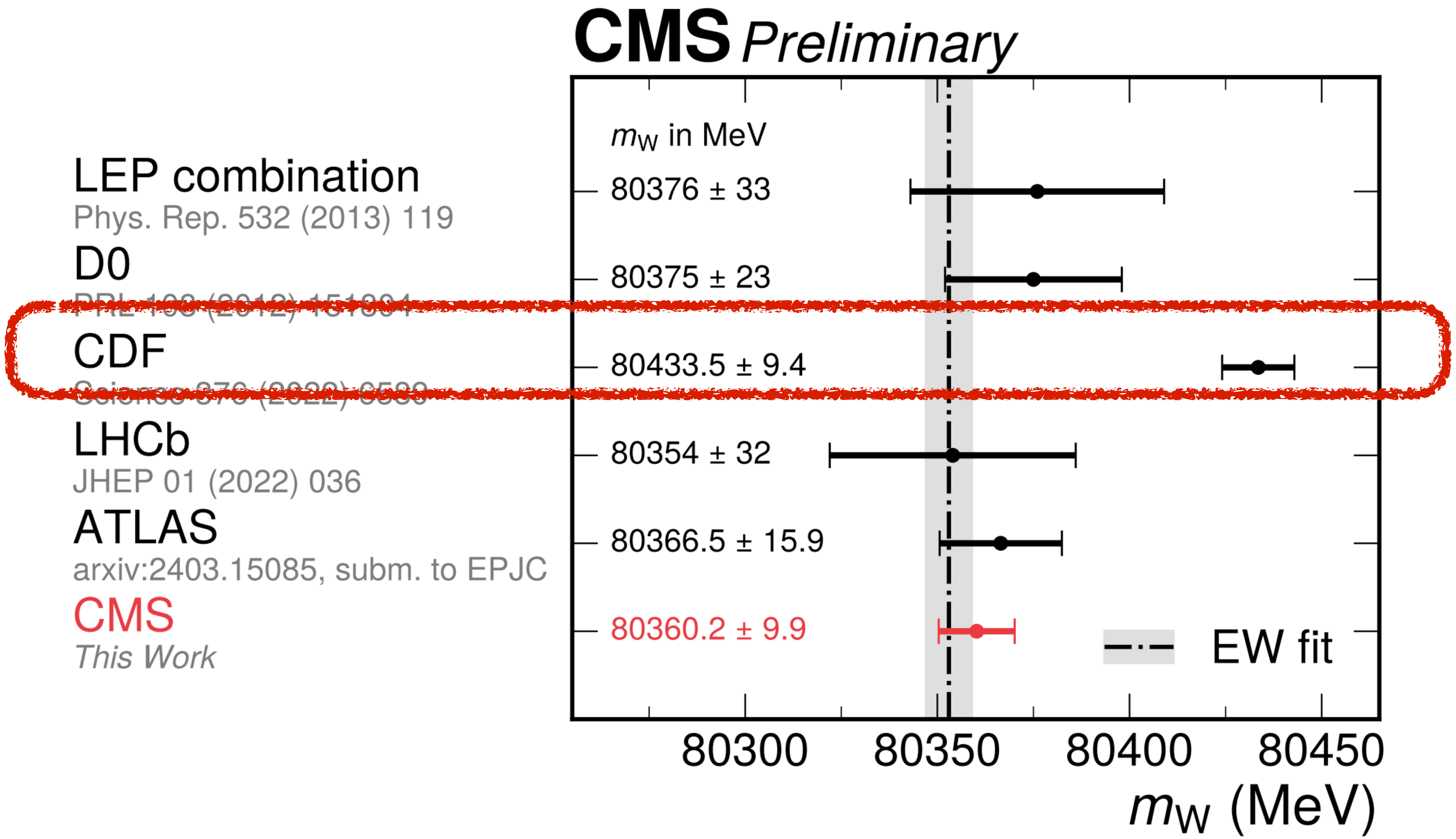
major progress on a broad array of particle physics topics

likelihood of success, robustness (e.g. multiple experiments)

cost-effective construction & operation,
low carbon footprint, novel technologies

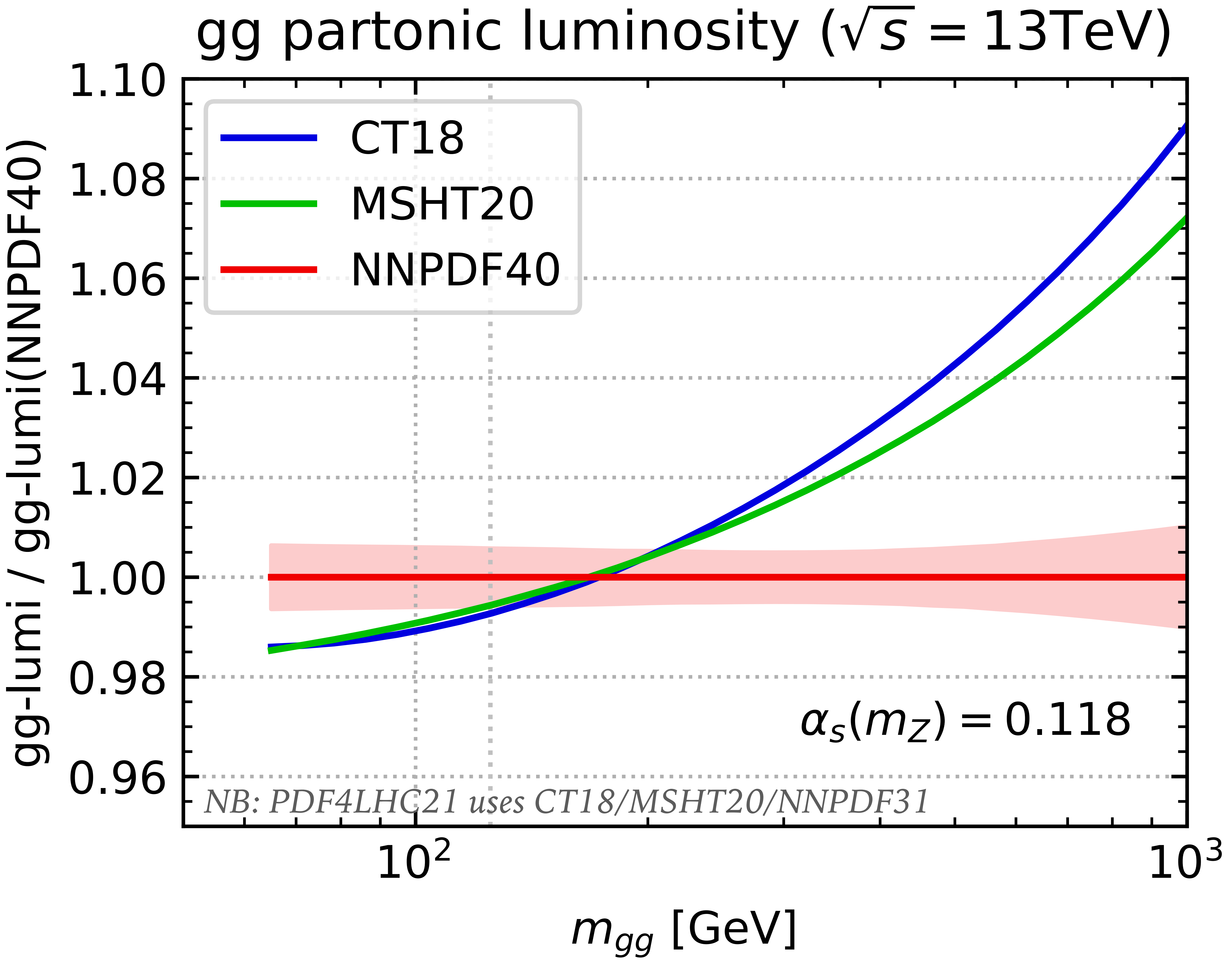
m_W measurements

https://cms.cern/news/cms-delivers-best-precision-measurement-w-boson-mass-lhc



do you believe the measurement when it **disagrees** with your expectations?

we don't know the precision limit of hadron colliders — but we may be close to reaching it



gg-lumi, ratio to PDF4LHC15 @ m_H

PDF4LHC15	1.0000	±	0.0184
PDF4LHC21	0.9930	±	0.0155
CT18	0.9914	±	0.0180
MSHT20	0.9930	±	0.0108
NNPDF40	0.9986	±	0.0058

$\times 3$

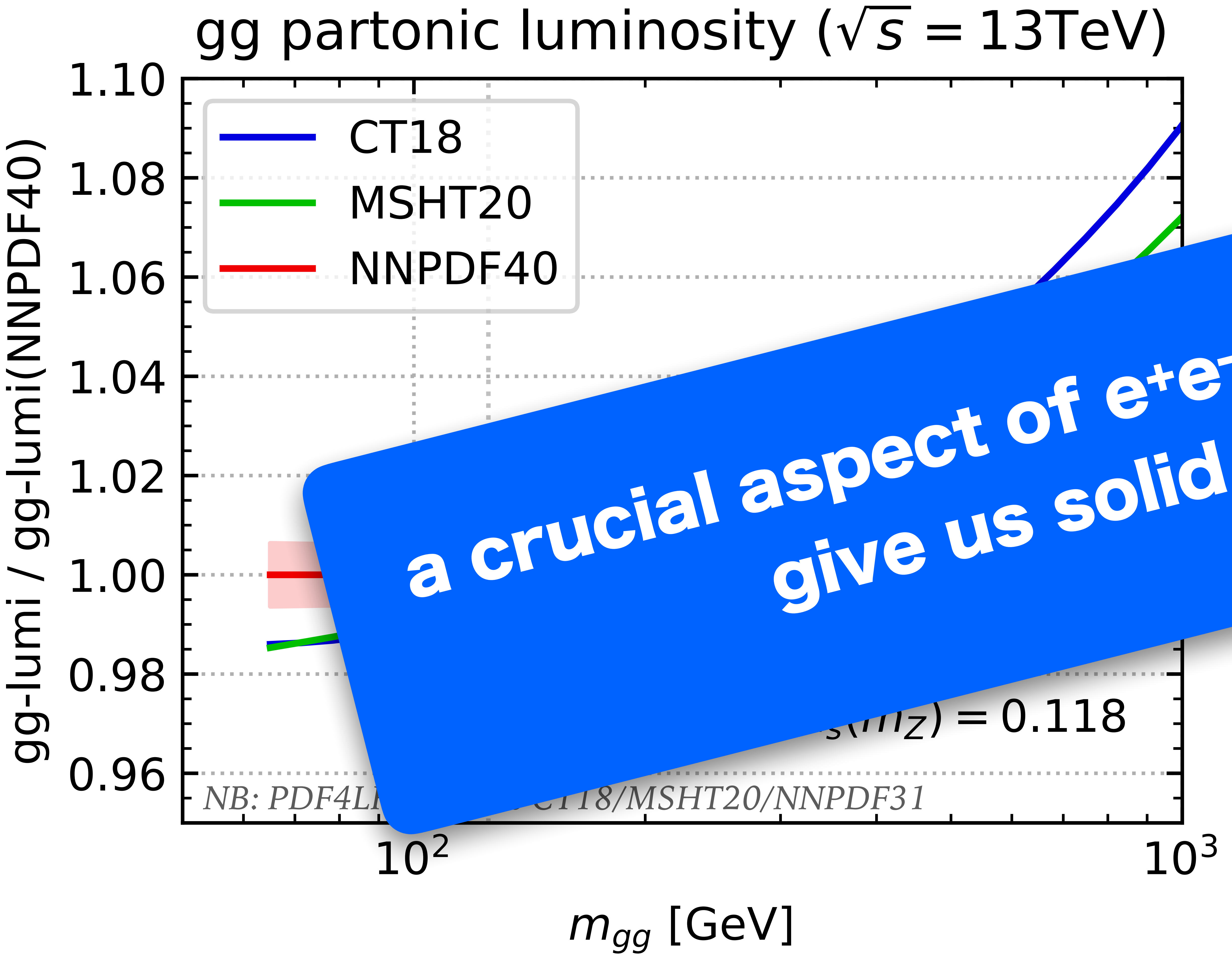
Parton Distribution Functions are one of several elements that may limit LHC/FCC-hh precision:

➤ essential for hadron-collider interpretation

➤ PDF fits are complex, e.g. involve (sometimes inconsistent) data, some of it close to non-perturbative scale

➤ only partial understanding of their limits

we don't know the precision limit of hadron colliders — but we may be close to reaching it



a crucial aspect of e⁺e⁻ colliders is that they give us solid foundations

gg-lumi, ratio to PDF4LHC15 @ m_H

PDF4LHC15	.0184
PD	0155
	0180
	108
	0.0058

×3

…Distribution Functions are one of several elements that may limit LHC/FCC-hh precision:

- essential for hadron-collider interpretation
- PDF fits are complex, e.g. involve (sometimes inconsistent) data, some of it close to non-perturbative scale
- only partial understanding of their limits

Results - Combination at 240 GeV

example of FCC-ee Higgs precision

Fitting using **CMS** tool **CombineTF** to extract σ.BR in each category

Monte Carlo stats uncertainties

Backgrounds are let fully floating

Expected sensitivity (%) of σ(ZH).BR(H⟶jj) at 68% CL **L = 10.8ab-1**

240 GeV	H⟶bb	H⟶cc	H⟶gg	H⟶ss	H⟶ZZ	H⟶WW	H⟶ττ
Z⟶ll	0.68	4.02	2.18	234	13.66	1.78	4.08
Z⟶qq	0.32	3.52	3.07	408.55	52.08	8.74	110.73
Z⟶νν (BNL)	0.33	2.27	0.94	137	19.84	1.89	21.76
Z⟶νν (APC)	0.36	2.18	1.10	151	15.29	1.51	11
Combined (BNL)	0.21	1.66	0.8	104.99	10.07	1.16	3.97
Combined (APC)	0.22	1.65	0.93	121	9.56	1.11	3.79