Higgs and the new fundamental interactions

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** on leave from CERN and CNRS*

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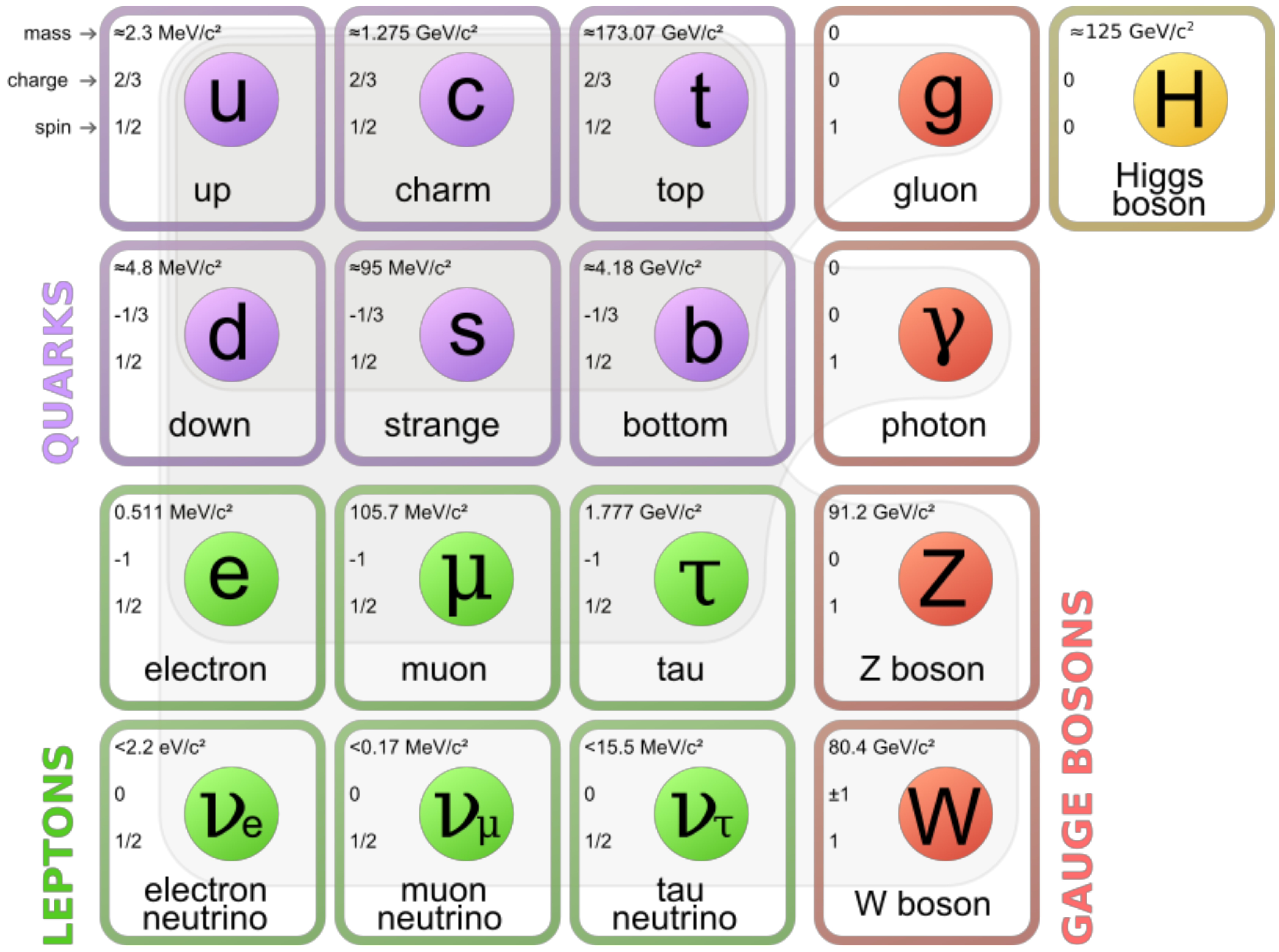
European Research Council
Established by the European Commission
THE ROYAL SOCIETY

“big unanswered questions”
about fundamental particles & their interactions
(dark matter, matter-antimatter asymmetry,
nature of dark energy, hierarchy of scales…)

v.

“big answerable questions”
and how we go about answering them

The Higgs boson



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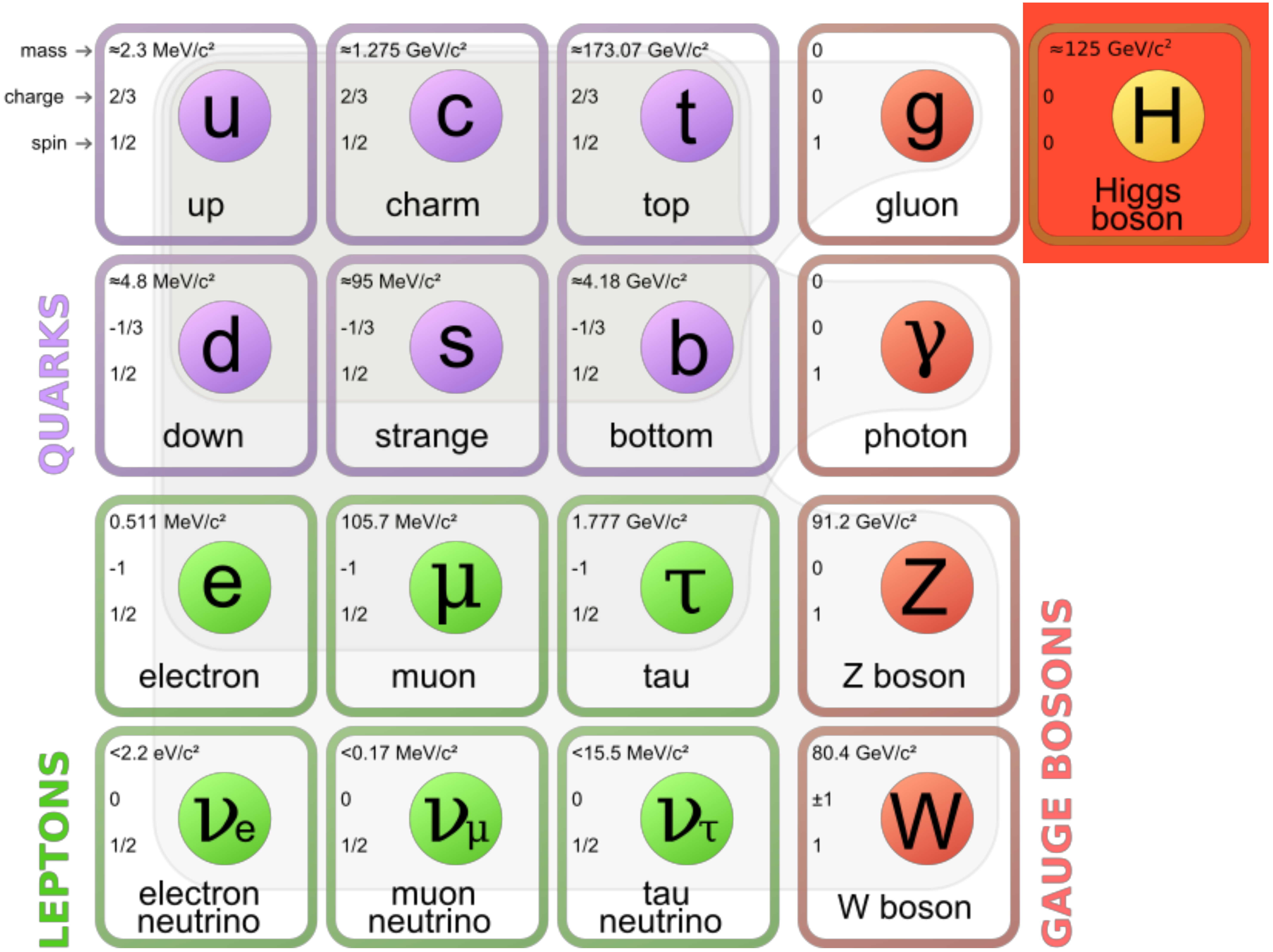
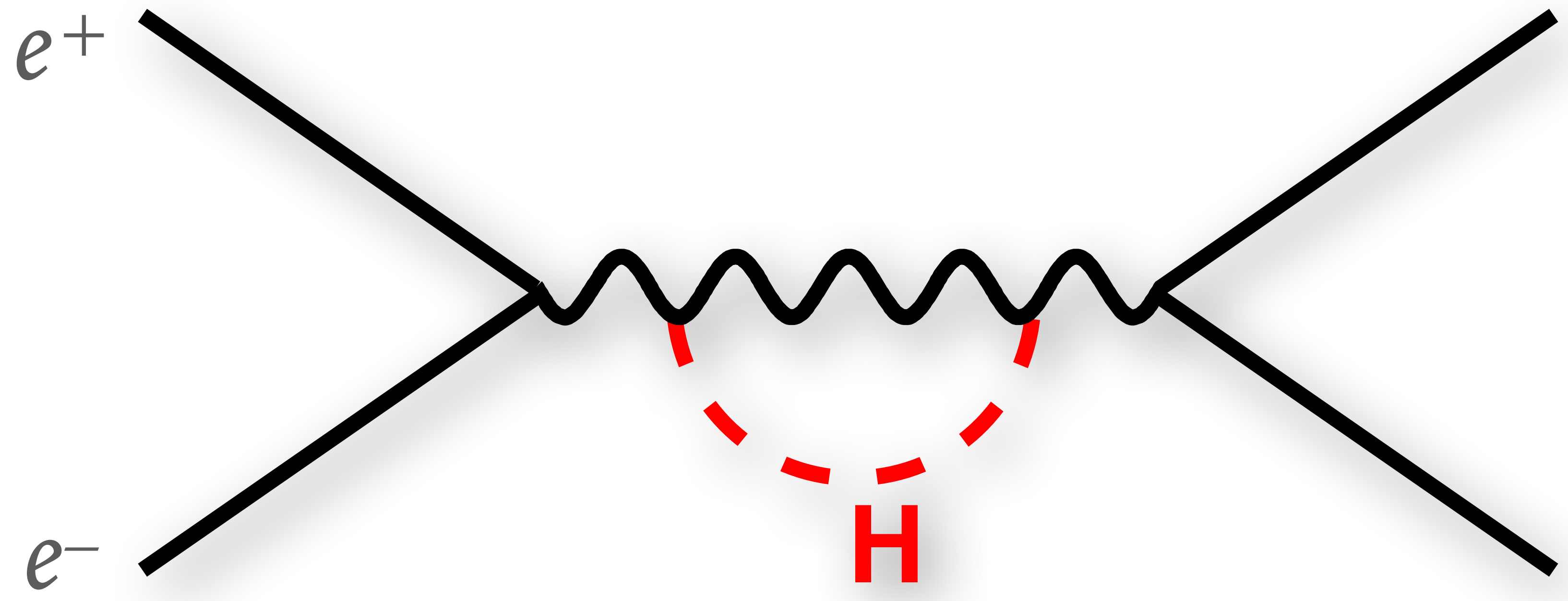
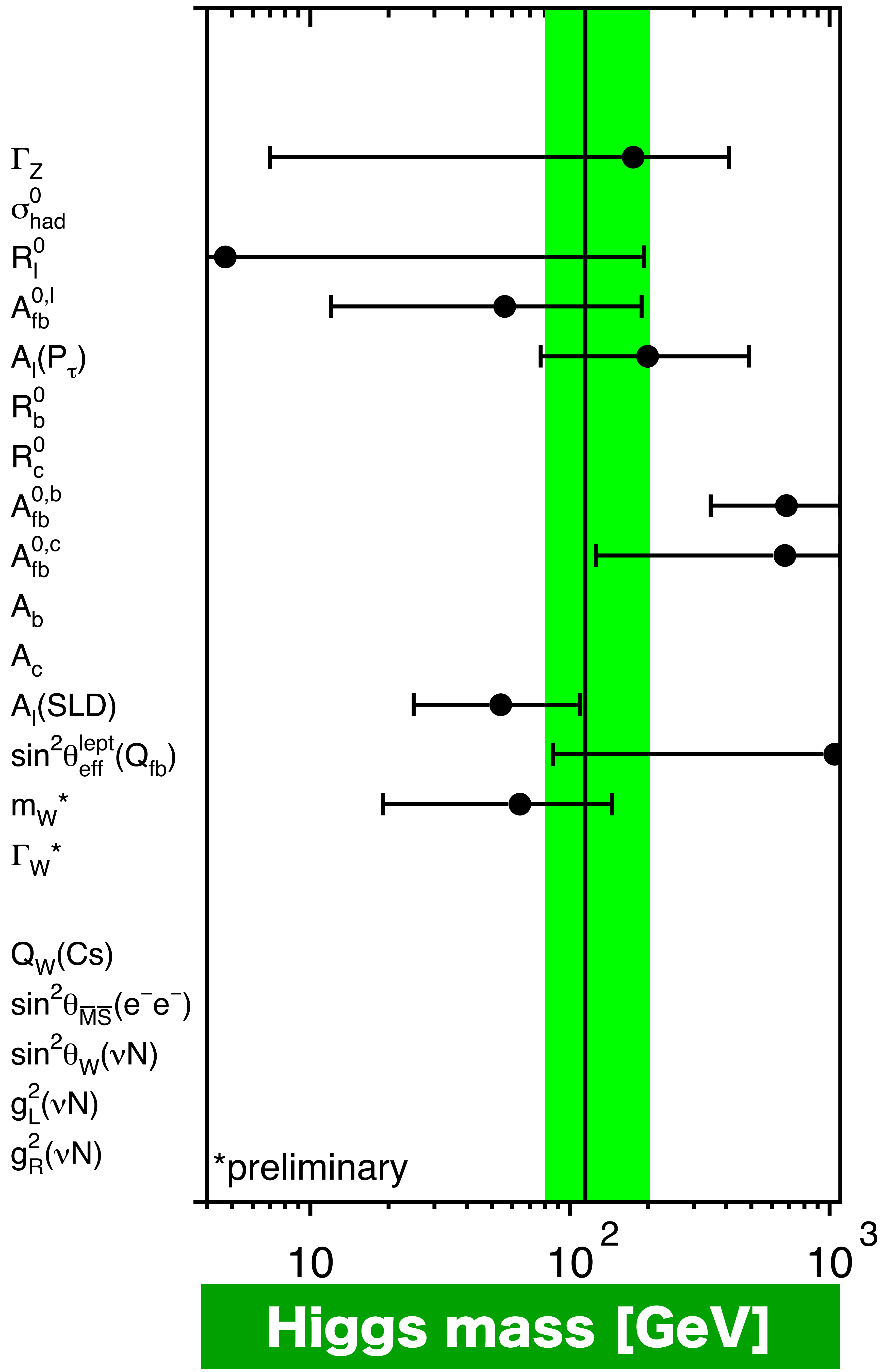




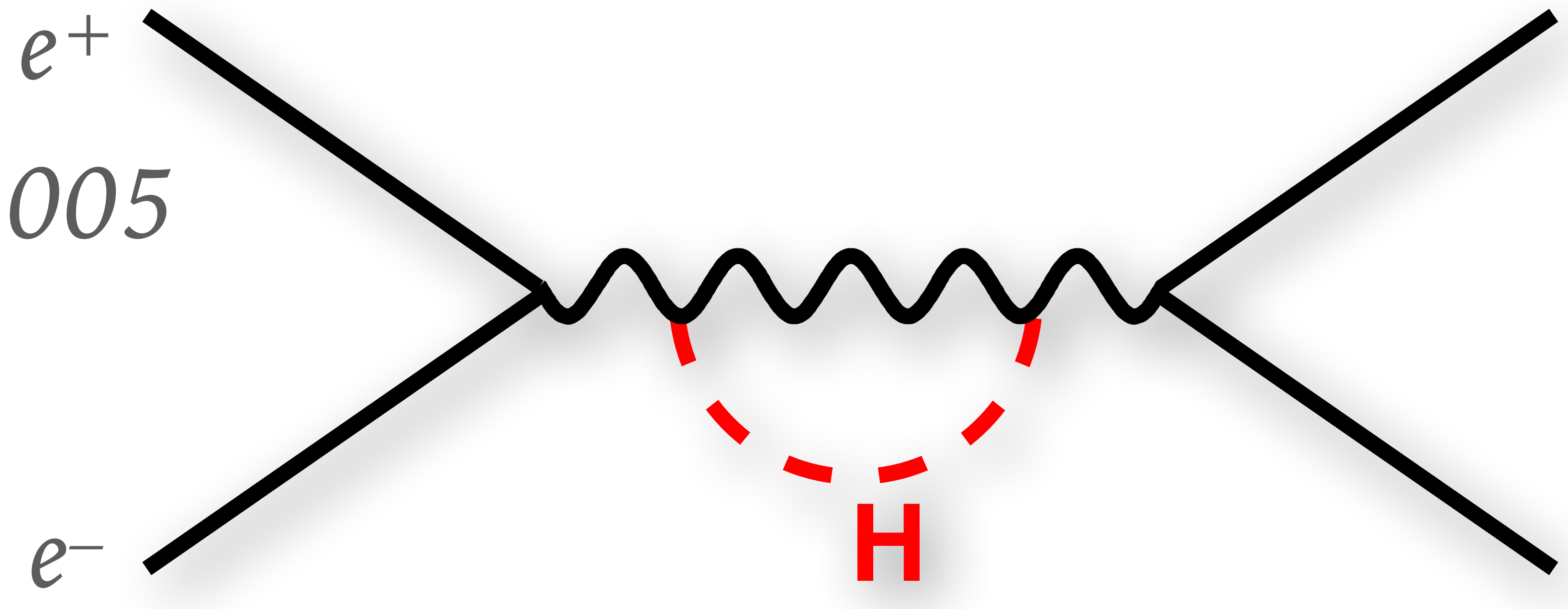
Higgs boson existence long known to be consistent with older e⁺e⁻ collider data (cf. LEP, 1989–2000 + SLD).

Tested through the small effect of virtual Higgs bosons on high-precision *(per-mil)* measurements.

Could be interpreted as a
weak Higgs mass constraint.



LEP electroweak working group, 2005
hep-ex/0509008



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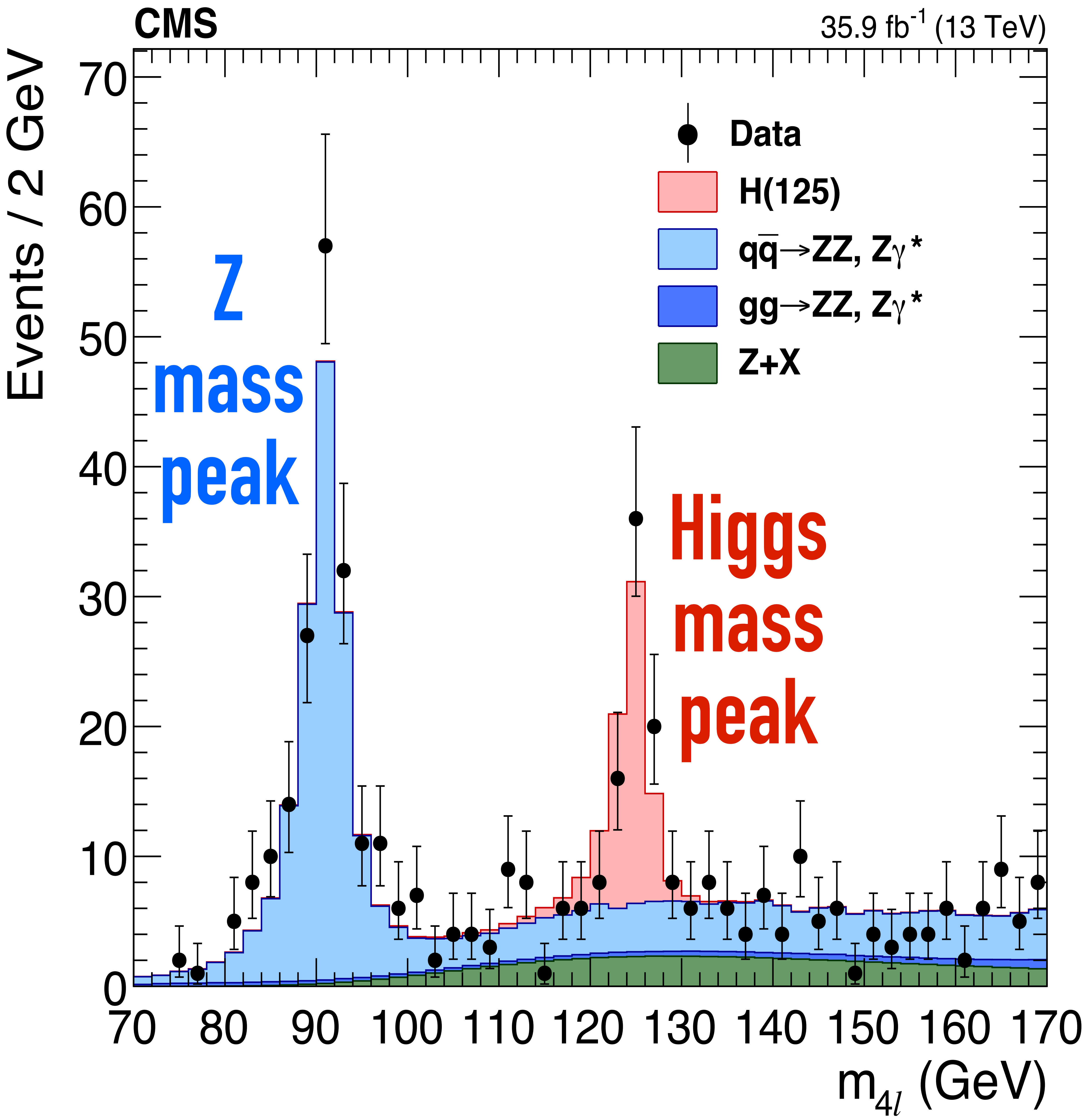
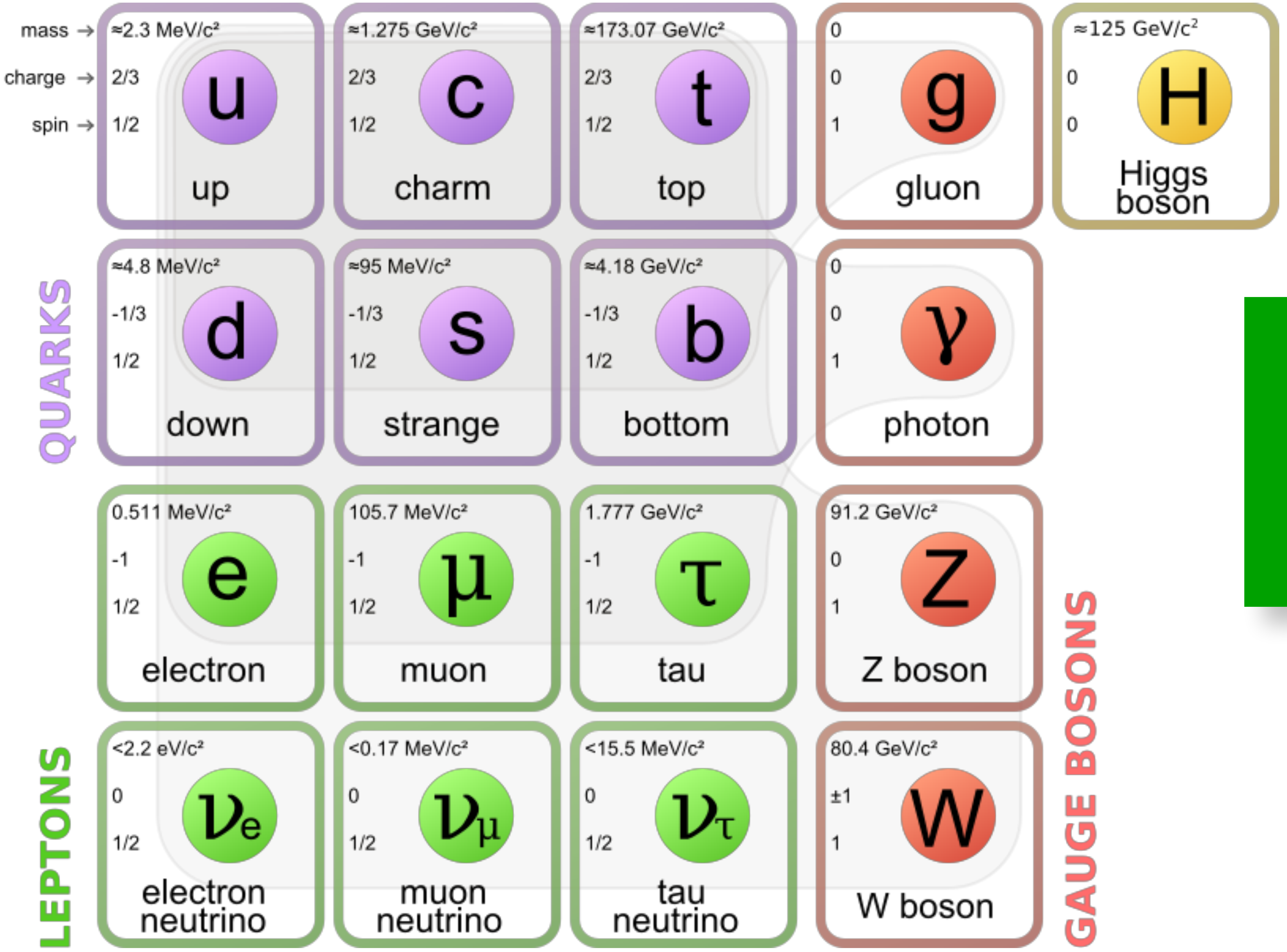


ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC):

2012 discovery of a Higgs-like boson

plot shows more recent data

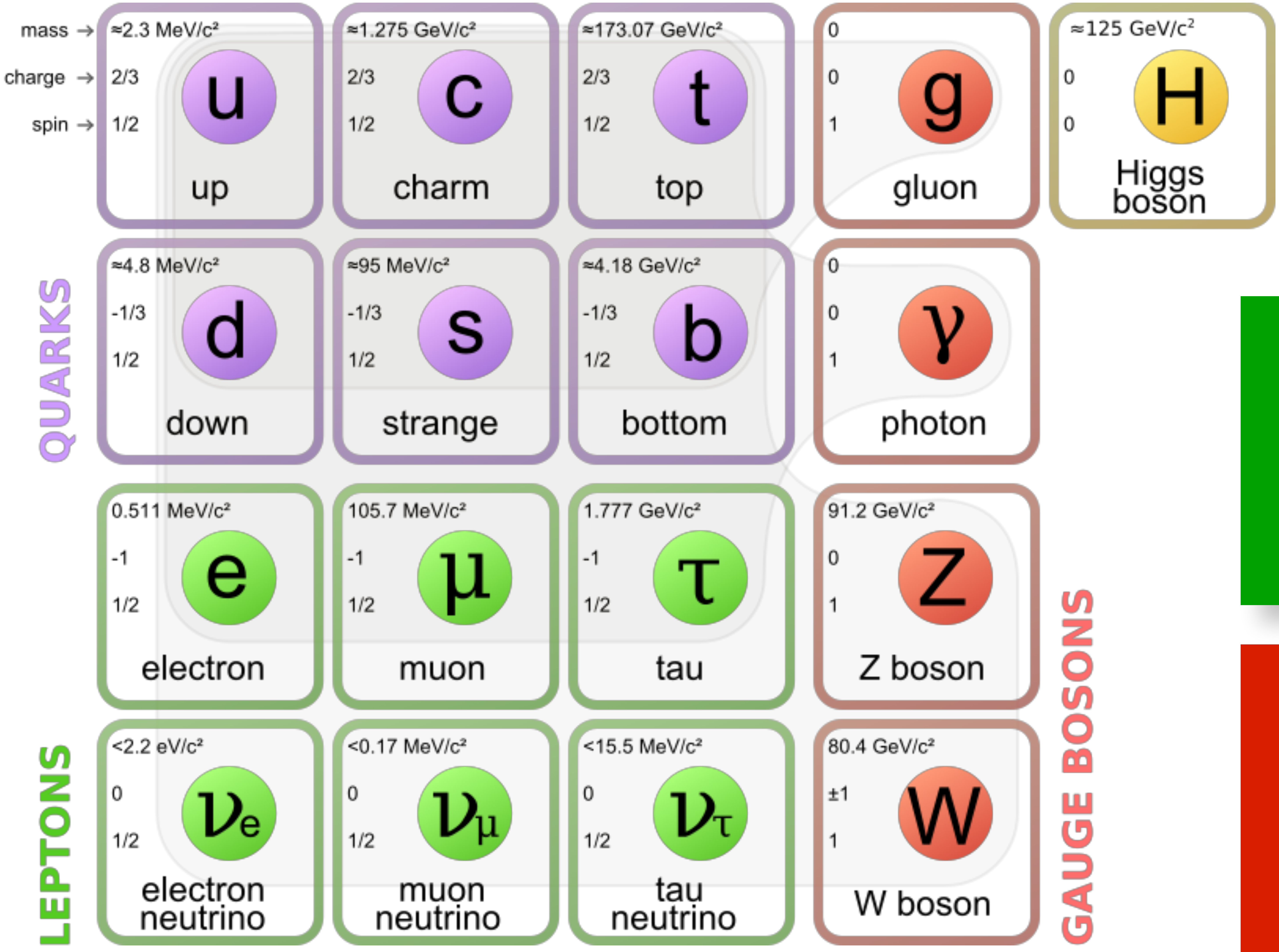
The Higgs boson (2012)



Success!

“The Standard Model is complete”

The Higgs boson (2012)



Success!

"The Standard Model is complete"

Crisis!

No supersymmetry, no extra dimensions, there's nothing left for us to do . . .

The New York Times

By DENNIS OVERBYE JUNE 19, 2017

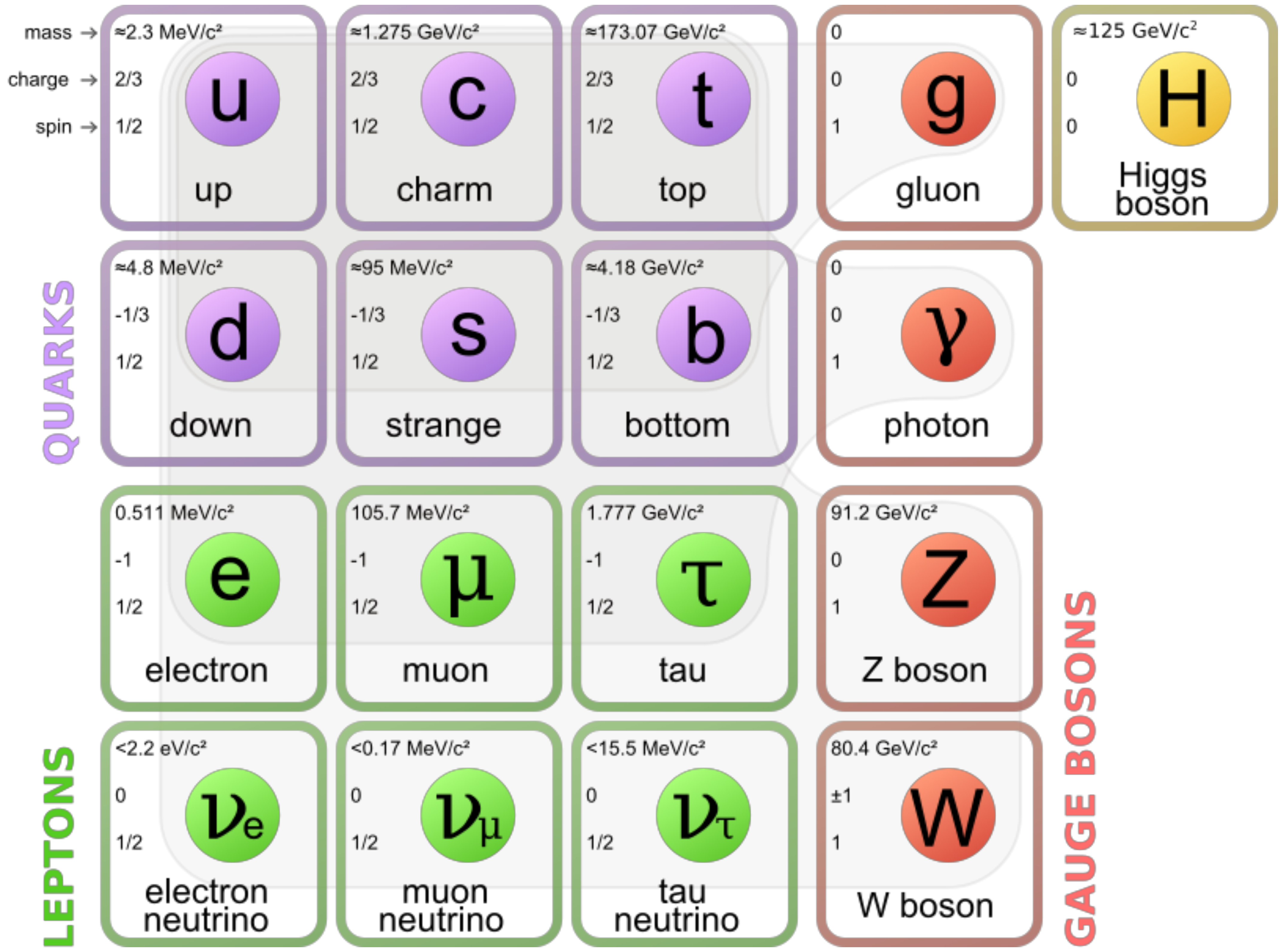
[…]

What if there is nothing new to discover? ***That prospect is now a cloud hanging over the physics community.***

[…]

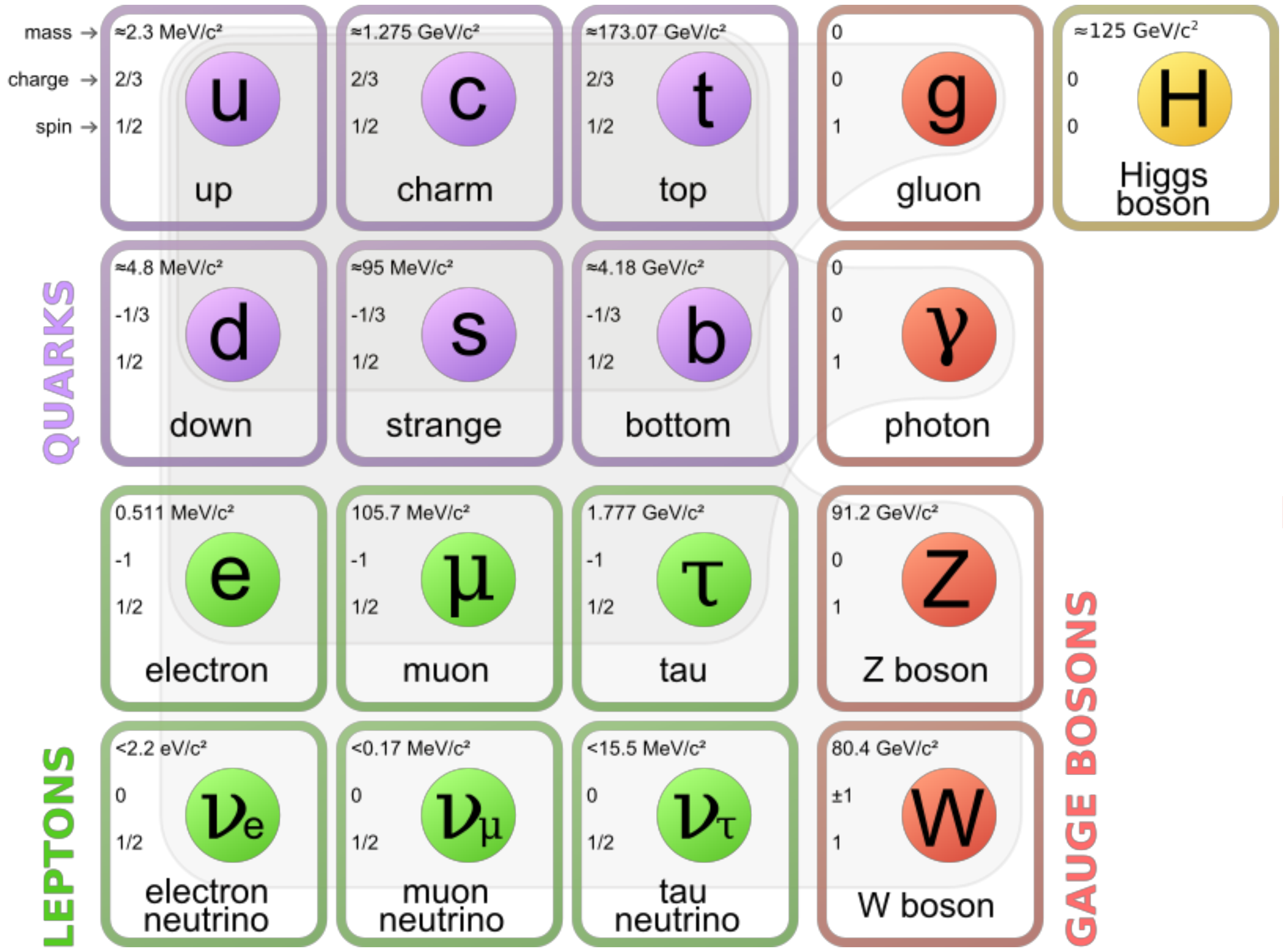
https://www.nytimes.com/2017/06/19/science/cern-large-hadron-collider-higgs-physics.html

what is the Standard Model?



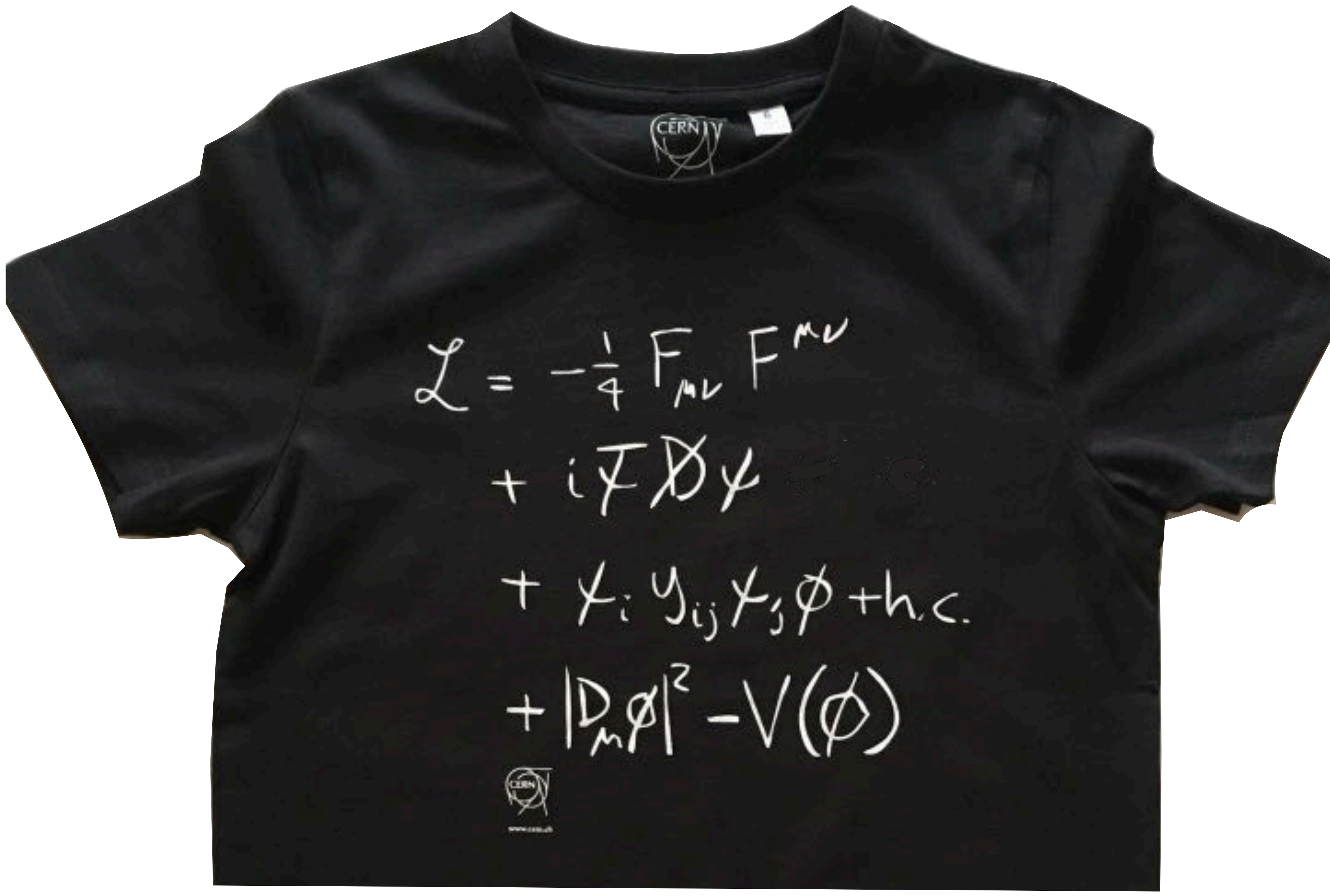
particles

what is the Standard Model?



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈125 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

+

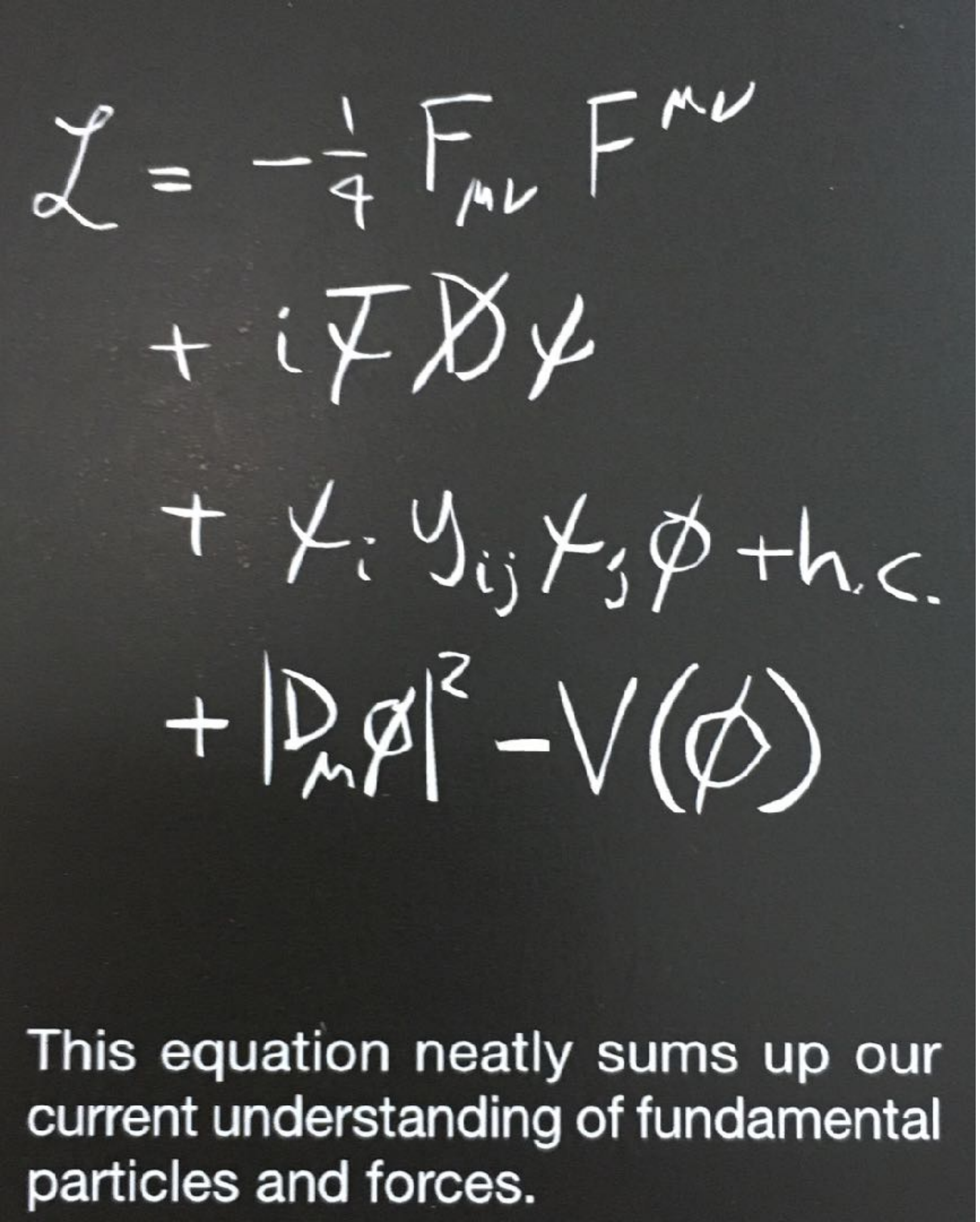


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

particles

interactions

STANDARD MODEL — KNOWABLE UNKNOWNS



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

This is what you get when you buy one of those famous CERN T-shirts

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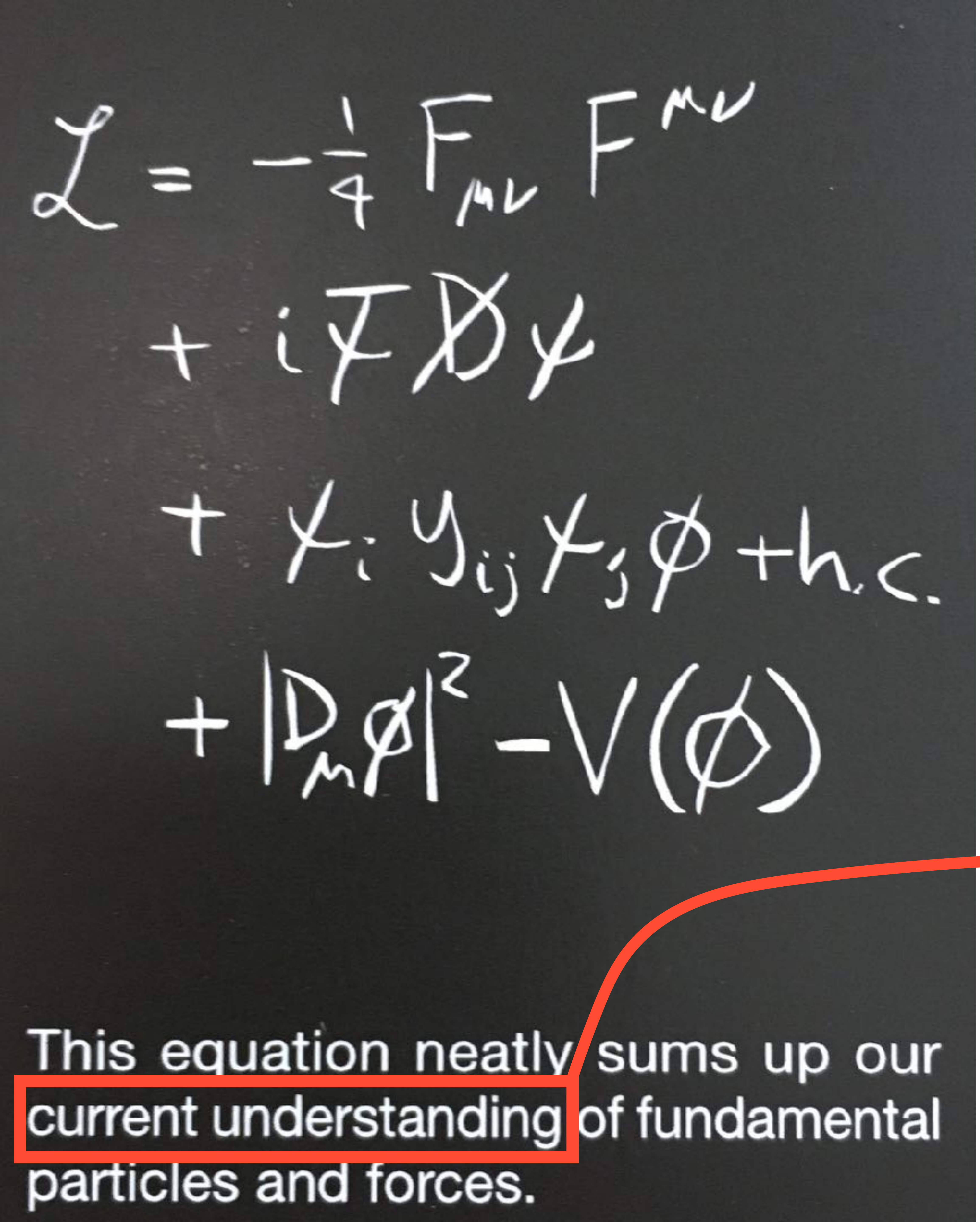

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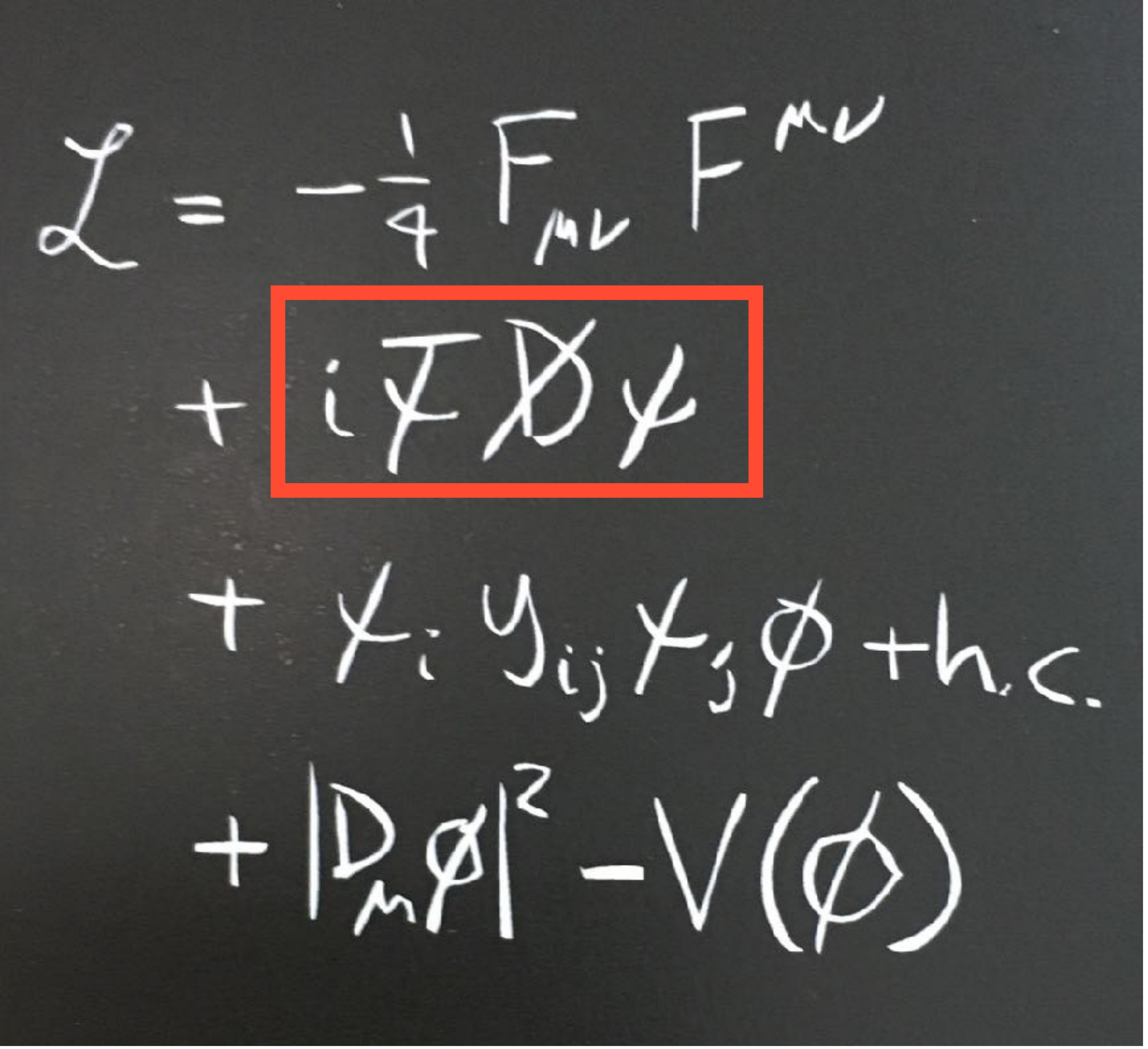
“understanding” = knowledge ?

“understanding” = assumption ?



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ \boxed{i\bar{\psi} \not{D} \psi}$$
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$$+ |D_\mu \phi|^2 - V(\phi)$$

NOTATION

A_μ : gauge field *photons, gluons, W,Z*

ψ : fermion field *quarks & leptons*

ϕ : Higgs field

$= \phi_0(\text{VEV}) + H(\text{Higgs})$

$$D_\mu = \partial_\mu + ieA_\mu \text{ etc.}$$

$$F_{\mu\nu} \sim [D_\mu, D_\nu]$$

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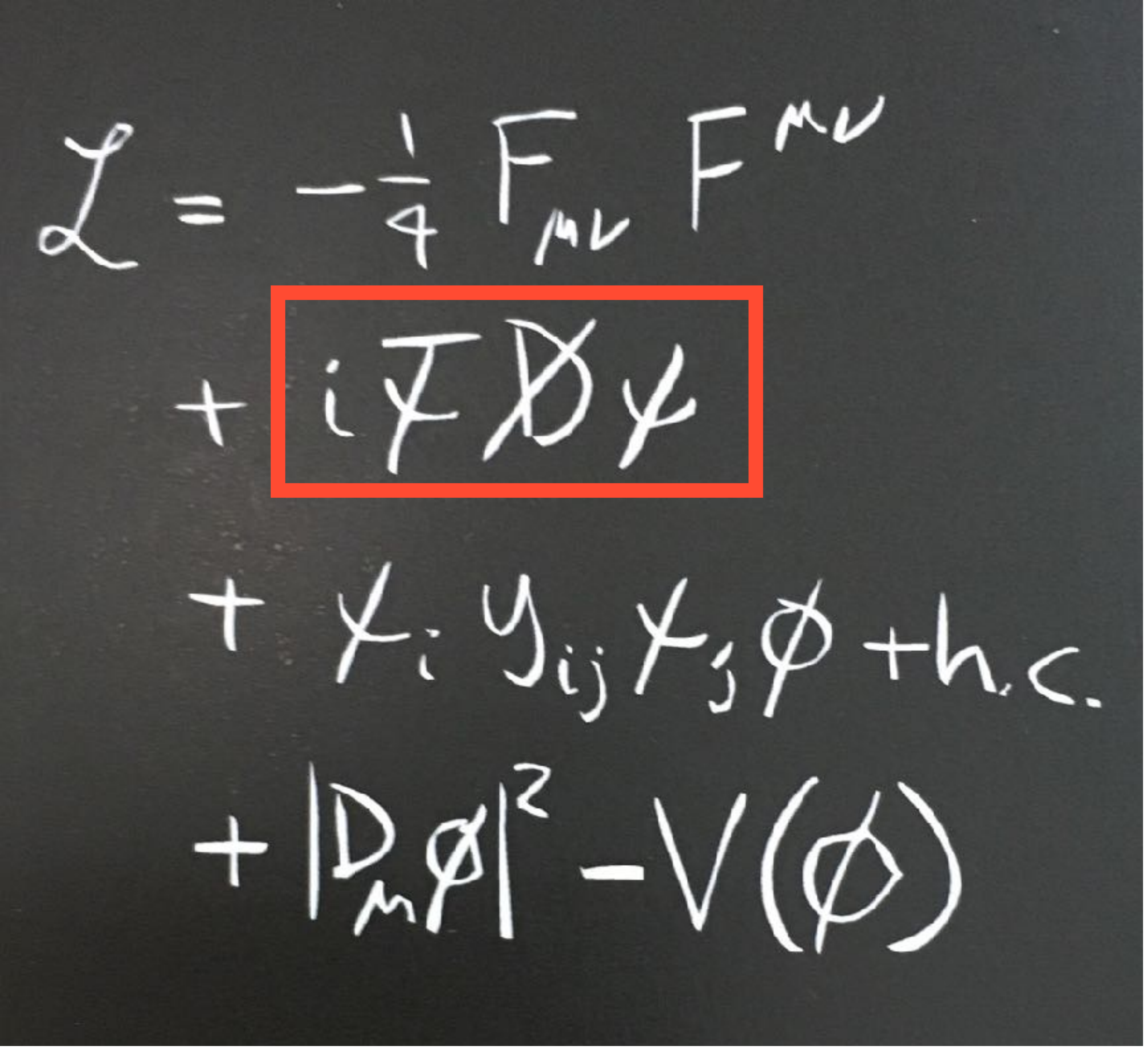

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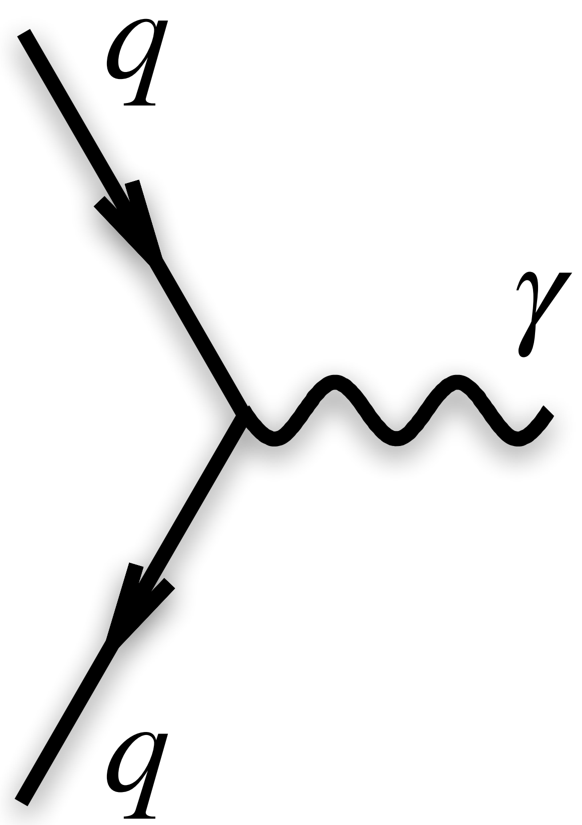
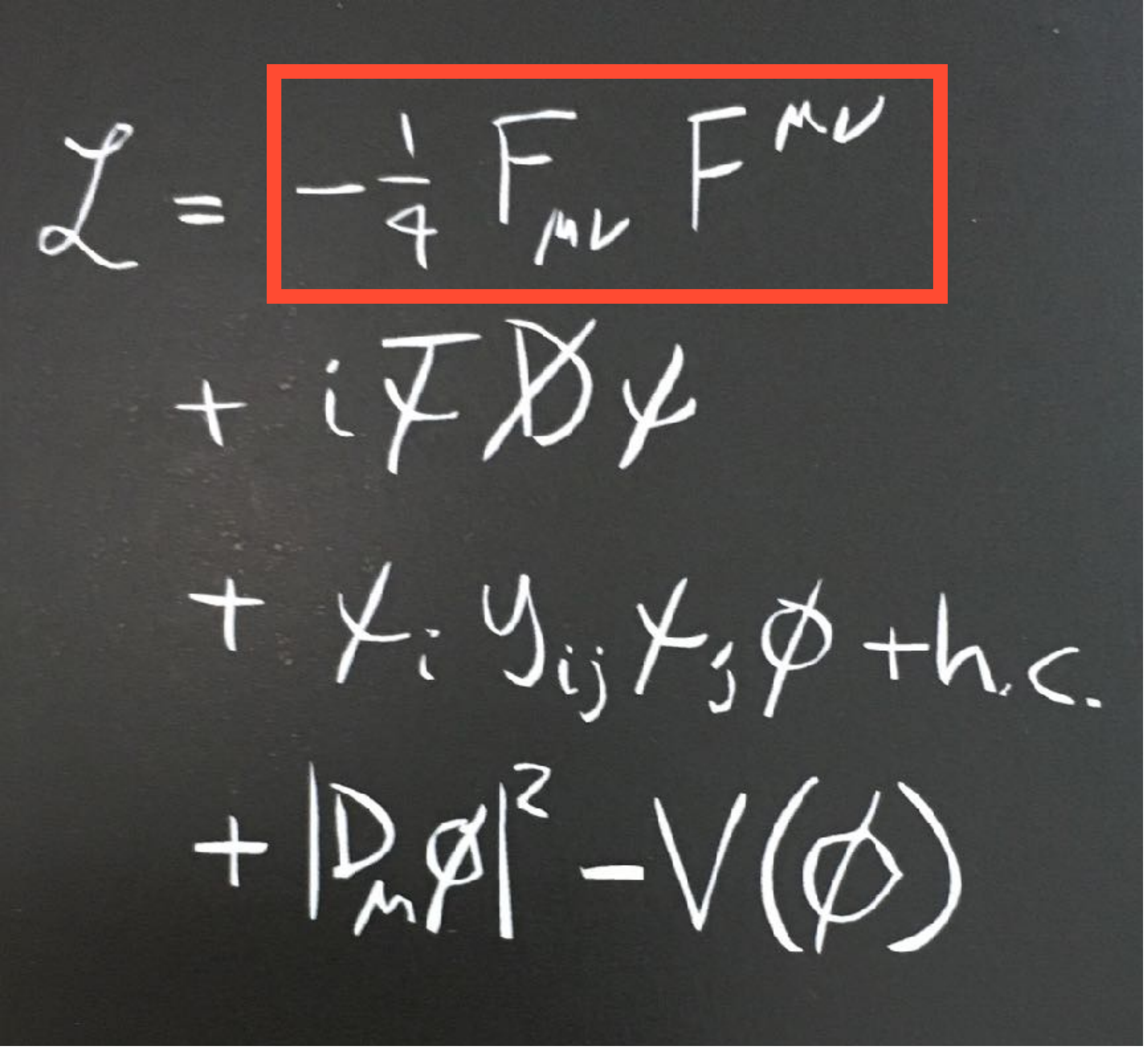
e.g. $\bar{\psi} D \psi \rightarrow \psi A_\mu \psi \rightarrow$ fermion-fermion-gauge vertex

i.e. terms of $\mathcal{L}$ map to particle interactions





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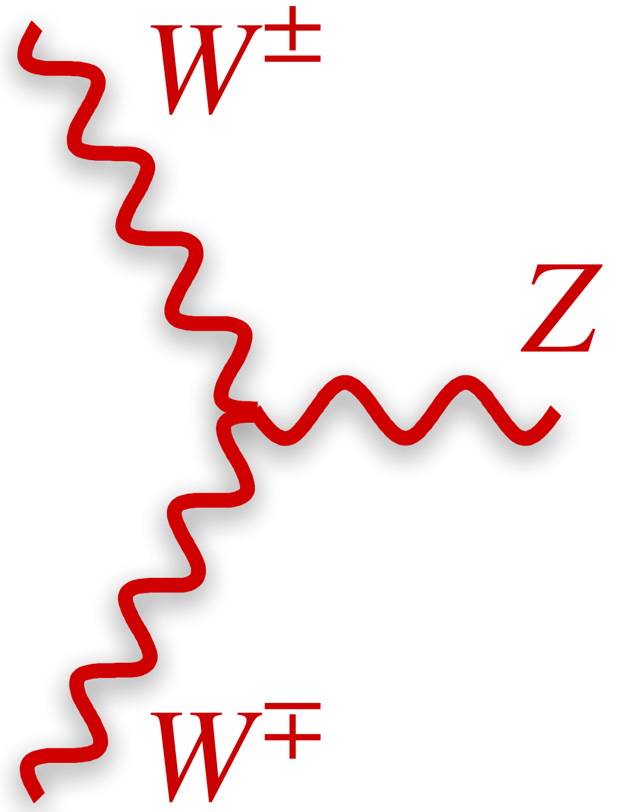
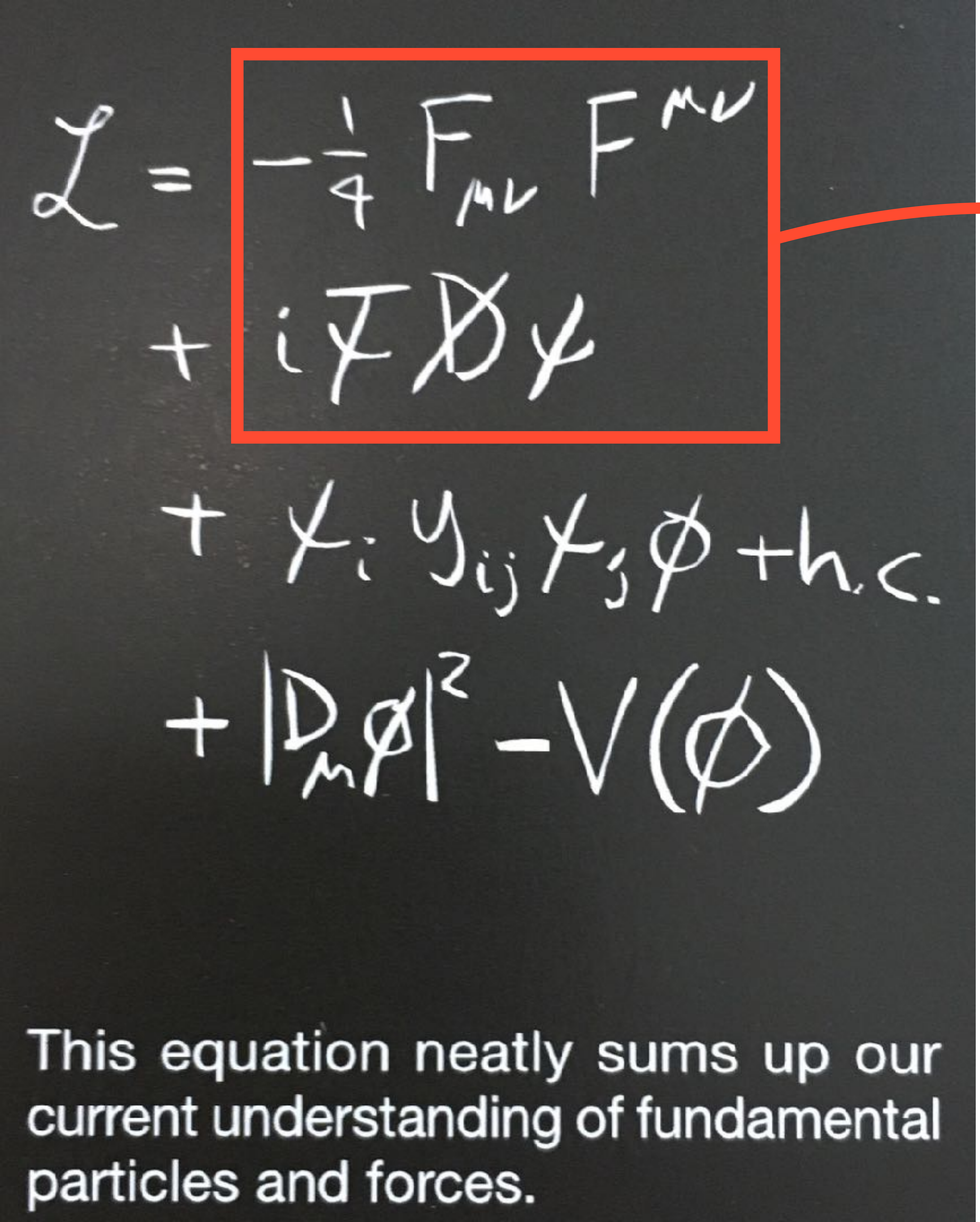
e.g. $F_{\mu\nu}F^{\mu\nu} \rightarrow A_\mu A_\nu \partial_\mu A_\nu \rightarrow$ triple-gauge vertex

i.e. terms of $\mathcal{L}$ map to particle interactions





$$\begin{aligned}\mathcal{L} &= -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ &+ i\bar{\psi}\not{D}\psi \\ &+ \psi_i y_{ij}\psi_j\phi + h.c. \\ &+ |D_\mu\phi|^2 - V(\phi)\end{aligned}$$

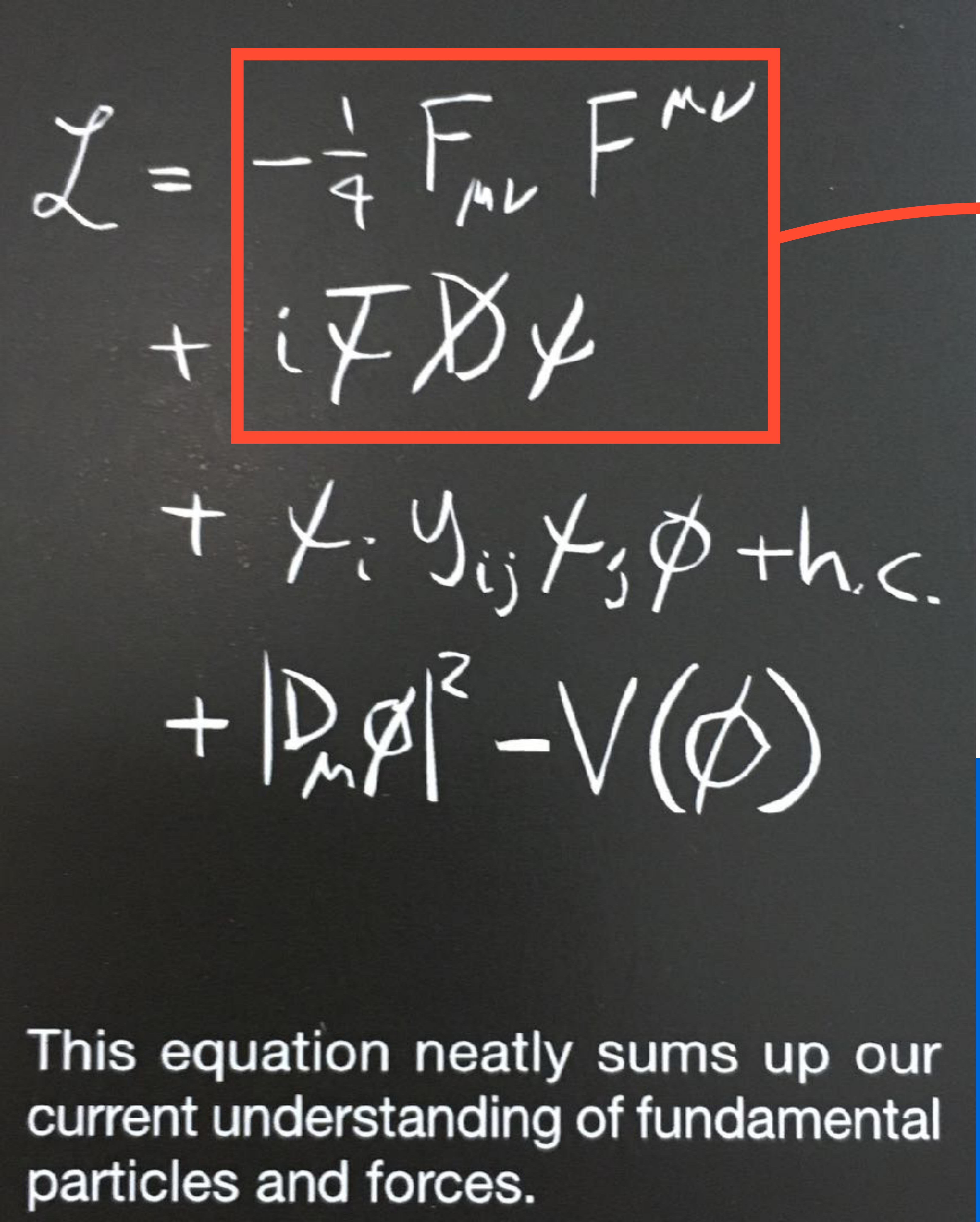
This equation neatly sums up our current understanding of fundamental particles and forces.

GAUGE PART

e.g. qqγ, qqZ, qqg, eνW, ggg, interactions — well established in ep, e^+e^-, pp collisions, etc.

≡ KNOWLEDGE

(also being studied at LHC — e.g. jets, DY/Z/W, V+jets, ttbar, etc.)



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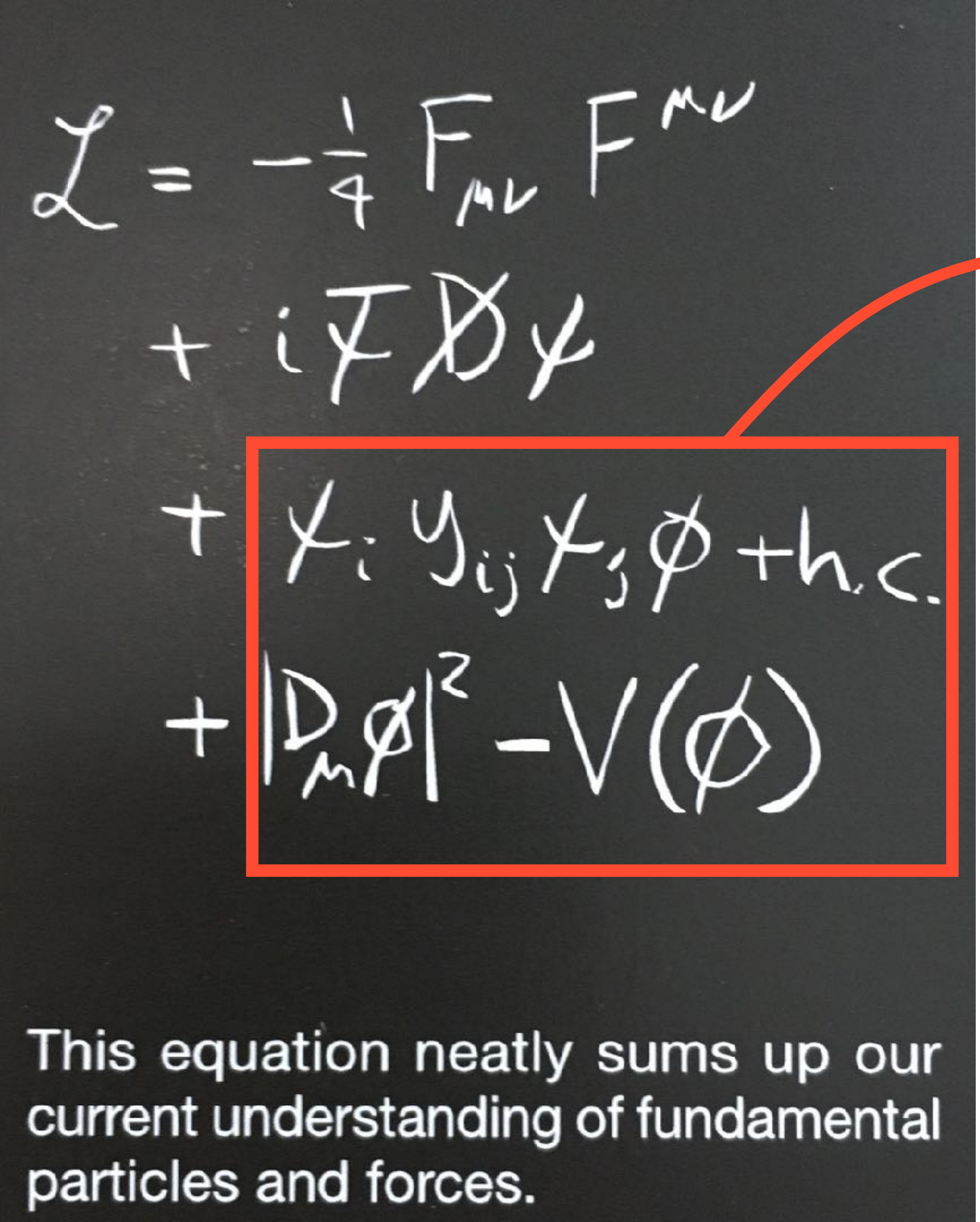
Many SM studies probe this part.

In some respects dates back to 1860’s, i.e. **Maxwell’s equations.**

If you test another corner of this (as one should), don’t be surprised if it works

Higgs sector



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$$+ \boxed{\psi_i y_{ij} \psi_j \phi + h.c.}$$

$$+ \boxed{|D_\mu \phi|^2 - V(\phi)}$$

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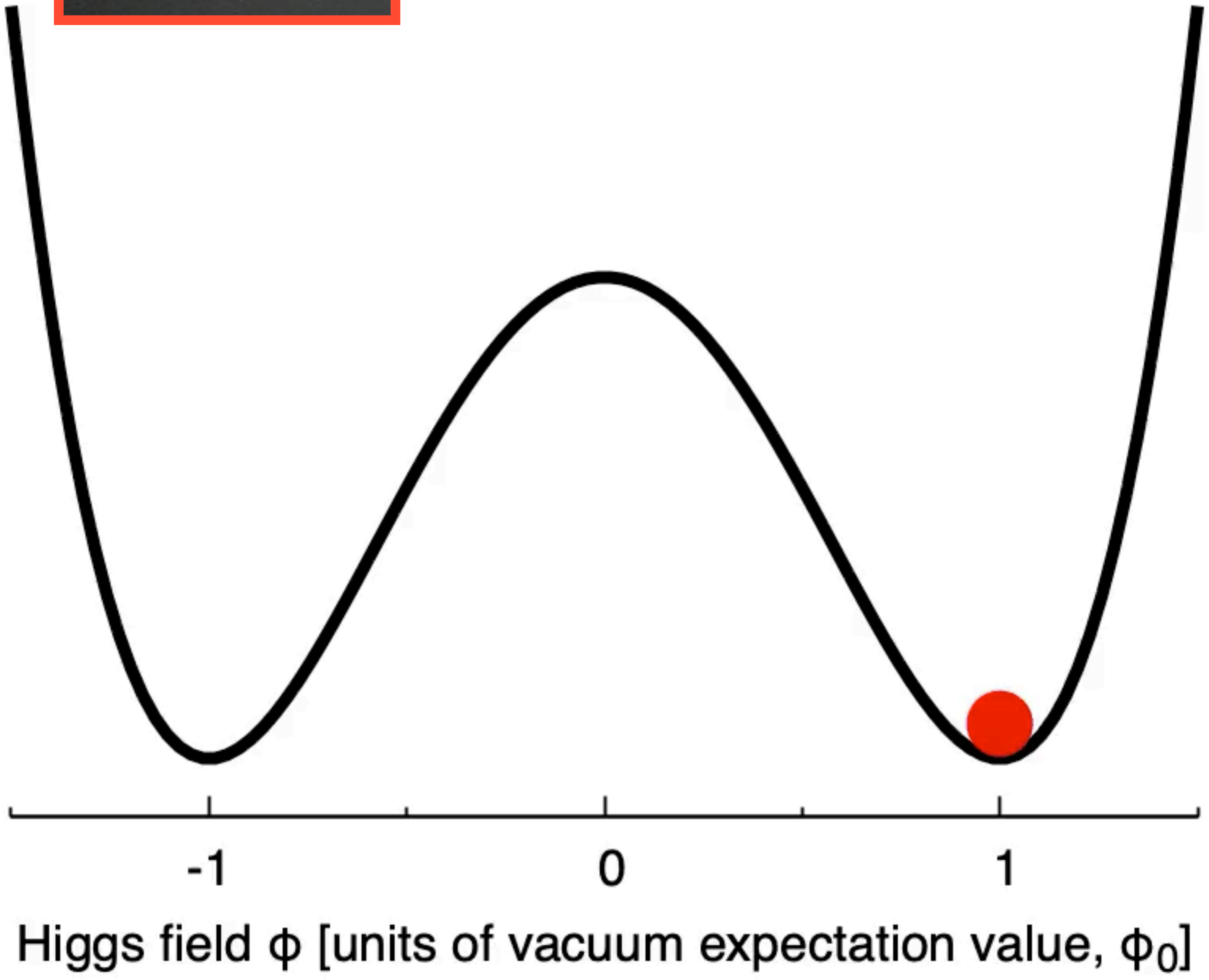
until 6 years ago none of these terms had ever been directly observed.

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



- φ is a field at every point in space (plot shows potential vs. 1 of 4 components, at 1 point in space)

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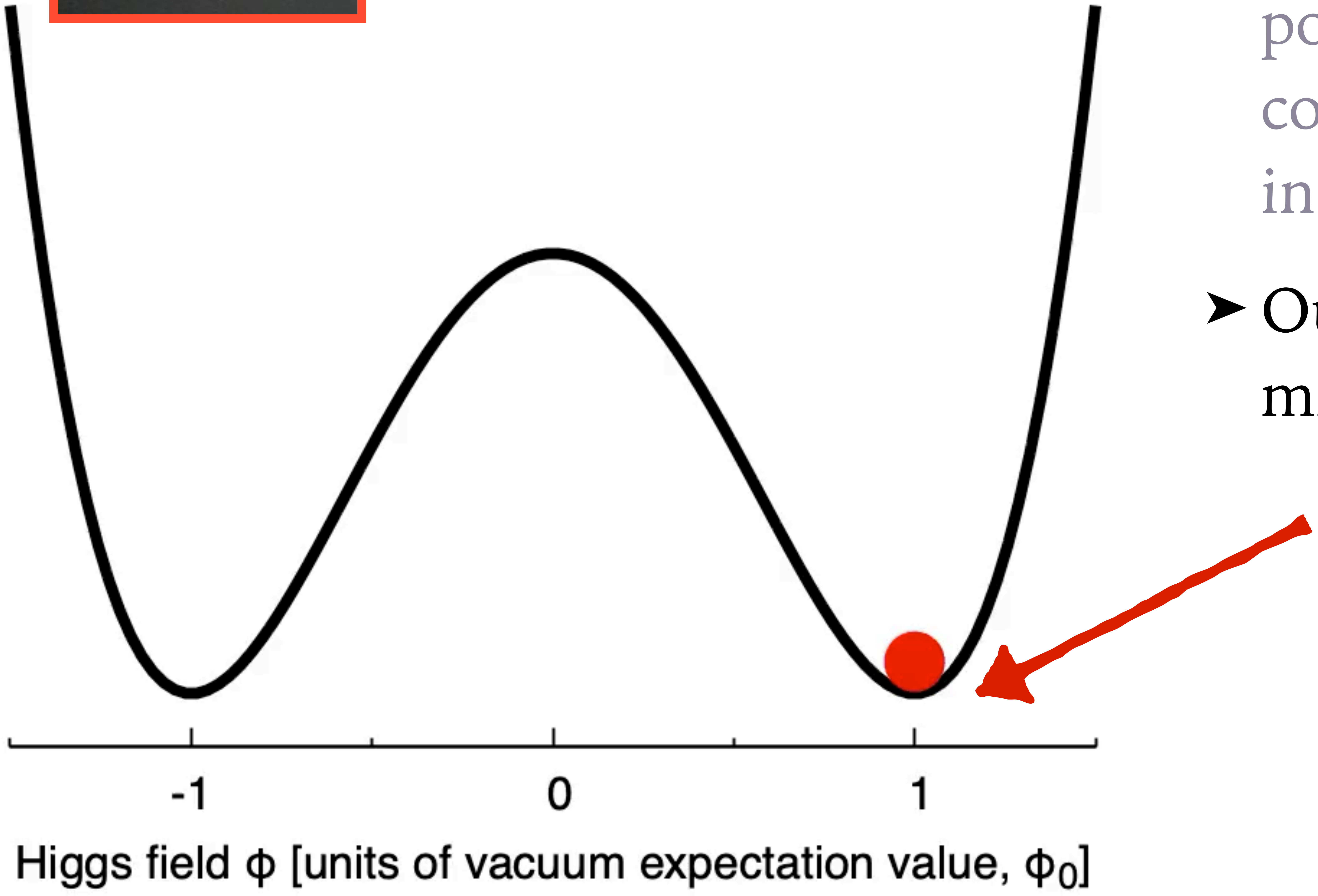

- φ is a field at every point in space (plot shows potential vs. 1 of 4 components, at 1 point in space)
- Our universe sits at minimum of V(φ), at

$$\phi = \phi_0 = \frac{\mu}{\sqrt{2\lambda}}$$

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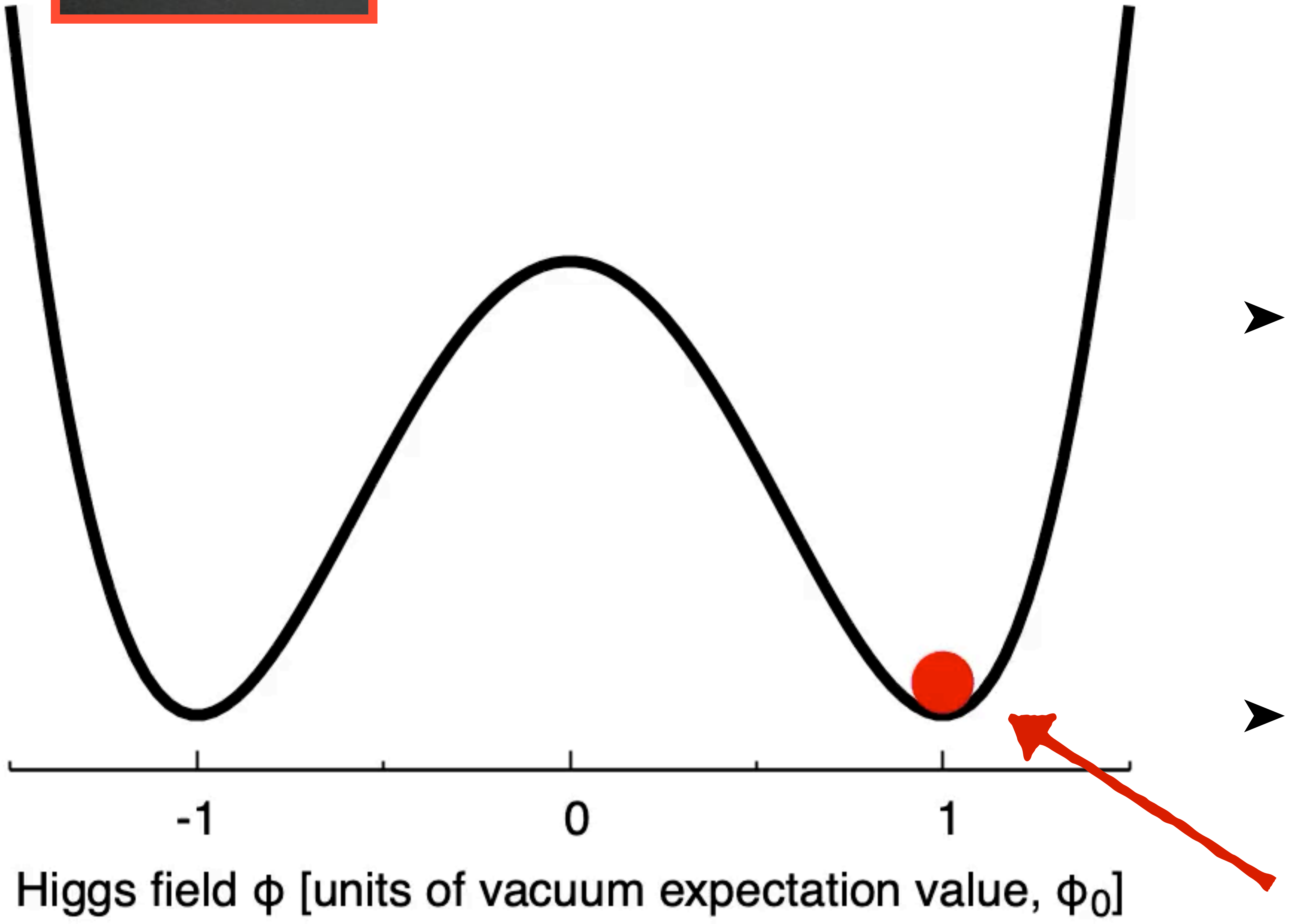

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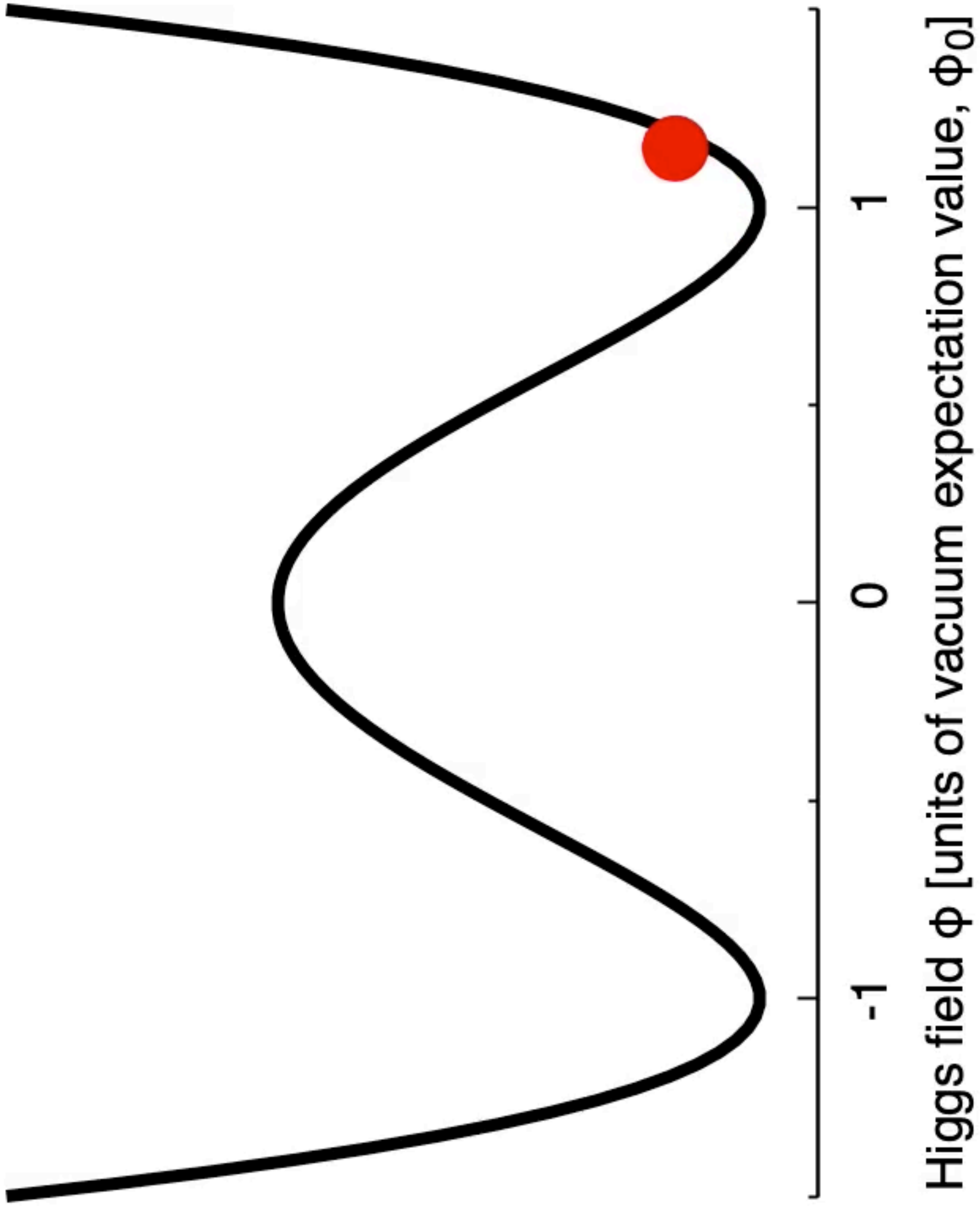
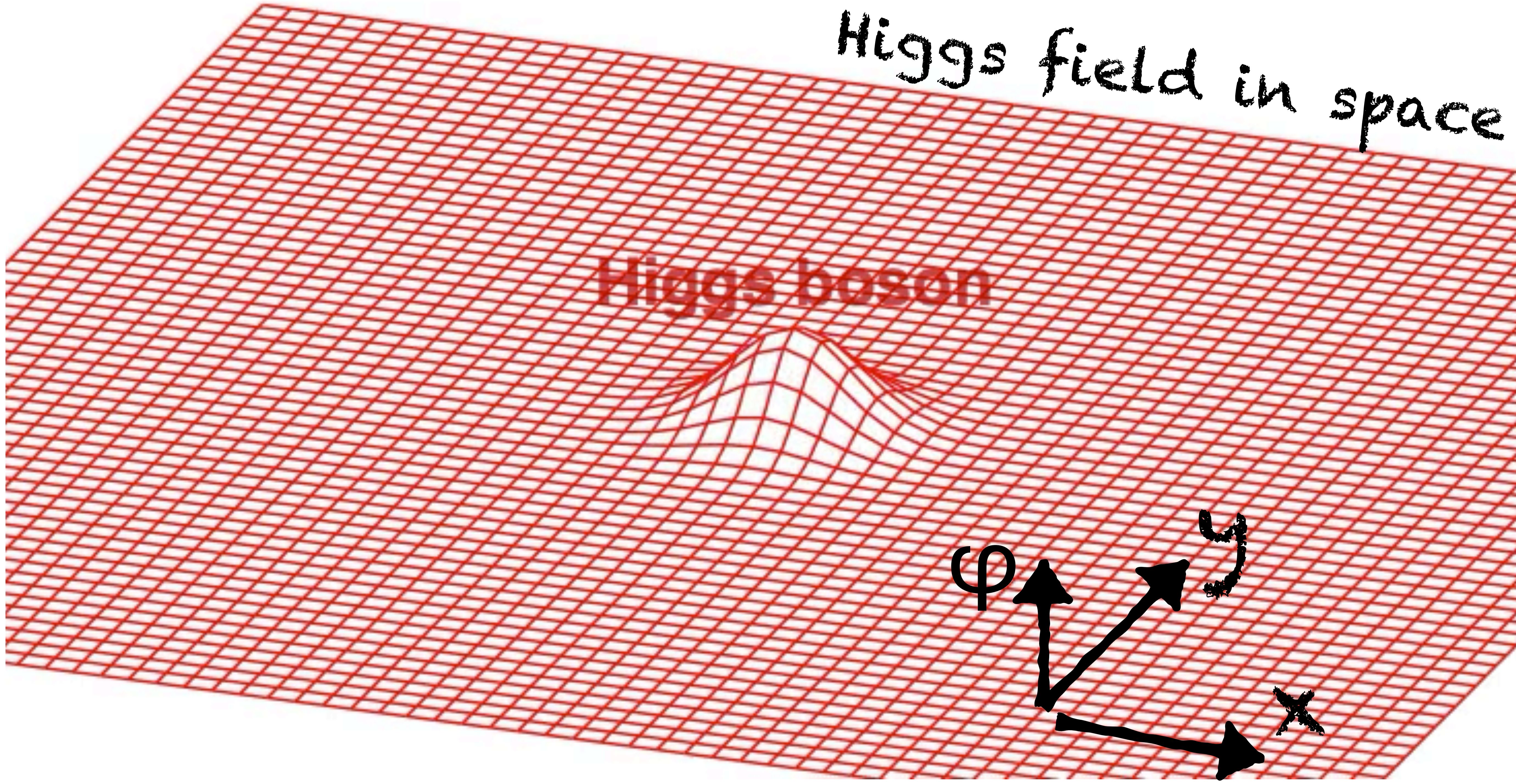
- Excitation of the φ field around φ_0 is a Higgs boson ($\varphi = \varphi_0 + H$)

$$\varphi = \varphi_0 + H$$

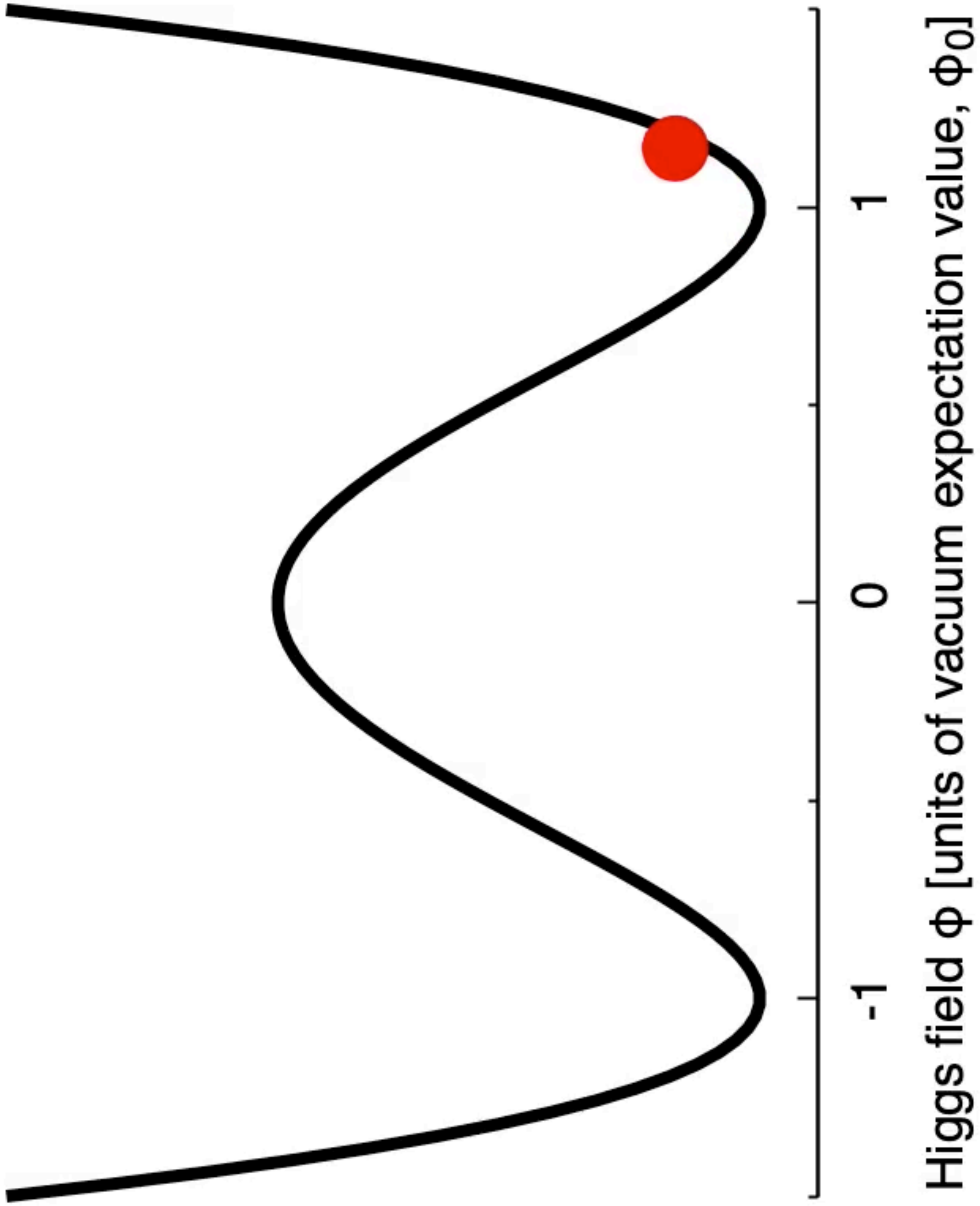


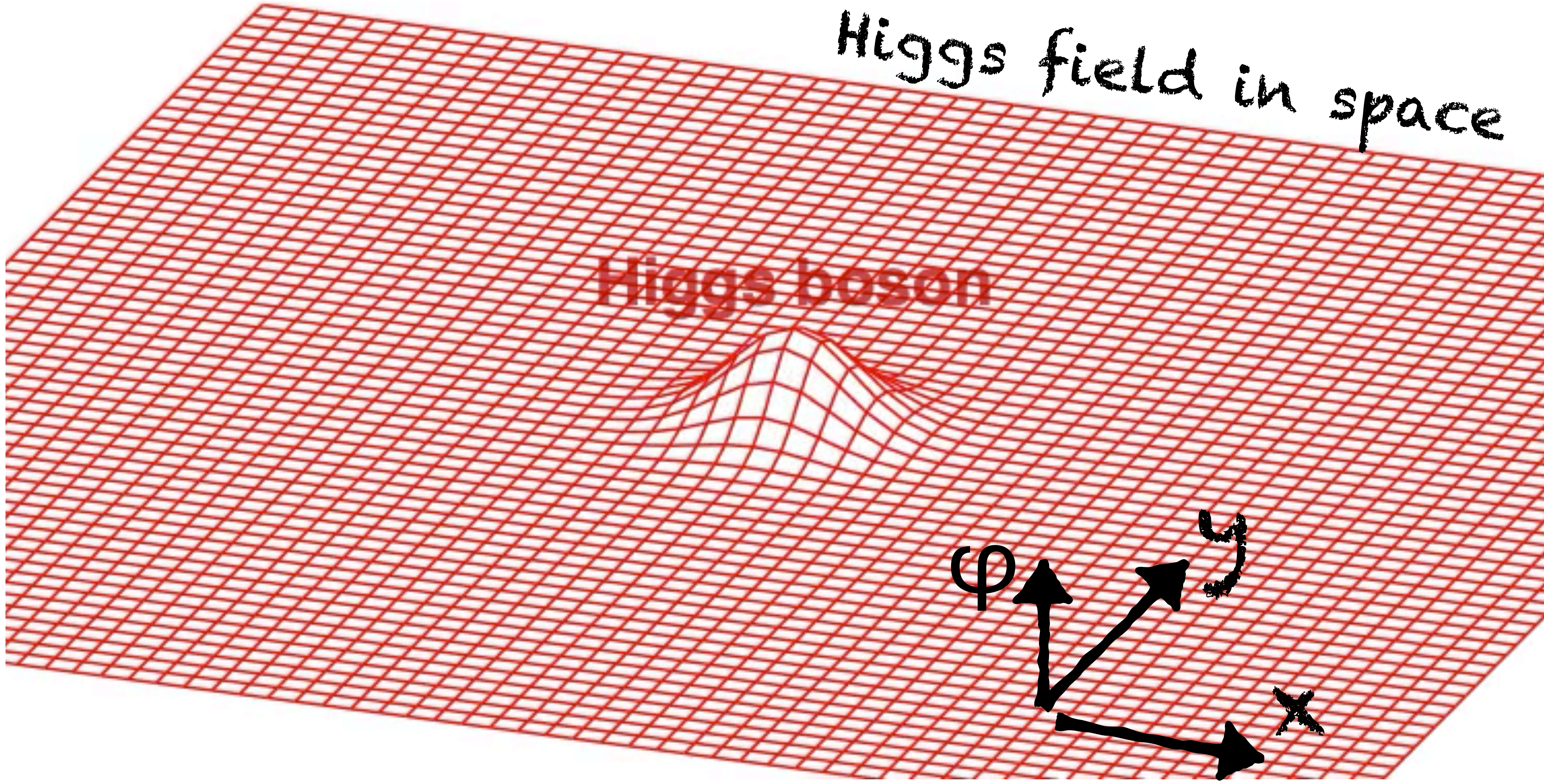


Higgs field can be different at each point in space

A Higgs boson at a given point in space is a localised fluctuation of the field

$$\varphi = \varphi_0 + H$$





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$\varphi = \varphi_0 + H$

established

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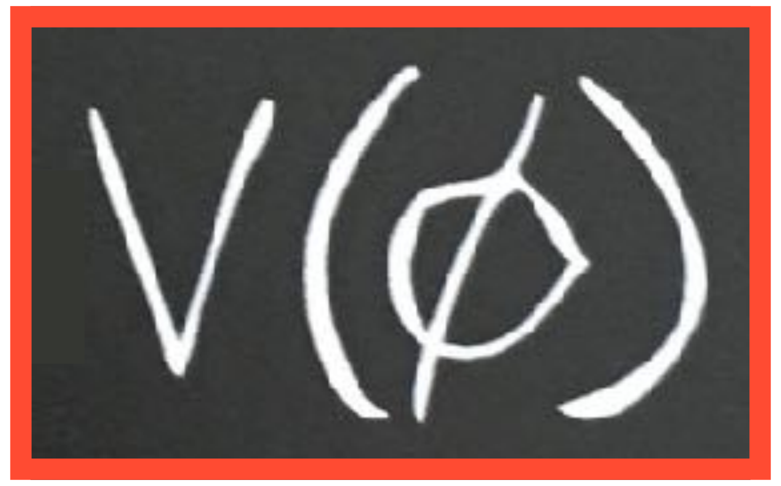
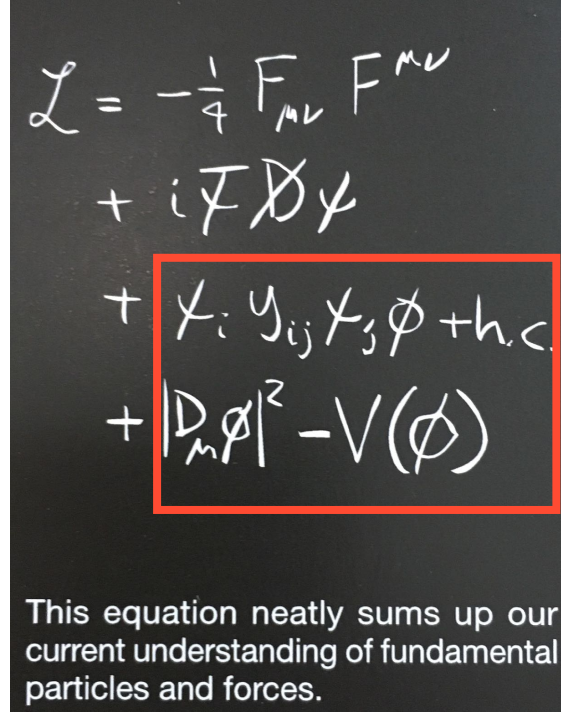


$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

hypothesis

what terms are there in the Higgs sector?

2. Gauge–Higgs term



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

$$|D_\mu \phi|^2 \rightarrow g^2 \phi_0^2 \, Z_\mu Z^\mu + 2 g^2 \phi_0 \, H \, Z_\mu Z^\mu + \ldots$$

Z-boson mass term

ZZH interaction term

$$\left[\begin{array}{l} (D_\mu)^2 \sim (\partial_\mu + igZ_\mu + \ldots)^2 \sim g^2 Z_\mu Z^\mu + \cdots \\ (\phi)^2 = (\phi_0 + H)^2 = \phi_0^2 + 2\phi_0 H + H^2 \end{array}\right]$$

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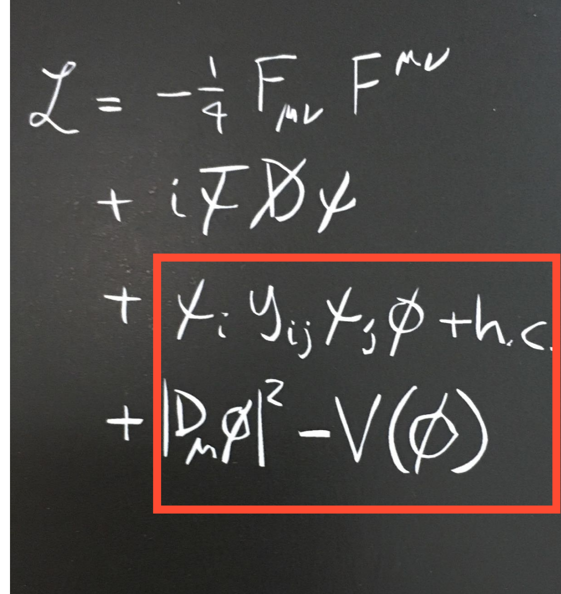
2. Gauge-Higgs term



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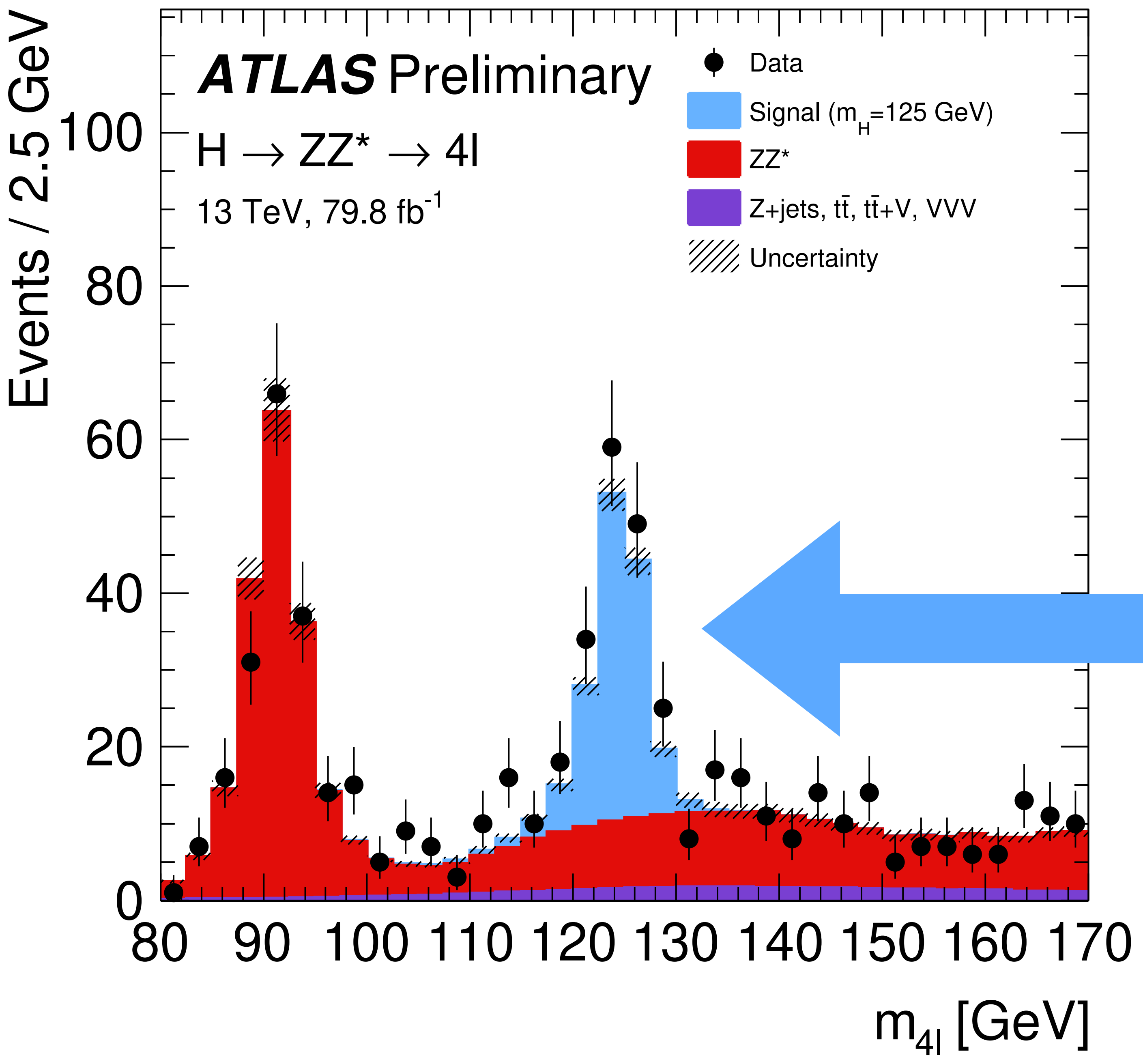

H → ZZ*

Higgs mechanism predicts specific relation between Z-boson mass and HZZ interaction

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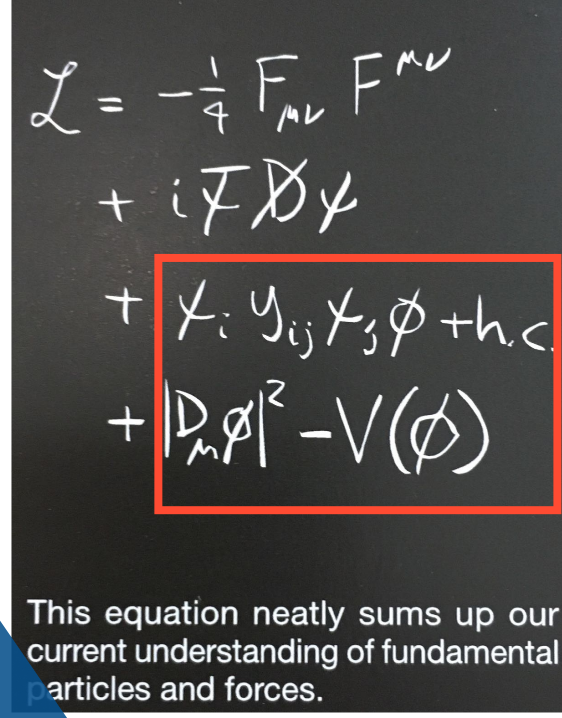
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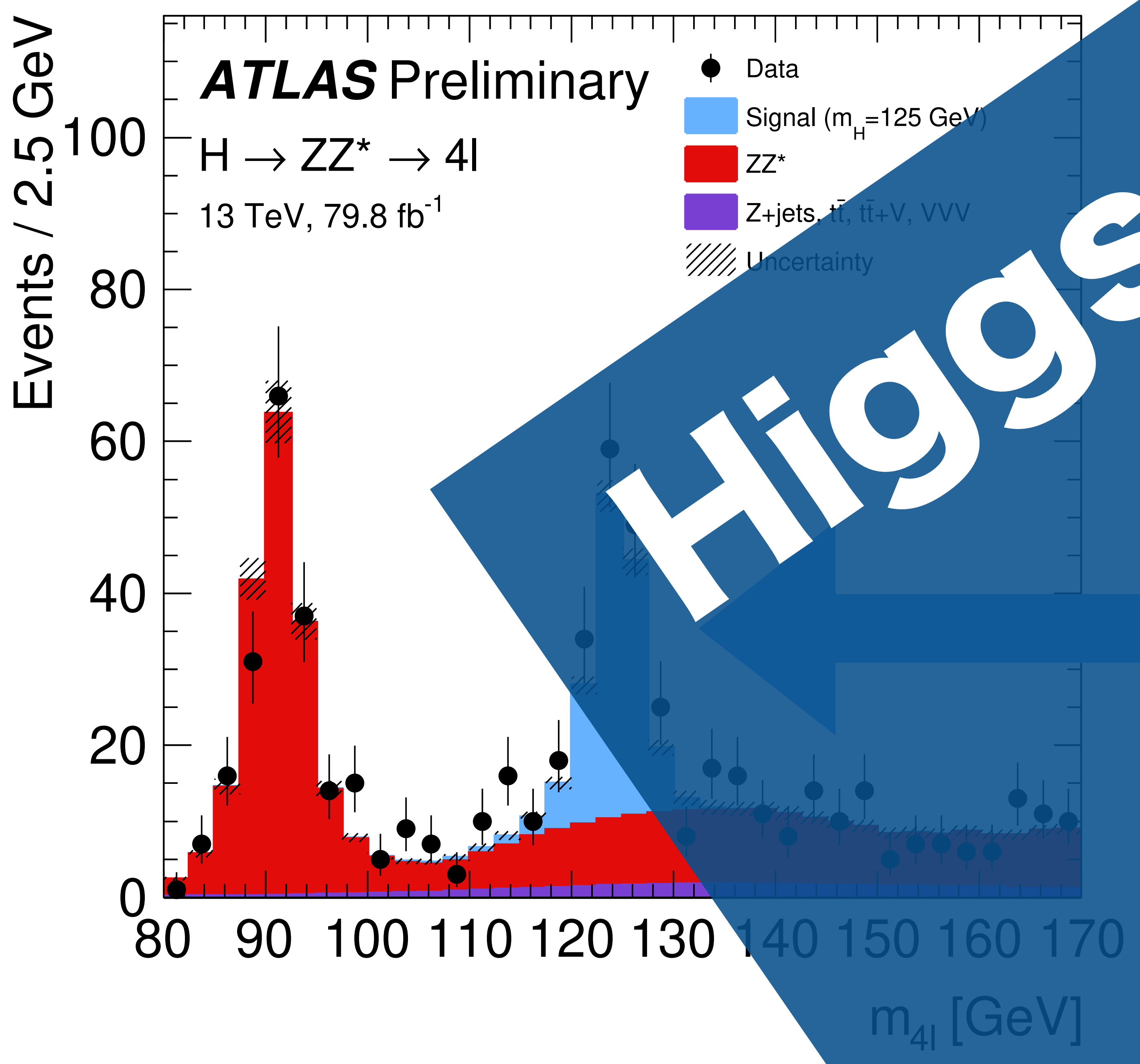
$$\rightarrow g^2\phi_0^2 Z_\mu Z^\mu + 2g^2\phi_0 H Z_\mu Z^\mu + \dots$$

Z boson mass term

ZZH interaction term

Higgs (BEH) mechanism for vector boson mass = 2013 Nobel prize



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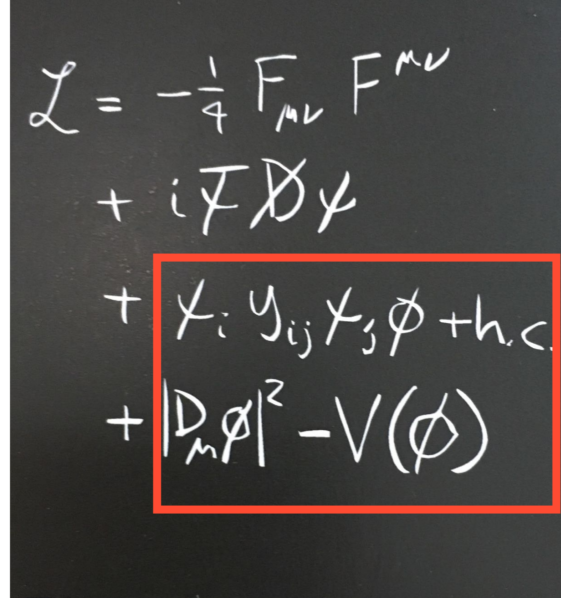
3. Fermion–Higgs (Yukawa) term



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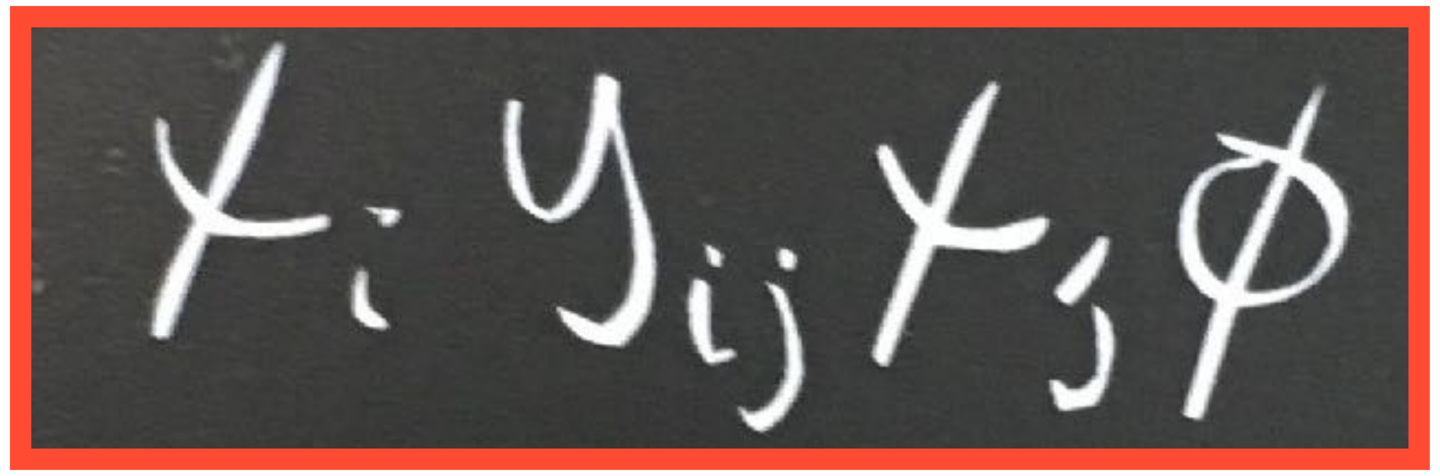

$$\boxed{\psi_i y_{ij} \psi_j \phi} \rightarrow y_{ij} \phi_0 \psi_i \psi_j + y_{ij} H \psi_i \psi_j$$

fermion mass term

$m_i = y_{ii} \phi_0$

fermion-fermion-Higgs interaction term;

coupling $\sim y_{ii}$

i	y_i	i	y_i
u	$2 \cdot 10^{-5}$	d	$3 \cdot 10^{-5}$
c	$8 \cdot 10^{-3}$	s	$6 \cdot 10^{-4}$
b	$3 \cdot 10^{-2}$	t	1
ν_e	$\sim 10^{-13}$?	e	$3 \cdot 10^{-6}$
ν_μ		μ	$6 \cdot 10^{-4}$
ν_τ		τ	$1 \cdot 10^{-4}$

$$\phi = \phi_0 + H$$

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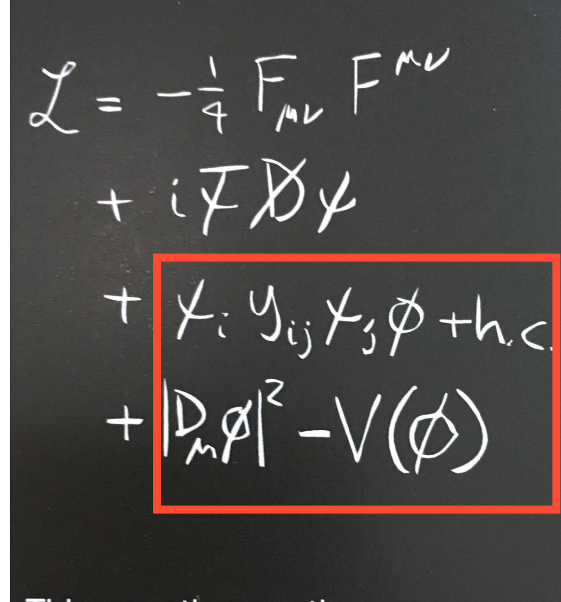

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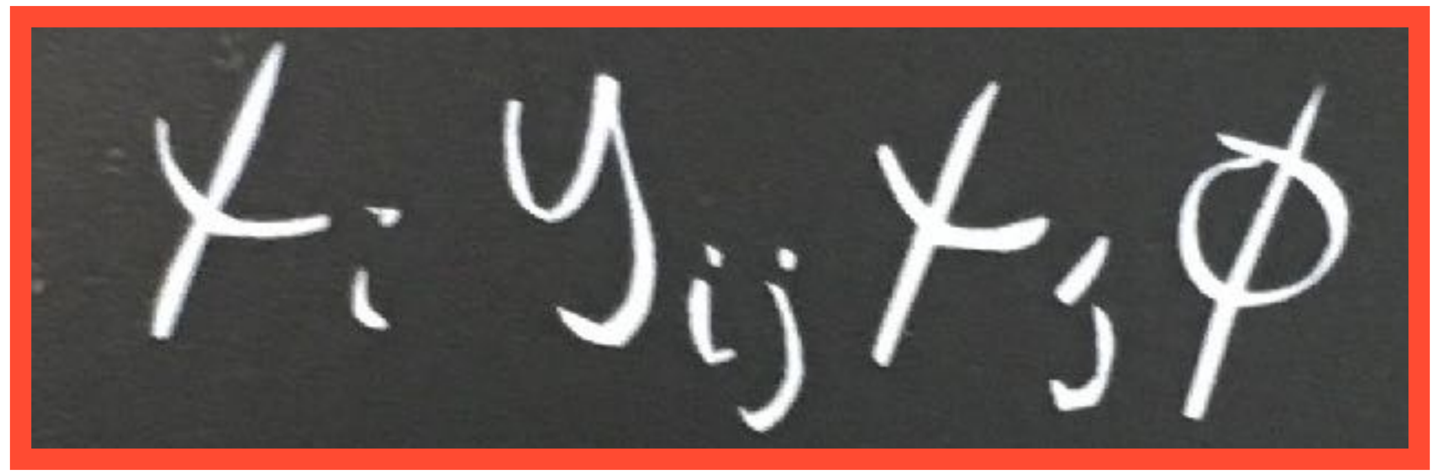

$$\psi_i y_{ij} \psi_j \phi$$

$$\to y_{ij}\phi_0\psi_i\psi_j \qquad y_{ij}H\psi_i\psi_j$$

fermion mass term

$m_i = y_{ii}\phi_0$

fermion-fermion-Higgs interaction term;

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ν_τ		τ	$1 \cdot 10^{-4}$

the subject of the next few slides

$$\phi = \phi_0 + H$$

concentrate on Yukawa interaction hypothesis

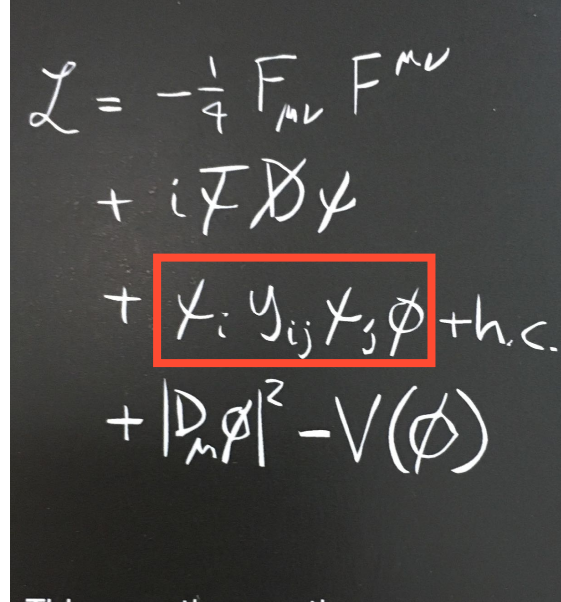
Yukawa couplings ~ fermion mass

first fundamental interaction that we probe at the quantum level where interaction strength is not quantised

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

Why do Yukawa couplings matter?

(1) Because, within SM conjecture, they're what give masses to all quarks



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

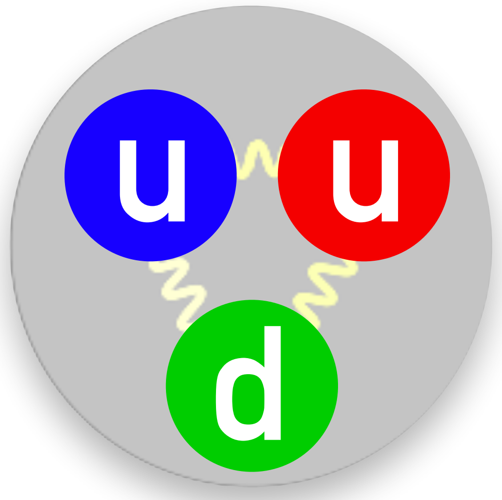
Up quarks (mass ~ 2.2 MeV) are lighter than
down quarks (mass ~ 4.7 MeV)

proton (up+up+down): 2.2 + 2.2 + 4.7 + … = 938.3 MeV
neutron (up+down+down): 2.2 + 4.7 + 4.7 + … = 939.6 MeV

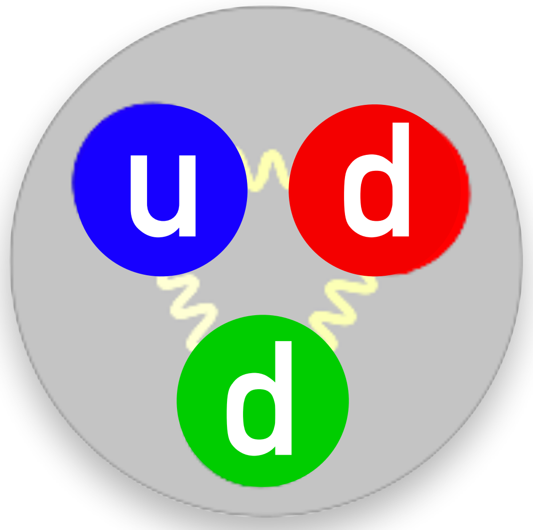
So protons are **lighter** than neutrons,
→ protons are stable.

Which gives us the hydrogen atom,
& chemistry and biology as we know it

proton
mass = 938.3MeV

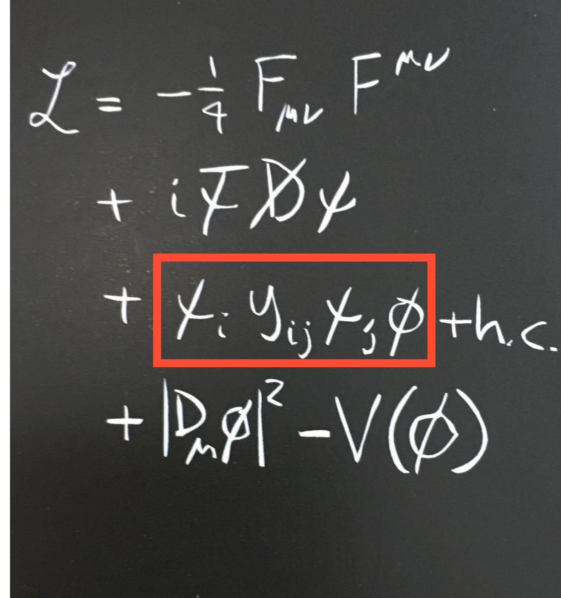


neutron
mass = 939.6MeV



Why do Yukawa couplings matter?

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



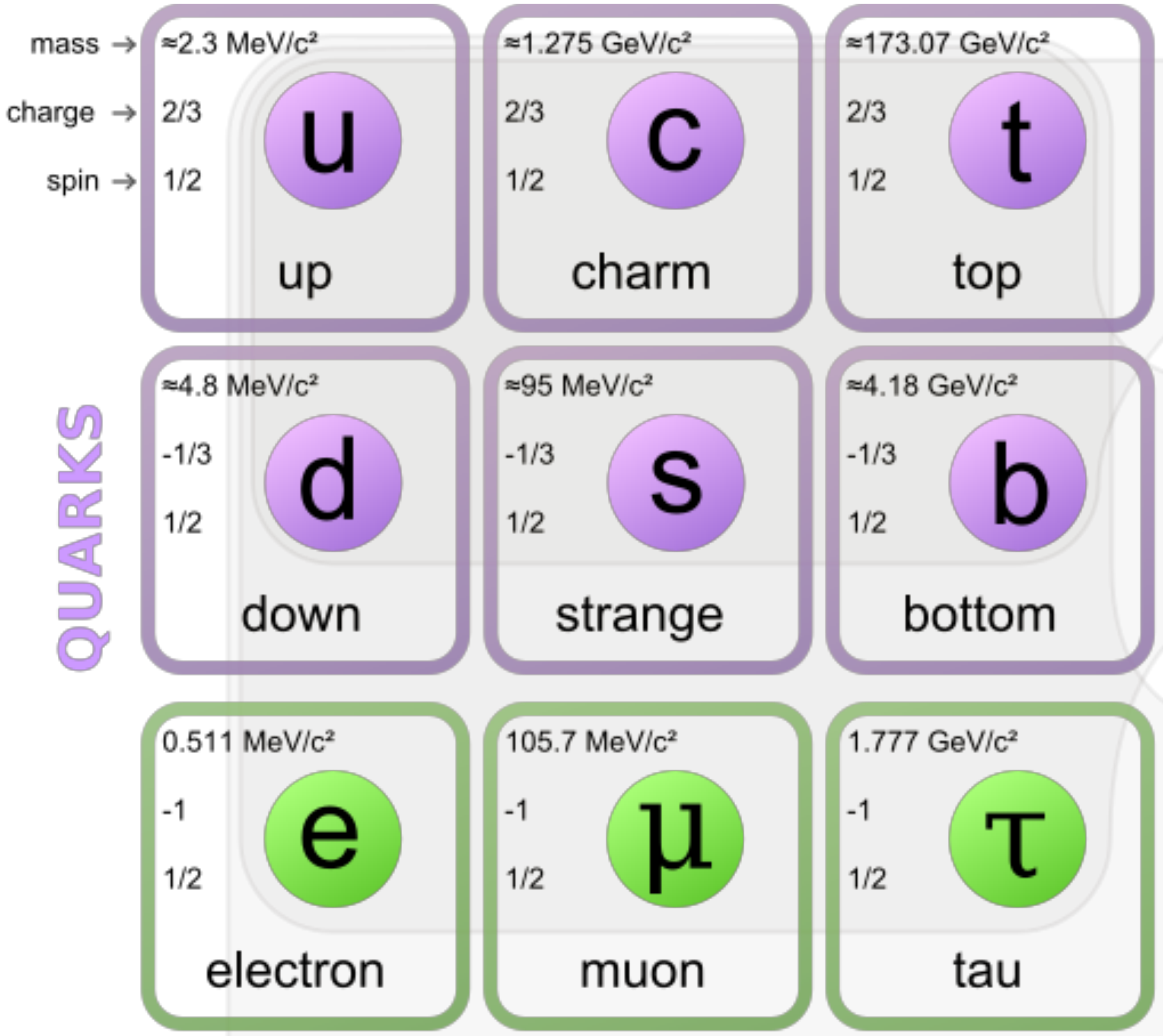
This equation neatly sums up our current understanding of fundamental particles and forces.

Bohr radius

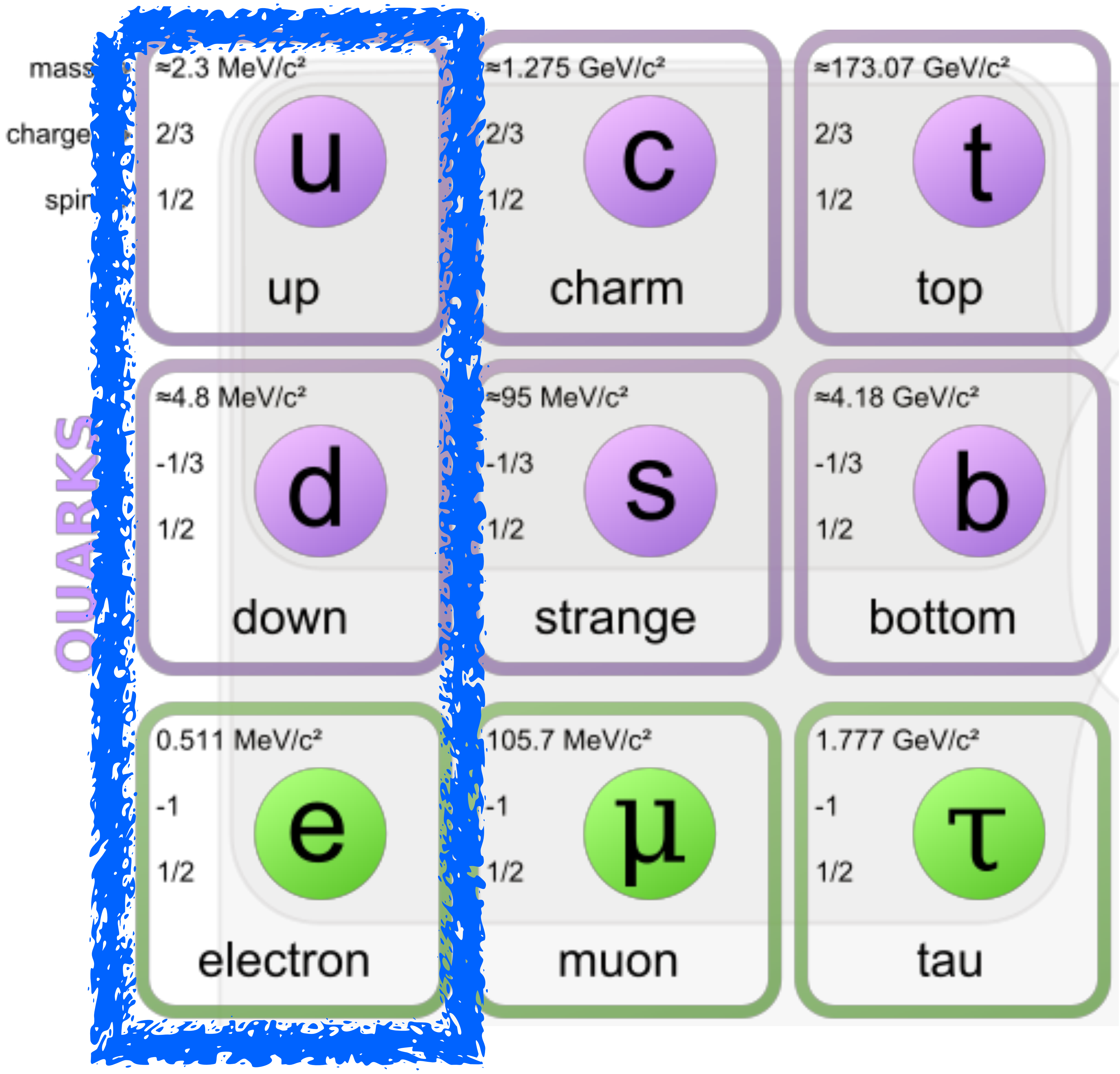
$$a_0 = \frac{4\pi\varepsilon_0 \hbar^2}{m_e e^2} = \frac{\hbar}{m_e\, c\, \alpha}$$

electron mass determines size of all atoms

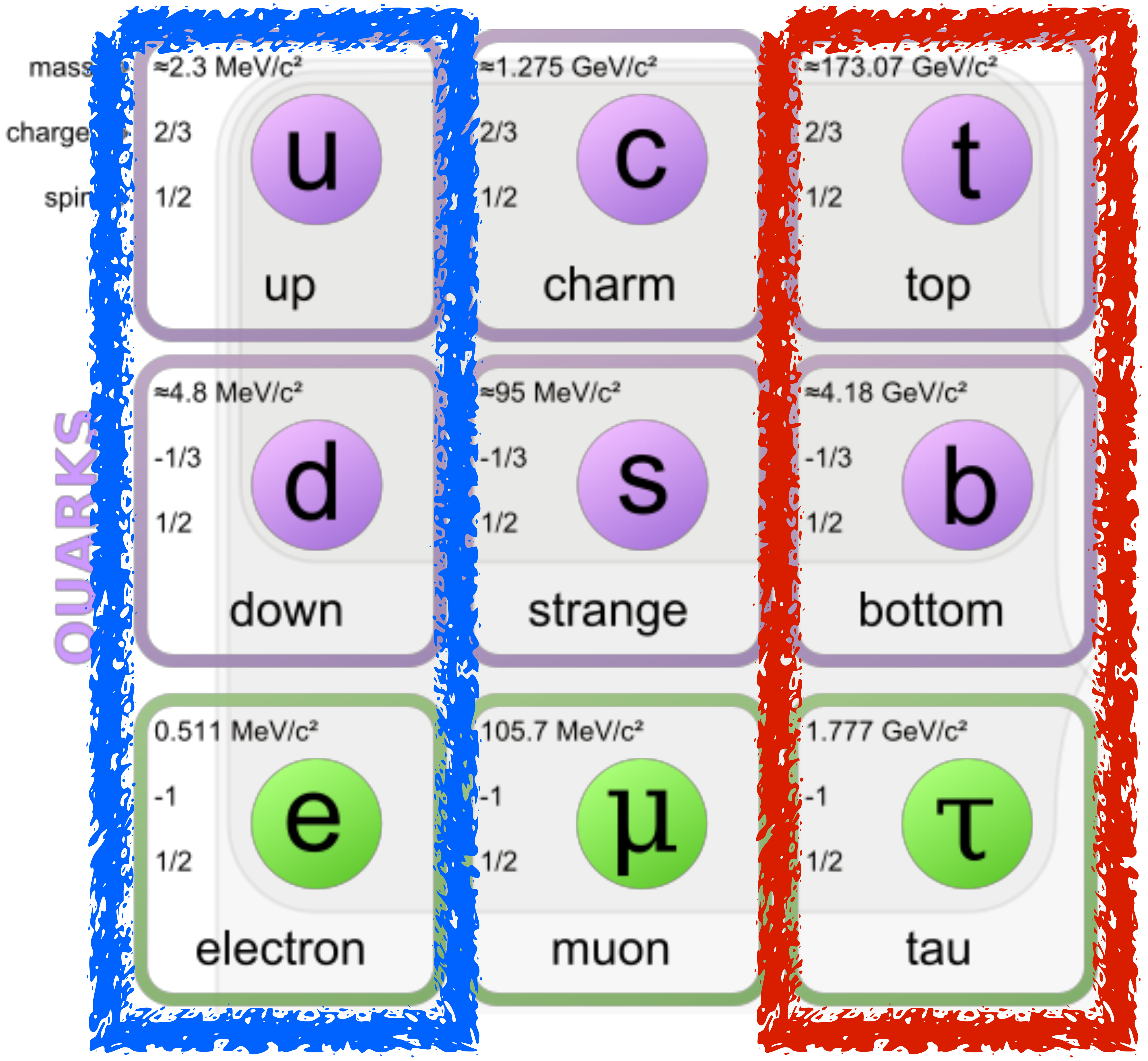
it sets energy levels of all chemical reactions



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau

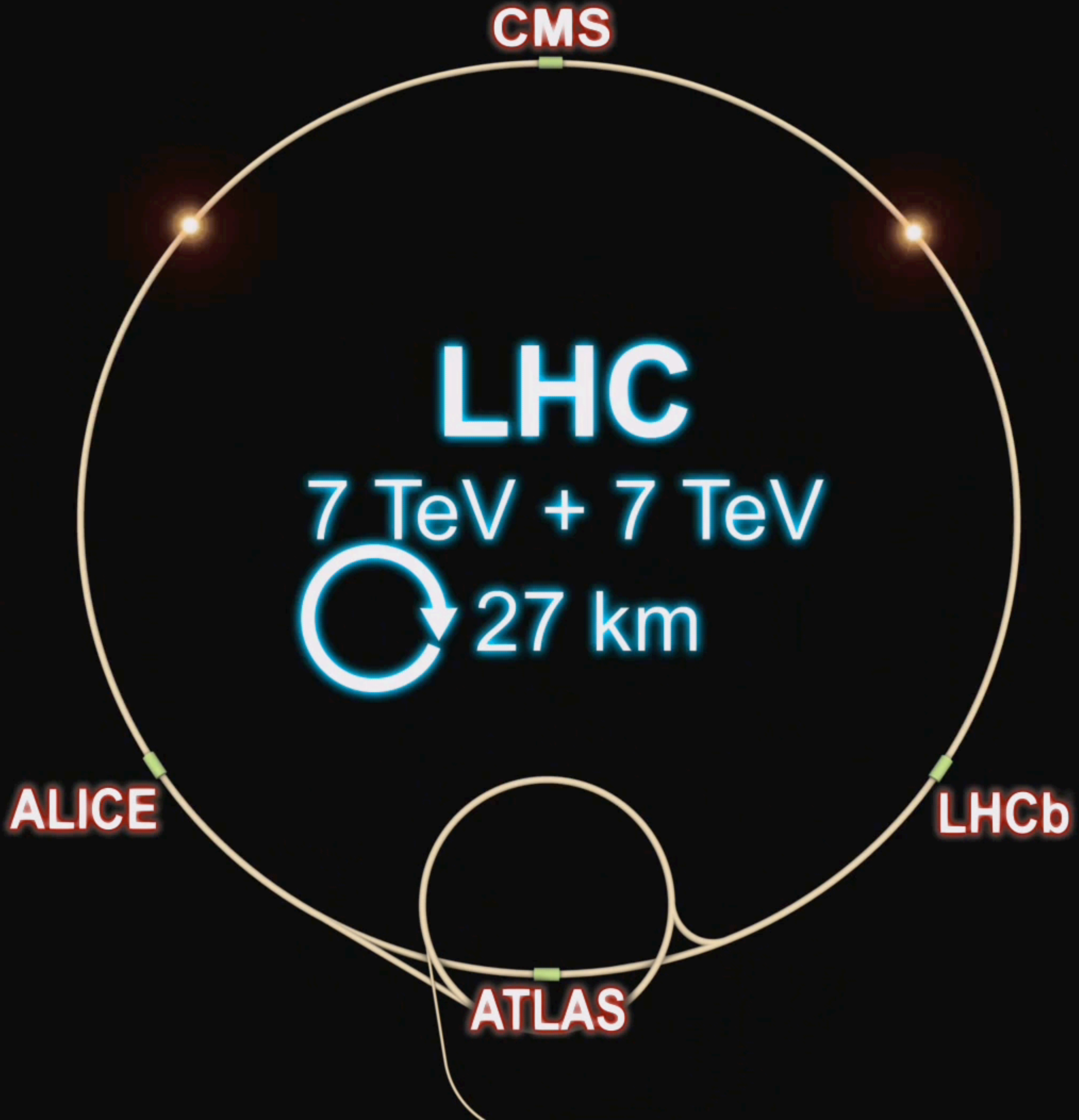


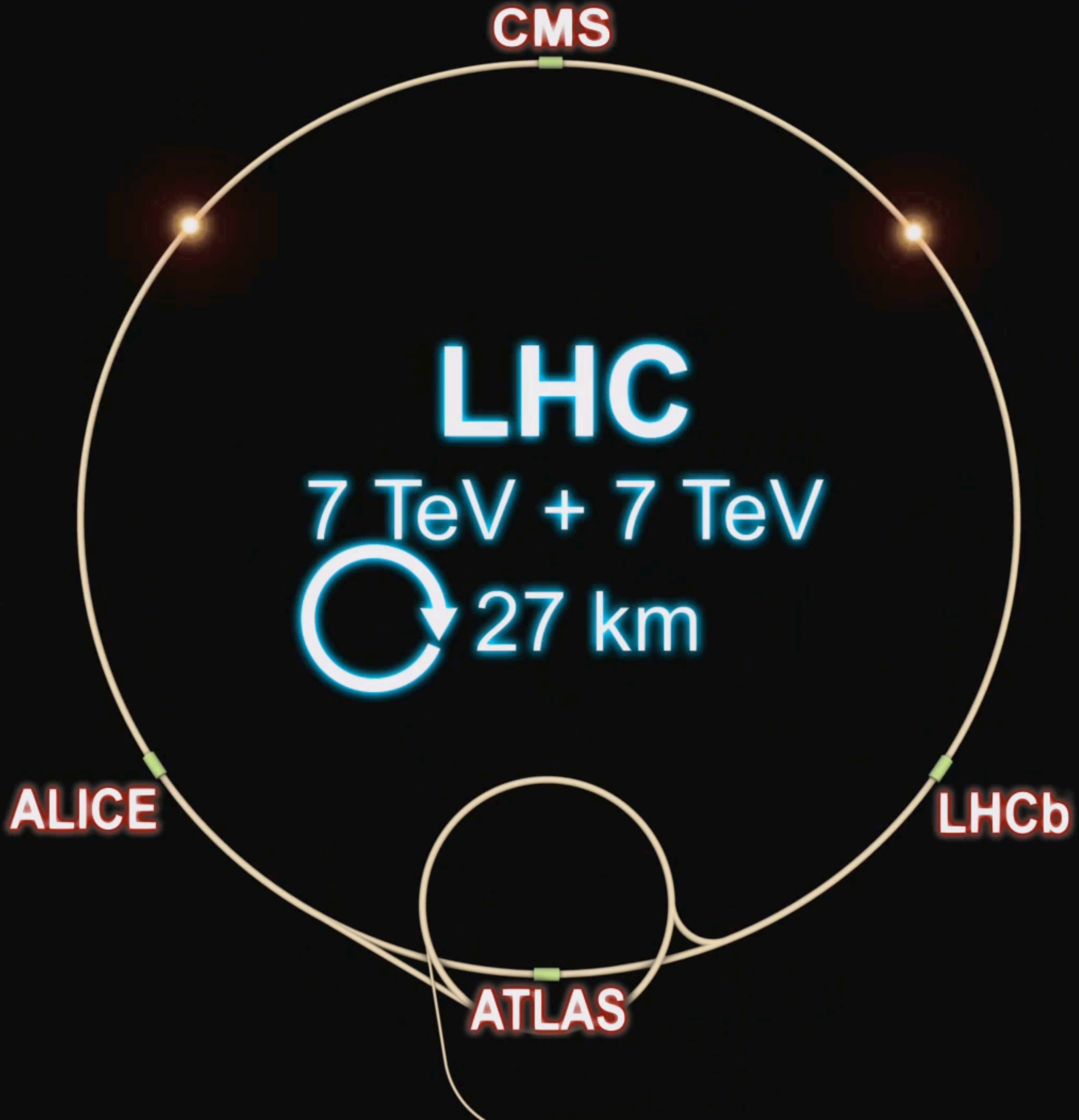
1st generation (us) has low mass because of weak interactions with Higgs field (and so with Higgs bosons): **too weak to test today**



1st generation (us) has low mass because of weak interactions with Higgs field (and so with Higgs bosons): too weak to test today

3rd generation (us) has high mass because of strong interactions with Higgs field (and so with Higgs bosons): can potentially be tested

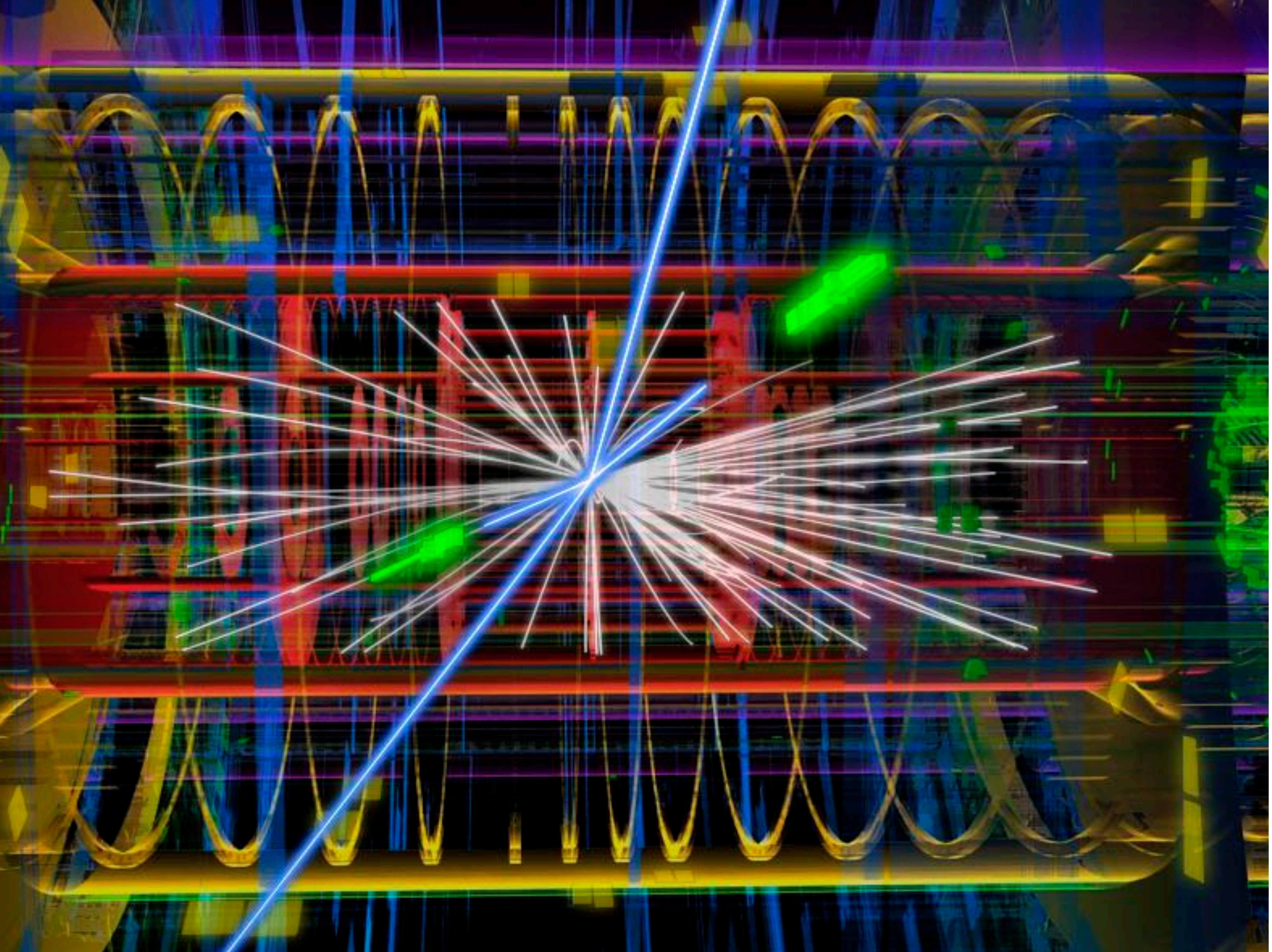

CMS
LHC
7 TeV + 7 TeV
27 km
ALICE
LHCb
ATLAS



LHC

7 TeV + 7 TeV

⟳ 27 km



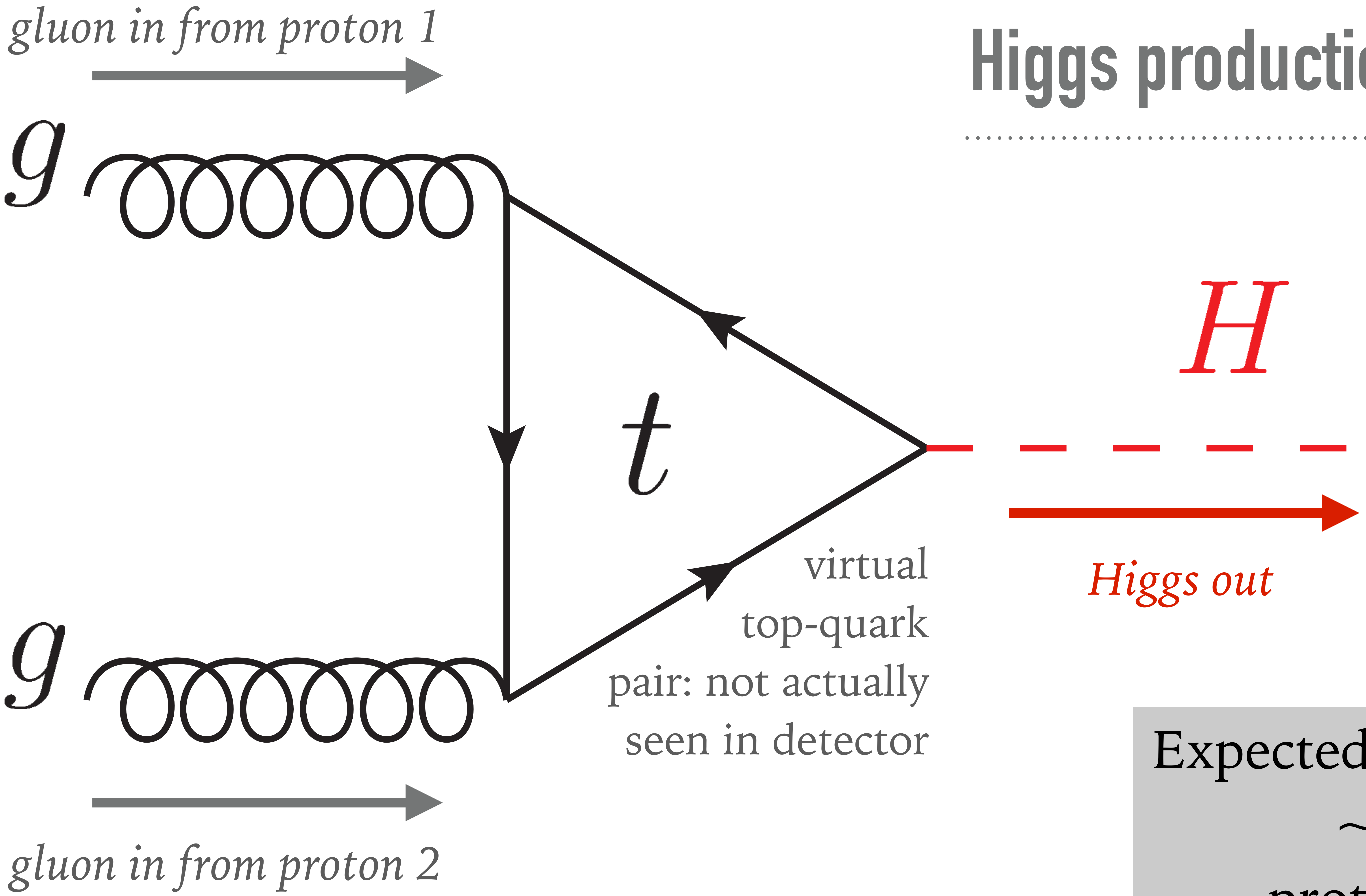
ATLAS & CMS @LHC

~up to 2 billion collisions/second

(+ lower rates at LHCb and ALICE)

what underlying processes tell us about Yukawa interactions?

Higgs production: the dominant channel



gluon in from proton 1

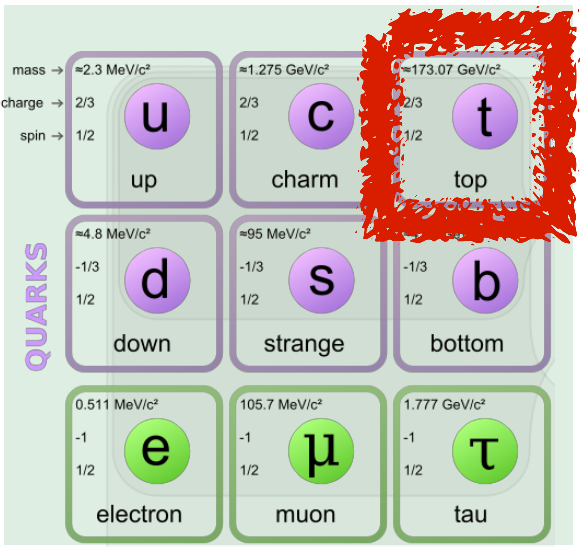
gluon in from proton 2

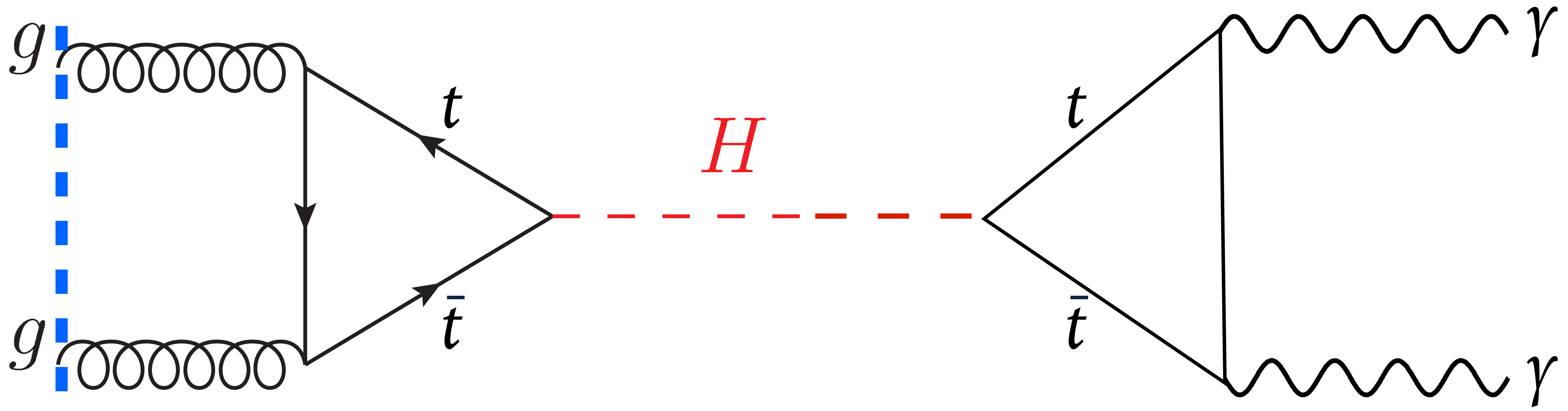
virtual
top-quark
pair: not actually
seen in detector

Higgs out

Expected to happen once for every
~2 billion inelastic
proton–proton collisions

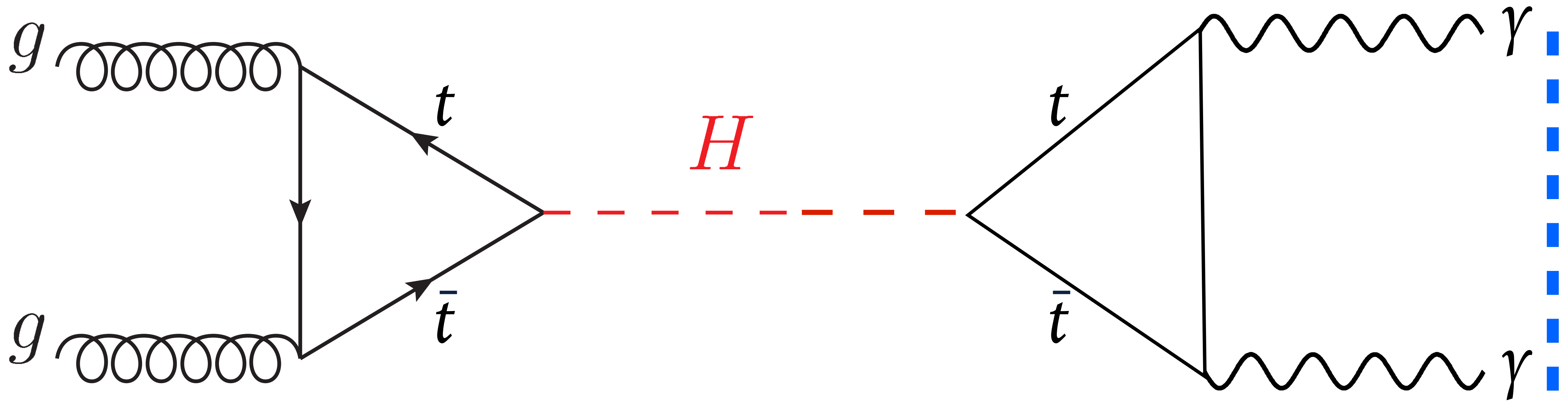
LHC data consistent with that
already at discovery in 2012





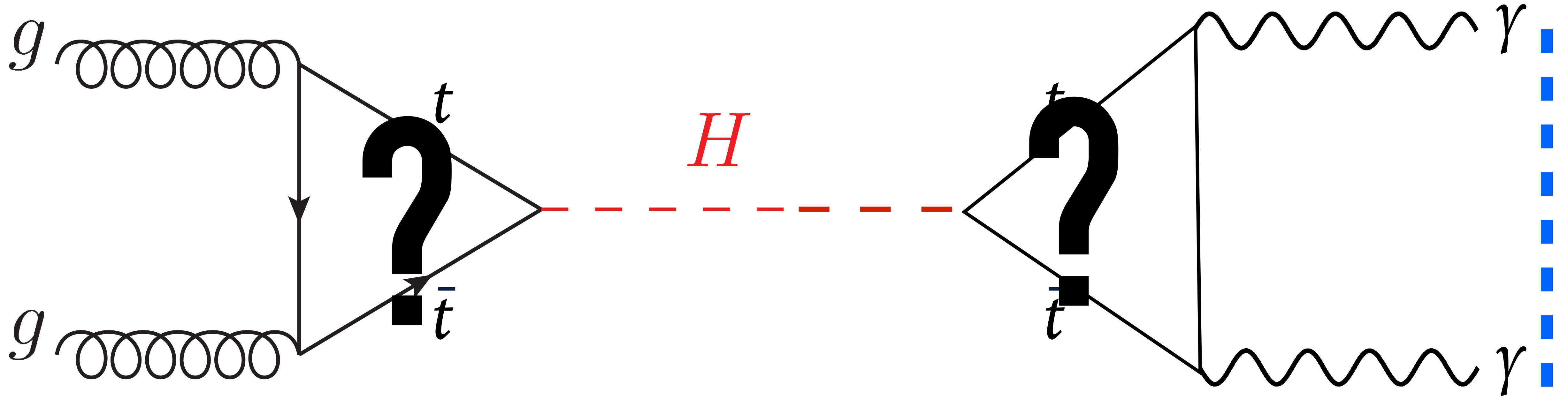
Higgs field in space

https://cern.ch/gsalam/higgs/repo/higgs-waves.mp4



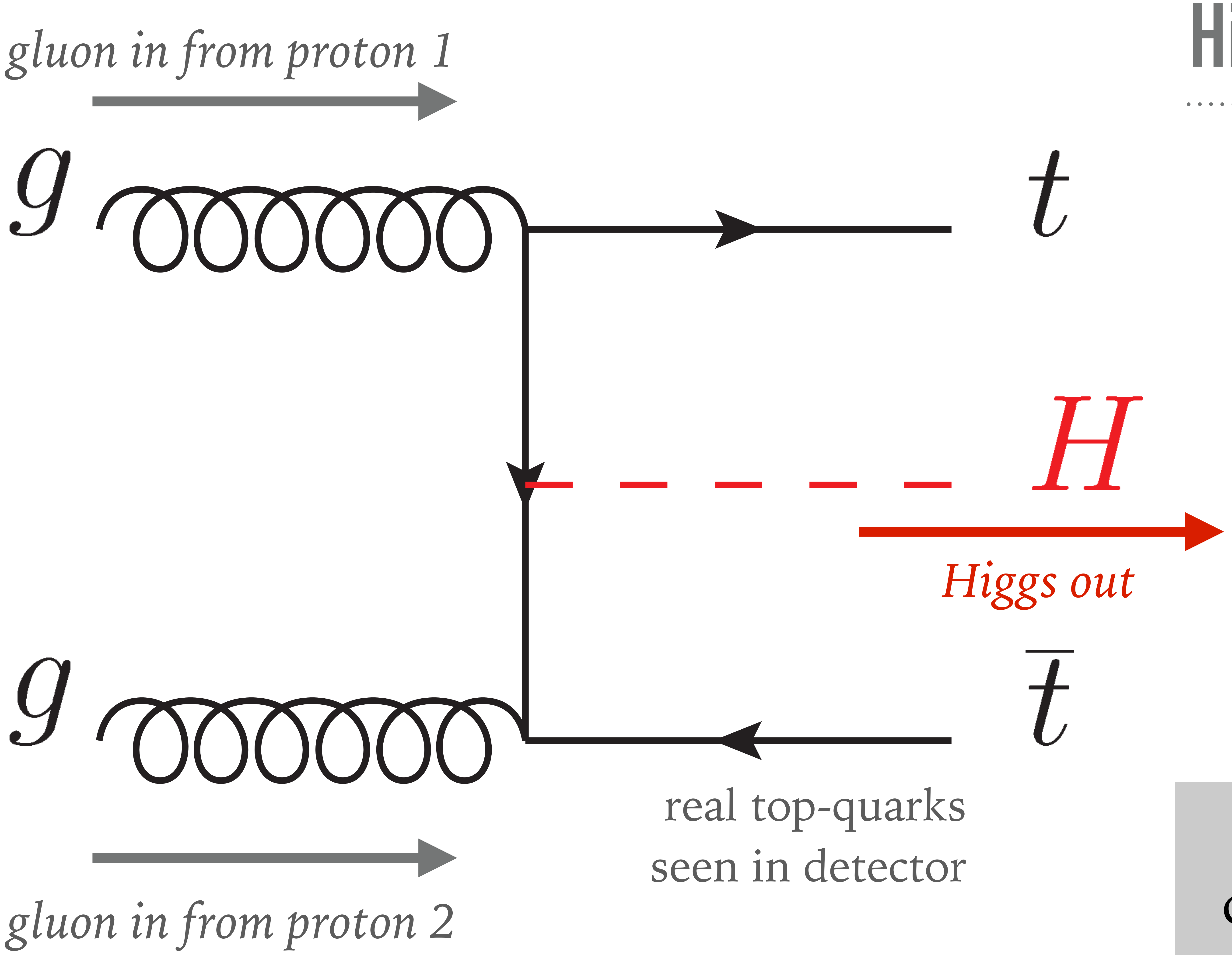
https://cern.ch/gsalam/higgs/repo/higgs-waves.mp4

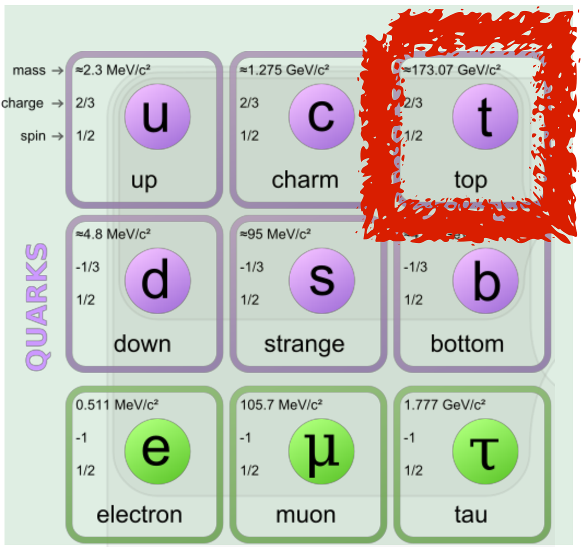
but how can you be sure the Higgs boson is really being radiated off a top-quark, i.e. that you're actually seeing a Yukawa coupling?



https://cern.ch/gsalam/higgs/repo/higgs-waves.mp4

Higgs production: the ttH channel



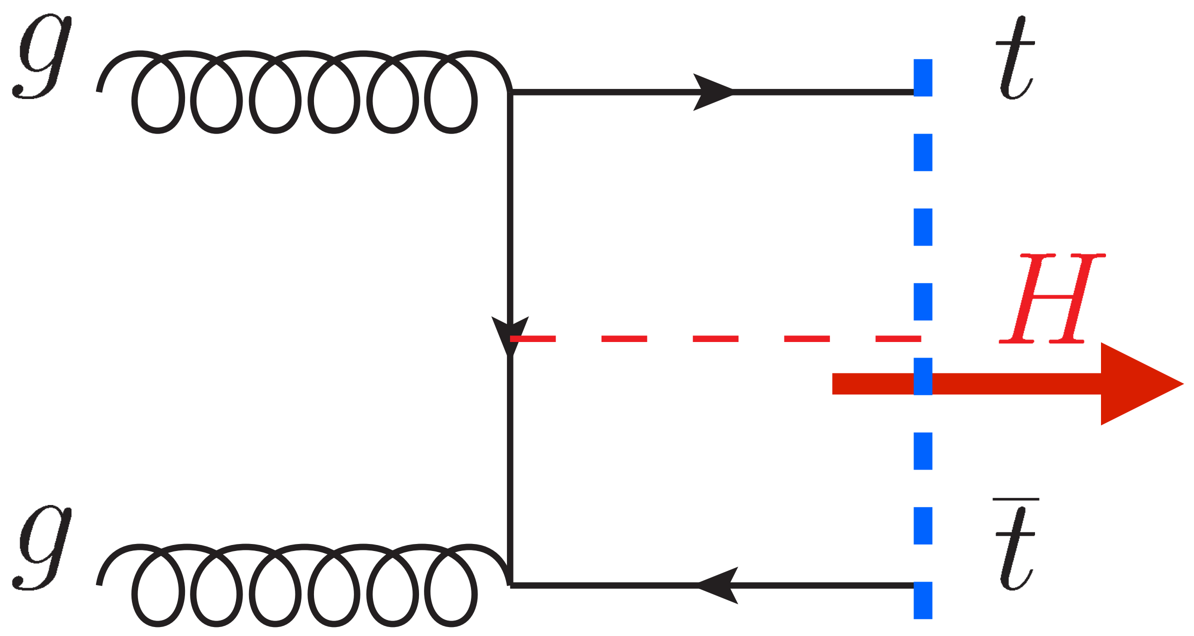


If SM top-Yukawa hypothesis is correct, expect 1 Higgs for every 1600 top-quark pairs.

(rather than 1 Higgs for every 2 billion pp collisions)

https://cern.ch/gsalam/higgs/repo/ttH.mp4

https://cern.ch/gsalam/higgs/repo/ttH.mp4



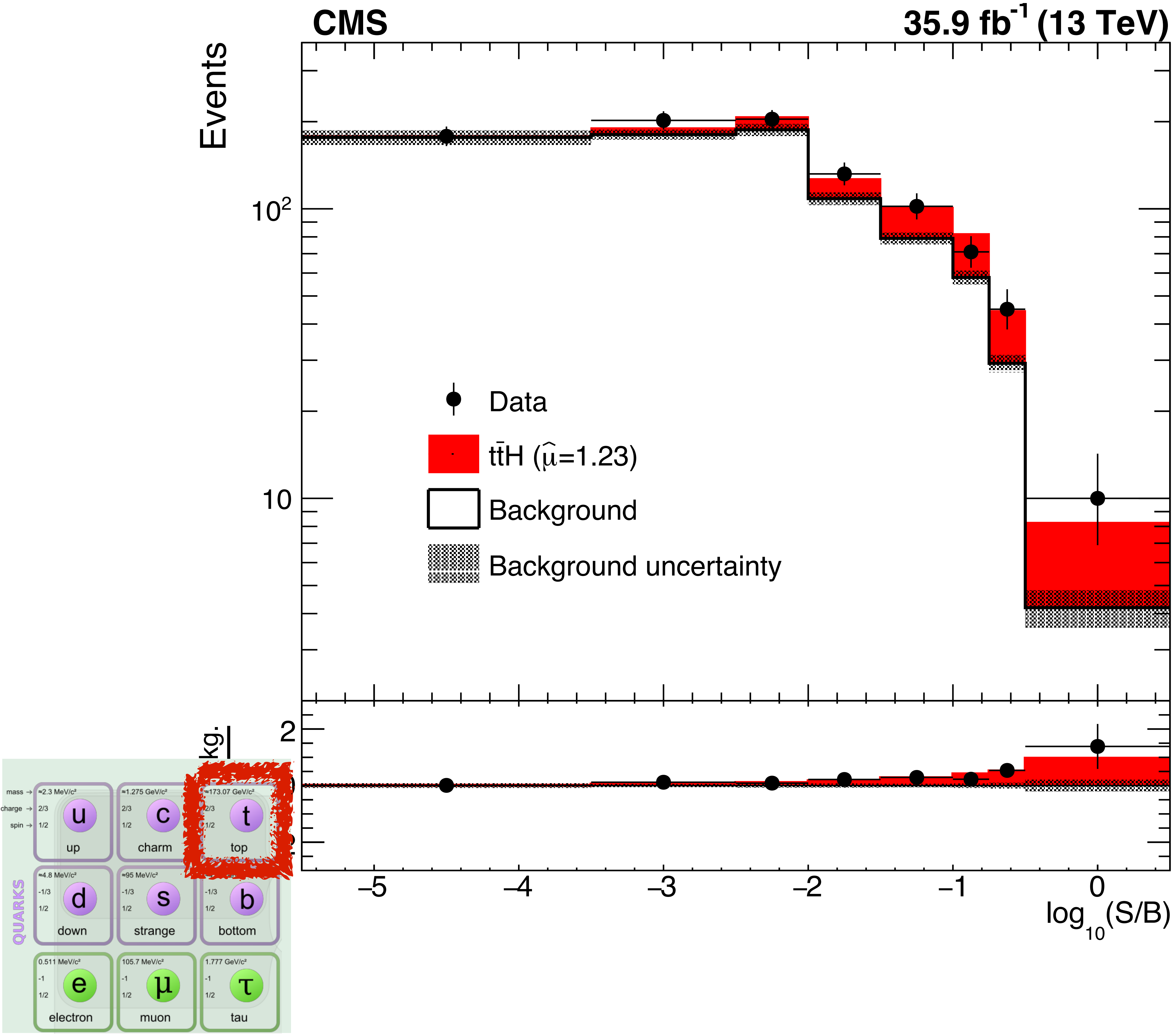
Higgs field in space

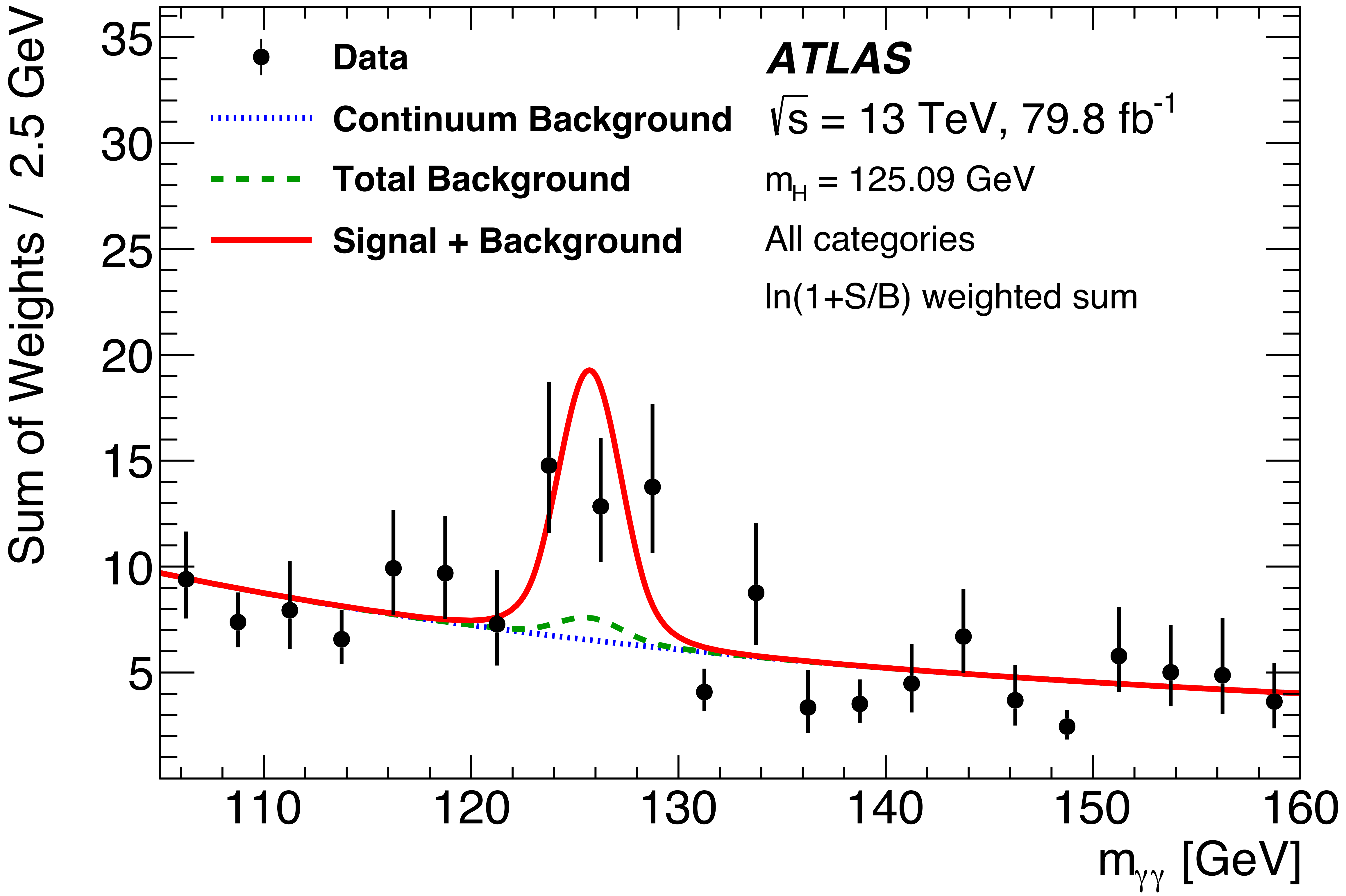
https://cern.ch/gsalam/higgs/repo/ttH.mp4

the news of the past year: ATLAS & CMS see events with top-quarks & Higgs simultaneously

CMS > 5-sigma ttH

ATLAS > 5-sigma ttH





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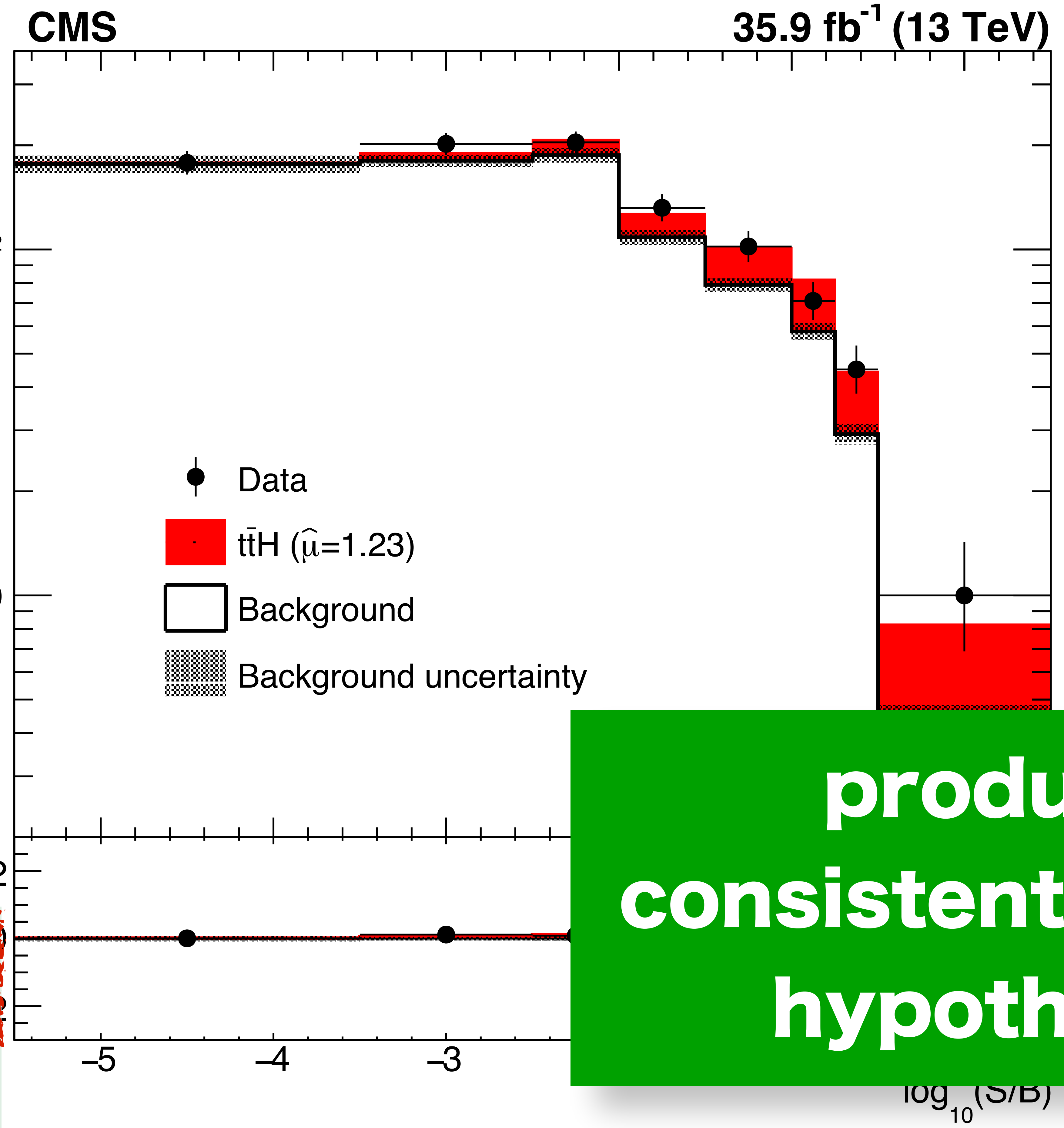
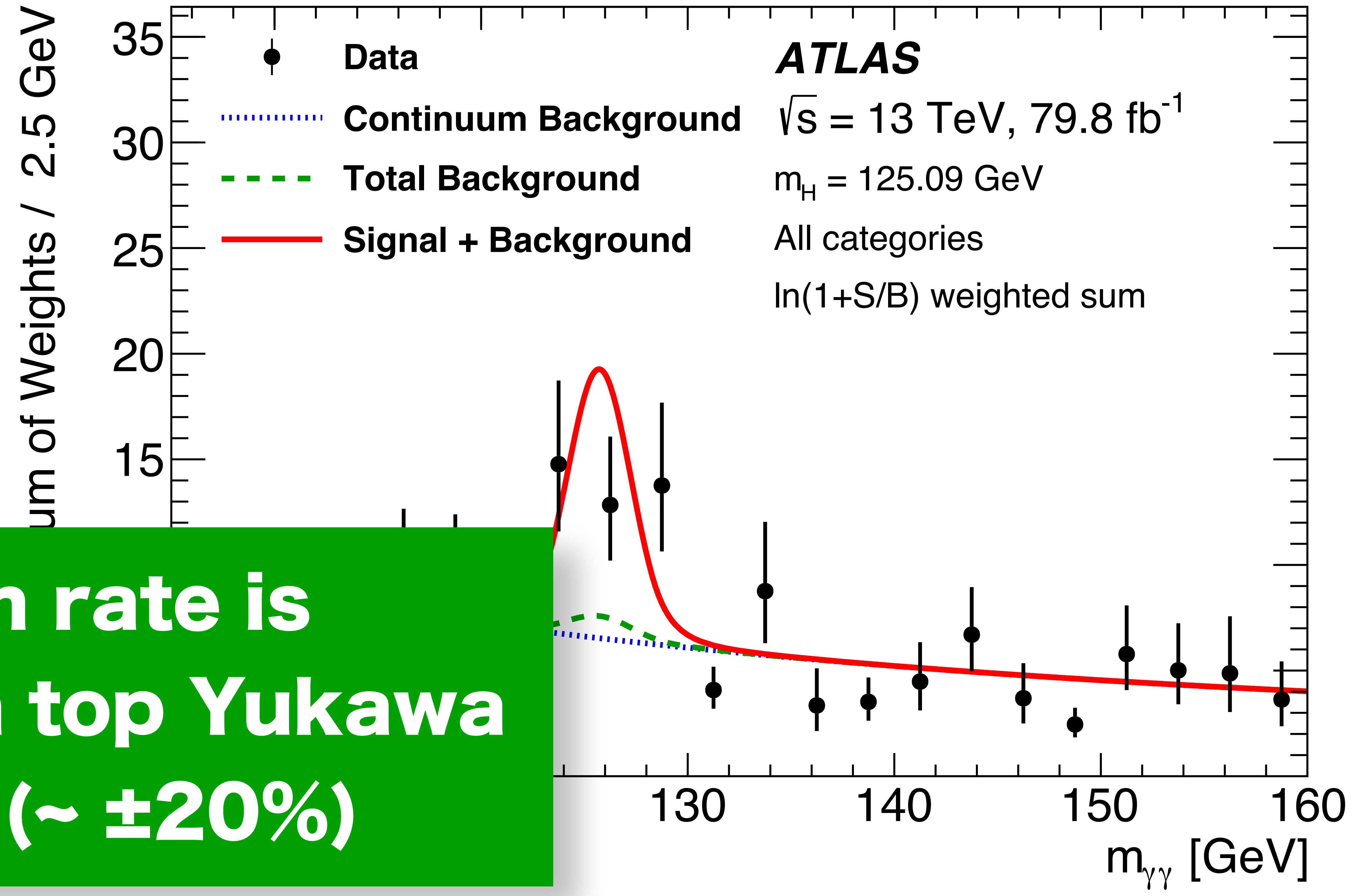
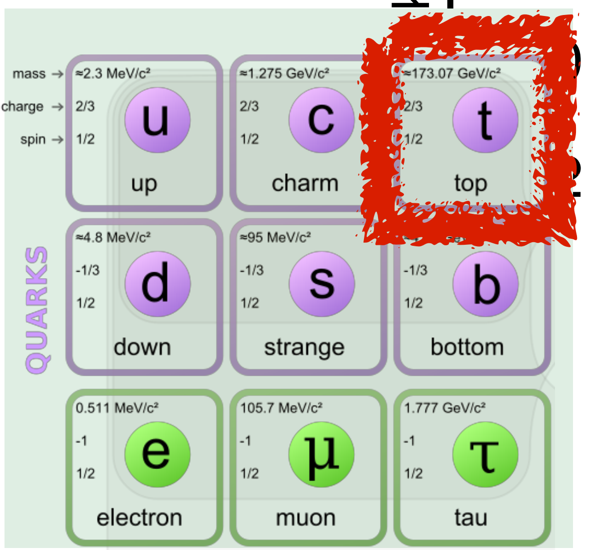
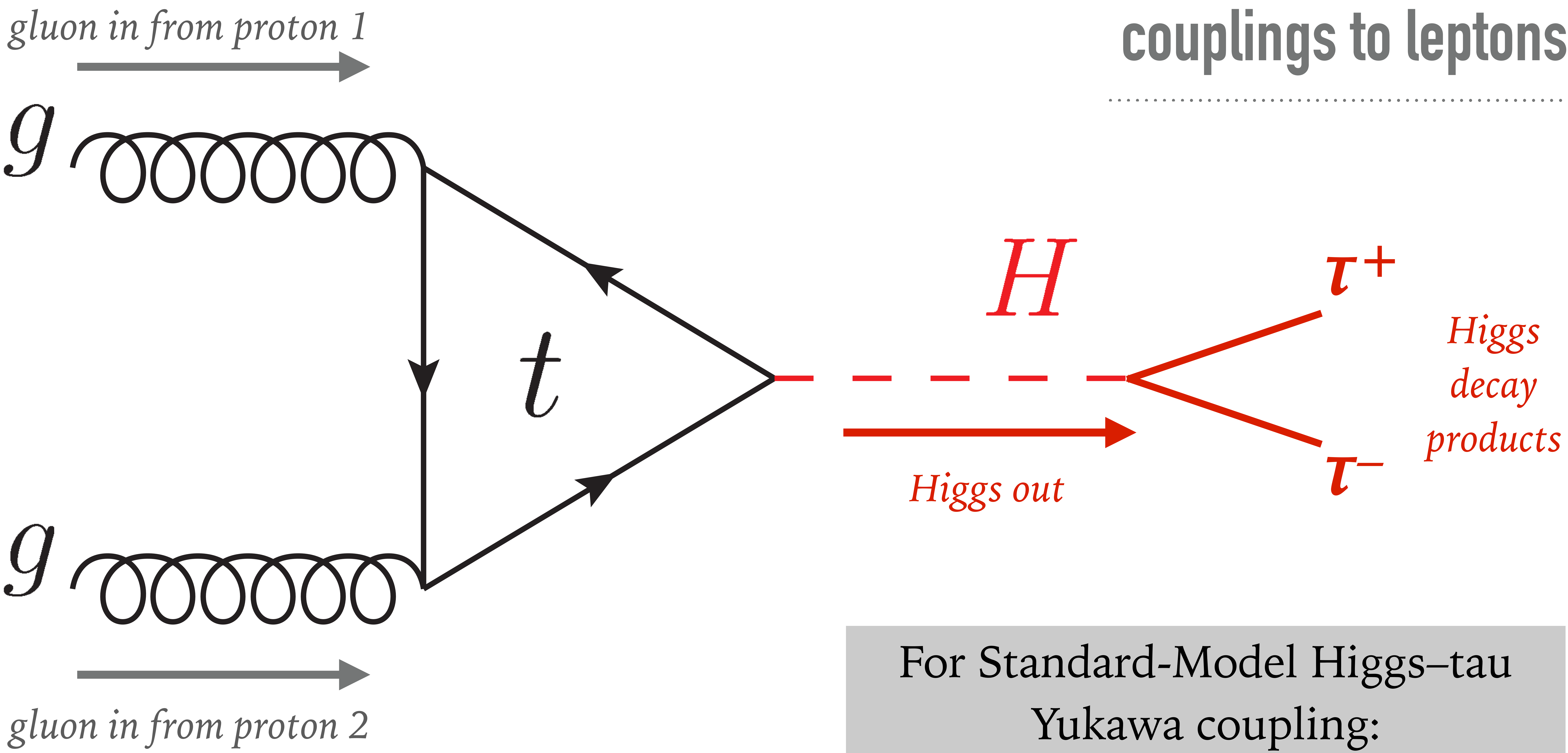




production rate is consistent with top Yukawa hypothesis (~ ±20%)

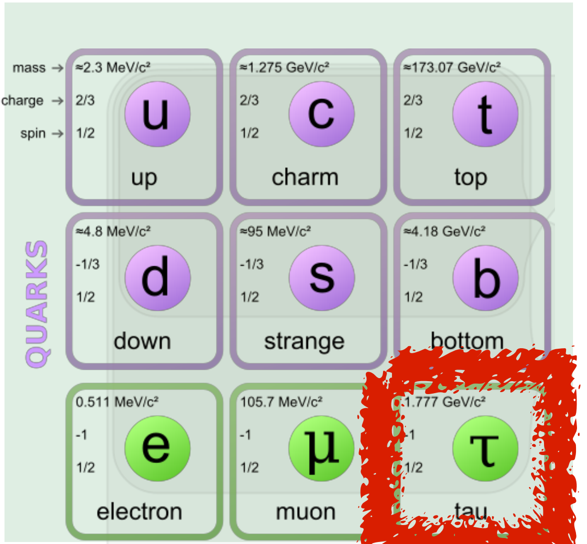


couplings to leptons?



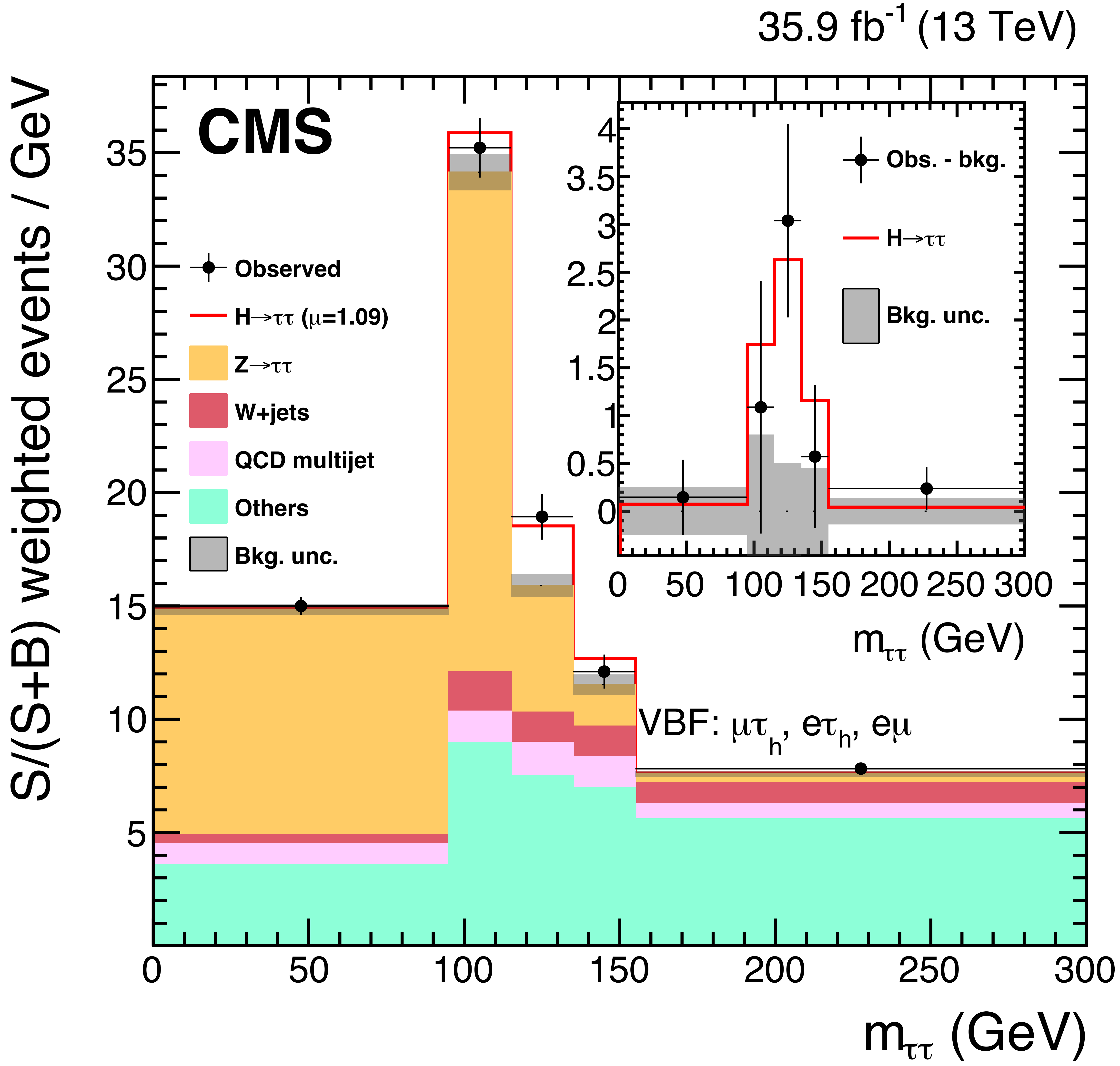
For Standard-Model Higgs–tau Yukawa coupling:

~ 1 in every 16 Higgs bosons decays to $\tau^+\tau^-$

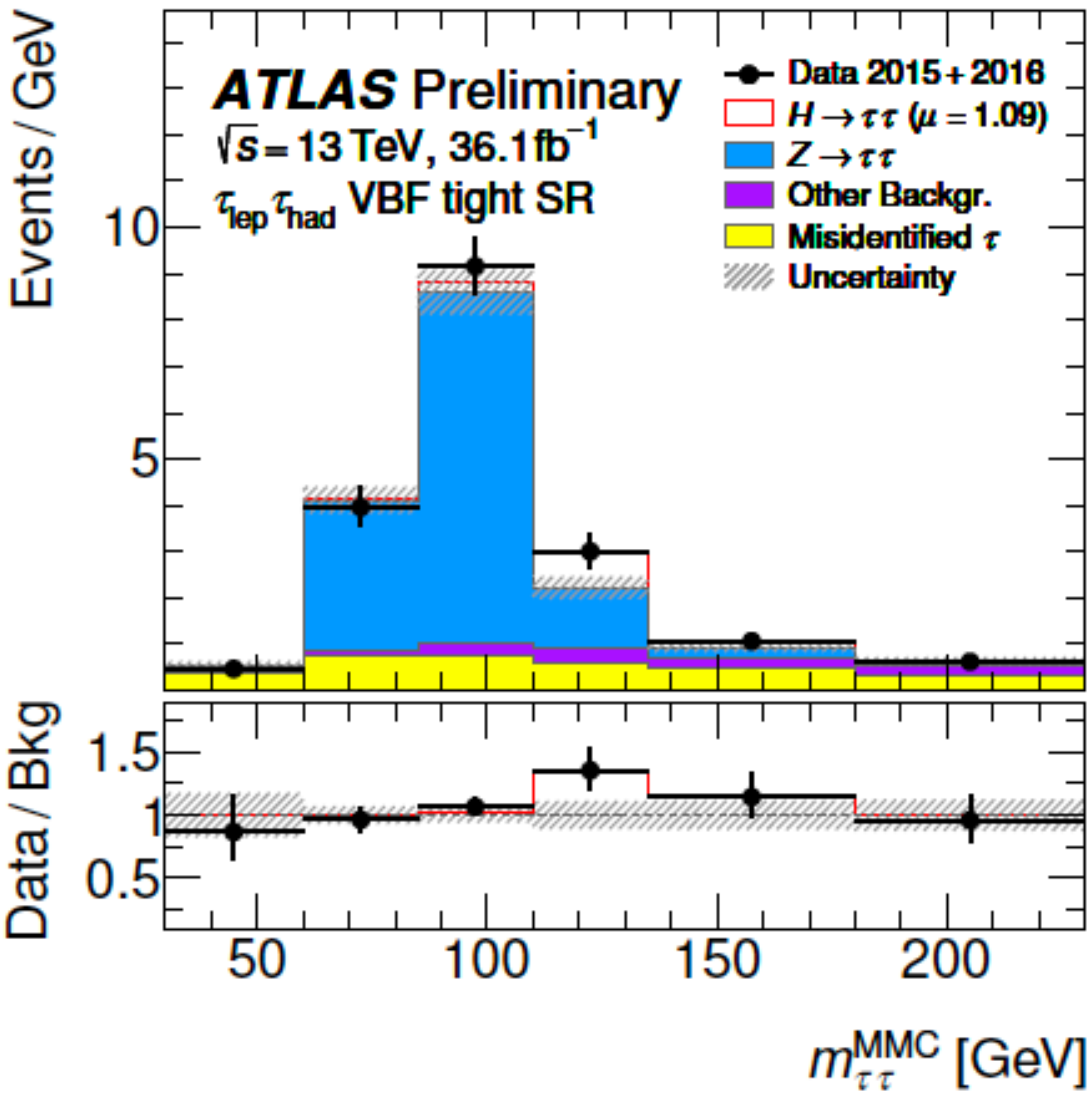


observation of H → ττ

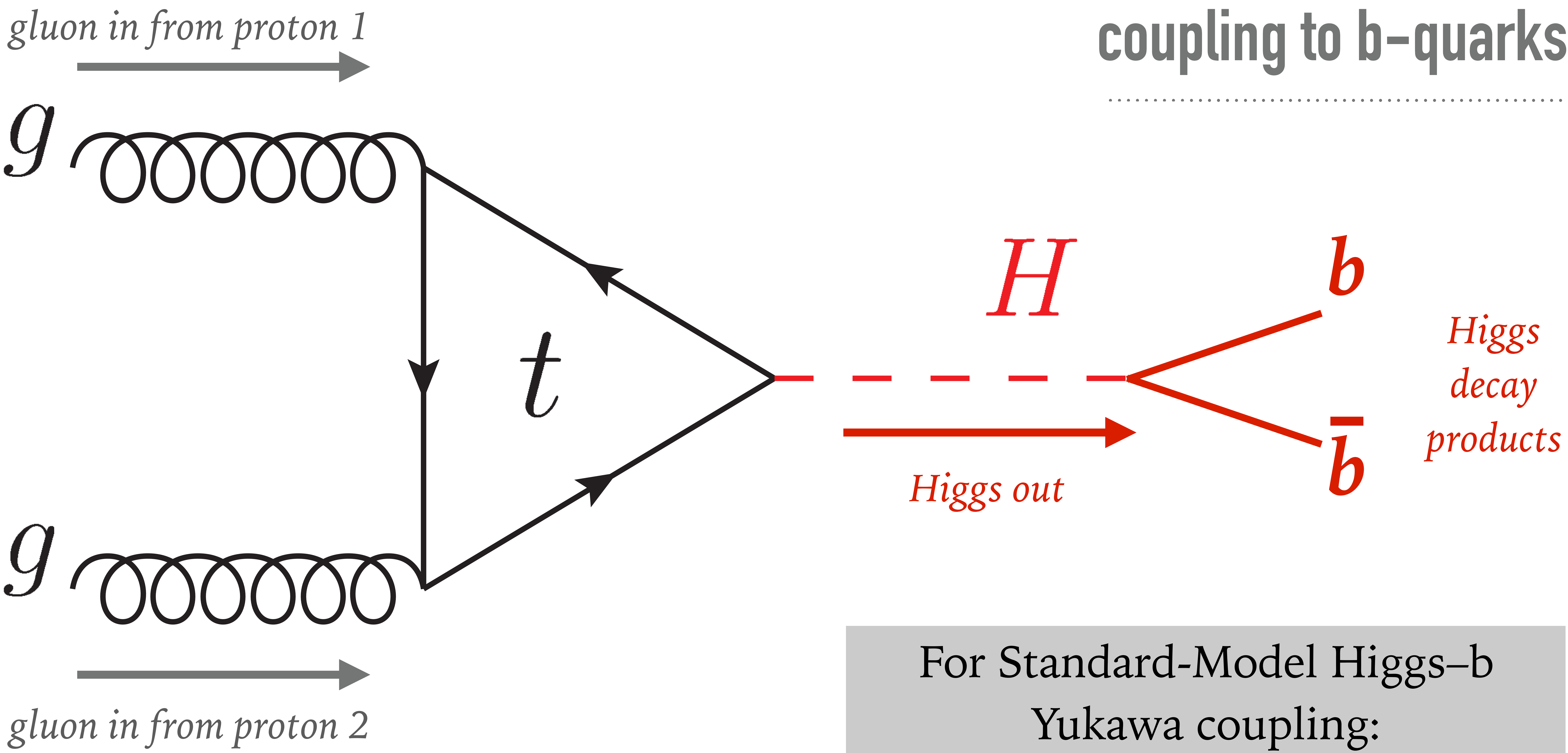
~2 years ago:
CMS >5-sigma H → $\tau\tau$



1 year ago:
ATLAS >5-sigma H → $\tau\tau$



coupling to b-quarks?



gluon in from proton 1

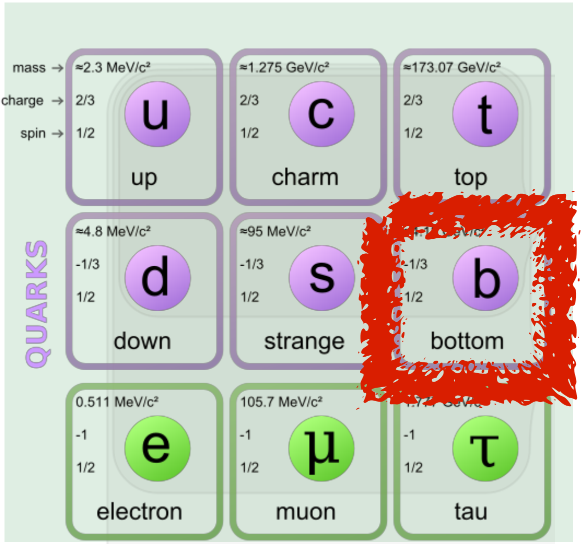
gluon in from proton 2

Higgs out

Higgs decay products

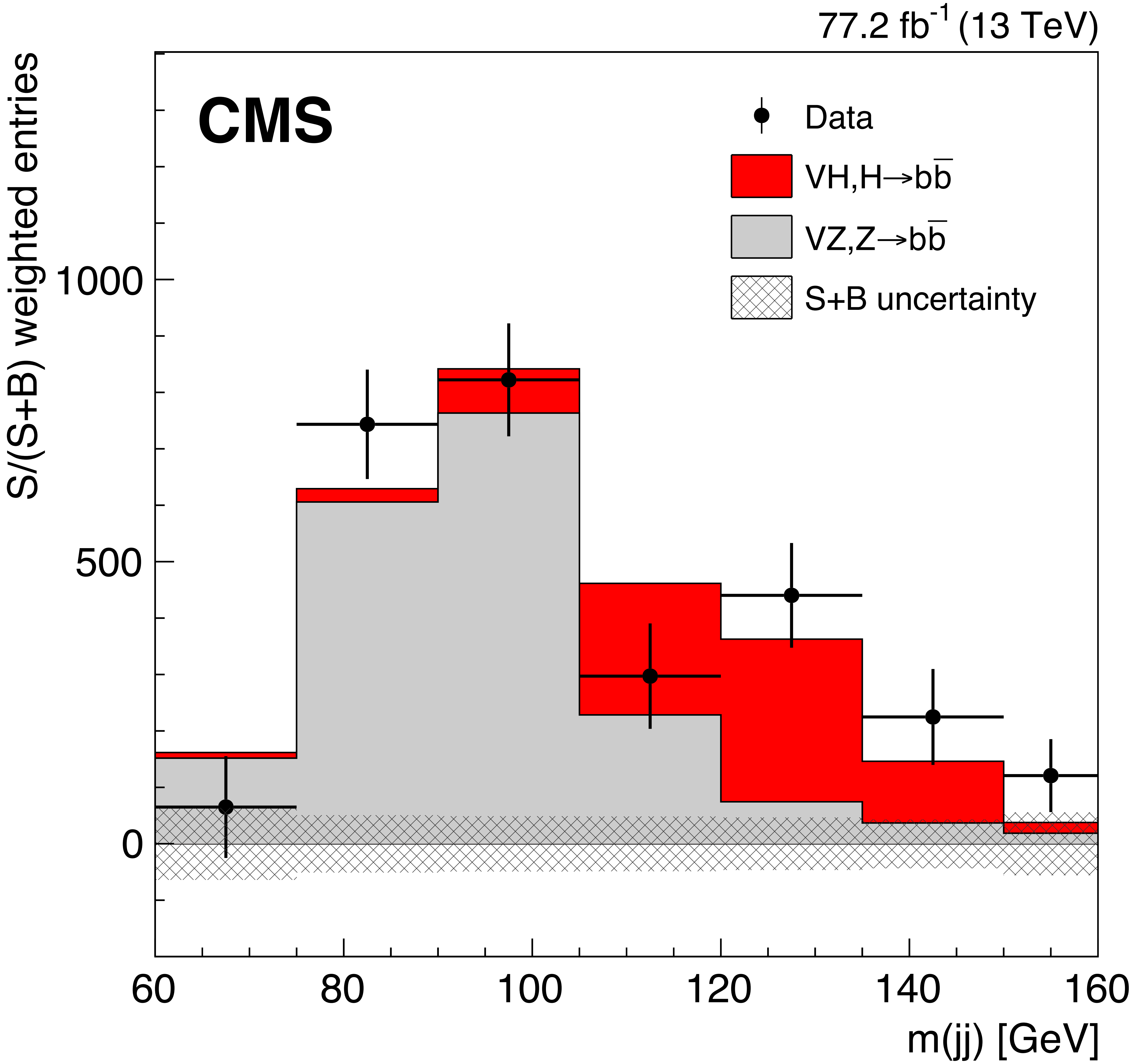
For Standard-Model Higgs–b Yukawa coupling:

~ 58% of Higgs bosons should decay to bb

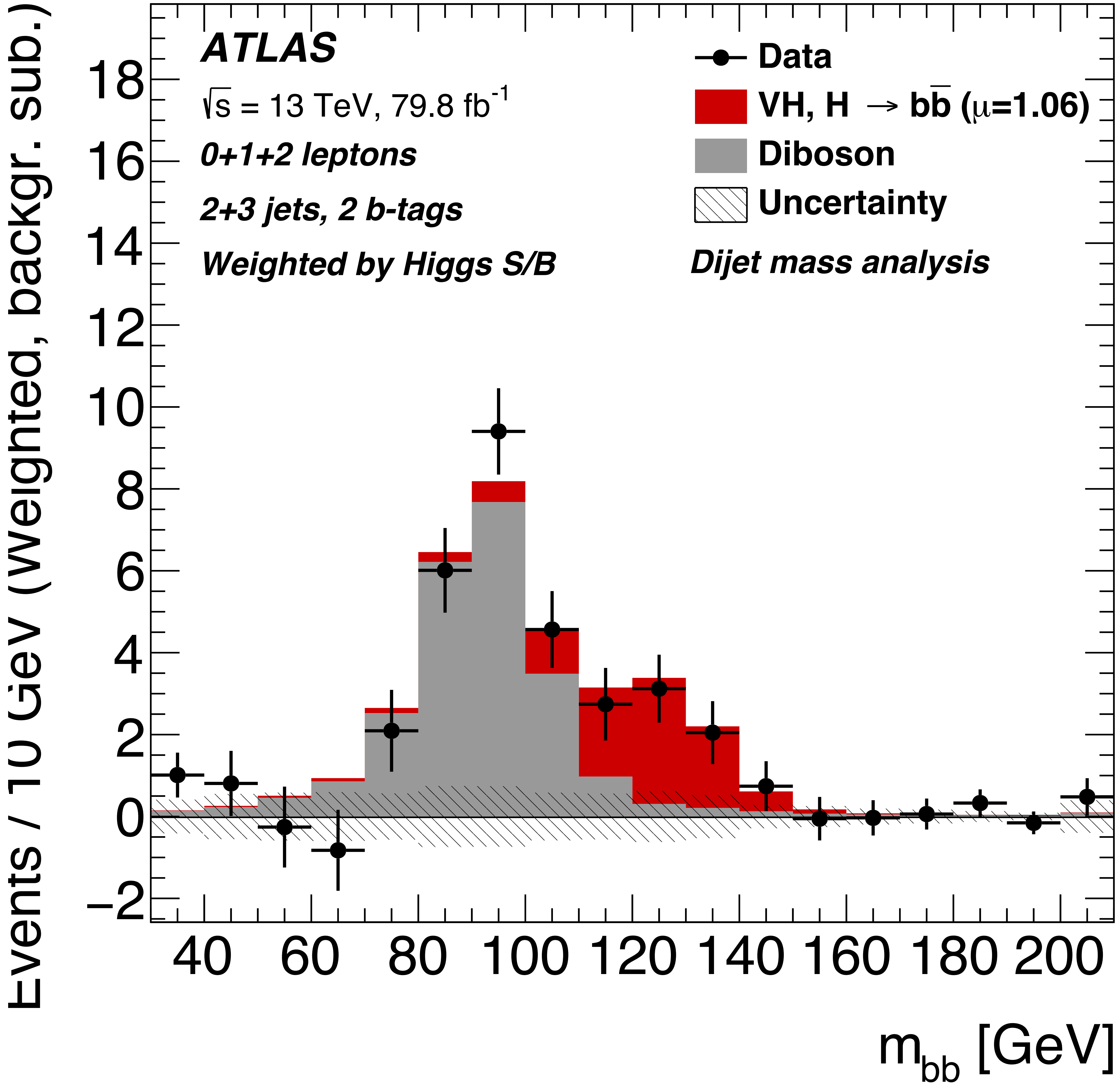


six months ago, observation of H → bb

CMS >5-sigma H → bb



ATLAS > 5-sigma H → bb



Analysis includes key idea from Butterworth, Davison, Rubin, GPS (PRL 100 (2008) 242001)

what could one be saying about it?

The >5σ observations of the ttH process and of H → ττ and H→ bb decays, independently by ATLAS and CMS, **firmly establish the existence of a new kind of fundamental interaction,** Yukawa interactions.

Yukawa interactions are important because they are:
(1) **qualitatively unlike any quantum interaction probed before** (effective charge not quantised),
(2) **hypothesized to be responsible for the stability of hydrogen,** and for determining the size of atoms and the energy scales of chemical reactions.

Establishing the pattern of Yukawa couplings across the full remaining set of quarks and charged leptons is one of the major challenges for particle physics today.

what could one be saying about it?

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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

what could one be saying about it?

This is a **fifth force, the "Higgs force"**

(up to you to decide whether you prefer to talk about new interactions or new force)

Is this any less important than the discovery of the Higgs boson itself?

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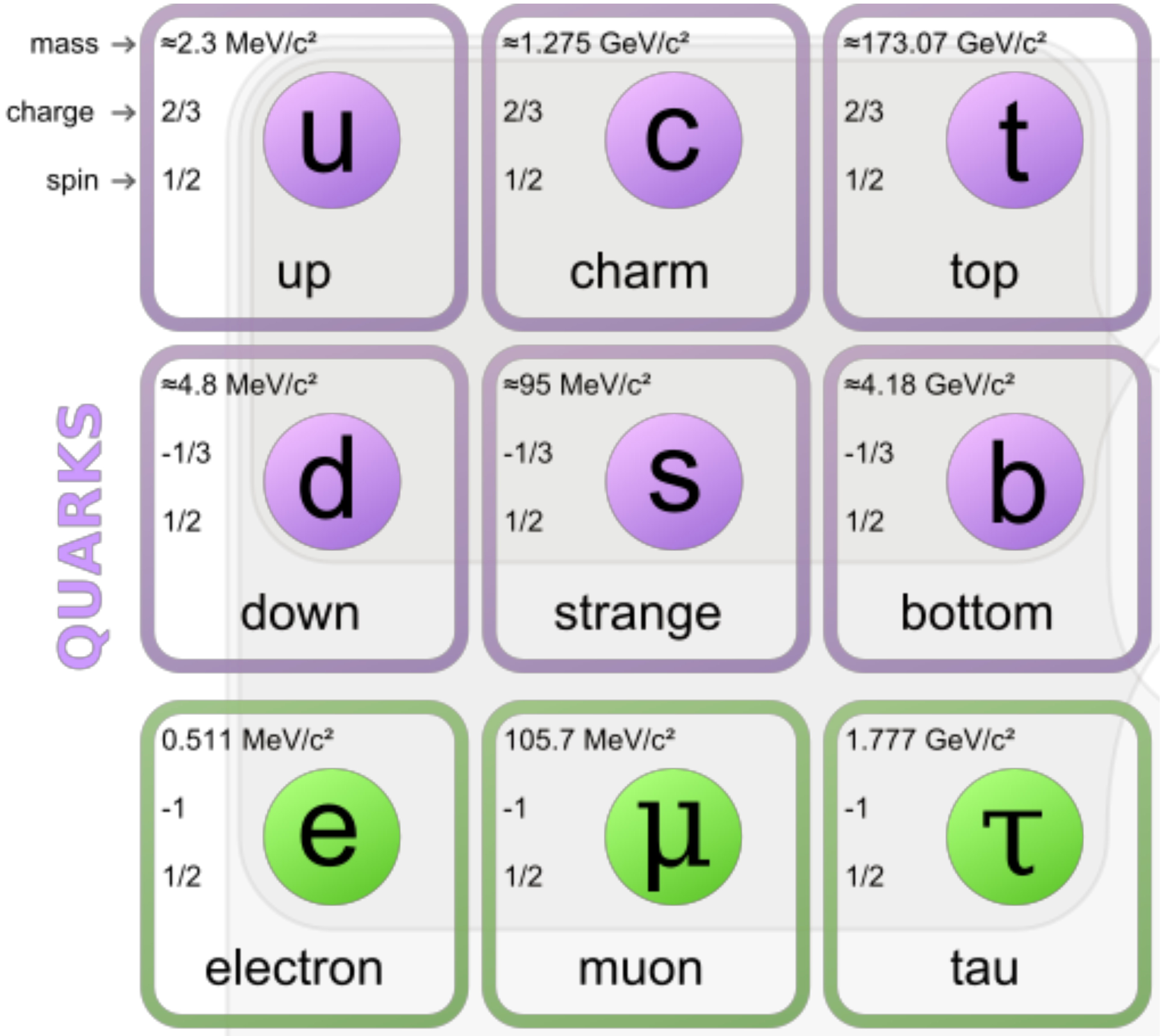
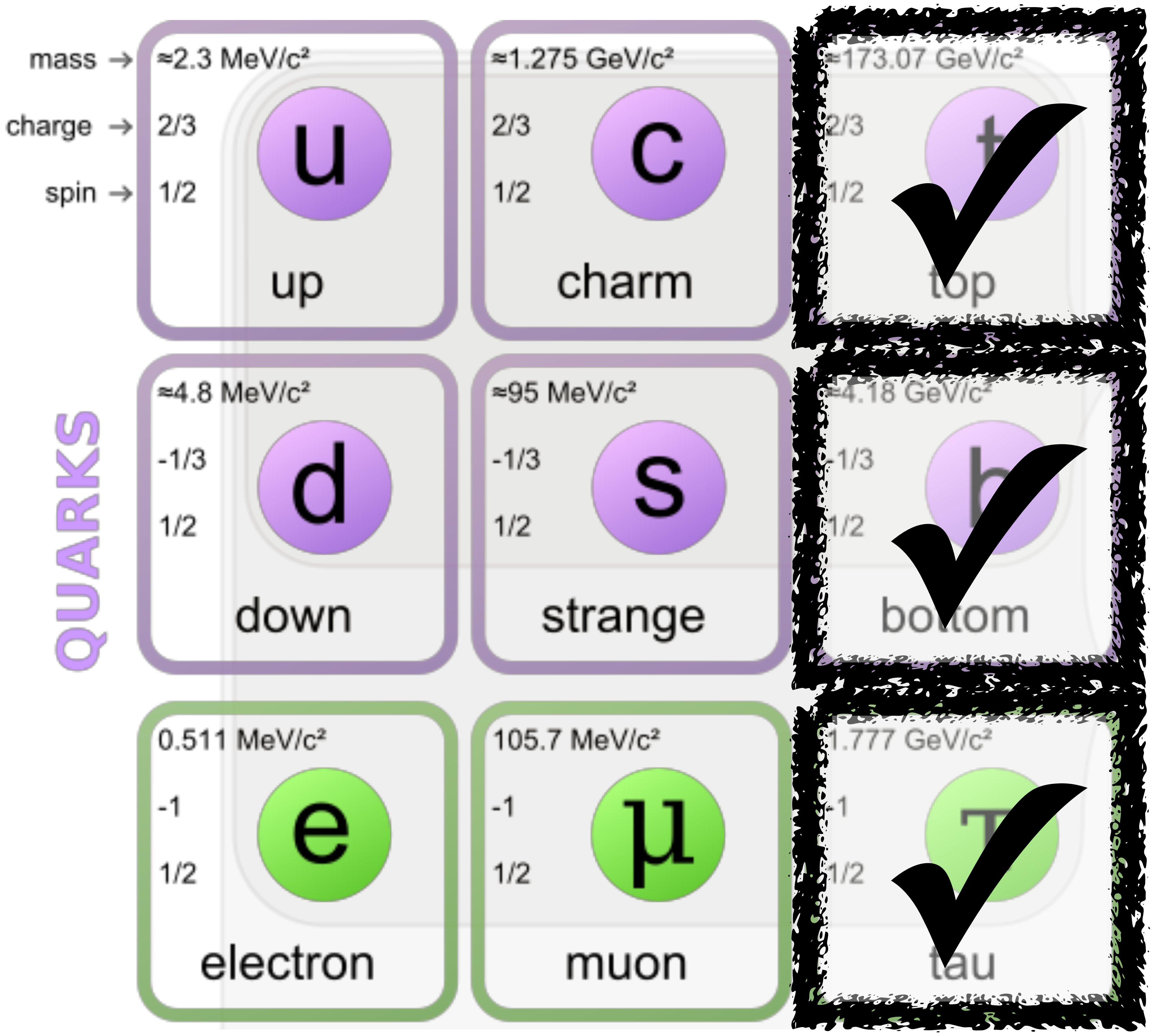
Yukawas


mass →
charge →
spin →
QUARKS
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau

Yukawas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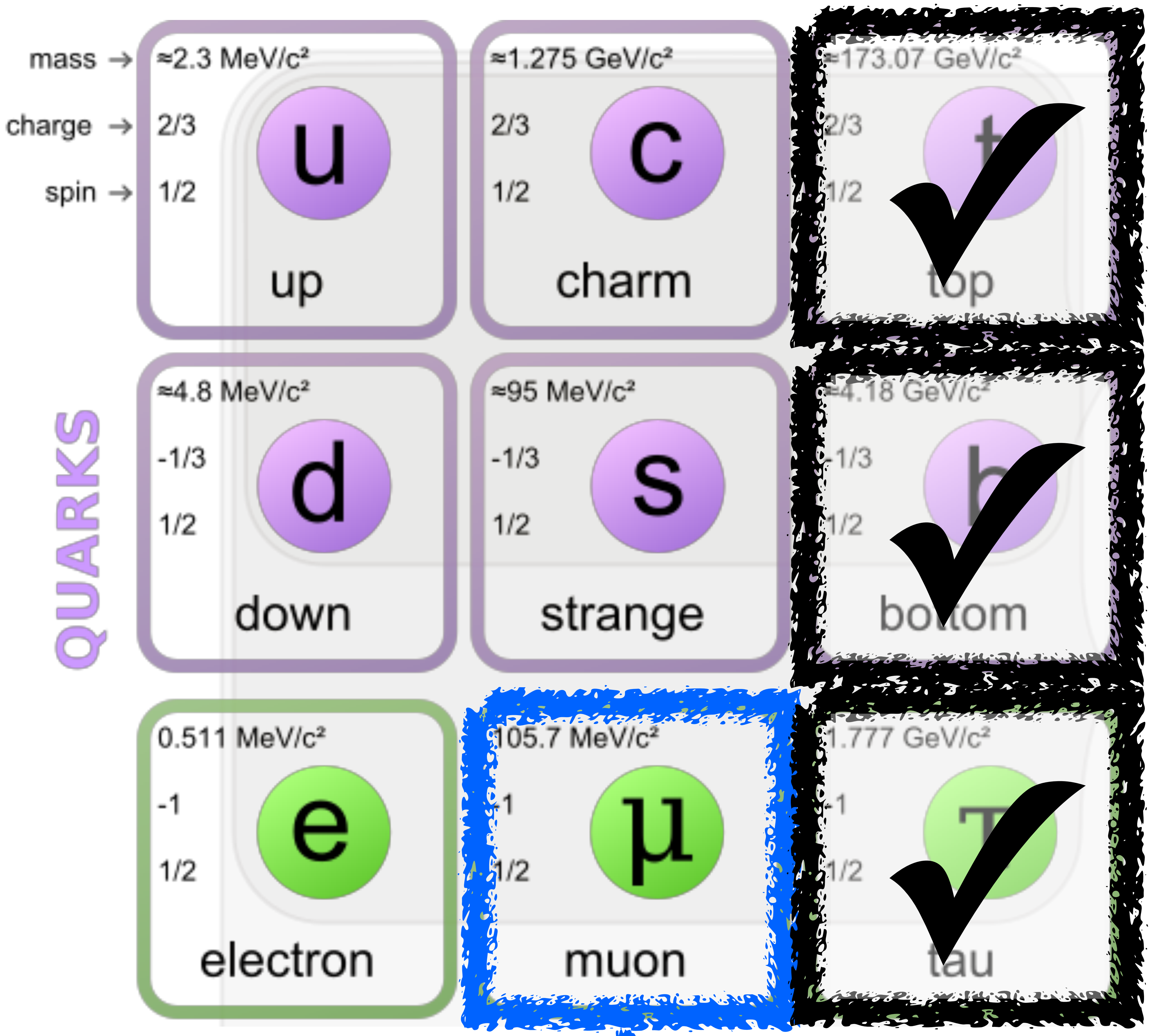
1/2
τ
tau
✓

Yukawas



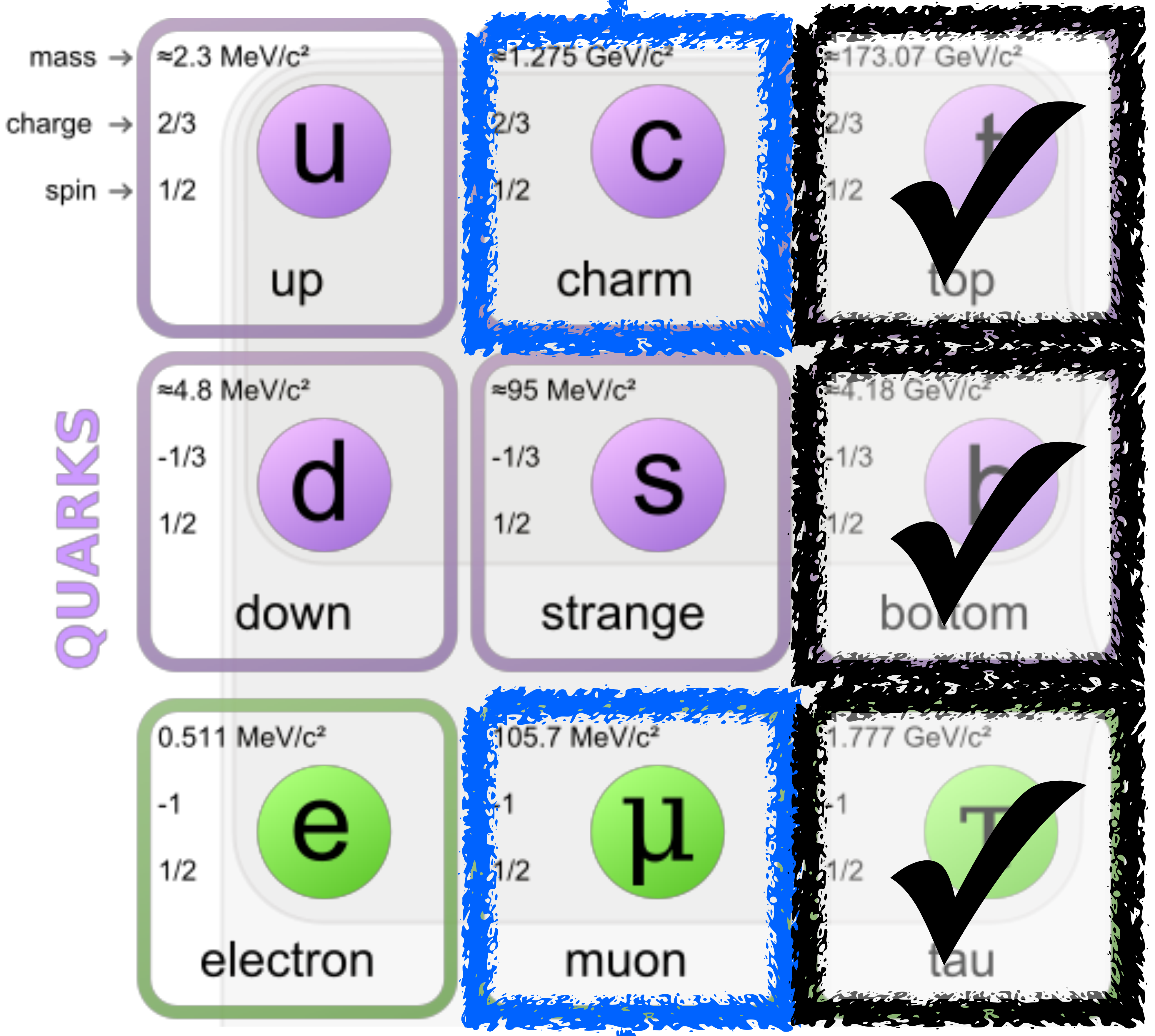
today: no evidence yet
(1 in 4570 decays)

observable at the LHC
within about 10 years.

Yukawas

today: no evidence yet
(1 in 35 decays)

needs an e^+e^-
or ep collider



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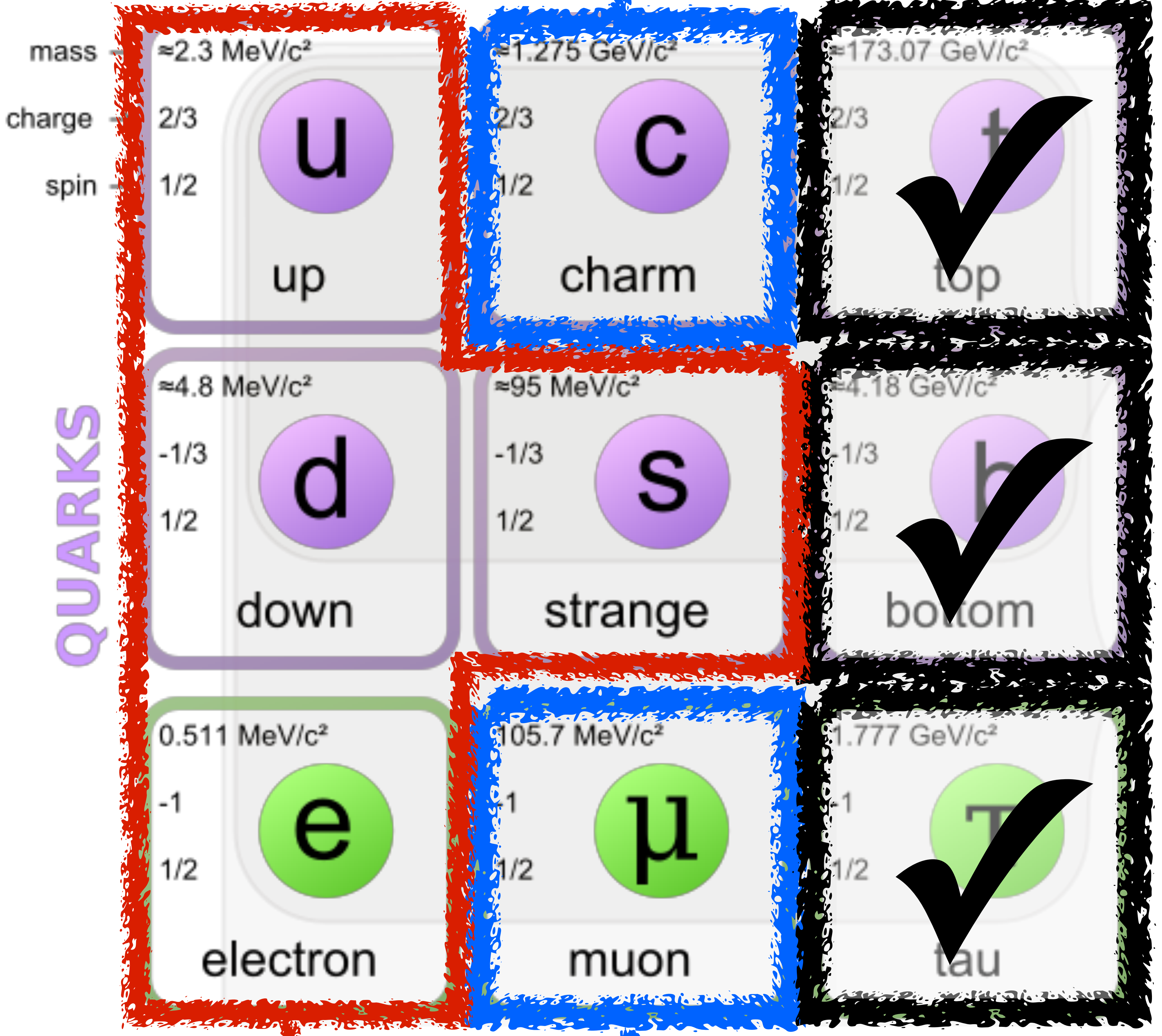


today: no evidence yet
(1 in 4000 decays)

no clear route to
establishing SM
couplings at 5σ

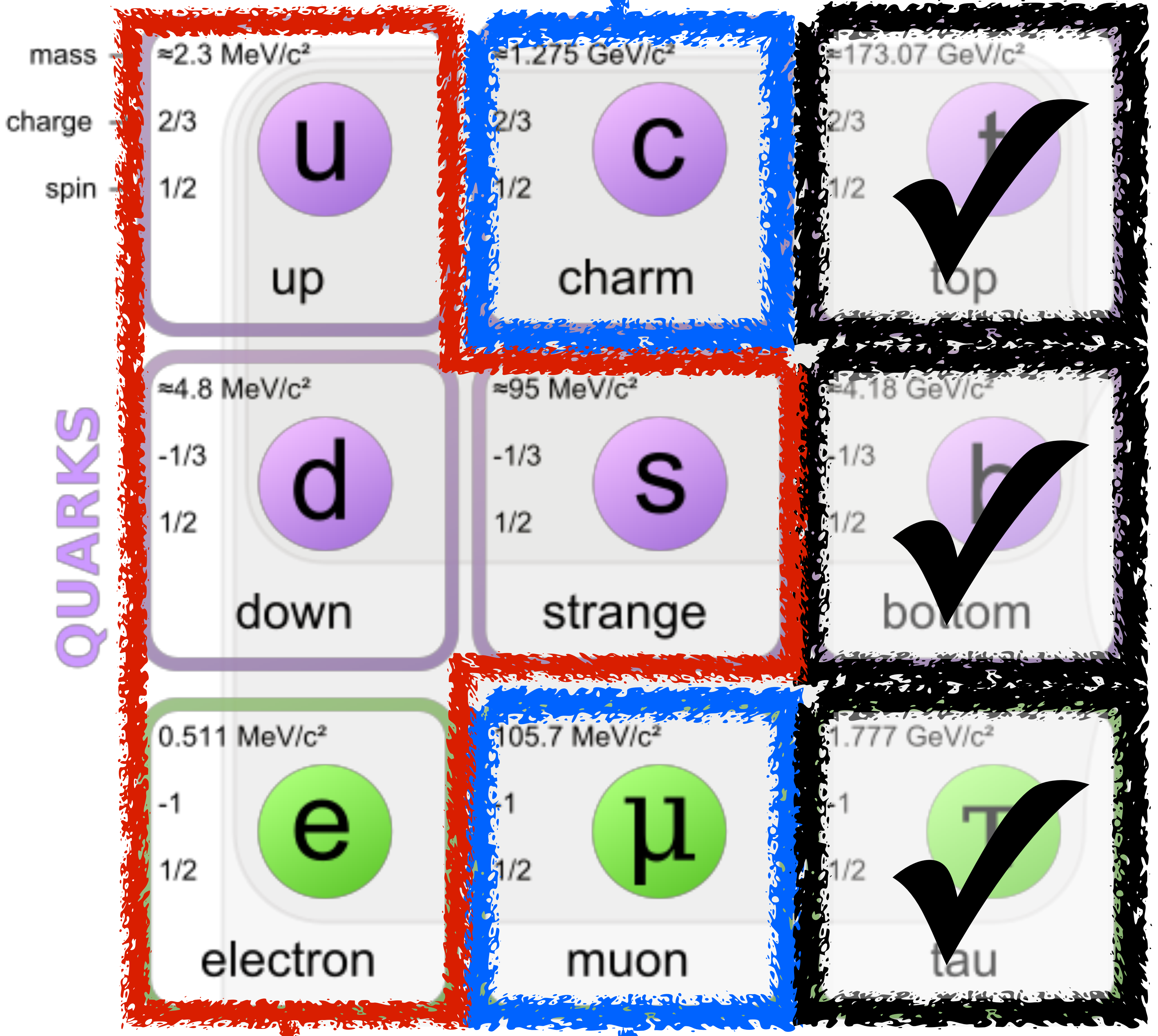
today: no evidence yet
(1 in 4570 decays)

observable at the LHC
within about 10 years.

Yukawas

today: no evidence yet
(1 in 35 decays)

needs an e^+e^-
or ep collider



overall normalisation
(related to Higgs width):

needs an e^+e^- collider

today: no evidence yet
(1 in 4000 decays)

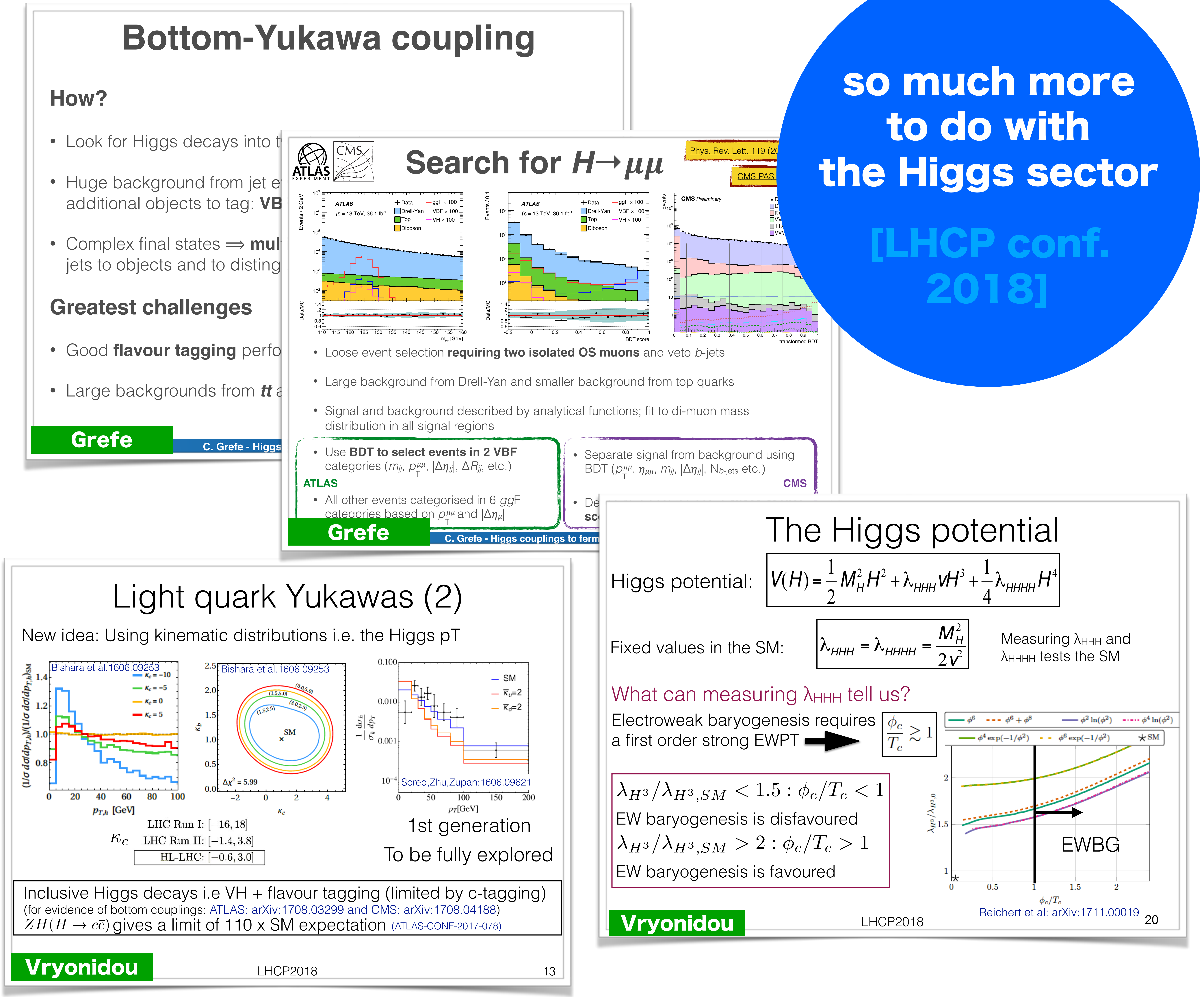
no clear route to
establishing SM
couplings at 5σ

today: no evidence yet
(1 in 4570 decays)

observable at the LHC
within about 10 years.

so much more to do with the Higgs sector

[LHCP conf. 2018]



Bottom-Yukawa coupling

How?

- Look for Higgs decays into t
- Huge background from jet e additional objects to tag: **VB**
- Complex final states ⟹ **mul** jets to objects and to disting

Greatest challenges

- Good **flavour tagging** perfo
- Large backgrounds from ***tt*** a

Grefe

C. Grefe - Higgs

Search for $H\to\mu\mu$

Phys. Rev. Lett. 119 (20

CMS-PAS-

- Loose event selection **requiring two isolated OS muons** and veto *b*-jets
- Large background from Drell-Yan and smaller background from top quarks
- Signal and background described by analytical functions; fit to di-muon mass distribution in all signal regions

ATLAS

- Use **BDT to select events in 2 VBF** categories (m_{jj}, $p_T^{\mu\mu}$, $|\Delta\eta_{jj}|$, ΔR_{jj}, etc.)
- All other events categorised in 6 *gg*F categories based on $p_T^{\mu\mu}$ and $|\Delta\eta_\mu|$

CMS

- Separate signal from background using BDT ($p_T^{\mu\mu}$, $\eta_{\mu\mu}$, m_{jj}, $|\Delta\eta_{jj}|$, N$_{b\text{-jets}}$ etc.)
- De sc

Grefe

C. Grefe - Higgs couplings to ferm

Light quark Yukawas (2)

New idea: Using kinematic distributions i.e. the Higgs pT

κ_c LHC Run I: $[-16, 18]$

LHC Run II: $[-1.4, 3.8]$

$\boxed{\text{HL-LHC: } [-0.6, 3.0]}$

1st generation

To be fully explored

Inclusive Higgs decays i.e VH + flavour tagging (limited by c-tagging)
(for evidence of bottom couplings: ATLAS: arXiv:1708.03299 and CMS: arXiv:1708.04188)
$ZH(H\to c\bar{c})$ gives a limit of 110 x SM expectation (ATLAS-CONF-2017-078)

Vryonidou

LHCP2018

13

The Higgs potential

Higgs potential: $\boxed{V(H)=\frac{1}{2}M_H^2H^2+\lambda_{HHH}vH^3+\frac{1}{4}\lambda_{HHHH}H^4}$

Fixed values in the SM: $\boxed{\lambda_{HHH}=\lambda_{HHHH}=\frac{M_H^2}{2v^2}}$

Measuring λHHH and λHHHH tests the SM

What can measuring λHHH tell us?

Electroweak baryogenesis requires a first order strong EWPT ➡ $\boxed{\frac{\phi_c}{T_c}\gtrsim 1}$

$\lambda_{H^3}/\lambda_{H^3,SM}<1.5:\phi_c/T_c<1$

EW baryogenesis is disfavoured

$\lambda_{H^3}/\lambda_{H^3,SM}>2:\phi_c/T_c>1$

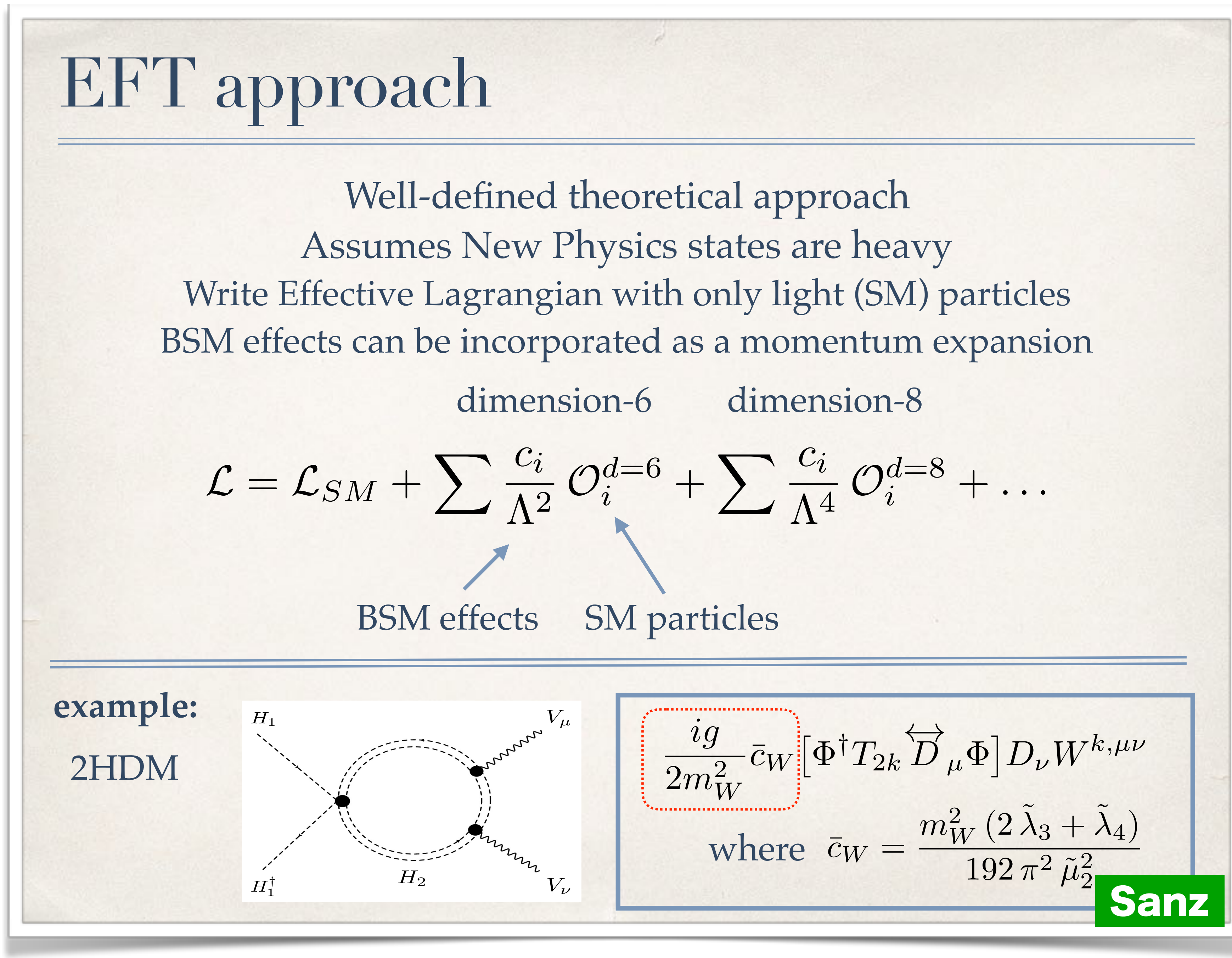
EW baryogenesis is favoured

Reichert et al: arXiv:1711.00019

Vryonidou

LHCP2018

20



EFT approach

Well-defined theoretical approach
Assumes New Physics states are heavy
Write Effective Lagrangian with only light (SM) particles
BSM effects can be incorporated as a momentum expansion

dimension-6 dimension-8

$$\mathcal{L}=\mathcal{L}_{SM}+\sum\frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6}+\sum\frac{c_i}{\Lambda^4}\mathcal{O}_i^{d=8}+\ldots$$

BSM effects SM particles

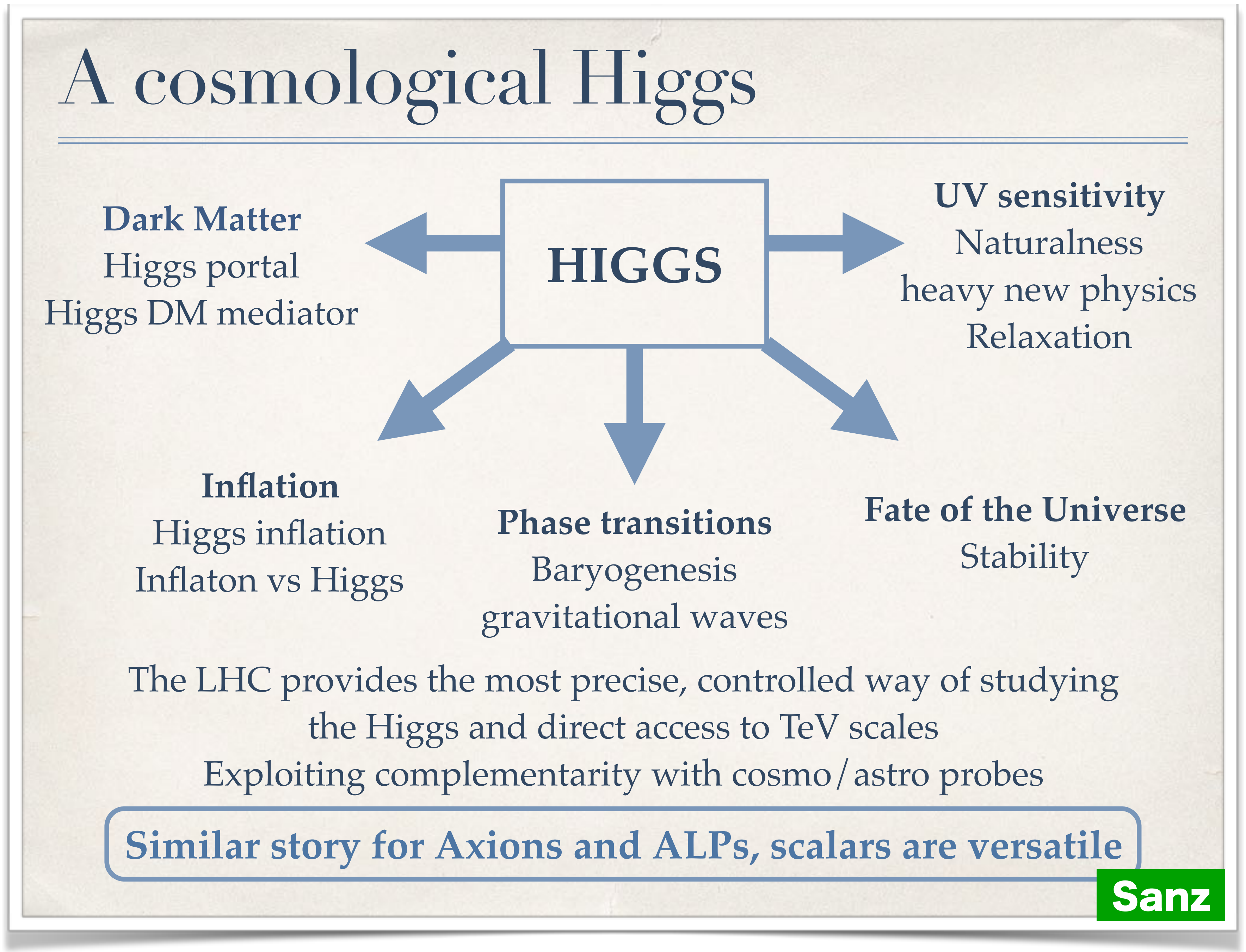
example:

2HDM

$$\frac{ig}{2m_W^2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu}$$

$$\text{where } \bar{c}_W=\frac{m_W^2\,(2\,\tilde{\lambda}_3+\tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2}$$

Sanz



A cosmological Higgs

HIGGS

Dark Matter
Higgs portal
Higgs DM mediator

UV sensitivity
Naturalness
heavy new physics
Relaxation

Inflation
Higgs inflation
Inflaton vs Higgs

Phase transitions
Baryogenesis
gravitational waves

Fate of the Universe
Stability

The LHC provides the most precise, controlled way of studying the Higgs and direct access to TeV scales
Exploiting complementarity with cosmo/astro probes

Similar story for Axions and ALPs, scalars are versatile

Sanz

for much of Higgs sector, we know what to do to get answers. What about other “big” questions

Nature of dark matter (& dark energy)

Fine-tuning (e.g. supersymmetry and similar)

Matter-antimatter asymmetry of the universe

[…]

> Finding dark matter and studying it will be the biggest challenge for the Large Hadron Collider's second run

-a large LHC experiment's spokesperson [2015]

https://www.pbs.org/newshour/science/large-hadron-collider-gears-find-dark-matter-new-particles-second-run

dark matter

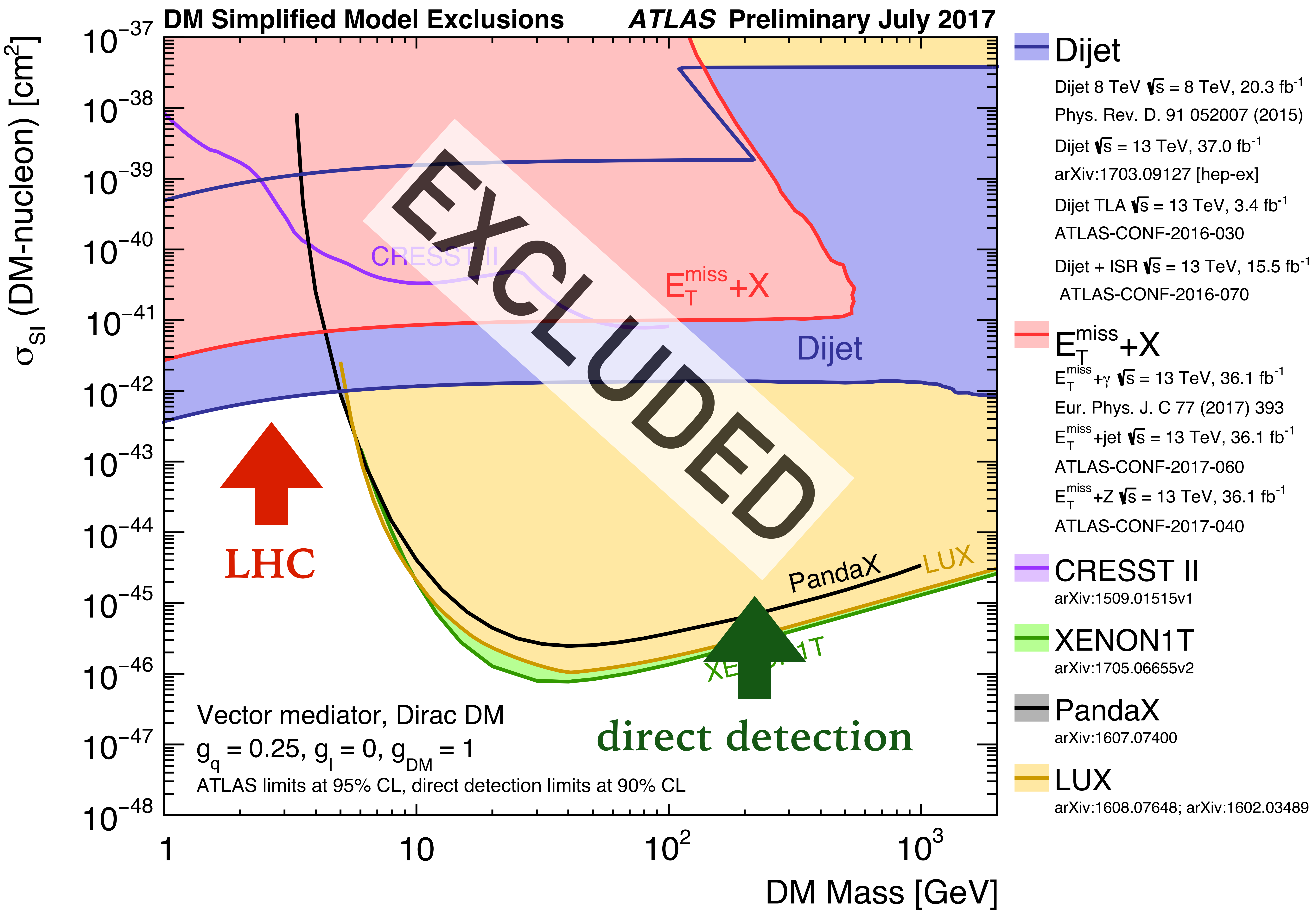
Rotation curve of spiral galaxy Messier 33

Looking beyond the SM: searches for dark matter at LHC & elsewhere

Classic dark-matter candidate: a weakly-interacting massive particle (**WIMP**, e.g. from supersymmetry).

Masses ~ GeV upwards

(search interpretations strongly model dependent)



musn't be (too) disappointed at lack of dark matter signal at LHC

Evidence for dark matter exists since the 1930s.

Today we know that

- **there are many possible models**
- **the range of parameters they span is large**

We must deploy full ingenuity in searching for dark matter, including at LHC.

But must also recognise that it has remained elusive for 80–90 years, and chances of finding it in any given year are small!

Snowmass non-WIMP dark matter report, 1310.8642

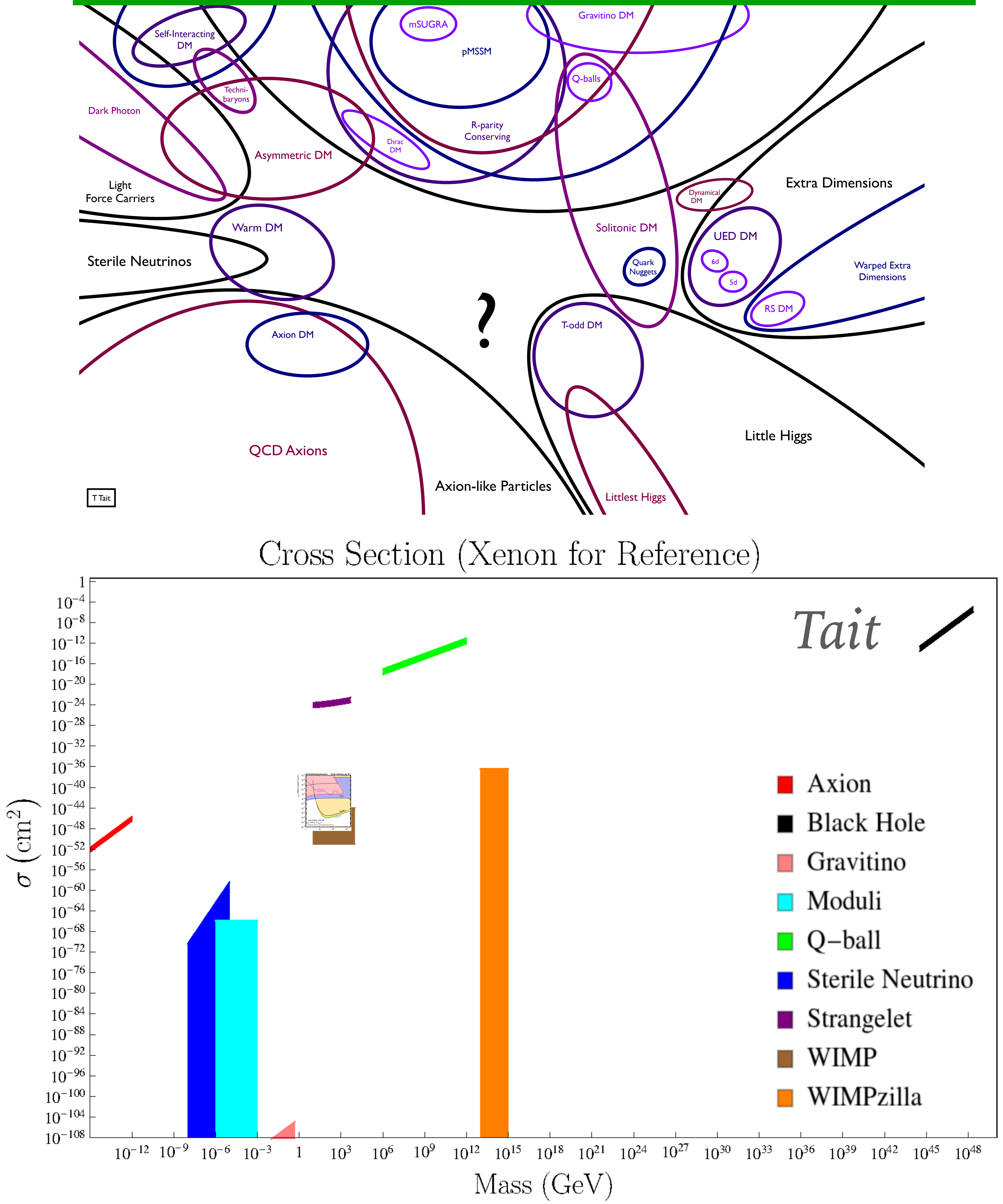


Figure 1. *Graphical representation of the (incomplete) landscape of candidates. Above, the landscape of dark matter candidates due to T. Tait. Below, the range of dark matter candidates' masses and interaction cross sections with a nucleus of Xe (for illustrative purposes) compiled by L. Pearce. Dark matter candidates have an enormous range of masses and interaction cross sections.*

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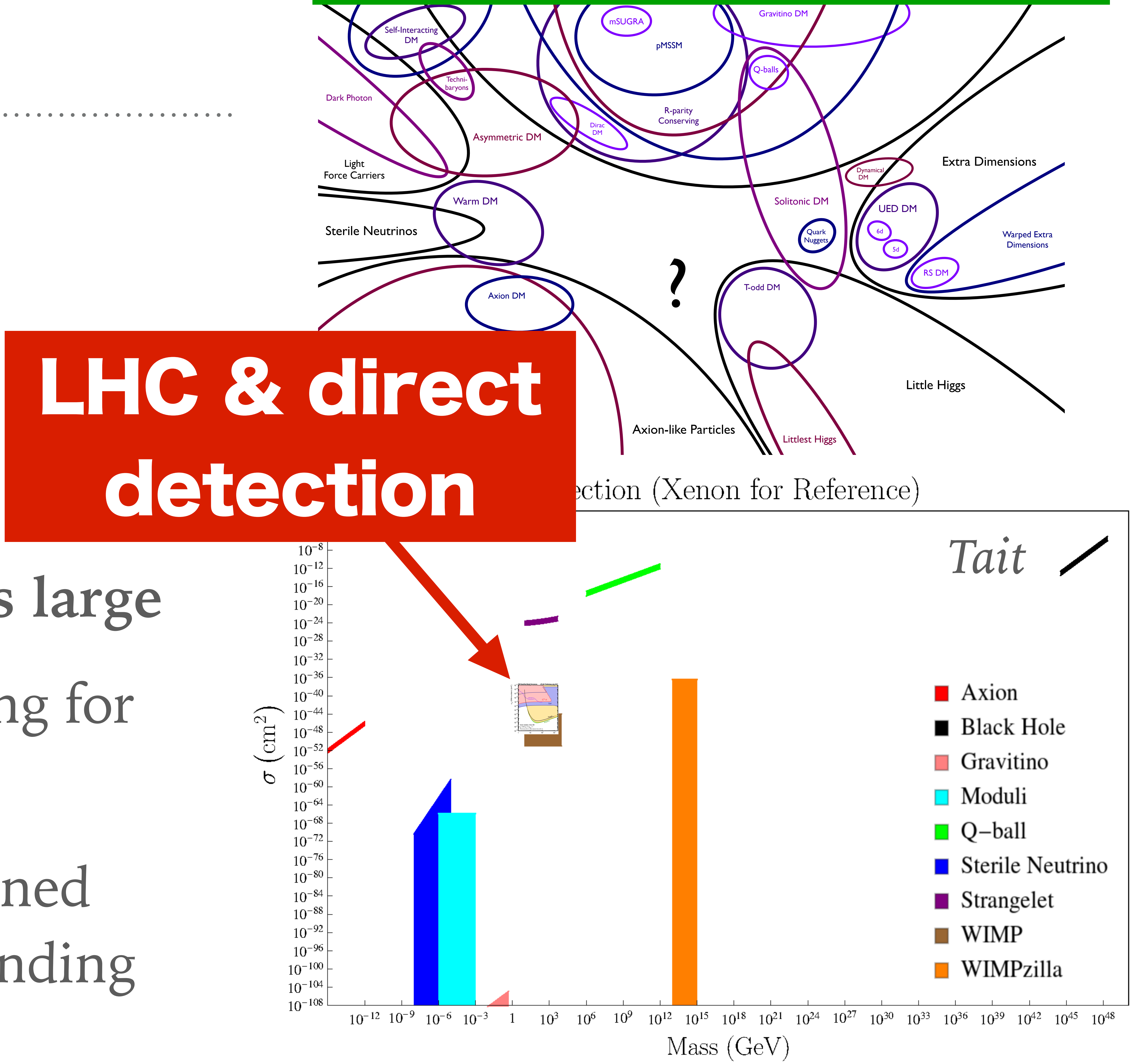

LHC & direct detection

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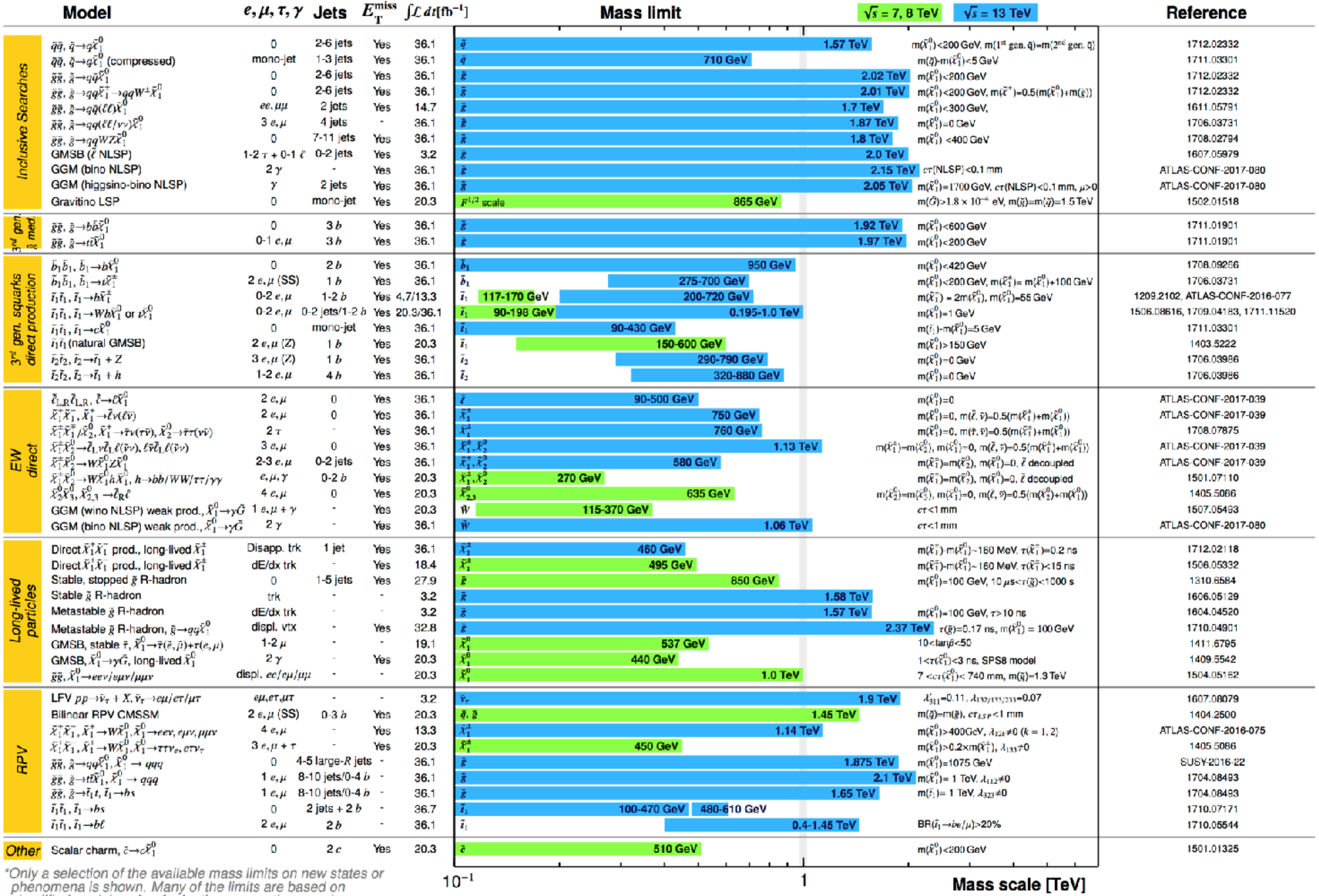
ATLAS SUSY Searches* - 95% CL Lower Limits

December 2017

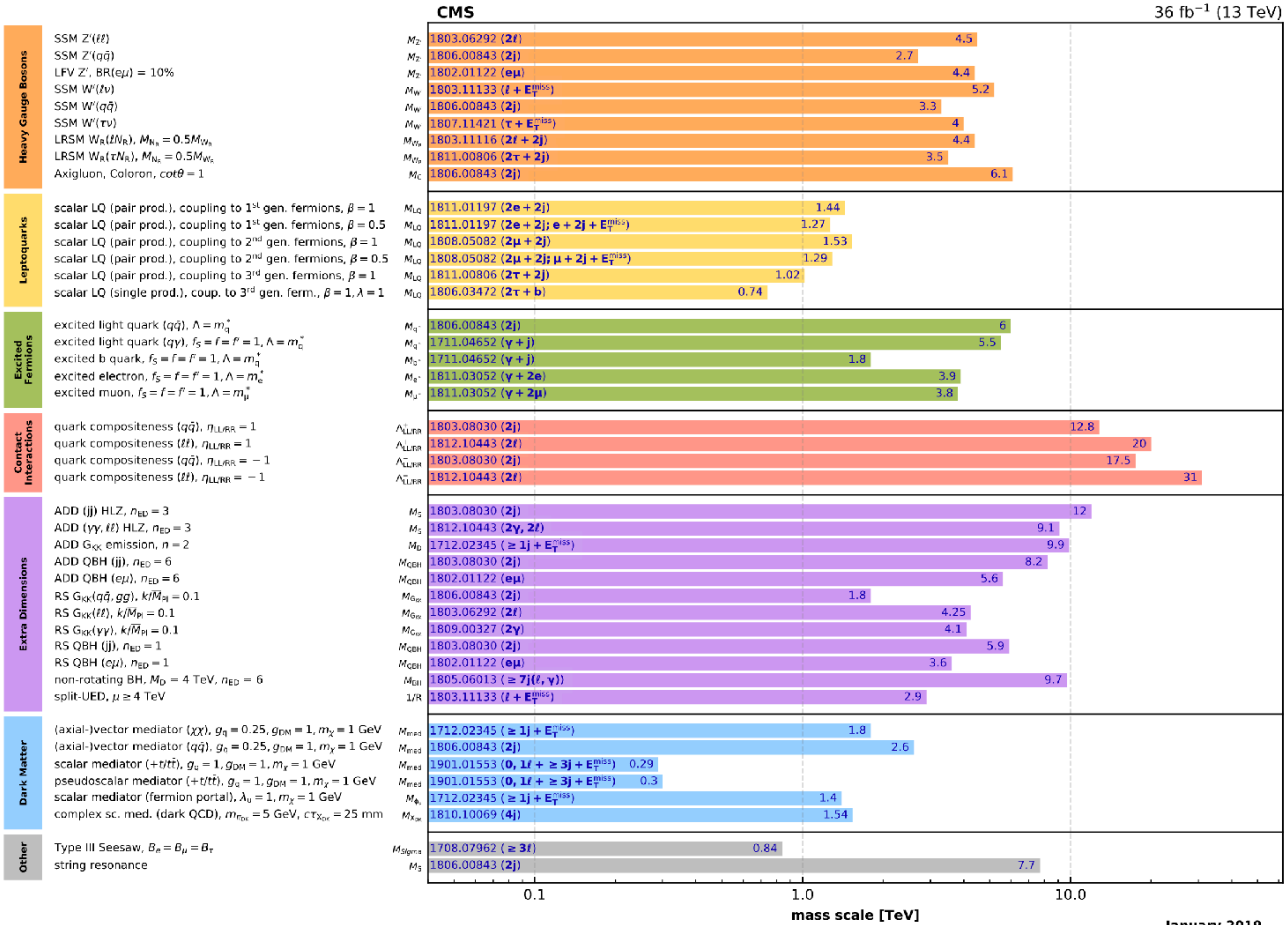
ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV



	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$		Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$	🟦 1.57 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1712.02332
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$	🟦 710 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	🟦 2.02 TeV	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	🟦 2.01 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	Yes	14.7	$\tilde{g}$	🟦 1.7 TeV	m($\tilde{\chi}_1^0$)<300 GeV,	1611.05791
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	$\tilde{g}$	🟦 1.87 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$	🟦 1.8 TeV	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$	🟦 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	36.1	$\tilde{g}$	🟦 2.15 TeV	$c\tau$(NLSP)<0.1 mm	ATLAS-CONF-2017-080
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	$\tilde{g}$	🟦 2.05 TeV	m($\tilde{\chi}_1^0$)=1700 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2017-080
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	🟩 865 GeV	m($\tilde{G}$)>1.8 × 10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	$\tilde{g}$	🟦 1.92 TeV	m($\tilde{\chi}_1^0$)<600 GeV	1711.01901
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	$\tilde{g}$	🟦 1.97 TeV	m($\tilde{\chi}_1^0$)<200 GeV	1711.01901
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	$\tilde{b}_1$	🟦 950 GeV	m($\tilde{\chi}_1^0$)<420 GeV	1708.09266
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	1 b	Yes	36.1	$\tilde{b}_1$	🟦 275-700 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^{\pm}$)= m($\tilde{\chi}_1^0$)+100 GeV	1706.03731
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0-2 e, μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$	🟩 117-170 GeV 🟦 200-720 GeV	m($\tilde{\chi}_1^{\pm}$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$	🟩 90-198 GeV 🟦 0.195-1.0 TeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	36.1	$\tilde{t}_1$	🟦 90-430 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	🟩 150-600 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1	$\tilde{t}_2$	🟦 290-790 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	$\tilde{t}_2$	🟦 320-880 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03986
EW direct	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	$\tilde{\ell}$	🟦 90-500 GeV	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}$	🟦 750 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}$	🟦 760 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	🟦 1.13 TeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	🟦 580 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	🟩 270 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	🟩 635 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	1 e, μ + γ	-	Yes	20.3	$\tilde{W}$	🟩 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	2 γ	-	Yes	36.1	$\tilde{W}$	🟦 1.06 TeV	$c\tau$<1 mm	ATLAS-CONF-2017-080
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^{\pm}$	🟦 460 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	1712.02118
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$	🟩 495 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	🟩 850 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$	🟦 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$	🟦 1.57 TeV	m($\tilde{\chi}_1^0$)=100 GeV, τ>10 ns	1604.04520
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$	displ. vtx	-	Yes	32.8	$\tilde{g}$	🟦 2.37 TeV	τ($\tilde{g}$)=0.17 ns, m($\tilde{\chi}_1^0$) = 100 GeV	1710.04901
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	🟩 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	🟩 440 GeV	1<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	🟩 1.0 TeV	7 <$c\tau$($\tilde{\chi}_1^0$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	🟦 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	🟩 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^{\pm}$	🟦 1.14 TeV	m($\tilde{\chi}_1^0$)>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e, μ + τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	🟩 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$	🟦 1.875 TeV	m($\tilde{\chi}_1^0$)=1075 GeV	SUSY-2016-22
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	🟦 2.1 TeV	m($\tilde{\chi}_1^0$)= 1 TeV, $\lambda_{112}\neq0$	1704.08493
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	🟦 1.65 TeV	m($\tilde{t}_1$)= 1 TeV, $\lambda_{323}\neq0$	1704.08493
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$	🟦 100-470 GeV 🟦 480-610 GeV		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e, μ	2 b	-	36.1	$\tilde{t}_1$	🟦 0.4-1.45 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	1710.05544
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$	🟩 510 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

CMS exotics searches



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

anomalies

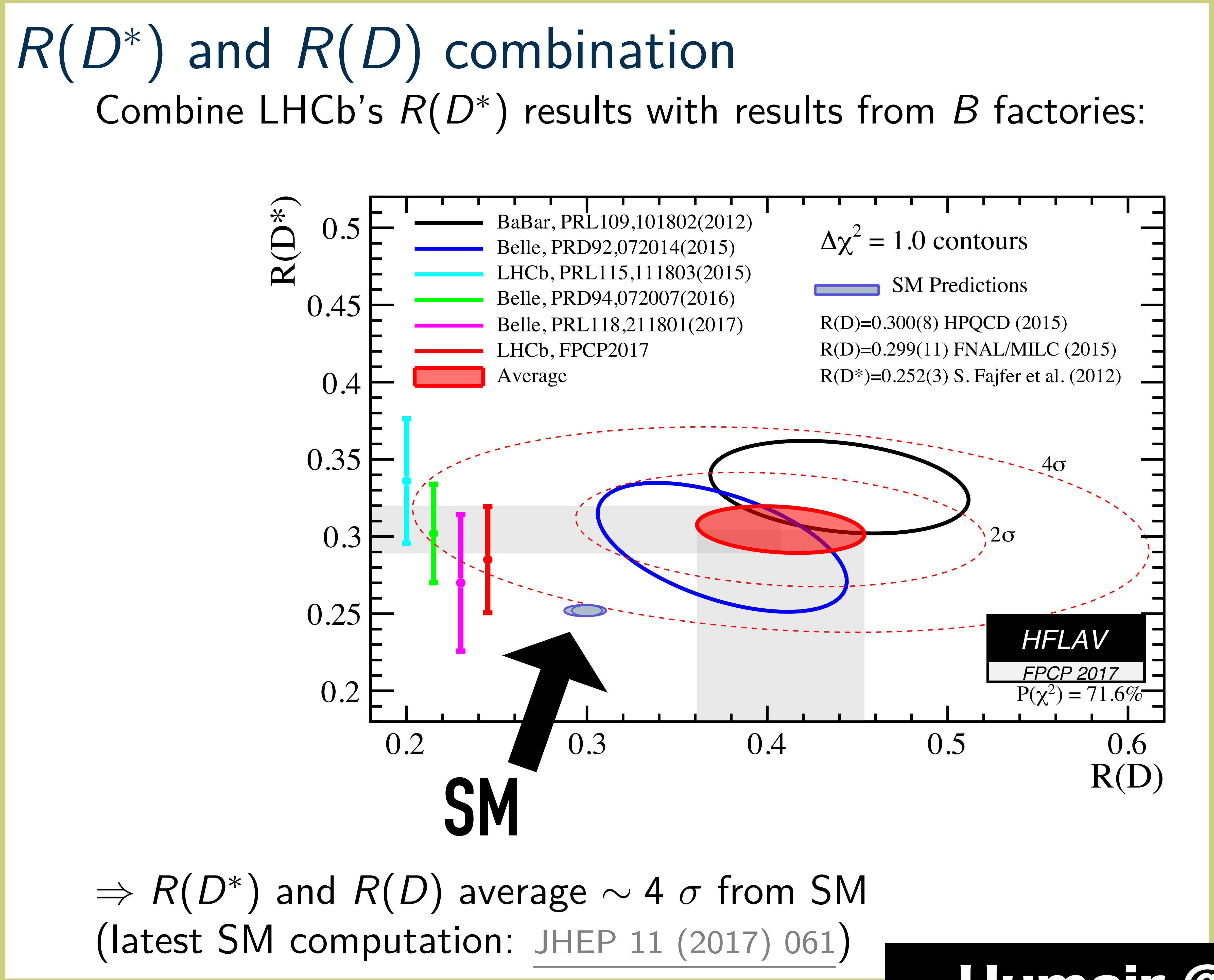
the current place where there are hints of something happening

charged current

neutral current

$$R(D^*) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

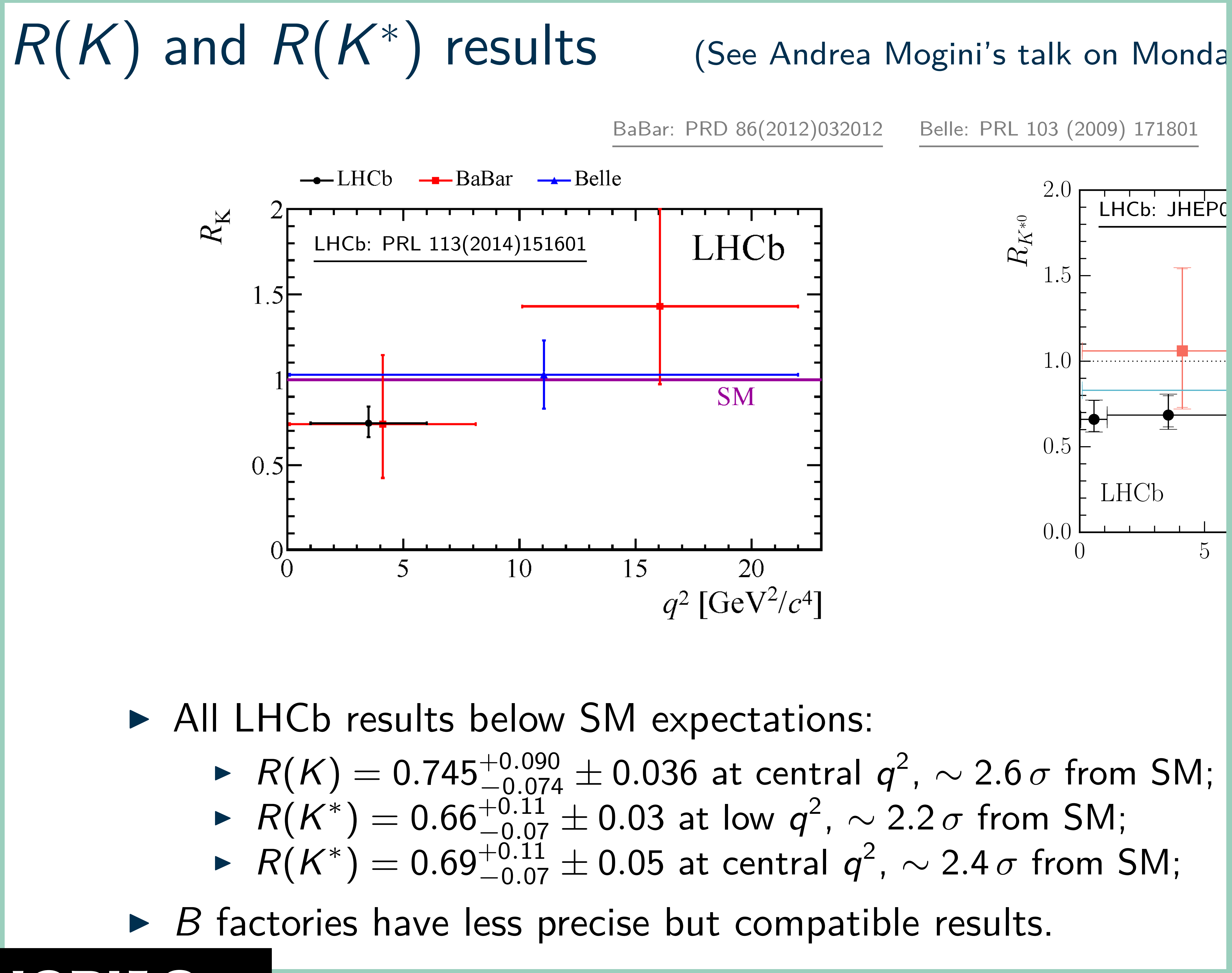
$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$



$R(D^*)$ and $R(D)$ combination

Combine LHCb's $R(D^*)$ results with results from B factories:

$\Rightarrow$ $R(D^*)$ and $R(D)$ average $\sim 4\ \sigma$ from SM
(latest SM computation: JHEP 11 (2017) 061)



$R(K)$ and $R(K^*)$ results

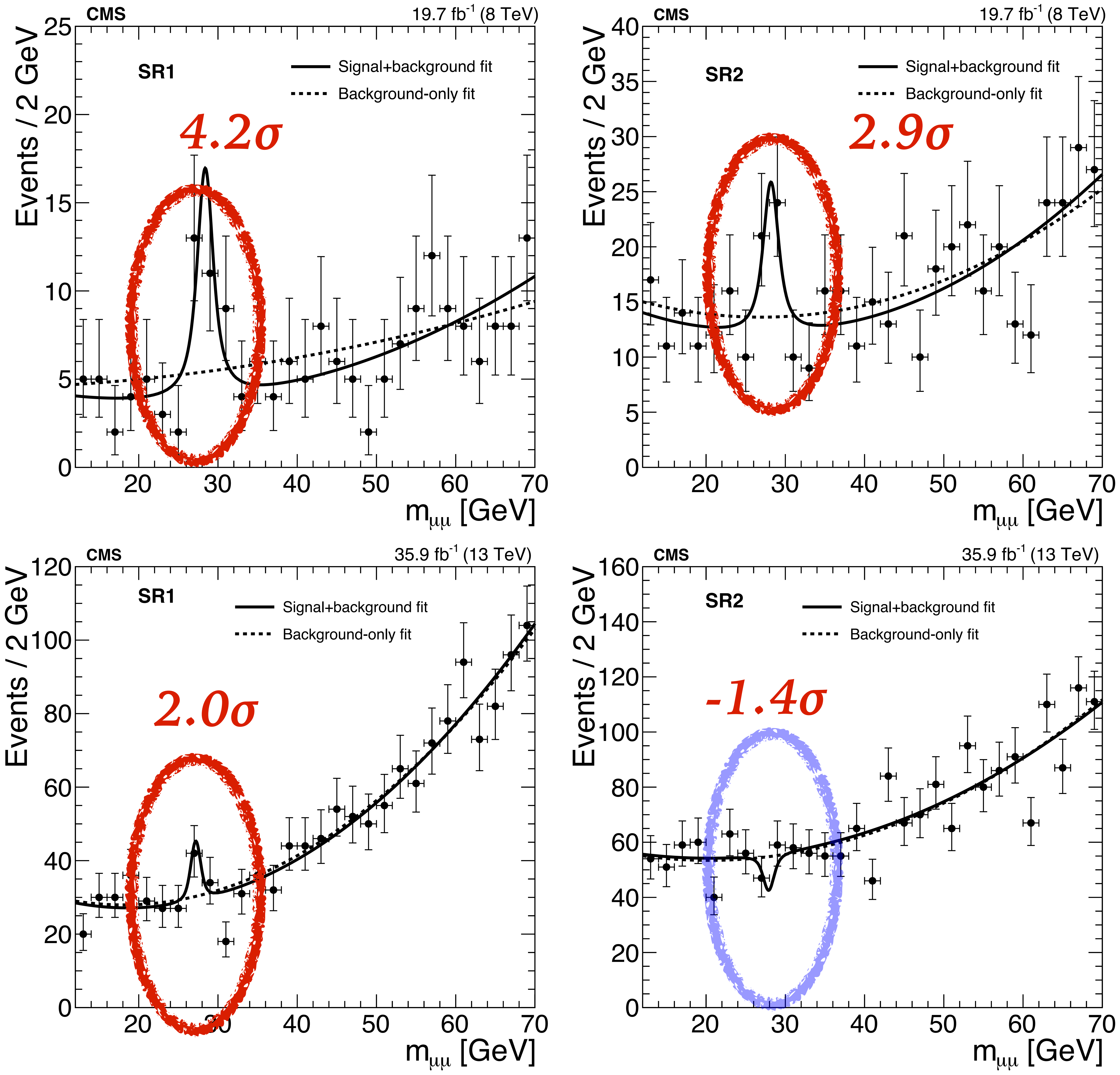
(See Andrea Mogini's talk on Monda

BaBar: PRD 86(2012)032012   Belle: PRL 103 (2009) 171801

- All LHCb results below SM expectations:
  - $R(K) = 0.745^{+0.090}_{-0.074} \pm 0.036$ at central q^2, $\sim 2.6\,\sigma$ from SM;
  - $R(K^*) = 0.66^{+0.11}_{-0.07} \pm 0.03$ at low q^2, $\sim 2.2\,\sigma$ from SM;
  - $R(K^*) = 0.69^{+0.11}_{-0.07} \pm 0.05$ at central q^2, $\sim 2.4\,\sigma$ from SM;
- B factories have less precise but compatible results.

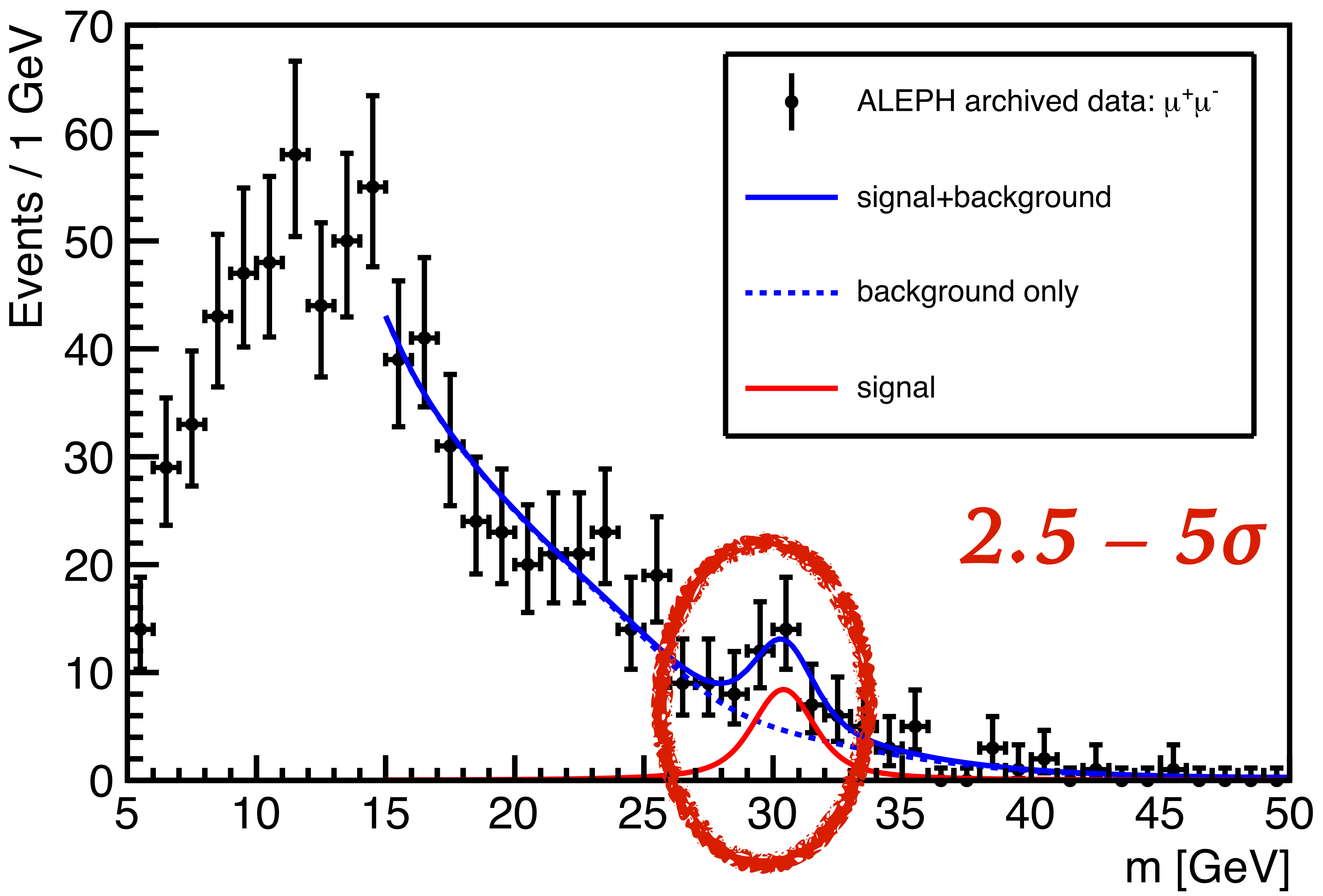
Humair @ LHCP'18

CMS pp → b j $\mu^+\mu^-$ + X



https://arxiv.org/abs/1808.01890

ALEPH e⁺e⁻ → b b $\mu^+\mu^-$ + X



https://arxiv.org/abs/1610.06536

and various non-collider anomalies

- DAMA
- Miniboone & LSND
- $g_\mu - 2$
- ^{8}Be 16.7 MeV e⁺e⁻ peak

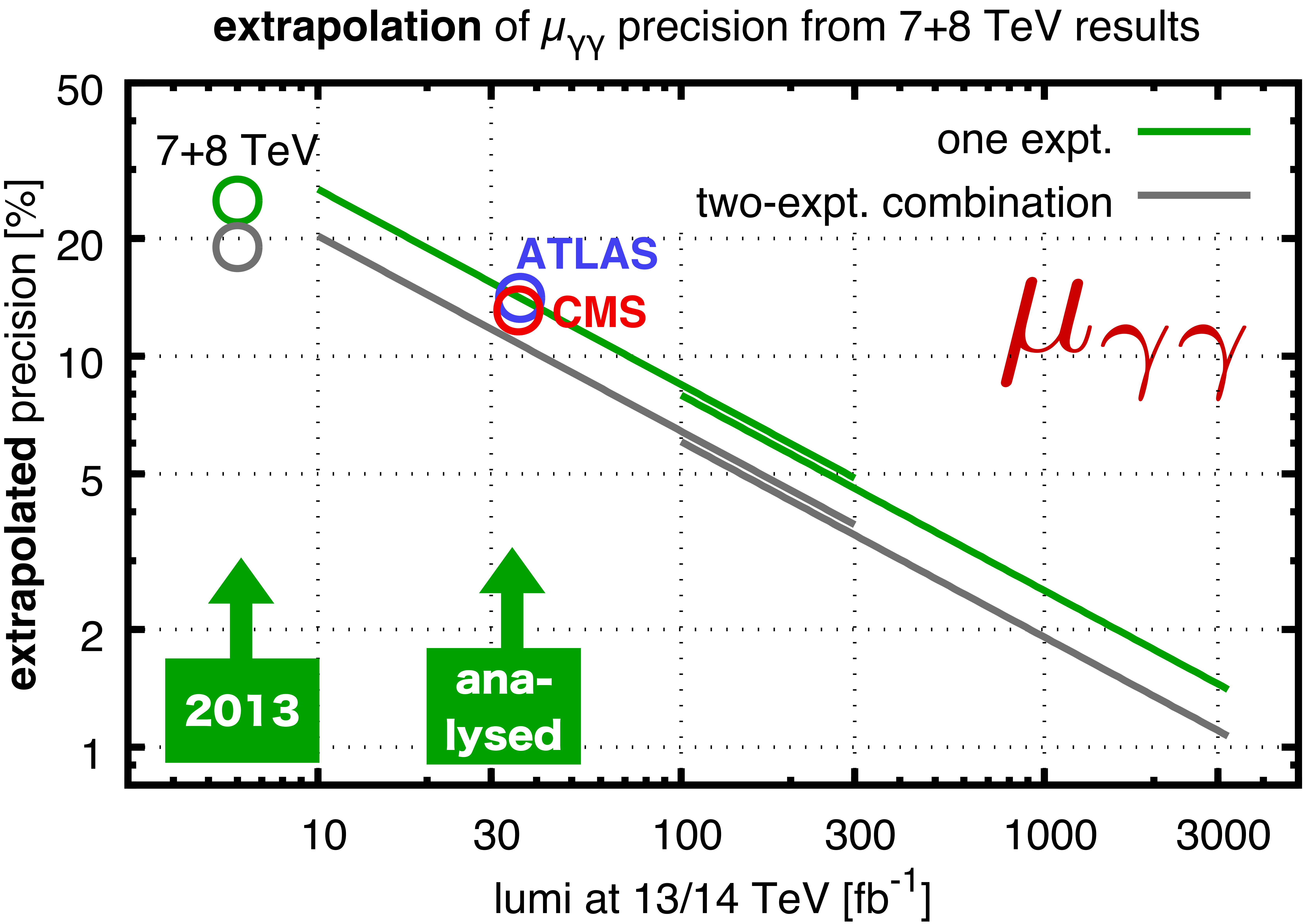
future progress?

---

(1) approved plans

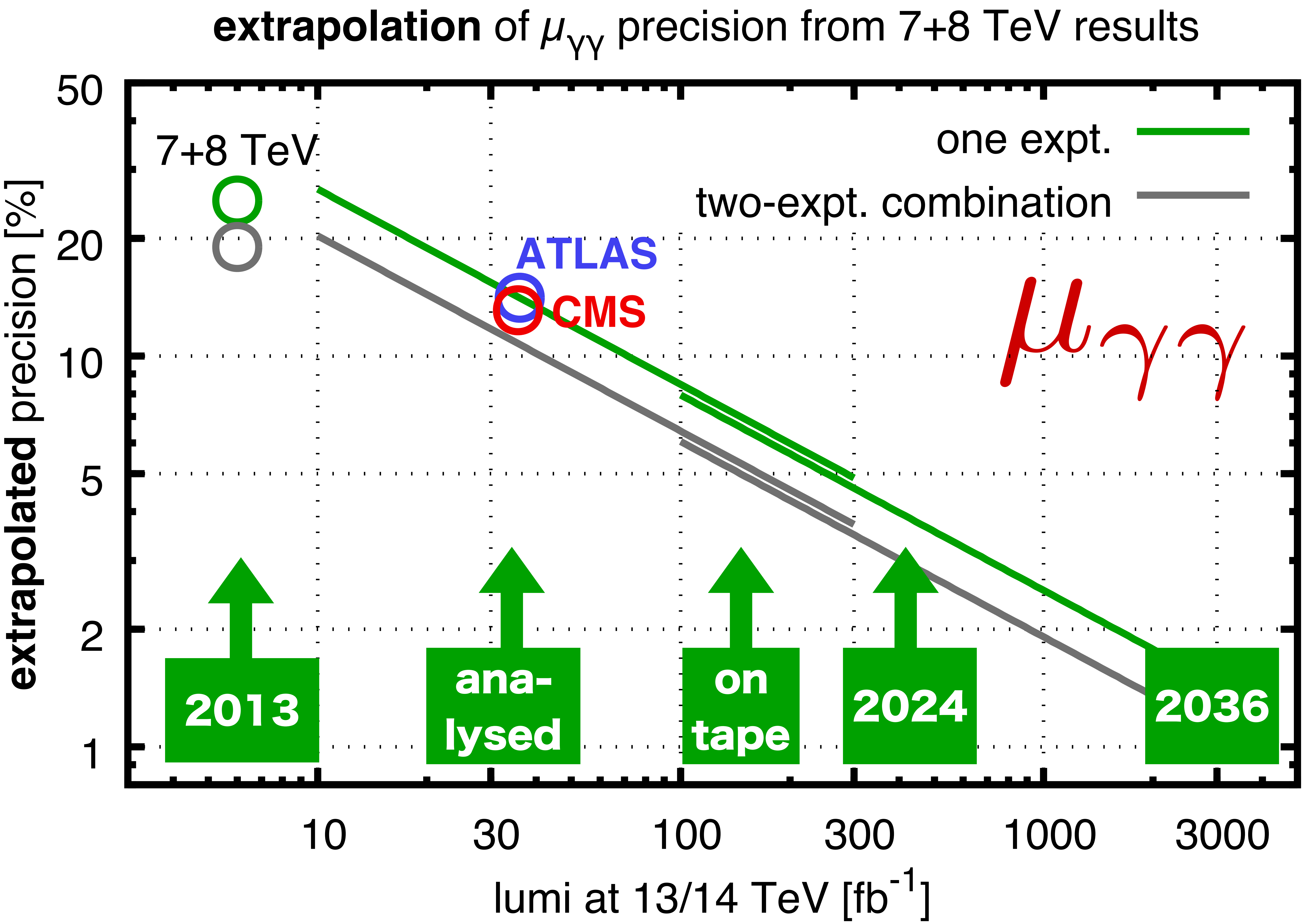
LHC will collect ∼40 times more data than used for the plots shown so far, though at mostly similar energy (13–14 TeV)

Higgs precision (H → γγ) : optimistic estimate v. luminosity & time



1 fb^{-1} = 10^{14} collisions

Higgs precision (H → γγ) : optimistic estimate v. luminosity & time

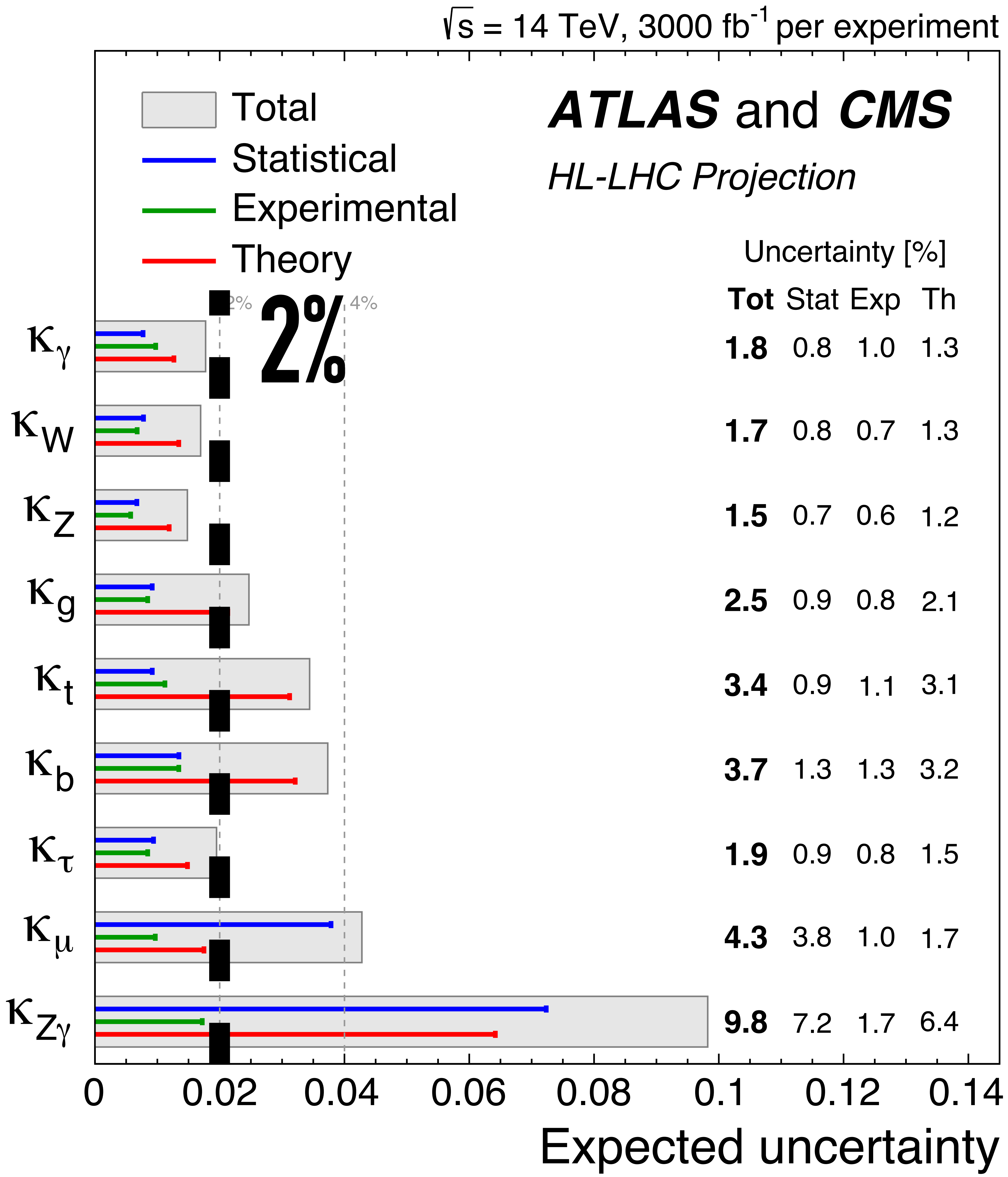


The LHC has the statistical potential to take Higgs physics from "observation" to 1–2% precision

But only if we learn how to connect experimental observations with theory at that precision

1 fb^{-1} = 10^{14} collisions

HL-LHC official Higgs coupling projections (by 2036)



Uncertainty [%]

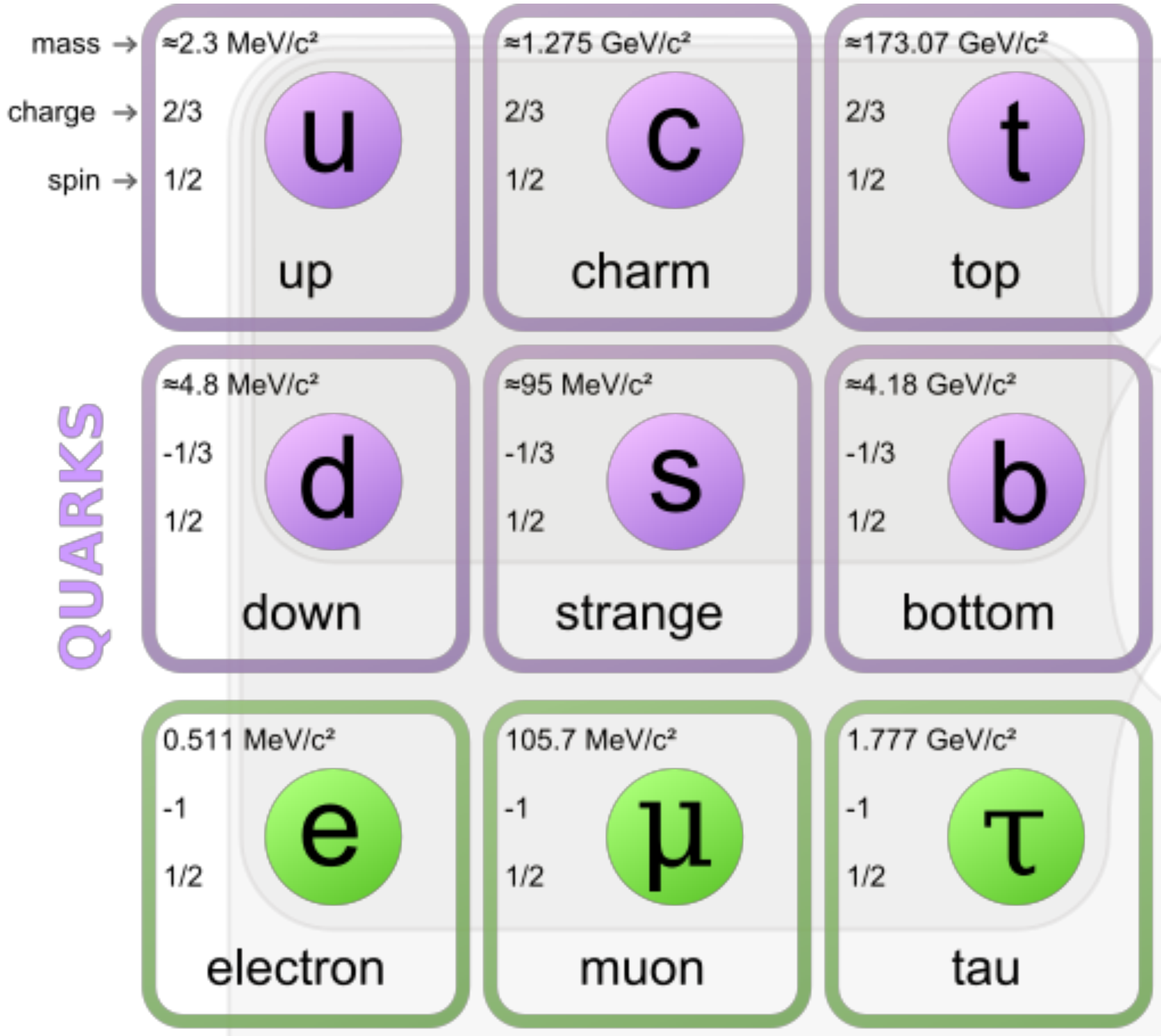
	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

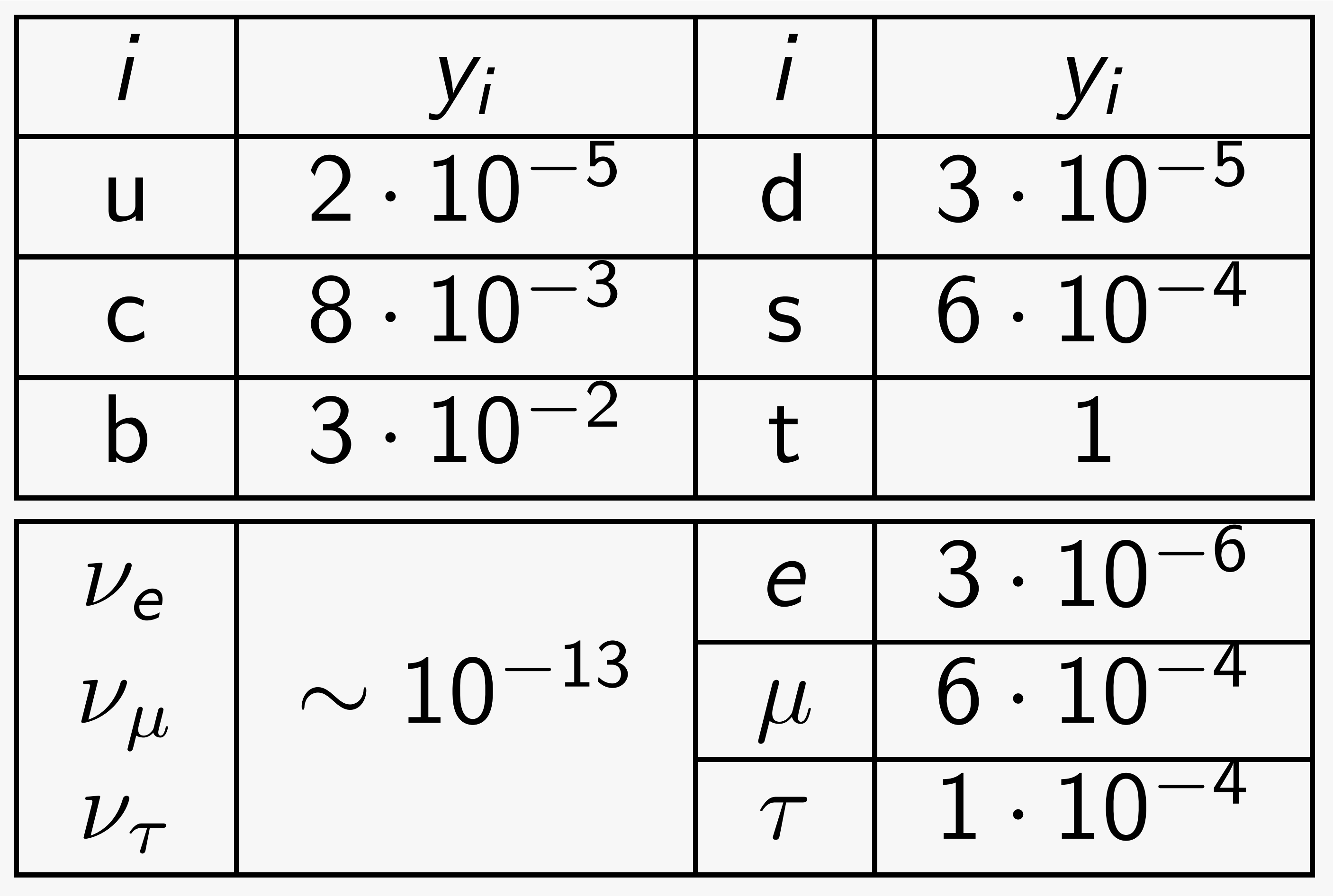
Right now, Higgs coupling precisions are in the 10-20% range.

We wouldn't consider electromagnetism established (textbook level) if we only knew it to 10%

HL-LHC can deliver 1–2% for a range of couplings

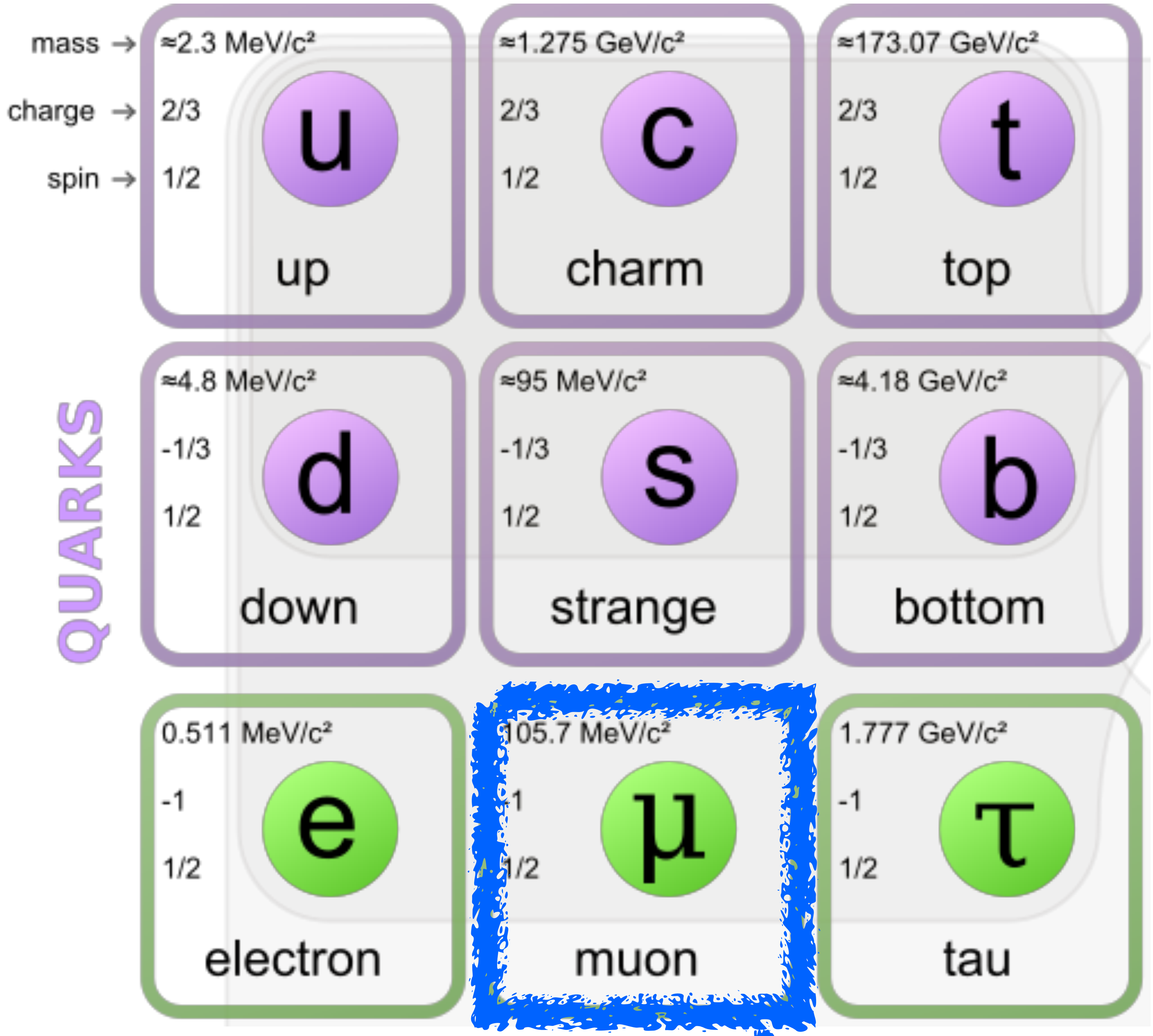
2nd-generation Yukawas at HL-LHC (H→ μμ)



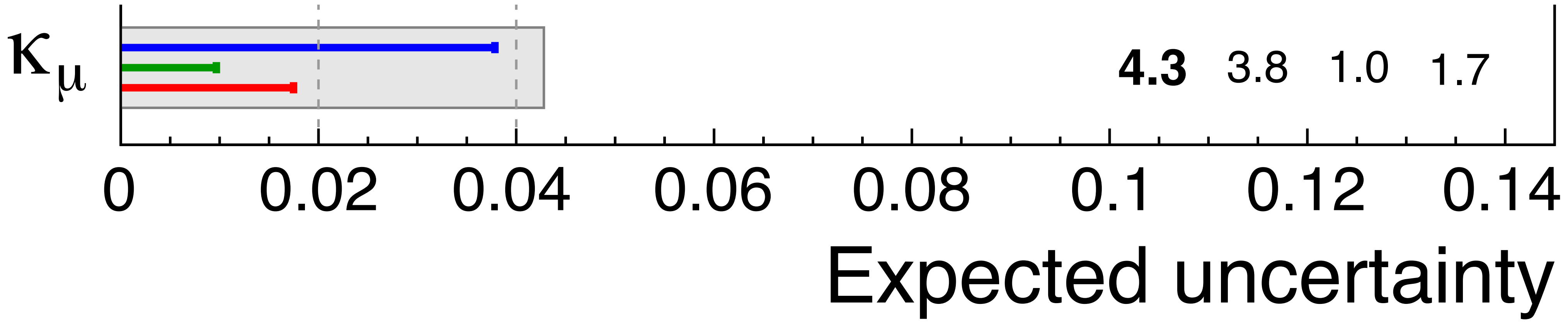


i	y_i	i	y_i
u	$2 \cdot 10^{-5}$	d	$3 \cdot 10^{-5}$
c	$8 \cdot 10^{-3}$	s	$6 \cdot 10^{-4}$
b	$3 \cdot 10^{-2}$	t	1
ν_e ν_μ ν_τ	$\sim 10^{-13}$	e	$3 \cdot 10^{-6}$
		μ	$6 \cdot 10^{-4}$
		τ	$1 \cdot 10^{-4}$

2nd-generation Yukawas at HL-LHC (H→ μμ)



i	y_i	i	y_i
u	$2 \cdot 10^{-5}$	d	$3 \cdot 10^{-5}$
c	$8 \cdot 10^{-3}$	s	$6 \cdot 10^{-4}$
b	$3 \cdot 10^{-2}$	t	1
ν_e	$\sim 10^{-13}$	e	$3 \cdot 10^{-6}$
ν_μ		μ	$6 \cdot 10^{-4}$
ν_τ		τ	$1 \cdot 10$



today: no evidence yet

(1 in 4570 decays)

observable at HL-LHC
(within about 10 years)

2nd & 1st generation Yukawas

- the hierarchy of masses between generations remains a mystery (even if it's one that some people consign to the "hopeless" category)
- Does not necessarily come from hierarchy of dimensionless Yukawa coefficients
- E.g. the Giudice-Lebedev mechanism (and follow-up work)

0804.1753

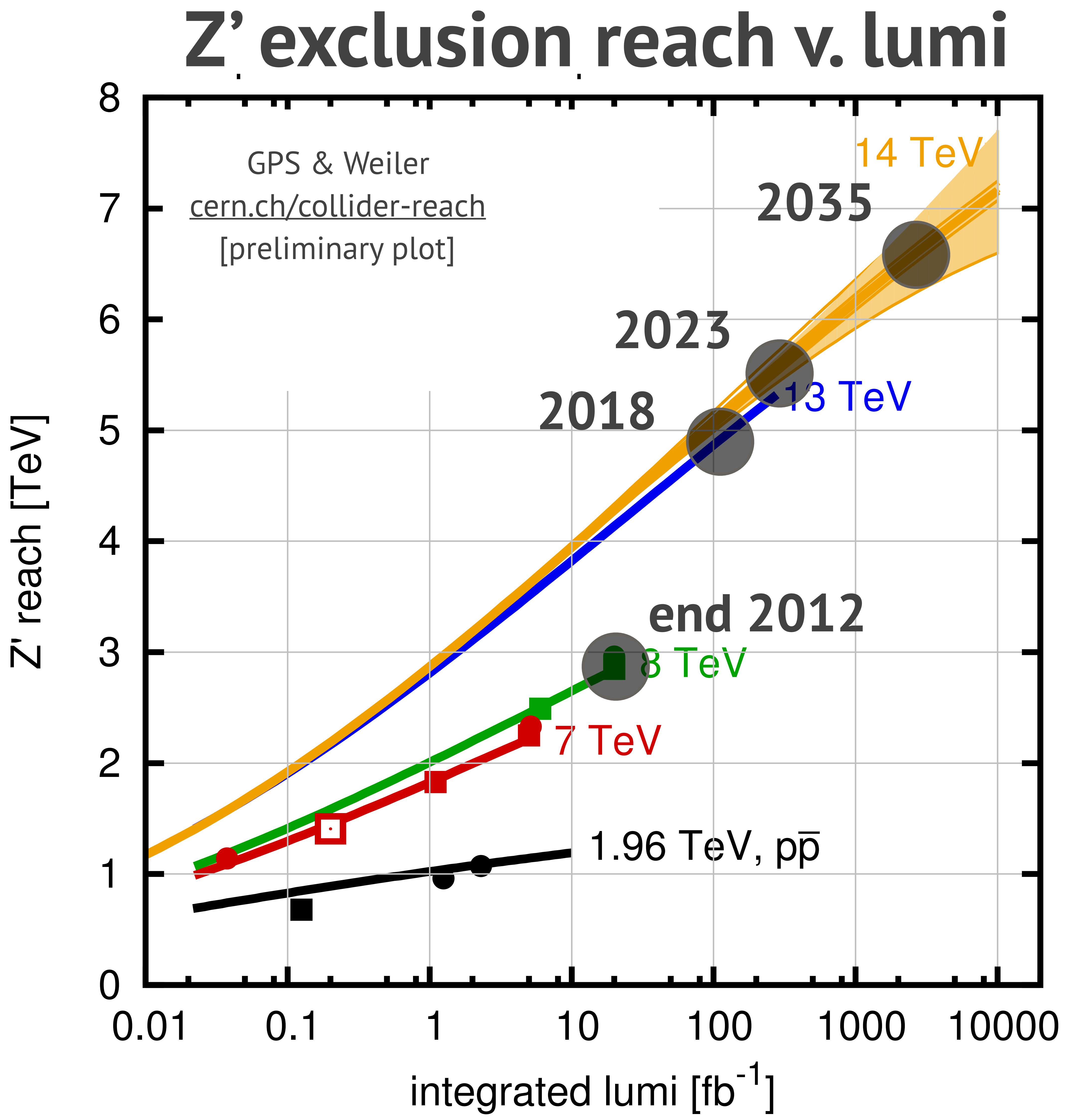
$$-\mathcal{L}_Y = Y_{ij}(\phi)\bar{\psi}_i\psi_j\phi + \text{h.c.} \qquad\qquad Y_{ij}(\phi) = c_{ij}\left(\frac{\phi^\dagger\phi}{M^2}\right)^{n_{ij}}$$

- smallness of certain masses is consequence of vev^2/M^2 suppression, not small c_{ij}
- measured Hqq interaction larger by factor $(2n_{ij} + 1)$
- cf. also various more recent discussions, e.g. by Bauer, Carena, Carmona

1801.00363

thanks to U. Haisch for a crash course on the models — any naivety is mine, not his

HL-LHC discovery potential



Today (analysed)

- 20 fb^{-1} @ 8 TeV
- 35-80 fb^{-1} @ 13 TeV

Future

- 2018 (recorded):
- 140 fb^{-1} @ 13 TeV
- 2023: ~400 fb^{-1} @ 1? TeV
- 2036: 3000 fb^{-1} @ 14 TeV

1 fb^{-1} = 10^{14} collisions

future progress?

---

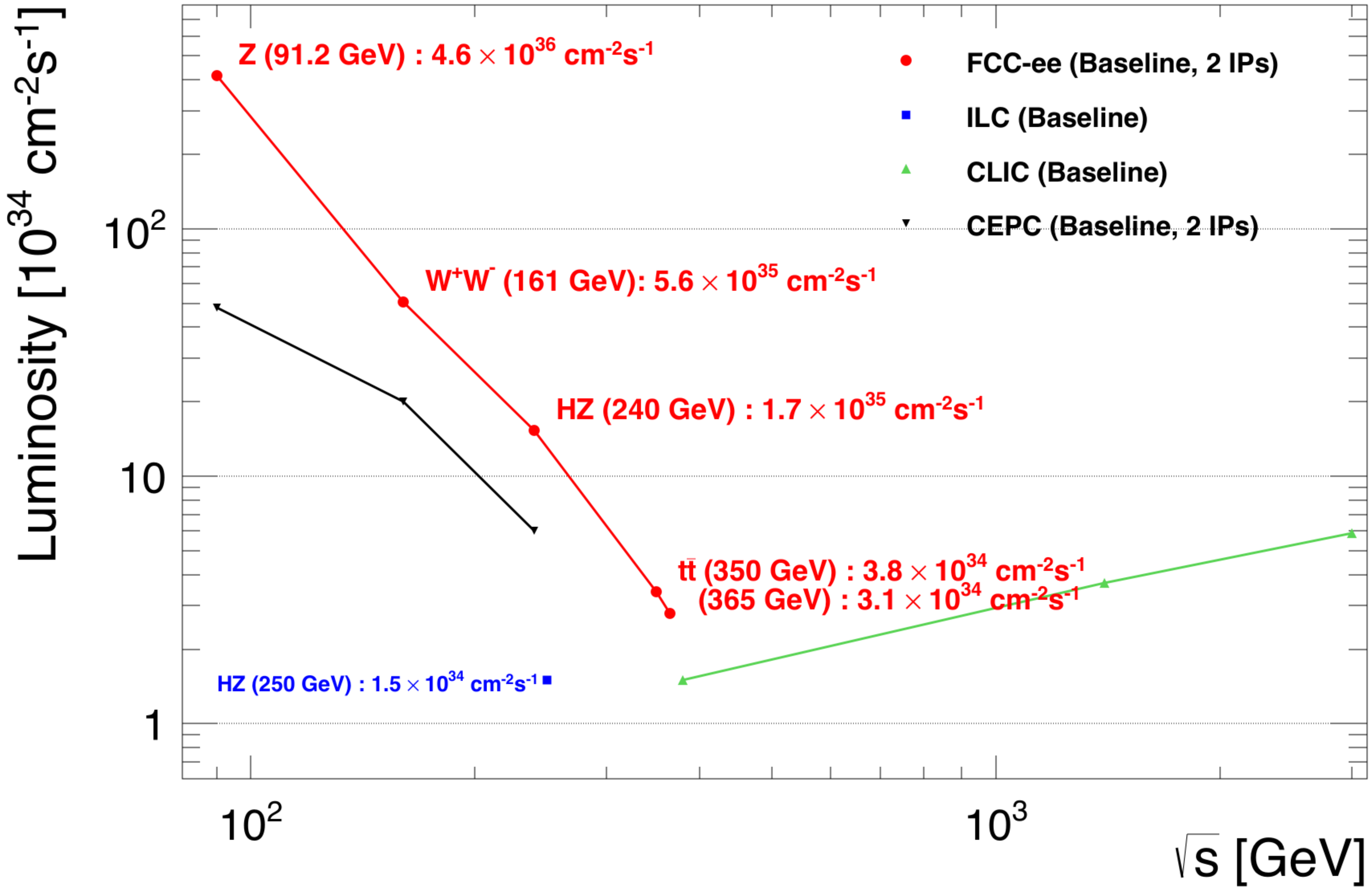
(2) proposed future colliders

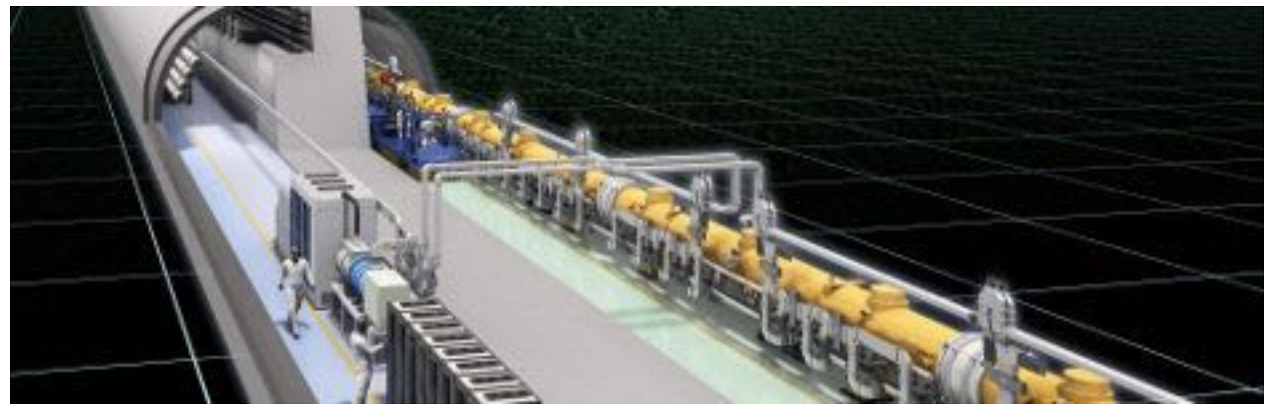
e^+e^-: ILC, CLIC, CepC, FCC-ee, LEP3

pp: CppC, HE-LHC, FCC-hh

ep: LHeC, FCC-eh

e+e− colliders: luminosity v. CoM energy





e^+e^- & eh colliders: coupling measurements (precision)

Collider	HL-LHC	ILC$_{250}$	CLIC$_{380}$	FCC-ee			FCC-eh
Luminosity (ab^{-1})	3	2	0.5	5 @ 240 GeV	+1.5 @ 365 GeV	+ HL-LHC	2
Years	25	15	7	3	+4	—	20
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.8	6.3	2.7	**1.3**	1.1	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.35	0.80	0.2	**0.17**	0.16	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.7	1.3	1.3	**0.43**	0.40	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.8	2.8	1.3	**0.61**	0.55	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	6.8	1.7	**1.21**	1.18	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	2.2	3.8	1.6	**1.01**	0.83	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.7	1.9	4.2	1.4	**0.74**	0.64	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	13	n.a.	10.1	**9.0**	3.9	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	6.4	n.a.	4.8	**3.9**	1.1	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	–	–	–	2.4	1.7
BR$_{EXO}$ (%)	SM	< 1.8	< 3.0	< 1.2	$< \mathbf{1.0}$	< 1.0	n.a.

e+e− & eh colliders: Higgs-charm (2nd generation) coupling

today: no evidence yet

(1 in 35 decays)

needs an e+e− or ep collider

Collider	HL-LHC	ILC_{250}	CLIC_{380}	FCC-ee			FCC-eh
Luminosity (ab^{-1})	3	2	0.5	5 @ 240 GeV	+1.5 @ 365 GeV	+ HL-LHC	2
Years	25	15	7	3	+4	—	20
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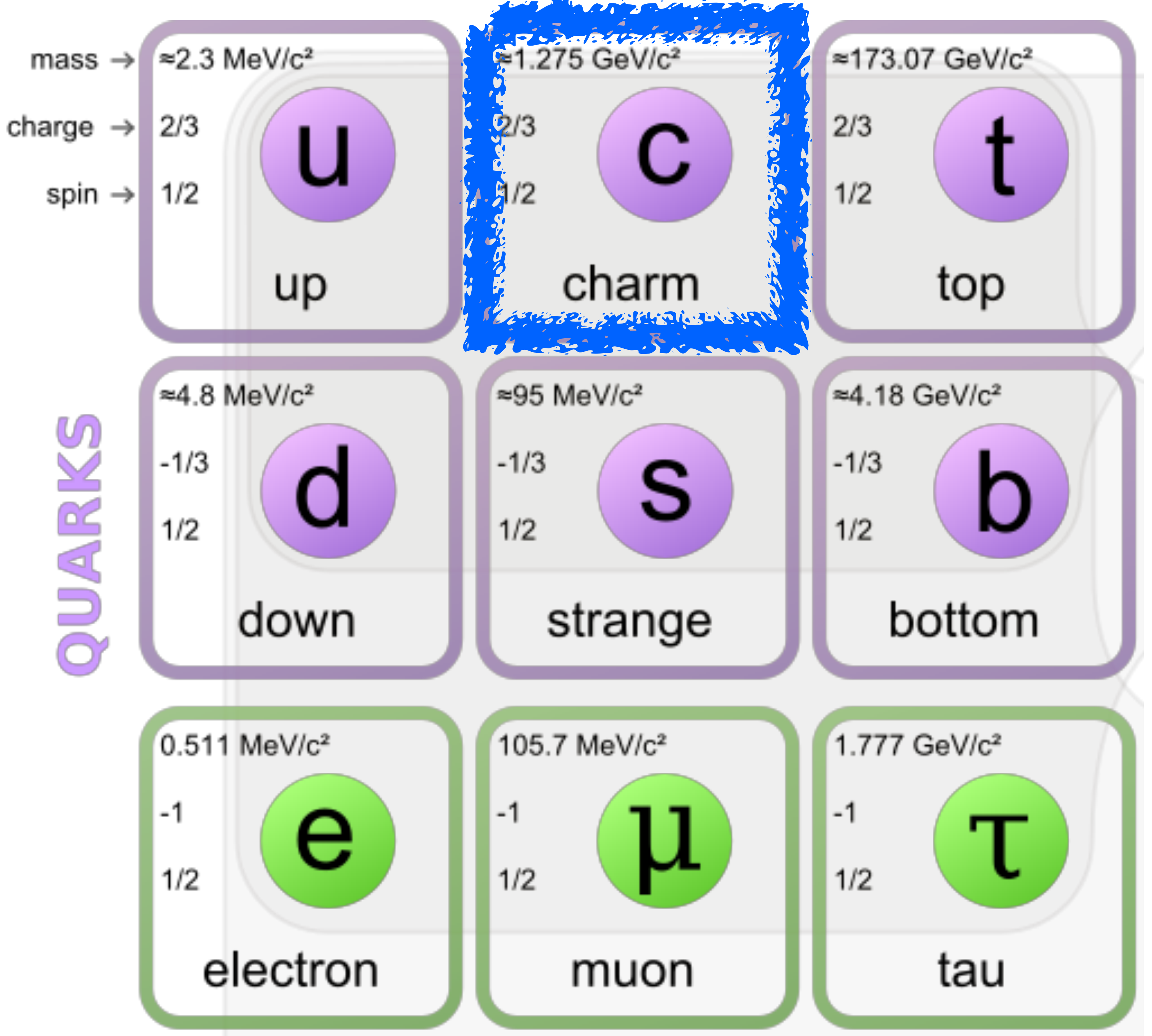
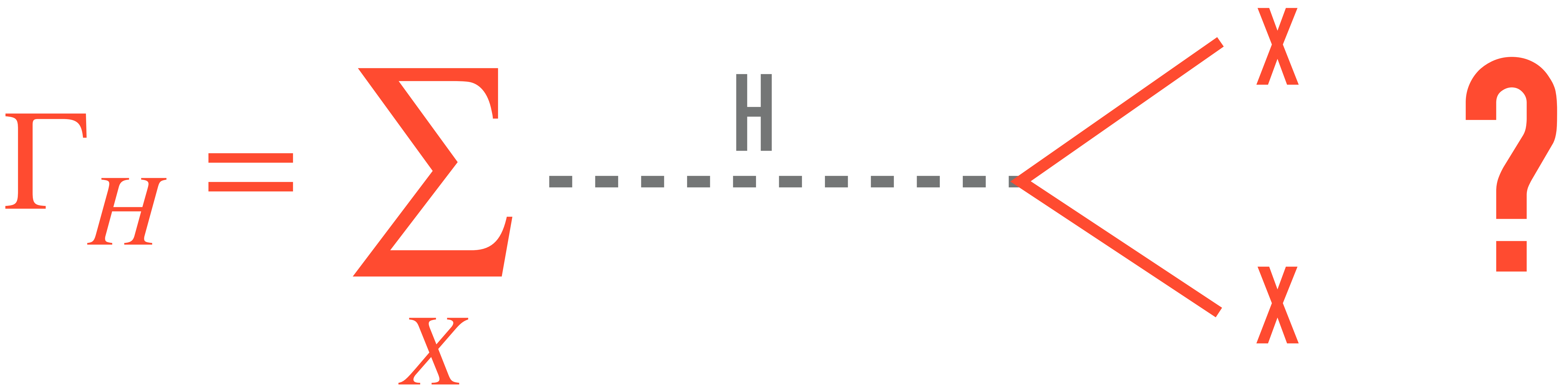
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	–	–	–	2.4	1.7
BR_{EXO} (%)	SM	< 1.8	< 3.0	< 1.2	$< \mathbf{1.0}$	< 1.0	n.a.



e⁺e⁻ colliders: total Higgs width (≡ lifetime)

All current fits need to make assumptions about the total Higgs width (sum over all decay channels, whether observed or not).

Only e⁺e⁻ colliders can measure this directly.



$$\Gamma_H = \sum_X$$

Collider	HL-LHC	ILC_{250}	CLIC_{380}	FCC-ee			FCC-eh
Luminosity (ab^{-1})	3	2	0.5	5 @ 240 GeV	+1.5 @ 365 GeV	+ HL-LHC	2
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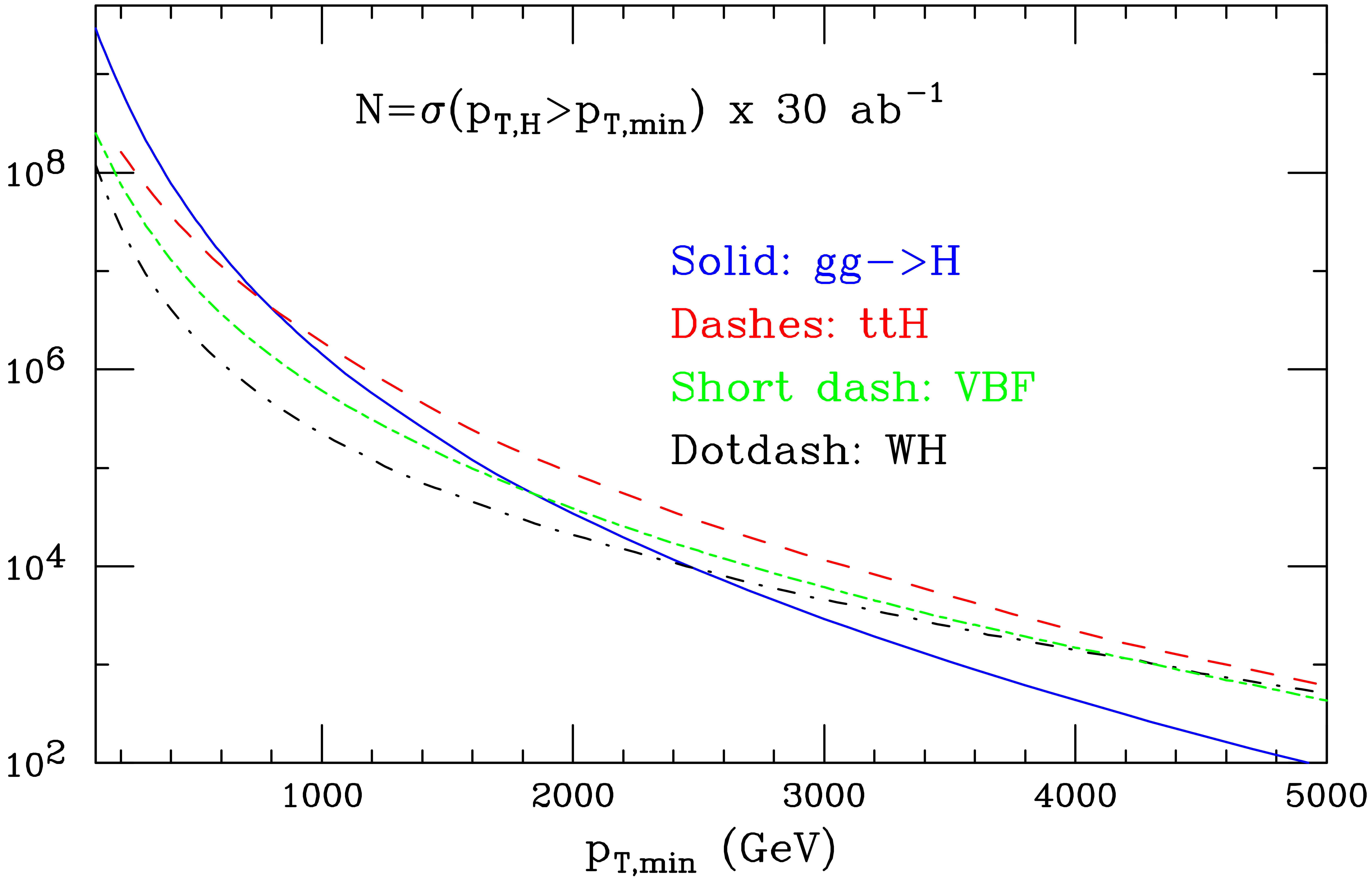
pp colliders (concentrate on FCC-hh)

Figure 2: Higgs production cross sections versus collision energies normalized to the 14 TeV rates.

Higgs production rate increases substantially with collider centre-of-mass energy

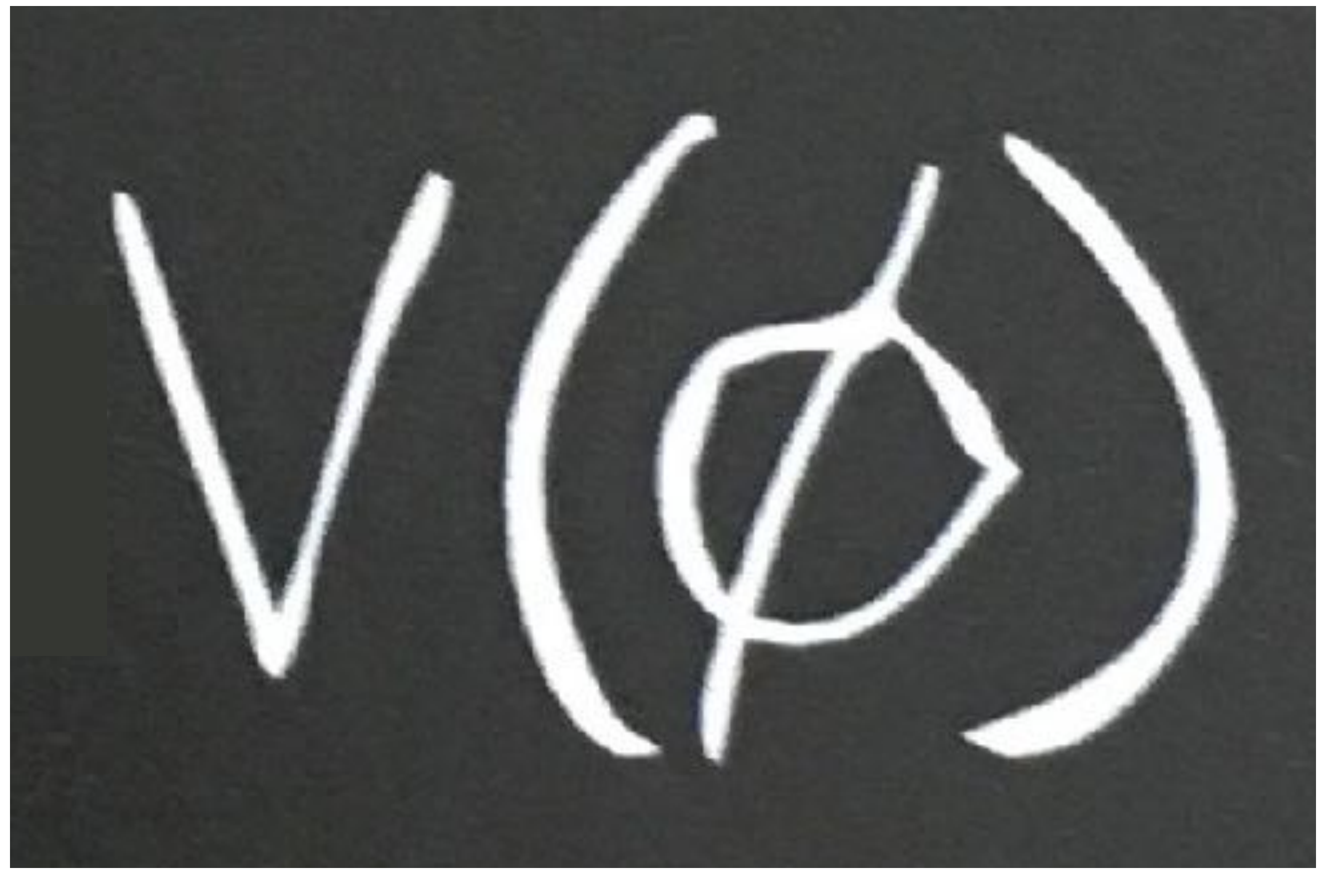
is Higgs interaction pointlike?

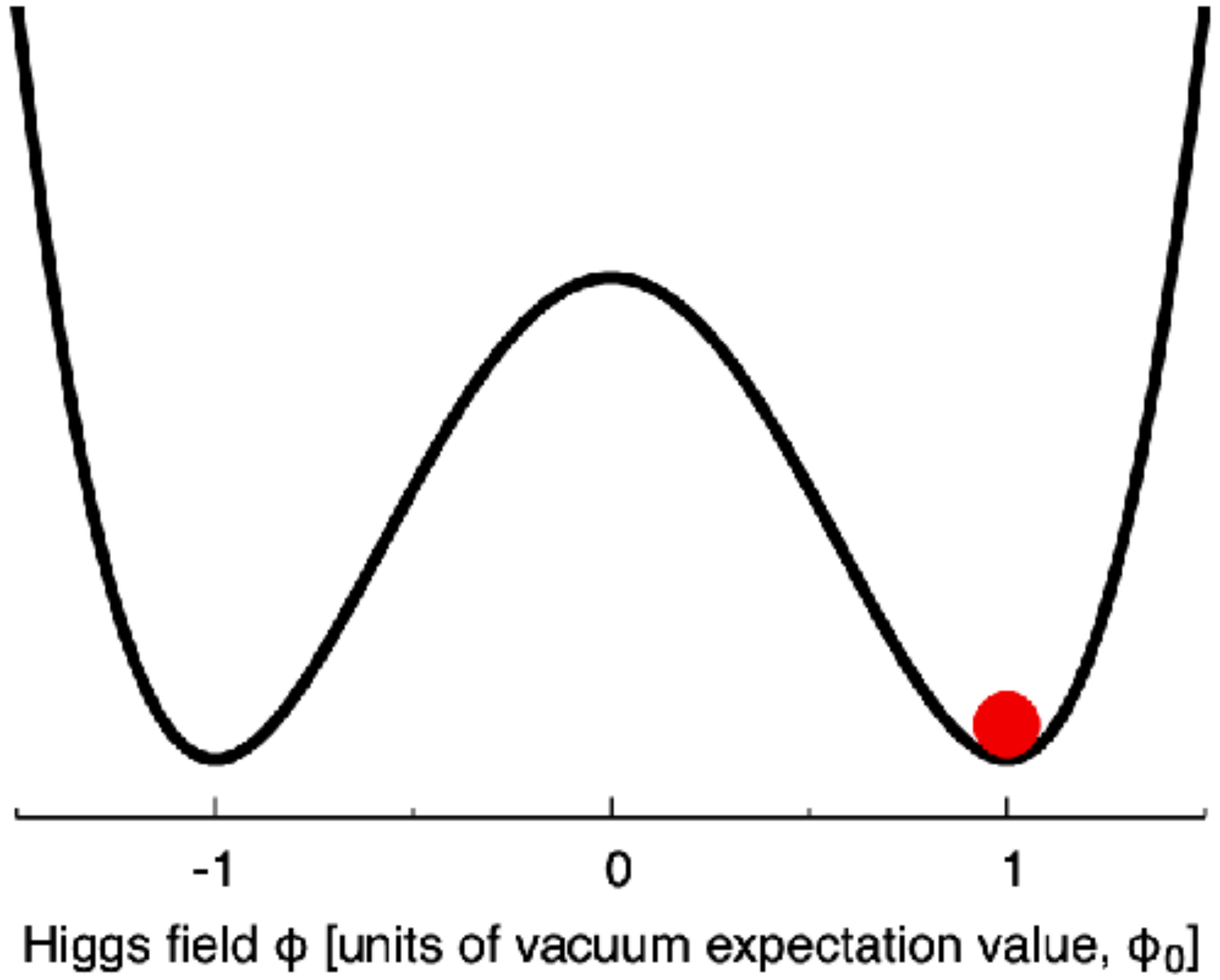


study in events with large momentum transfers

high-p_T
or offshell Higgs

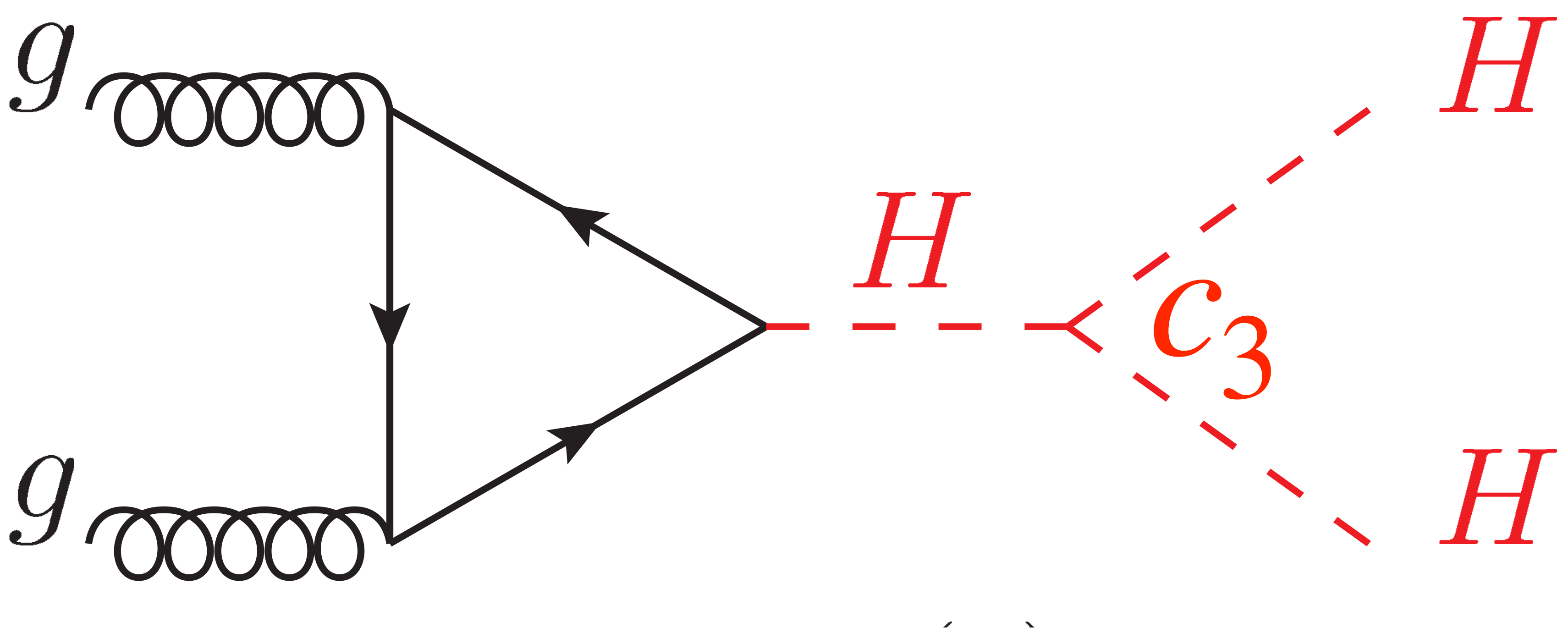
$V(\Phi) = m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$?



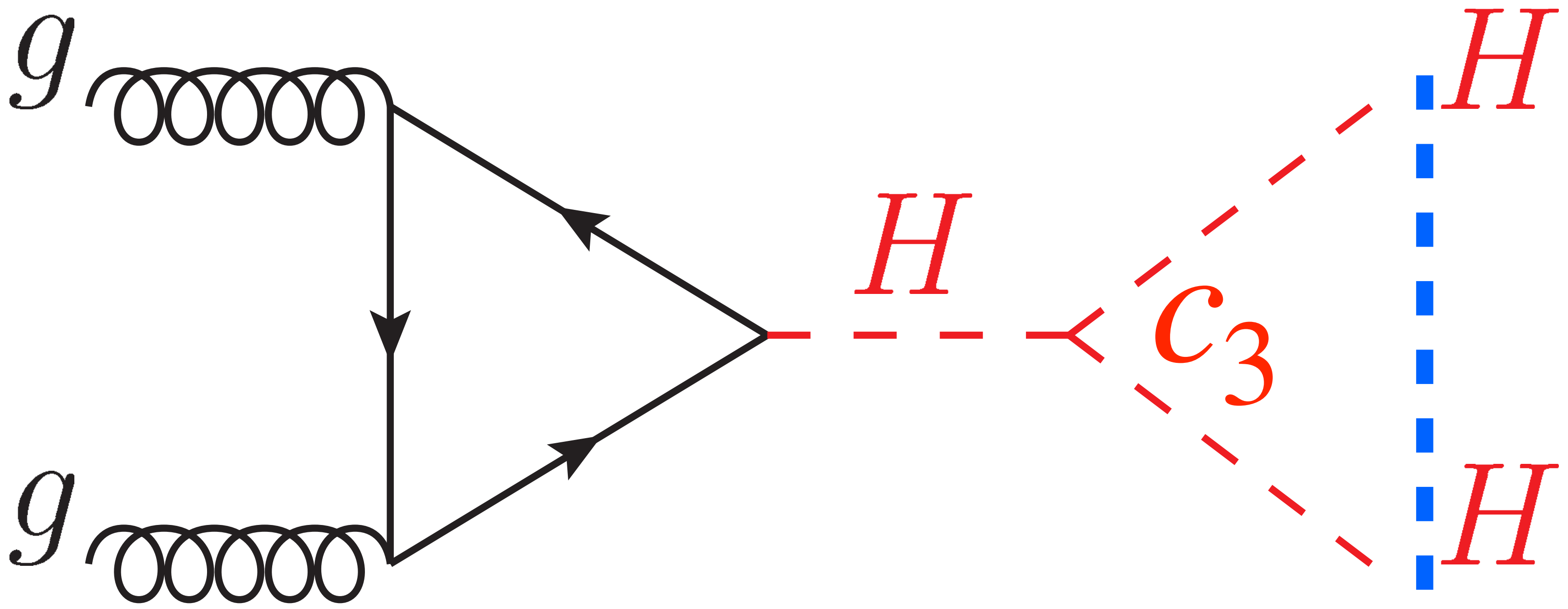


- **The Higgs potential holds together the rest of the standard model (keystone)**
- so far (as a fundamental potential) only ever seen in textbooks!
- $-\varphi^2 + \varphi^4$ implies specific Taylor expansion around $\varphi=\varphi_0$:

$$V(\phi_0 + H) = V_0 + \frac{1}{2}m_H^2 H^2 + c_3 H^3 + \cdots$$



https://cern.ch/gsalam/higgs/repo/HH.mp4

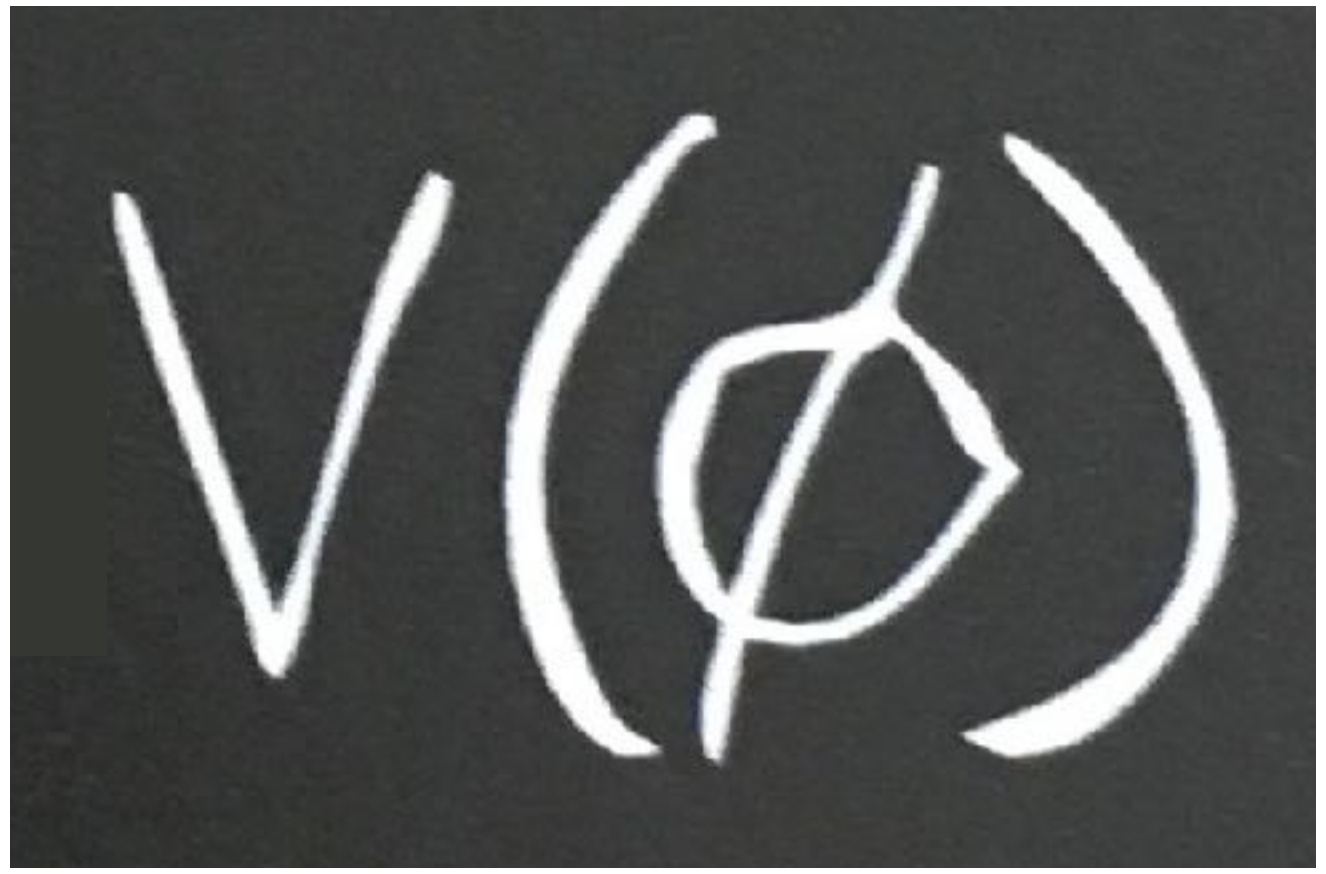


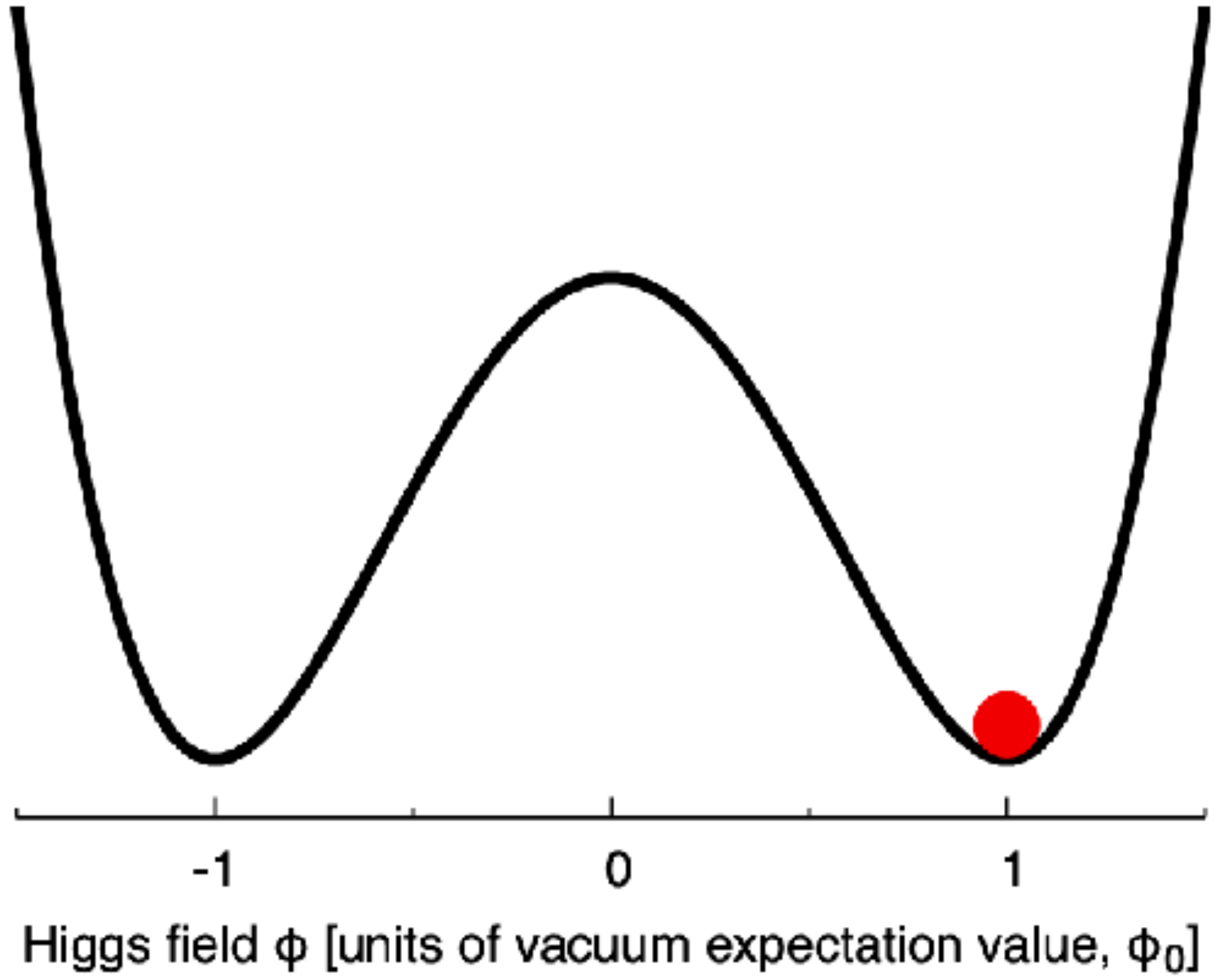
https://cern.ch/gsalam/higgs/repo/HH.mp4

Higgs field in space

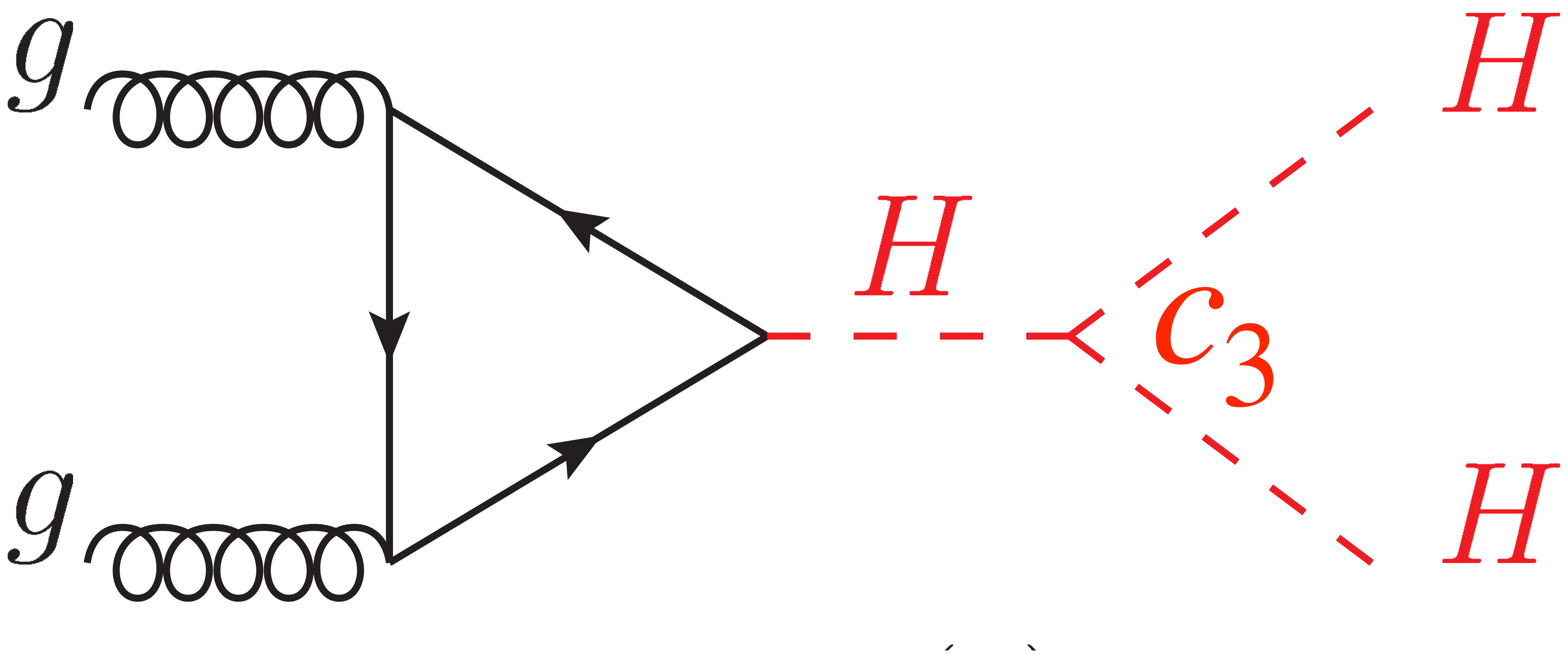
https://cern.ch/gsalam/higgs/repo/HH.mp4

$V(\Phi) = m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$?



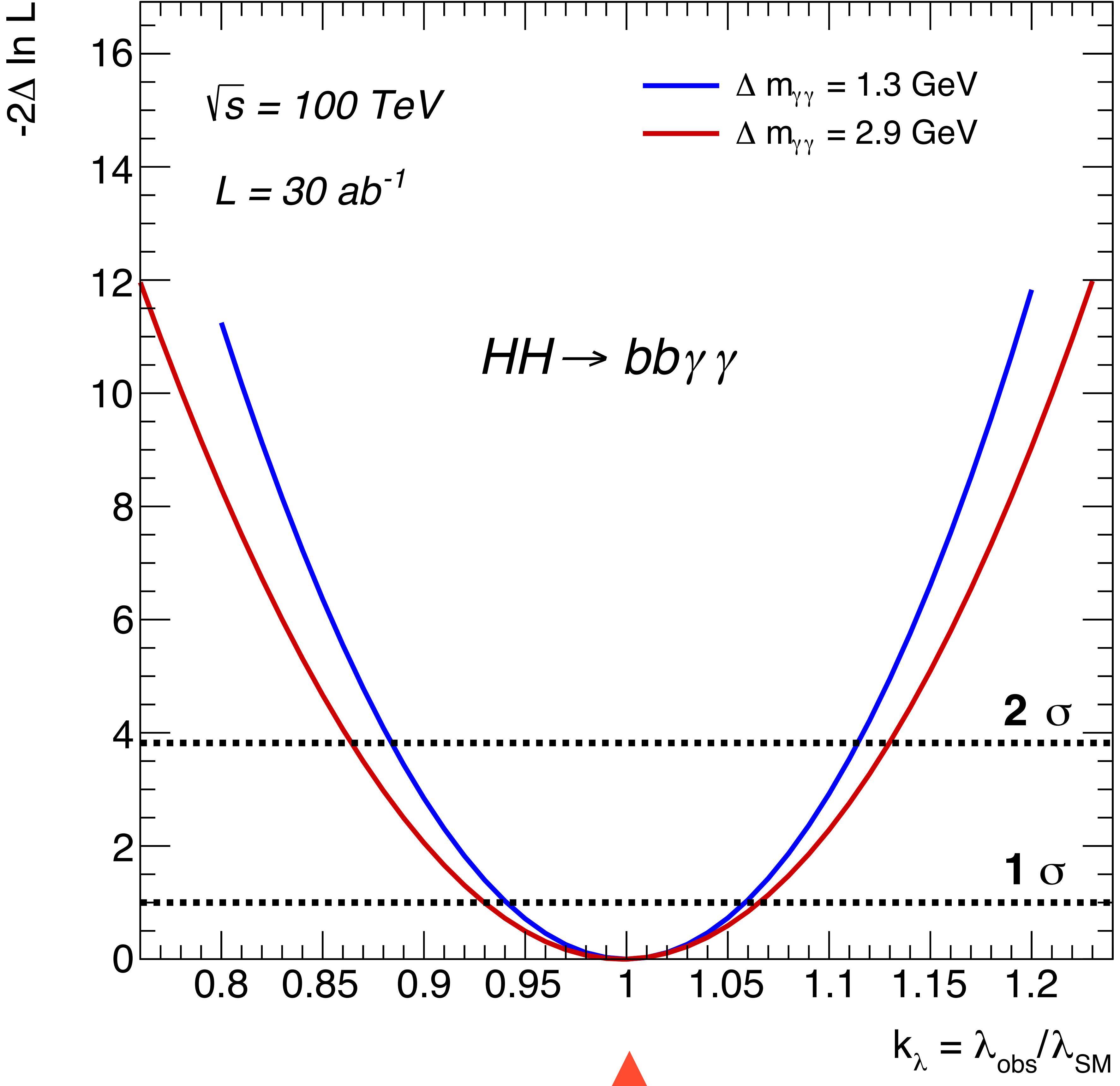


FCC-hh channel	$b\bar{b}\gamma\gamma$	$b\bar{b}ZZ^*[\to 4\ell]$
c_3 precision	6.5%	14%

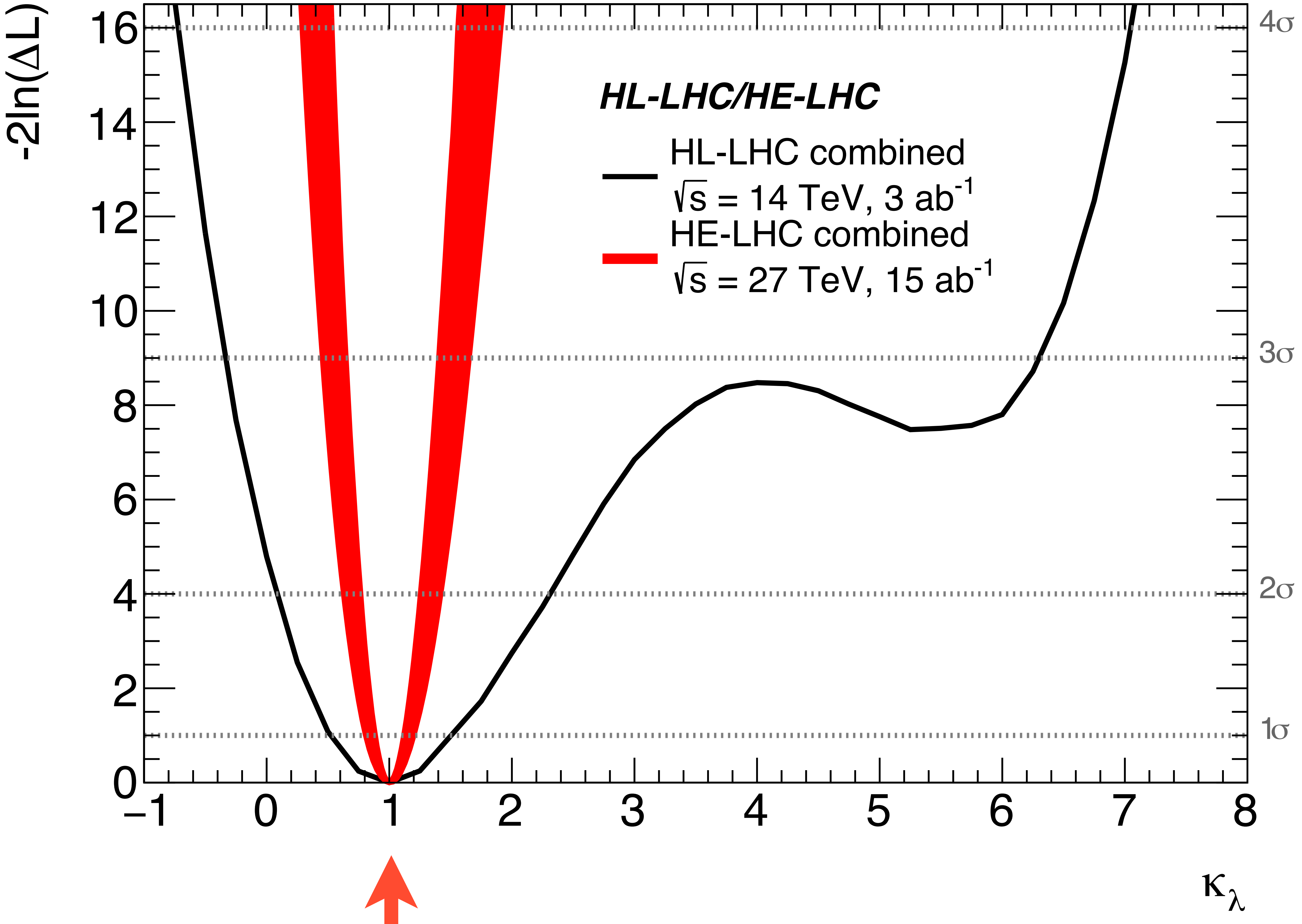


FCC triple Higgs v. LHC and HE-LHC

FCC



HE-LHC and HL-LHC

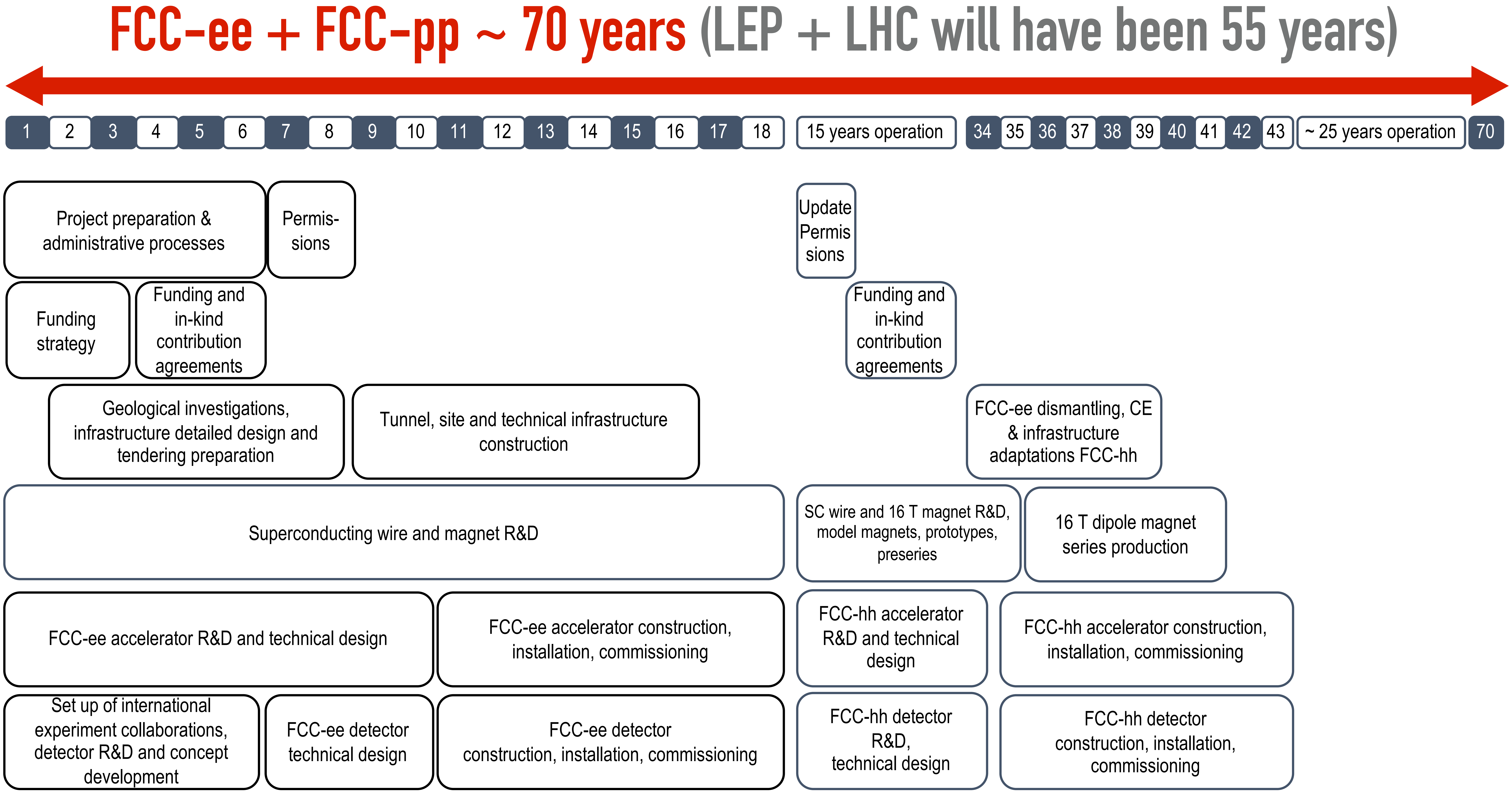


note different scales

EUROPEAN STRATEGY FOR PARTICLE PHYSICS

The European Strategy for Particle Physics is the cornerstone of Europe's decision-making process for the long-term future of the field. Mandated by the CERN Council, it is formed through a broad consultation of the grass-roots particle physics community, it actively solicits the opinions of physicists from around the world, and it is developed in close coordination with similar processes in the US and Japan in order to ensure coordination between regions and optimal use of resources globally.

ongoing (2018 – 2020)



FCC-ee + FCC-pp ~ 70 years (LEP + LHC will have been 55 years)

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 | 15 years operation | 34 35 36 37 38 39 40 41 42 43 | ~ 25 years operation | 70

Project preparation & administrative processes

Permis-sions

Update Permis sions

Funding strategy

Funding and in-kind contribution agreements

Funding and in-kind contribution agreements

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

Superconducting wire and magnet R&D

SC wire and 16 T magnet R&D, model magnets, prototypes, preseries

16 T dipole magnet series production

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

Set up of international experiment collaborations, detector R&D and concept development

FCC-ee detector technical design

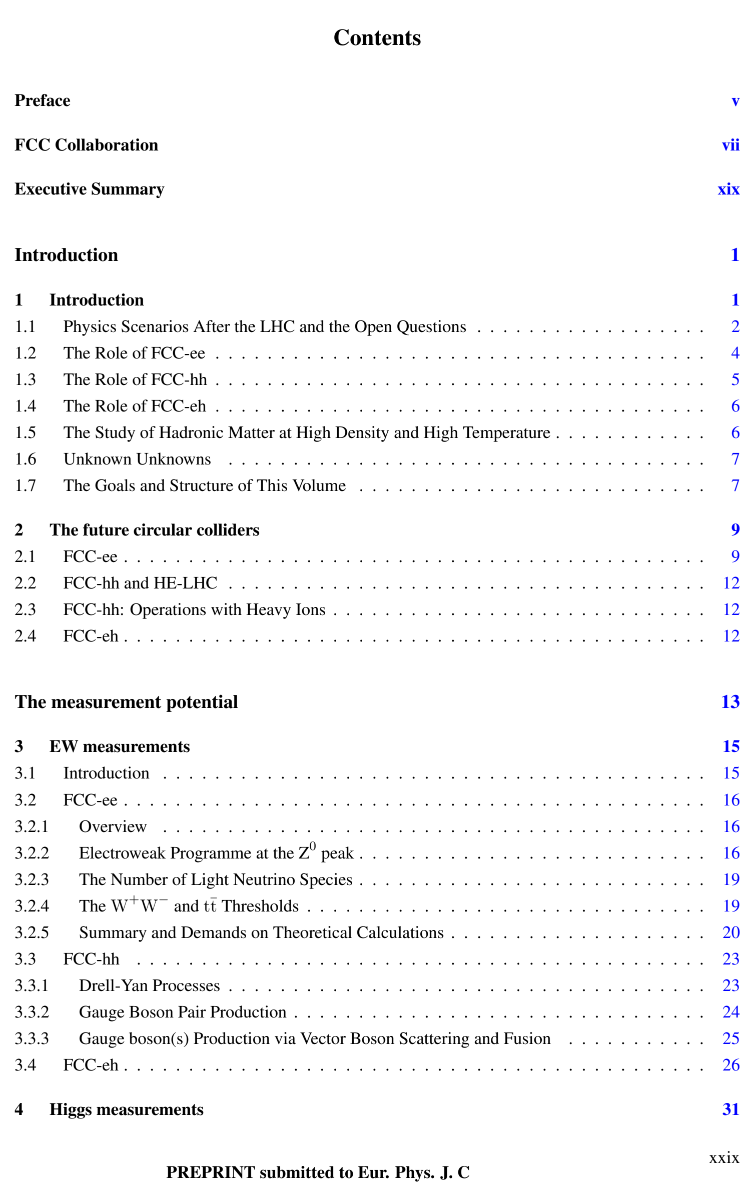
FCC-ee detector construction, installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

Figure 9: Overview of implementation timeline for the integral FCC program, starting in 2020. Numbers in the top row indicate the year. Physics operation for FCC-ee would start towards the end-2030s; physics operation for FCC-hh would start in the mid-2060s.

FCC physics CDR, table of contents (one of several volumes)



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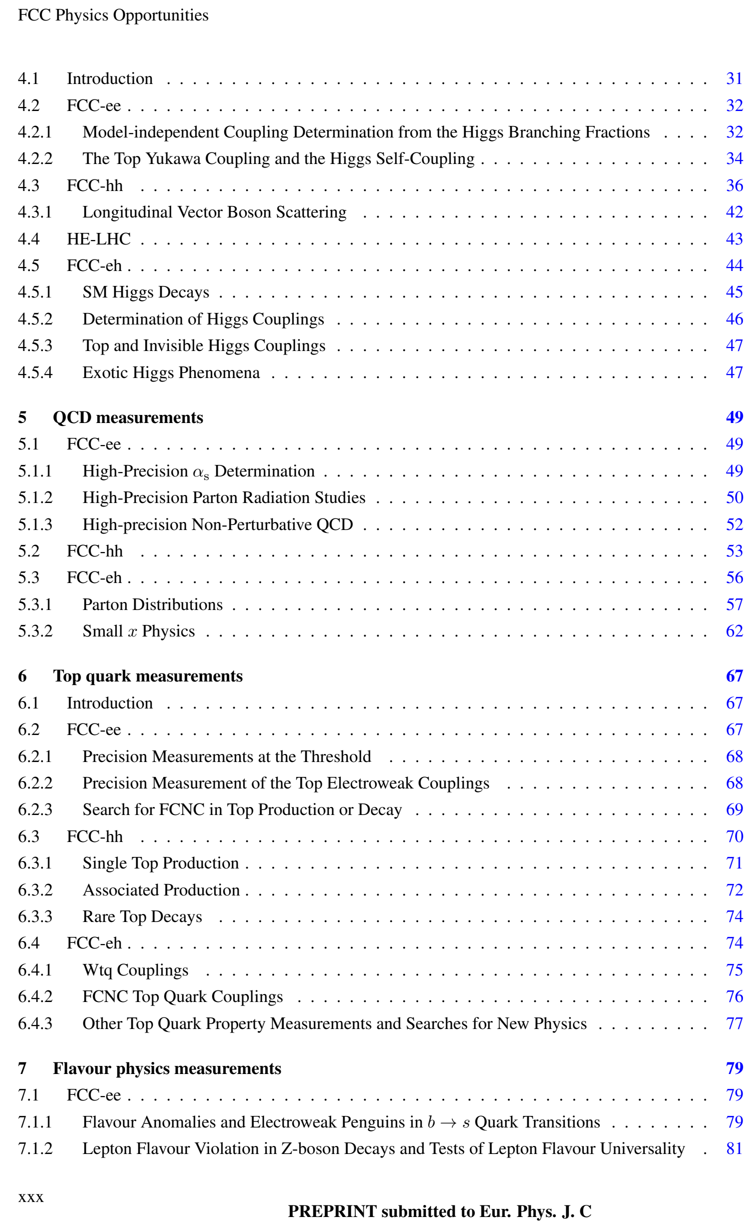

FCC Physics Opportunities

xxx

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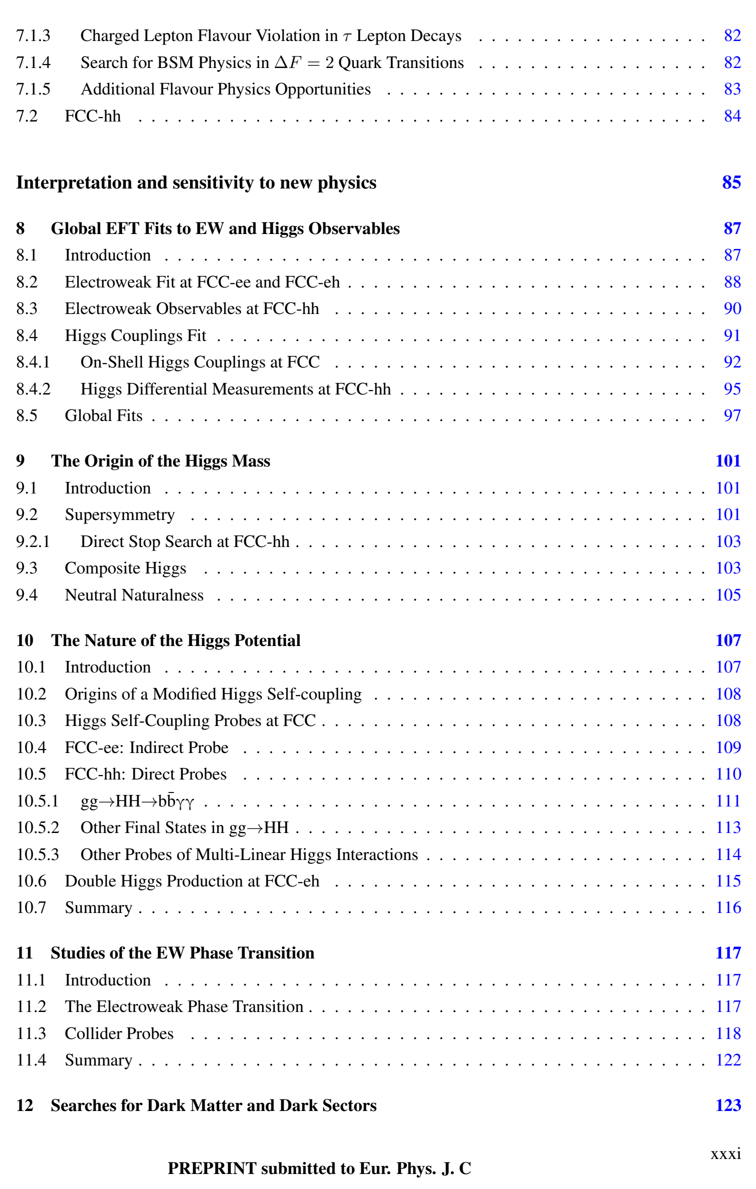

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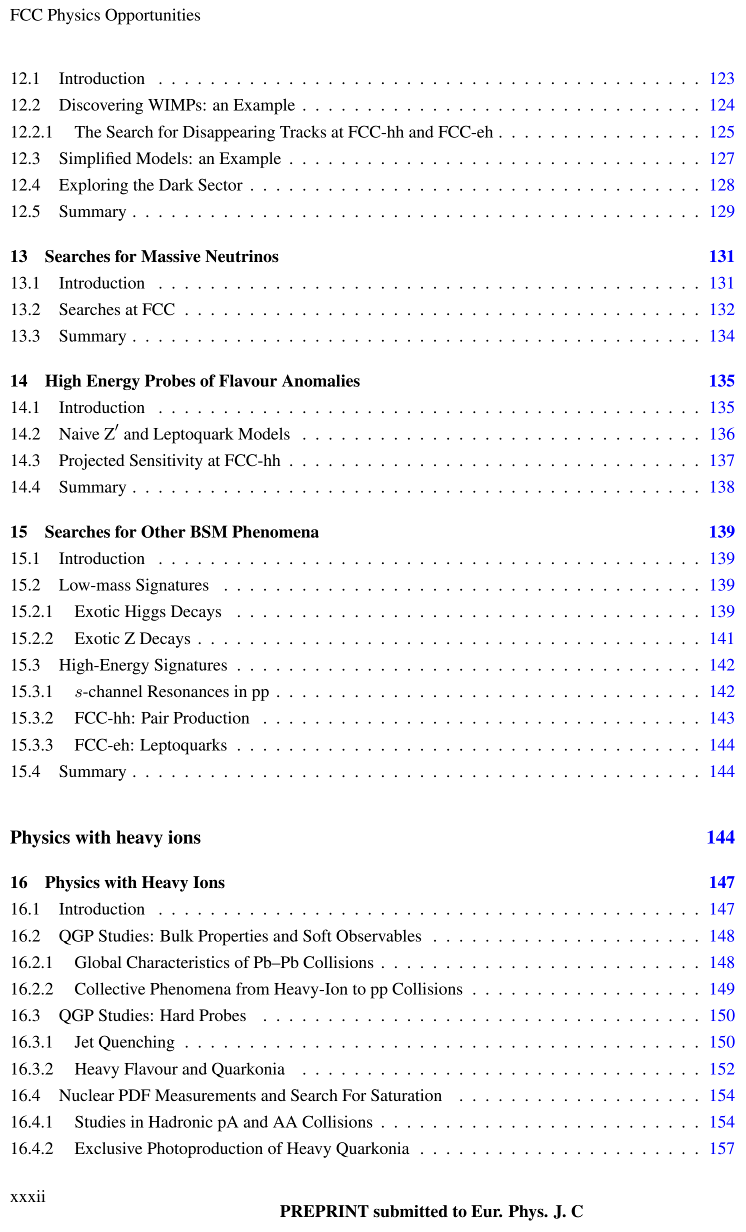

FCC Physics Opportunities

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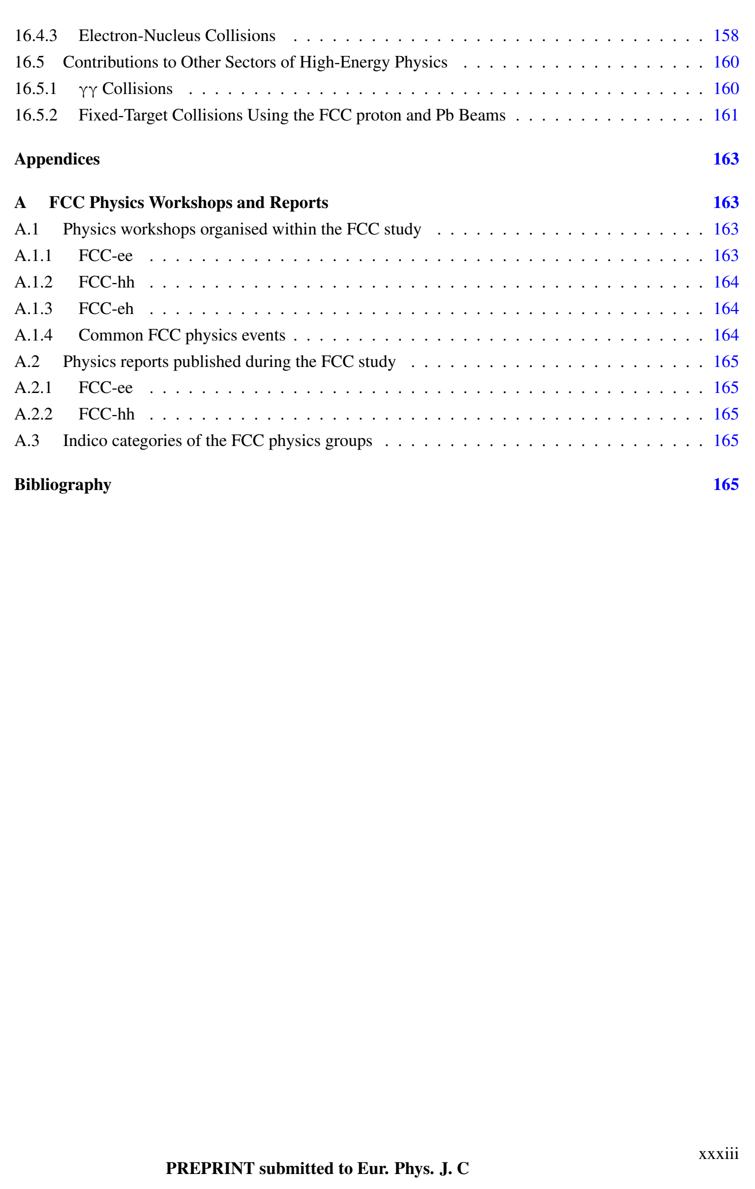

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closing

> I personally expect supersymmetry to be discovered at the LHC

-a Nobel prize-winning theorist [2008]

http://cerncourier.com/cws/article/cern/35456

The New York Times

Opinion

GRAY MATTER

A Crisis at the Edge of Physics

By Adam Frank and Marcelo Gleiser

June 5, 2015

“the standard model, despite the glory of its vindication, is also a dead end. It offers no path forward […]”

The New York Times

Opinion

GRAY MATTER

A Crisis at the Edge of Physics

By Adam Frank and Marcelo Gleiser

June 5, 2015

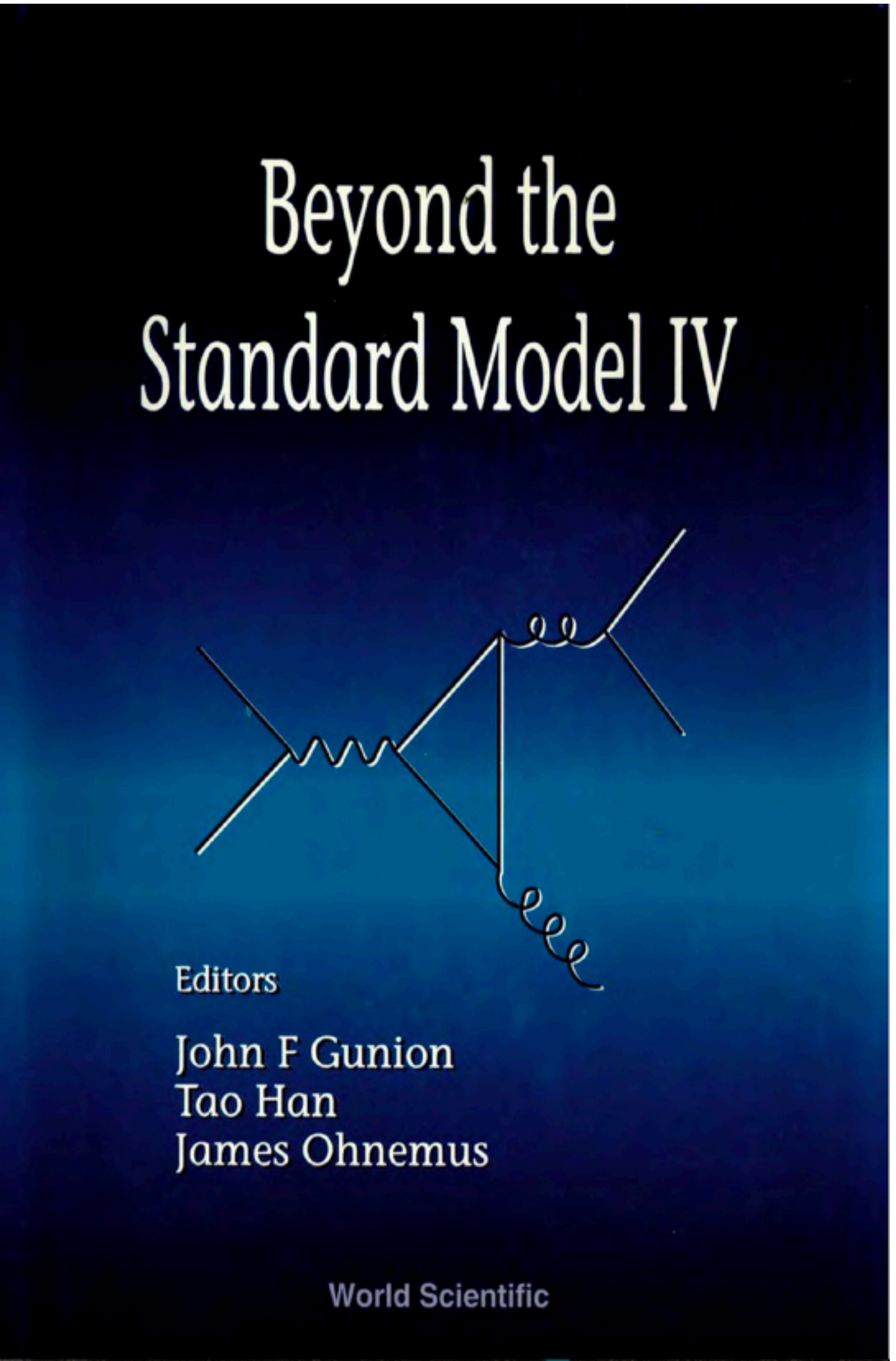
I disagree.

Because the non-gauge part of the standard model is far from being fullly explored.

3 Yukawas out of 9
We know nothing
about the self
coupling

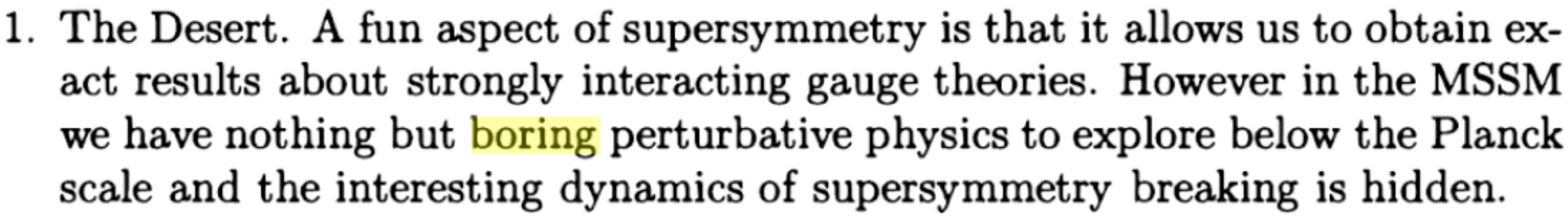
“the standard model, despite the glory of its vindication, is also a dead end. It offers no path forward […]”

it would be so much more exciting if we'd discovered new physics, right?



not everyone would agree

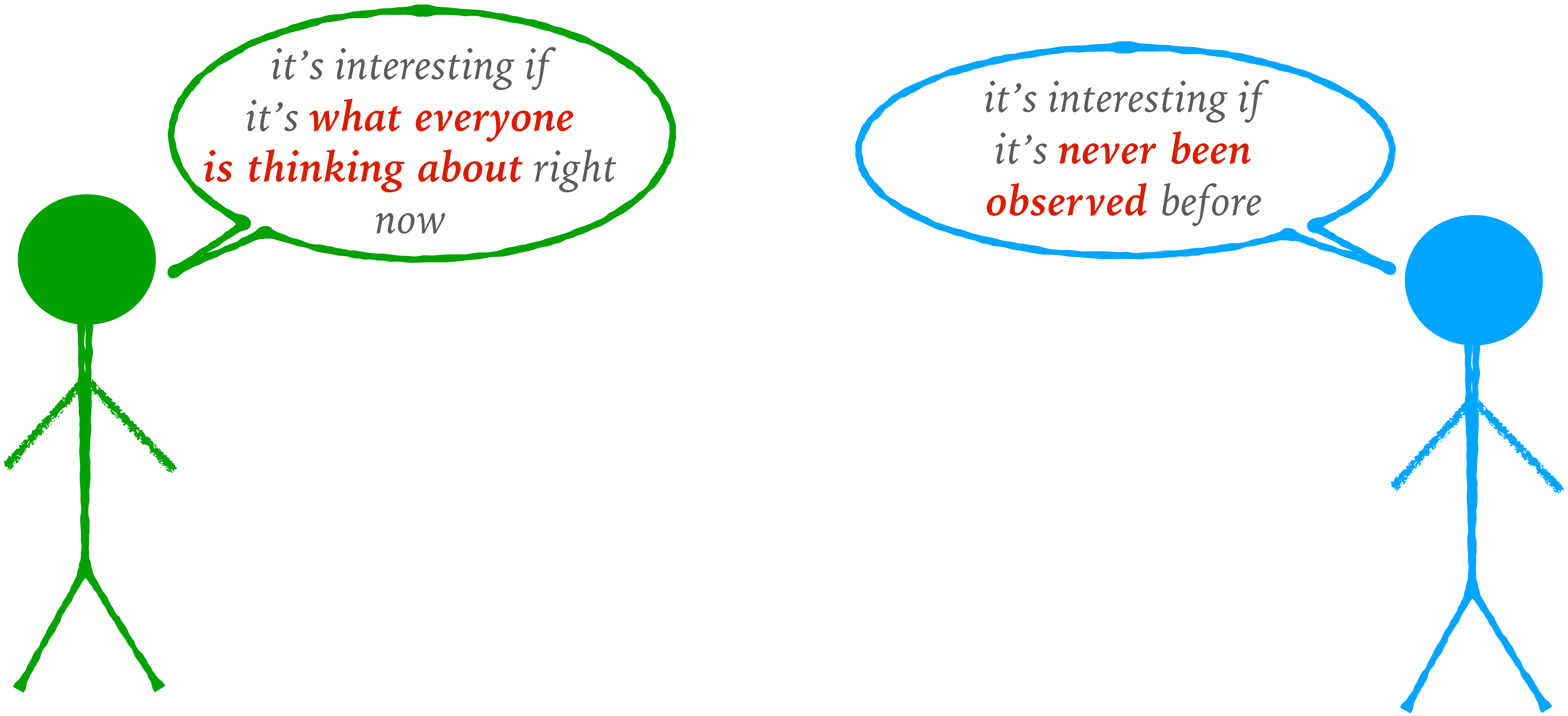
Back in 1995:



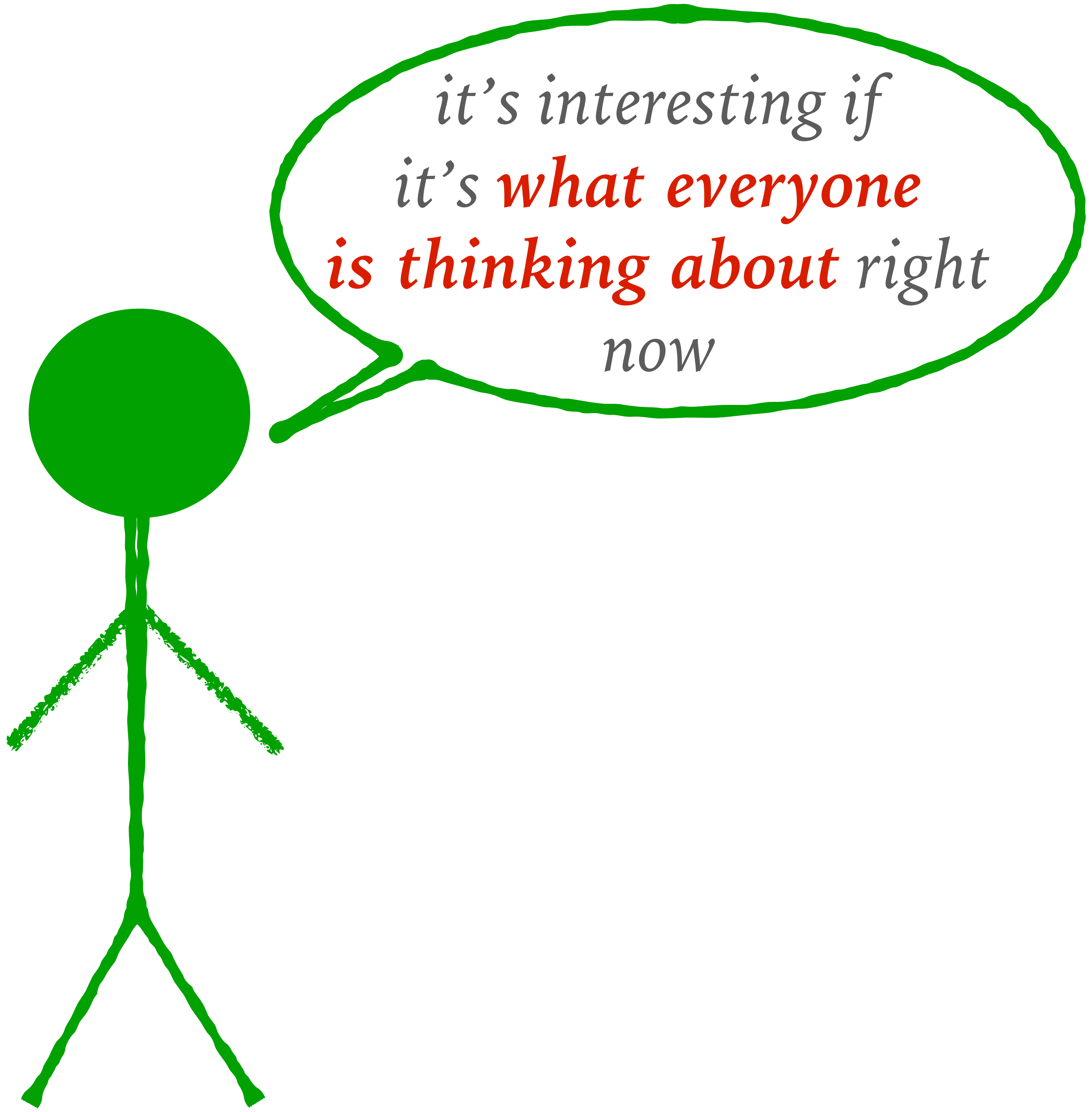
1. The Desert. A fun aspect of supersymmetry is that it allows us to obtain exact results about strongly interacting gauge theories. However in the MSSM we have nothing but boring perturbative physics to explore below the Planck scale and the interesting dynamics of supersymmetry breaking is hidden.

some theorists

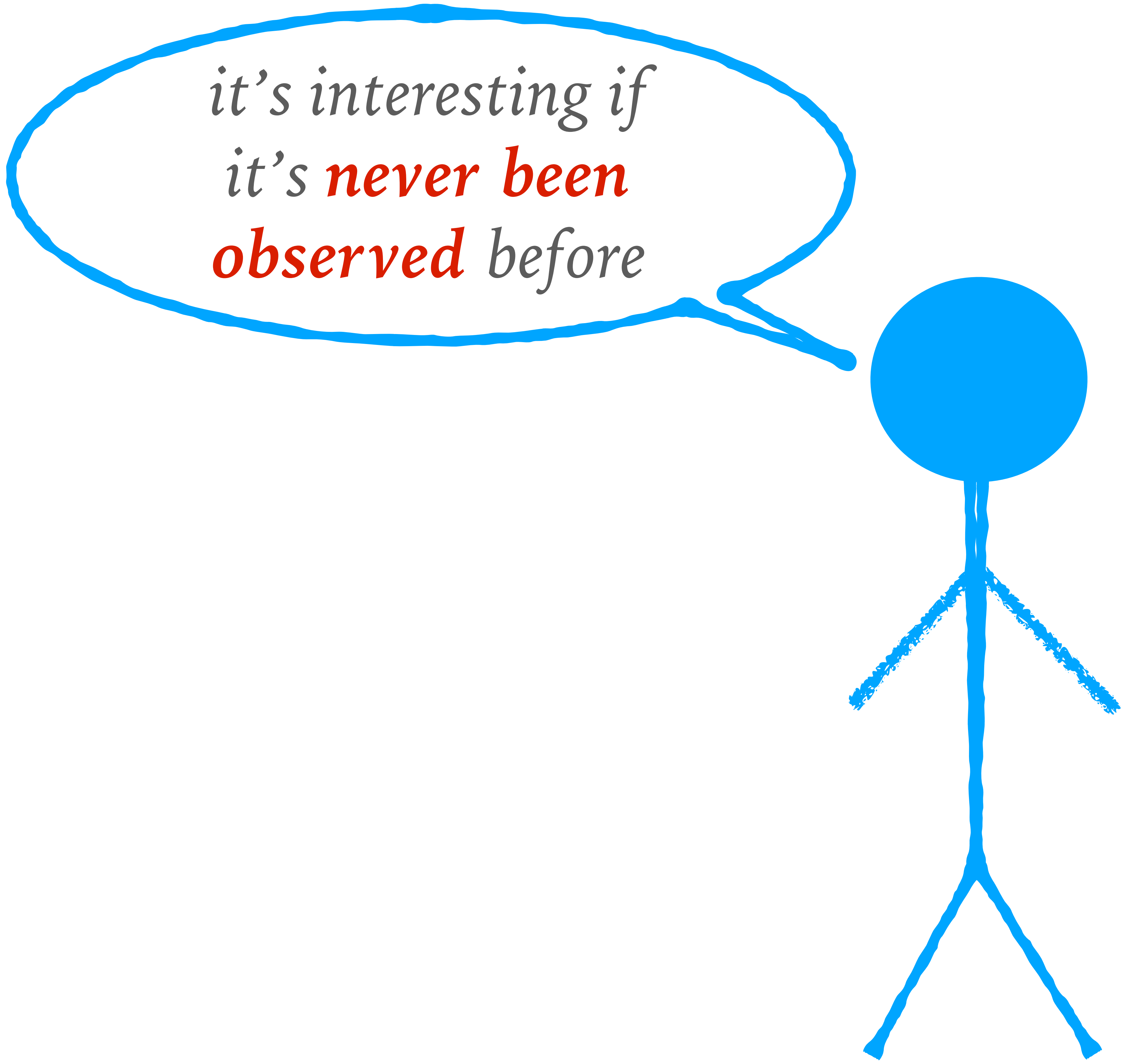
experimenter



some theorists



experimenter



both have a point

(don't let one side dampen the other side's interest)

we must not underestimate our ignorance about the Higgs sector, nor the value of exploring and establishing it

e.g. accessing Yukawa couplings beyond the 3rd generation,
the triple-Higgs coupling → Higgs-field potential, SM keystone,
& the pathway from discovery to precision

meanwhile, the search for new physics continues

with much scope for inventing ingenious search techniques, and identifying novel models that could be probed

(And finding other things to do with the particles we have)

searches, Higgs & other SM physics share in common

the need to think about how we relate the
underlying Lagrangian of particle physics
with observations of $\sim 10^{16}$ *high-energy proton collisions*