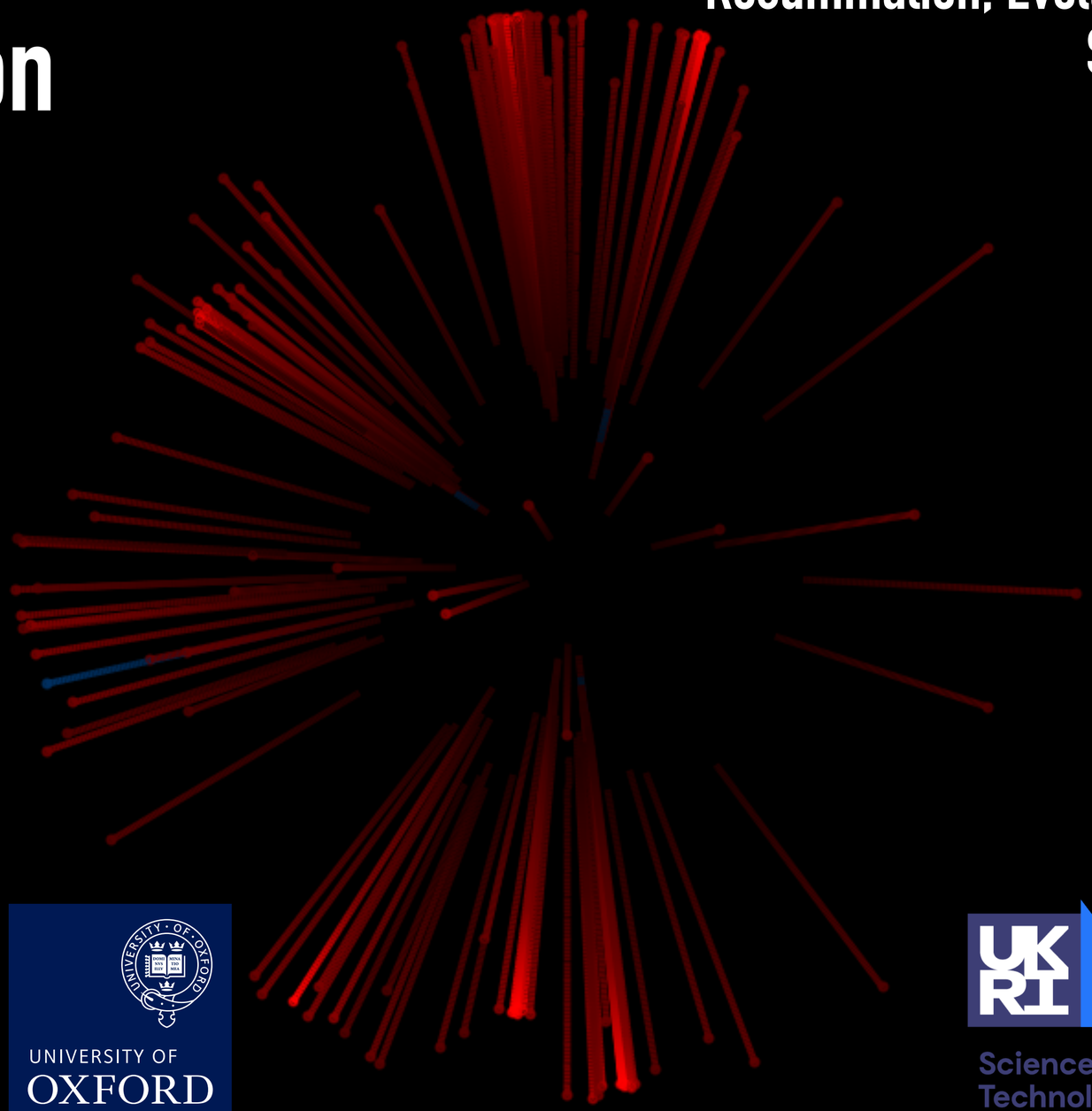
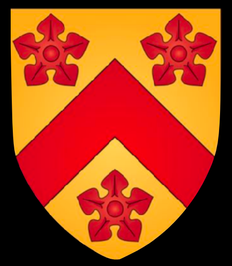
Colliders, Higgs and the strong interaction

IGFAE Colloquium
Resummation, Evolution Factorization 2026
Santiago de Compostela
20 October 2026

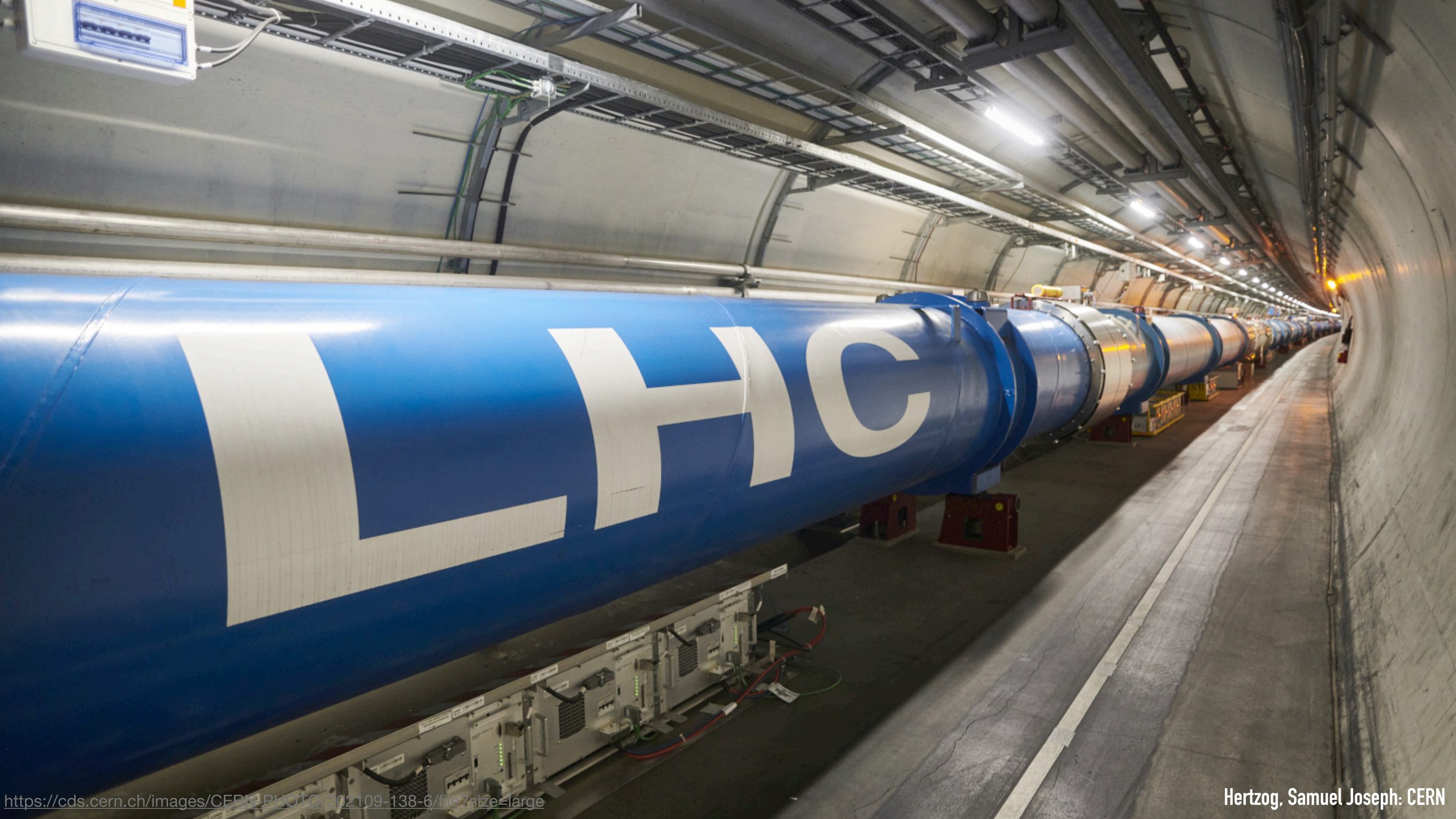


Gavin Salam
Rudolf Peierls Centre for Theoretical Physics
& All Souls College, Oxford



Science and Technology Facilities Council

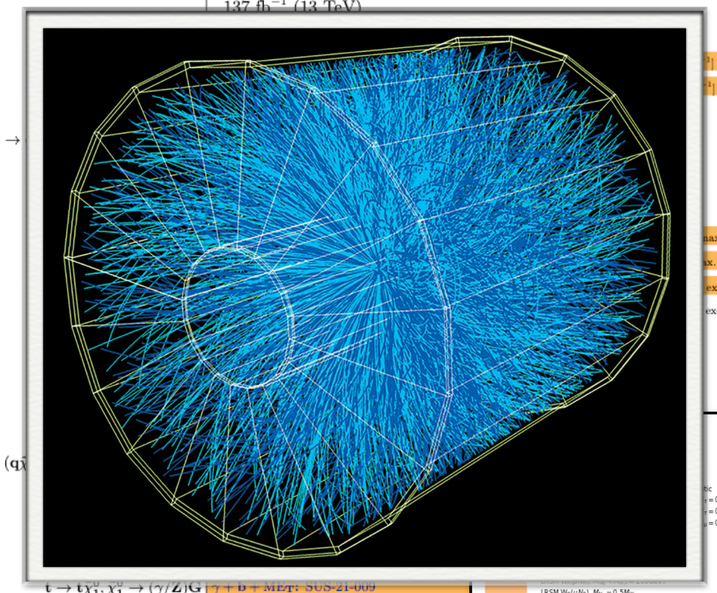




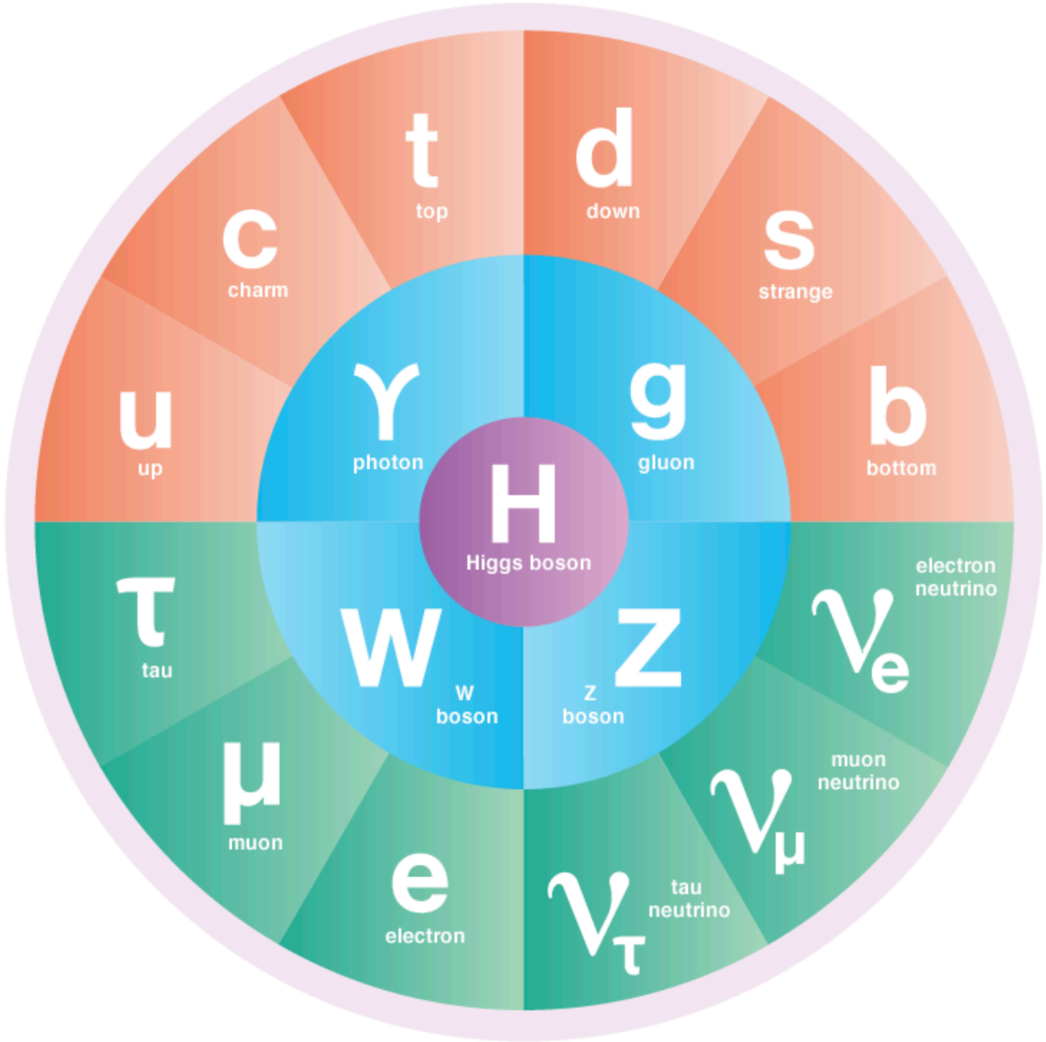
https://cds.cern.ch/images/CERN-PHOTO-202109-138-6/file?size=large

Hertzog, Samuel Joseph: CERN

LHC explores in huge number of directions.



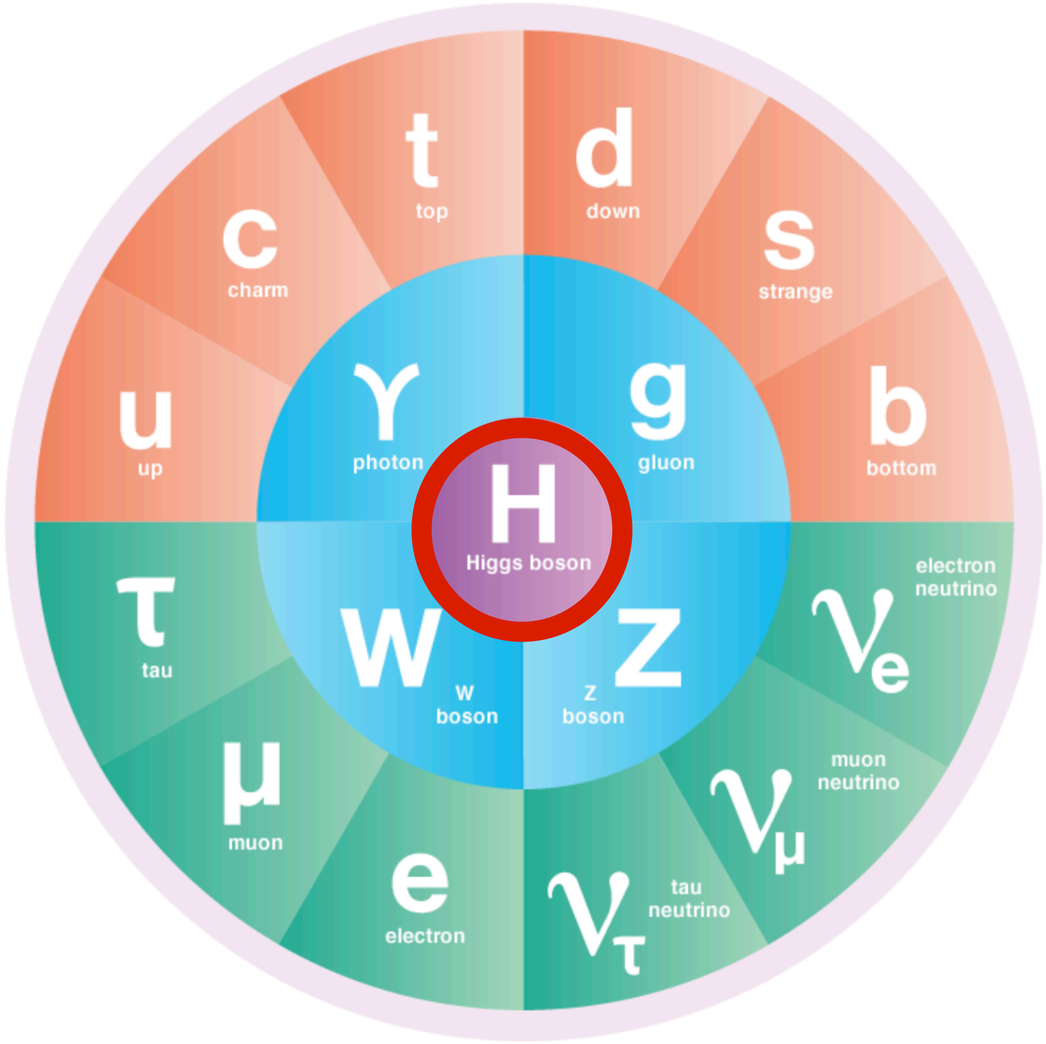
The Standard Model (SM)



particles

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

The Standard Model (SM)

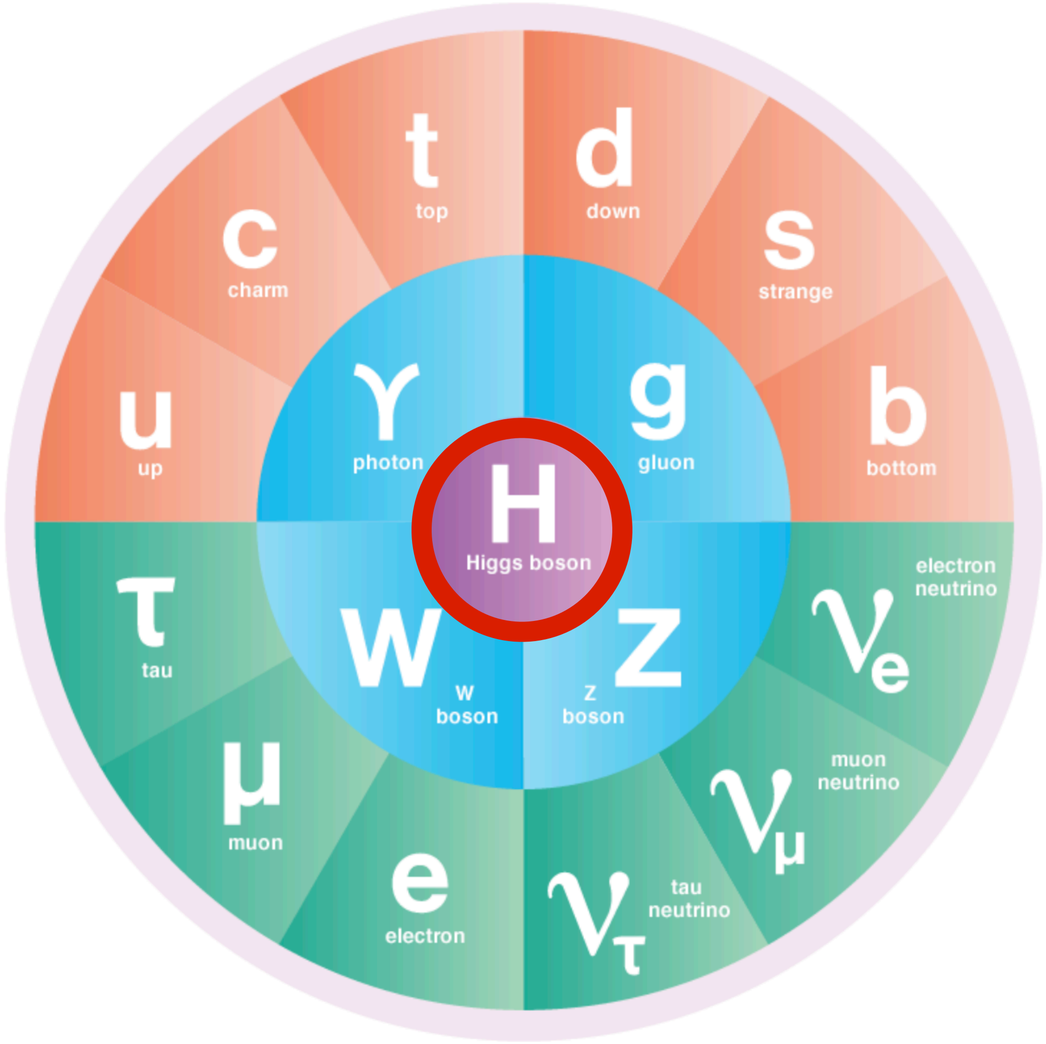


particles

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

"the standard-model (SM) is complete"

The Standard Model (SM)



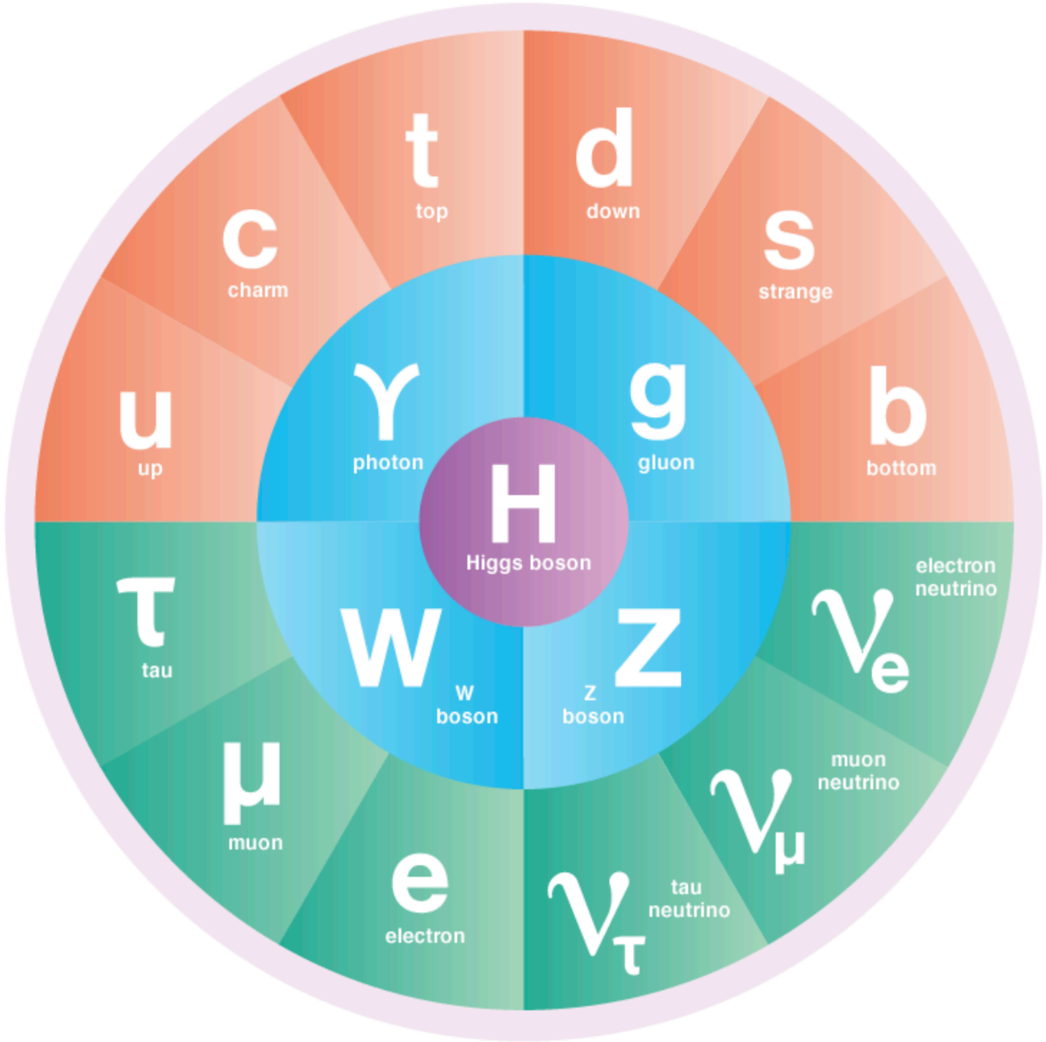
particles

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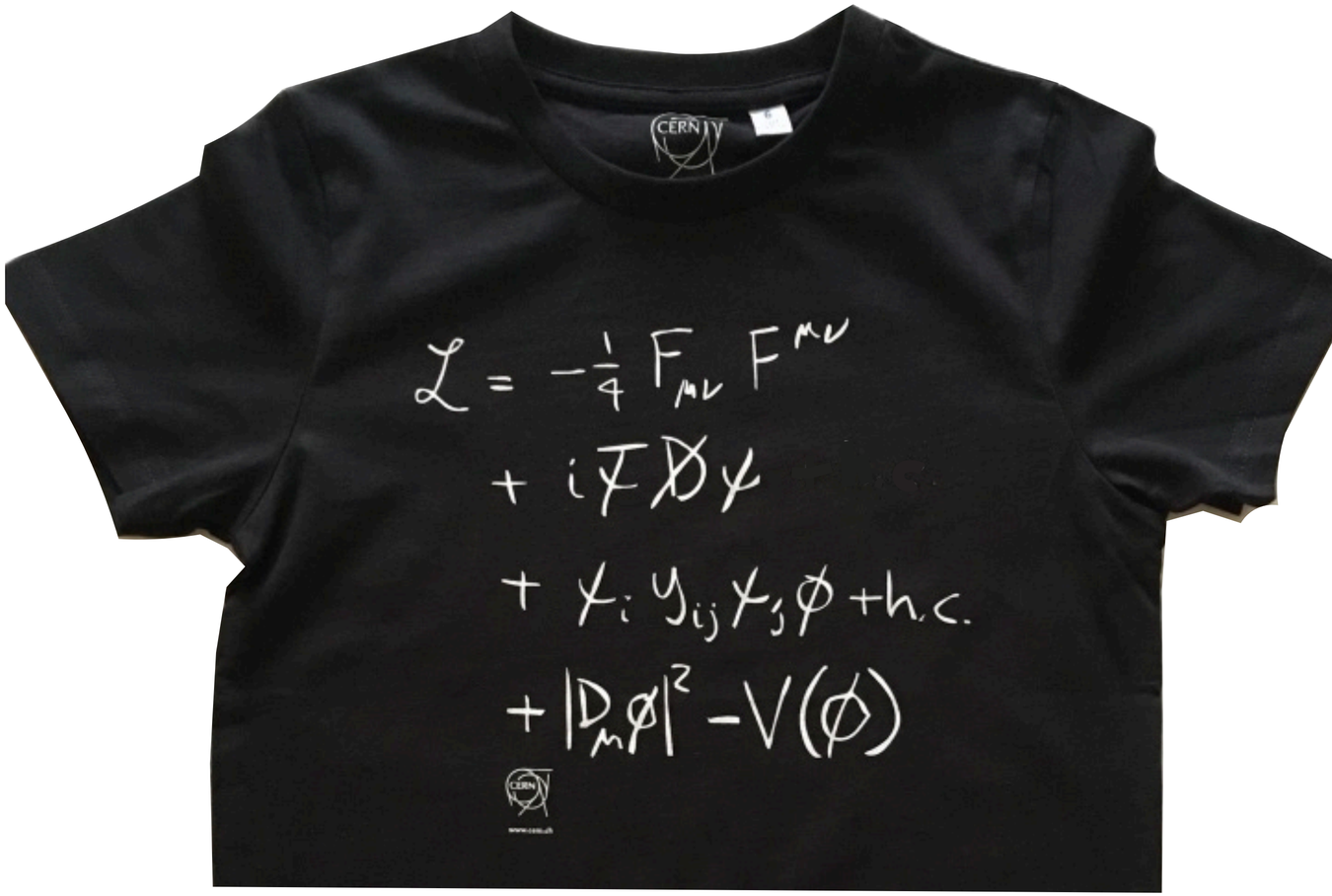
"the standard-model (SM) is complete"

?

The Standard Model (SM)



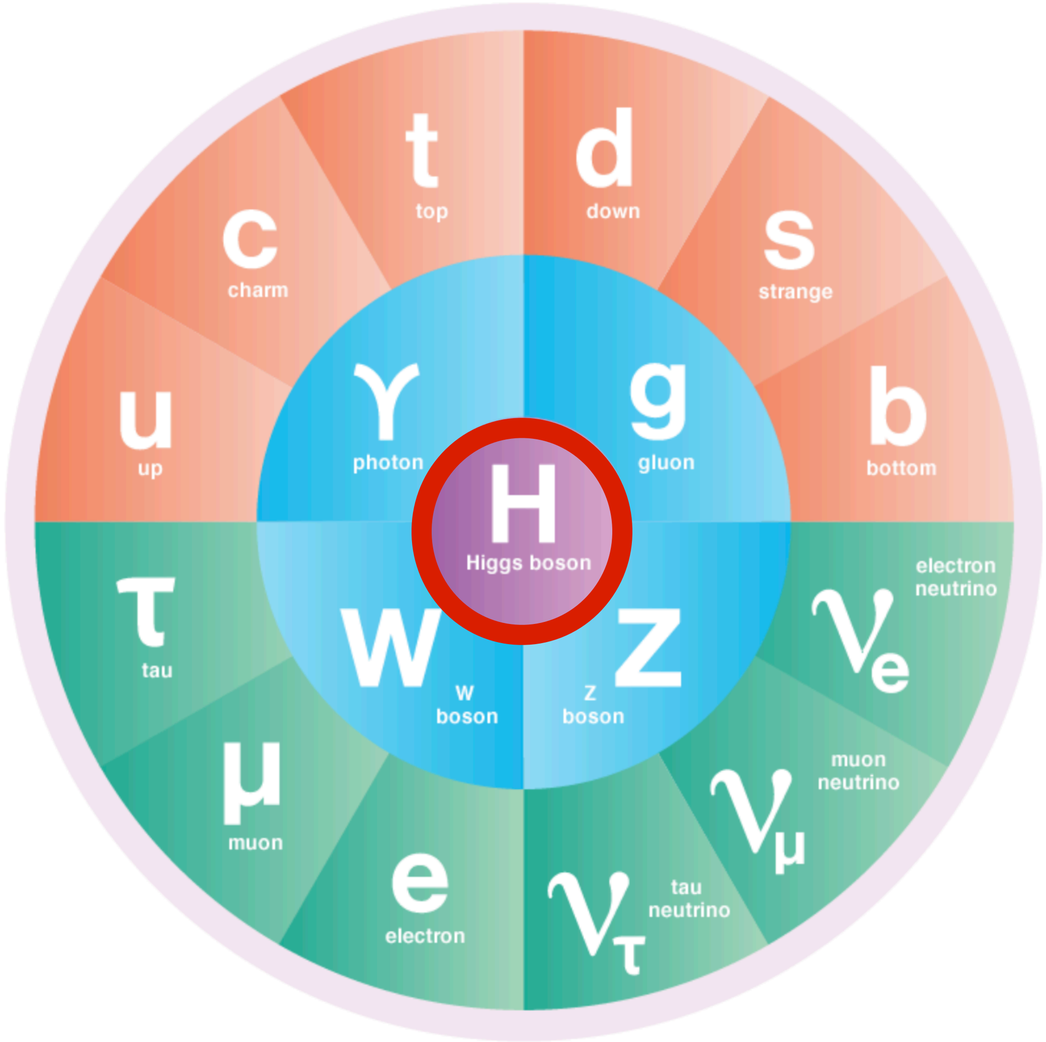
particles

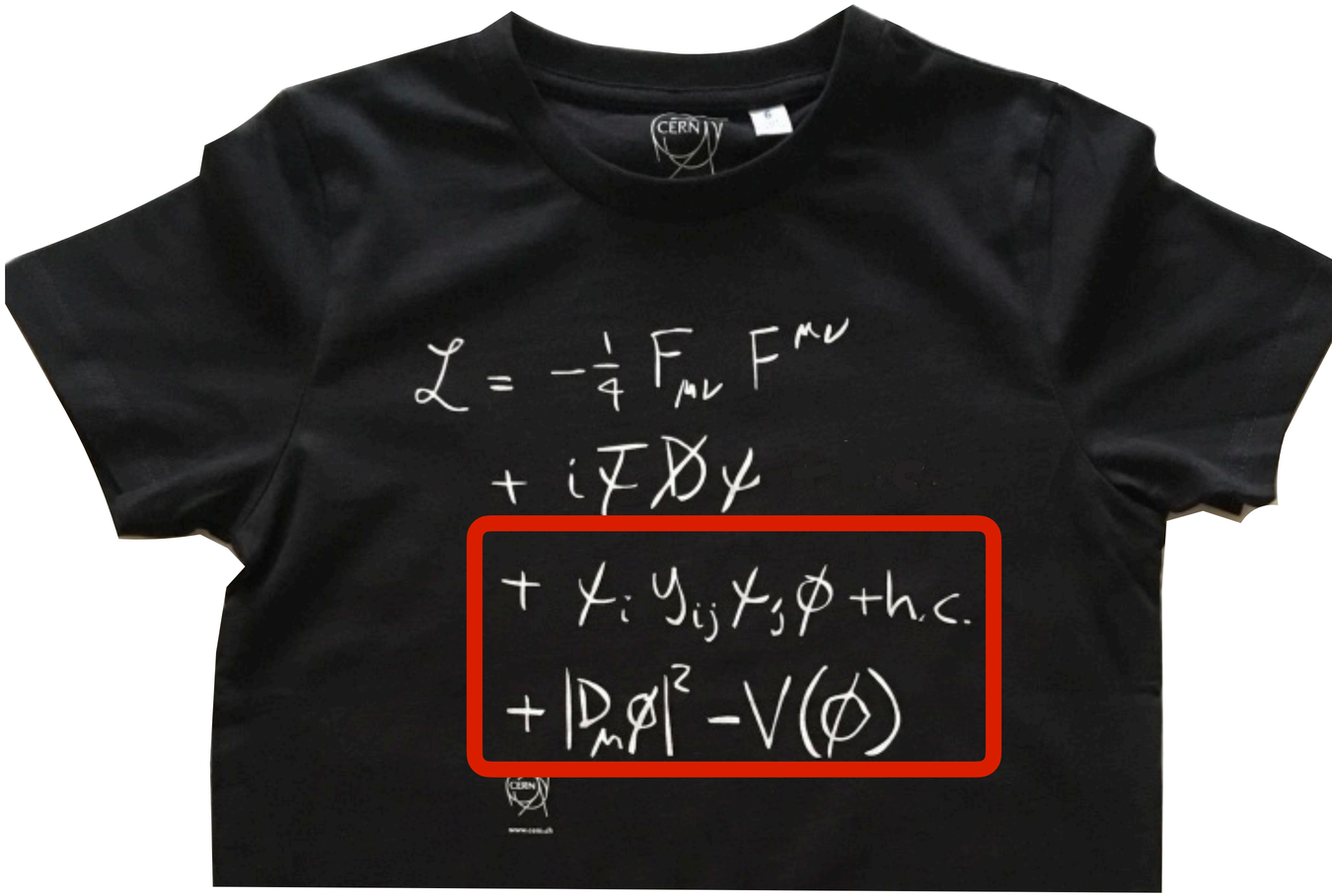


interactions

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

The Standard Model (SM)





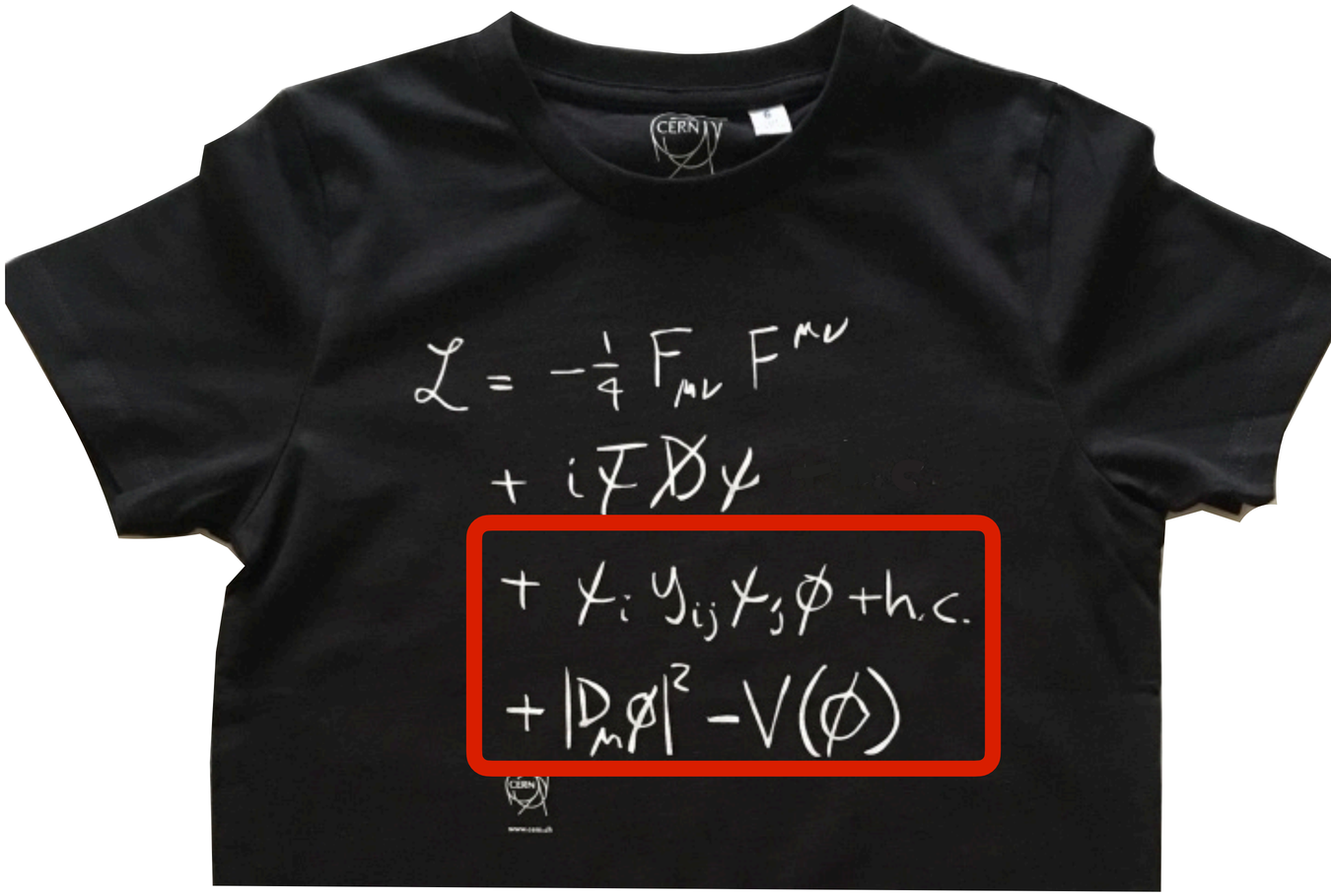
particles

interactions

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The Standard Model (SM)

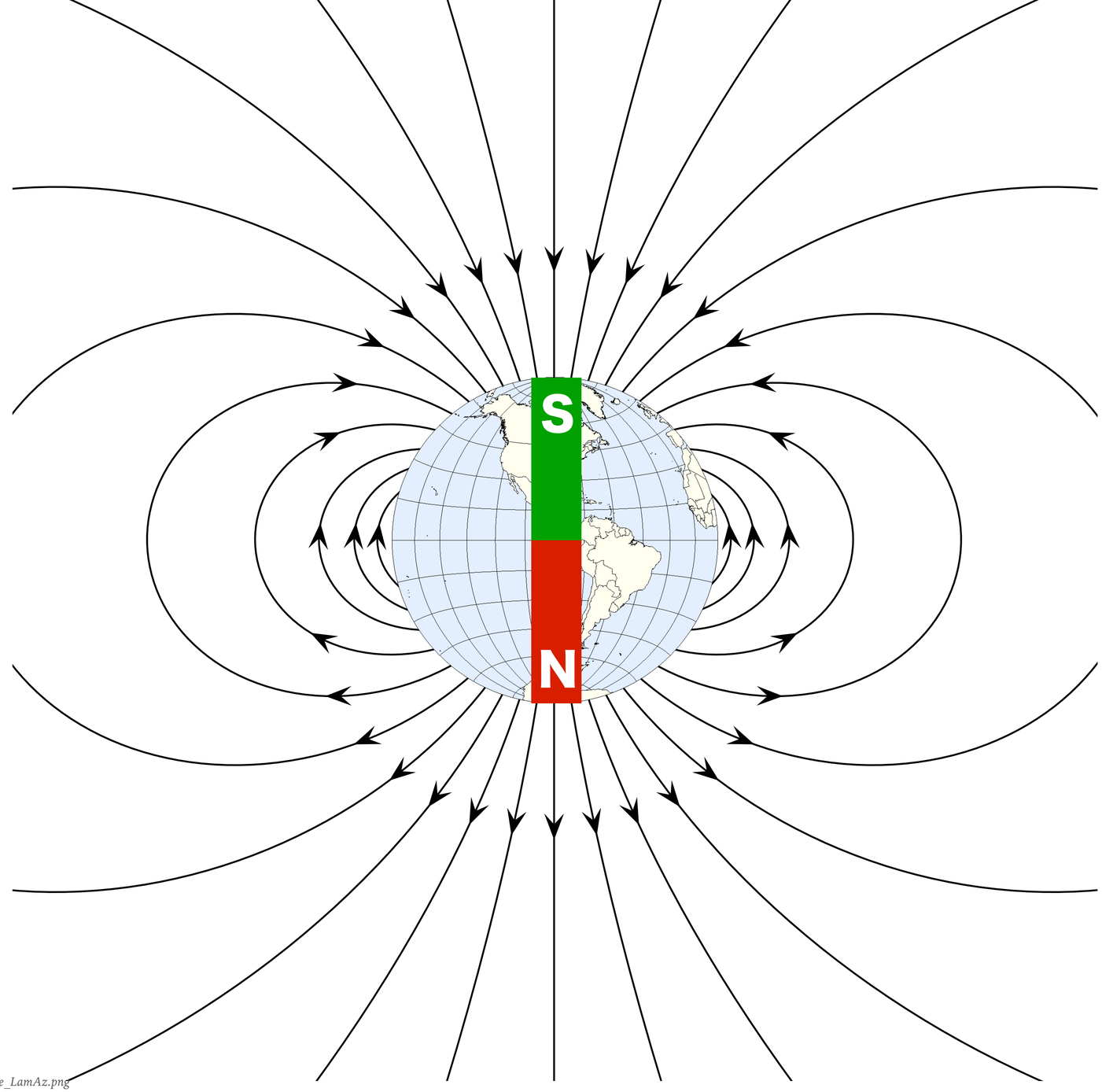
our experimental exploration of the Higgs-related SM interactions is only just starting



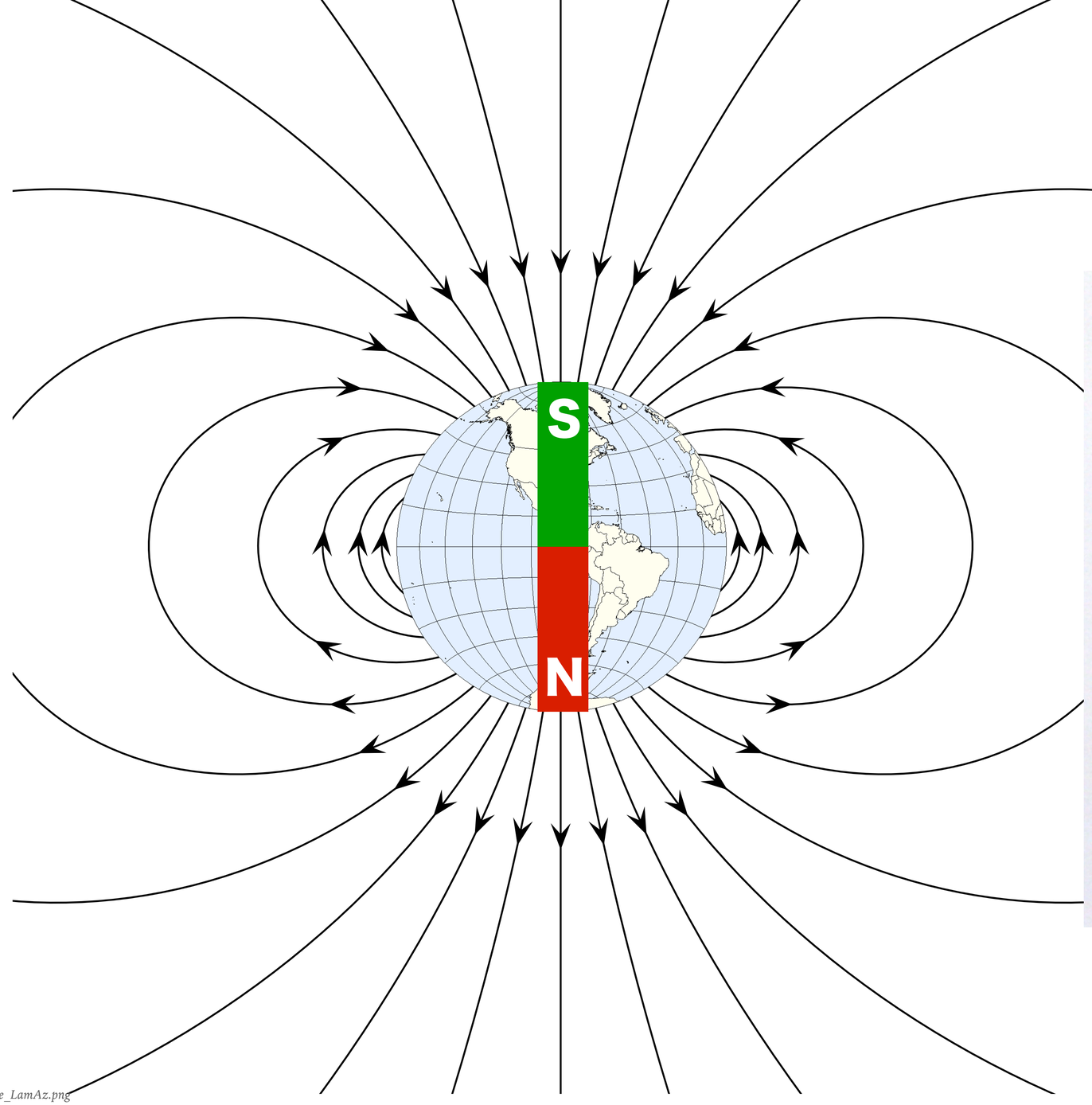
parts of this talk adapted from "The Higgs boson turns ten", GPS, Zanderighi and Wang

Nature 607 (2022) 7917, 41-47

interactions



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





https://upload.wikimedia.org/wikipedia/commons/d/da/Compasses_orienteering.jpg

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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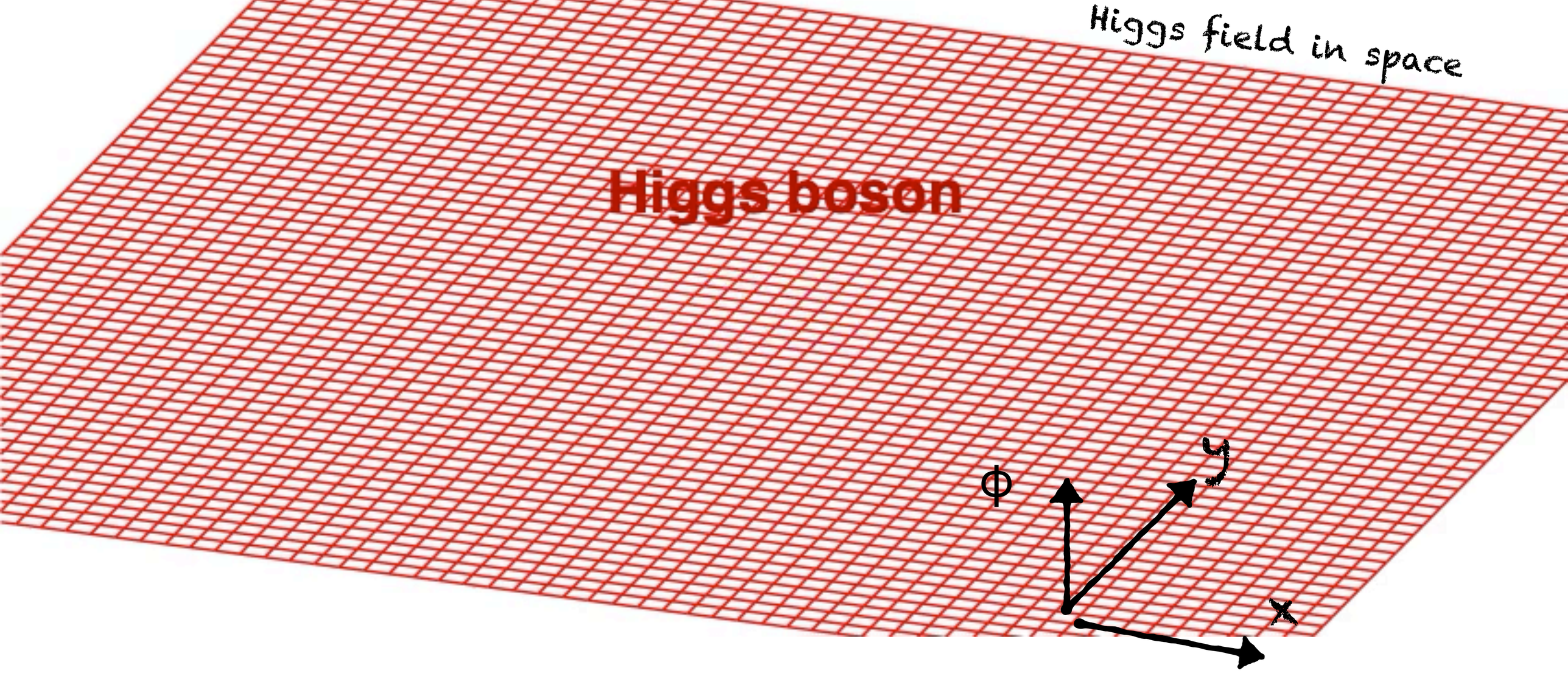
S

HIGGS FIELD

N

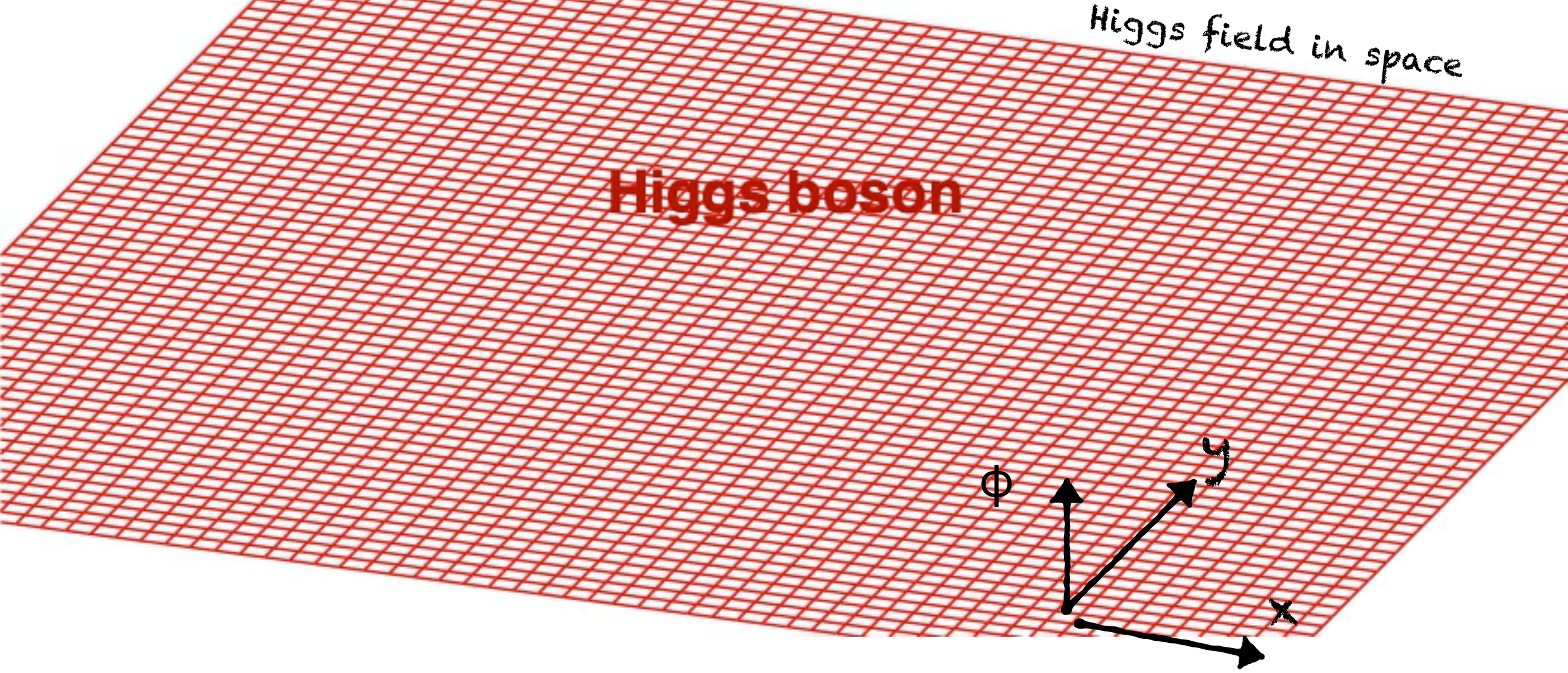


Large Hadron Collider @ CERN



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

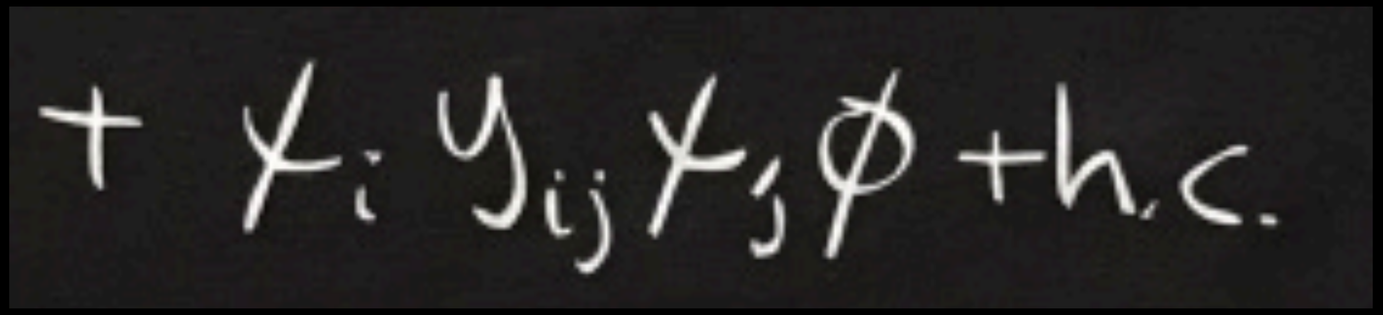


Higgs field (ϕ) can be different at each point in space

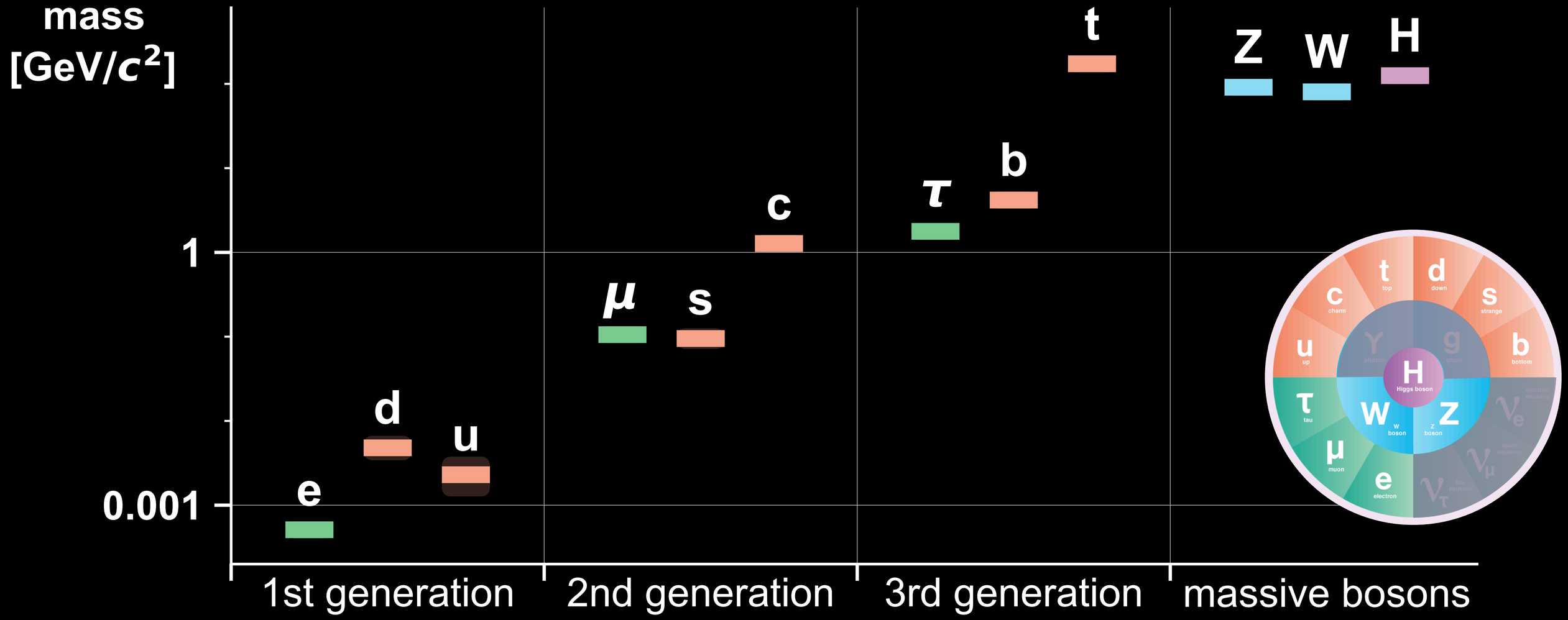
A Higgs boson at a given point in space is a fluctuation of the field

a core hypothesis of Standard Model

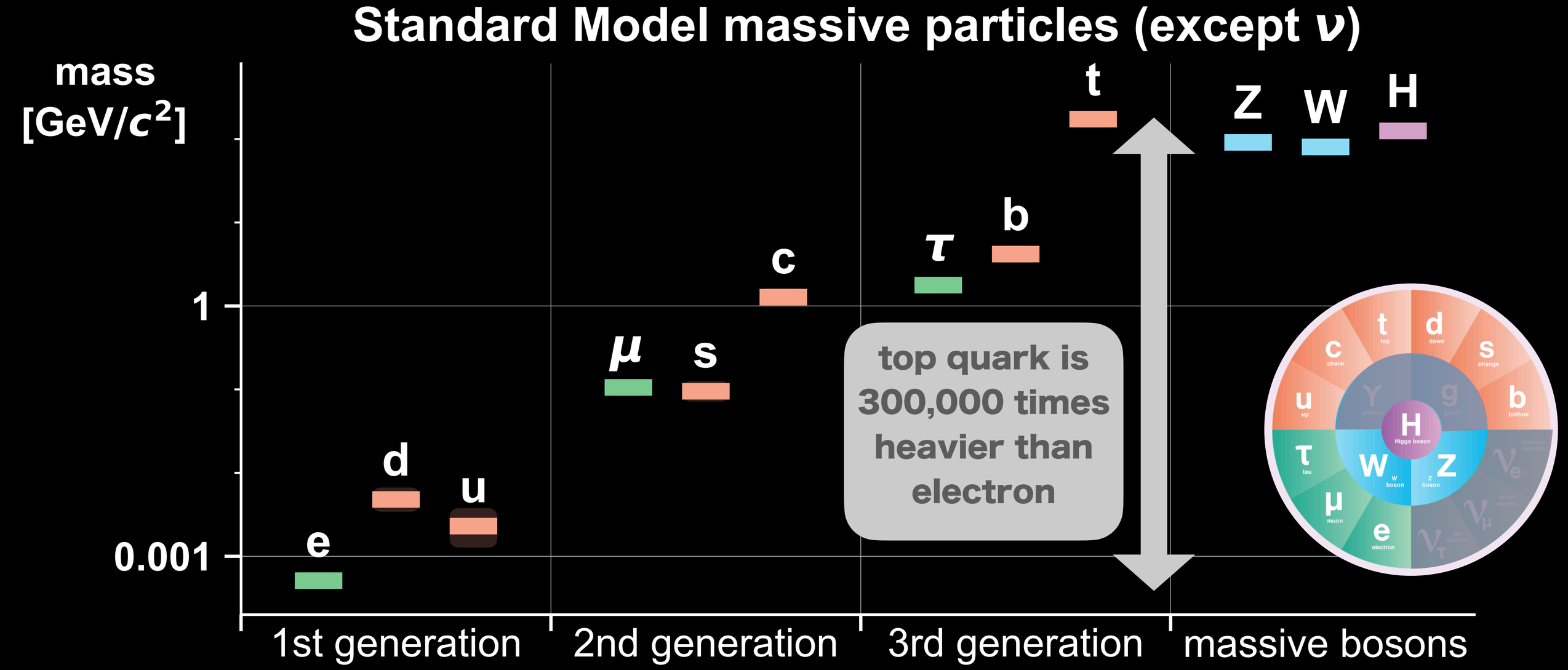
fundamental particles get their mass from interaction with the Higgs field

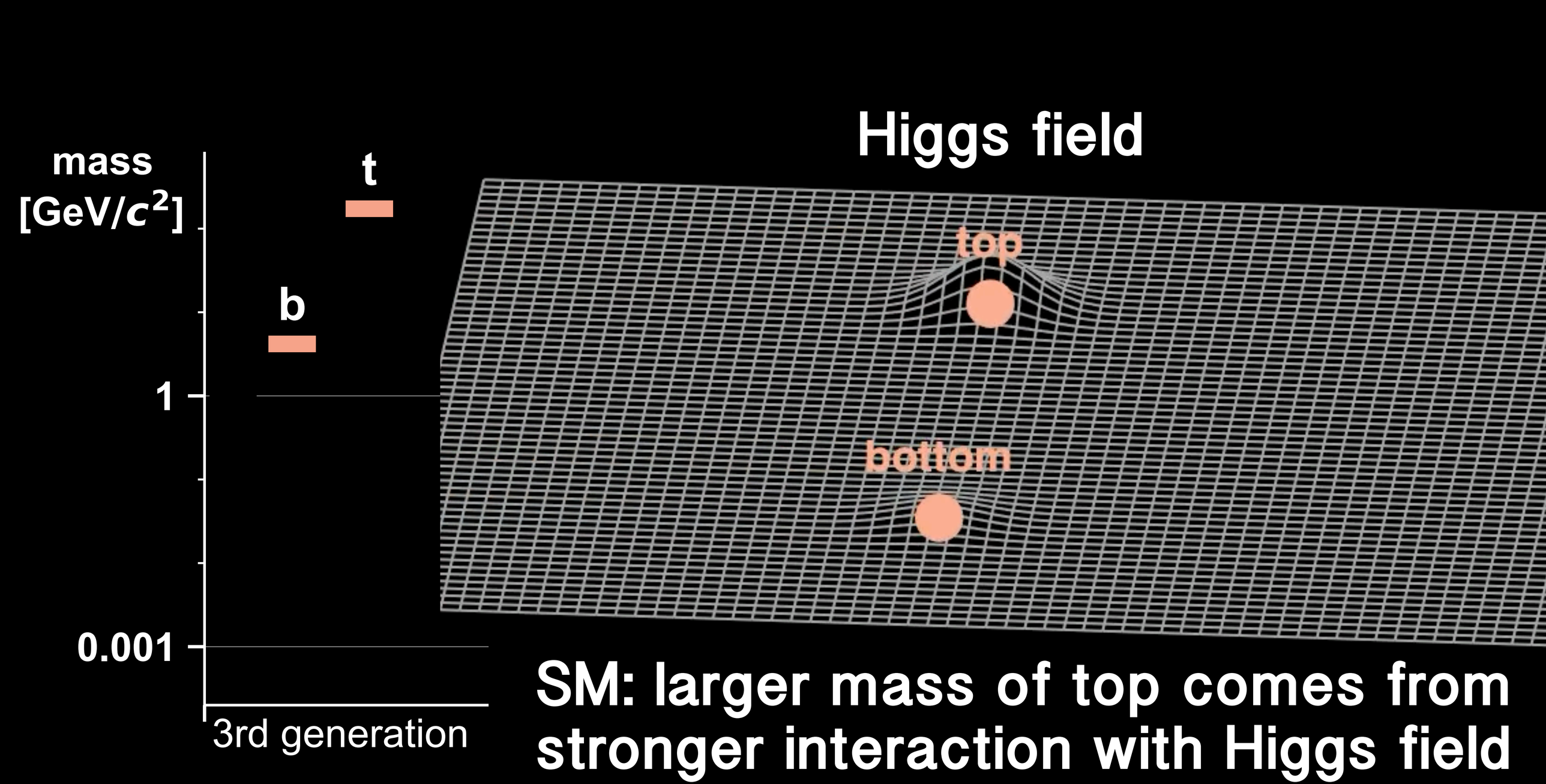


Standard Model massive particles (except ν)

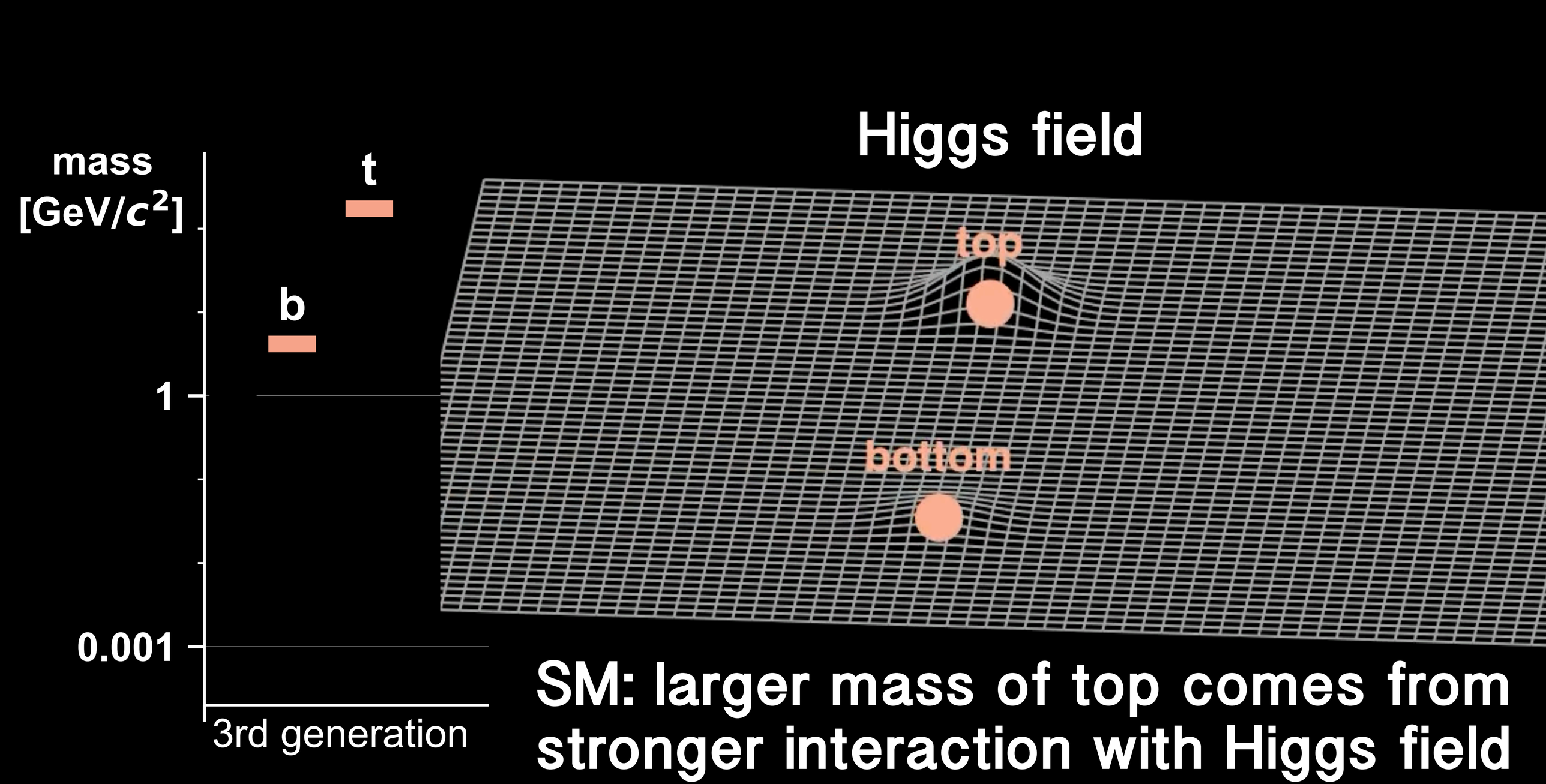


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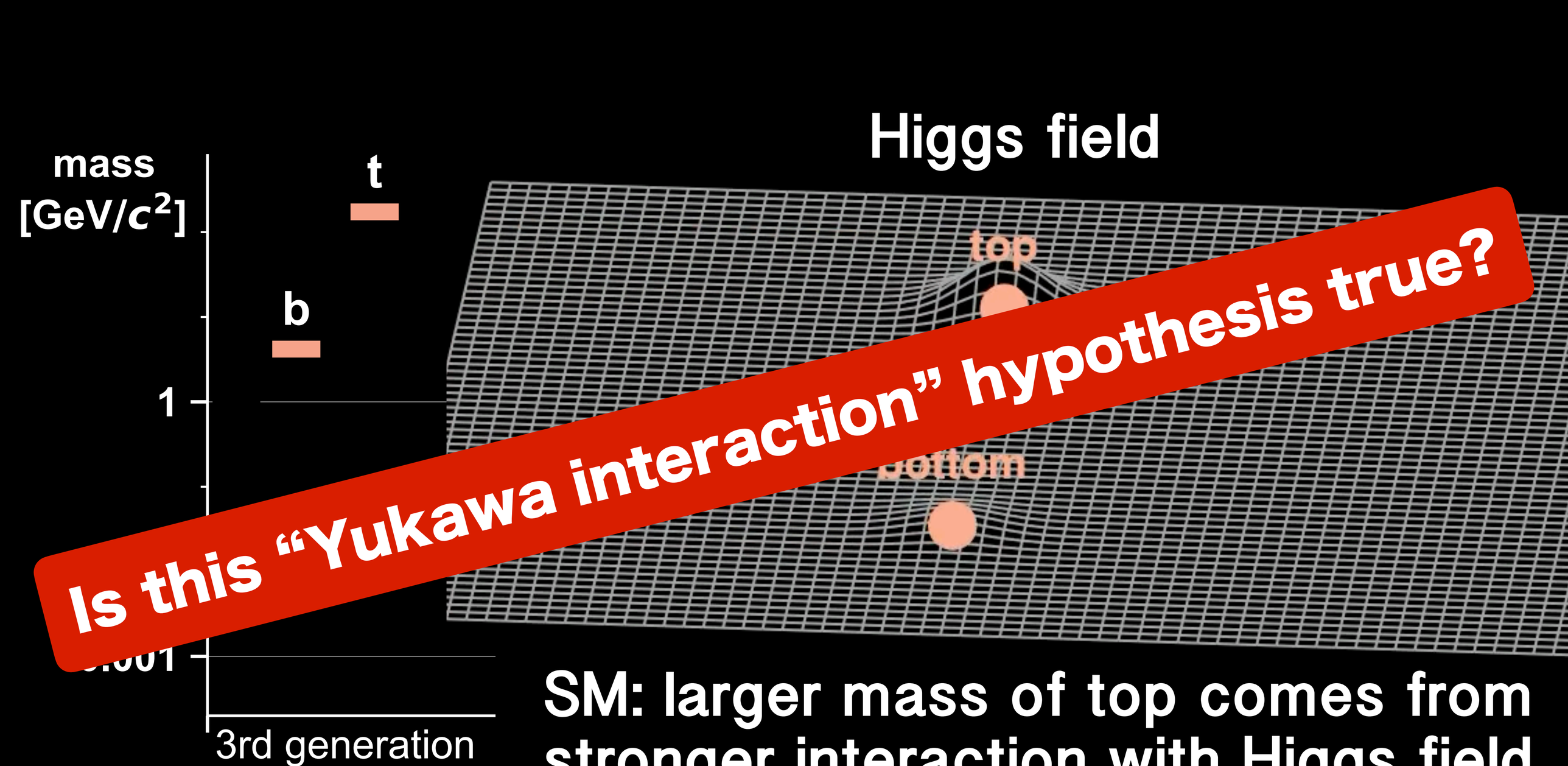




SM: larger mass of top comes from stronger interaction with Higgs field

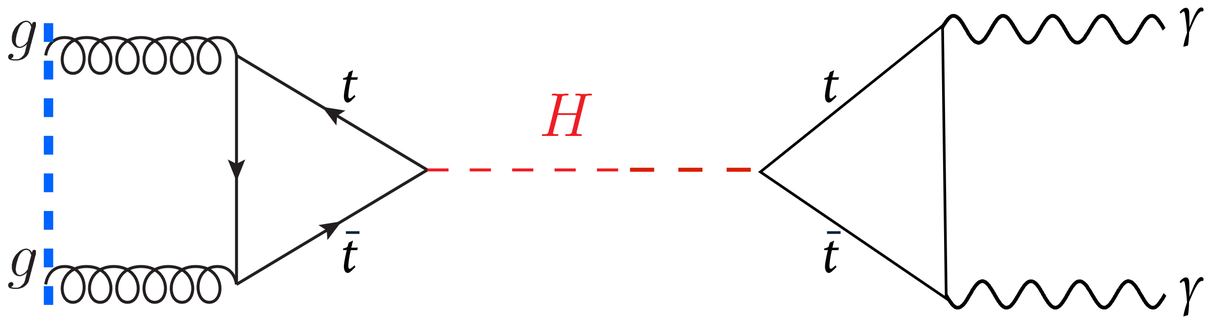


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SM: larger mass of top comes from stronger interaction with Higgs field

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



luon

gluo

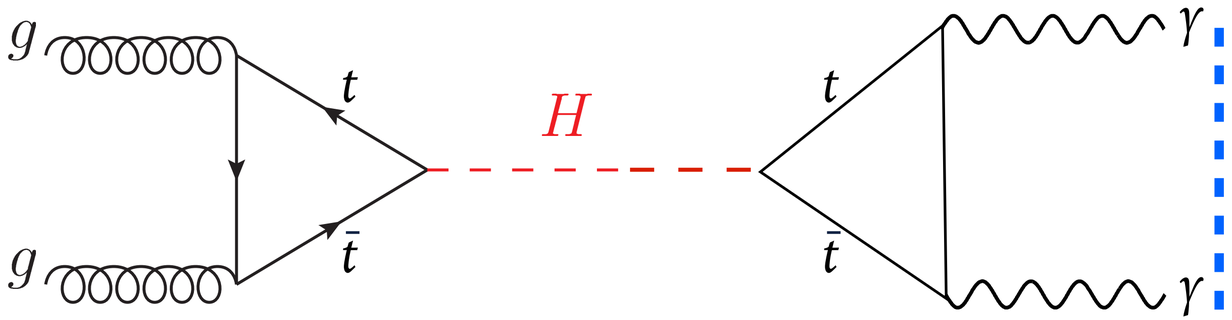
Φ

y

x

Higgs field in space

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



luon

gluo

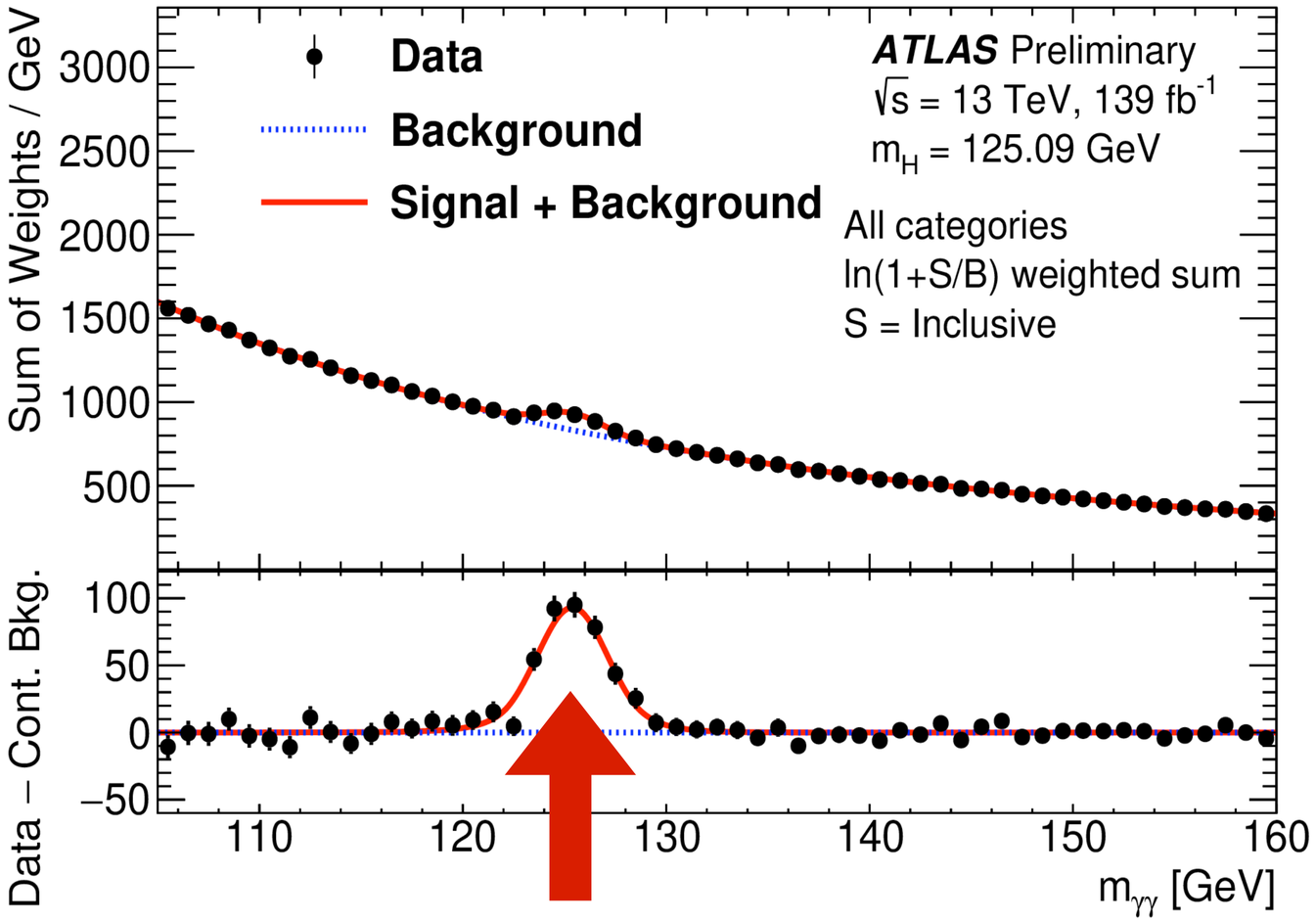
Φ

y

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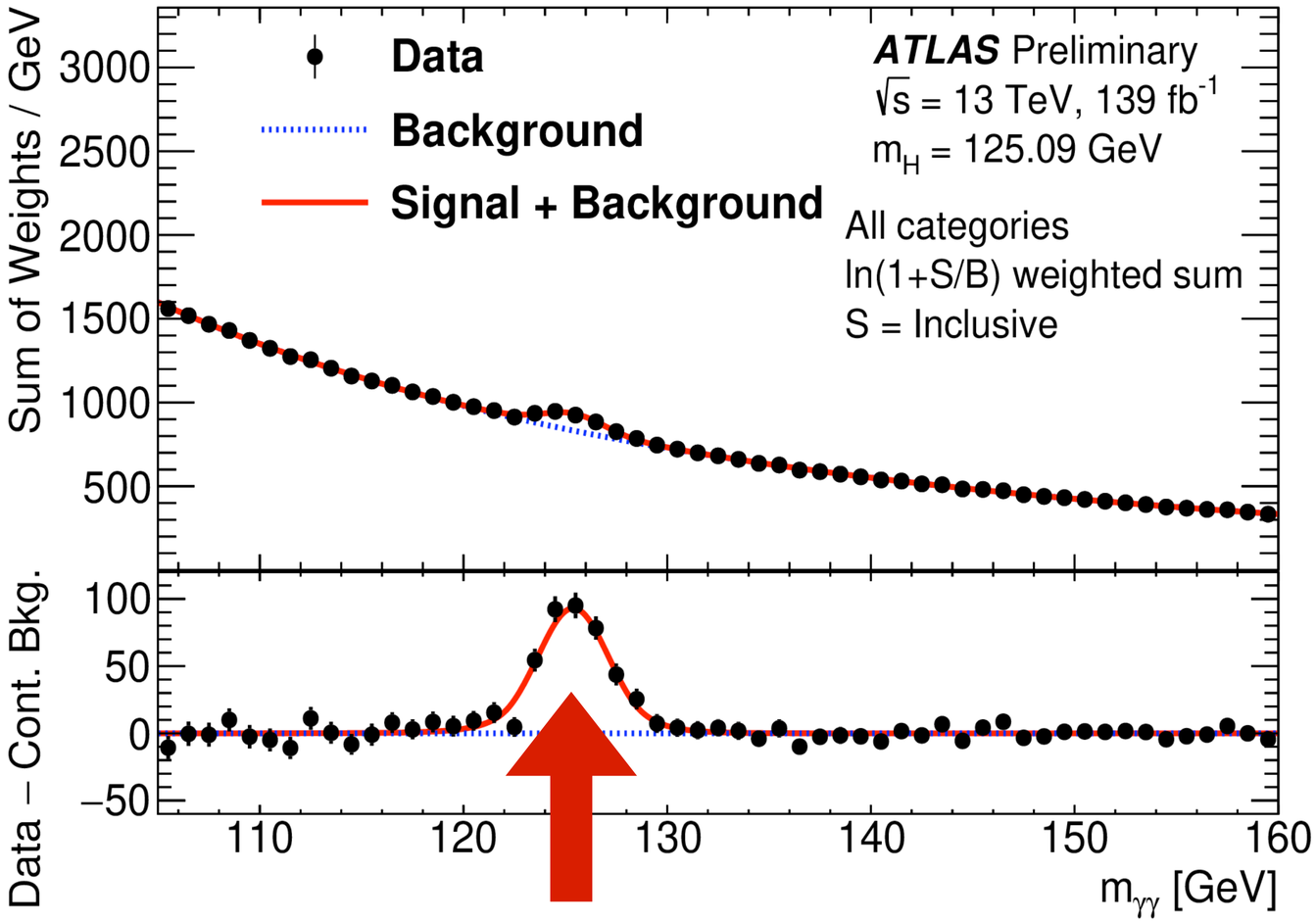
Higgs field in space

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

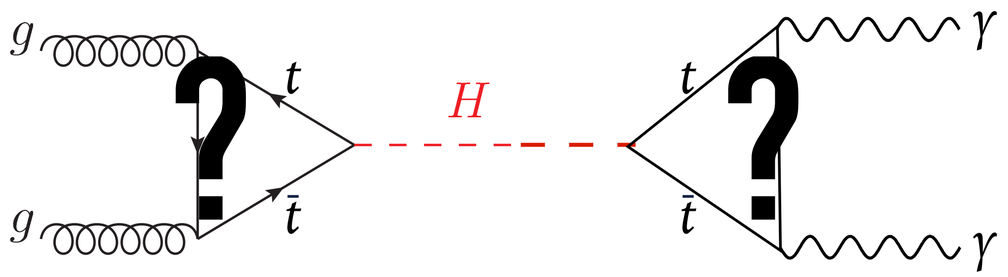


more events at specific energy = Higgs bosons

- 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



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?

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

Share this

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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indirect observation

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

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)
Swedish
Swedish (pdf)

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

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.

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

Nobel Prize in Physics 2017

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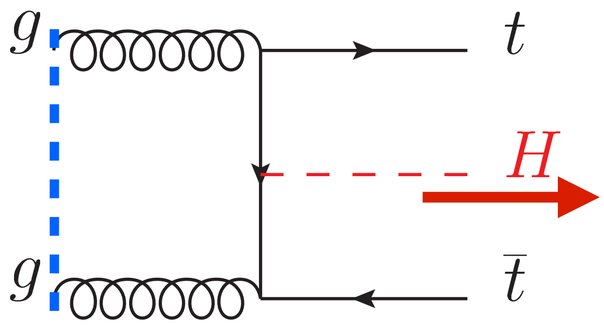
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https://cern.ch/gsalam/higgs

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luon

gluo

Φ

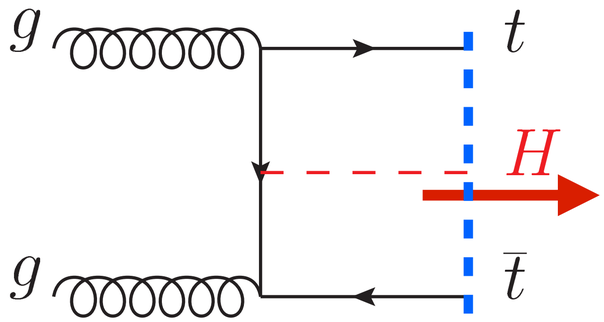
y

x

Higgs field in space

https://cern.ch/gsalam/higgs

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luon

gluo

Φ

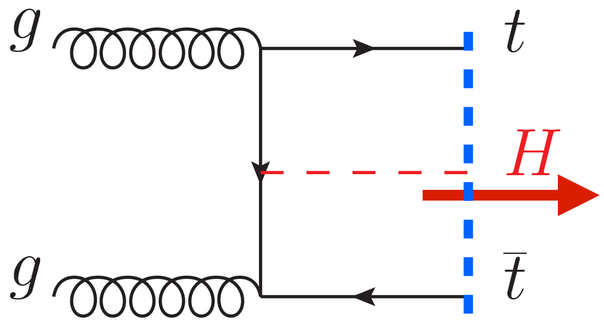
y

x

Higgs field in space

https://cern.ch/gsalam/higgs

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luon

gluo

Φ

y

x

Higgs field in space

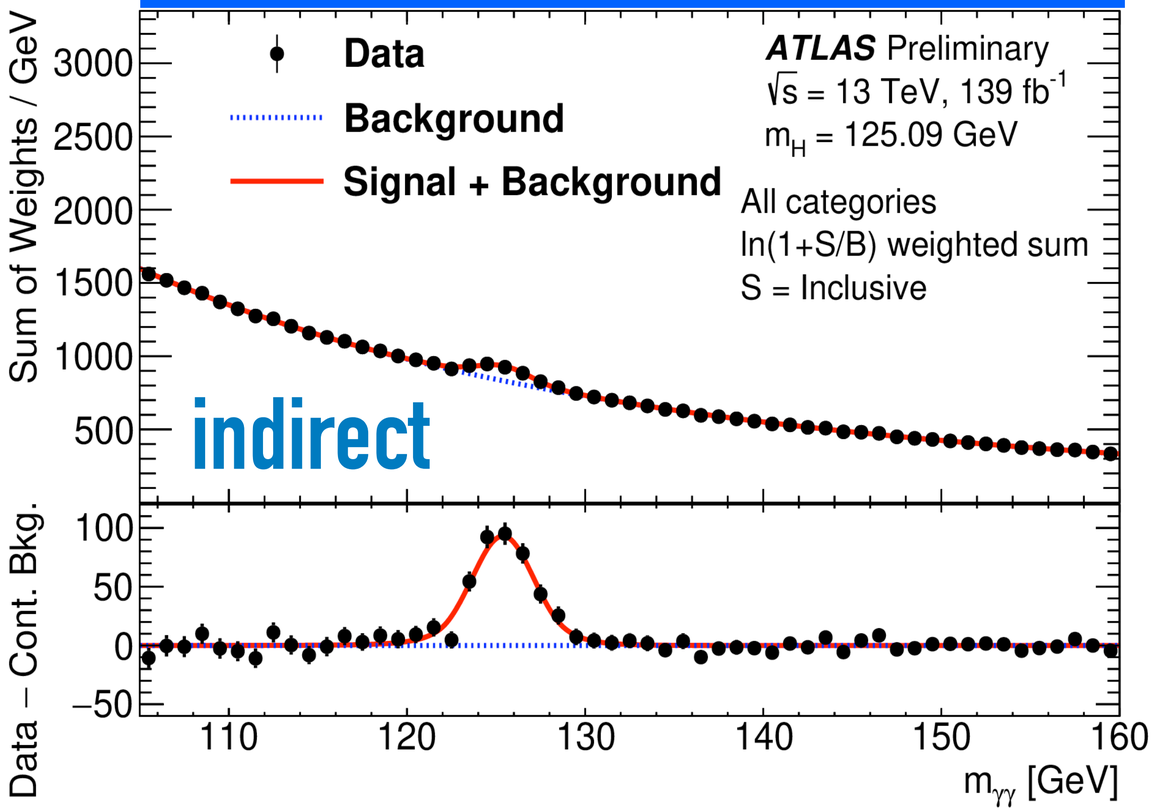
Situation at start of LHC (2009)

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

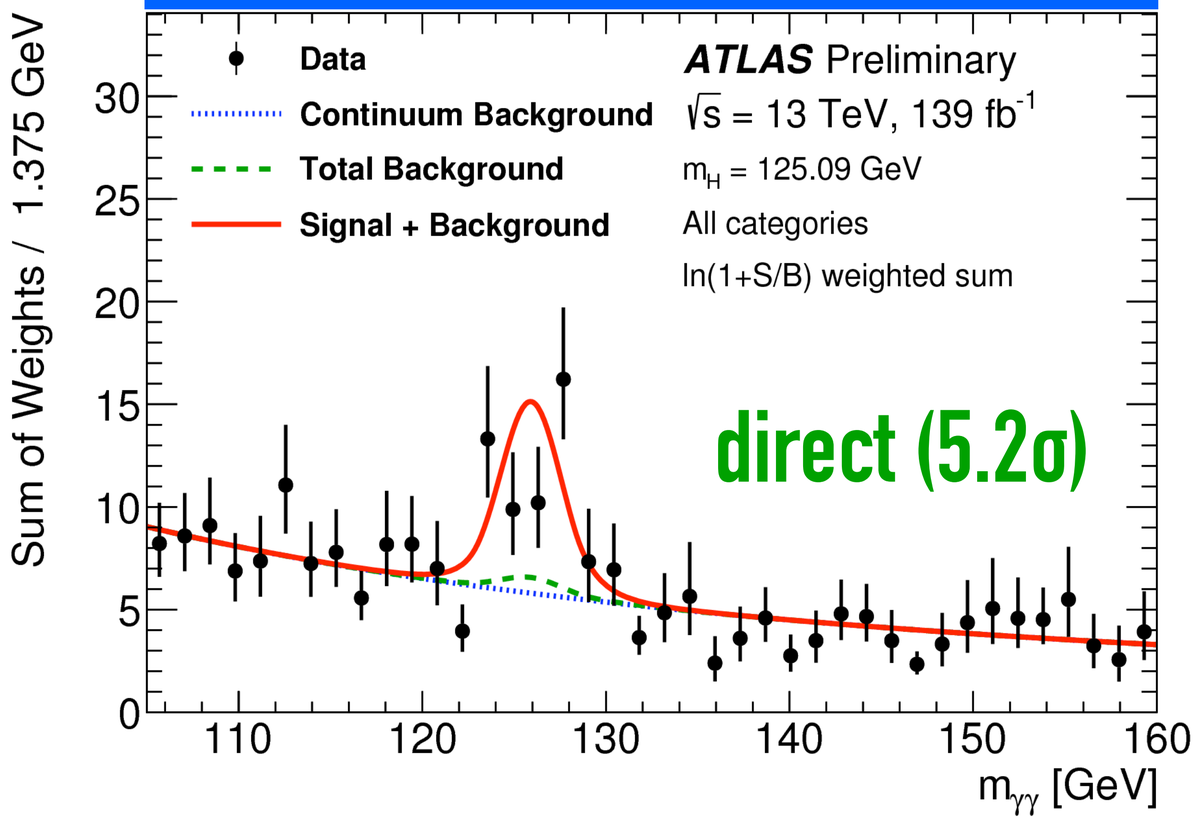
[from introduction to arXiv:0910.5472,
summarising ATLAS and CMS ttH(→bb) studies at that point]

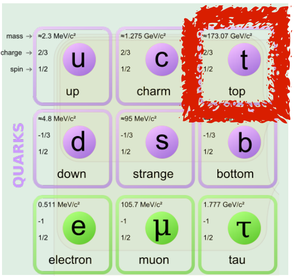
since 2018: ATLAS & CMS see (at >5σ) events with top-quarks & Higgs simultaneously

Higgs = one in 2 billion events



1 in 2,000 events with top quarks



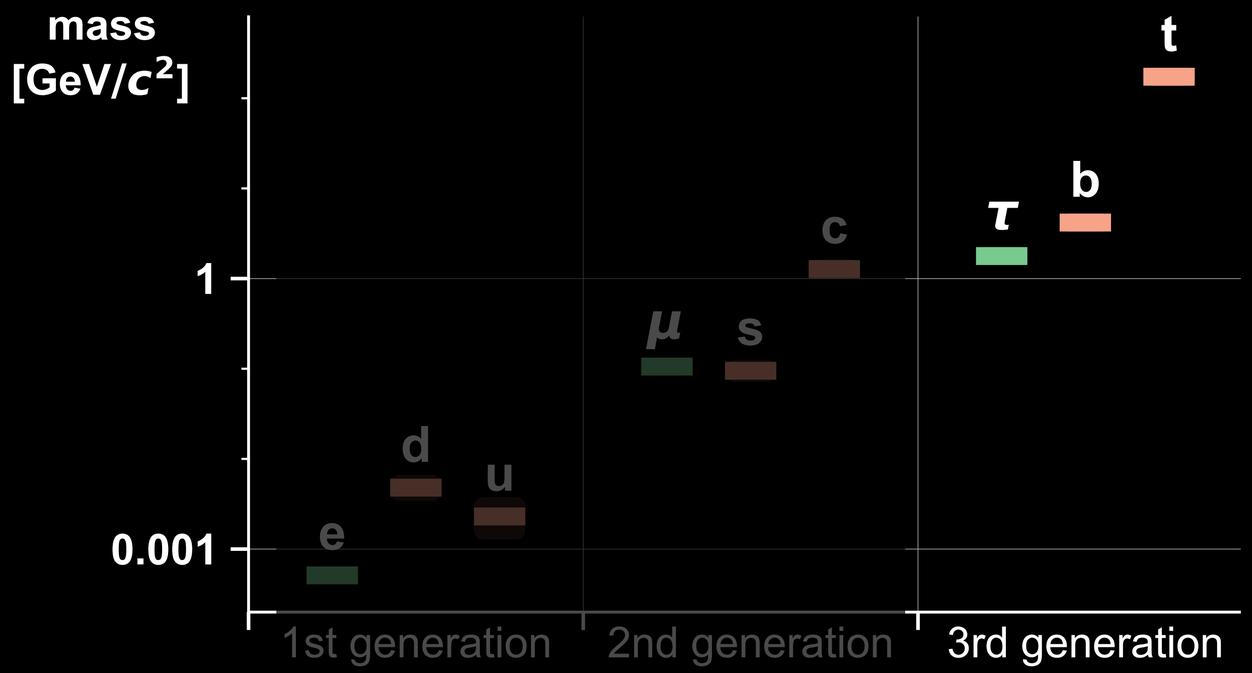


enhanced fraction of Higgs bosons in events with top quarks

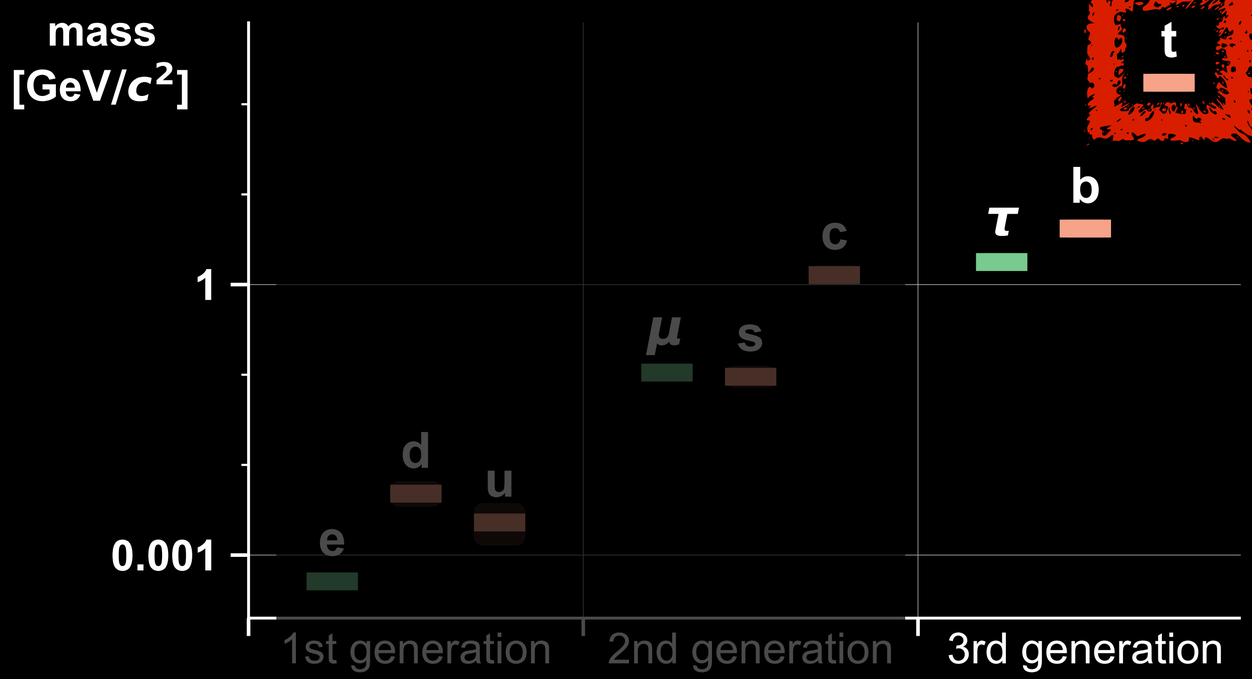
→ direct observation of Higgs interaction with tops

(consistent with SM to c. ±25%)

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

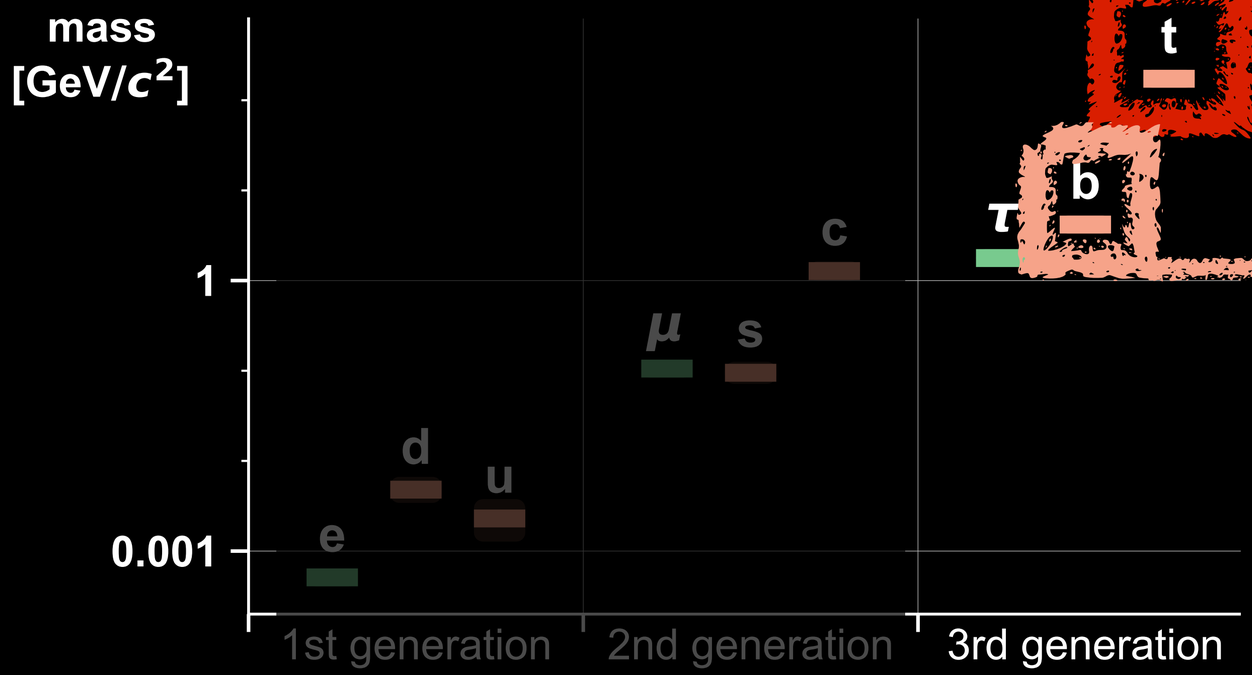


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by observing H in association with top quarks

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

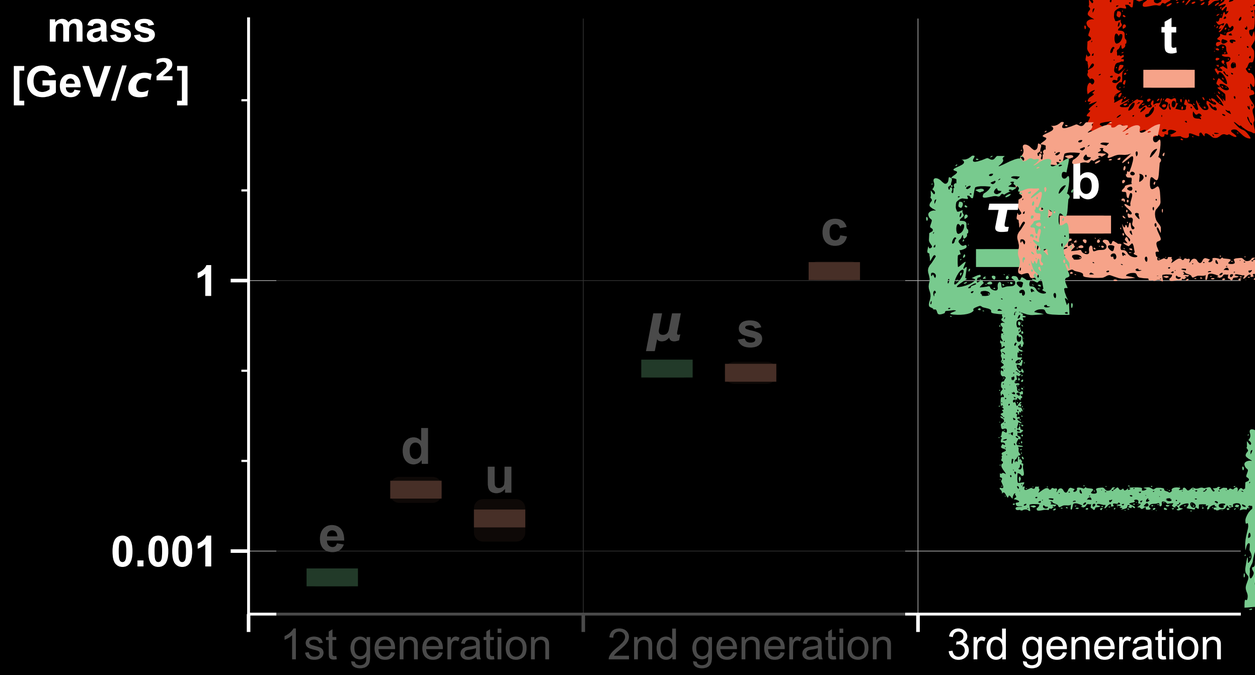


by observing H in association with top quarks

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

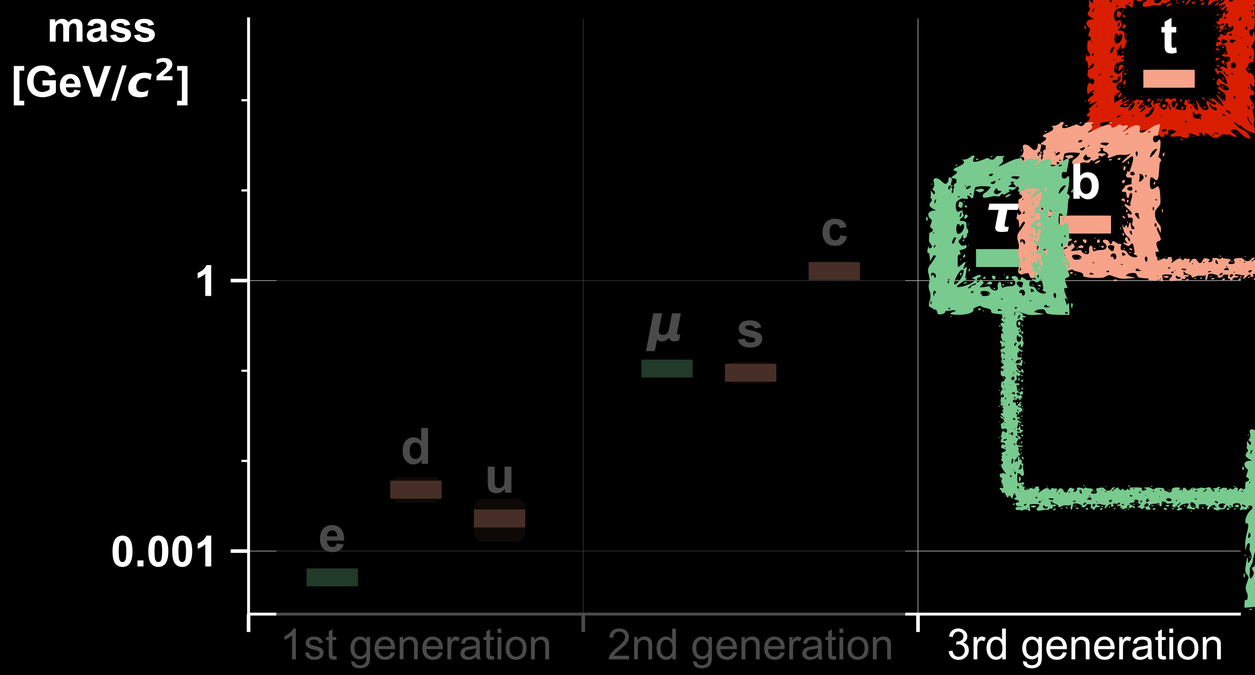


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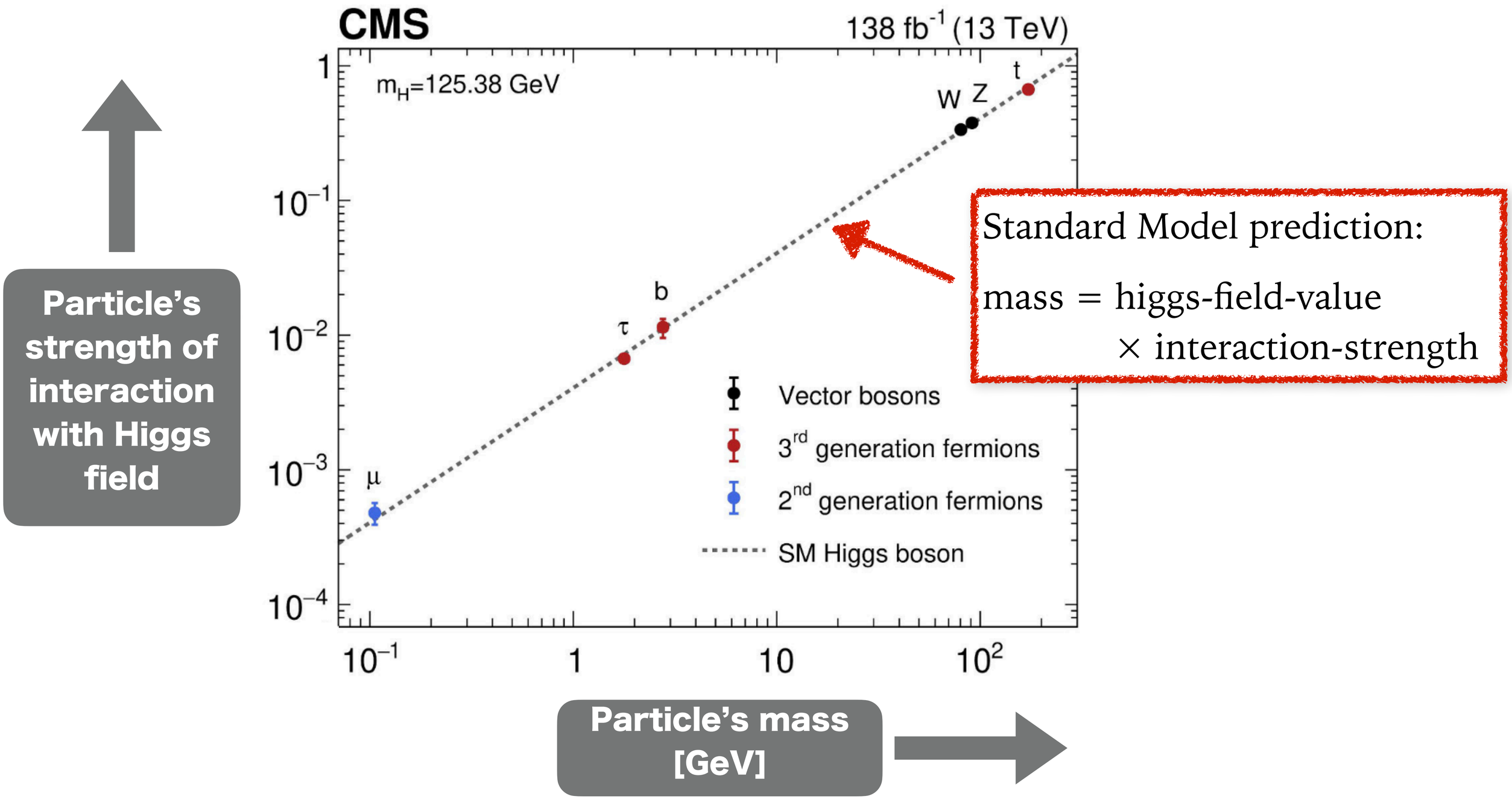


by observing H in association with top quarks

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

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


CMS
138 fb^{-1} (13 TeV)
m_H=125.38 GeV
t
W Z
b
τ
μ
Vector bosons
3rd generation fermions
2nd generation fermions
SM Higgs boson
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-1}
1
10
10^2
Particle's strength of interaction with Higgs field
Particle's mass [GeV]
Standard Model prediction:
mass = higgs-field-value
× interaction-strength

what could one be saying about it?

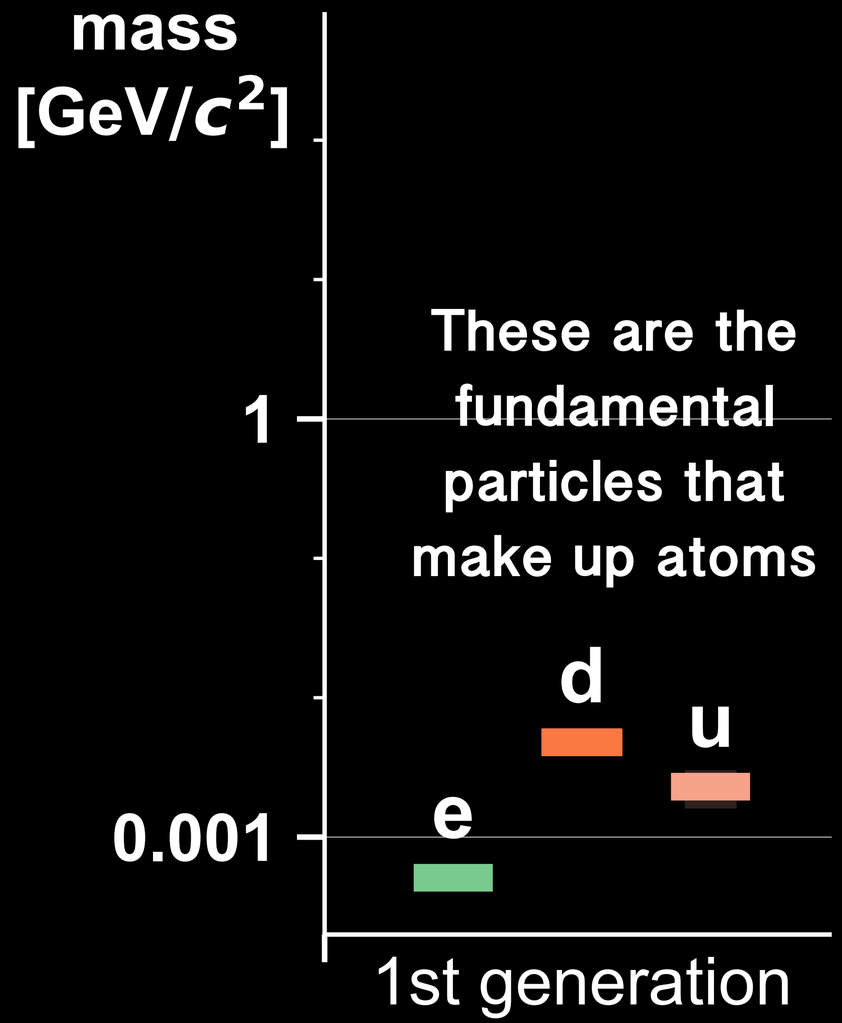
For a full set of particles (3rd generation) that are like the ones we're made of, the LHC has demonstrated that their mass is not an intrinsic property, but is generated by an interaction with a non-zero Higgs field.

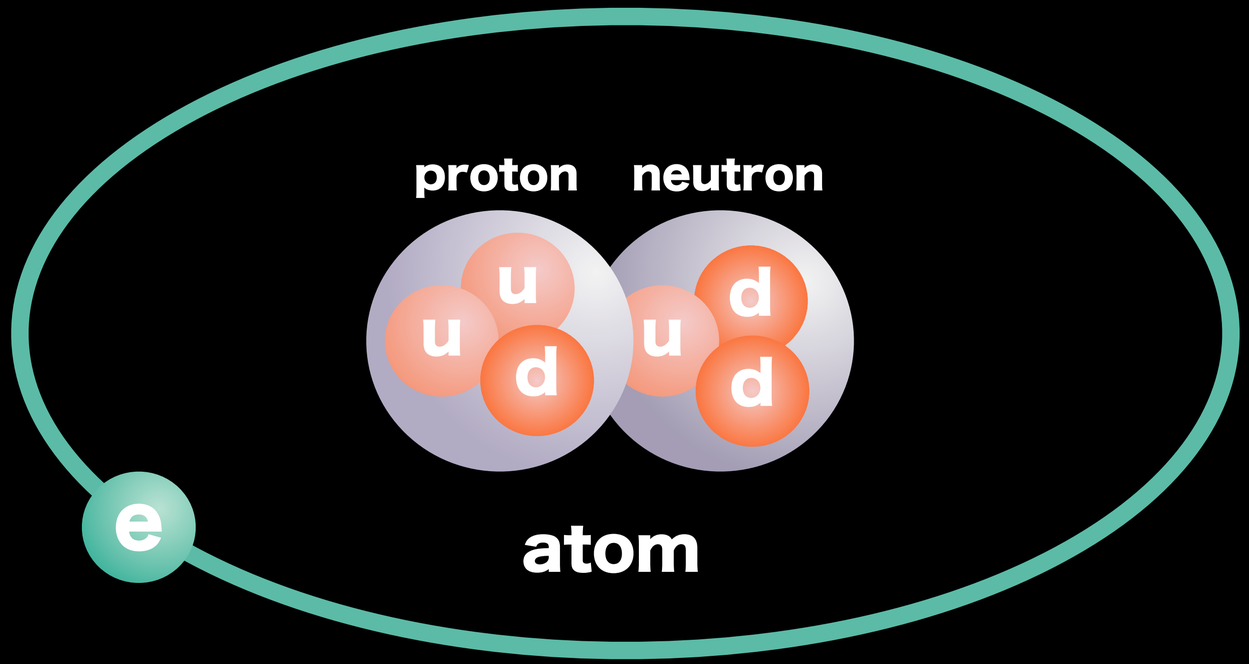
A field is something that can in principle be controlled and modified. Could the masses of elementary particles conceivably also be controlled and modified? Science fiction…

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

My opinion: no

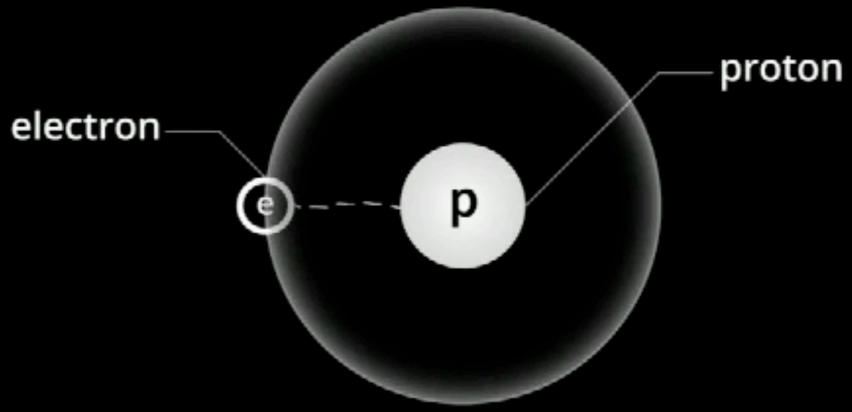
NB: most of mass of proton and neutron comes from other sources

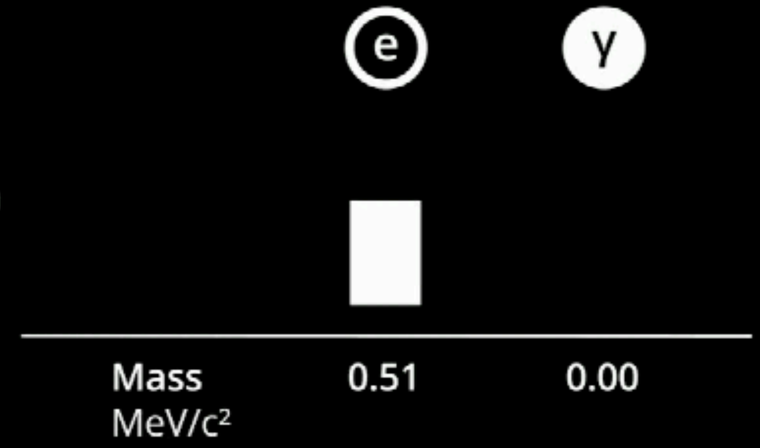




Bohr radius of atom

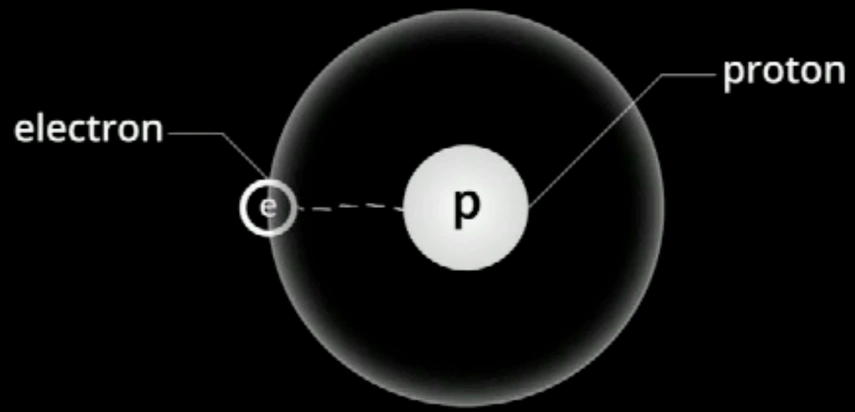
$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e c\alpha} \propto \frac{1}{y_e}$$





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

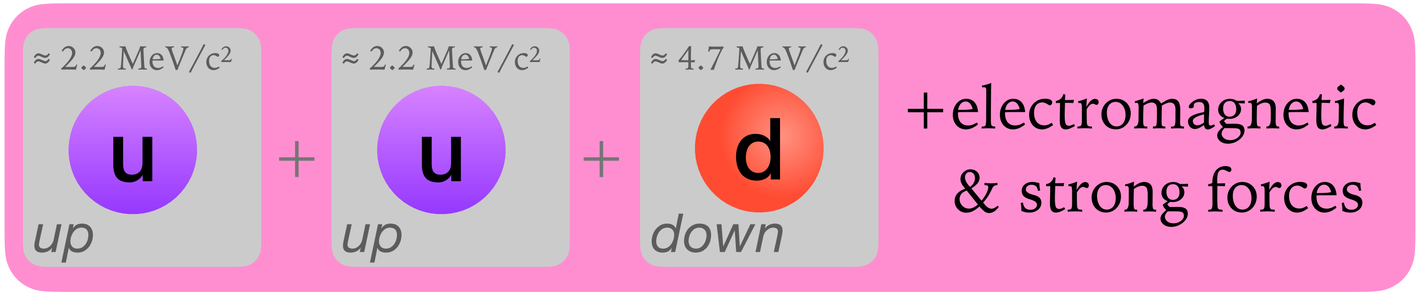
https://videos.cern.ch/record/2757407





2.2 MeV **2.2 MeV** 4.7 MeV

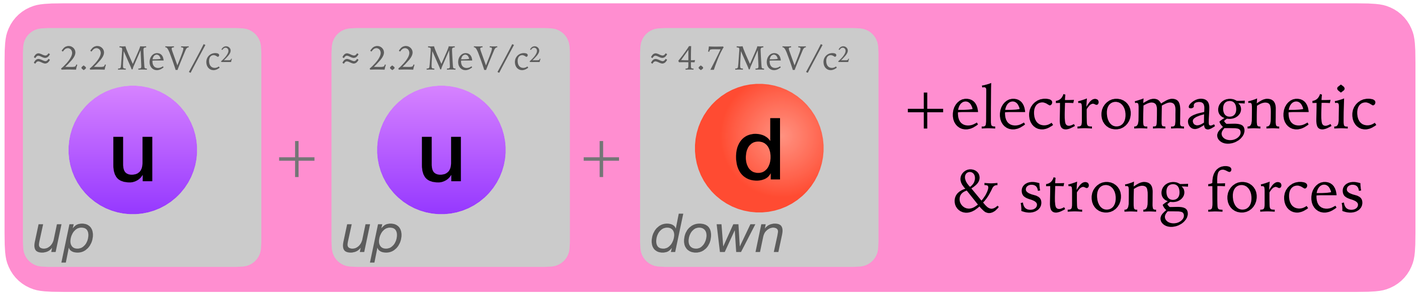
proton:



$\simeq$ **938.3 MeV**

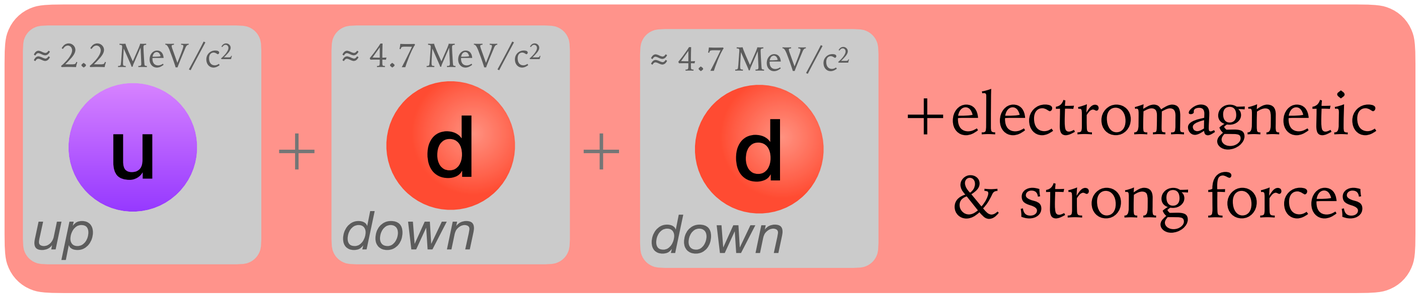
2.2 MeV **2.2 MeV** 4.7 MeV

proton:



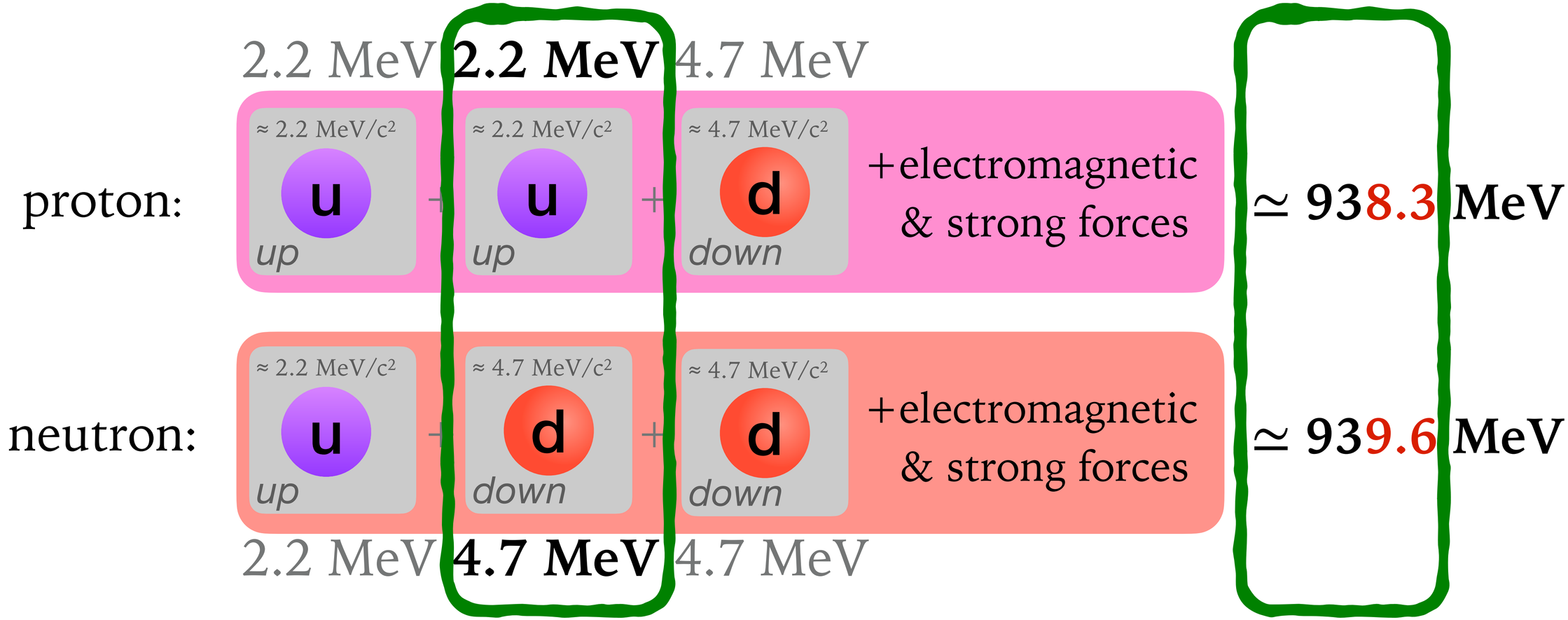
$\simeq$ **938.3 MeV**

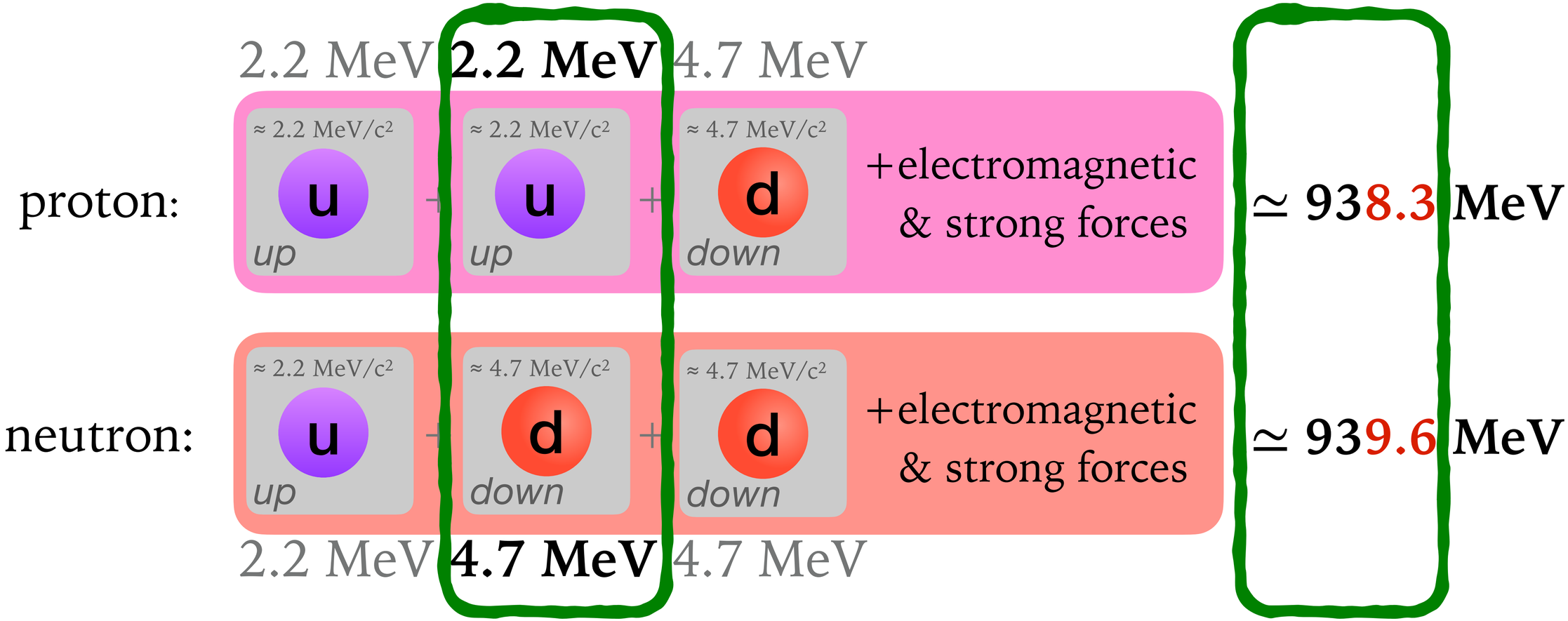
neutron:



$\simeq$ **939.6 MeV**

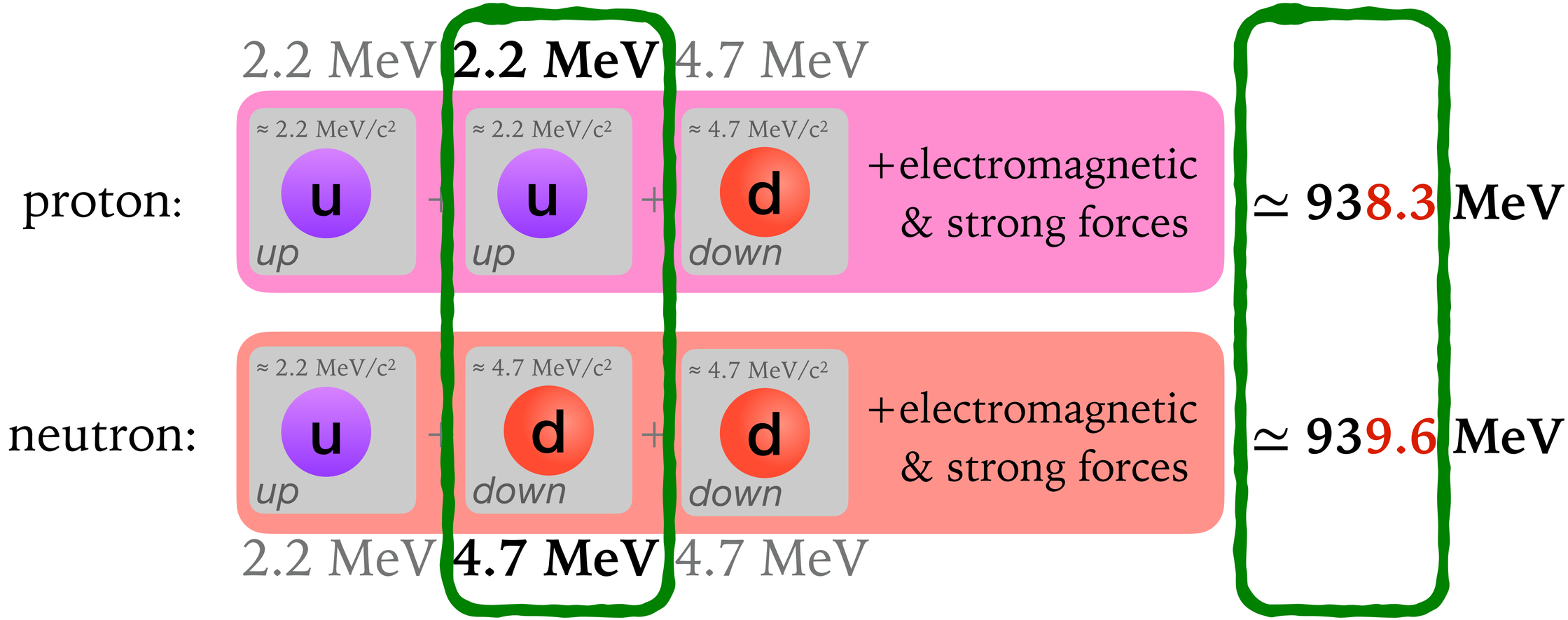
2.2 MeV **4.7 MeV** 4.7 MeV


2.2 MeV
2.2 MeV
4.7 MeV
proton:
≈ 2.2 MeV/c²
u
up
+
≈ 2.2 MeV/c²
u
up
+
≈ 4.7 MeV/c²
d
down
+electromagnetic & strong forces
≃ 938.3 MeV
neutron:
≈ 2.2 MeV/c²
u
up
+
≈ 4.7 MeV/c²
d
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+electromagnetic & strong forces
≃ 939.6 MeV
2.2 MeV
4.7 MeV
4.7 MeV



Protons are **lighter** than neutrons→ protons are stable.

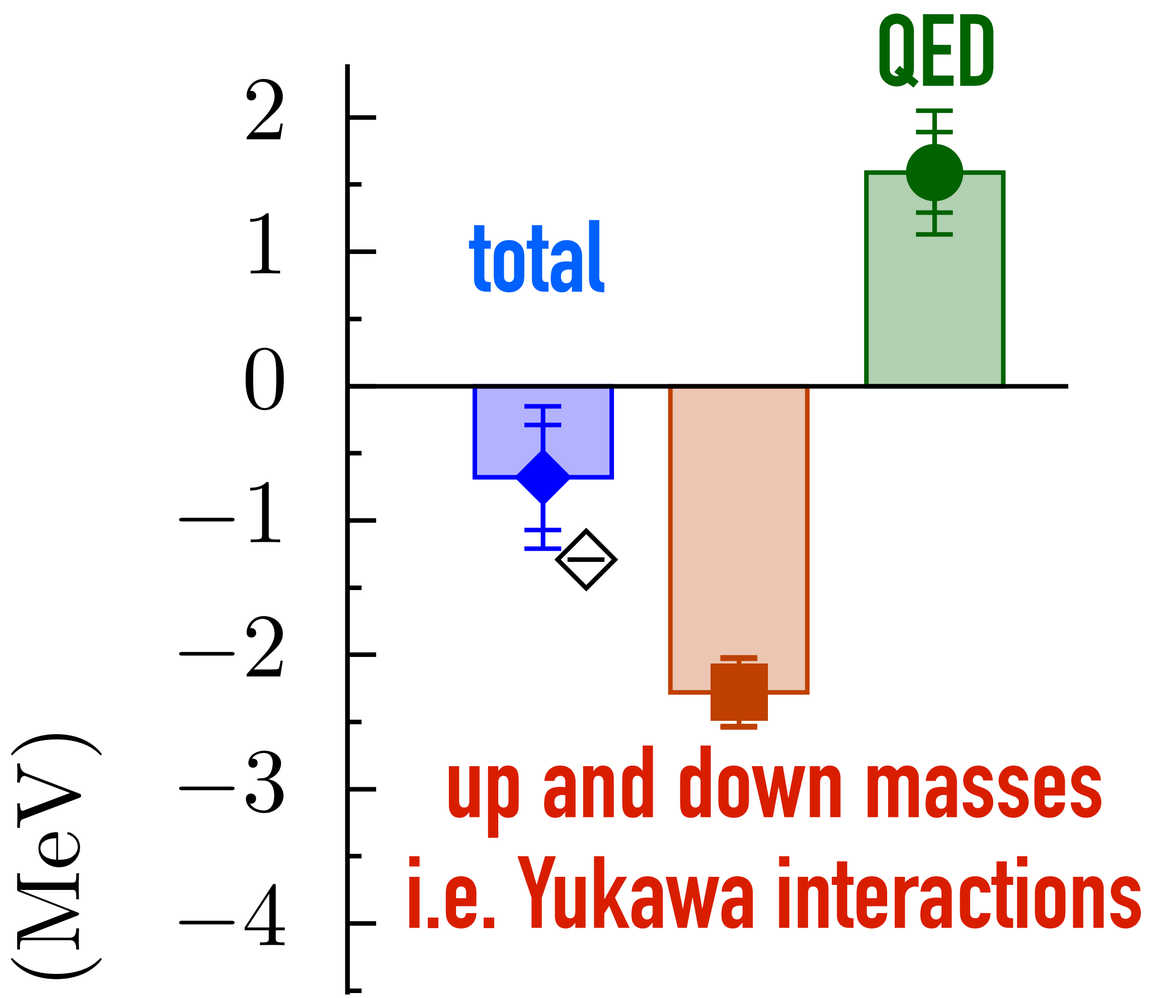
Giving us the hydrogen atom, & chemistry and biology as we know it



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

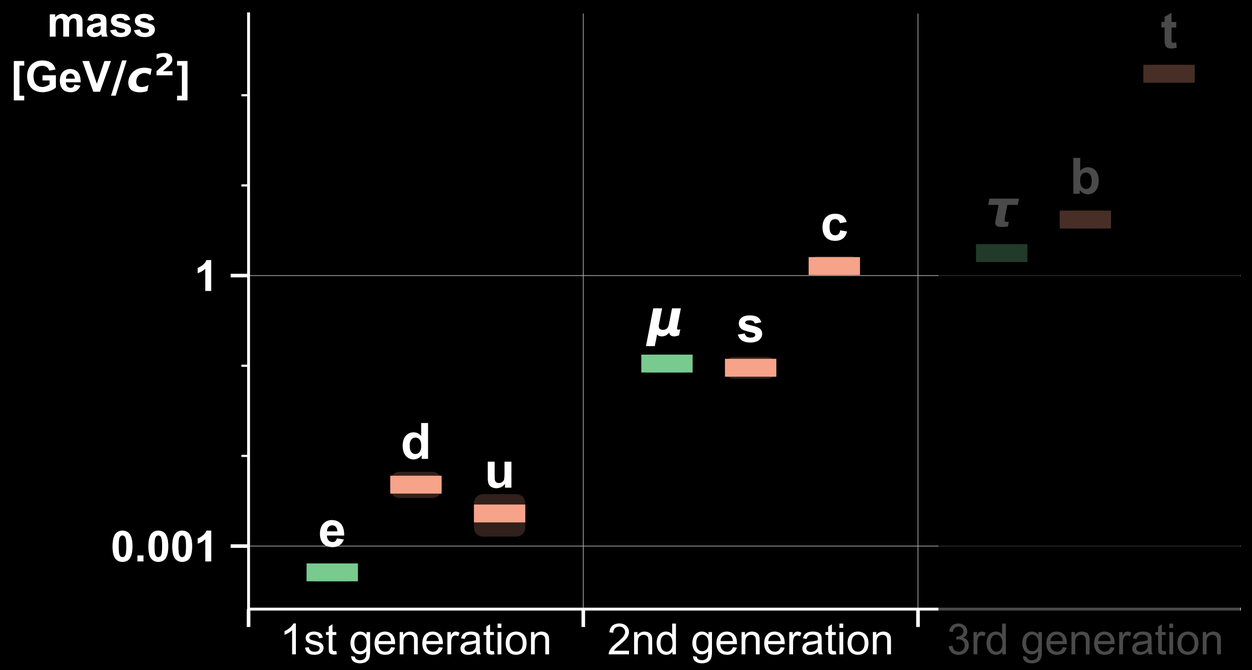
proton – neutron mass difference



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

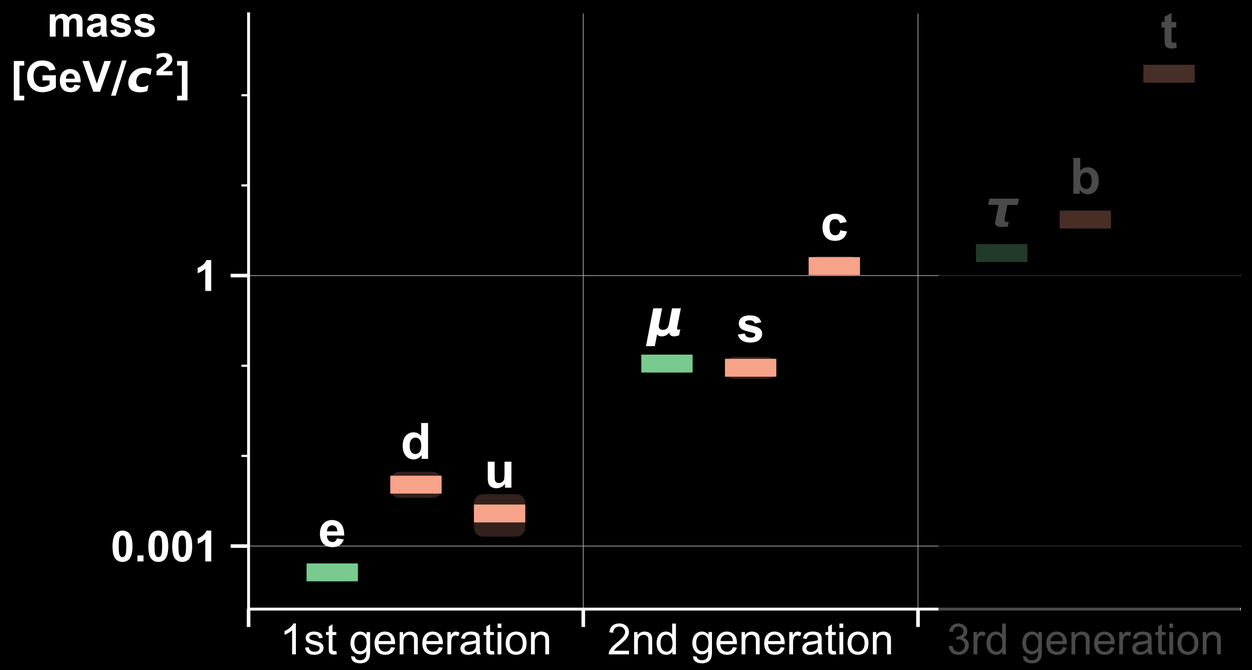
— it's in textbooks, but is it nature?



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

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

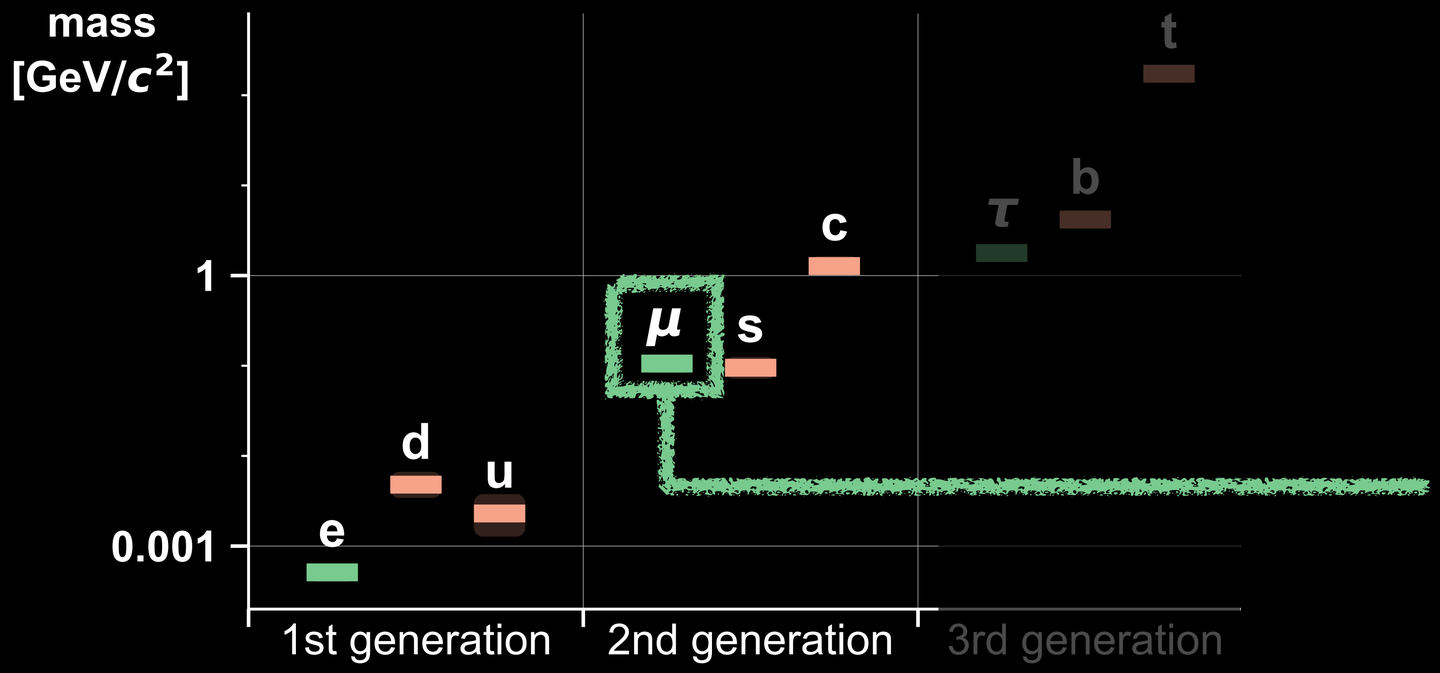
→ the more difficult it is establish if it actually gets mass from interactions with the Higgs field



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

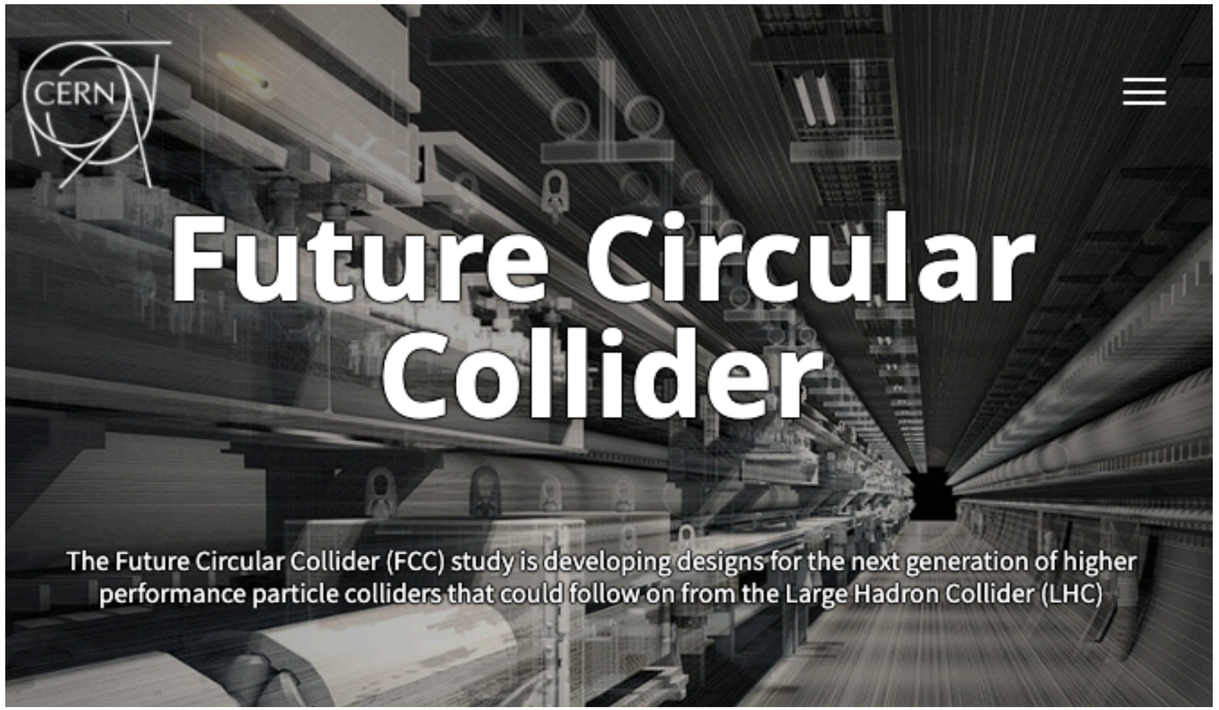
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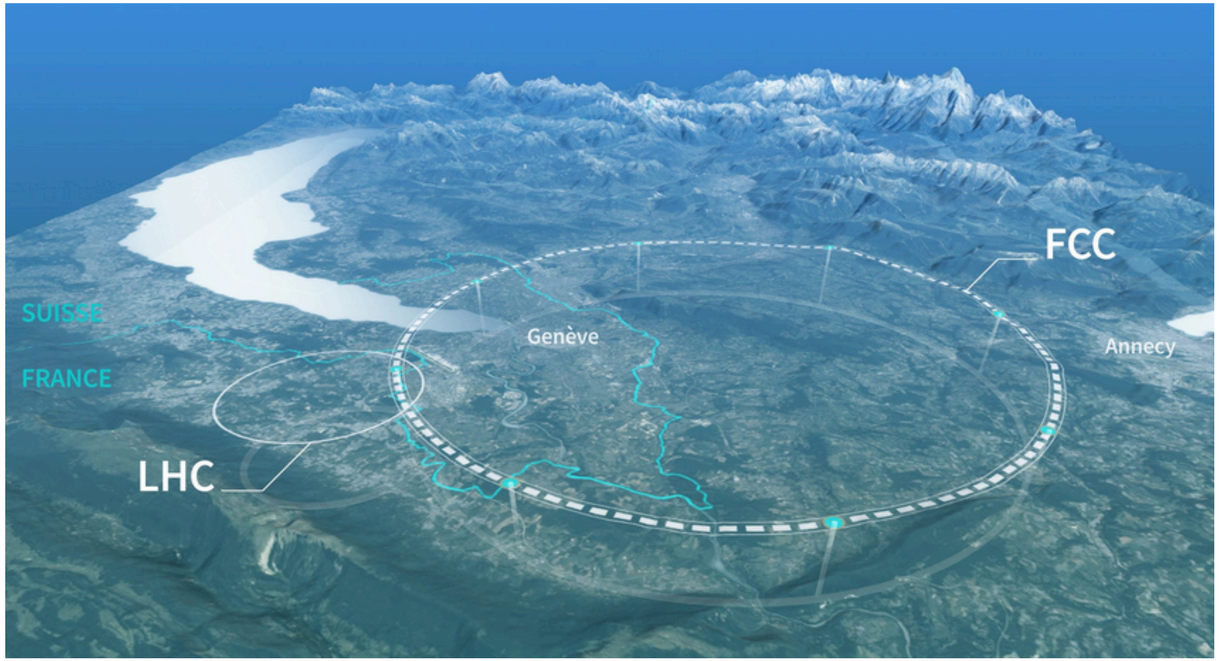
→ the more difficult it is establish if it actually gets mass from interactions with the Higgs field



a major LHC goal of the next years (in existing Run-3 data or at 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]





FCC IN A NUTSHELL

Timeline

- **2025**: Release of the FCC Feasibility Study report
- **2028**: Decision by CERN Member States and international partners

Tunnel

- **90.7 km** circumference
- **180 – 400 m** depths for access shafts
- **8 surface sites** (7 in France, 1 in Switzerland)

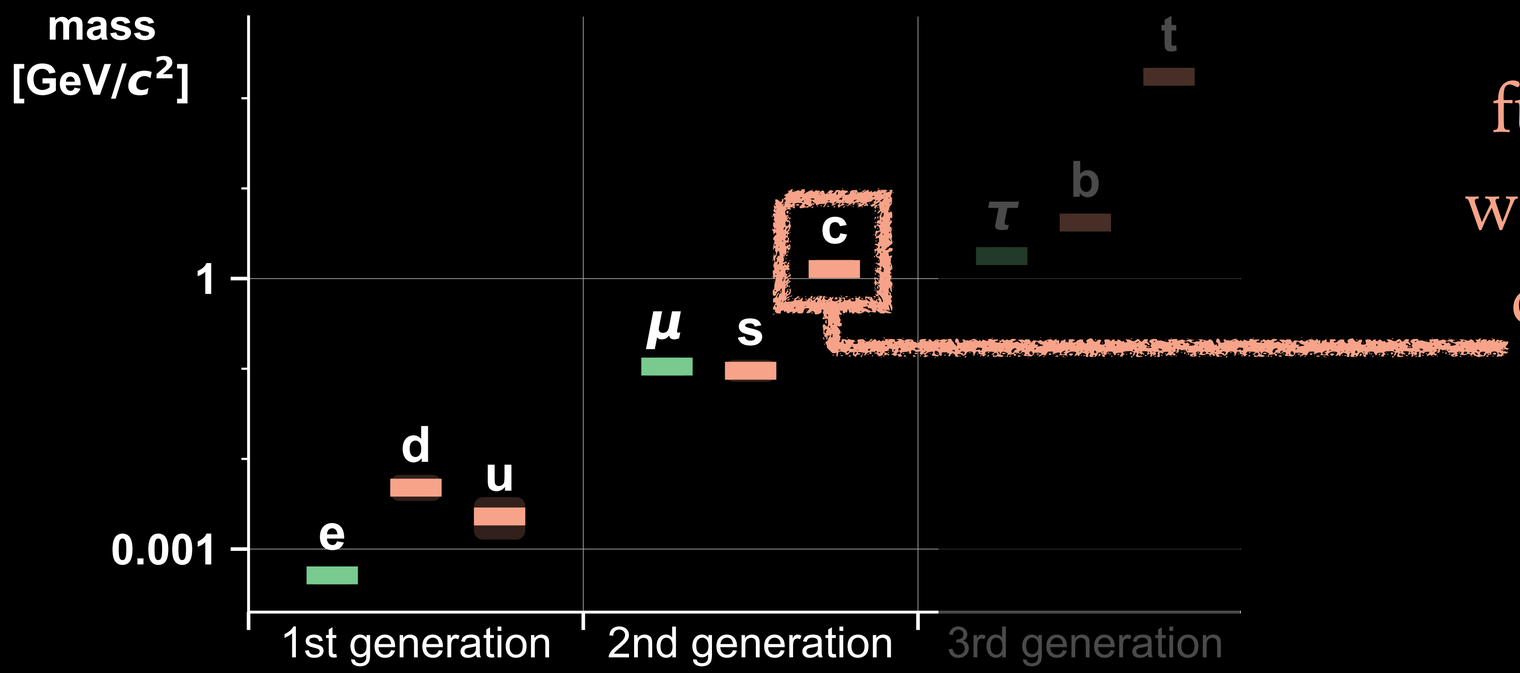
Two stages

- **FCC-ee** (precision measurements) about 15 years from the **late 2040s**
- **FCC-hh** (high energy) about 25 years from the **2070s**

Costs/benefits

- **15 billion CHF**, spread over about **12 years** for FCC-ee with four experiments
- **Positive** socio-economic benefit–cost ratio
- About **800 000** person-years of employment created

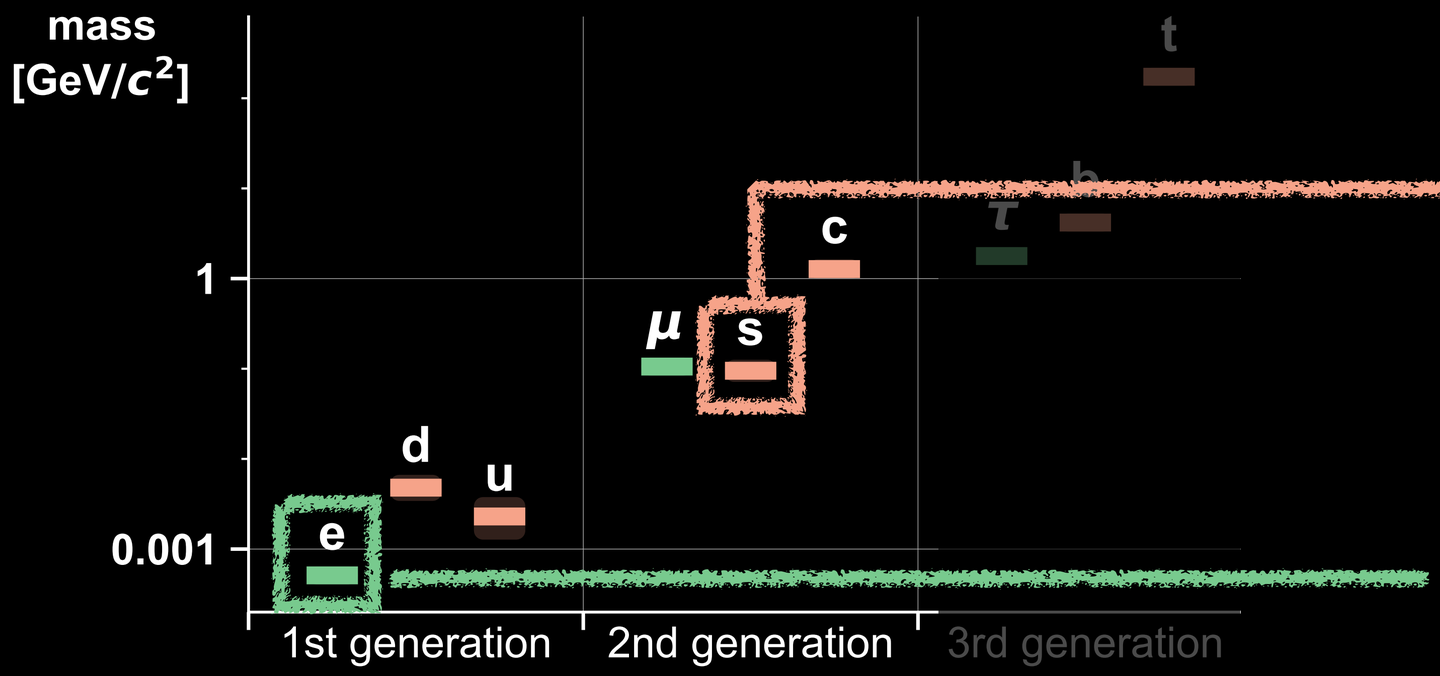
What of future colliders



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



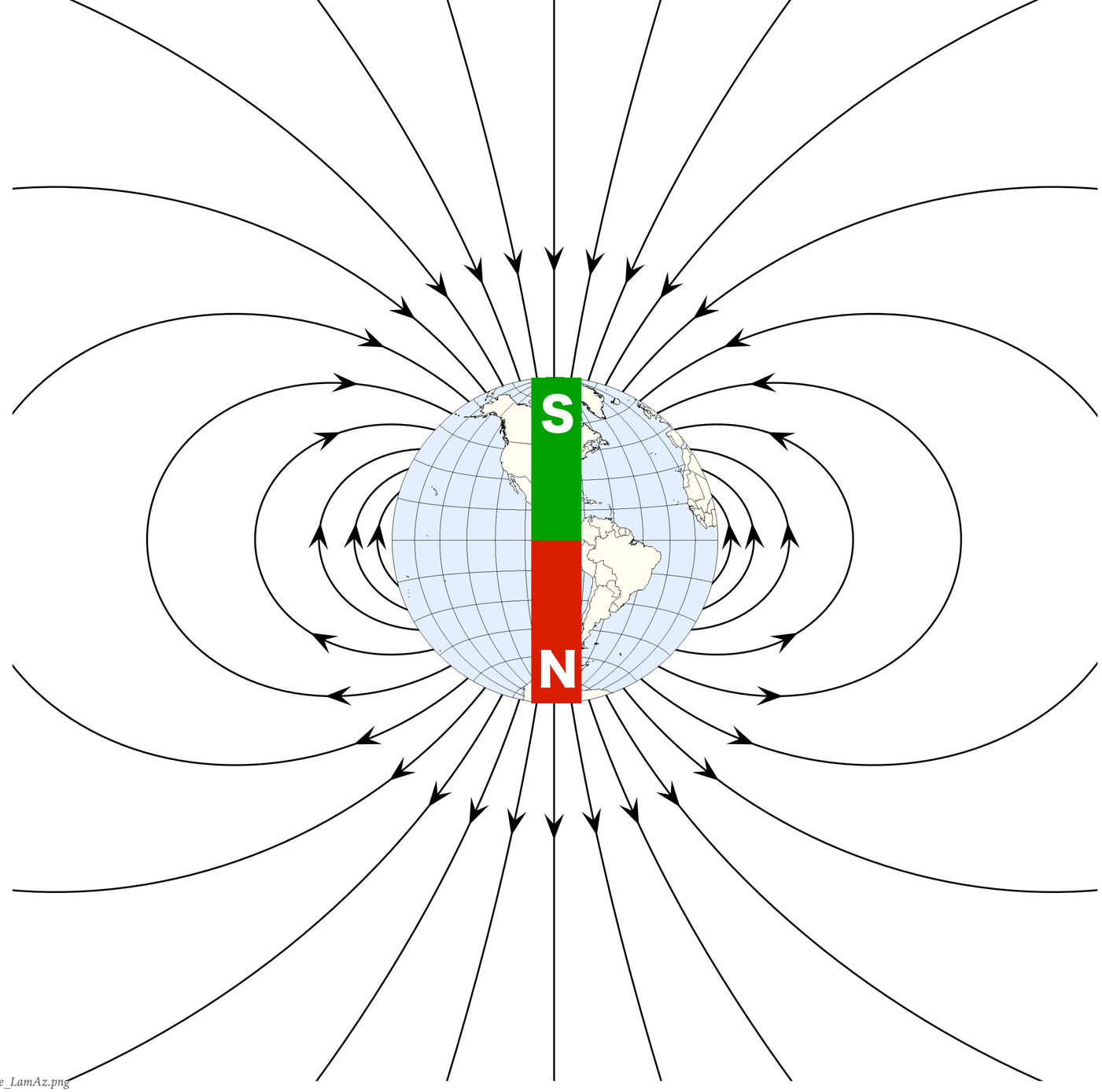
It's becoming clear that strange quark and electron "Yukawas" are just barely at the edge of reach of FCC-ee

Discovering origin of electron mass would be a huge accomplishment

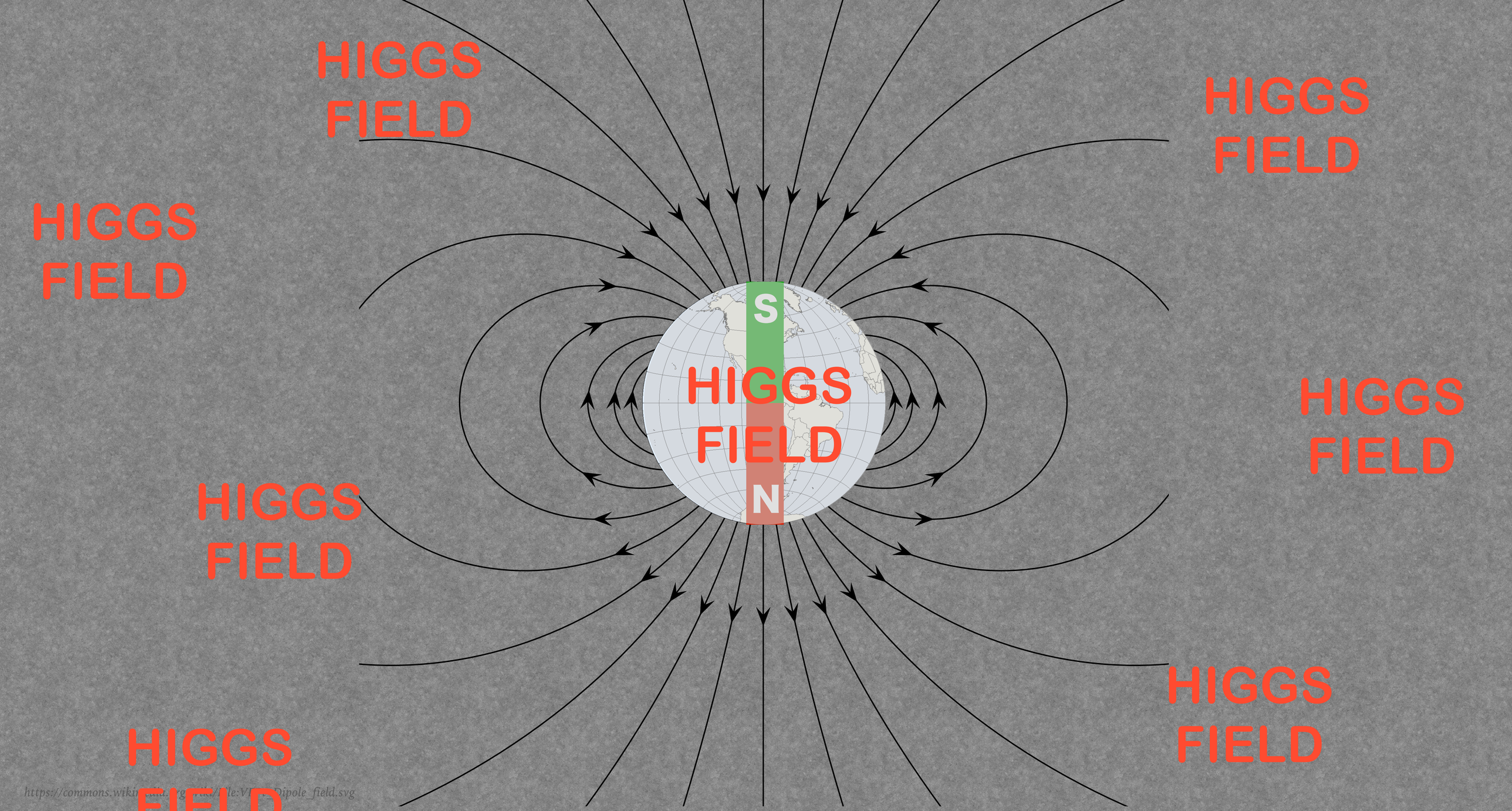
electron Yukawa: see d'Enterria, Poldaru, Wojcik, 2107.02686

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

Why is the Higgs field non-zero?

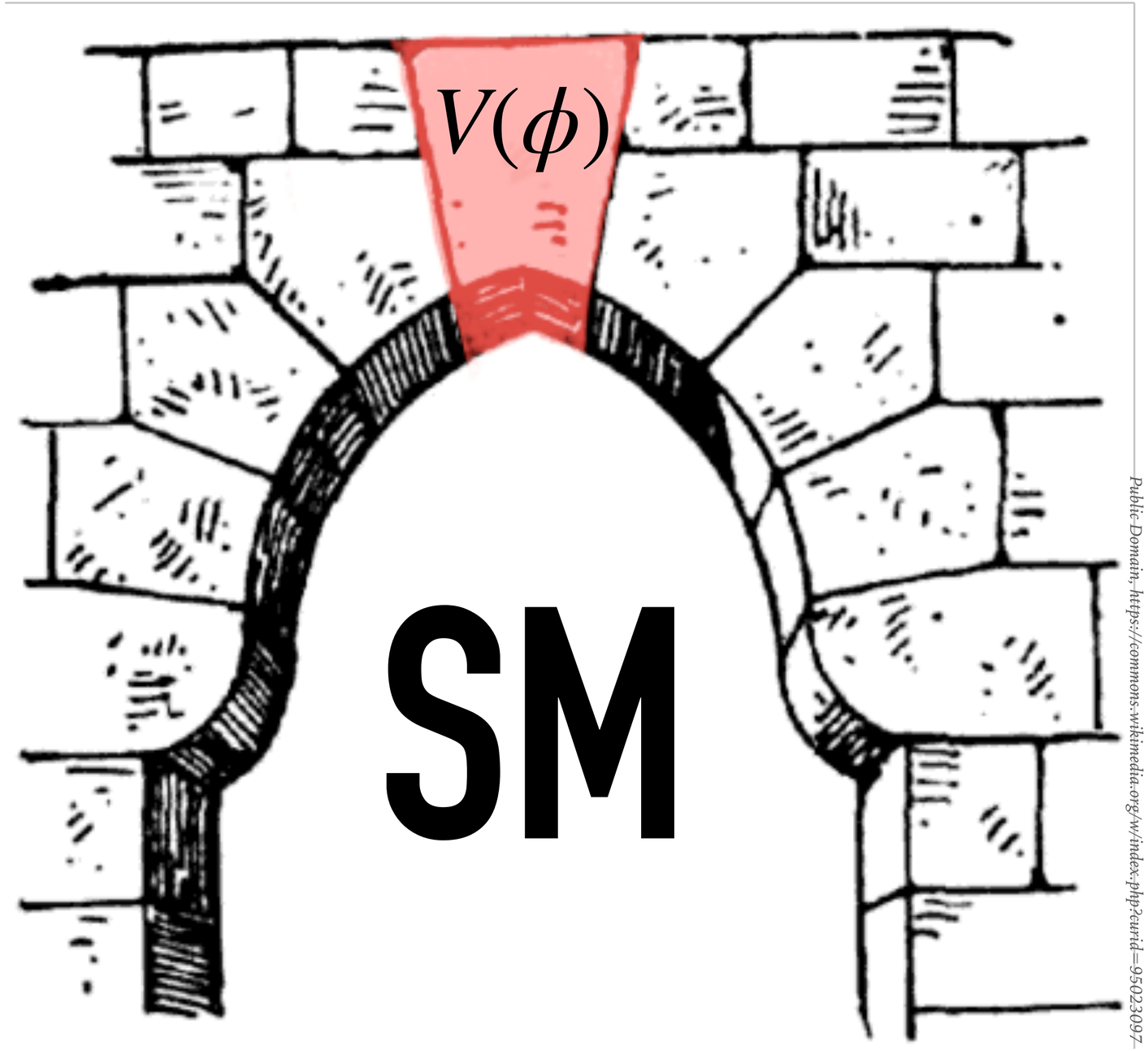


https://commons.wikimedia.org/wiki/File:VFPt_Dipole_field.svg
https://en.wikipedia.org/wiki/Western_Hemisphere#/media/File:Western_Hemisphere_LamAz.png



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

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



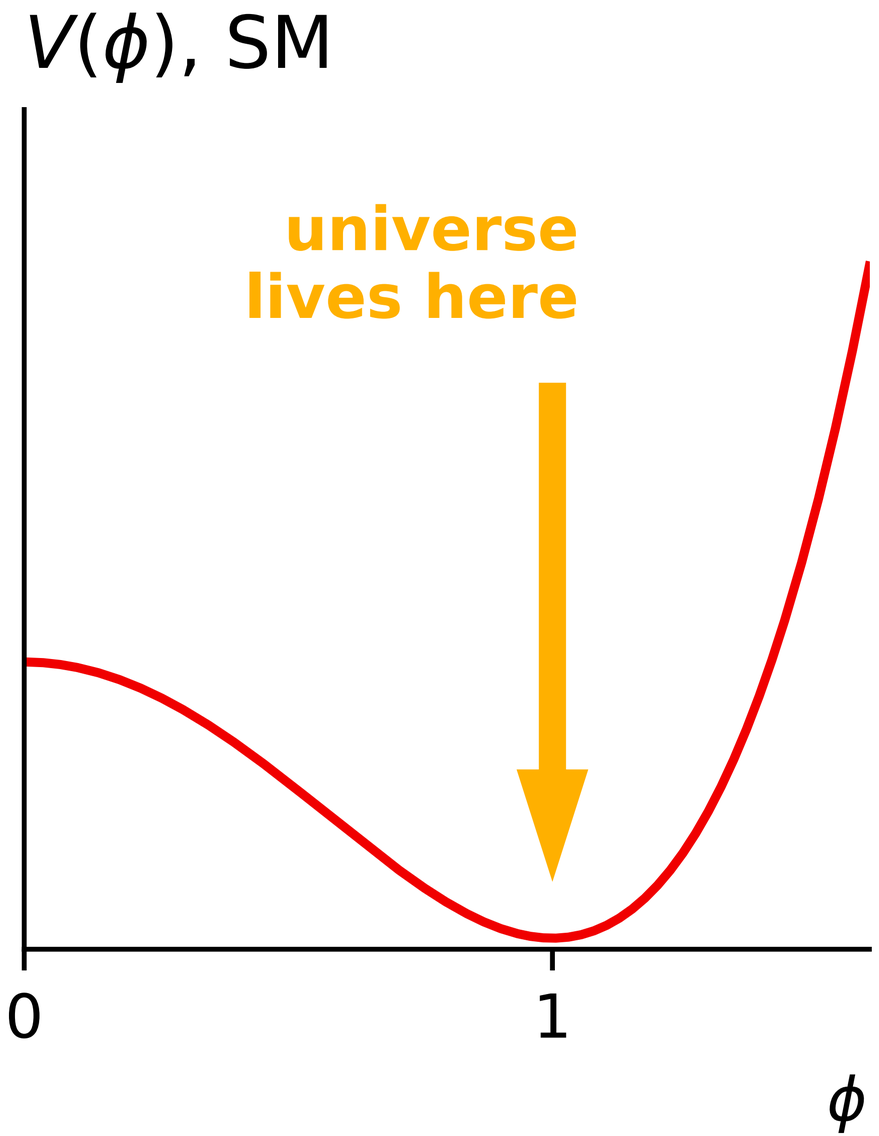
Public Domain, https://commons.wikimedia.org/w/index.php?curid=95023097

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

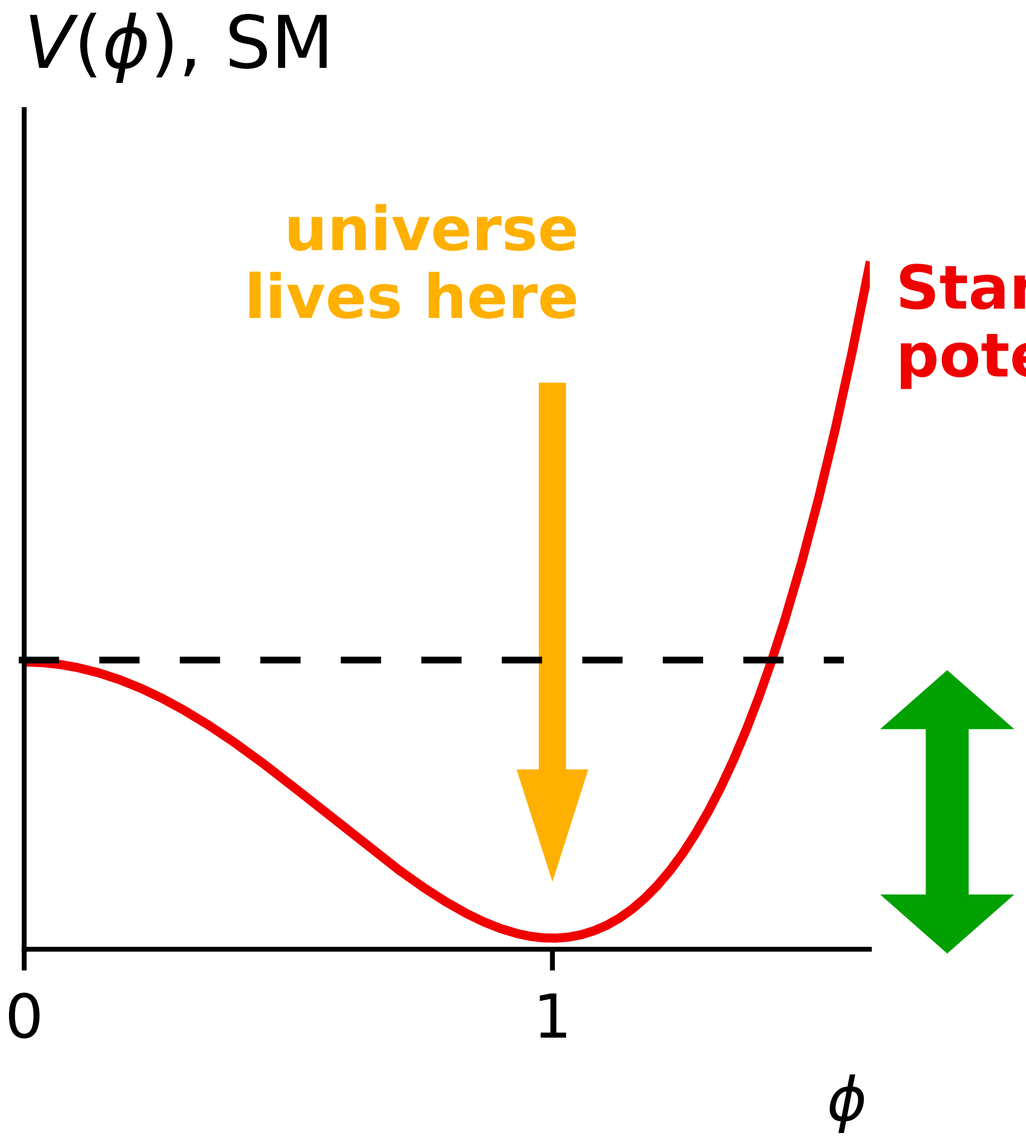


The Higgs field is non-zero because that ensures the lowest potential energy

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

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

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

Estadio Verónica Boquete de San Lazaro, photo by JonnyJonny

https://en.wikipedia.org/wiki/Estadio_Ver%C3%B3nica_Boquete_de_San_L%C3%A1zaro#/media/File:Estadio_Multiusos_de_San_Lazaro.jpg





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Earth at neutron star density

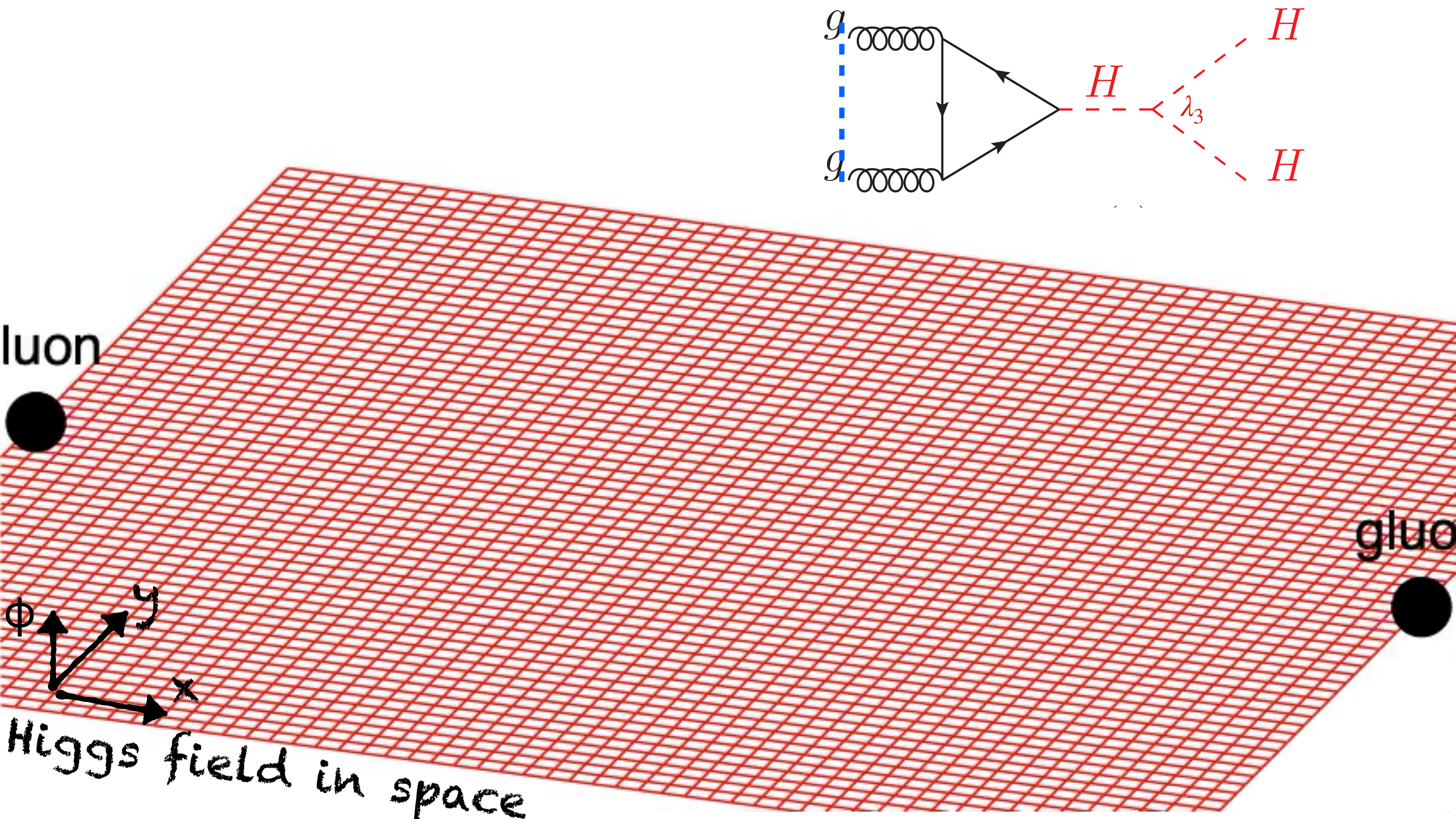
https://en.wikipedia.org/wiki/Globe#/media/File:World_Globe_Map.jpg
https://en.wikipedia.org/wiki/Old_fashioned_glass#/media/File:Old_Fashioned_Glass.jpg
Estadio Verónica Boquete de San Lazaro, photo by JonnyJonny
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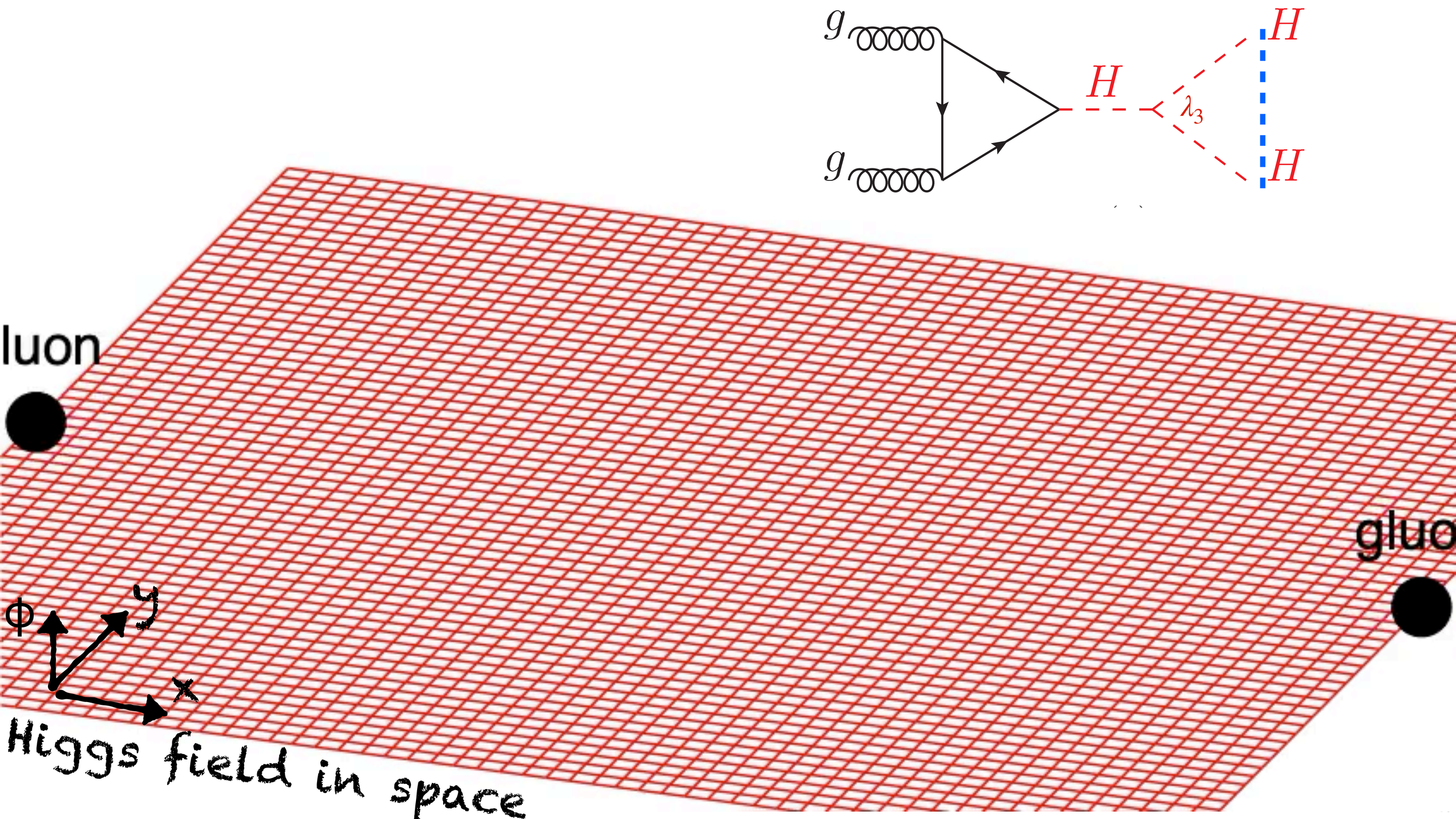


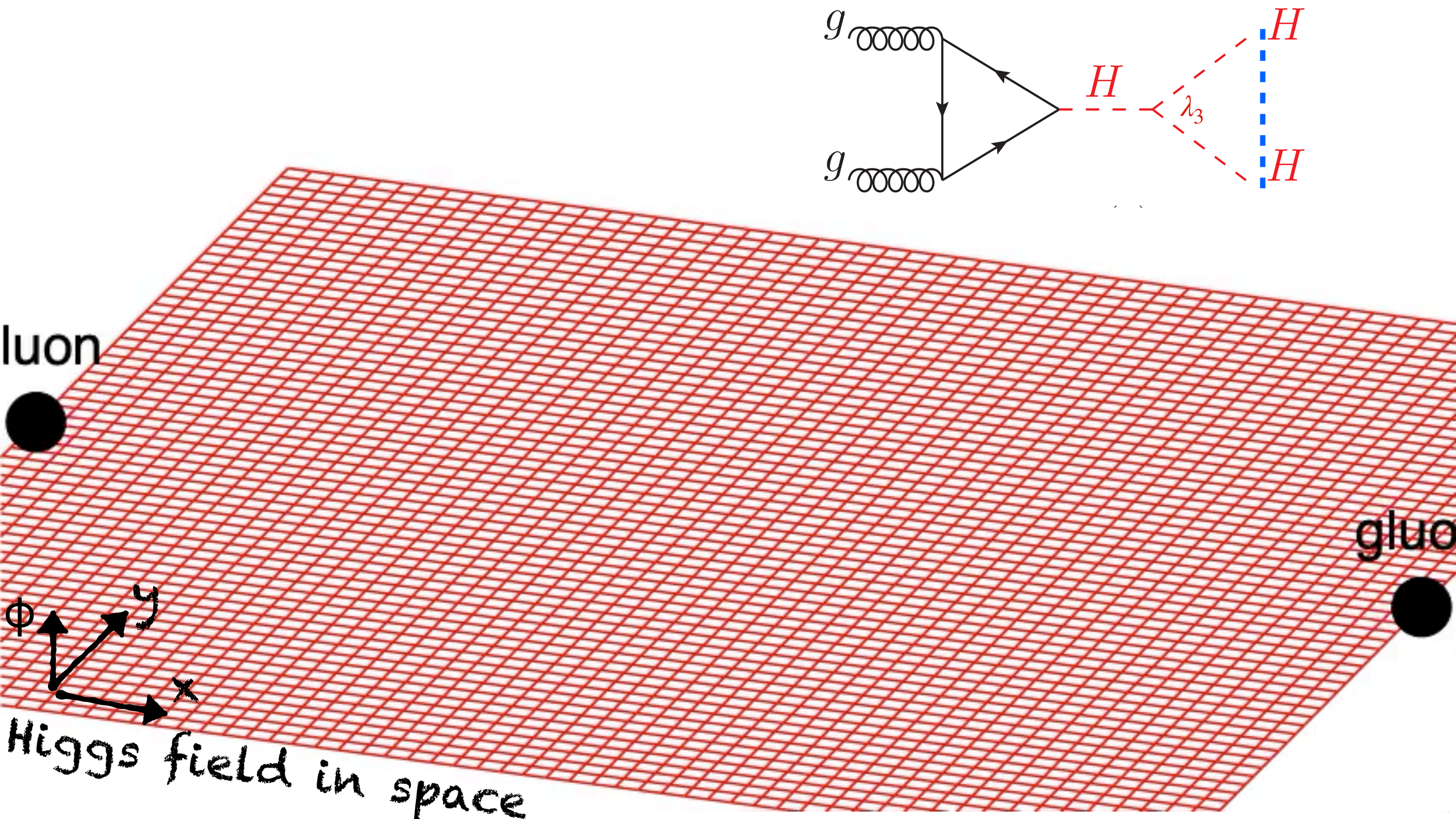
Earth at neutron star density



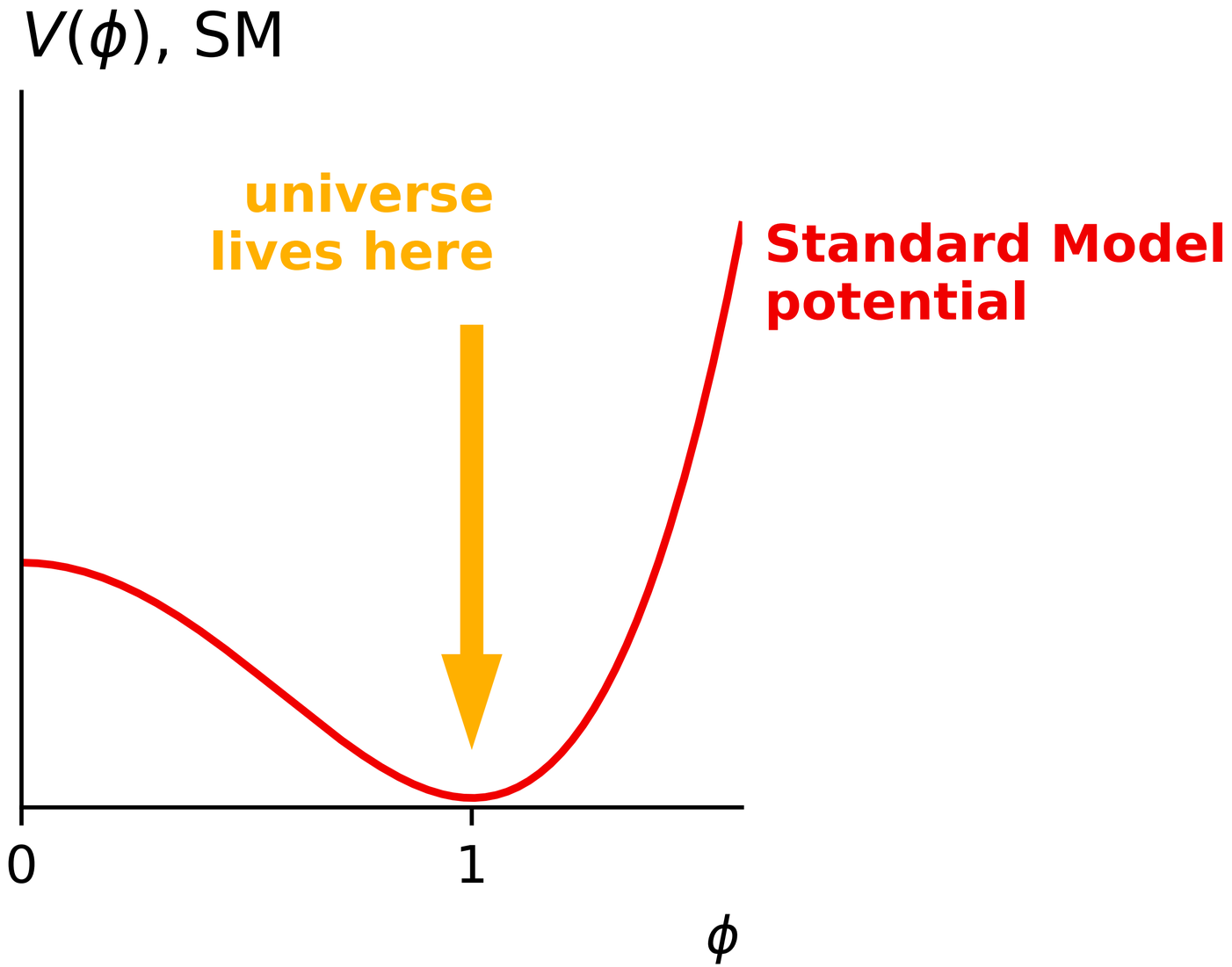
Earth at Higgs potential density


g
g
H
H
H
λ_3
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
λ3
H
H
luon
gluo
Φ
y
x
Higgs field in space

Higgs potential

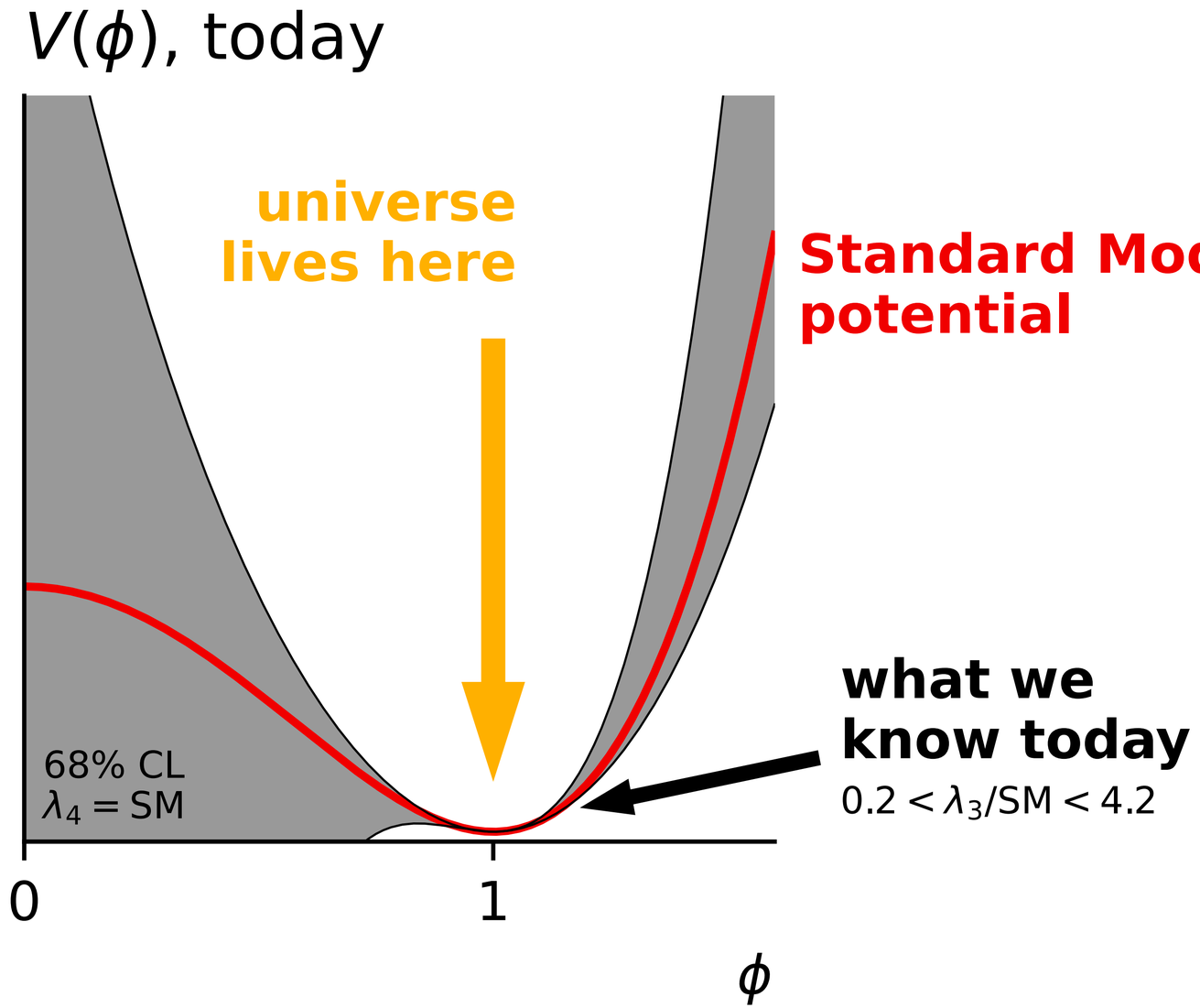


Studying H→HH probes specific mathematical property of the potential's shape:

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

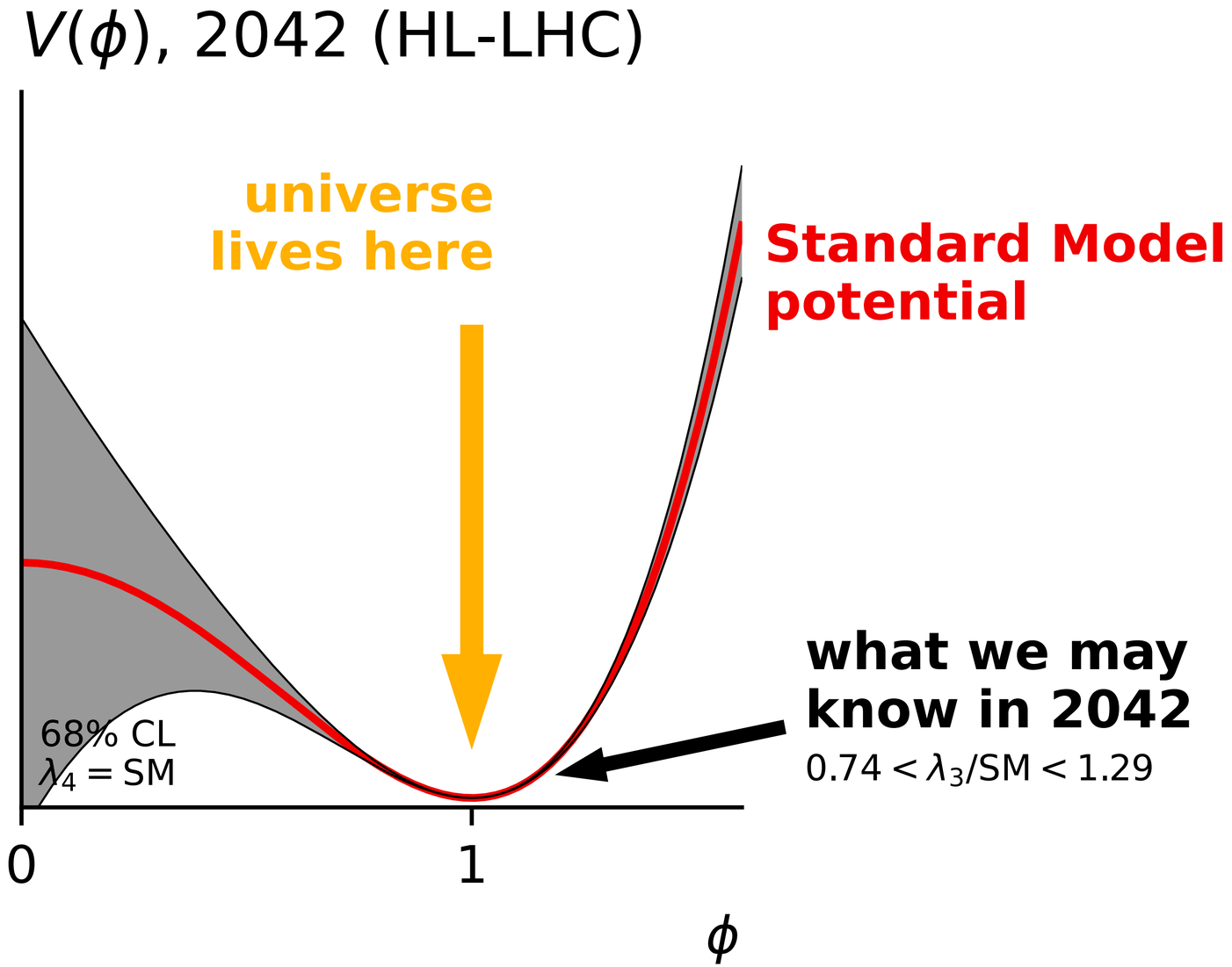


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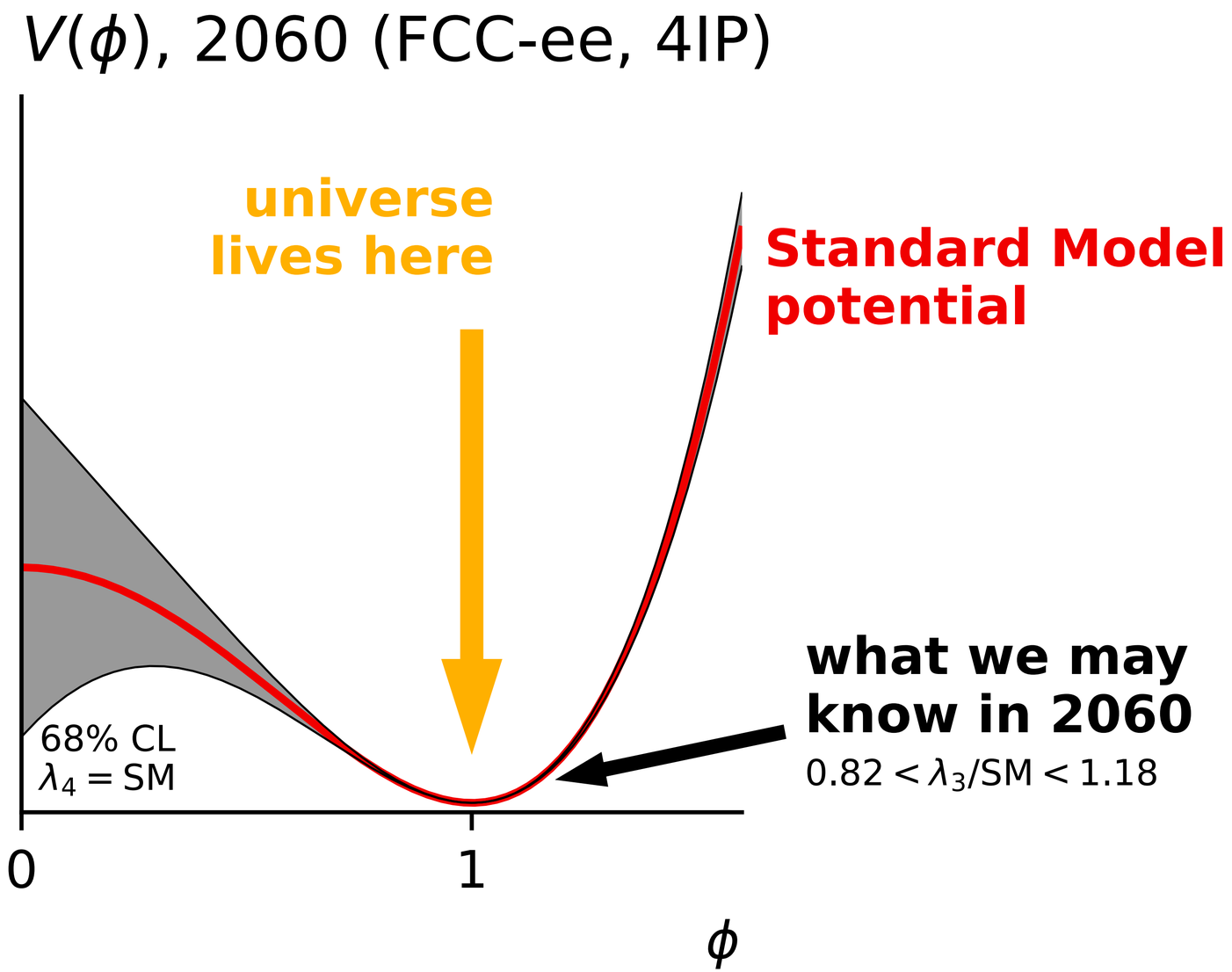


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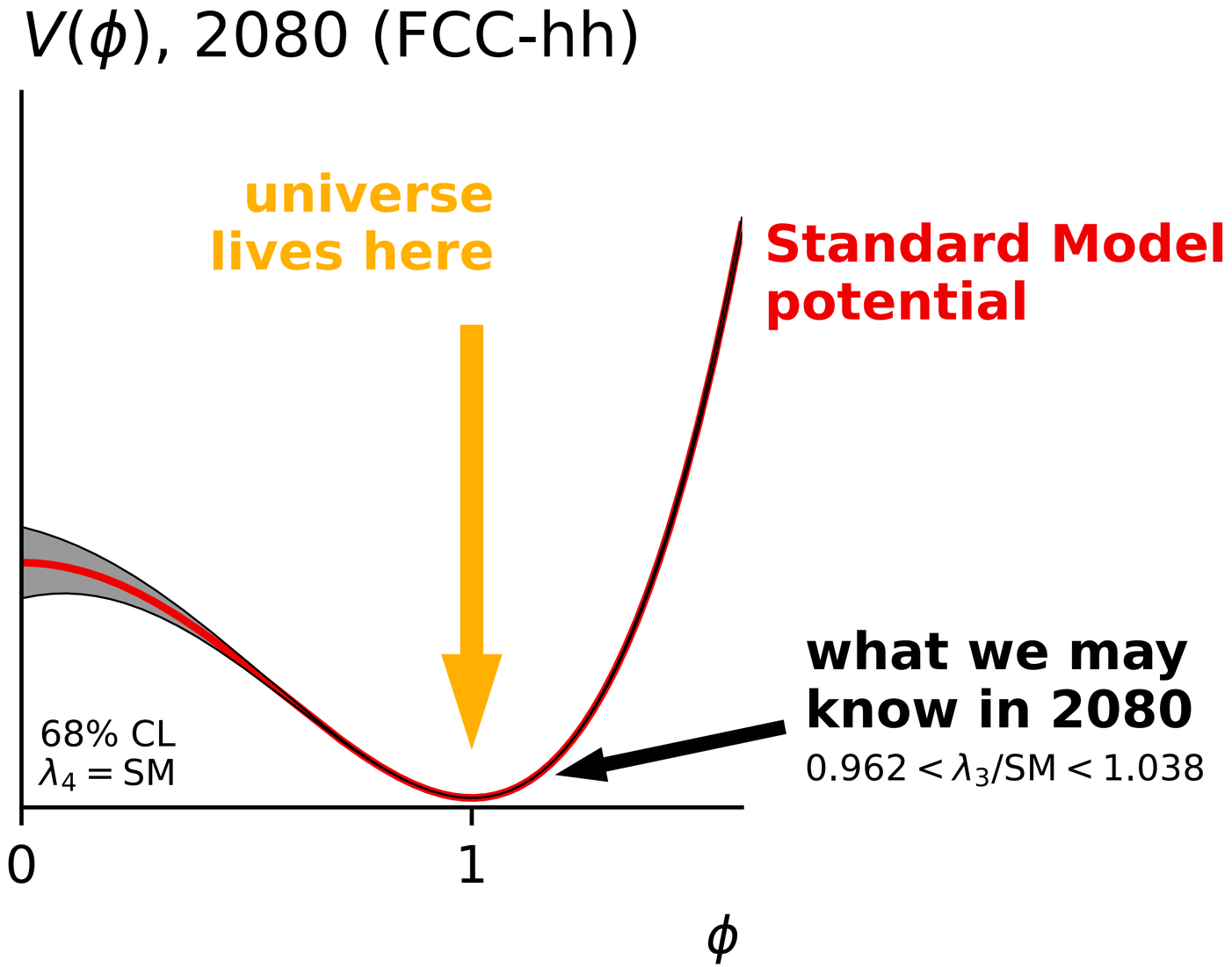


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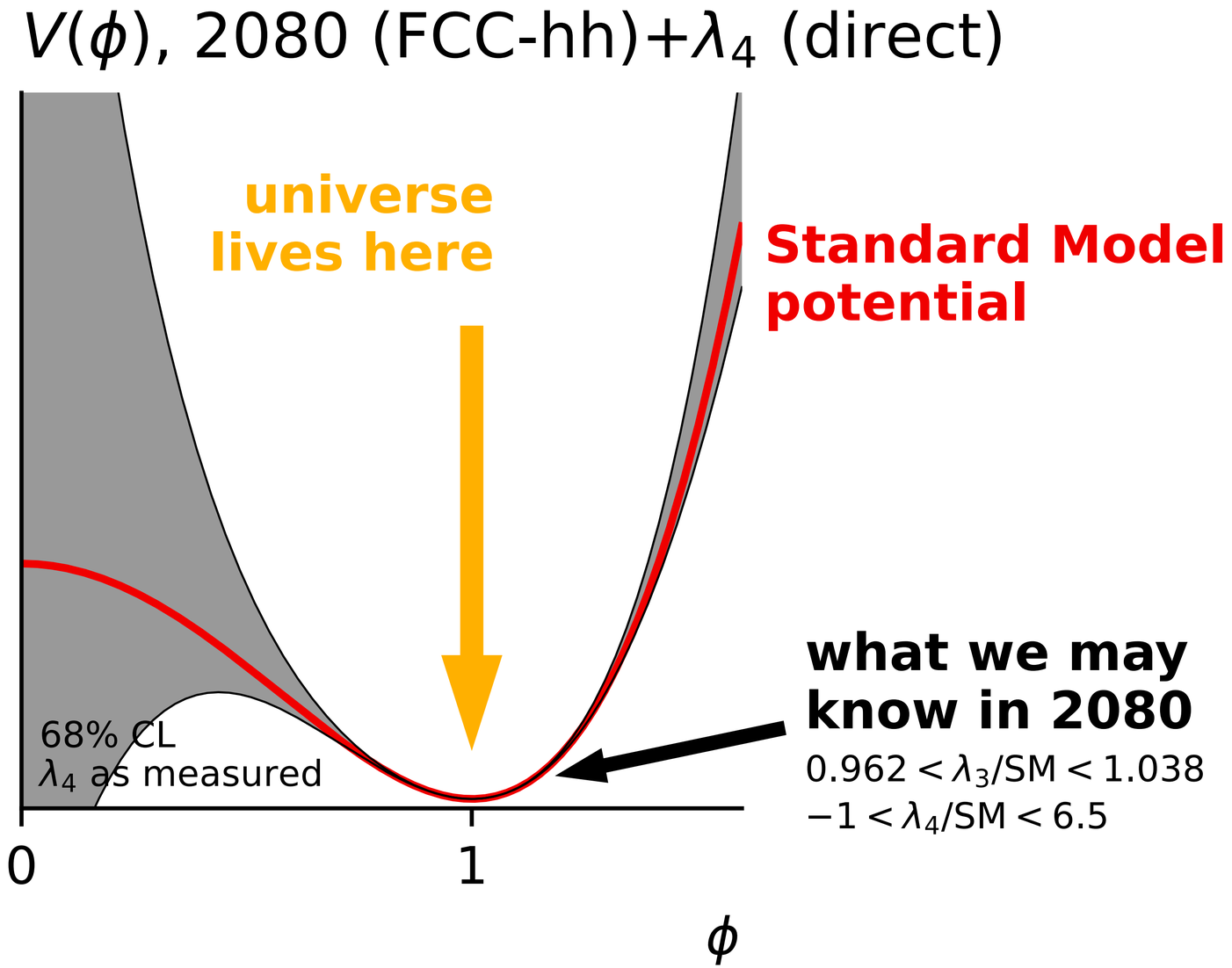


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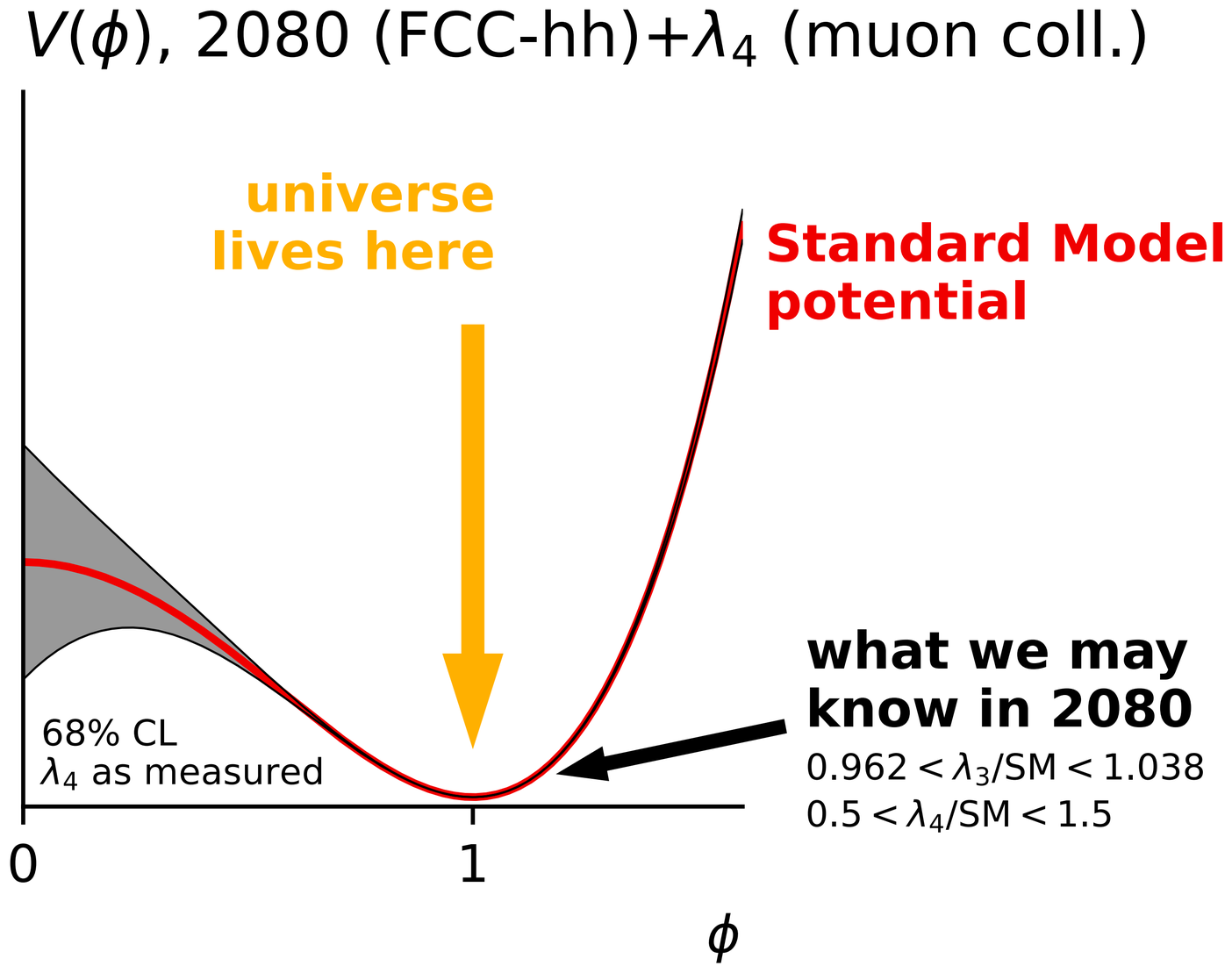


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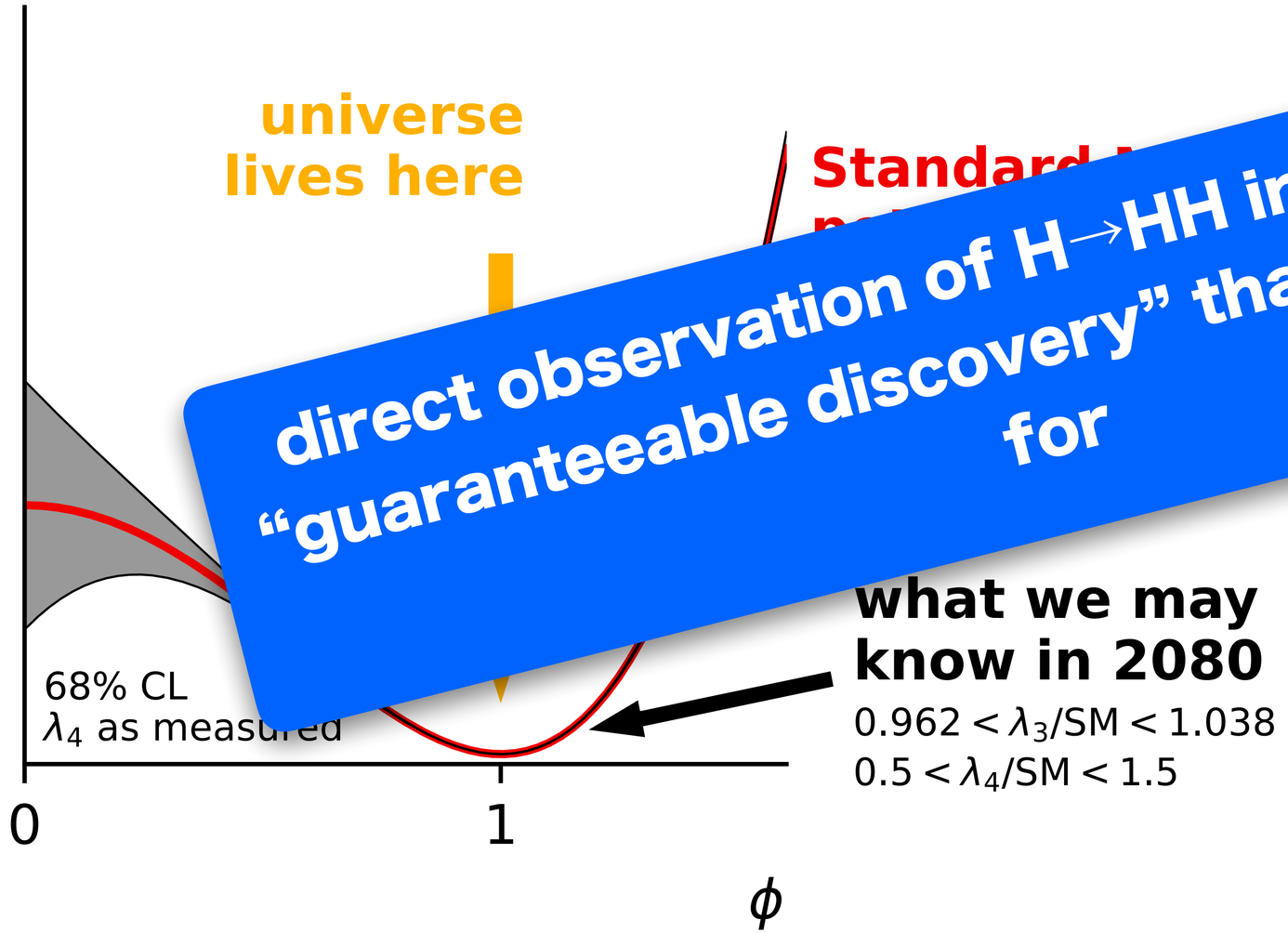
Studying H→HH probes specific mathematical property of the potential's shape:

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

[reconstruction in plot assumes higher derivatives as in SM]

Higgs potential

$V(\phi)$, 2080 (FCC-hh)+λ_4 (muon coll.)



what we may know in 2080

$0.962 < \lambda_3/\mathrm{SM} < 1.038$

$0.5 < \lambda_4/\mathrm{SM} < 1.5$

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

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

[reconstruction in plot assumes higher derivatives as in SM]

Almost every problem of the Standard Model originates from Higgs interactions

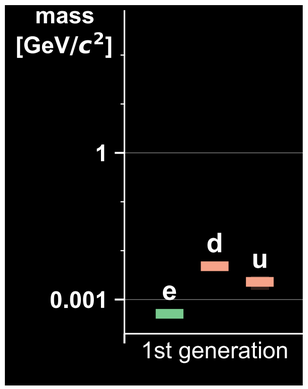
$$\mathscr{L} = y\,H\,\psi\,\bar{\psi} + \mu^2\,|H|^2 - \lambda\,|H|^4 - V_0$$

flavour

naturalness

stability

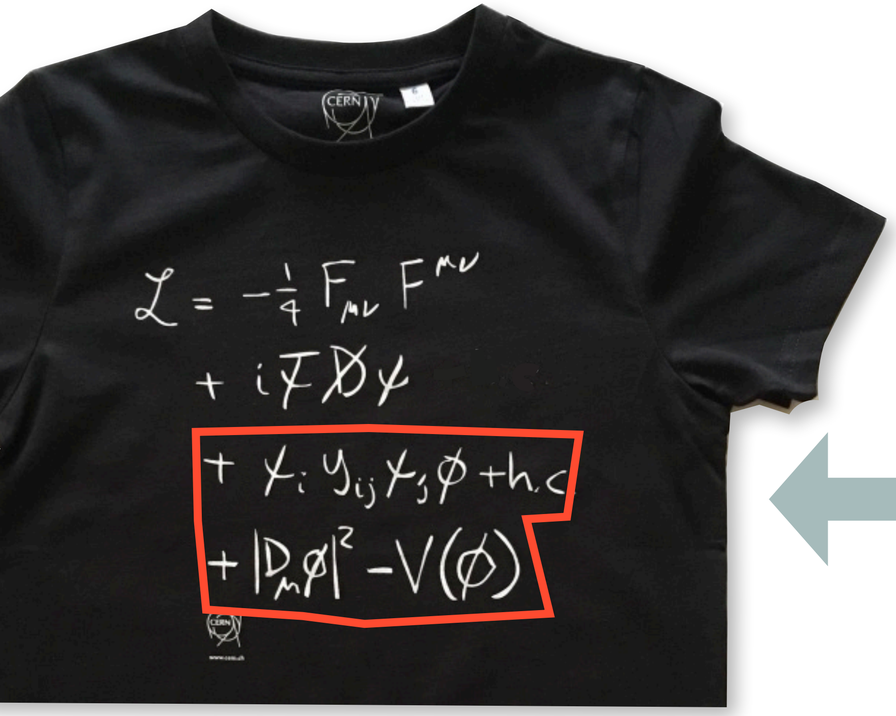
cosmological constant



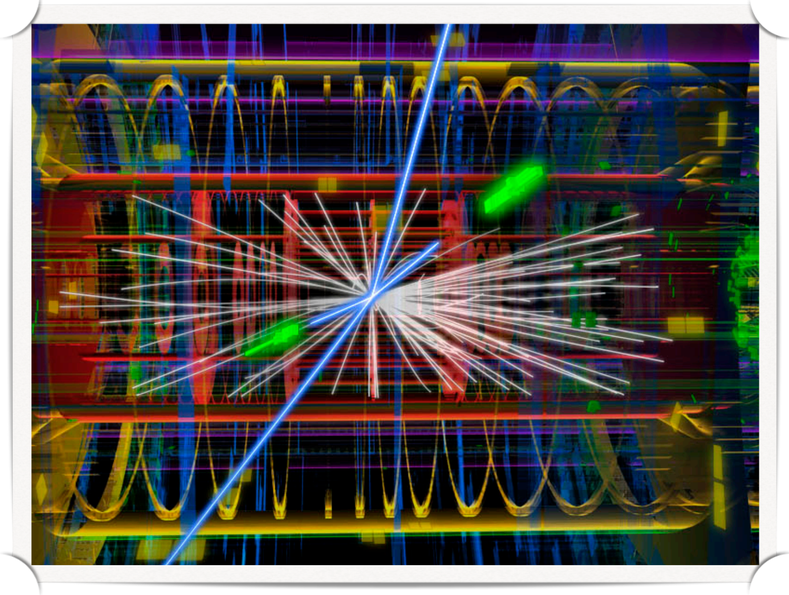


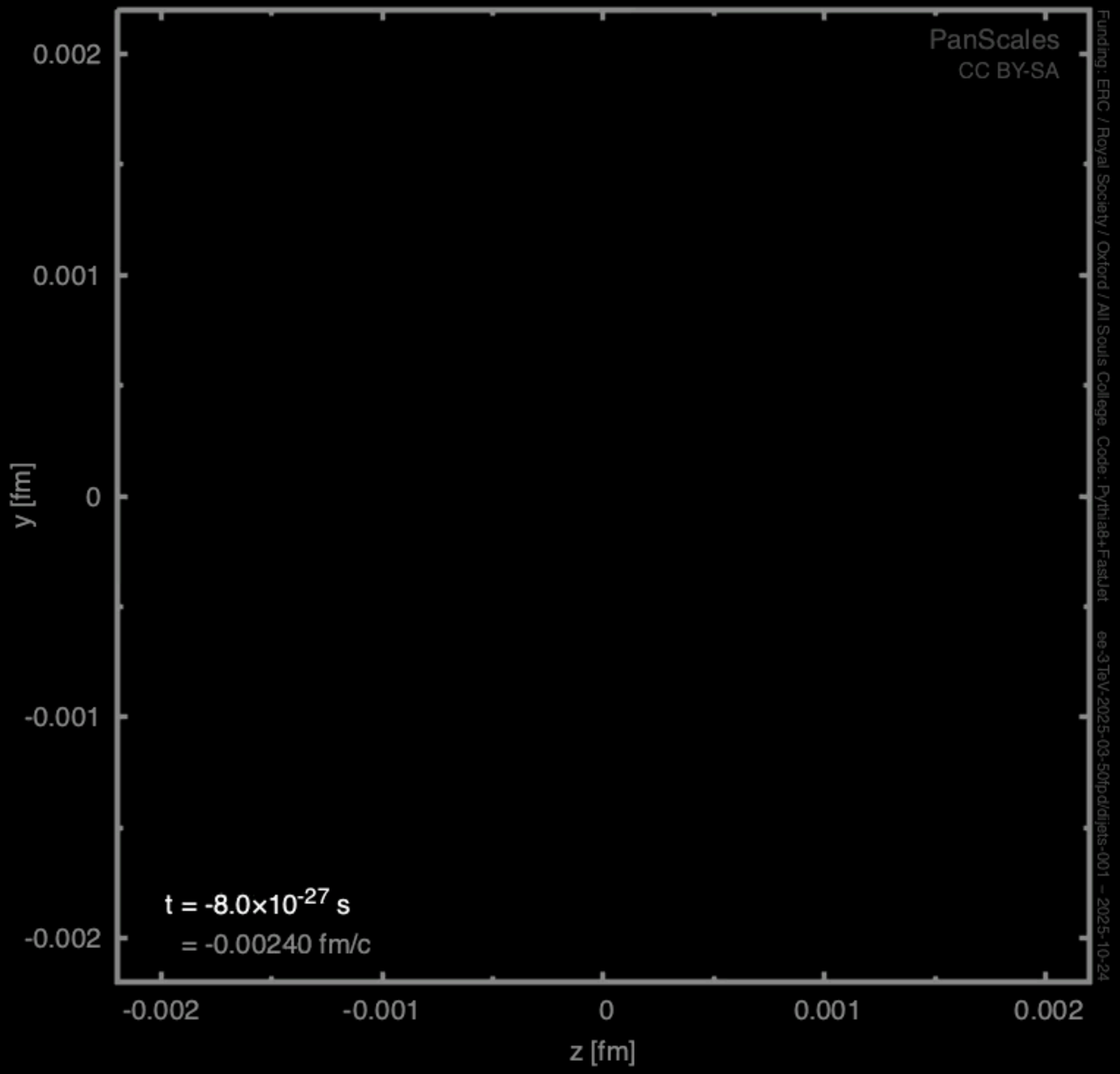
UNDERLYING THEORY

EXPERIMENTAL DATA



how do you make quantitative connection?



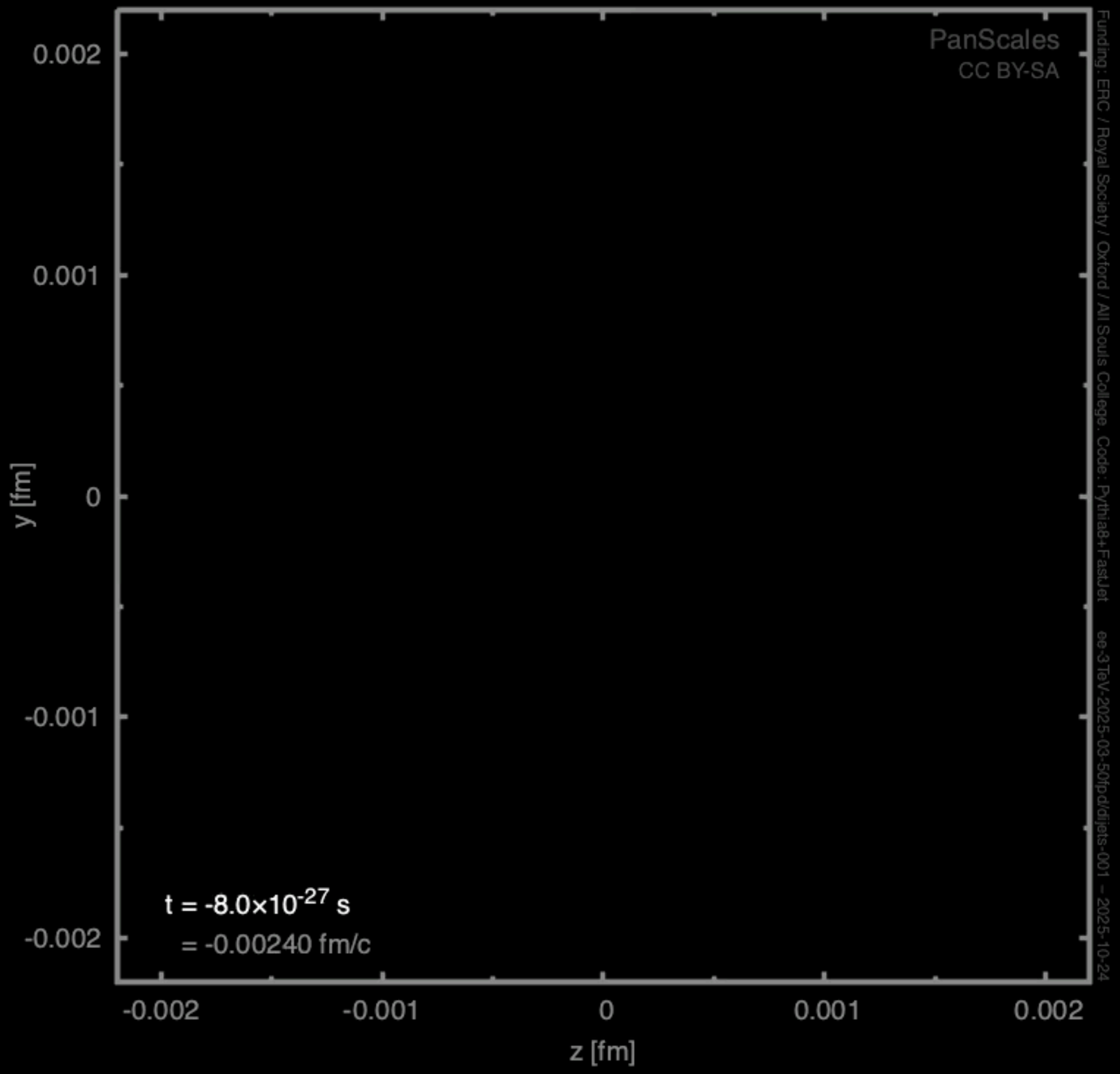


incoming beam particle

intermediate particle (quark or gluon)

final particle (hadron)

Event evolution spans 7 orders of magnitude in space-time



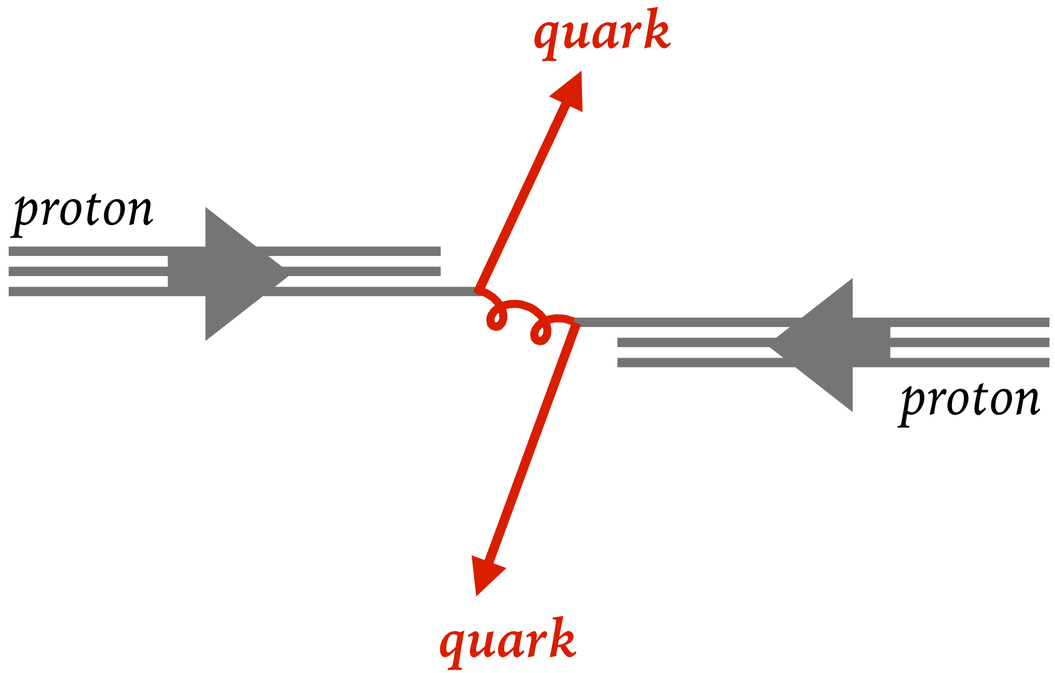
incoming beam particle

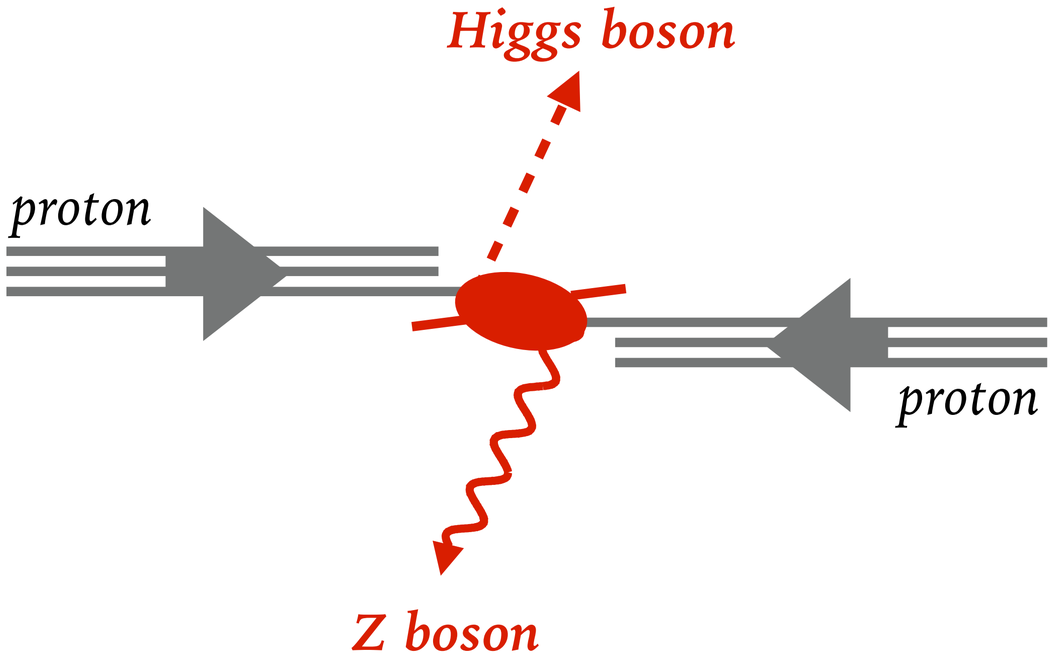
intermediate particle (quark or gluon)

final particle (hadron)

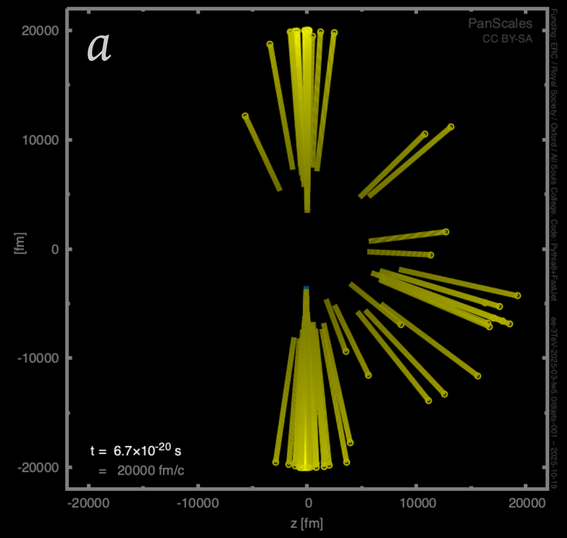
Event evolution spans 7 orders of magnitude in space-time

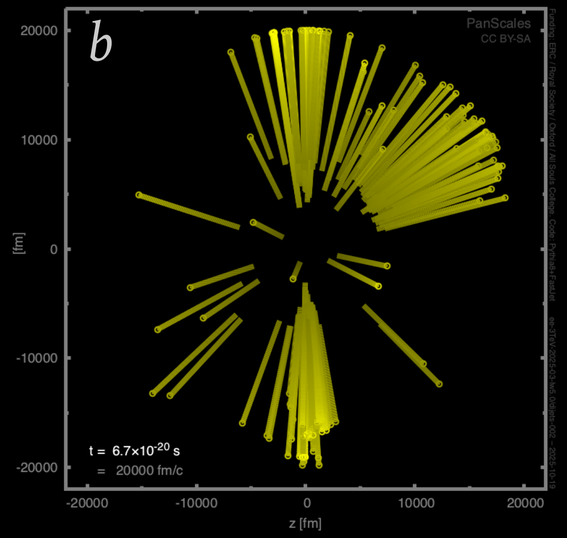
The essence of interpreting collider data (1)

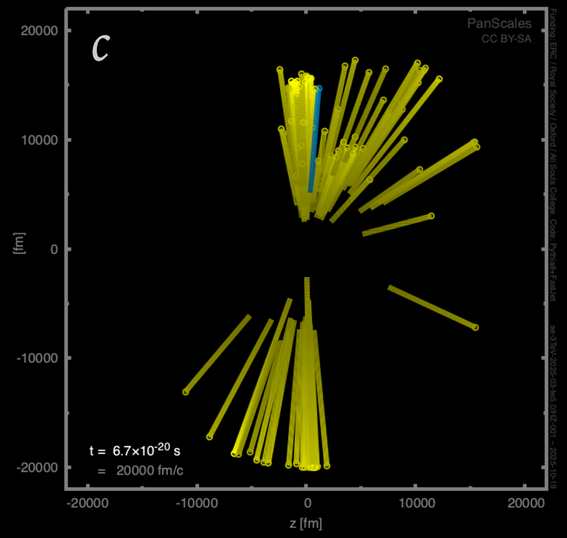


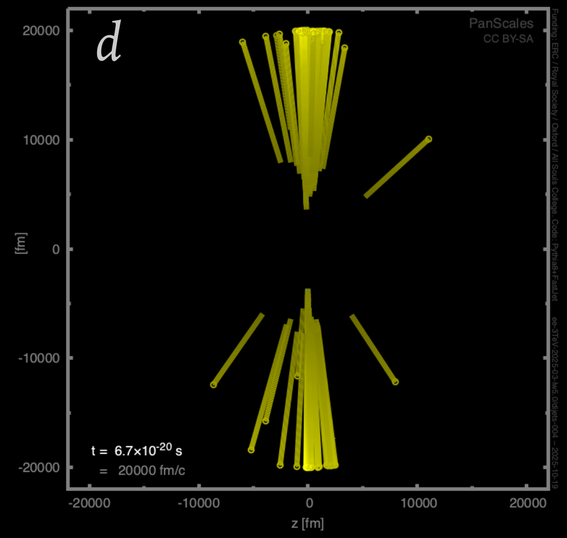


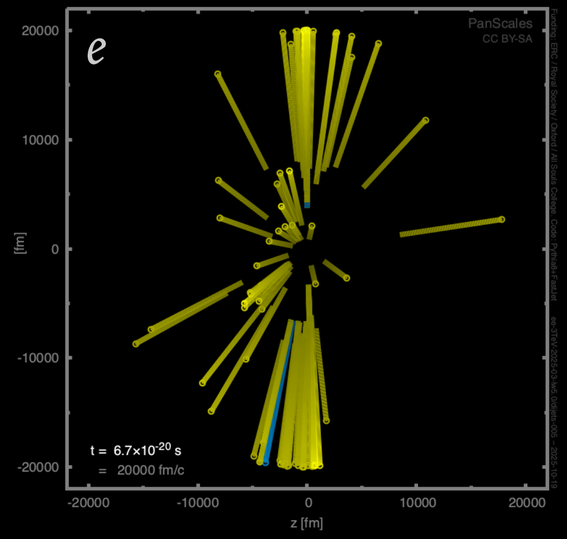
Given hundreds of measured particles from a collision,
which of these two reactions occurred?

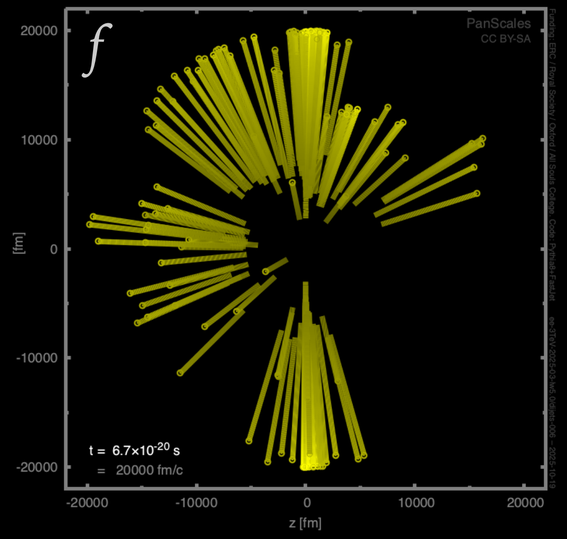

a
PanScales
CC BY-SA
t = 6.7×10^-20 s
= 20000 fm/c
[fm]
z [fm]

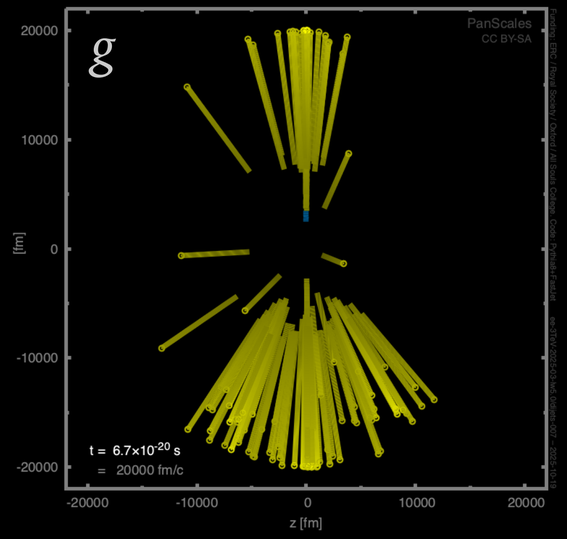

b
PanScales
CC BY-SA
t = 6.7×10^-20 s
= 20000 fm/c
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z [fm]

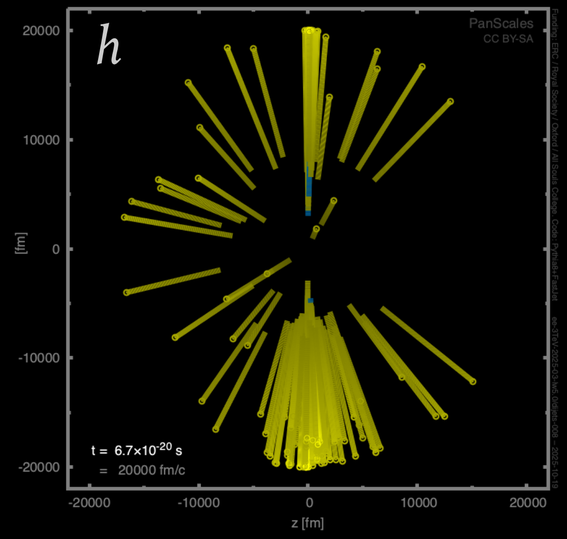

c
PanScales
CC BY-SA
t = 6.7×10^-20 s
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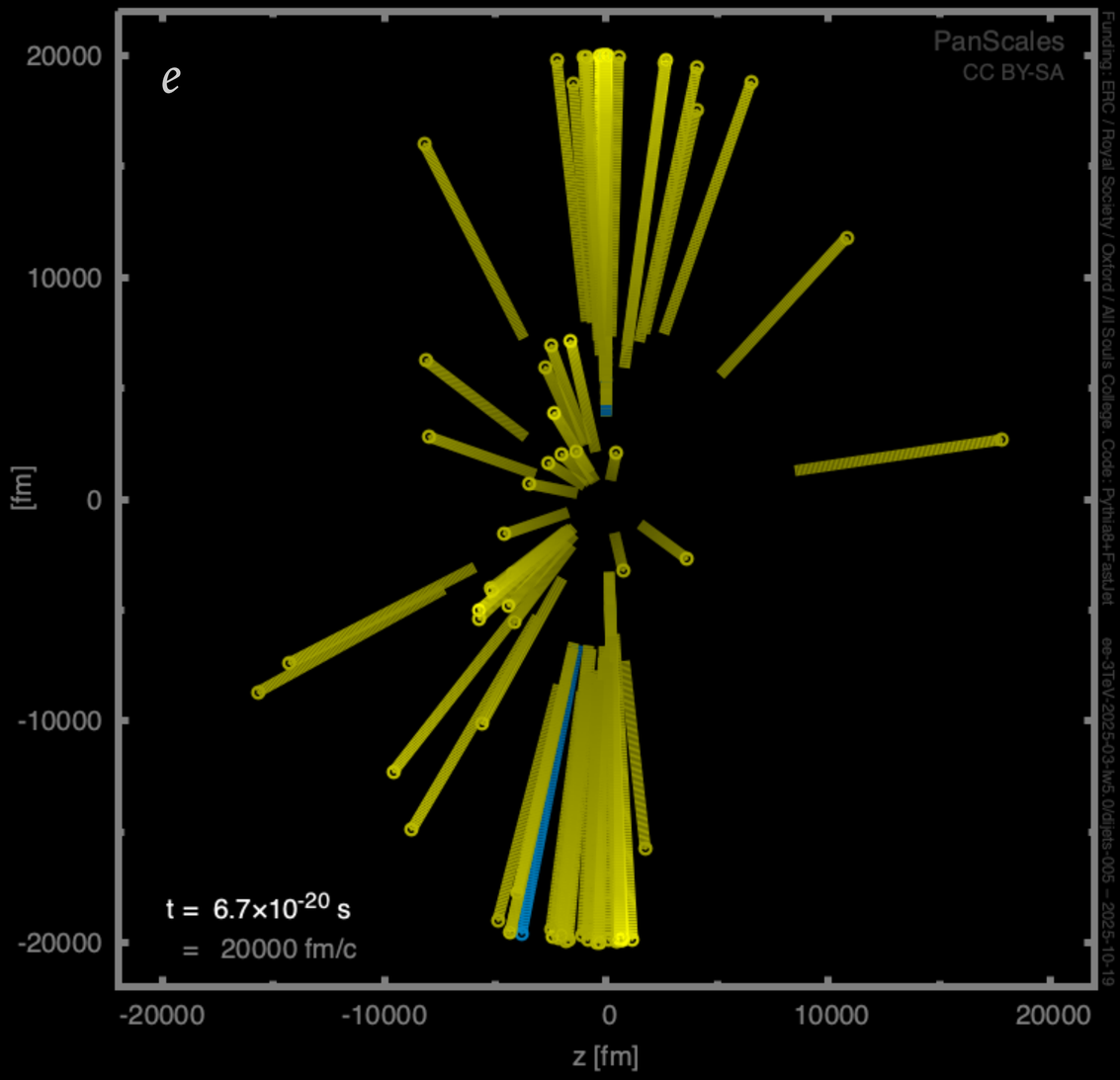

d
PanScales
CC BY-SA
t = 6.7×10^-20 s
= 20000 fm/c
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z [fm]

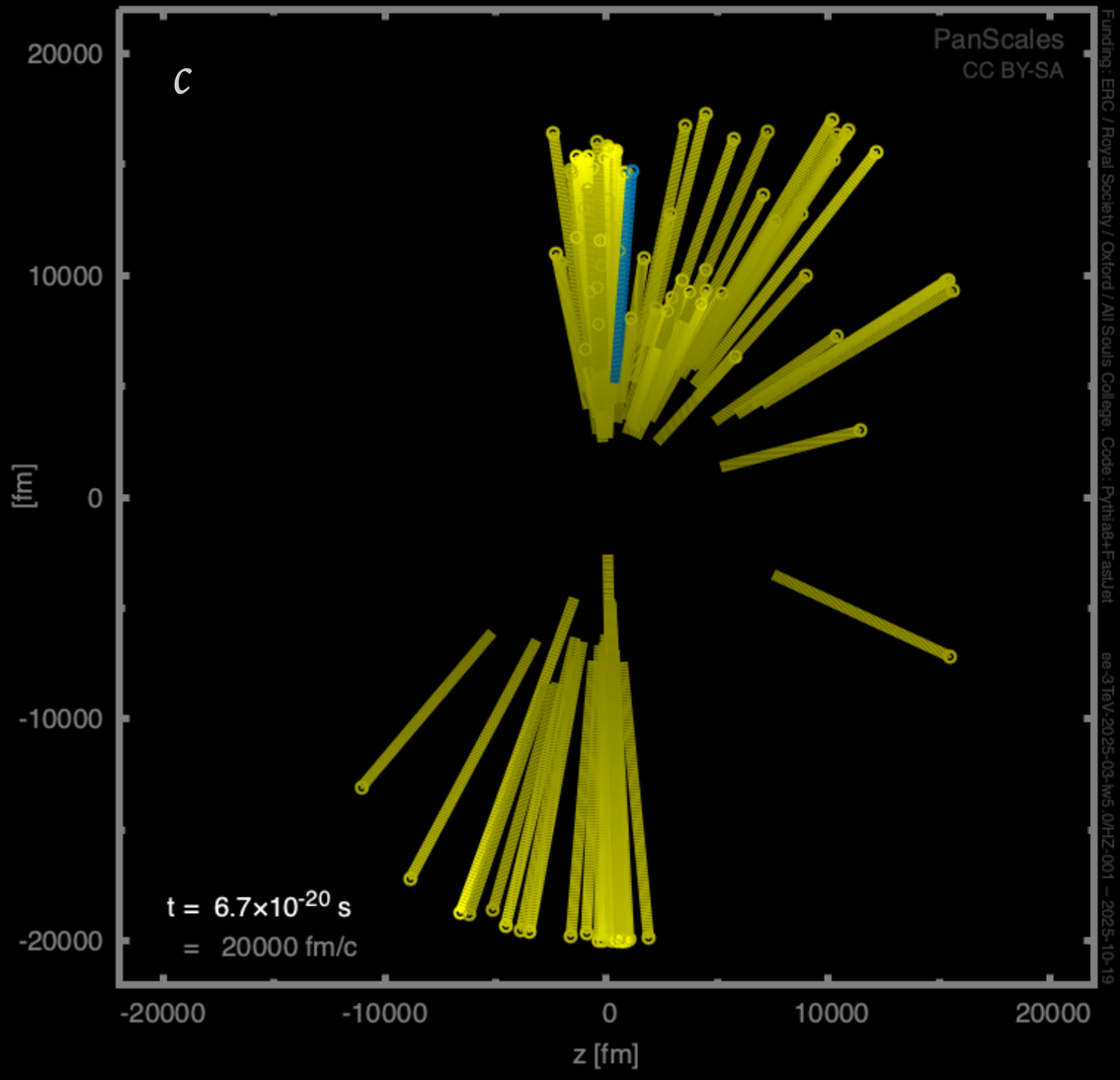

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PanScales
CC BY-SA
t = 6.7×10^-20 s
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z [fm]

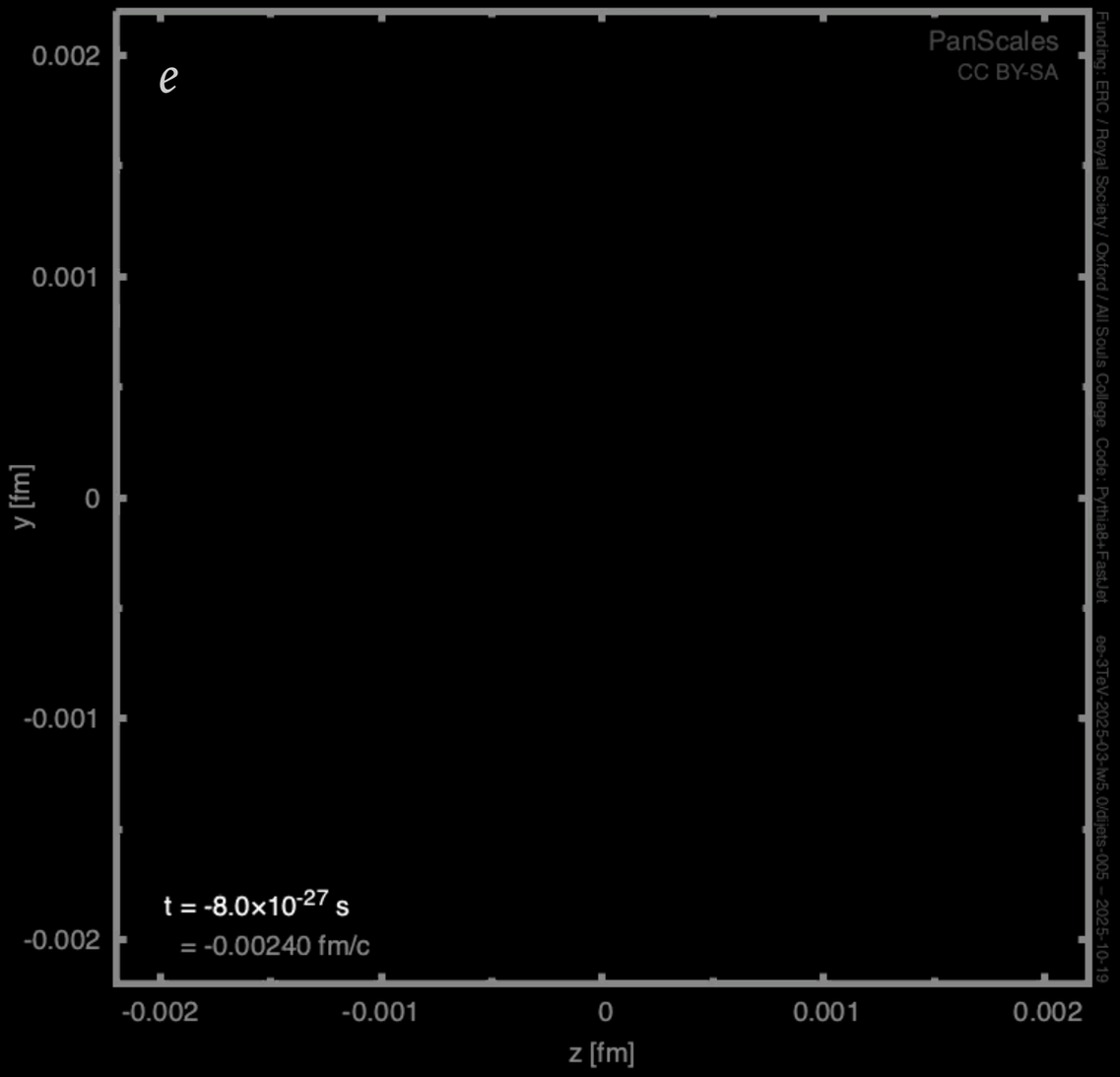

f
PanScales
CC BY-SA
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z [fm]

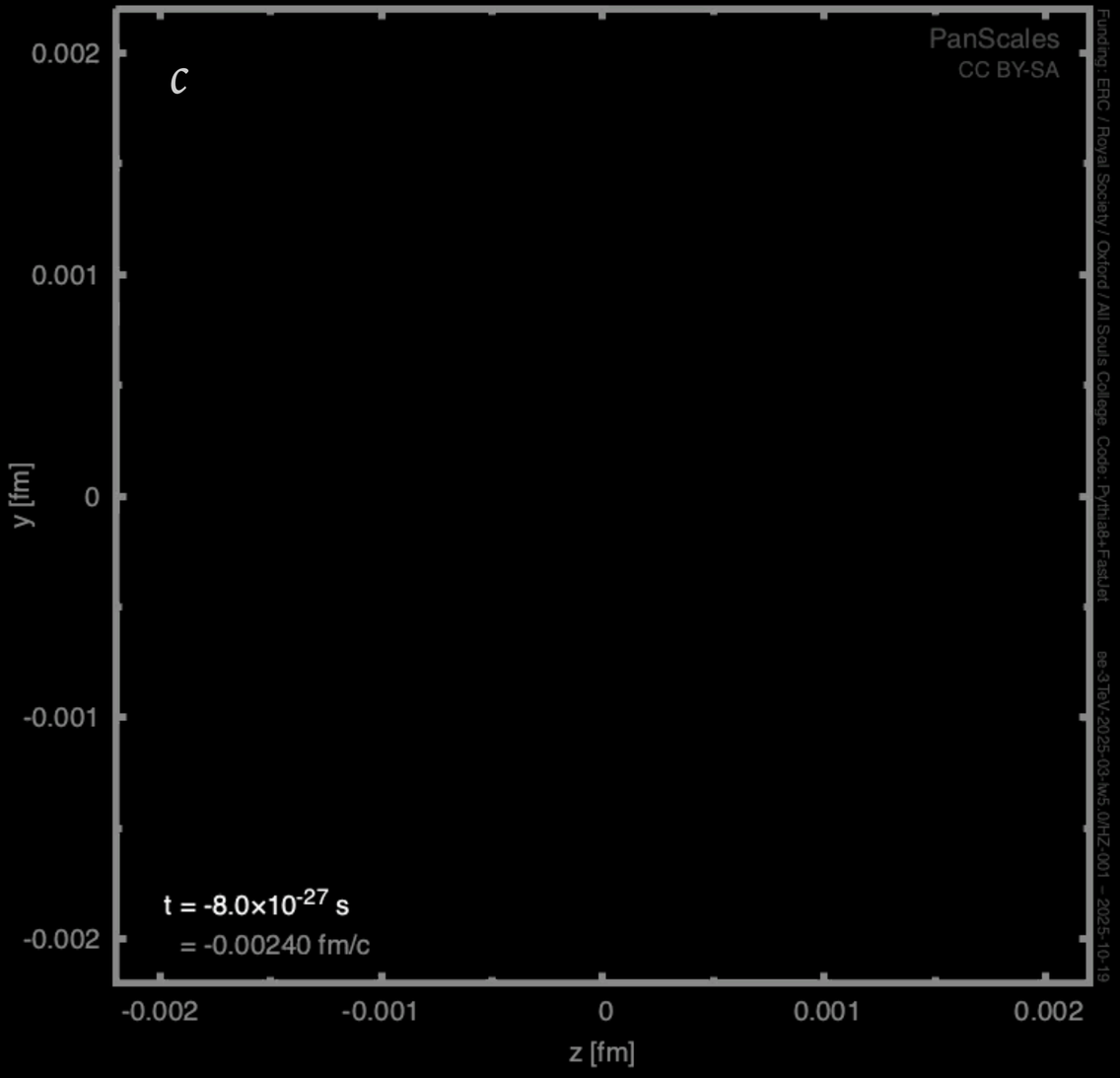

g
PanScales
CC BY-SA
t = 6.7×10^-20 s
= 20000 fm/c
[fm]
z [fm]


h
PanScales
CC BY-SA
t = 6.7×10^-20 s
= 20000 fm/c
[fm]
z [fm]

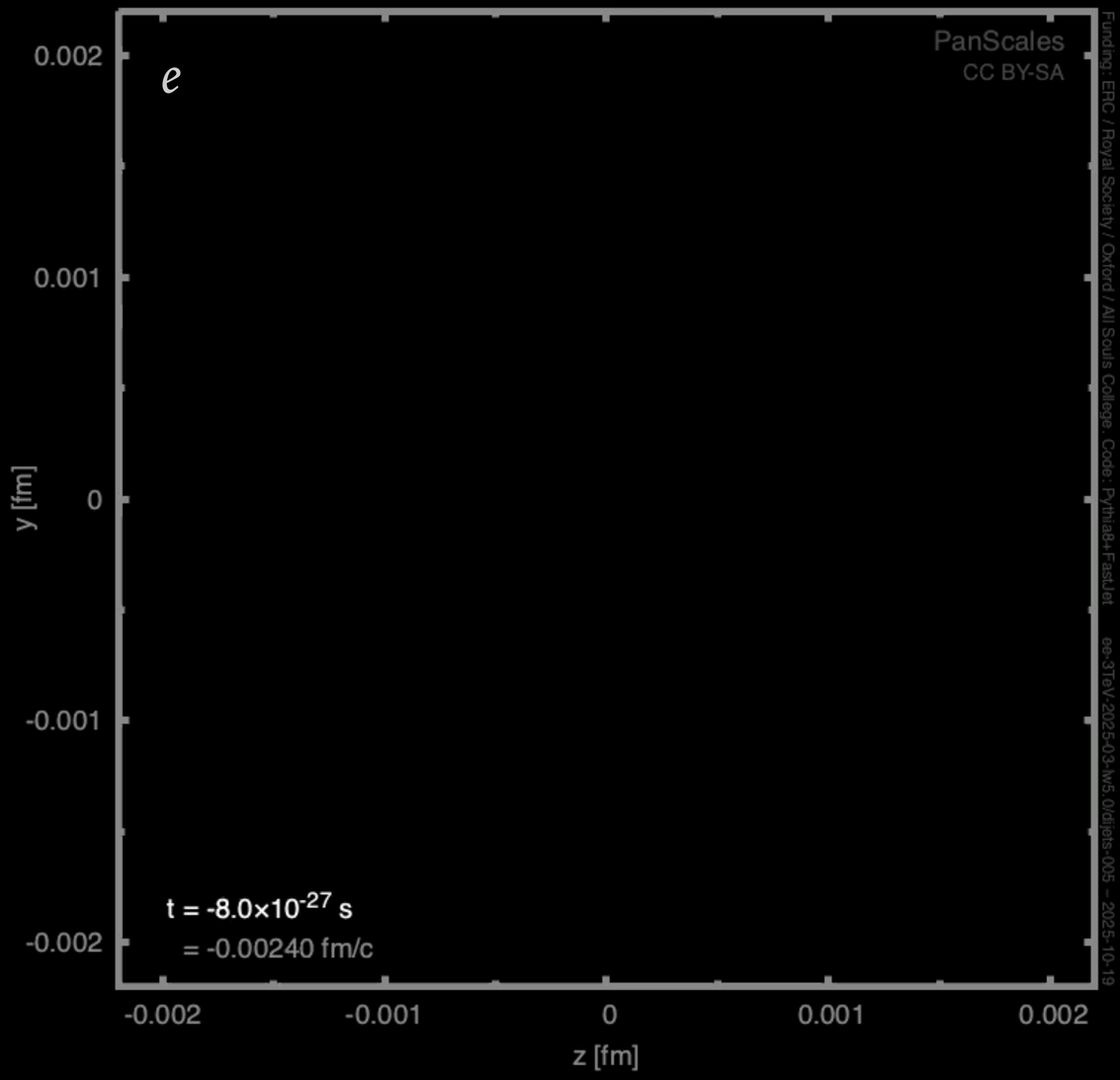

e
PanScales
CC BY-SA
t = 6.7×10^-20 s
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10000
0
-10000
-20000
Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet ee-3TeV-2025-03-lw5.0/djets-005 – 2025-10-19


c
PanScales
CC BY-SA
t = 6.7×10^-20 s
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z [fm]
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10000
0
-10000
-20000
Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet ee-3TeV-2025-03-lw5.0/HZ-001 – 2025-10-19

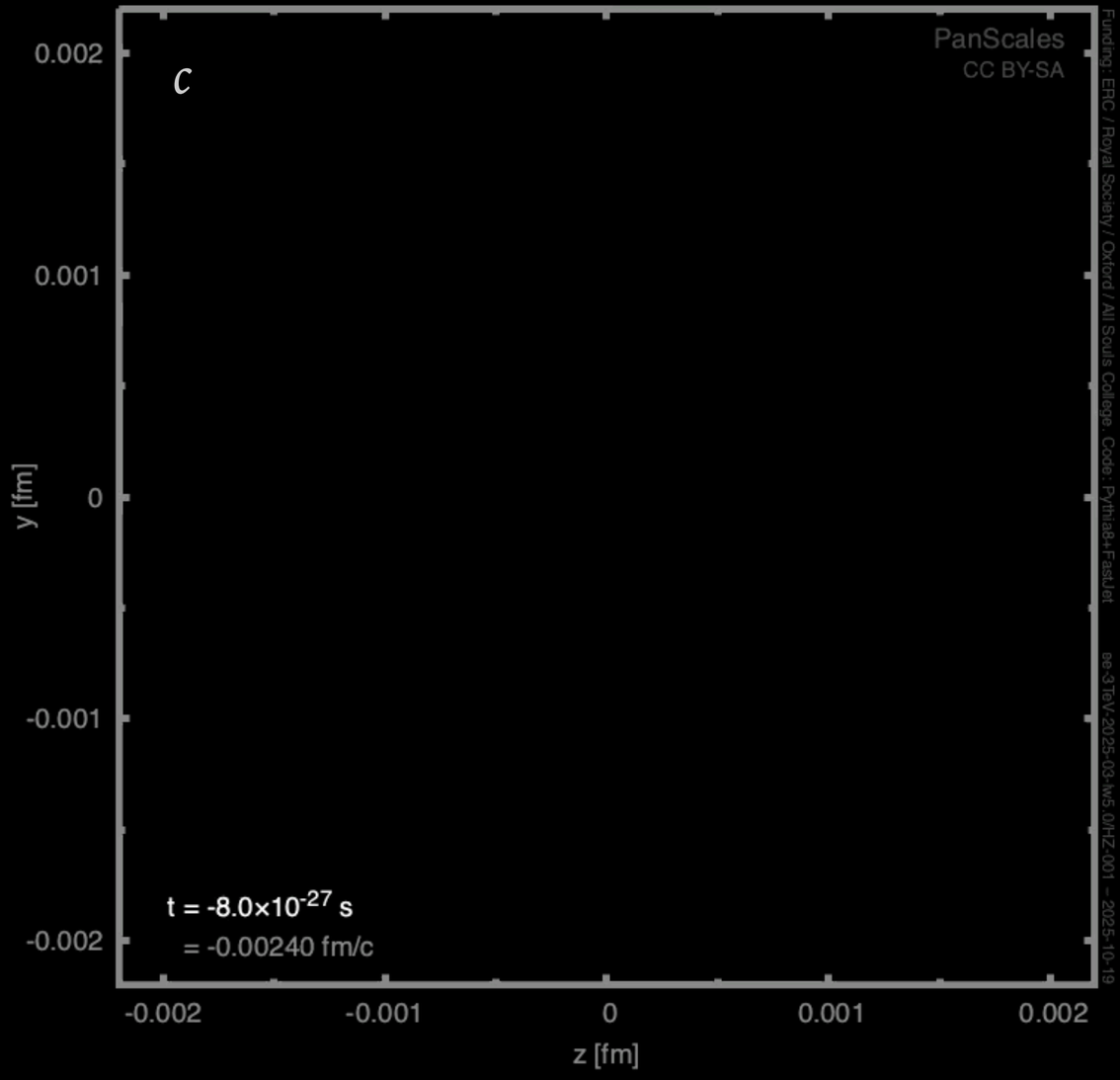

e
PanScales
CC BY-SA
t = -8.0×10^-27 s
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0.002
0.001
0
-0.001
-0.002
y [fm]
-0.002
-0.001
0
0.001
0.002
z [fm]
Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet
ee-3TeV-2025-03-iw5.0/dijets-005 – 2025-10-19


c
PanScales
CC BY-SA
t = -8.0×10^-27 s
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0.002
0.001
0
-0.001
-0.002
y [fm]
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-0.001
0
0.001
0.002
z [fm]
Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet
ee-3TeV-2025-03-iw5.0/HZ-001 – 2025-10-19

pure QCD event

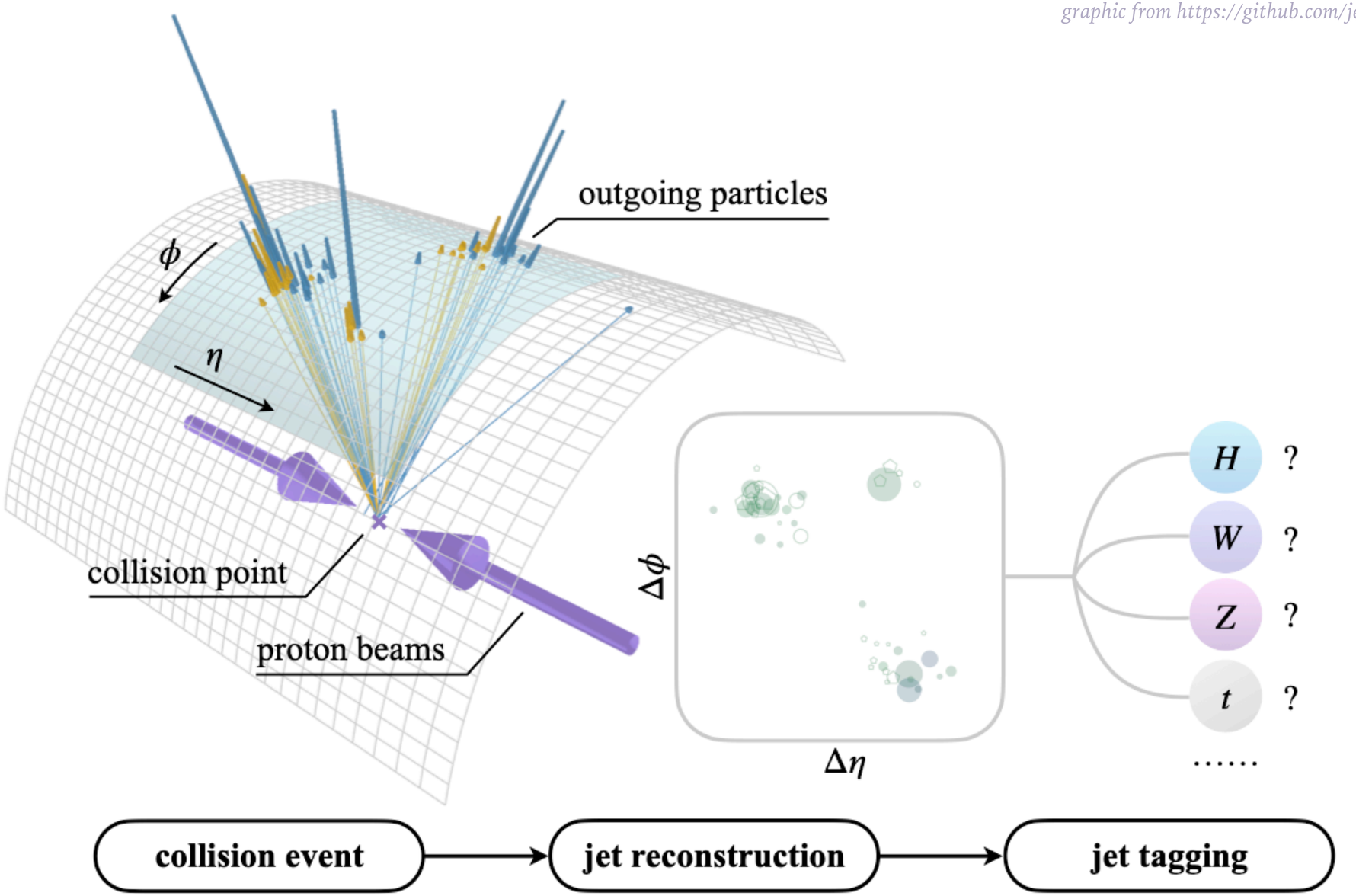


event with Higgs & Z boson decays

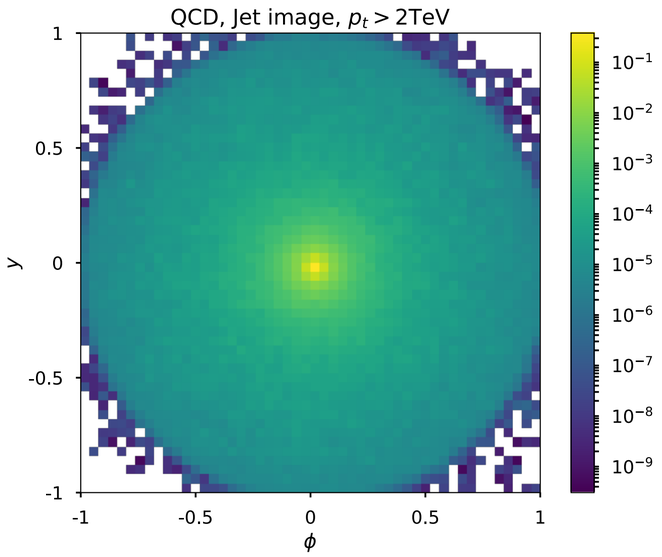


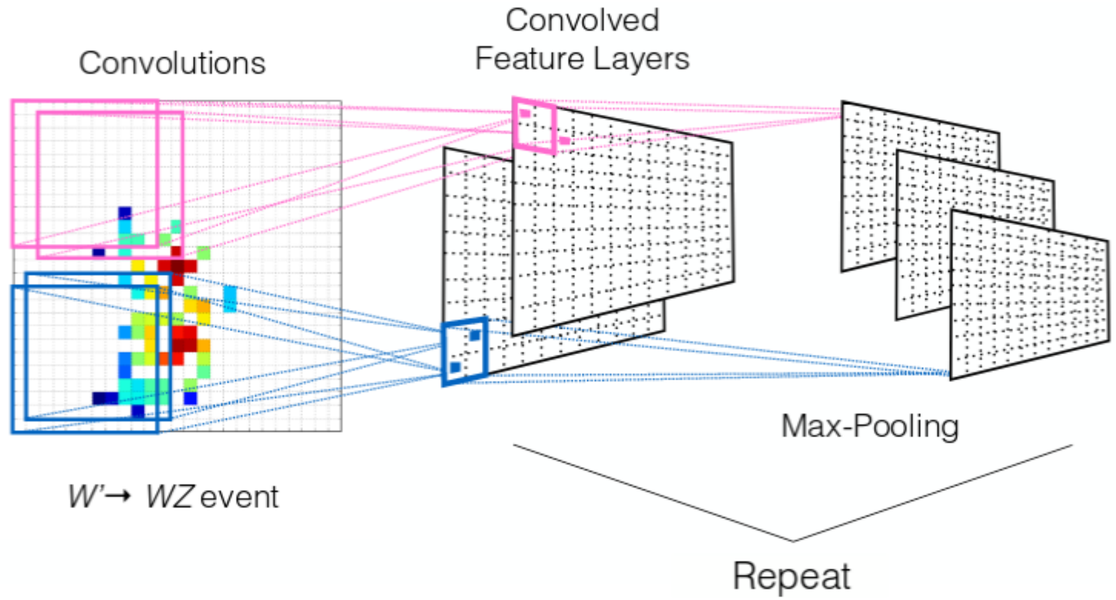
Did the jet of particles come from a quark or a W-boson? → Use machine learning

graphic from https://github.com/jet-universe/particle_transformer



Did the jet of particles come from a quark or a W-boson? → Use machine learning



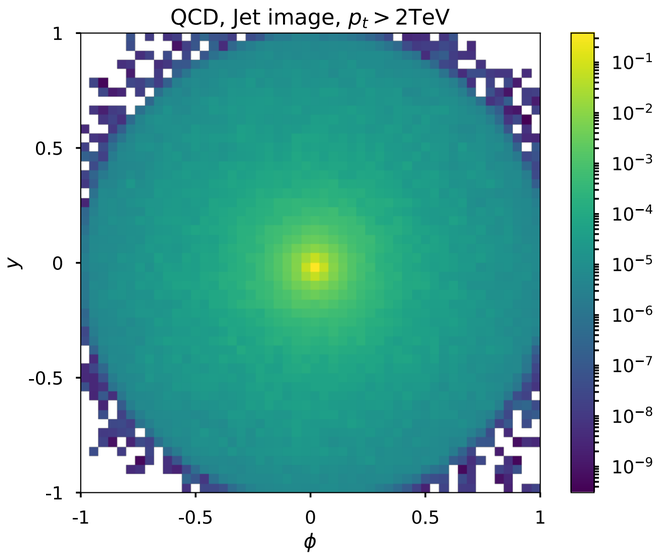


2021 Young Experimental Physicist
EPS HEPP prize

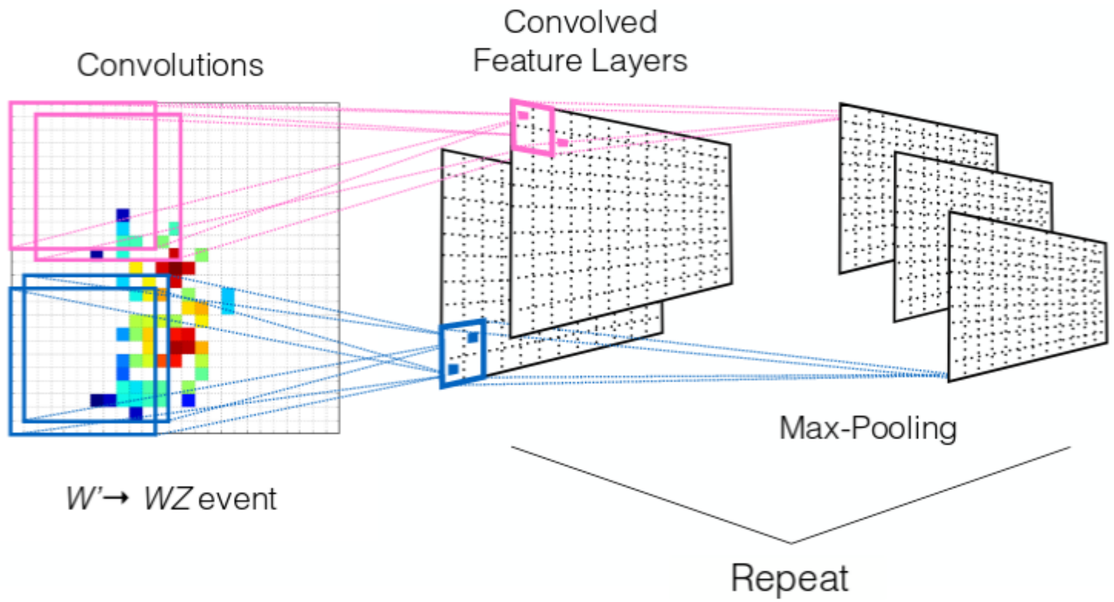
[Cogan, Kagan, Strauss, Schwartzman JHEP 1502 (2015) 118]

[de Oliveira, Kagan, Mackey, Nachman, Schwartzman JHEP 1607 (2016) 069]

Did the jet of particles come from a quark or a W-boson? → Use machine learning

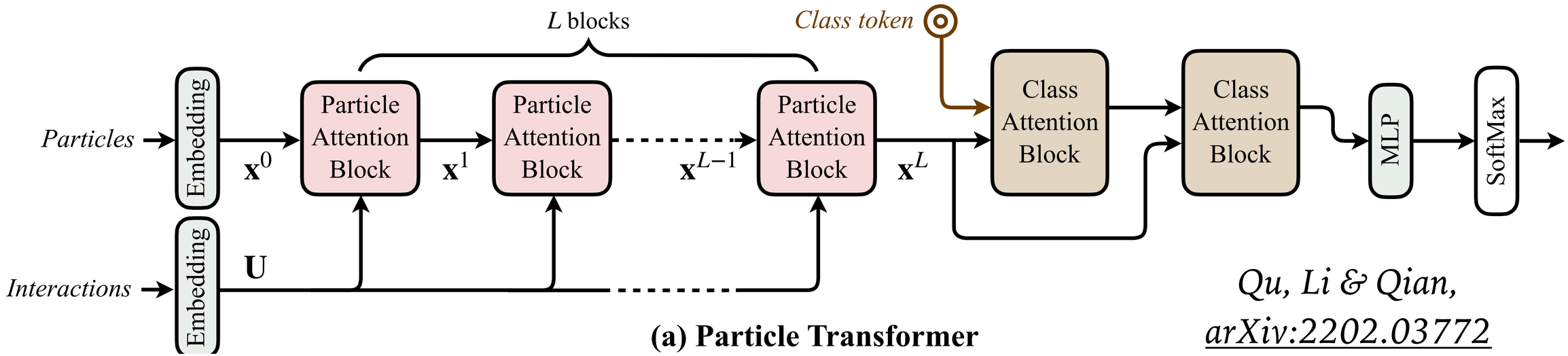


2021 Young Experimental Physicist
EPS HEPP prize



[Cogan, Kagan, Strauss, Schwartzman JHEP 1502 (2015) 118]

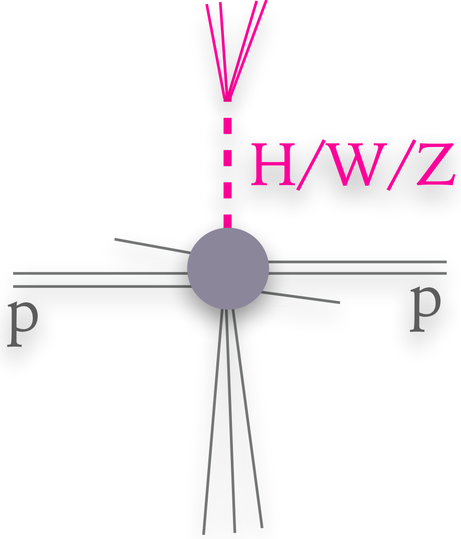
[de Oliveira, Kagan, Mackey, Nachman, Schwartzman JHEP 1607 (2016) 069]

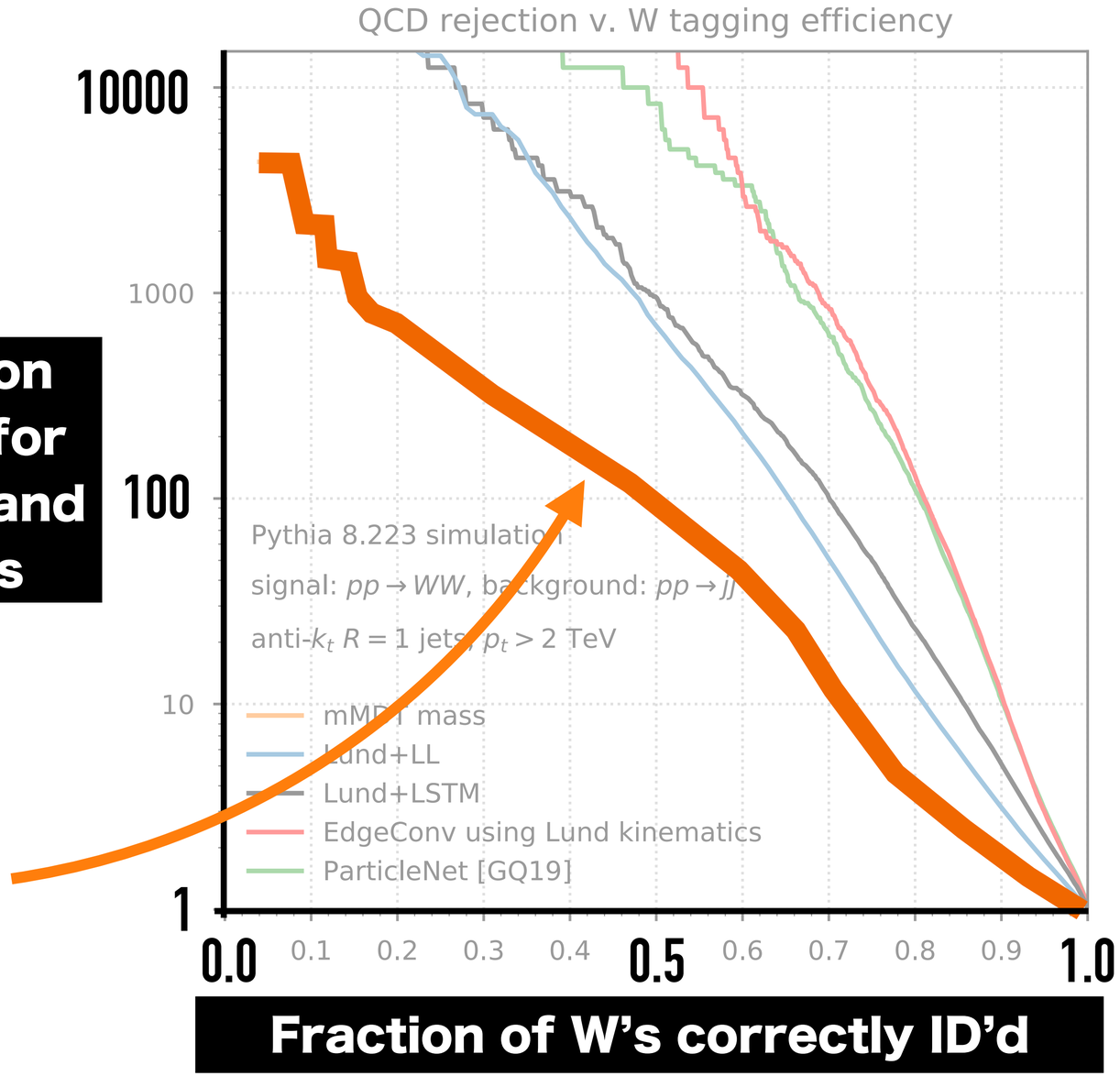


Qu, Li & Qian,
arXiv:2202.03772

using full jet/event information for H/W/Z-boson tagging

adapted from Dreyer & Qu 2012.08526

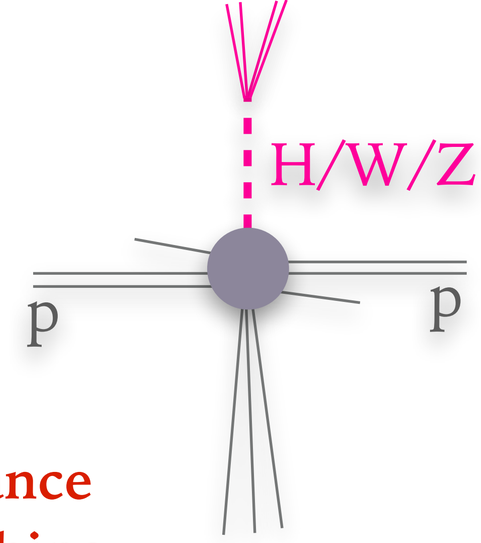


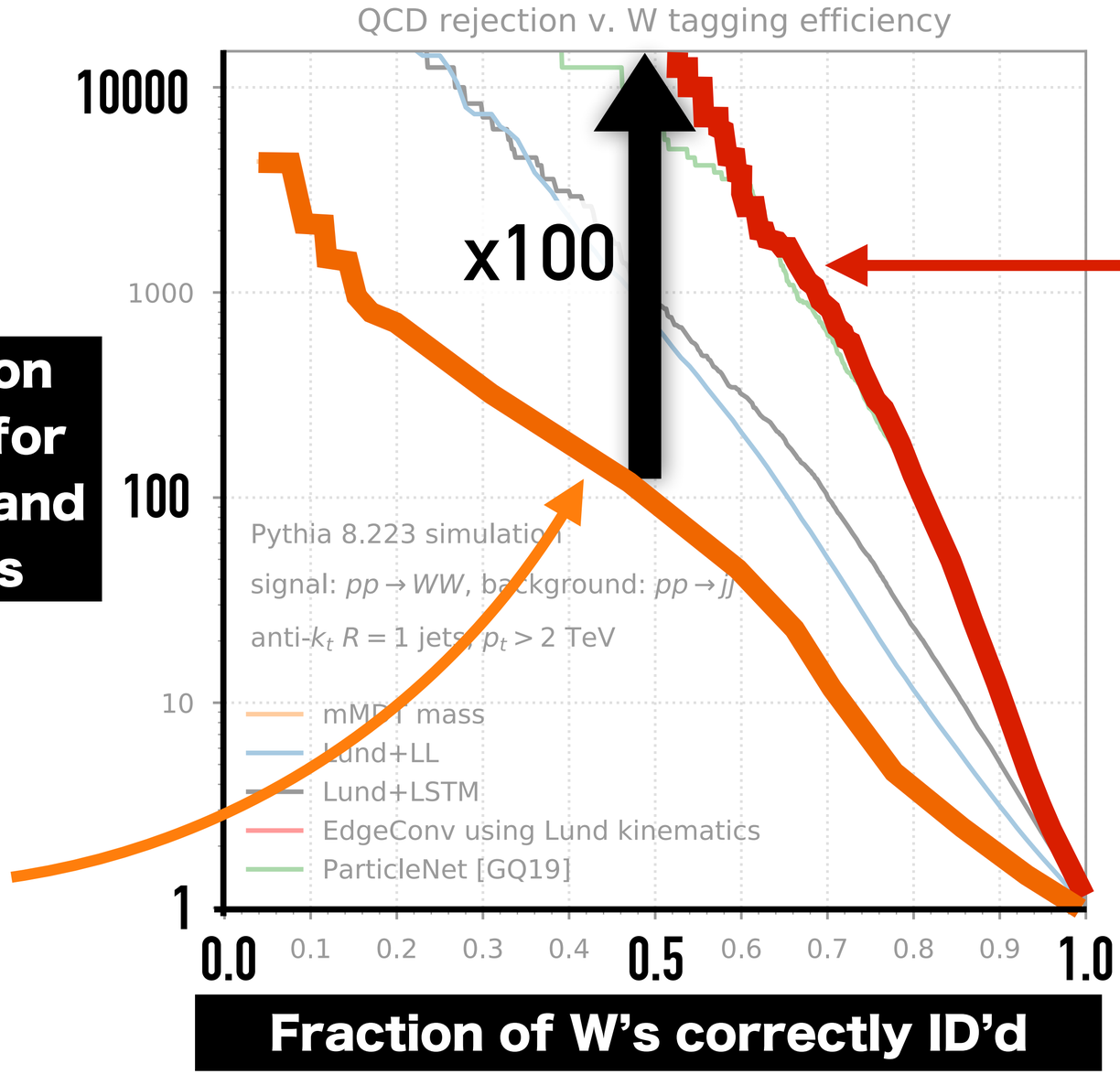


Tools that look just for 2-prong decay W → quark + anti-quark

using full jet/event information for H/W/Z–boson tagging

adapted from Dreyer & Qu 2012.08526





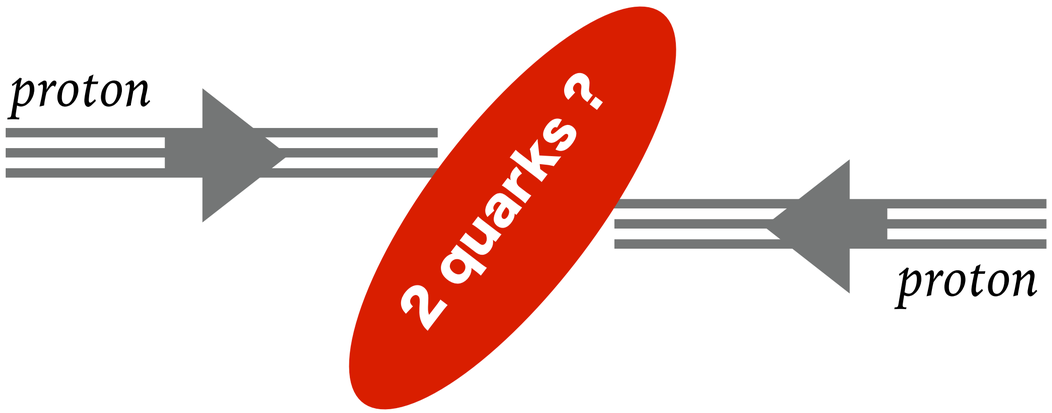
rejection factor for quarks and gluons

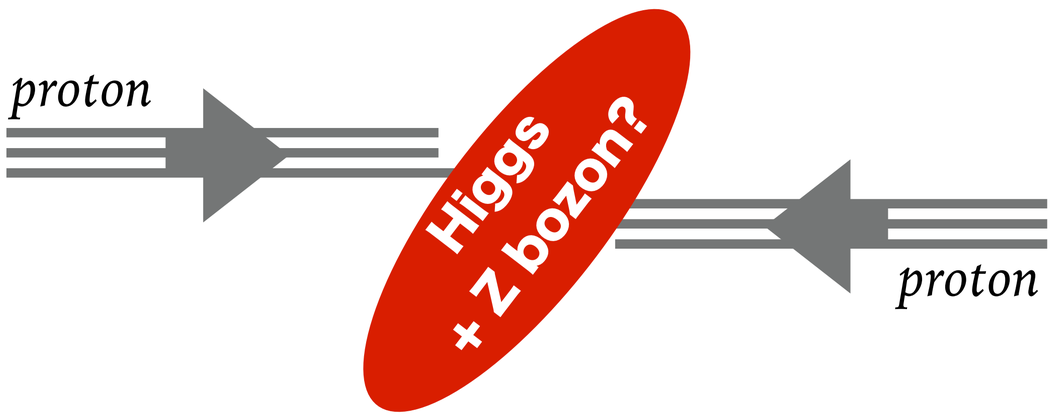
Performance with machine learning, using all jet particles (2021 tools)

100x better

Tools that look just for 2-prong decay W → quark + anti-quark

The essence of interpreting collider data (2)





Collider physics is **quantitative**.

To test a hypothesis (e.g. Standard Model), you ask:

How many Higgs bosons will be produced?

How many of those will be correctly identified?

→ compare that expectation to data

The paradigm: Feynman diagrams and perturbation theory

Nobel Prize in Physics 1965

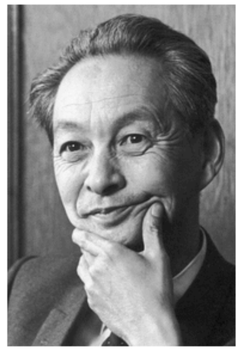


Photo from the Nobel Foundation archive.
Sin-Itiro Tomonaga
Prize share: 1/3



Photo from the Nobel Foundation archive.
Julian Schwinger
Prize share: 1/3



Photo from the Nobel Foundation archive.
Richard P. Feynman
Prize share: 1/3

The Nobel Prize in Physics 1965 was awarded jointly to Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman "for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"

Nobel Prize in Physics 1999

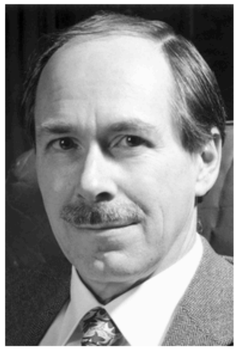


Photo from the Nobel Foundation archive.
Gerardus 't Hooft
Prize share: 1/2

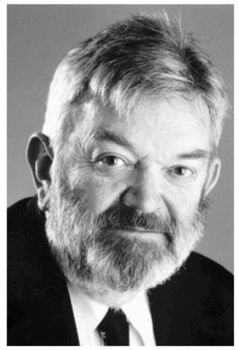


Photo from the Nobel Foundation archive.
Martinus J.G. Veltman
Prize share: 1/2

The Nobel Prize in Physics 1999 was awarded jointly to Gerardus 't Hooft and Martinus J.G. Veltman "for elucidating the quantum structure of electroweak interactions in physics"

Nobel Prize in Physics 2004

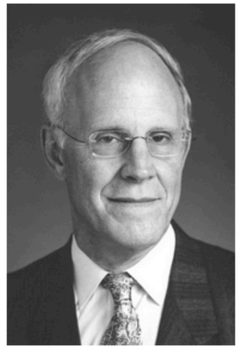


Photo from the Nobel Foundation archive.
David J. Gross
Prize share: 1/3



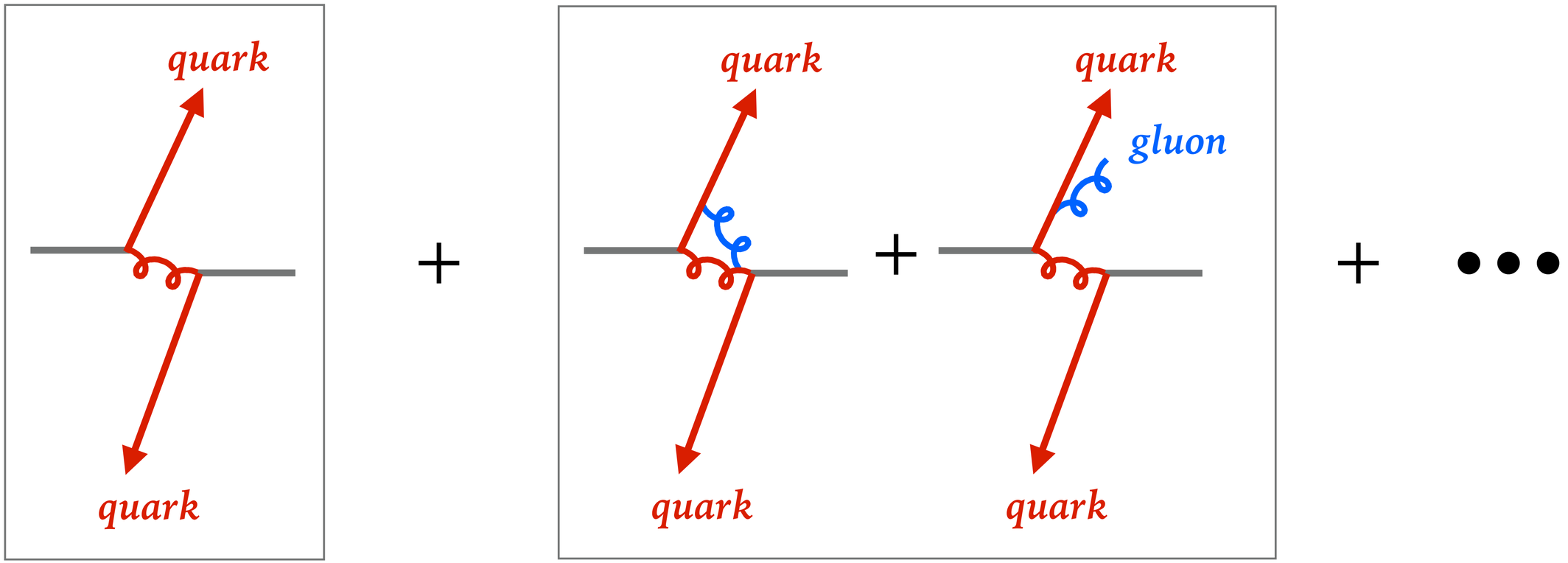
Photo from the Nobel Foundation archive.
H. David Politzer
Prize share: 1/3



Photo from the Nobel Foundation archive.
Frank Wilczek
Prize share: 1/3

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek "for the discovery of asymptotic freedom in the theory of the strong interaction"

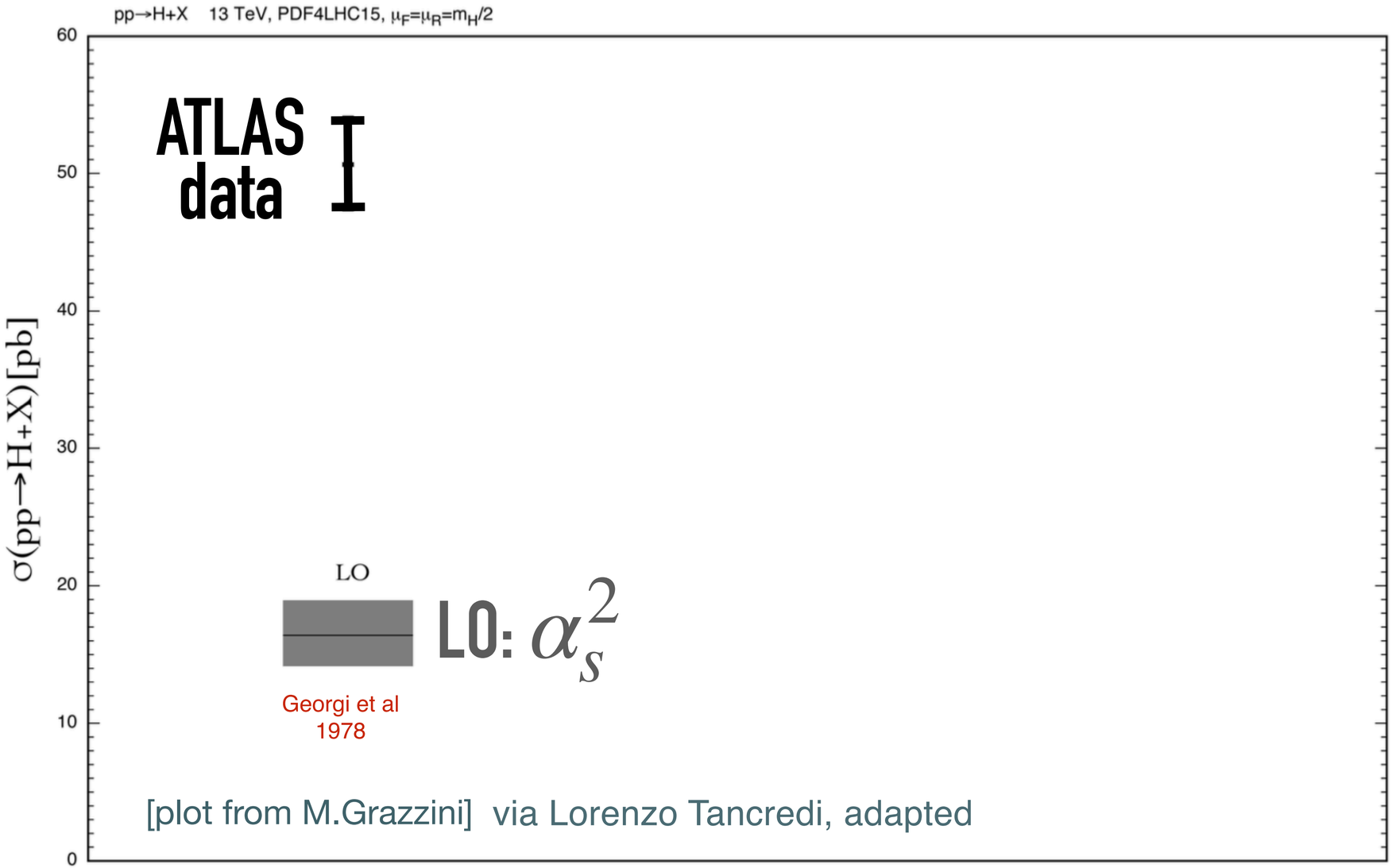
The standard paradigm: Feynman diagrams and perturbation theory



leading order

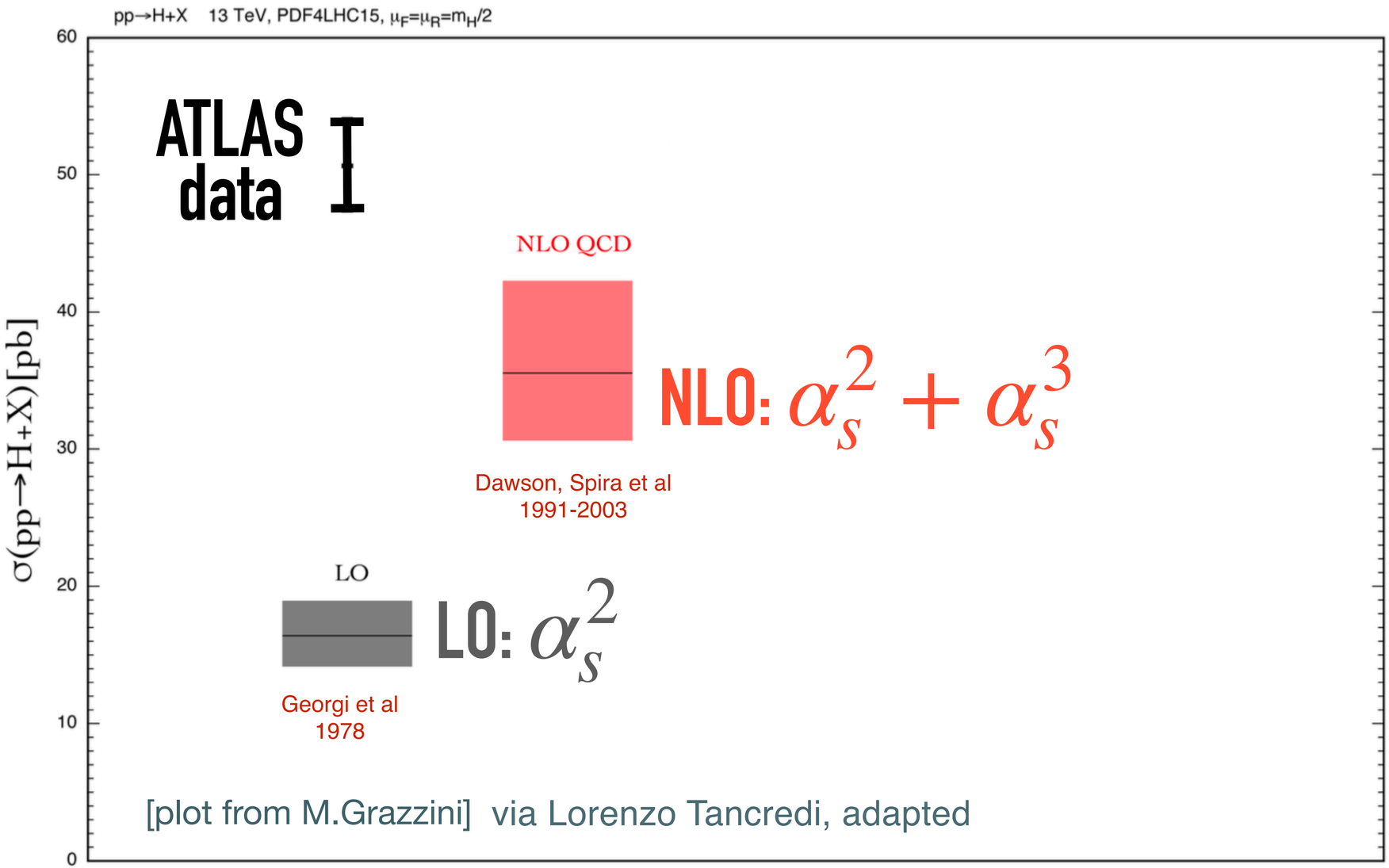
next-to-leading order

Higgs Boson Cross Section



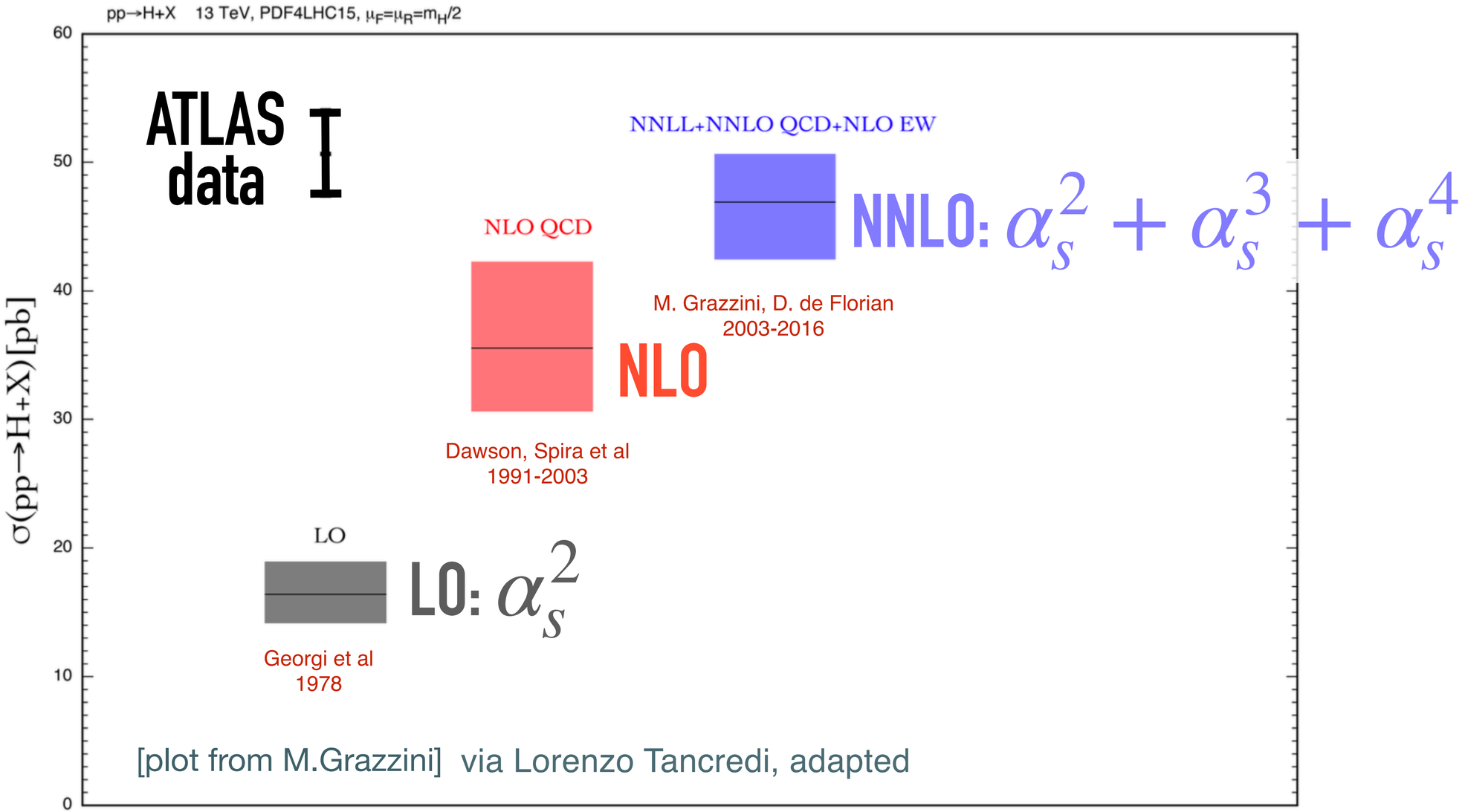
[plot from M.Grazzini] via Lorenzo Tancredi, adapted

Higgs Boson Cross Section



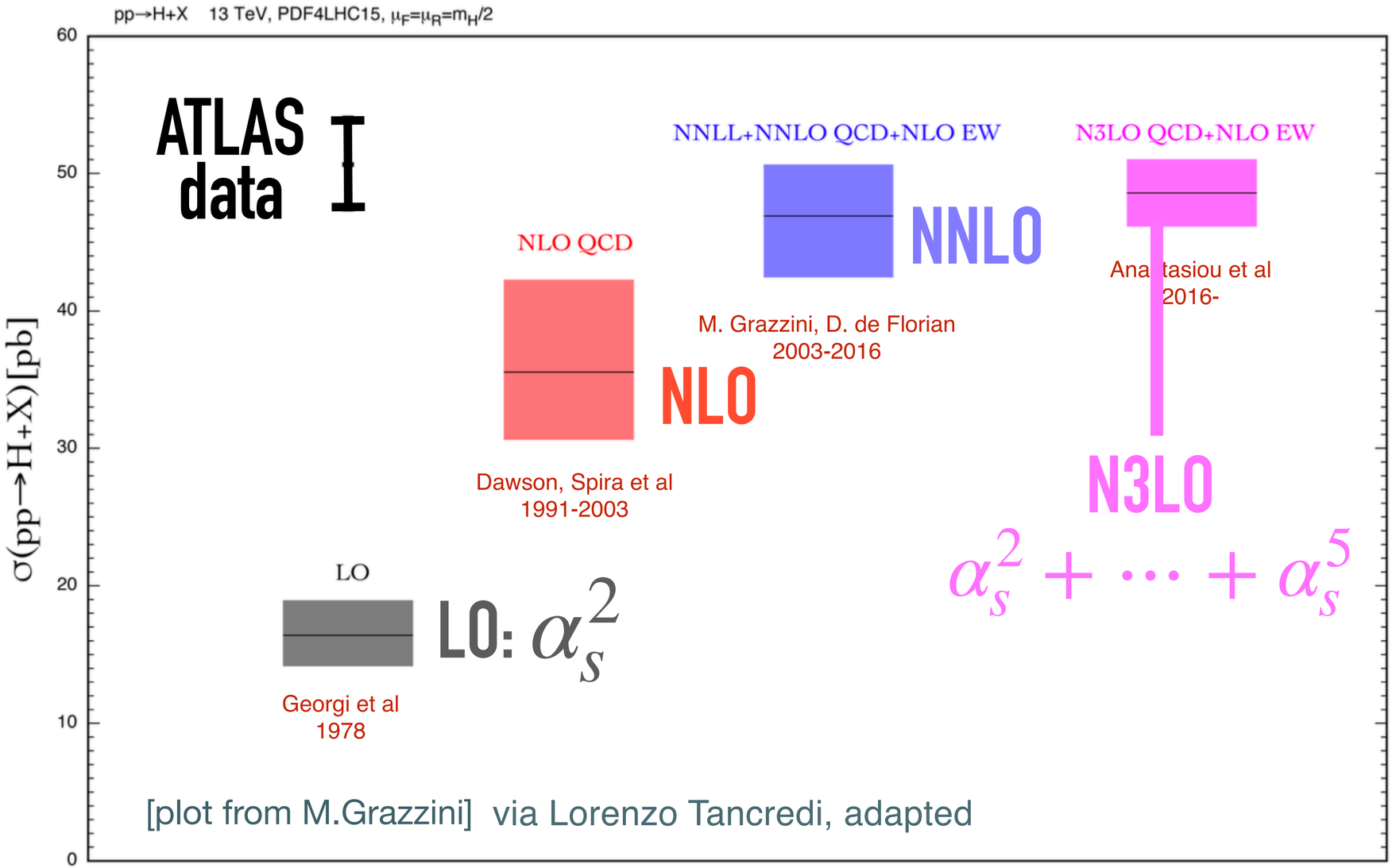
[plot from M.Grazzini] via Lorenzo Tancredi, adapted

Higgs Boson Cross Section



[plot from M.Grazzini] via Lorenzo Tancredi, adapted

Higgs Boson Cross Section



[plot from M.Grazzini] via Lorenzo Tancredi, adapted

from Juan Cruz Martinez's talk

The NNLO ~~revolution~~ standard

NLO is a solved (automated) problem. NNLO not so much, but many calculations are already available

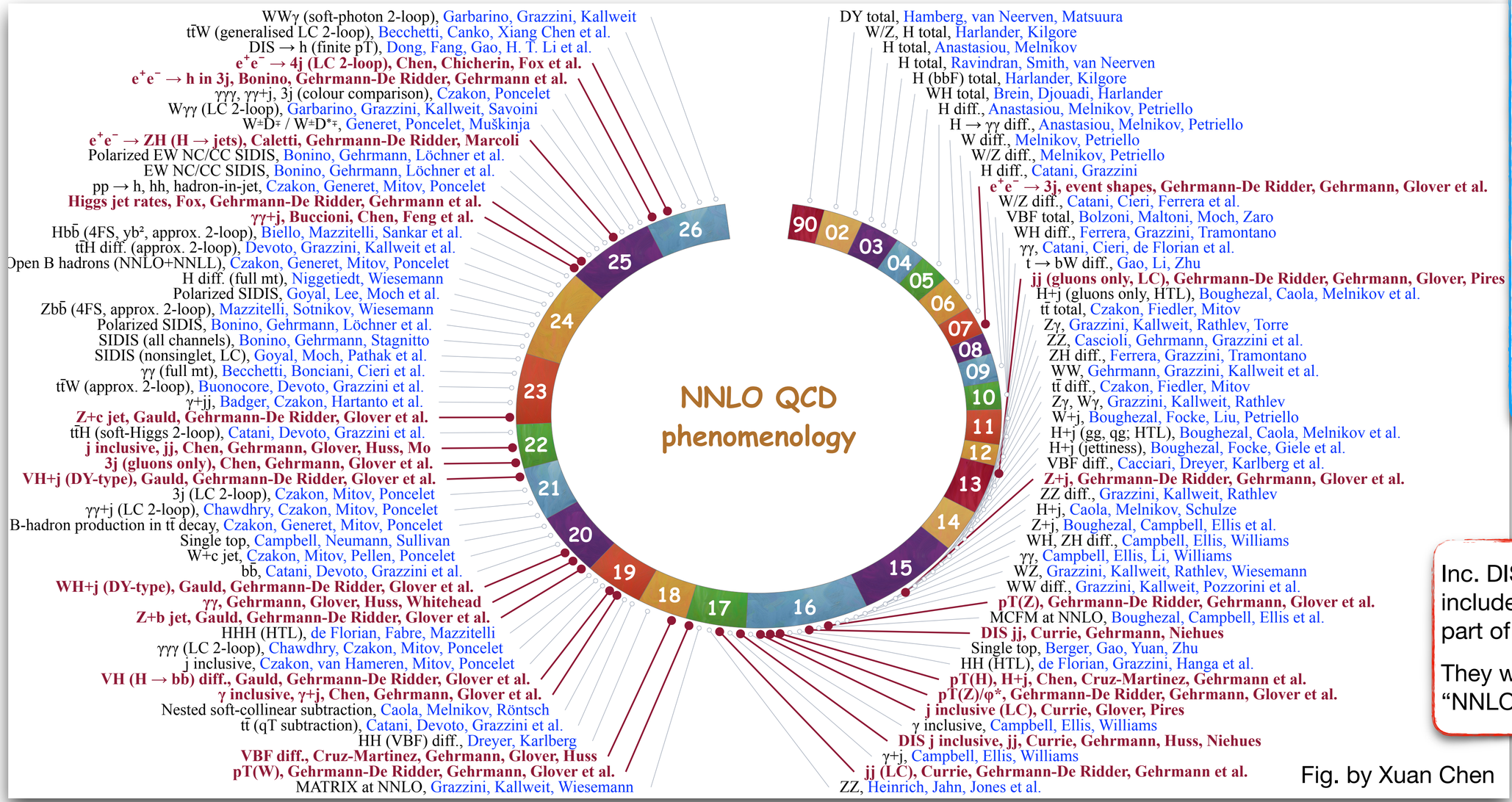


Fig. by Xuan Chen

Many of these are nowadays included in NNLO PDF fits for:

- DY (NC & CC)
- V + jet
- TTBAR
- Single Top
- Jets and dijets
- Prompt photon

Inc. DIS and DGLAP evolution not included in this list, but known (and part of PDF fits) since a long time.

They were the true driver of the "NNLO" label in PDFs.

from Juan Cruz Martinez's talk

The NNLO ~~revolution~~ standard

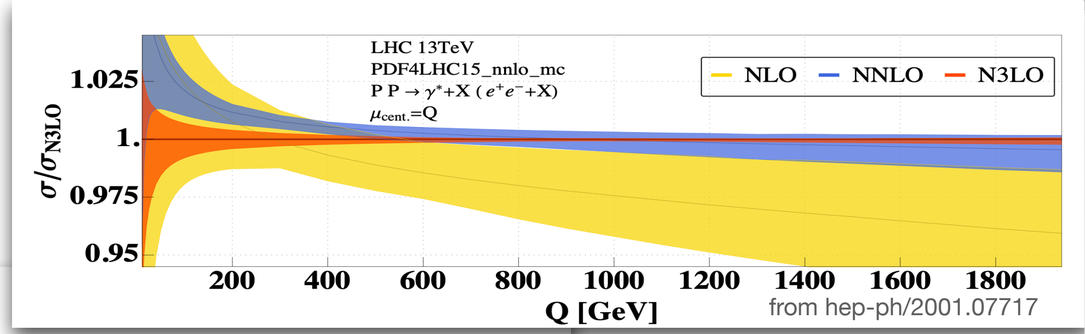
NLO is a solved (automated) problem. NNLO not so much, but many calculations are already available

WWγ (soft-photon 2-loop), Garbarino, Grazzini, Kallweit
ttW (generalised LC 2-loop), Becchetti, Canko, Xiang Chen et al.
DIS → h (finite pT), Dong
$e^+e^- \to 4j$ (LC 2-loop), C
$e^+e^- \to h$ in 3j, Bonino, Gehrmann-De R
γγγ, γγ+j, 3j (colour comparis
Wγγ (LC 2-loop), Garbarino, Grazzi
$W^\pm D^\mp$ / $W^\pm D^{*\mp}$, Generet, I
$e^+e^- \to ZH$ (H → jets), Caletti, Gehrmann-De
Polarized EW NC/CC SIDIS, Bonino, Gehrmann,
EW NC/CC SIDIS, Bonino, Gehrmann, I
pp → h, hh, hadron-in-jet, Czakon, Generet, Mit
Higgs jet rates, Fox, Gehrmann-De Ridder, Gehr
γγ+j, Buccioni, Chen, F
Hbb̄ (4FS, yb², approx. 2-loop), Biello, Mazzitelli, Sanl
ttH diff. (approx. 2-loop), Devoto, Grazzini, Kallwe
Open B hadrons (NNLO+NNLL), Czakon, Generet, Mitov, Po
H diff. (full mt), Niggetiedt, Wiese
Polarized SIDIS, Goyal, Lee, Moch
Zbb̄ (4FS, approx. 2-loop), Mazzitelli, Sotnikov, Wiesem
Polarized SIDIS, Bonino, Gehrmann, Löchner e
SIDIS (all channels), Bonino, Gehrmann, Stagn
SIDIS (nonsinglet, LC), Goyal, Moch, Pathak et
γγ (full mt), Becchetti, Bonciani, Cieri et
ttW (approx. 2-loop), Buonocore, Devoto, Grazzini et
γ+jj, Badger, Czakon, Hartanto et
Z+c jet, Gauld, Gehrmann-De Ridder, Glover et
ttH (soft-Higgs 2-loop), Catani, Devoto, Grazzini et
j inclusive, jj, Chen, Gehrmann, Glover, Huss,
3j (gluons only), Chen, Gehrmann, Glover e
VH+j (DY-type), Gauld, Gehrmann-De Ridder, Glover e
3j (LC 2-loop), Czakon, Mitov, Ponc
γγ+j (LC 2-loop), Chawdhry, Czakon, Mitov, Pon
B-hadron production in tt̄ decay, Czakon, Generet, Mitov, Por
Single top, Campbell, Neumann, St
W+c jet, Czakon, Mitov, Pellen, P
bb̄, Catani, Devoto, Grazz
WH+j (DY-type), Gauld, Gehrmann-De Ridder, Gl
γγ, Gehrmann, Glover, Huss,
Z+b jet, Gauld, Gehrmann-De Ridder,
HHH (HTL), de Florian, Fab
γγγ (LC 2-loop), Chawdhry, Czakon, M
j inclusive, Czakon, van Hameren,
VH (H → bb) diff., Gauld, Gehrmann-De Ri
γ inclusive, γ+j, Chen, Gehr
Nested soft-collinear subtraction, Caol
tt̄ (qT subtraction), Catani
HH (VE
VBF diff., Cruz-Martine
pT(W), Gehrmann-De Ri
MATRIX at NNL

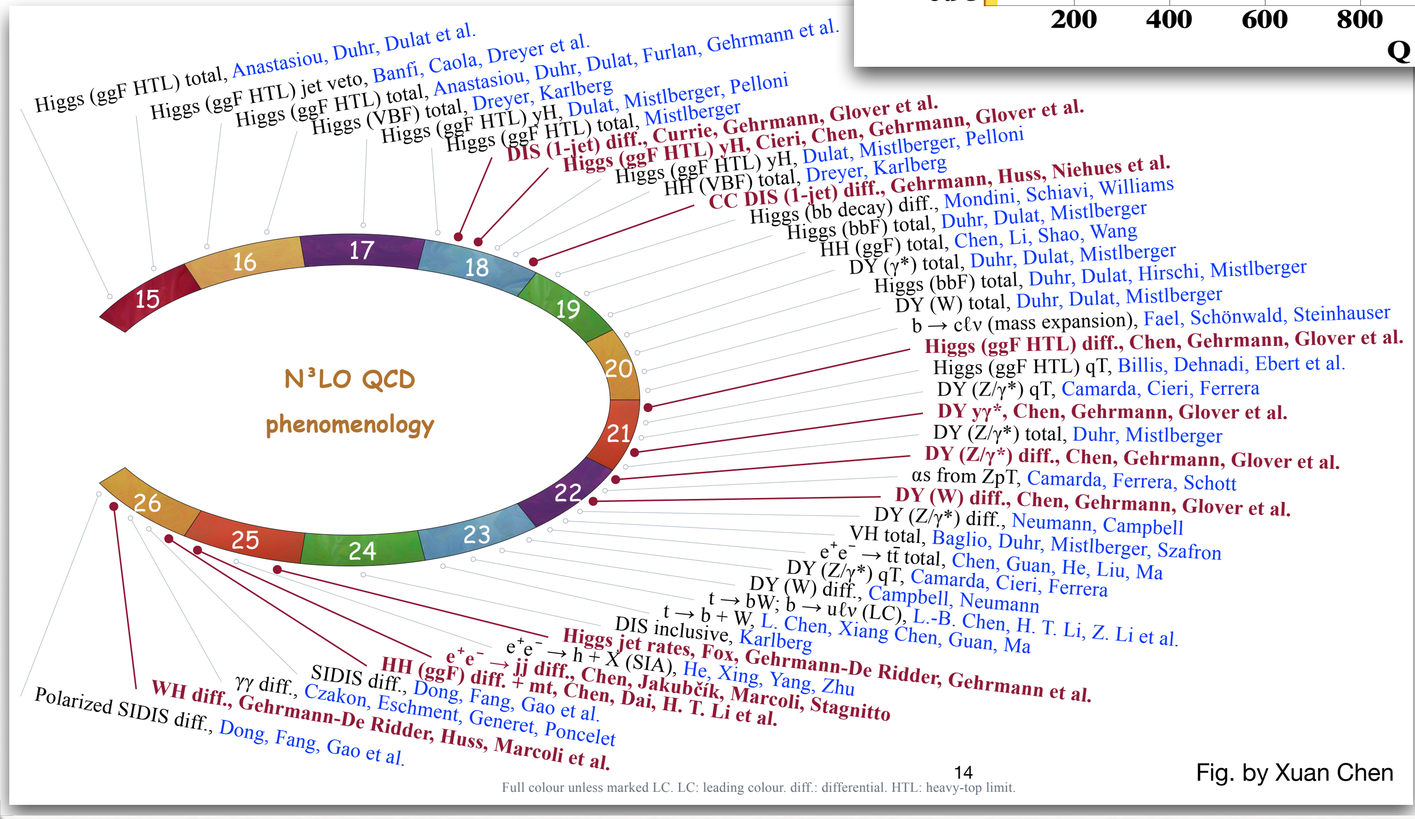
DY total, Hamberg, van Neerven, Matsuura
W/Z, H total, Harlander, Kilgore

Many of these are nowadays included in NNLO PDF fits

The N3LO revolution



from hep-ph/2001.07717



Full colour unless marked LC. LC: leading colour. diff.: differential. HTL: heavy-top limit.

Fig. by Xuan Chen

And what about DIS?

✓ Massless coefficients

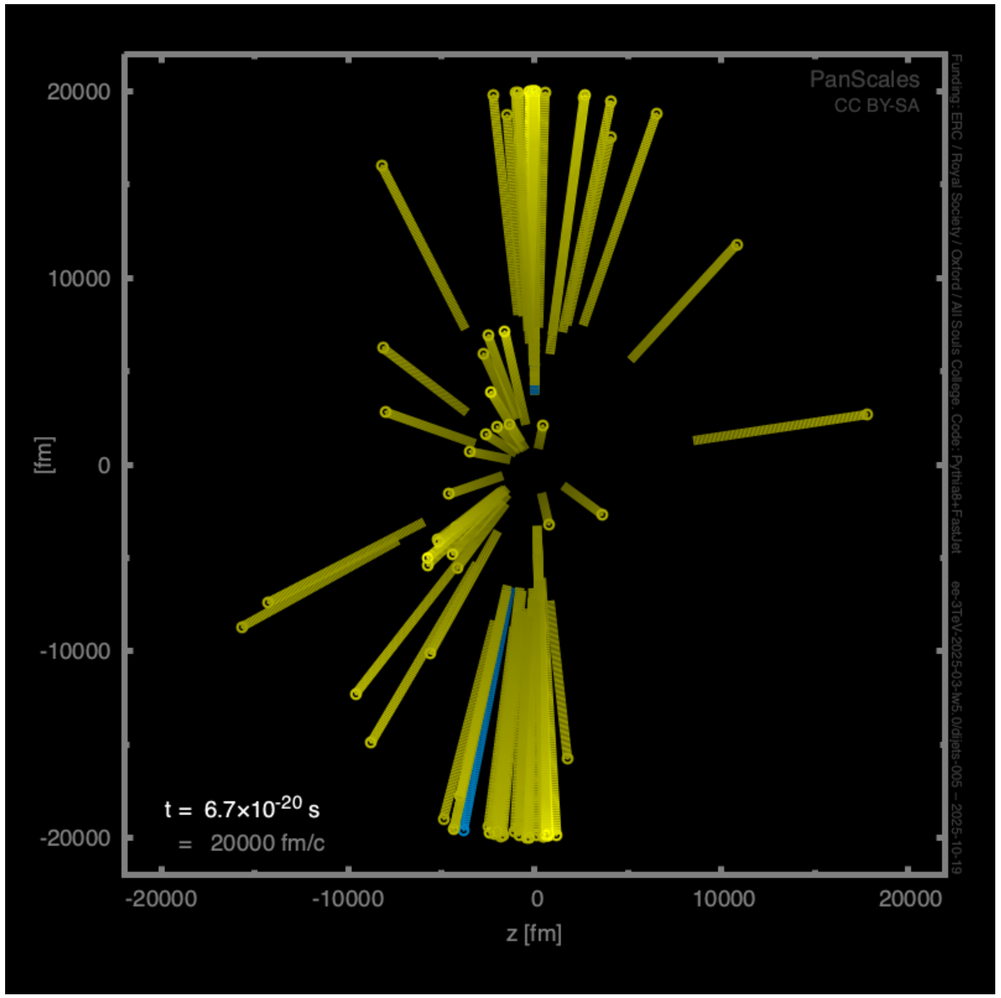
Available at N3LO, also in the form of interpolation grids and public codes.

X Massive coefficients

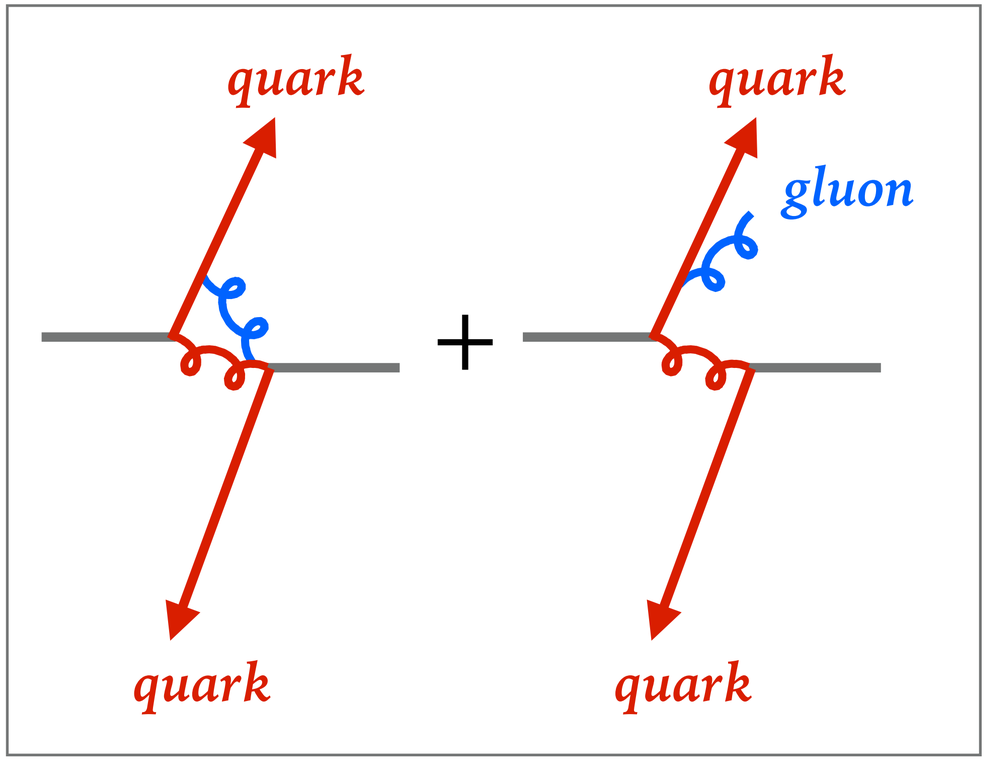
Available at $\mathcal{O}(\alpha_s^3)$ with some approximations.

In practice, the approximation has a small effect on the PDF determination (see e.g., hep-ph/2606.25498)

The problem: real events and power-house calculational tool look totally different



$\neq$



next-to-leading order

What a NLO calculation gives you (here, Event2, $e^+e^- \to q\bar{q}$)

LO (2-particle) tree-level event
with weight 1.00000
px, py, pz, E = -1.32 -1.38 -49.96 50.00
px, py, pz, E = 1.32 1.38 49.96 50.00

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NLO (3-particle) tree-level event
with **weight 16.7749**
px, py, pz, E = -1.60 -1.75 -49.87 49.93
px, py, pz, E = 1.31 1.36 49.25 49.29
px, py, pz, E = 0.30 0.39 0.62 0.79

LO event ($q\bar{q}$)

NLO event, with real emission

~ LO event + extra soft gluon

and **large positive weight**

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px, py, pz, E = 0.30 0.39 0.62 0.79

NLO (2-particle) virtual subtraction event
with **weight -1.5868**
px, py, pz, E = -1.32 -1.38 -49.96 50.00
px, py, pz, E = 1.32 1.38 49.96 50.00

NLO (2-particle) virtual subtraction event
with **weight -15.1855**
px, py, pz, E = -1.61 -1.75 -49.94 50.00
px, py, pz, E = 1.61 1.75 49.94 50.00

NLO (2-particle) virtual finite event
with weight 0.0501, multiplying (alphas/2pi)
px, py, pz, E = -1.32 -1.38 -49.96 50.00
px, py, pz, E = 1.32 1.38 49.96 50.00

LO event ($q\bar{q}$)

NLO event, with real emission
~ LO event + extra soft gluon
and **large positive weight**

NLO event, “virtual” correction
~ LO event
and **large negative weight**

event weights are ~ probabilities

- real life doesn't have negative probabilities
- real life doesn't have (near-)divergent probabilities
- you can evade these problems in perturbation theory if you ask very limited kinds of questions, i.e. nearly always summing real & virtual divergences (infrared safe observable, single momentum scale)*
- but experiments don't limit themselves to those kinds of questions

* though there can still be nasty surprises, cf. Chen et al 2102.07607, GPS & Slade 2106.08329

Feynman diagrams → simulations



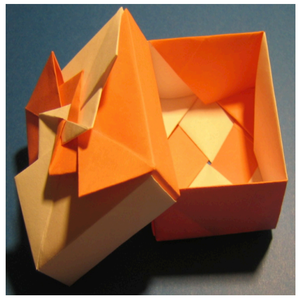
Herwig 7



Pythia 8



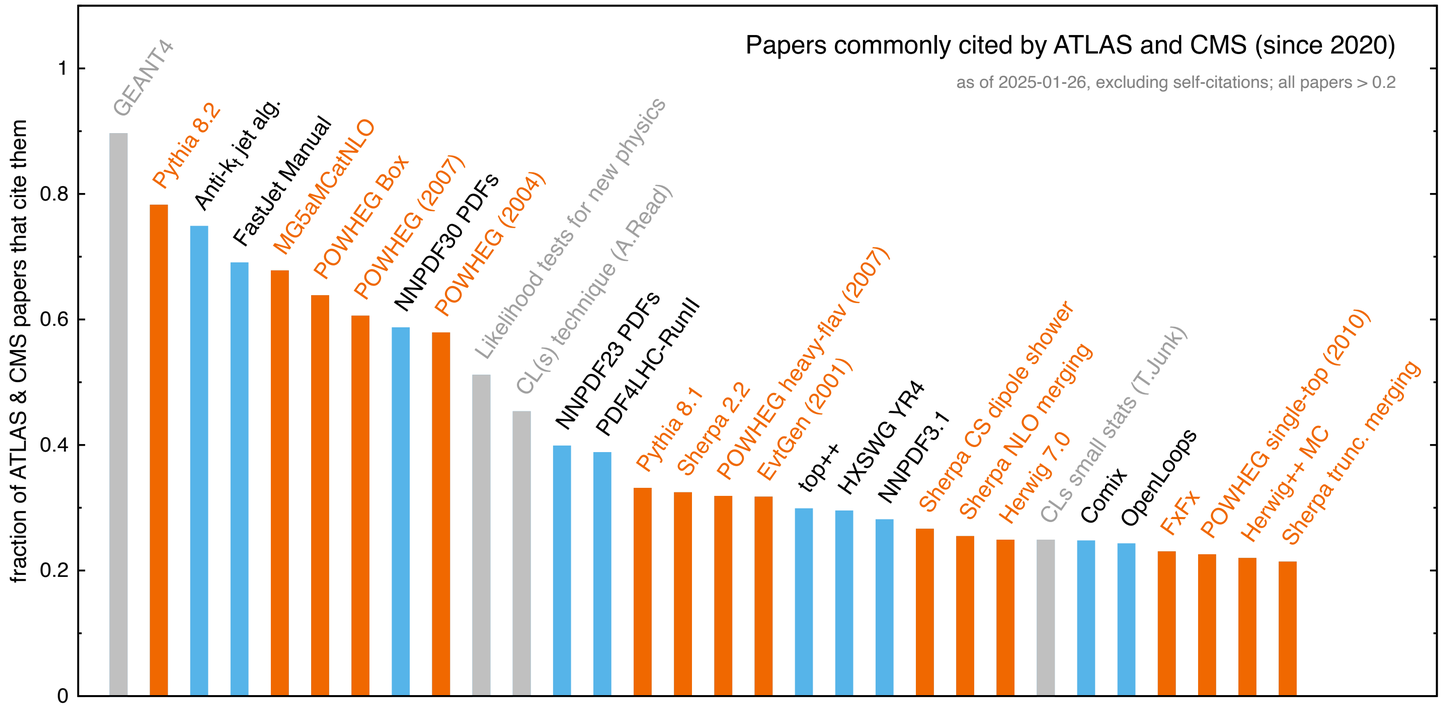
Sherpa 3



POWHEG

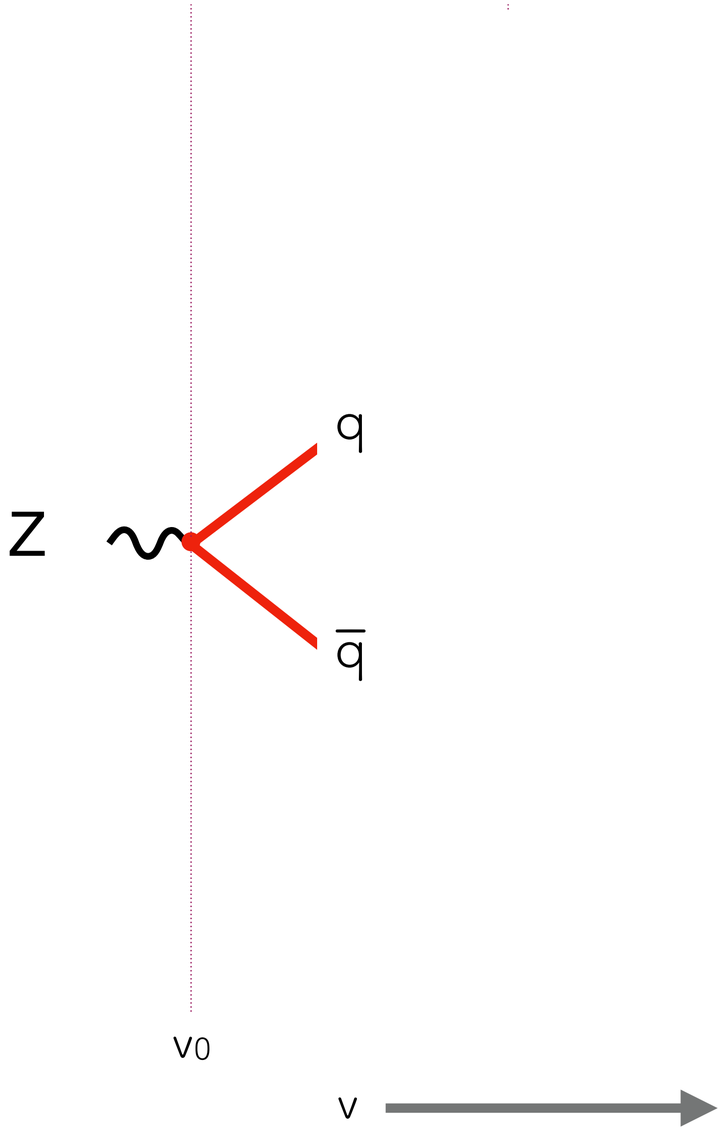


MG5_aMC@NLO



used in ~95% of ATLAS/CMS publications
they do an amazing job of simulating vast swathes of data;
collider physics would be unrecognisable without them

QCD parton shower: an evolution equation (in evolution scale v, e.g. trans.mom.)

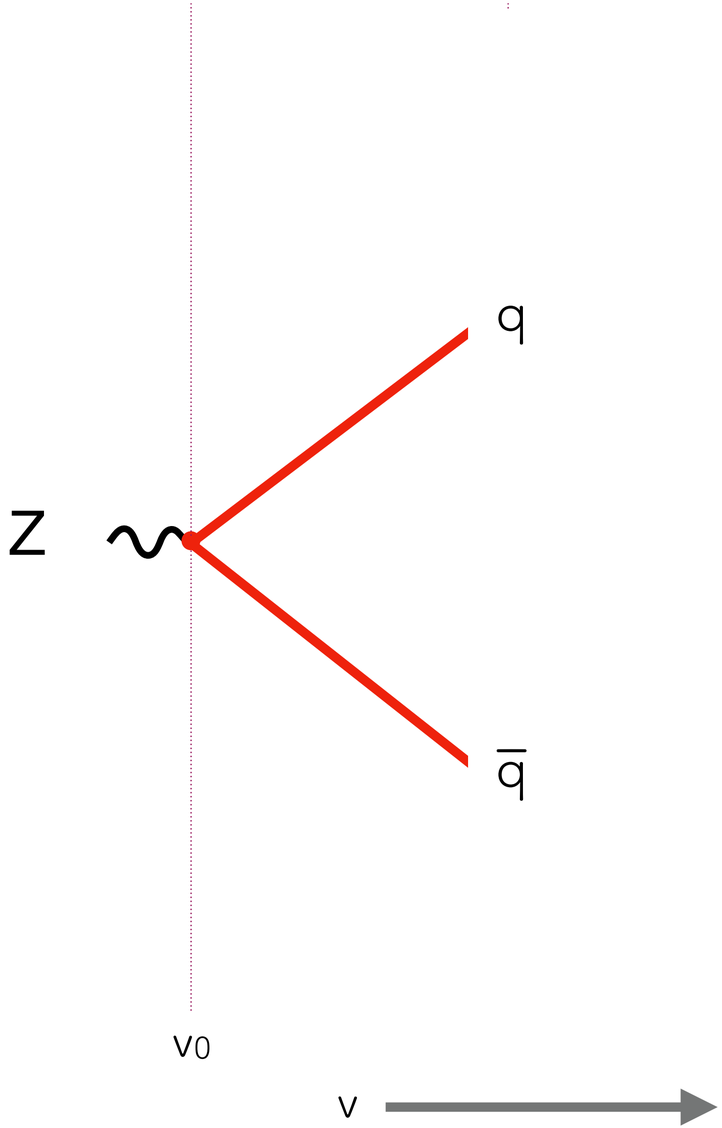


Start with quark (q) antiquark ($\bar{q}$) state.

Throw a random number to determine down to what scale state persists unchanged

$$\frac{dP_2(v)}{dv} = -f^{q\bar{q}}_{2\to 3}(v)\, P_2(v)$$

QCD parton shower: an evolution equation (in evolution scale v, e.g. trans.mom.)

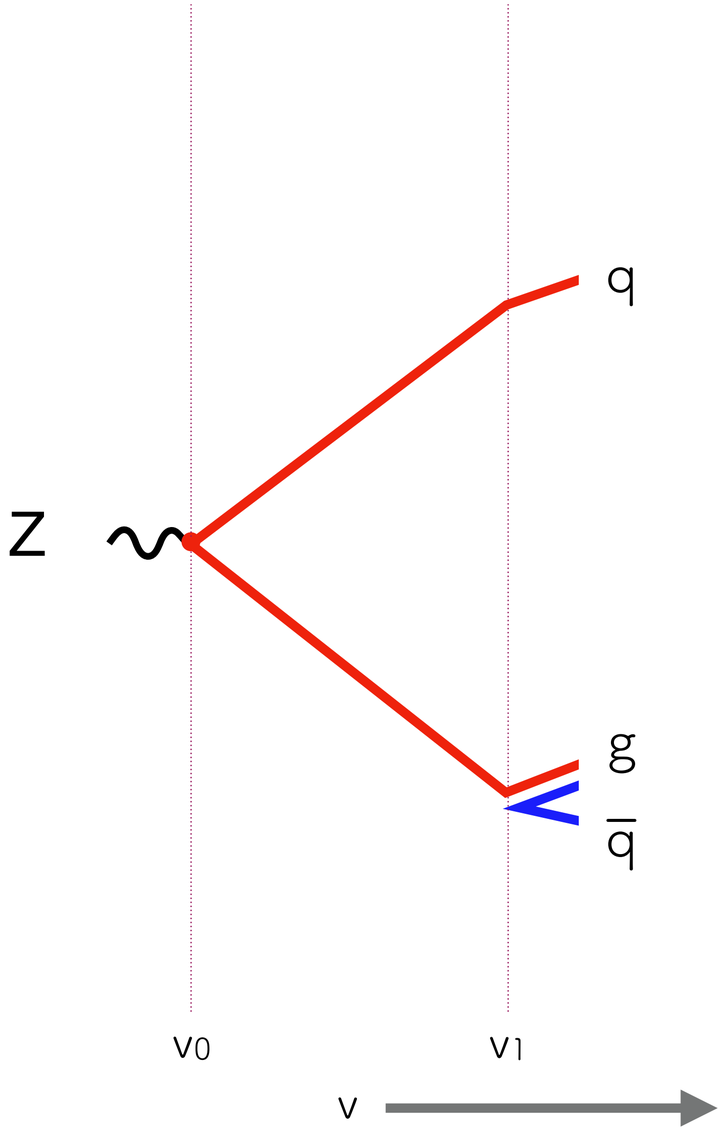


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$$\frac{dP_2(v)}{dv} = -f^{q\bar{q}}_{2\to 3}(v)\, P_2(v)$$

QCD **parton shower**: an evolution equation (in **evolution scale v**, e.g. trans.mom.)



Start with quark (q) antiquark ($\bar{q}$) state.

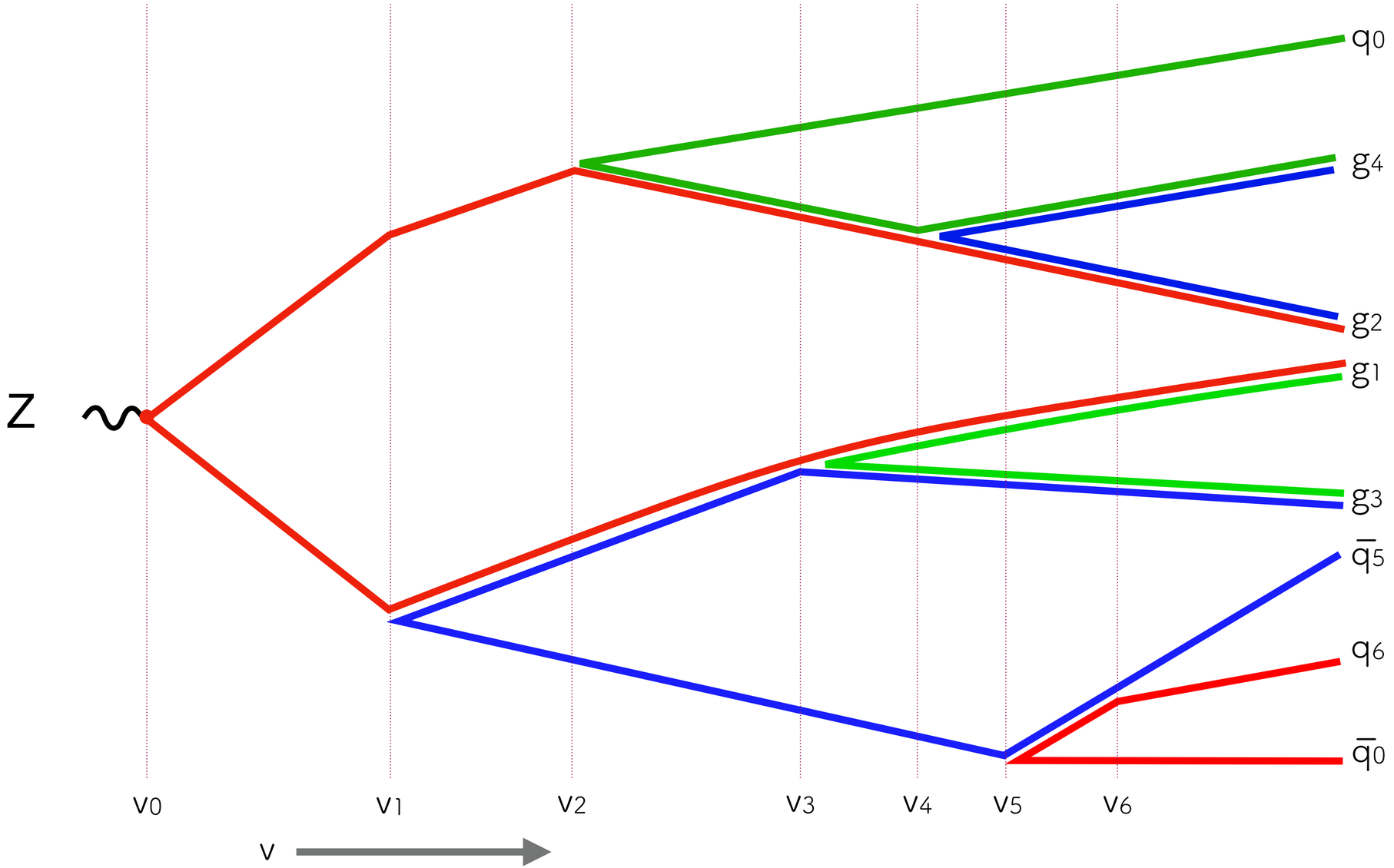
Throw a random number to determine down to what scale state persists unchanged

At some point, **state splits** (2→3, i.e. emits gluon). Evolution equation changes

$$\frac{dP_3(v)}{dv} = -\left[f^{qg}_{2\to3}(v) + f^{g\bar{q}}_{2\to3}(v)\right] P_3(v)$$

gluon (g) here is drawn as two parallel lines

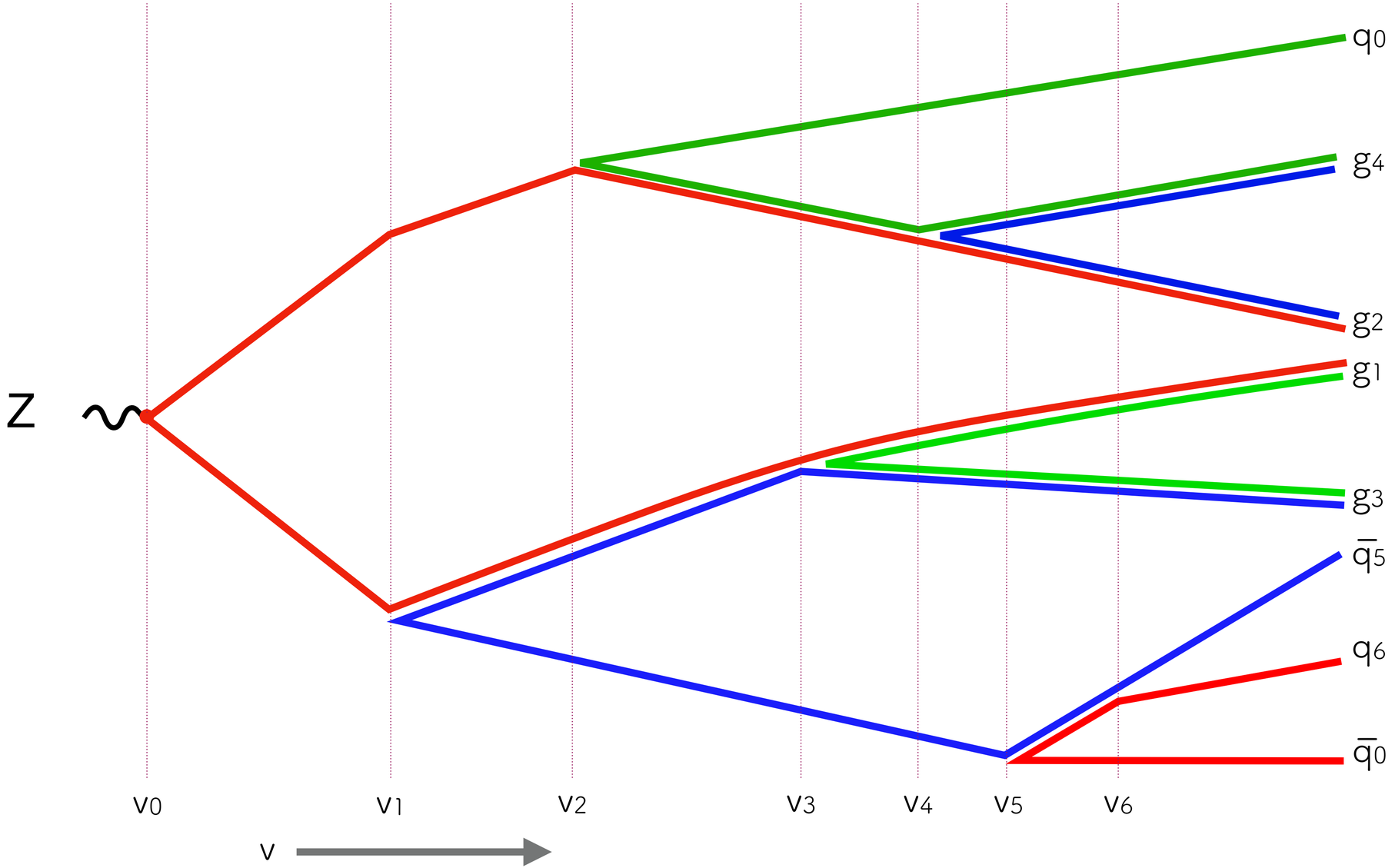
QCD parton shower: an evolution equation (in evolution scale v, e.g. trans.mom.)



self-similar evolution continues until it reaches a non-perturbative scale

illustration by K. Hamilton

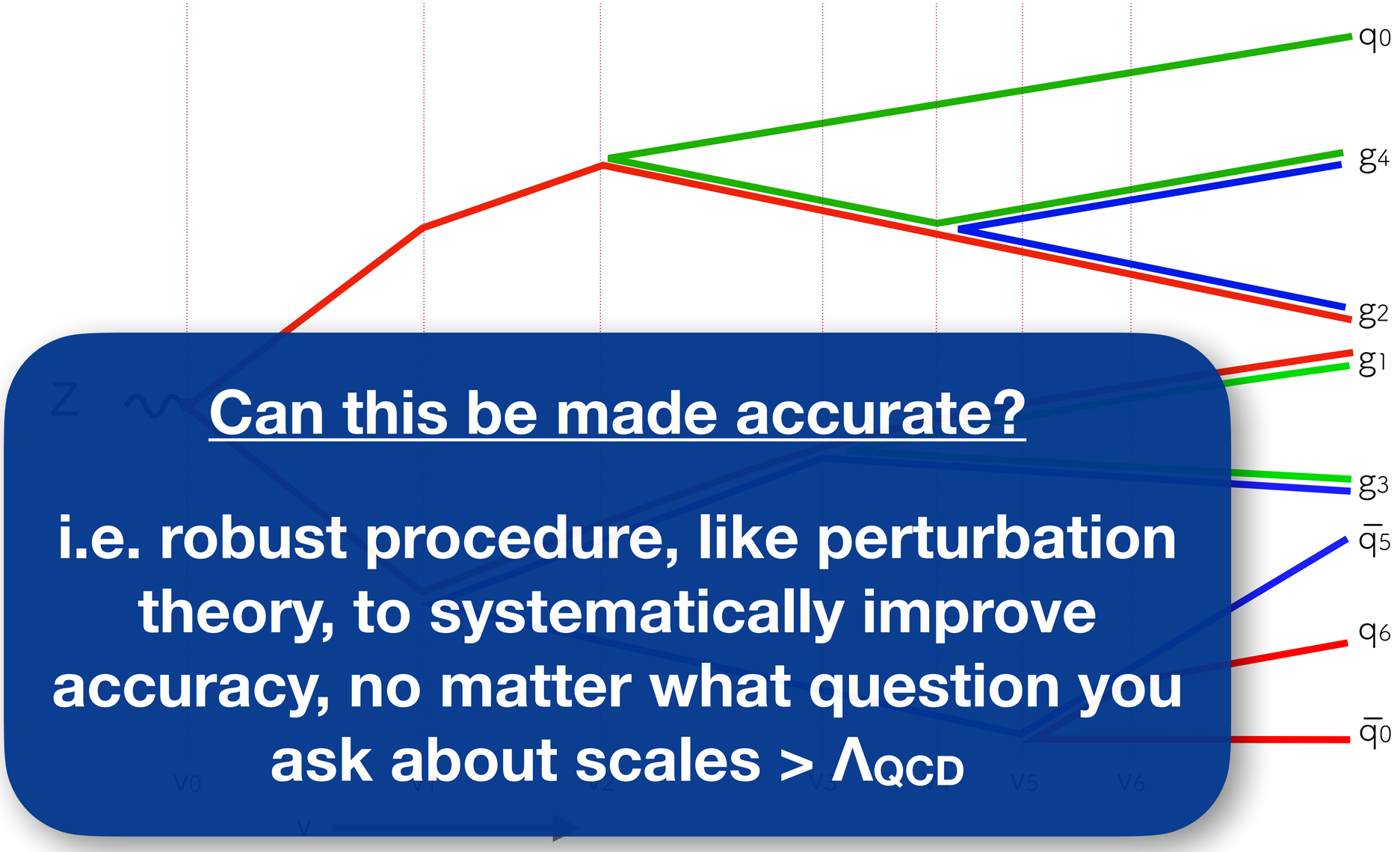
QCD parton shower: an evolution equation (in evolution scale v, e.g. transverse momentum)



self-similar evolution continues until it reaches a non-perturbative scale

branchings widely separated in space–time treated as ~independent

QCD parton shower: an evolution equation (in evolution scale v, e.g. transverse momentum)



self-similar evolution continues until it reaches a non-perturbative scale

branchings widely separated in space–time treated as ~independent

Can this be made accurate?

i.e. robust procedure, like perturbation theory, to systematically improve accuracy, no matter what question you ask about scales > Λ_{QCD}



Samuel Bates
Oxford



Melissa van Beekveld
NIKHEF



Mrinal Dasgupta
Manchester



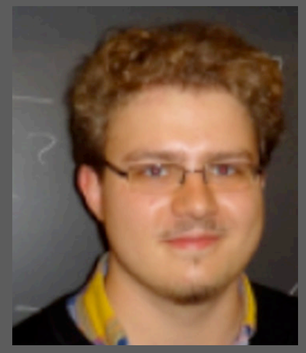
Basem El-Menoufi
Turin



Silvia Ferrario Ravasio
Turin



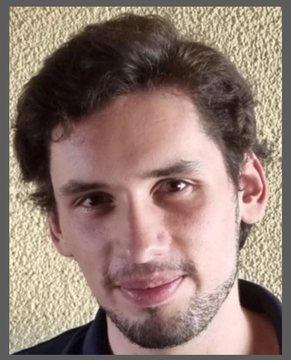
Keith Hamilton
Univ. Coll. London



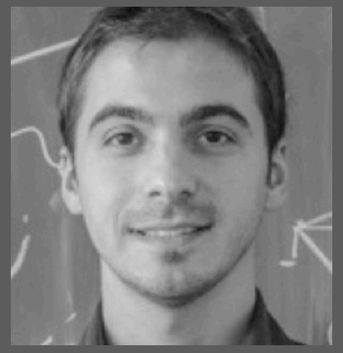
Alexander Karlberg
MPP



Matvei Kuzmin
Oxford



Marco A. C. Leitão
LIP, IPhT



Pier Francesco Monni
CERN



GPS
Oxford



Nicolas Schalch
Oxford



Ludovic Scyboz
Monash



Alba Soto-Ontoso
Granada



Grégory Soyez
IPhT, Saclay

PanScales

A project to bring logarithmic understanding and accuracy to parton showers



Silvia Zanoli
Oxford

Former members



Frédéric Dreyer



Jack Helliwell



Rok Medves



Rob Verheyen



Scarlett Woolnough

Conclusions

Collider particle physics is a rich and diverse subject

Core exploration of the Higgs sector has only just started

- Many aspects are (hypothesized to be) crucial for the world around us
- Major targets for future colliders: e.g. triple-Higgs interaction $\Longleftrightarrow$ Higgs potential

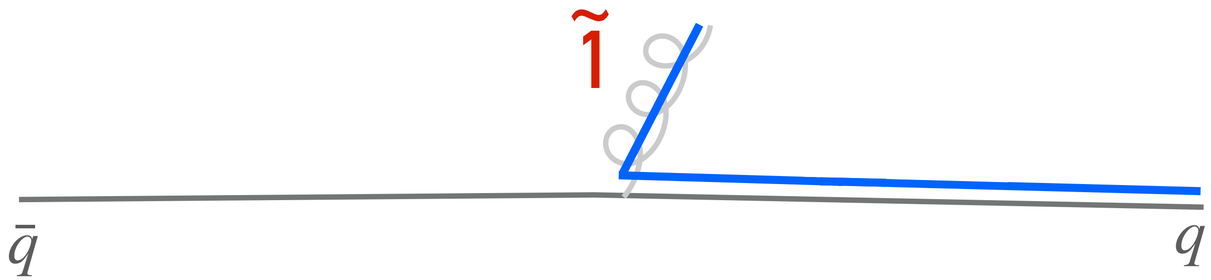
Central to quantitative collider physics is the strong interaction

- quest for accuracy brings huge challenges & QCD is delivering on multiple fronts
- one of those fronts is the question of how to span disparate momentum scales in simulations: major conceptual steps over past years & soon to be available for practical use.

backup

1. Momentum conservation: the core of any shower

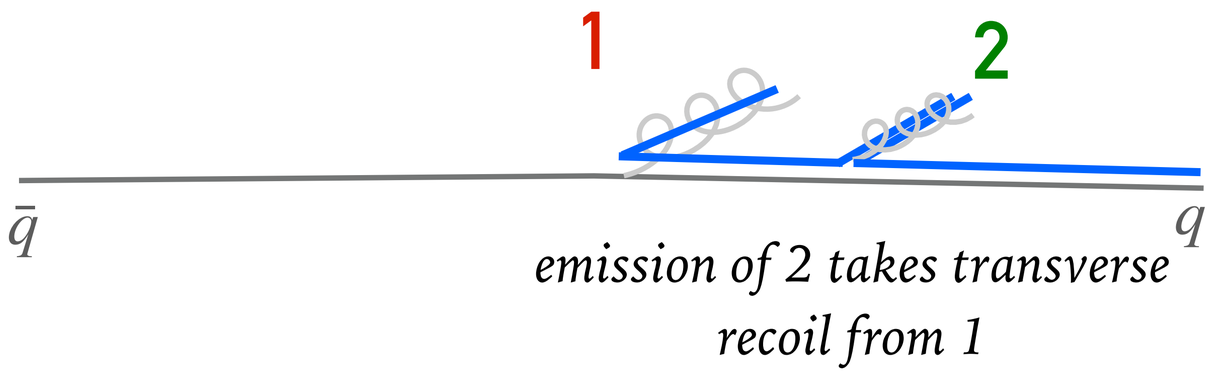
Dipole showers conserve momentum at each step. Traditional dipole-local recoil:



$$\mathrm{d}\mathcal{P}^{\mathrm{FS}}_{\tilde{\imath}\to ik} = \frac{\alpha_s(k_\perp^2)}{2\pi}\frac{\mathrm{d}k_\perp^2}{k_\perp^2}\frac{\mathrm{d}z}{z}\frac{\mathrm{d}\varphi}{2\pi}N_{ik}^{\mathrm{sym}}\left[zP_{\tilde{\imath}\to ik}(z)\right]$$

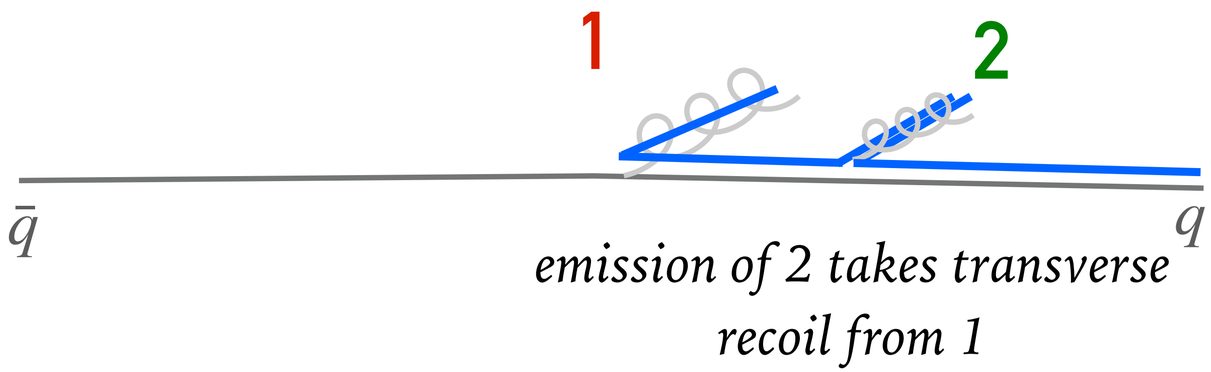
1. Momentum conservation: the core of any shower

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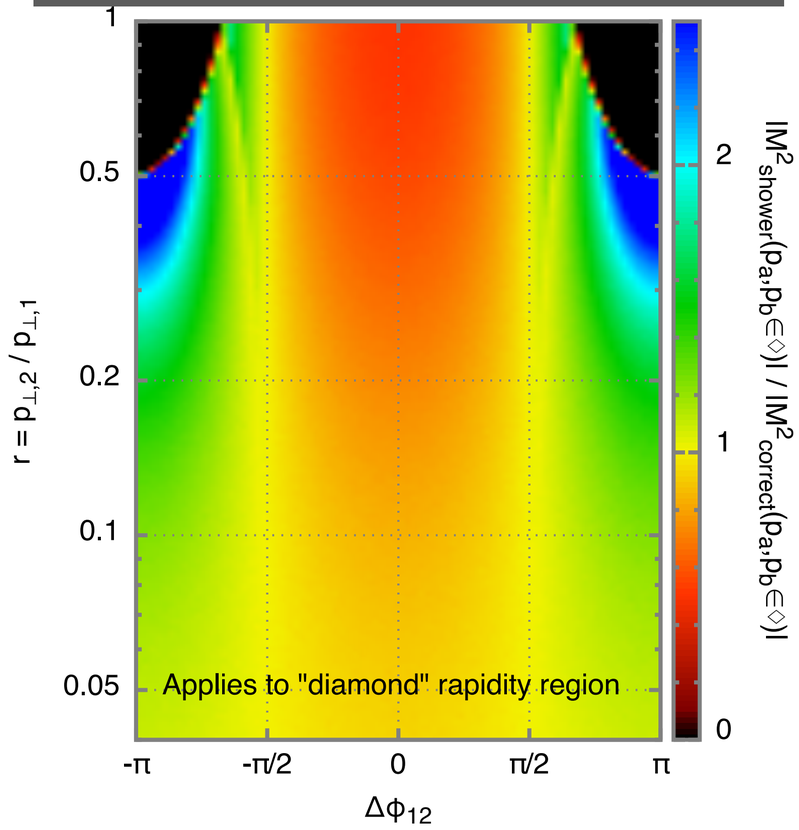


Shower initially generated matrix element for particle $\tilde{1}$, whose momentum differs (by ~ 50%) from final particle 1.

Matrix element is incorrect wrt final momentum 1.

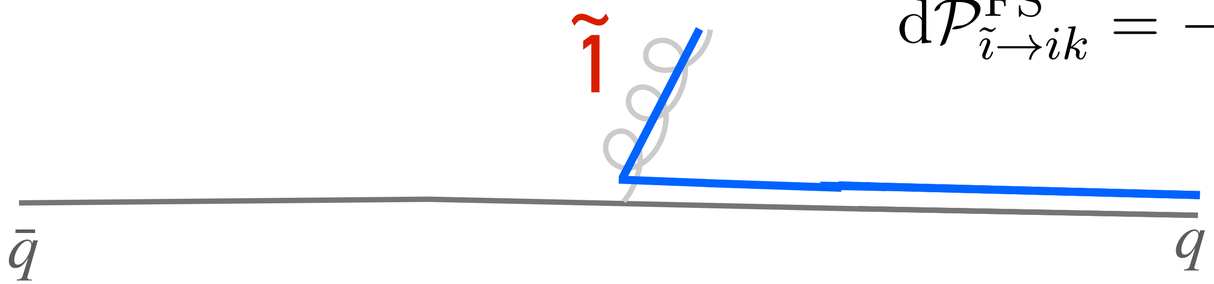
First observed: Andersson, Gustafson, Sjogren '92
Closely related effect present for Z p_t: Nagy & Soper 0912.4534
Impact on log accuracy across many observables: Dasgupta, Dreyer, Hamilton, Monni, GPS, 1805.09327

ratio of effective shower matrix element to exact one



1. Correct recoil rule: no side effects on other distant emissions

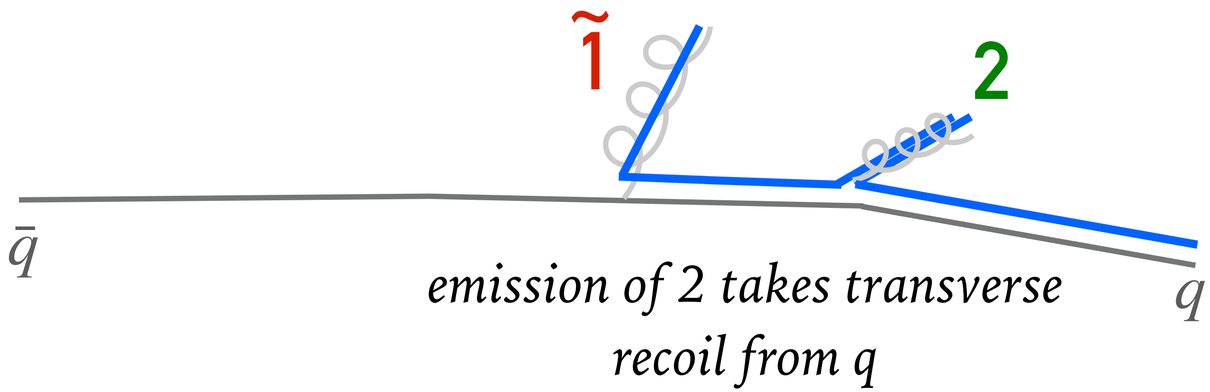
One approach



$$\mathrm{d}\mathcal{P}^{\mathrm{FS}}_{\tilde{i}\to ik} = \frac{\alpha_s(k_\perp^2)}{2\pi}\frac{\mathrm{d}k_\perp^2}{k_\perp^2}\frac{\mathrm{d}z}{z}\frac{\mathrm{d}\varphi}{2\pi}N_{ik}^{\mathrm{sym}}\left[zP_{\tilde{i}\to ik}(z)\right]$$

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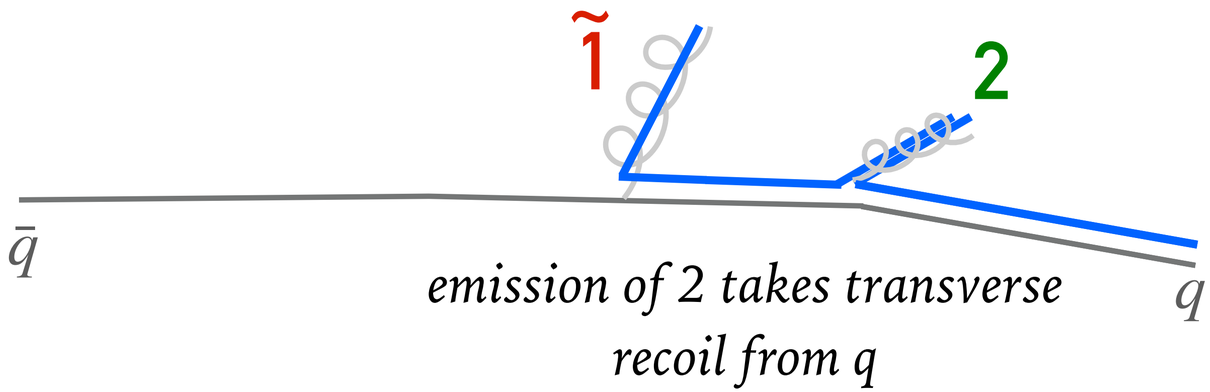
One approach

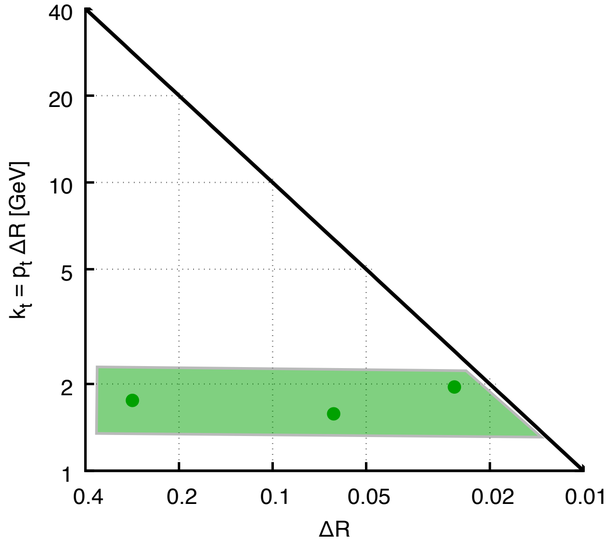


θ_{1q} left almost unchanged if ⊥ recoil from emission of 2 taken by (much harder) q

1. Correct recoil rule: no side effects on other distant emissions

One approach



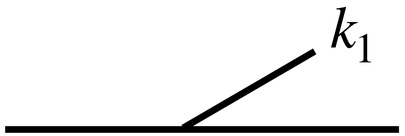


θ_{1q} left almost unchanged if ⊥ recoil from emission of 2 taken by (much harder) q

Can be achieved in multiple ways:

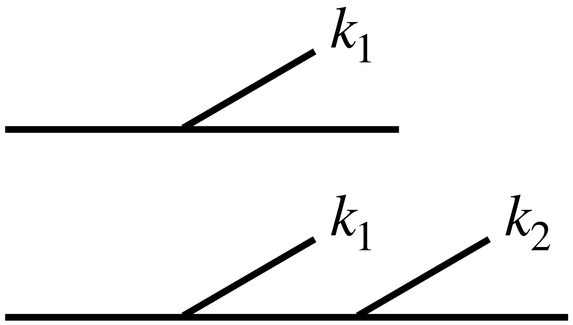
- global transverse recoil
  (Dasgupta et al 2002.11114, "**PanGlobal**"; Holguin Seymour & Forshaw 2003.06400; Alaric 2208.06057 + ⋯, Apollo, 2403.19452)
- local transverse recoil, with non-standard shower ordering & dipole partition
  (2002.11114 "**PanLocal**"; Nagy & Soper 0912.4534 + ⋯, "Deductor")

Towards NNLL: each new emission's distribution conditional on previous emission



Distribute k_1 according to $M^2(k_1)$

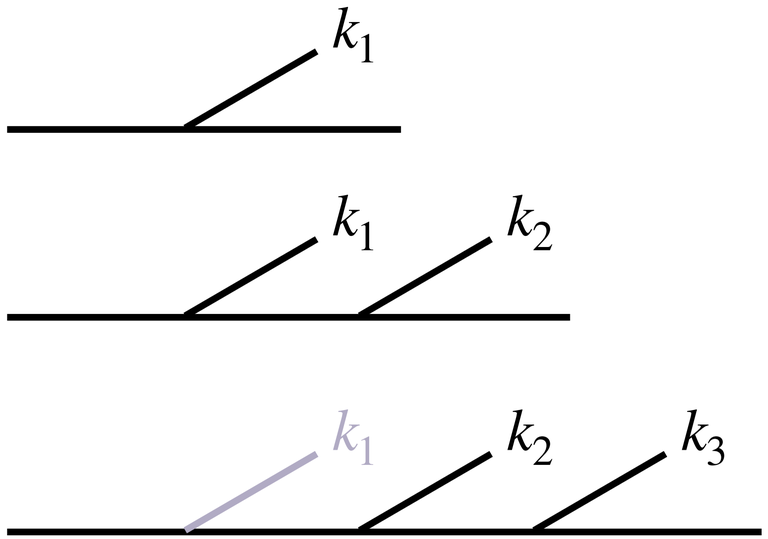
Towards NNLL: each new emission's distribution conditional on previous emission



Distribute k_1 according to $M^2(k_1)$

Distribute k_2 according to $M^2(k_1, k_2)/M^2(k_1)$

Towards NNLL: each new emission's distribution conditional on previous emission

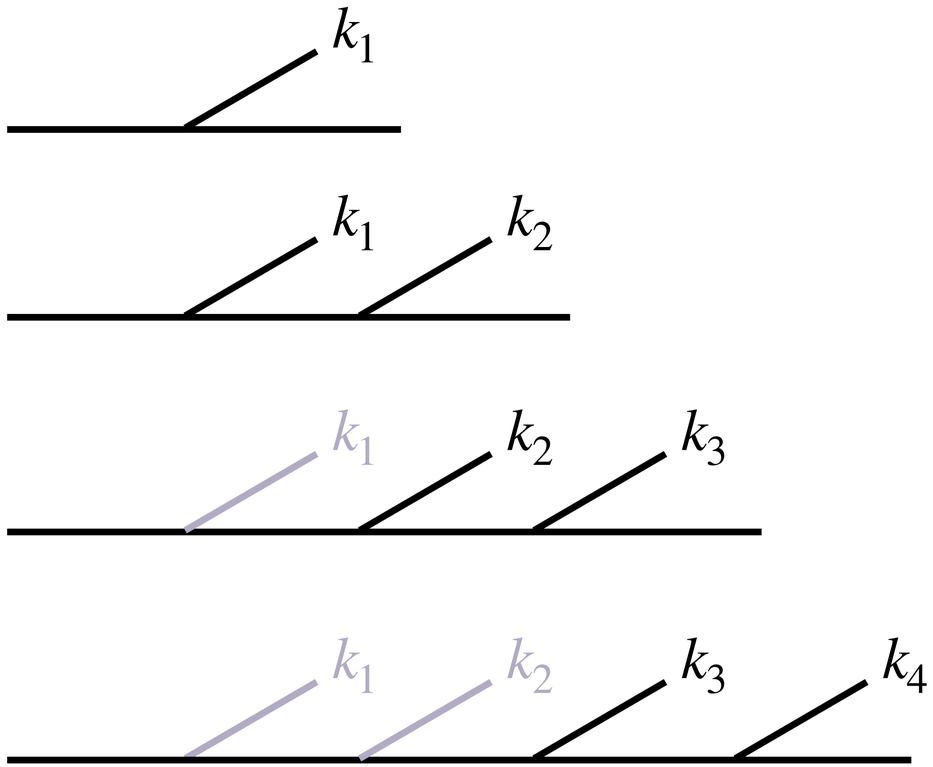


Distribute k_1 according to $M^2(k_1)$

Distribute k_2 according to $M^2(k_1, k_2)/M^2(k_1)$

Distribute k_3 according to $M^2(k_2, k_3)/M^2(k_2)$

Towards NNLL: each new emission's distribution conditional on previous emission



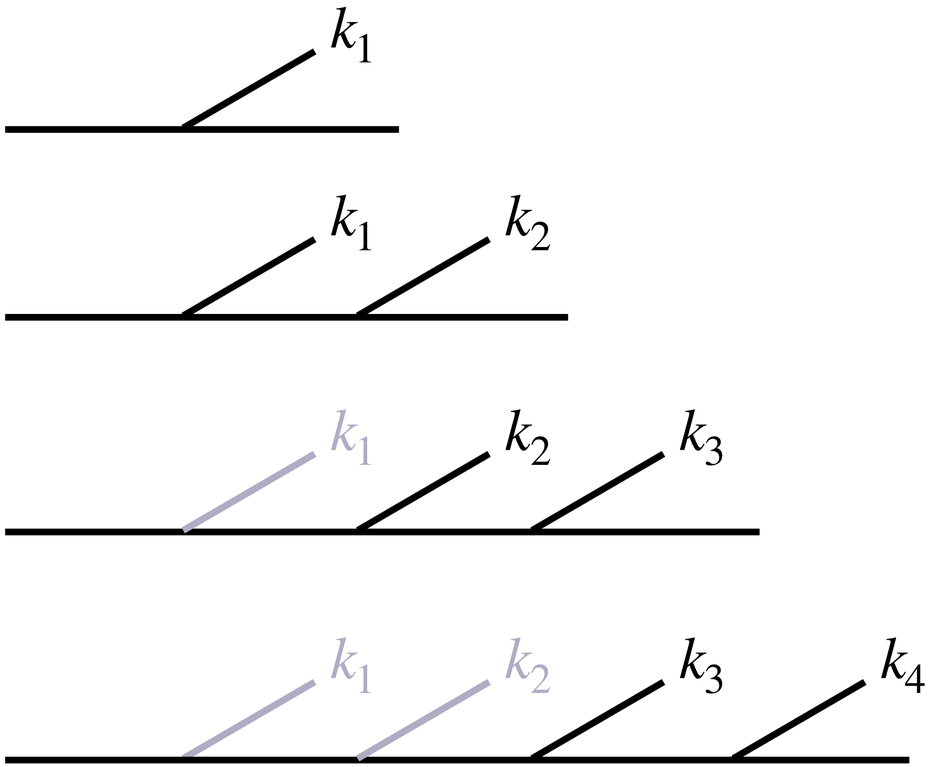
Distribute k_1 according to $M^2(k_1)$

Distribute k_2 according to $M^2(k_1, k_2)/M^2(k_1)$

Distribute k_3 according to $M^2(k_2, k_3)/M^2(k_2)$

Distribute k_4 according to $M^2(k_3, k_4)/M^2(k_3)$

Towards NNLL: each new emission's distribution conditional on previous emission



Distribute k_1 according to $M^2(k_1)$

Distribute k_2 according to $M^2(k_1, k_2)/M^2(k_1)$

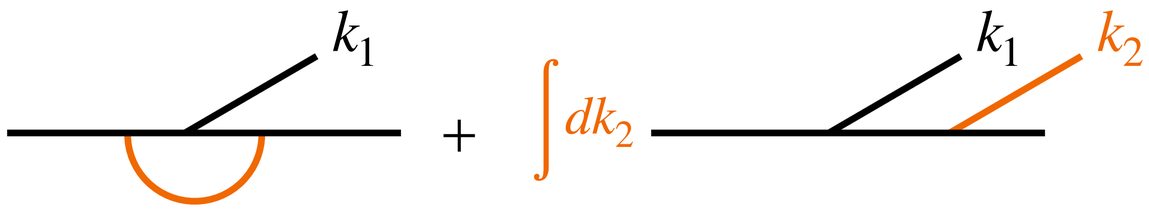
Distribute k_3 according to $M^2(k_2, k_3)/M^2(k_2)$

Distribute k_4 according to $M^2(k_3, k_4)/M^2(k_3)$

Relies on factorisation: e.g. $M^2(k_1, k_2, k_3, k_4)/M^2(k_1, k_2, k_3) \to M^2(k_3, k_4)/M^2(k_3)$
if 3 and 4 well separated in Lund plane from 1 and 2

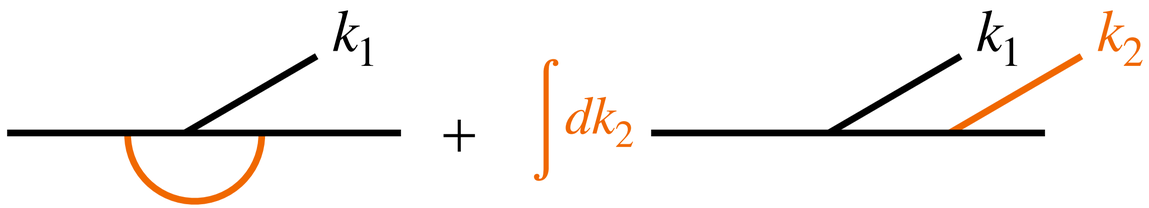
[factorised matrix elements given in Dokshitzer, Marchesini & Oriani '92, Campbell & Glover, hep-ph/9710255, Catani & Grazzini hep-ph/9810389, etc. + actual finite, positive, log-consistent formulation of iteration Ferrario Ravasio et al, arXiv:2307.11142]

Account for virtual corrections associated with each emission

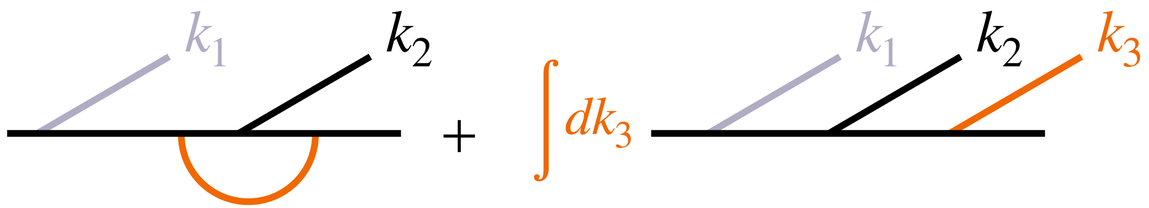


NLO correction to k_1 emission intensity sums loop correction and all possible scenarios for the next emission

Account for virtual corrections associated with each emission



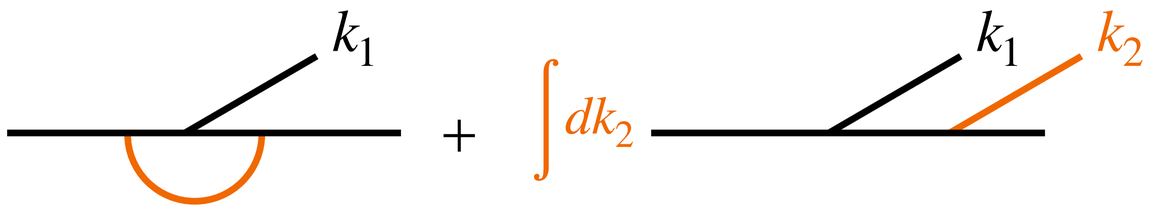
NLO correction to k_1 emission intensity sums loop correction and all possible scenarios for the next emission



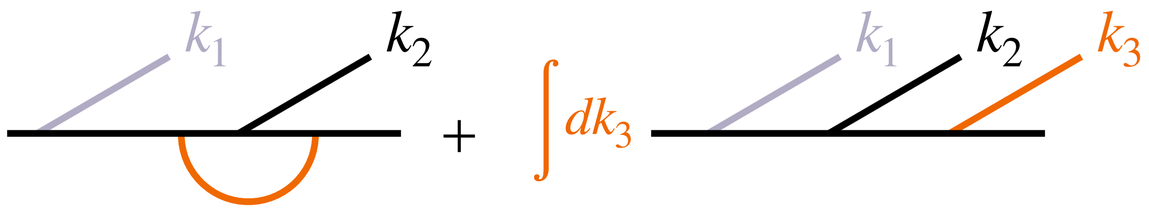
NLO correction to k_2 emission intensity sums loop correction and all possible scenarios for the next emission

etc.

Account for virtual corrections associated with each emission



NLO correction to k_1 emission intensity sums loop correction and all possible scenarios for the next emission



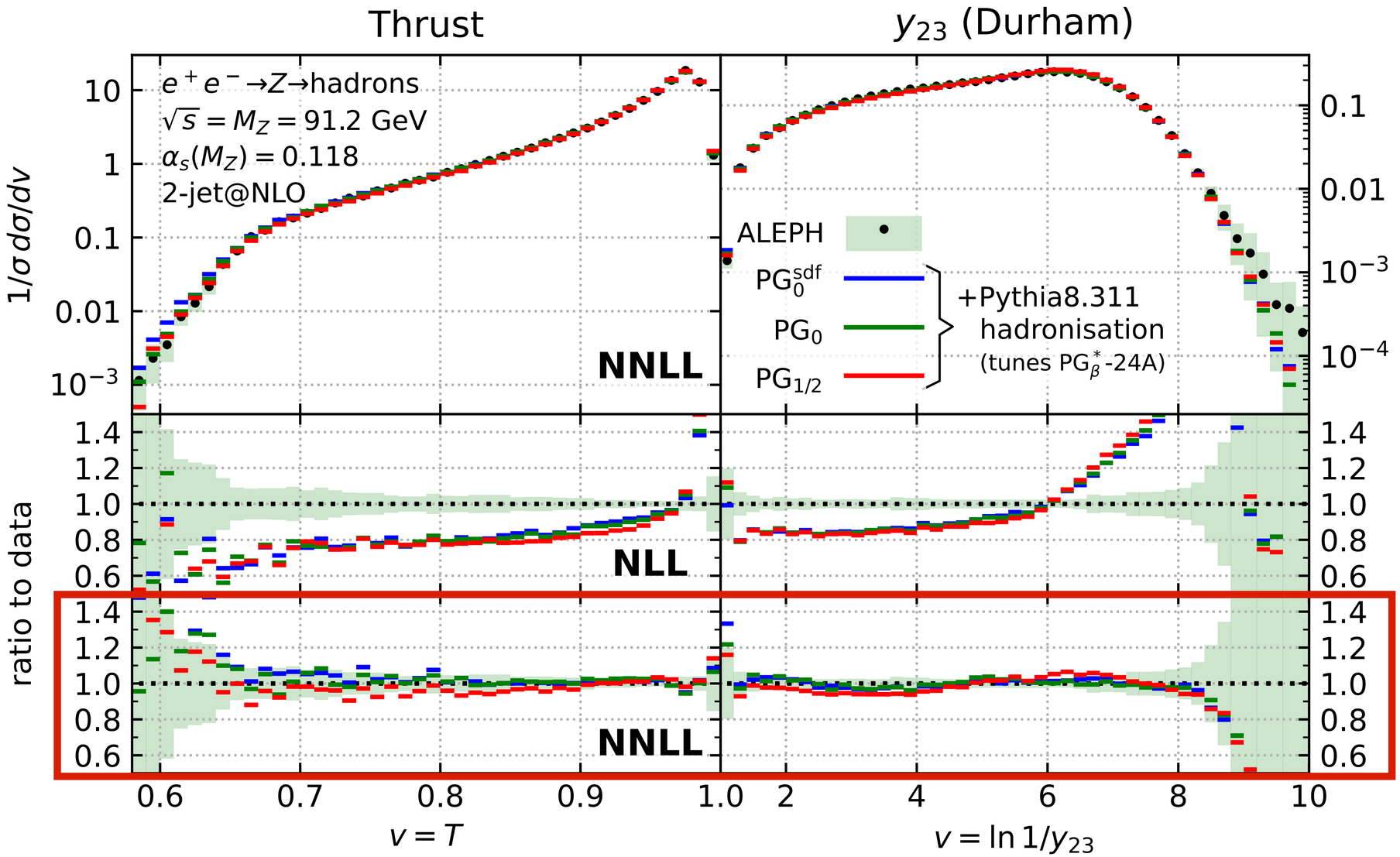
NLO correction to k_2 emission intensity sums loop correction and all possible scenarios for the next emission

etc.

Again relies on factorisation, e.g. when 1 and 2 are well separated in the Lund plane + careful nesting, cf. van Beekveld, Dasgupta, El-Menoufi, Helliwell, Monni, GPS 2409.08316 (see also Hartgring, Laenen & Skands, 1303.4974, Campbell et al 2108.07133 at fixed order)

van Beekveld et al, 2406.02661

Comparing to LEP event-shape data



NNLL brings 20% effects ($\sim \alpha_s$)

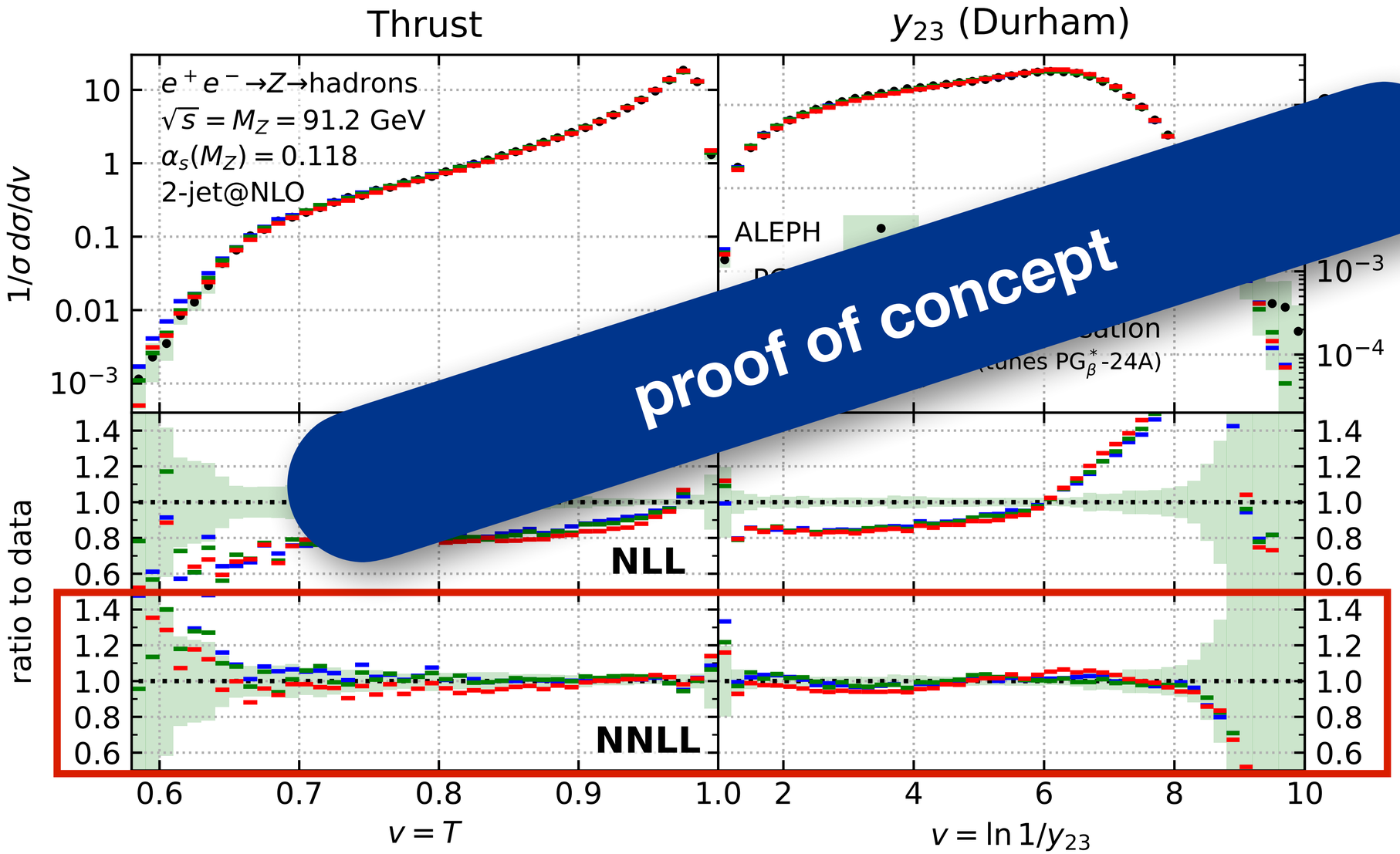
Dramatically improves agreement with data, using a "normal" $\alpha_s = 0.118$

NB: 3-jet @ NLO still missing for robust pheno conclusions

← NNLL

van Beekveld et al, 2406.02661

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