CERN Council Retreat
Sinaia, Romania
29 August 2024

Collider Physics and some future goals

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THE ROYAL SOCIETY

UNIVERSITY OF OXFORD

UKRI
Science and Technology Facilities Council

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)

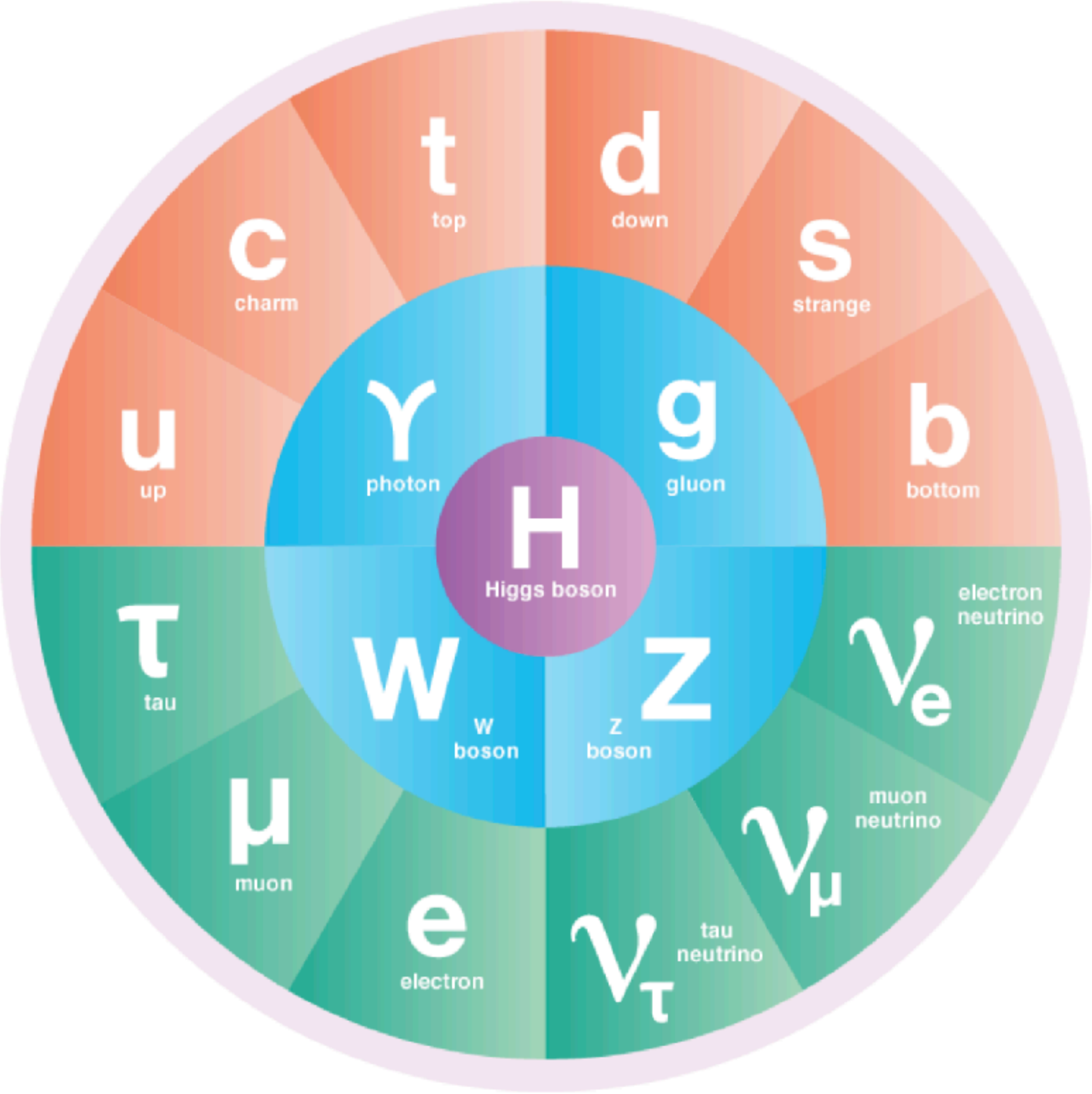
cost-effective construction & operation,
low carbon footprint, novel technologies

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

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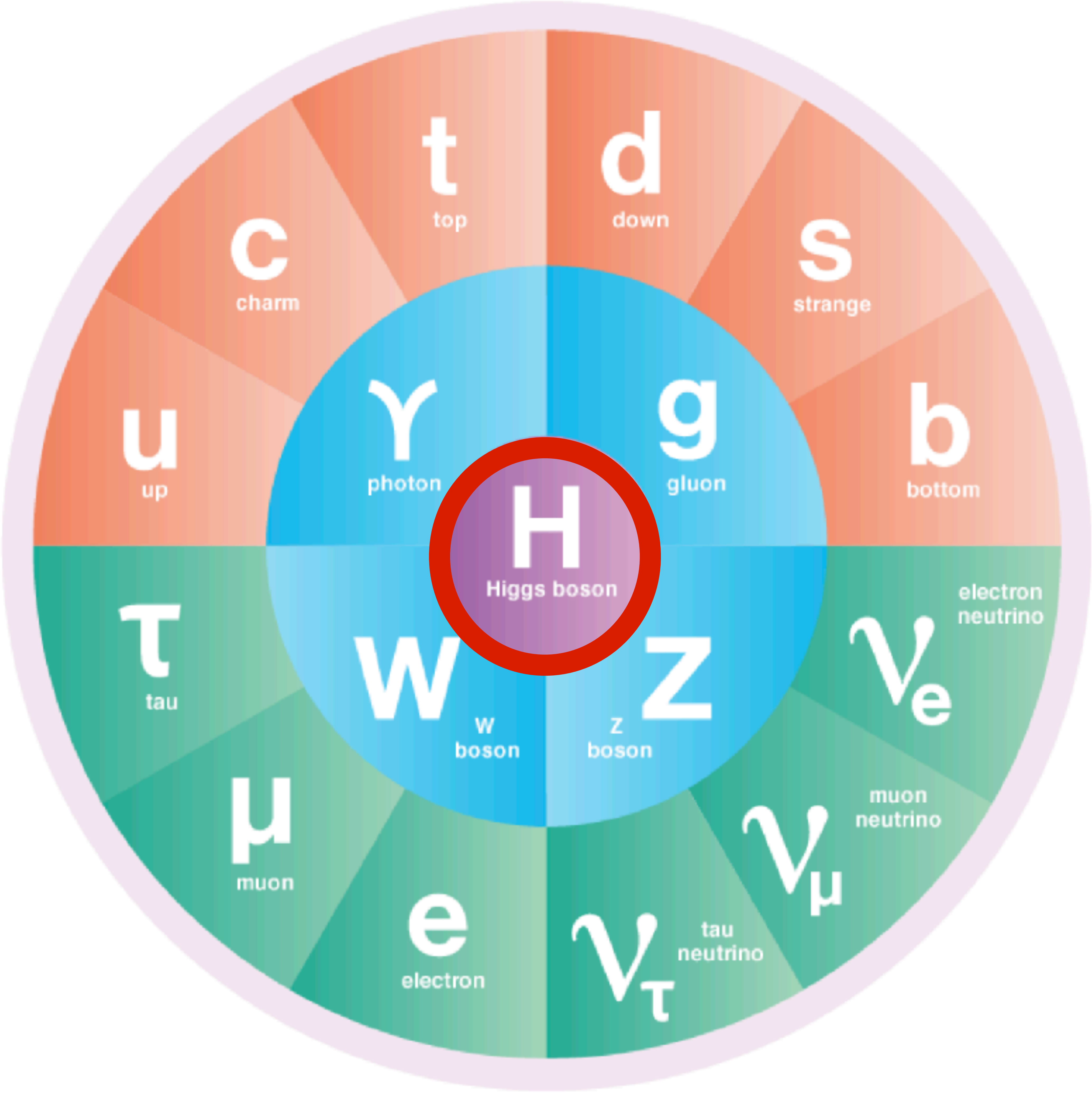

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“the standard-model (SM)
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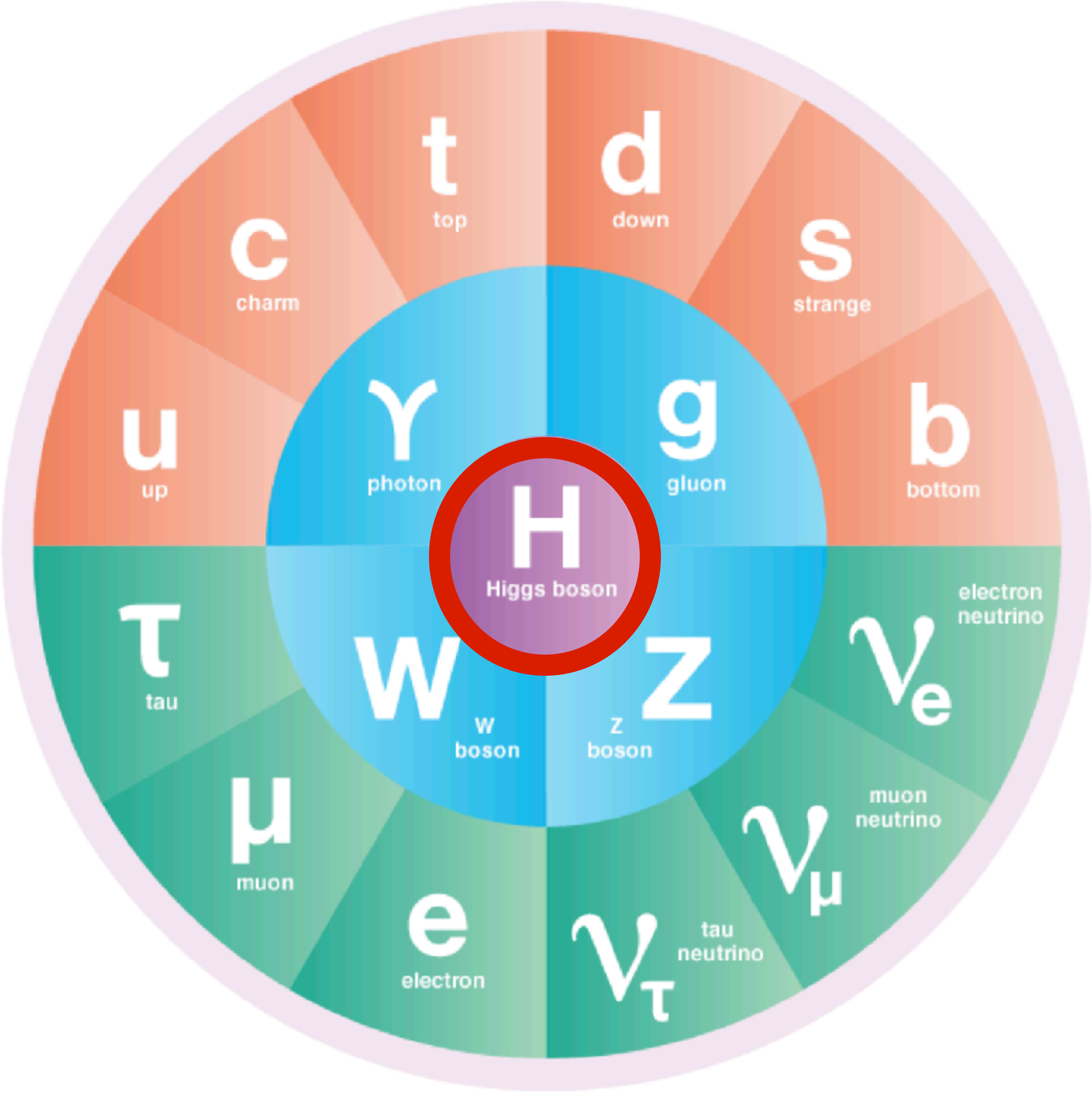

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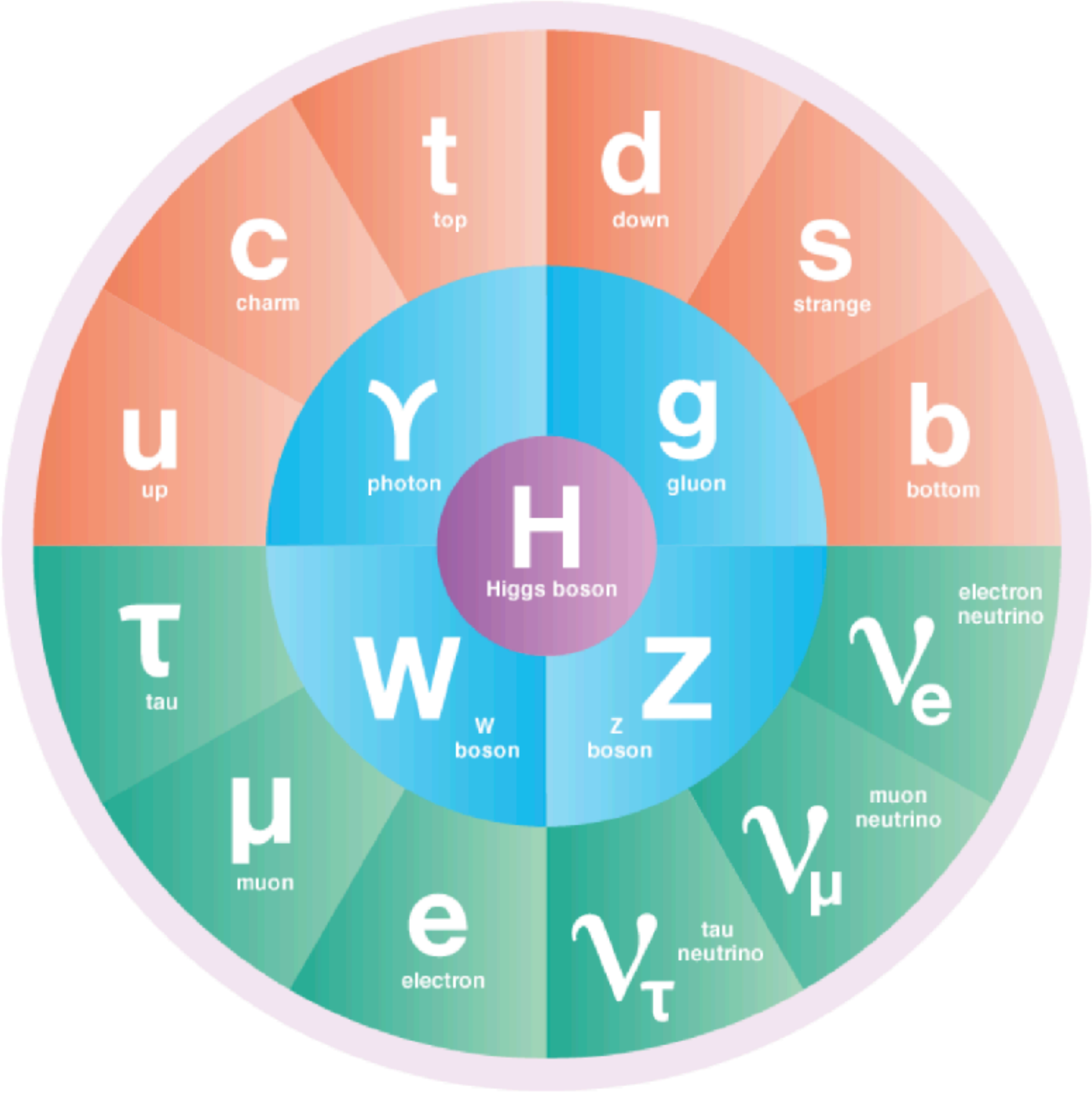

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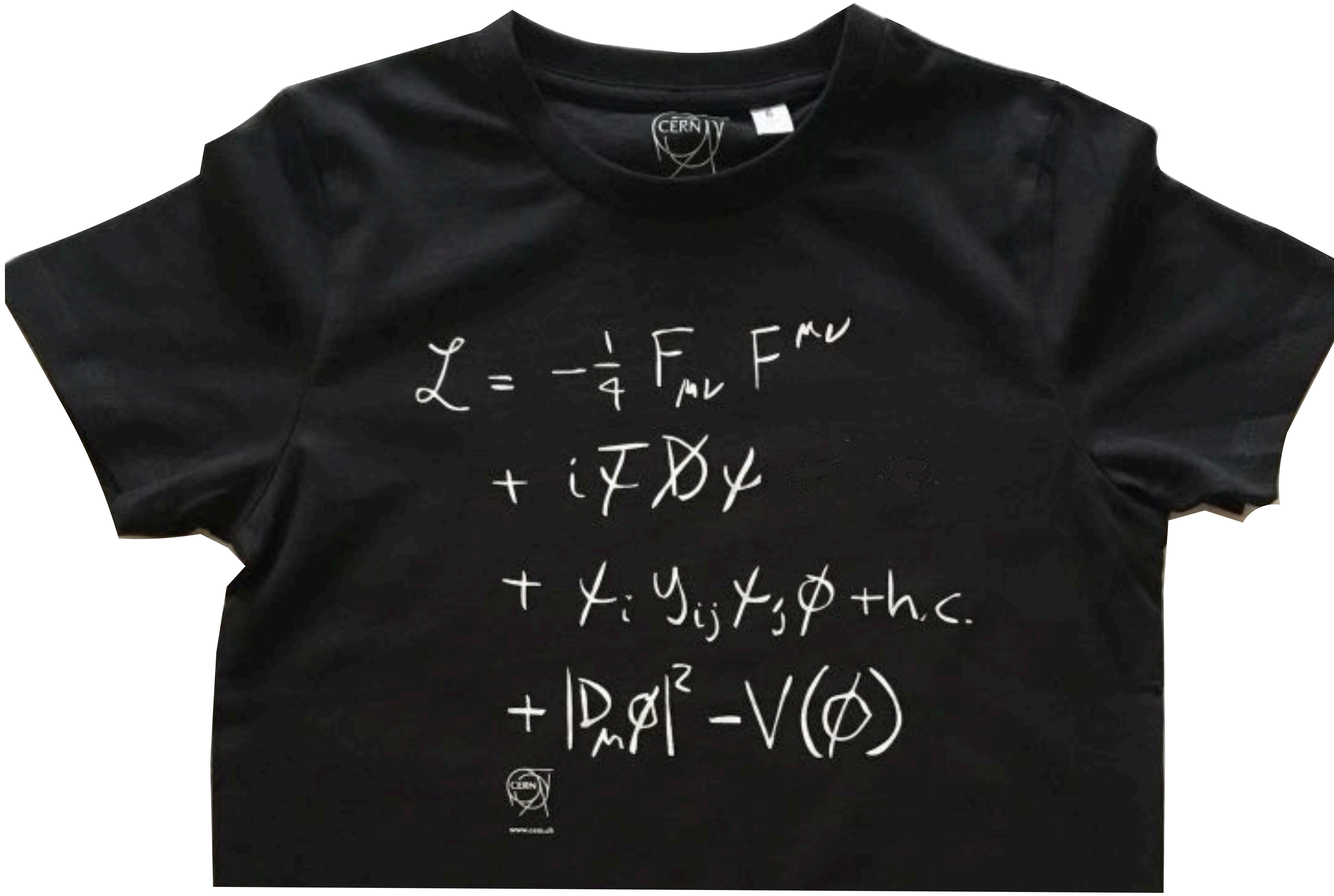

interactions

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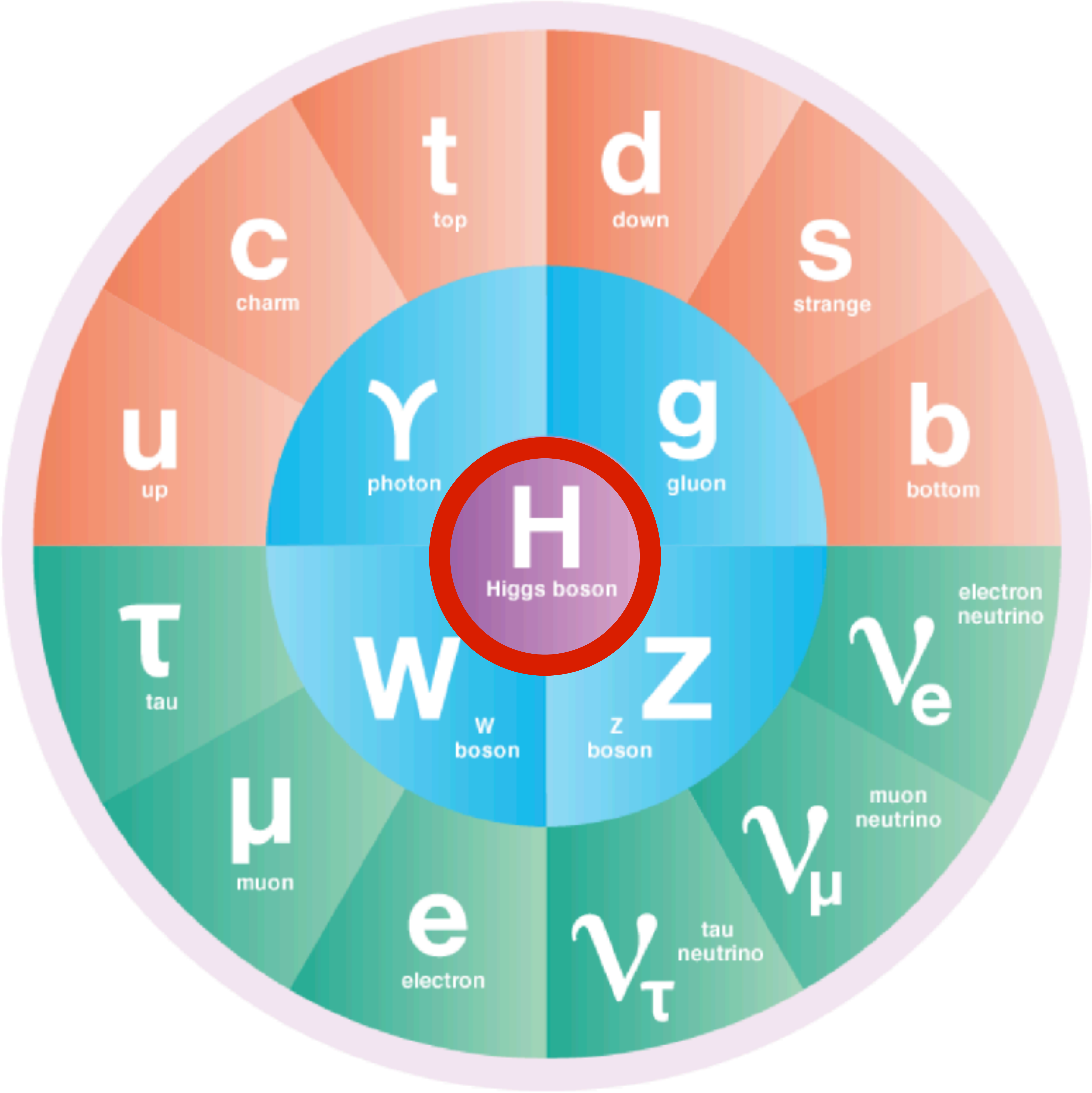

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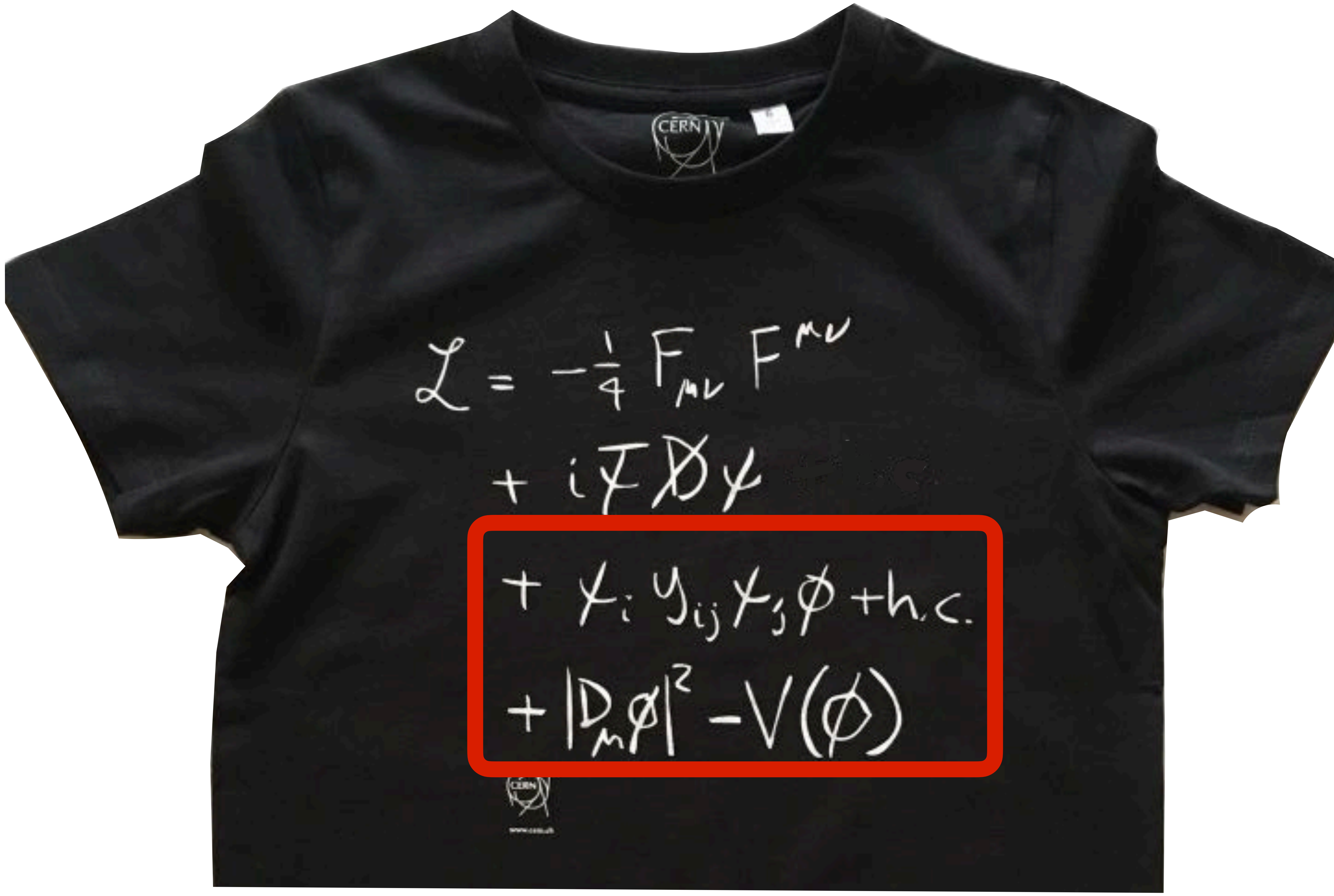

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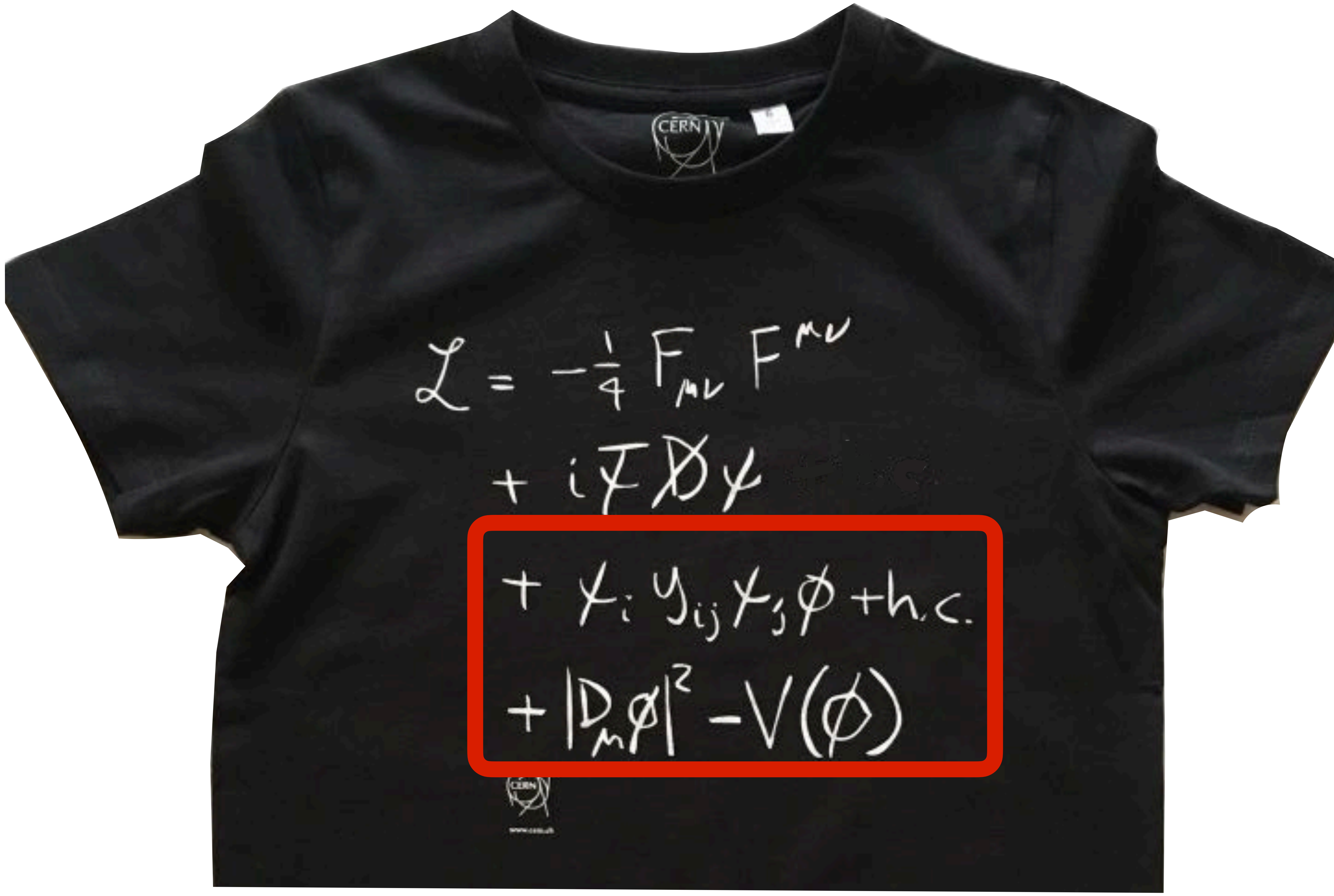
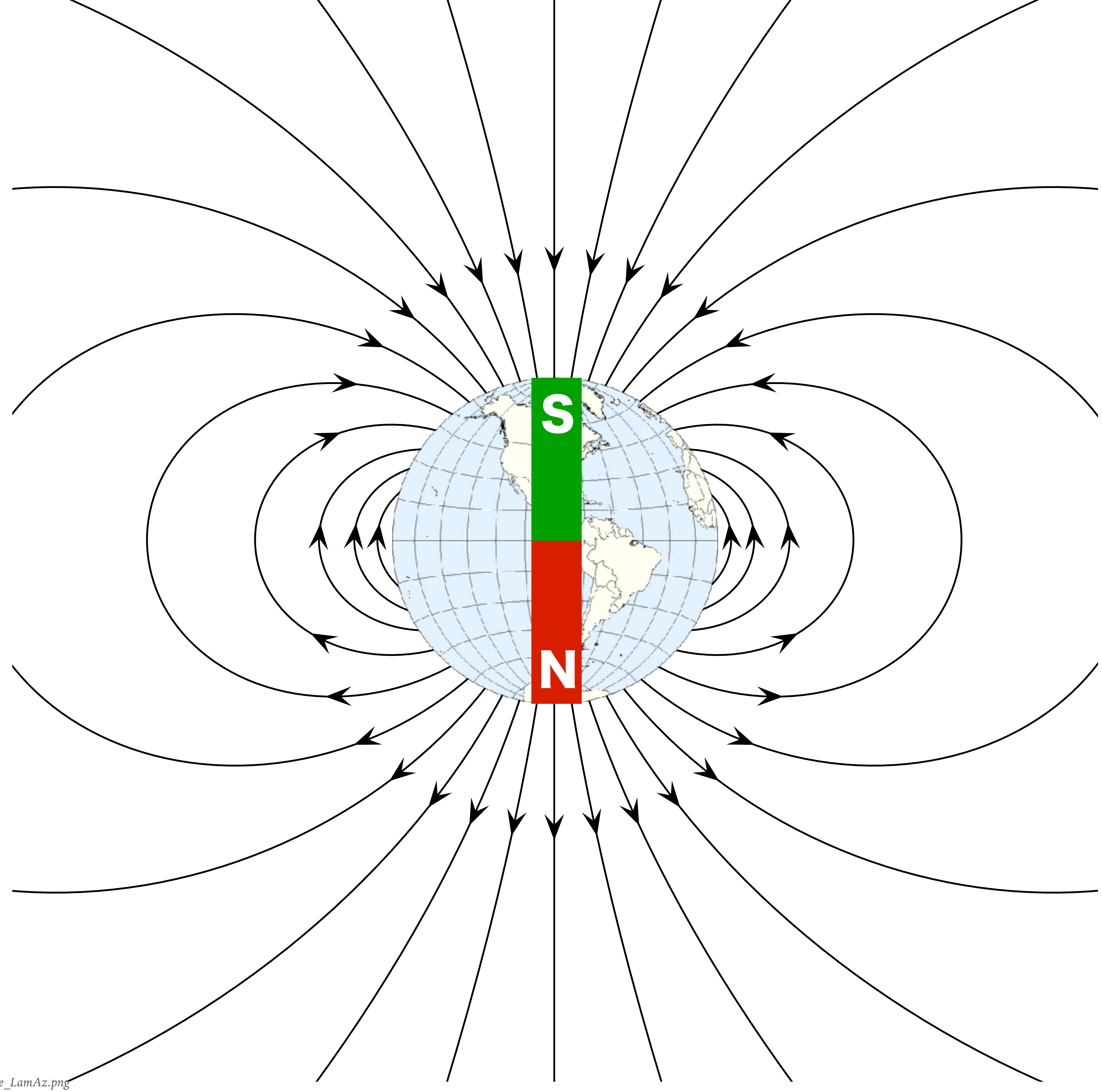
our experimental exploration of the Higgs-related SM interactions is only just starting



interactions

Higgs physics

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



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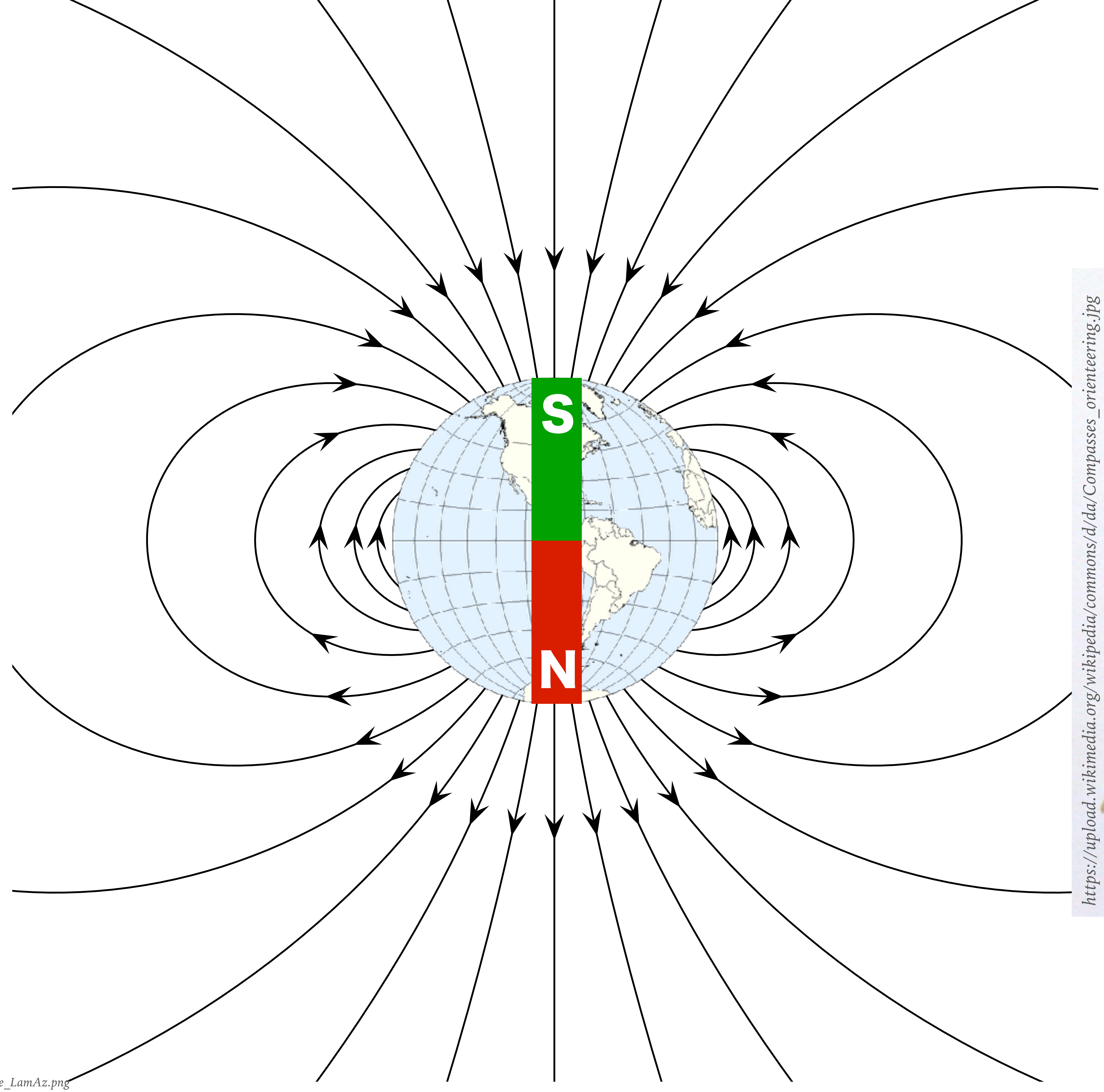

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HIGGS FIELD

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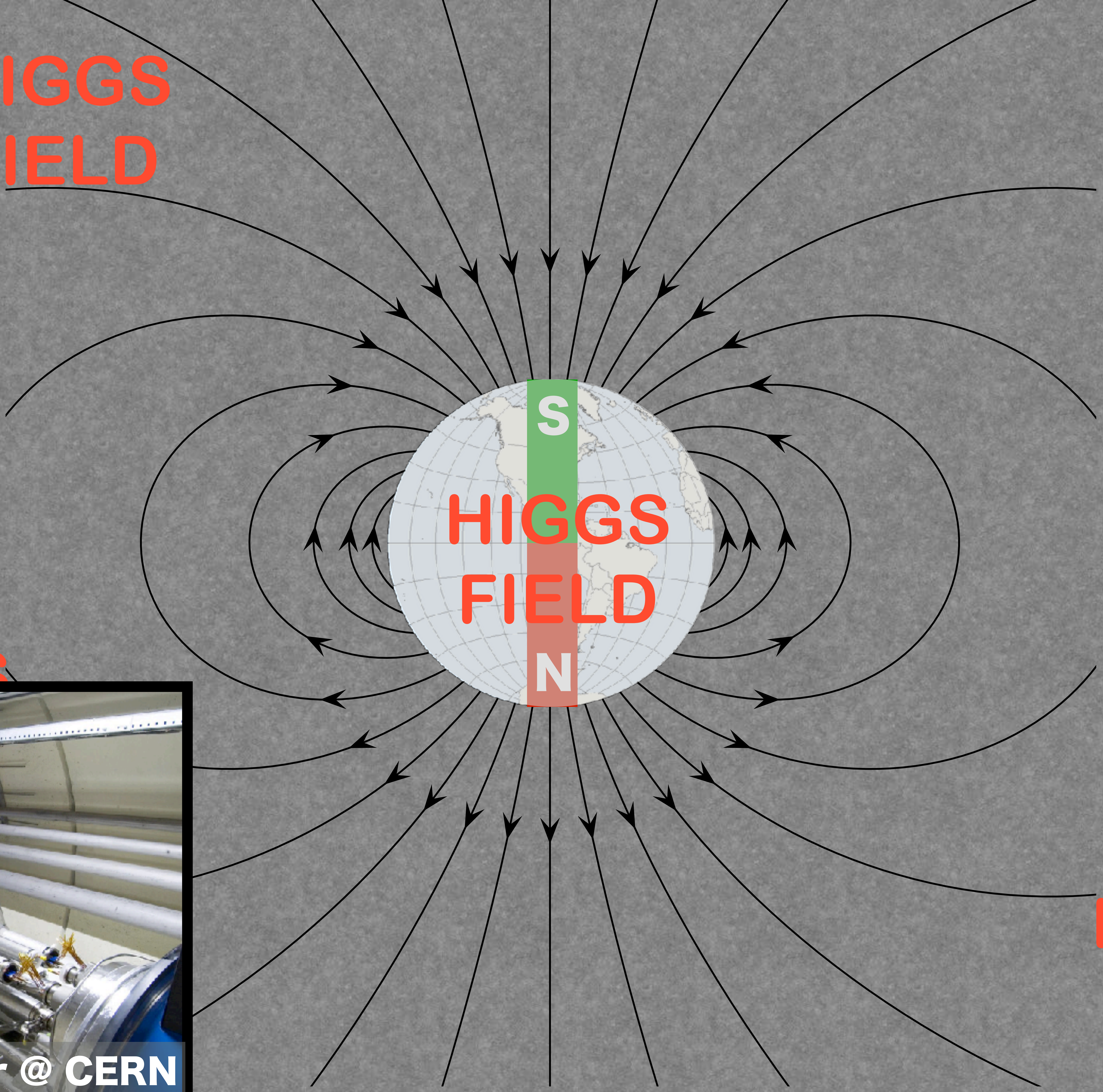

HIGGS FIELD


Large Hadron Collider @ CERN

HIGGS 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

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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

Standard Model massive particles (except ν)

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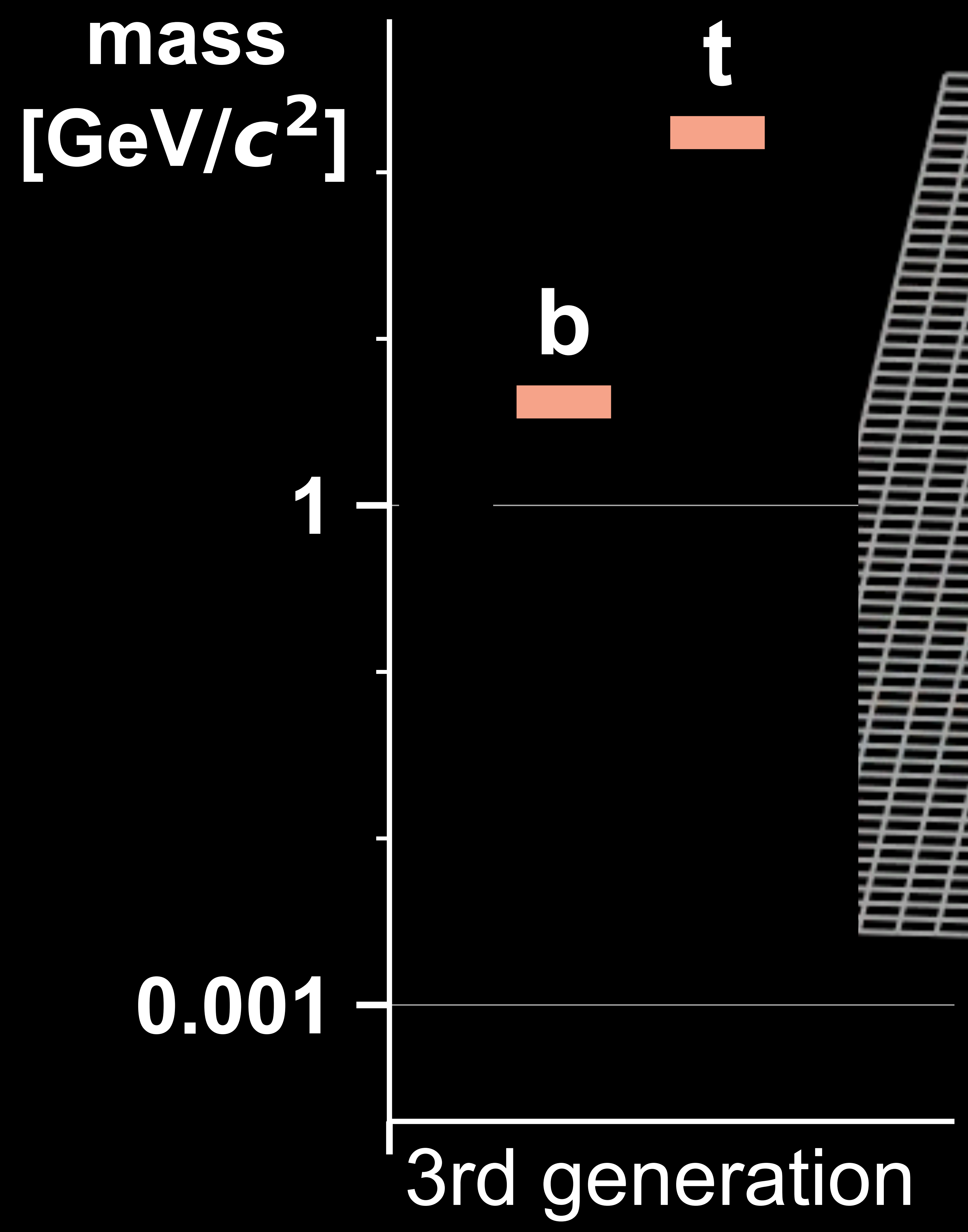
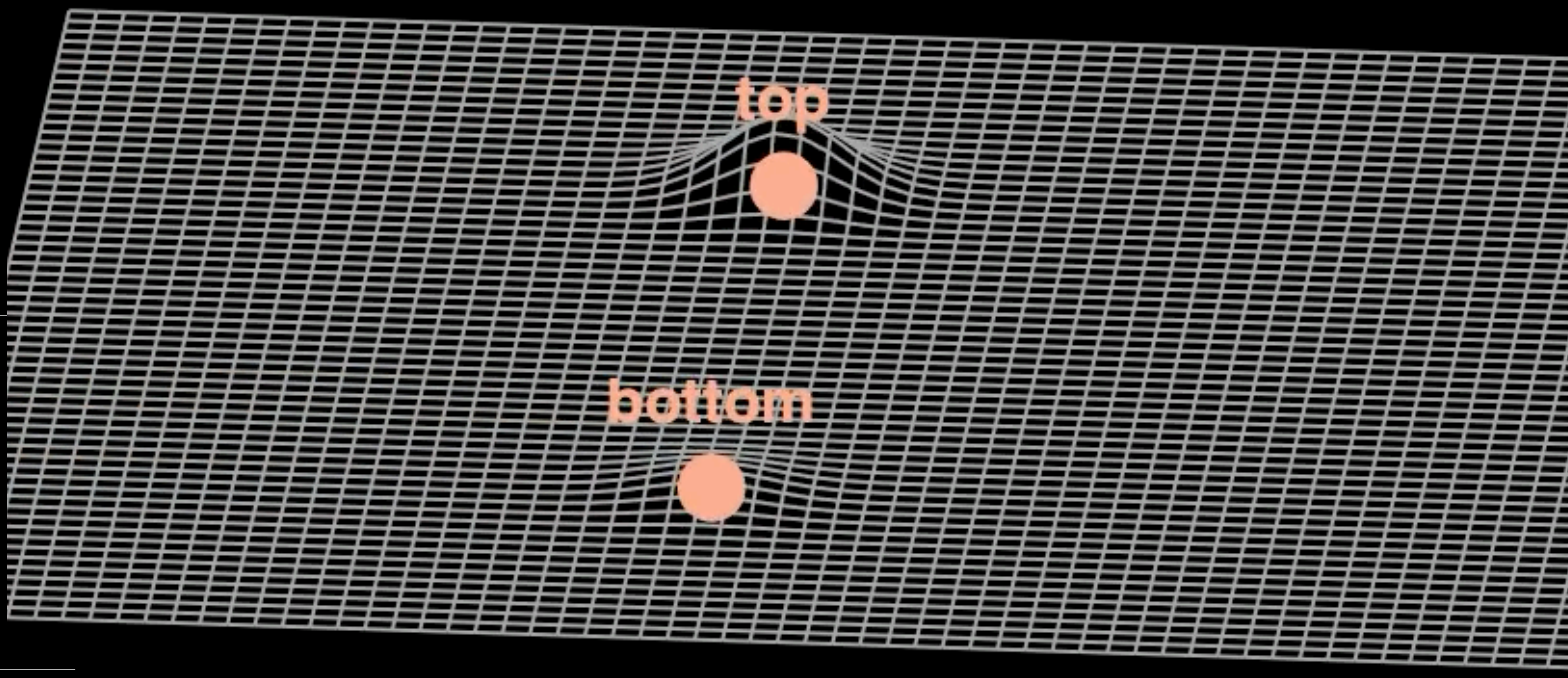
Higgs field

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

Higgs field





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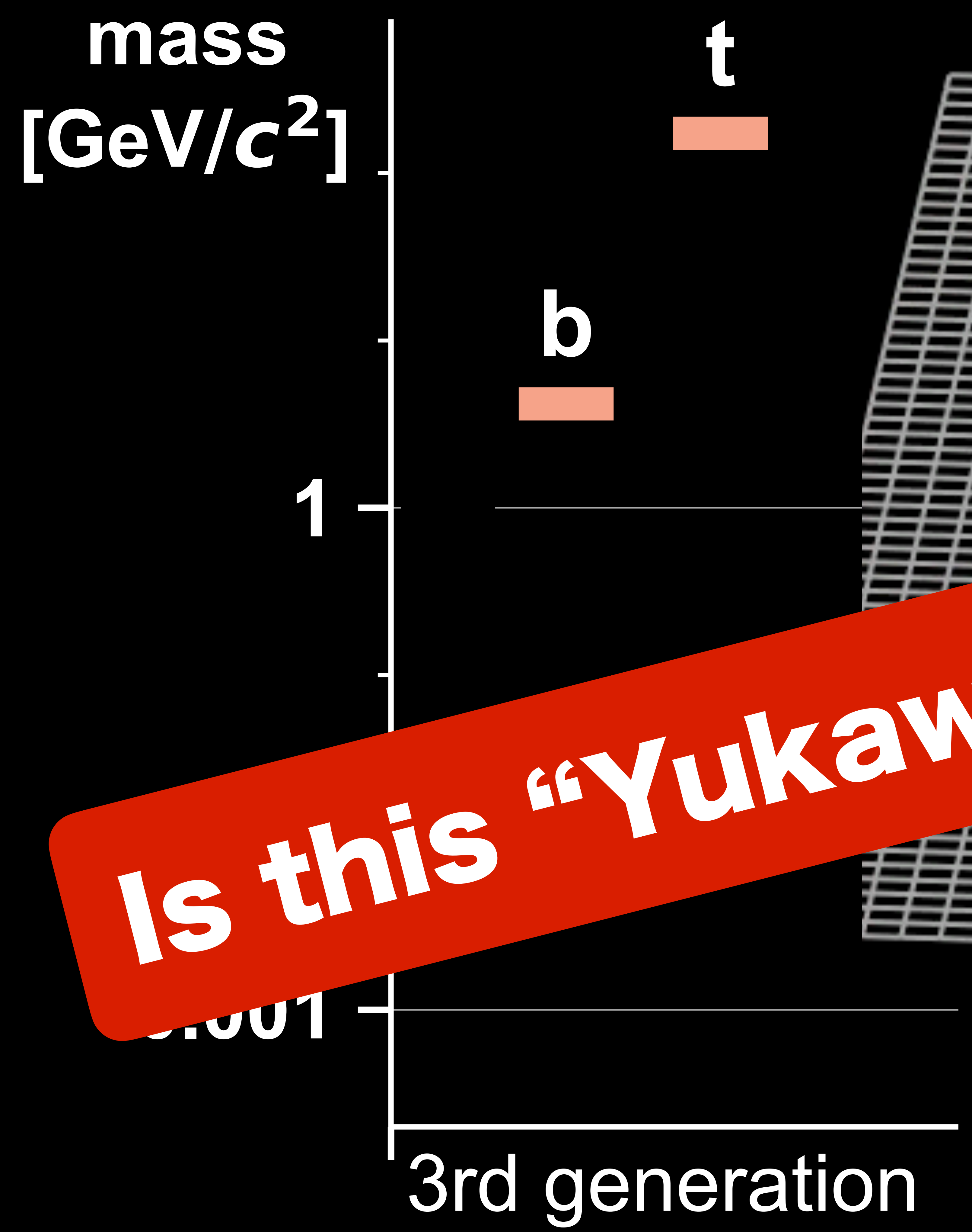

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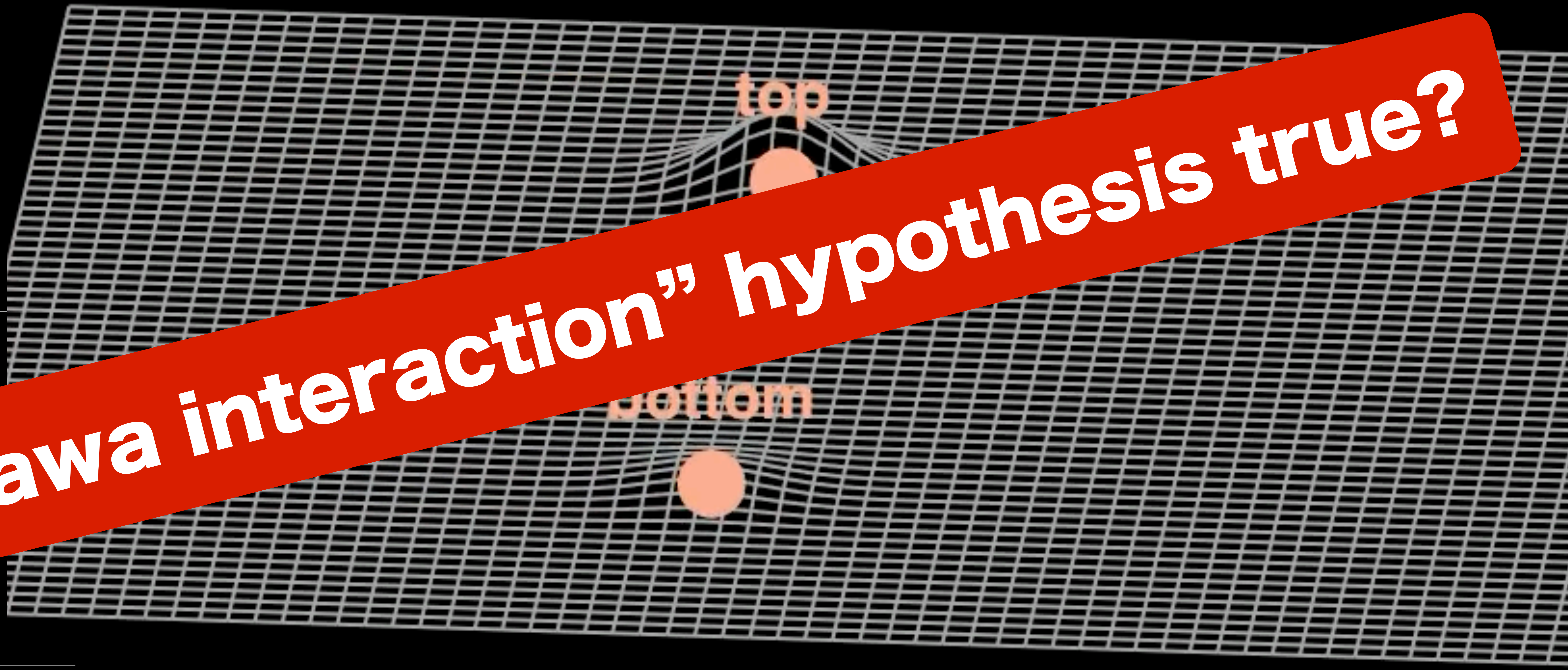
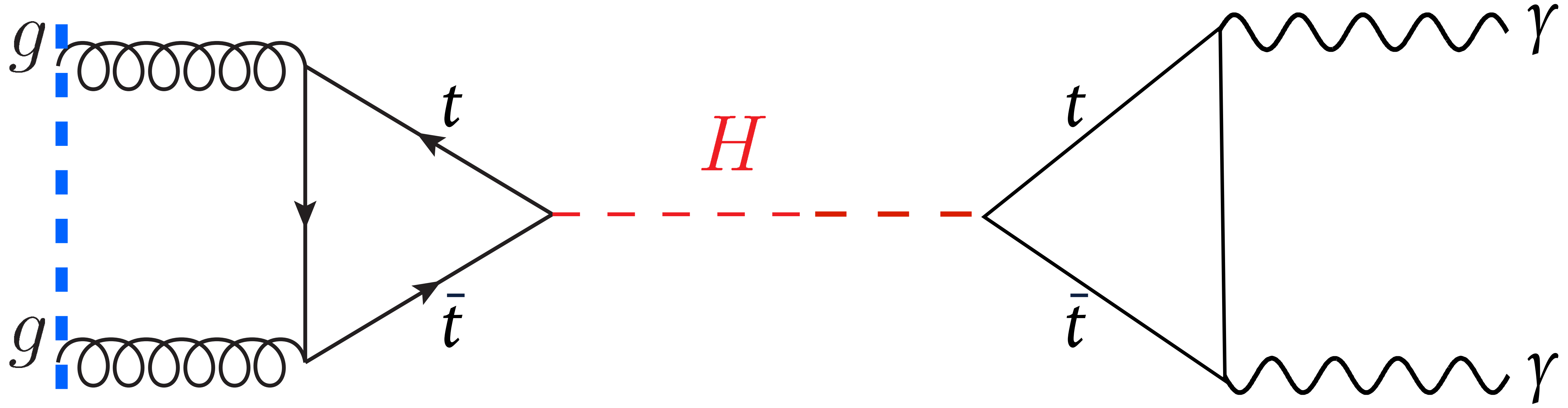


Is this “Yukawa interaction” hypothesis true?

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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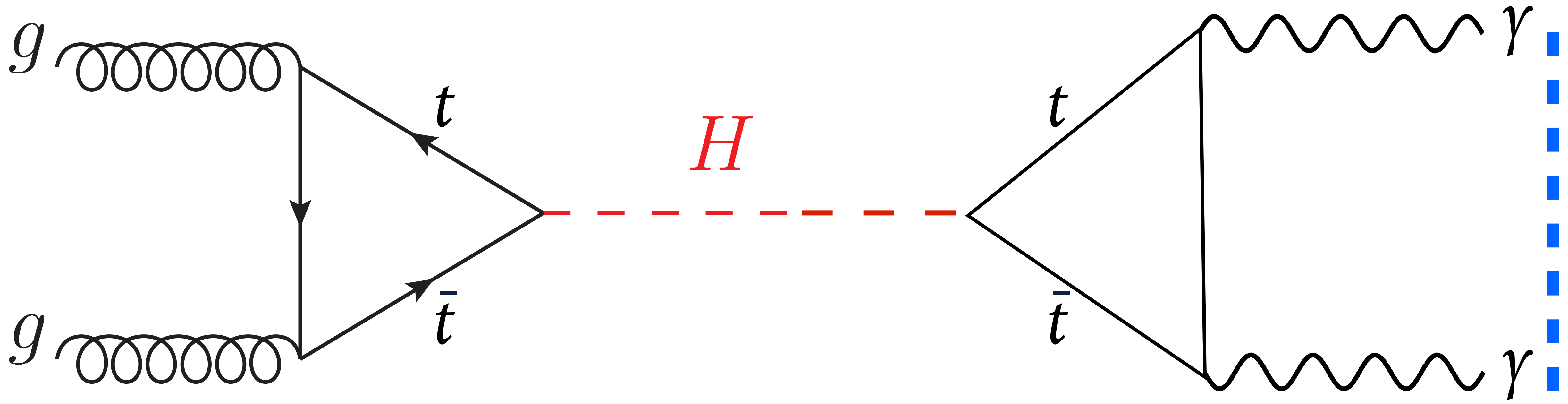
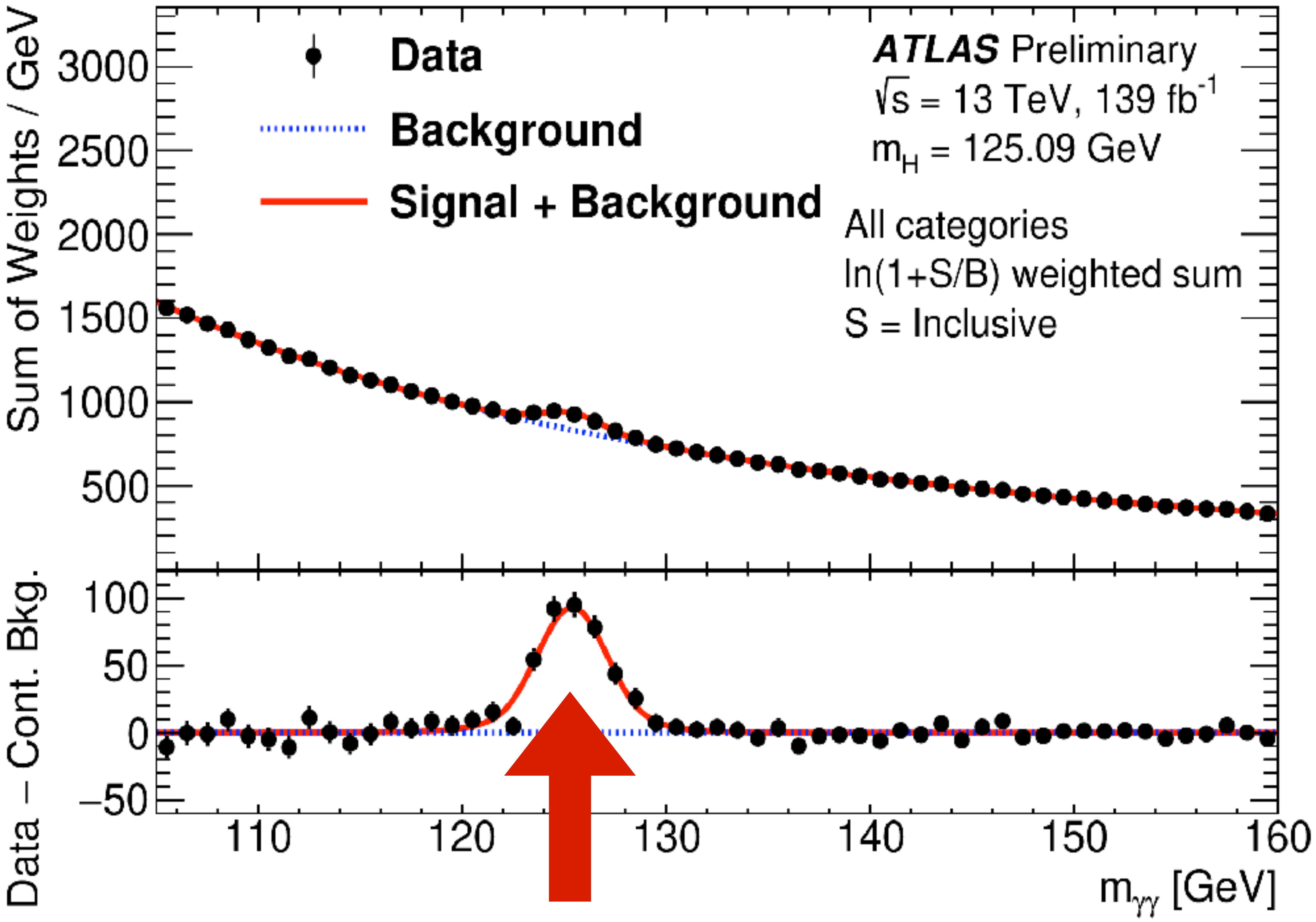


- Record events with two photons;
- classify and count them according to the energy of the two photons (γ)



more events at specific energy = Higgs bosons

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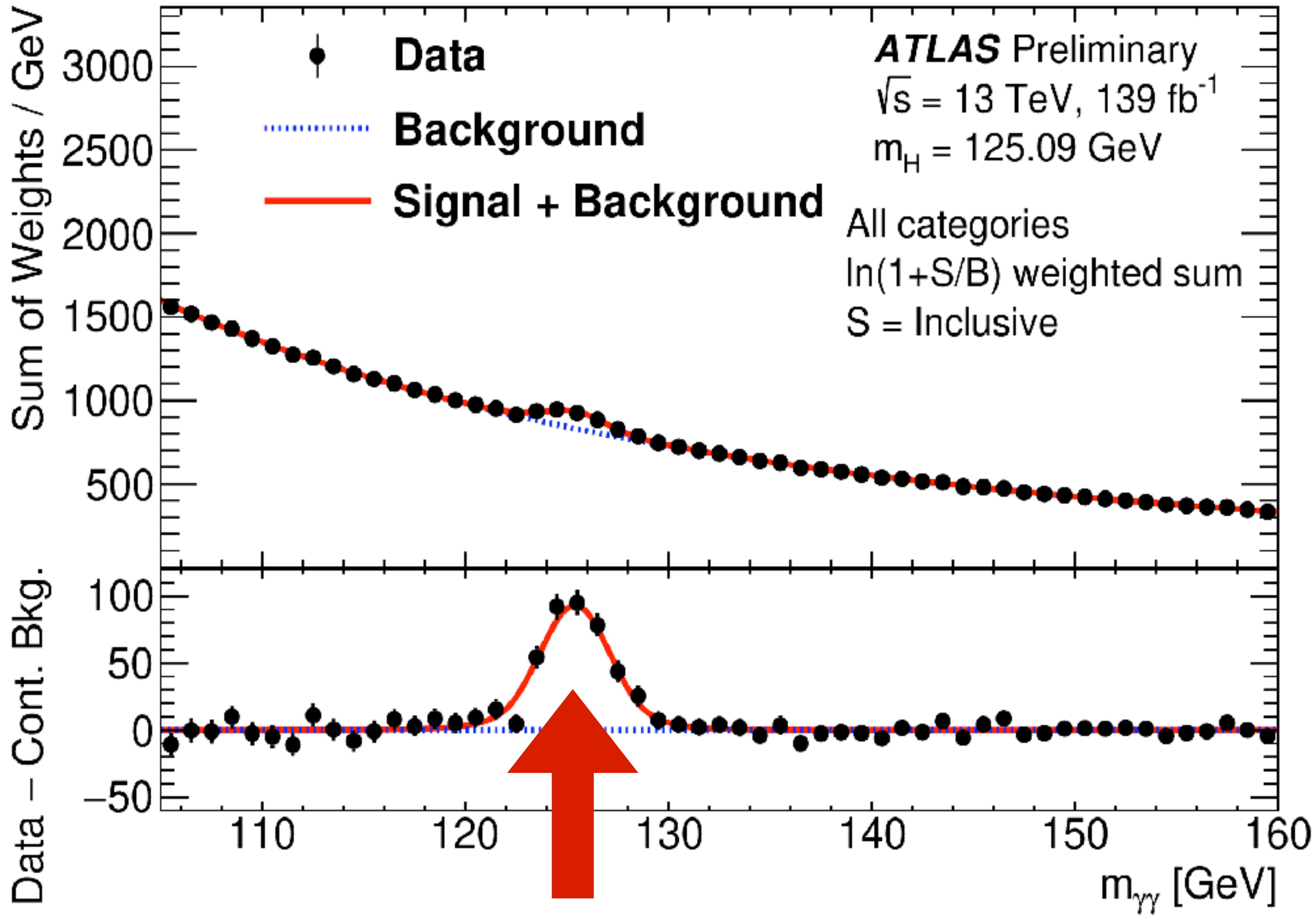

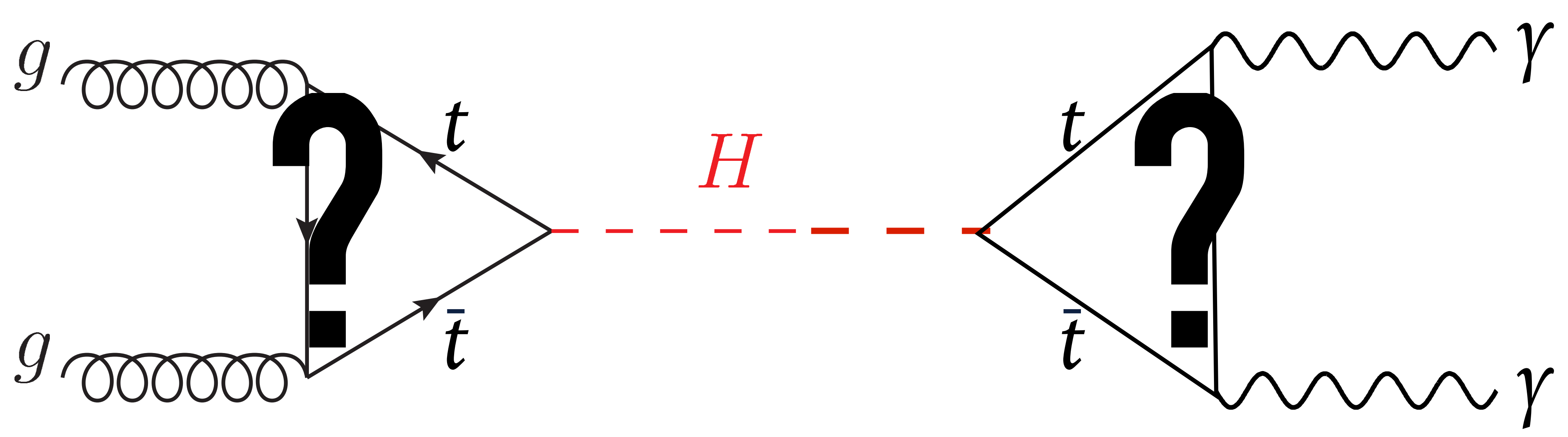

rate of events consistent with SM to ~10%

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

more events at specific energy = Higgs bosons

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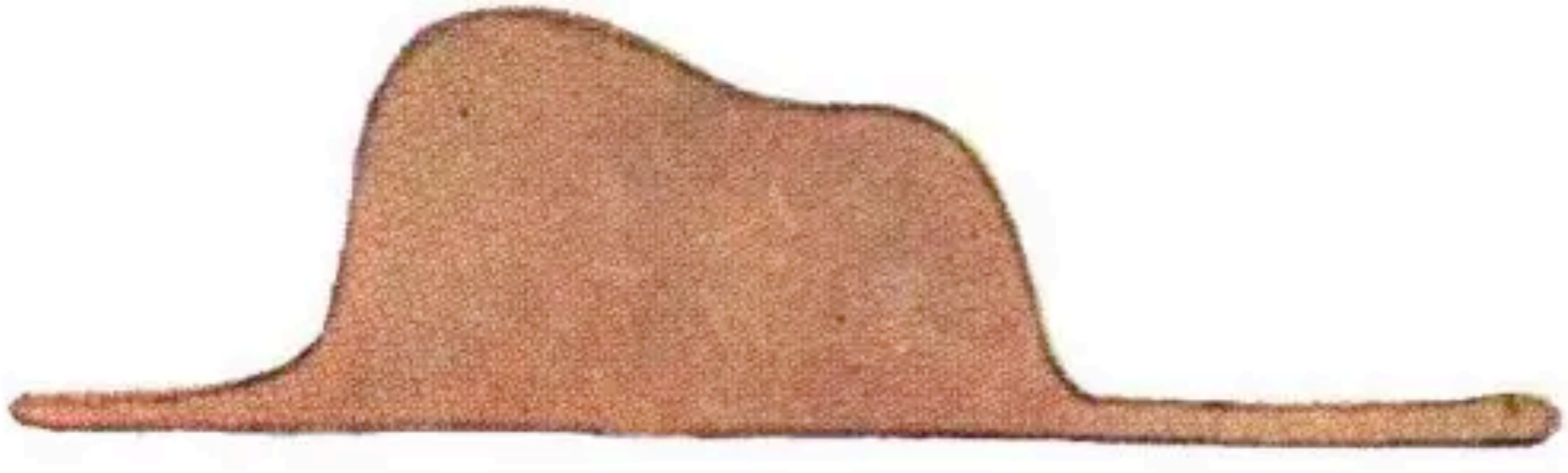

« Pourquoi un chapeau ferait-il peur ? »

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

Le Petit Prince, Antoine de Saint-Exupéry

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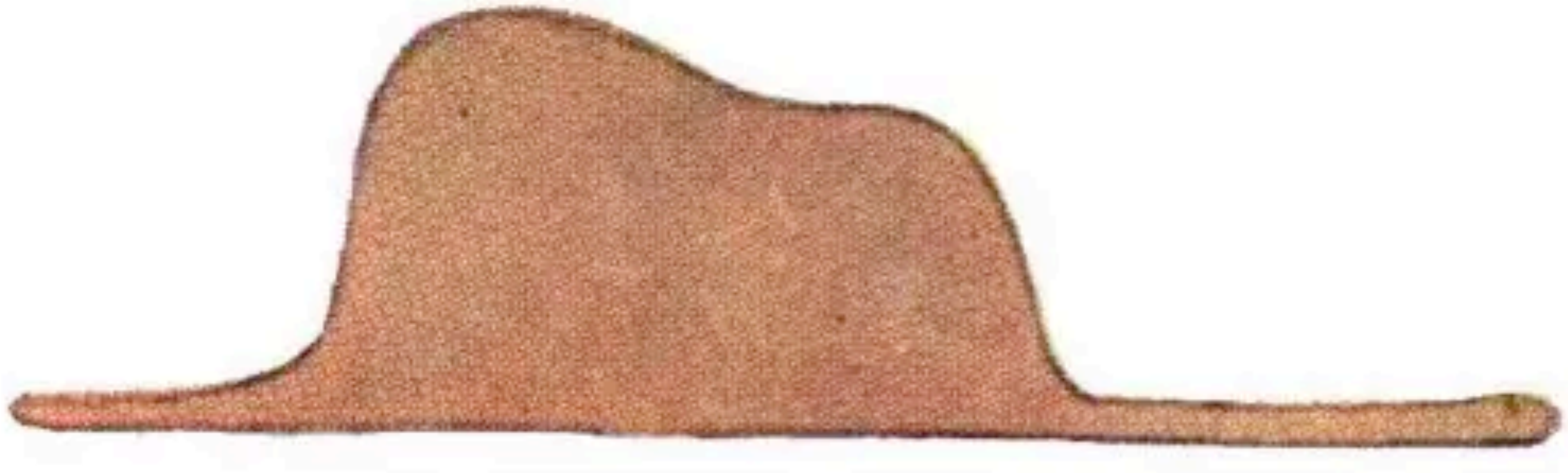

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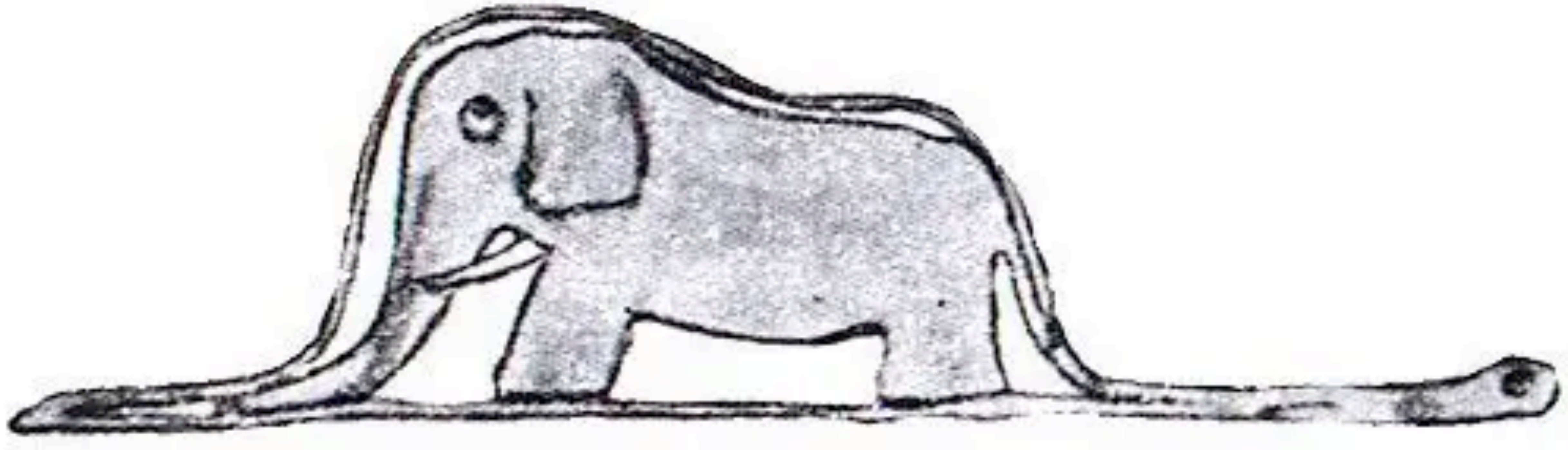

Mon dessin numéro 2

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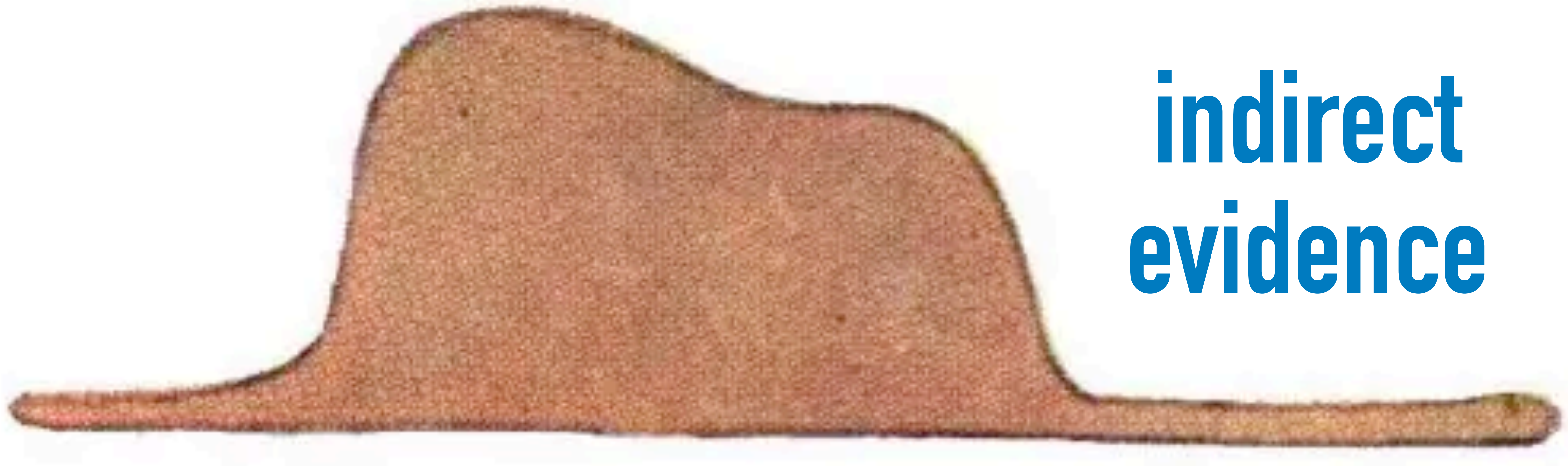

indirect evidence

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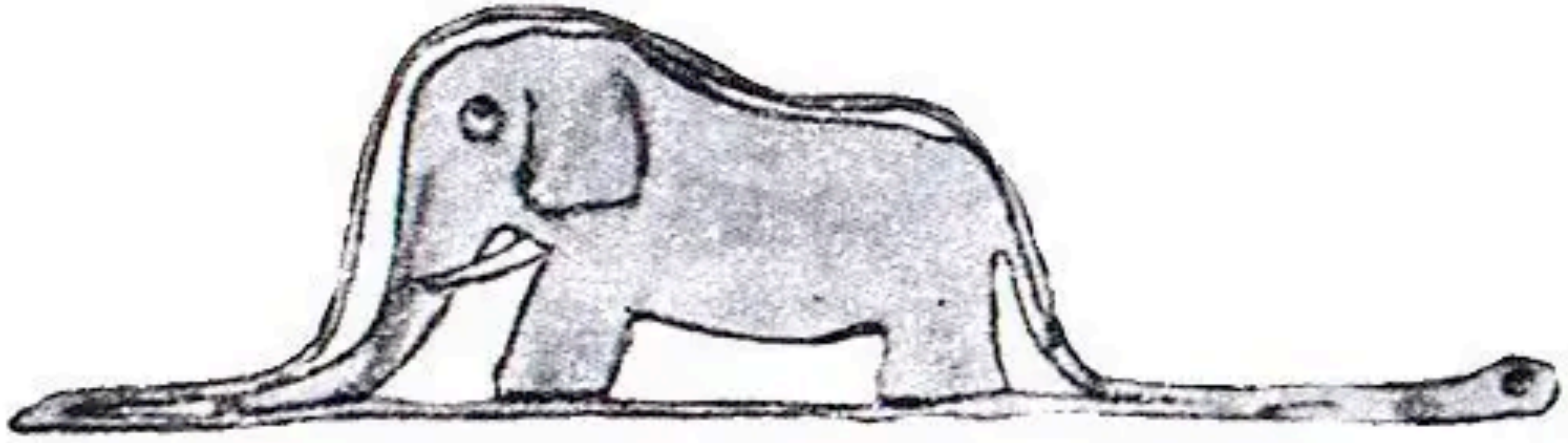

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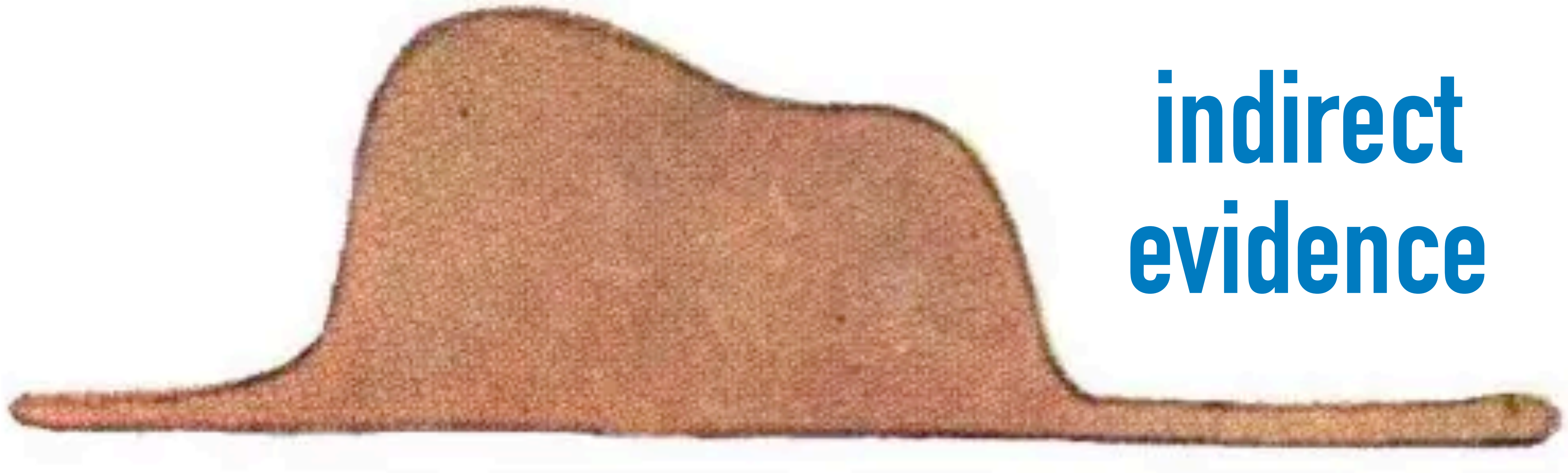

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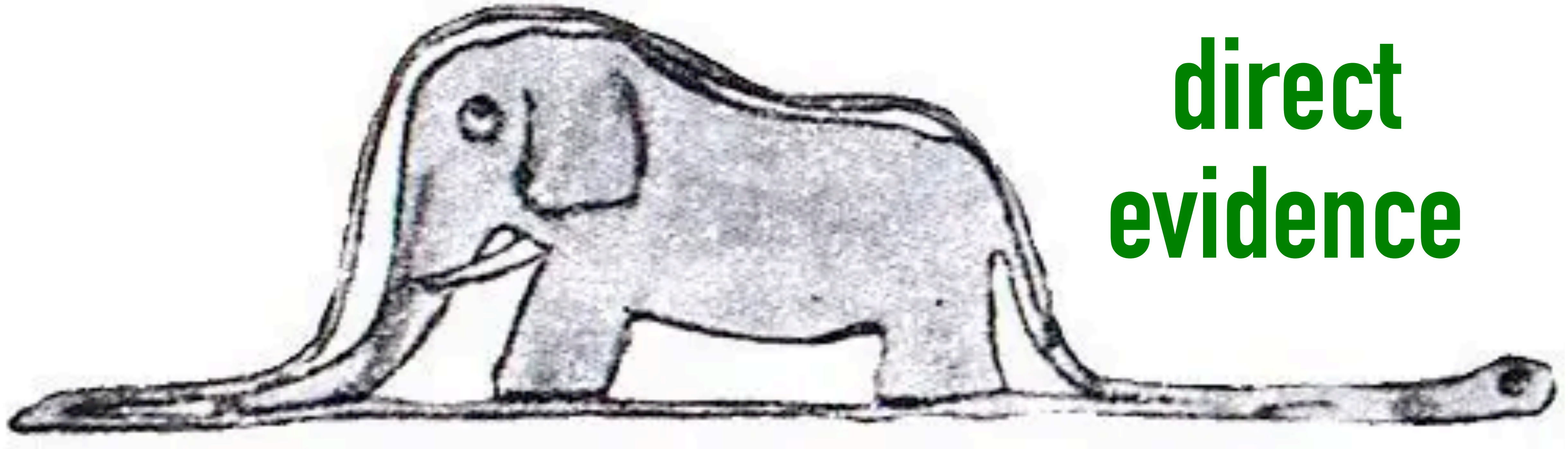

direct evidence

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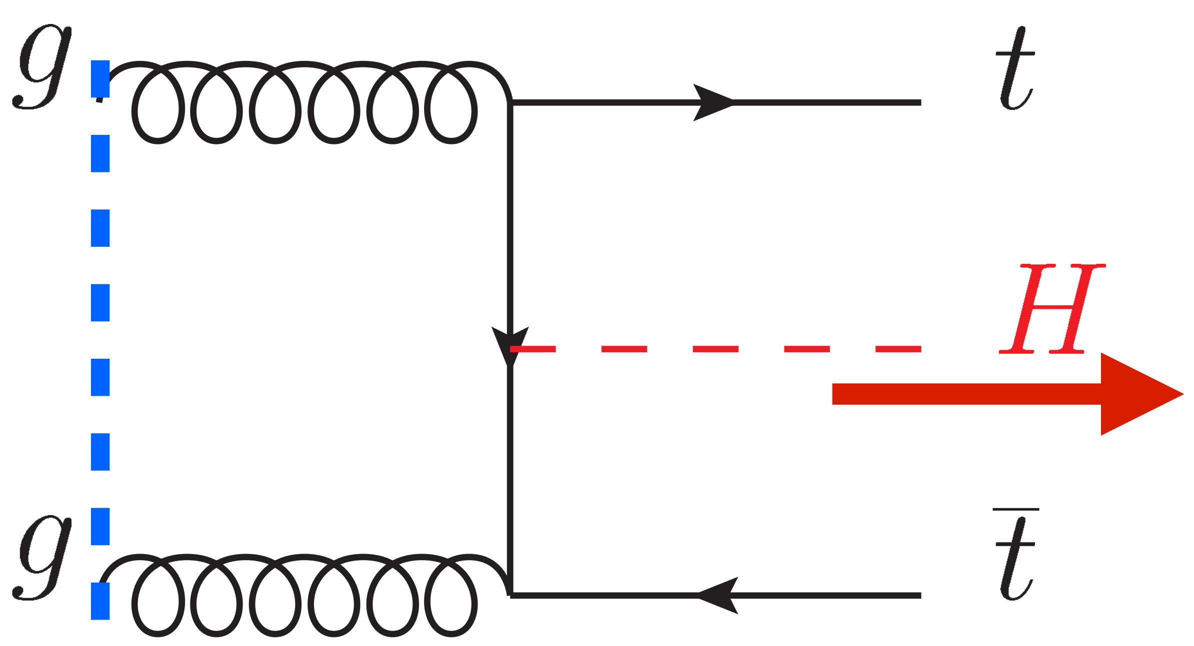
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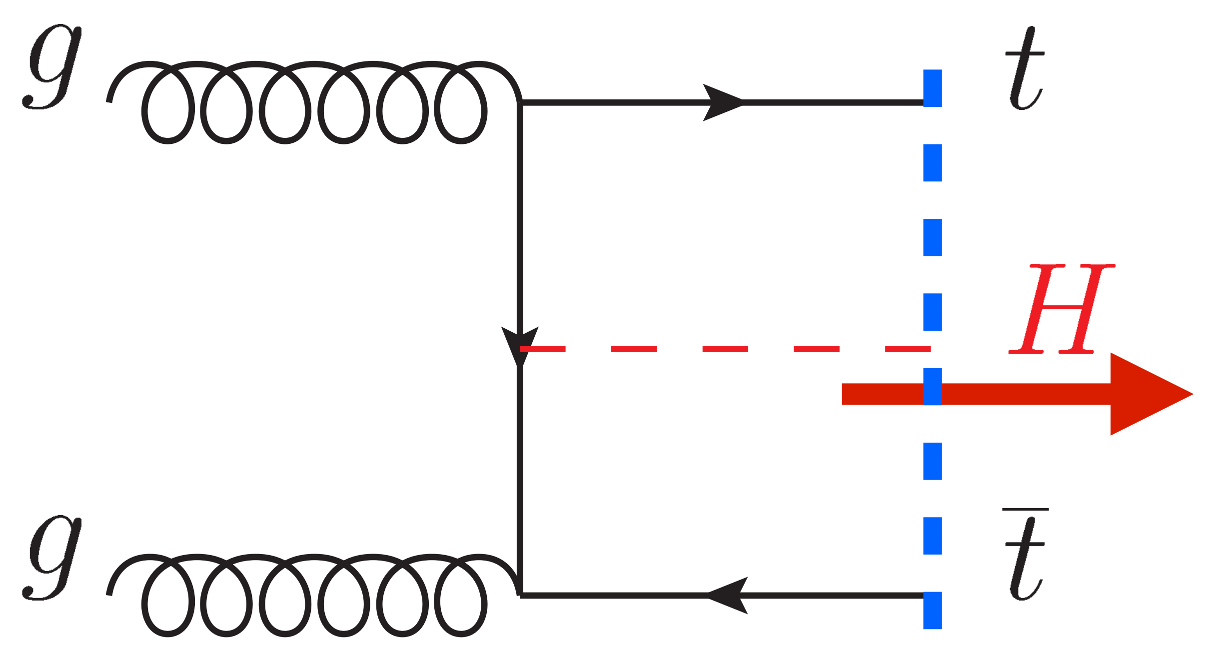
Higgs field in space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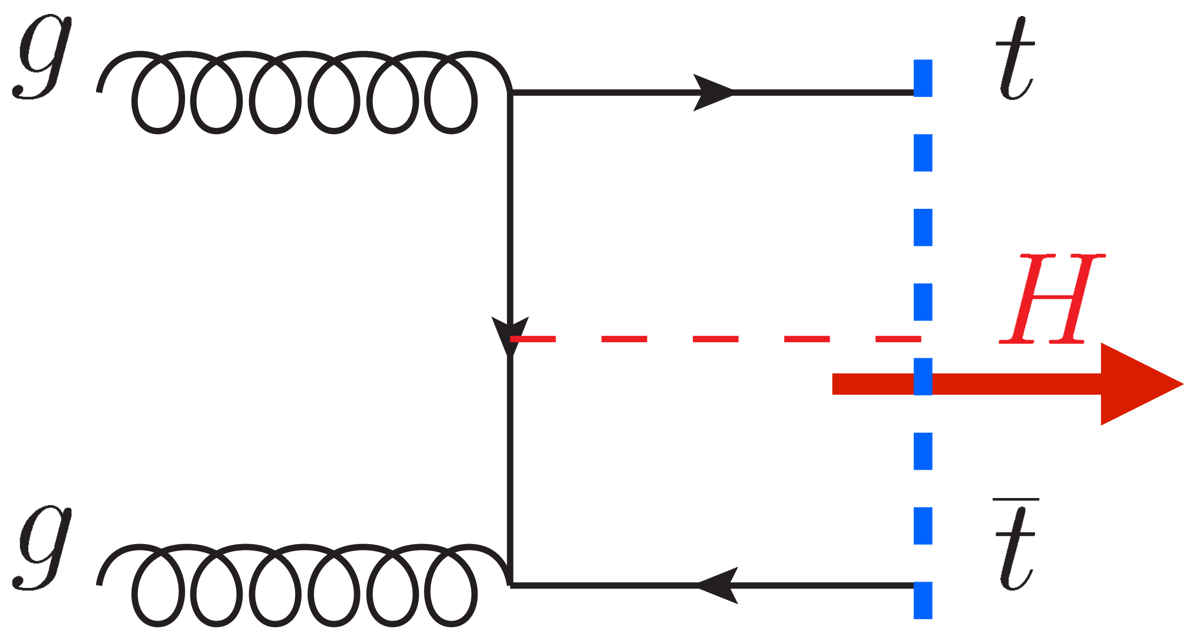
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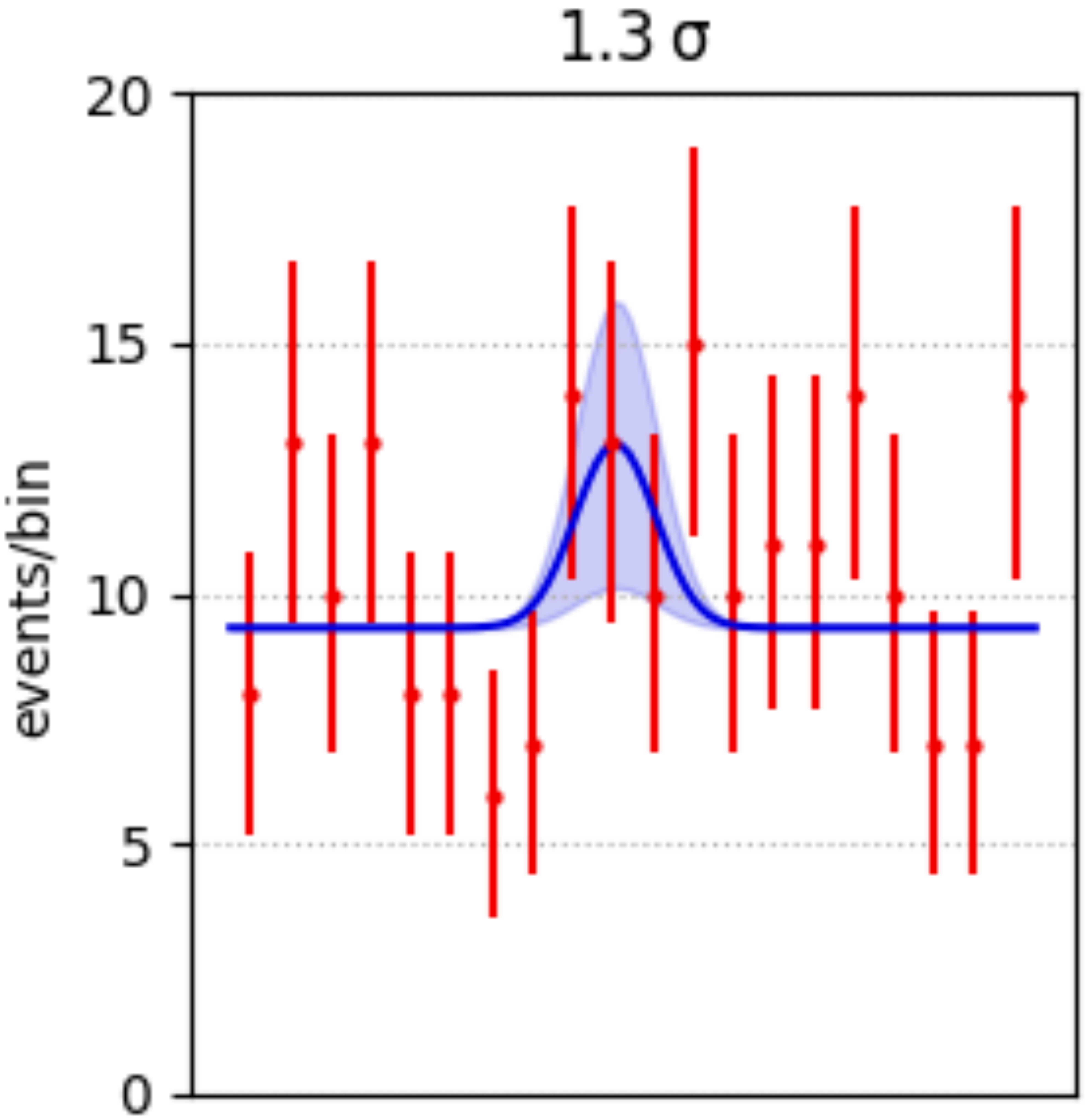
Situation at start of LHC (2009)

"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]



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

3σ: "evidence"
(if you're not expecting it, don't be surprised if it goes away with more data!)

5σ: "observation"
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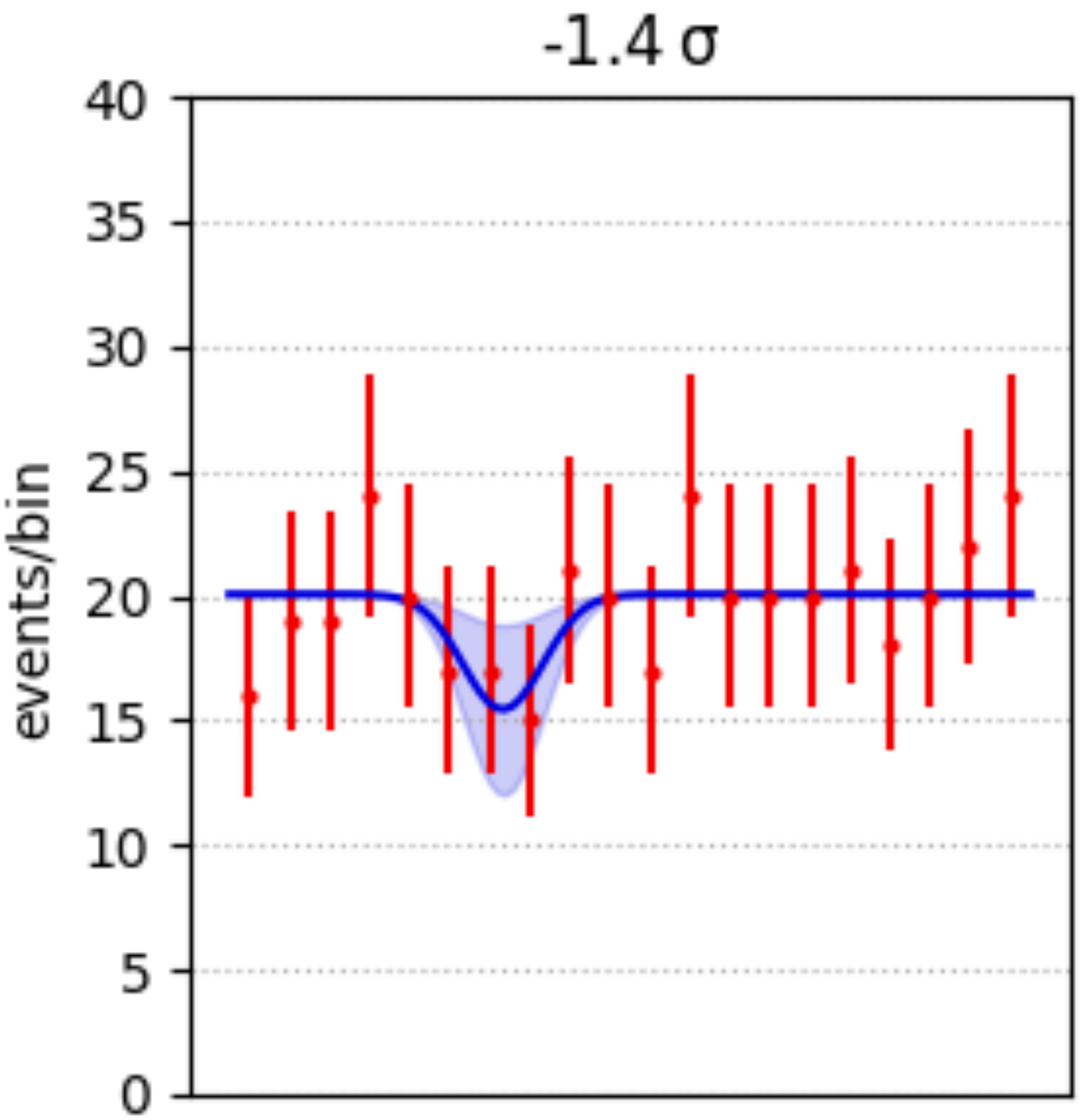

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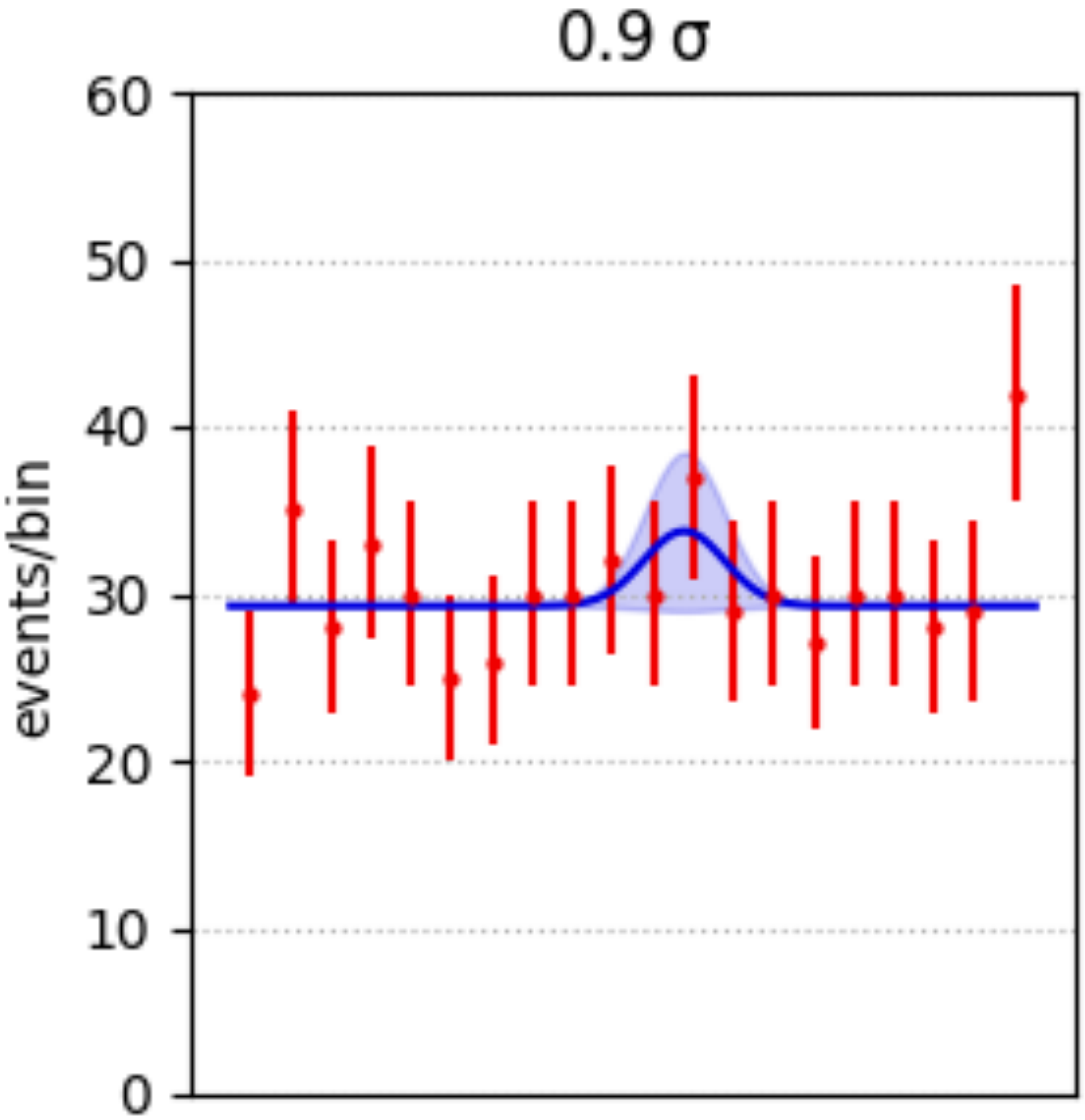

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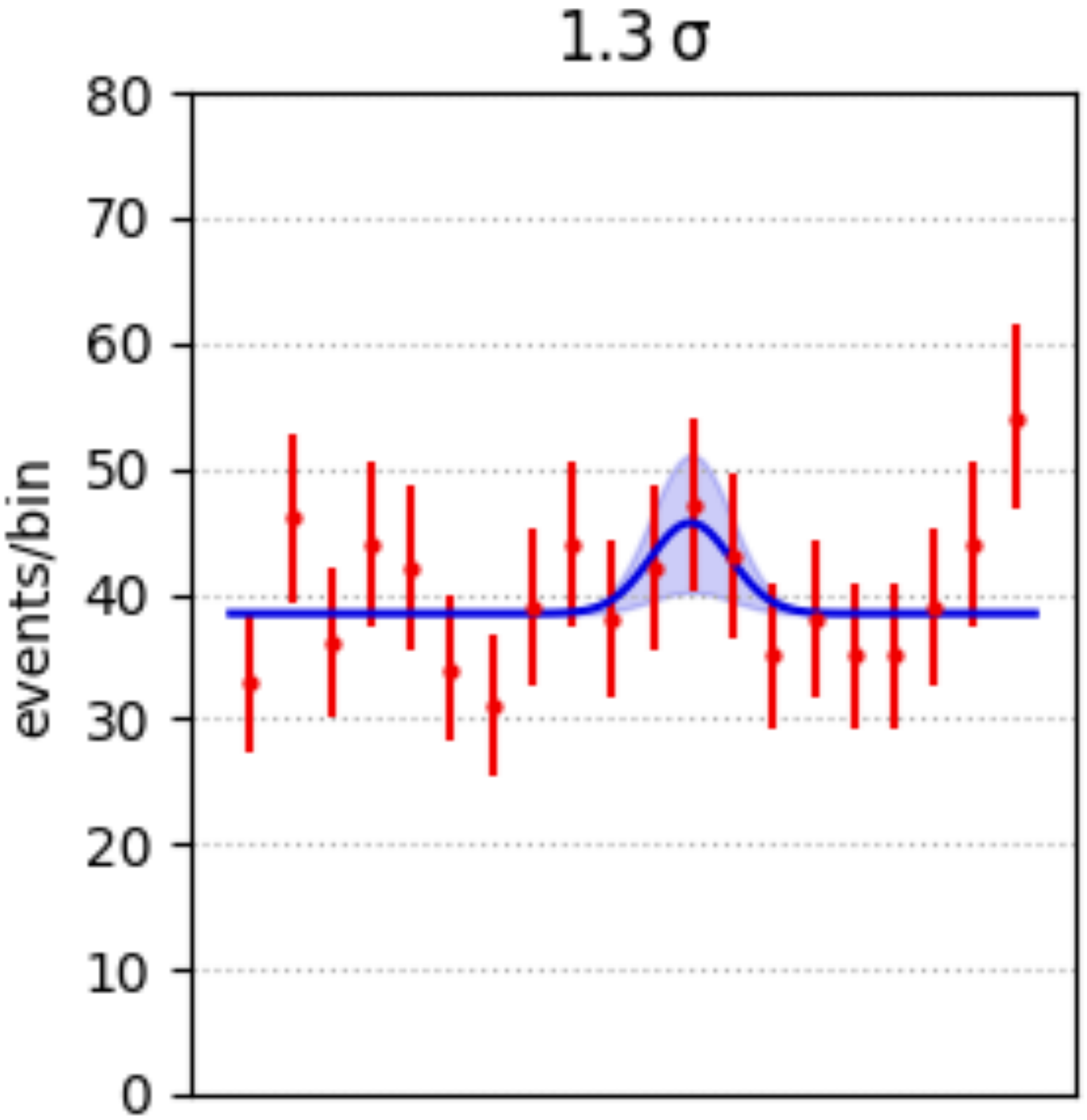

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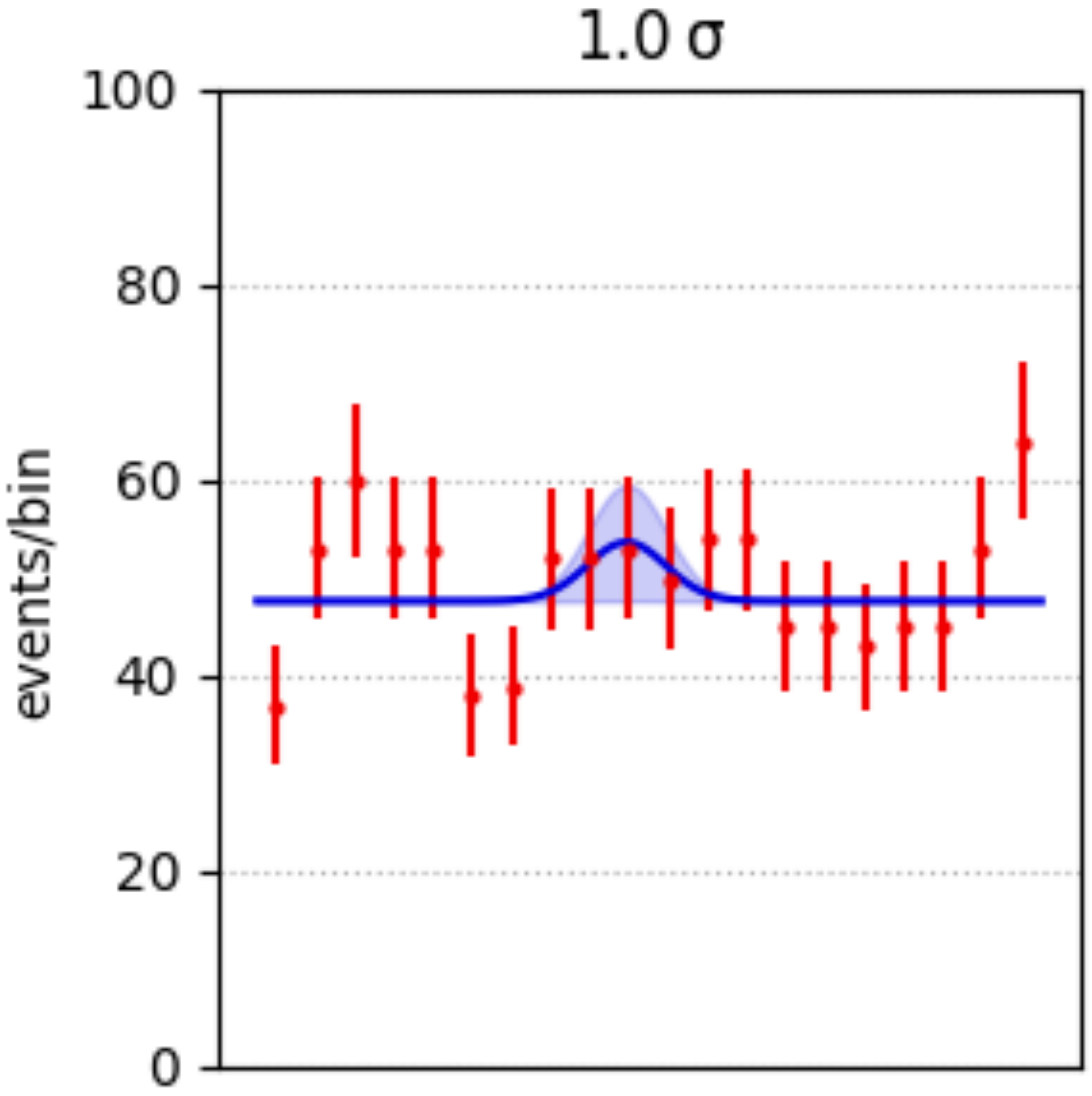

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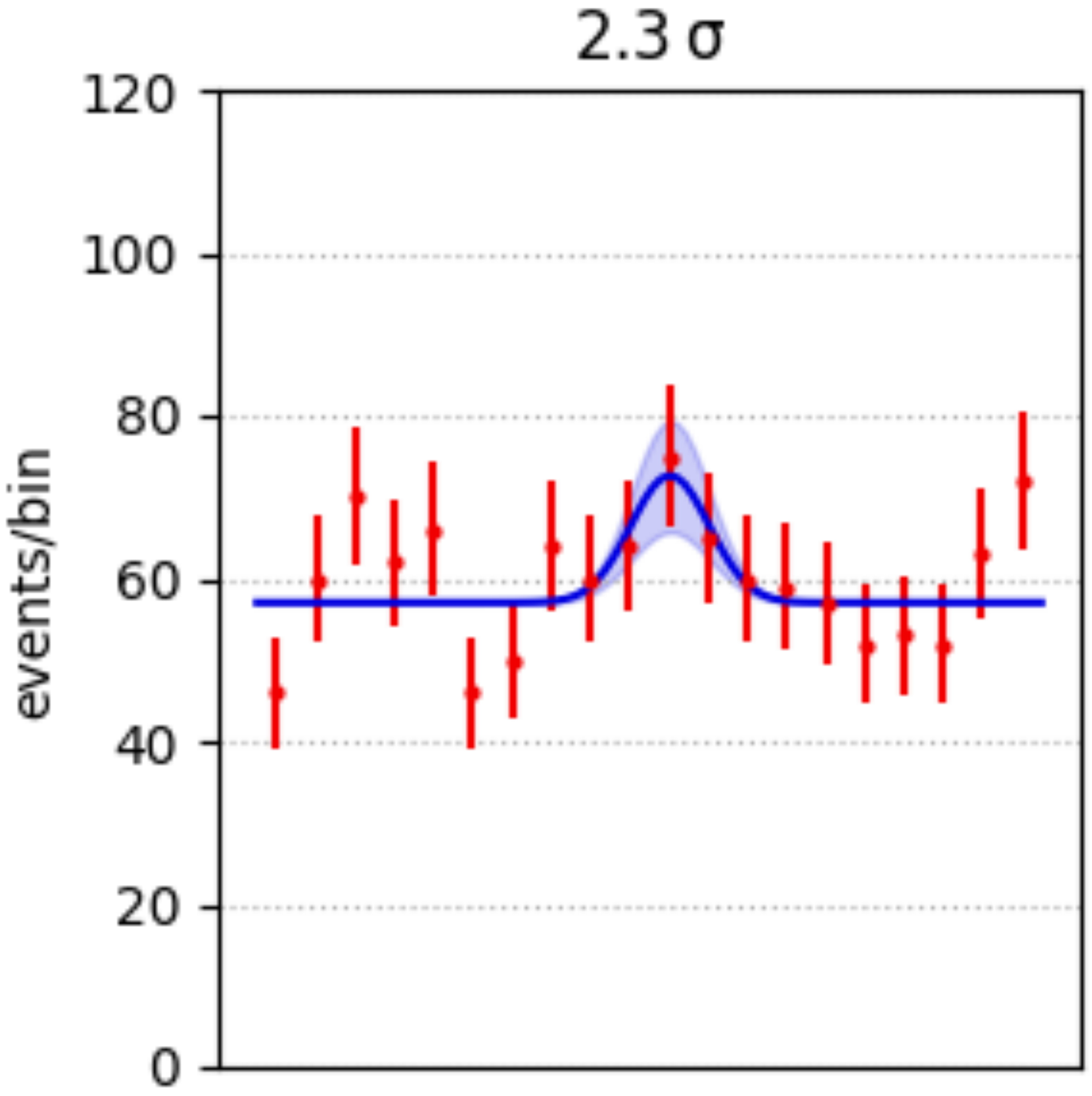

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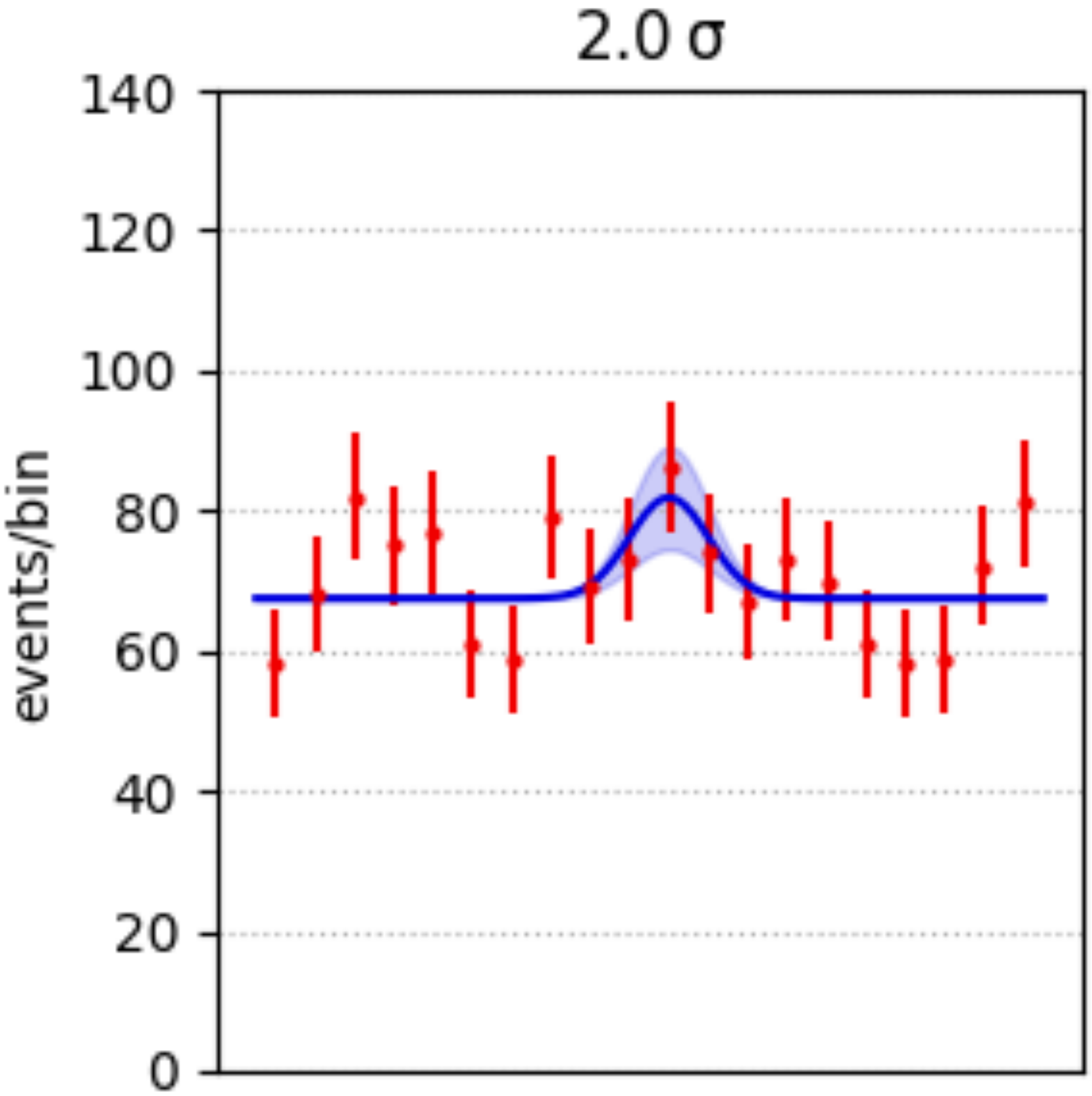

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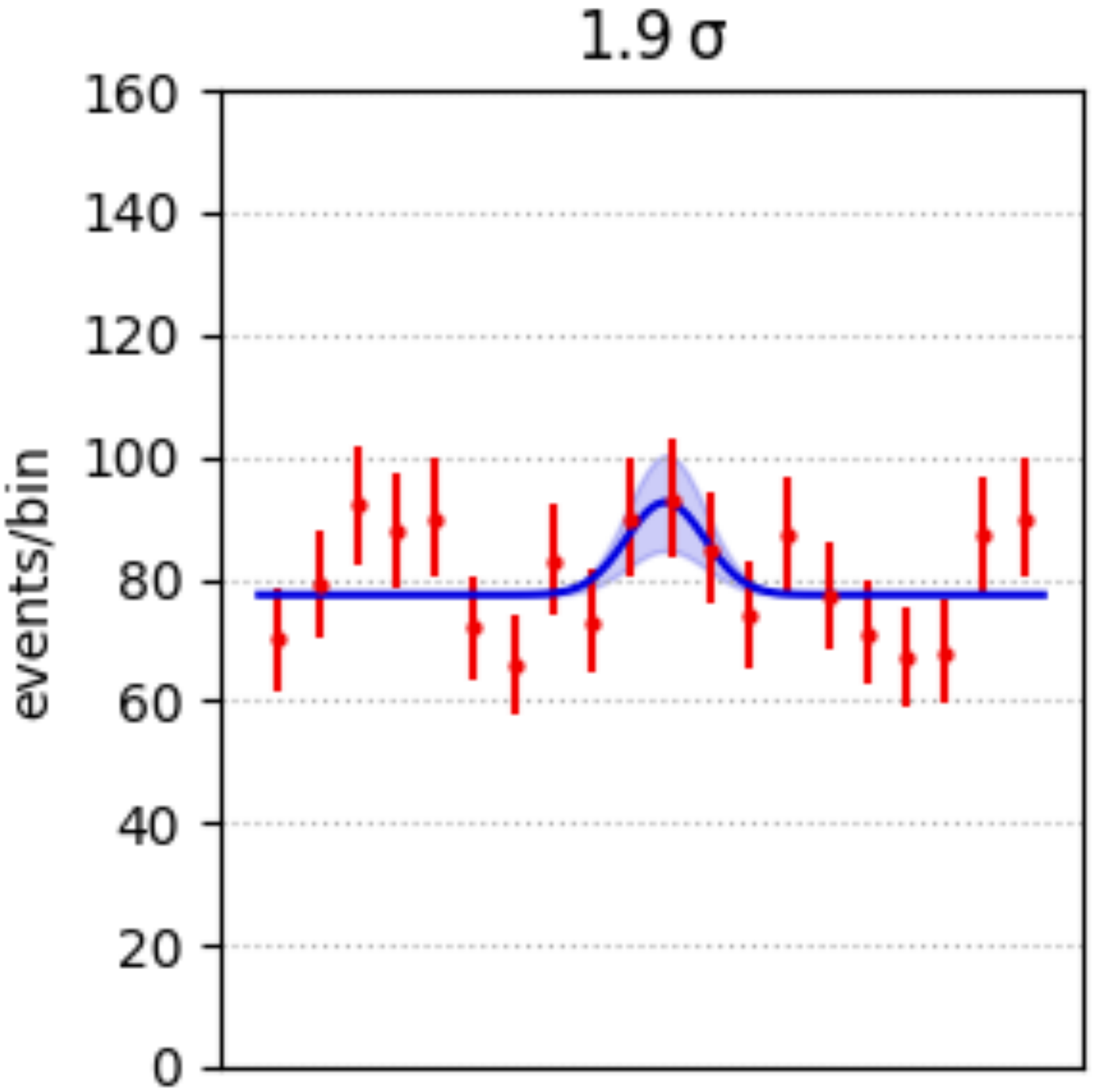

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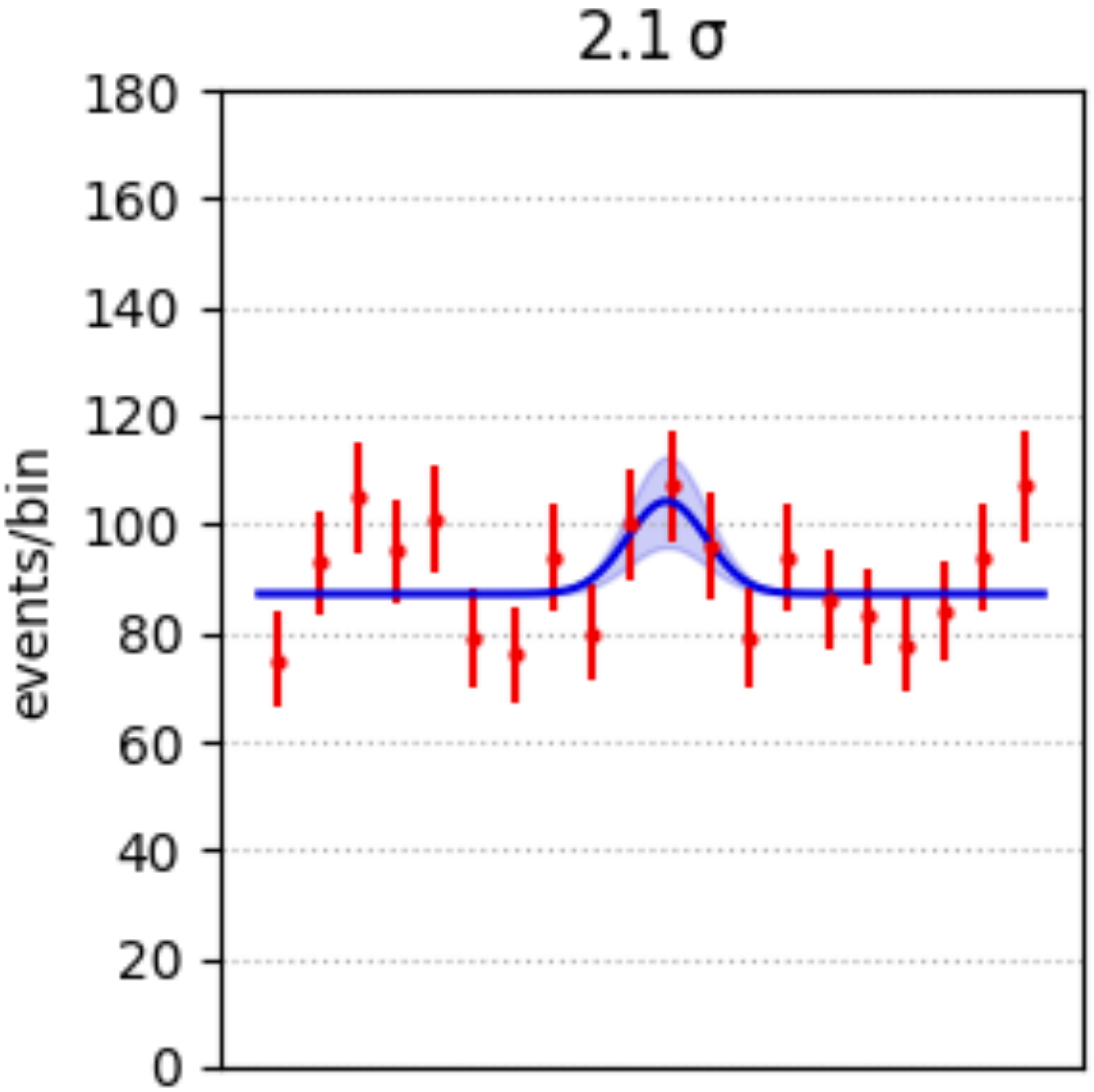

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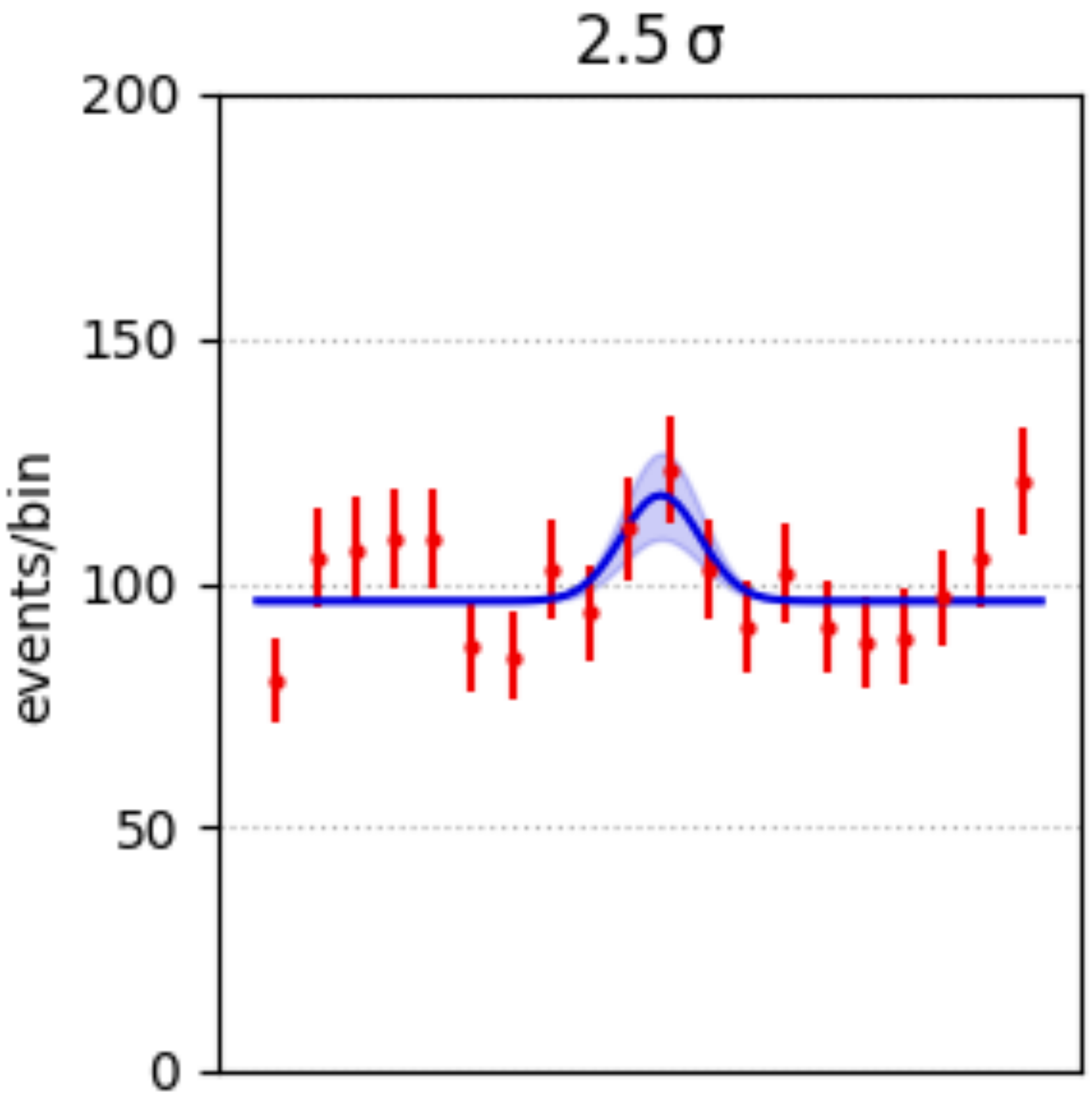

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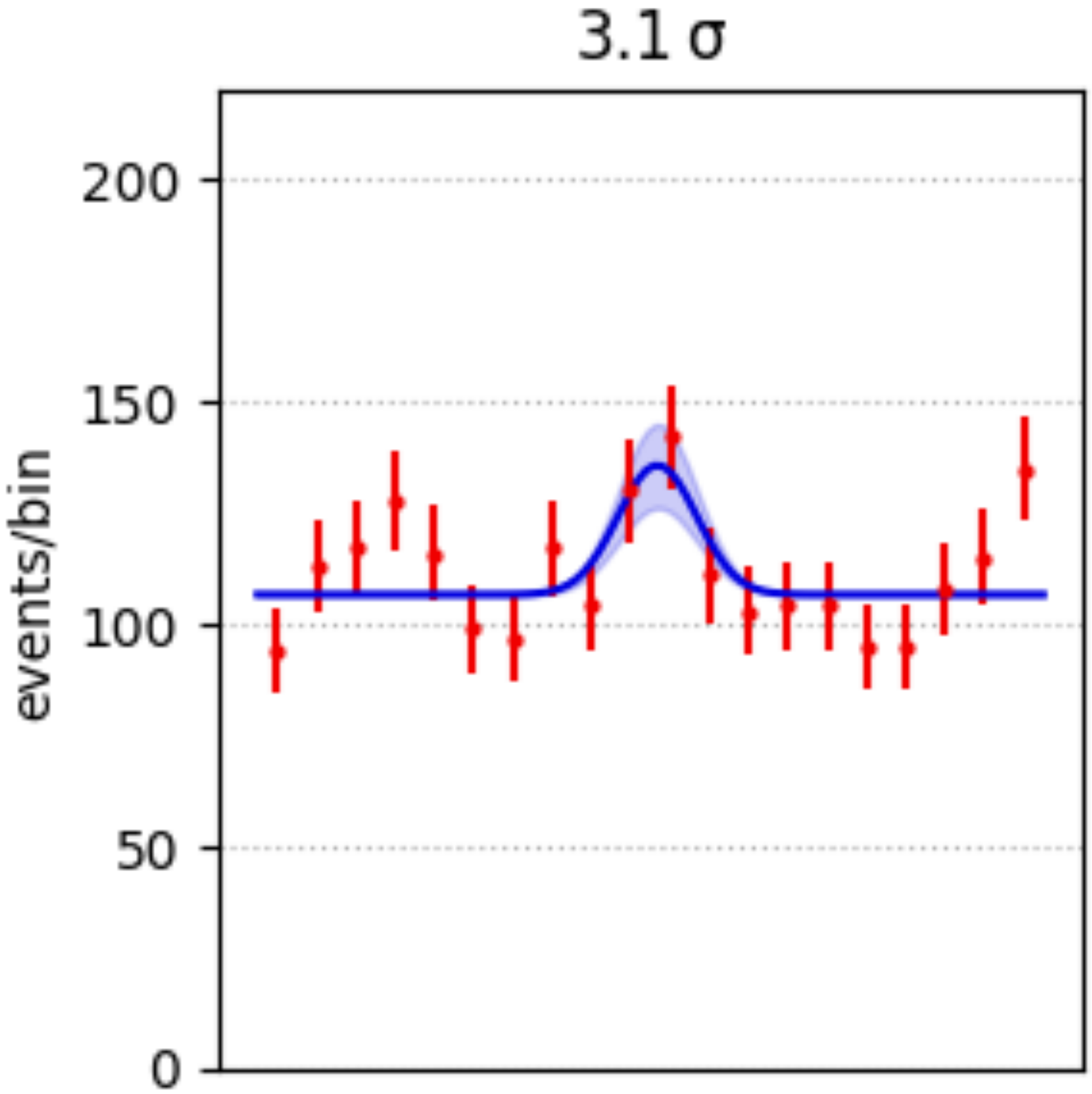

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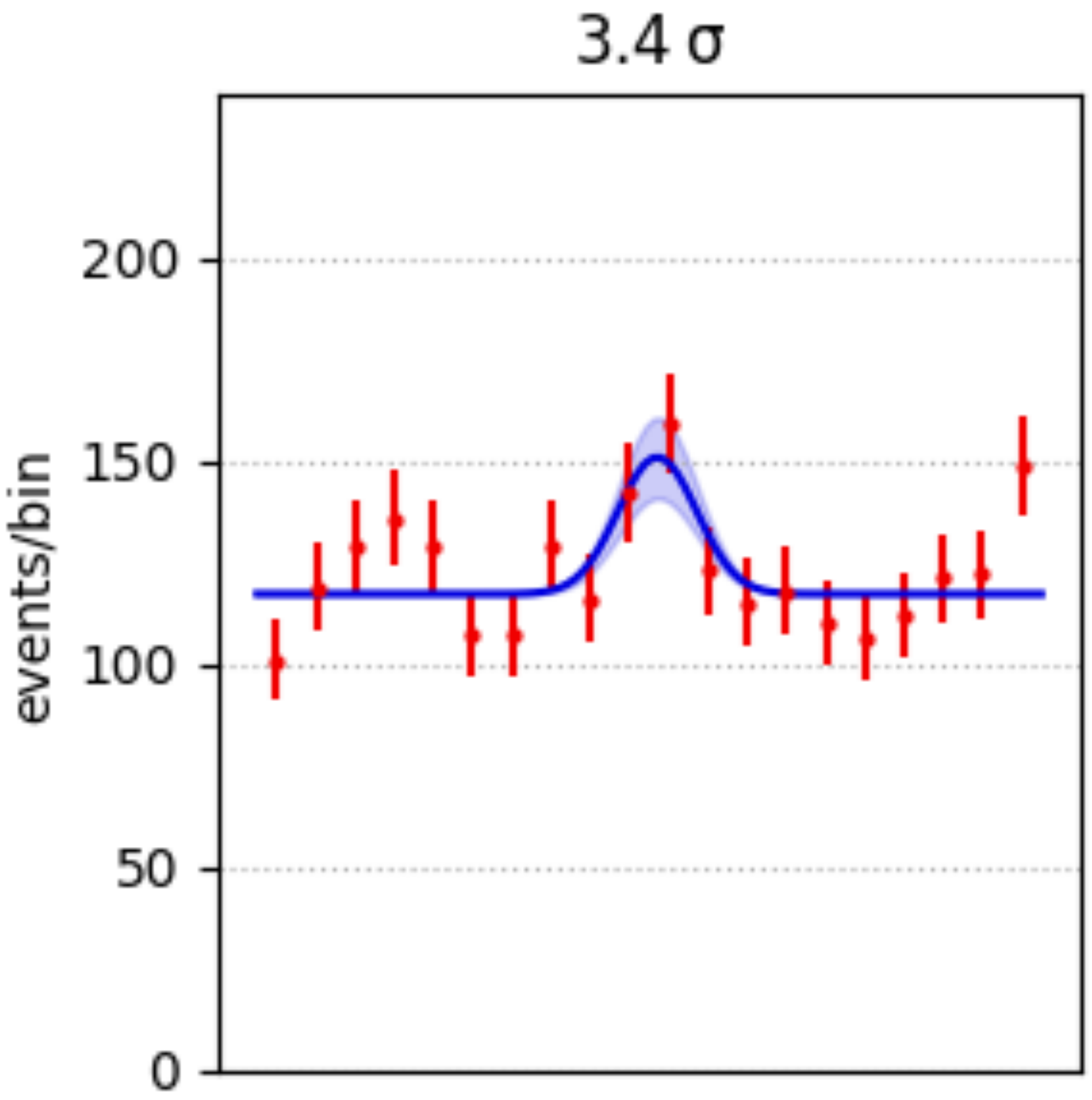

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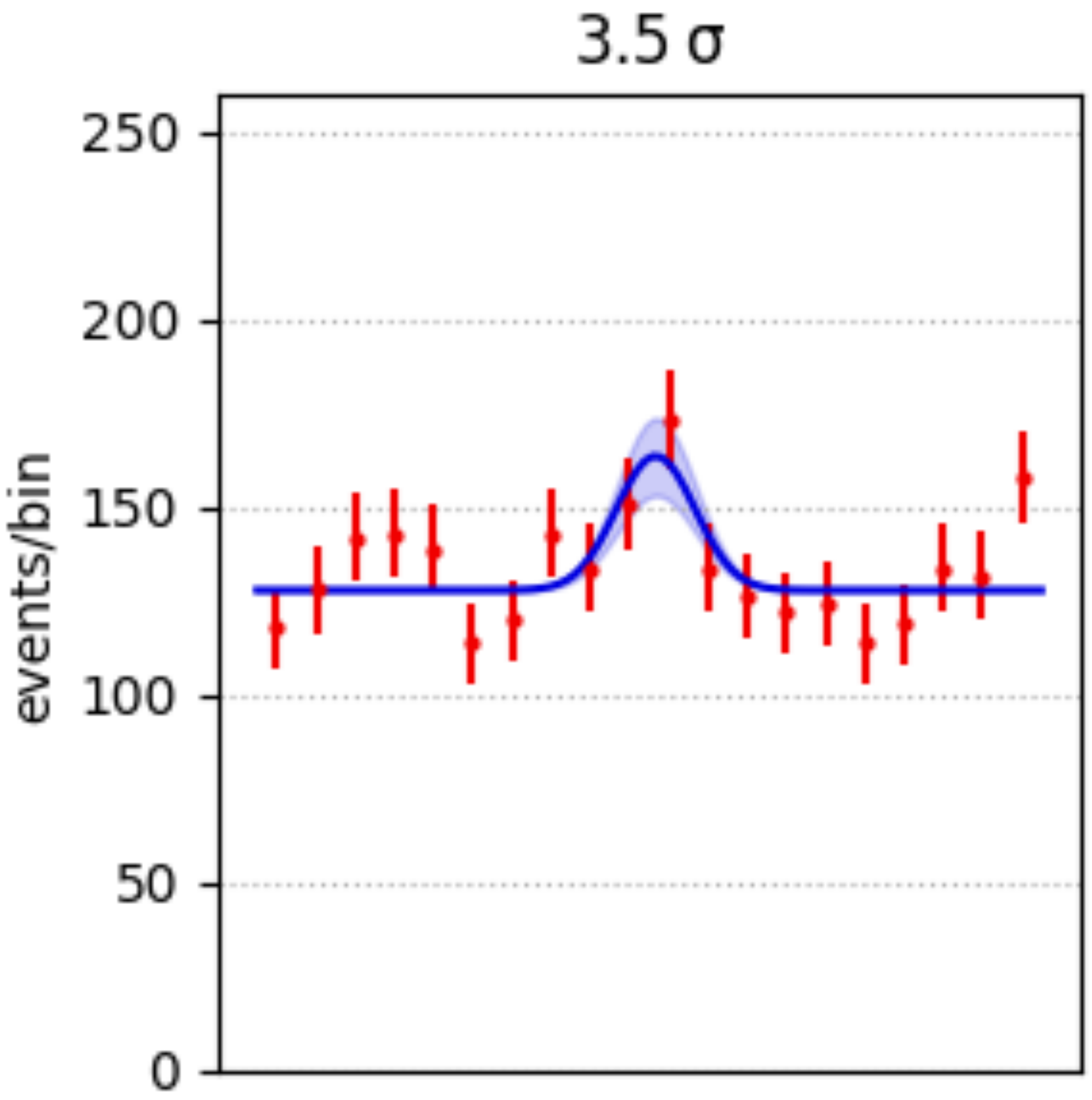

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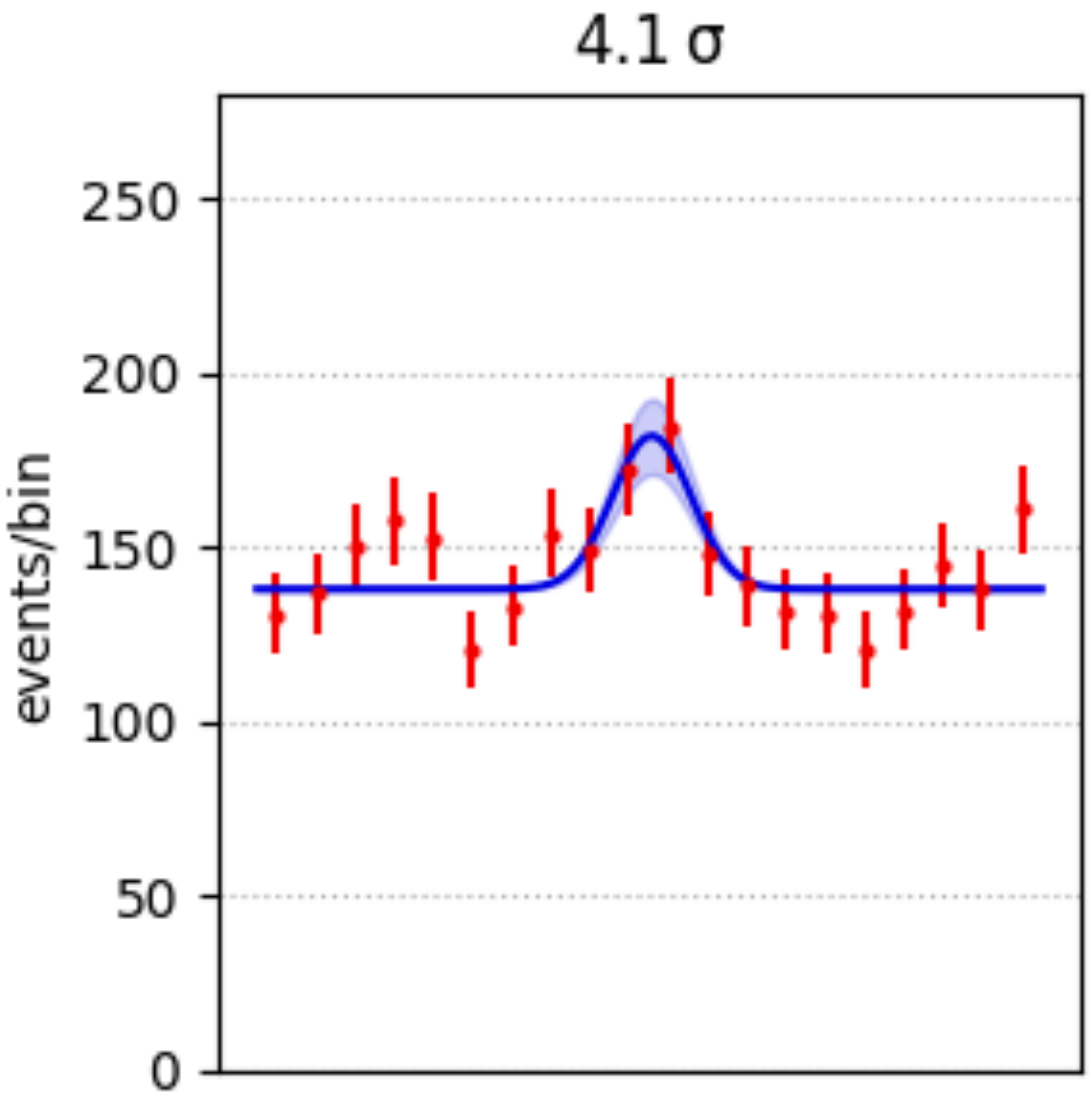

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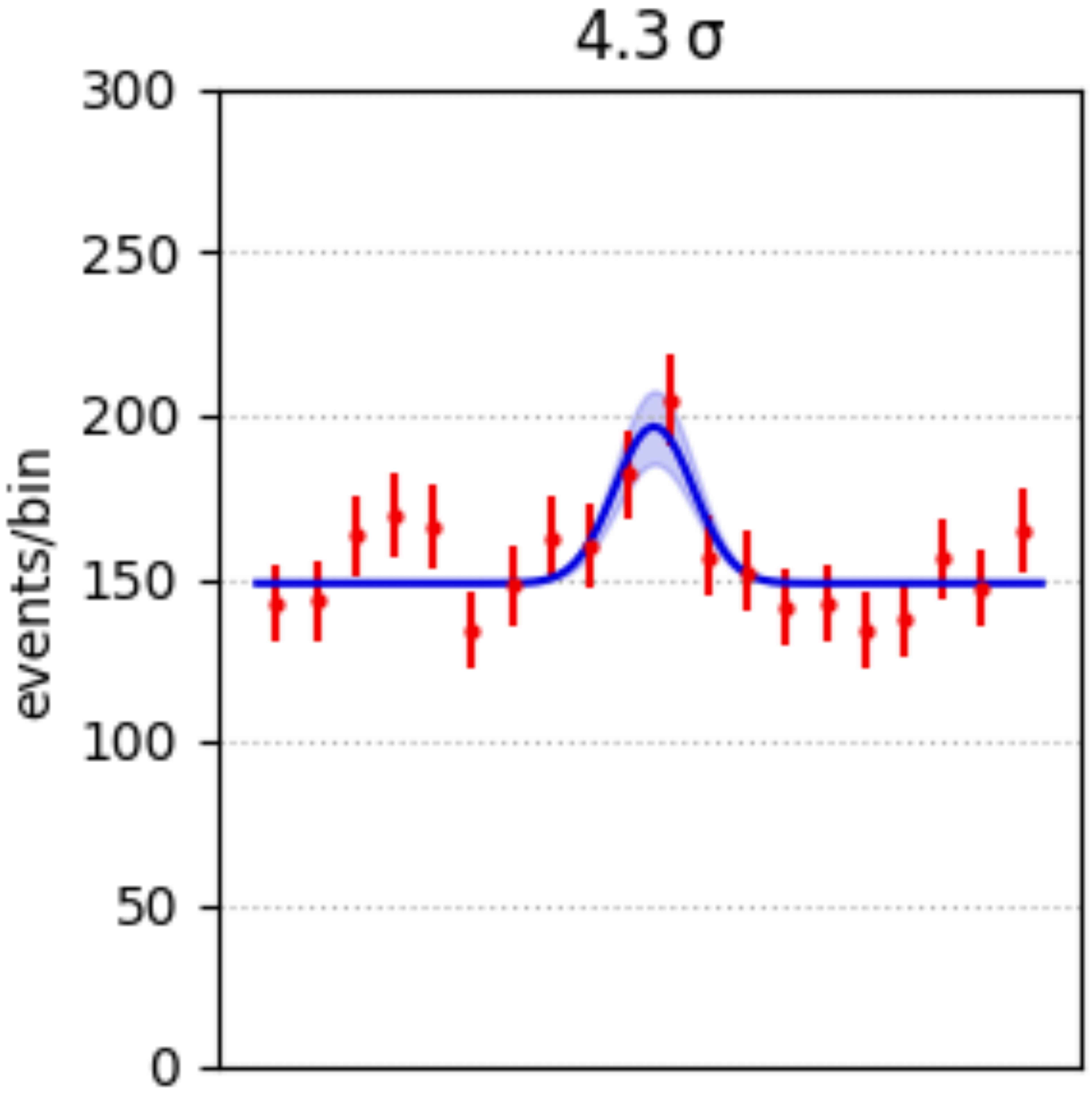

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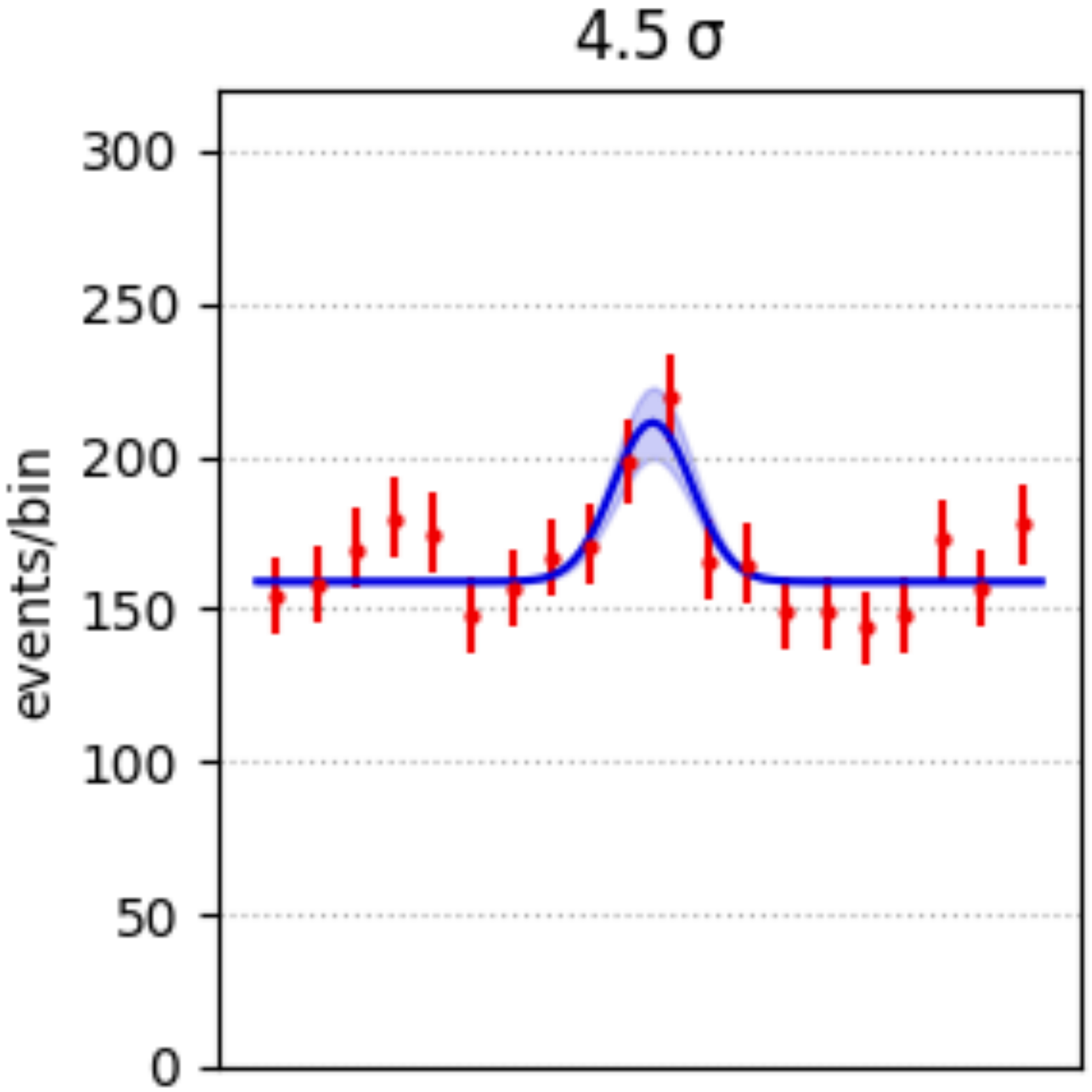

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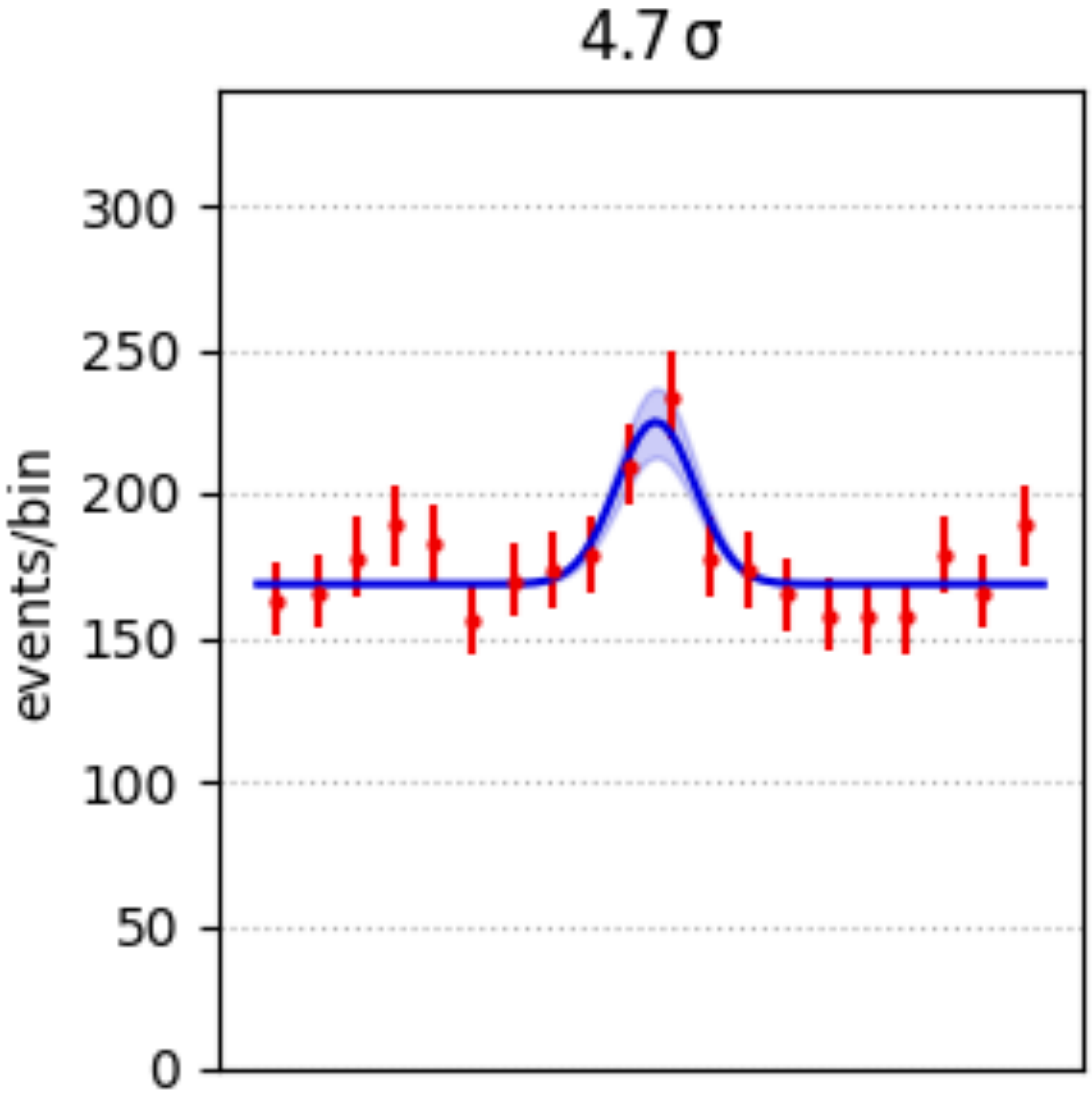

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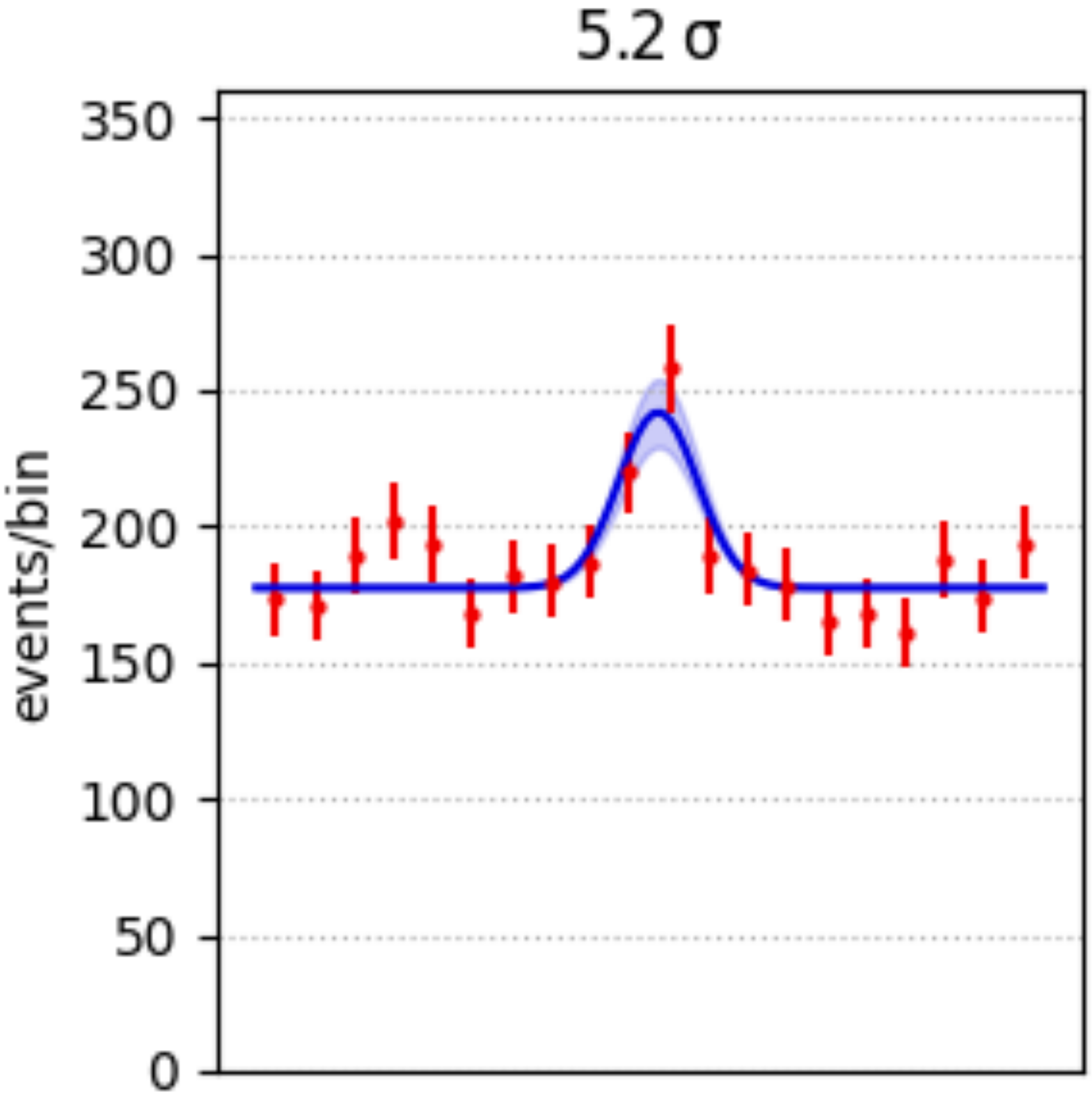


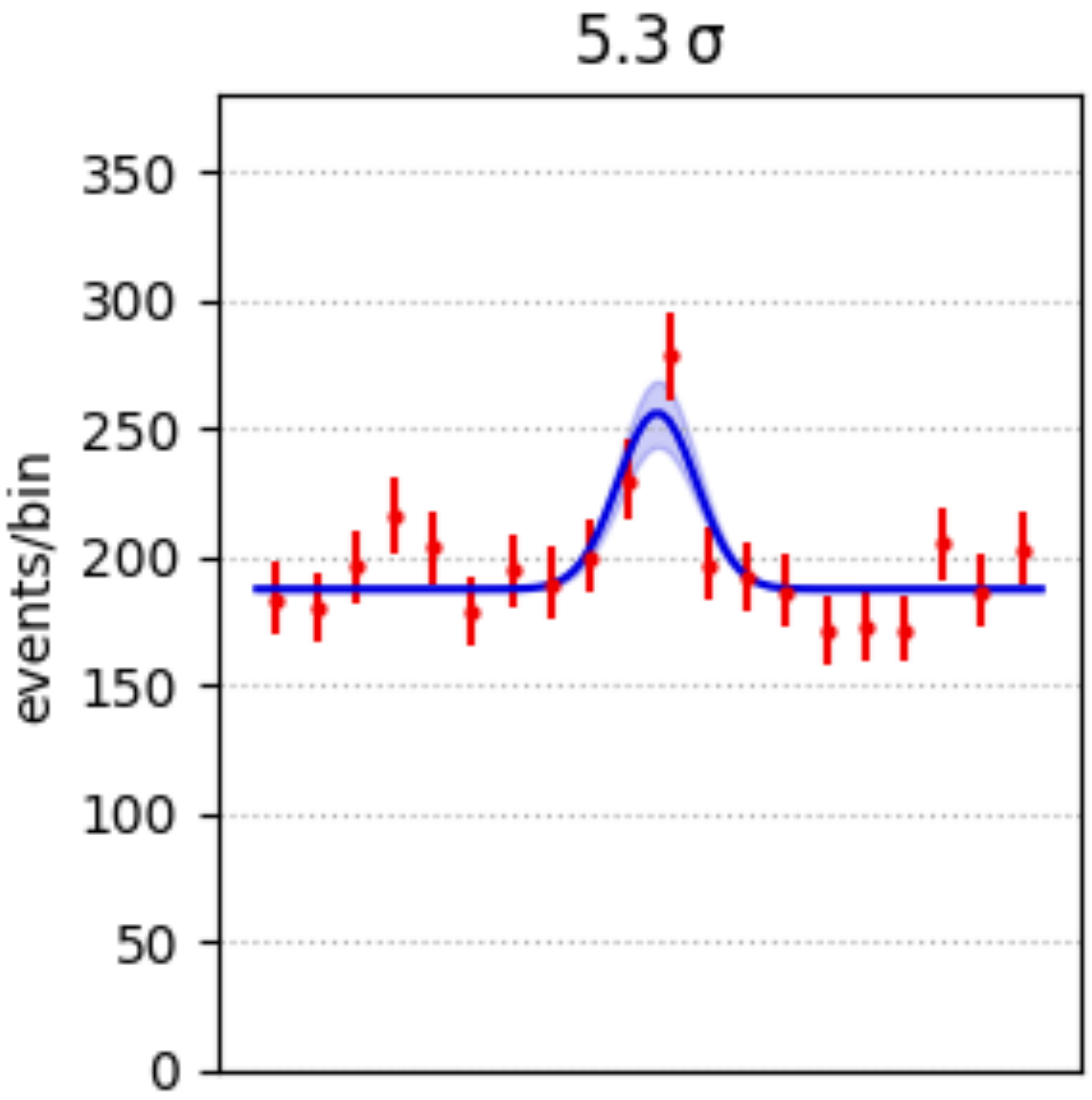
Number of σ measures statistical significance of a signal:
i.e. (size of signal) / uncertainty

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

Particle physics conventions

3σ: “evidence”
(if you’re not expecting it, don’t be surprised if it goes away with more data!)

5σ: “observation”
(should be robust)



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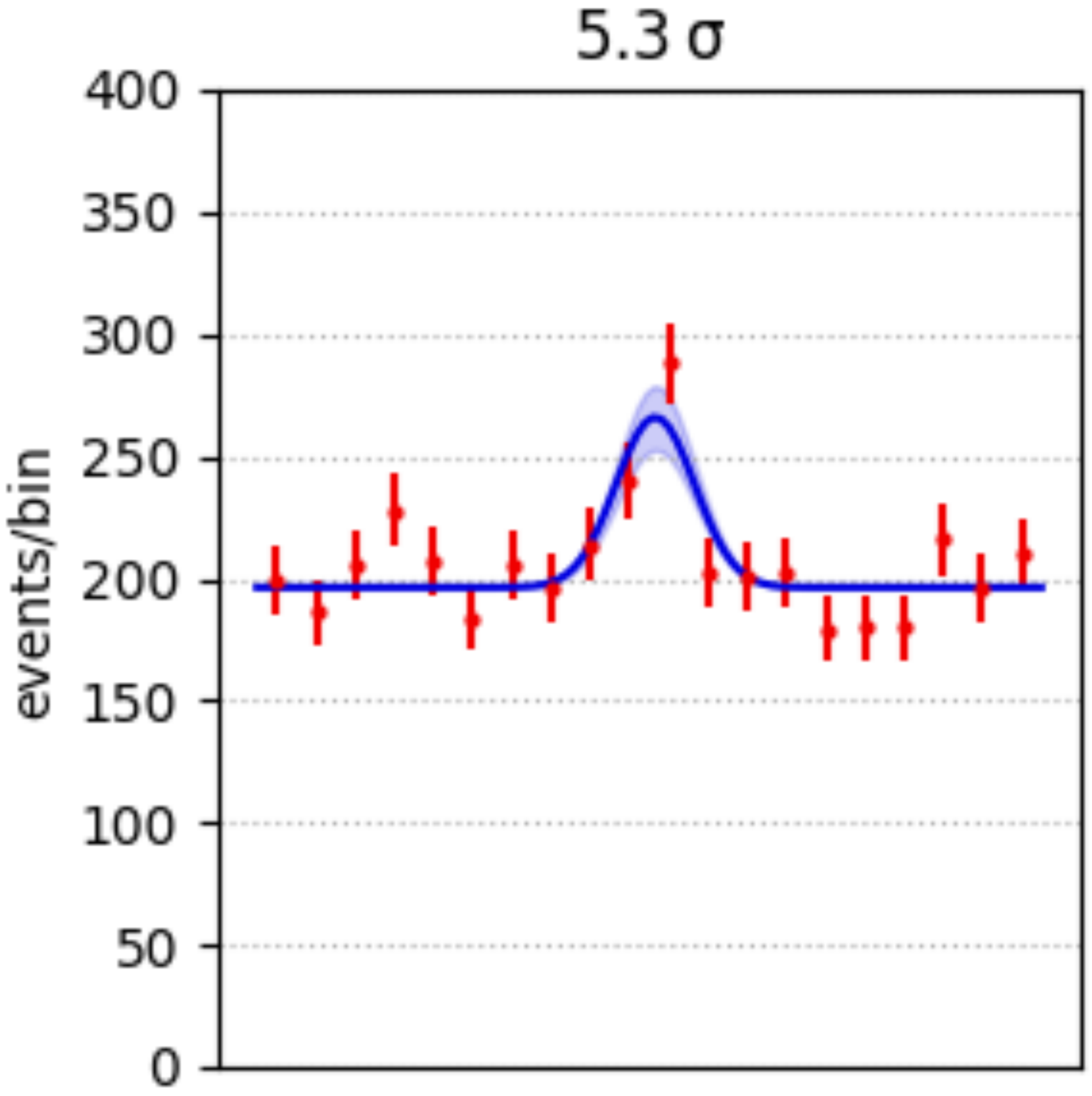

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Particle physics conventions

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

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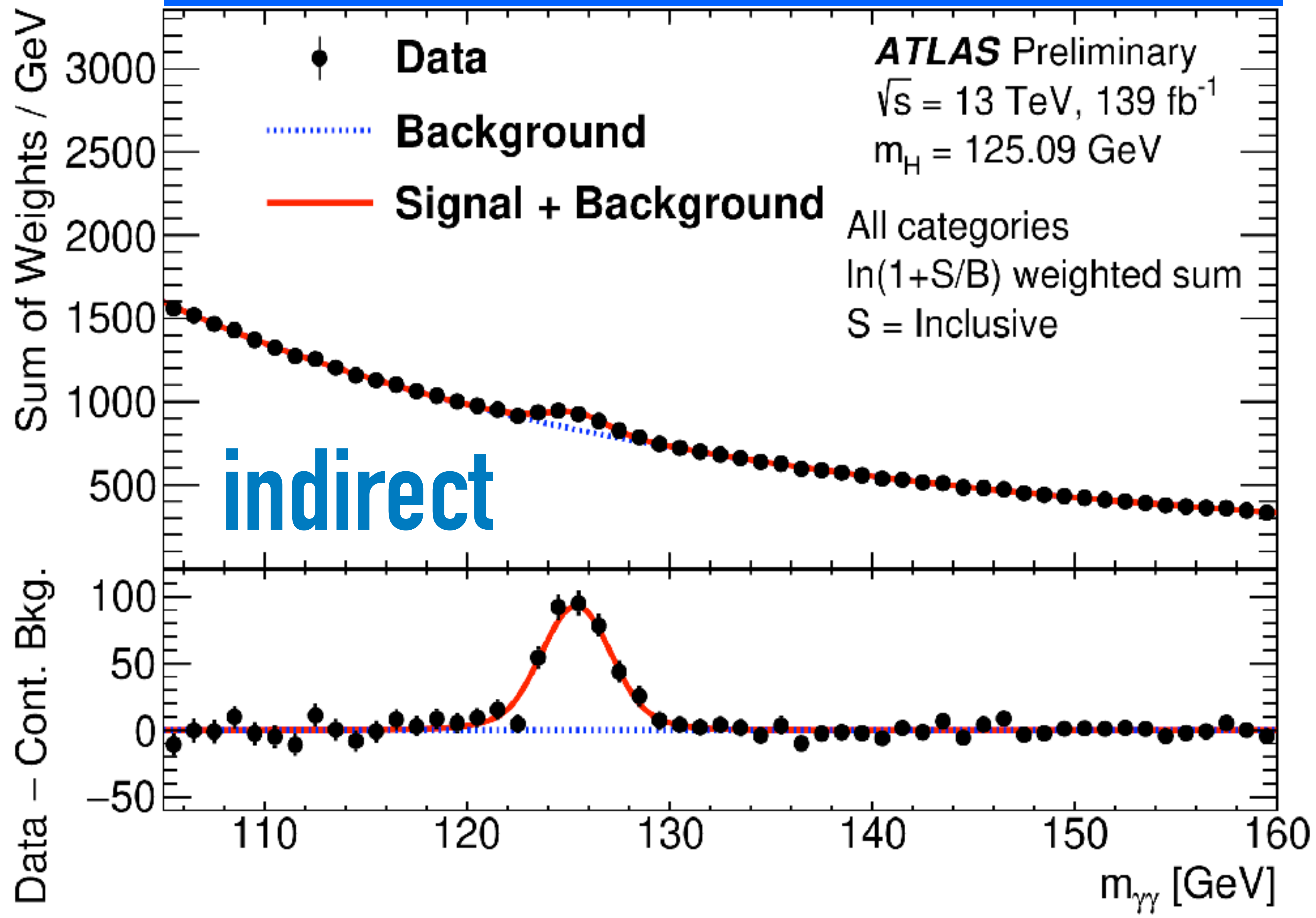
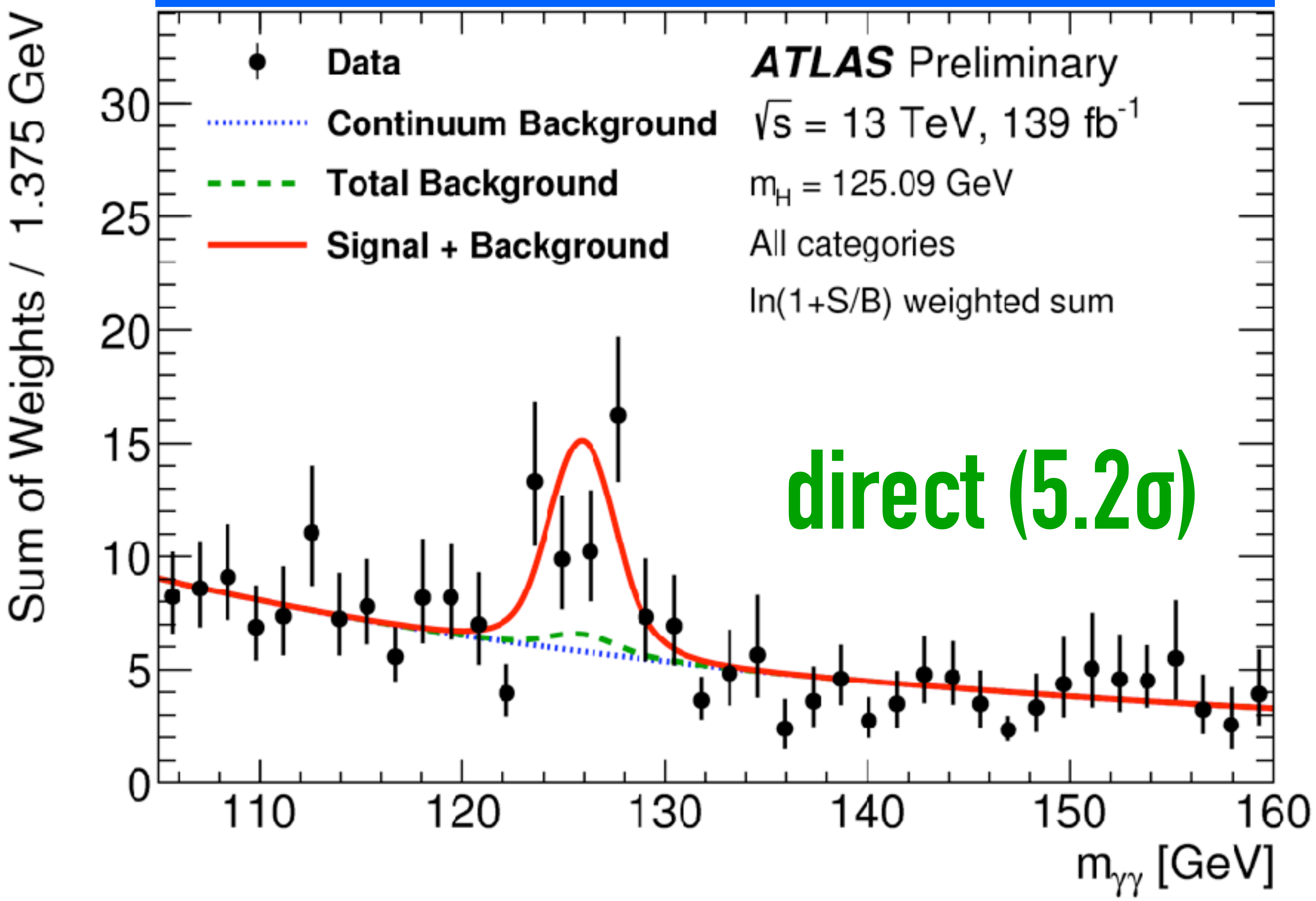
(should be robust)

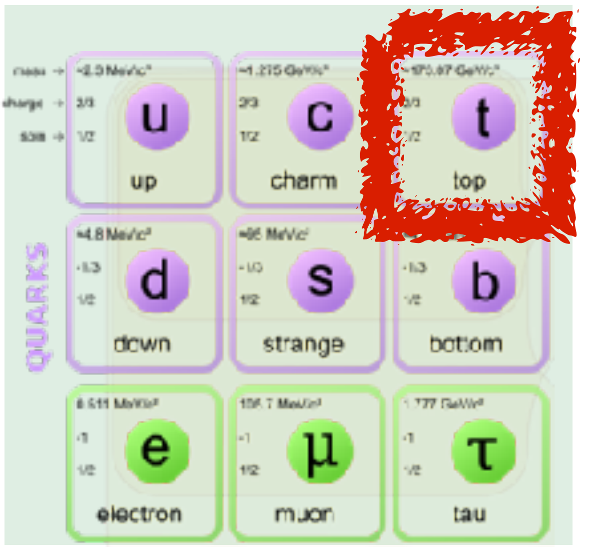
since 2018: ATLAS & CMS see (at >5σ) events with top-quarks & Higgs simultaneously

Higgs = one in 2 billion events



1 in 2,000 events with top quarks



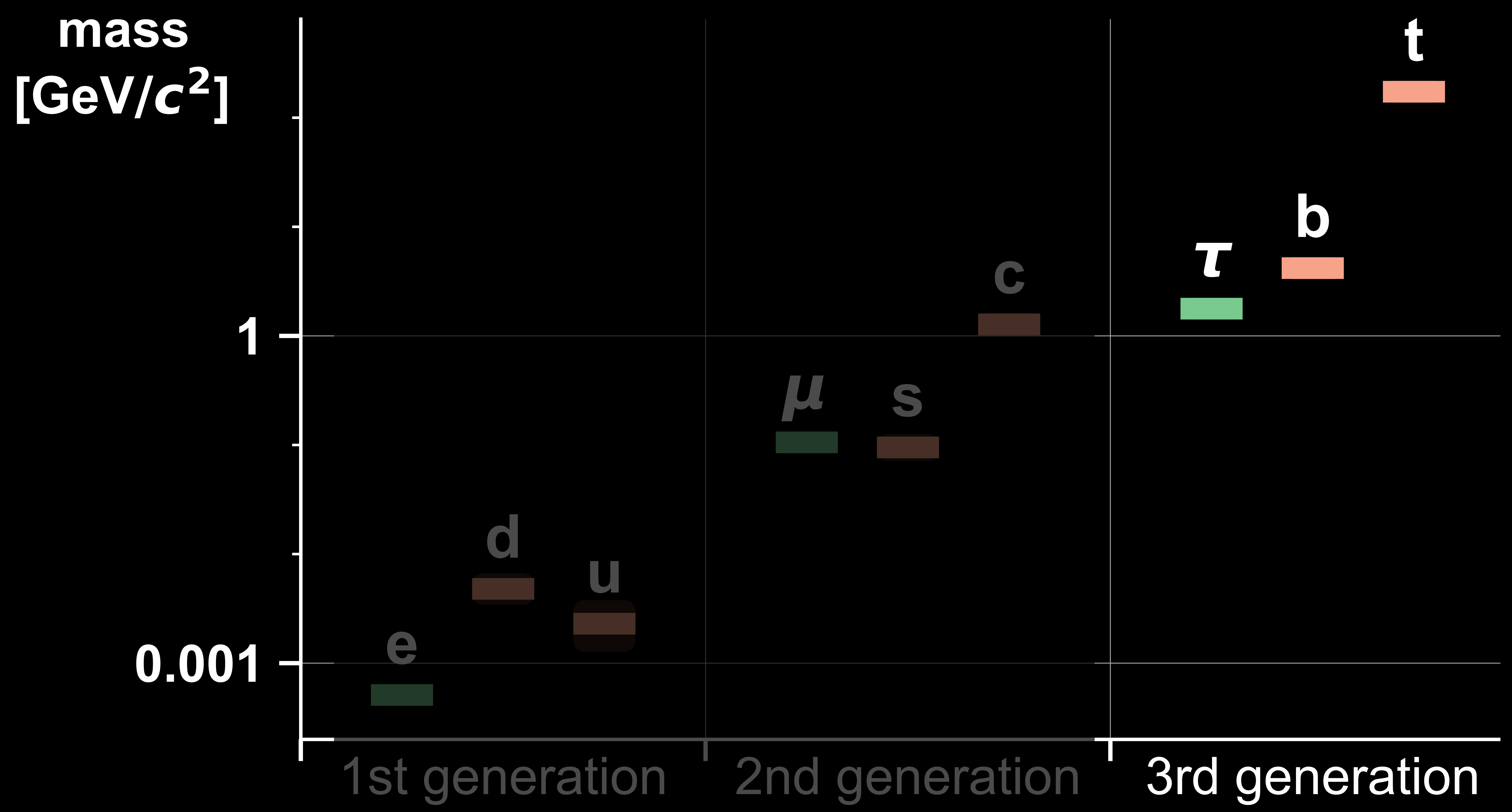


enhanced fraction of Higgs bosons in events with top quarks

→ direct observation of Higgs interaction with tops

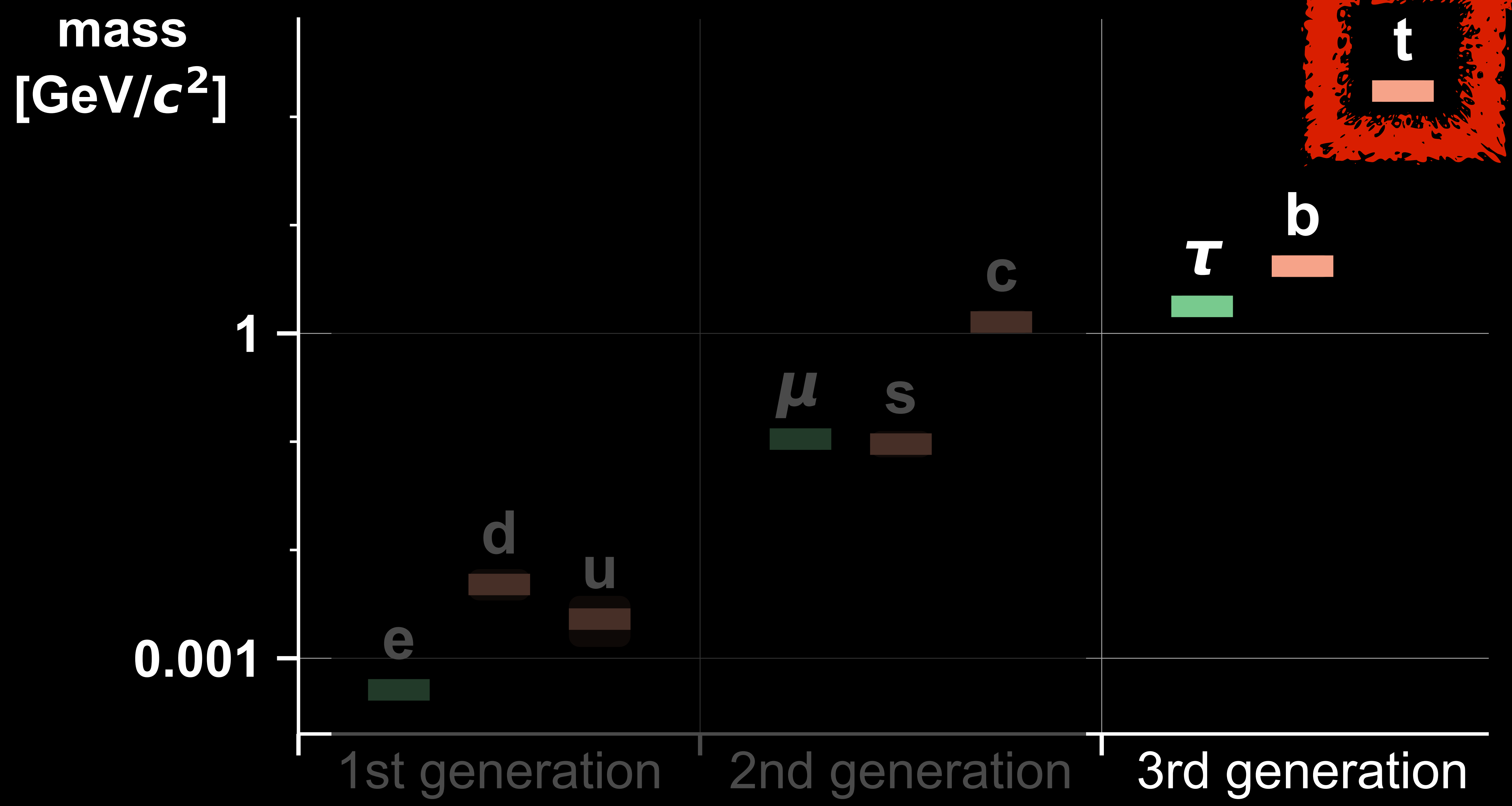
(consistent with SM to c. ±25%)

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



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

by observing H in association with top quarks



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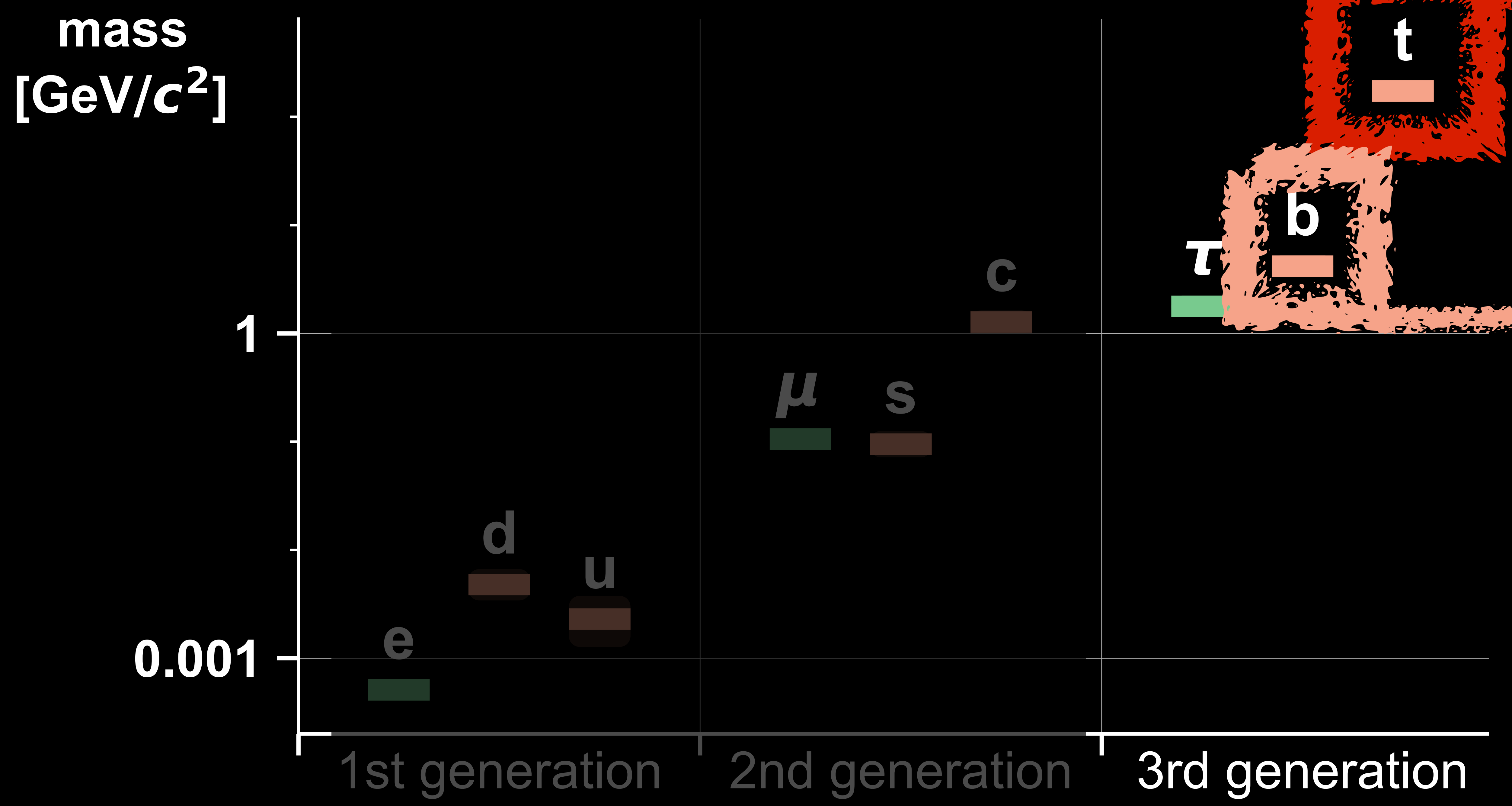
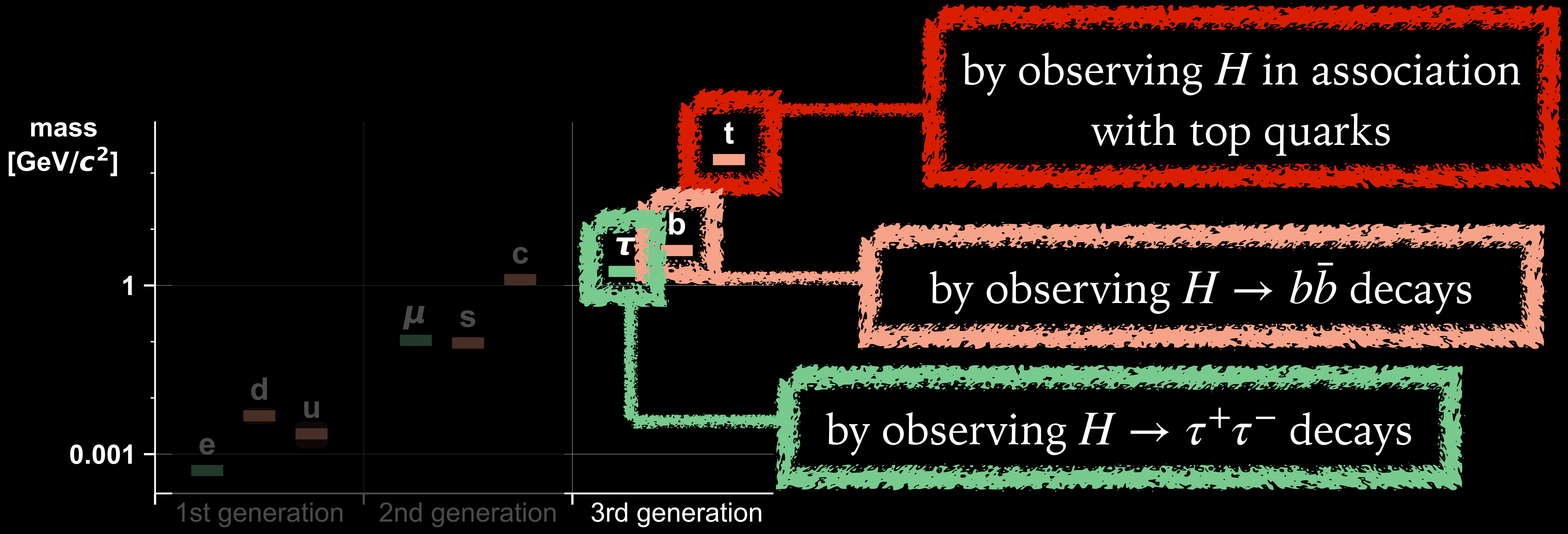


by observing H in association with top quarks

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

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



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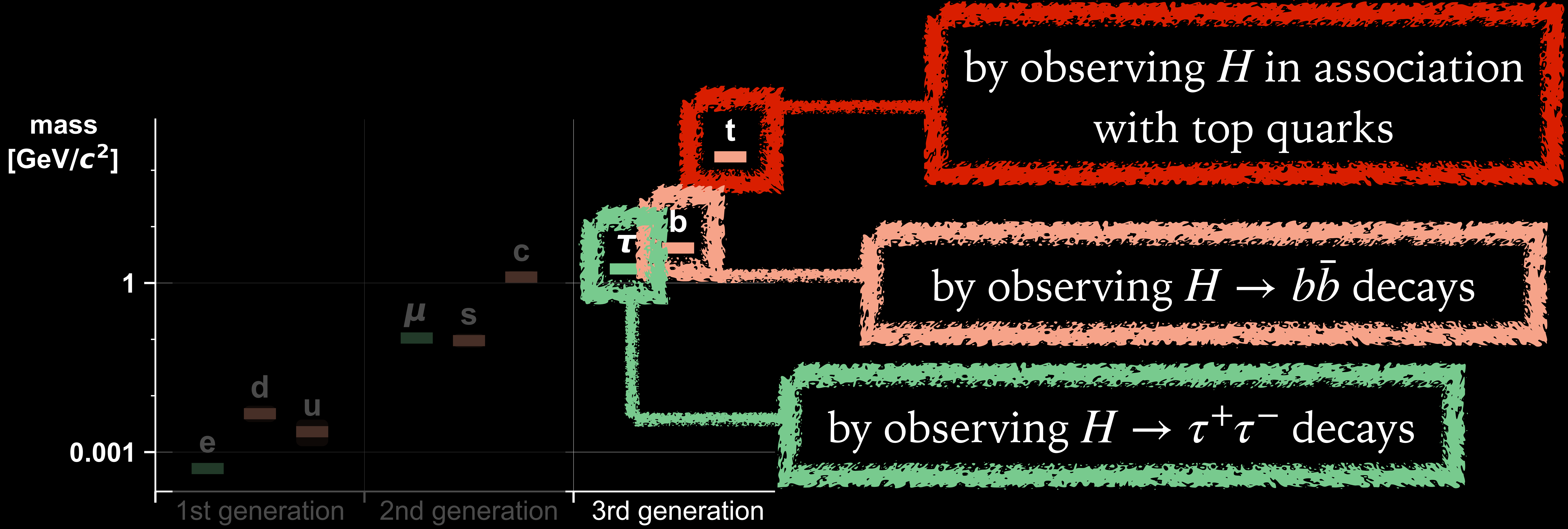
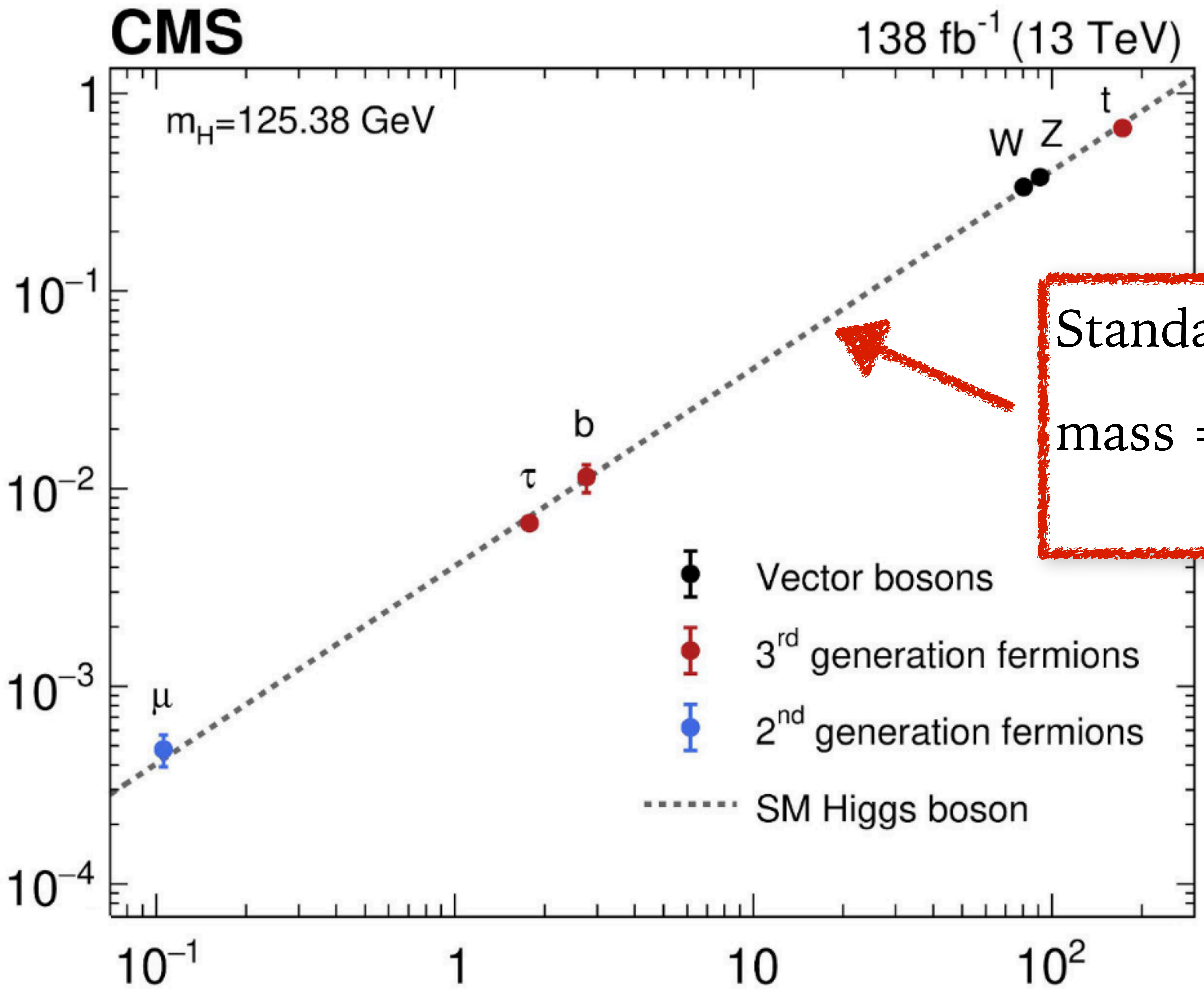


Full 3rd generation Yukawas were not part of the LHC design case. Amazing achievement of LHC experiments to have directly observed them

Particle's strength of interaction with Higgs field



Standard Model prediction:

mass = higgs-field-value × interaction-strength

Particle's mass [GeV]

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.

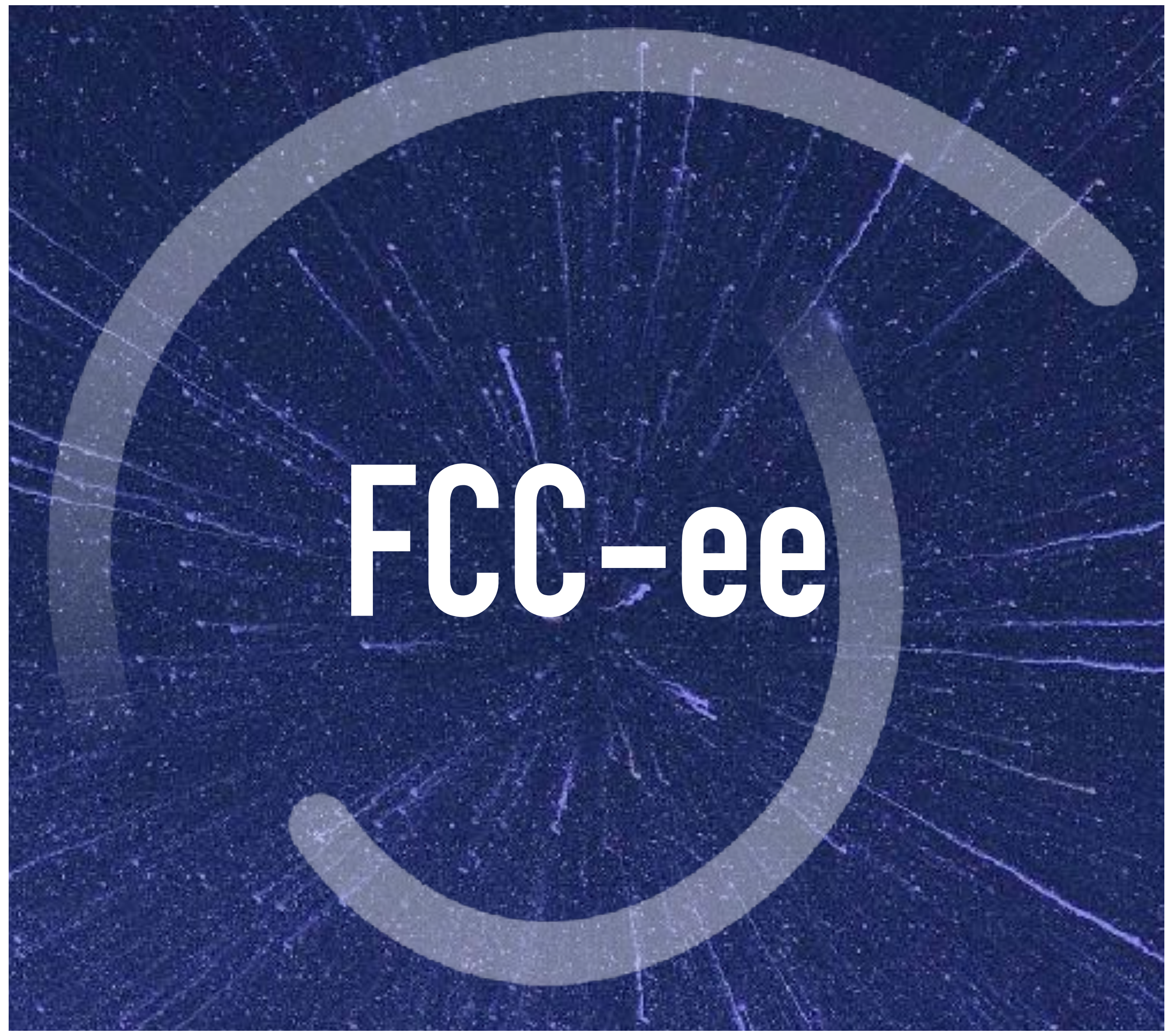
A field is something that can in principle be modified. And so the masses of particles could conceivably also be modified

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

My opinion: no

2029–2041

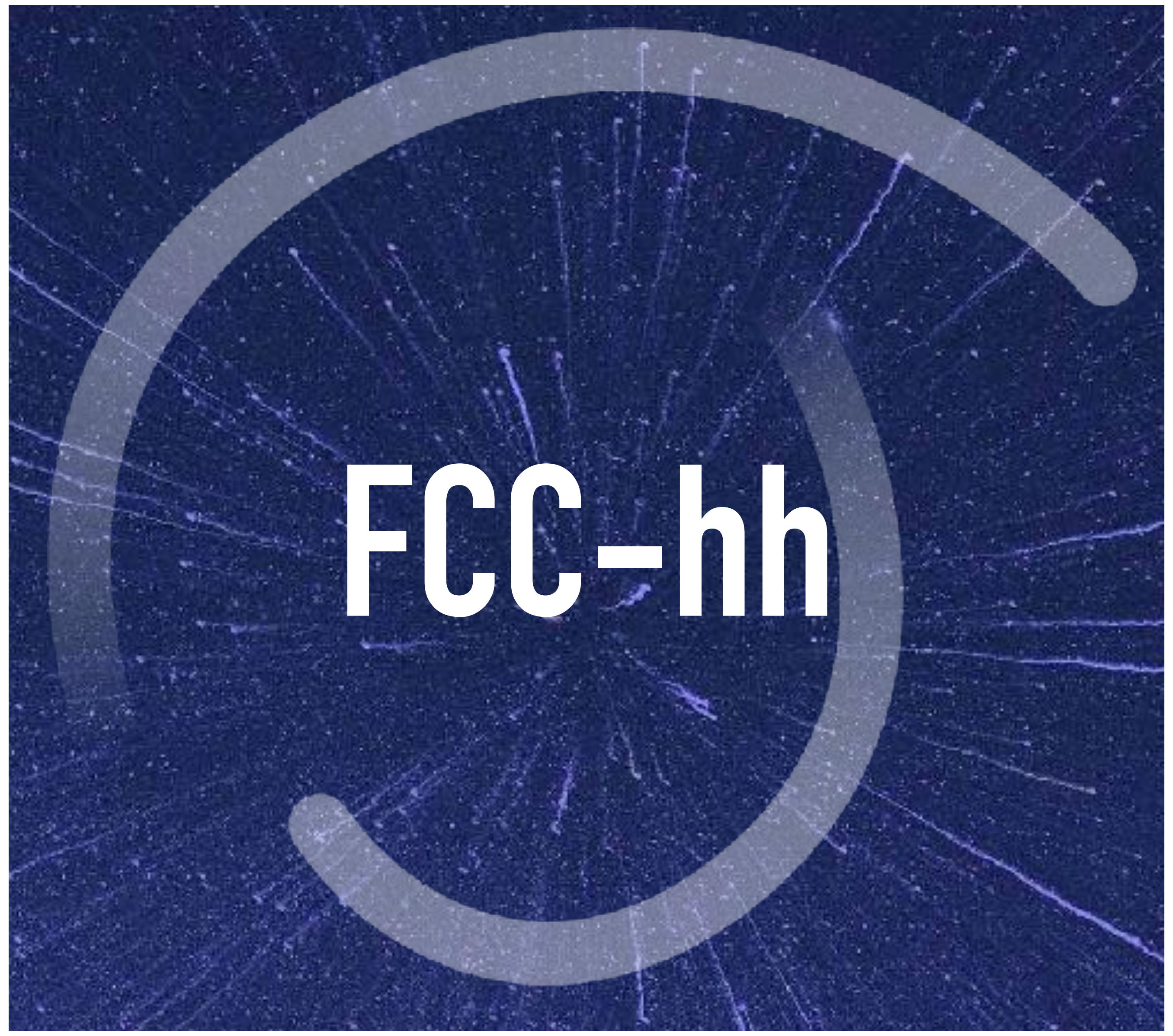
proton–proton
14,000 GeV energy
10× more collisions
than LHC



2045–2060(c.)

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

[or CEPC@China,
ILC, CLIC]

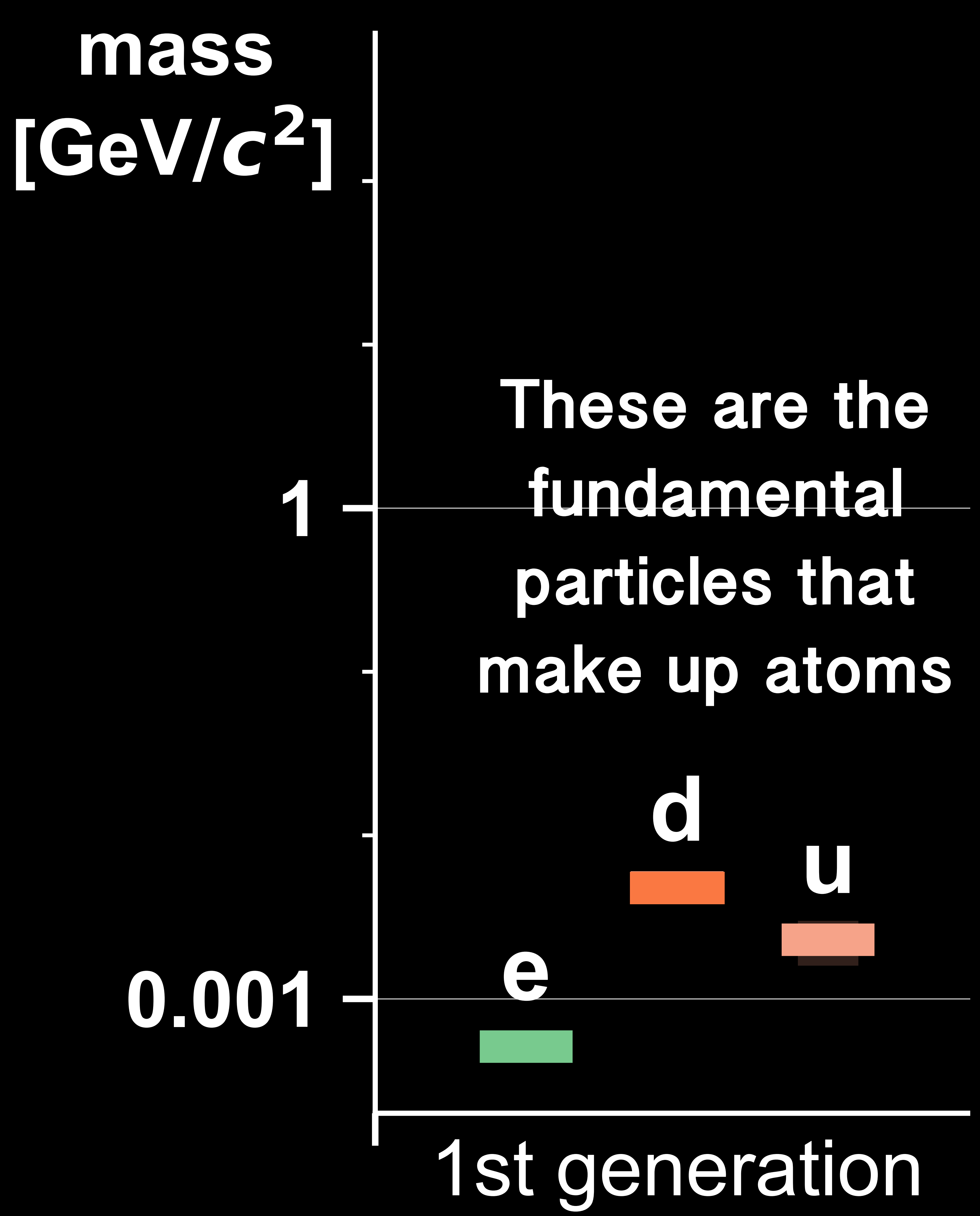


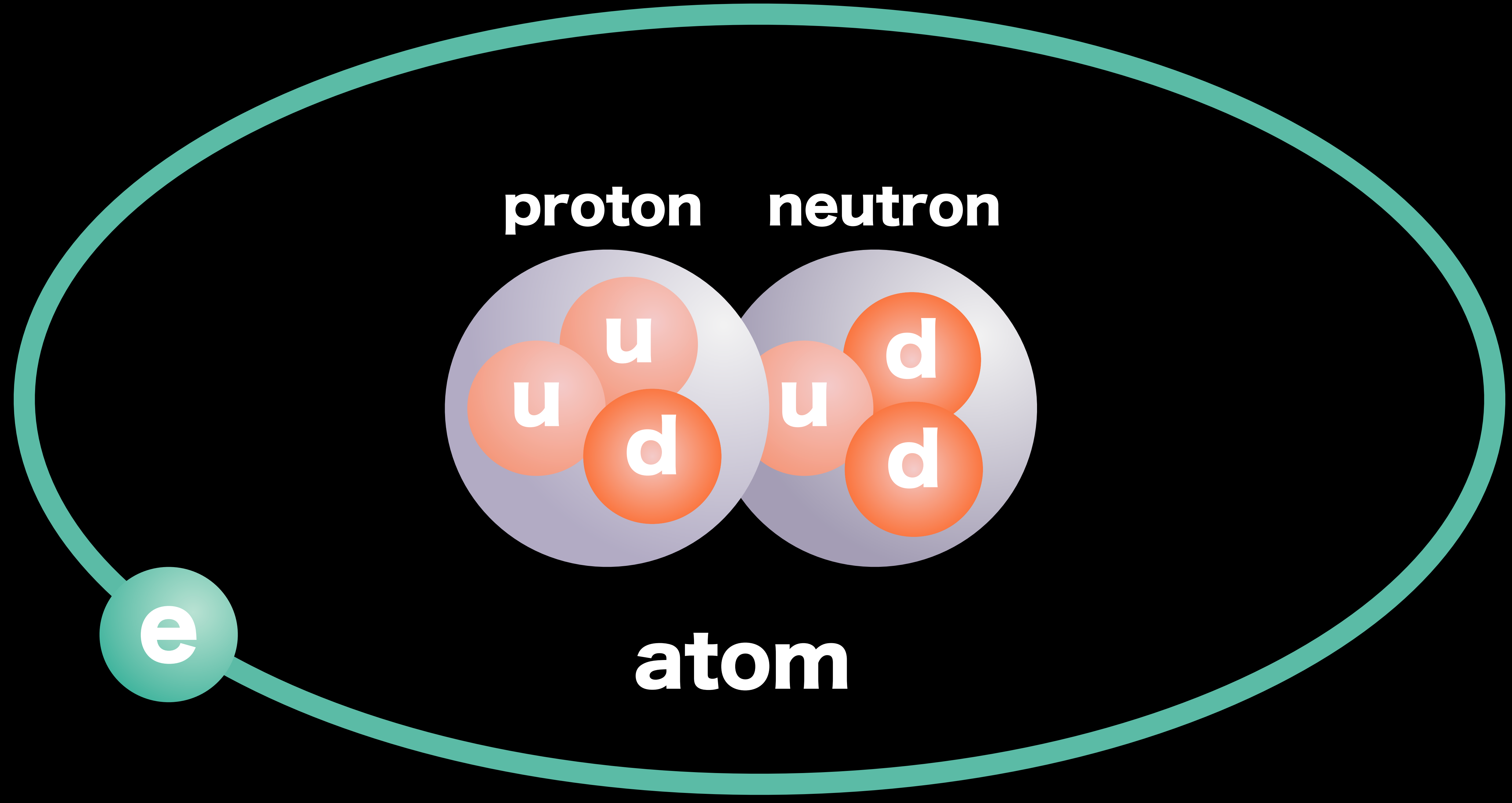
2070–2090(c.)

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

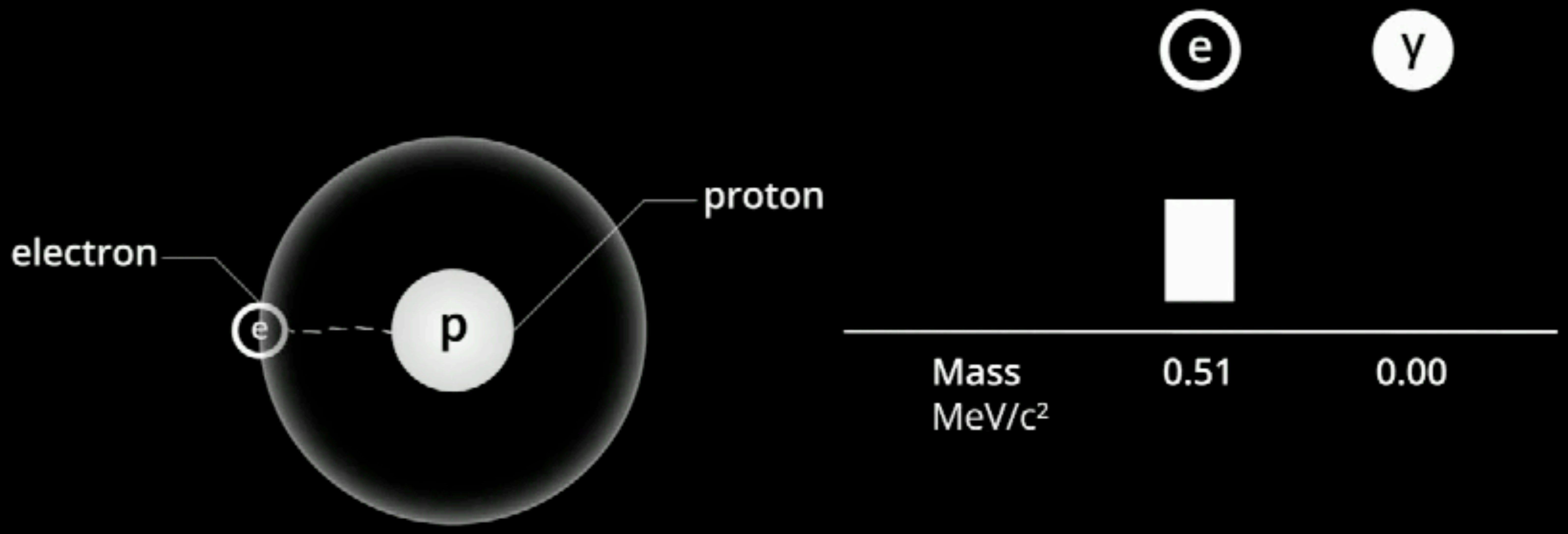
or SppS@China
or muon collider

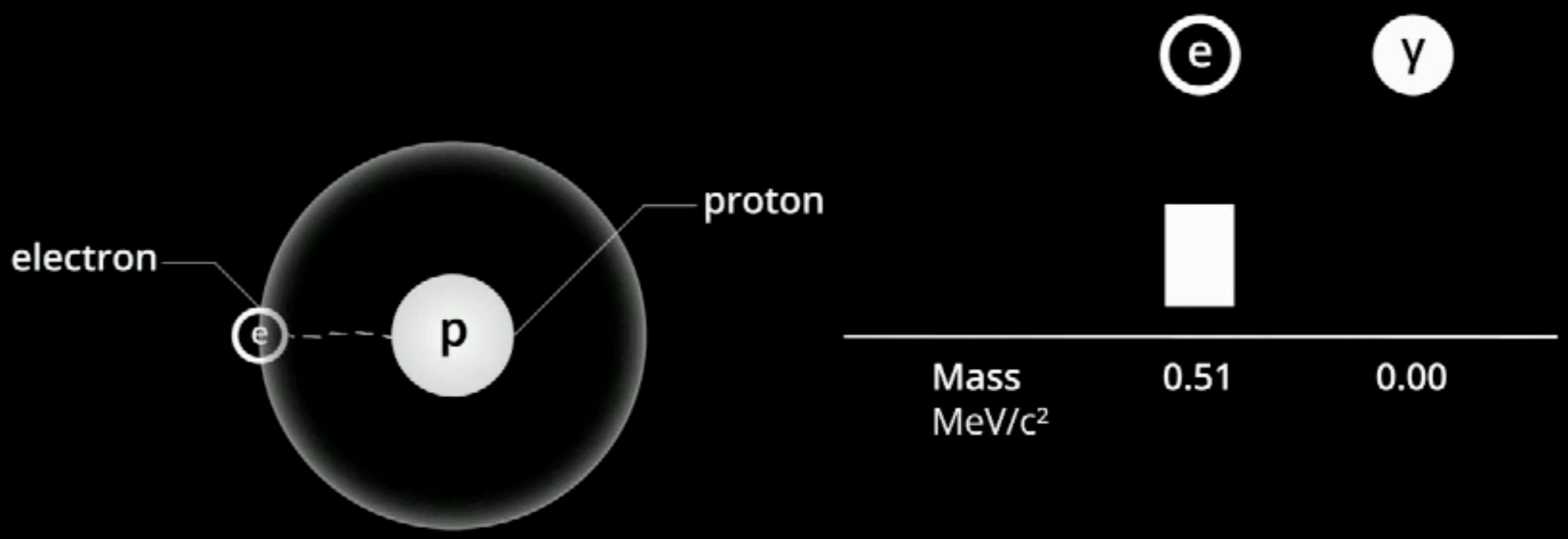
NB: most of mass of proton and neutron comes from other sources





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





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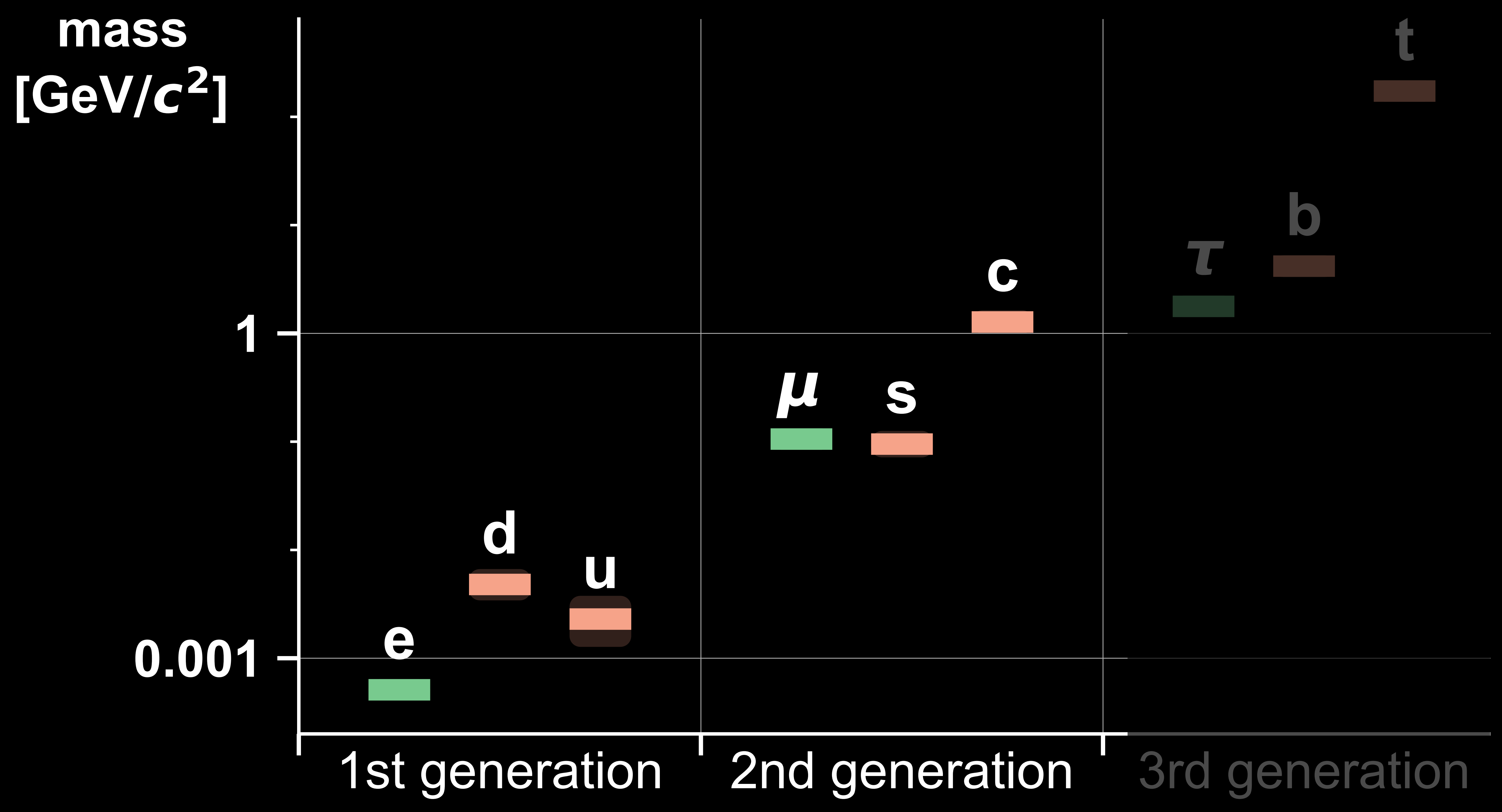
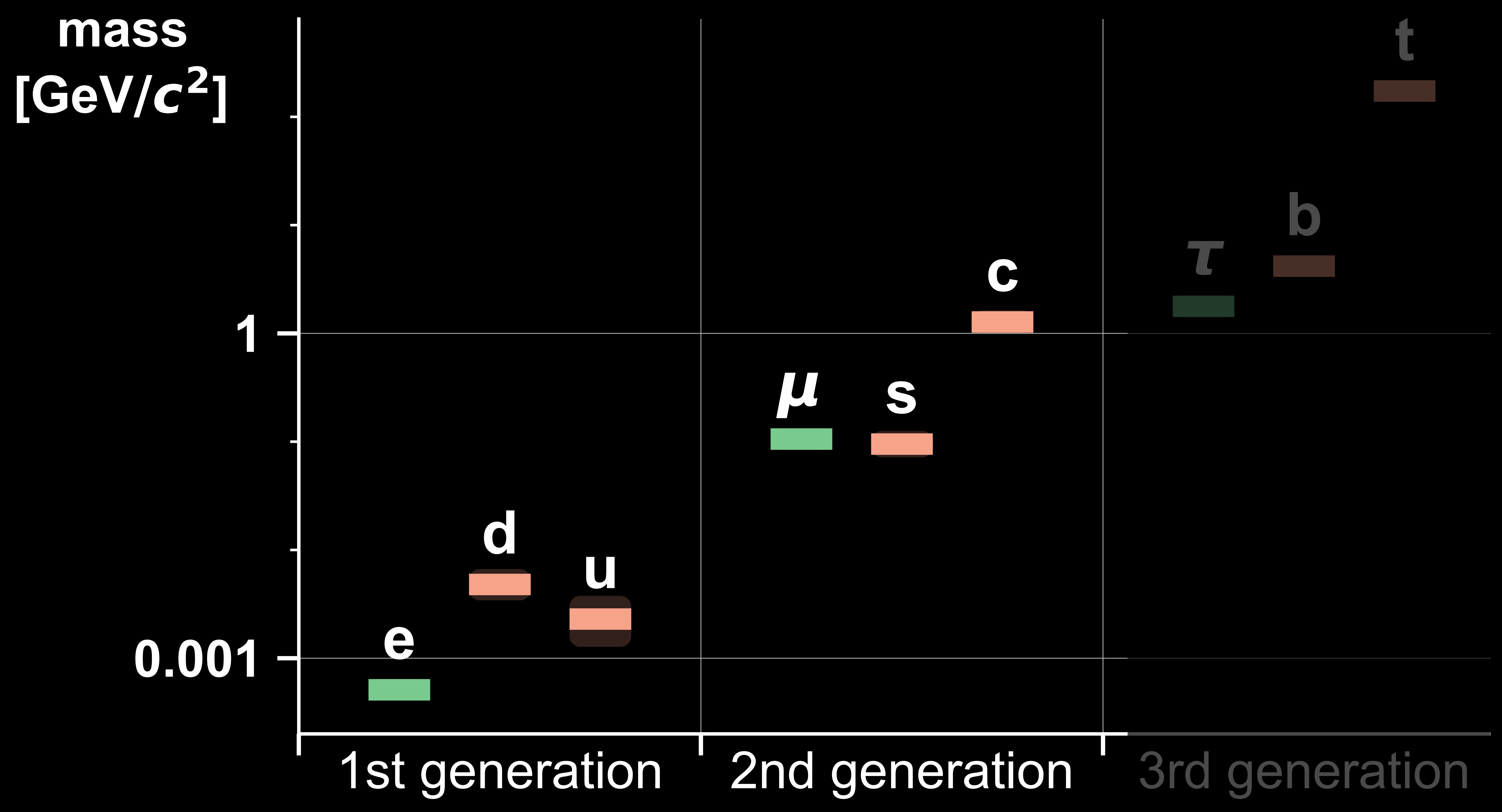


a BIG question of particle physics is whether all of these particles acquire their mass in the same way

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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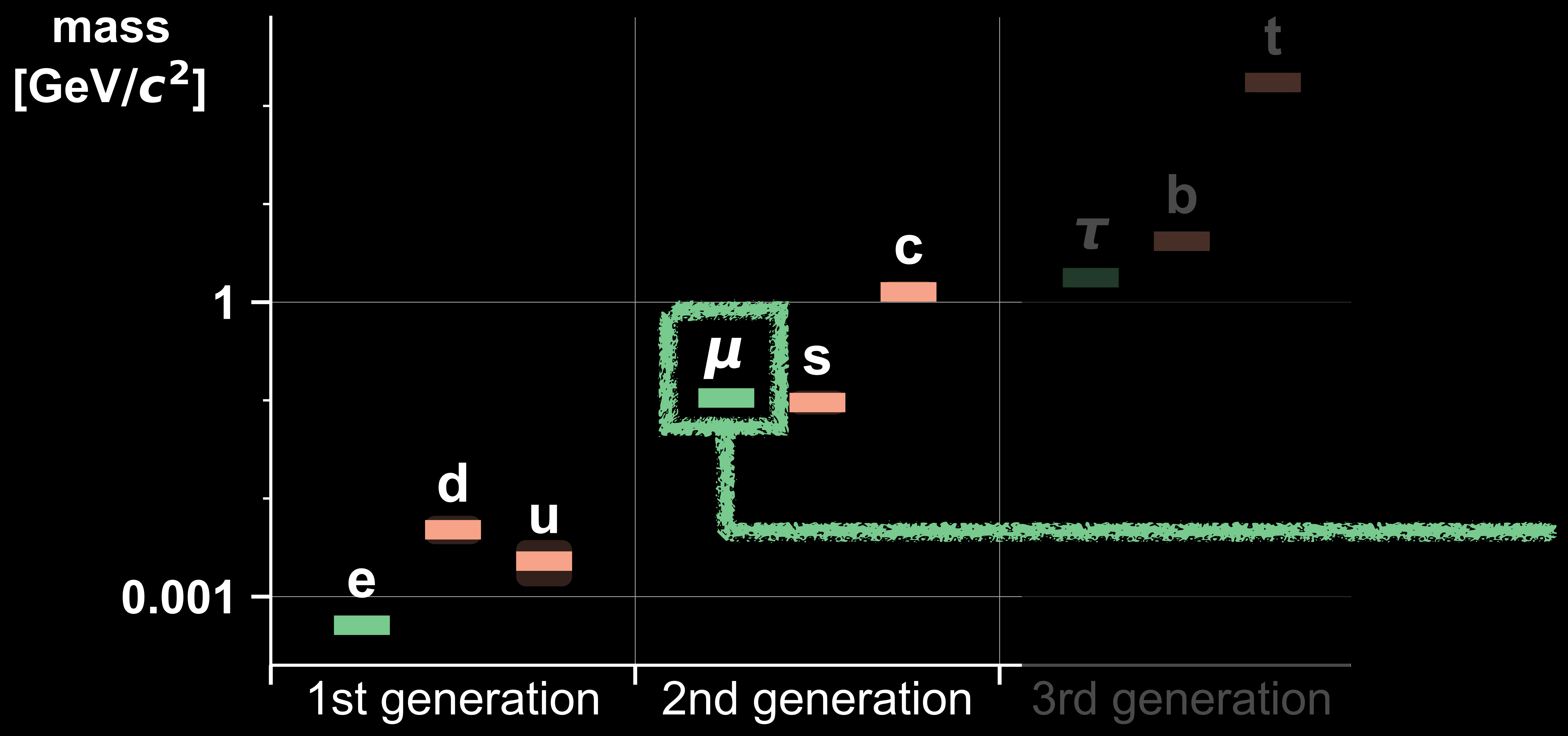
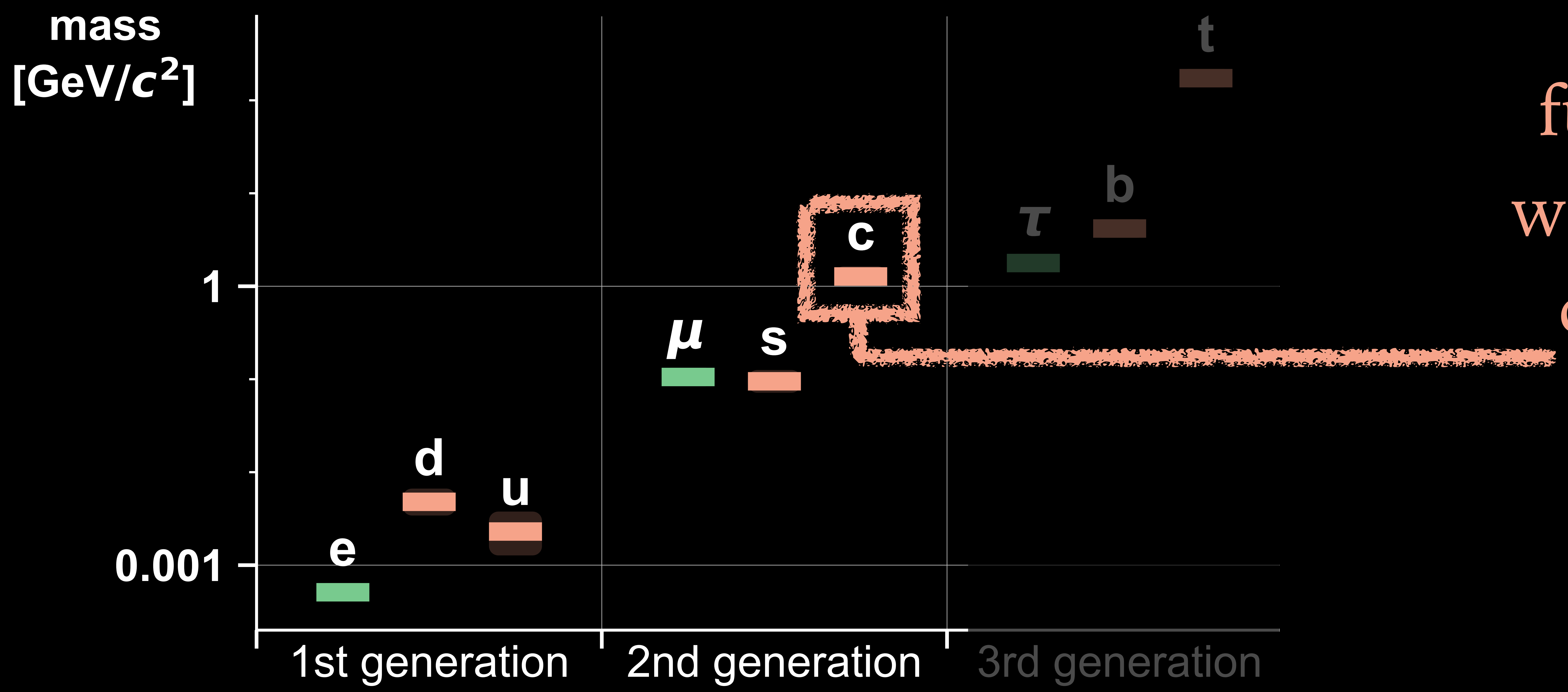


a major LHC goal of the next years (Run-3 or HL-LHC) will be to establish, for the first time, whether a 2nd generation particle also acquires its mass in the same way

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

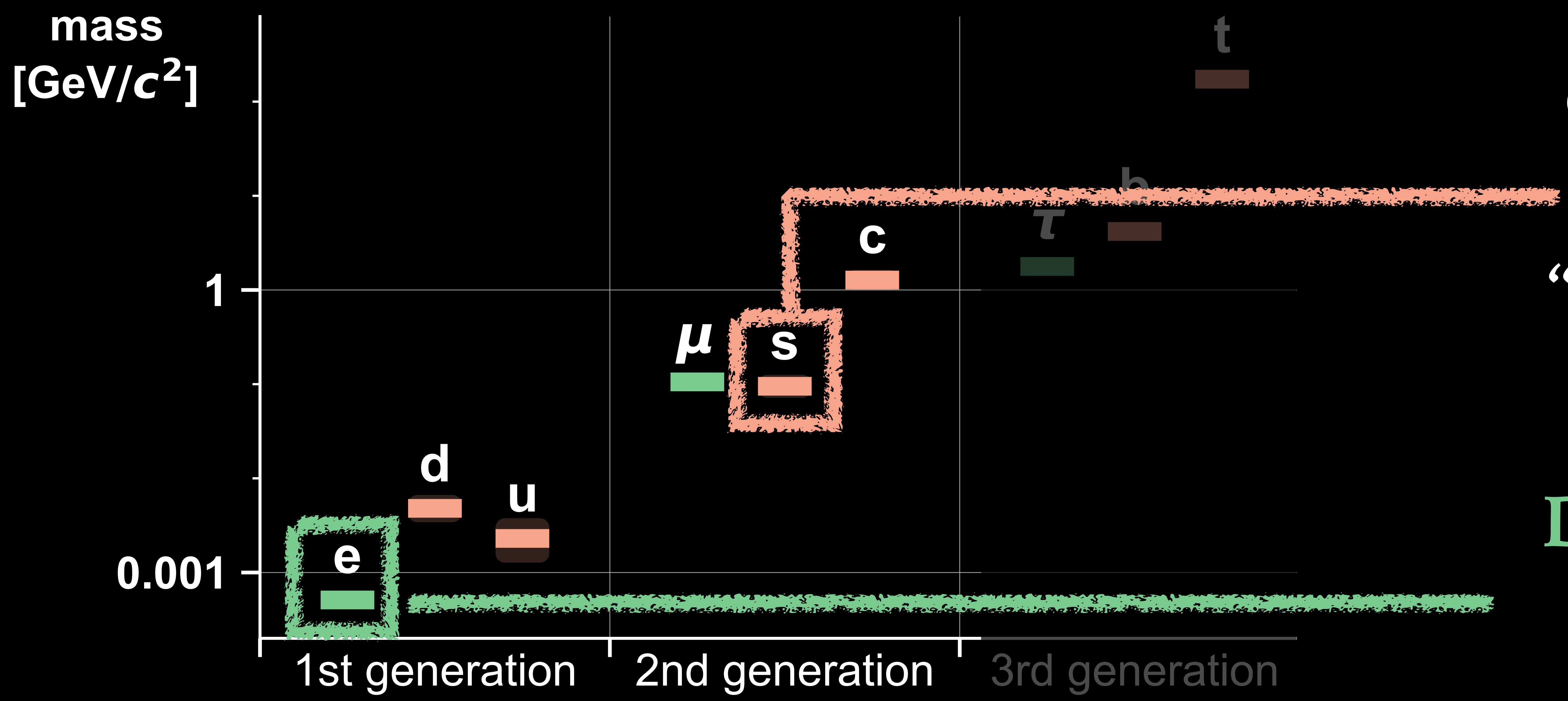
What of FCC-ee?



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 FCC-ee?



As FCC-ee case has been explored it's become clear that strange quark and electron "Yukawas" are just barely at the edge of reach

Discovering origin of electron mass would be a huge accomplishment

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

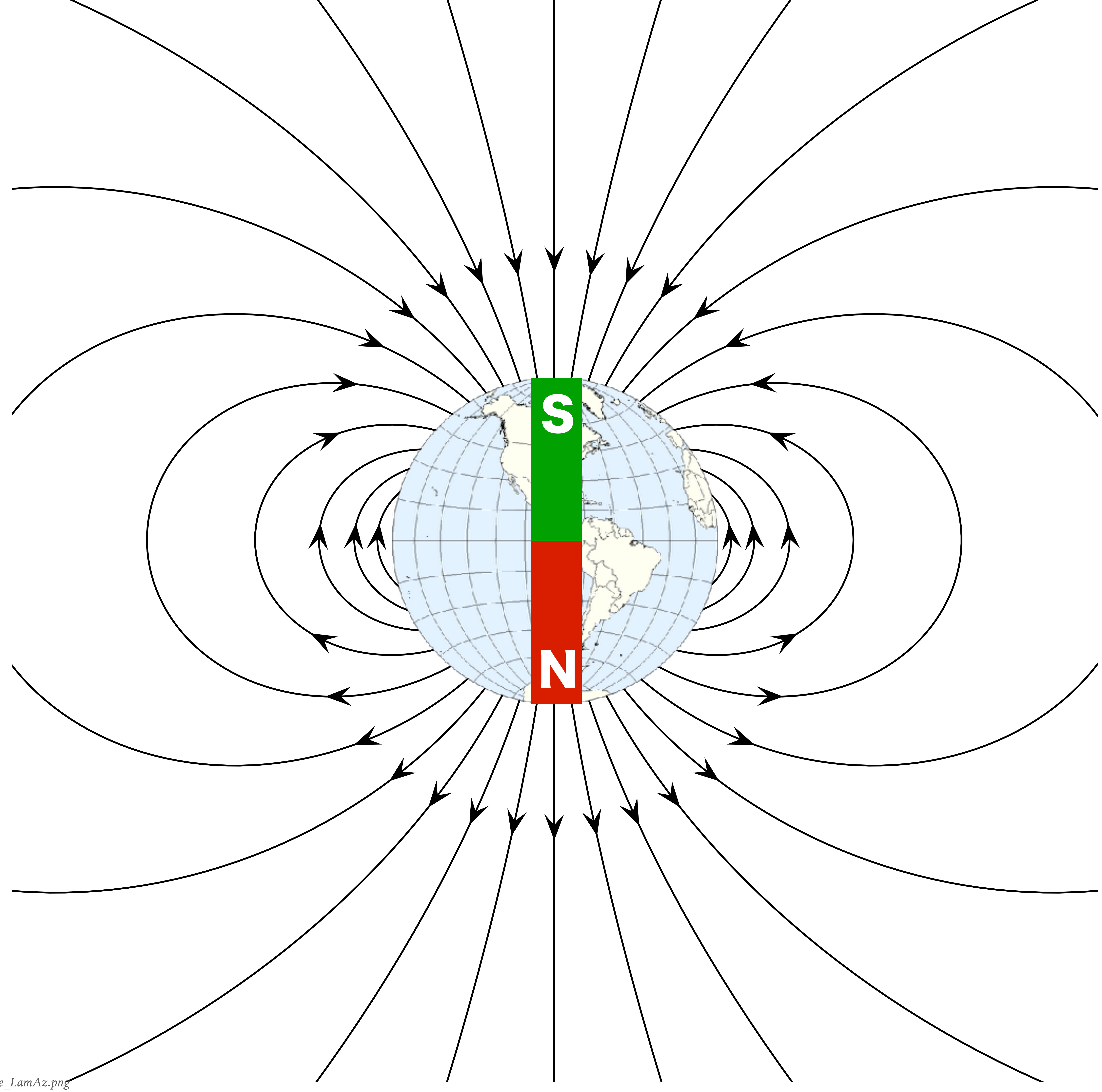
major progress on a broad array of particle physics topics

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?

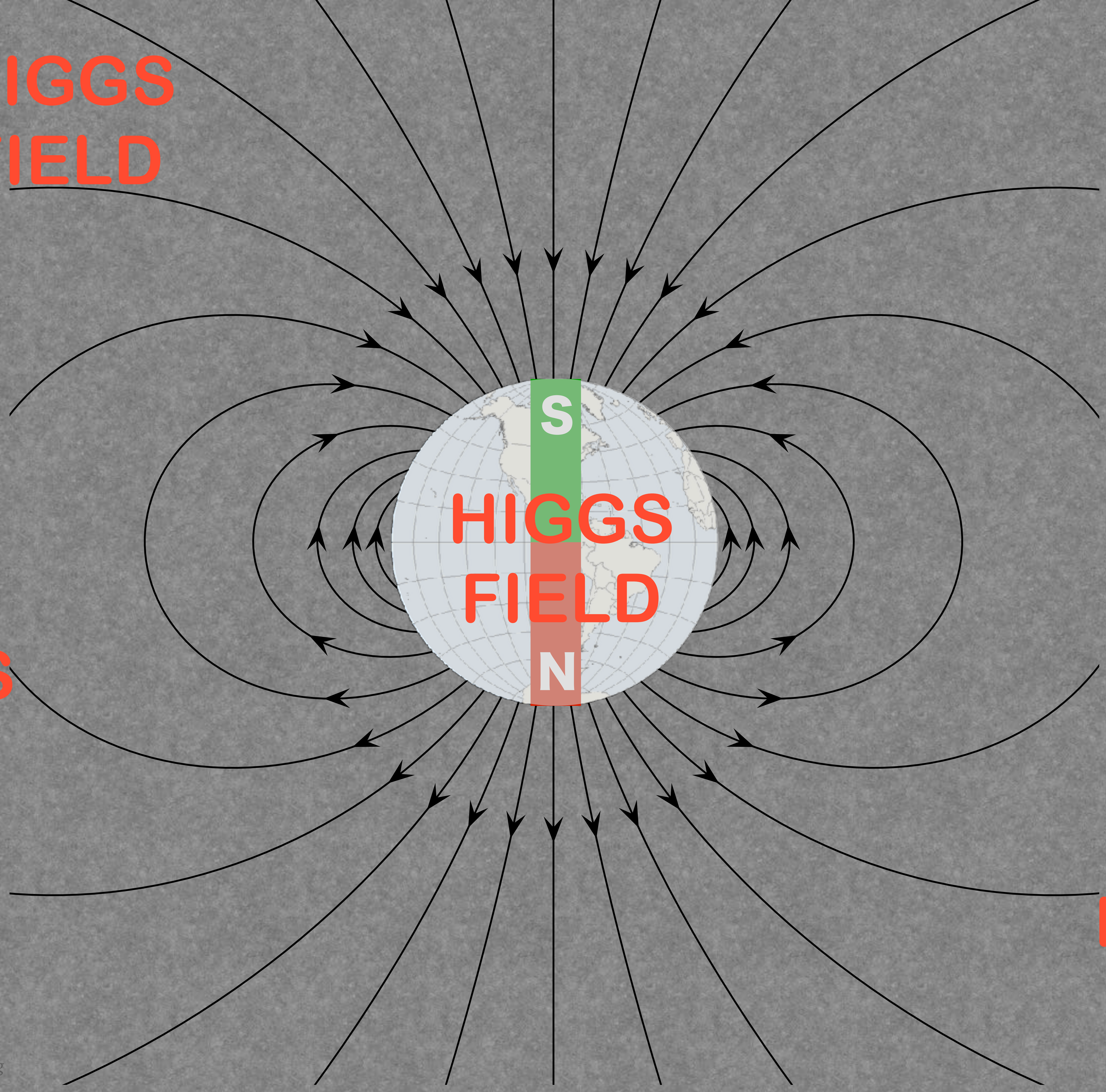


https://commons.wikimedia.org/wiki/File:VFPt_Dipole_field.svg
https://en.wikipedia.org/wiki/Western_Hemisphere#/media/File:Western_Hemisphere_LamAz.png

HIGGS FIELD

HIGGS FIELD

HIGGS FIELD



HIGGS FIELD

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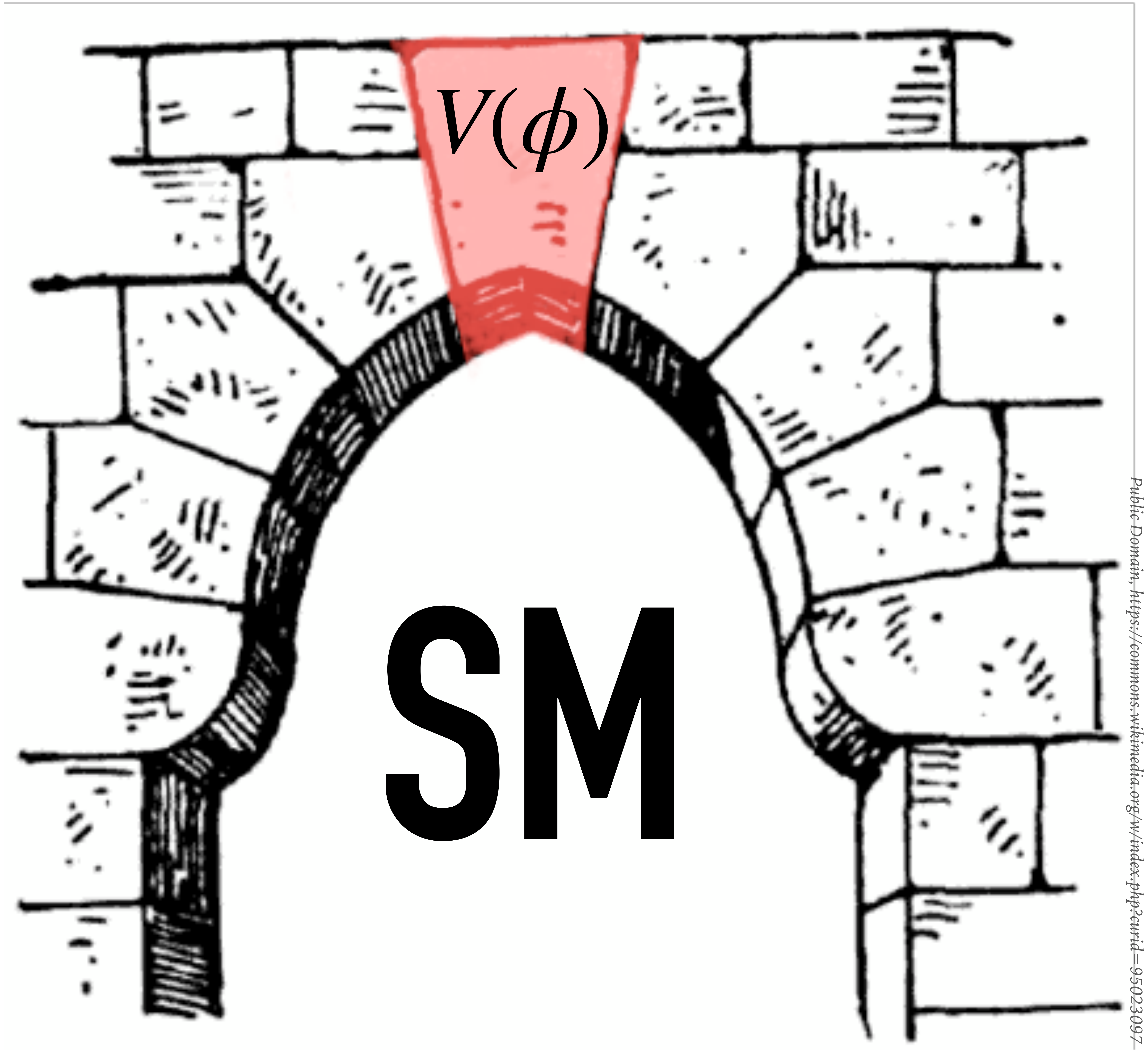
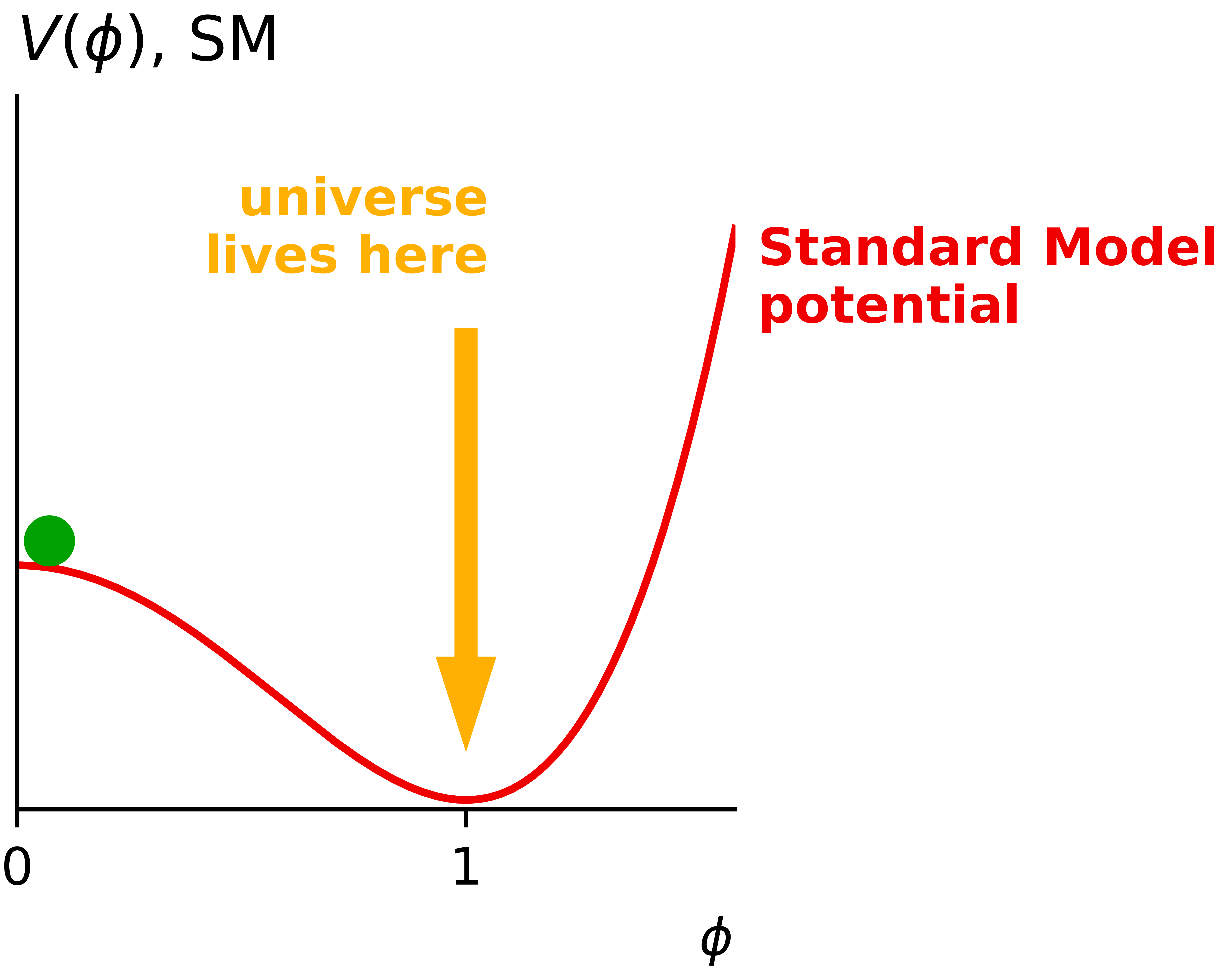


unique among all the fields we know, the Higgs field is the only one that is non-zero "classically"

Why?
Higgs potential?

Keystone of SM

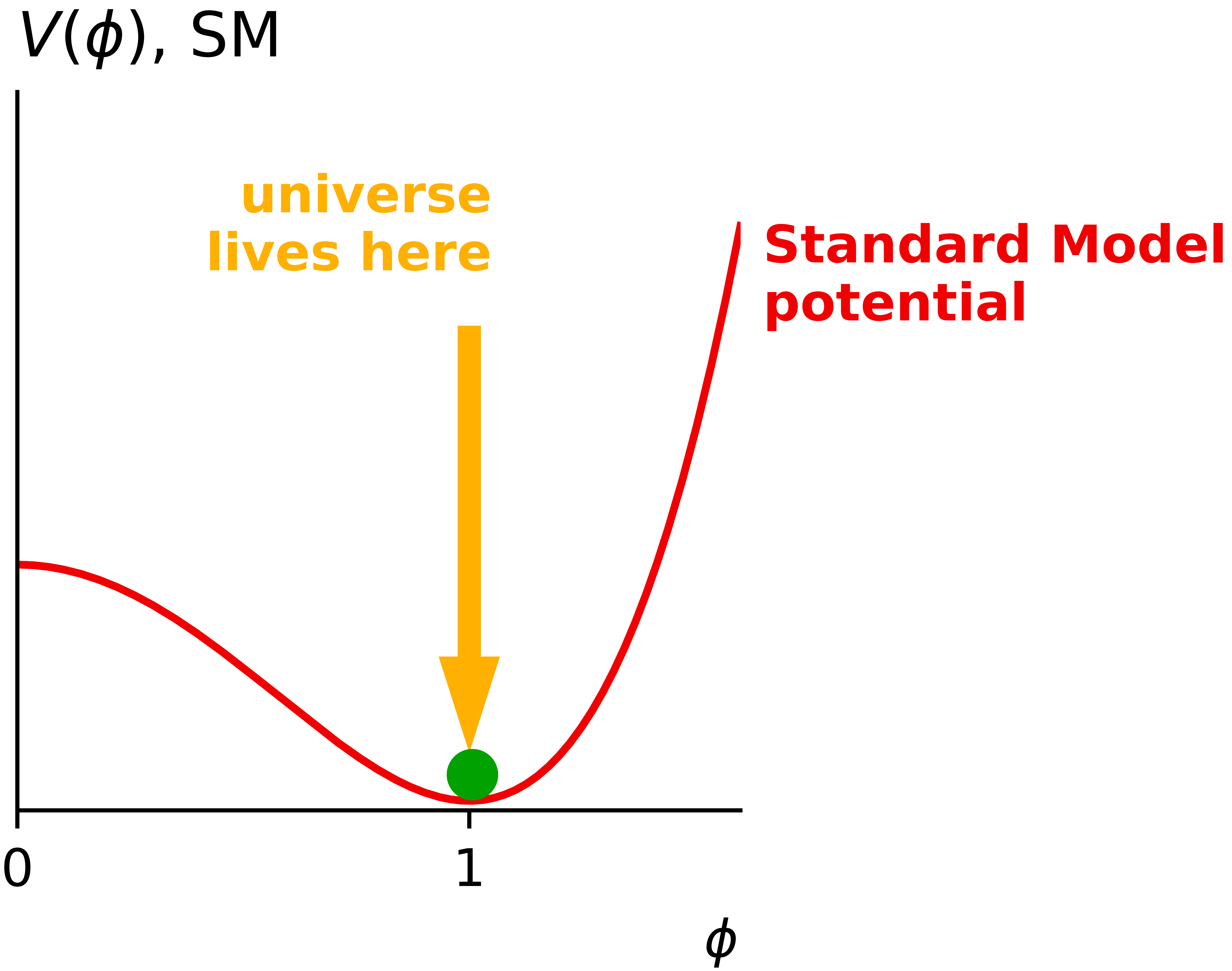
Higgs potential



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



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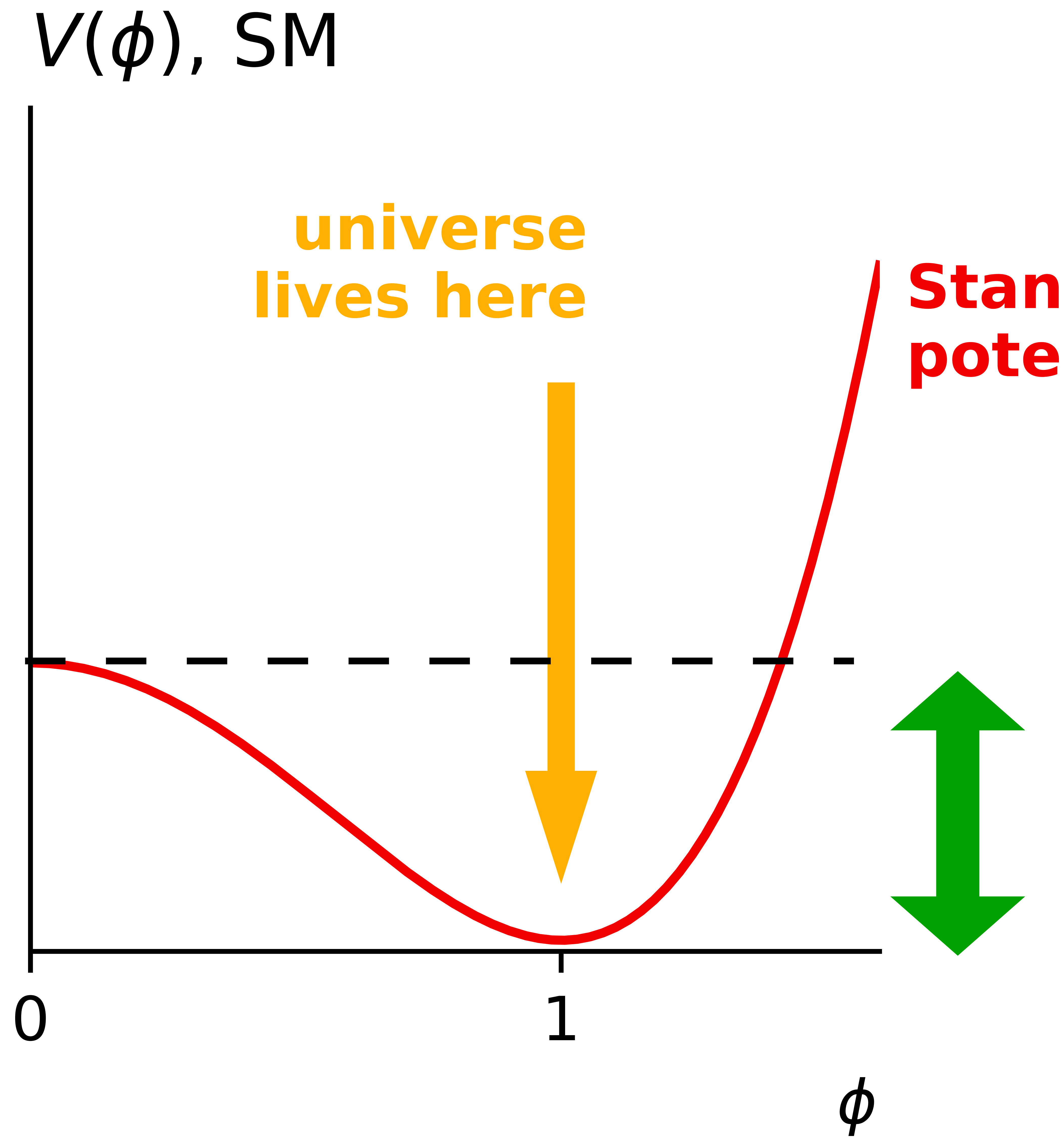
Higgs potential — remember: it's an energy density



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://en.wikipedia.org/wiki/File:Arena,_Ajax_stadion,_Amsterdam.JPG

Earth at neutron star density

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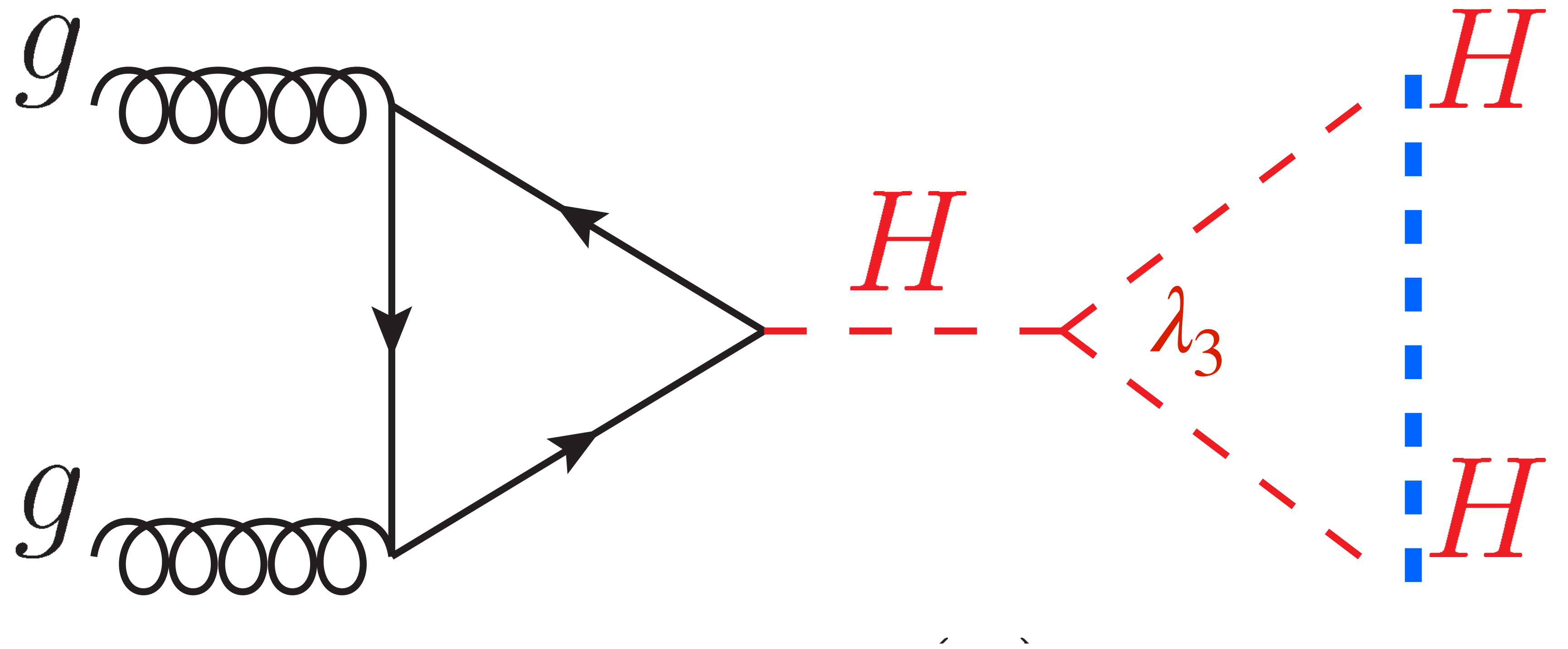
Earth at neutron star density

Earth at Higgs potential density

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

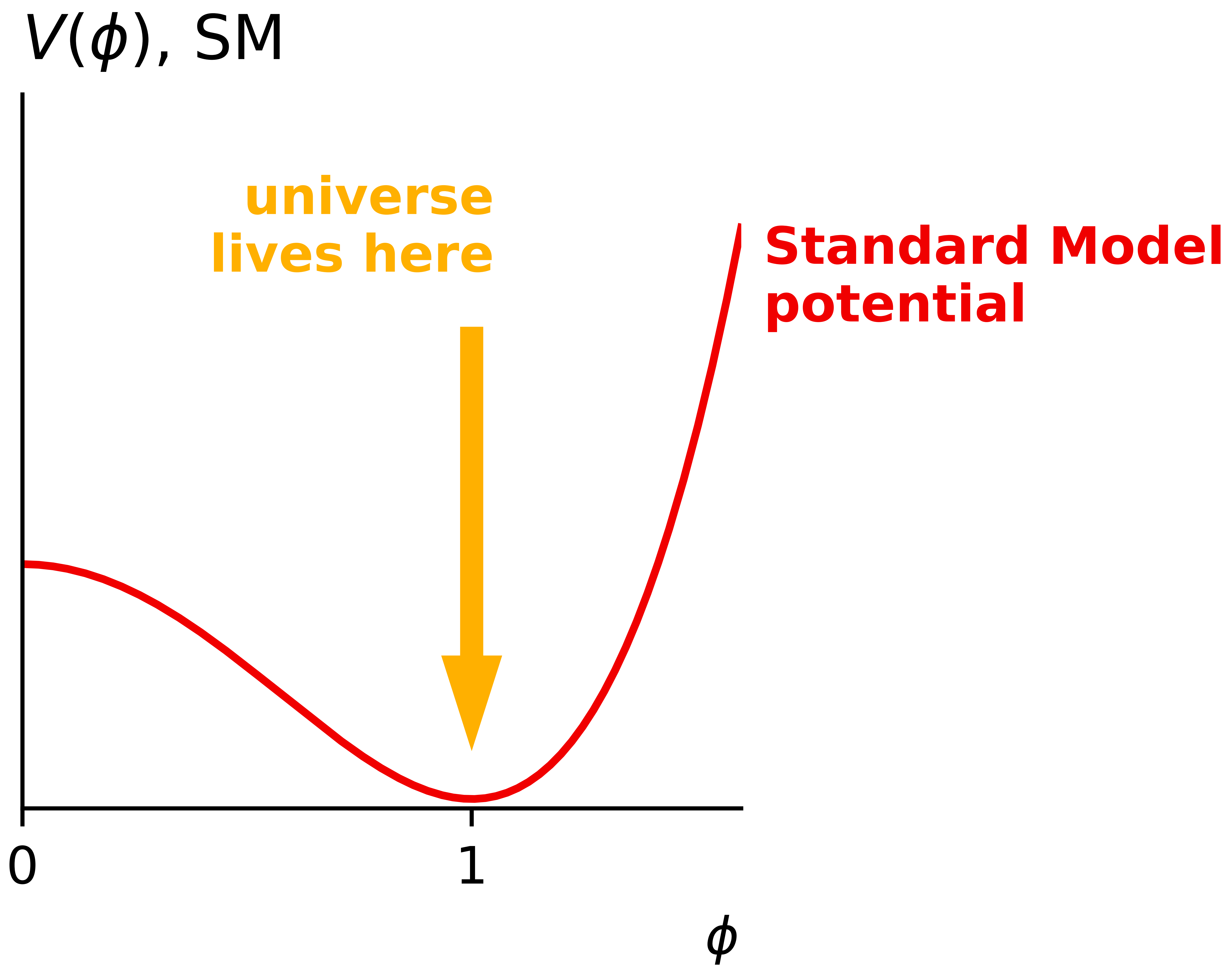


g
g
H
λ3
H
H

luon
gluo
Φ
y
x
Higgs field in space


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

Higgs potential

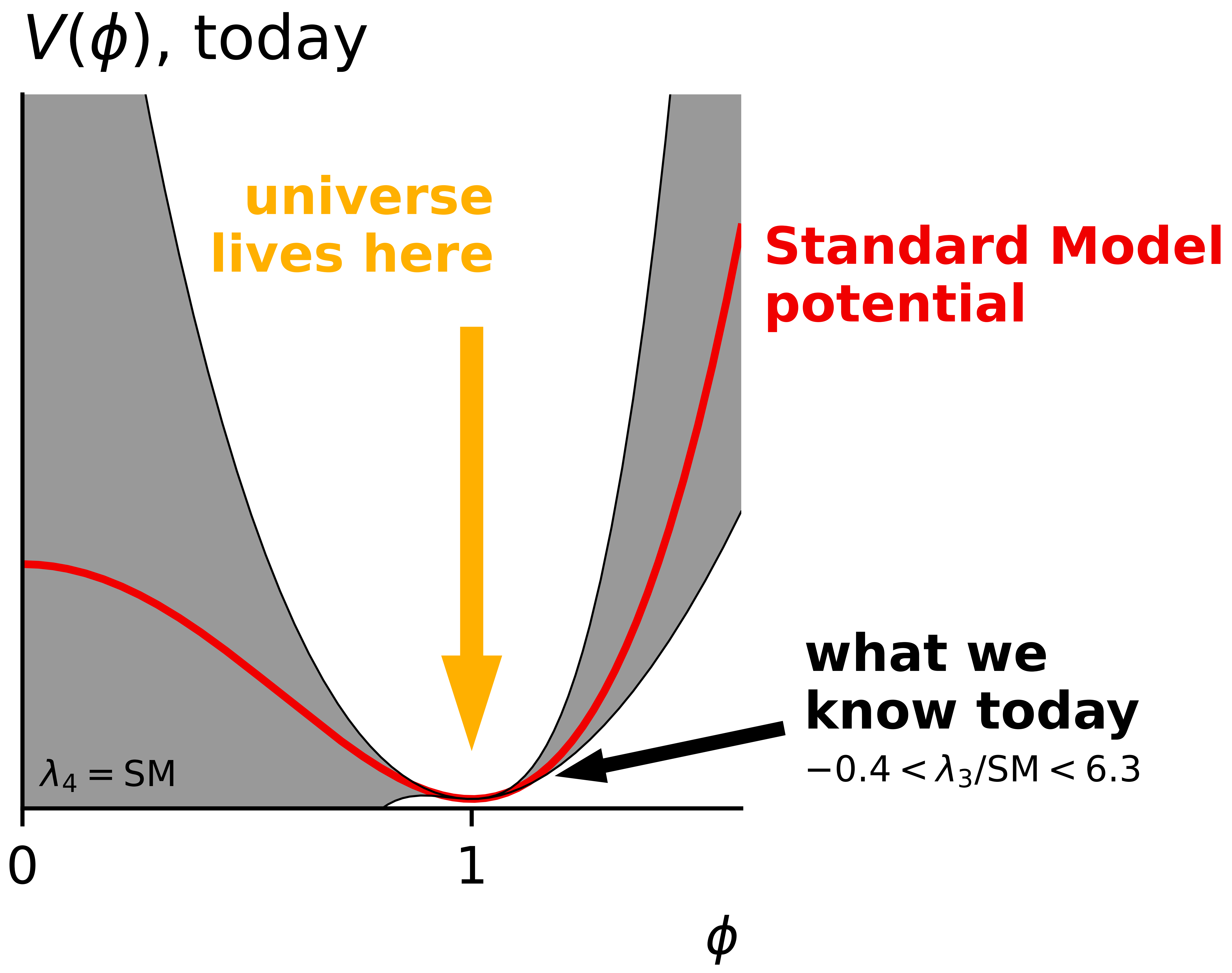


Studying H→HH probes specific mathematical property of the potential's shape:

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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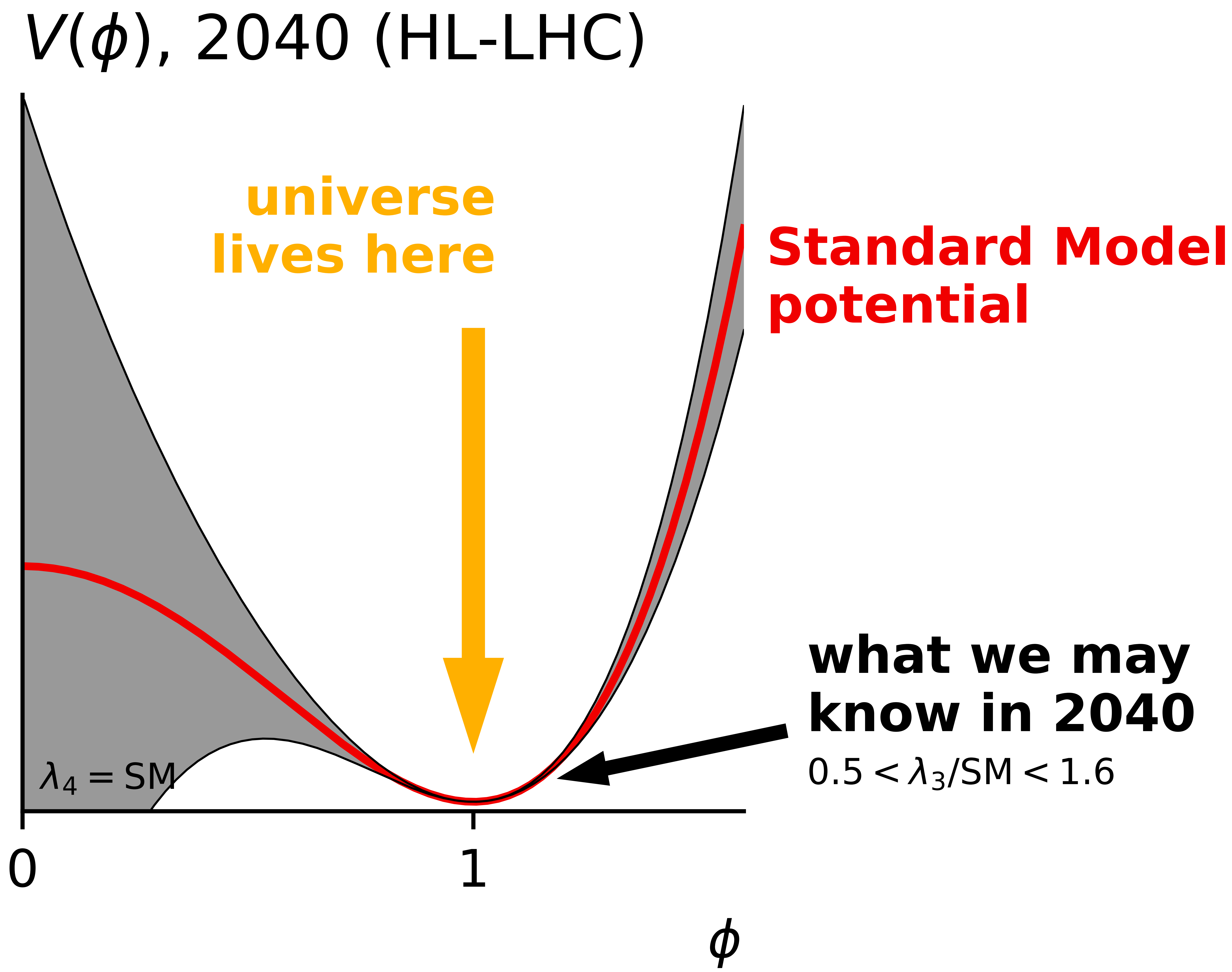

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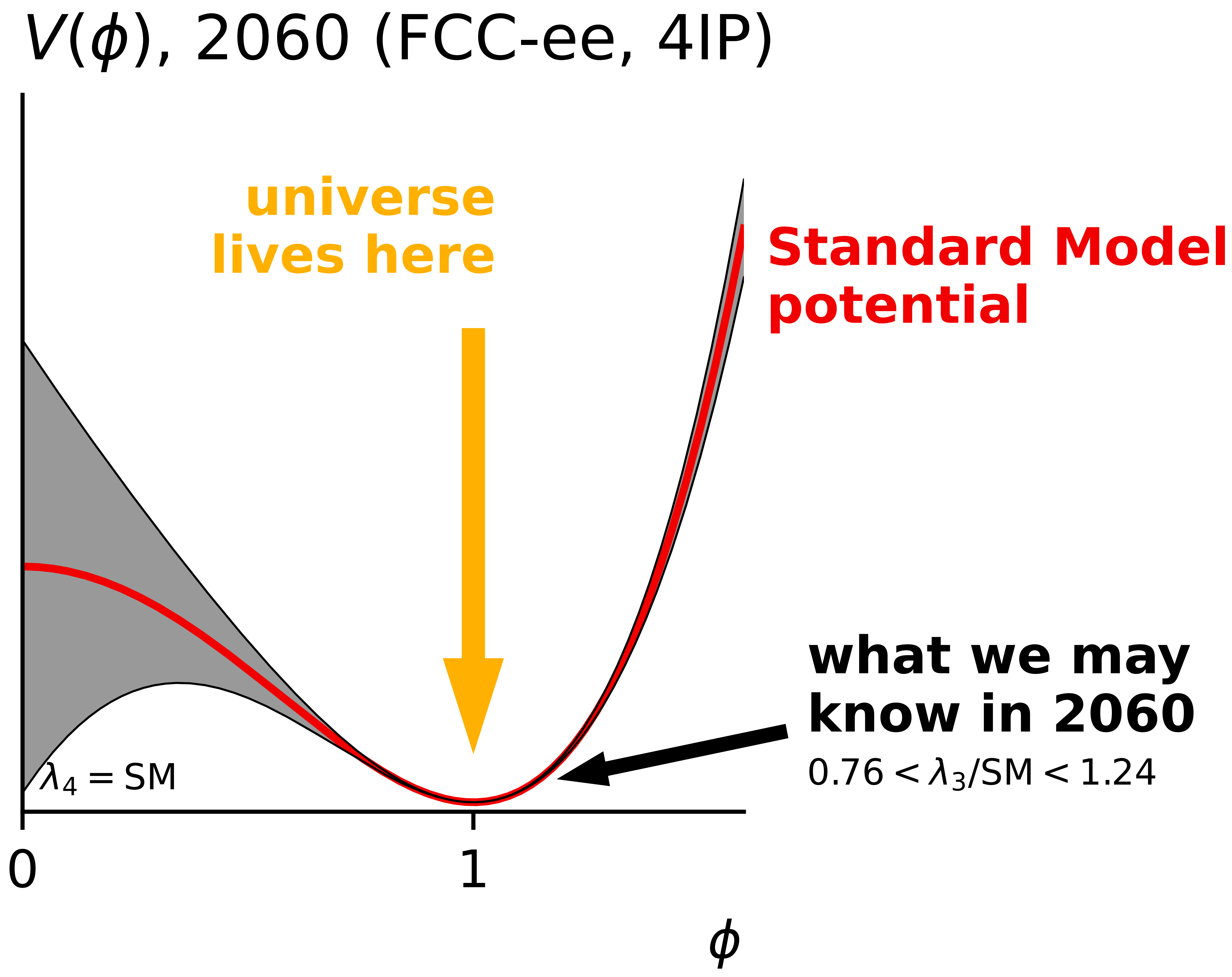

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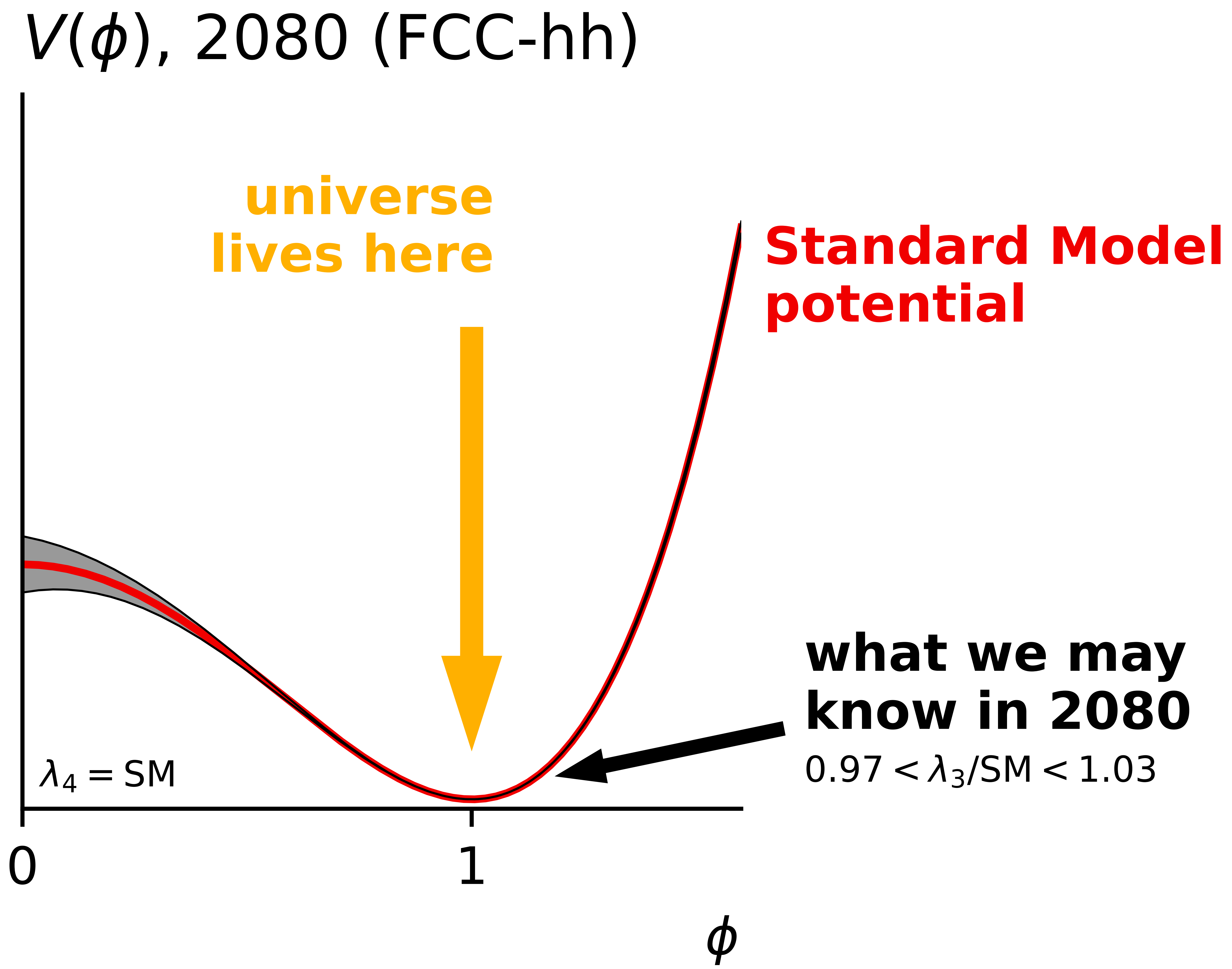

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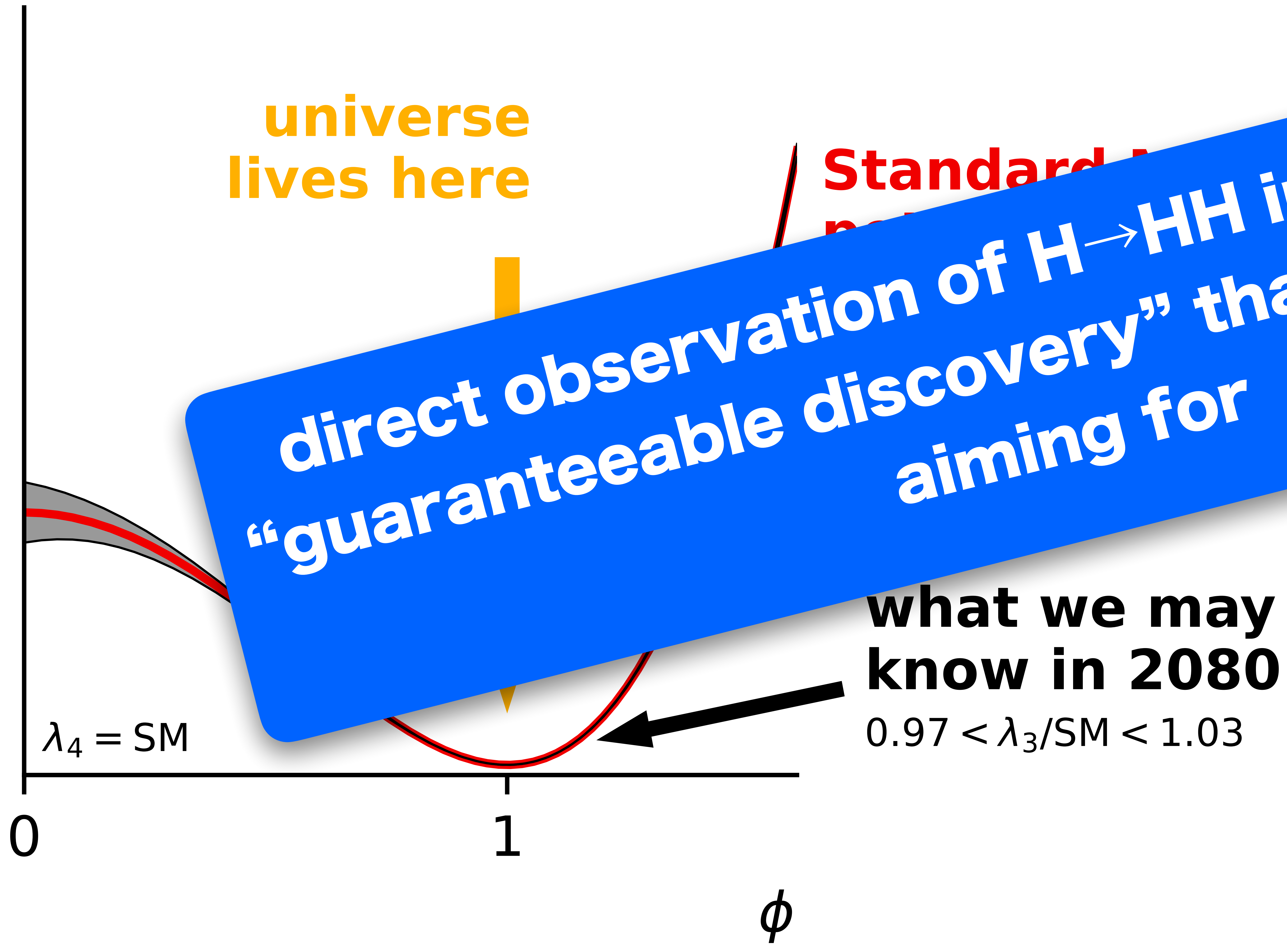
Higgs potential

$V(\phi)$, 2080 (FCC-hh)



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

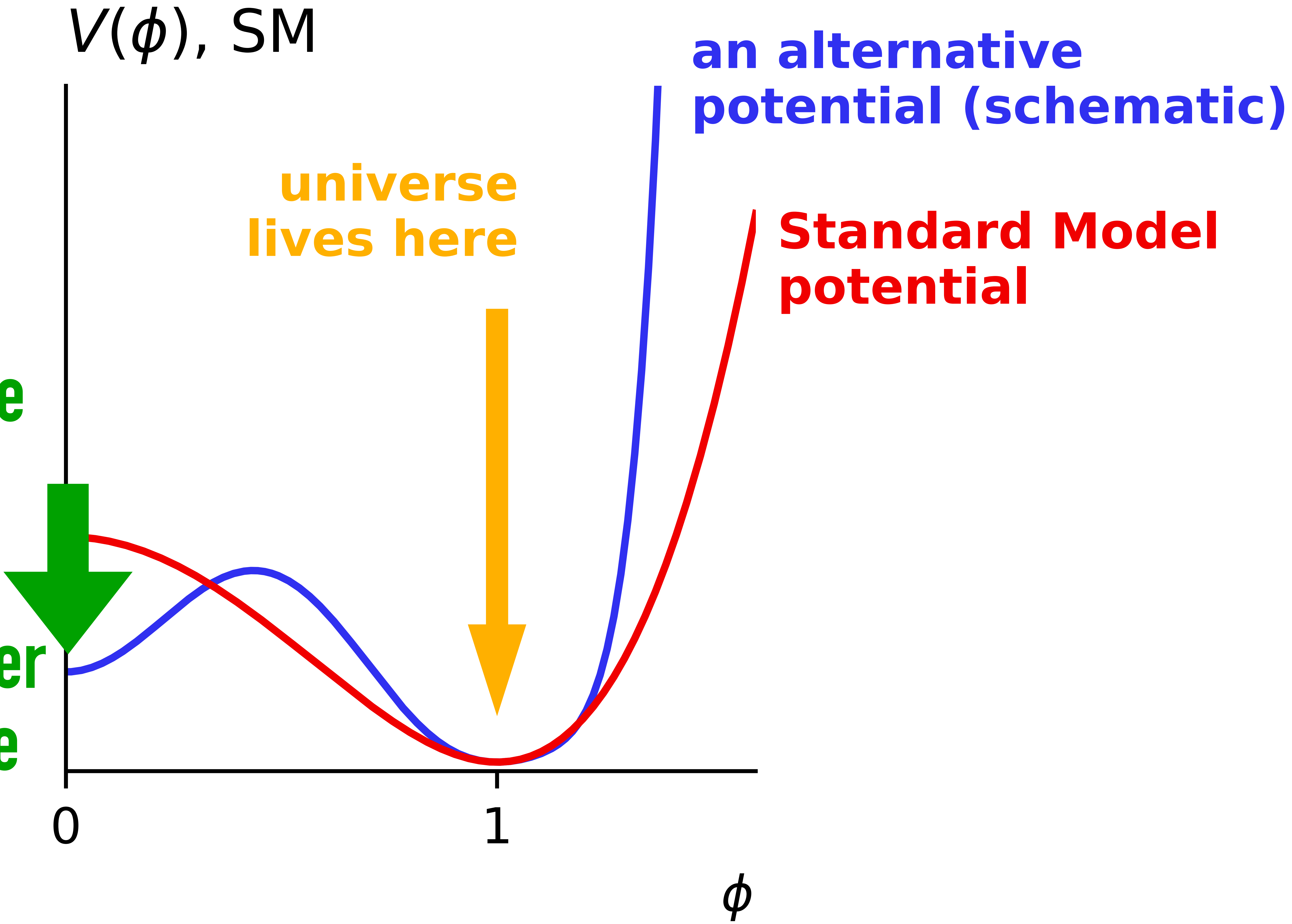
Studying H→HH probes
spe… …tical property
…l's shape:
…ive (λ_3),
…metric it is
at the minimum

[reconstruction in plot assumes higher derivatives as in SM]

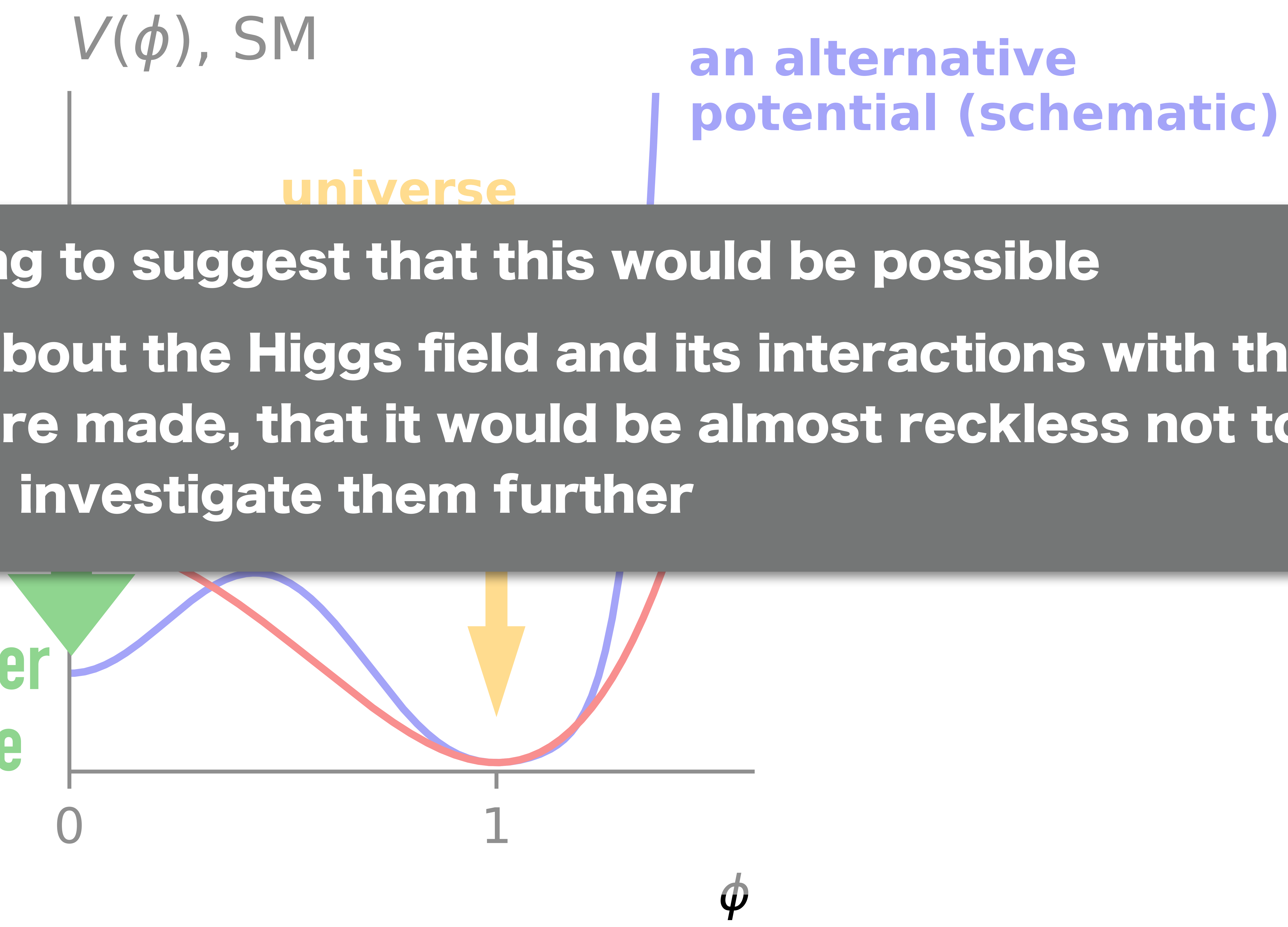
Science fiction

could we make a bubble with zero Higgs field?

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



Science fiction



there is nothing to suggest that this would be possible

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

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

desirable features of 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

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*

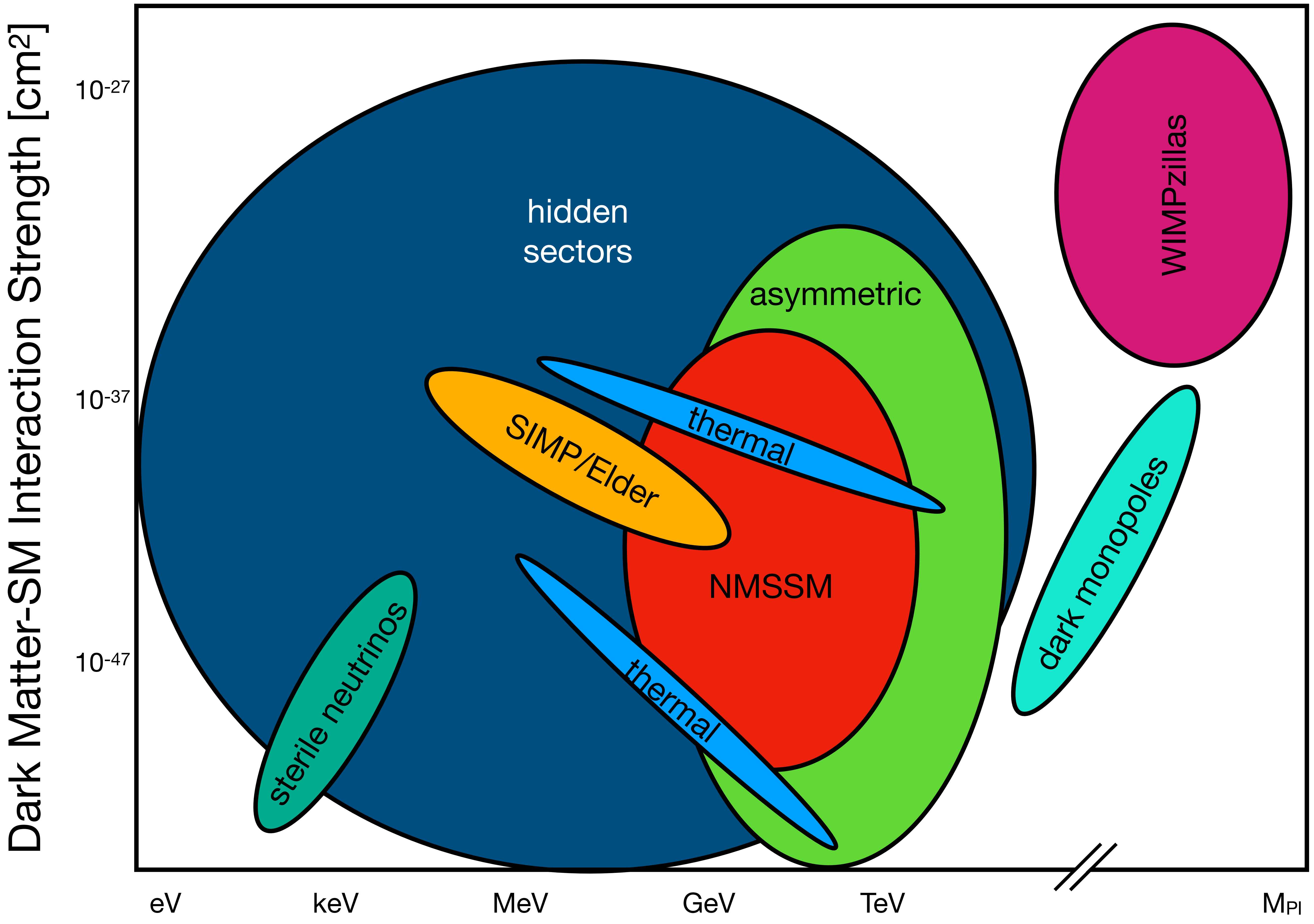
Thank you, Particle Physicists

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

Almost every problem of the Standard Model originates from Higgs interactions

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

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

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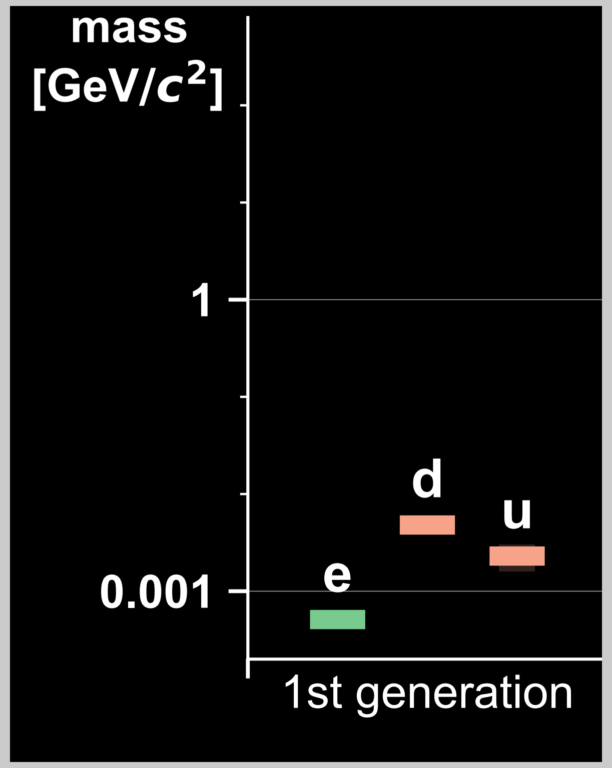

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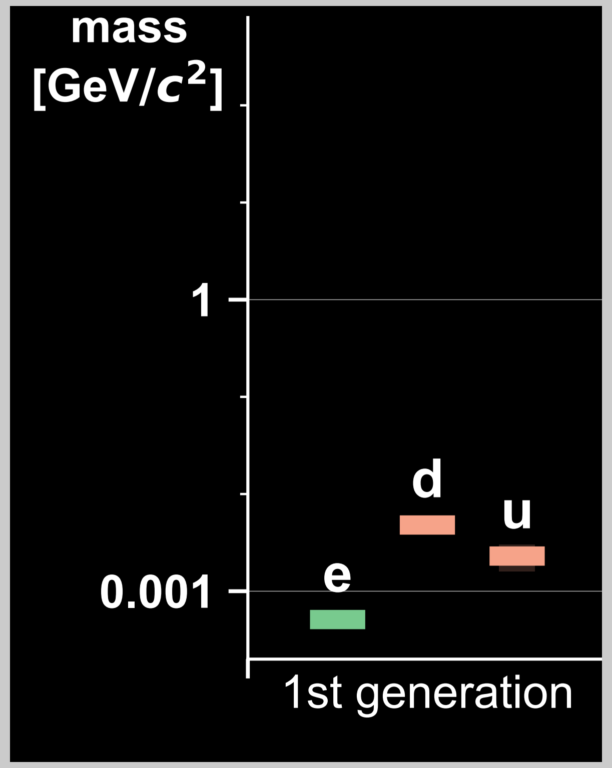

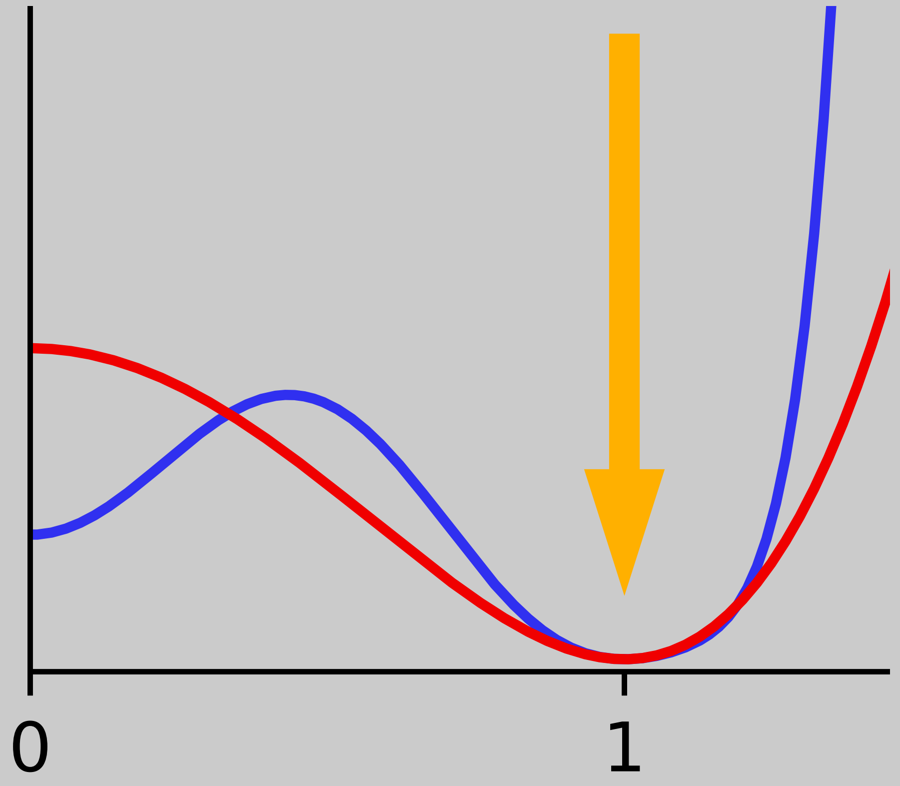

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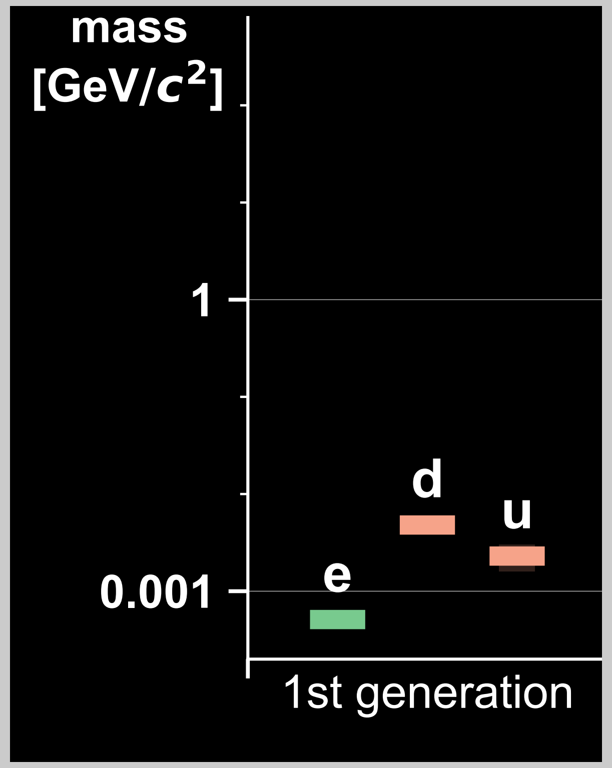
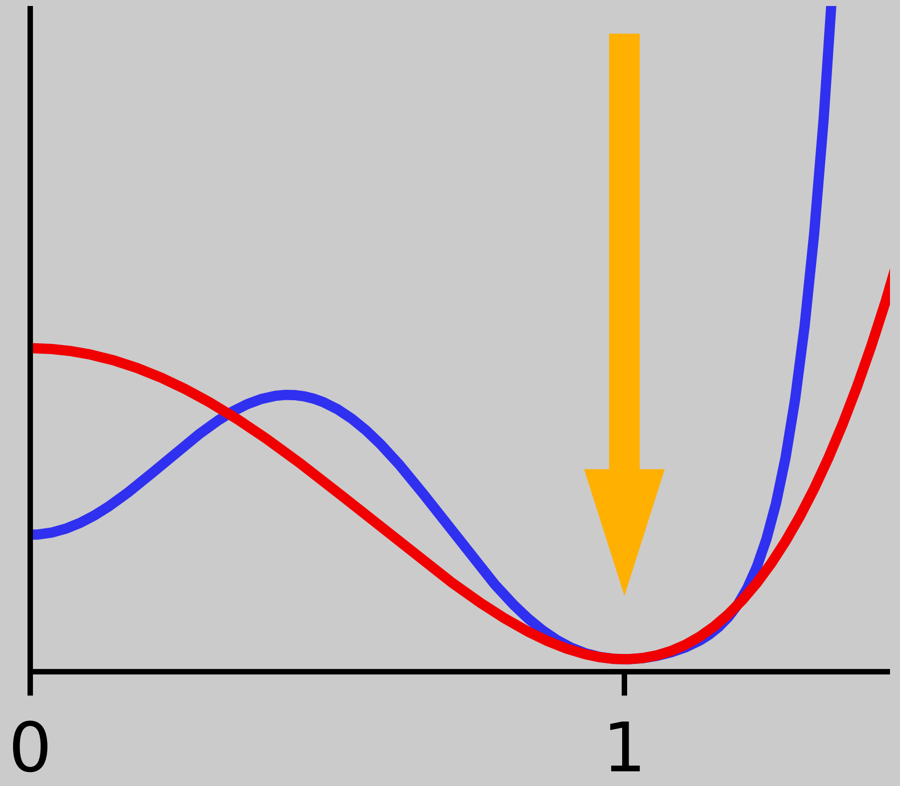
flavour · *naturalness* · *stability* · *cosmological constant*





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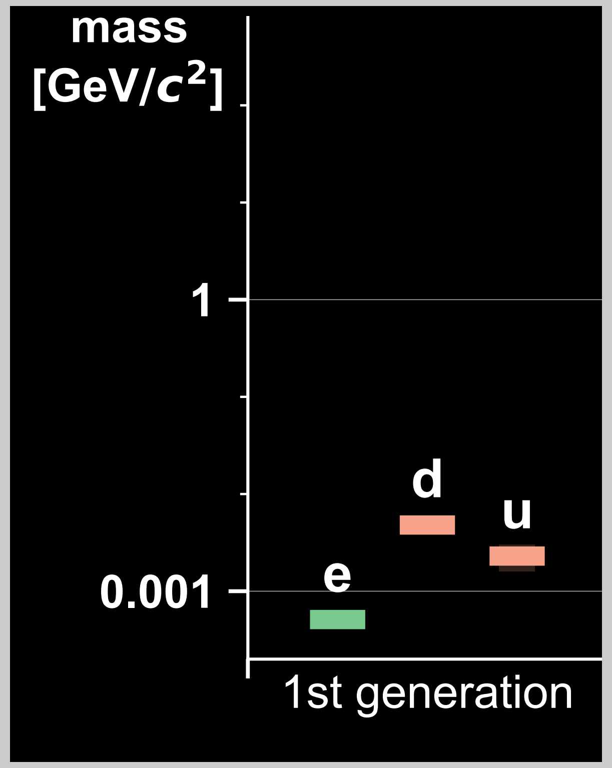
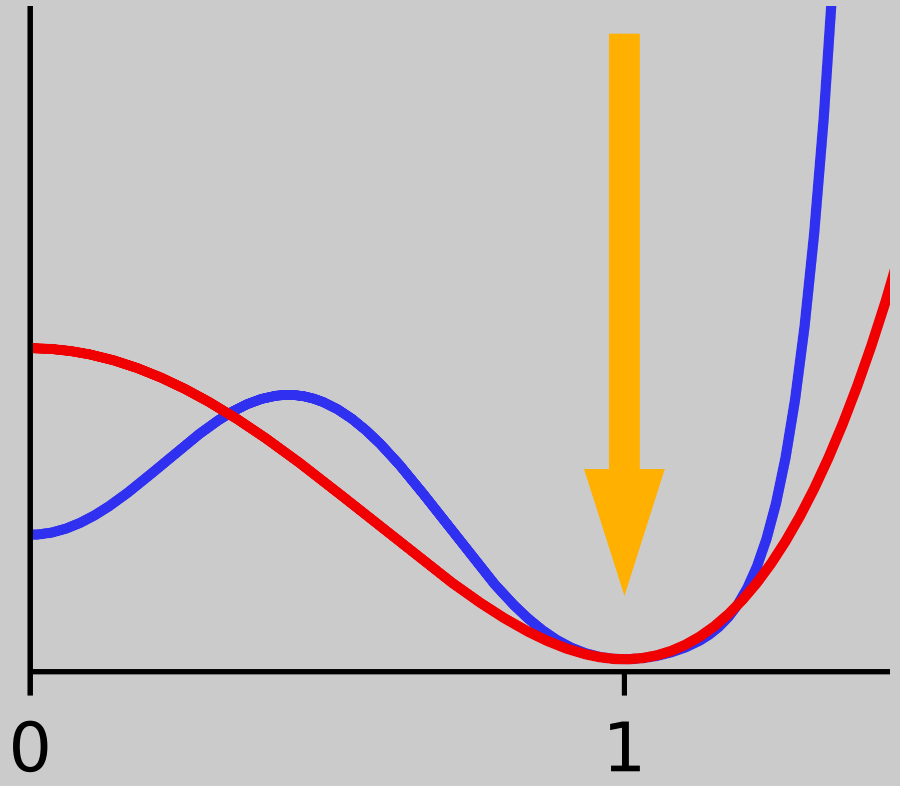
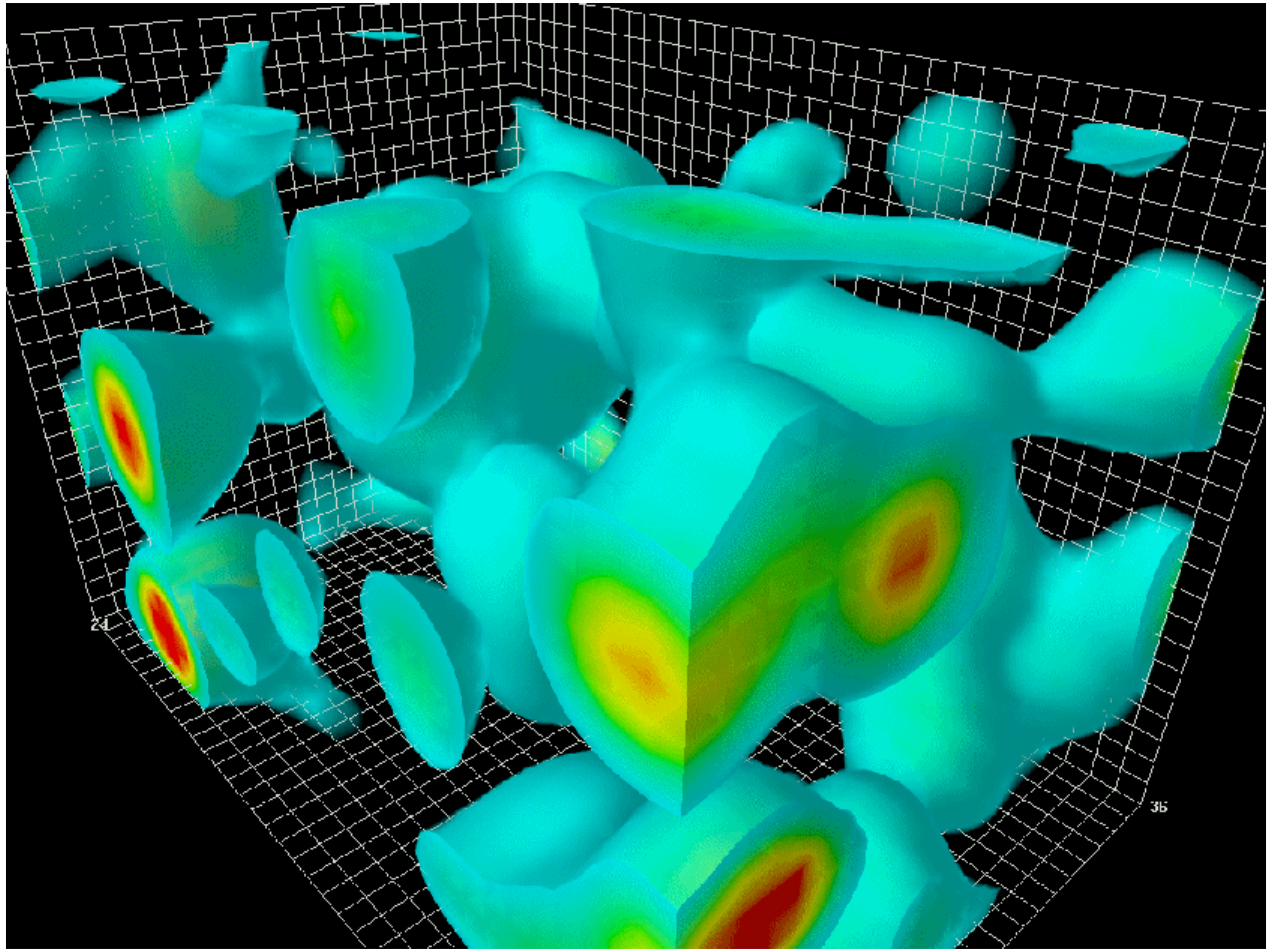
flavour | *naturalness* | *stability* | *cosmological constant*





Naturalness in particle physics

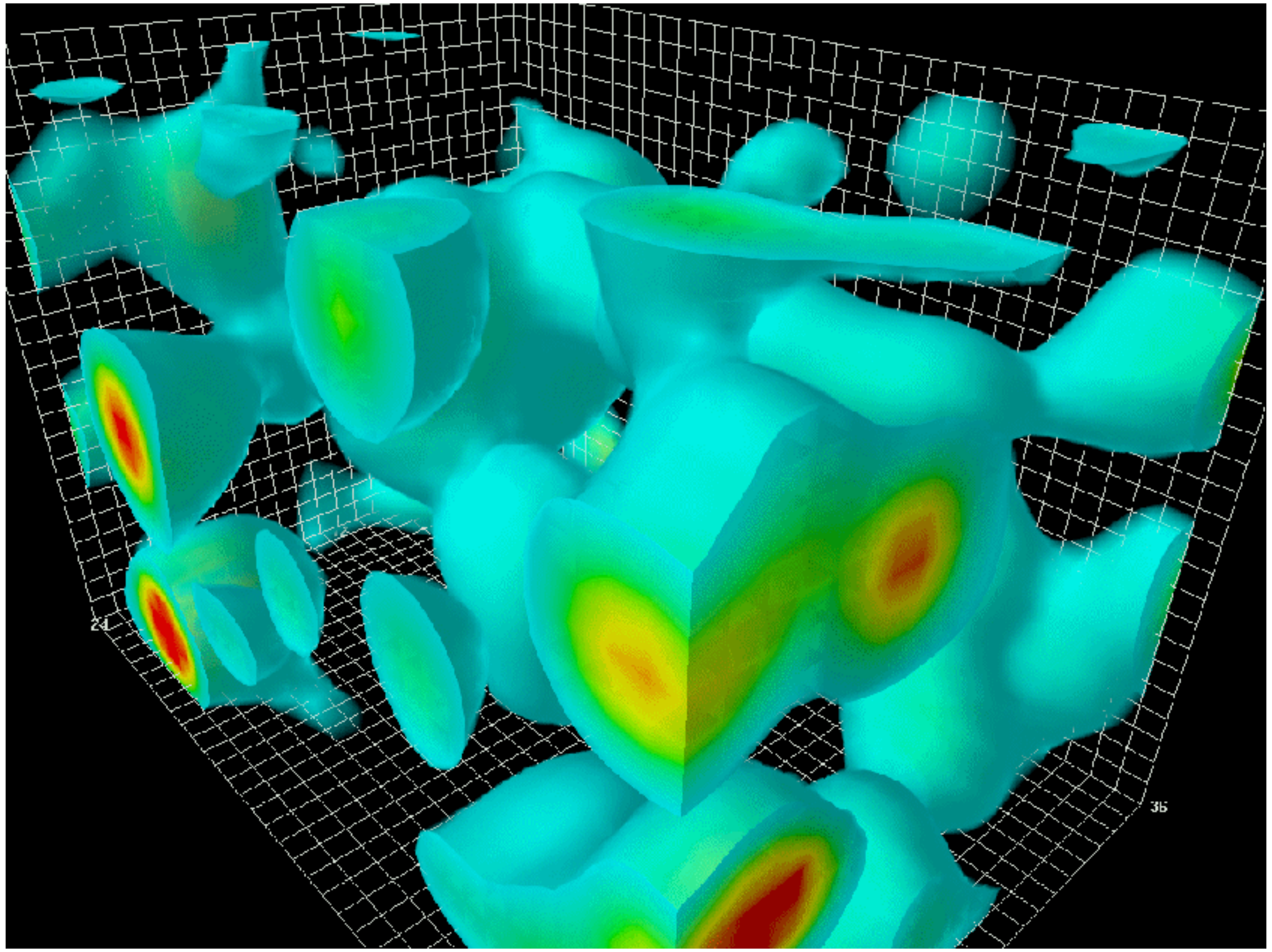


http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/index.html
NB: shows QCD quantum fluctuations, so not directly those connected with the Higgs mass

- 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

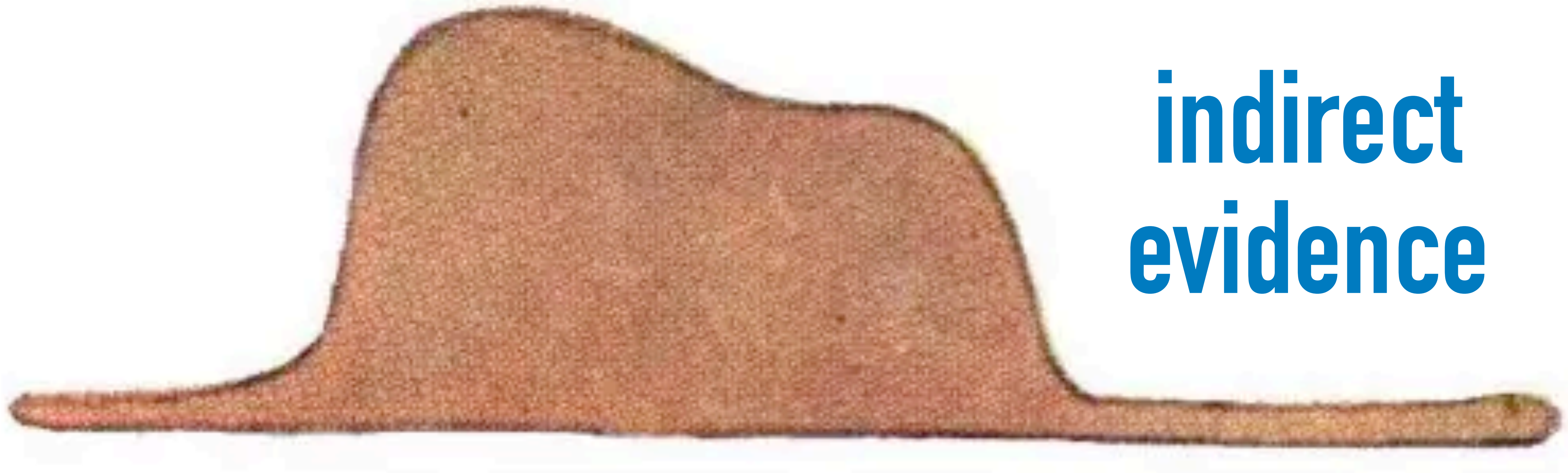


http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/index.html
NB: shows QCD quantum fluctuations, so not directly those connected with the Higgs mass

- 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]

Mon dessin numéro 1



indirect evidence

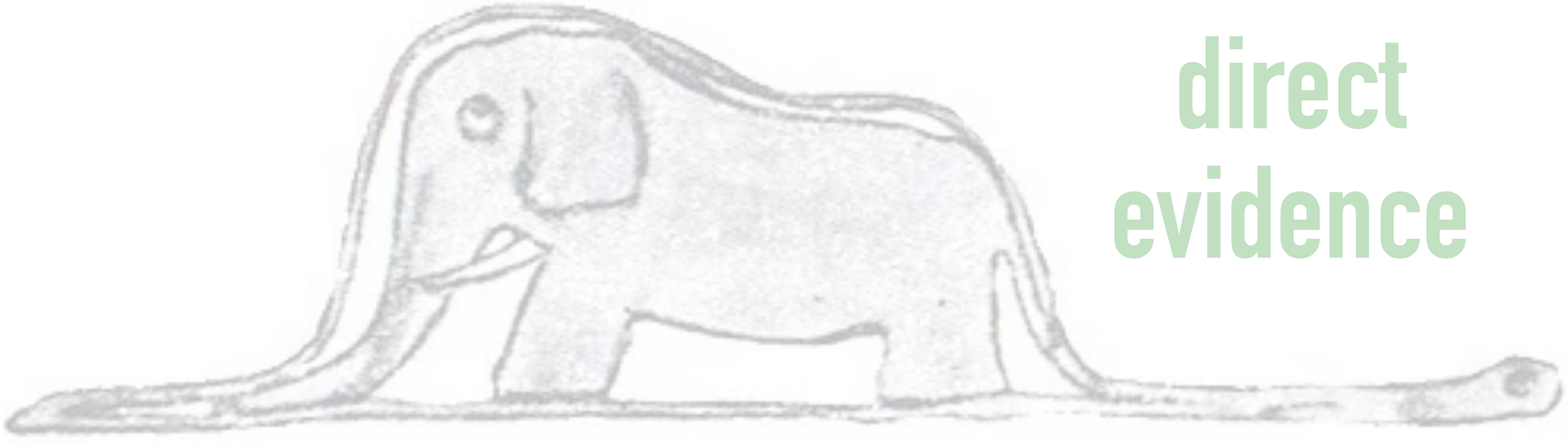
« Pourquoi un chapeau ferait-il peur ? »

“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. »

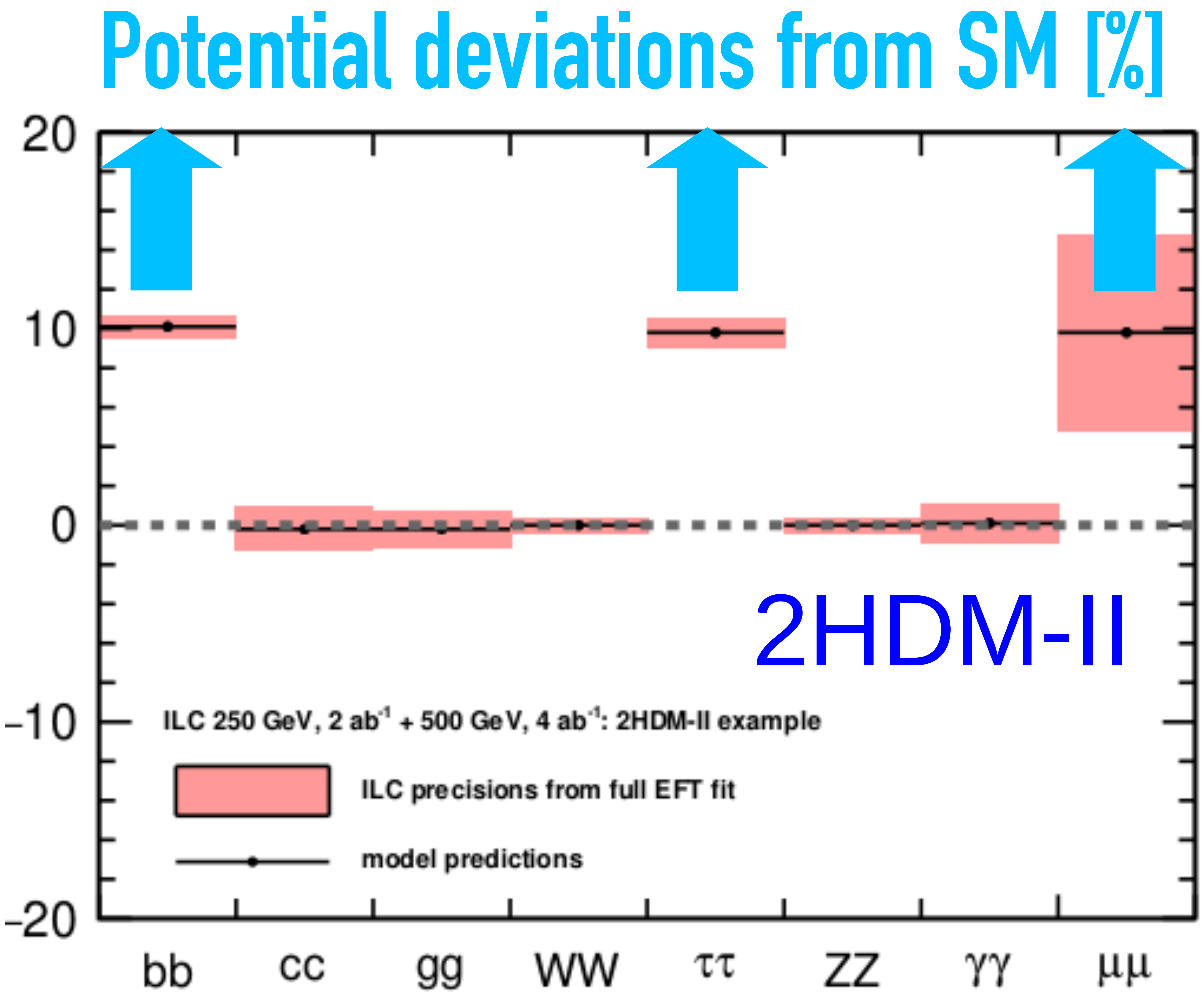
“My drawing was not a picture of a hat. It was a picture of a boa constrictor digesting an elephant.”



direct evidence

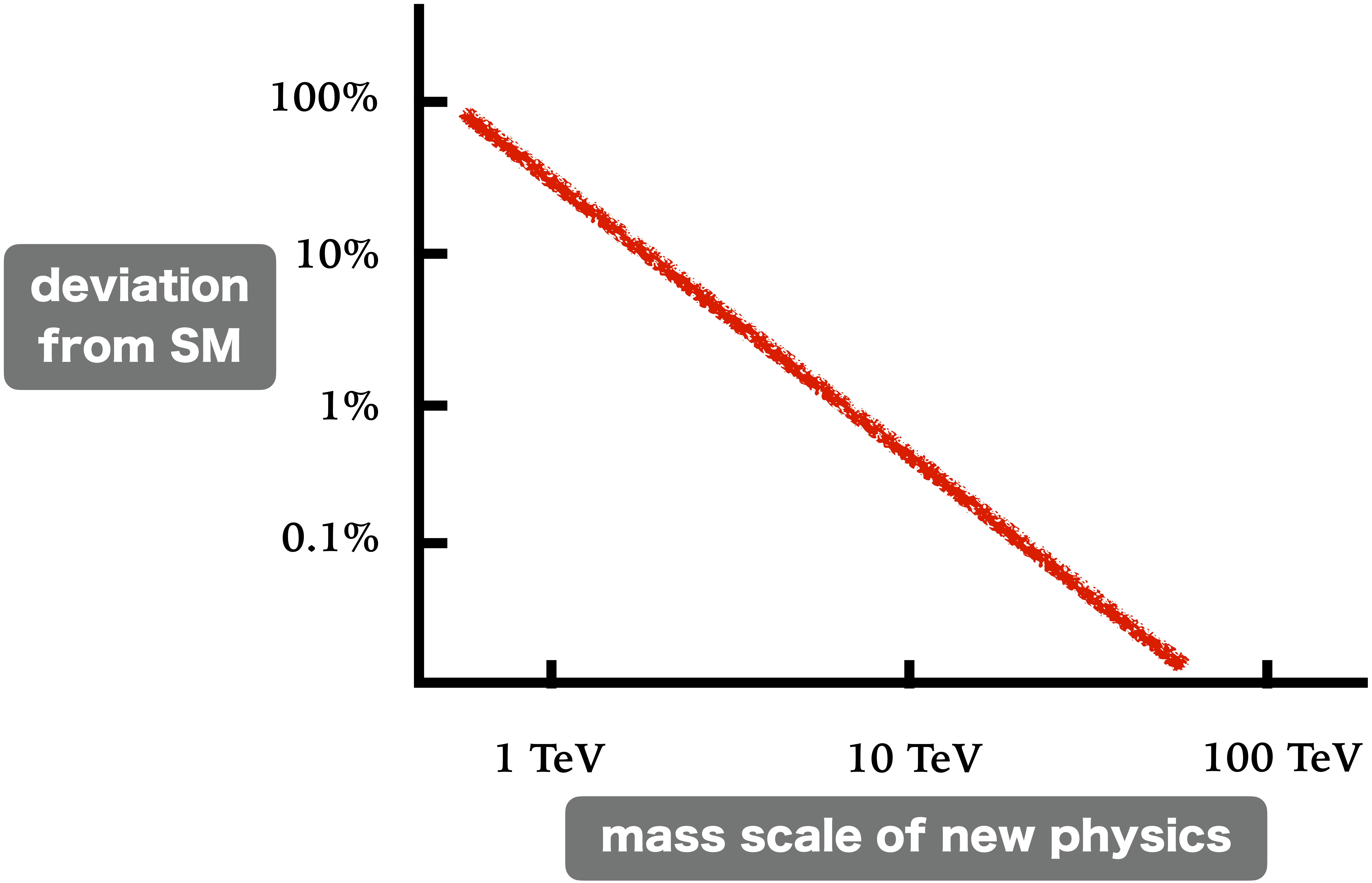
Mon dessin numéro 2

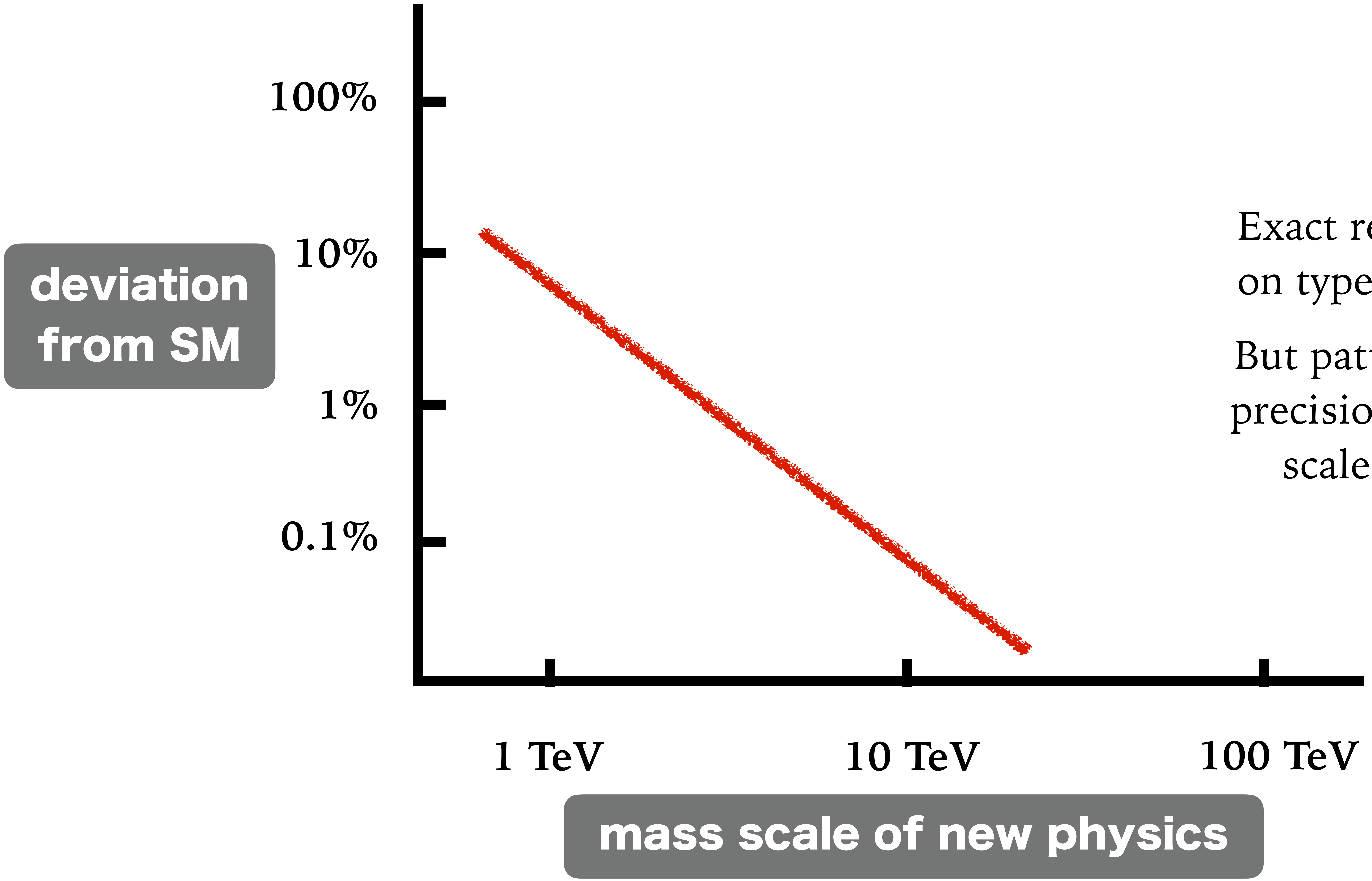
measuring many distinct interactions is crucial in indirect searches



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

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

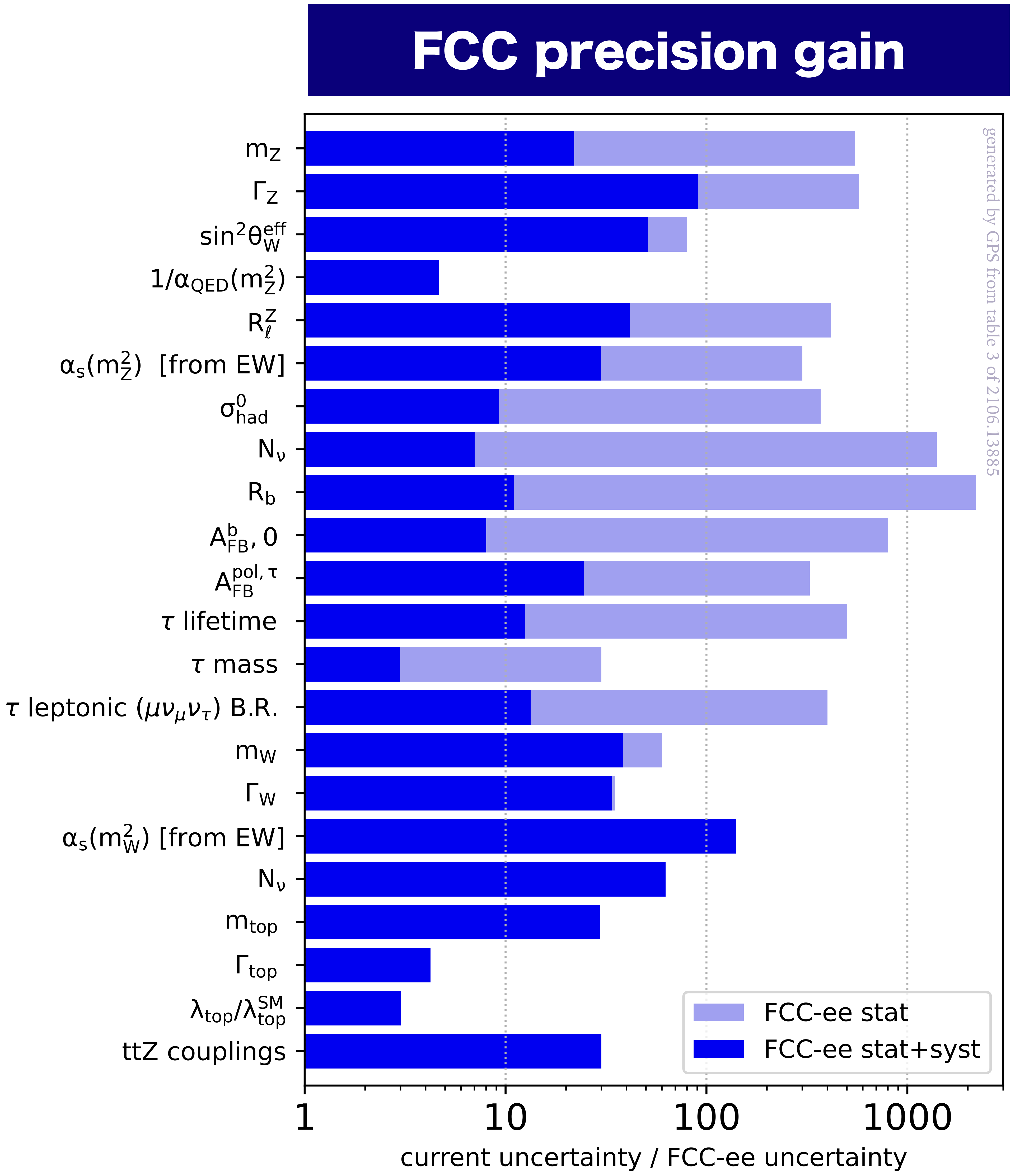

100%
10%
1%
0.1%
deviation from SM
1 TeV
10 TeV
100 TeV
mass scale of new physics



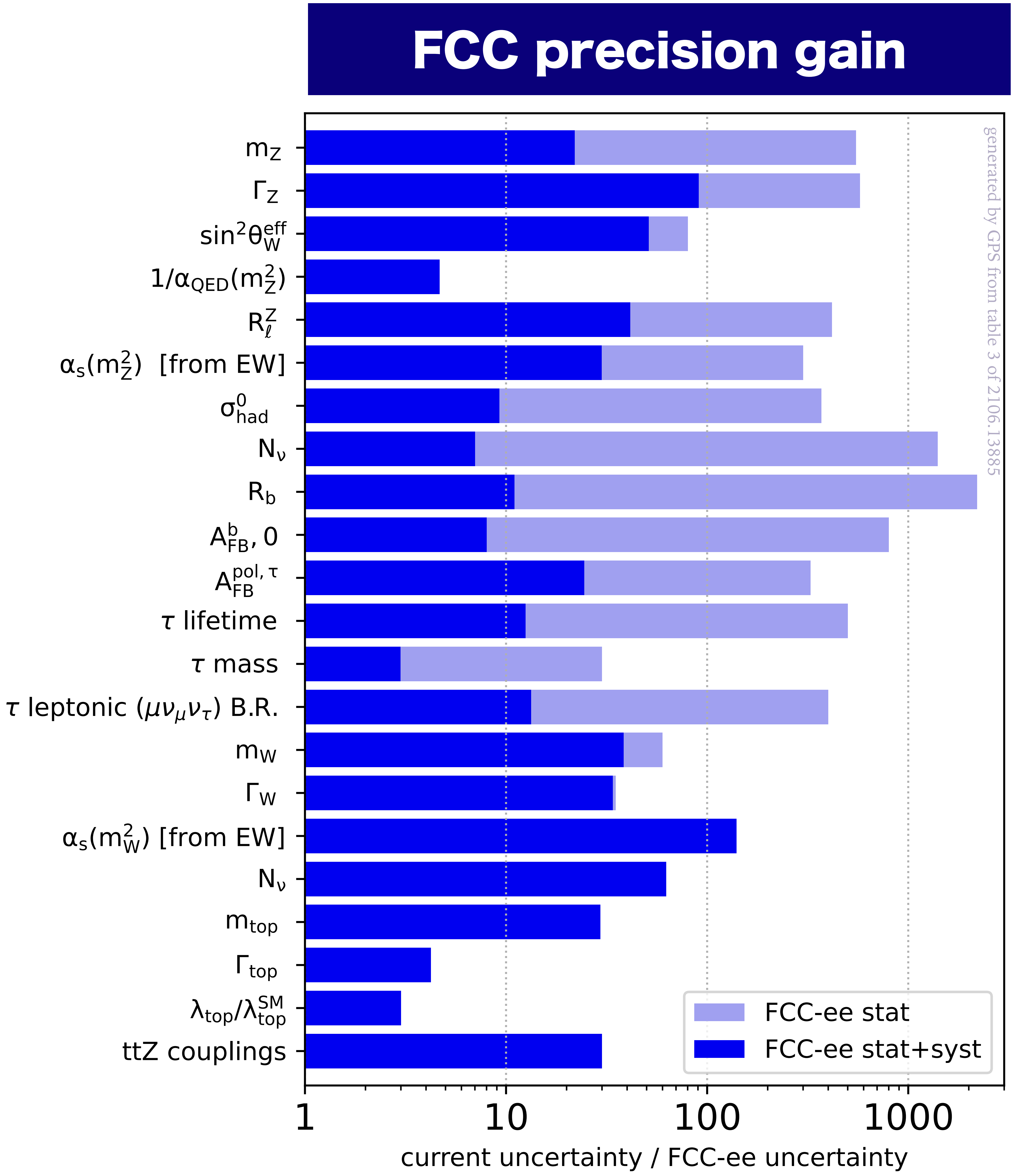
Exact relation depends on type of new physics

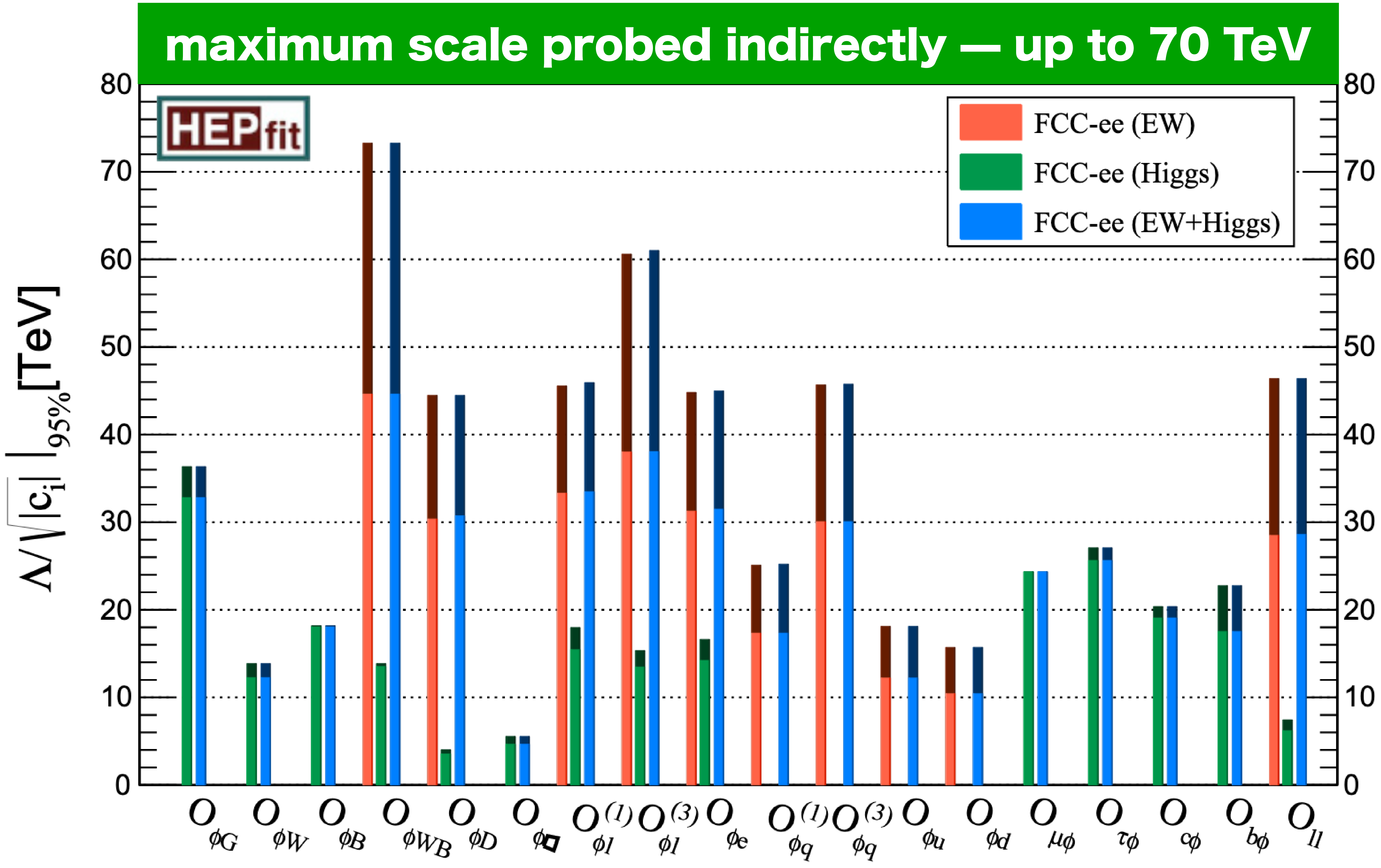
But pattern that higher precision probes higher scales is universal

increase in precision at FCC-ee is equivalent to $\times\ 4-5$ increase in energy reach

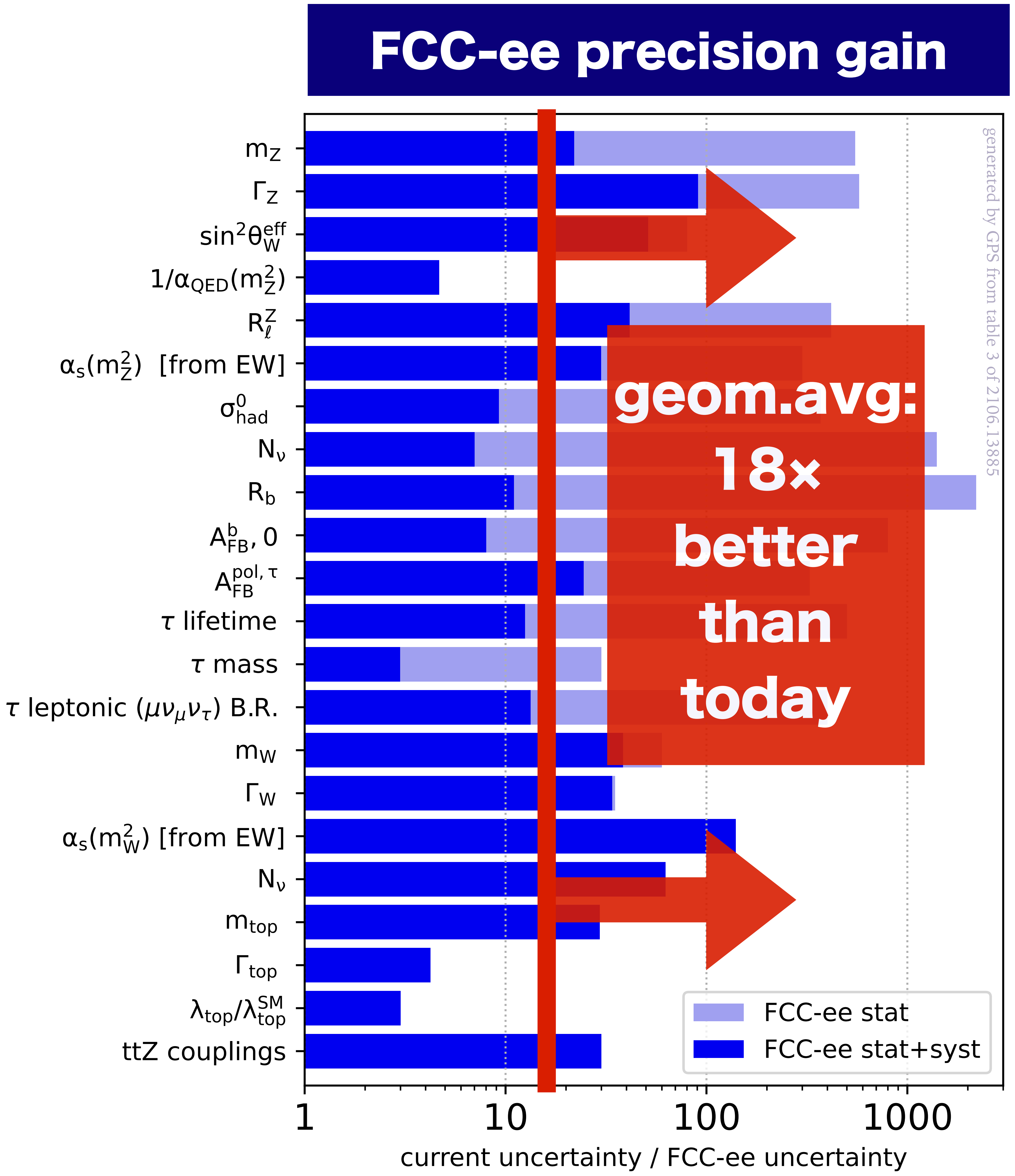


increase in precision at FCC-ee is equivalent to × 4 – 5 increase in energy reach





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



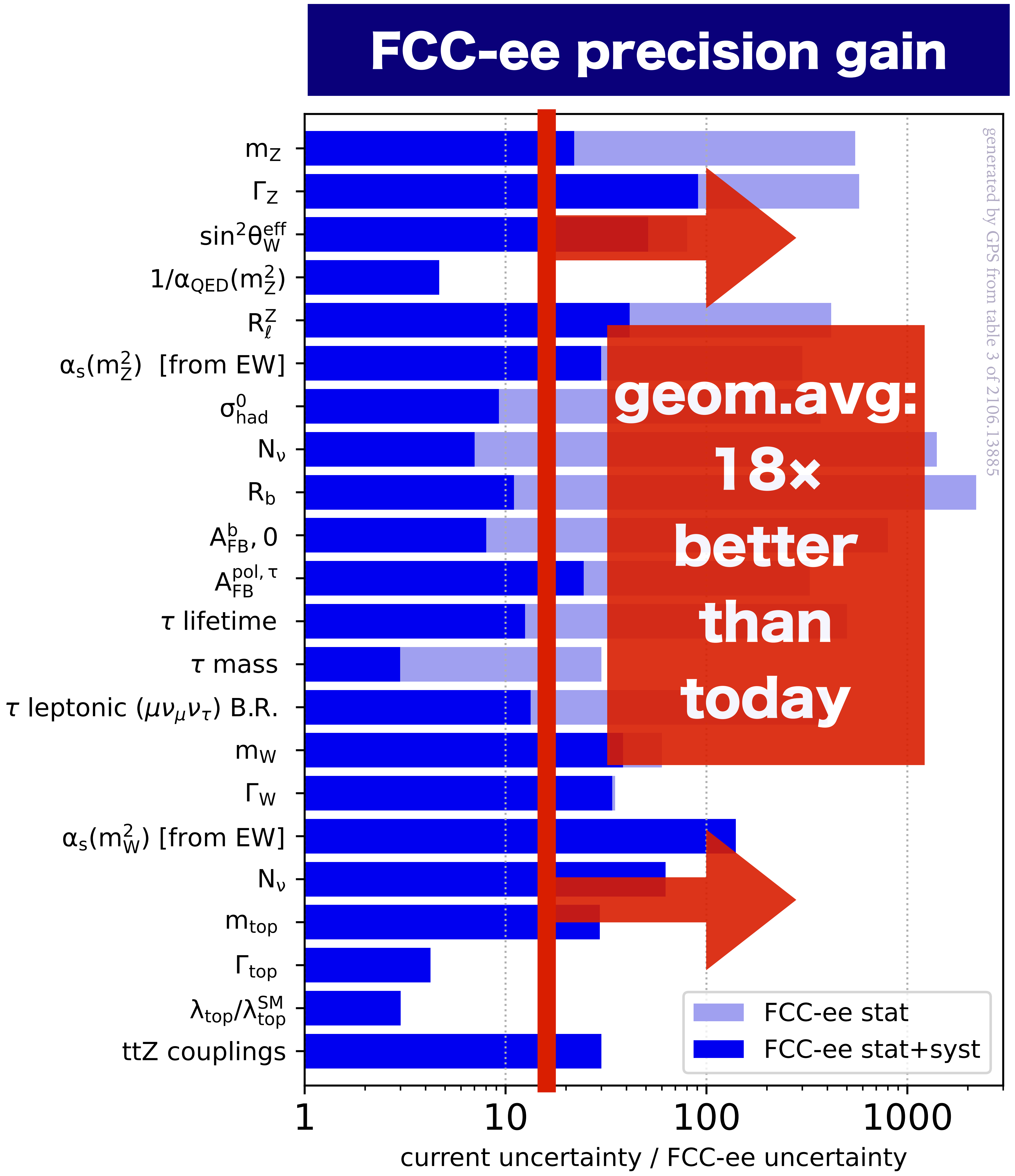
Two messages

- with a rough estimate for systematics, FCC-ee brings a big step forward (geom.avg. = × 18, across ≳ 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

indirect evidence

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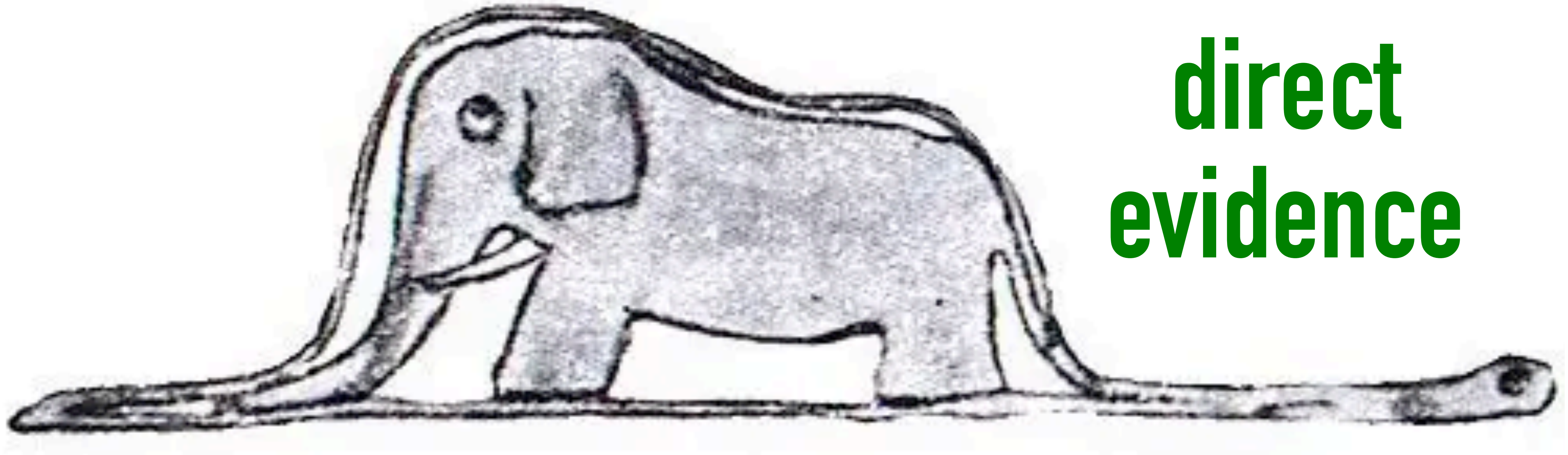
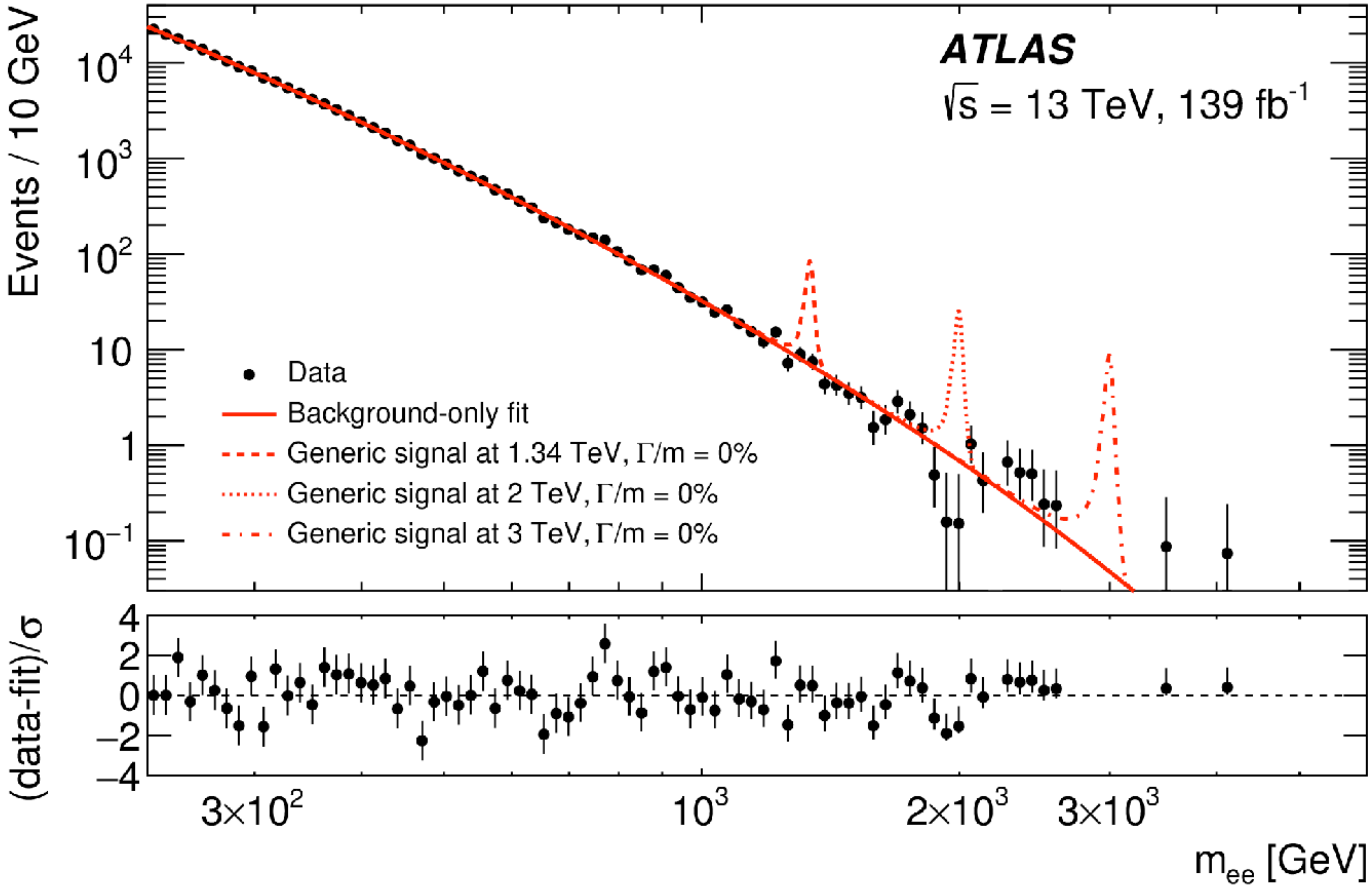


direct evidence

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 $Z'_{\rm SSM}$ 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}, μμ 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)

step up in energy for direct searches?

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

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

Exclusion limit ~ 6.7 TeV

(electron and muon channels, single experiment)

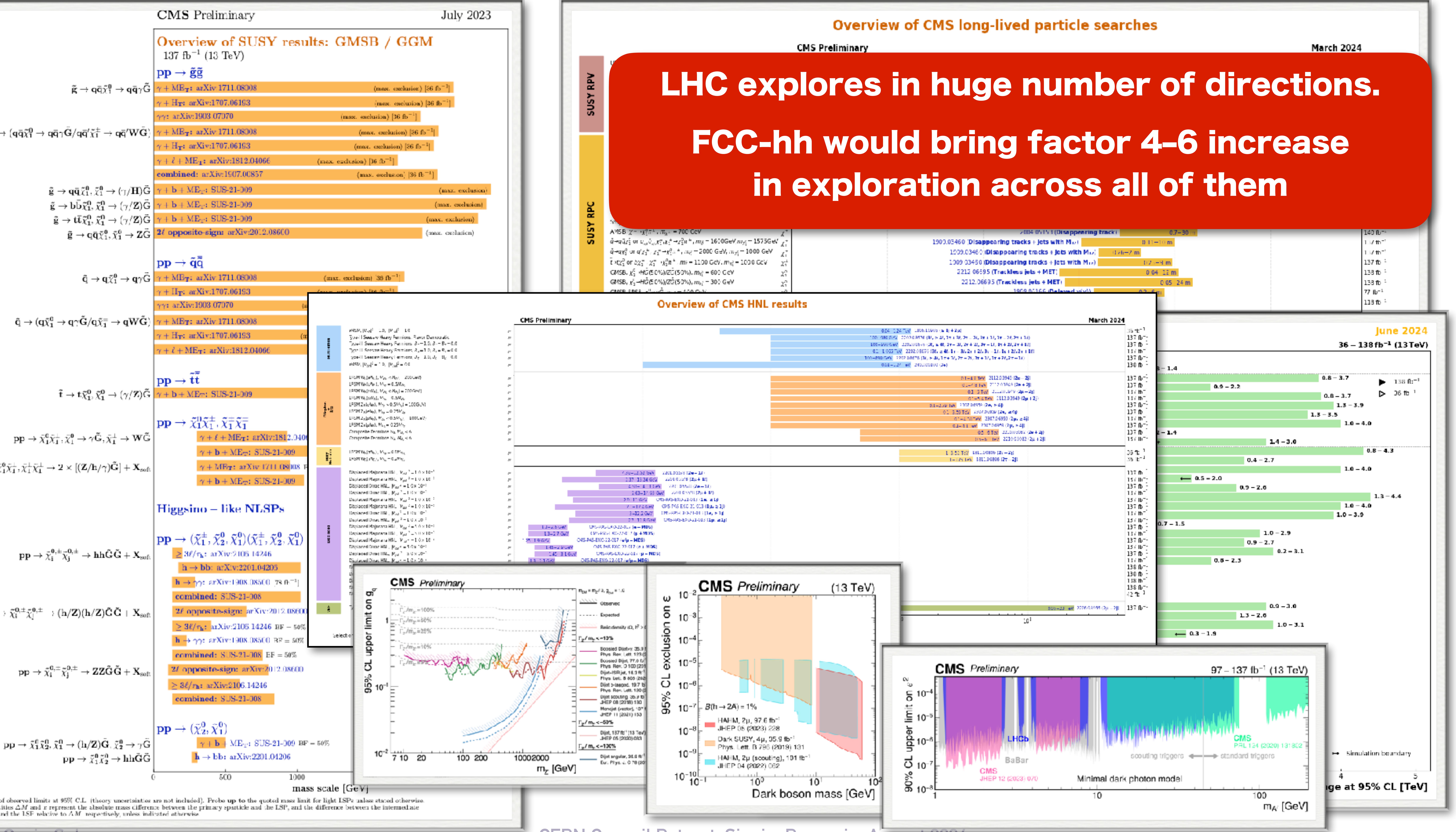
× 6.1 →

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 $\sim$ **$\times$ 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