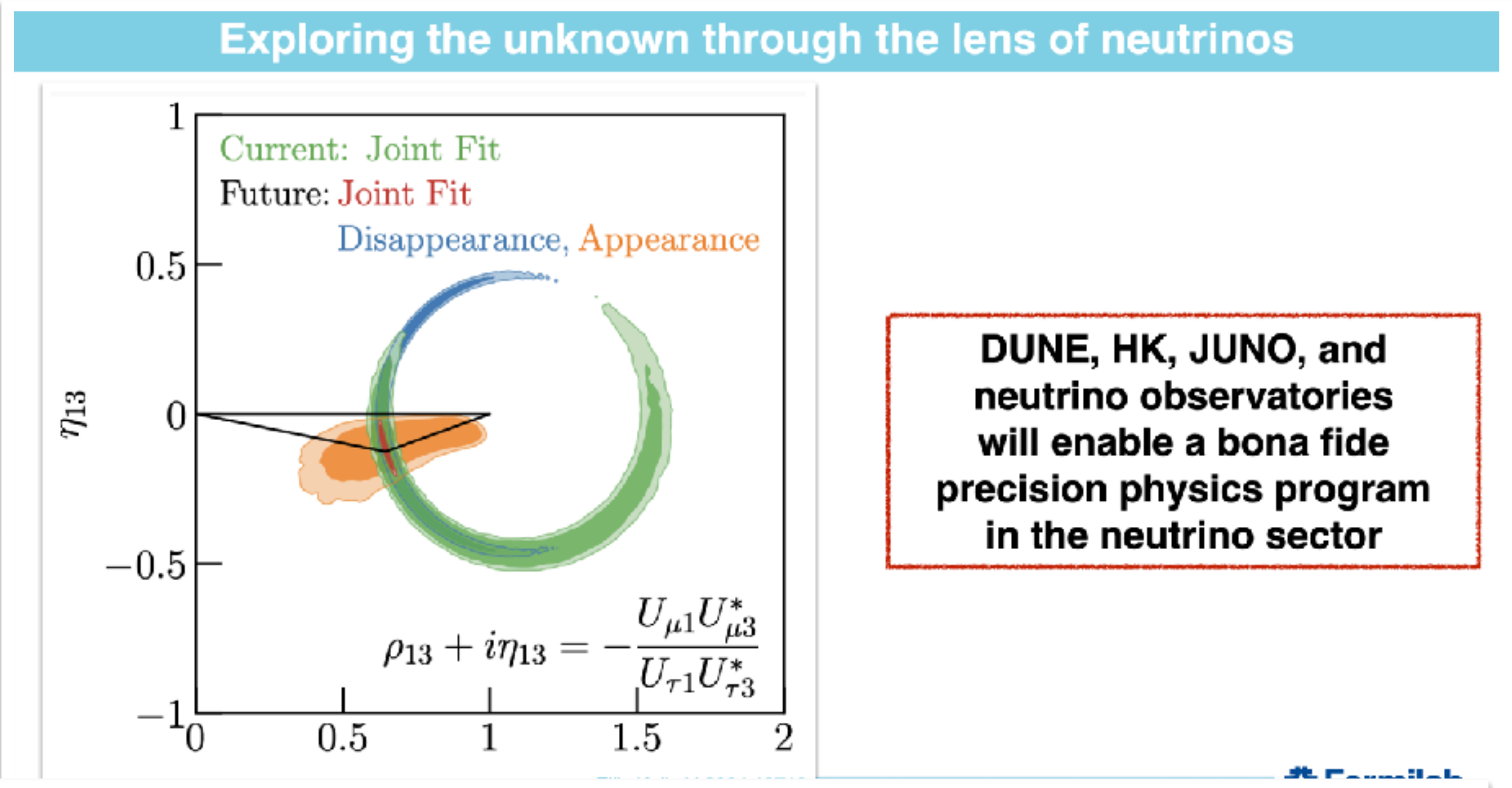
13th ICFA Seminar on
Future Perspectives in High-Energy Physics
28 November – 1 December 2023
DESY, Hamburg

The future of HEP: our motivation

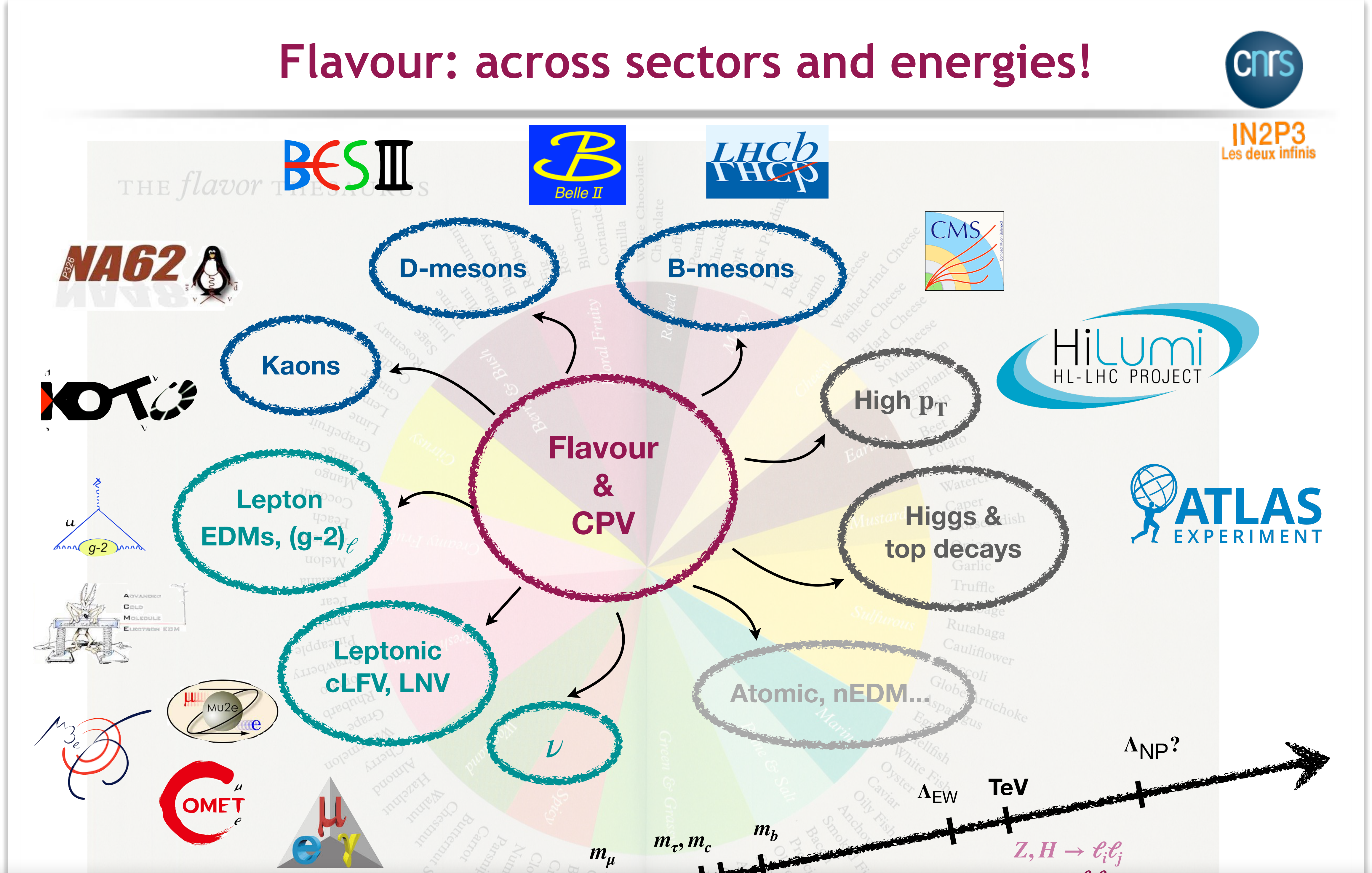
Gavin Salam
University of Oxford & All Souls College

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



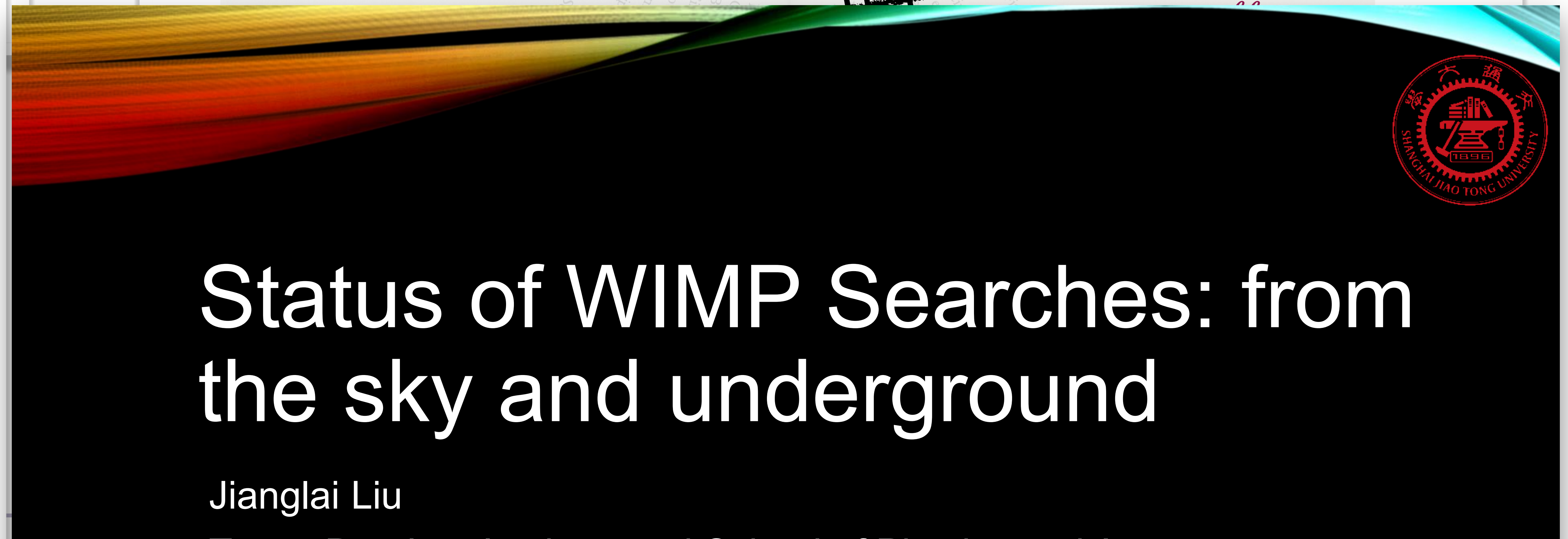
Exploring the unknown through the lens of neutrinos

DUNE, HK, JUNO, and neutrino observatories will enable a bona fide precision physics program in the neutrino sector



Flavour: across sectors and energies!

The Electron Ion Collider



Status of WIMP Searches: from the sky and underground

Jianglai Liu

top-down

figure out the best collider you can realistically build

establish what physics it will probe

bottom up

establish what you want to learn

figure out how to build a collider that will best achieve it

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

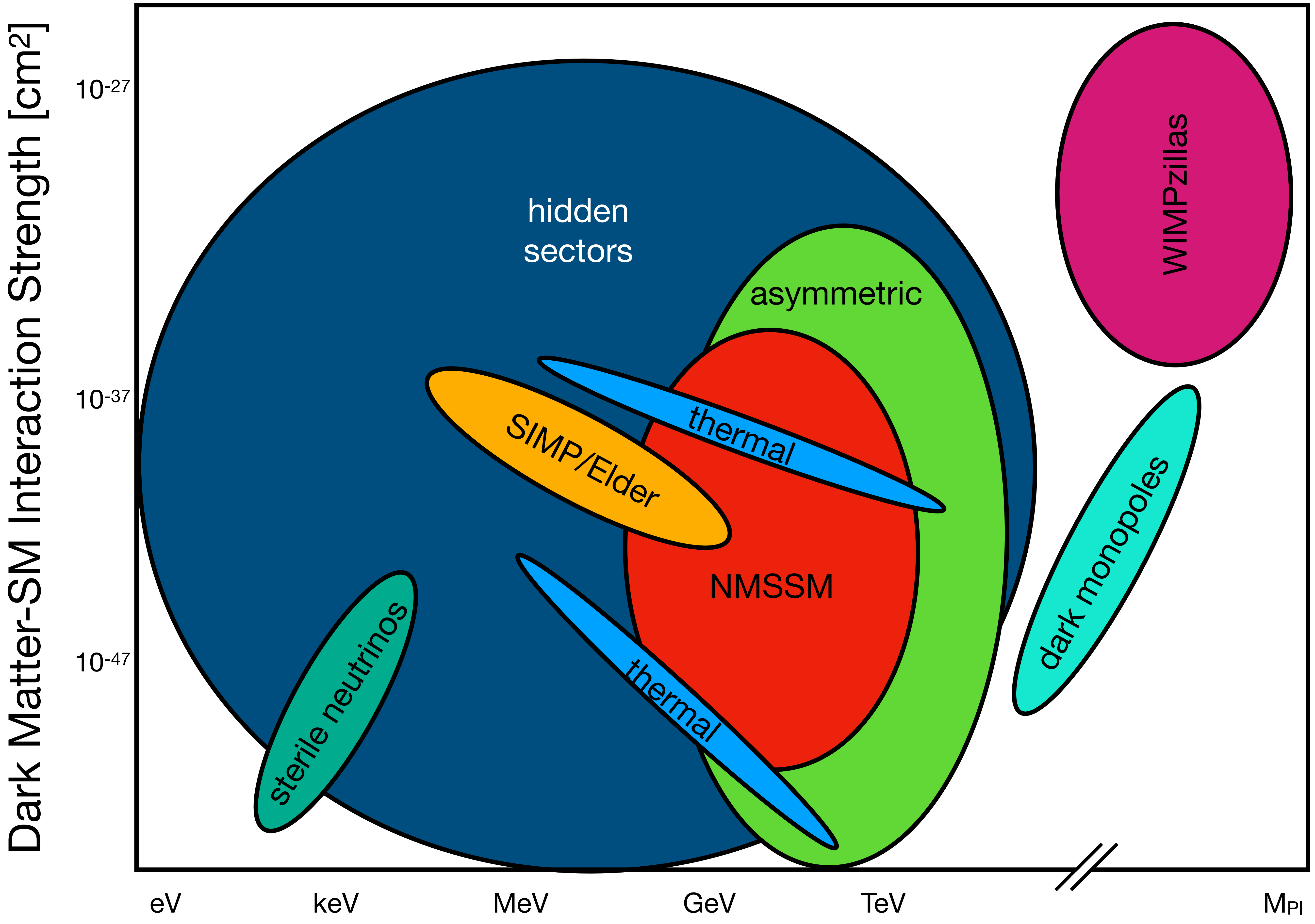
- *a dark matter candidate*
- *an explanation for the fermion masses*
- *an explanation of matter-antimatter asymmetry*
- *an axion, to solve the strong CP problem*
- *a solution to fine tuning the EW scale*
- *a solution to fine tuning the cosmological constant*

Thank you, Particle Physicists

ps: please, no anthropics

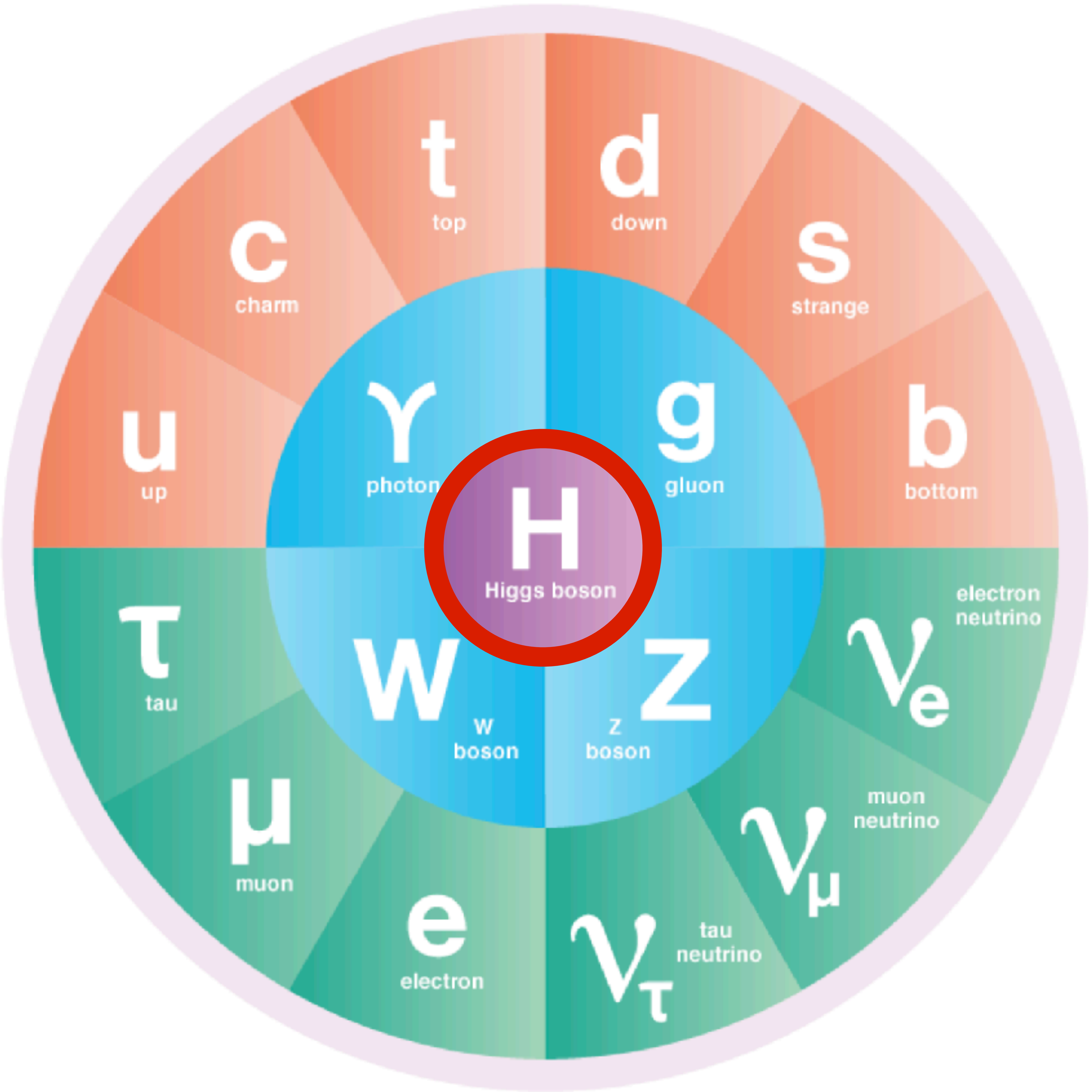
we have so far been unlucky in getting answers to these many questions

Snowmass Dark Matter report, 2209.07426



30 orders of magnitude in interaction strength

30 orders of magnitude in mass



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

the standard-model particle set is complete

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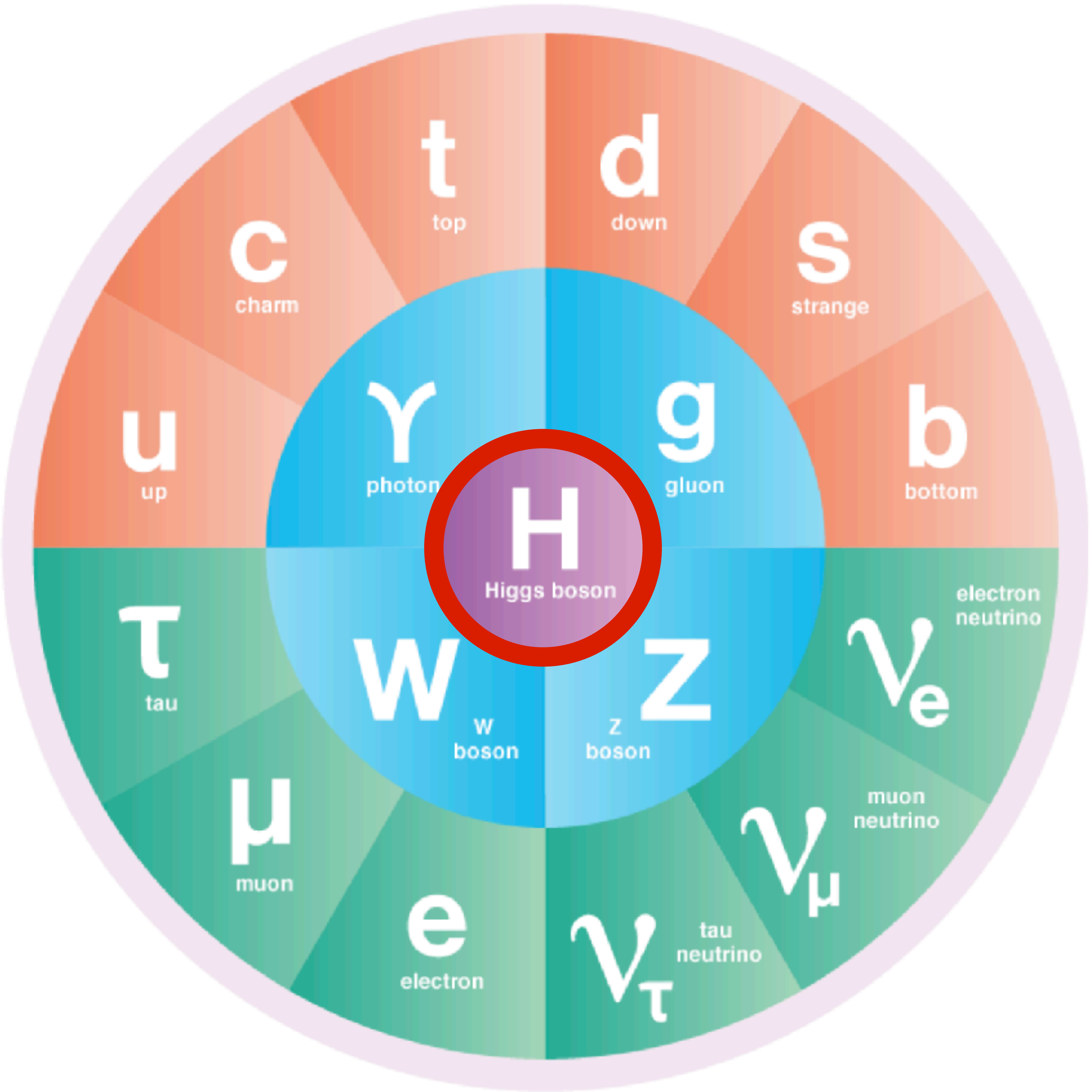
PORTUGIESENVIERTEL
Baumwall (Elbphilharmonie)
ap San Diego
Am Sandtorkai
Elbphilharmonie Hamburg
Übersee
Grasbrookhafen
Überseeq
STRAND
Strandhafen
Hamburger
Norder



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)?

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

Higgs physics

Higgs is the last particle of the SM.

So the SM is complete, right?

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

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

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).

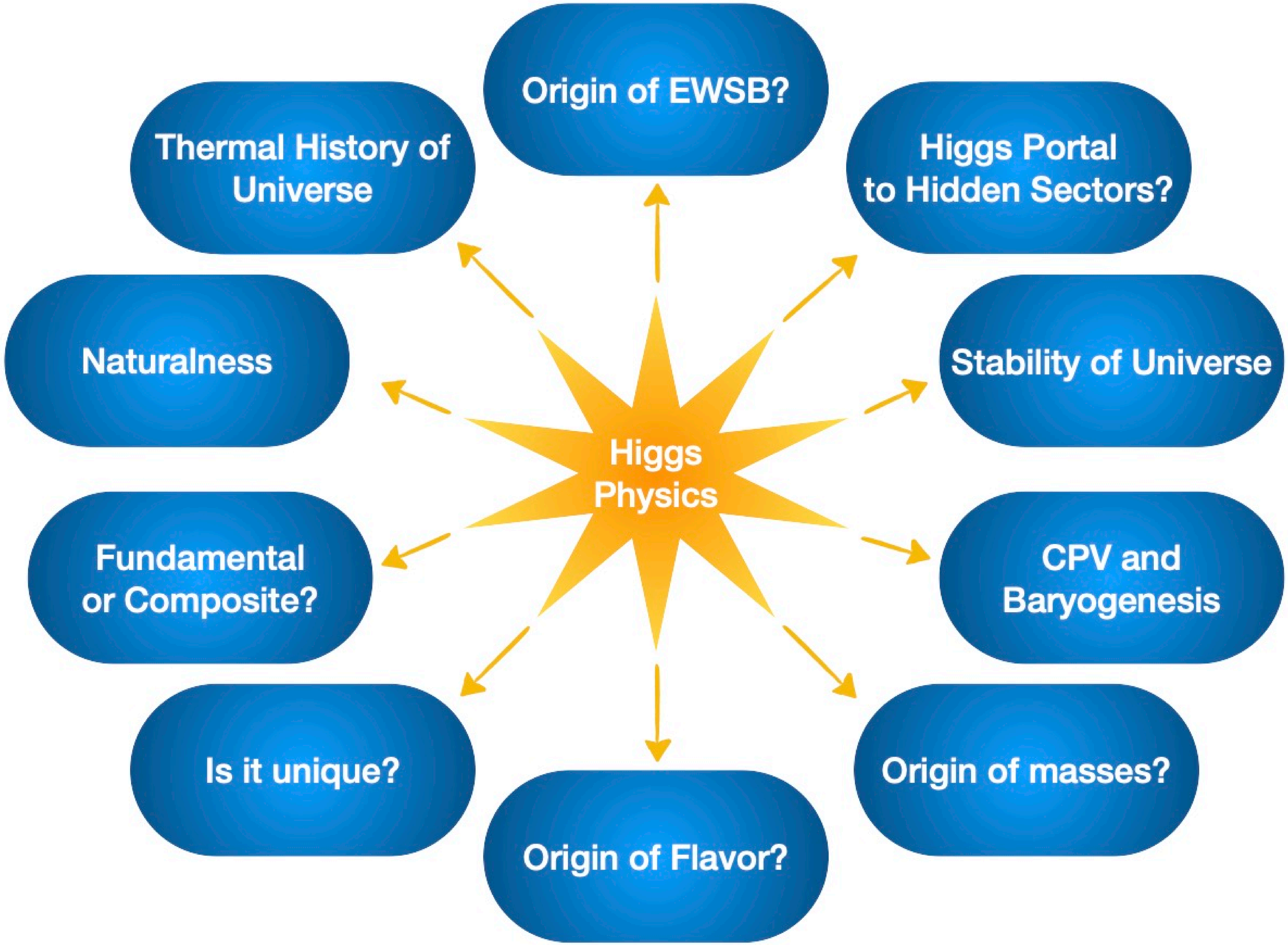
Holds the SM together.

Unobserved

typeset from Gian Giudice original

Almost every problem of the Standard Model originates from Higgs interactions

$$\mathscr{L} = \underset{\substack{\big\uparrow \\ \text{flavour}}}{y} H \psi \bar{\psi} + \underset{\substack{\big\uparrow \\ \text{naturalness}}}{\mu^2} |H|^2 - \underset{\substack{\big\uparrow \\ \text{stability}}}{\lambda} |H|^4 - \underset{\substack{\Big\uparrow \\ \text{cosmological constant}}}{V_0}$$



Higgs Physics

Origin of EWSB?

Higgs Portal to Hidden Sectors?

Stability of Universe

CPV and Baryogenesis

Origin of masses?

Origin of Flavor?

Is it unique?

Fundamental or Composite?

Naturalness

Thermal History of Universe

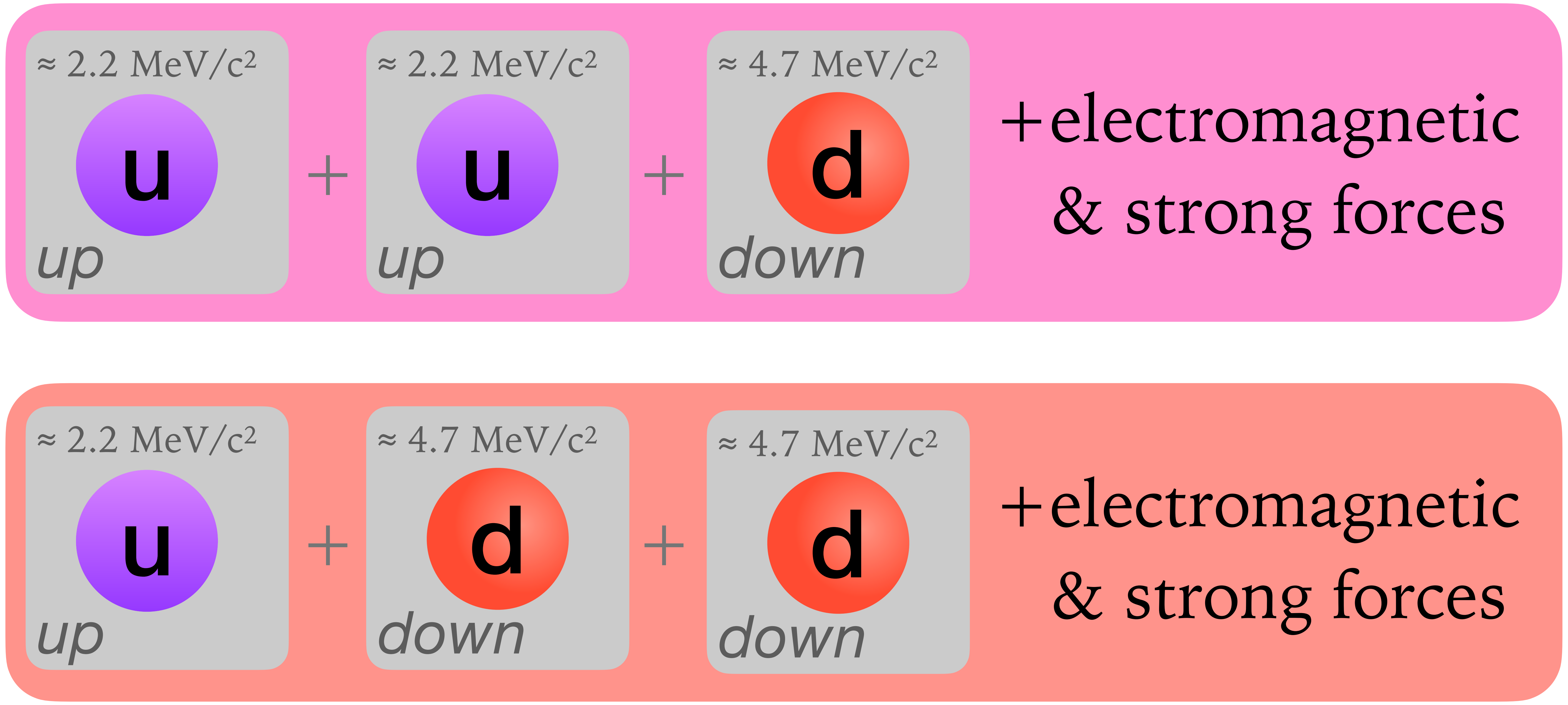
Yukawa interaction hypothesis

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)

2.2 MeV **2.2 MeV** 4.7 MeV



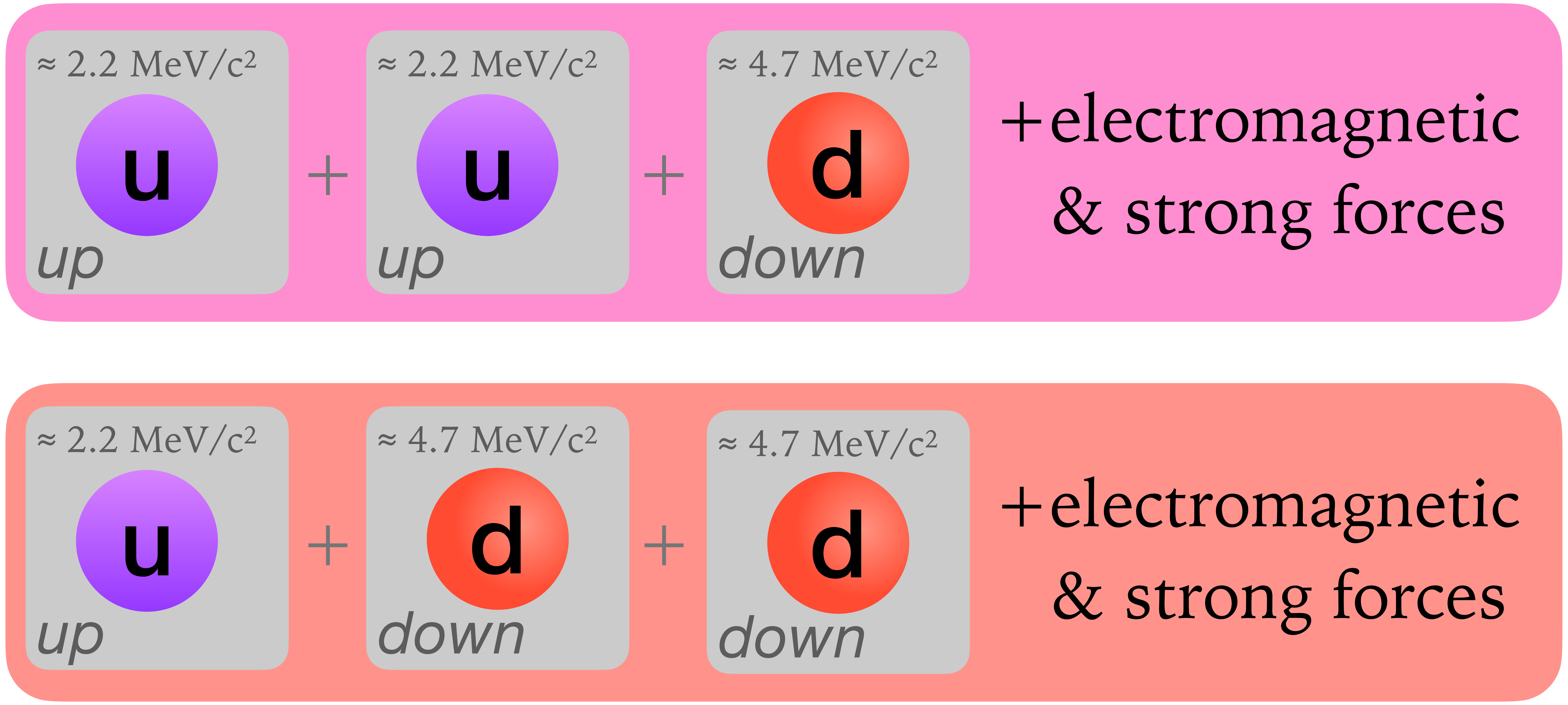
proton: +electromagnetic & strong forces $\simeq$ **938.3 MeV**

neutron: +electromagnetic & strong forces $\simeq$ **939.6 MeV**

2.2 MeV **4.7 MeV** 4.7 MeV

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

2.2 MeV **2.2 MeV** 4.7 MeV



proton: +electromagnetic & strong forces ≃ **93**8.3 **MeV**

neutron: +electromagnetic & strong forces ≃ **93**9.6 **MeV**

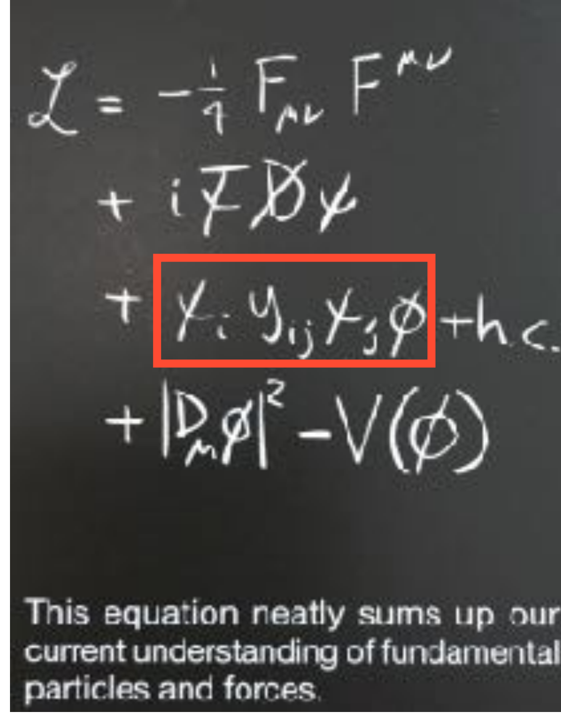
2.2 MeV **4.7 MeV** 4.7 MeV

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

Supposedly because up quarks interact more weakly with the Higgs field than down quarks

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

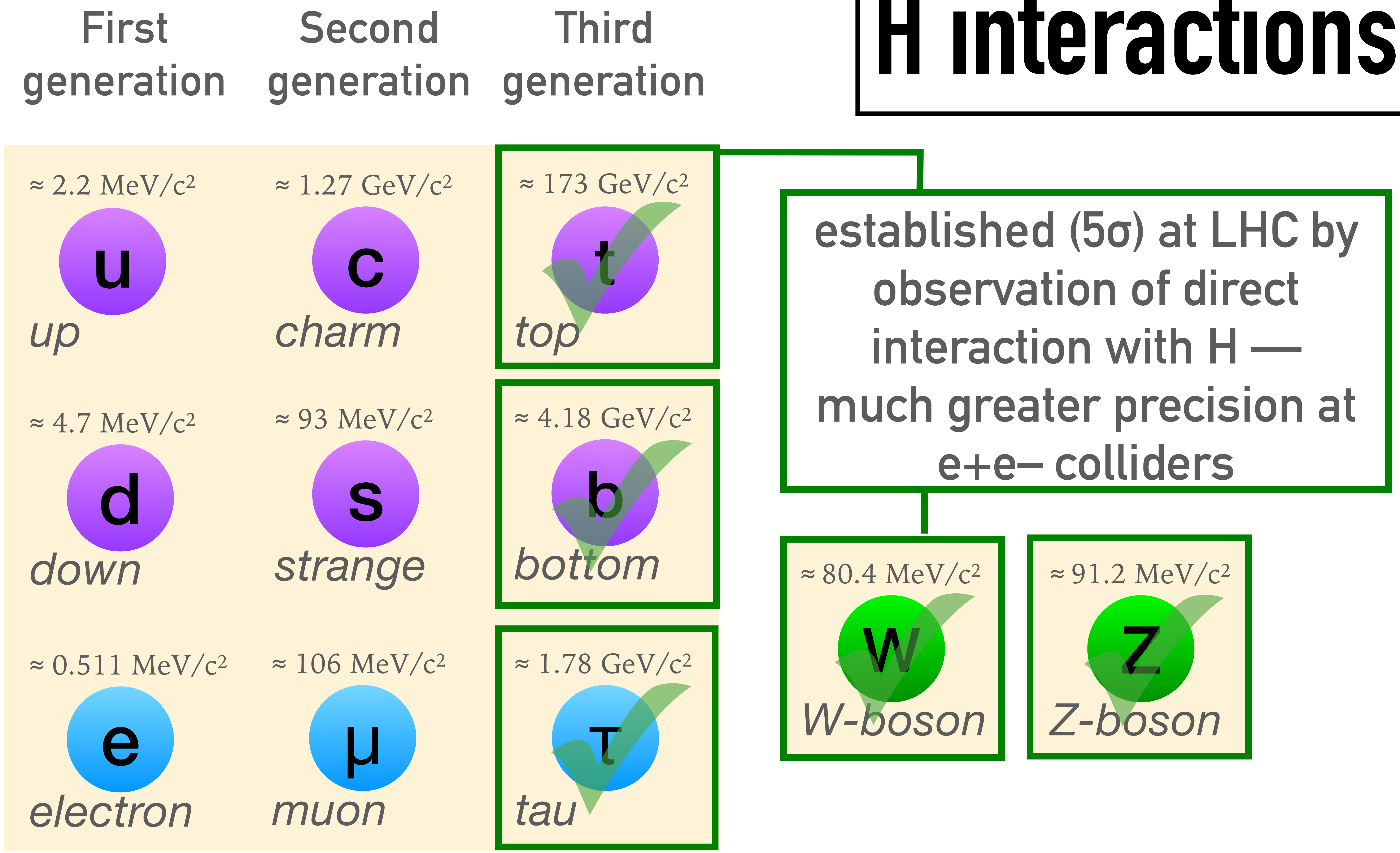
$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e c\alpha} \propto \frac{1}{y_e}$$

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 electron get their masses from Yukawa interactions

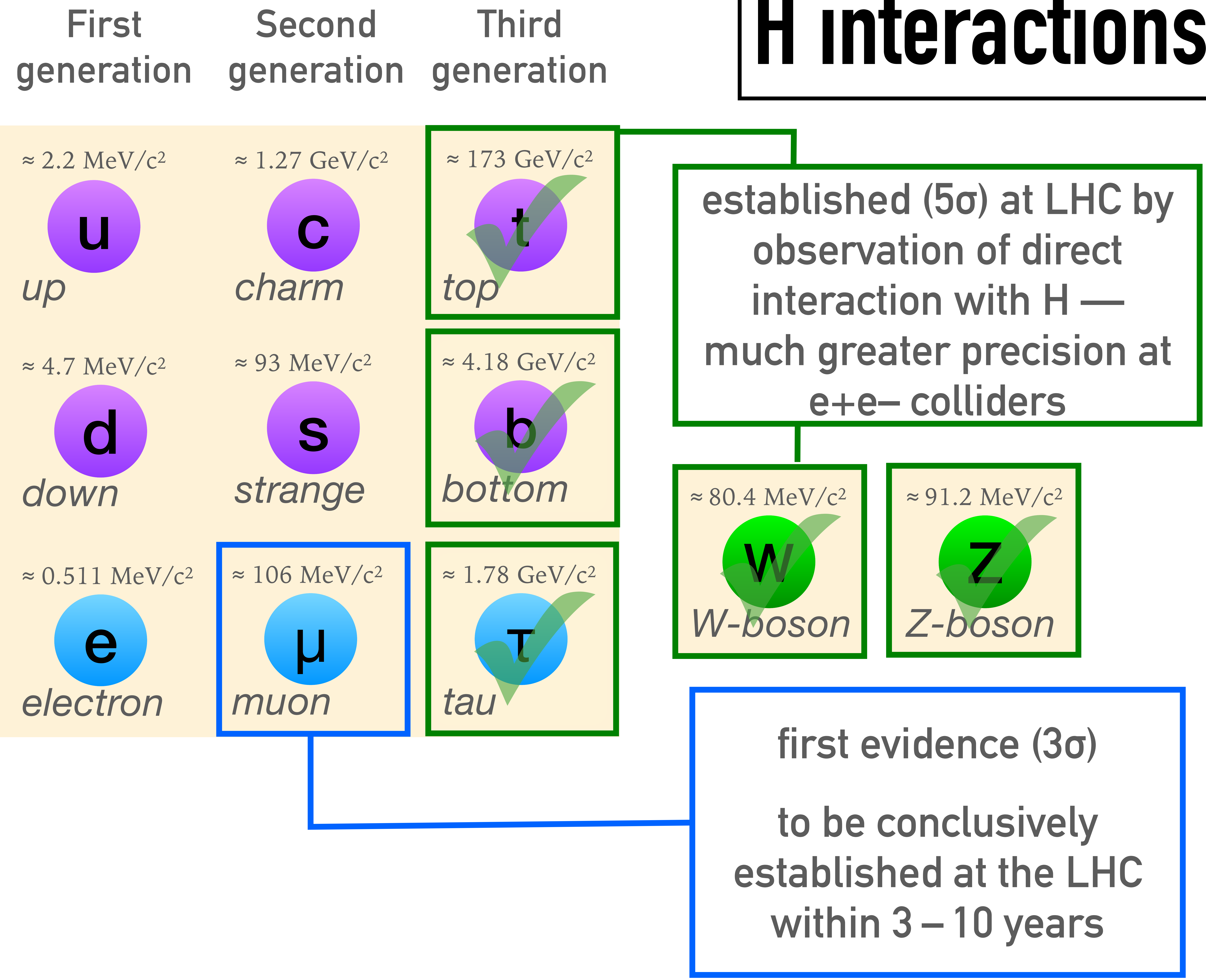
— it's in textbooks, but is it nature?

H interactions



established (5σ) at LHC by observation of direct interaction with H — much greater precision at e+e– colliders

H interactions

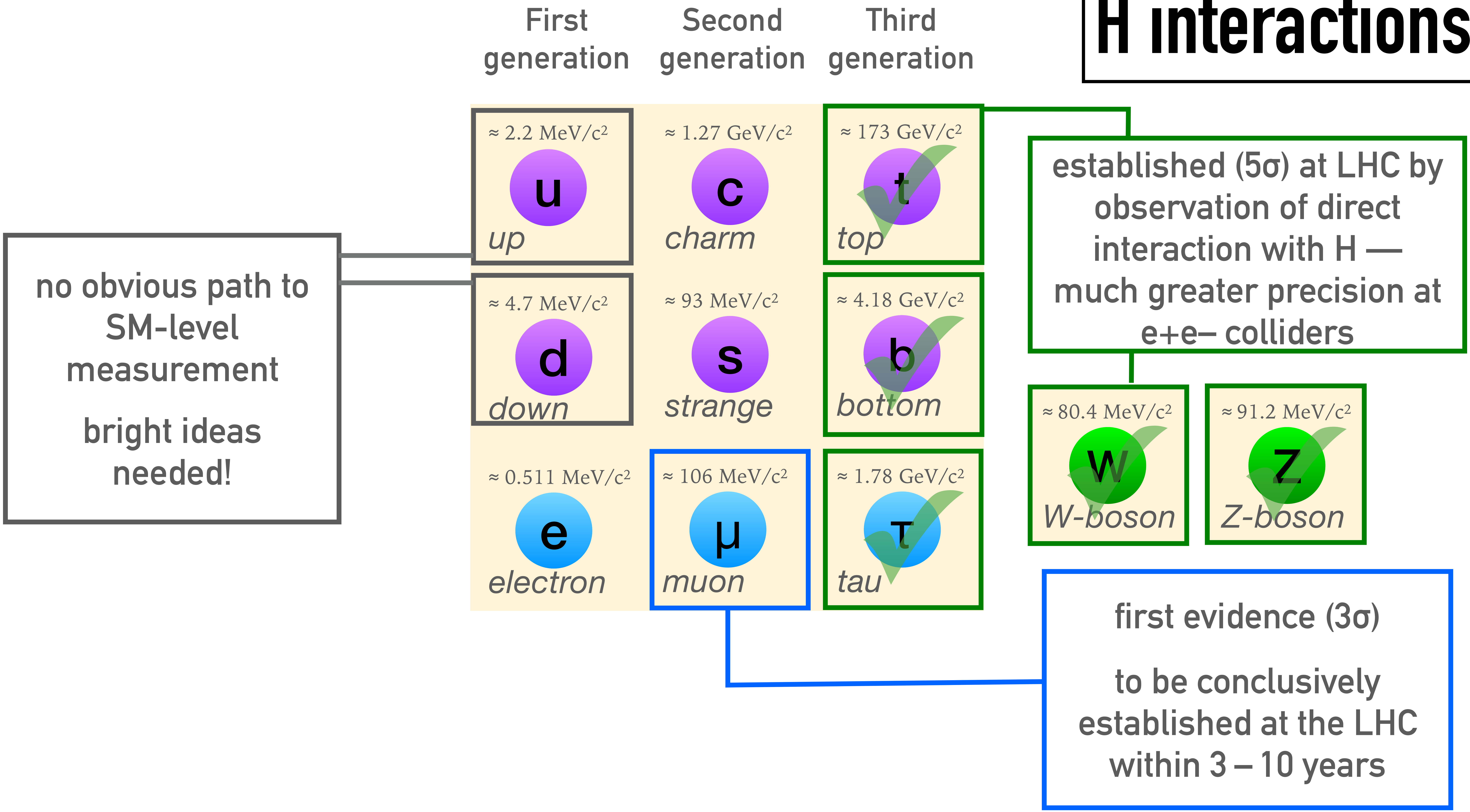


established (5σ) at LHC by observation of direct interaction with H — much greater precision at e+e– colliders

first evidence (3σ)

to be conclusively established at the LHC within 3 – 10 years

H interactions



no obvious path to SM-level measurement

bright ideas needed!

established (5σ) at LHC by observation of direct interaction with H — much greater precision at e+e– colliders

first evidence (3σ)

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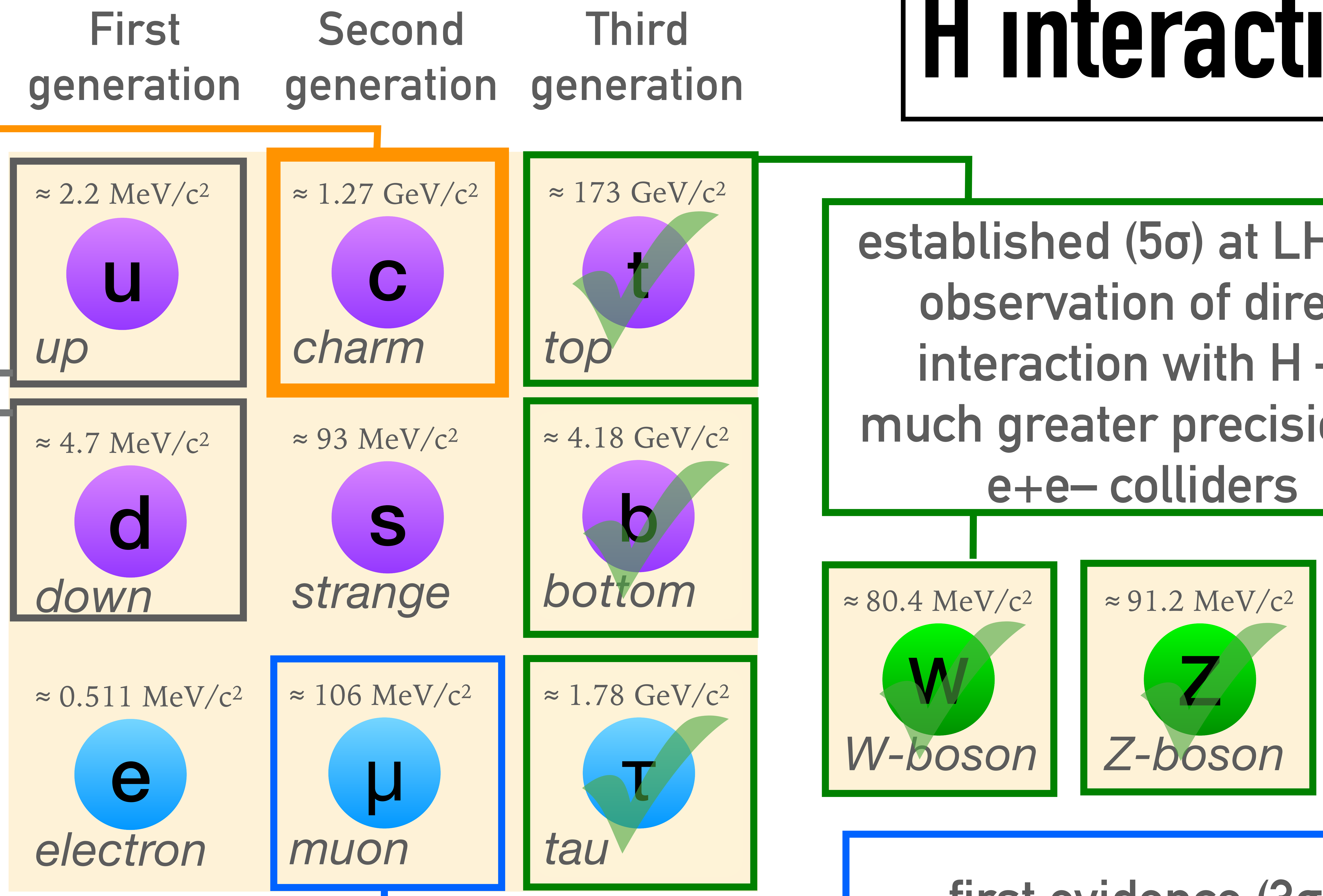
H interactions

no evidence yet

guaranteed at future e^+e^- colliders

no obvious path to SM-level measurement

bright ideas needed!



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H interactions

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?

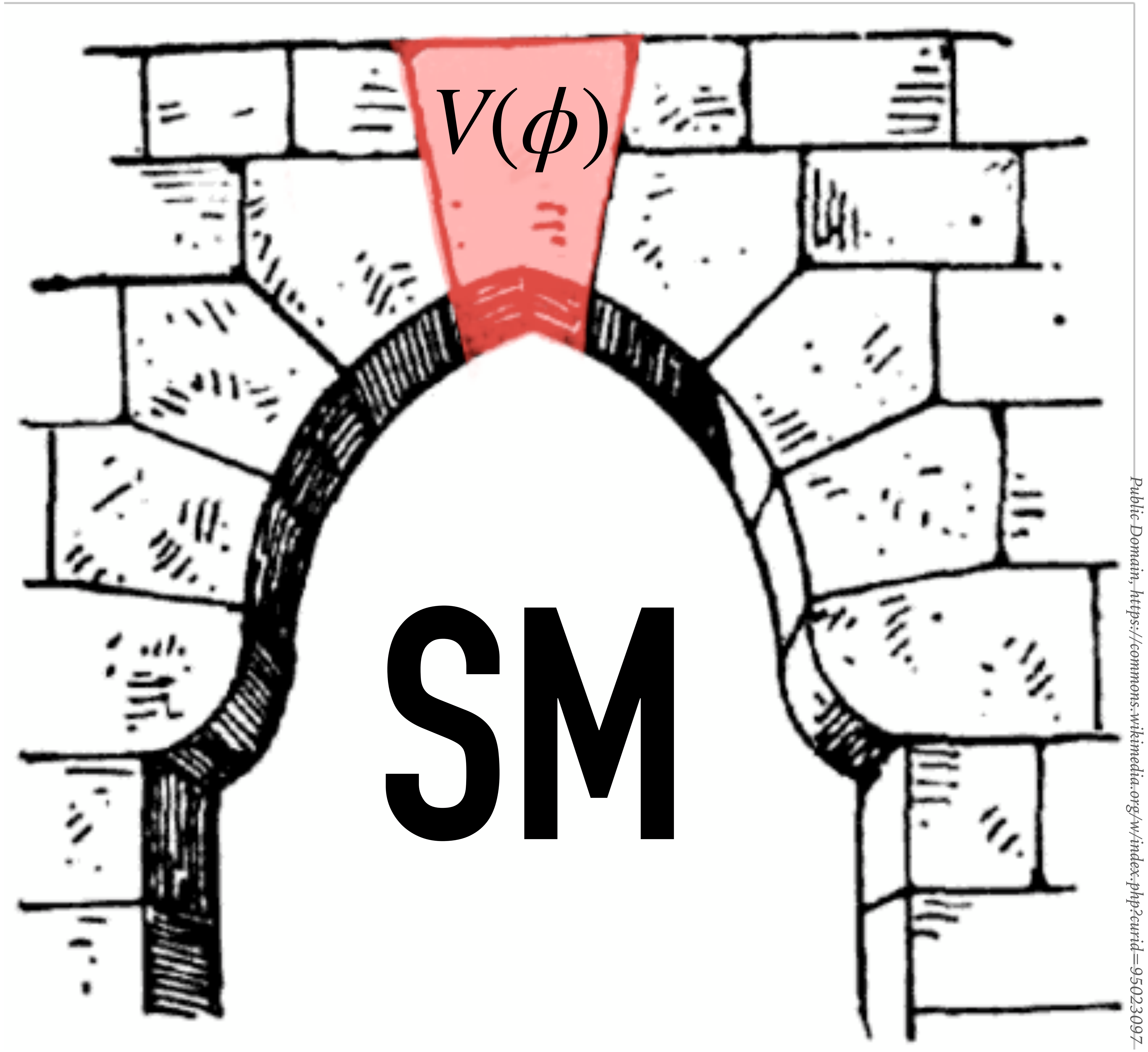
established (5σ) at LHC by observation of direct interaction with H — much greater precision at e+e– colliders

first evidence (3σ)

to be conclusively established at the LHC within 3 – 10 years

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**



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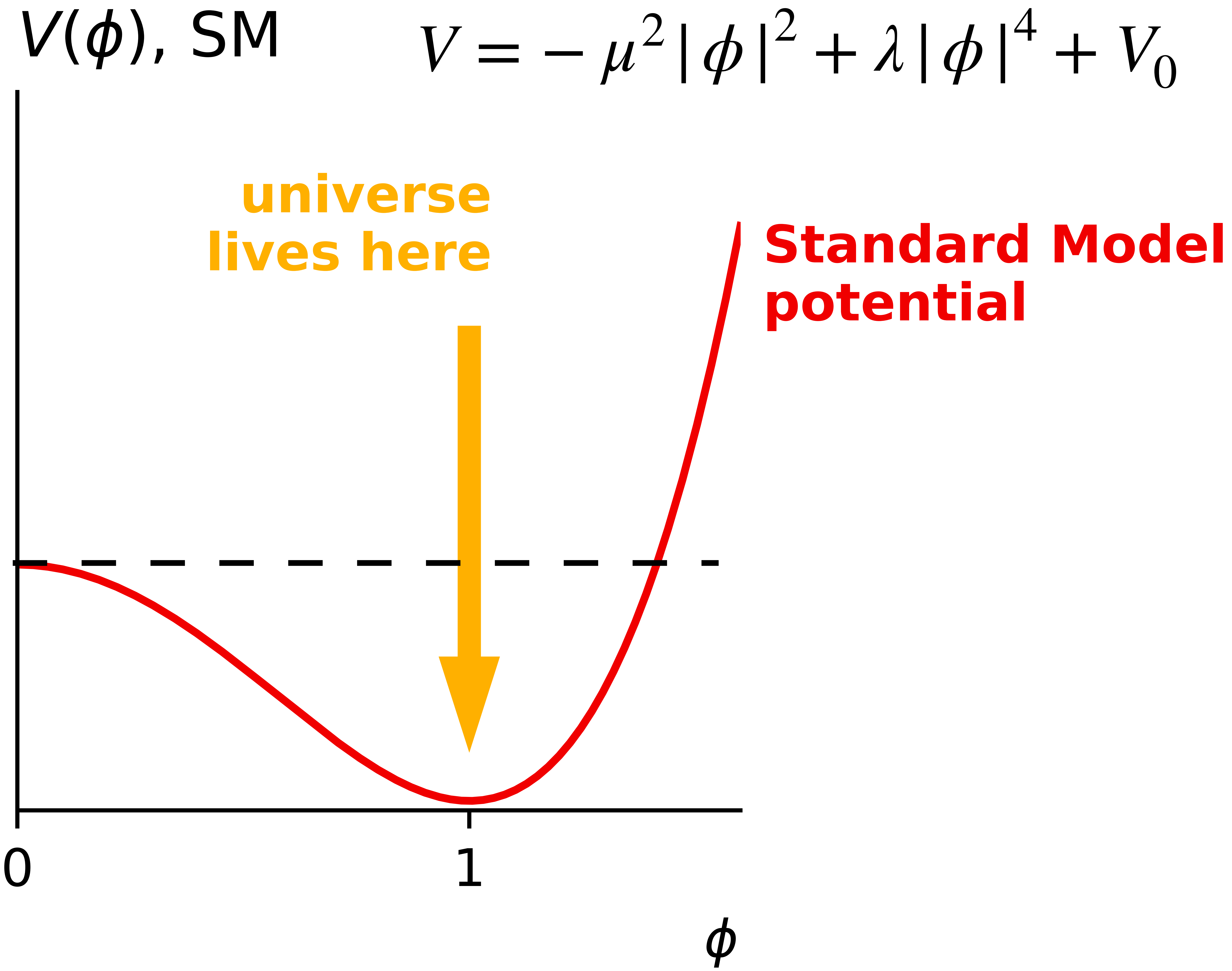
the Higgs potential

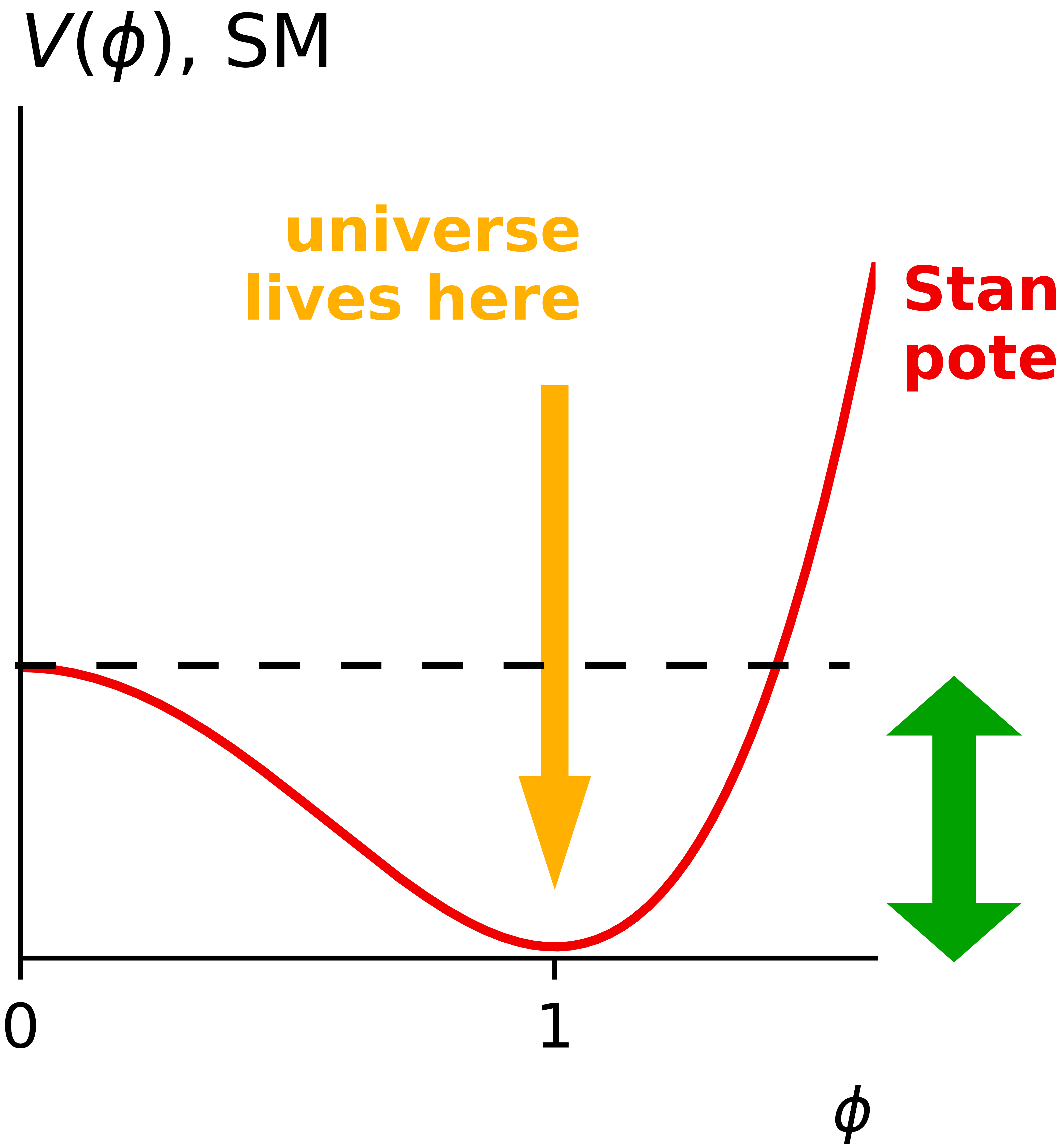
Higgs potential



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

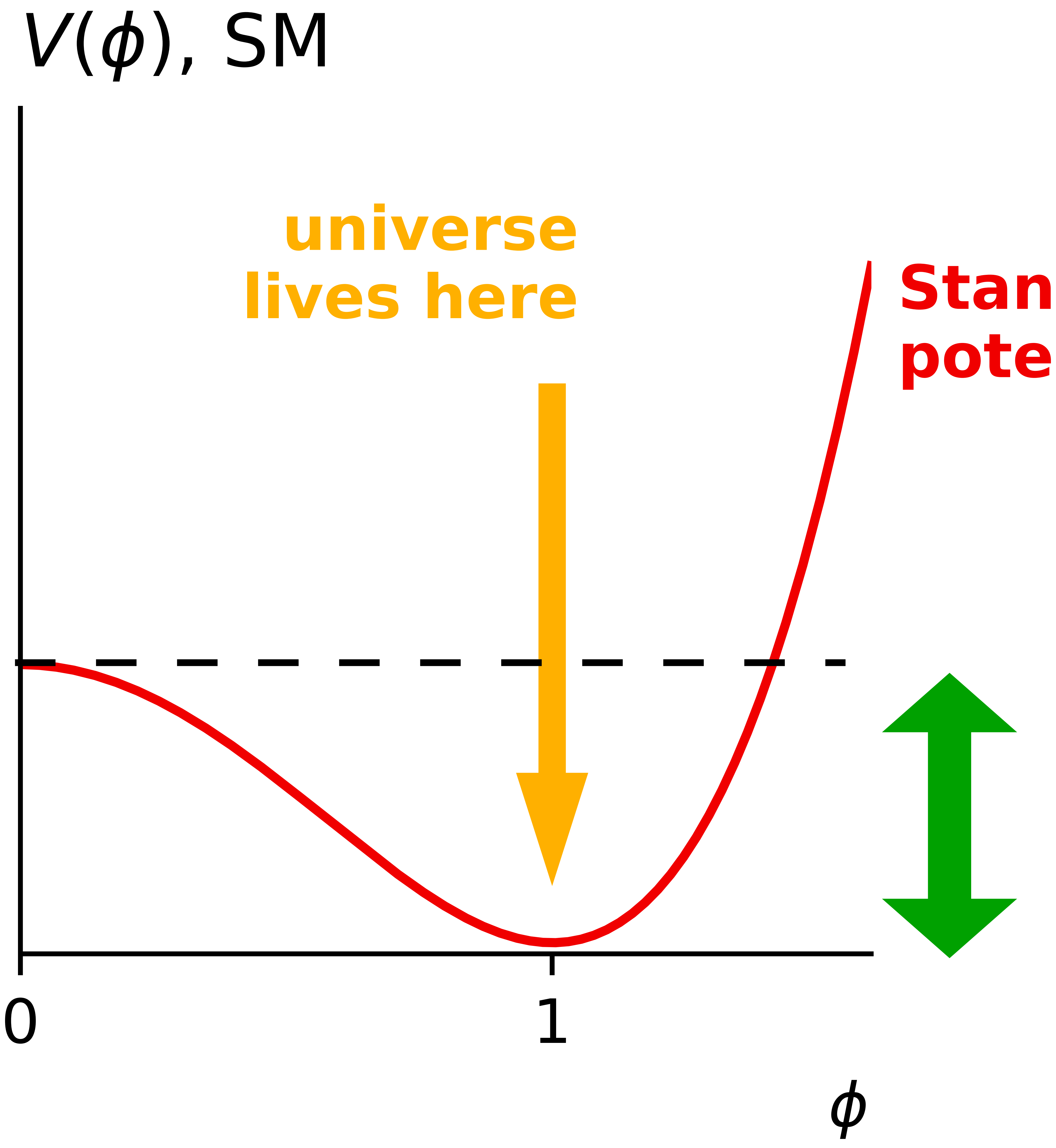
Higgs potential



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 $1.5 \times 10^{10}\,\mathrm{GeV/fm^3}$
i.e. >**10 billion times nuclear density**

Mass density of $2.6 \times 10^{28}\,\mathrm{kg/m^3}$

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
https://de.wikipedia.org/wiki/Volksparkstadion#/media/Datei:RK_1009_9831_Volksparkstadion.jpg

Earth at neutron star density

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
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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

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

- 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

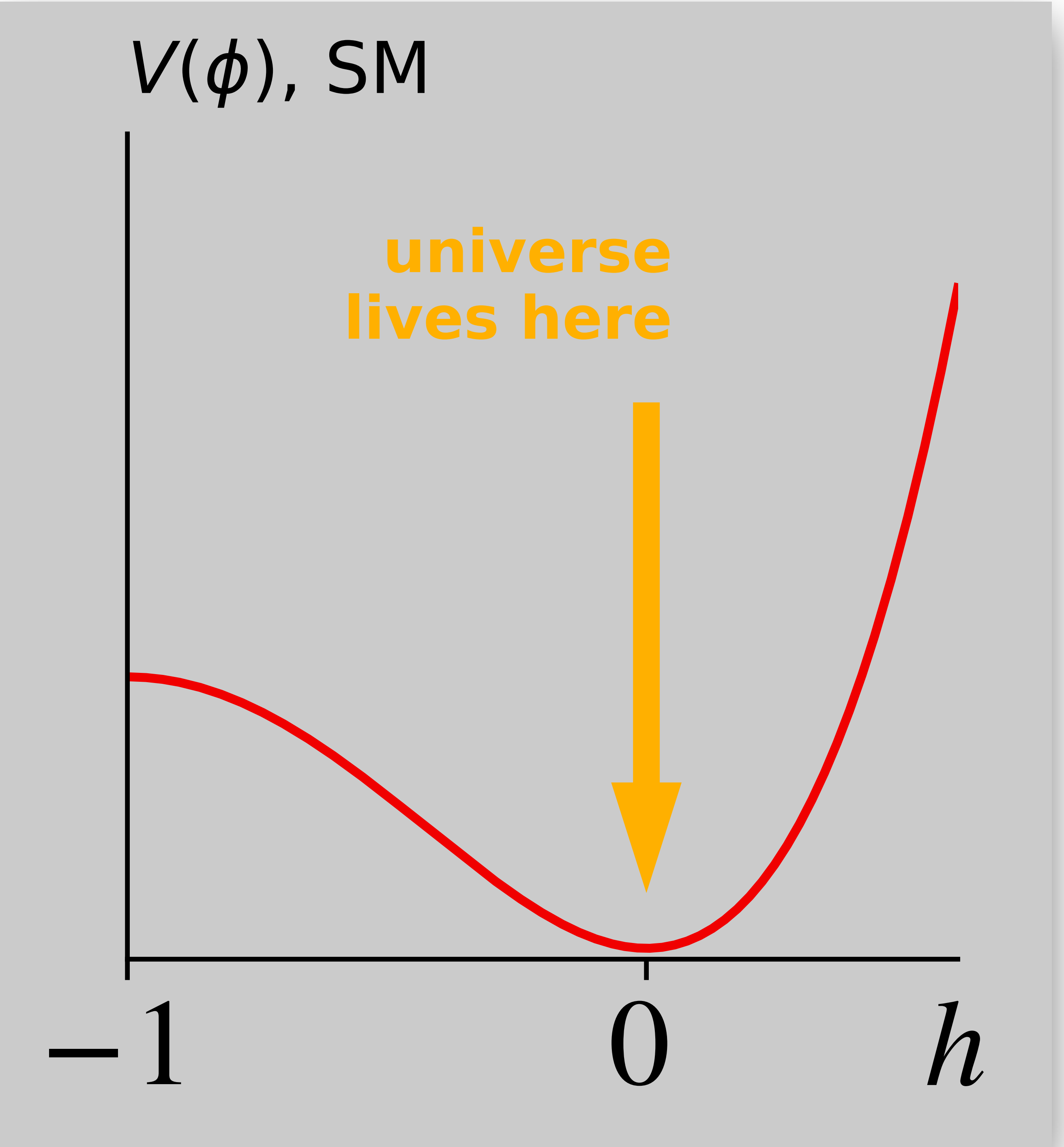
The potential expanded around the minimum

- 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]



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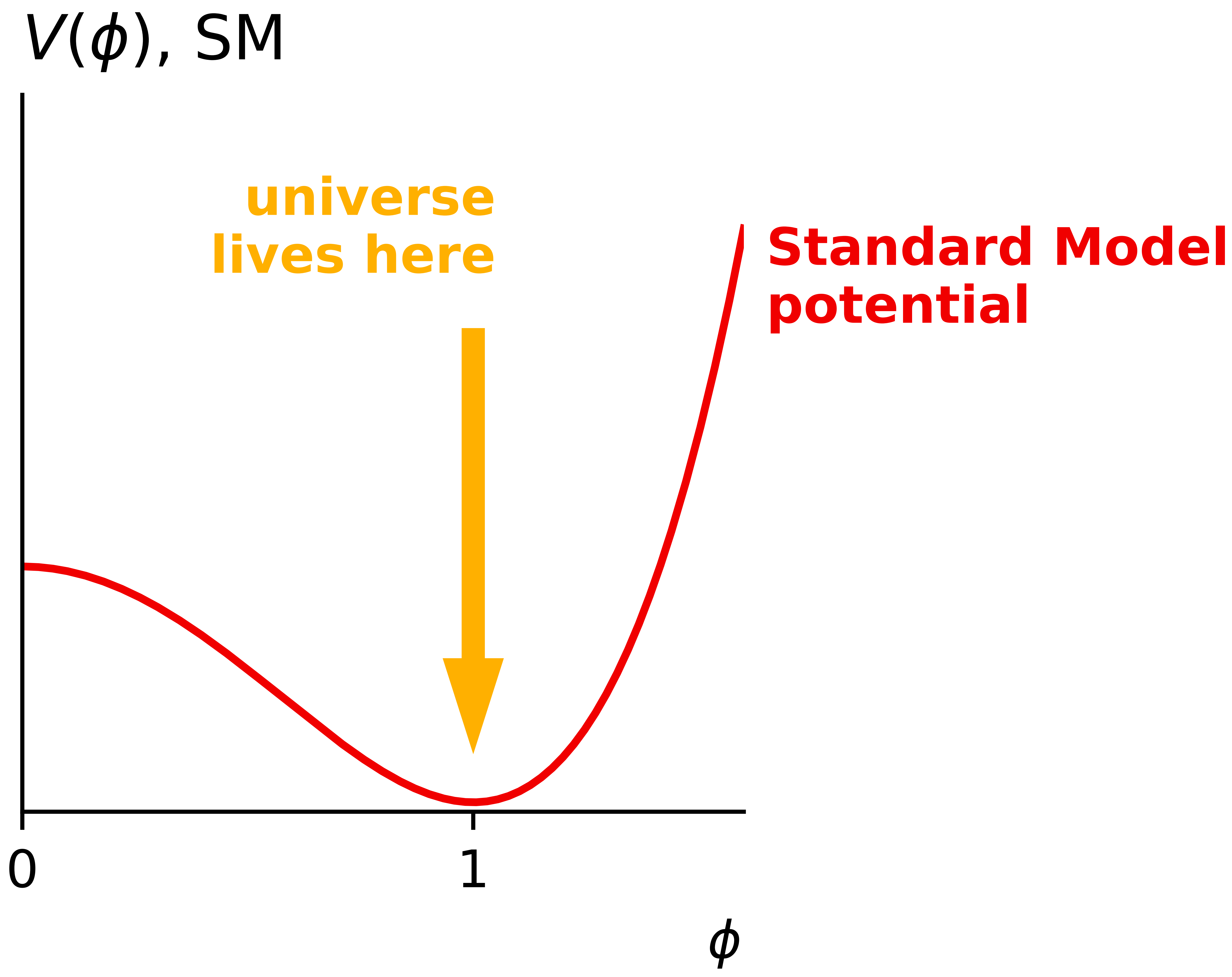
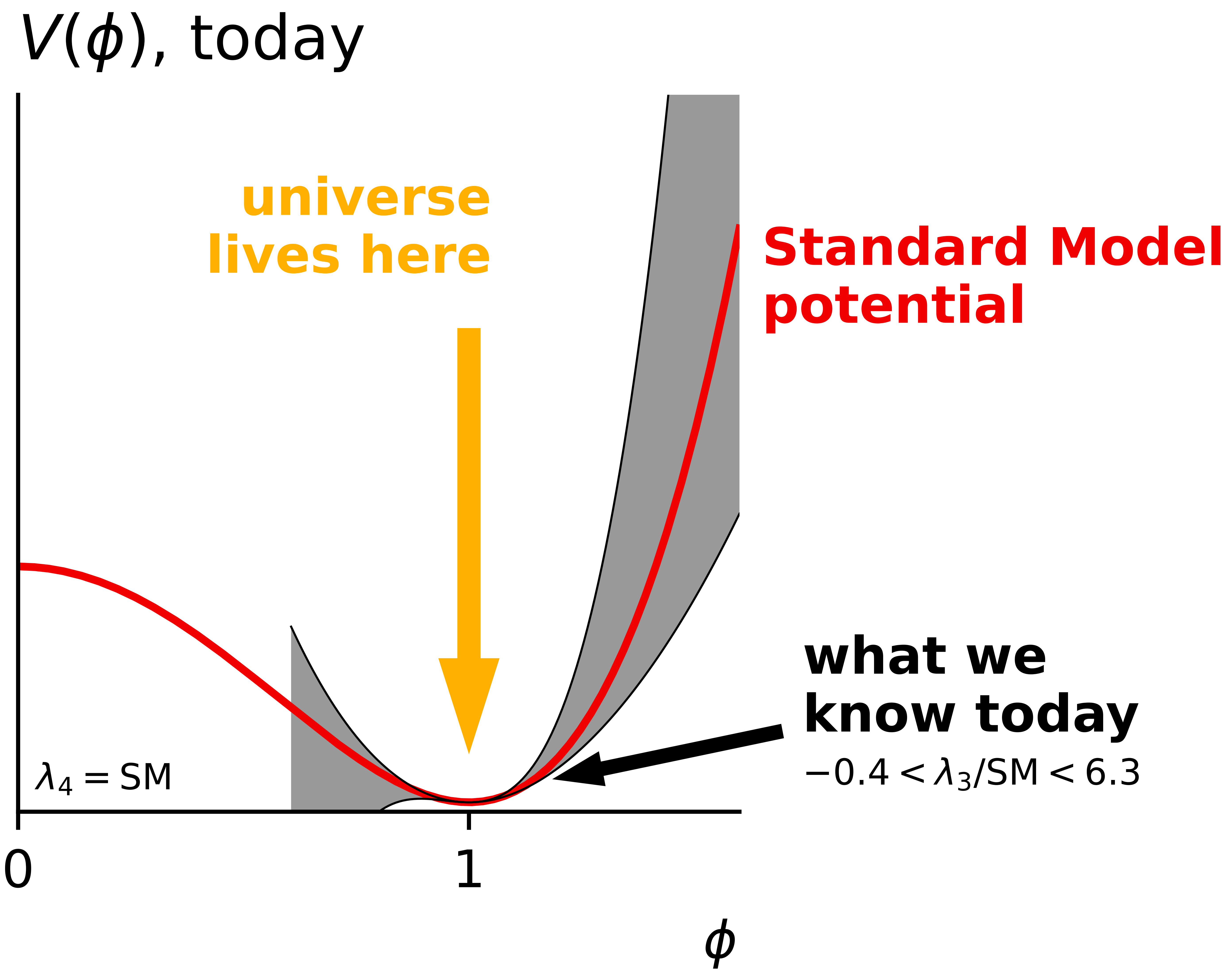
observation of HHH interaction is a “guaranteed discovery” that HEP should be aiming for

Higgs potential



- this is a cartoon
- caution needed: e.g. realistic BSM models do not just modify the potential, but may bring extra scalars
  (often modify other couplings, but not always, e.g. 2209.00666)
- even if we take the picture seriously we may want to consider impact of limited constraints on λ_4
  (figures show either SM or FCC-hh constraint; how many coincidences are needed for a BSM model to leave λ_3 untouched while modifying λ_4?)

Higgs potential



universe lives here

Standard Model potential

what we know today

$-0.4 < \lambda_3/\text{SM} < 6.3$

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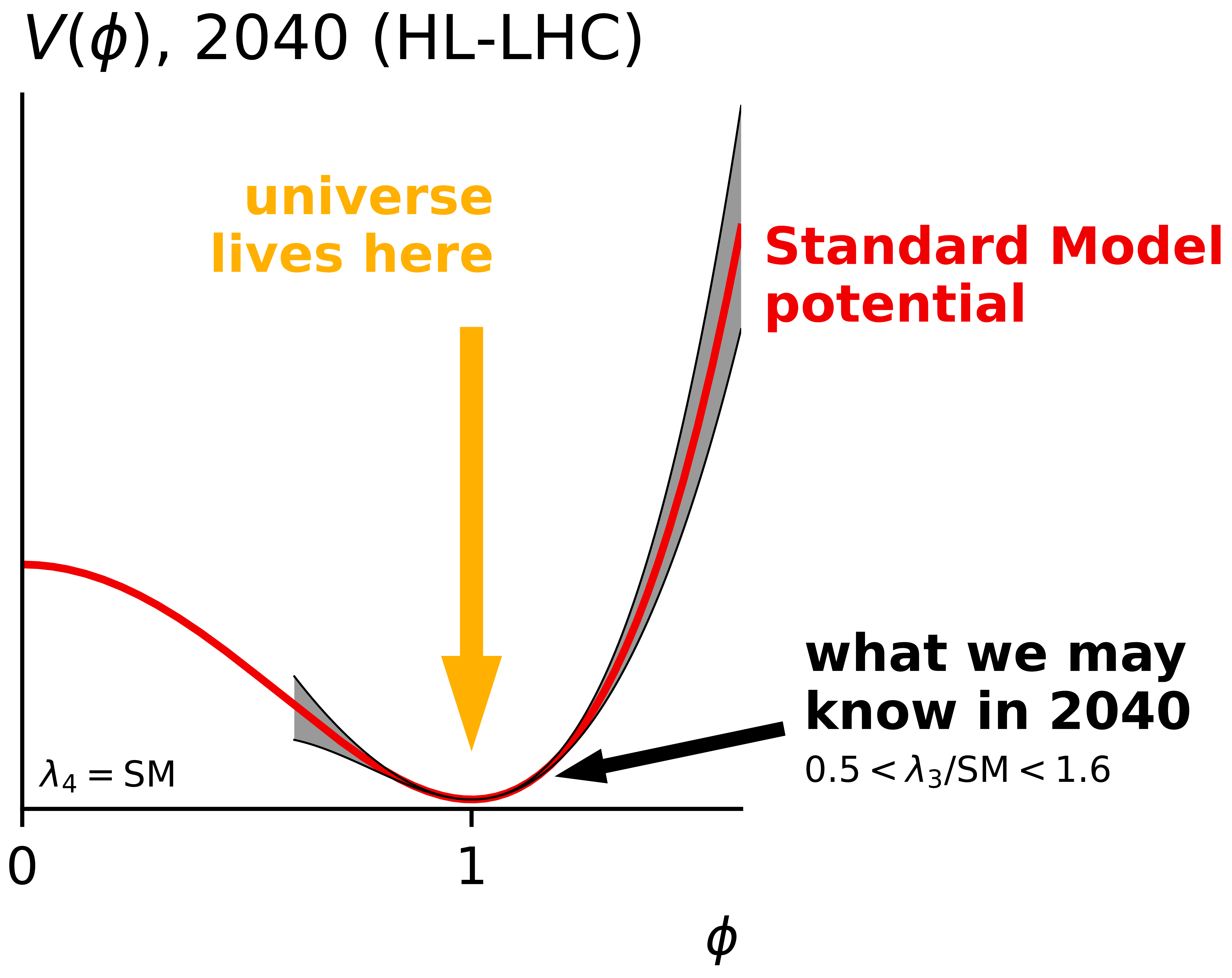

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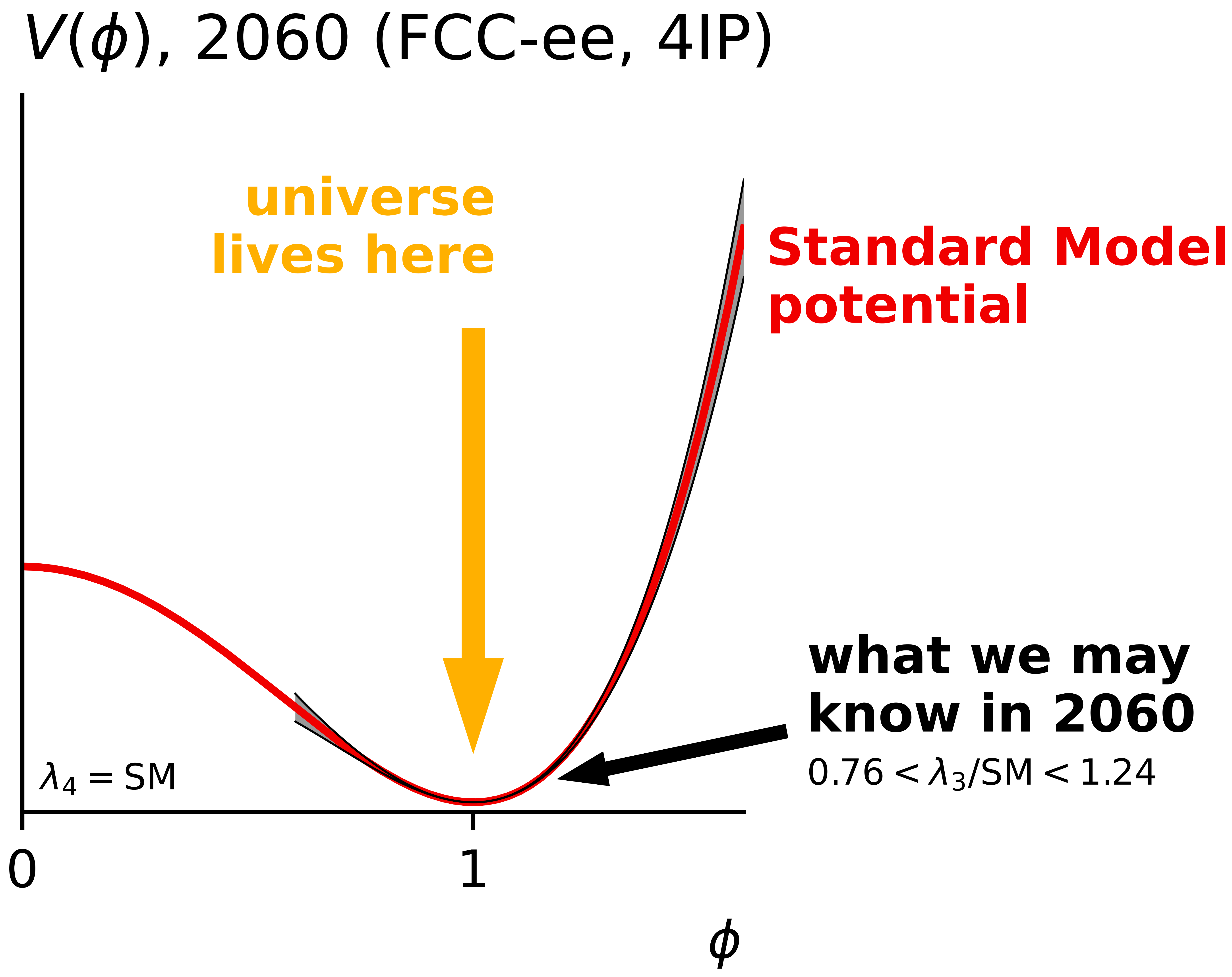

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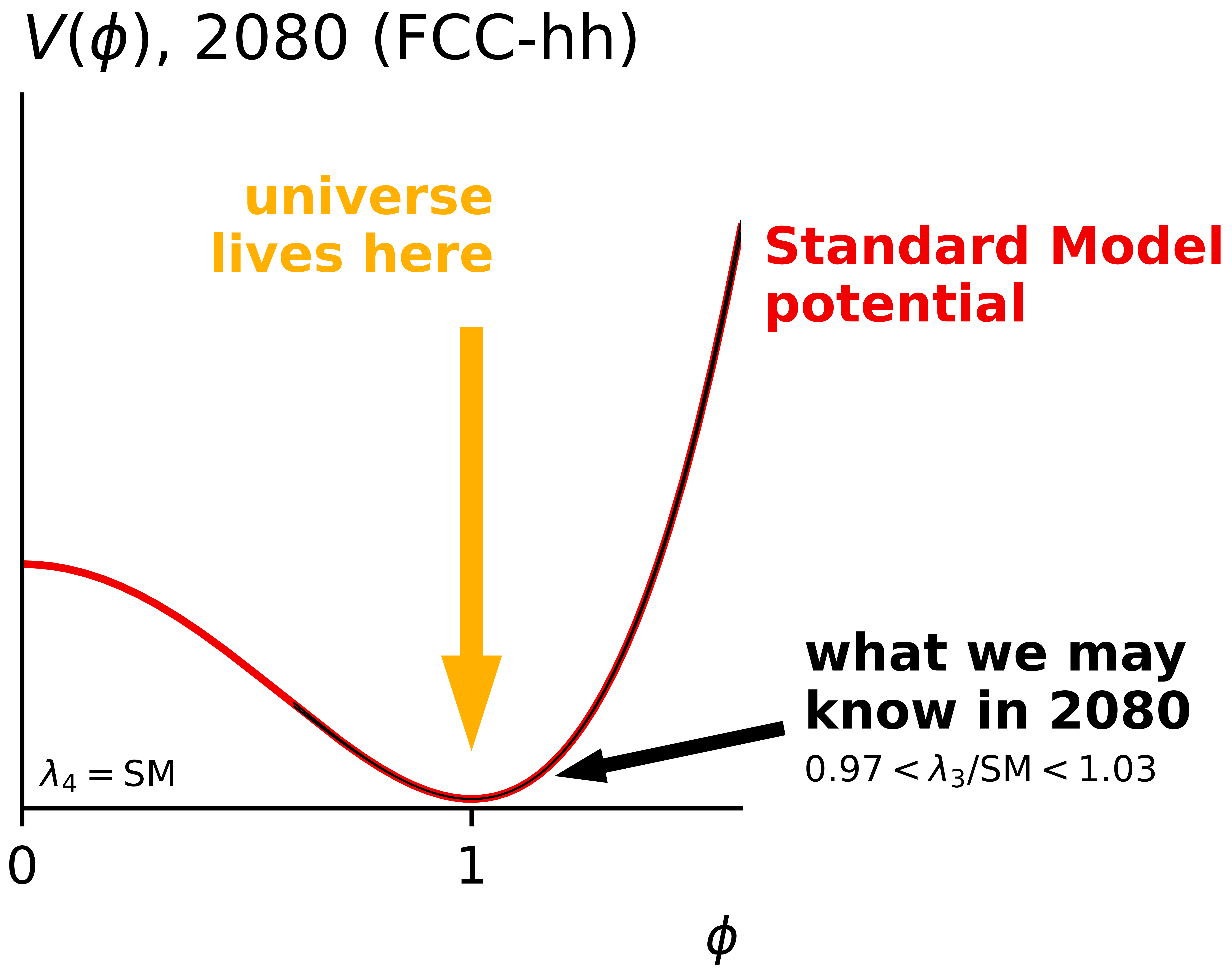

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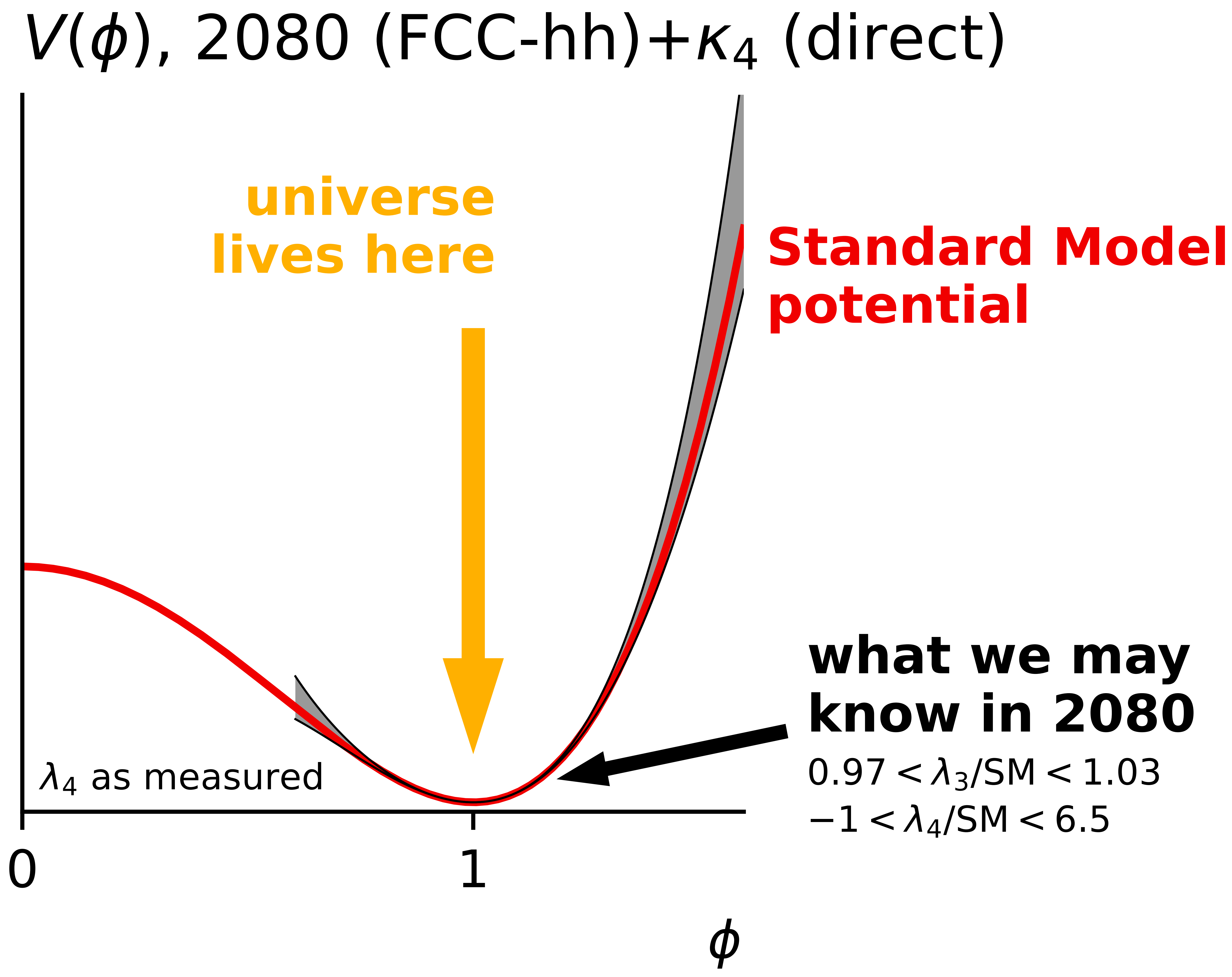

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desirable features of the next major HEP project(s)?

an important target to be reached ~ guaranteed discovery

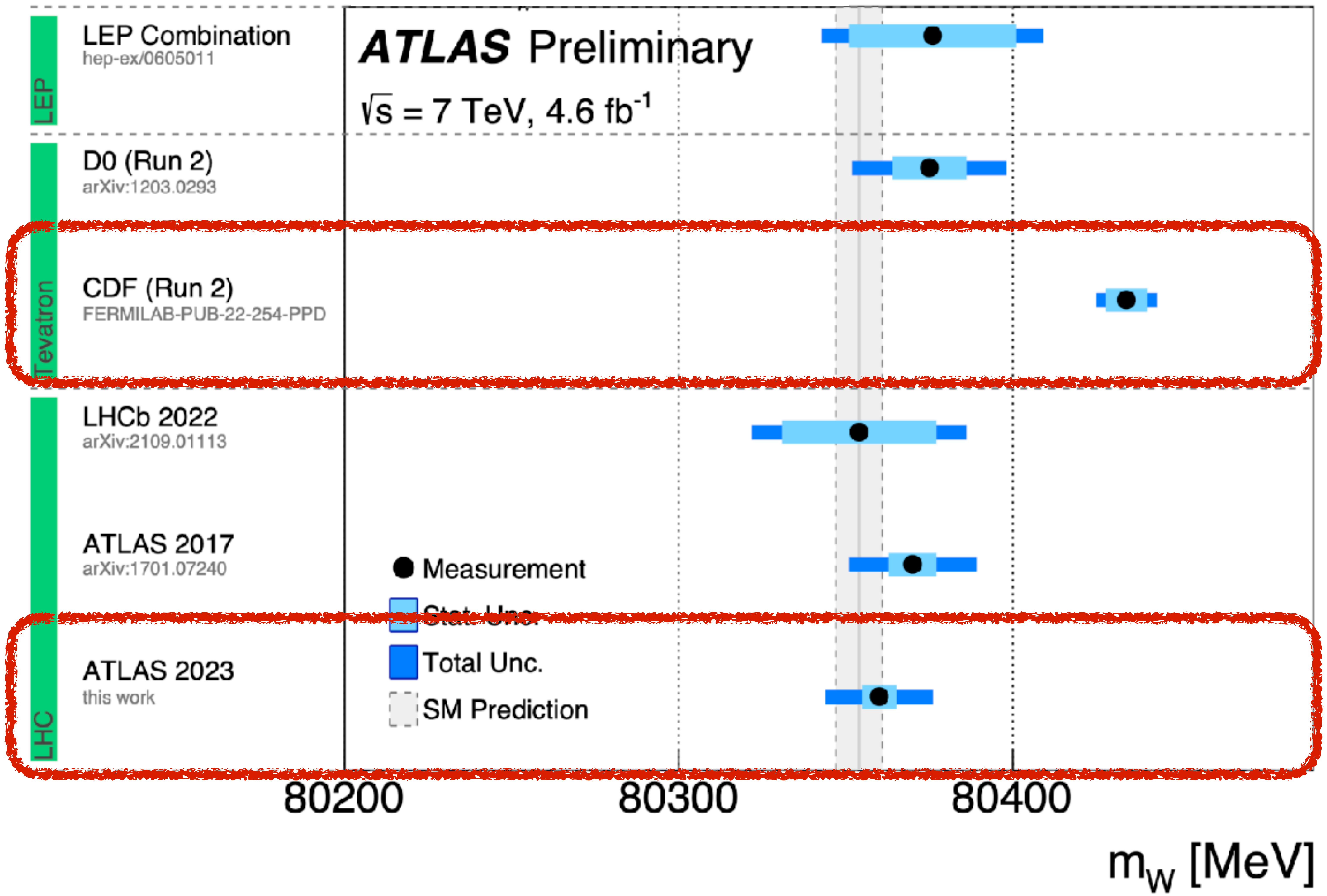
exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

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

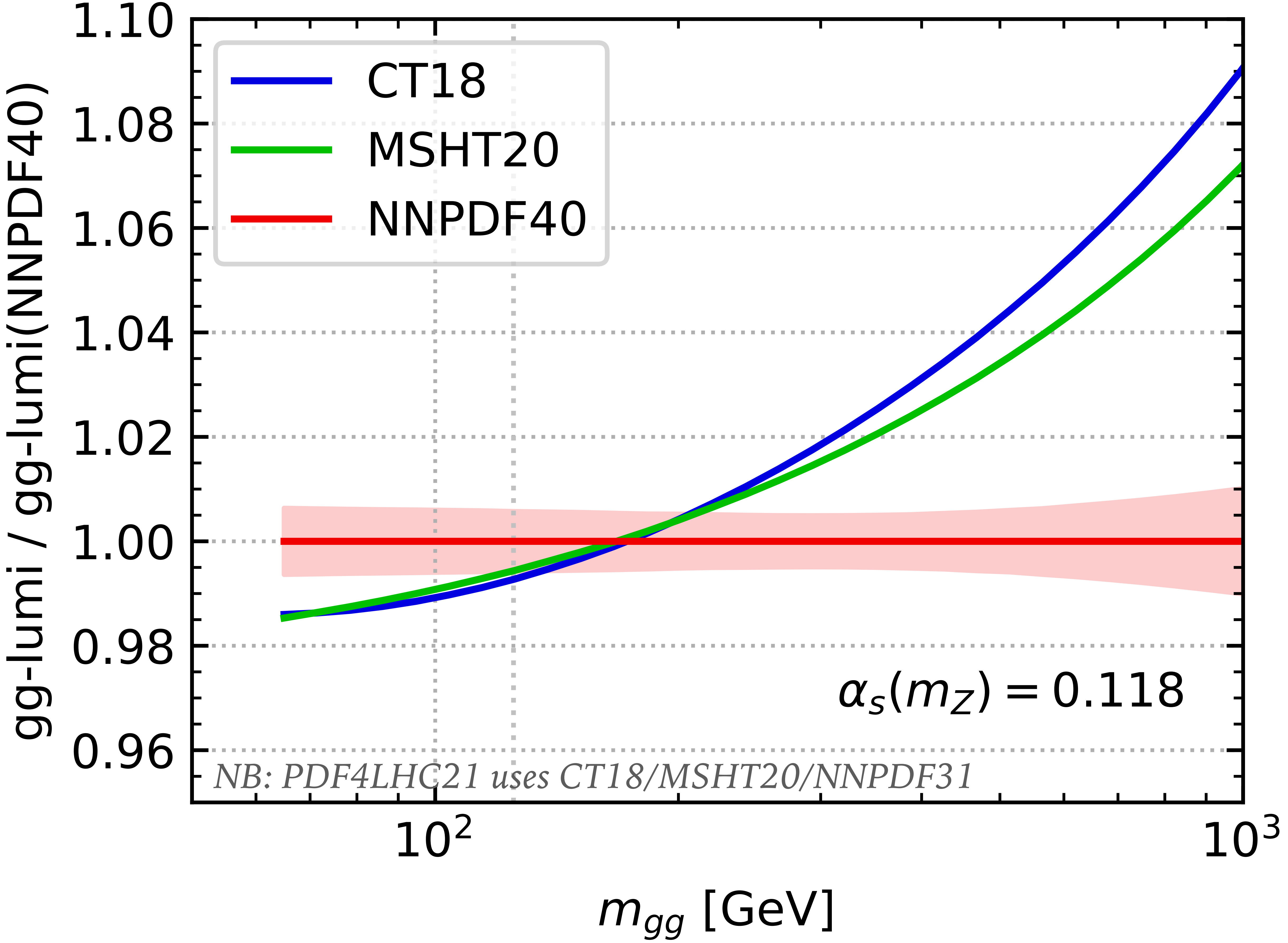
cost-effective construction & operation,
low carbon footprint, novel technologies

m_W measurements



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 partonic luminosity ($\sqrt{s} = 13$TeV)

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

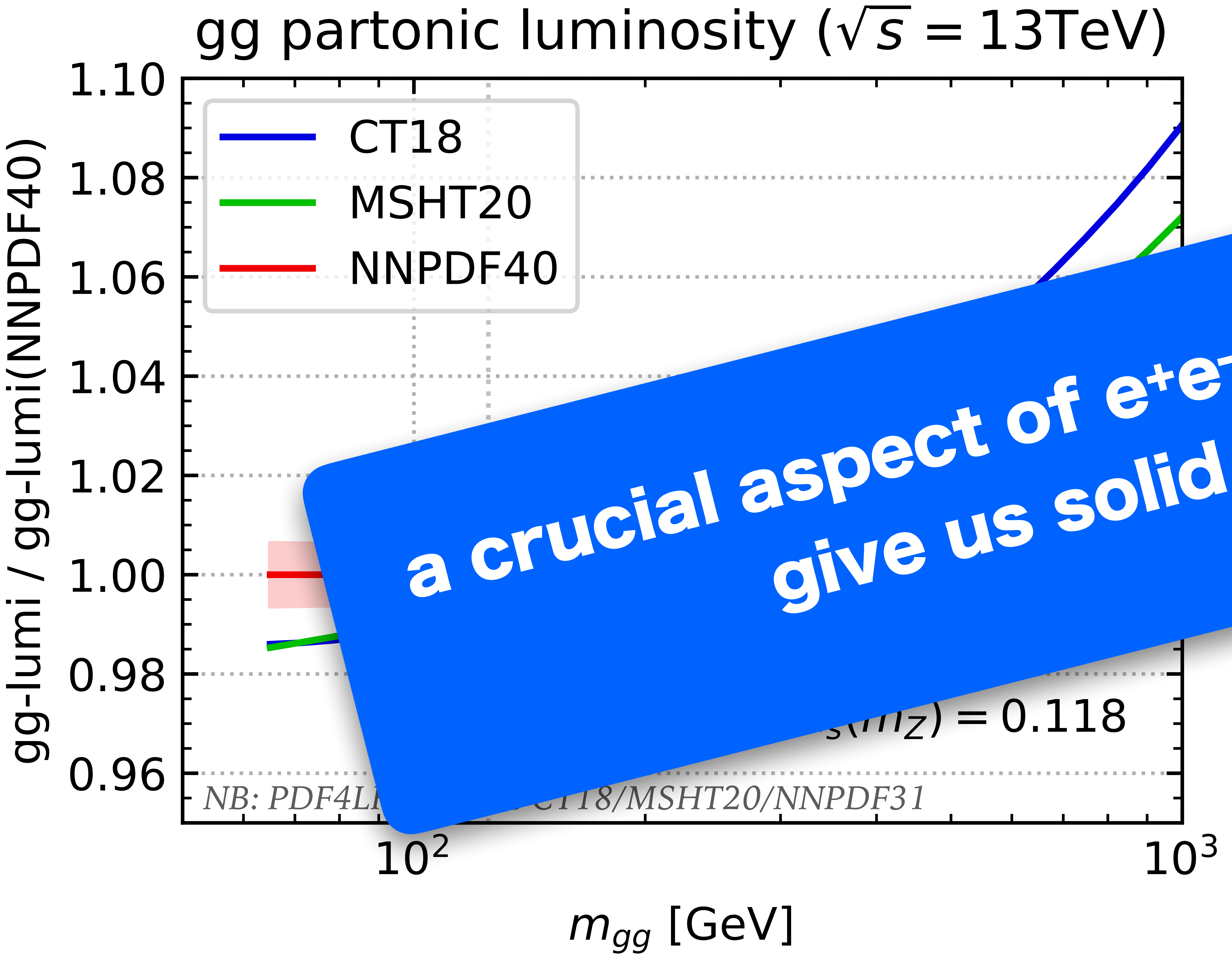
× 3

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

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'_{SSM} as a simple measure of progress
(perhaps not very "exciting", but 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)

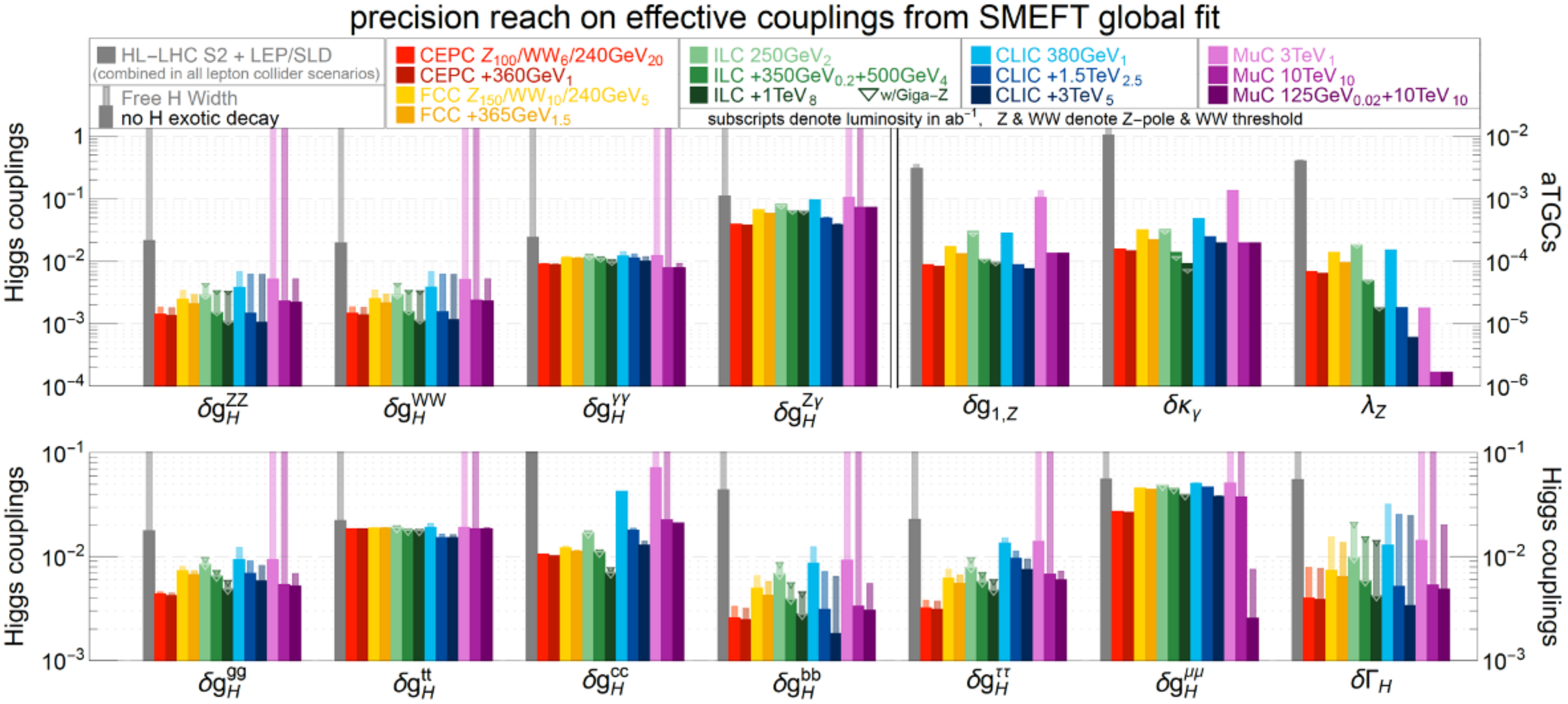
× 5.6 →

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

Exclusion limit ~ 6.7 TeV

(electron and muon channels, single experiment)

increase in precision



https://arxiv.org/abs/2206.08326

increase in precision is like × 4 – 5 increase in energy reach

https://arxiv.org/abs/2206.08326

step up in energy for direct searches?

I like the Z'_{SSM} as a simple measure of progress
(perhaps not very "exciting", but 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
(perhaps not very "exciting", but 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

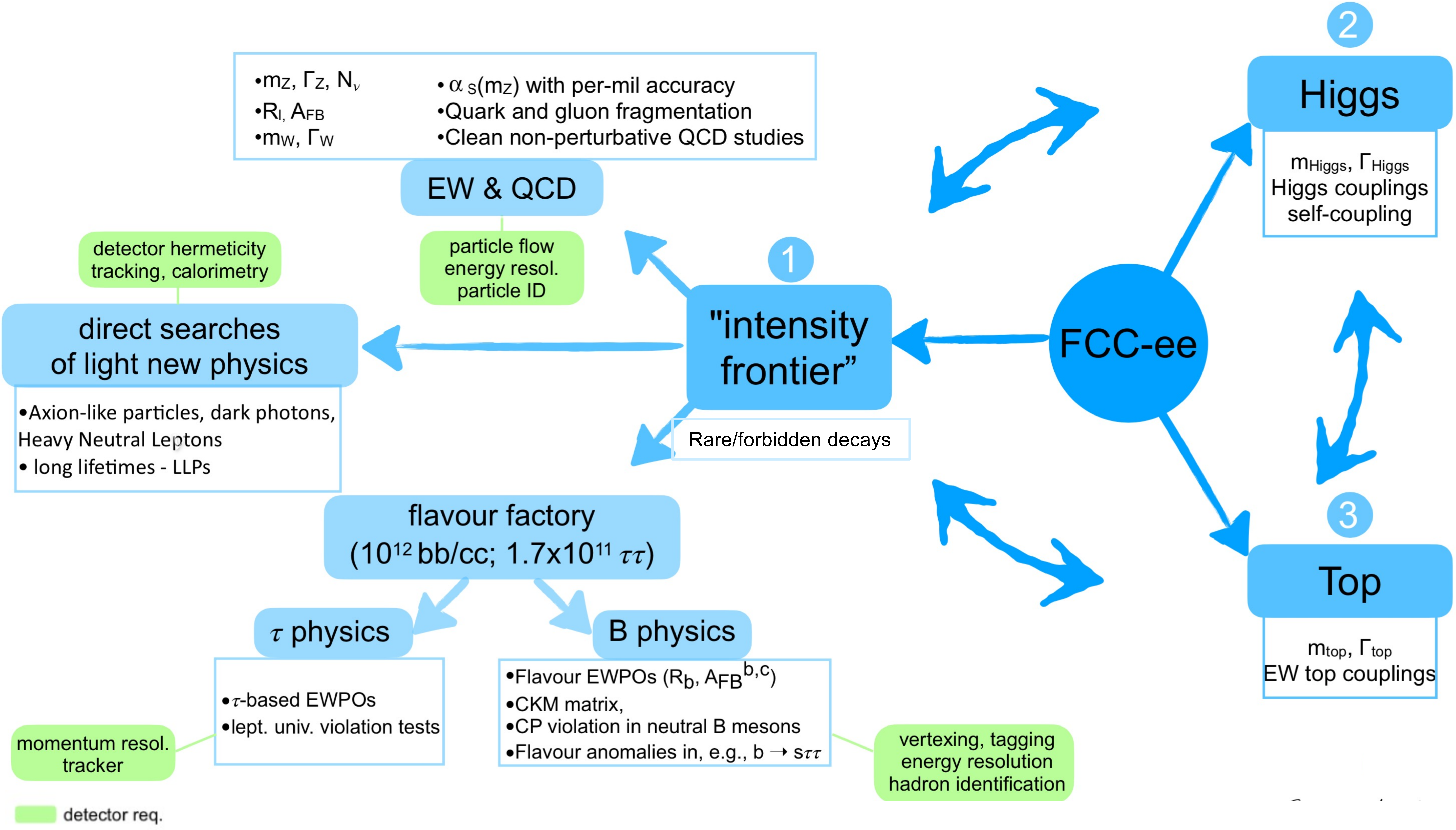
exploration into the unknown by a significant factor in energy

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

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



- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W
- $\alpha_S(m_Z)$ with per-mil accuracy
- Quark and gluon fragmentation
- Clean non-perturbative QCD studies

EW & QCD

particle flow
energy resol.
particle ID

detector hermeticity
tracking, calorimetry

direct searches of light new physics

- Axion-like particles, dark photons, Heavy Neutral Leptons
- long lifetimes - LLPs

① **"intensity frontier"**

Rare/forbidden decays

FCC-ee

② **Higgs**

m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

③ **Top**

m_{top}, Γ_{top}
EW top couplings

flavour factory
(10^{12} bb/cc; 1.7x10^{11} $\tau\tau$)

τ physics

- τ-based EWPOs
- lept. univ. violation tests

momentum resol.
tracker

B physics

- Flavour EWPOs (R_b, $A_{FB}^{b,c}$)
- CKM matrix,
- CP violation in neutral B mesons
- Flavour anomalies in, e.g., $b \to s\tau\tau$

vertexing, tagging
energy resolution
hadron identification

🟩 detector req.

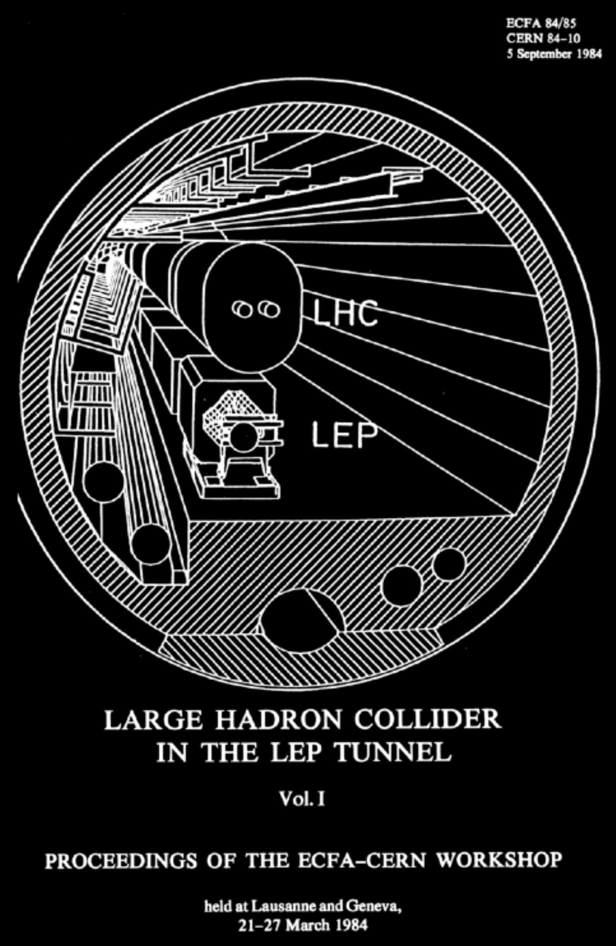
Slide from C. Grojean @ FCC Week'22

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 no-lose theorem in establishing (or disproving) SM origin of electron mass at circular e^+e^- colliders?
- The **step up in energy reach** that we expect is $\sim$ **$\times\ 4 - 5$**
  - 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

via Nathaniel Craig @ CERN-TH naturalness workshop



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

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.

backup

What does $2.6{\times}10^{28}$ kg/m^3 mean?

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

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

What does 2.6×10^{28} kg/m^3 mean?

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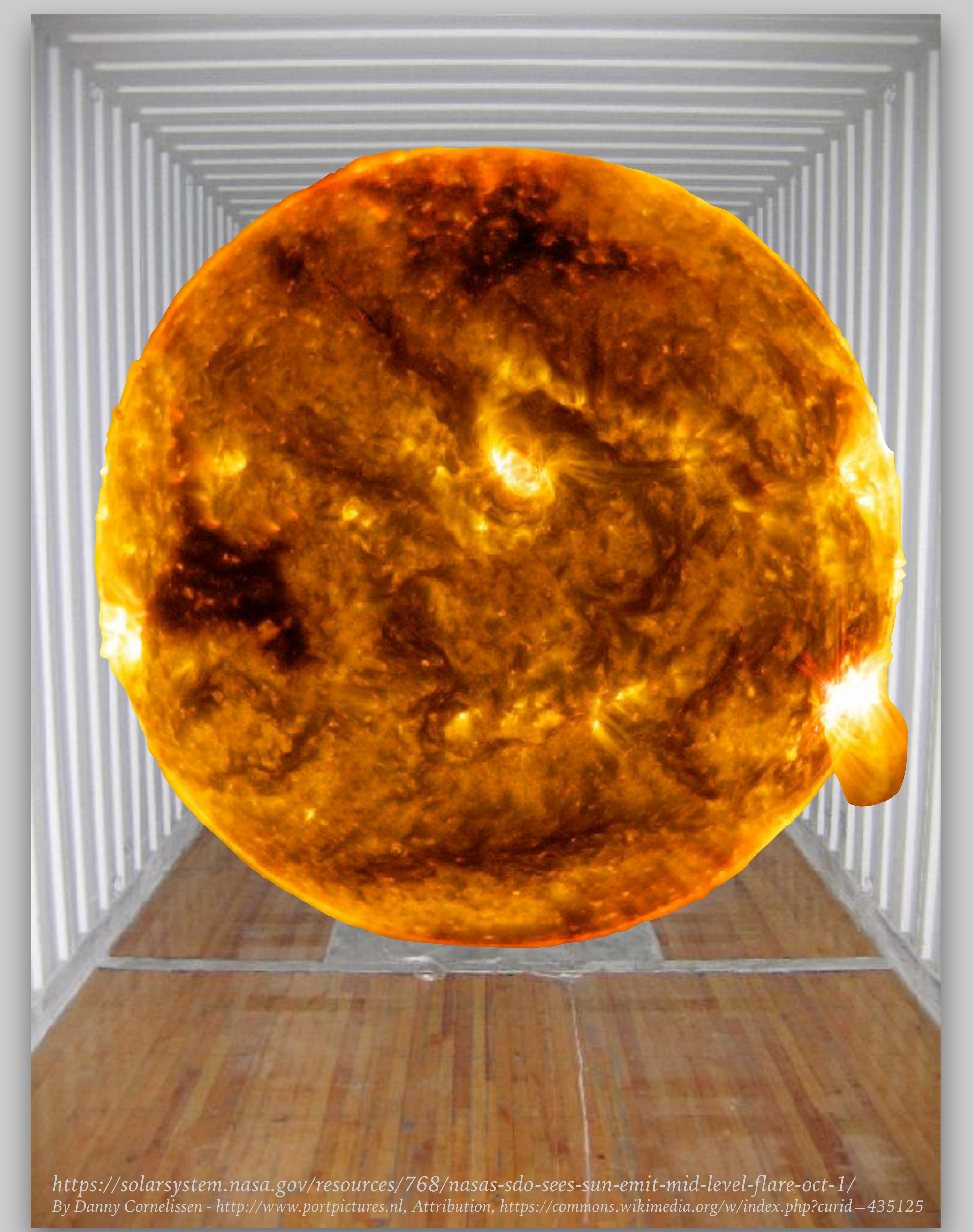


https://solarsystem.nasa.gov/resources/768/nasas-sdo-sees-sun-emit-mid-level-flare-oct-1/

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

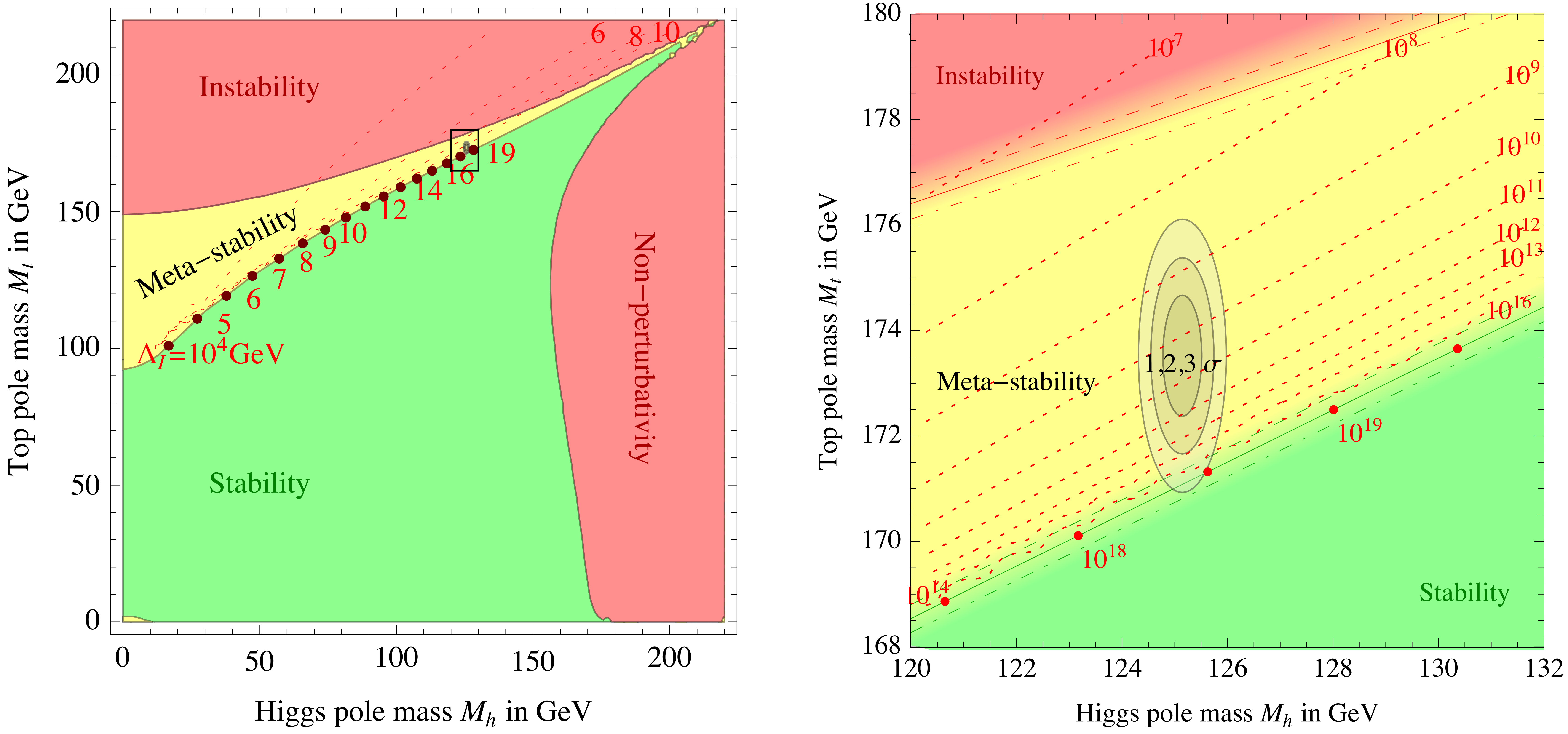
densities in kg/m^3

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

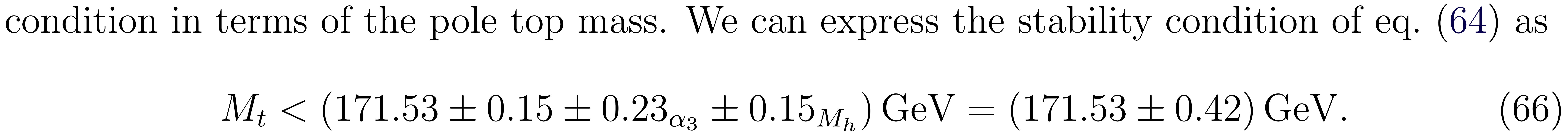
Table 3.3: Values for 1σ sensitivity on the S and T parameters. In all cases the value shown is after combination with HL-LHC. For ILC and CLIC the projections are shown with and without dedicated running at the Z-pole. All other oblique parameters are set to zero. The intrinsic theory uncertainty is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

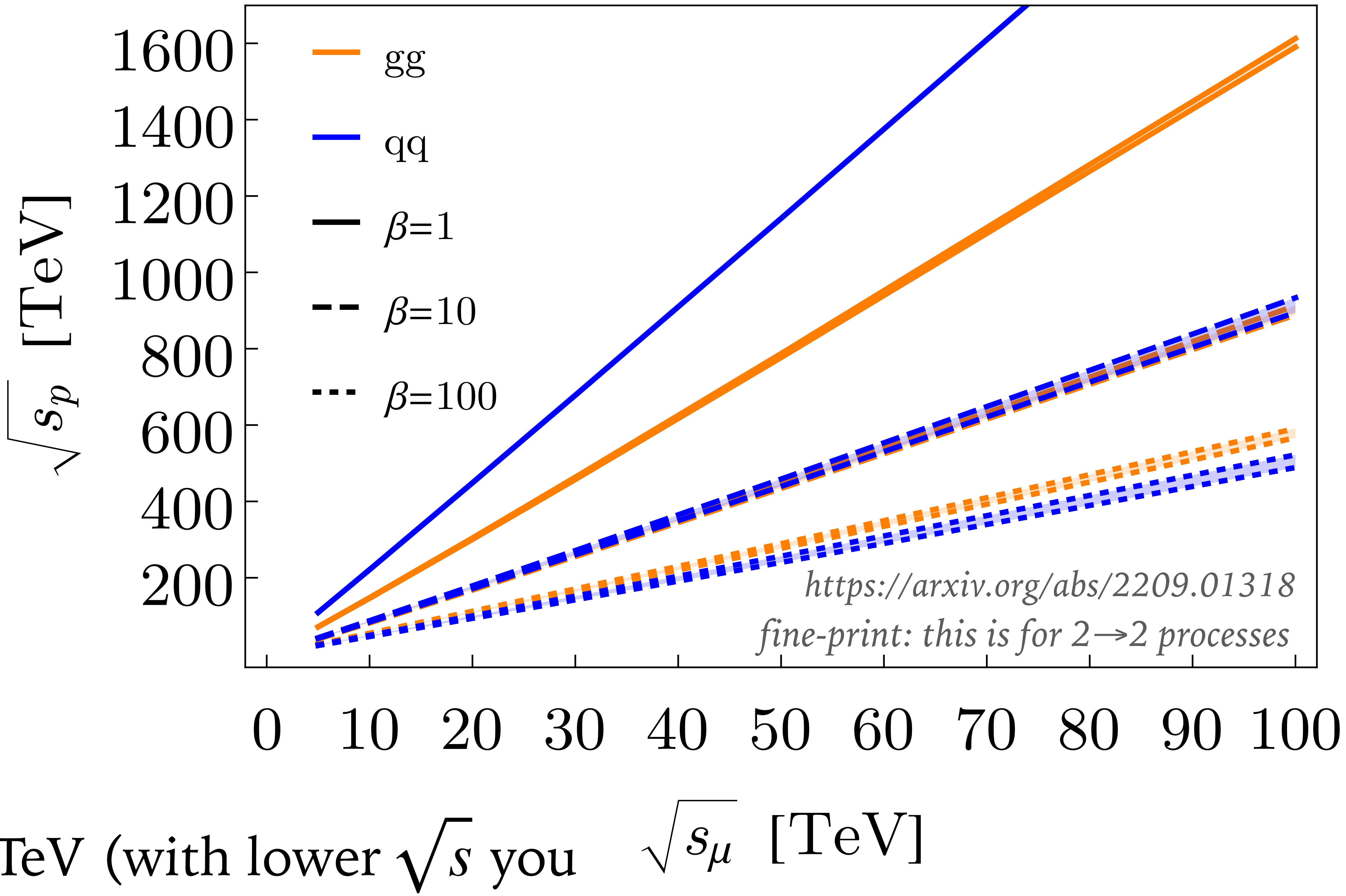
$$M_t < (171.53 \pm 0.15 \pm 0.23_{\alpha_3} \pm 0.15_{M_h})\,\mathrm{GeV} = (171.53 \pm 0.42)\,\mathrm{GeV}. \tag{66}$$

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.

Fig. 3 of Snowmass Muon Collider Forum Report



https://arxiv.org/abs/2209.01318

fine-print: this is for 2→2 processes

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