IST Physics Colloquium
Lisbon, Portugal
19 February 2025

A Perspective on the Future of High-Energy Collider Physics

Gavin Salam
University of Oxford & All Souls College

THE ROYAL SOCIETY

UNIVERSITY OF OXFORD

UKRI
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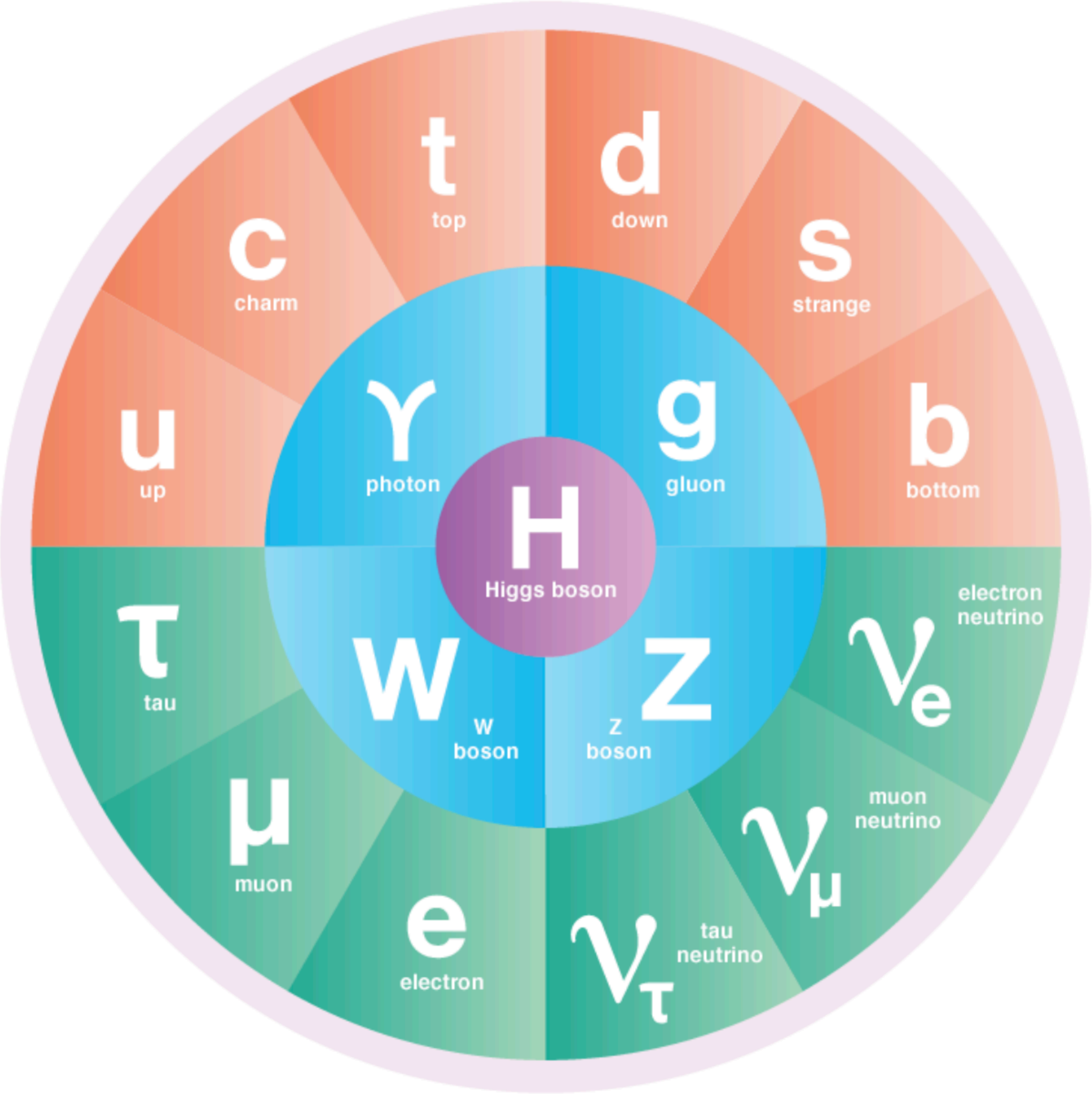
What are the fundamental forces and building blocks of the universe?

Why do they have the properties that we observe?

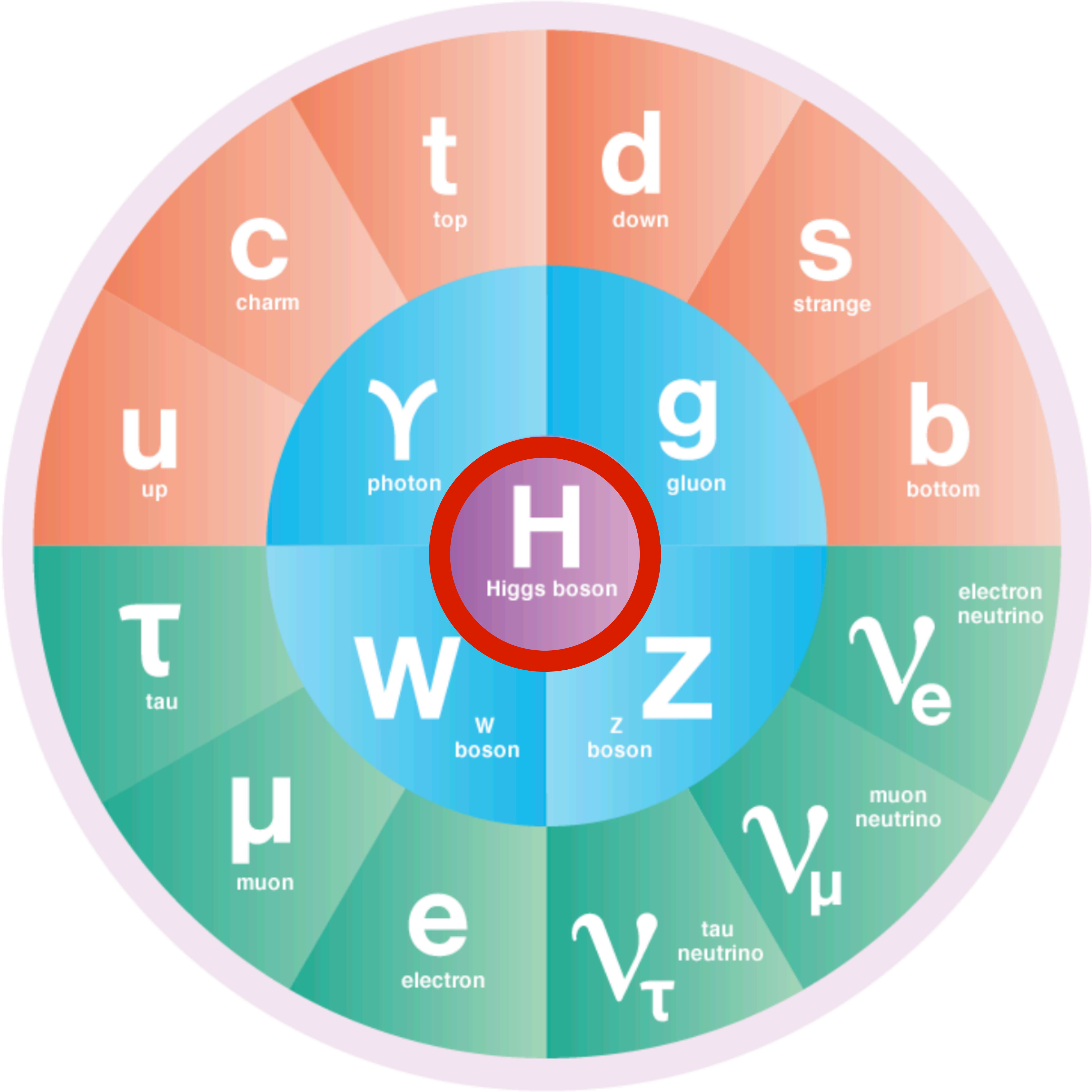
The Standard Model (SM)



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

particles

The Standard Model (SM)



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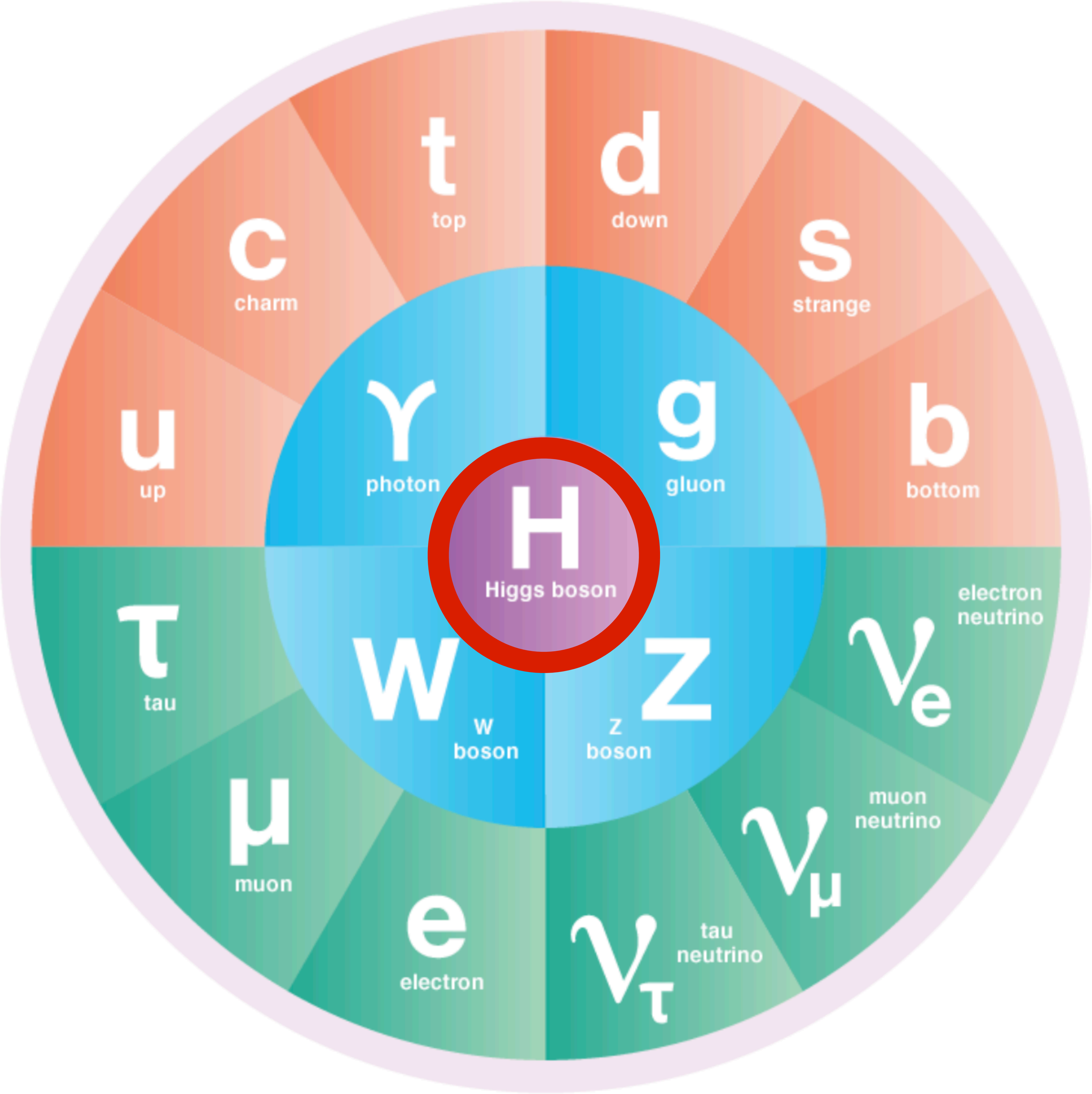
particles

“the standard-model (SM) is complete”

The Standard Model (SM)



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?

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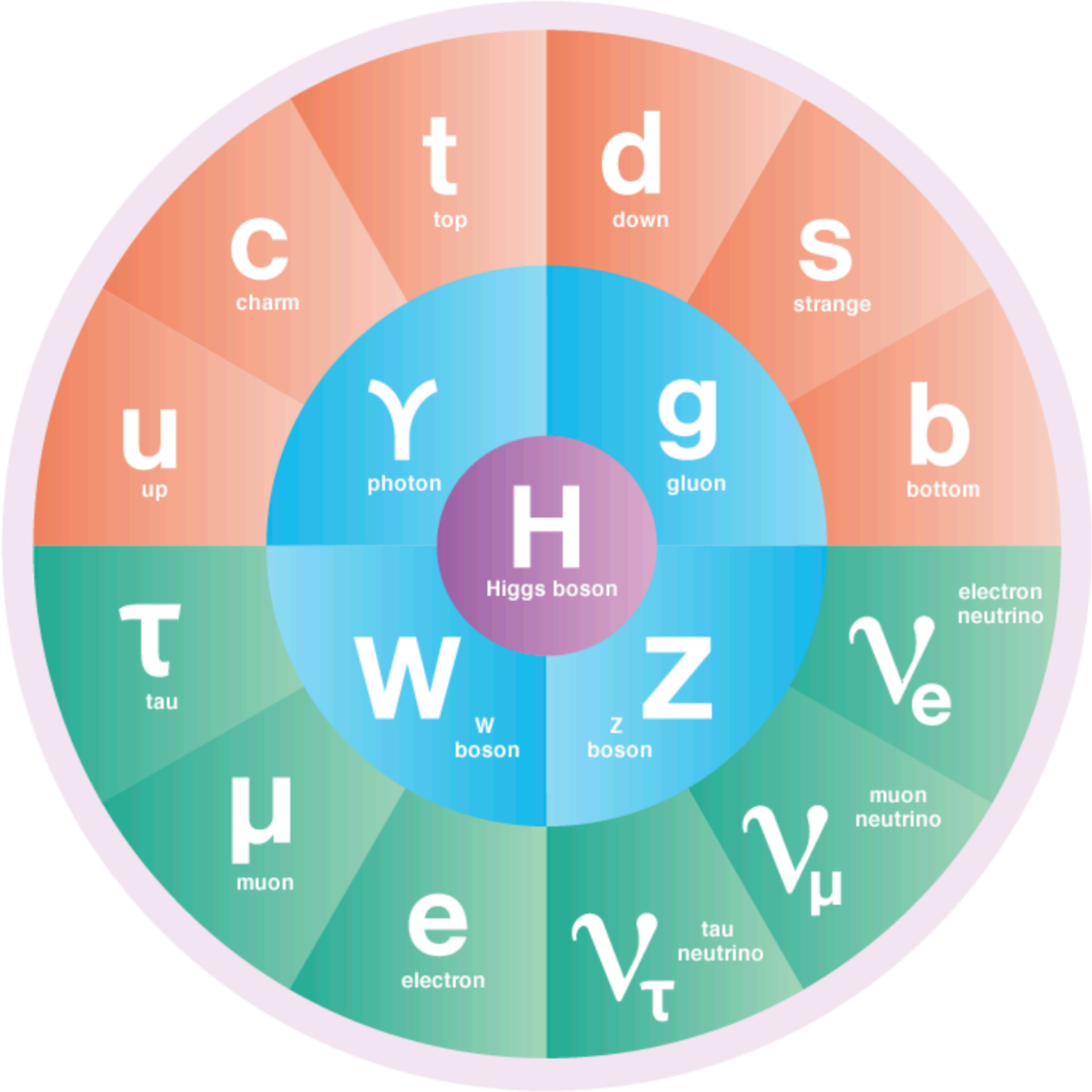

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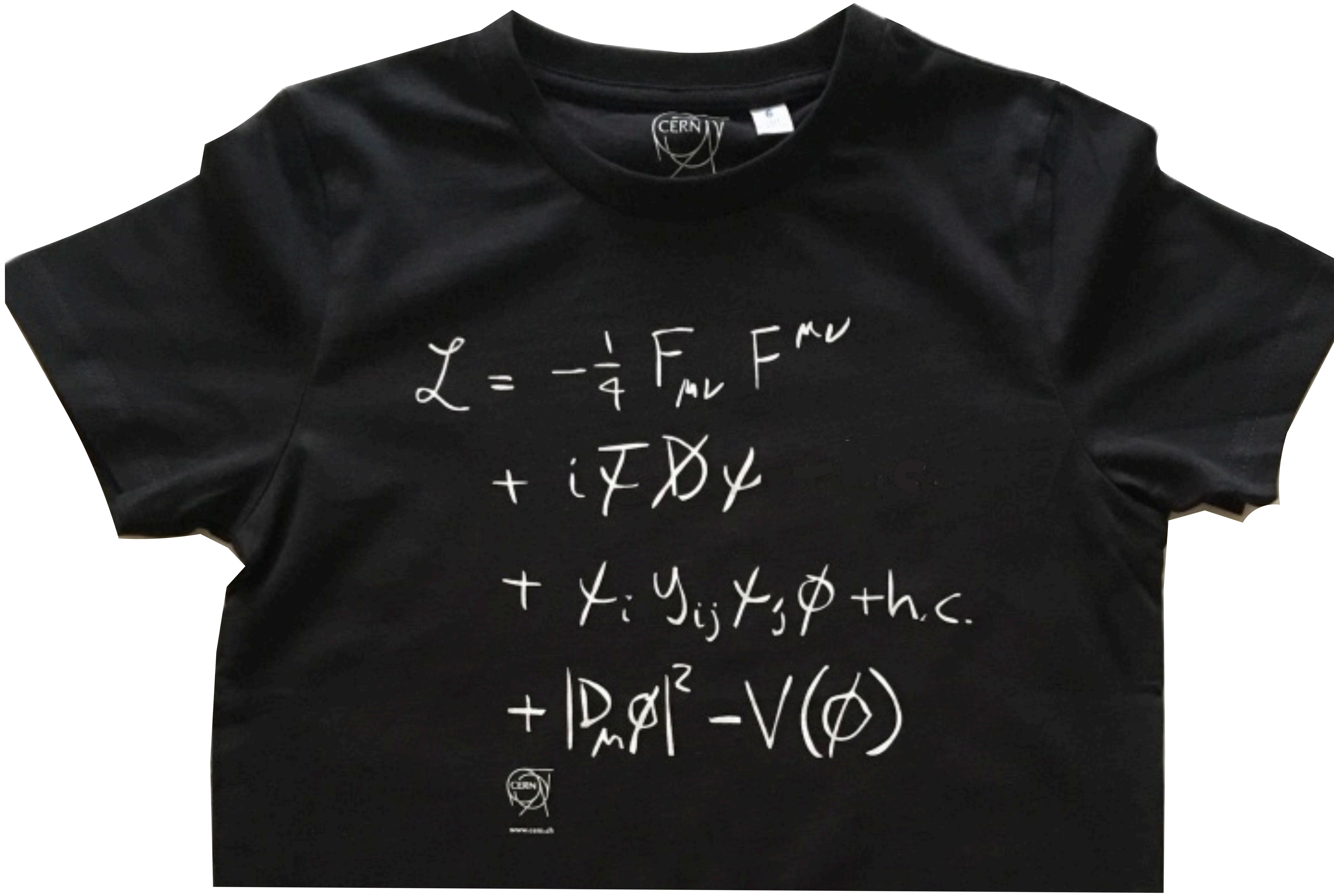
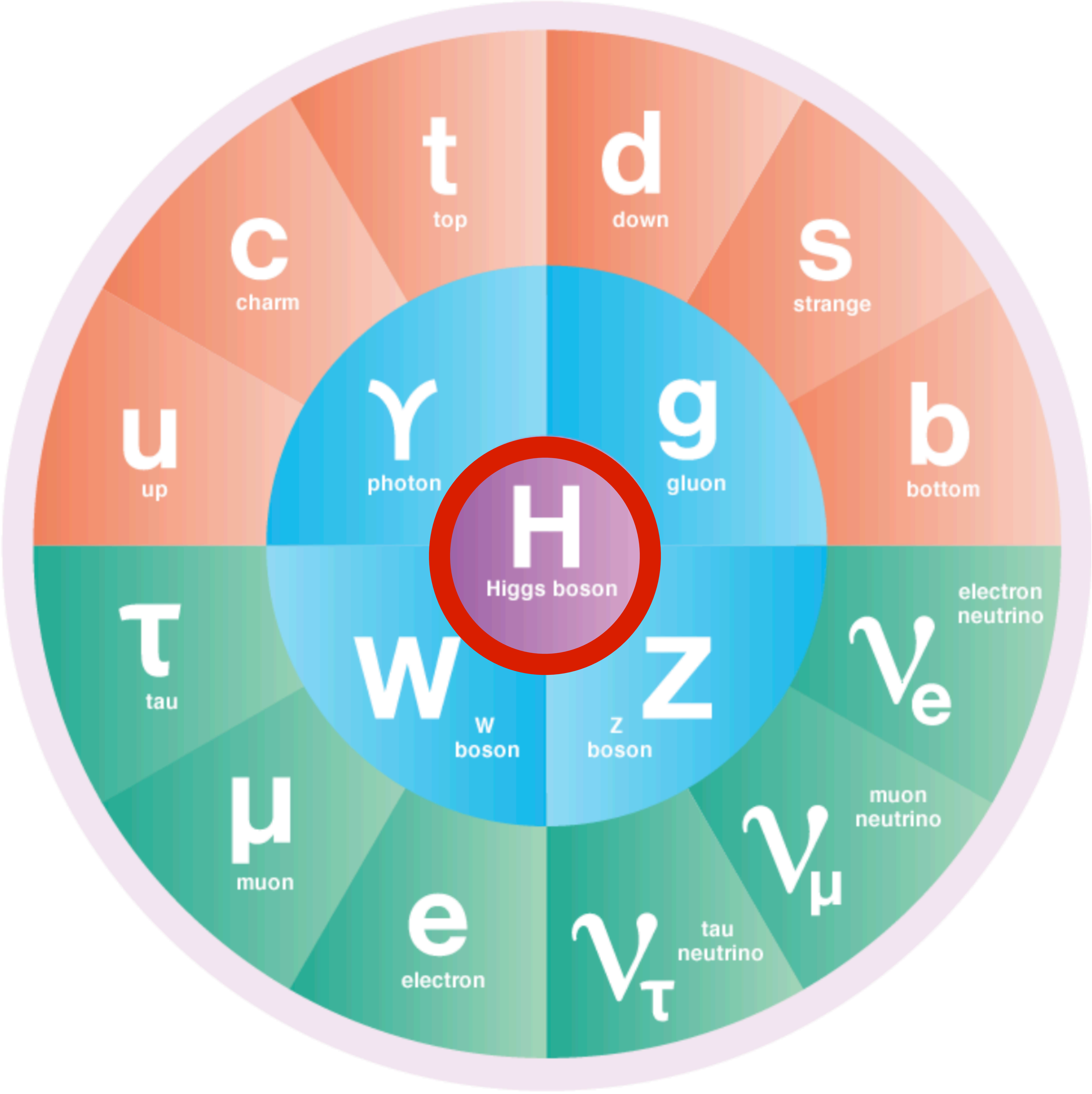


$$\begin{aligned}\mathcal{L} = &-\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ &+ i\bar{\psi} \not{D} \psi \\ &+ \psi_i y_{ij} \psi_j \phi + h.c. \\ &+ |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

interactions

The Standard Model (SM)

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



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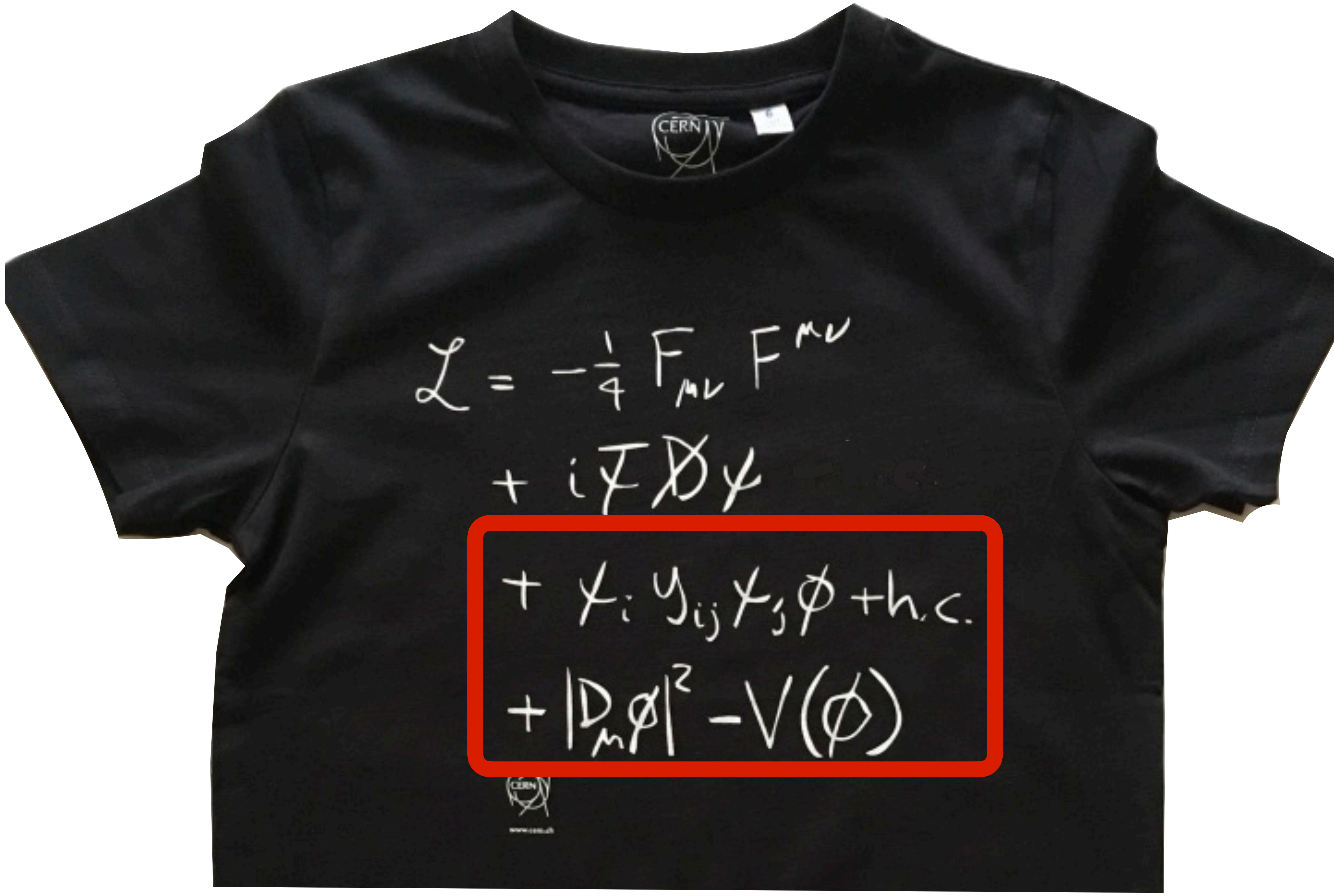
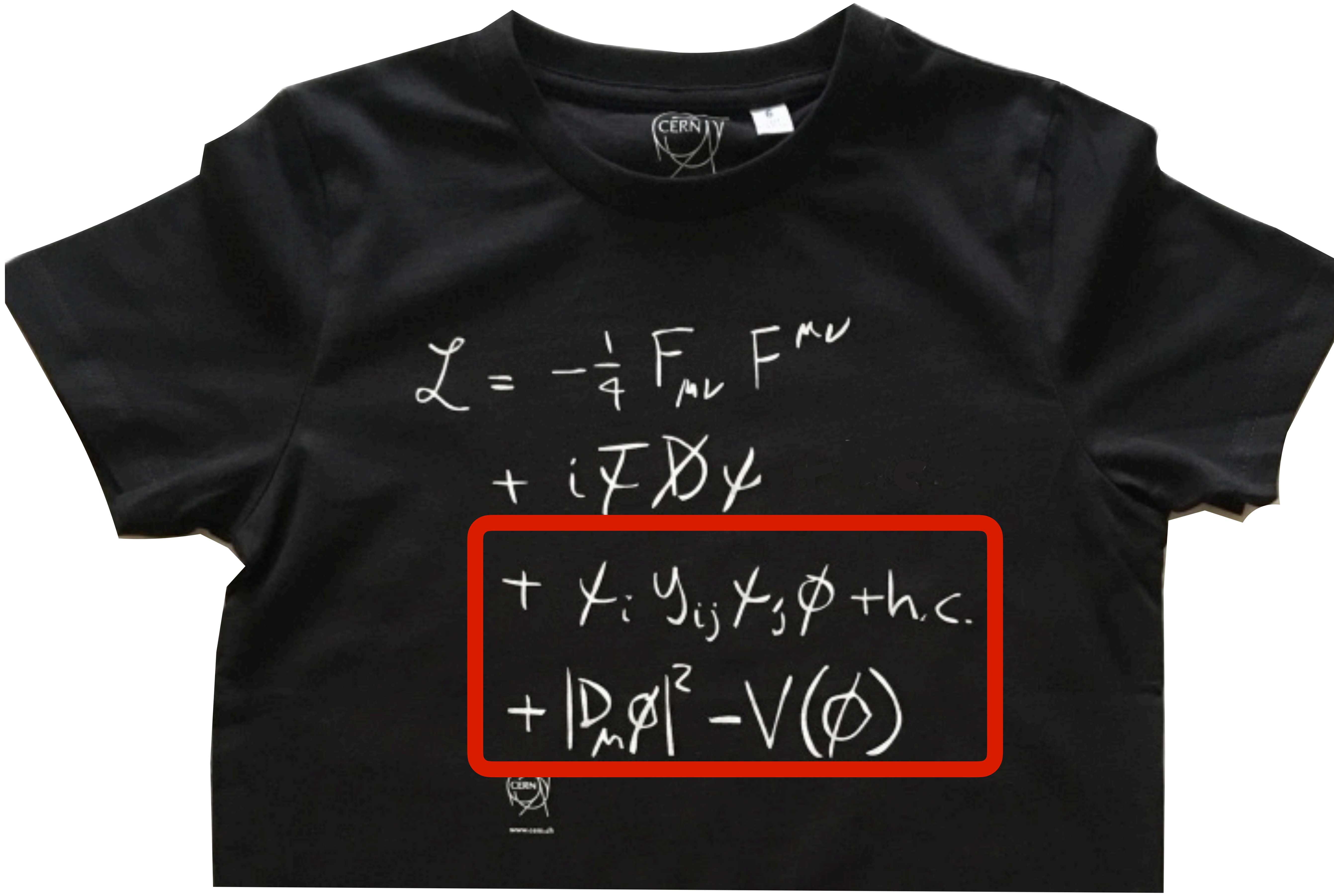


interactions

The Standard Model (SM)

our experimental exploration of the Higgs-related SM interactions is only just starting

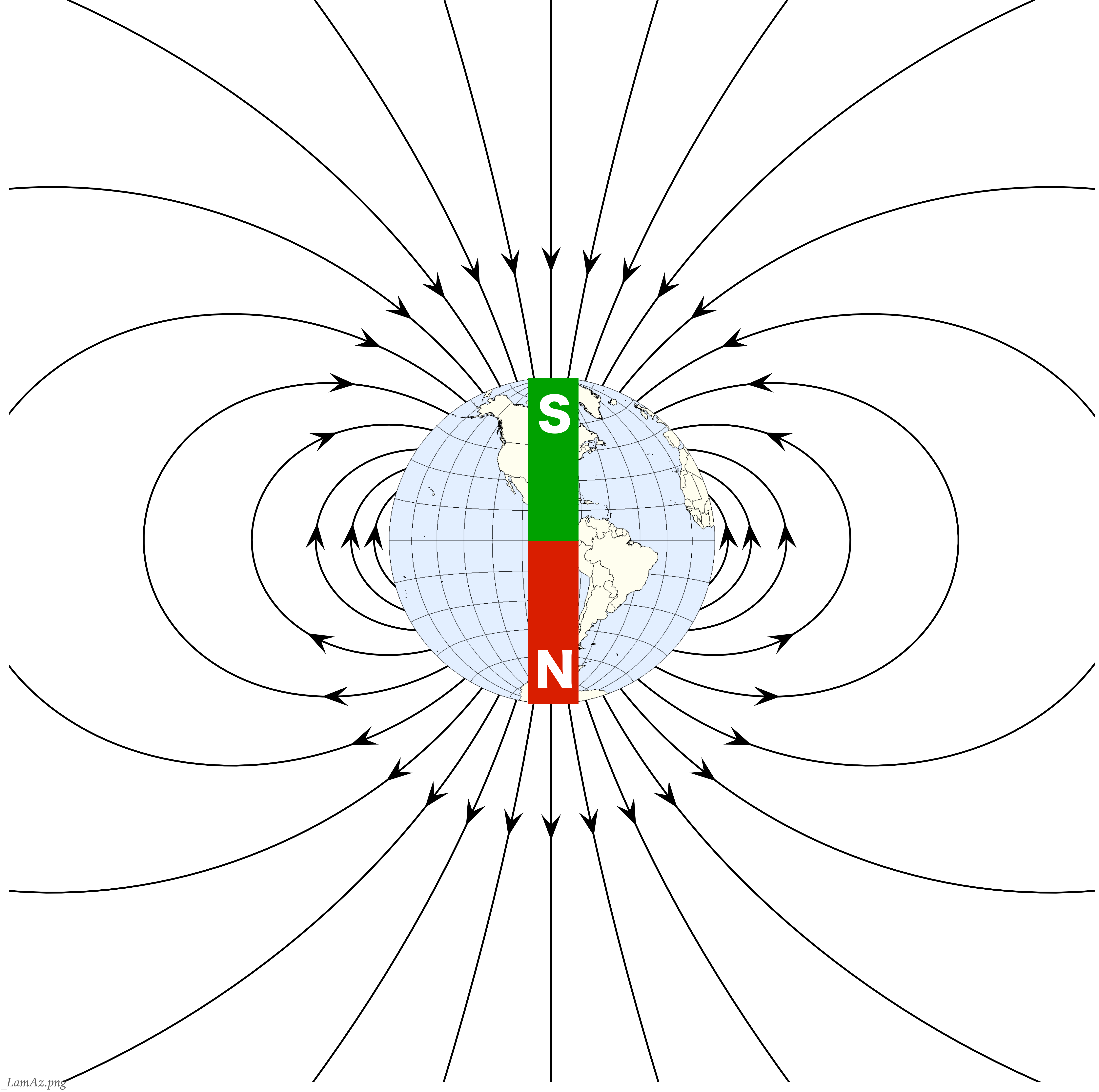


interactions

Higgs physics

The Higgs boson is the last particle of the SM,
with interactions unlike any we had studied before

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



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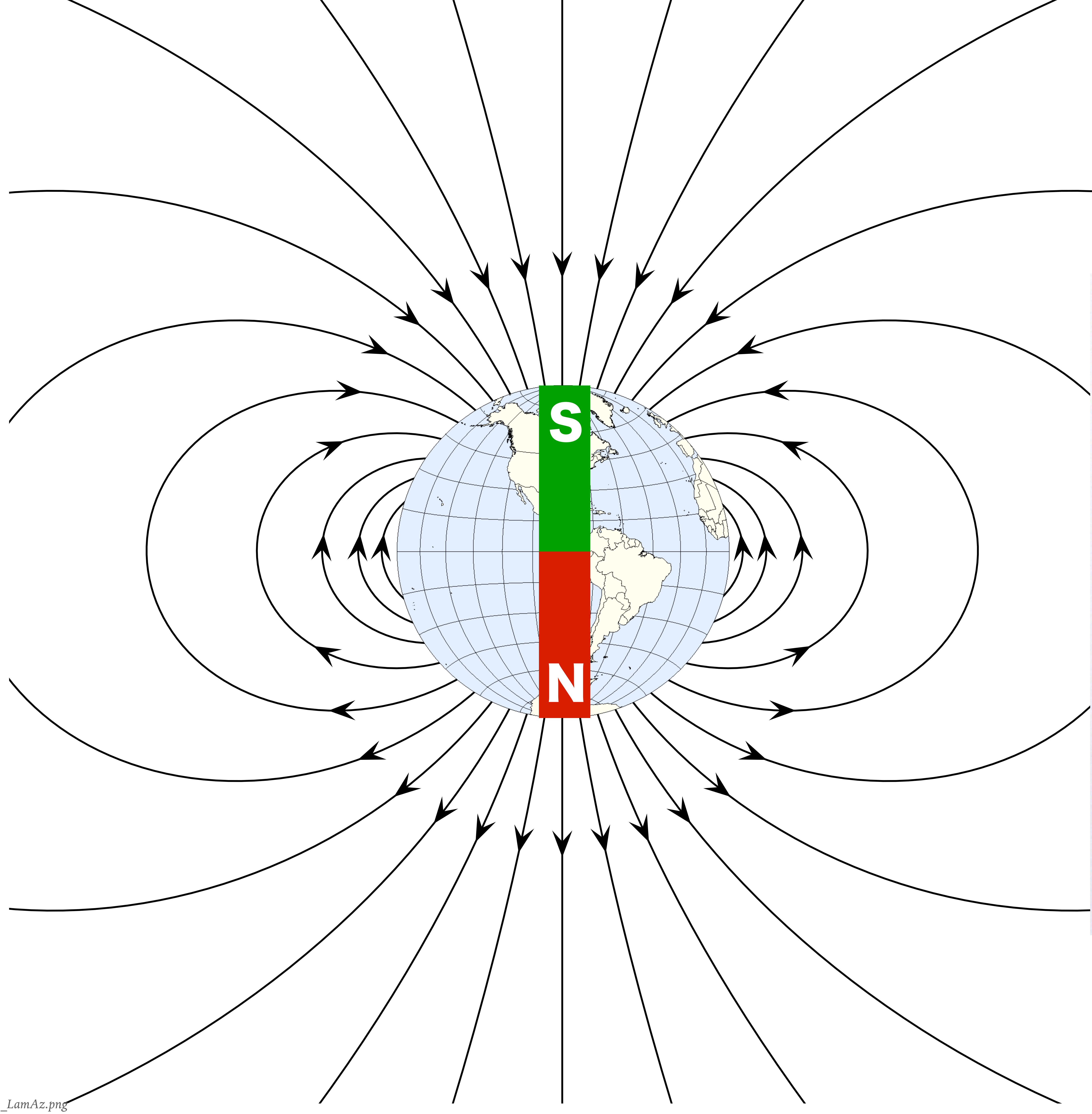
https://en.wikipedia.org/wiki/Western_Hemisphere#/media/File:Western_Hemisphere_LamAz.png

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HIGGS
FIELD

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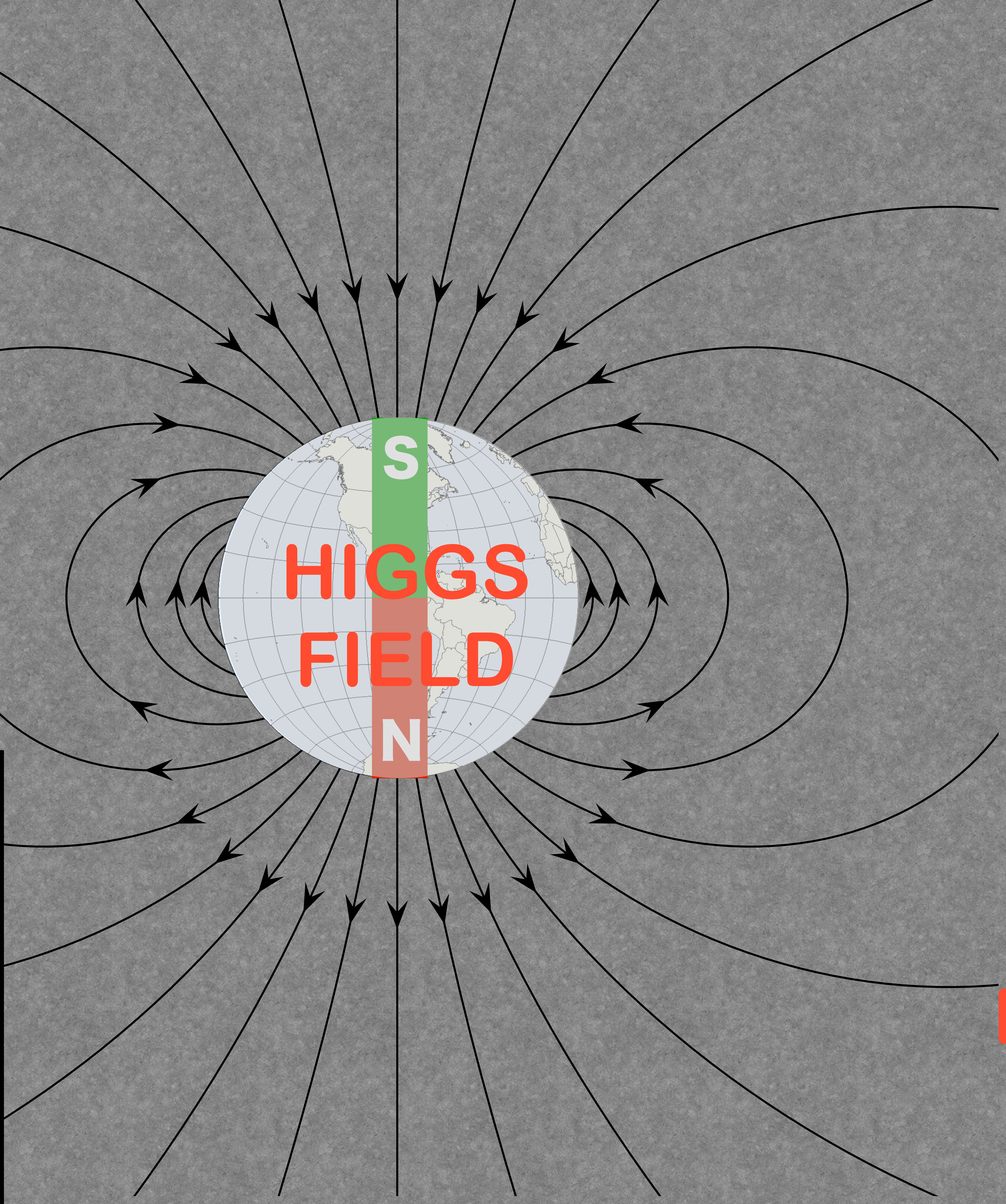

HIGGS
FIELD

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HIGGS


Large Hadron Collider @ CERN

Higgs field (ϕ) can be different at each point in space

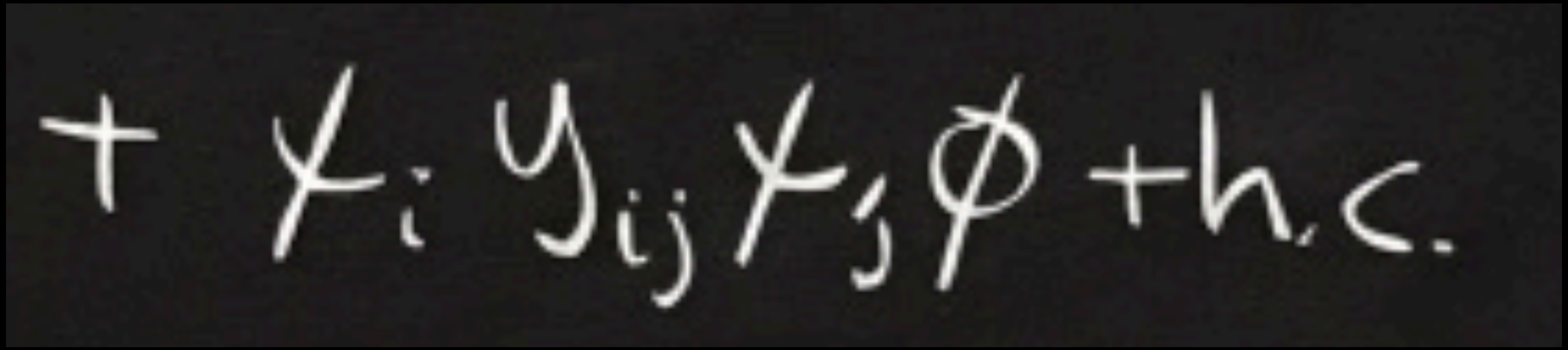
A Higgs boson at a given point in space is a fluctuation of the field

Higgs field (ϕ) can be different at each point in space

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

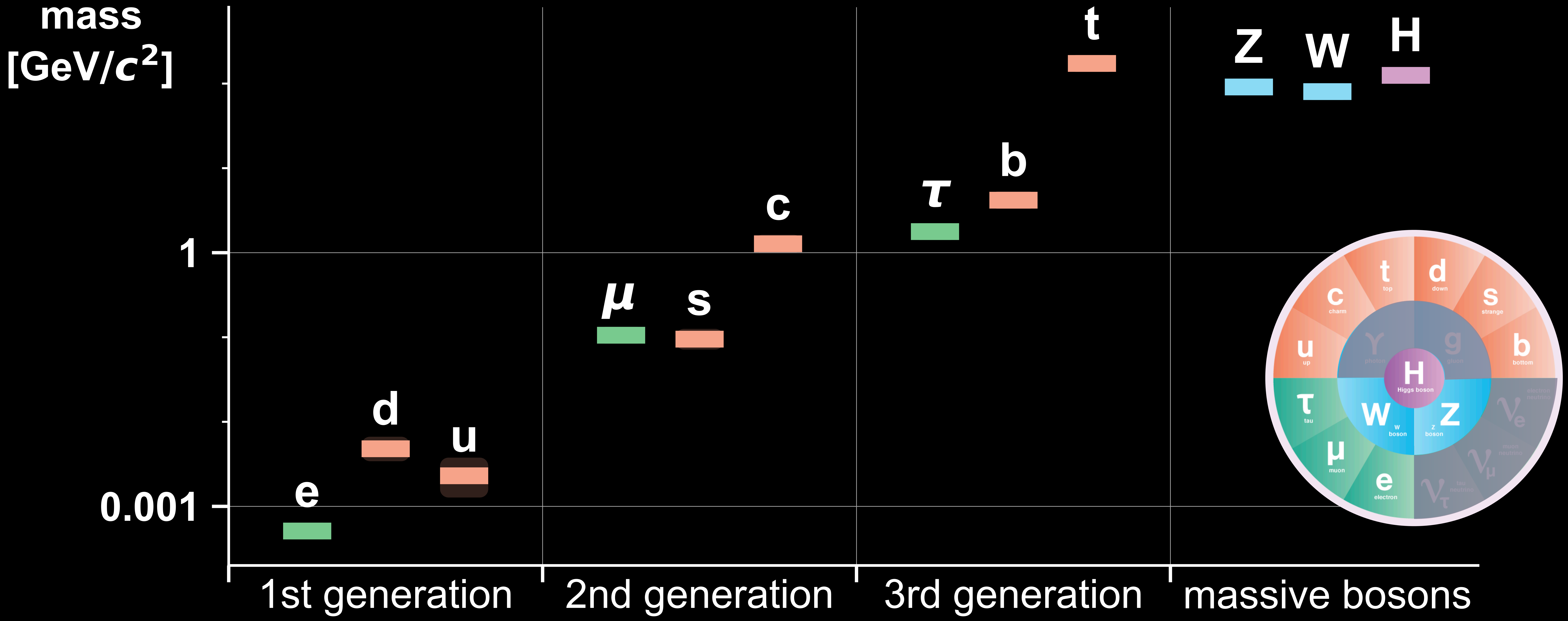
a core hypothesis of Standard Model

fundamental particles get their mass from interaction with the Higgs field



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

Standard Model massive particles (except ν)



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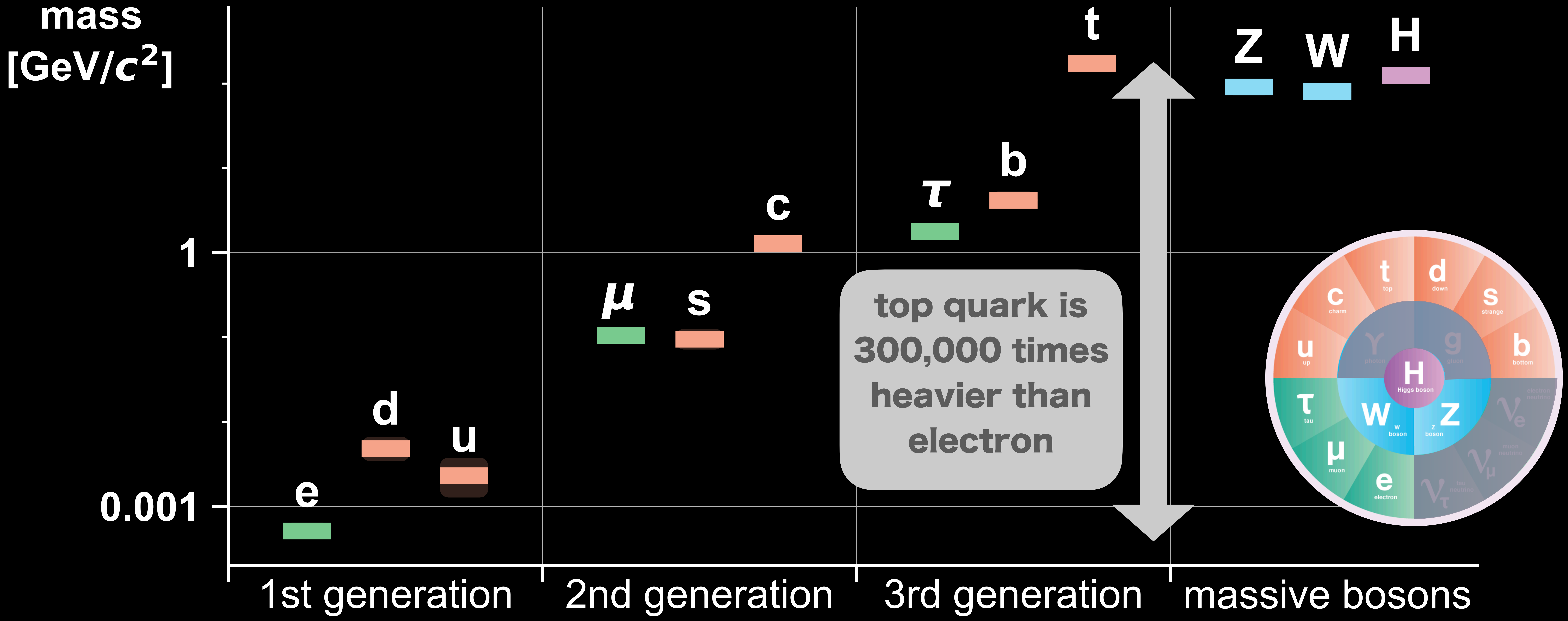
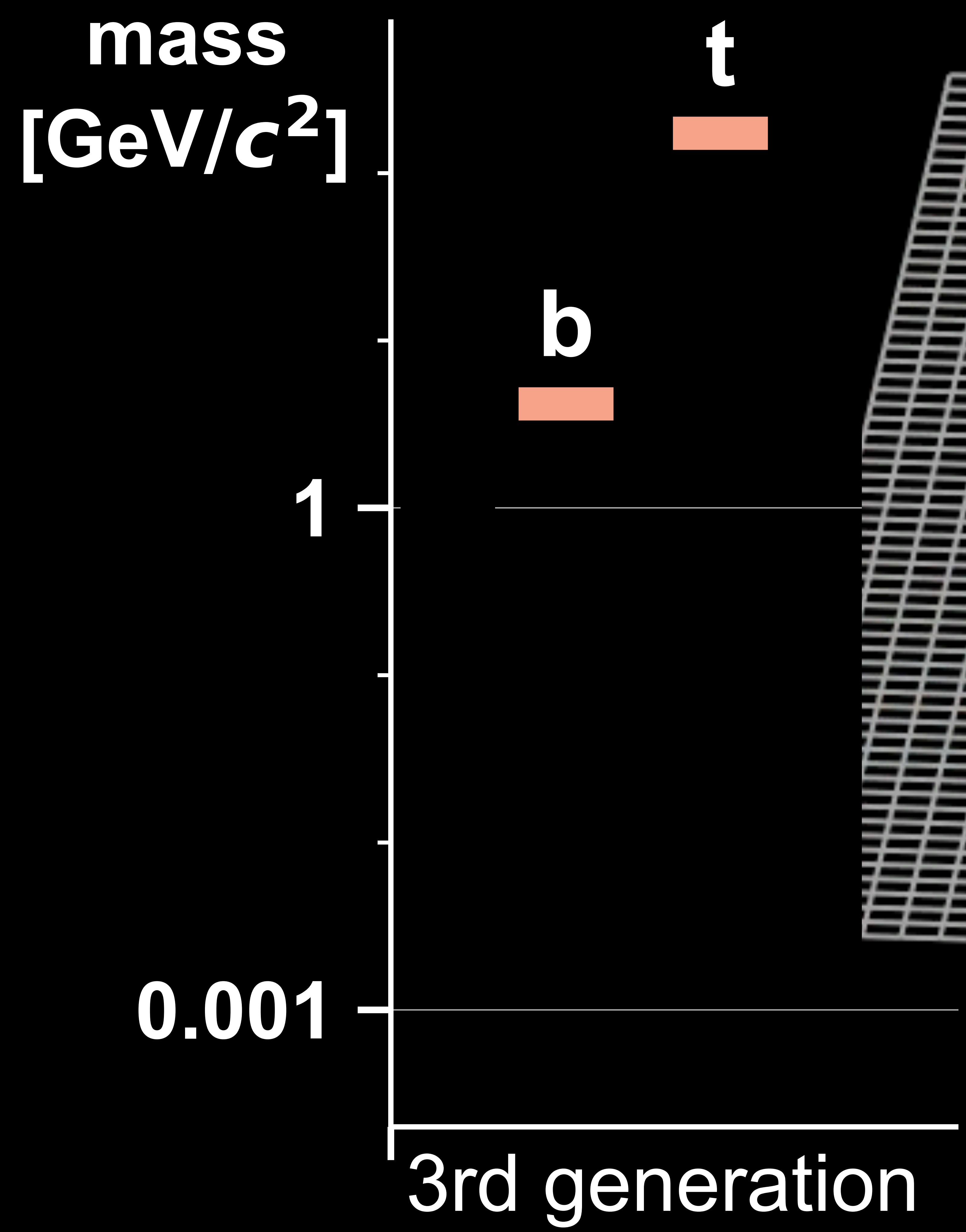
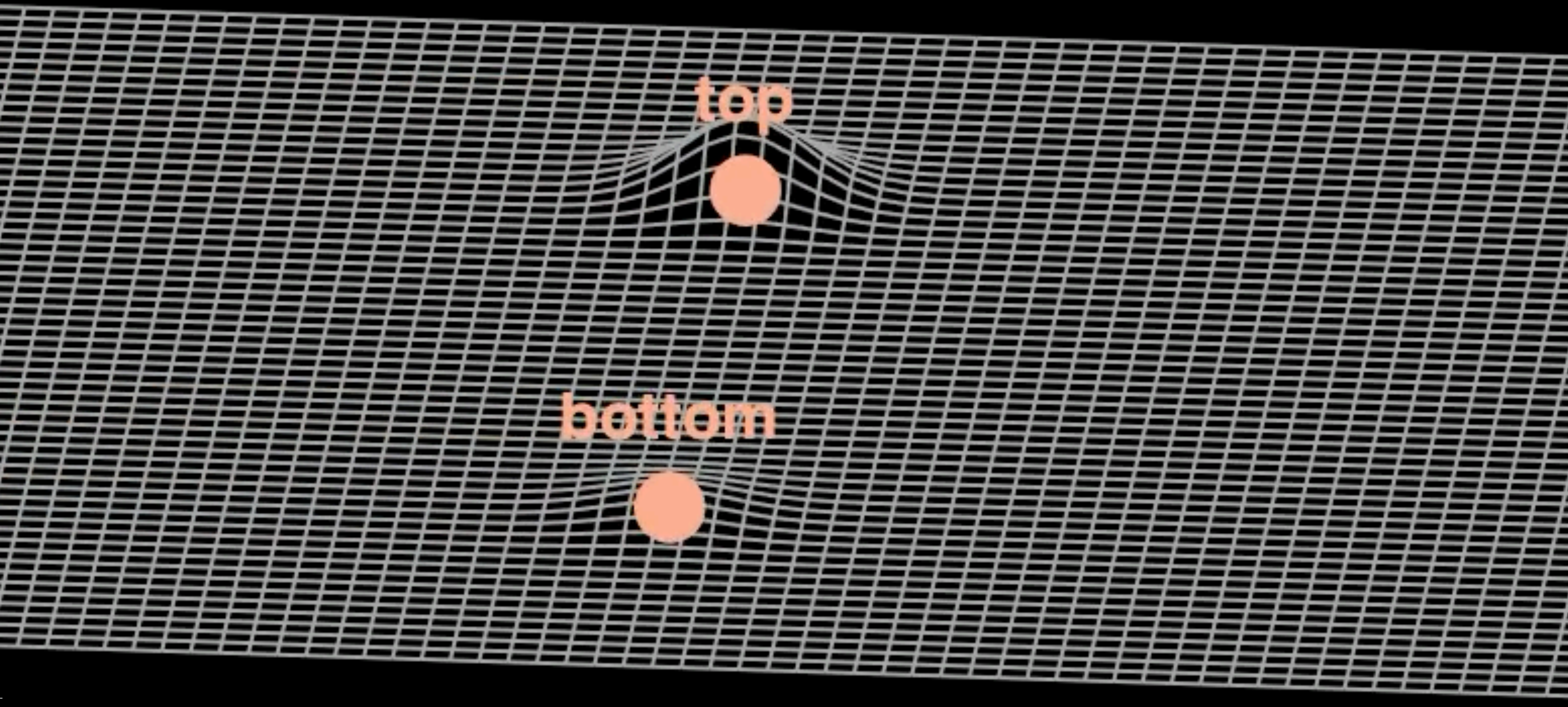


top quark is 300,000 times heavier than electron



Higgs field



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

Higgs field

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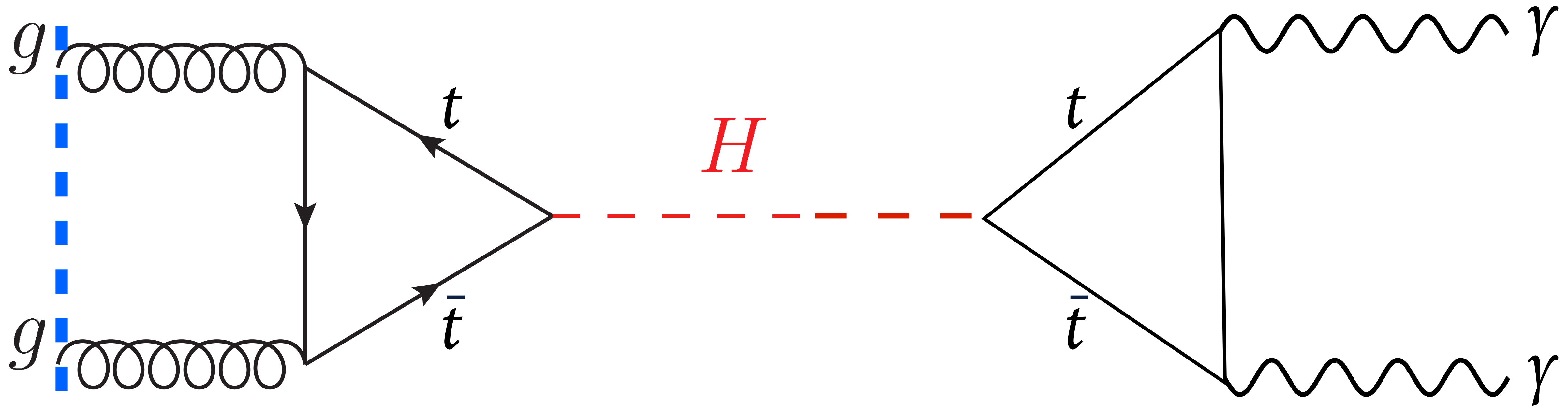
Higgs field

Is this "Yukawa interaction" hypothesis true?

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

An LHC collision of the kind that led to the Higgs boson discovery



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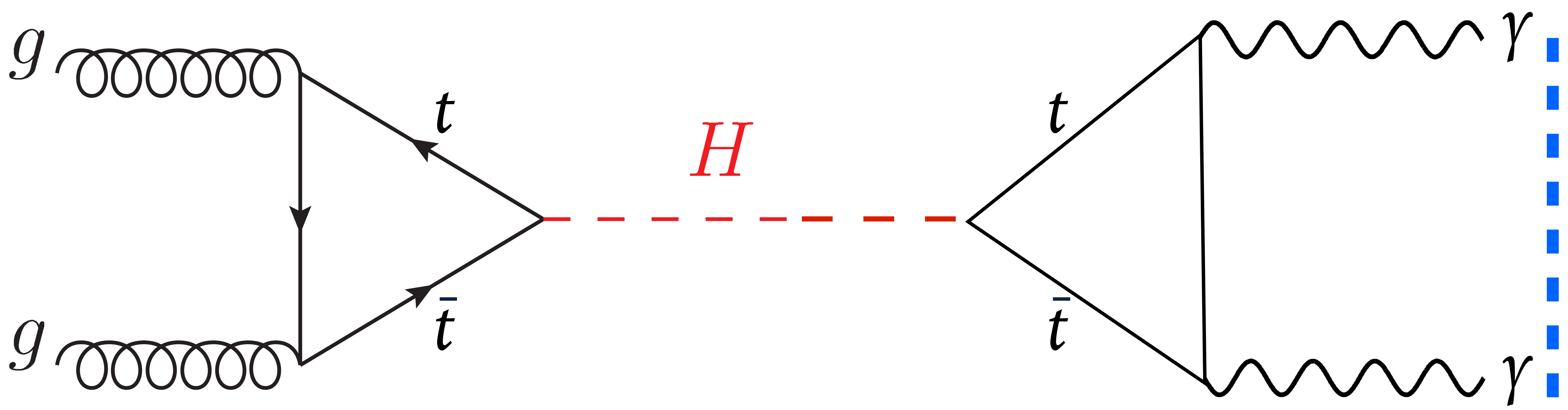
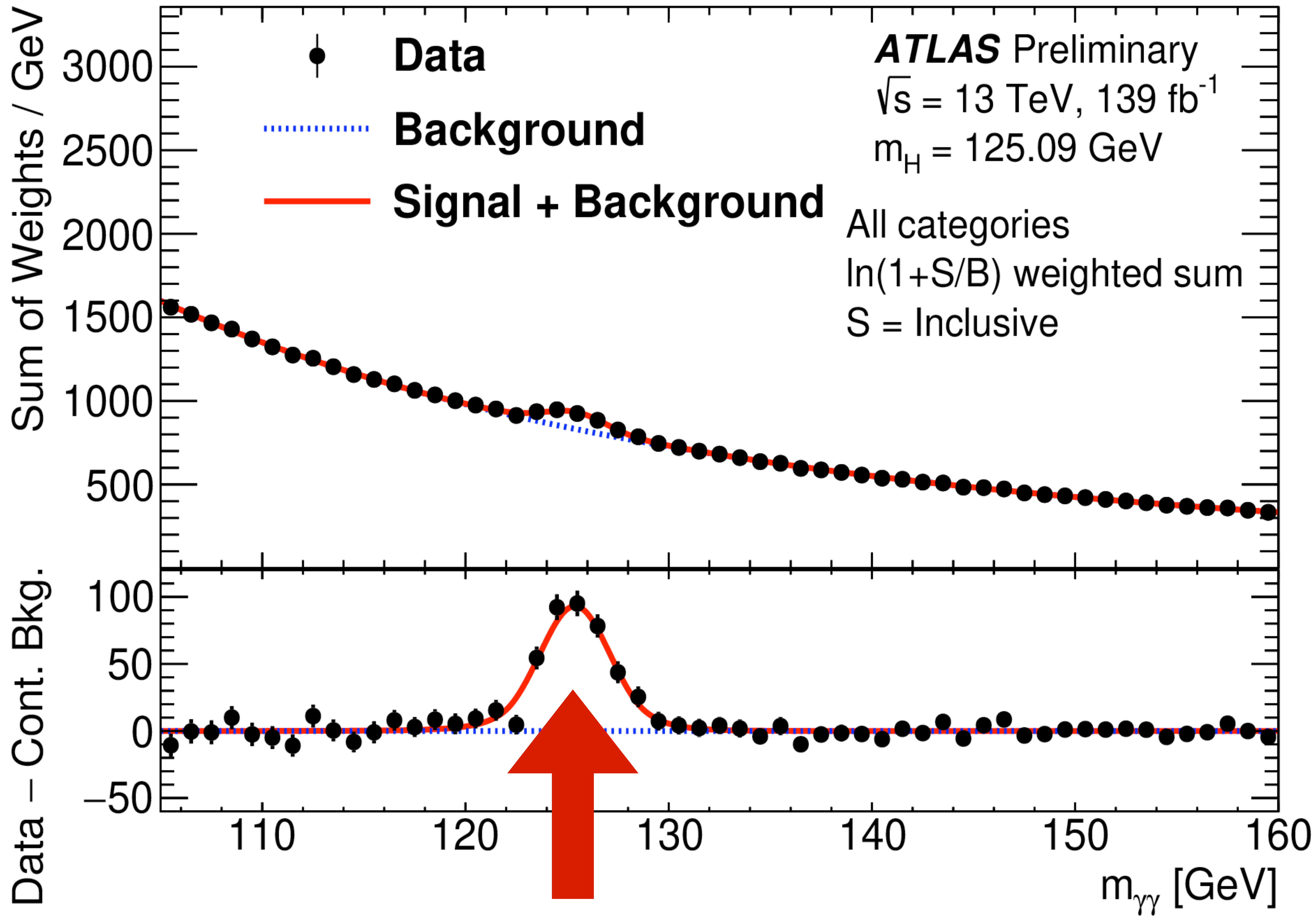


- Record events with two photons;
- classify and count them according to the invariant mass of the two photons (γ)



more events at specific energy = Higgs bosons

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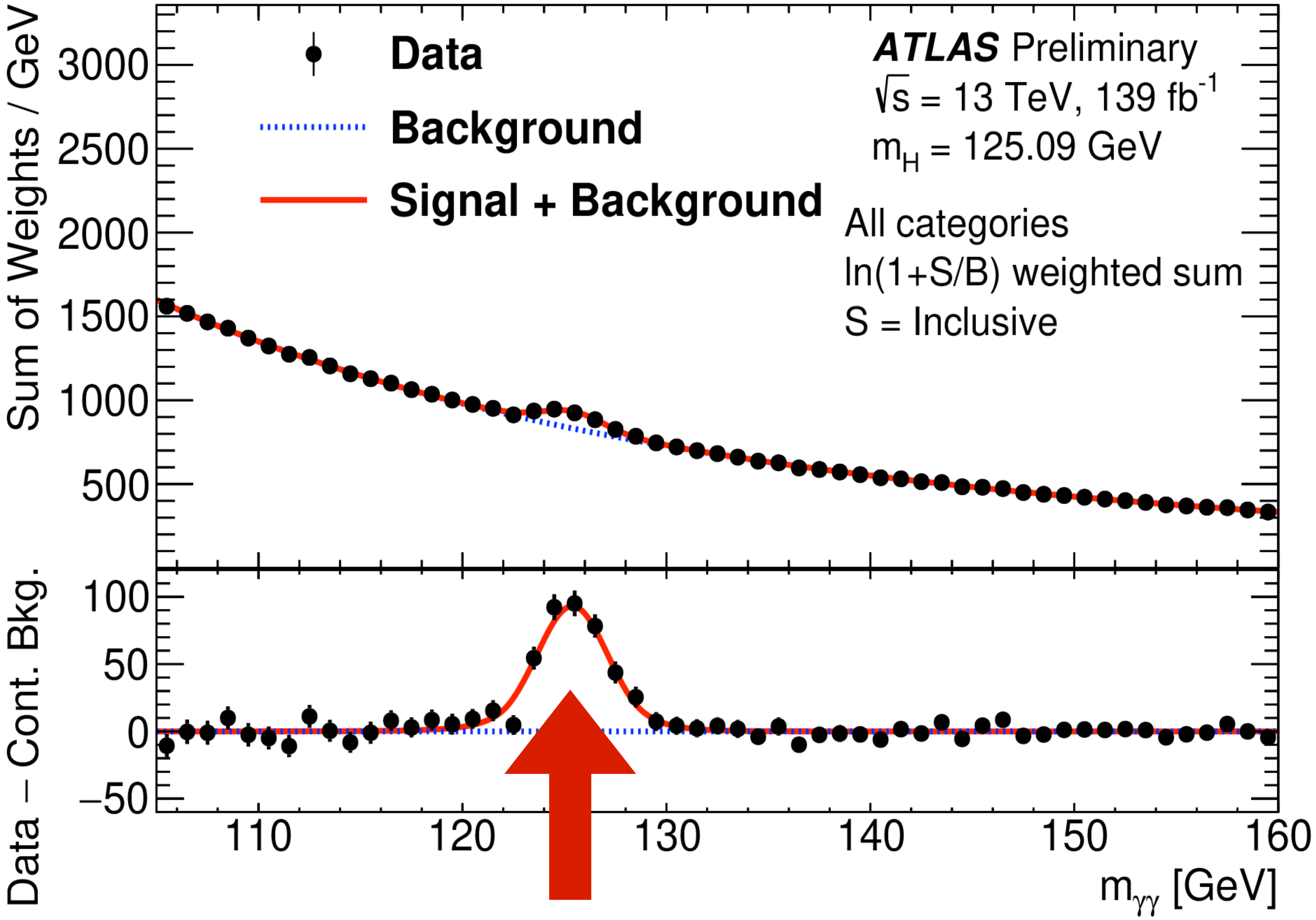

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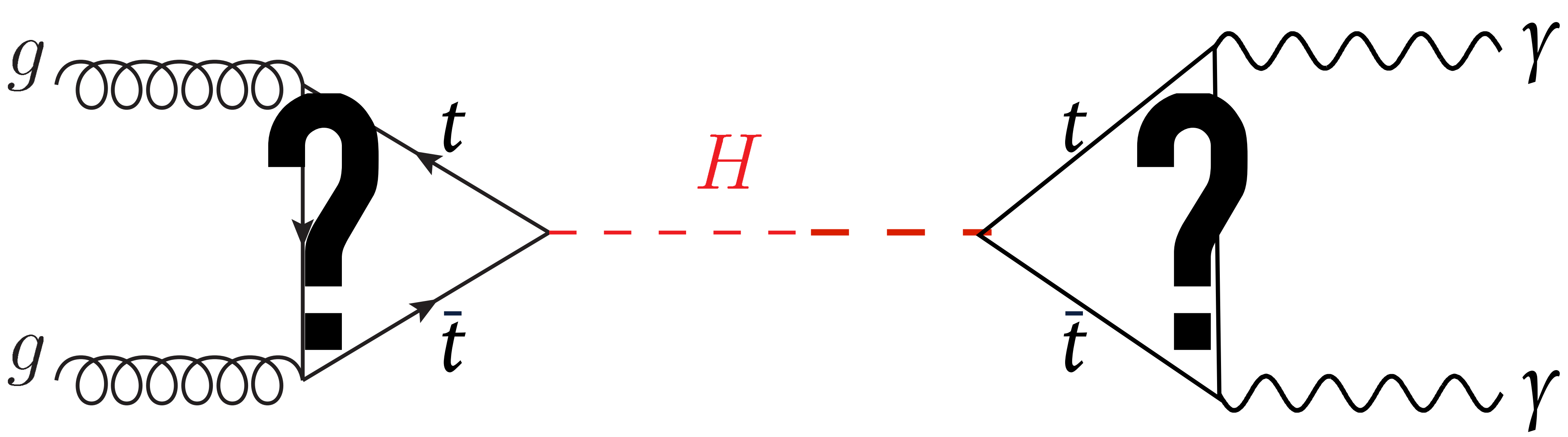
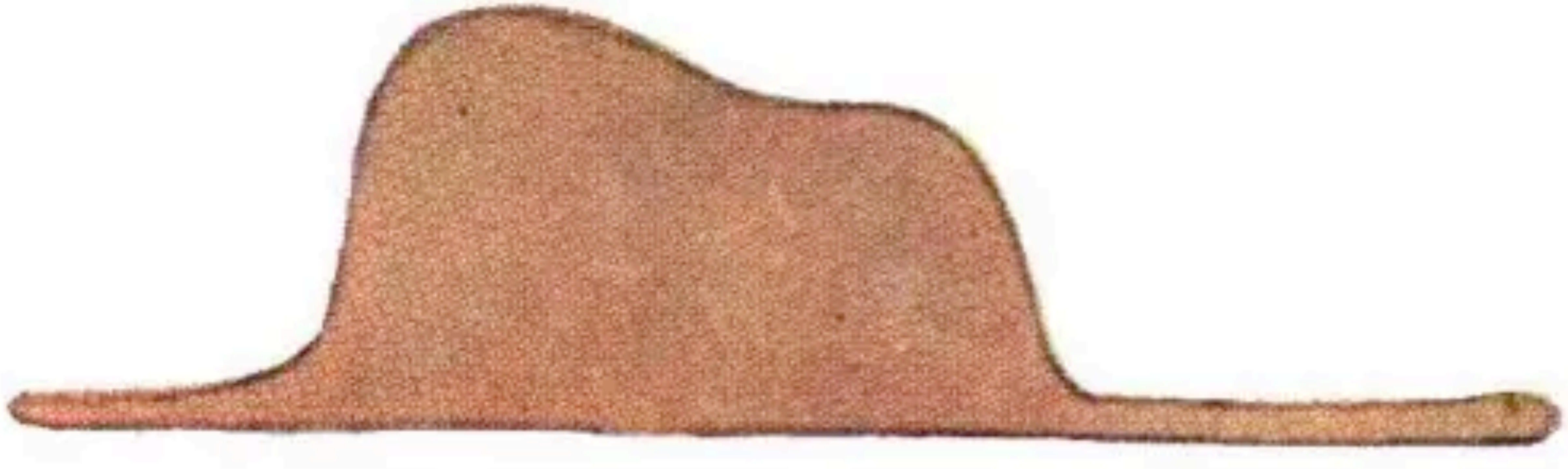


rate of events consistent with SM to ~10%

but how can you be sure it’s a top-quark that’s in the intermediate stages?

Mon dessin numéro 1

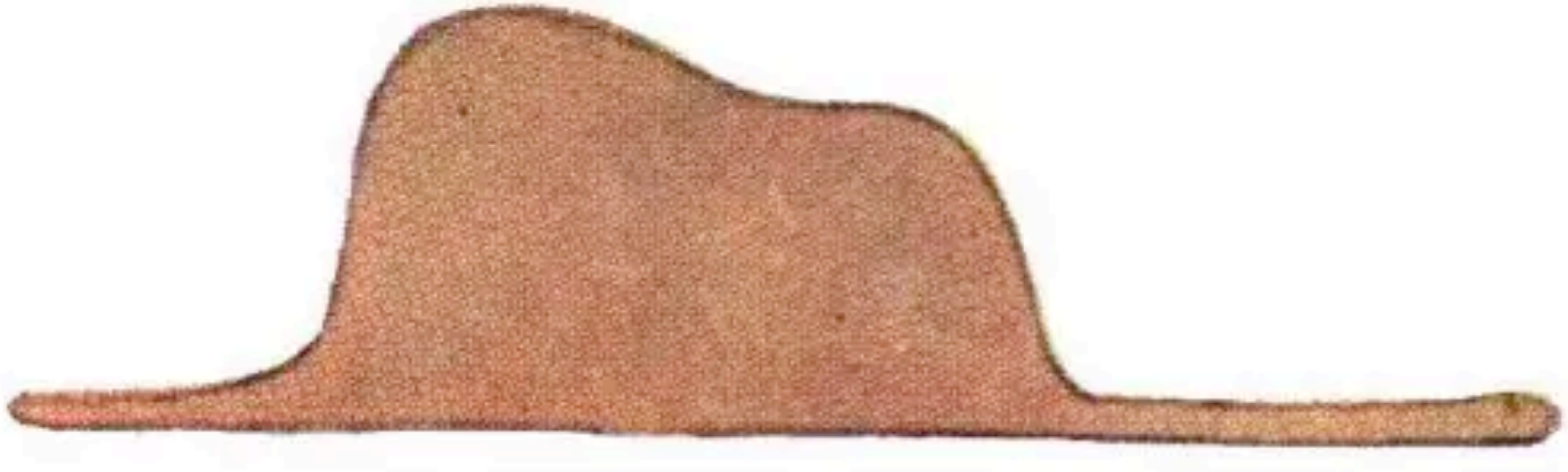


« Pourquoi un chapeau ferait-il peur ? »

“Why should any one be frightened by a hat?”

Le Petit Prince, Antoine de Saint-Exupéry

Mon dessin numéro 1



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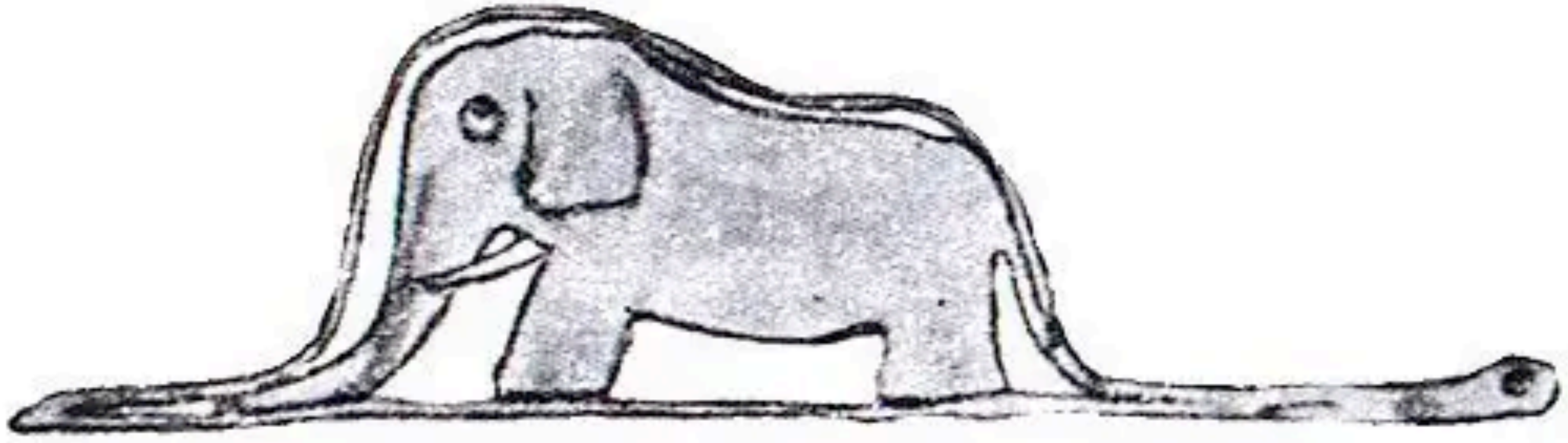
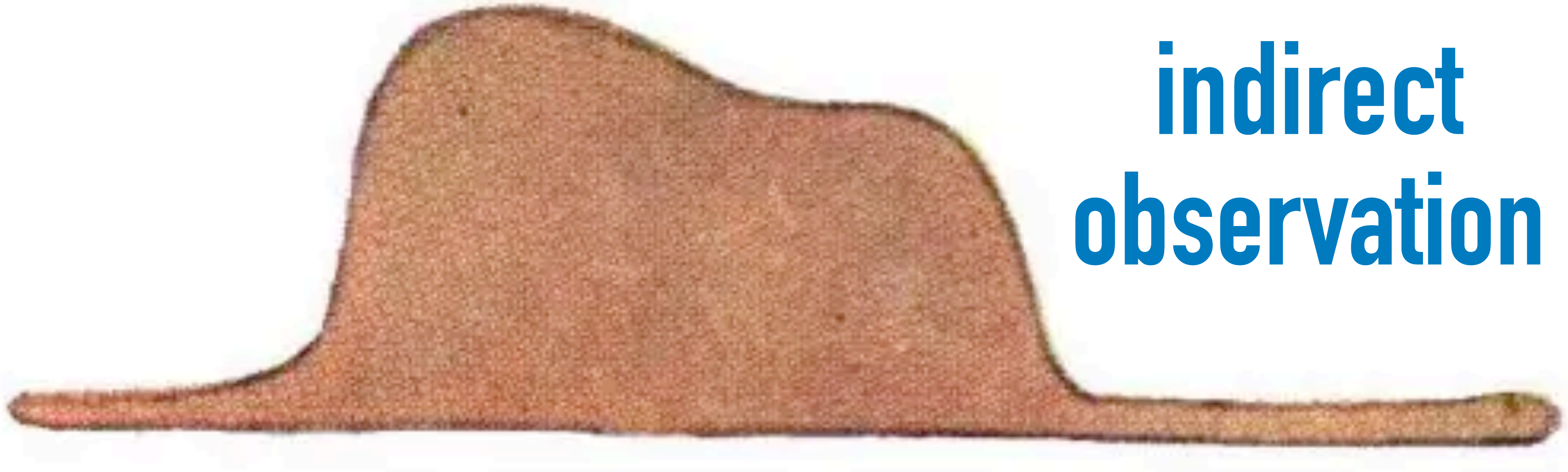
“My drawing was not a picture of a hat. It was a picture of a boa constrictor digesting an elephant.”



Mon dessin numéro 2

Mon dessin numéro 1



indirect observation

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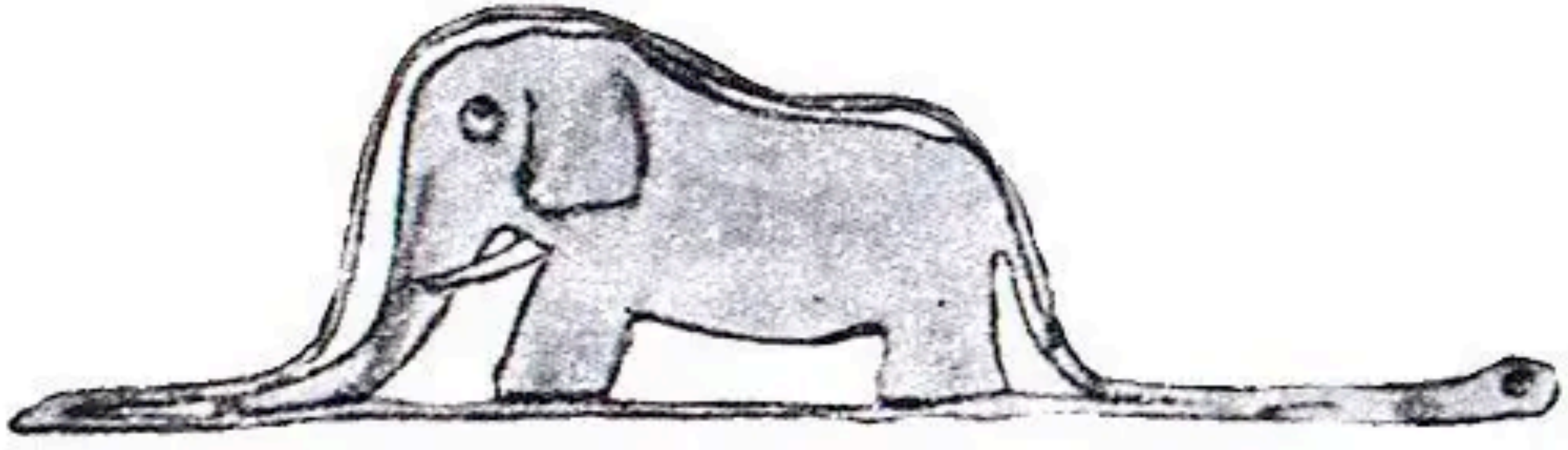

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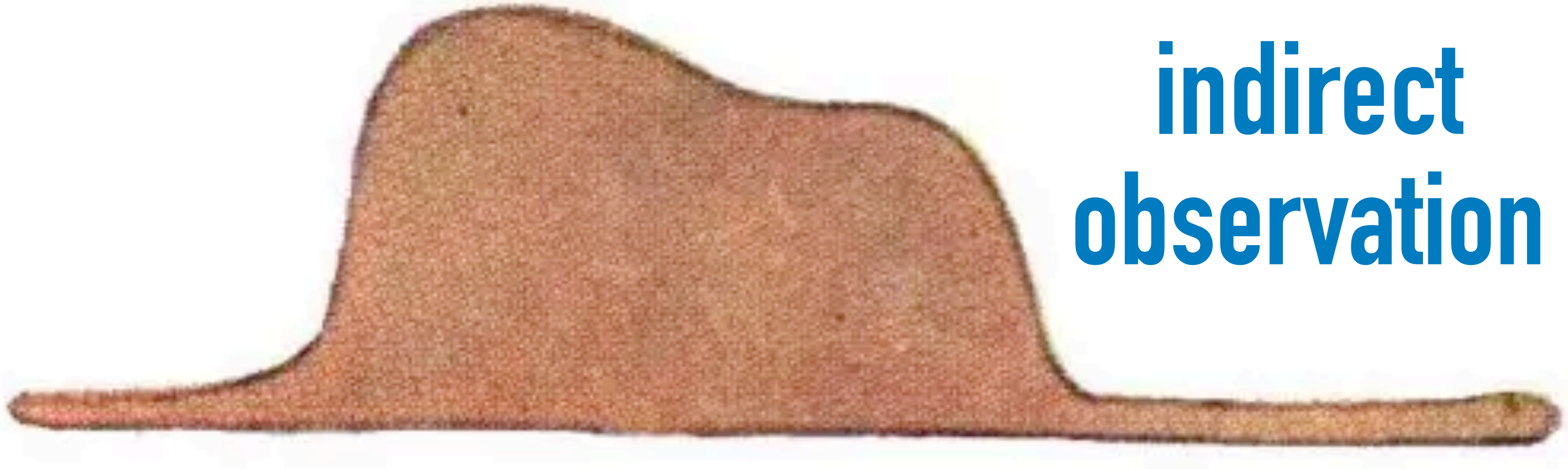

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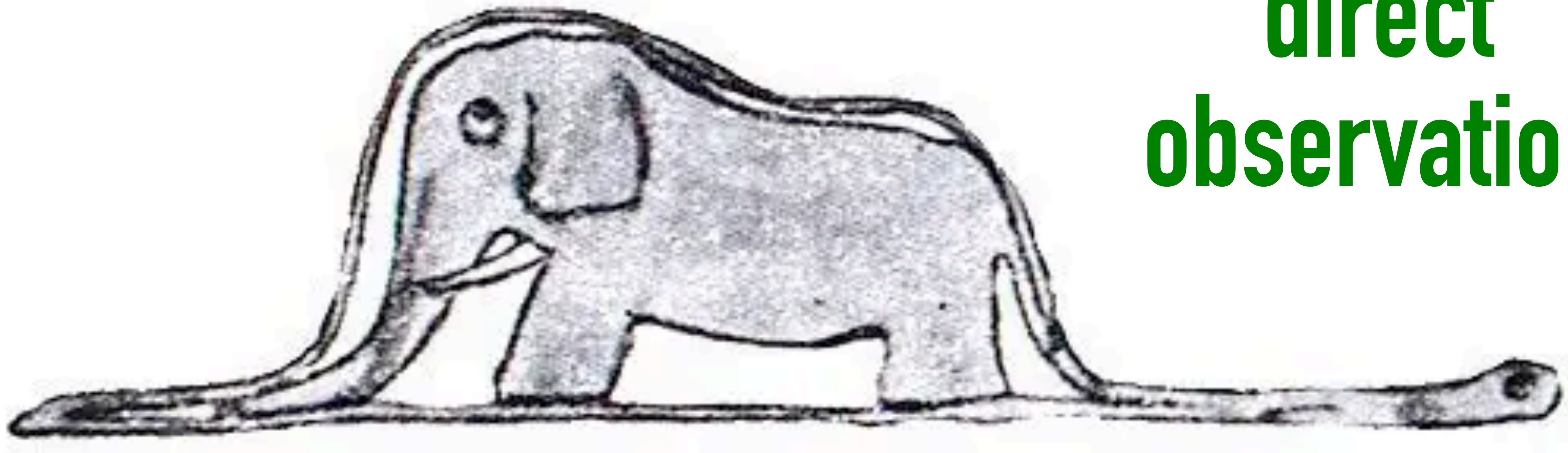
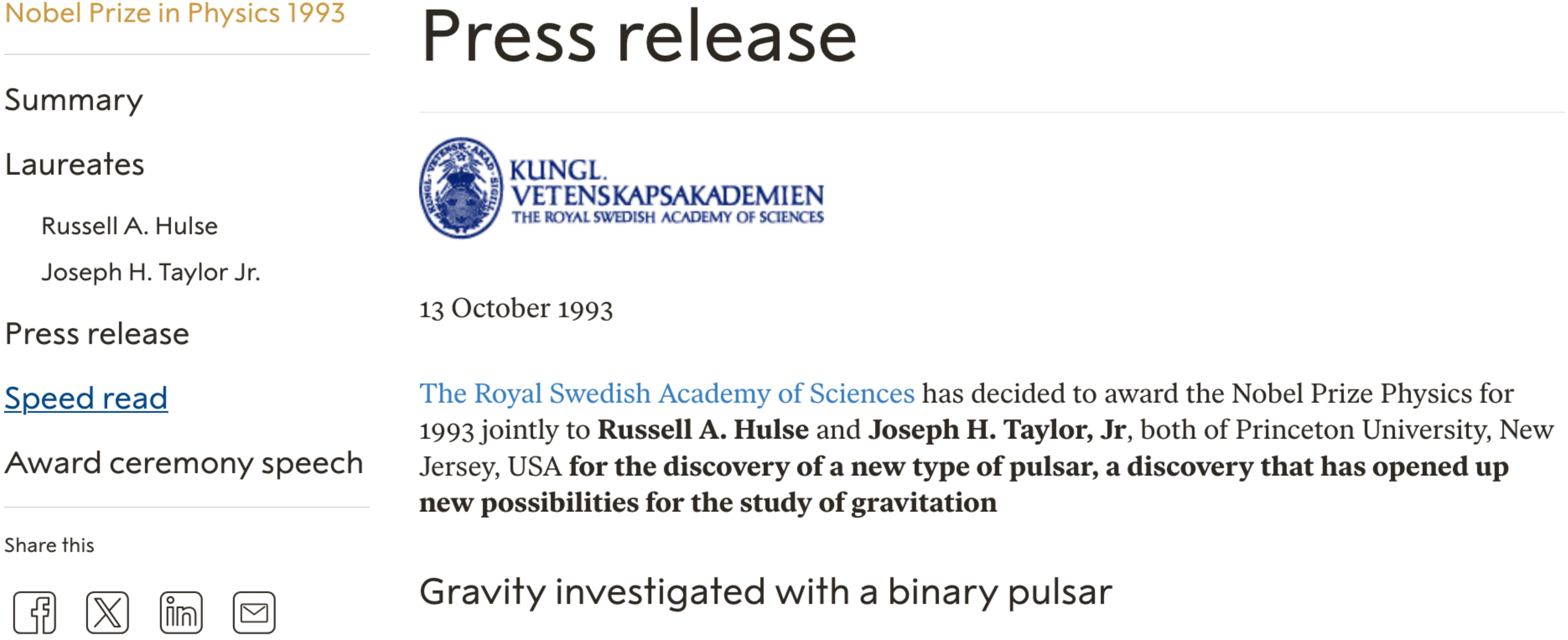


direct observation

Mon dessin numéro 2

https://www.nobelprize.org/prizes/physics/1993/press-release/



Nobel Prize in Physics 1993

Summary

Laureates

- Russell A. Hulse
- Joseph H. Taylor Jr.

Press release

Speed read

Award ceremony speech

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Press release

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

13 October 1993

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize Physics for 1993 jointly to **Russell A. Hulse** and **Joseph H. Taylor, Jr**, both of Princeton University, New Jersey, USA **for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation**

Gravity investigated with a binary pulsar

A very important observation was made when the system had been followed for some years […] **reduction of the orbit period by about 75 millionths of a second per year** […] **because the system is emitting energy in the form of gravitational waves** in accordance with what Einstein in 1916 predicted should happen to masses moving relatively to each other. […] the theoretically calculated value from the relativity theory agrees to within about one half of a percent with the observed value. The first report of this effect was made by Taylor and co-workers at the end of 1978, four years after the discovery of the binary pulsar was reported.

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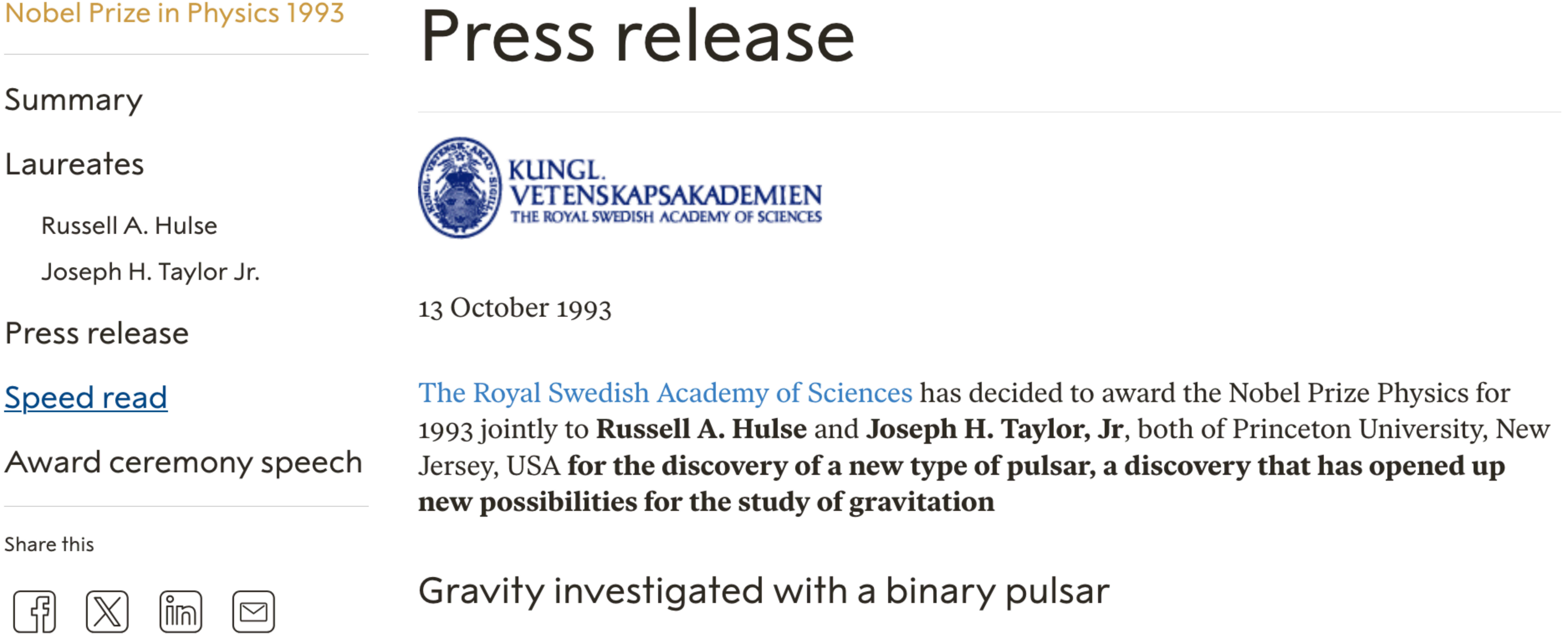

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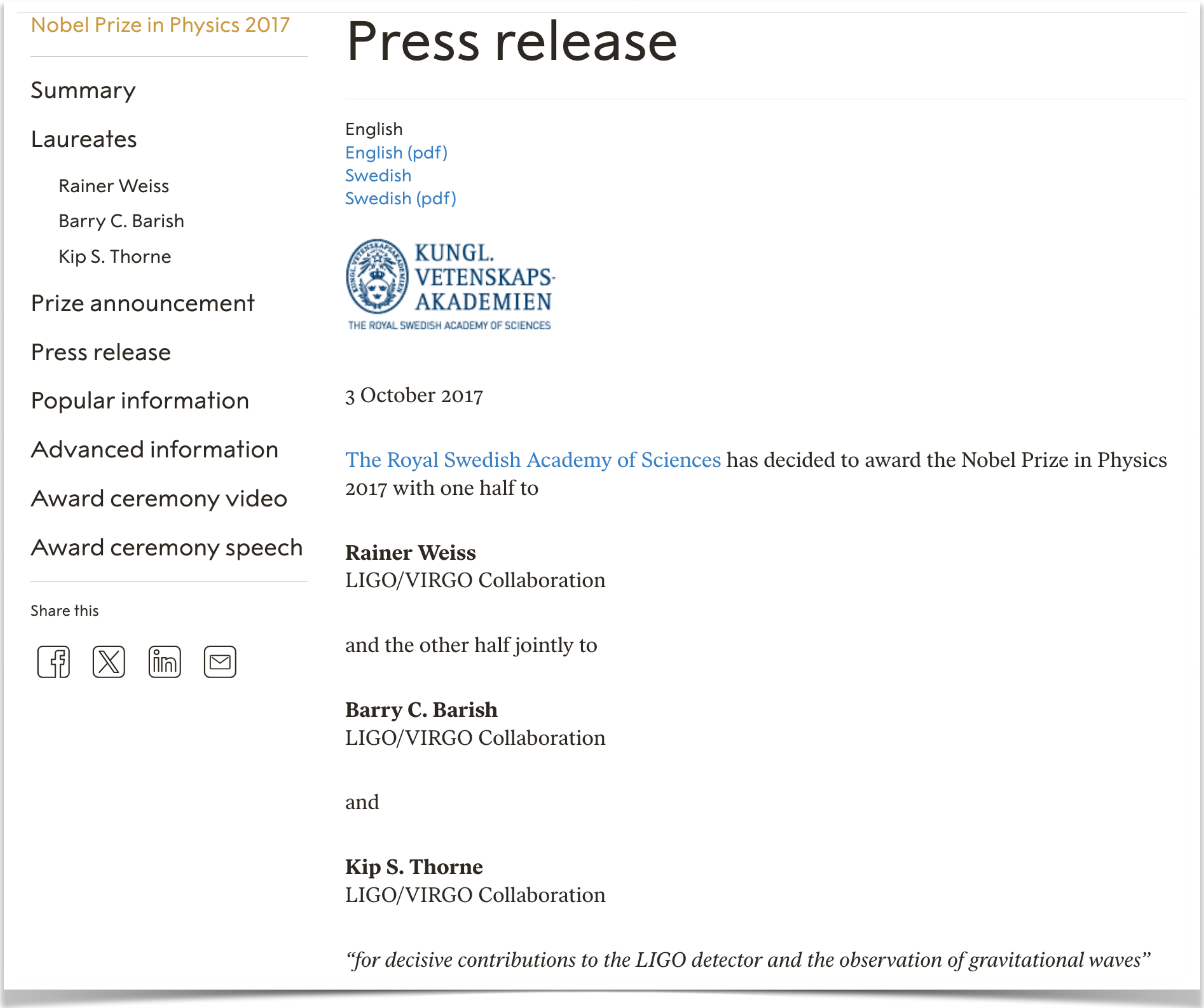
https://www.nobelprize.org/prizes/physics/2017/press-release/



Press release

3 October 2017

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2017 with one half to

Rainer Weiss
LIGO/VIRGO Collaboration

and the other half jointly to

Barry C. Barish
LIGO/VIRGO Collaboration

and

Kip S. Thorne
LIGO/VIRGO Collaboration

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

Gravitational waves finally captured

On 14 September 2015, the universe's gravitational waves were observed for the very first time. The waves, which were predicted by Albert Einstein a hundred years ago, came from a collision between two black holes. It took 1.3 billion years for the waves to arrive at the LIGO detector in the USA.

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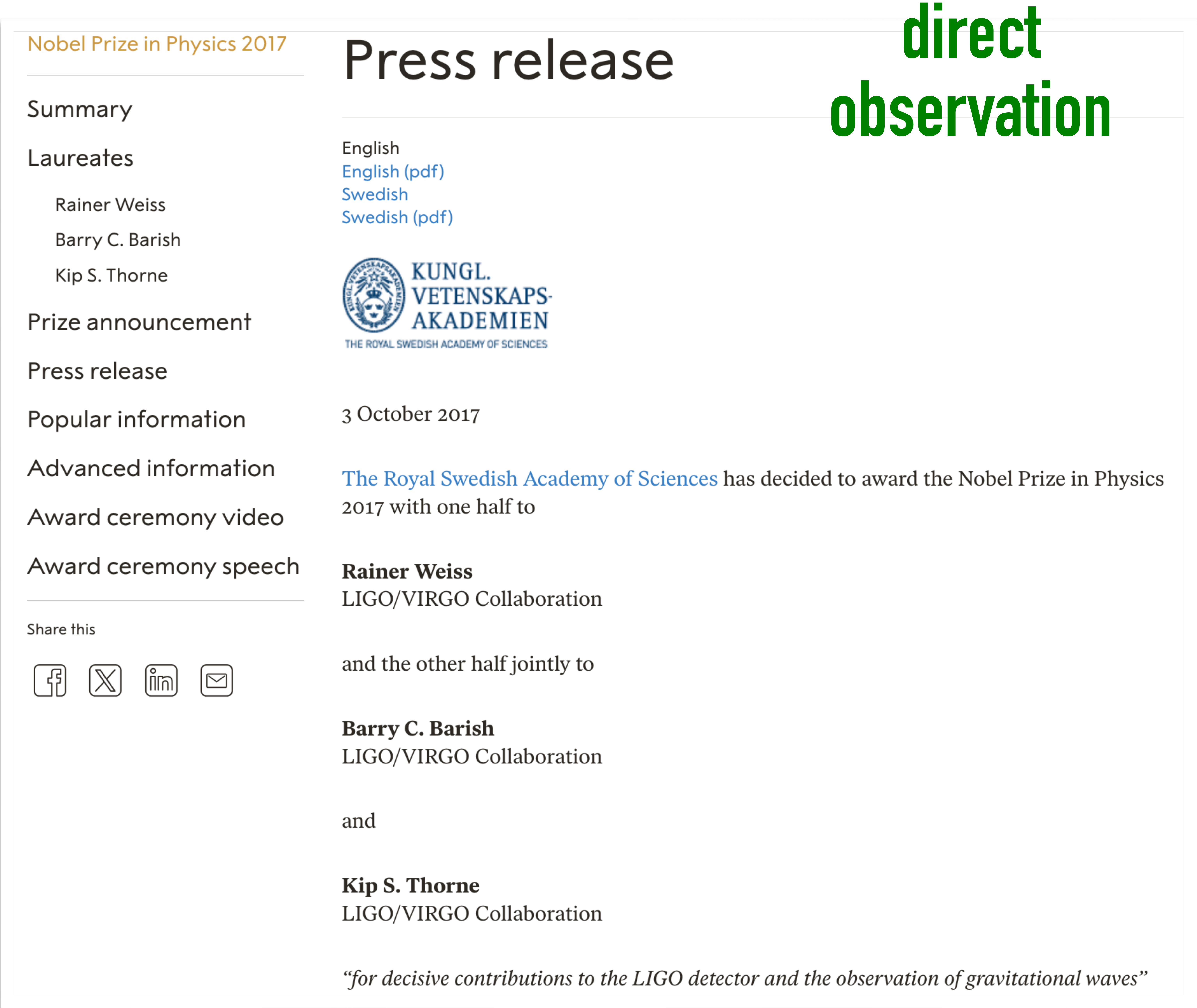

Nobel Prize in Physics 2017

- Summary
- Laureates
  - Rainer Weiss
  - Barry C. Barish
  - Kip S. Thorne
- Prize announcement
- Press release
- Popular information
- Advanced information
- Award ceremony video
- Award ceremony speech

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Press release

English
English (pdf)
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Higgs field in space


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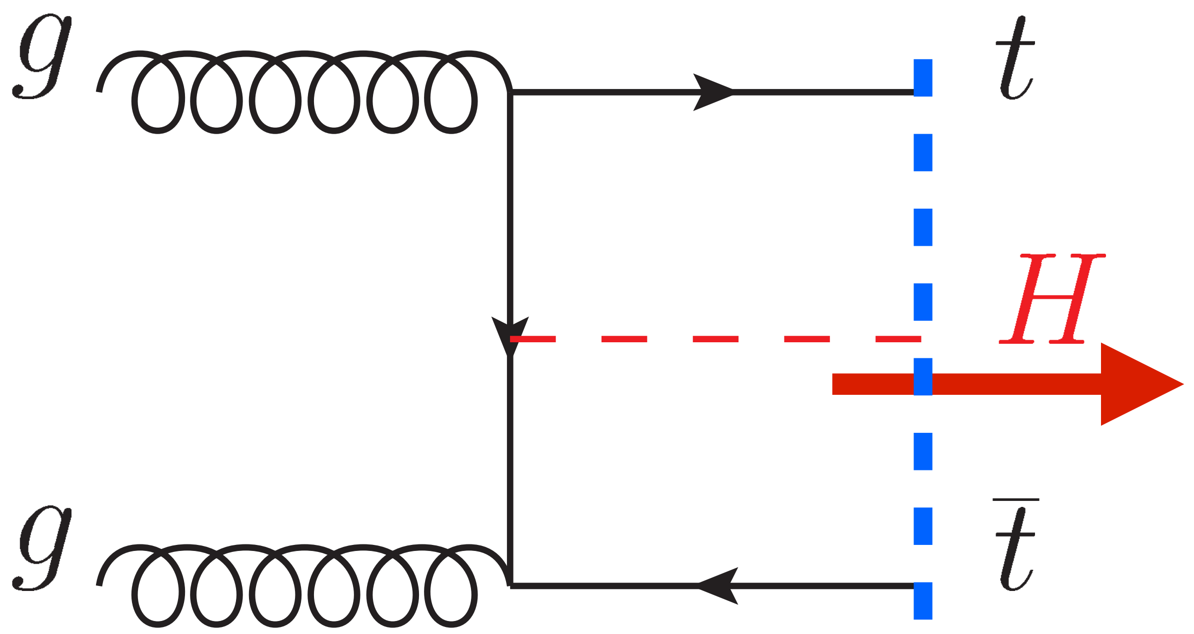
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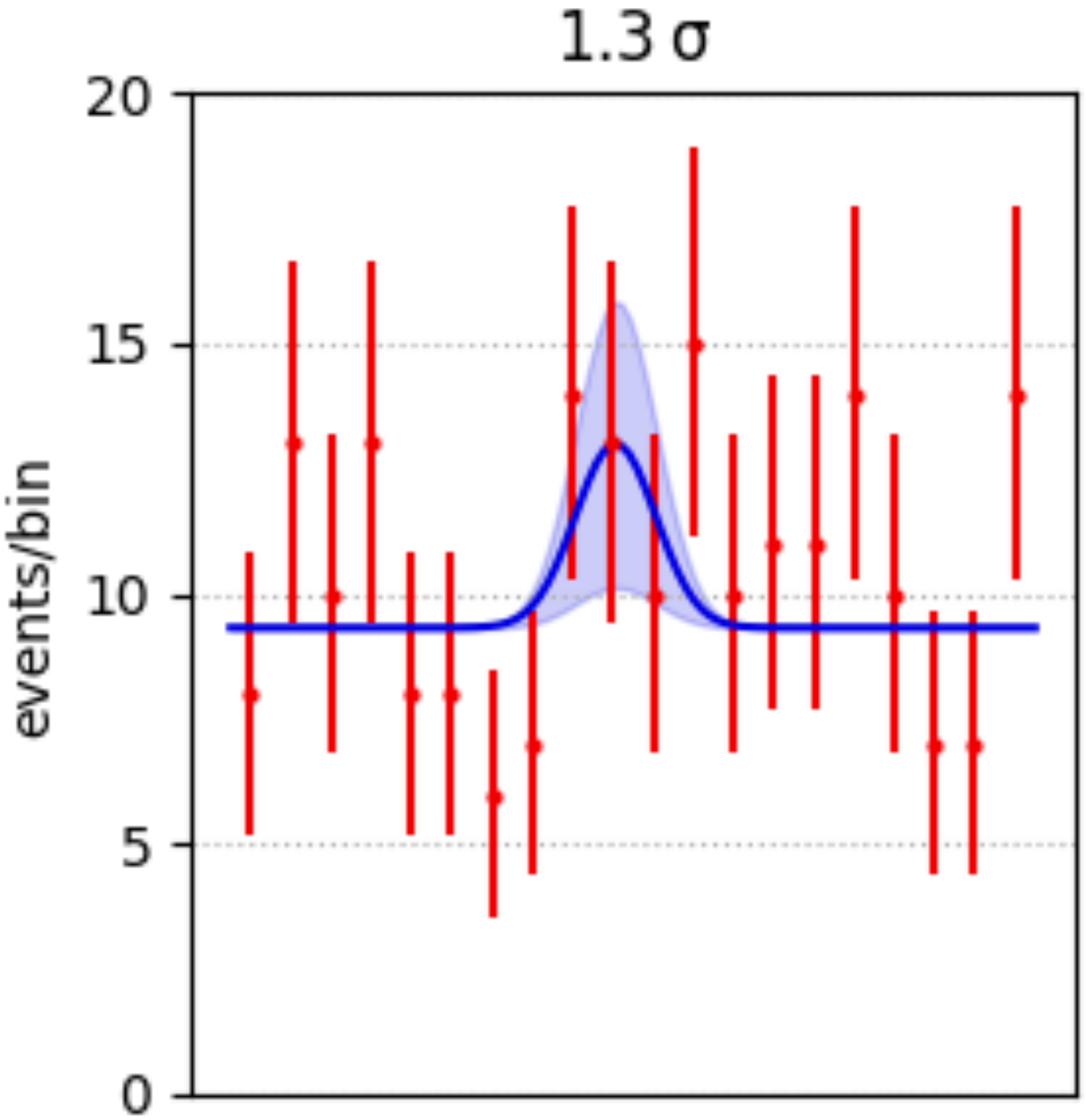
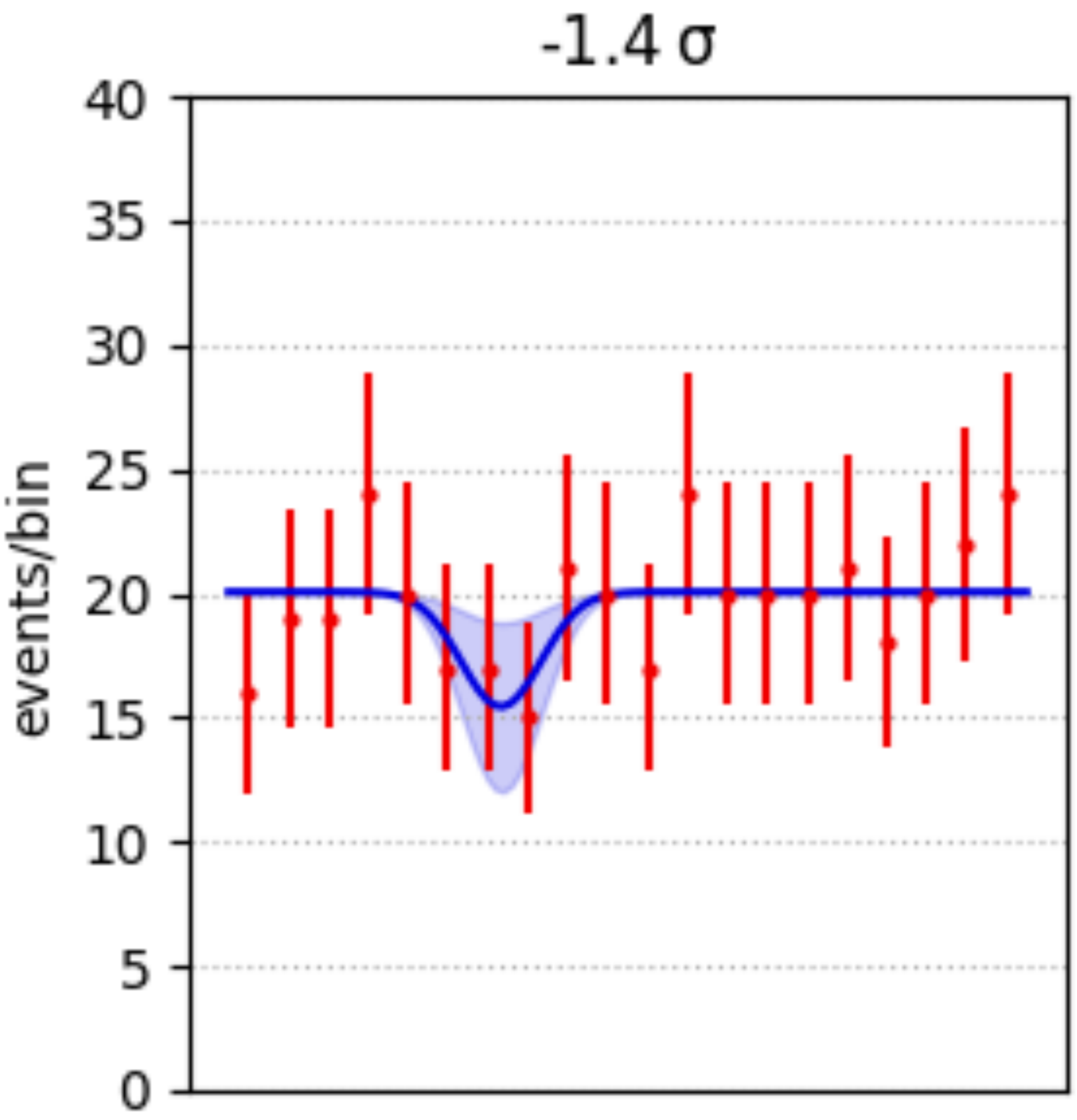


Number of σ measures statistical significance of a signal:
i.e. (size of signal) / uncertainty

Indicates how sure you can be that you are seeing a genuine signal rather than a statistical fluctuation



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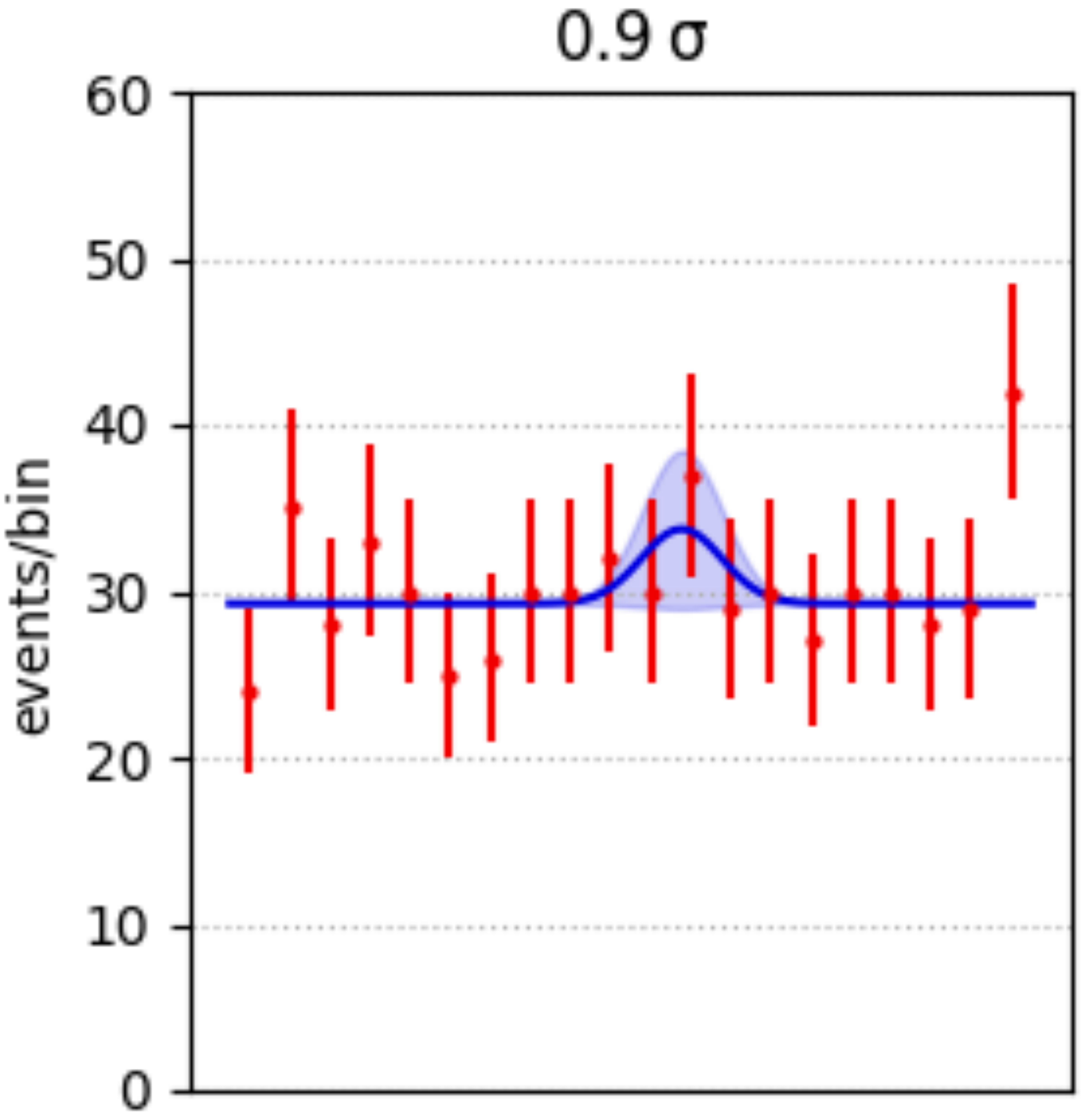

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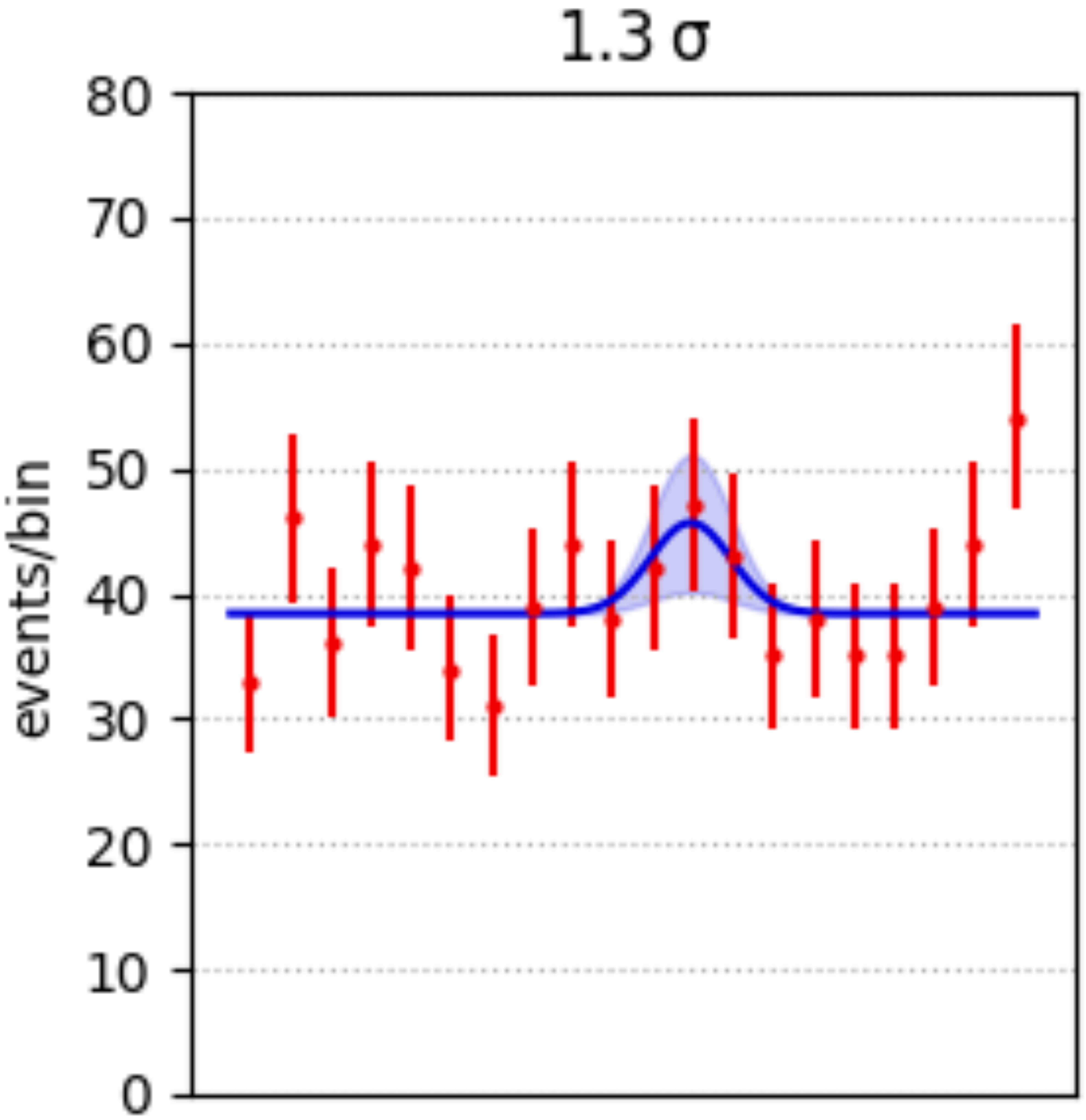

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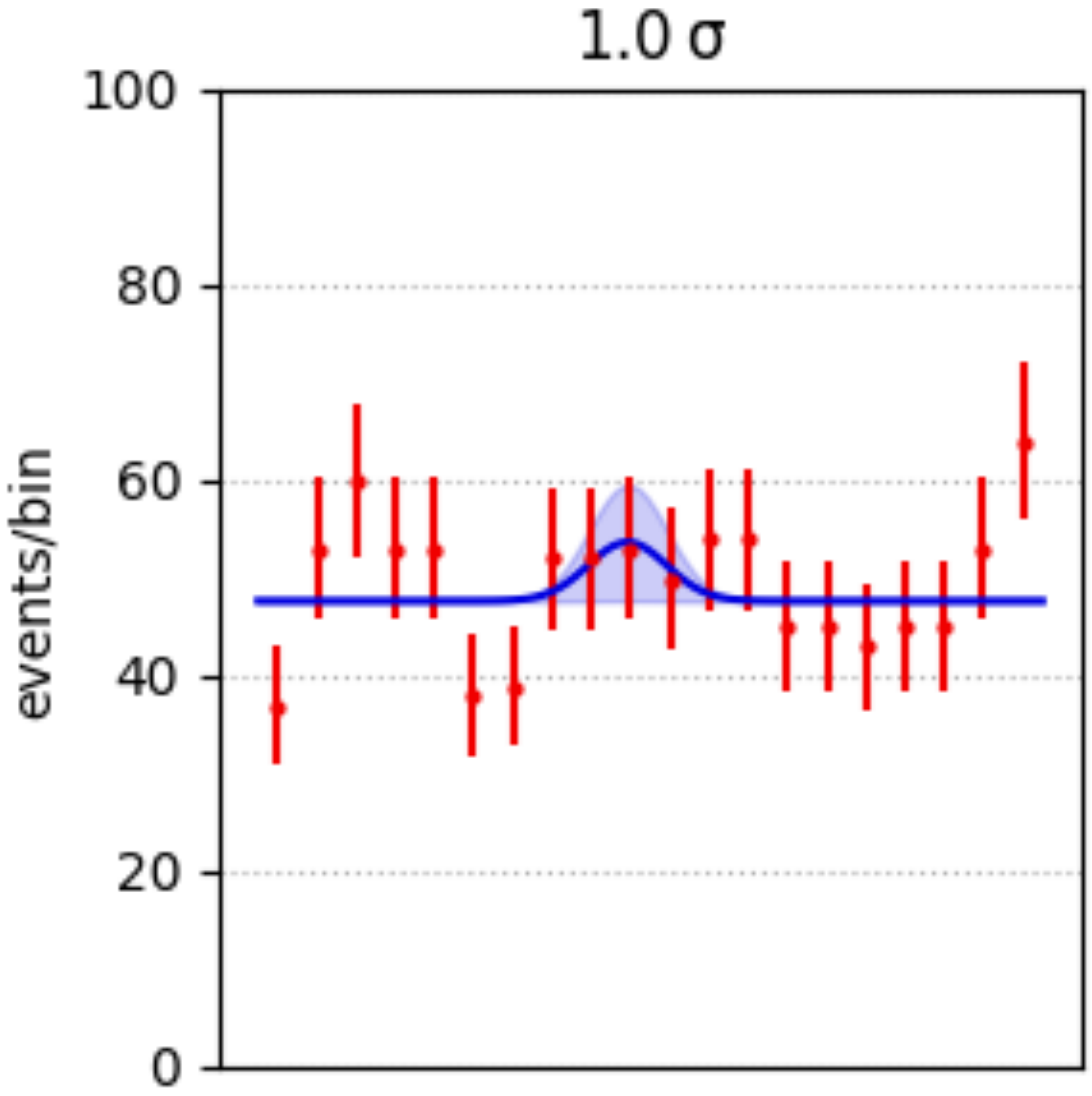

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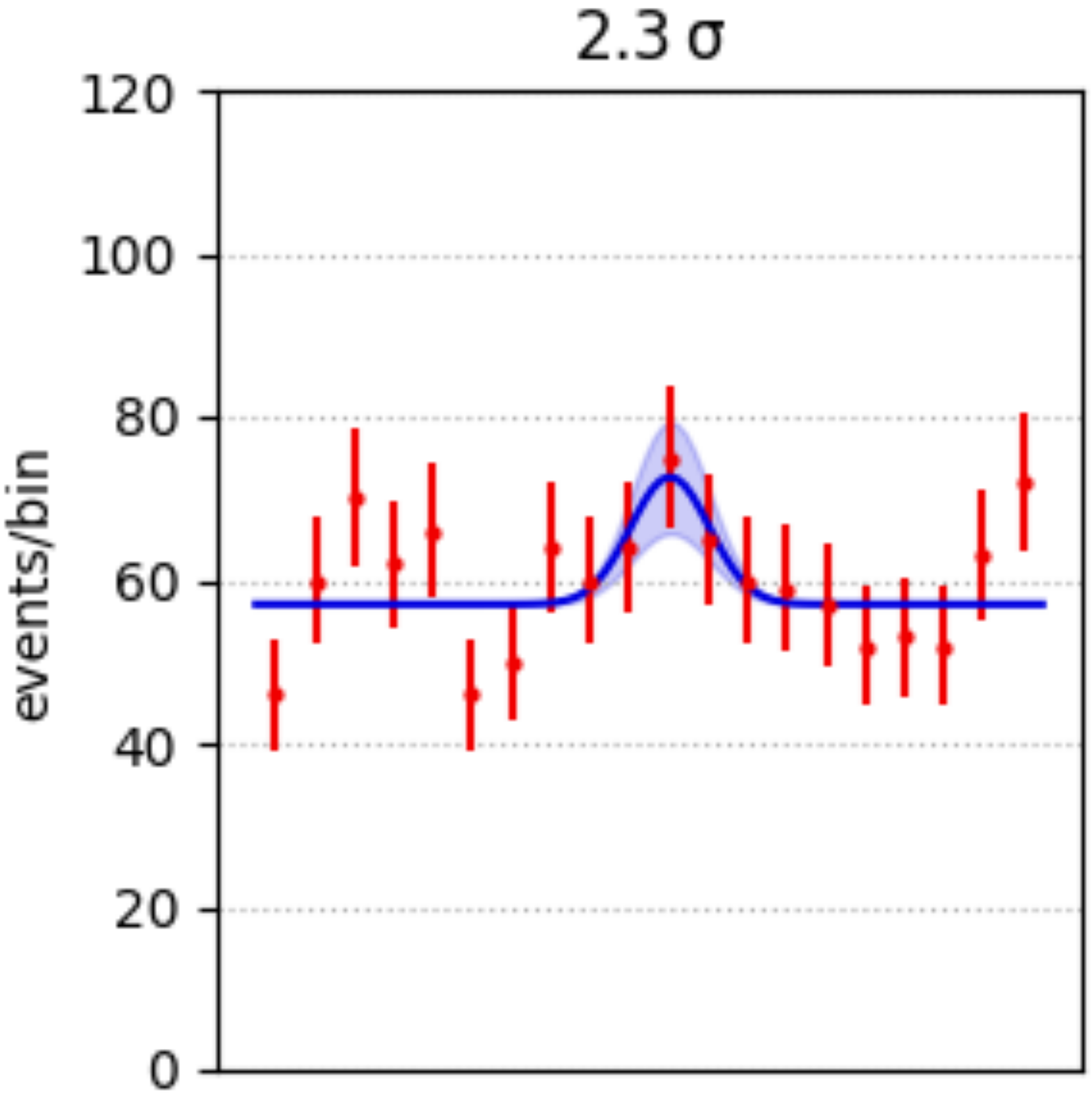

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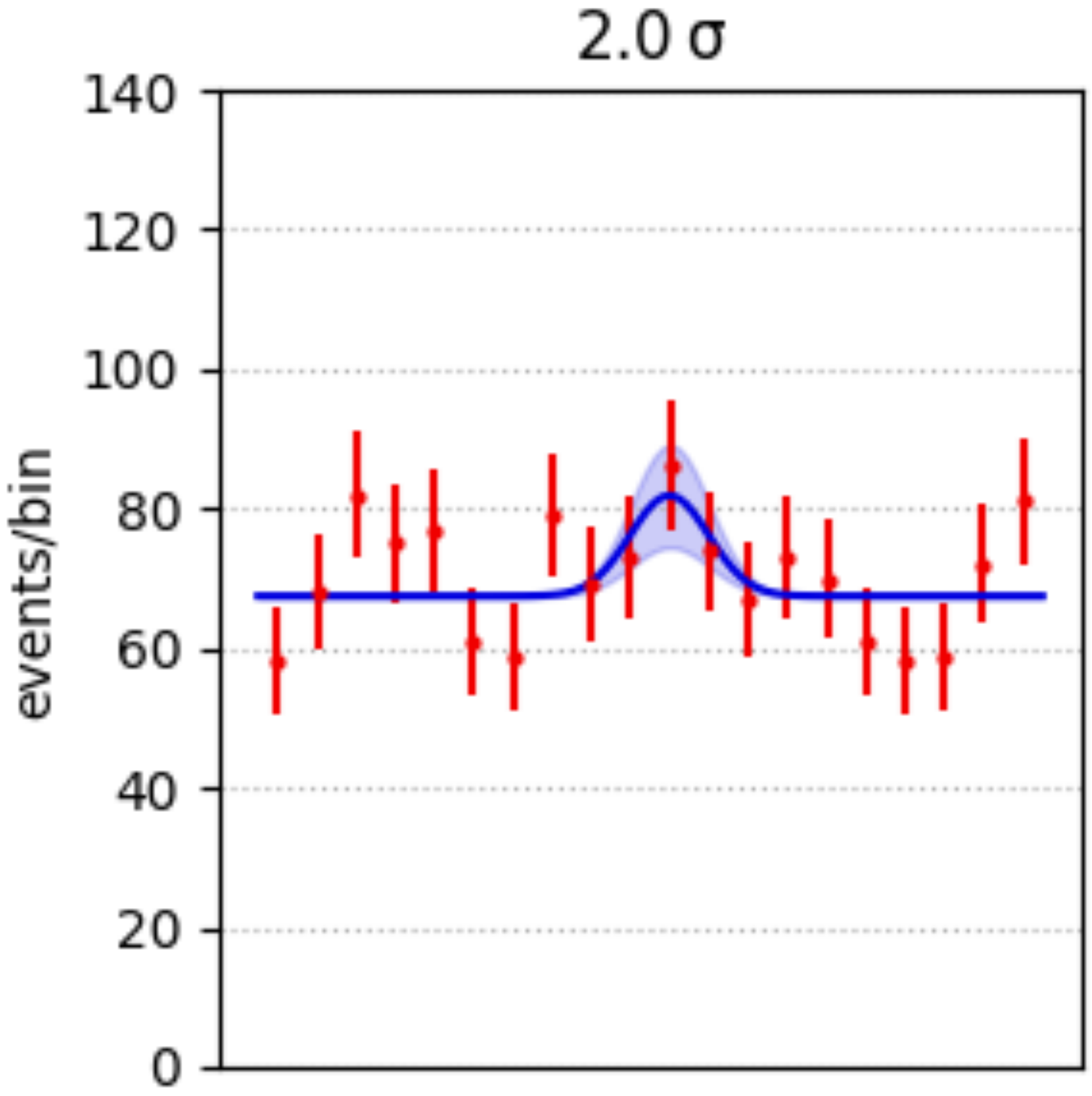

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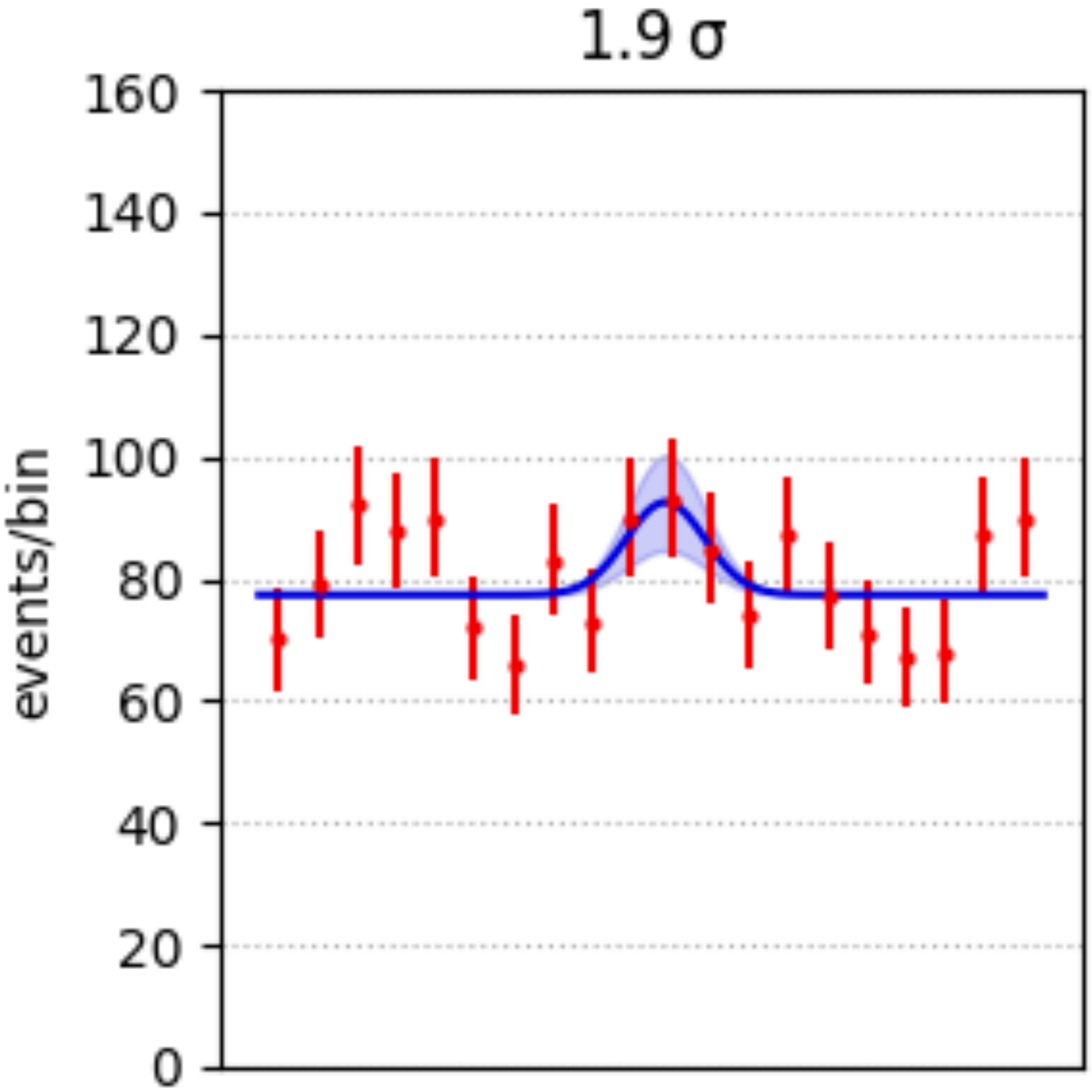

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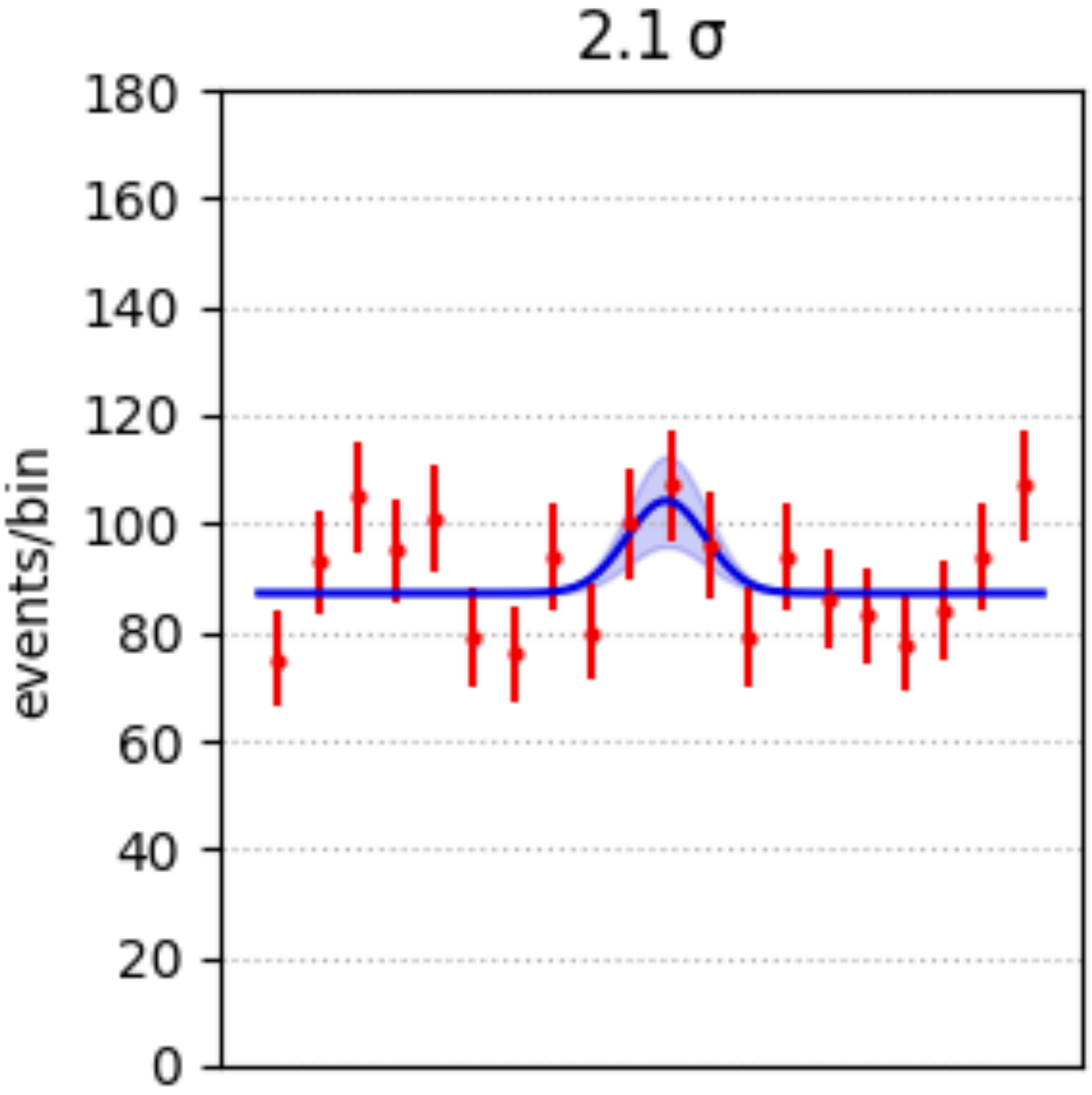

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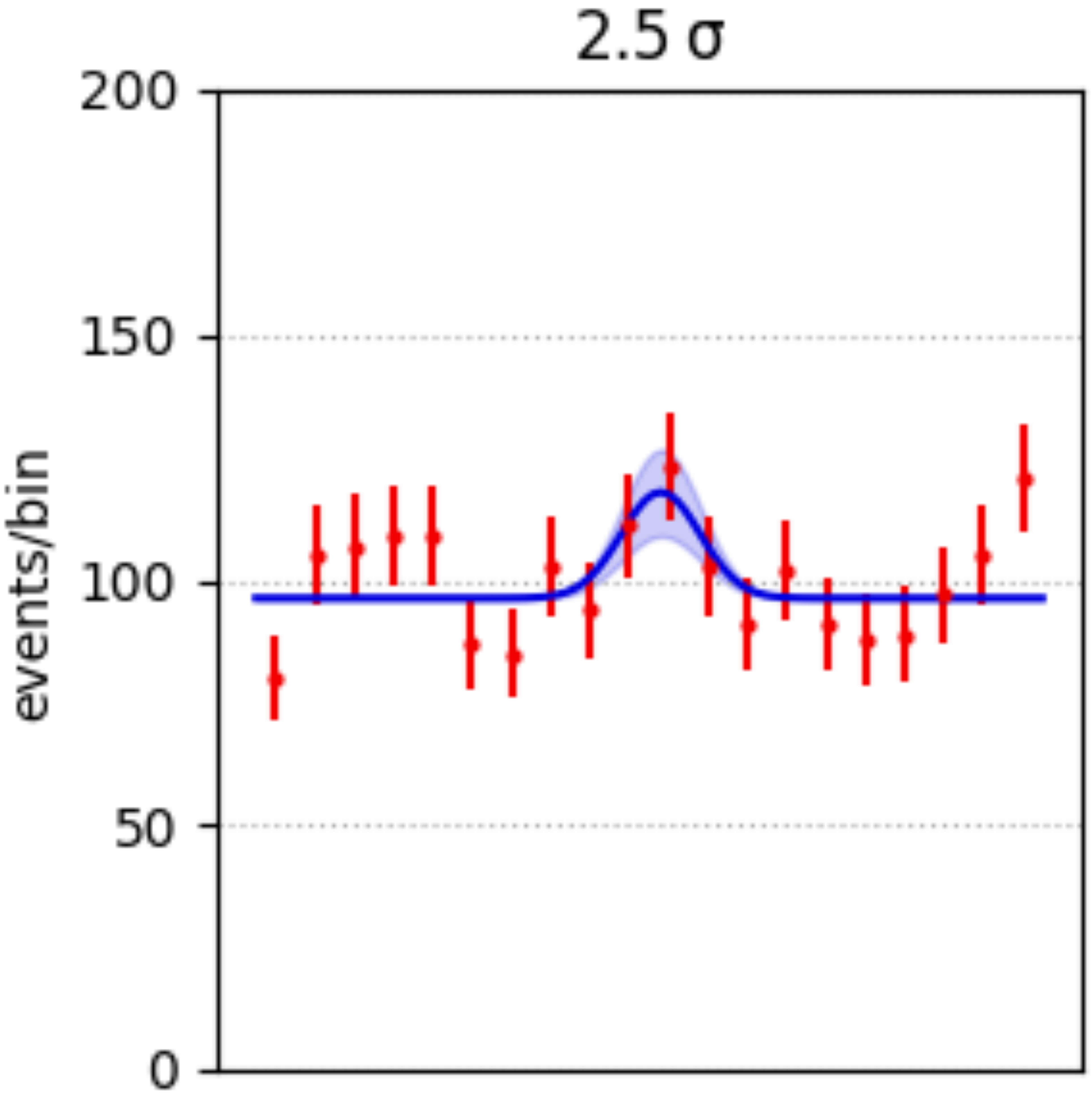

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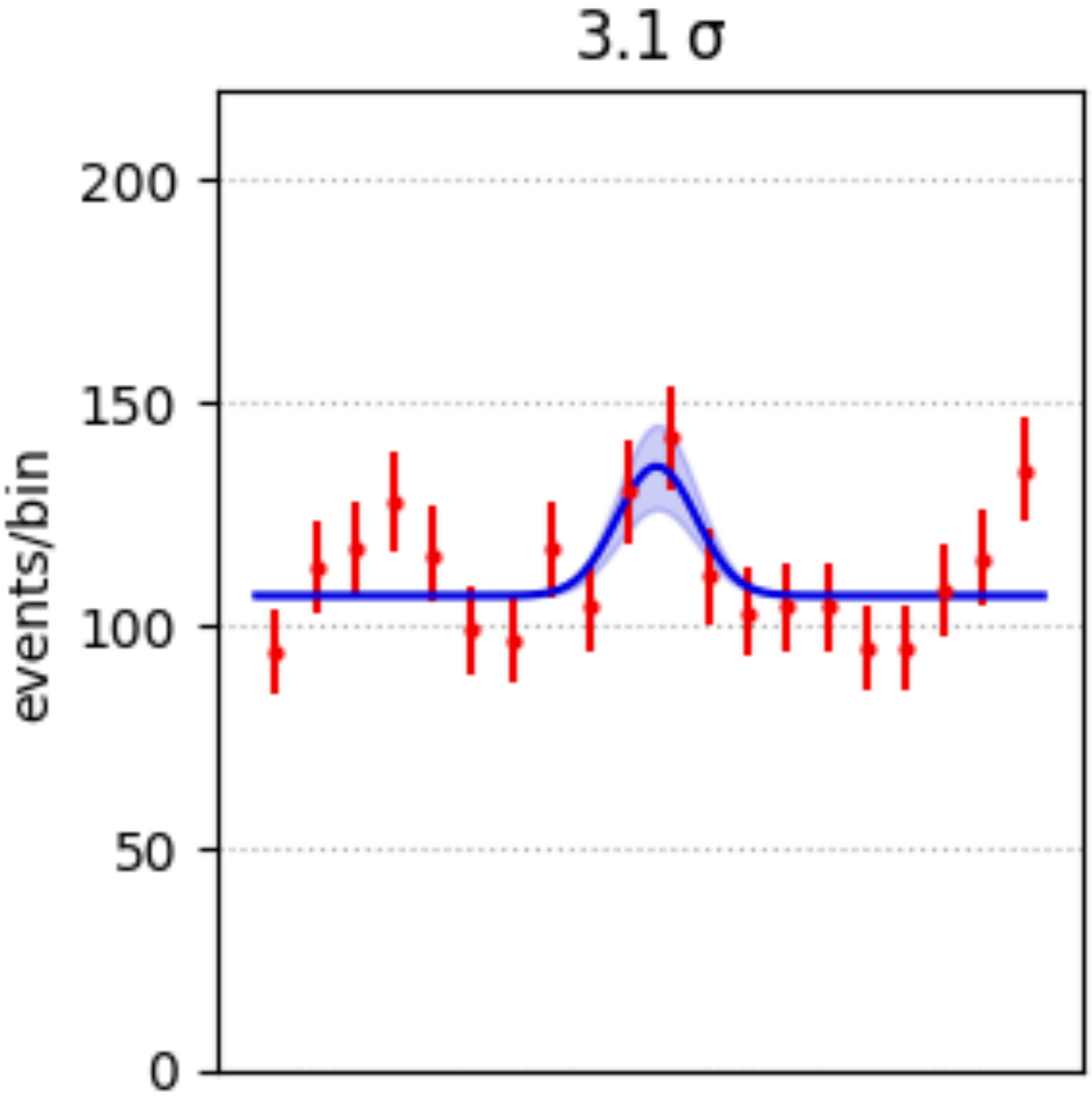

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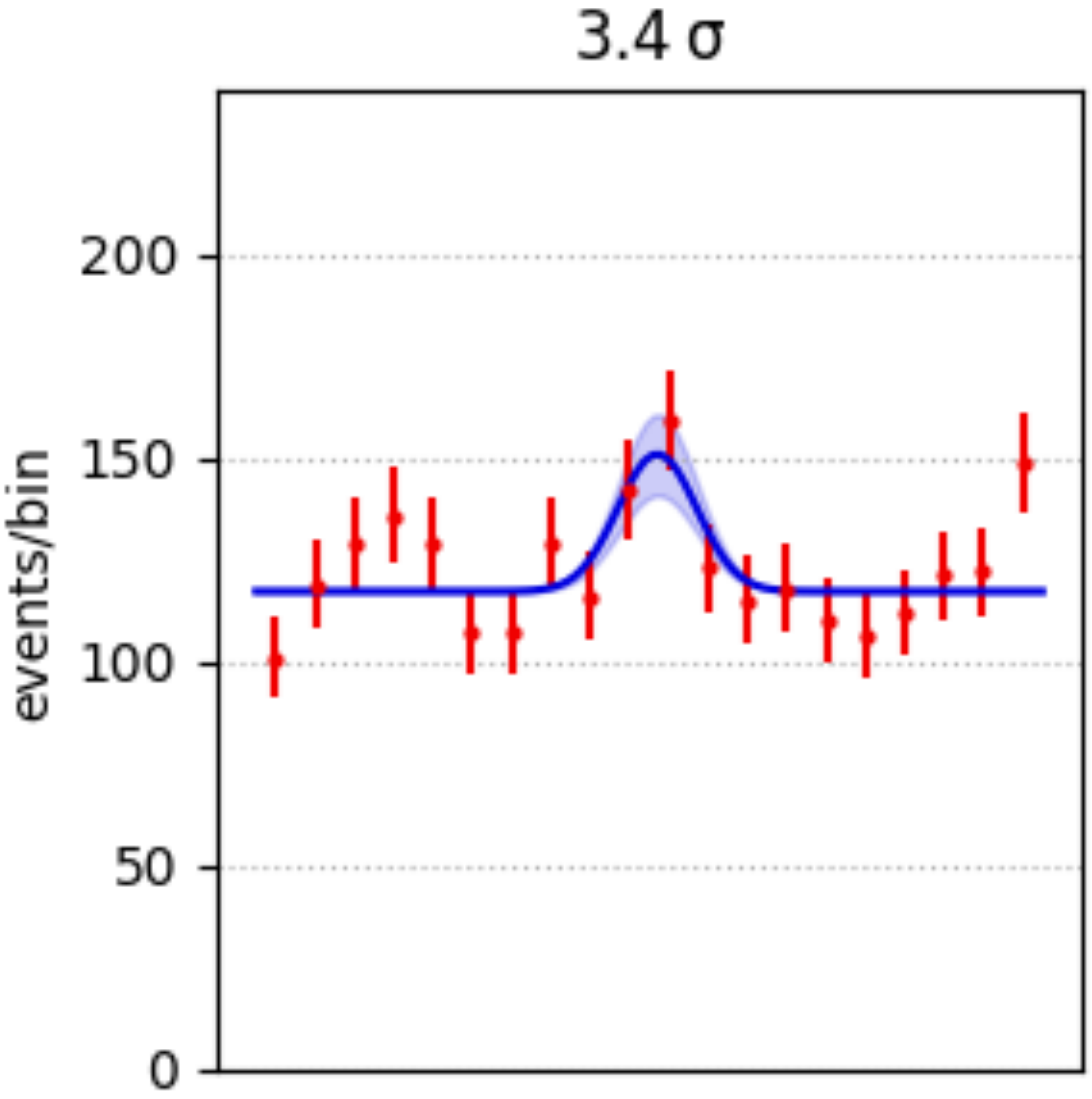
Particle physics conventions

3σ: "evidence"

(if you're not expecting it, don't be surprised if it goes away with more data!)



Number of σ measures statistical significance of a signal:
i.e. (size of signal) / uncertainty

Indicates how sure you can be that you are seeing a genuine signal rather than a statistical fluctuation

Particle physics conventions

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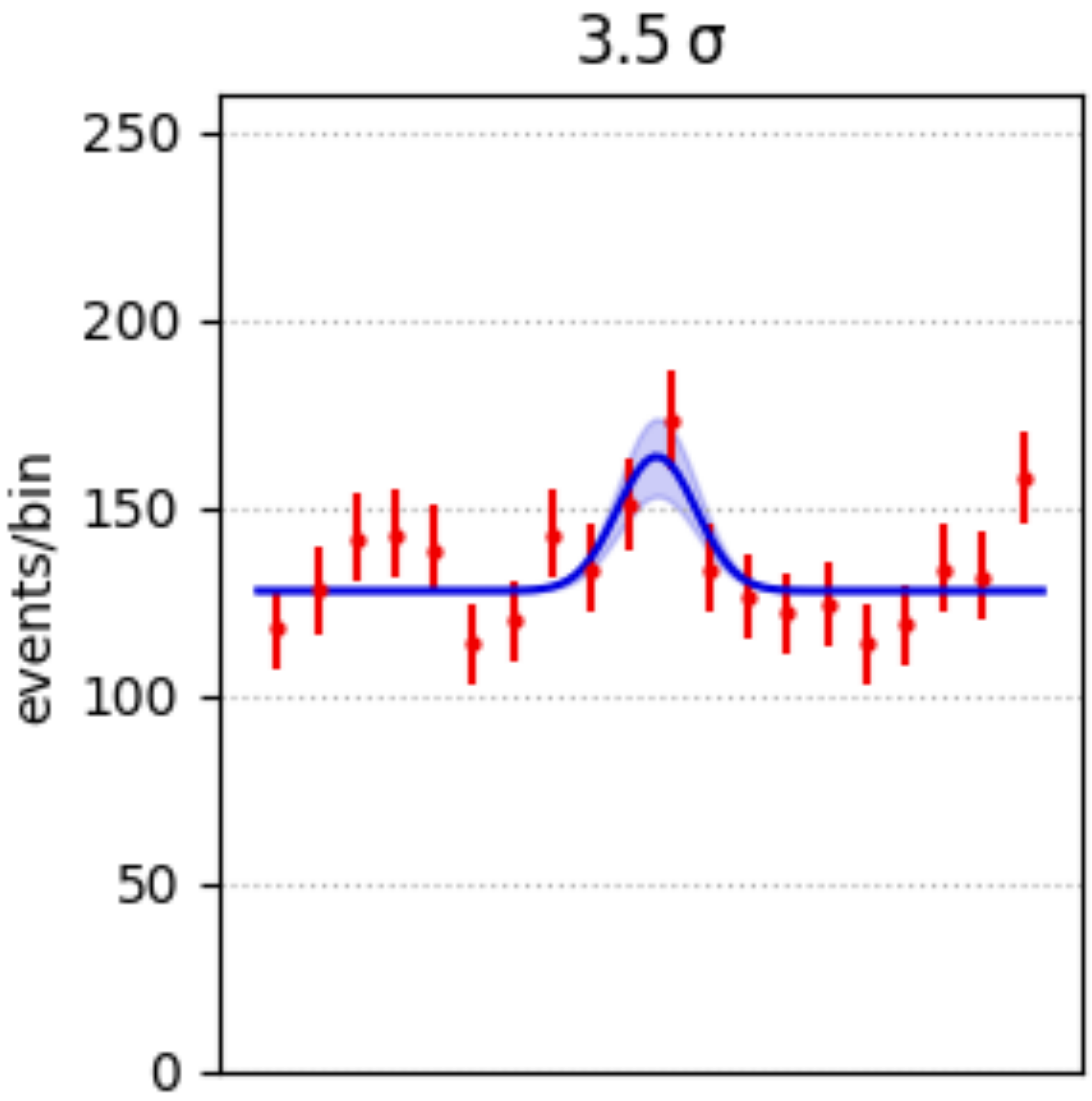

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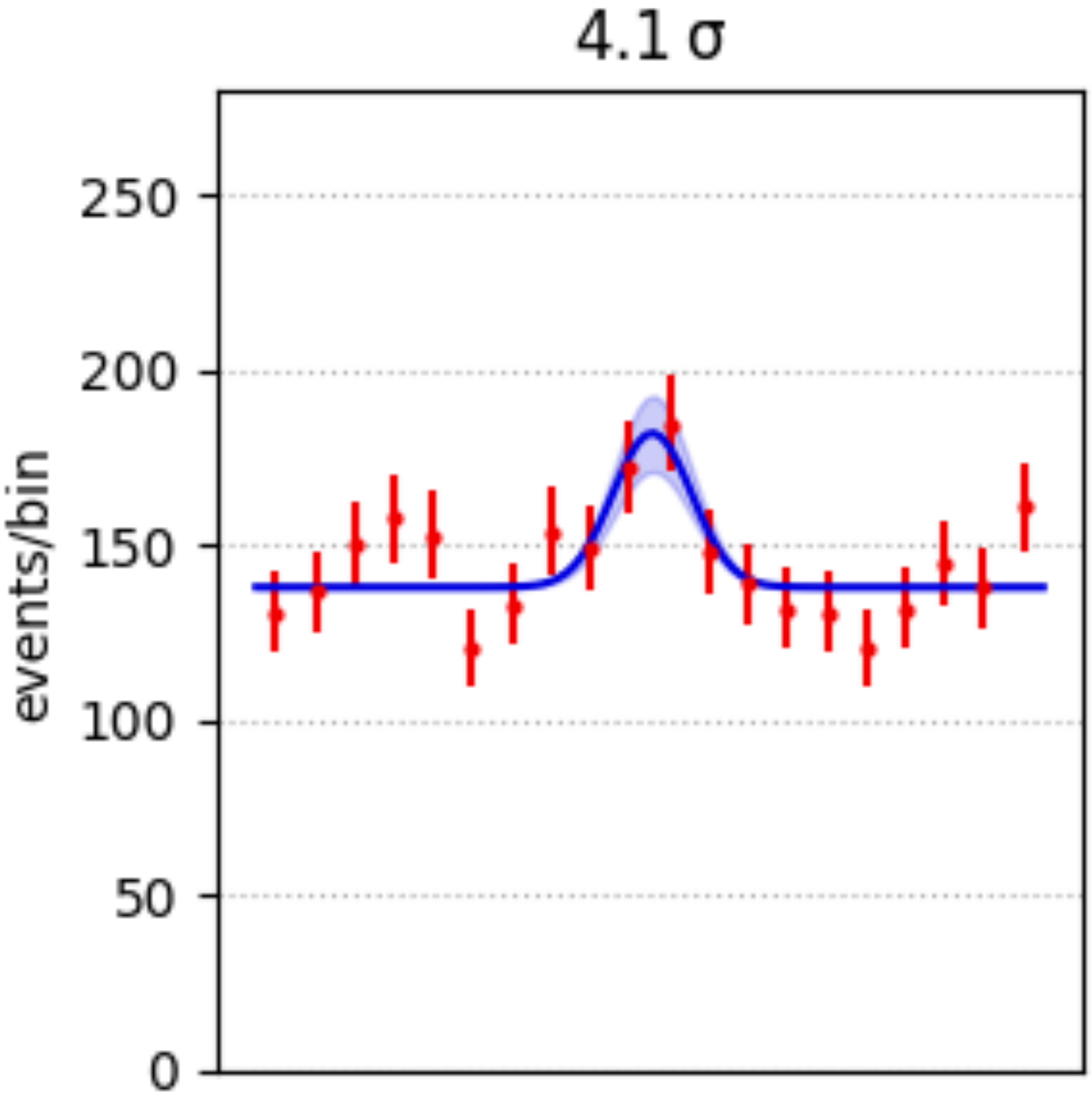

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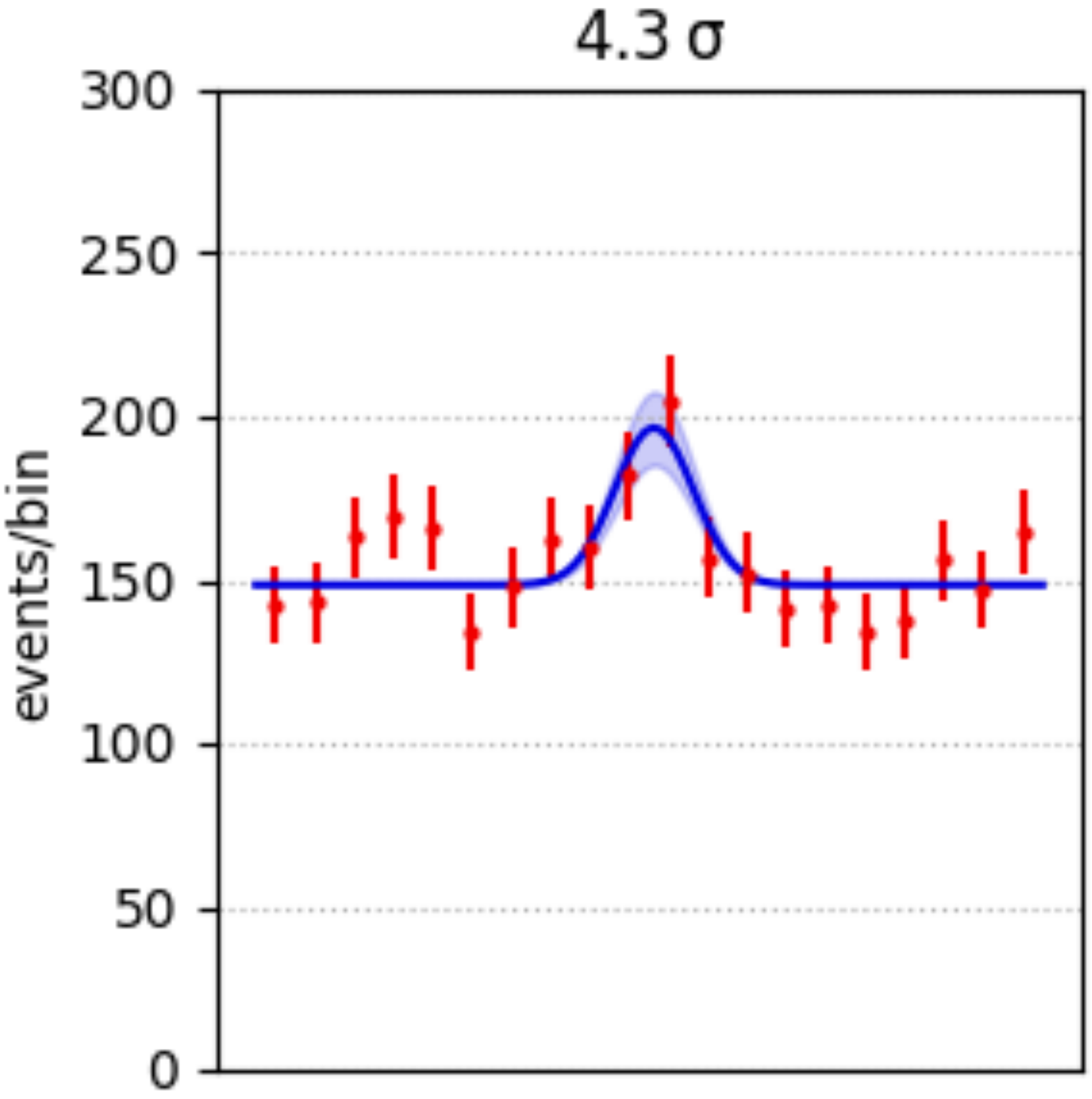

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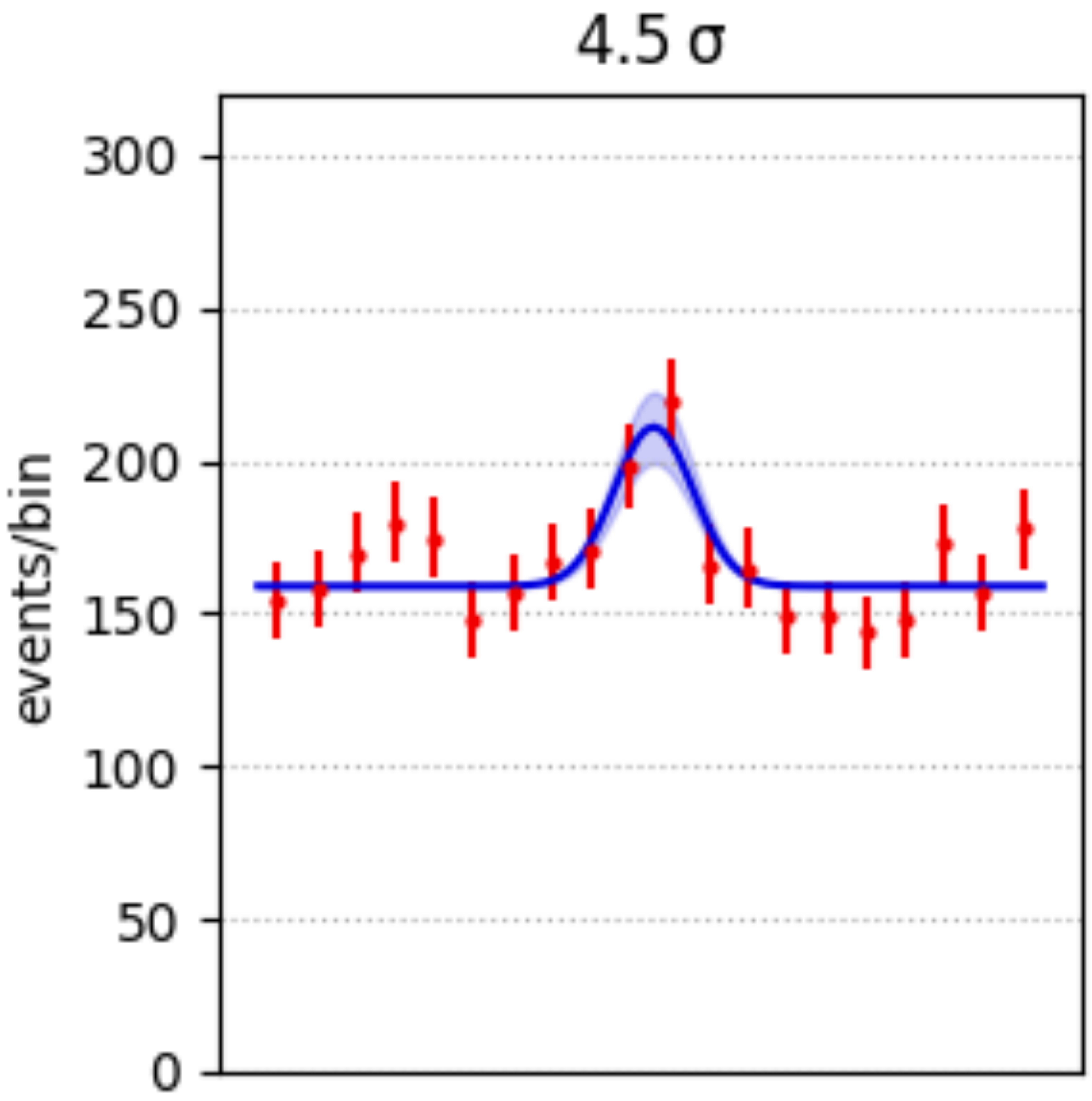

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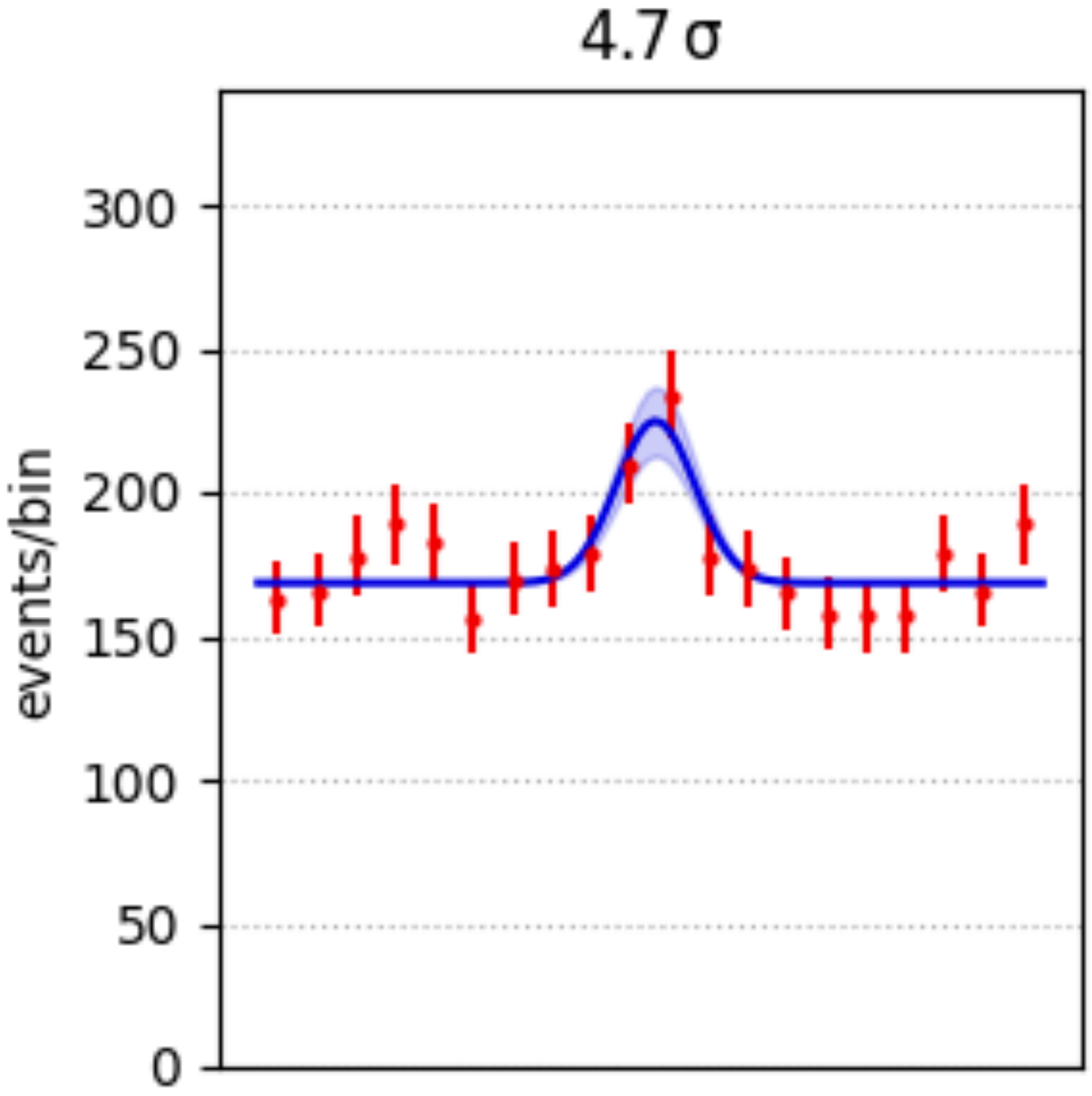

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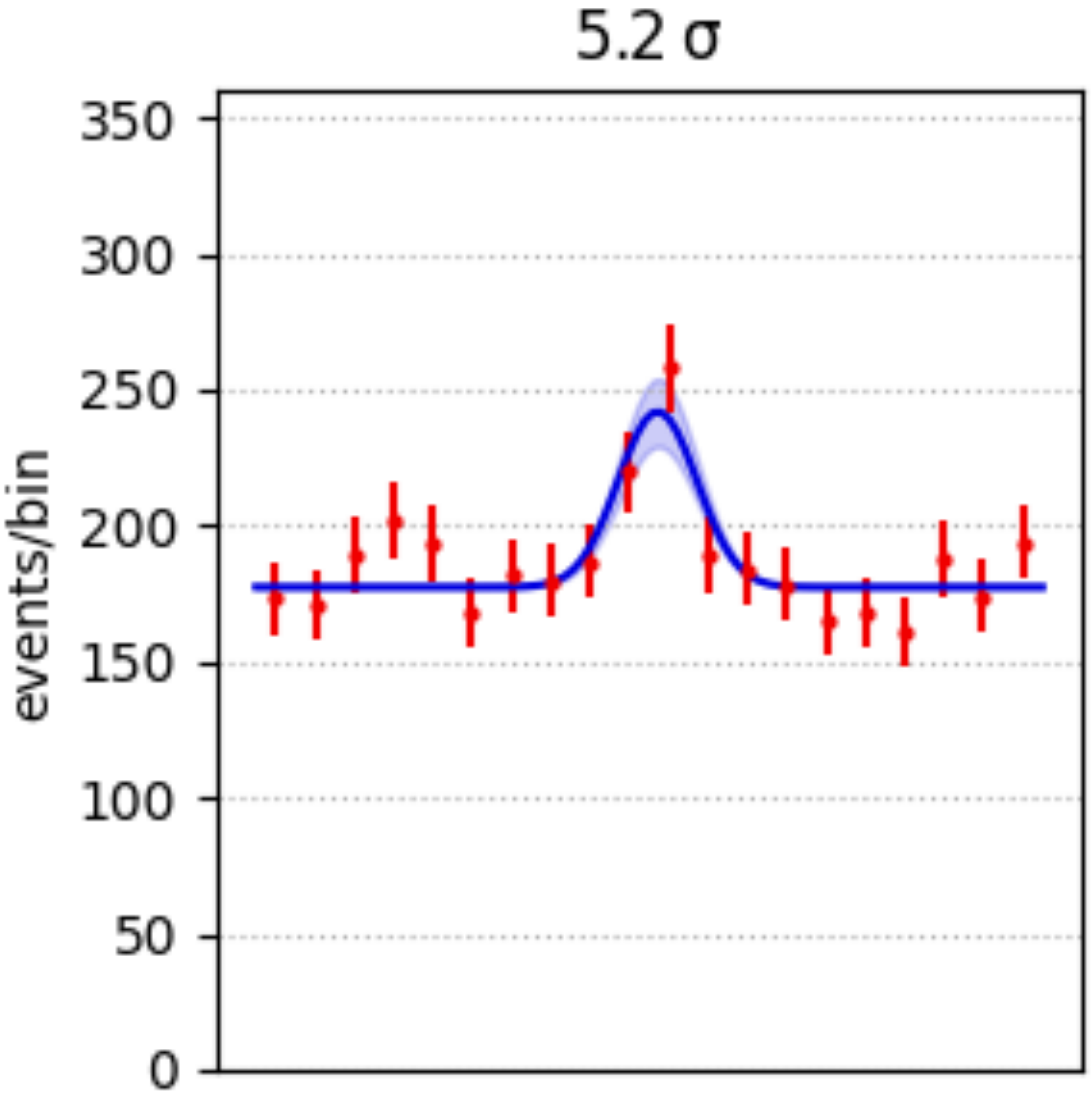

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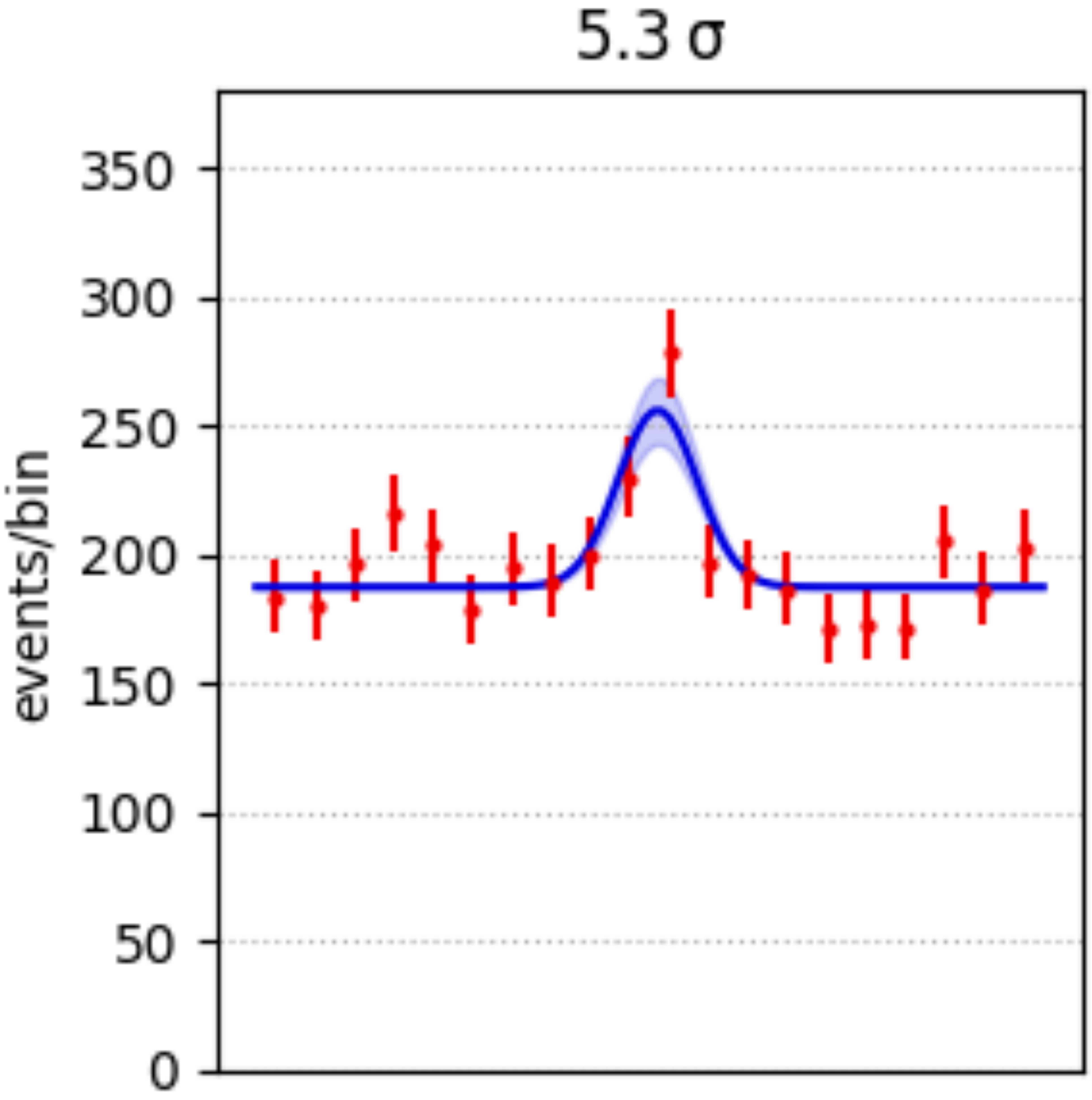
5σ: "observation"

(should be robust)



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Particle physics conventions

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5σ: "observation"

(should be robust)

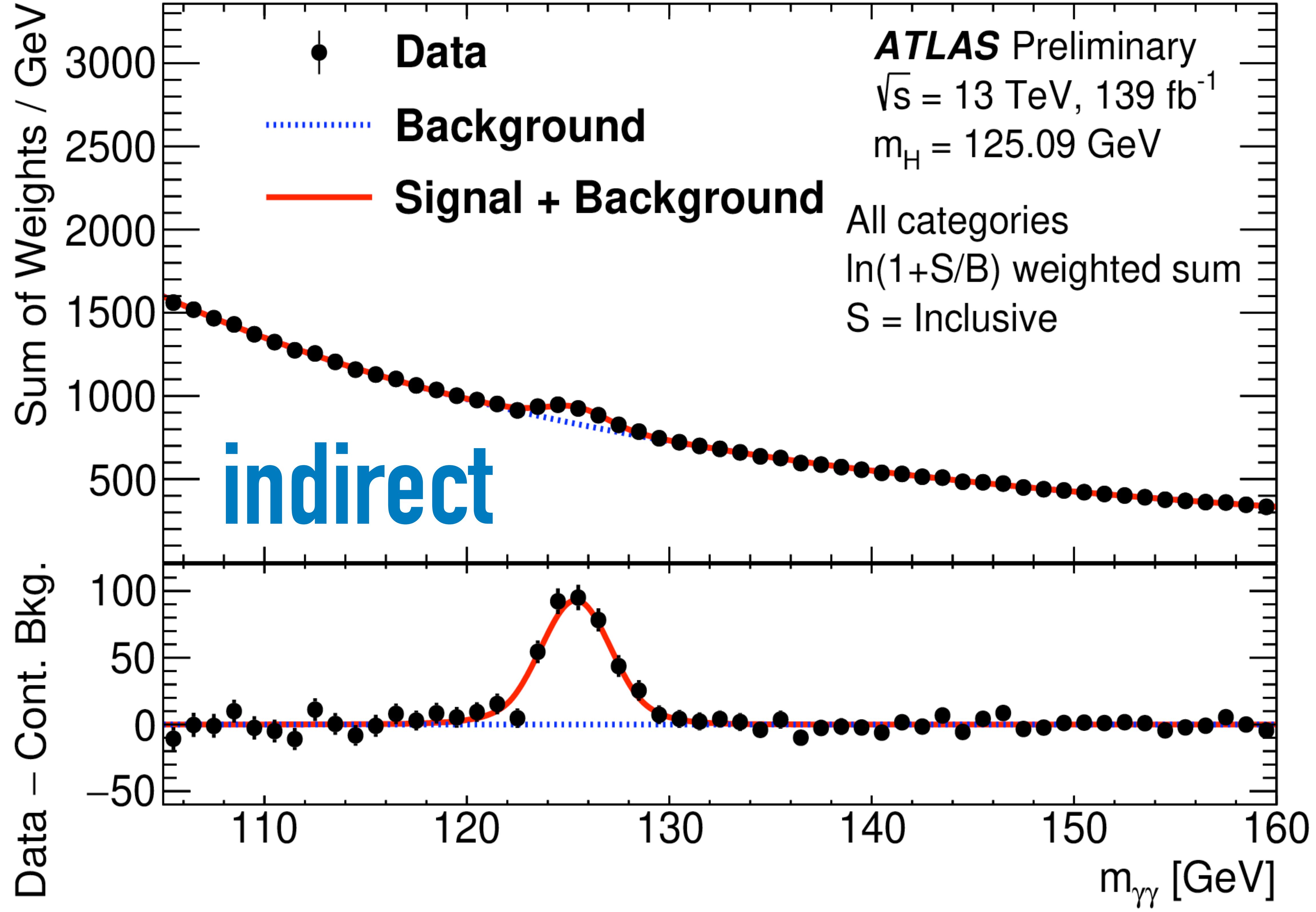
Situation at start of LHC (2009)

"Due to a (too) low signal-to-background ratio S/B ~ 1/9 [ttH] channel might not reach a 5σ significance for any luminosity."

[from introduction to arXiv:0910.5472,
summarising ATLAS and CMS ttH(→bb) studies at that point]

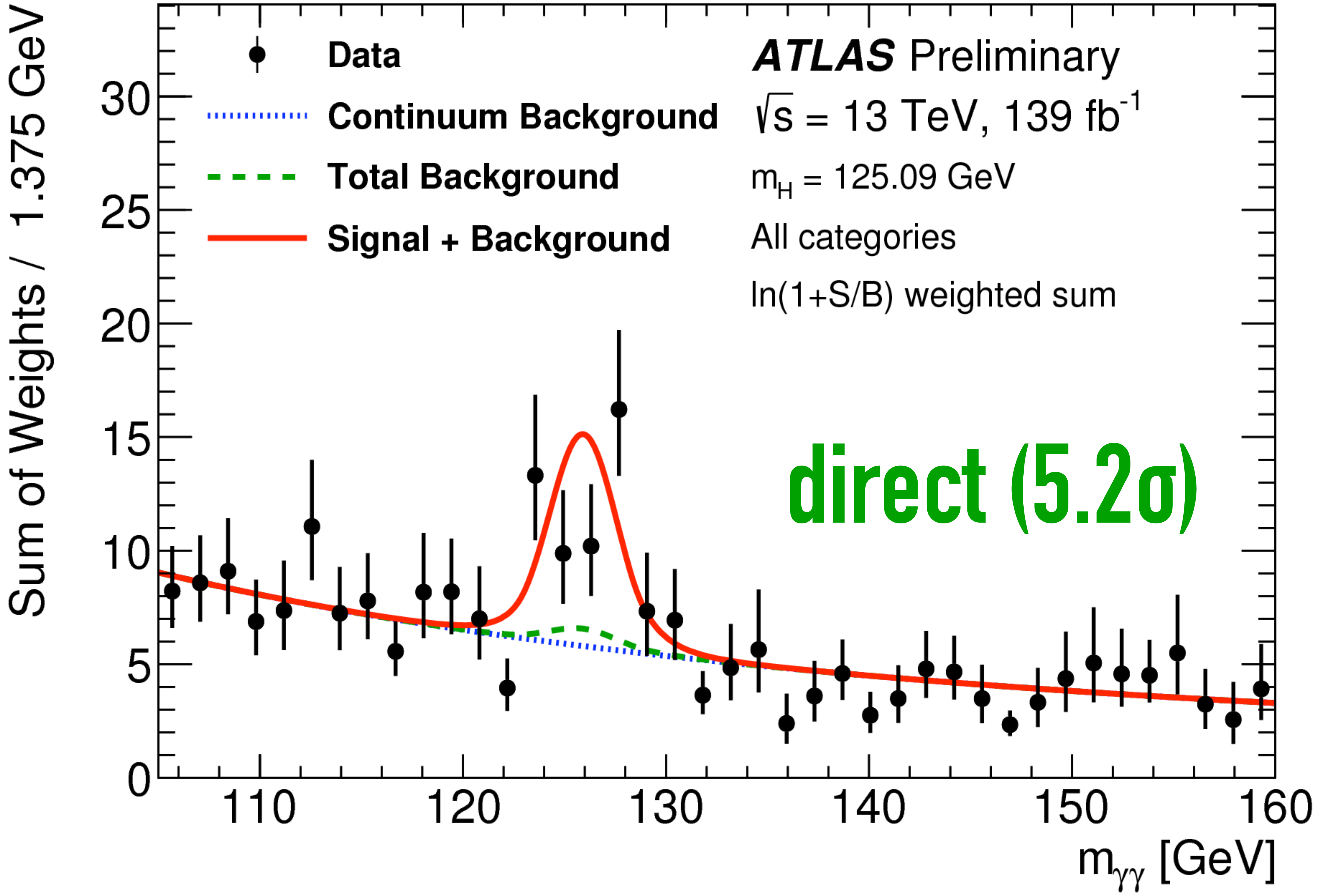
since 2018: ATLAS & CMS see (at >5σ) events with top-quarks & Higgs simultaneously

Higgs = one in 2 billion events

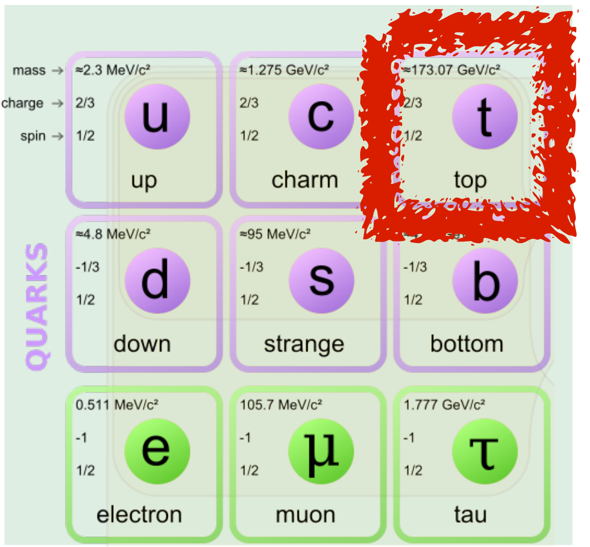


indirect

1 in 2,000 events with top quarks



direct (5.2σ)

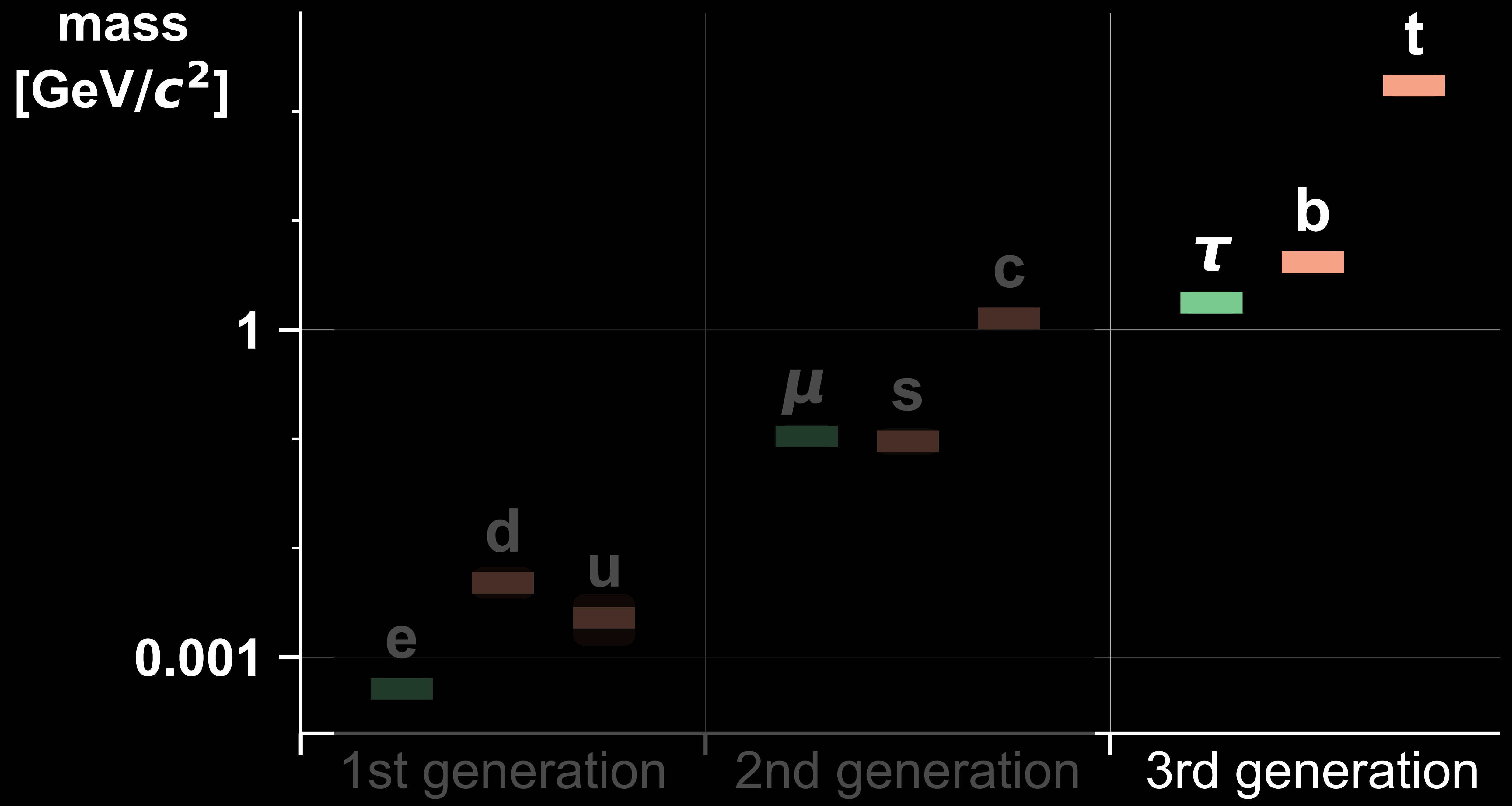


enhanced fraction of Higgs bosons in events with top quarks

→ direct observation of Higgs interaction with tops

(consistent with SM to c. ±25%)

Discovery of 3rd generation—Higgs field interactions by ATLAS & CMS ~ 2018



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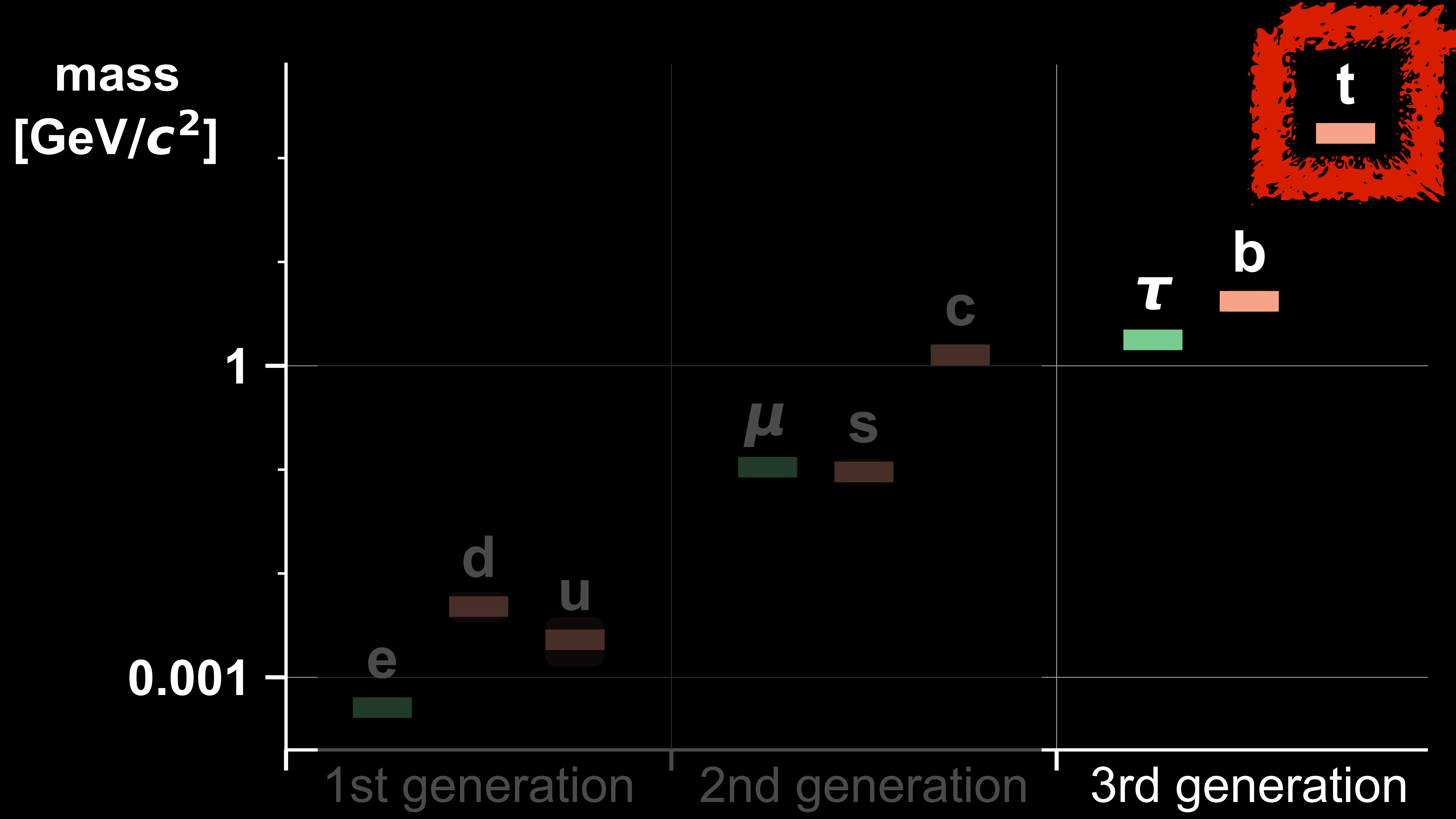
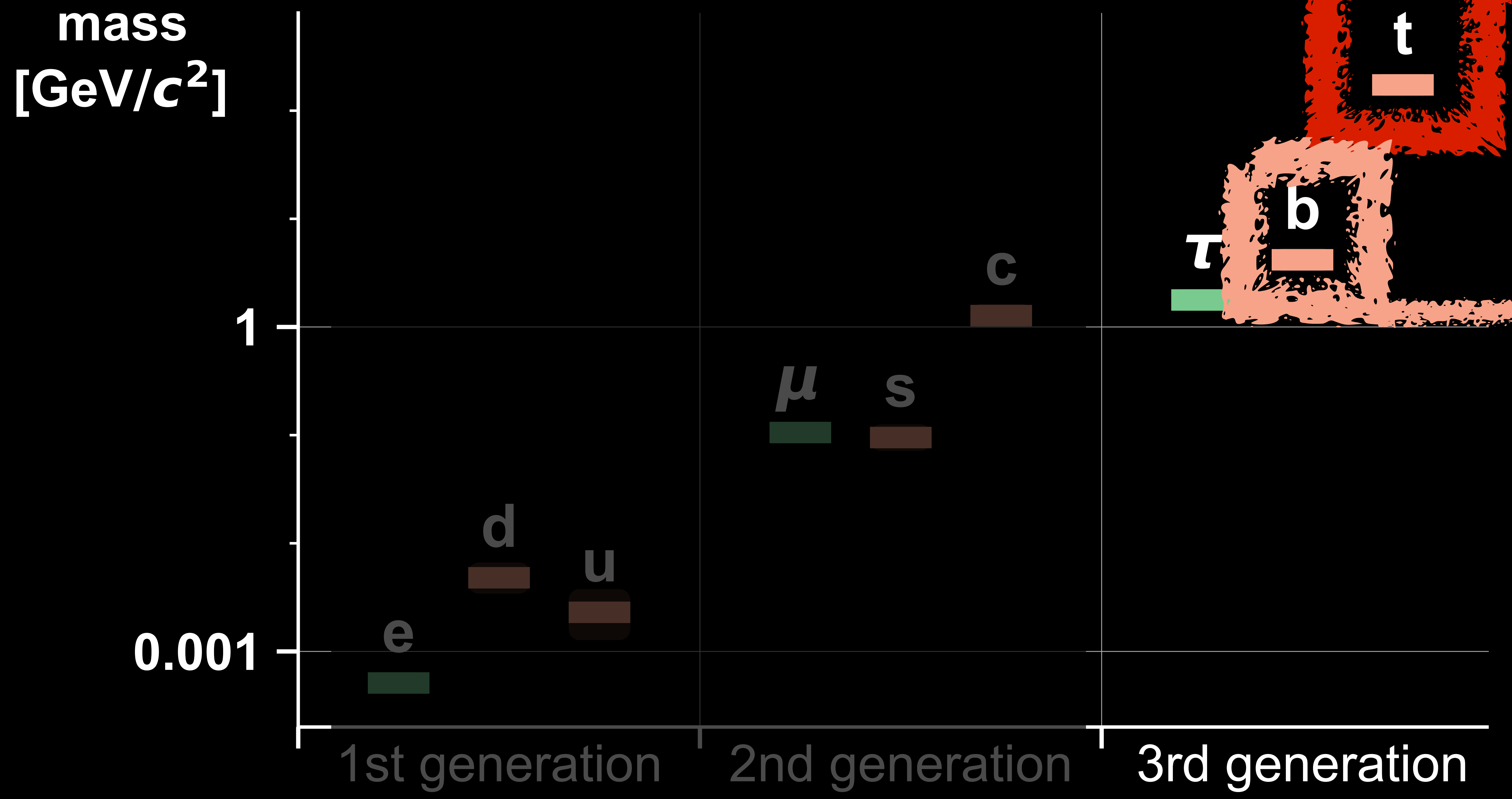


by observing H in association with top quarks

Discovery of 3rd generation—Higgs field interactions by ATLAS & CMS ~ 2018

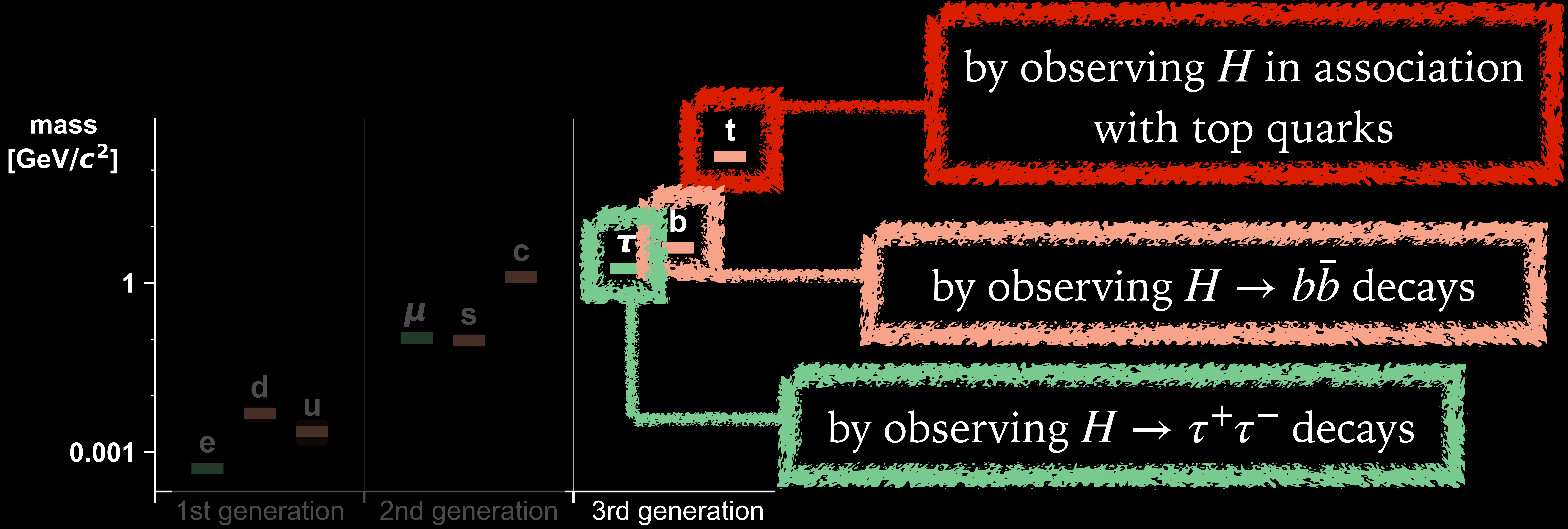


by observing H in association with top quarks

by observing $H \to b\bar{b}$ decays

in part with approach from Butterworth, Davison, Rubin & GPS '08

Discovery of 3rd generation—Higgs field interactions by ATLAS & CMS ~ 2018



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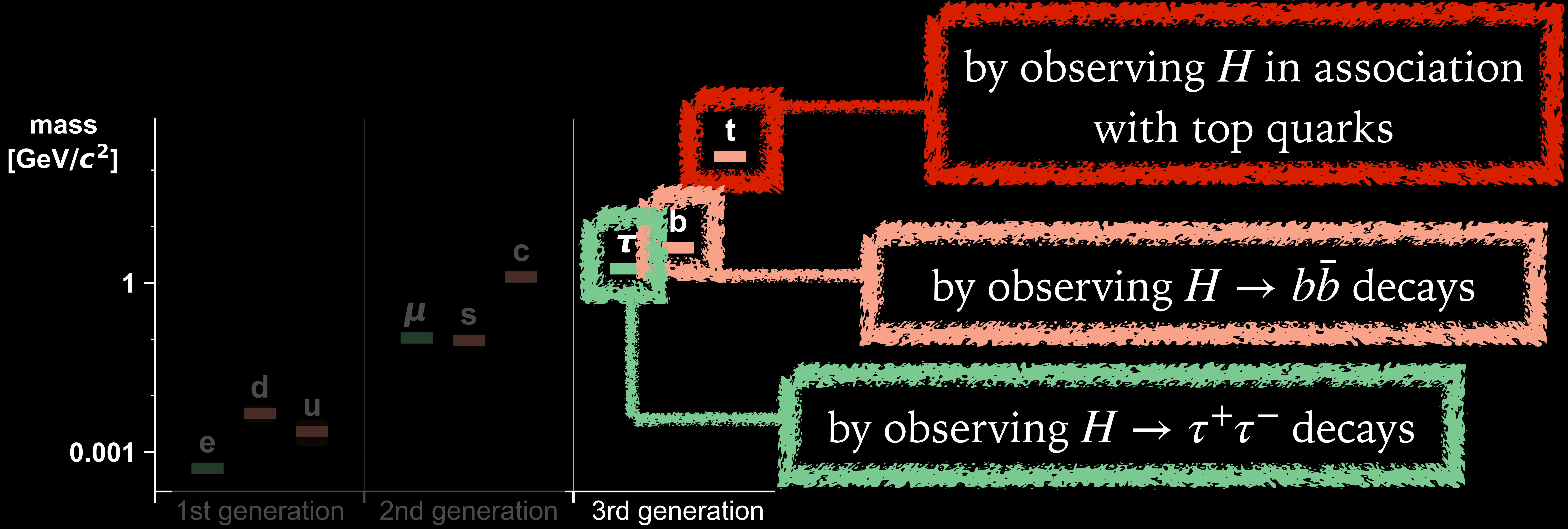

by observing H in association with top quarks

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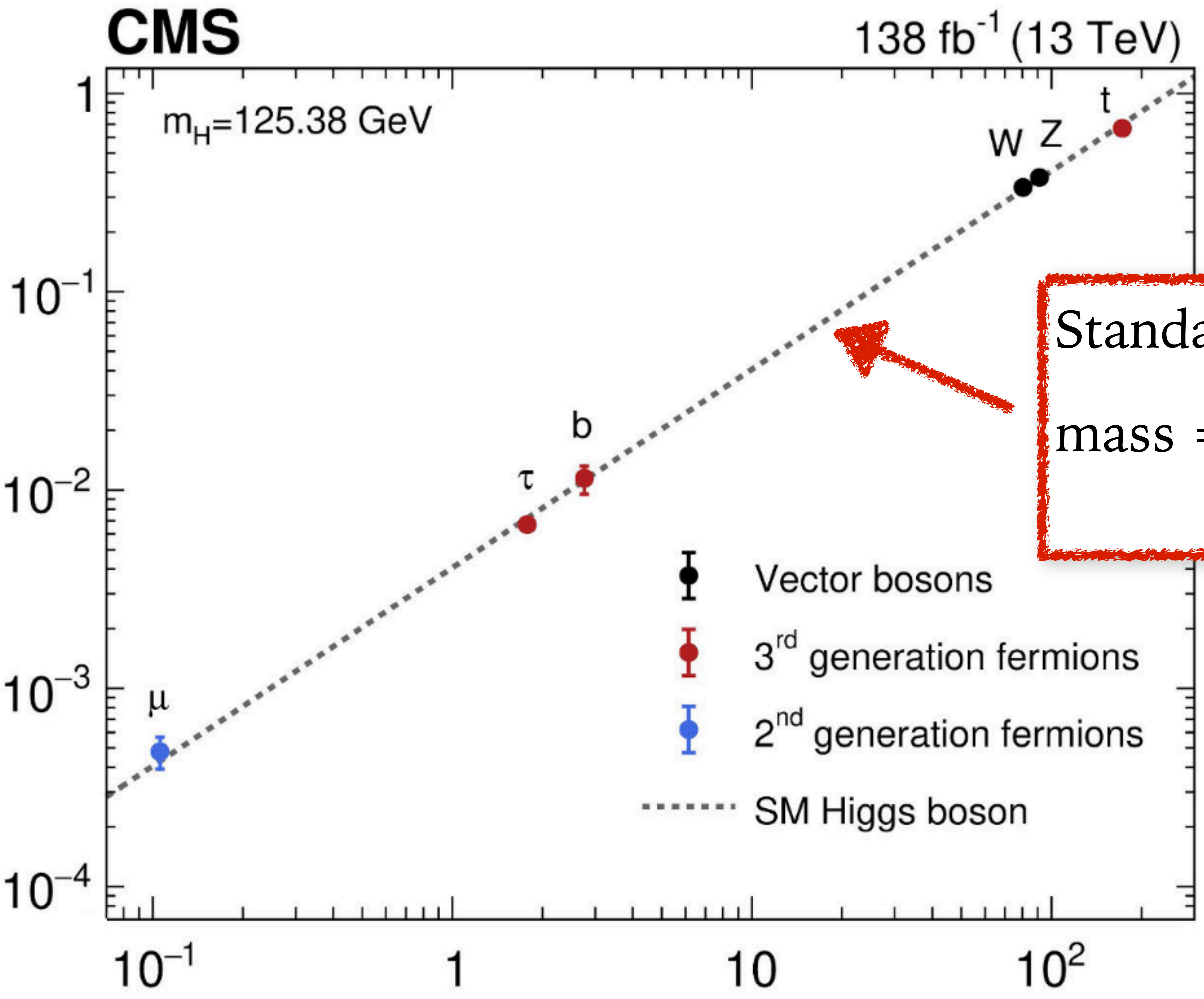
by observing $H \to \tau^+\tau^-$ decays

Full 3rd generation Yukawas were not part of the LHC design case.
Amazing achievement of LHC experiments to have directly observed them



Particle's strength of interaction with Higgs field

Particle's mass [GeV]

Standard Model prediction:

$$\text{mass} = \text{higgs-field-value} \times \text{interaction-strength}$$

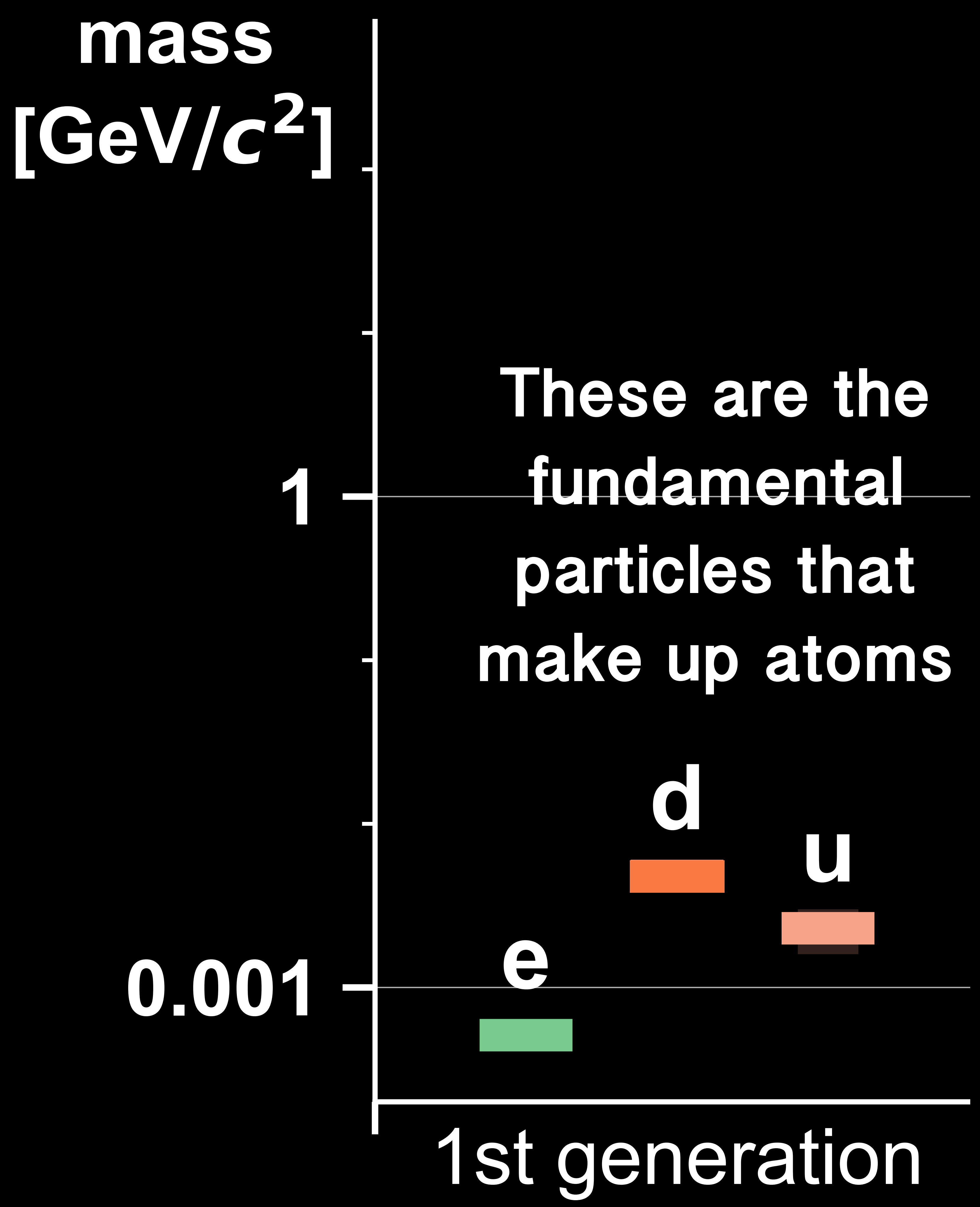
what could one be saying about it?

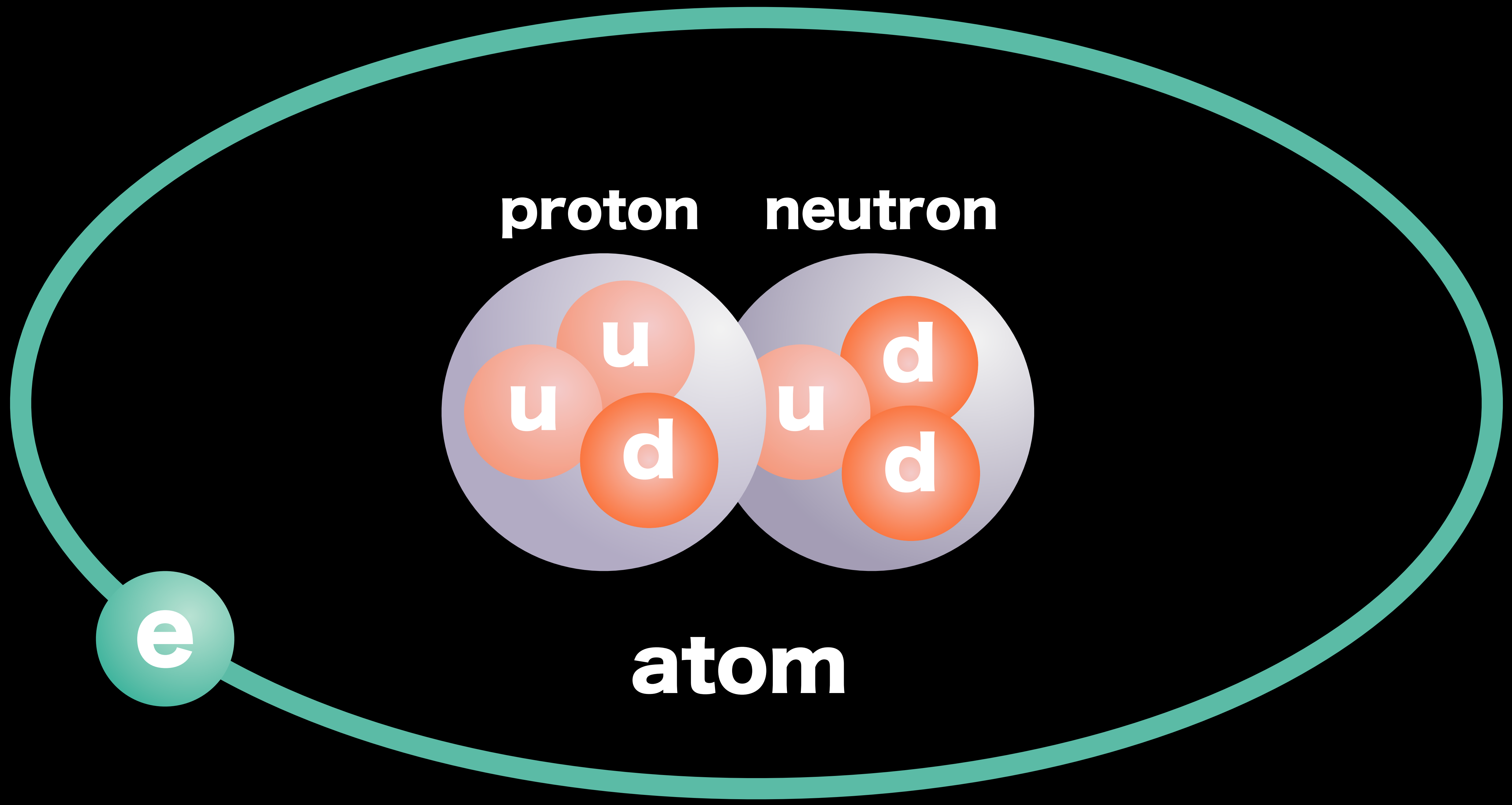
For a full set of particles (3rd generation) that are like the ones we're made of, the LHC has demonstrated that their mass is not an intrinsic property, but is generated by an interaction with a non-zero Higgs field.

A field is something that can in principle be controlled and modified.
Could the masses of elementary particles conceivably also be controlled and modified? Science fiction…

Is this any less important than the discovery of the Higgs boson itself?
My opinion: no

NB: most of mass of proton and neutron comes from other sources

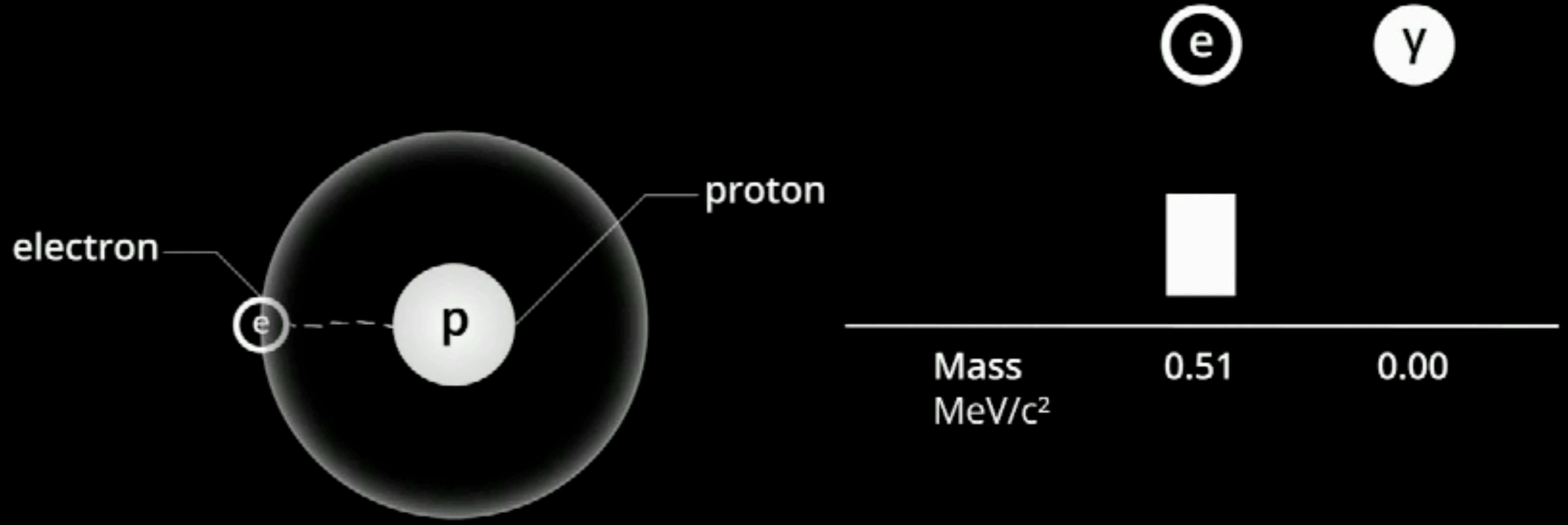

These are the fundamental particles that make up atoms

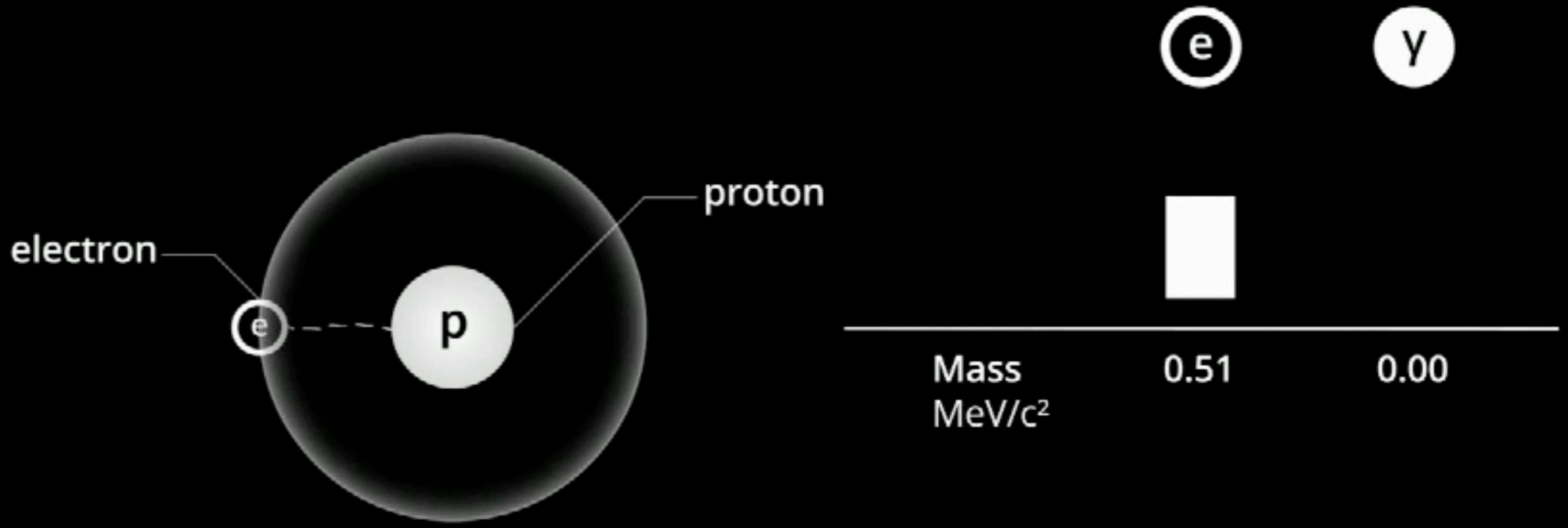


Bohr radius of atom

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

https://videos.cern.ch/record/2757407

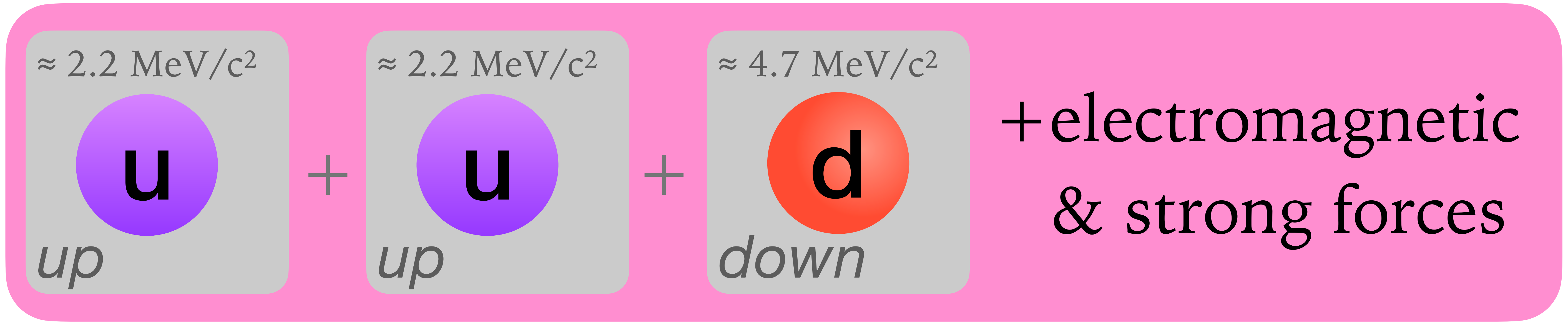




https://videos.cern.ch/record/2757407

2.2 MeV **2.2 MeV** 4.7 MeV

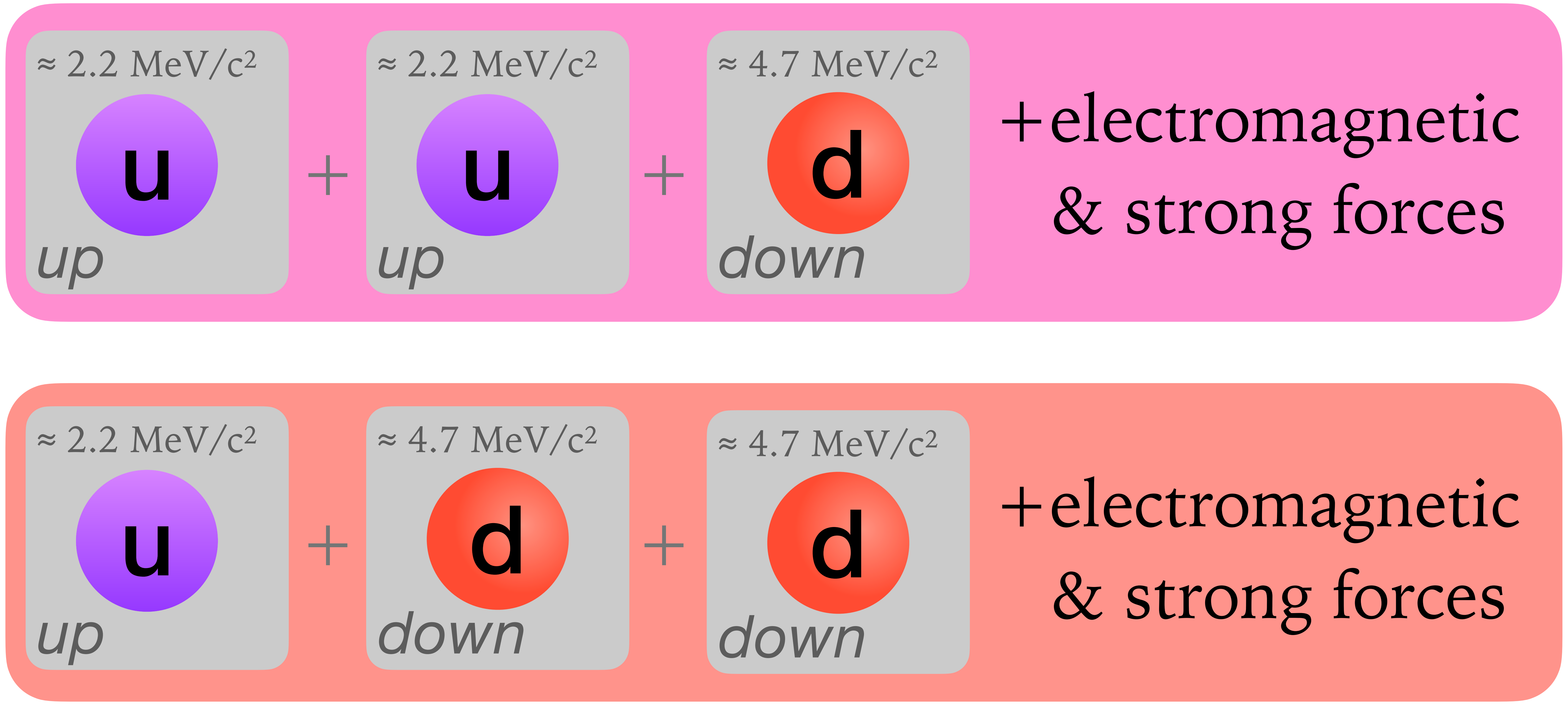
proton:



+electromagnetic & strong forces

$\simeq$ **938.3 MeV**

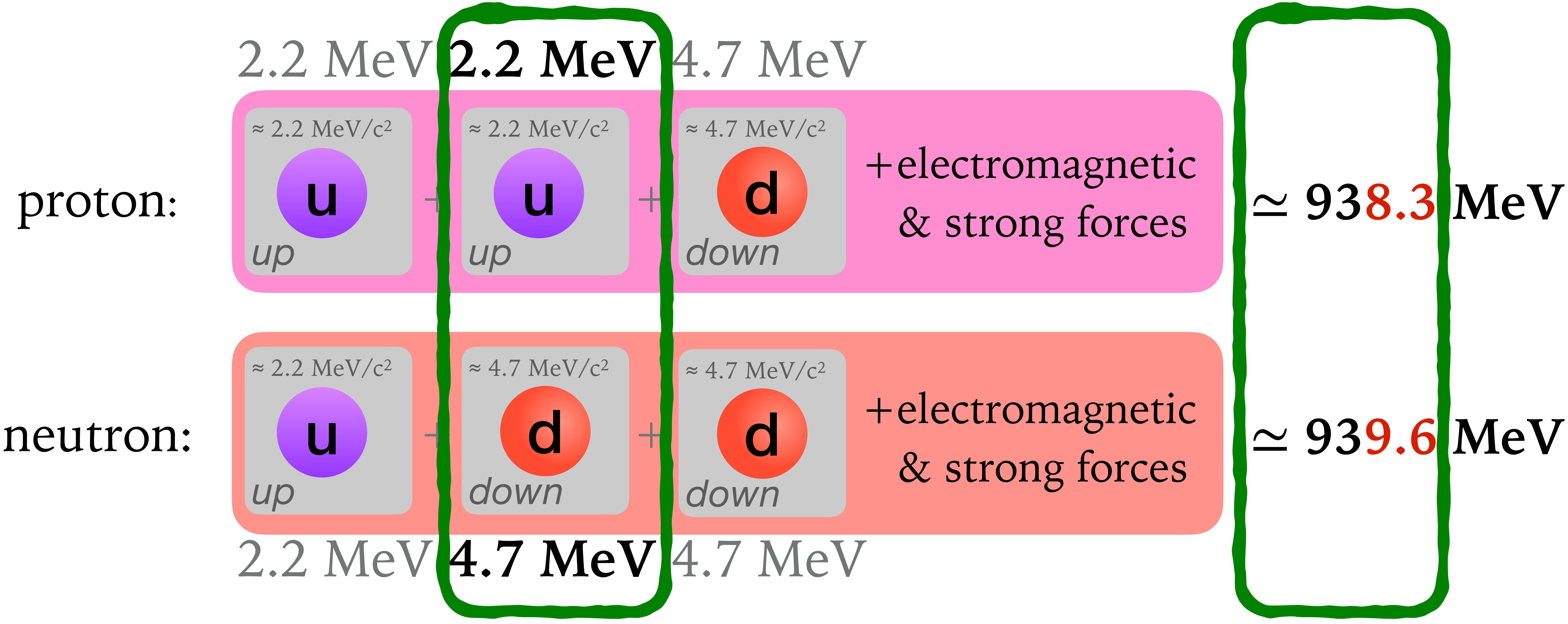
2.2 MeV **2.2 MeV** 4.7 MeV



proton: $\simeq$ **938.3 MeV**

neutron: $\simeq$ **939.6 MeV**

2.2 MeV **4.7 MeV** 4.7 MeV



2.2 MeV **2.2 MeV** 4.7 MeV

proton: ≈ 2.2 MeV/c^2 u *up* + ≈ 2.2 MeV/c^2 u *up* + ≈ 4.7 MeV/c^2 d *down* +electromagnetic & strong forces $\simeq$ **938.3 MeV**

neutron: ≈ 2.2 MeV/c^2 u *up* + ≈ 4.7 MeV/c^2 d *down* + ≈ 4.7 MeV/c^2 d *down* +electromagnetic & strong forces $\simeq$ **939.6 MeV**

2.2 MeV **4.7 MeV** 4.7 MeV

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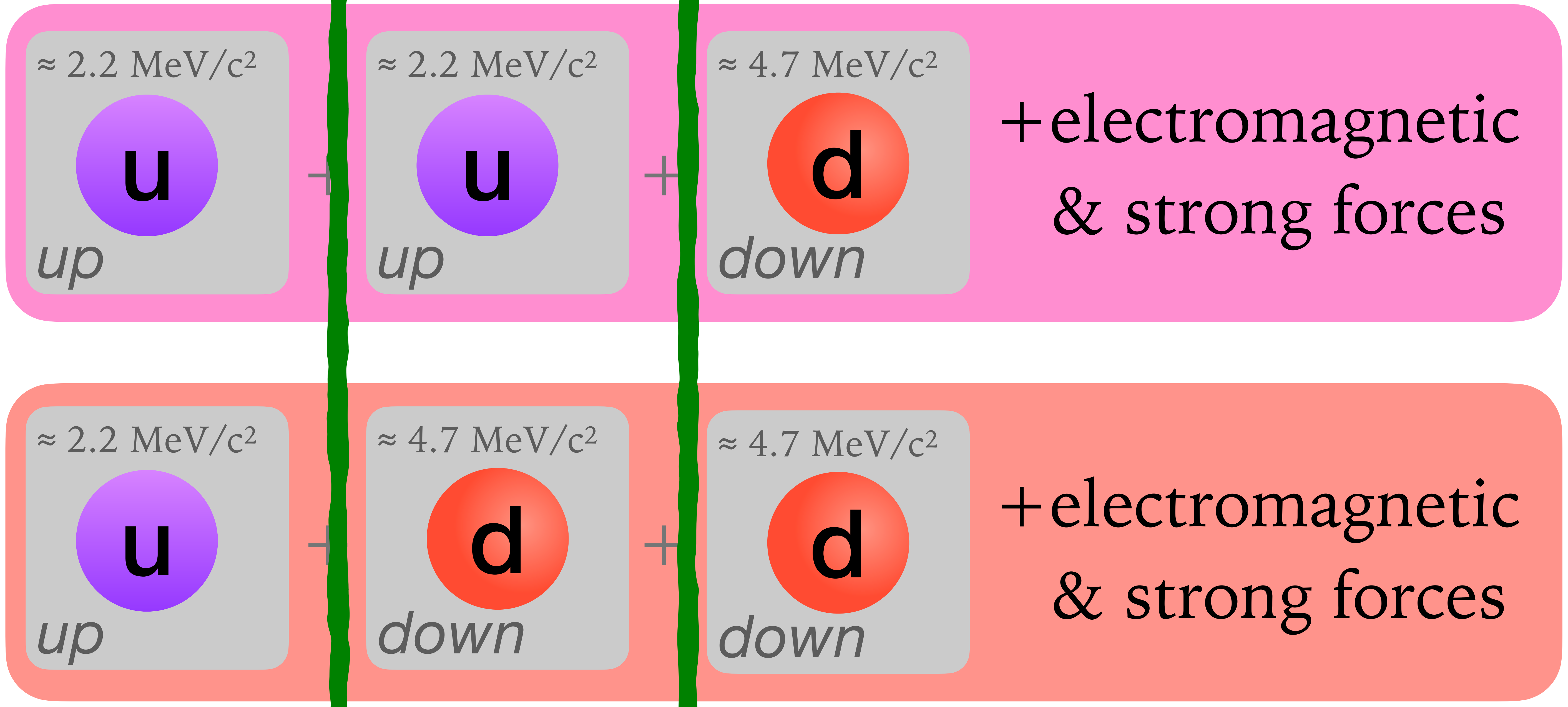


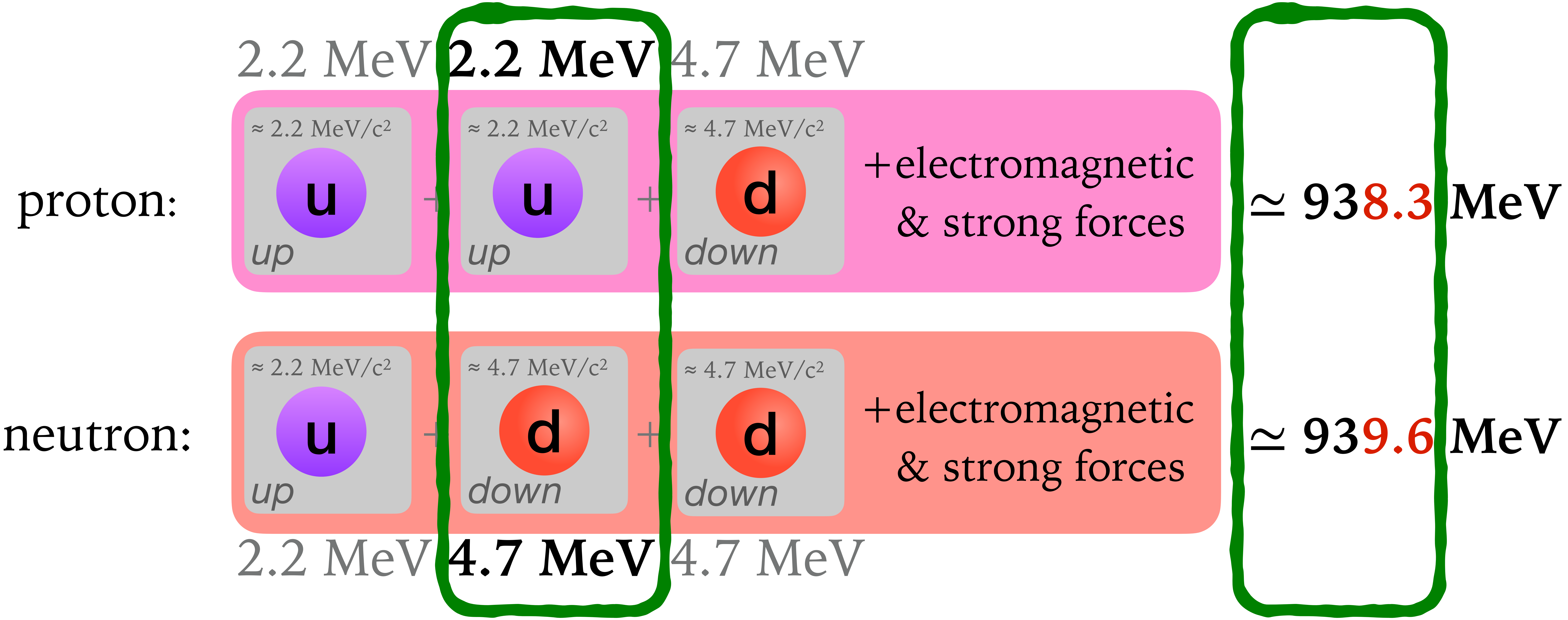
proton: u + u + d +electromagnetic & strong forces **≃ 938.3 MeV**

neutron: u + d + d +electromagnetic & strong forces **≃ 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



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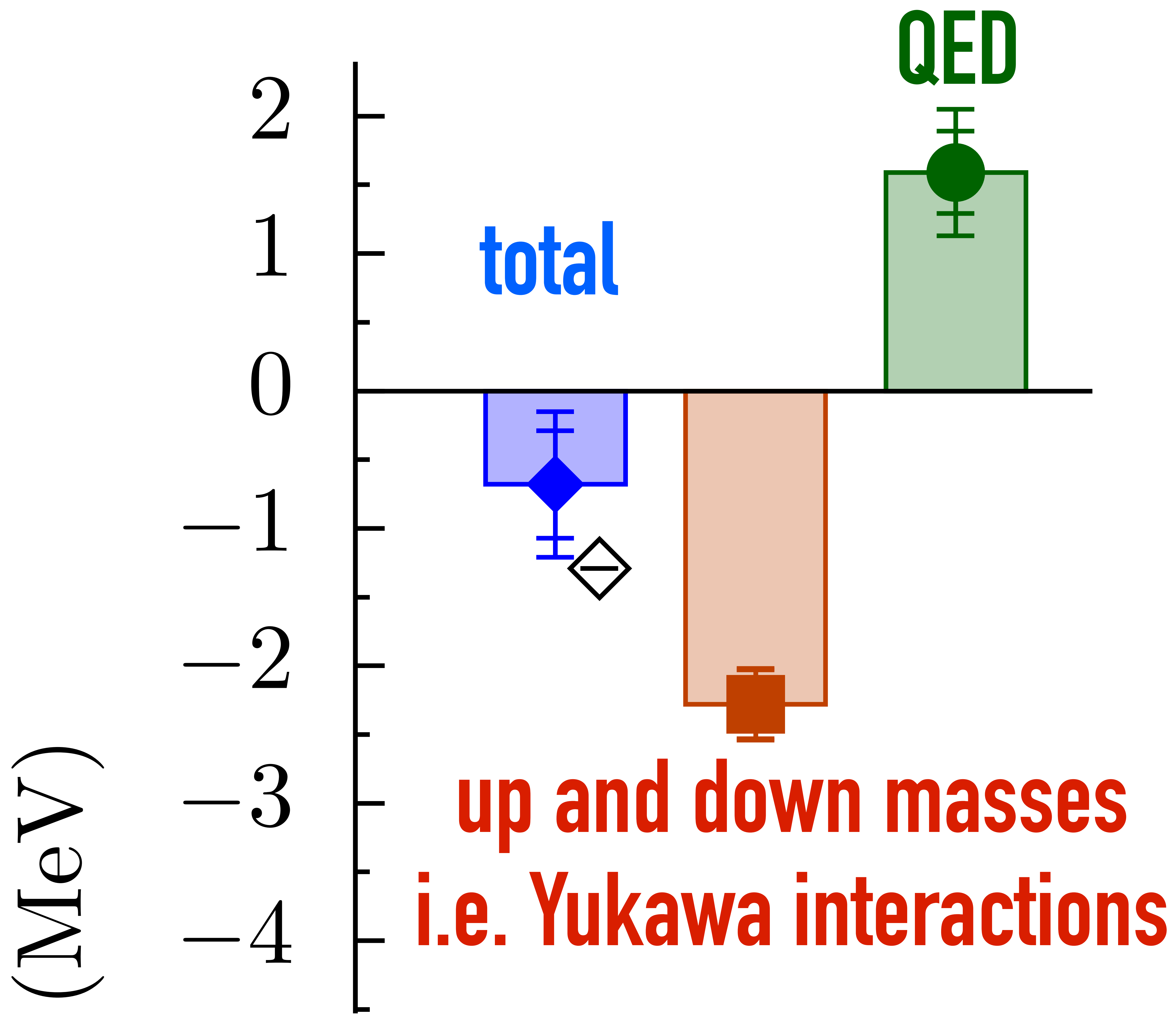
2.2 MeV **4.7 MeV** 4.7 MeV

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

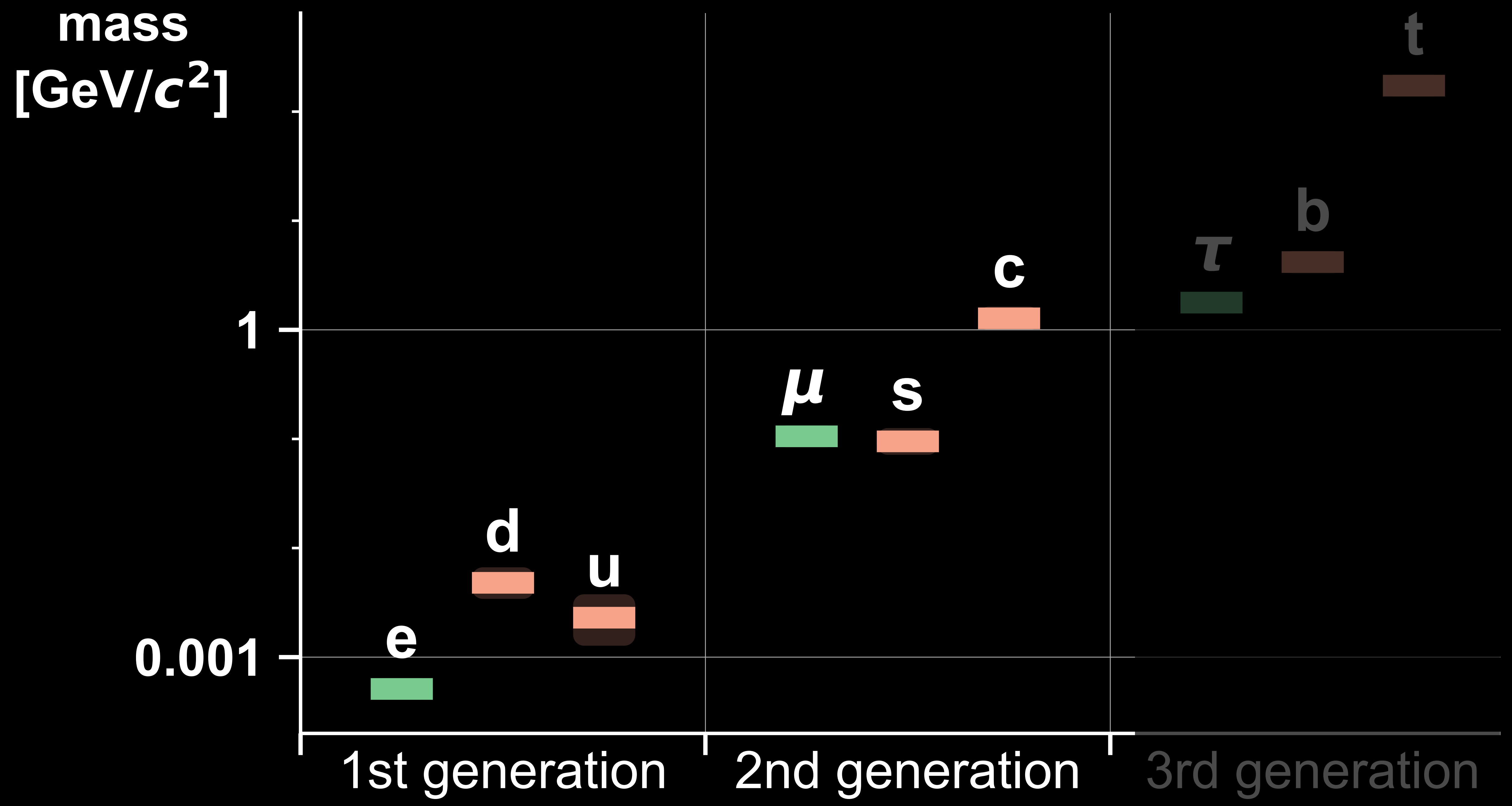
Supposedly because up quarks interact more weakly with the Higgs field than down quarks

proton – neutron mass difference



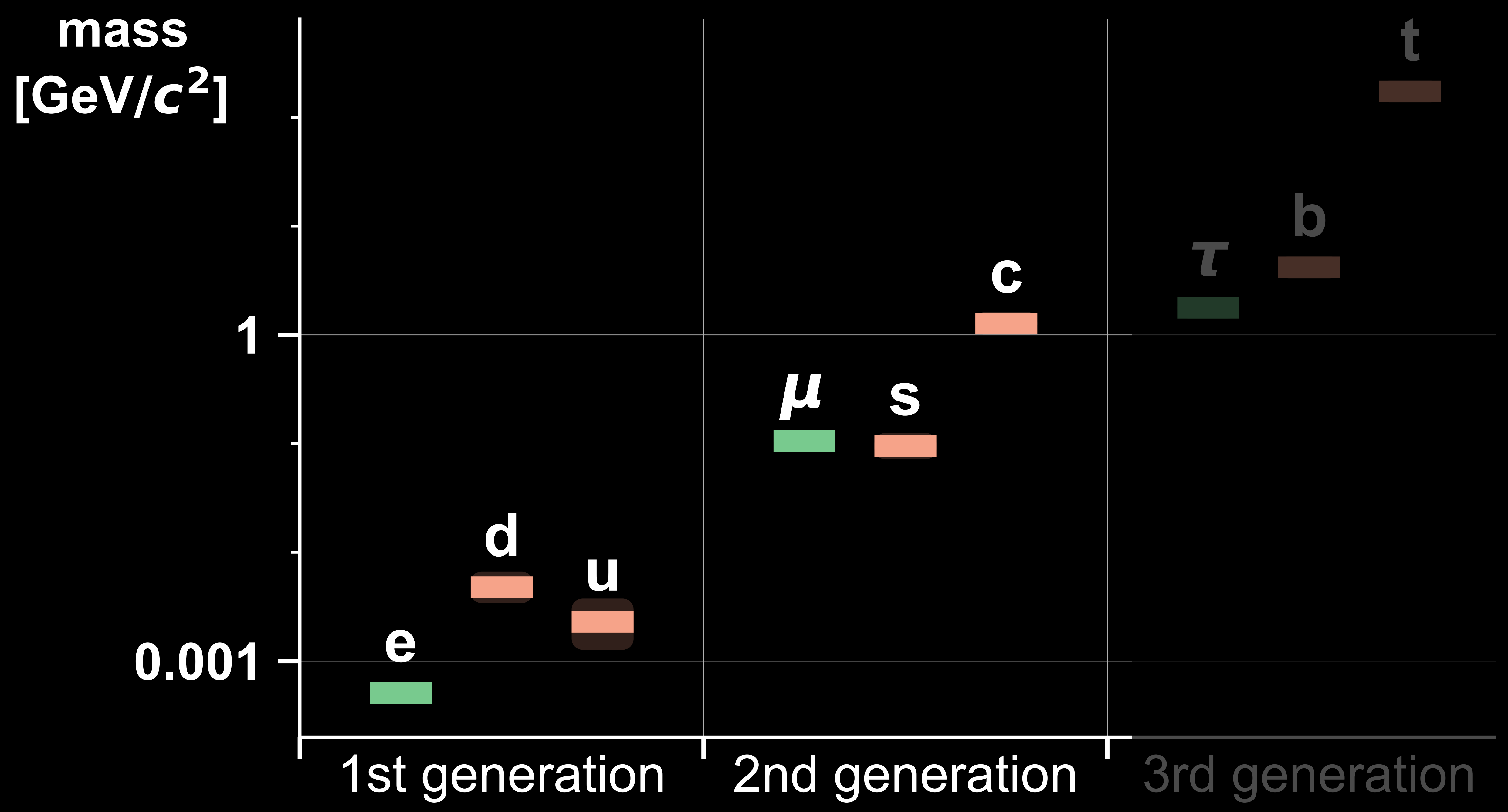
Lattice calculation
(BMW collab.)
1306.2287
1406.4088

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?



a BIG question of particle physics is whether all of these particles acquire their mass in the same way

In SM <u>hypothesis</u>: the lighter the particle, the less it interacts with the Higgs field
→ the more difficult it is establish if it actually gets mass from interactions with the Higgs field



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European Strategy
Update

2024 to 2026

EUROPEAN STRATEGY FOR PARTICLE PHYSICS

[…] cornerstone of Europe’s decision-making process for the long-term future of the field

[…] develop a visionary and concrete plan that greatly advances knowledge in fundamental physics through the realisation of the next flagship collider at CERN, and to prioritize alternative options to be pursued if the preferred plan turns out not to be feasible or competitive.

HiLumi
HL-LHC PROJECT

2029–2041

proton–proton
14,000 GeV energy
10× more collisions
than LHC

approved & upgrade under construction

FCC-ee

2045–2060(c.)

electron–positron
91–365 GeV energy
300,000× more
collisions than LEP

[or CEPC@China,
ILC, CLIC]

FCC-hh

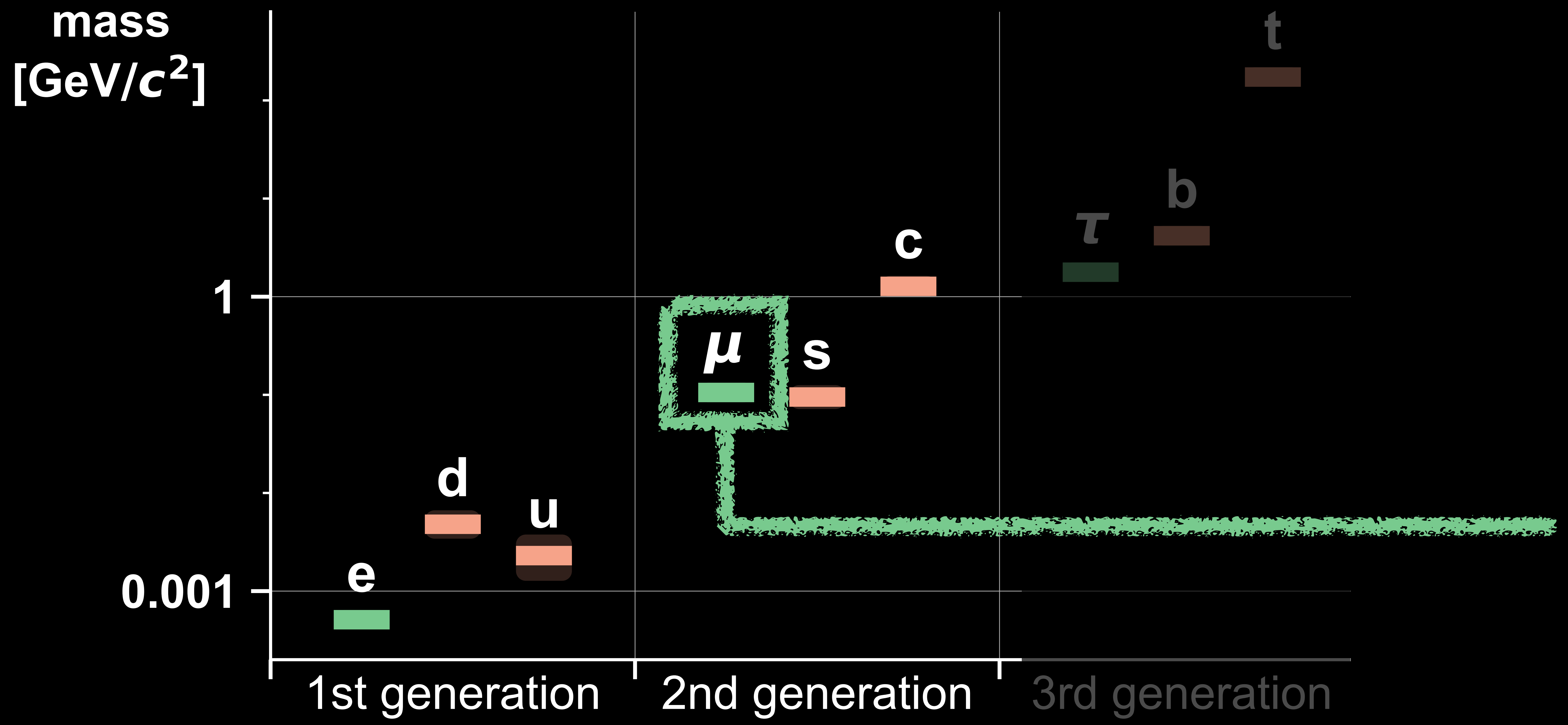
2070–2090(c.)

proton–proton
~100,000 TeV energy
10× more collisions
than HL-LHC

or SppS@China
or muon collider

In SM hypothesis: the lighter the particle, the less it interacts with the Higgs field

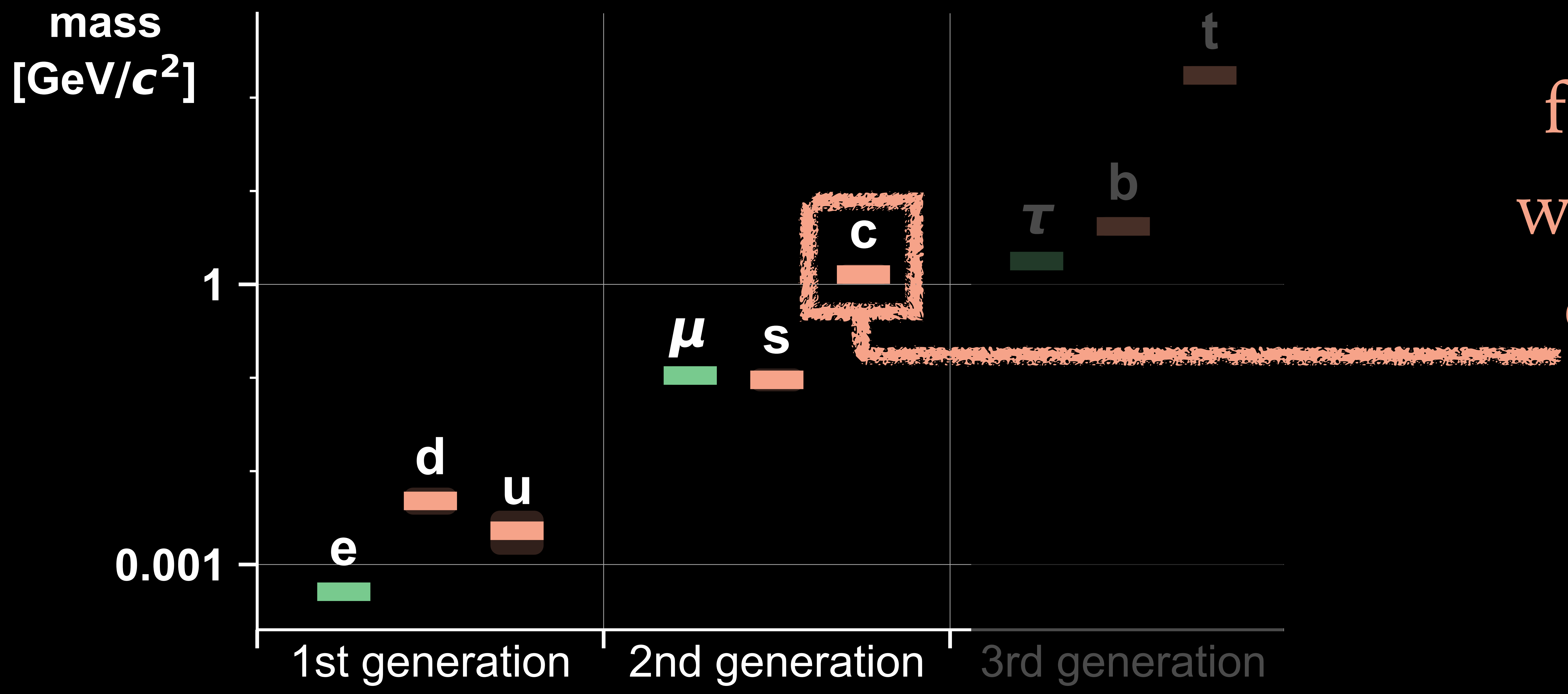
→ the more difficult it is establish if it actually gets mass from interactions with the Higgs field



a major LHC goal of the next years (Run-3 or HL-LHC) will be to establish, for the first time, whether a 2nd generation particle also acquires its mass in the same way

[ATLAS/CMS have first indications, but not yet 5σ]

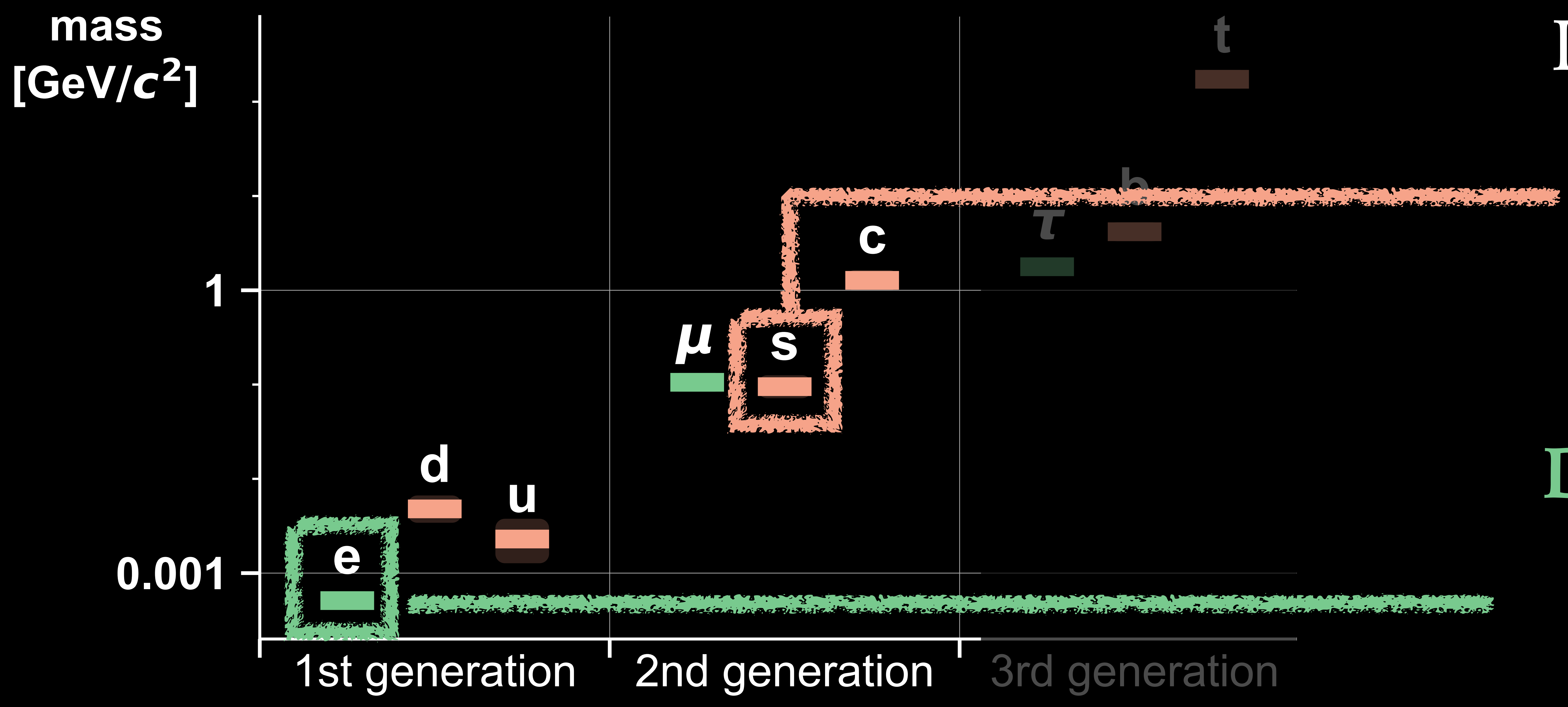
What of future colliders



quarks and yet-lighter particles
are much harder

future e^+e^- collider, if built, will clearly establish if charm-quarks get their mass from Higgs-field interactions

What of future colliders



It’s becoming clear that strange quark and electron “Yukawas” are just barely at the edge of reach of FCC-ee

Discovering origin of electron mass would be a huge accomplishment

electron Yukawa: see d’Enterria, Poldaru, Wojcik, 2107.02686

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

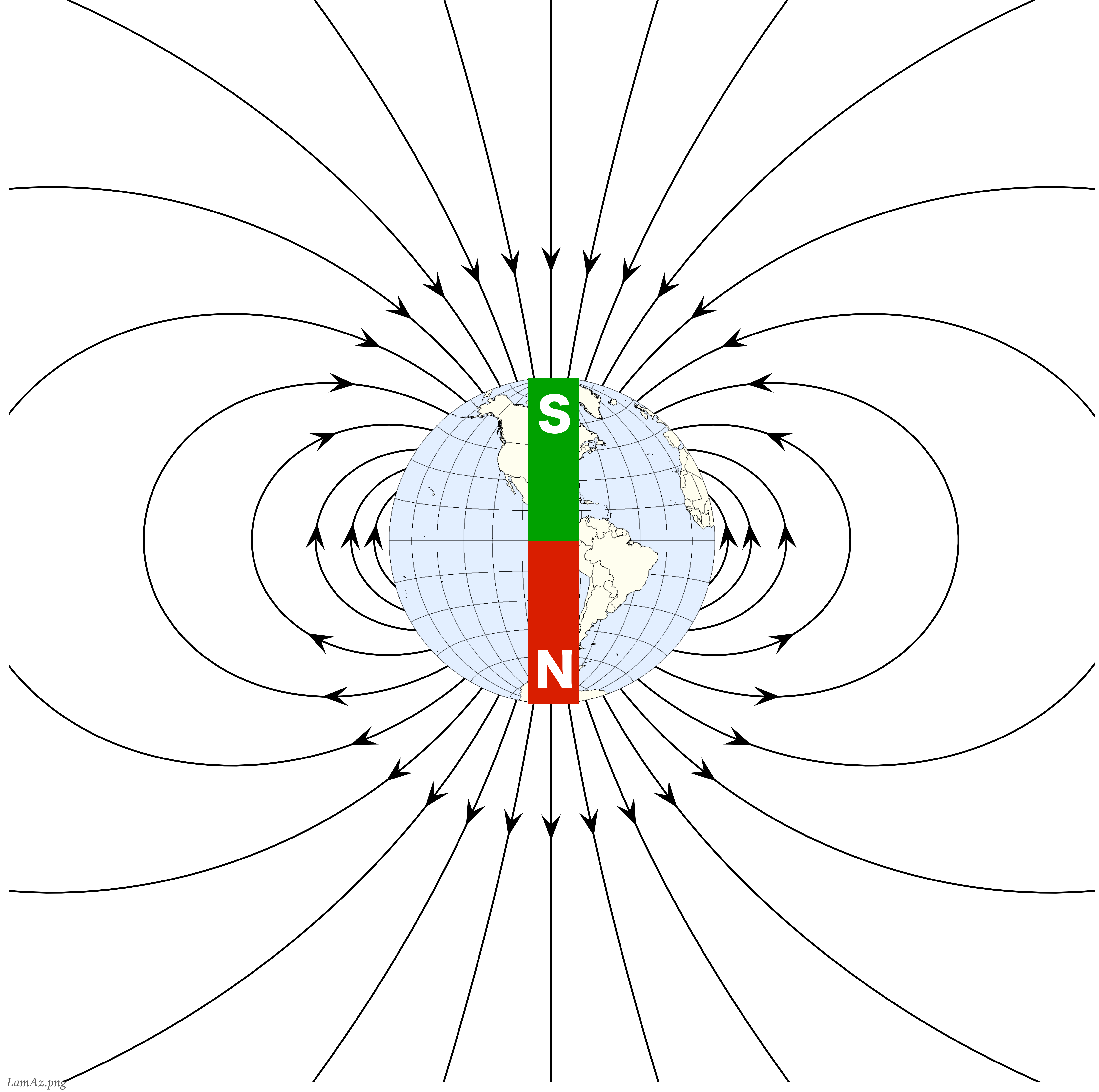
major progress on a broad array of particle physics topics

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

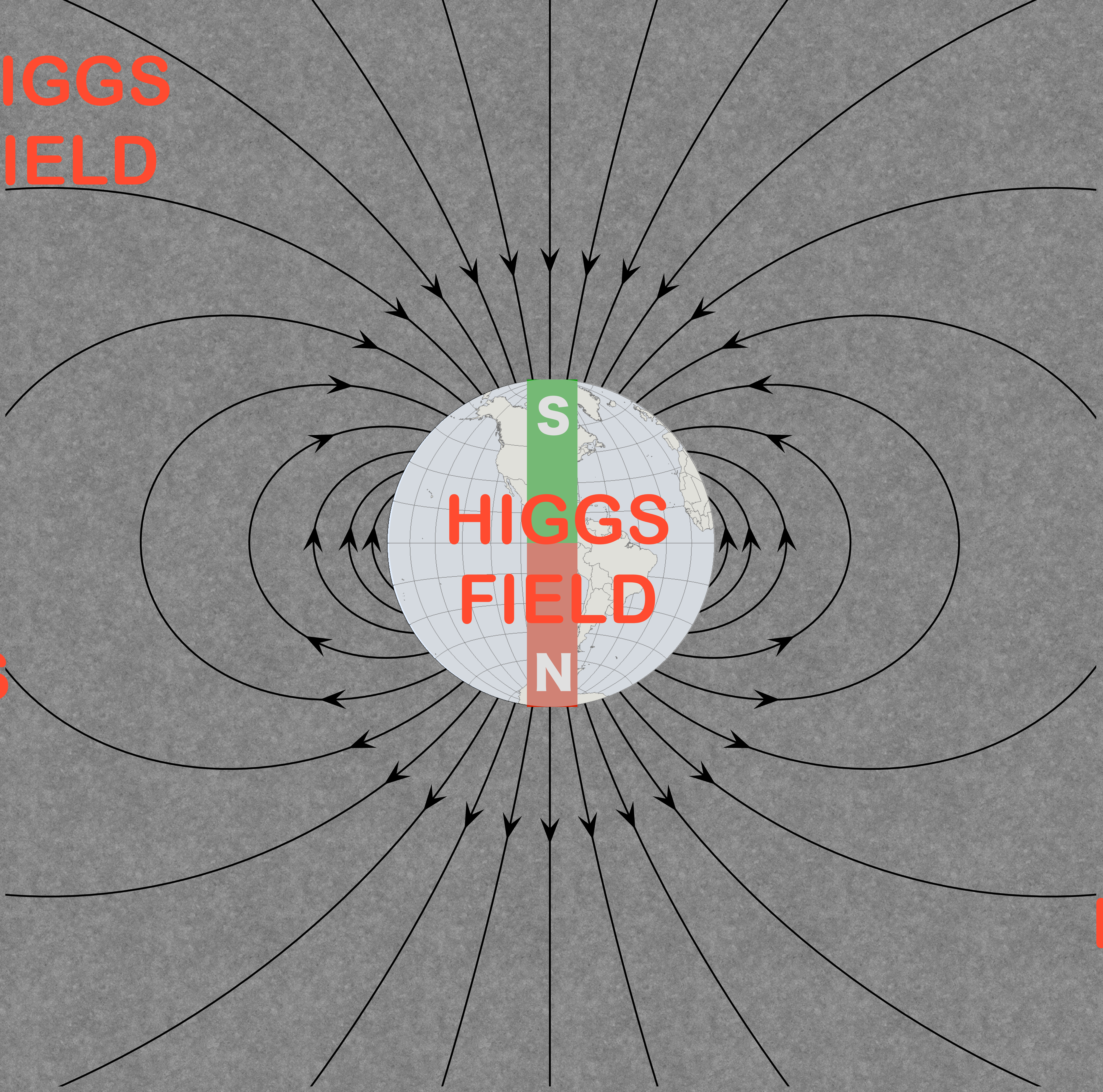
cost-effective construction & operation,
low carbon footprint, novel technologies

fundamental particles only get mass if the Higgs field is non-zero

Why is the Higgs field non-zero?



https://commons.wikimedia.org/wiki/File:VFPt_Dipole_field.svg
https://en.wikipedia.org/wiki/Western_Hemisphere#/media/File:Western_Hemisphere_LamAz.png



HIGGS
FIELD

HIGGS
FIELD

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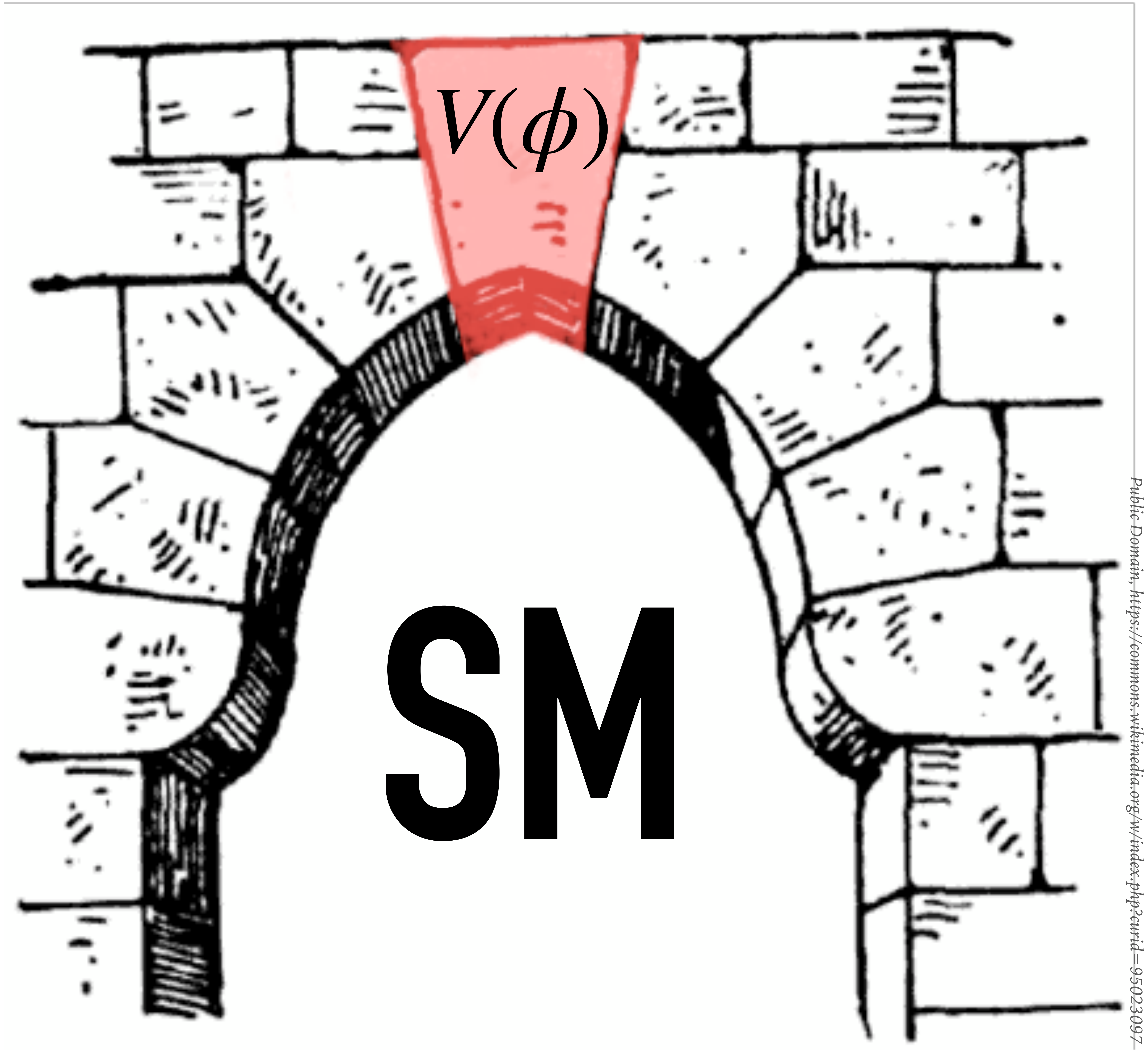
https://commons.wikimedia.org/wiki/File:VFPt_Dipole_field.svg

https://en.wikipedia.org/wiki/Western_Hemisphere#/media/File:Western_Hemisphere_LamAz.png



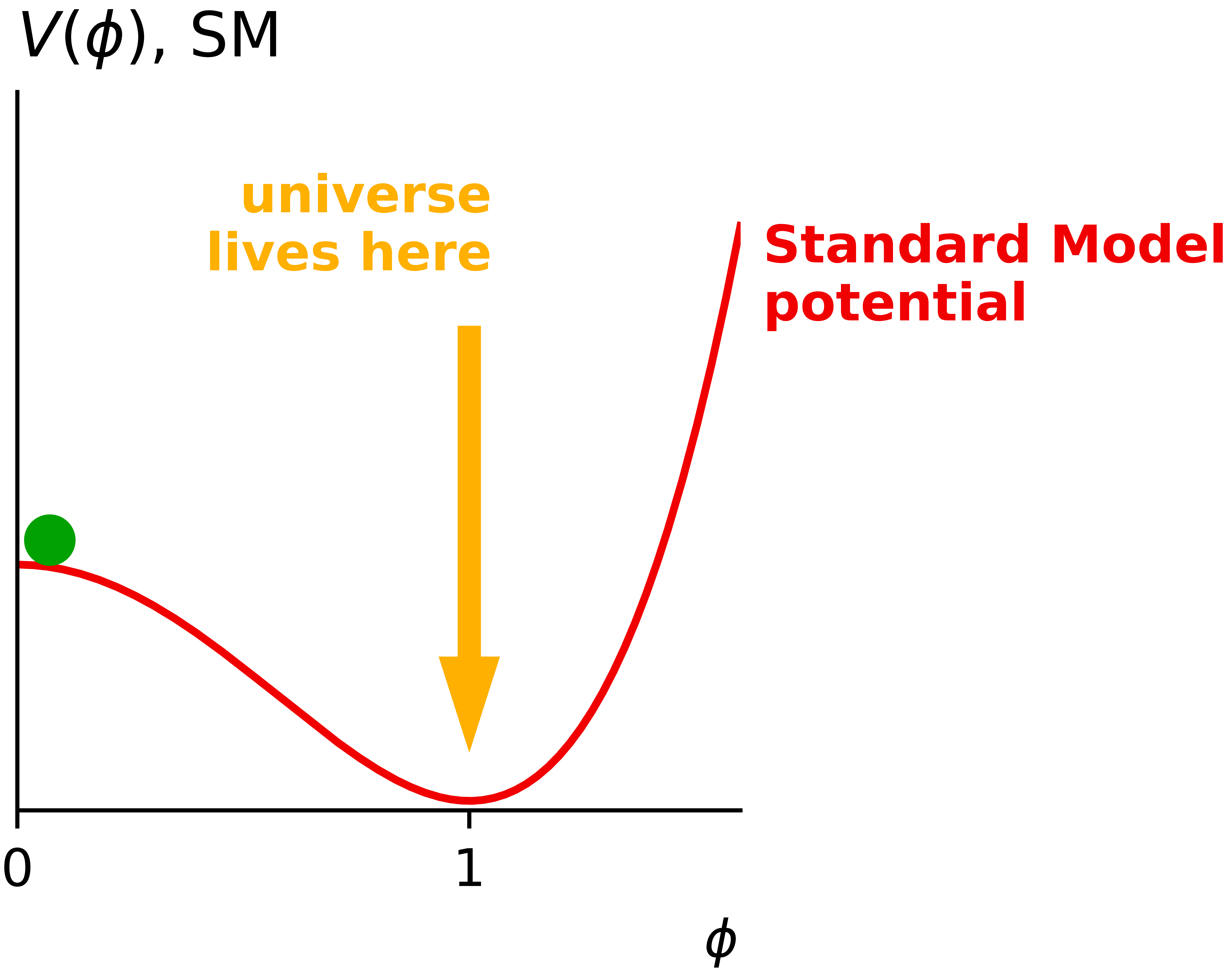
Public Domain, https://commons.wikimedia.org/w/index.php?curid=9502309

unique among all the fields we know, the Higgs field is the only one that is non-zero "classically"

Why?
Higgs potential?

Keystone of SM

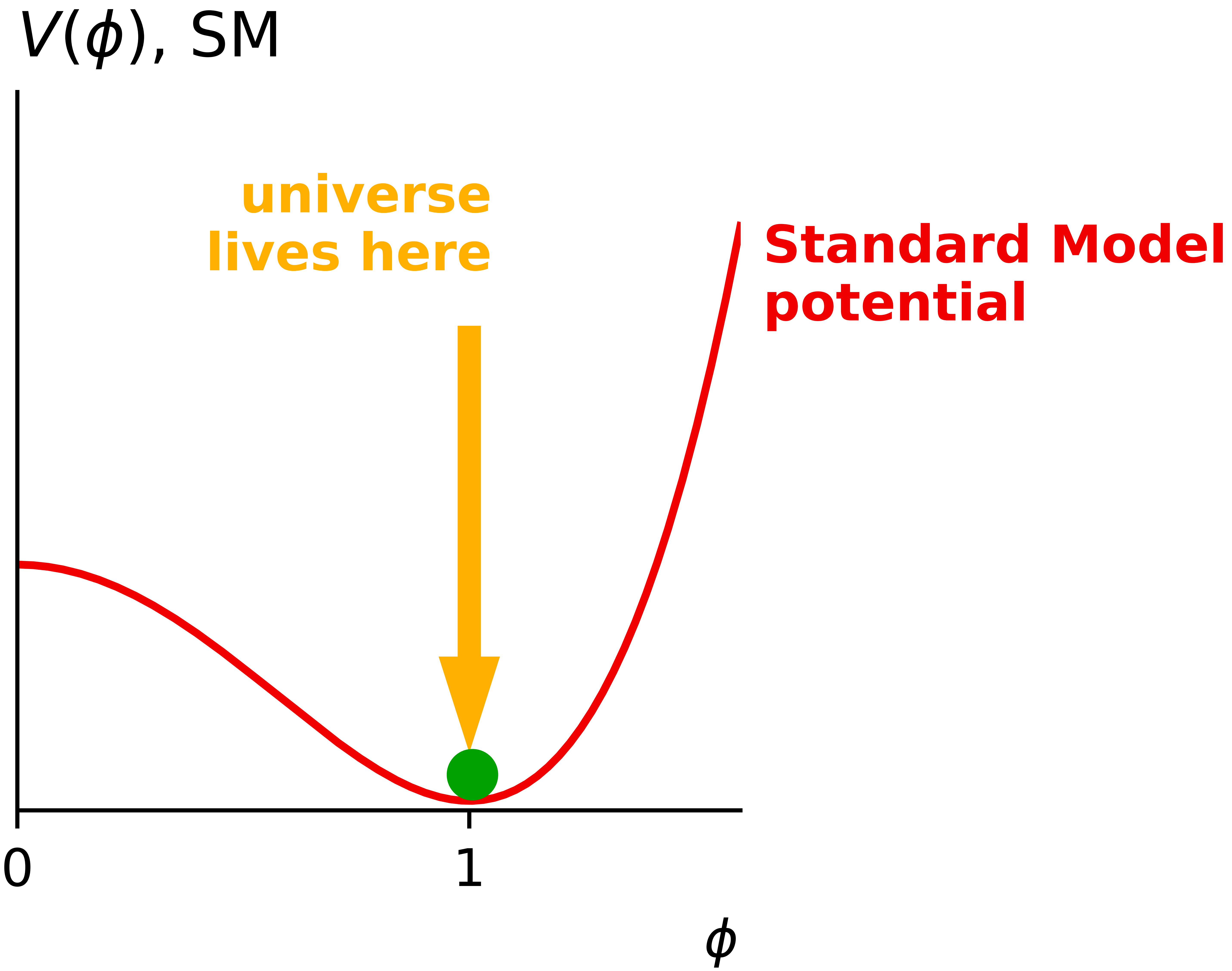
Higgs potential



The Higgs field is non-zero because that ensures the lowest potential energy

The SM proposes a very specific form for the potential as a function of the Higgs field

Higgs potential



The Higgs field is non-zero because that ensures the lowest potential energy

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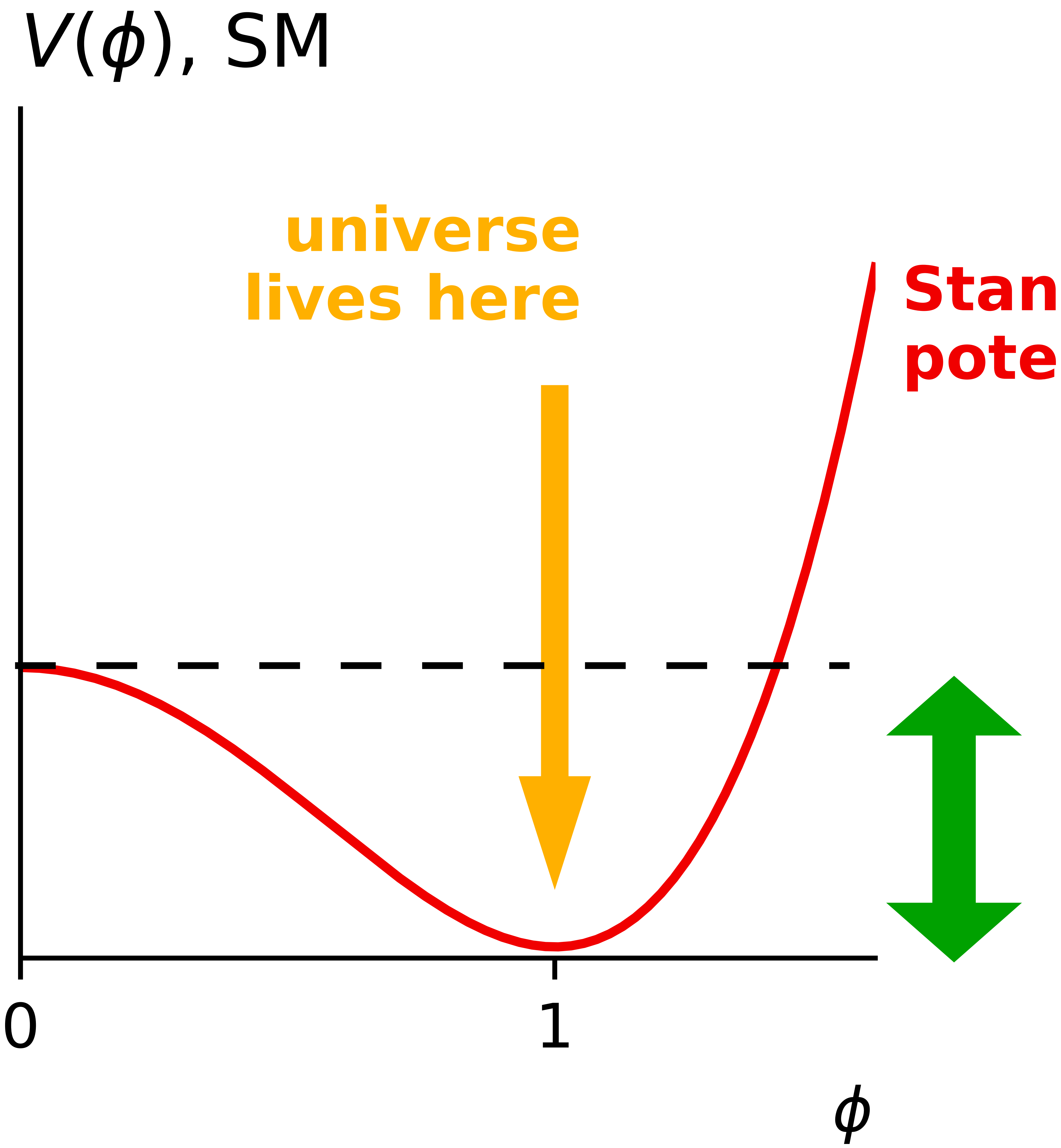
Higgs potential – remember: it's an energy density



Corresponds to an energy density of $1.5 \times 10^{10}\,\mathrm{GeV/fm^3}$

$E = mc^2 \rightarrow$ Mass density of $2.6 \times 10^{28}\,\mathrm{kg/m^3}$

i.e. **>40 billion times nuclear 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
https://commons.wikimedia.org/wiki/File:Estadio_da_Luz_no_ar_!.JPG CC BY-SA 3.0 Biling

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
https://commons.wikimedia.org/wiki/File:Estadio_da_Luz_no_ar_!.JPG CC BY-SA 3.0 Biling

Earth at neutron star density

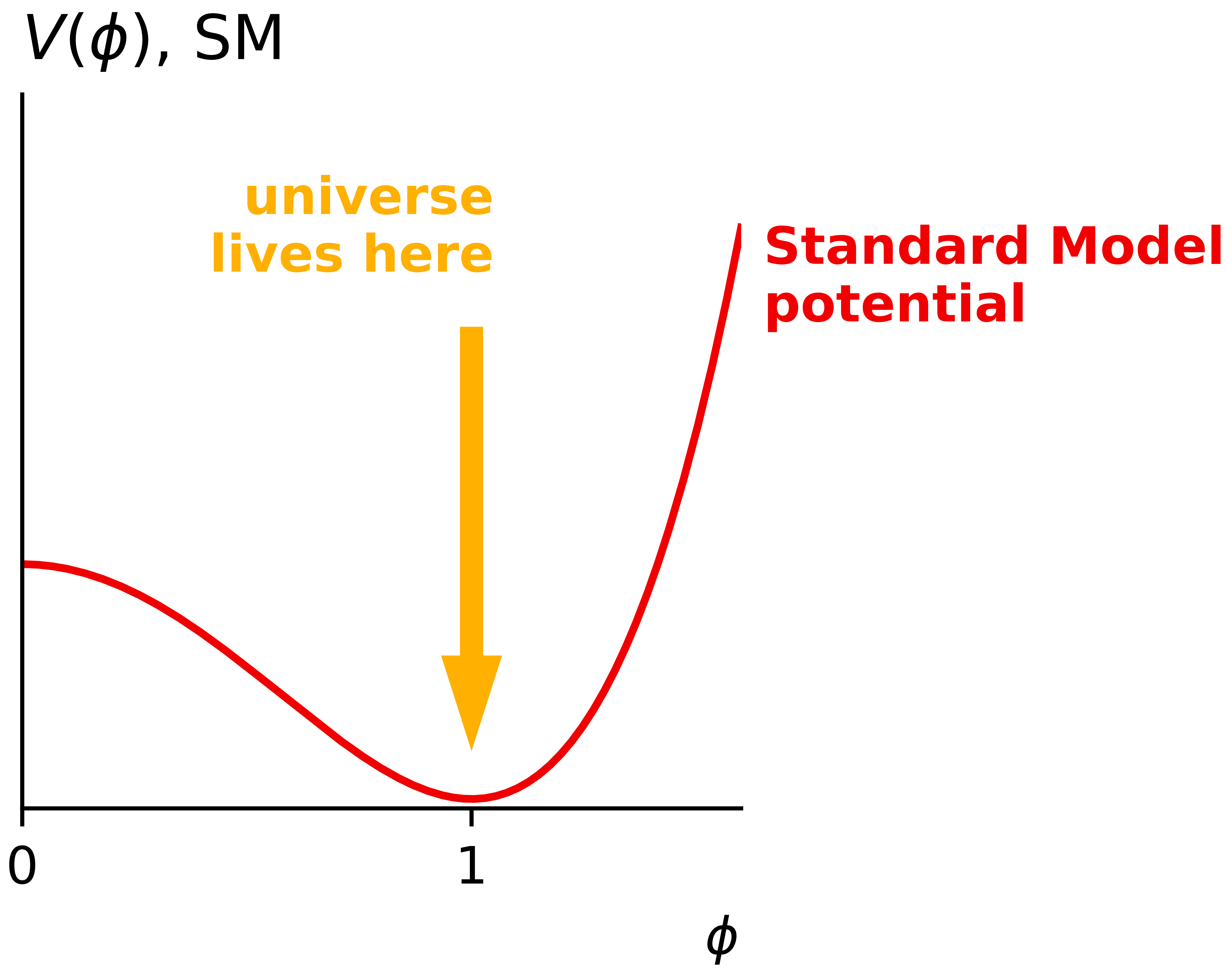
Earth at Higgs potential density


g
g
H
λ3
H
H
luon
gluo
Φ
y
x
Higgs field in space


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


g
g
H
λ3
H
H
luon
gluo
Φ
y
x
Higgs field in space

Higgs potential

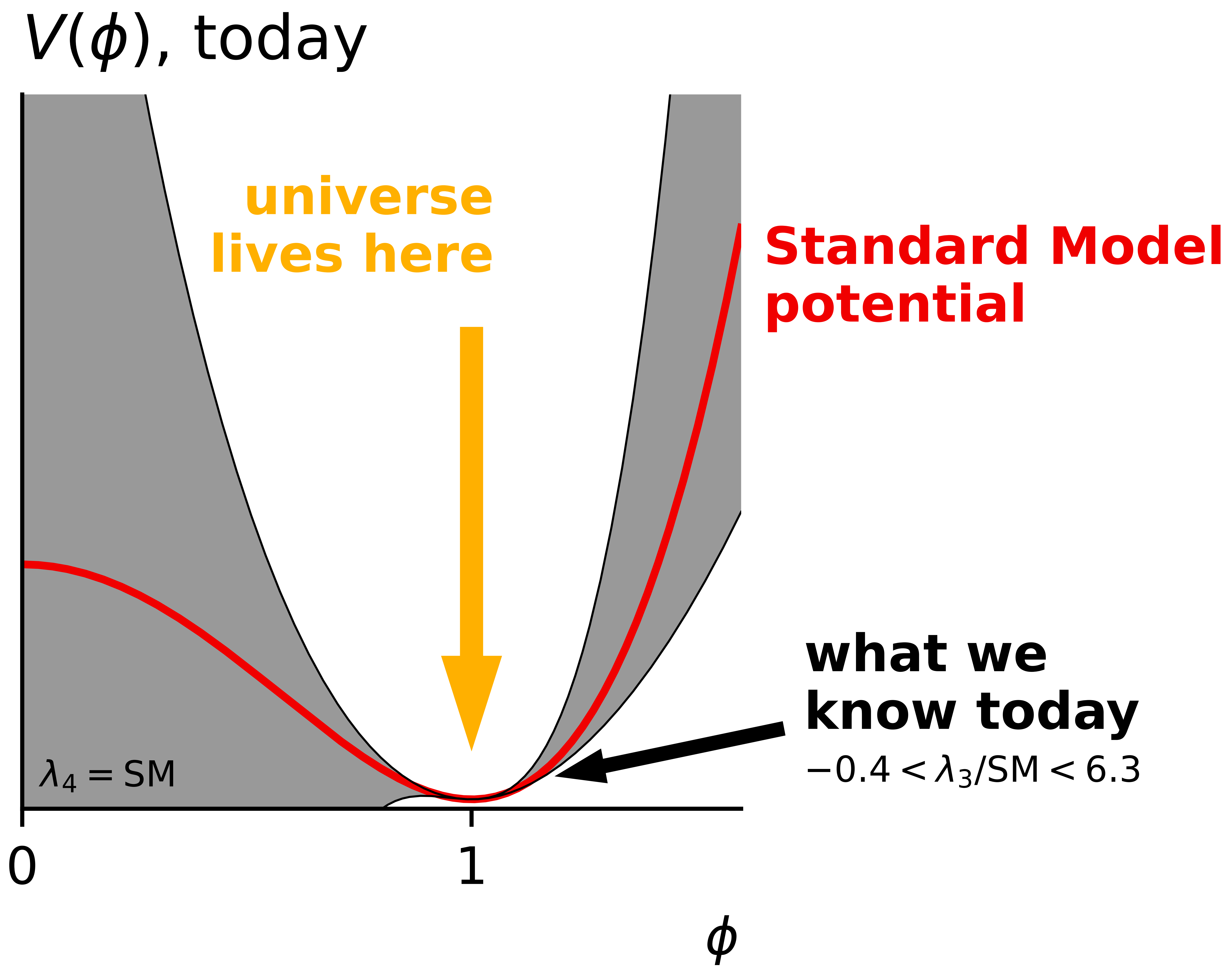


Studying H→HH probes specific mathematical property of the potential's shape:

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

[reconstruction in plot assumes higher derivatives as in SM]

Higgs potential



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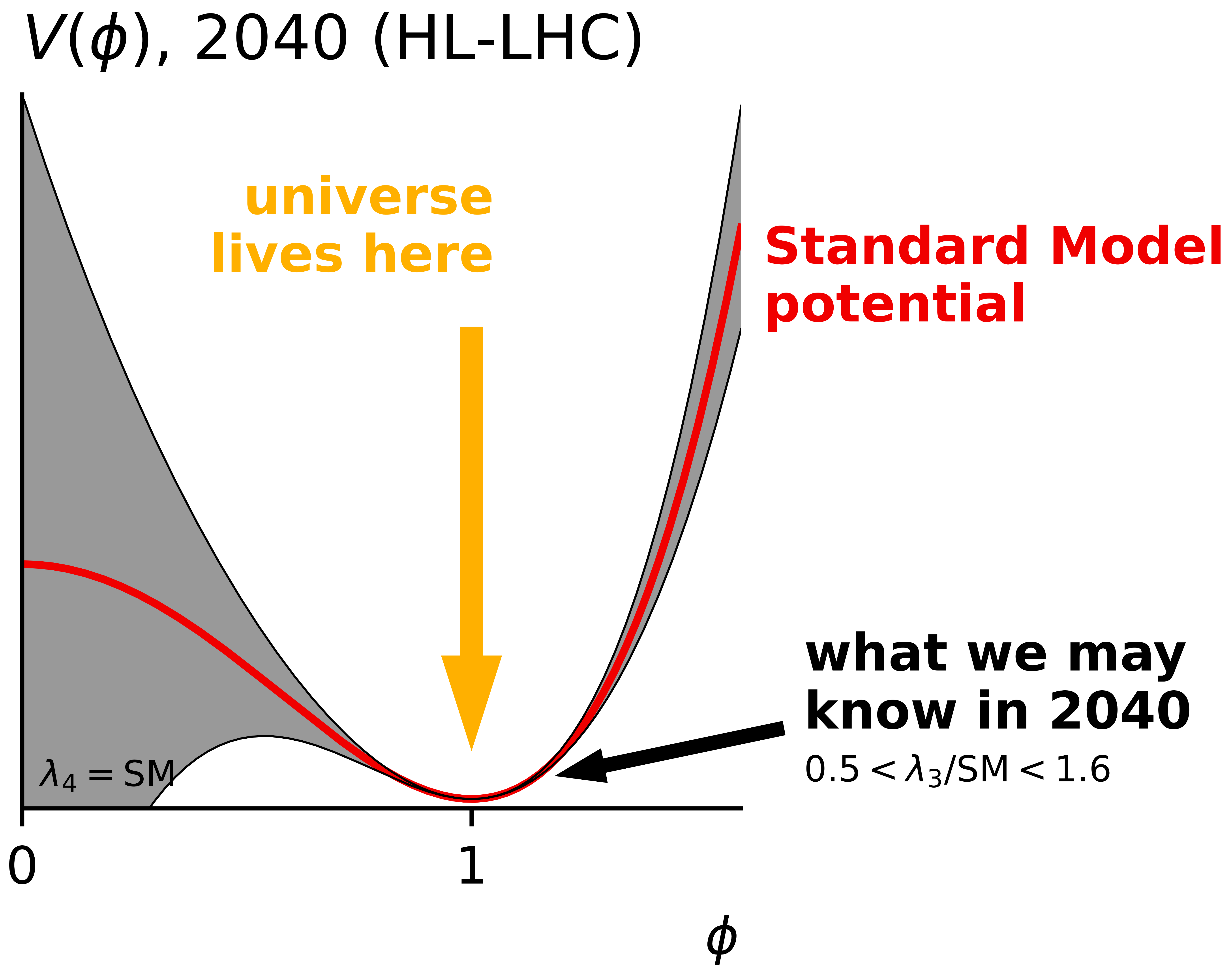

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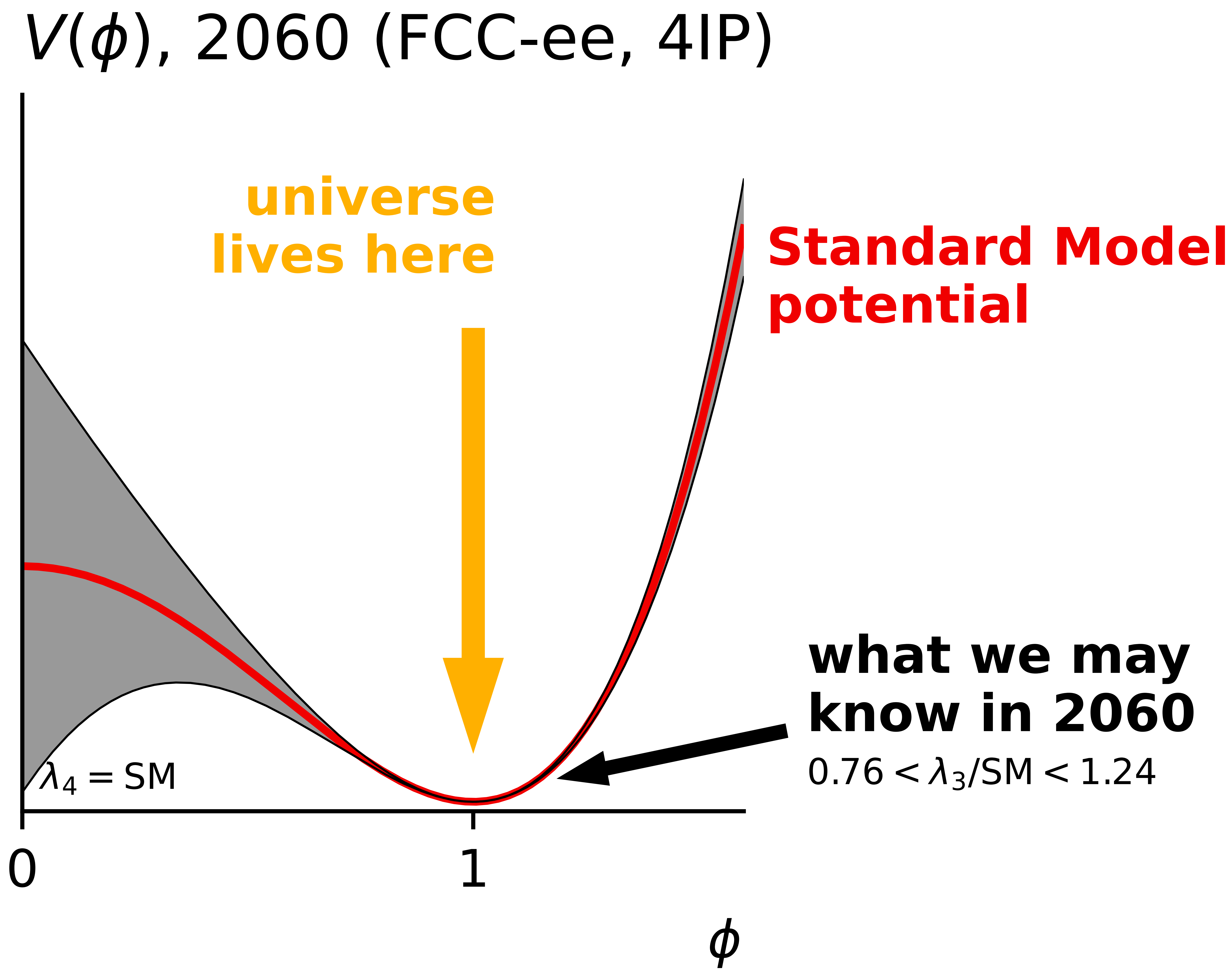
Higgs potential

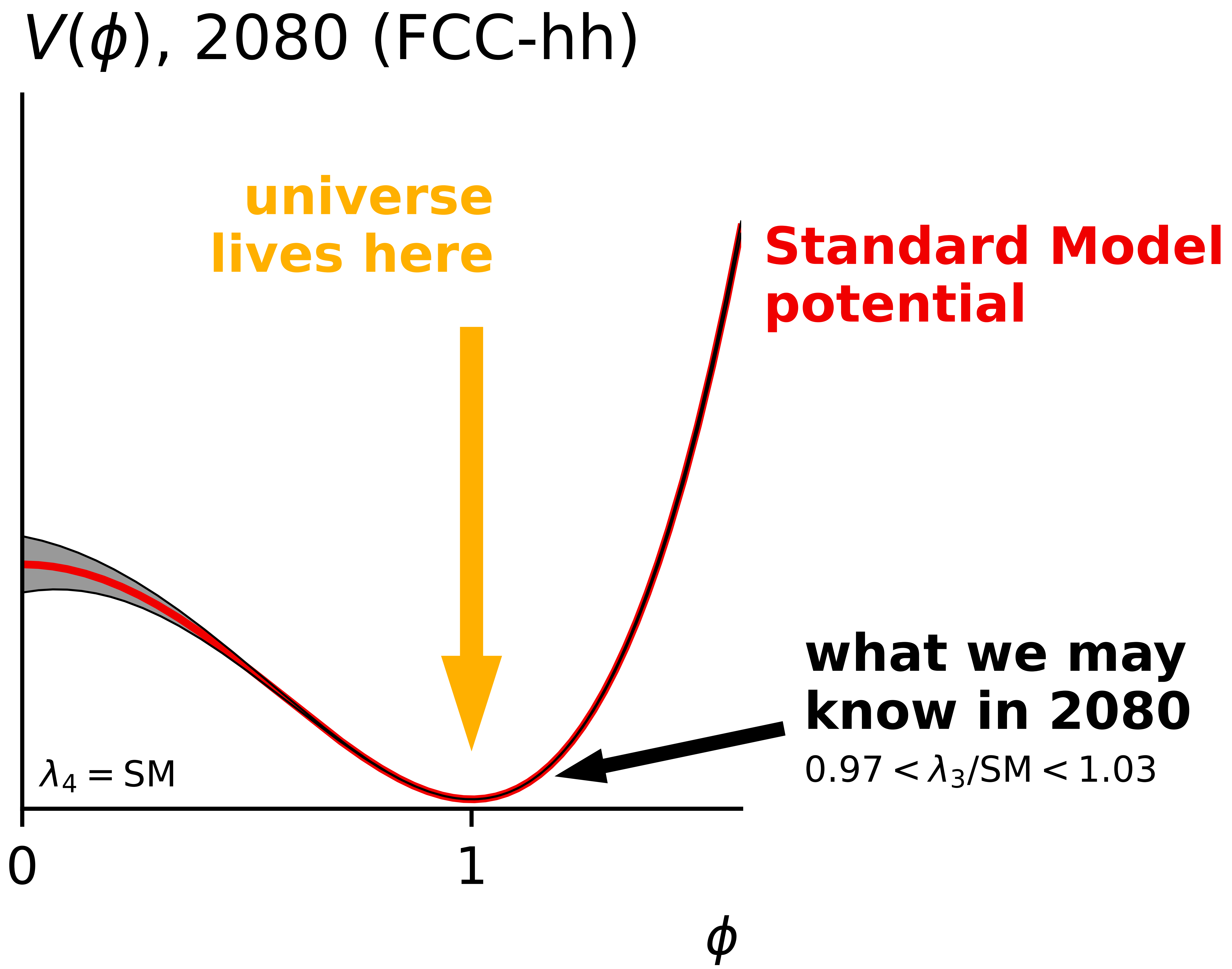


Studying H→HH probes specific mathematical property of the potential's shape:

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

[reconstruction in plot assumes higher derivatives as in SM]

Higgs potential



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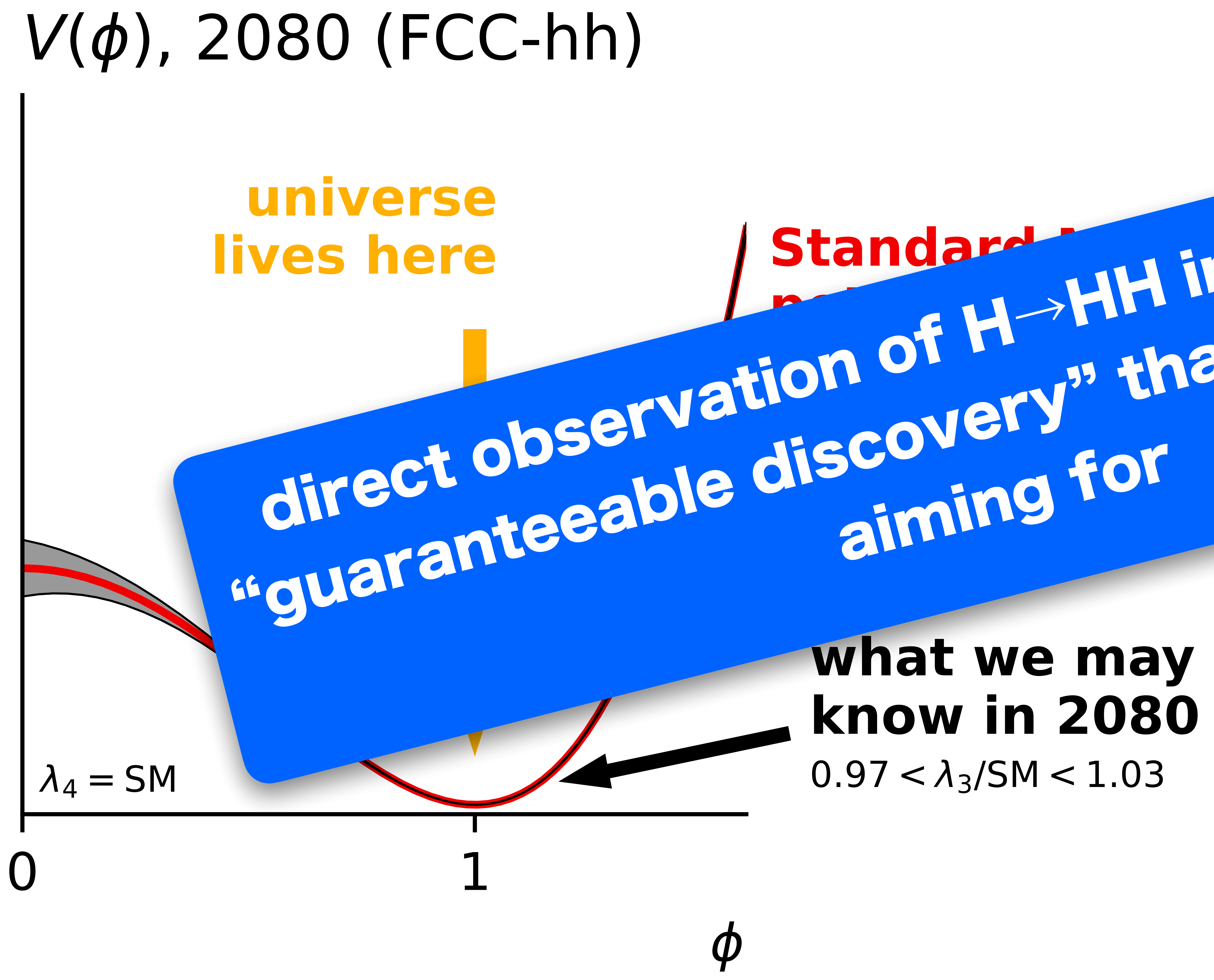

direct observation of H→HH interaction is a “guaranteeable discovery” that HEP should be aiming for

Studying H HH probes
spe tical property
l’s shape:
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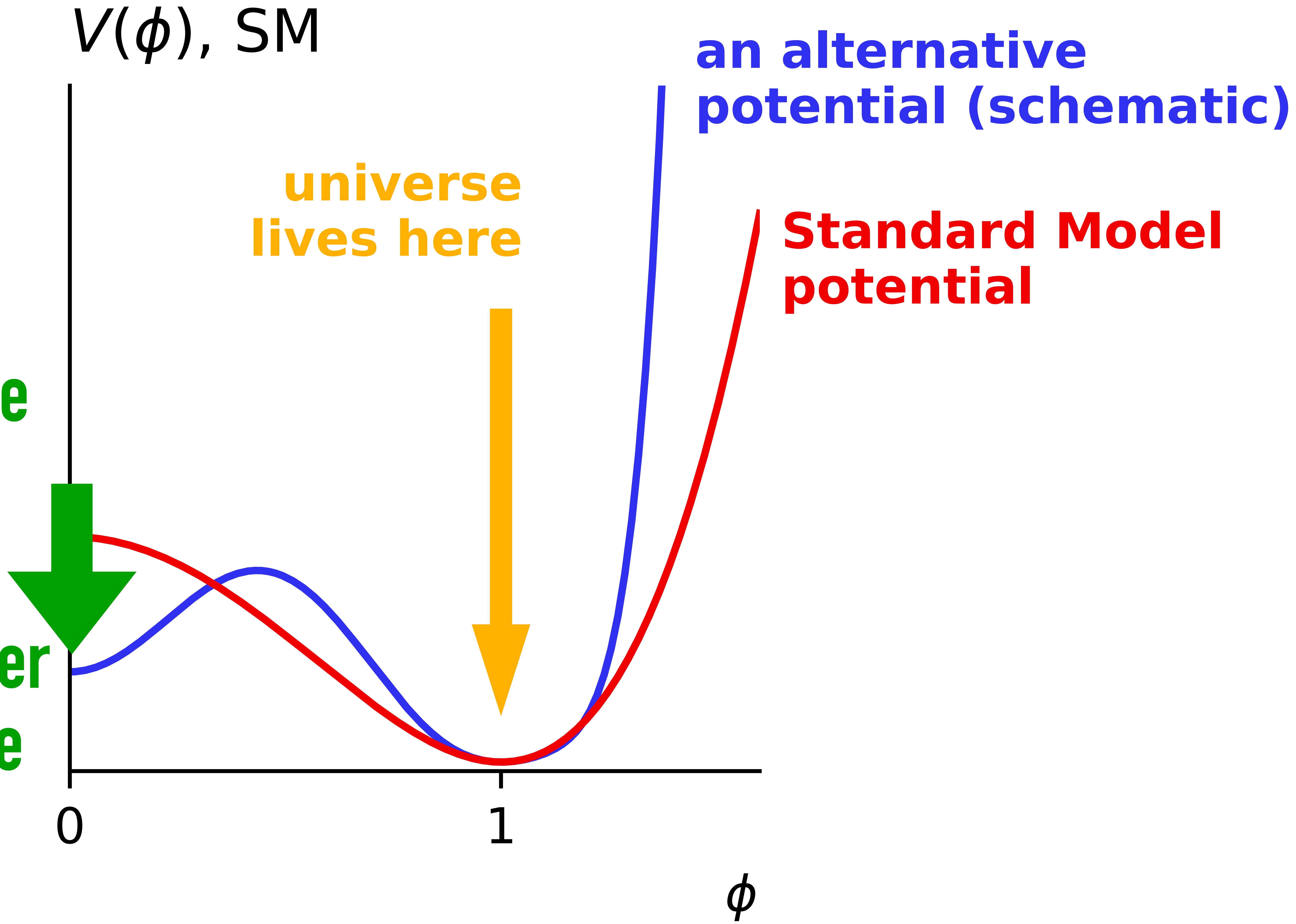
[reconstruction in plot assumes higher derivatives as in SM]

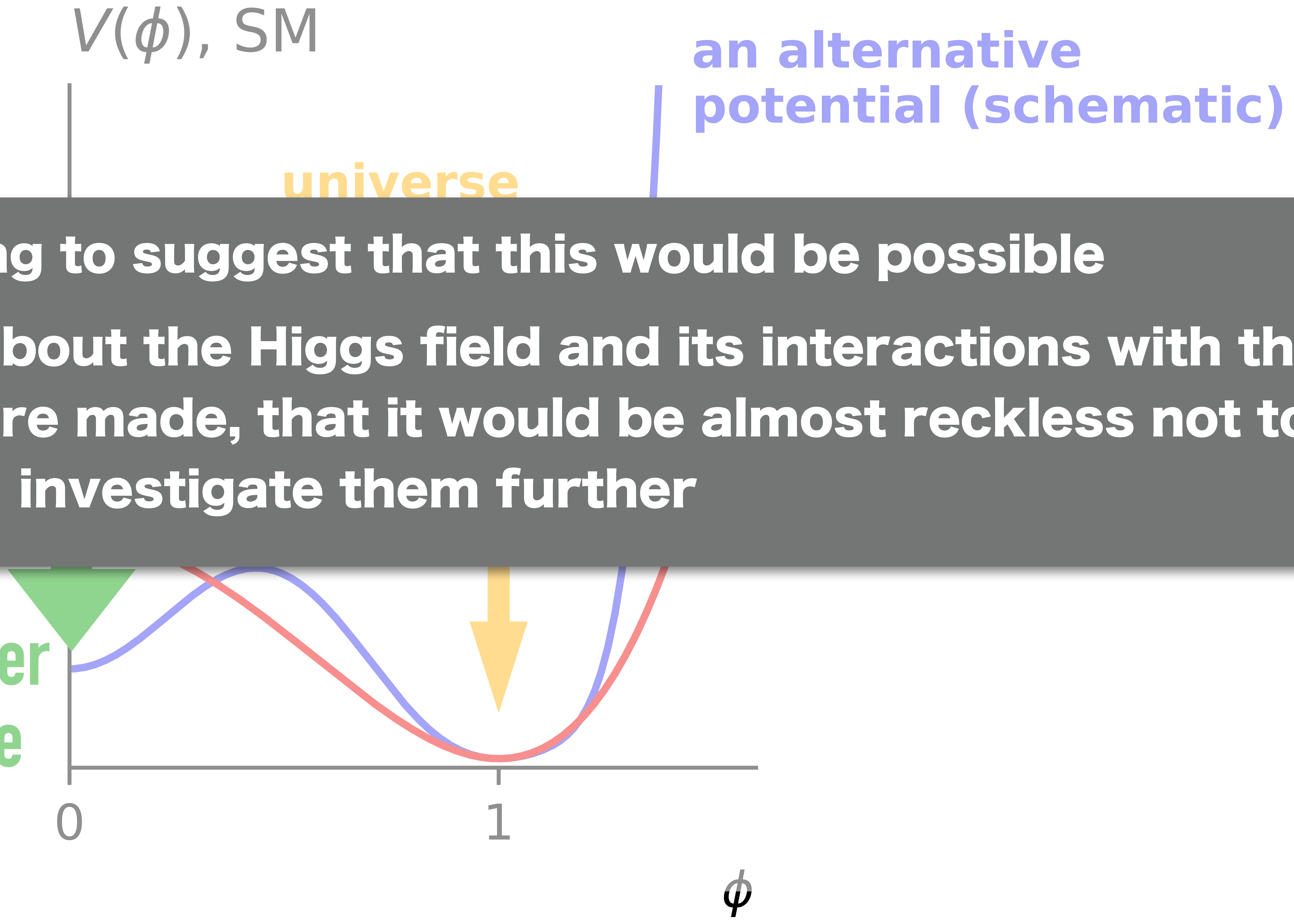
Science fiction



could we make a bubble with zero Higgs field?

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

Science fiction



there is nothing to suggest that this would be possible

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

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

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

an important target to be reached ~ guaranteed discovery

exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

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

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

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

Dear Santa Claus,

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

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

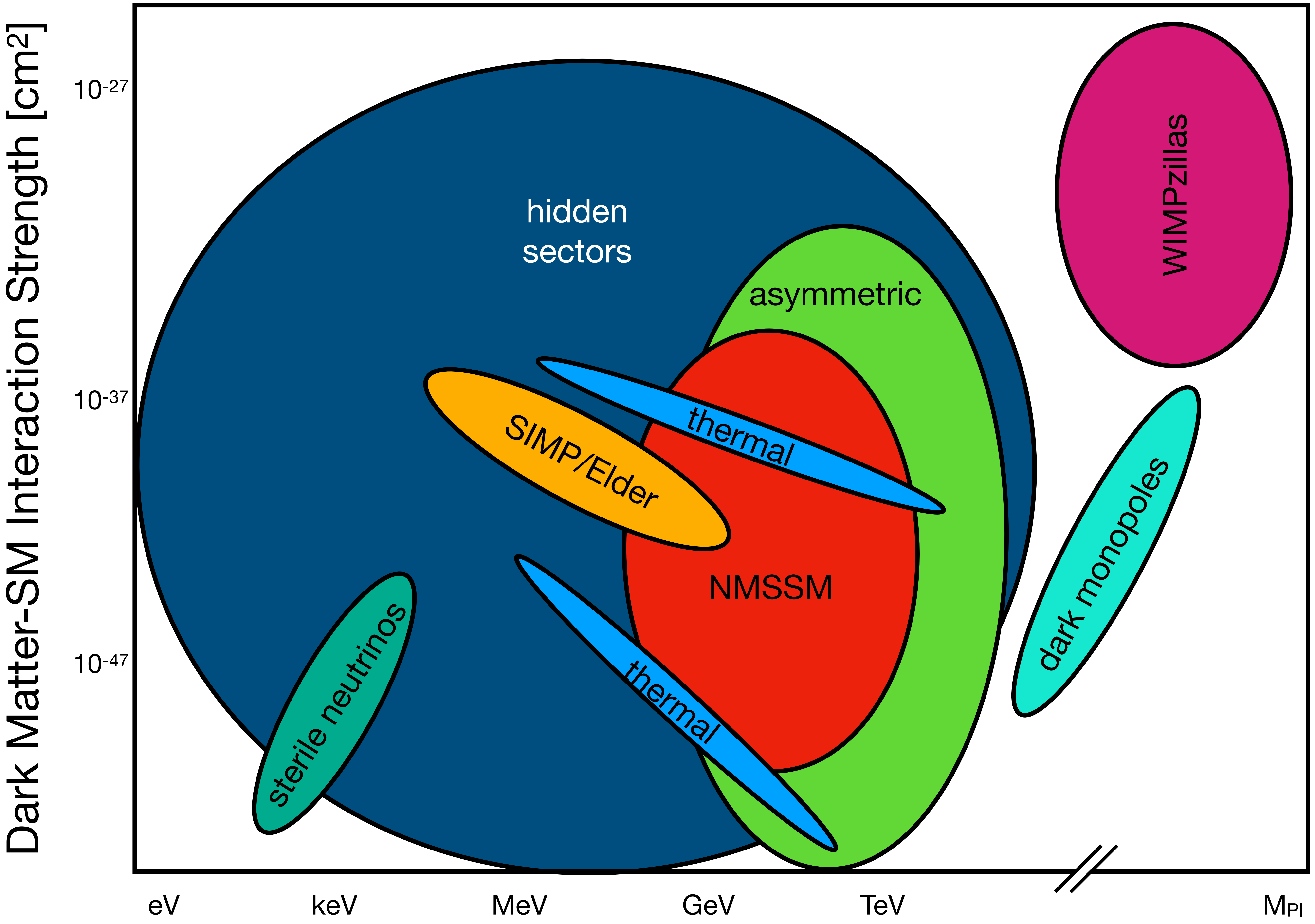
Thank you, Particle Physicists

ps: please, no anthropics

these questions remain deep mysteries, which we continue to explore

Snowmass Dark Matter report, 2209.07426

30 orders of magnitude in interaction strength



30 orders of magnitude in mass

typeset from Gian Giudice original for Fabiola Gianotti

Every problem of the SM originates from Higgs interactions

$$\mathcal{L} = \underset{\underset{\text{flavour}}{\uparrow}}{\lambda} H \psi \bar{\psi} + \underset{\underset{\text{naturalness}}{\uparrow}}{\mu^2} |H|^2 - \underset{\underset{\text{stability}}{\uparrow}}{\lambda} |H|^4 - \underset{\underset{\text{C.C.}}{\uparrow}}{V_0}$$

typeset from Gian Giudice original for Fabiola Gianotti

Almost every problem of the Standard Model originates from Higgs interactions

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

typeset from Gian Giudice original for Fabiola Gianotti

Almost every problem of the Standard Model originates from Higgs interactions

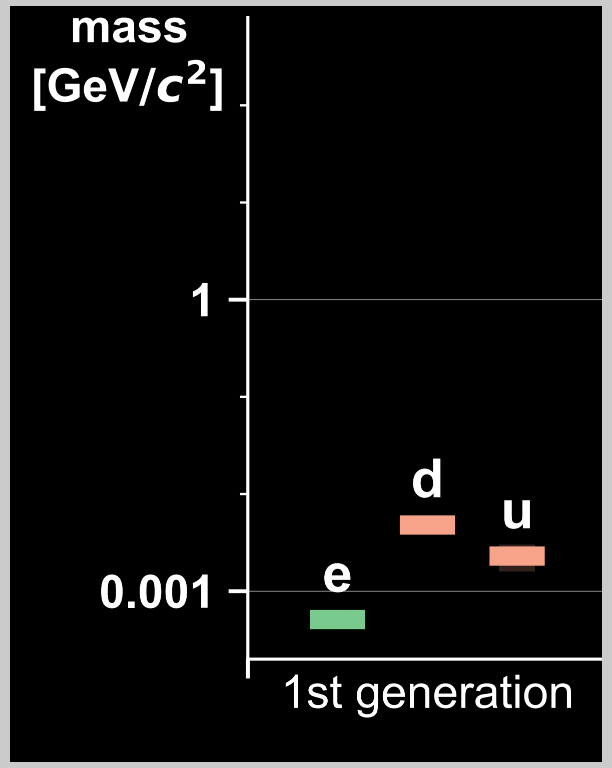
$$\mathscr{L} = y H \psi \bar{\psi} + \mu^2 |H|^2 - \lambda |H|^4 - V_0$$

flavour

naturalness

stability

cosmological constant



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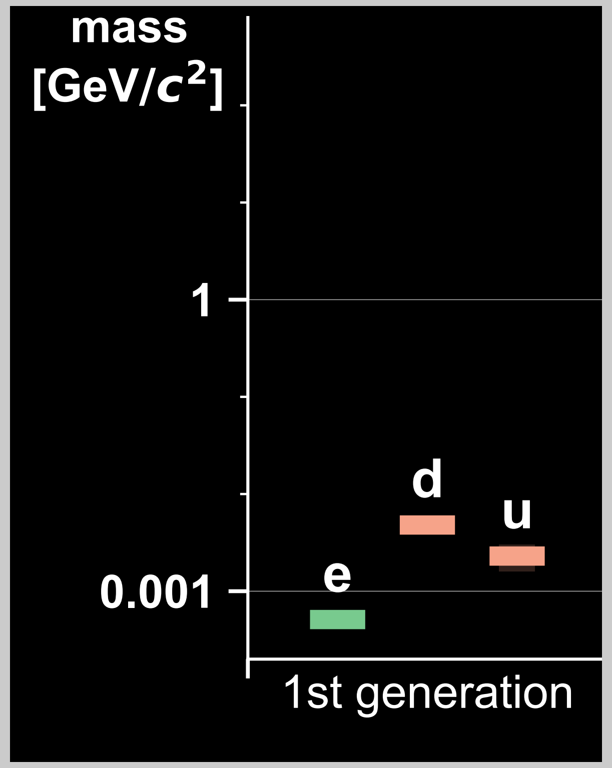

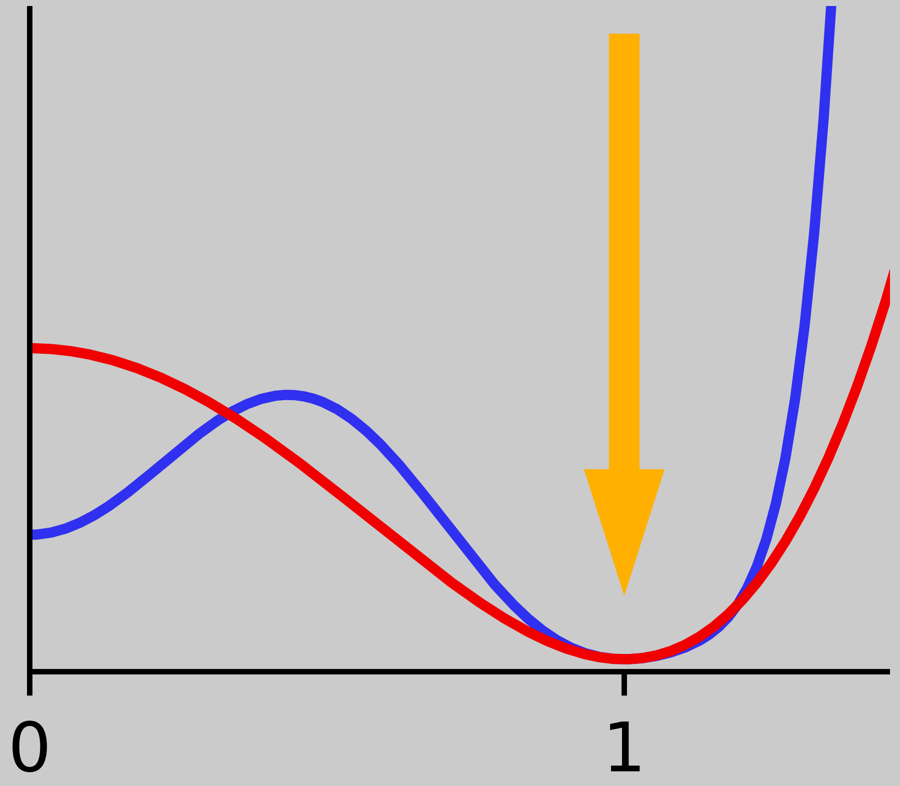

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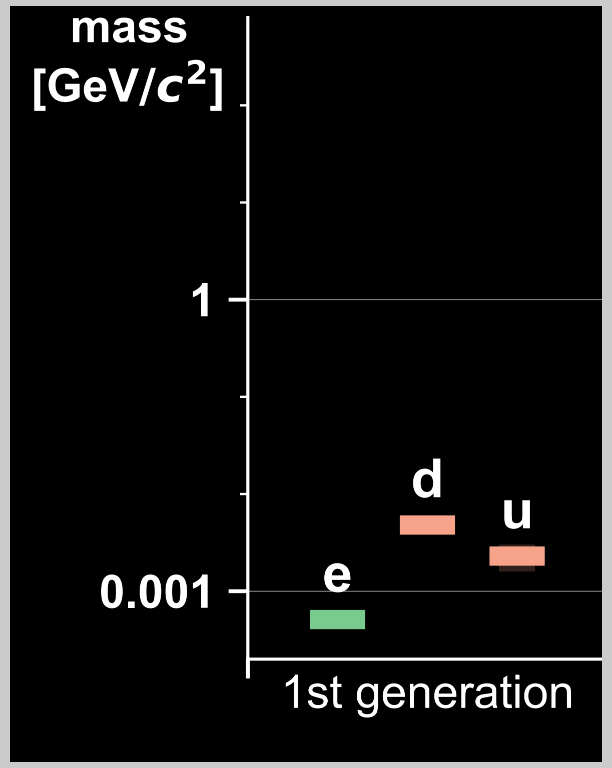
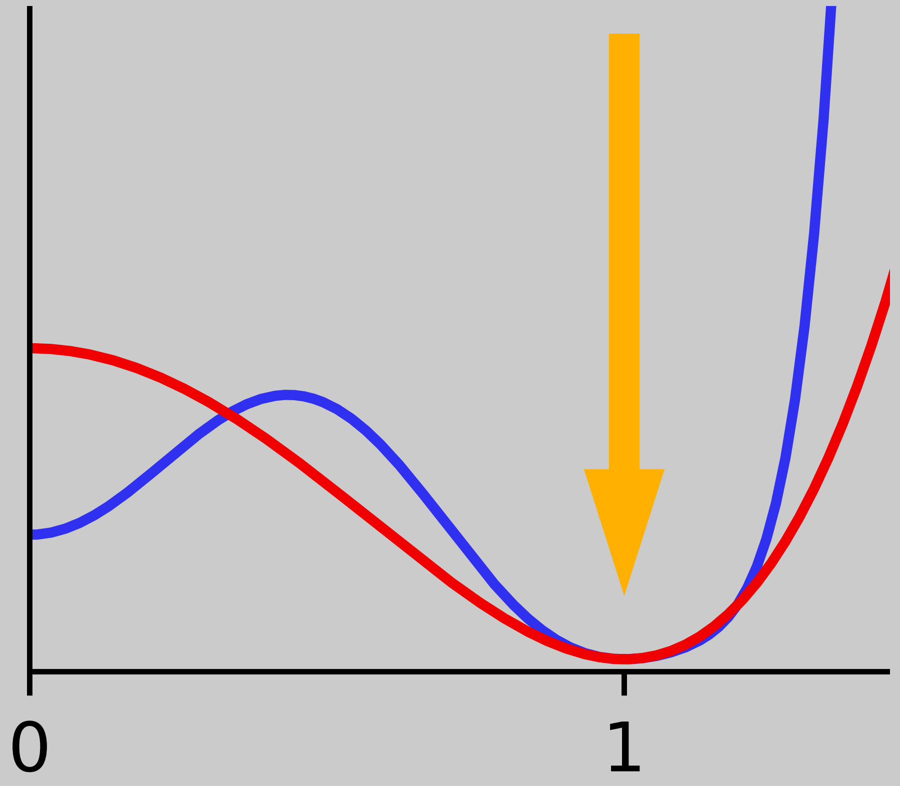


naturalness

stability



cosmological constant

typeset from Gian Giudice original for Fabiola Gianotti

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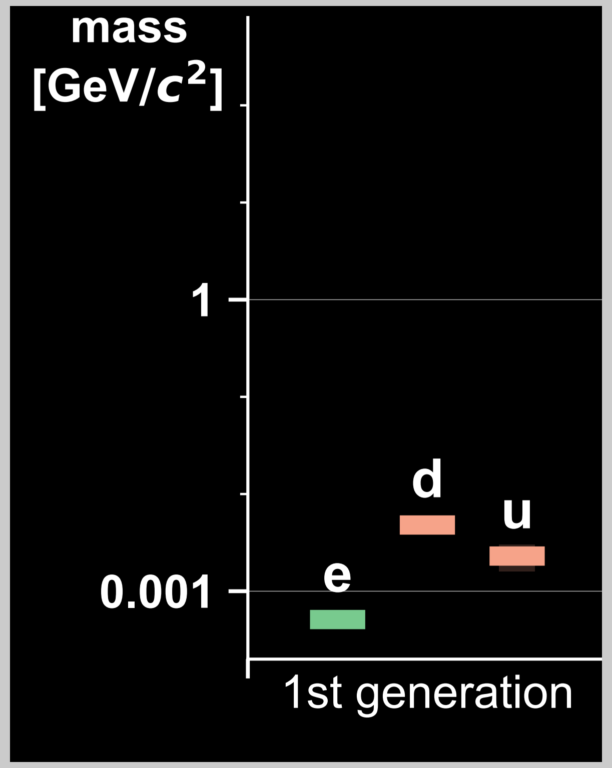
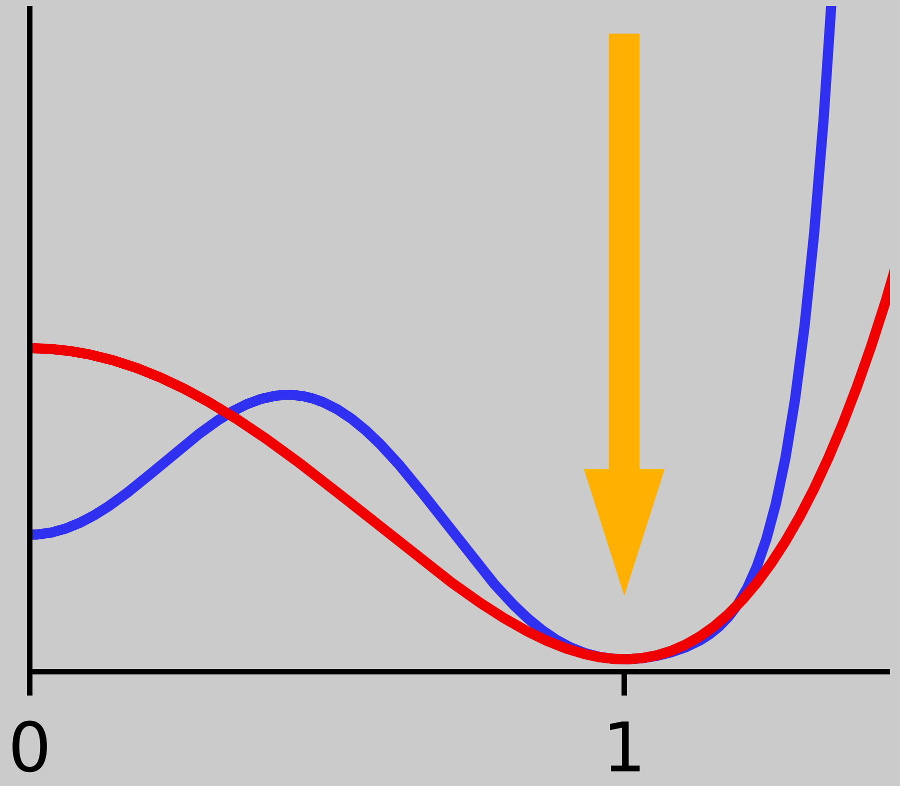


naturalness

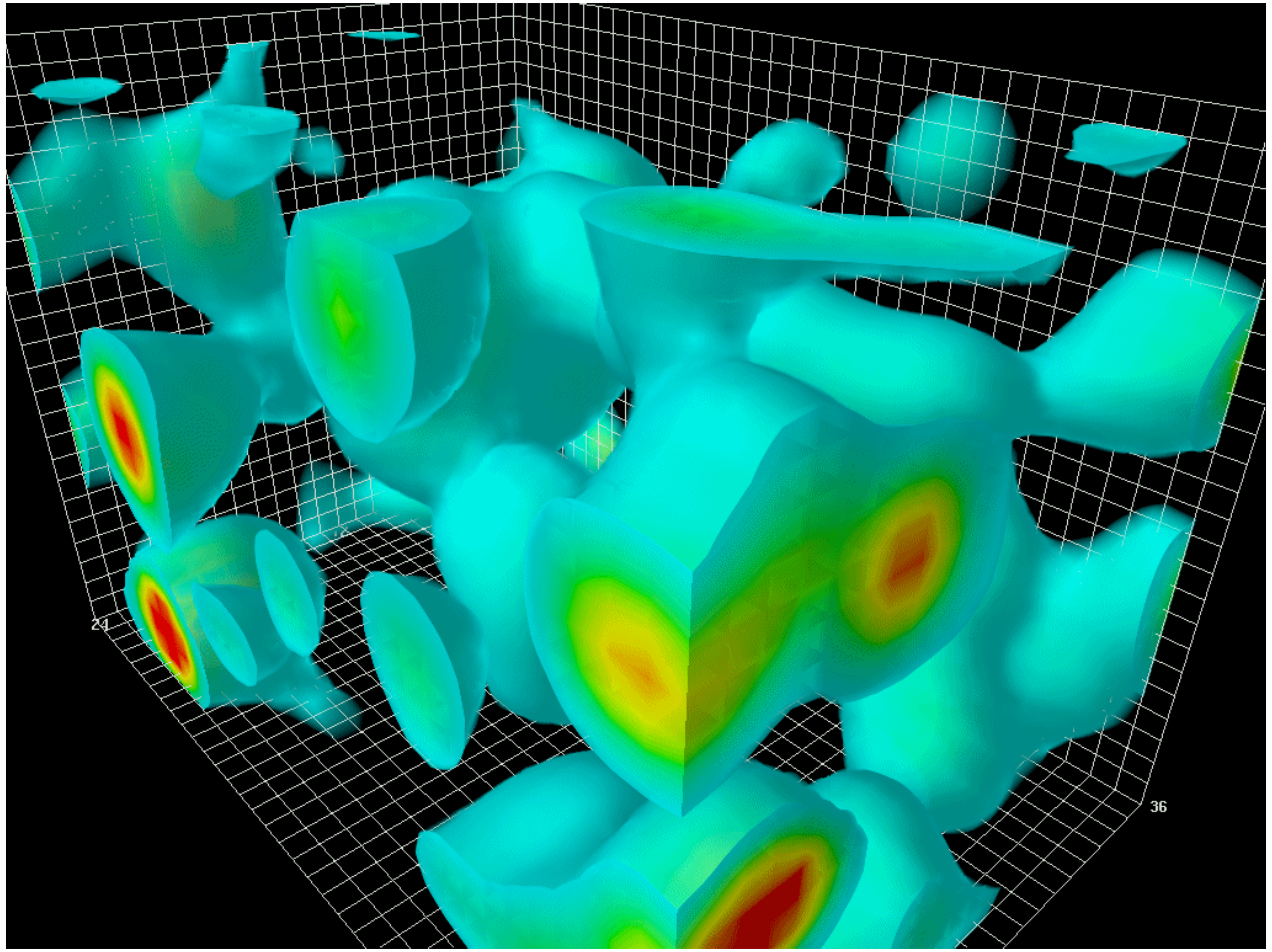
?

stability



cosmological constant

Naturalness in particle physics

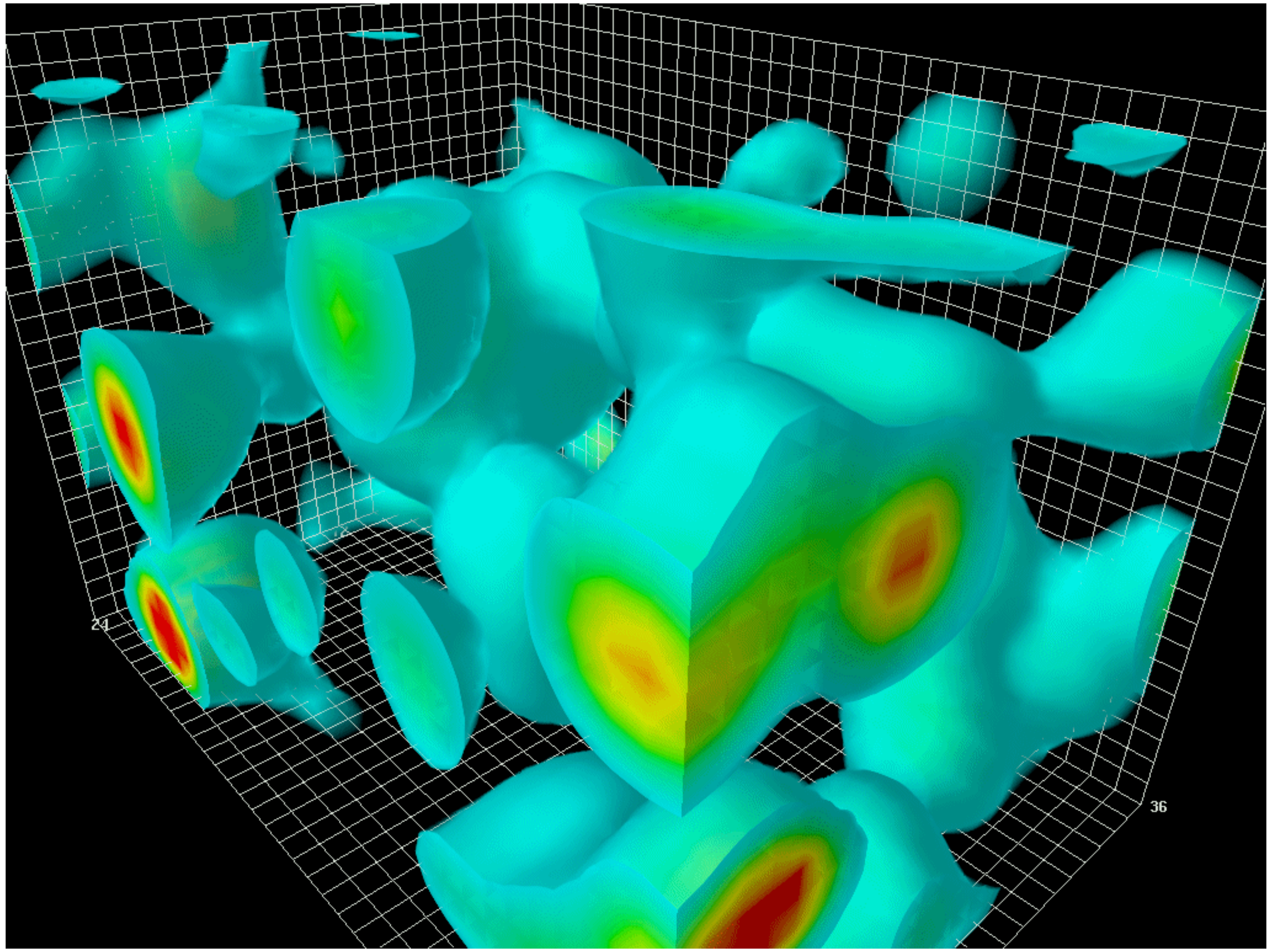


http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/index.html
NB: shows QCD quantum fluctuations, so not directly those connected with the Higgs mass

- quantum fluctuations act on the Higgs sector, trying to drive up the Higgs boson's mass, as far as it can go
- widespread belief among physicists: only thing that could provide an upper limit is some yet-to-be discovered new physics
- and it shouldn't be too much heavier than the Higgs mass (i.e. accessible at LHC or next colliders)

[an alternative is some huge cosmic coincidence; or that we have a deep misunderstanding of underlying physics]

Naturalness in particle physics



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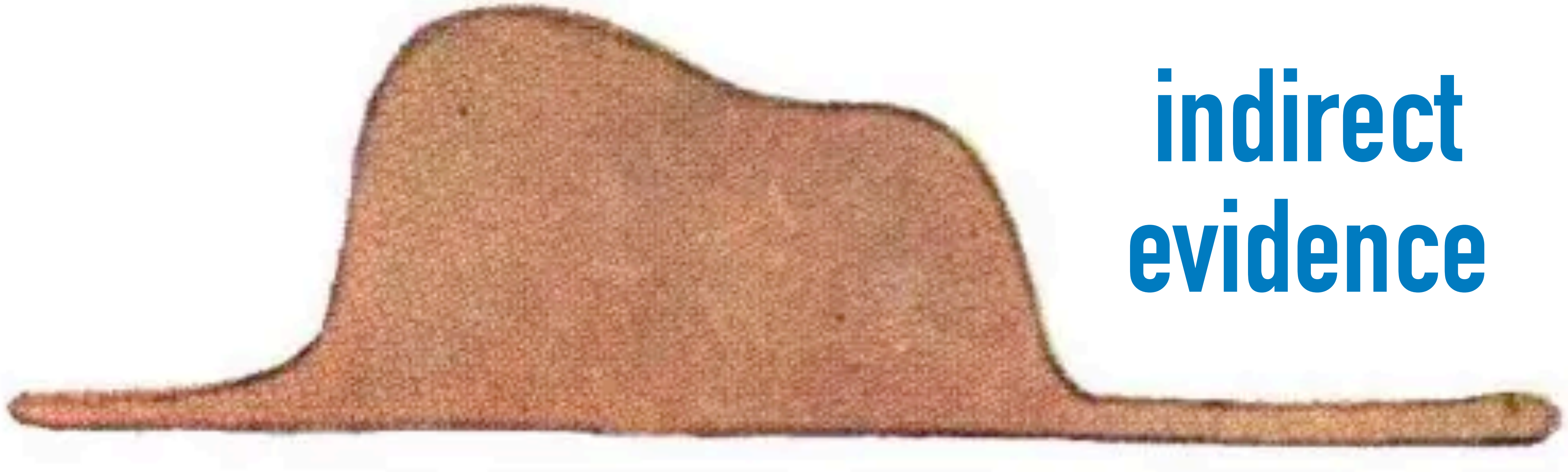
Mon dessin numéro 1



indirect evidence

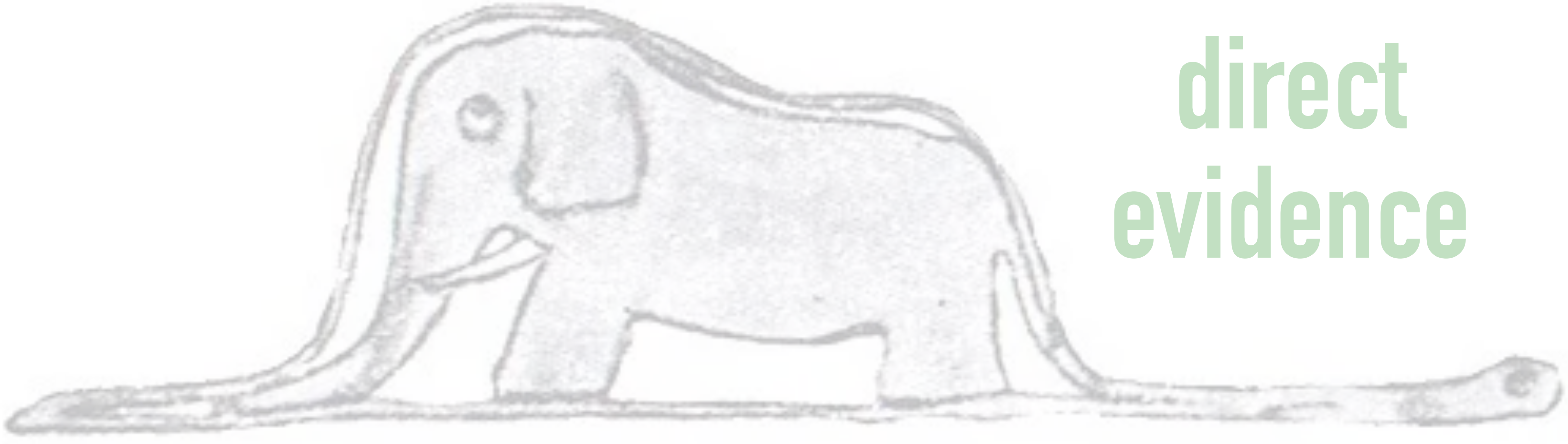
« Pourquoi un chapeau ferait-il peur ? »

“Why should any one be frightened by a hat?”

Le Petit Prince, Antoine de Saint-Exupéry

« Mon dessin ne représentait pas un chapeau. Il représentait un serpent boa qui digérait un éléphant. »

“My drawing was not a picture of a hat. It was a picture of a boa constrictor digesting an elephant.”

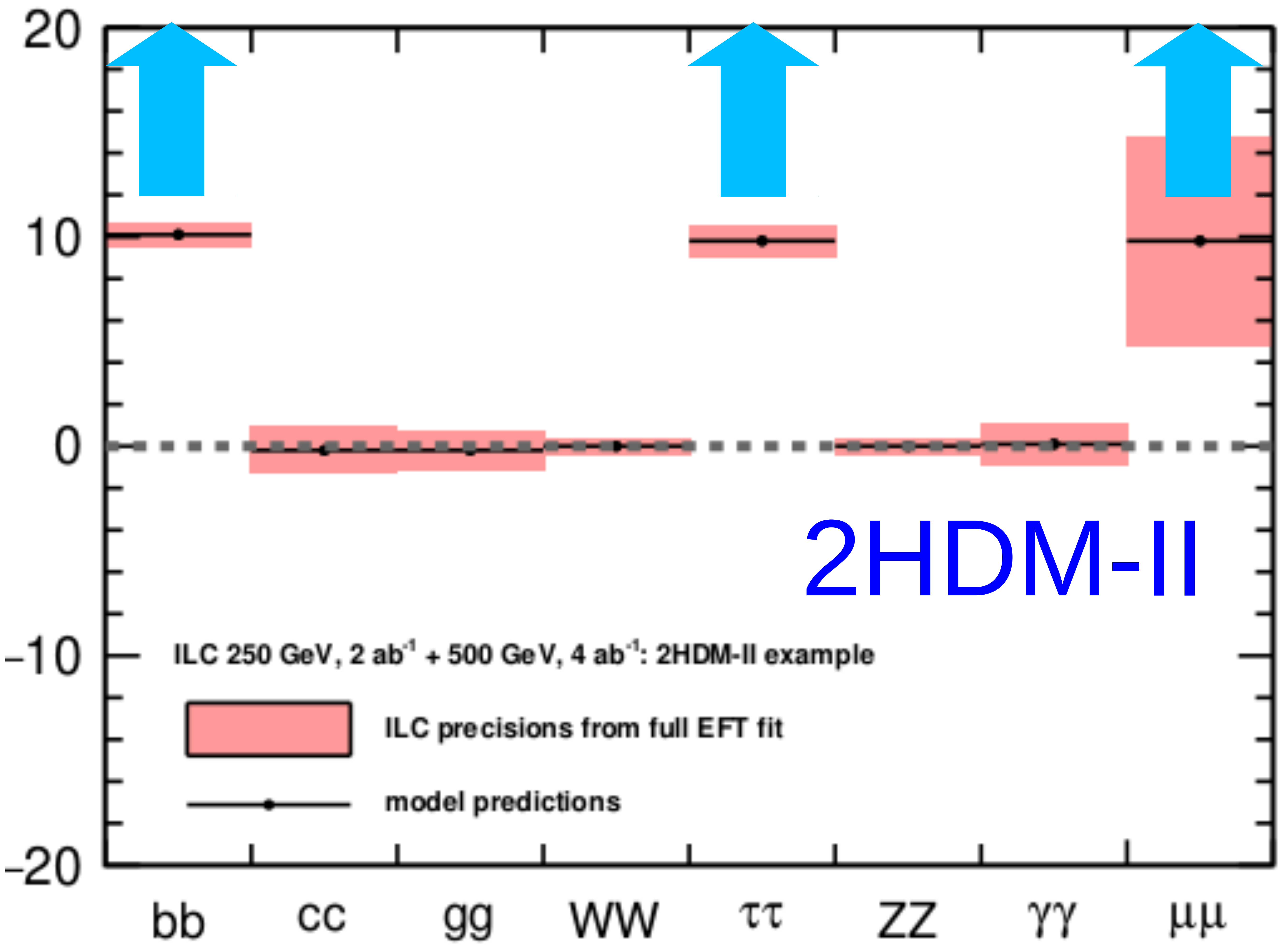


direct evidence

Mon dessin numéro 2

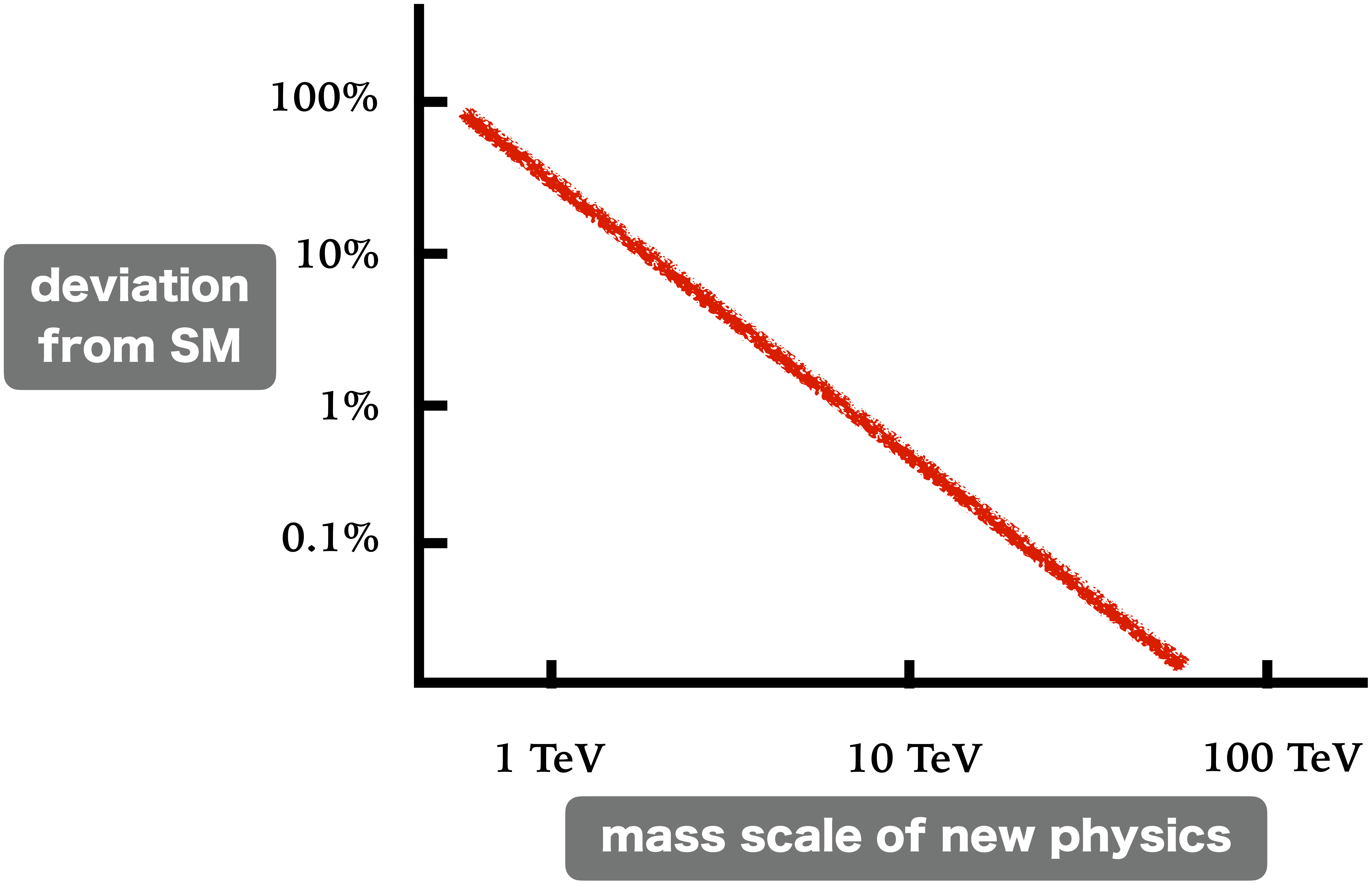
measuring many distinct interactions is crucial in indirect searches

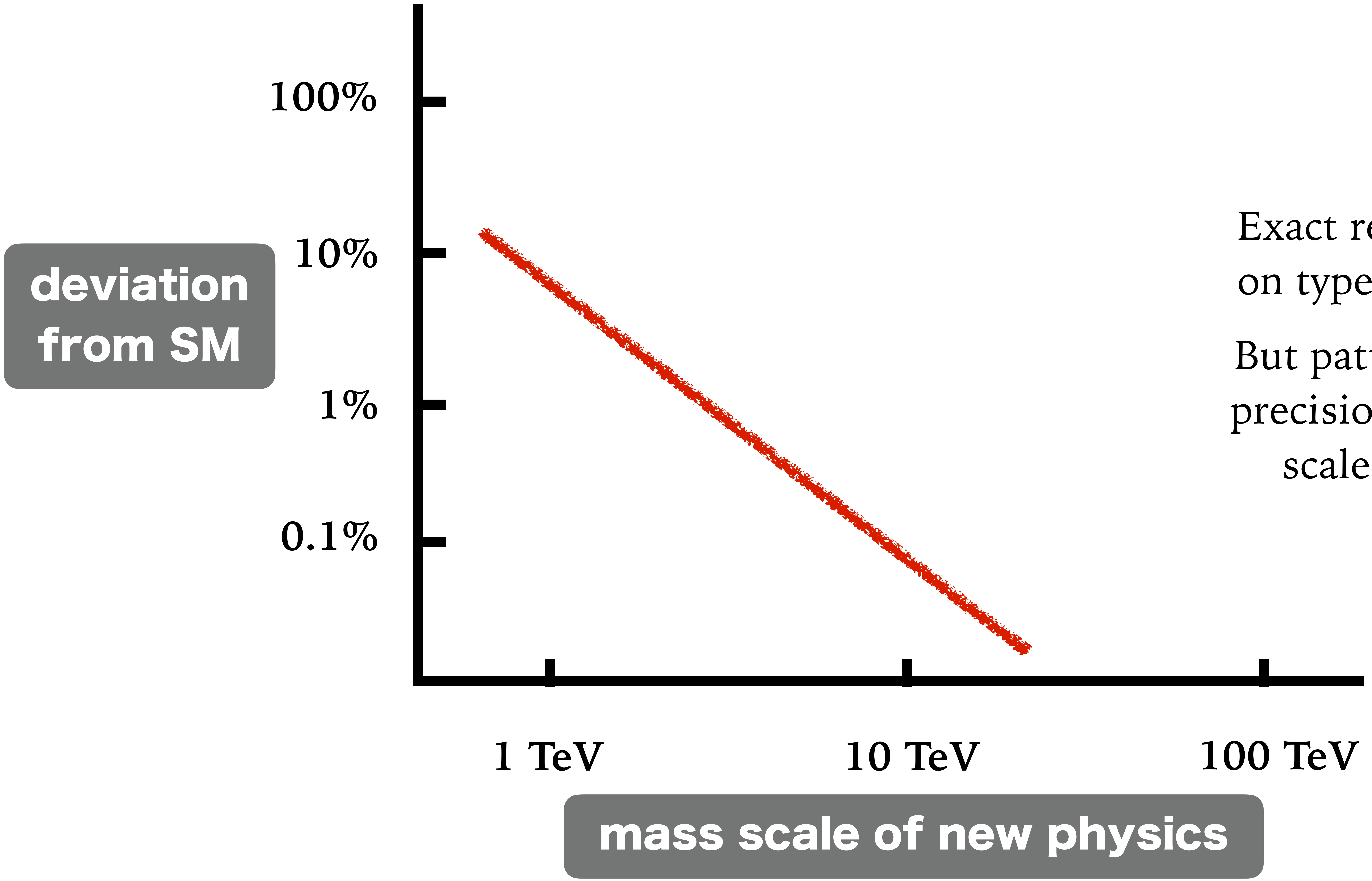
Potential deviations from SM [%]



Pattern of any deviations would be “fingerprint” of new physics

Illustration from ILC studies
(linear electron-positron collider)
& slide by D. Jeans @ICHEP 2020


100%
10%
1%
0.1%
deviation from SM
1 TeV
10 TeV
100 TeV
mass scale of new physics

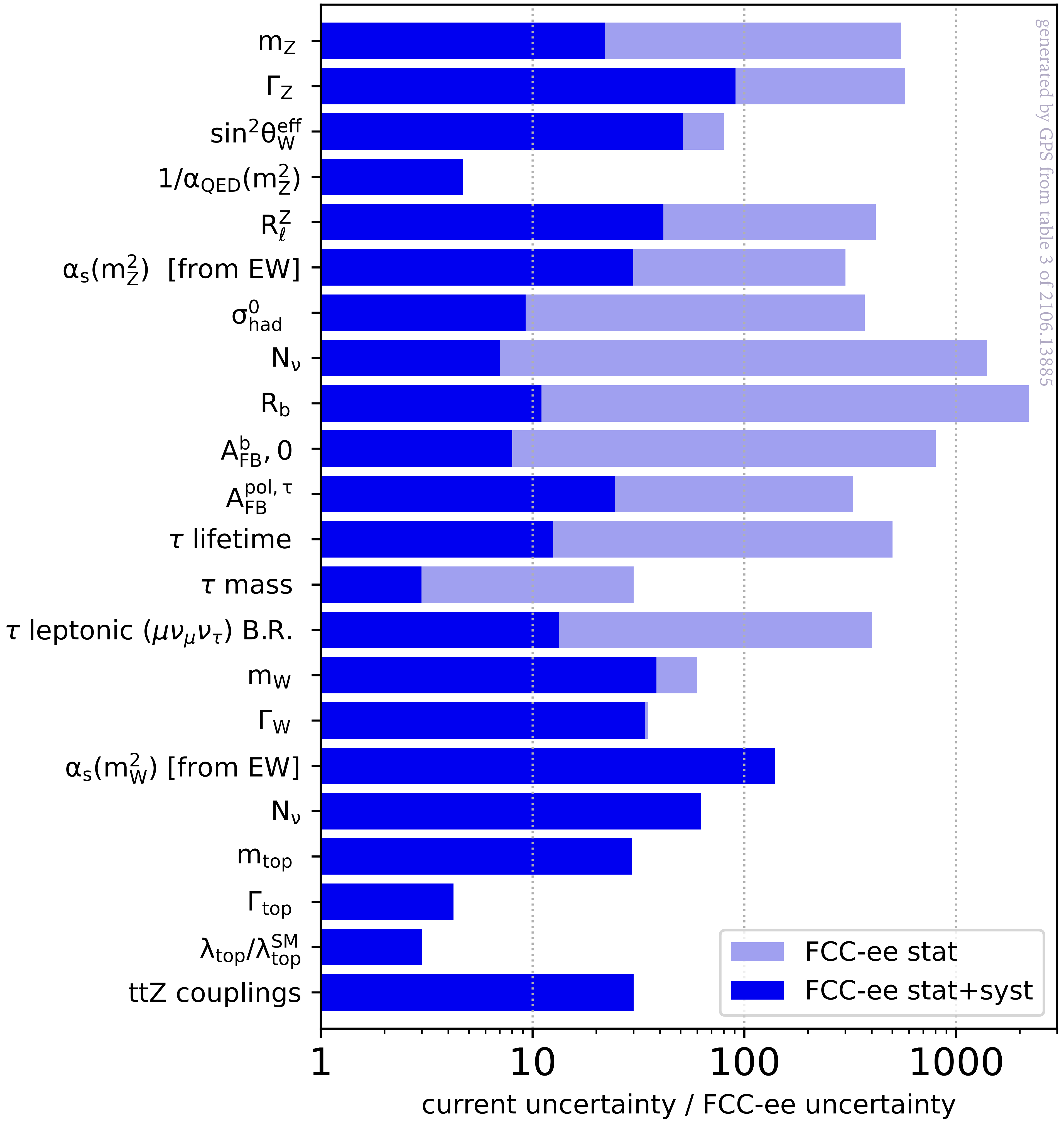


Exact relation depends on type of new physics

But pattern that higher precision probes higher scales is universal

increase in precision at FCC-ee is equivalent to × 4 – 5 increase in energy reach

FCC precision gain



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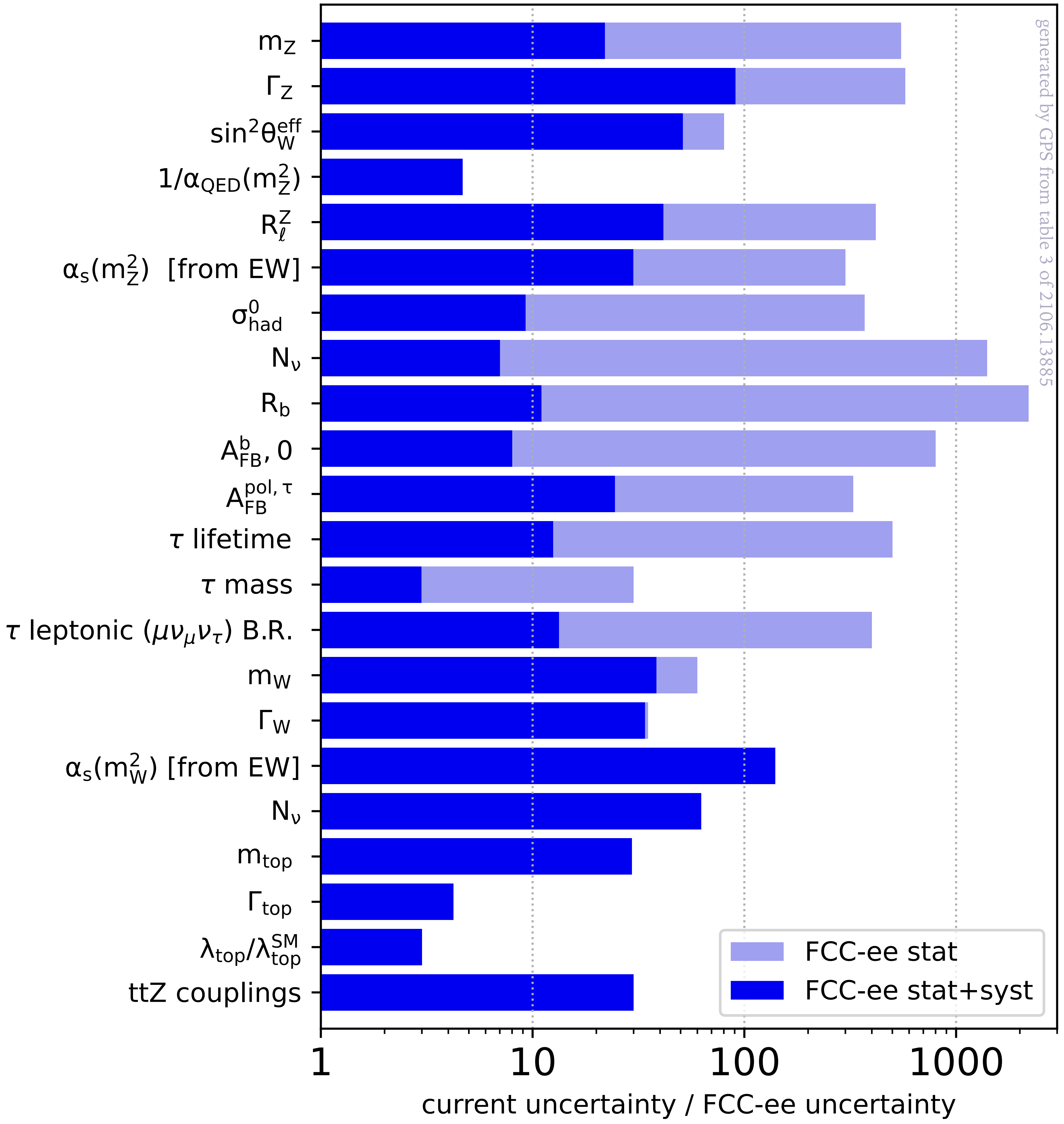
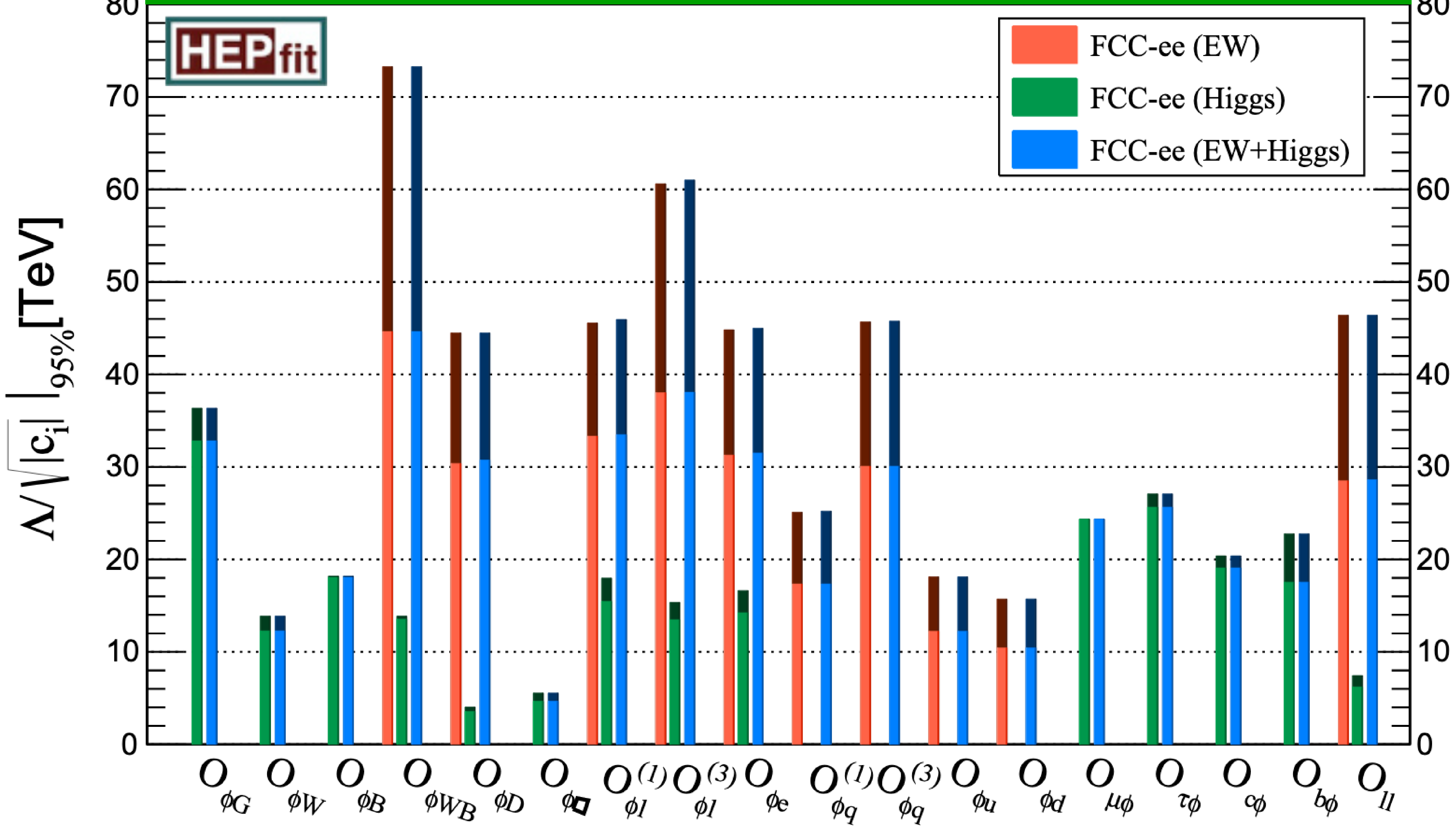


maximum scale probed indirectly — up to 70 TeV



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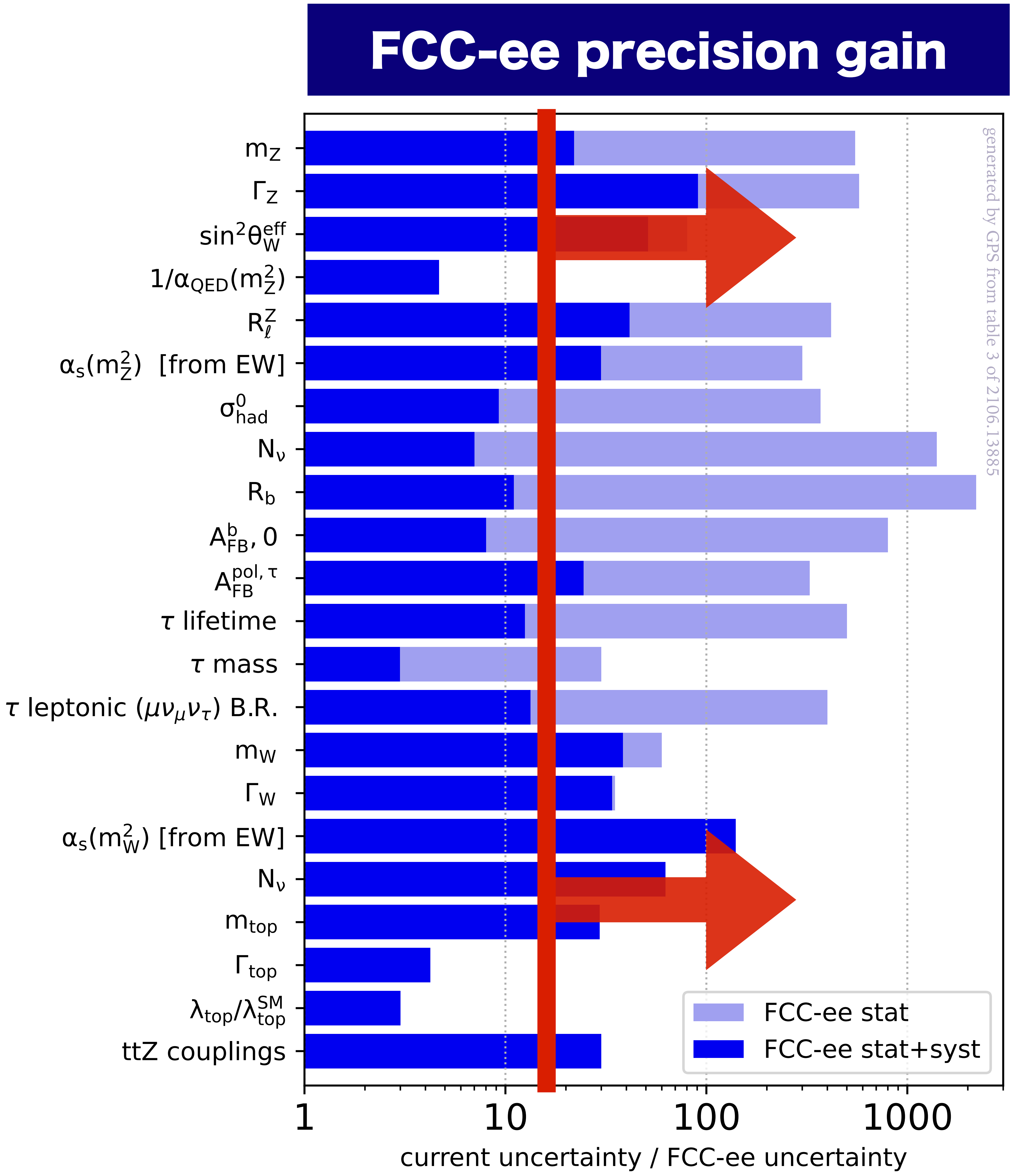


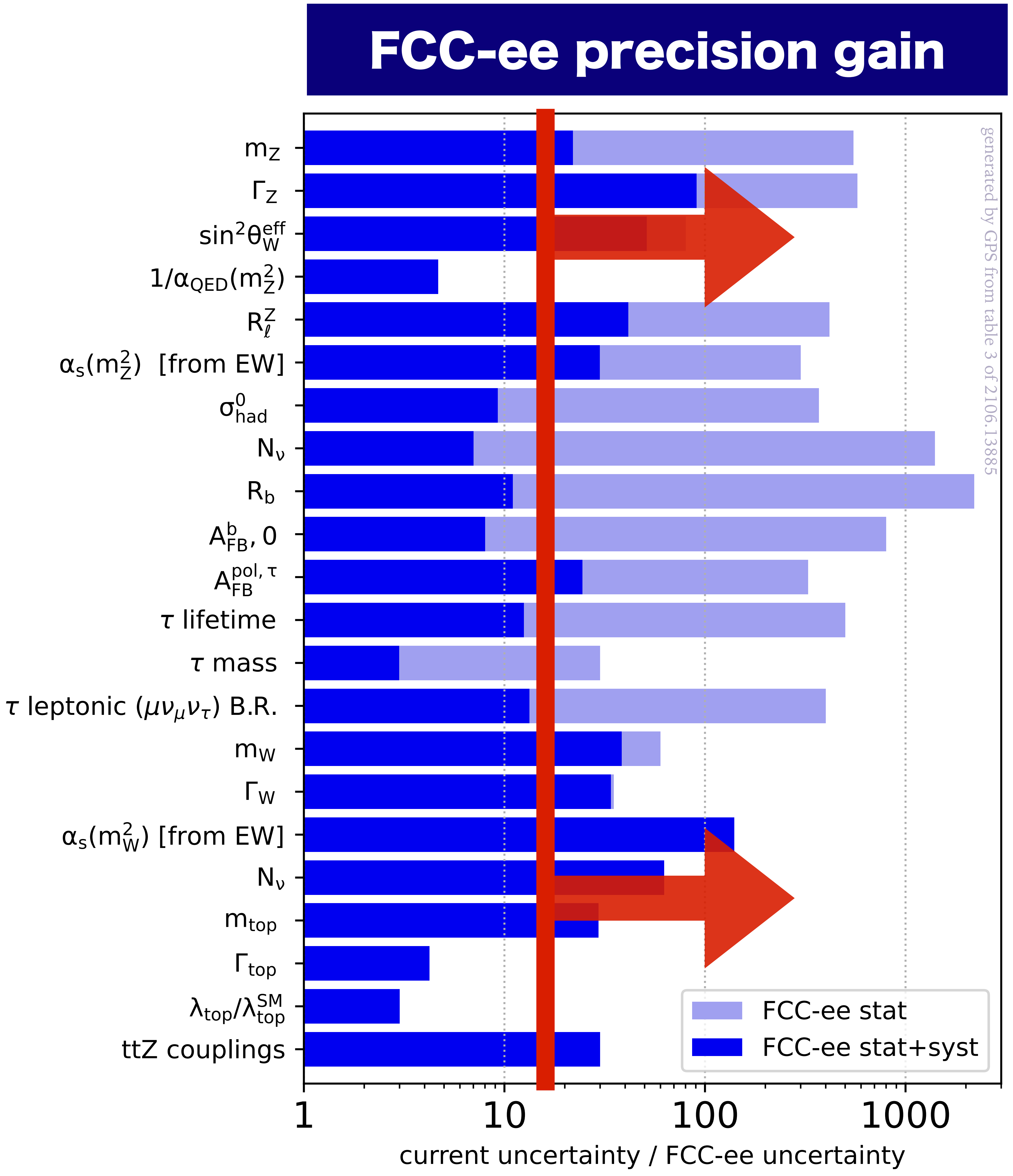
Two messages

- with a rough estimate for systematics, FCC-ee brings a big step forward (geom.avg. = × 18, across $\gtrsim$ 20 observables)
- still huge scope for thinking about how to improve systematics (gain of up to further × 100 in some cases)

This is the fun part for us as physicists!

and will call for joint efforts by experiment/theory/accelerator physicists

precision has intrinsic value



Provides foundations for the continued exploration of the field.

Because it ensures firm knowledge of starting point.

Mon dessin numéro 1

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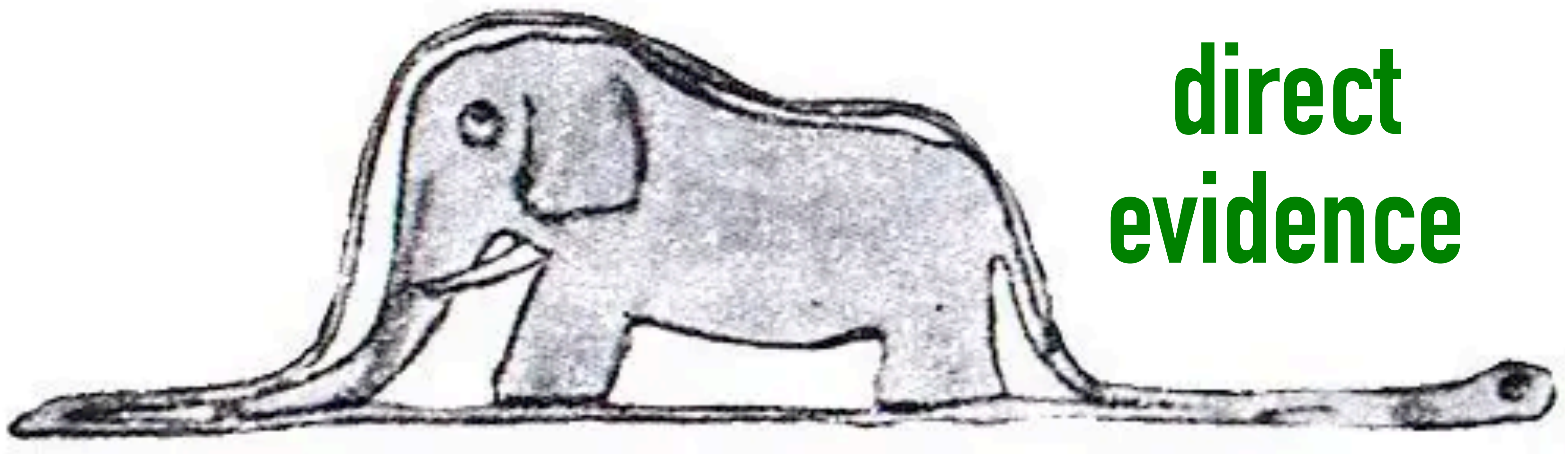
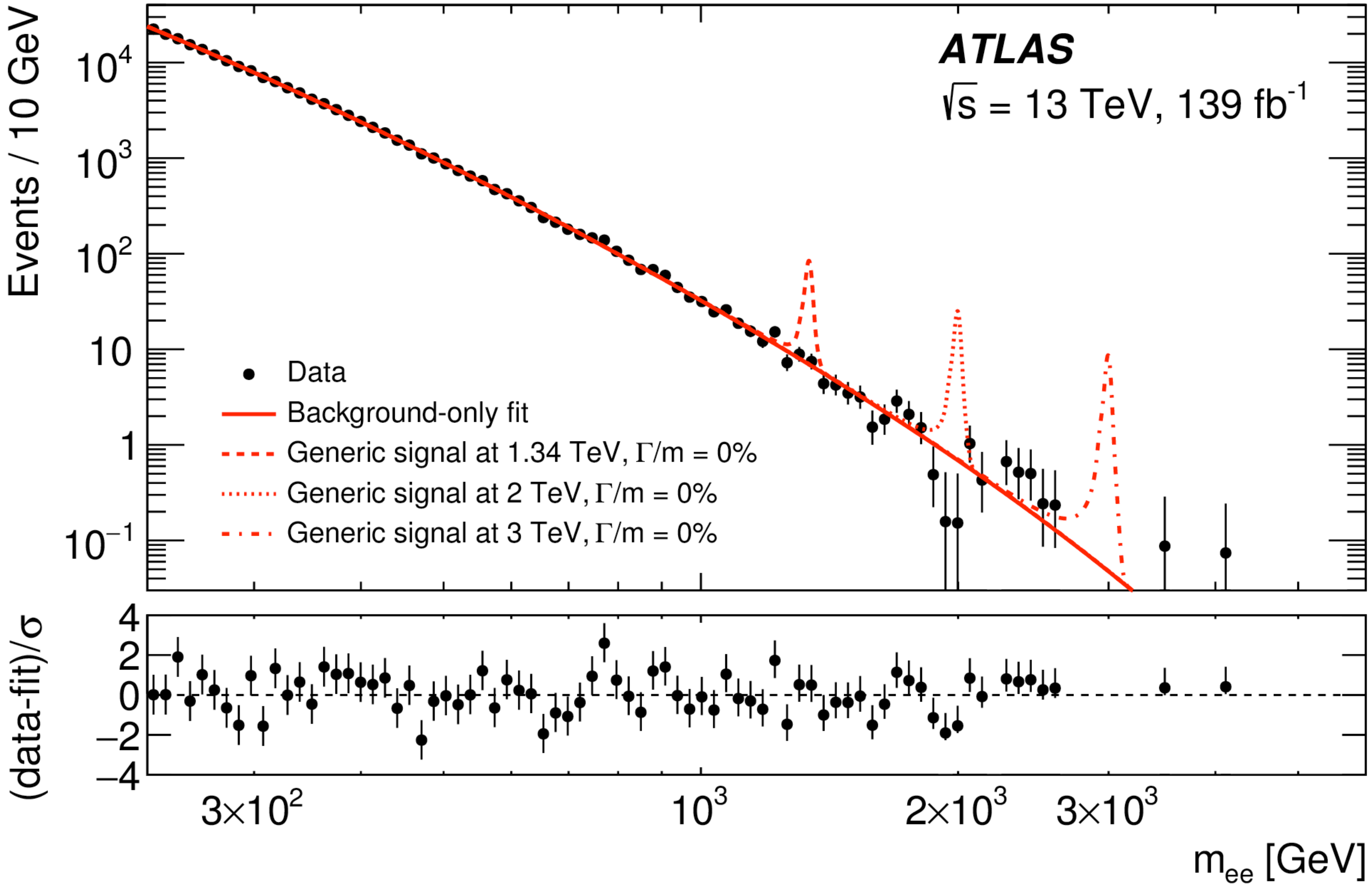


direct evidence

Mon dessin numéro 2

Example of a direct search (Z′) at LHC



what should we expect as a step up in energy?

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

Tevatron (Fermilab, USA)
$p\bar{p}$, 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}, $\mu\mu$ only)

× 5.6 →

replicated across myriad search channels

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

Exclusion limit ~ 6.7 TeV

(electron and muon channels, single experiment)

what should we expect as a step up in energy?

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

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

Exclusion limit ~ 6.7 TeV

(electron and muon channels,
single experiment)

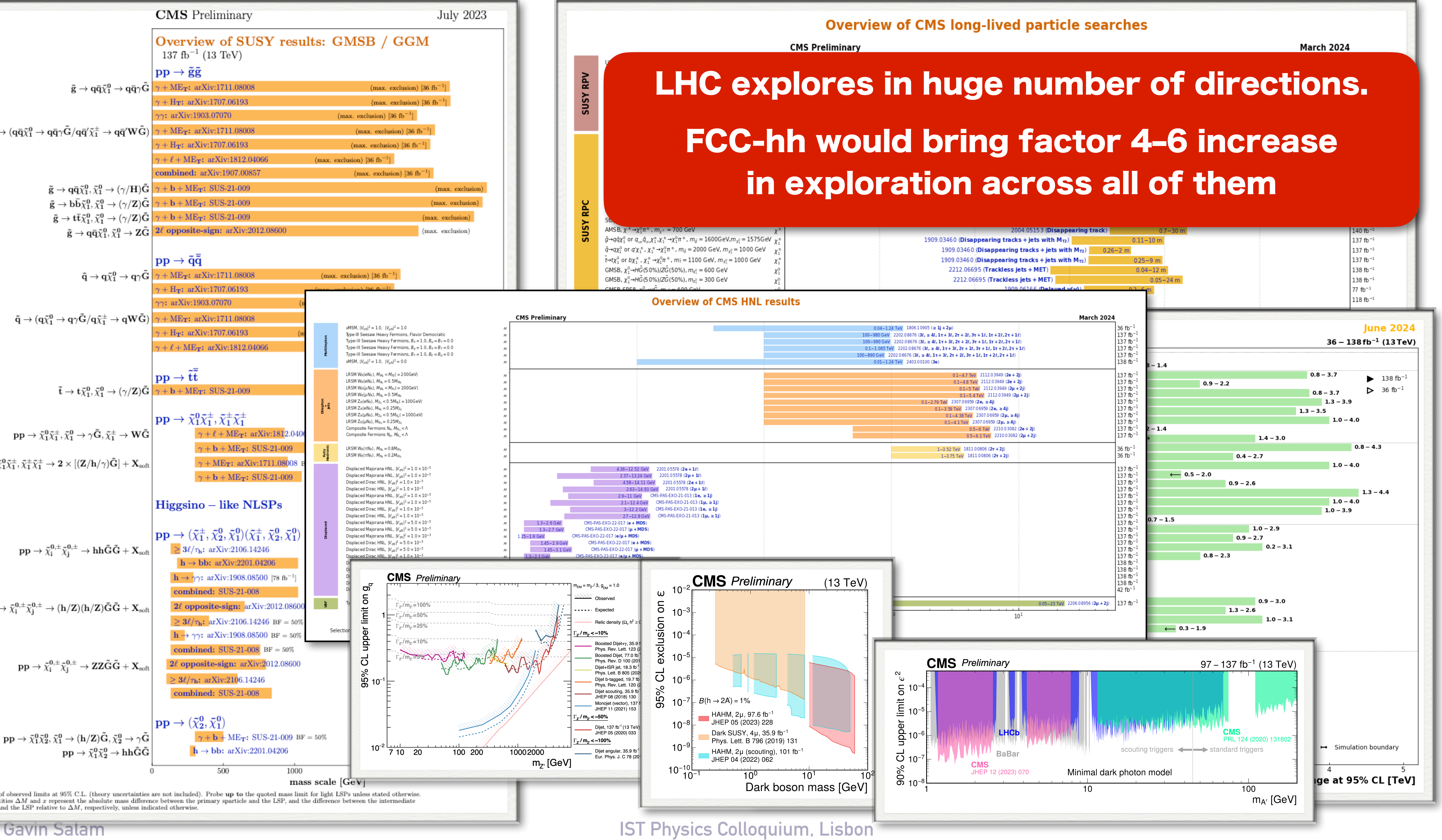
× 6.1

replicated across myriad search channels

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)



LHC explores in huge number of directions.

FCC-hh would bring factor 4–6 increase in exploration across all of them

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 guaranteed discovery in establishing (or disproving) SM origin of electron mass at circular e^+e^- colliders?
- The **step up in energy reach** that we expect is $\sim$ **× 4 – 5**
    - e^+e^- colliders (esp. FCC-ee/CEPC) deliver that mostly in "indirect" sensitivity, through precision increase $\sim \times 18$
    - FCC-hh would deliver that in direct search sensitivity, exploring in a huge number of directions
- **Diversity and robustness of the programme** = essential part of their strength