GETTING THE MOST FROM THE HIGGS BOSON

PROF. DR. FREYA BLEKMAN

Graz, 23 September 2026

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

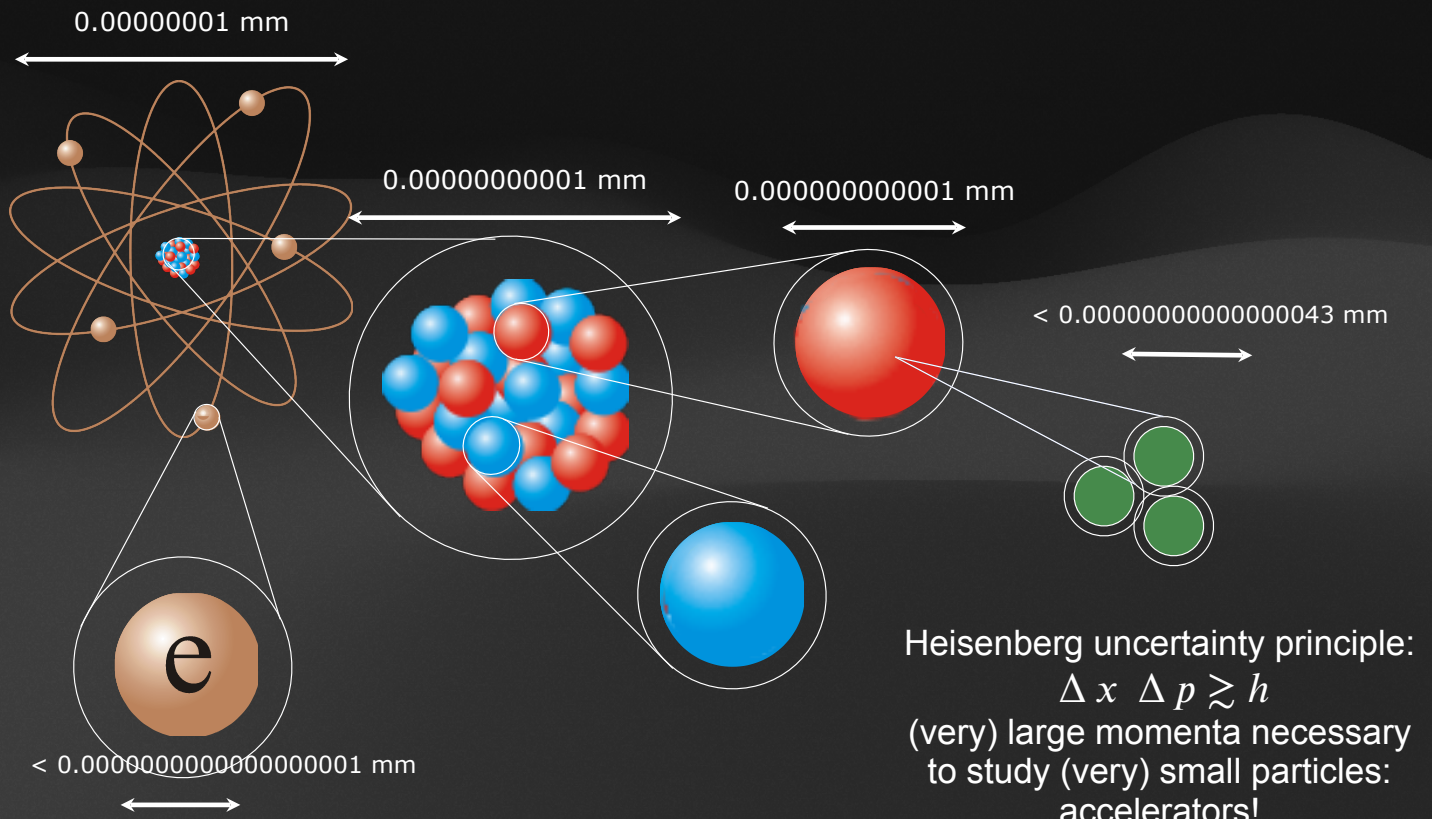
DESY.

UHH
QUANTUM UNIVERSE

UHH Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

KHMW
Voor Wetenschap en Samenleving.
Sinds 1752.

Scales of the subatomic world

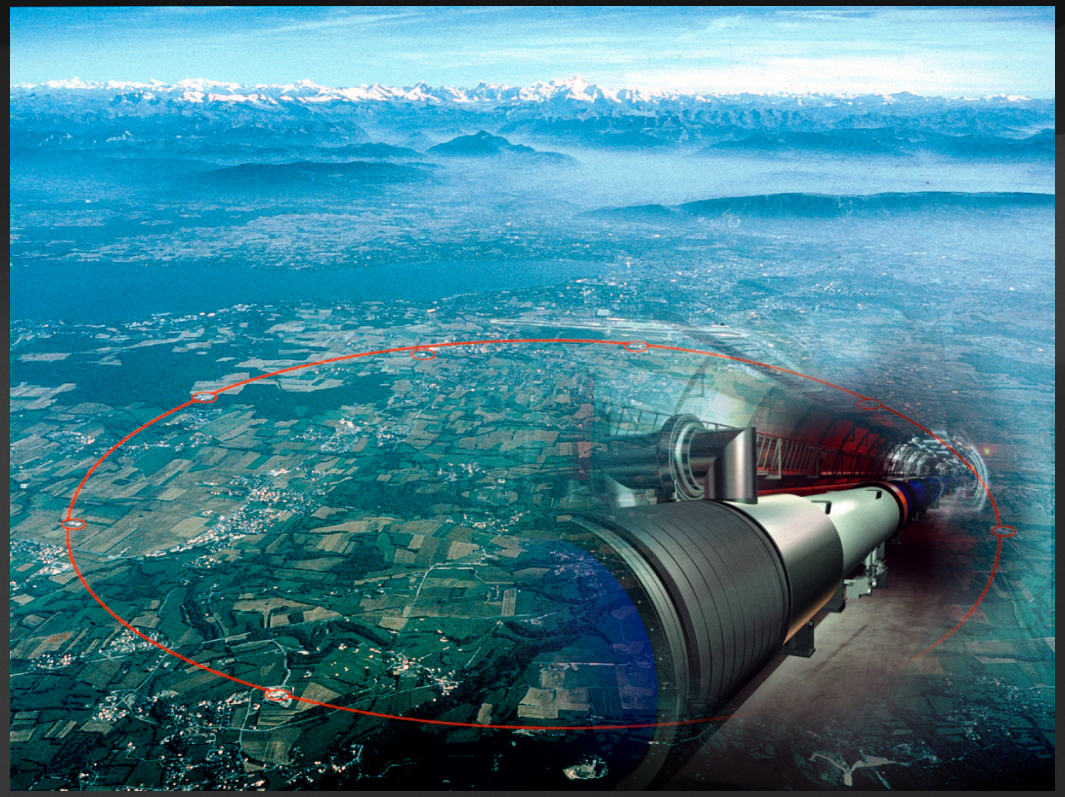


Heisenberg uncertainty principle:

$$\Delta x \ \Delta p \gtrsim h$$

(very) large momenta necessary to study (very) small particles: accelerators!

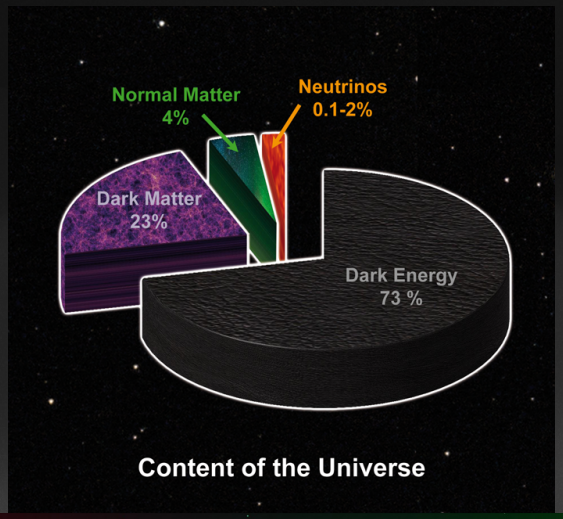
HIGH MOMENTA = COLLIDERS!

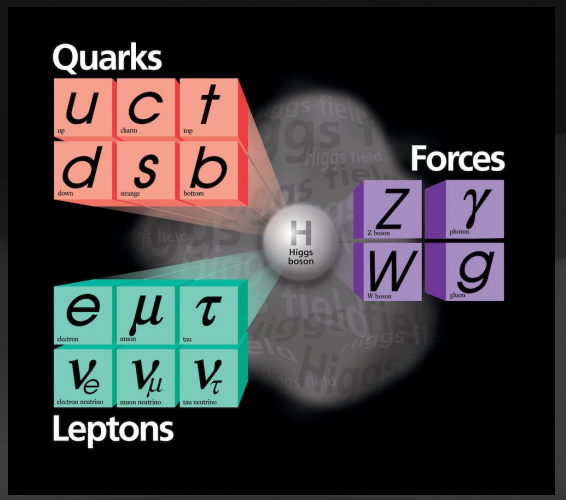


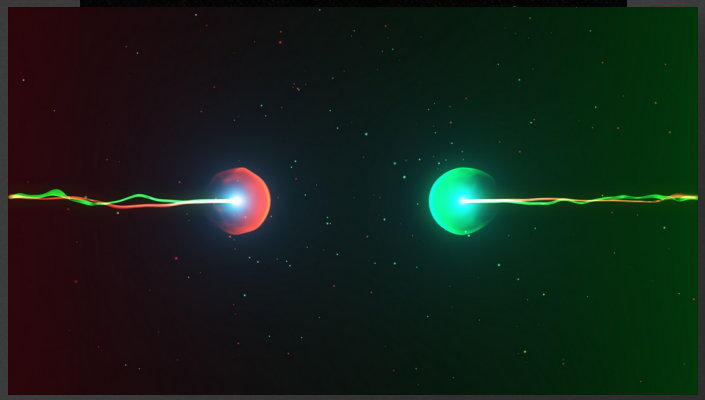
Still tiny energies compared to space!


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

GREAT! BUT…?!?

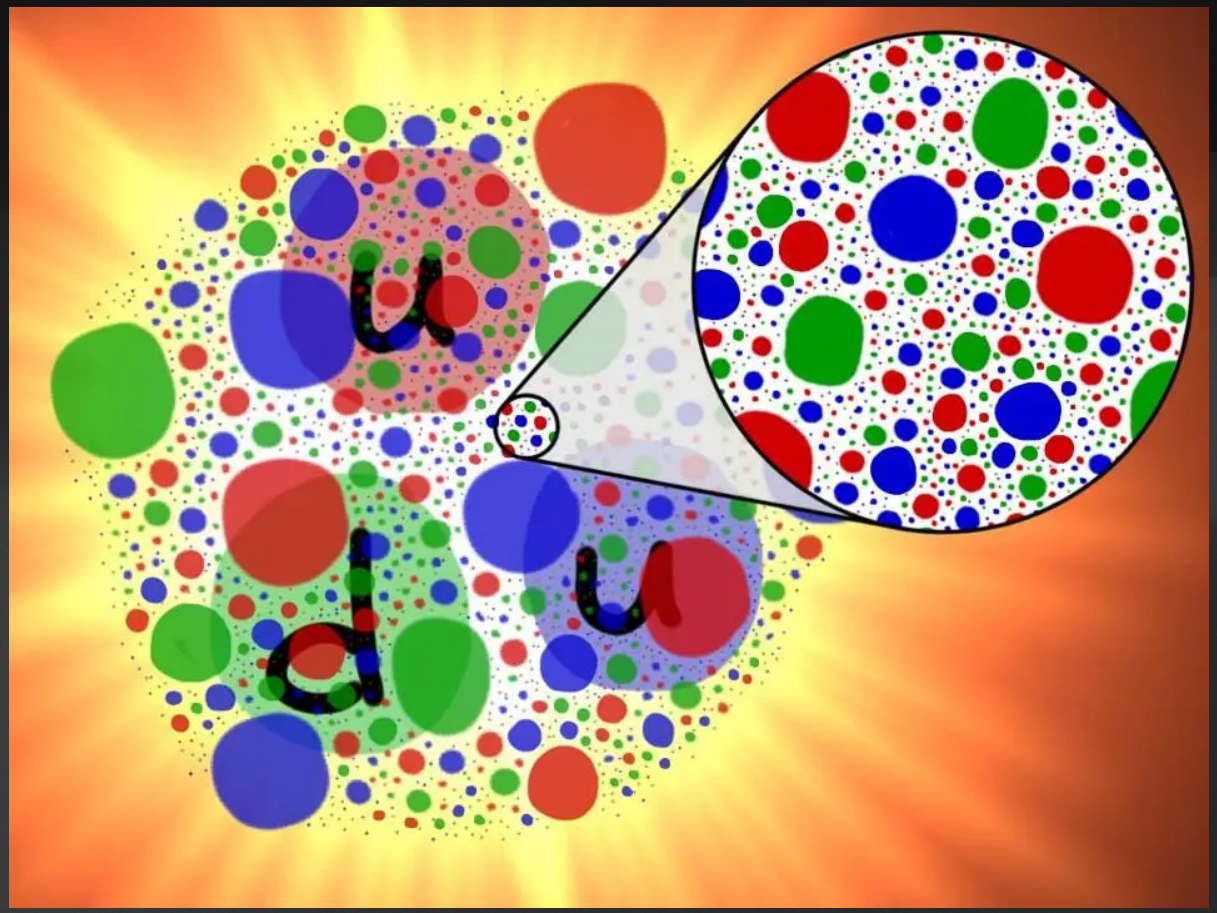

Normal Matter
4%
Neutrinos
0.1-2%
Dark Matter
23%
Dark Energy
73 %
Content of the Universe


Quarks
u c t
d s b
Forces
Z γ
W g
H
Higgs boson
e μ τ
Leptons

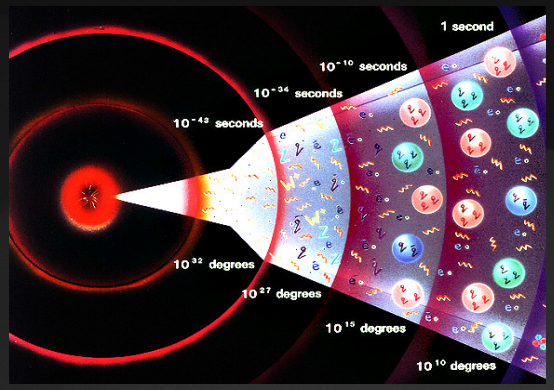


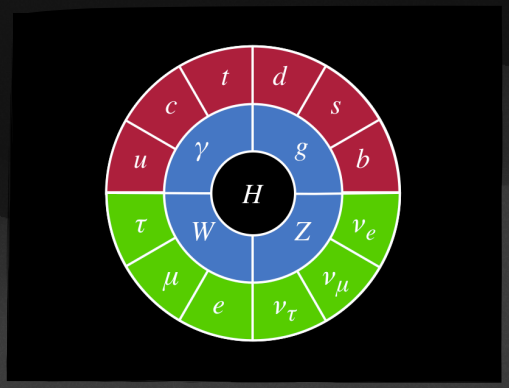

τ
e

GREAT! BUT…?!?



WHAT HAPPENED (JUST) AFTER THE BIG BANG?



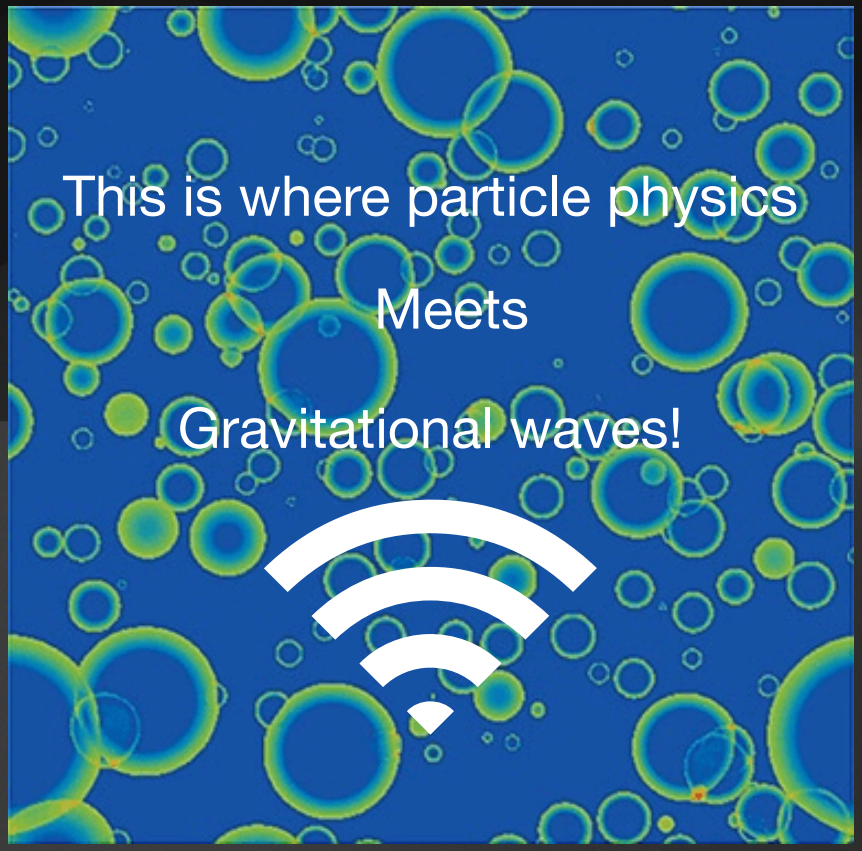


T ≅ 160 GeV



This is known as the Electroweak phase transition

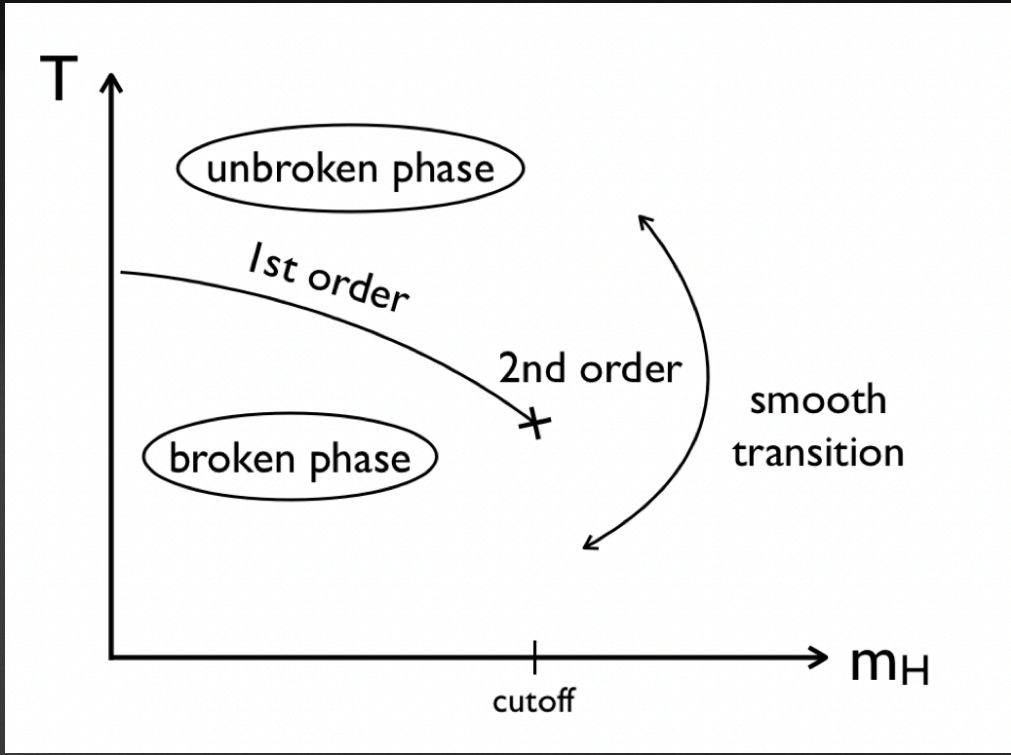
WHAT HAPPENED (JUST) AFTER THE BIG BANG?





Simulation of Higgs-bubble nucleation and expansion history during a first-order electroweak phase transition,
Ref: JCAP 04 014, See also: CERN courier July 2022

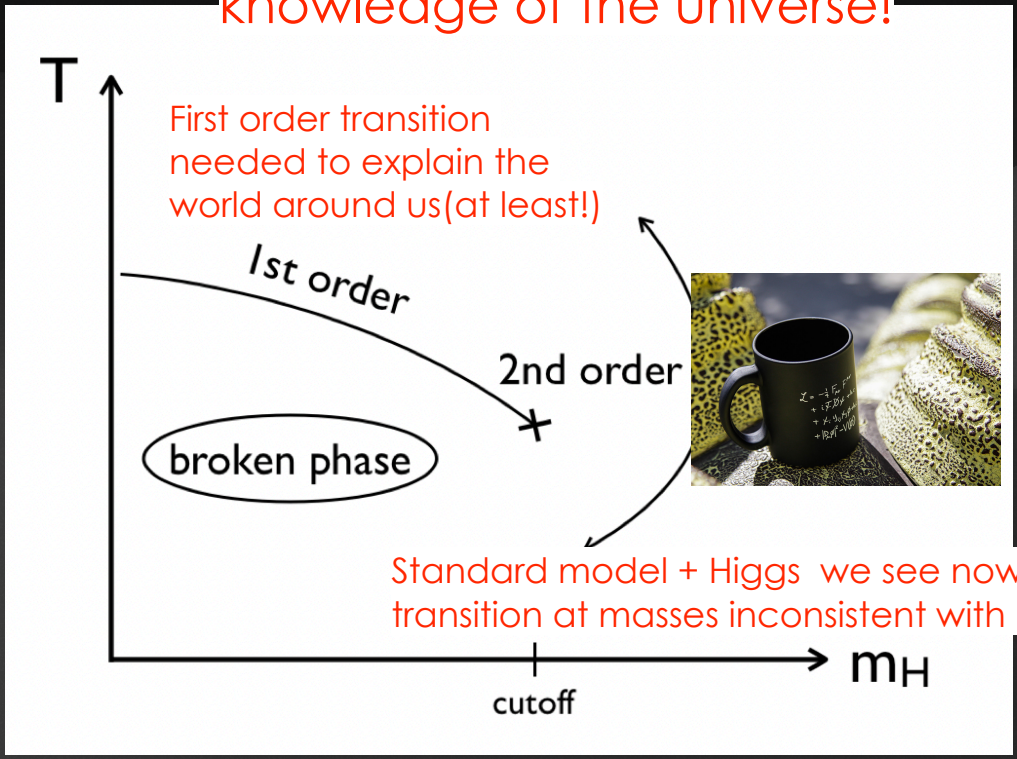
ELECTROWEAK PHASE TRANSITION



Papaefstathiou, A., White, G. The electro-weak phase transition at colliders: confronting theoretical uncertainties and complementary channels. *J. High Energ. Phys.* **2021**, 99 (2021), arXiv:2010.00597

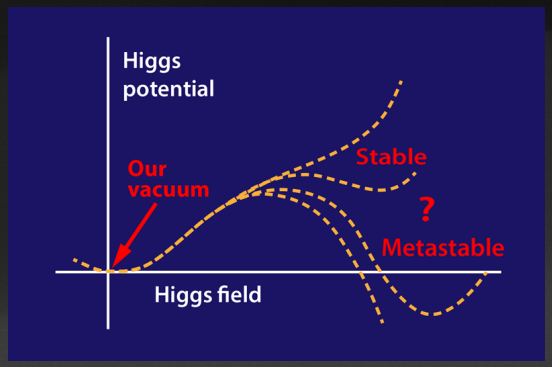
ELECTROWEAK PHASE TRANSITION

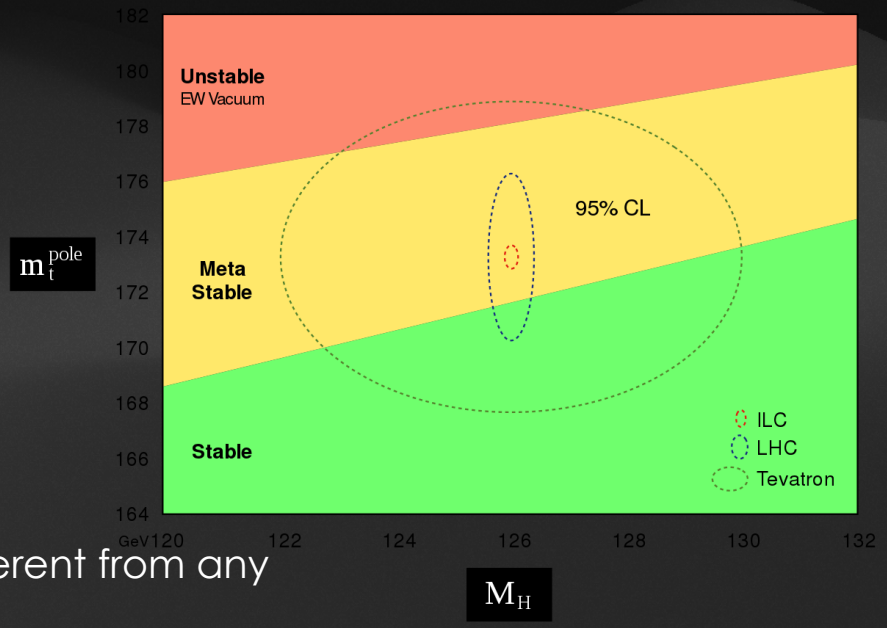
The SM + Higgs mechanism alone is inconsistent with our knowledge of the universe!



Papaefstathiou, A., White, G. The electro-weak phase transition at colliders: confronting theoretical uncertainties and complementary channels. *J. High Energ. Phys.* **2021**, 99 (2021), arXiv:2010.00597

HIGGS AND THE STANDARD MODEL

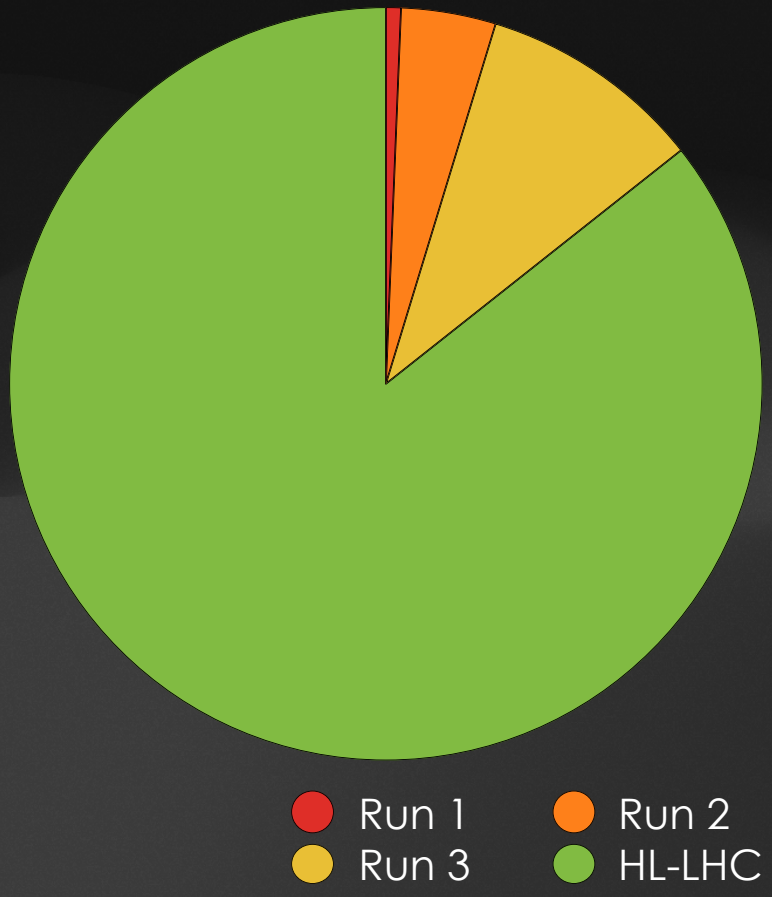




Completely new particle - very different from any particle that was studied in past
that is after 15 years, known to some accuracy

Linked to puzzling questions in fundamental physics

LHC IS JUST GETTING STARTED



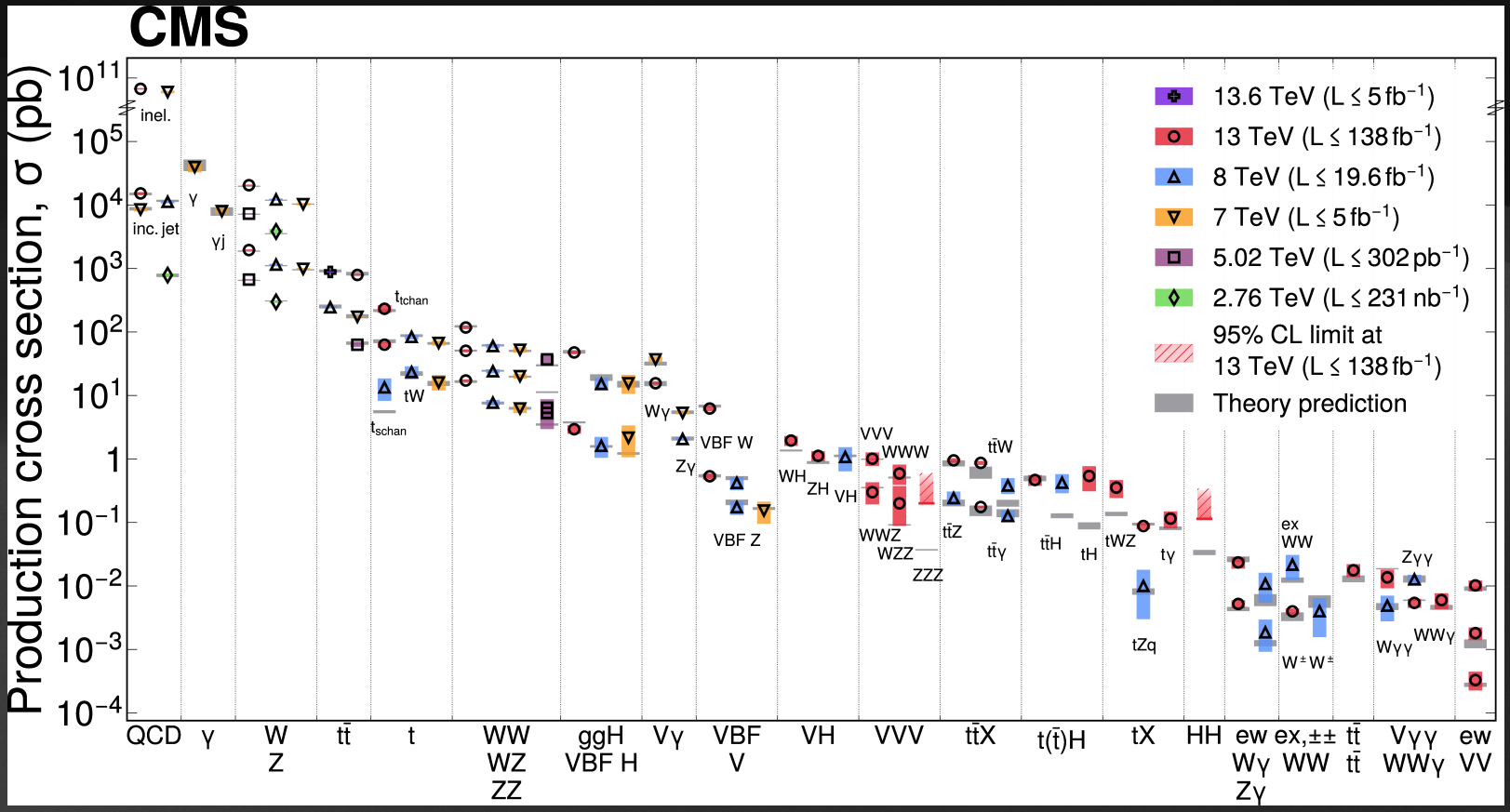
Regularly forgotten:

We have examined about 9% of the LHC data

There can still be surprises

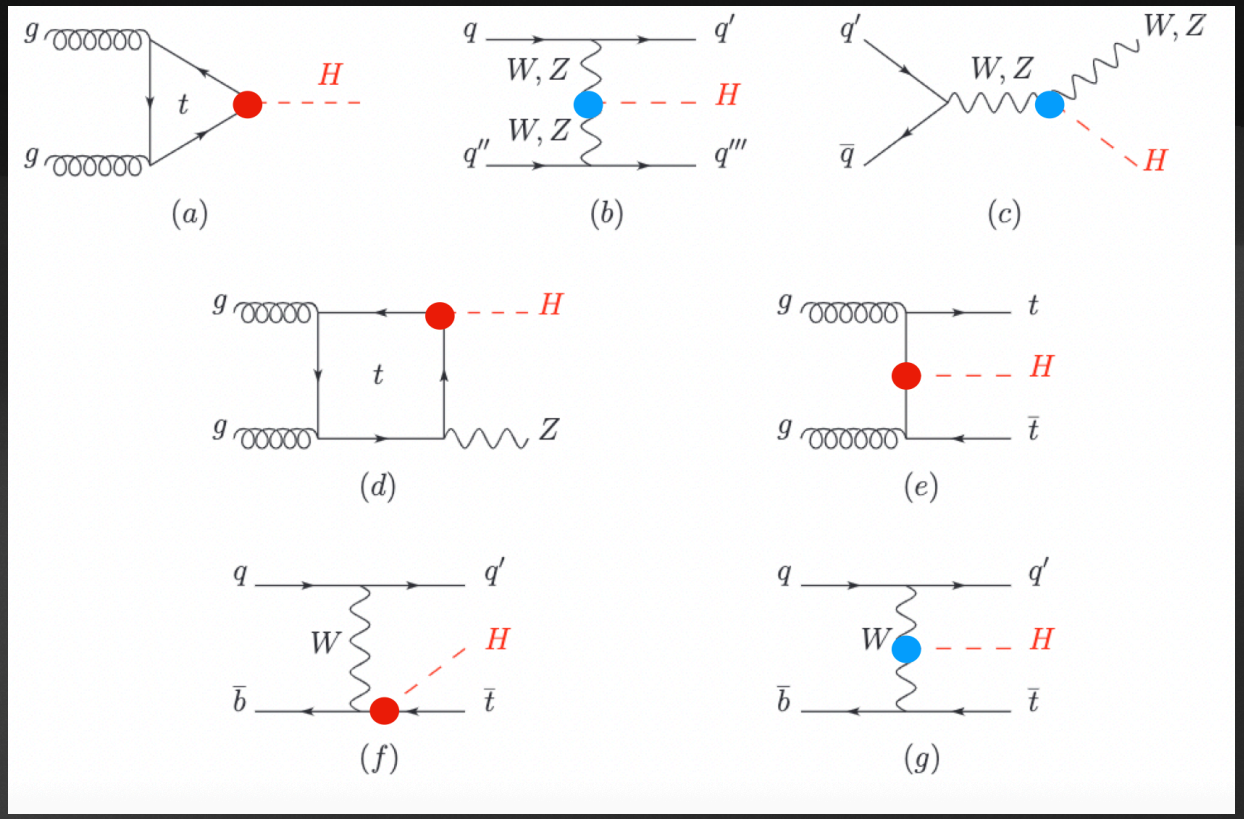
And any future collider should be able to study surprises too!

STANDARD MODEL AT THE LHC: ORDERS OF MAGNITUDE



Ref: CMS "stairway to discovery" SM crosss section paper SMP-23-004 arxiv:2045.18661 (Physics Reports)

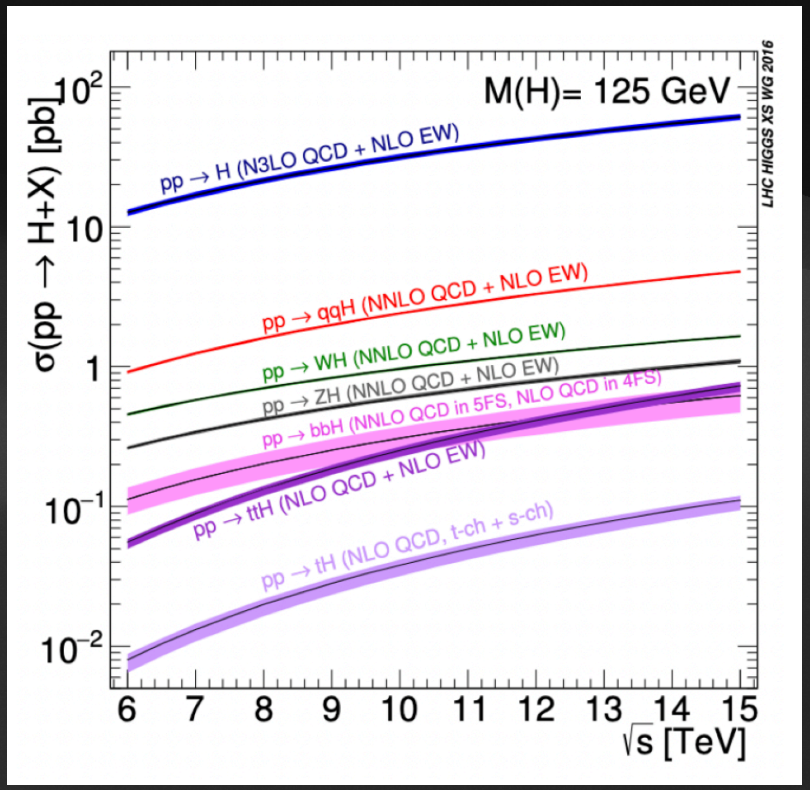
HOW TO MAKE A HIGGS BOSON*



* according to the standard model

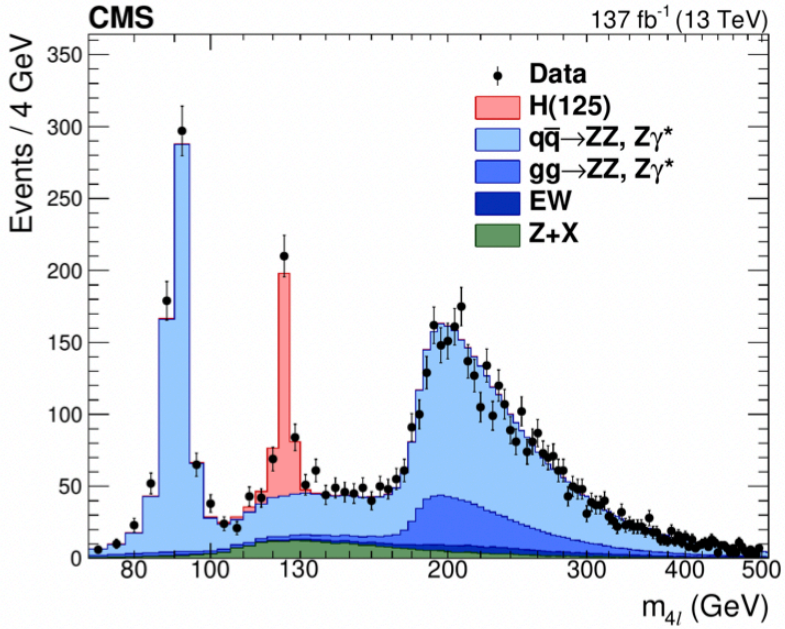
HOW TO SPOT A HIGGS BOSON*

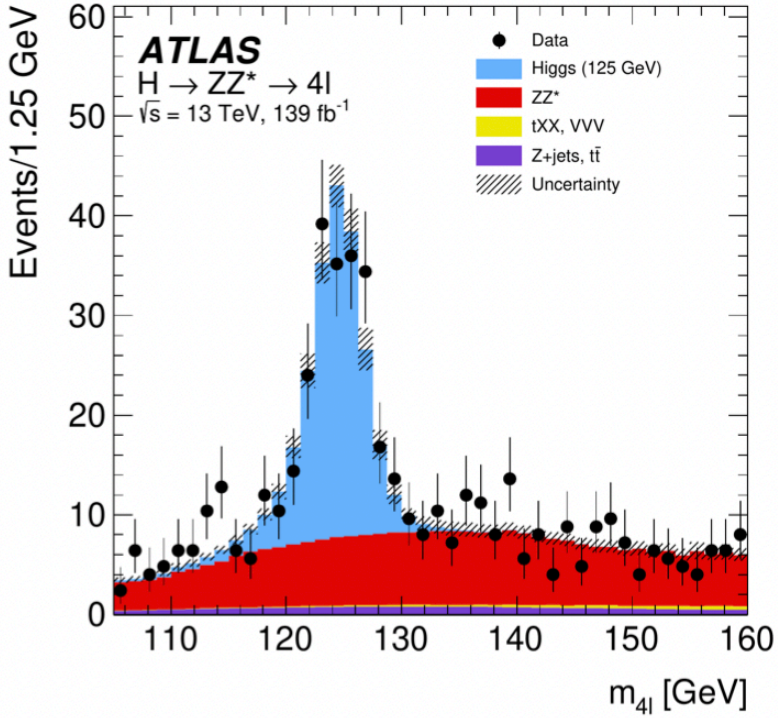
Decay	BR [%]
bb	57.7
ττ	6.32
cc	2.91
μμ	0.022
WW	21.5
gg	8.57
ZZ	2.64
γγ	0.23
Zγ	0.15
ΓH [MeV]	4.15



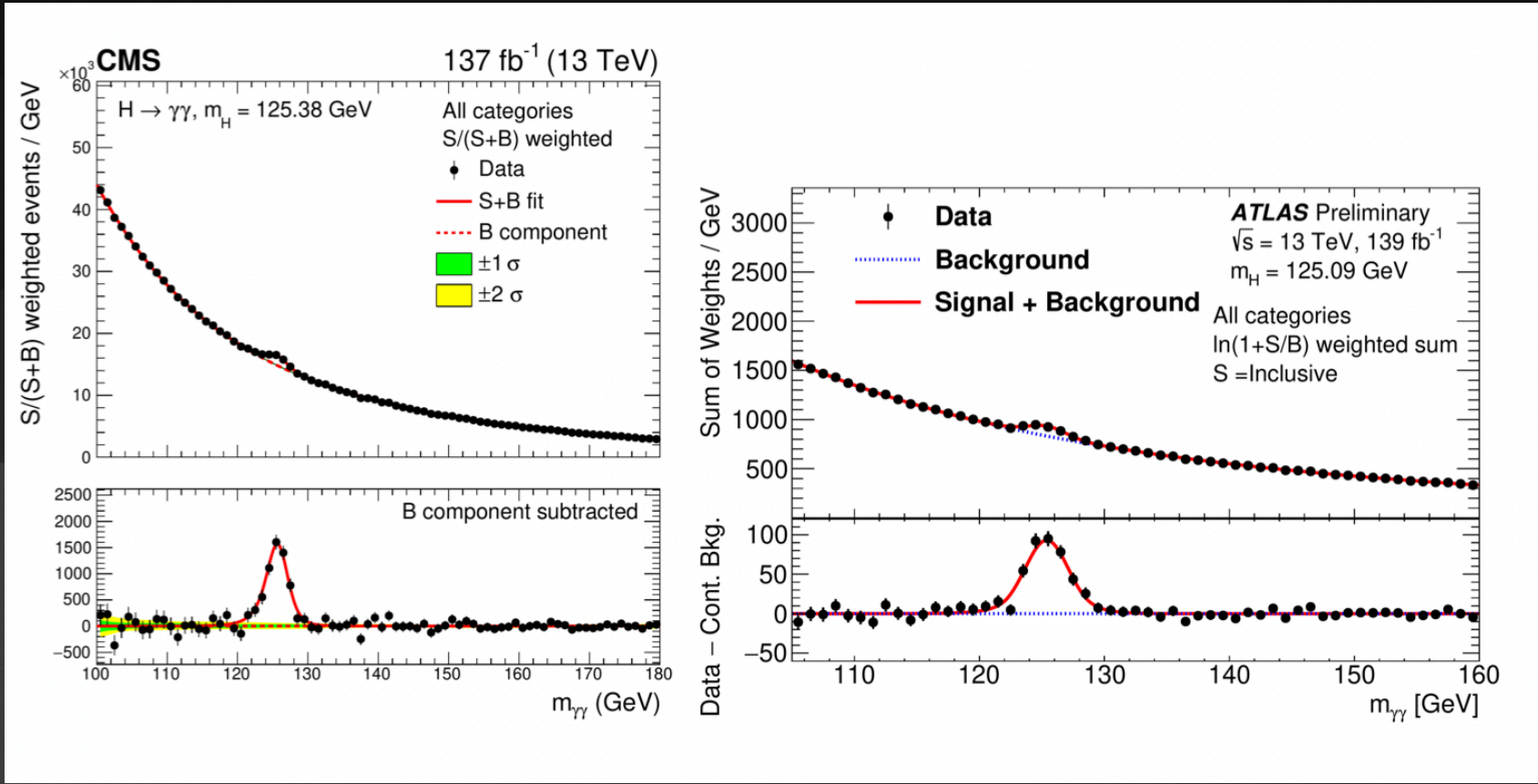
* according to the standard model

HIGGS BOSONS!

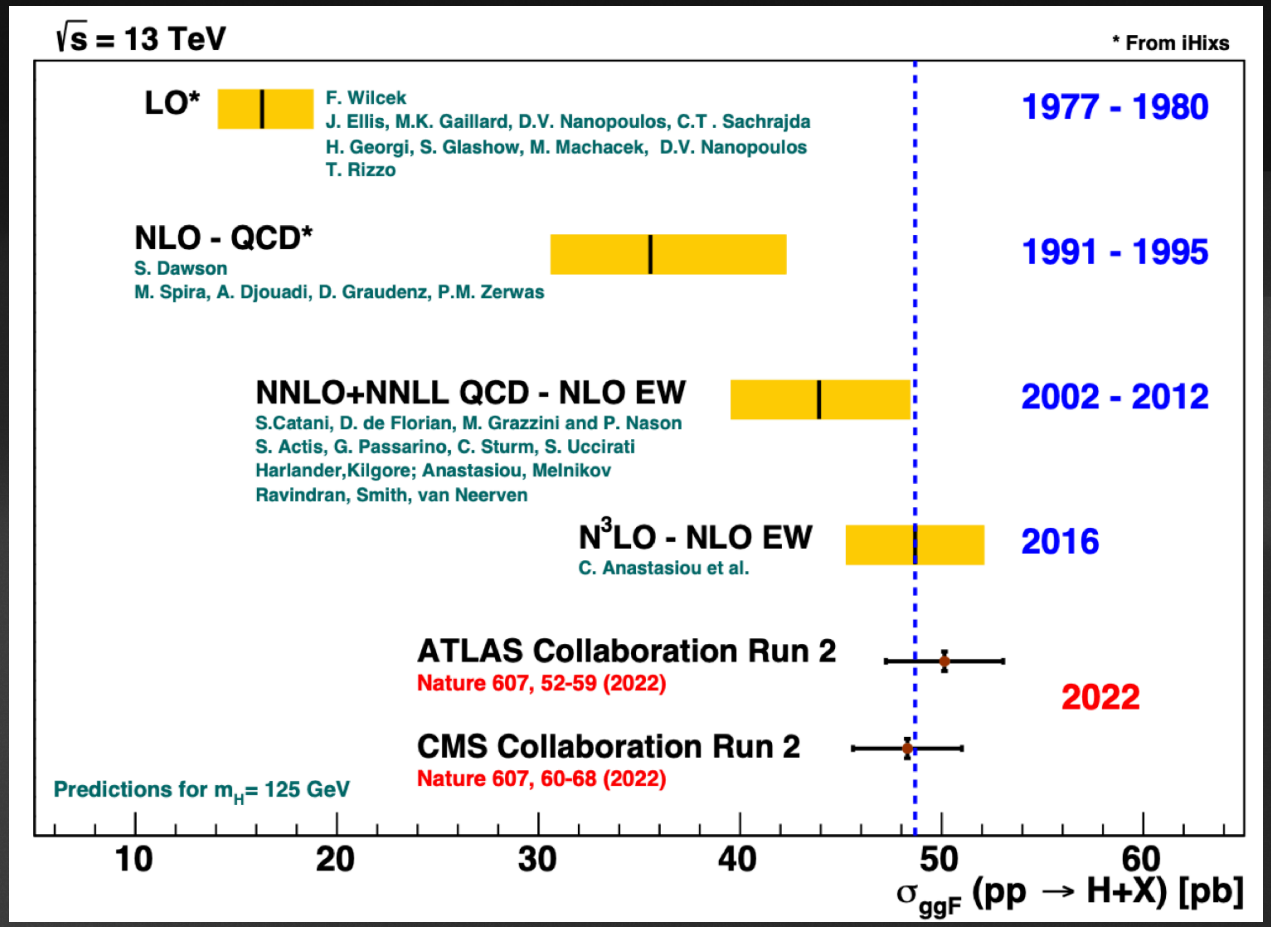




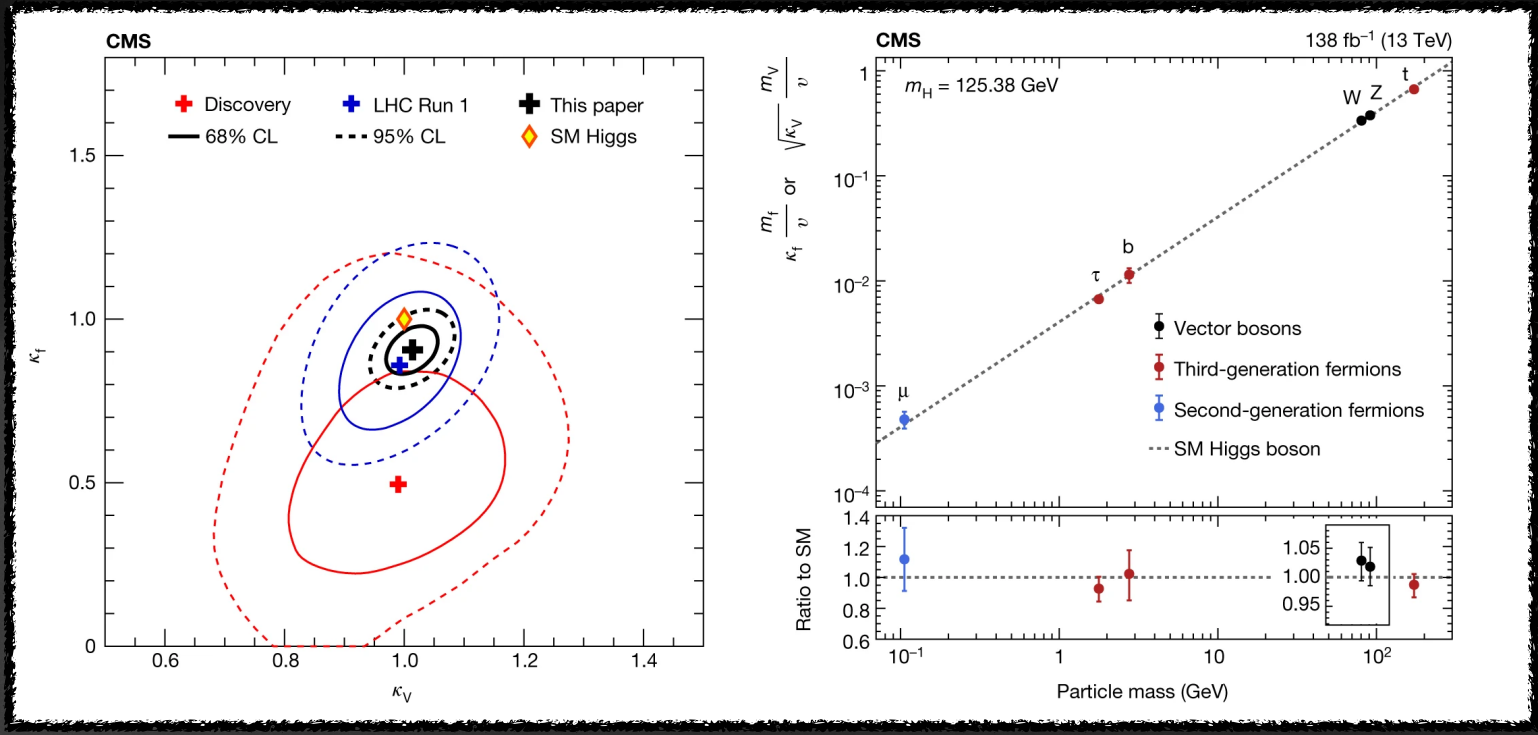
HIGGS BOSONS!



COMPARING TO THEORY

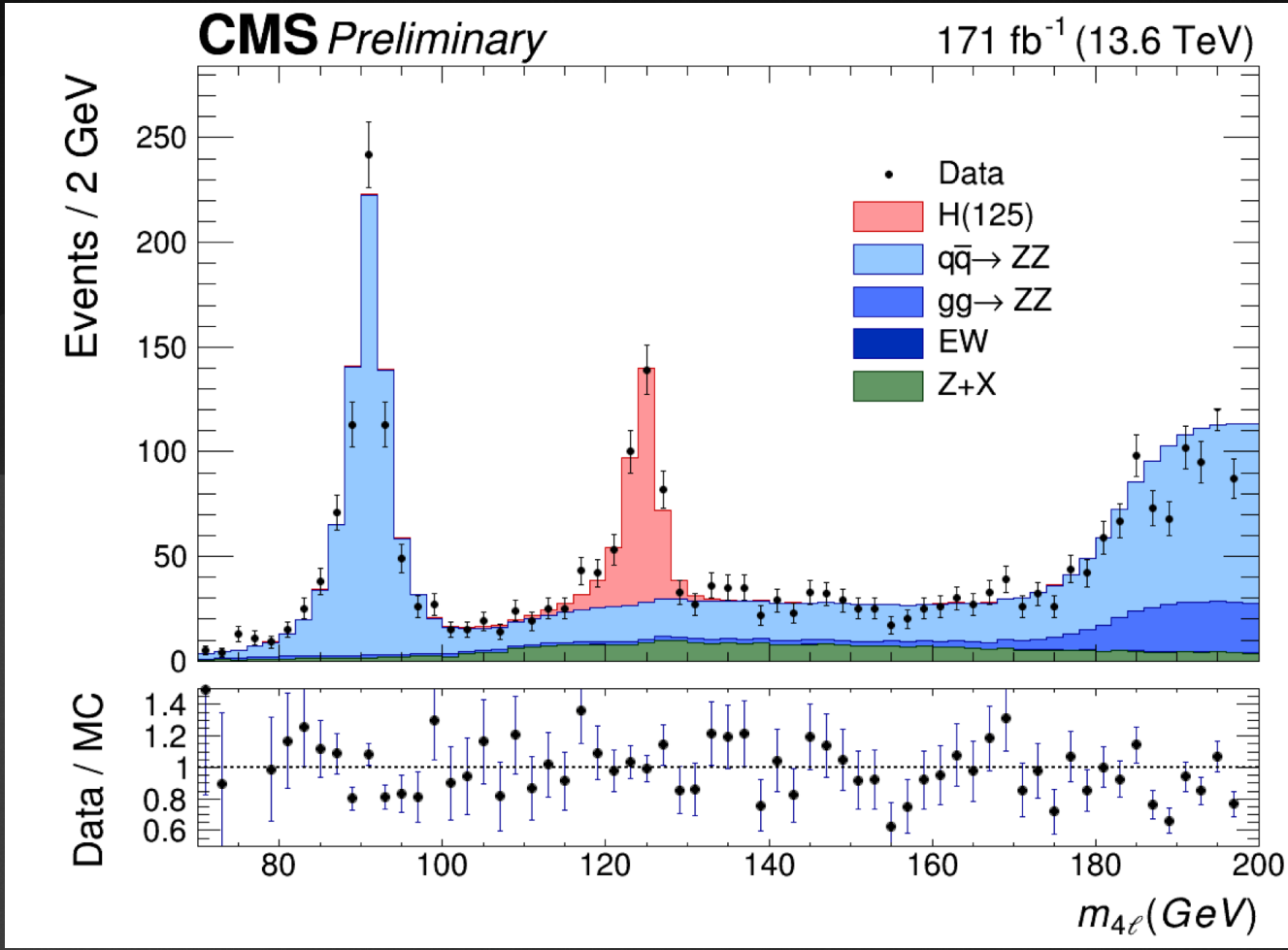


HIGGS AT THE LHC

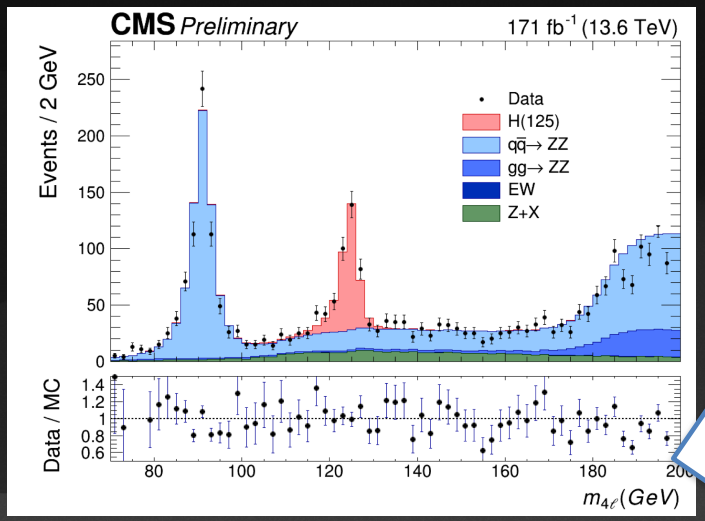


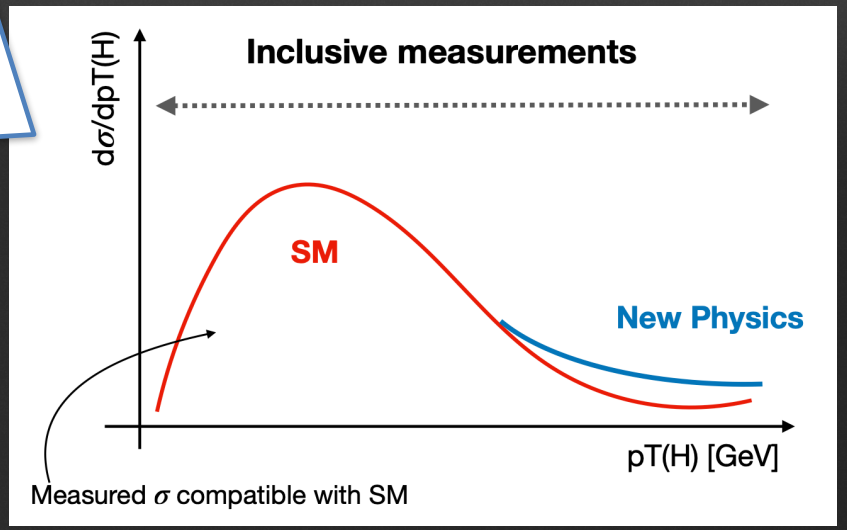
The CMS Collaboration. A portrait of the Higgs boson by the CMS experiment ten years after the discovery. *Nature* **607**, 60–68 (2022). arXiv:2207.00043

CAN WE DO MORE NOW? YES!

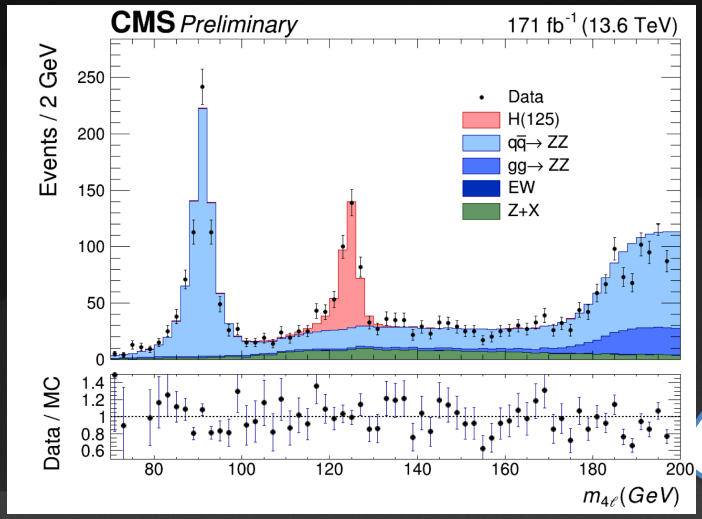


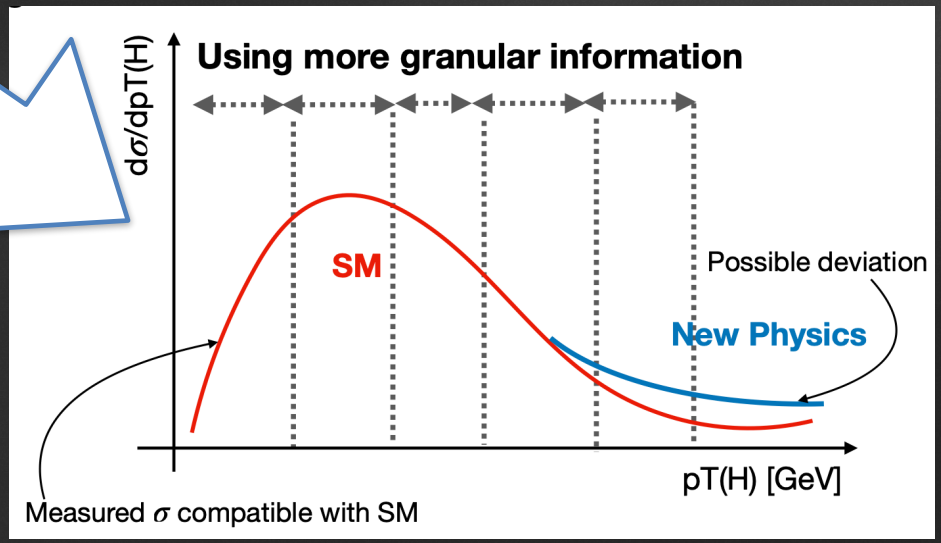
CAN WE DO MORE NOW? YES!



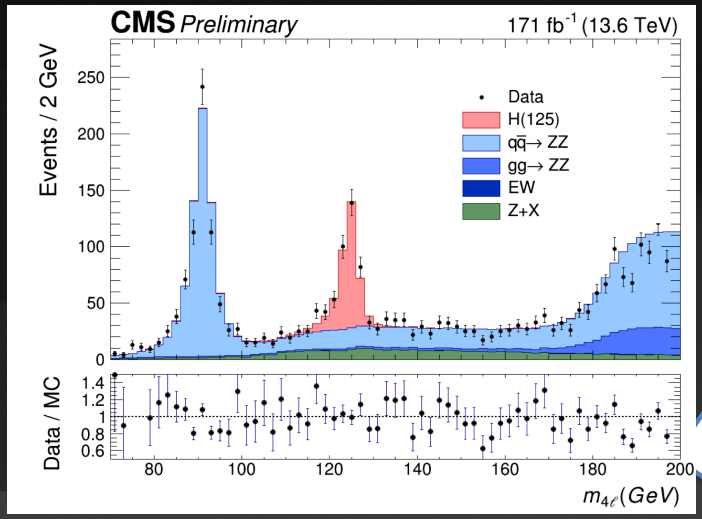


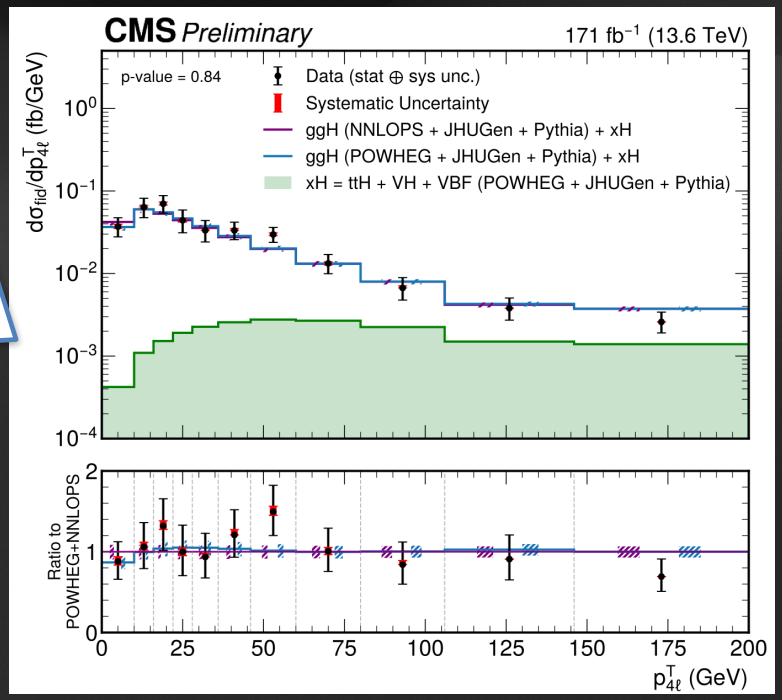
CAN WE DO MORE NOW? YES!



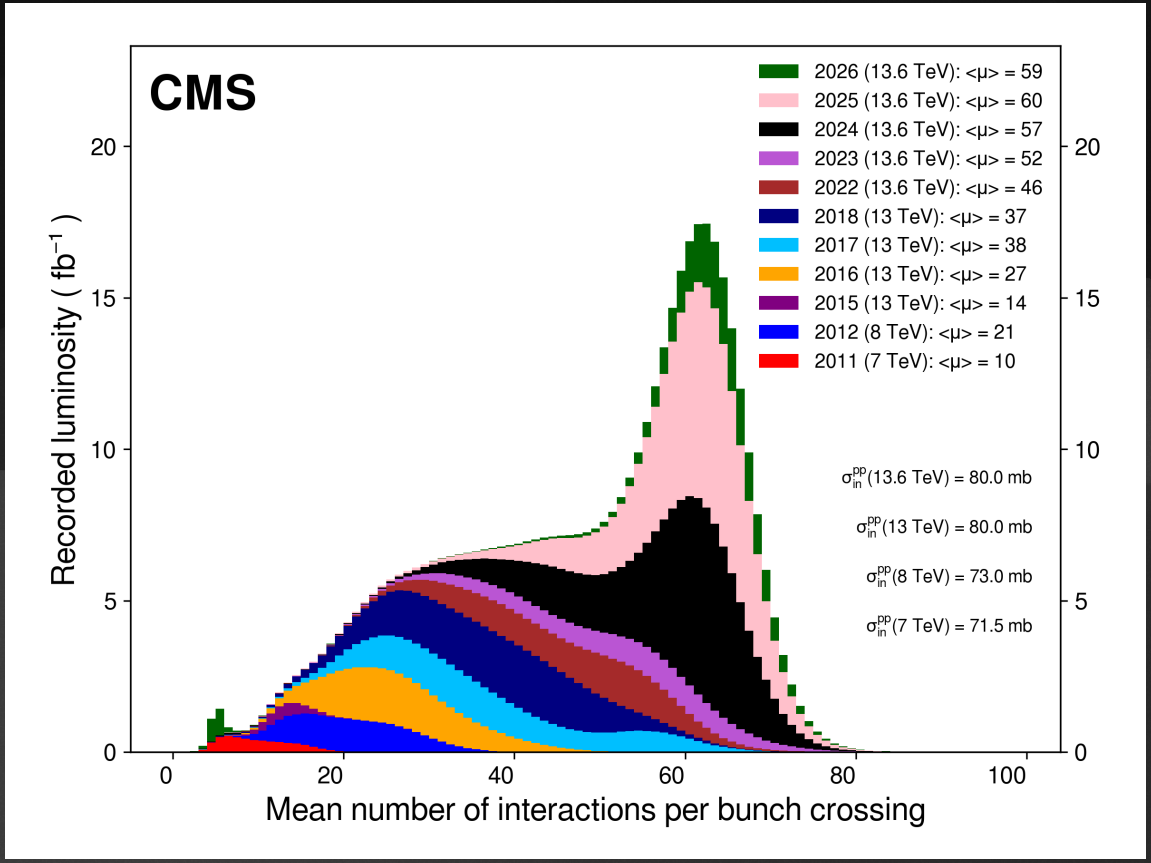


CAN WE DO MORE NOW? YES!





LHC PERFORMANCE OVER THE YEARS



So many collisions…

Too many collisions?

socials: freyablekman

THE CMS TRIGGER PARKING AND SCOUTING



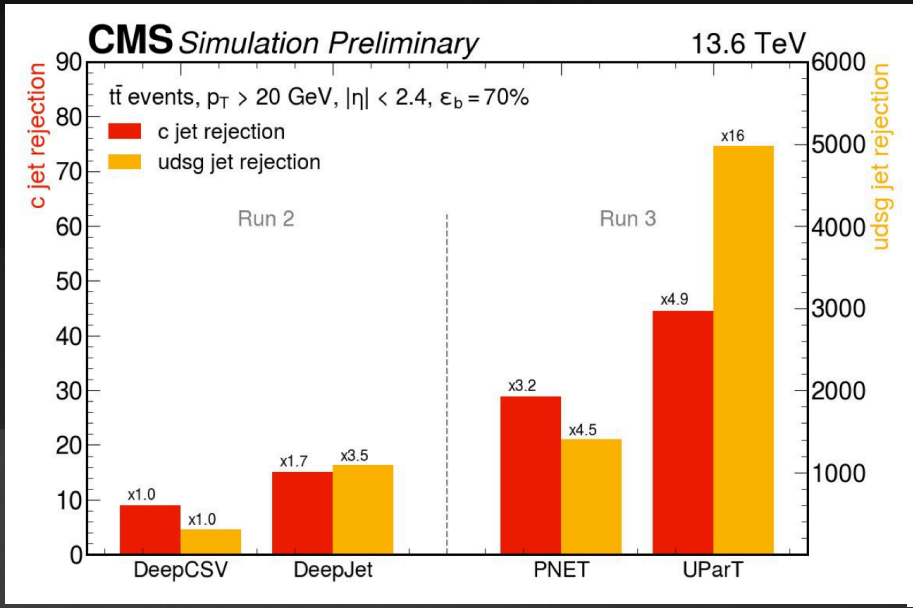
socials: freyablekman

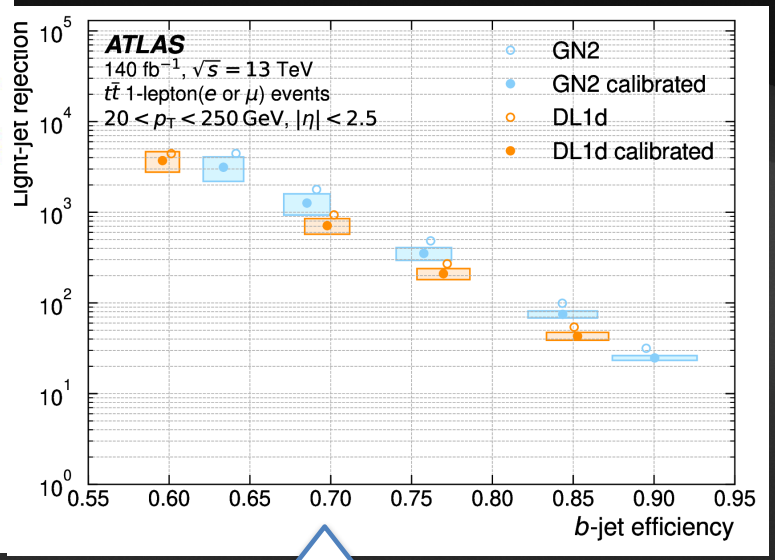
THAT ALSO MEANS… EVEN MORE MACHINE LEARNING!

- Collider results are usually very heavy in ML
- Most methods are supervised deep learning classification or reconstruction networks, often trained on simulations
  - Our simulations are very good - but they do have limitations!
  - (Generative) ML also being introduced into the simulations. No realistic studies on end-to-end reliability yet



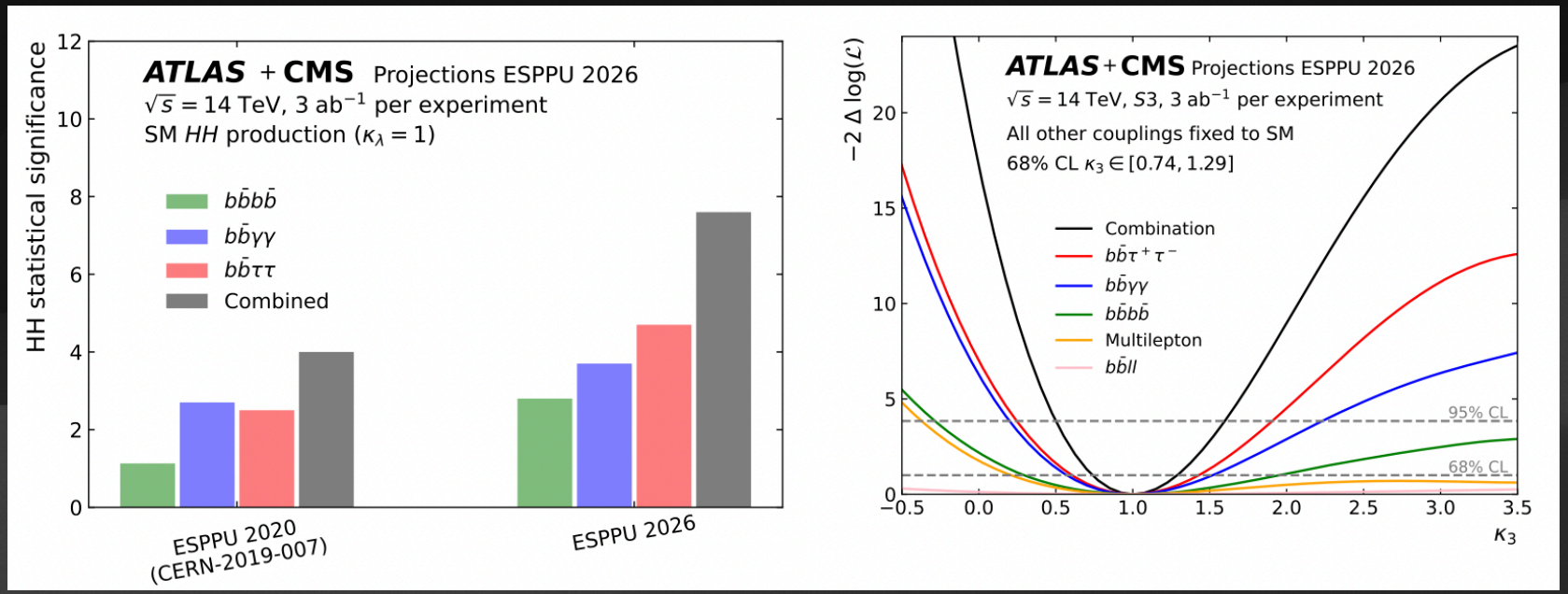
THE CUTTING EDGE!





CMS @ 70% efficiency (for b jets)

GAINS…: DI-HIGGS PRODUCTION

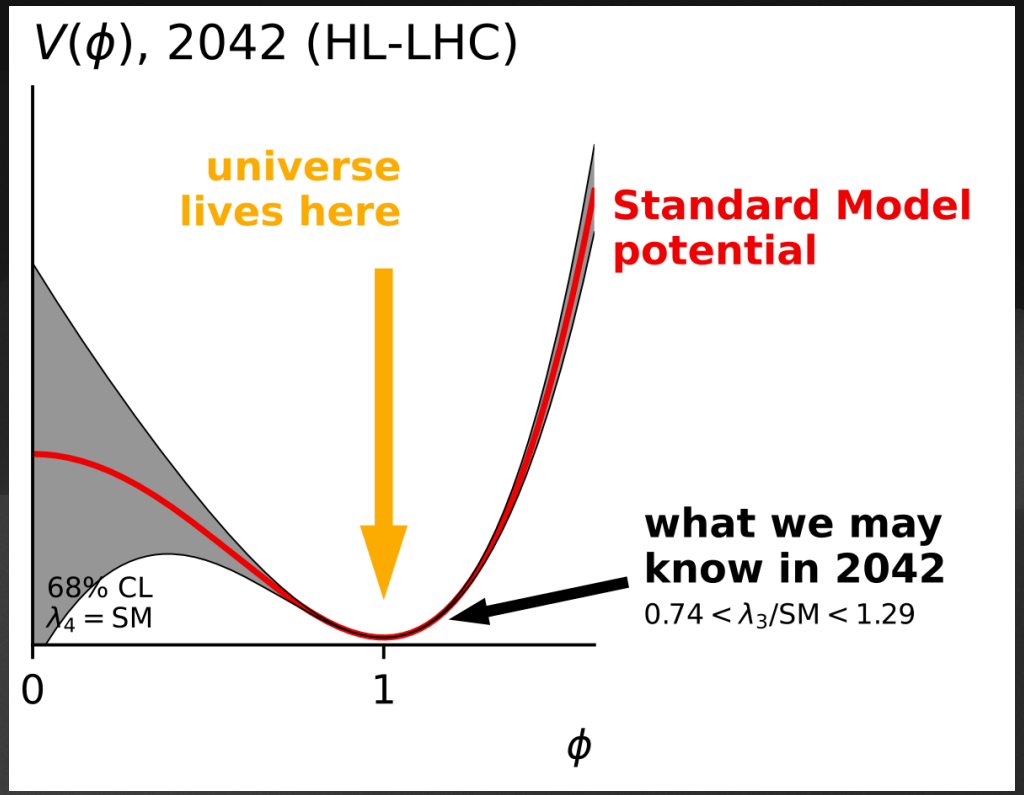


SM trilinear coupling parameter λ_3, ($\kappa_3 = \lambda_3/\lambda^{SM}_3$) can be measured with -26% +29% precision in S3 scenario with 3 ab^{-1} in ATLAS+CMS combination !!!

Big strides in reconstruction techniques and background rejection
(definitely not scaling by luminosity compared to previous EPPSU updates)
clear that HH will be observed soon already - maybe 3 s.d. evidence likely end of Run 3, 7+ s.d. at end of HL-LHC
HHH: 86 times the SM (S3 scenario, 3 ab^{-1})

Recommended further reading (comments on how to improve with e+e-): "The Higgs trilinear coupling in the SMEFT at the HL-LHC and the FCC-ee", ter Hoeve et.al.,

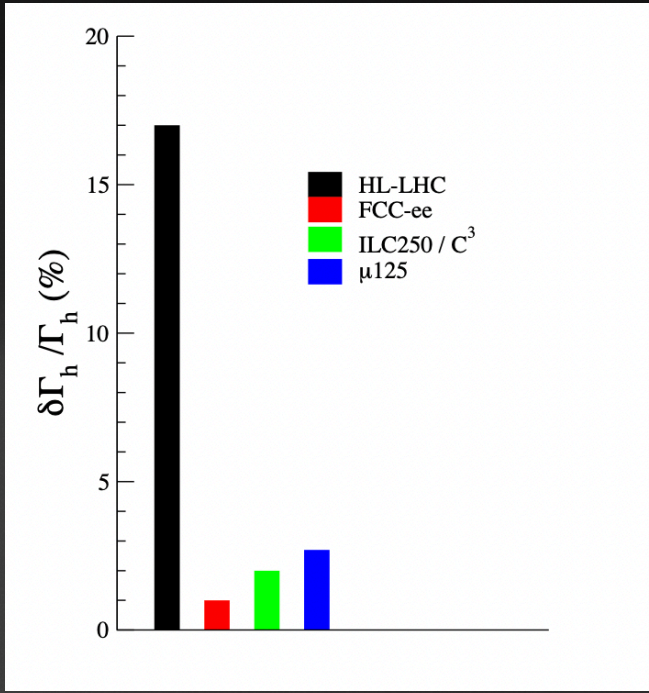
THE BROUT-ENGLERT-HIGGS POTENTIAL



Plot: Gavin Salam

- To do better, we would need a collider
- But not a ee-collider
  - Something like muon collider or FCC-hh

HIGGS AND THE STANDARD MODEL AFTER HL-LHC

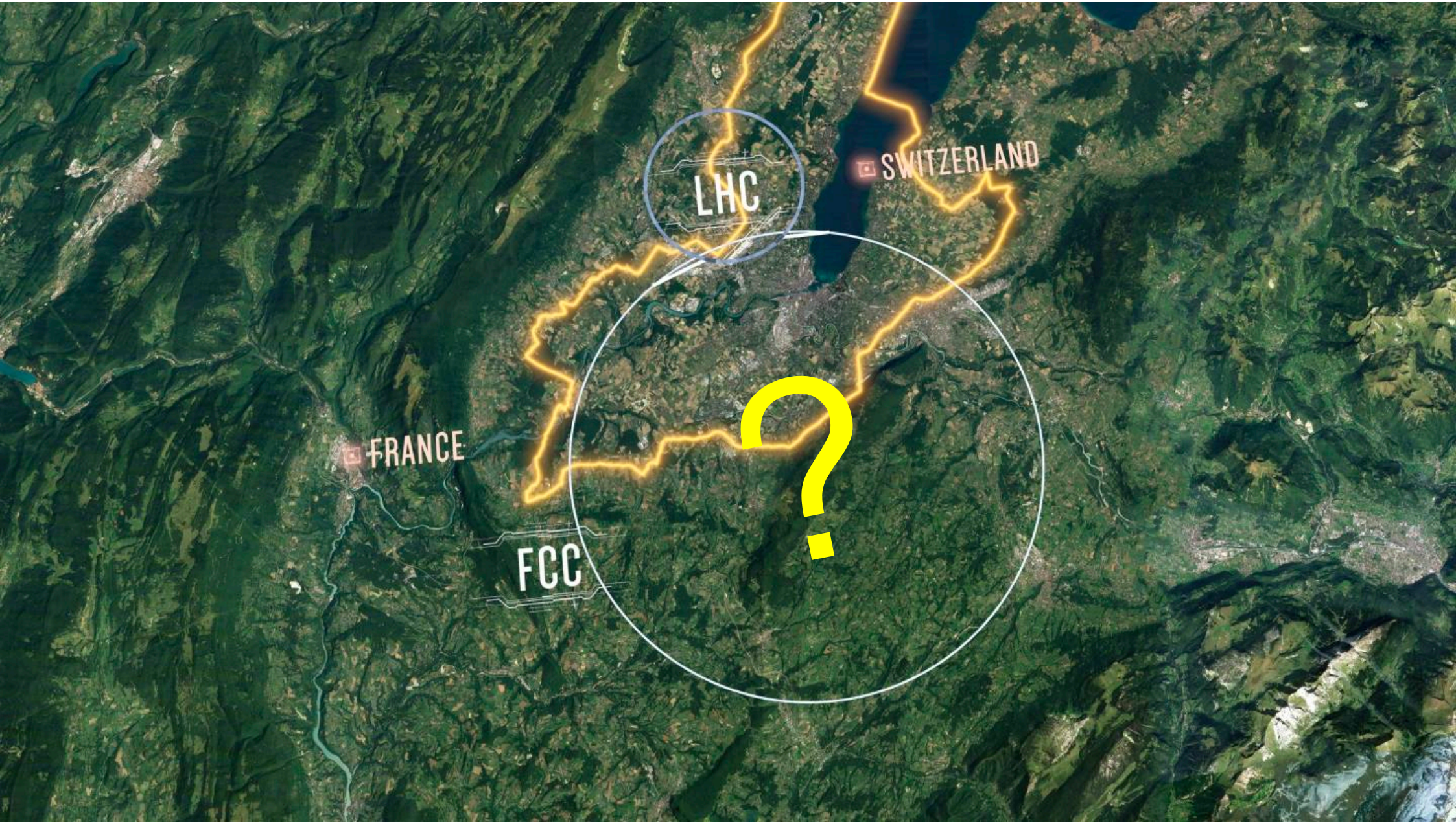


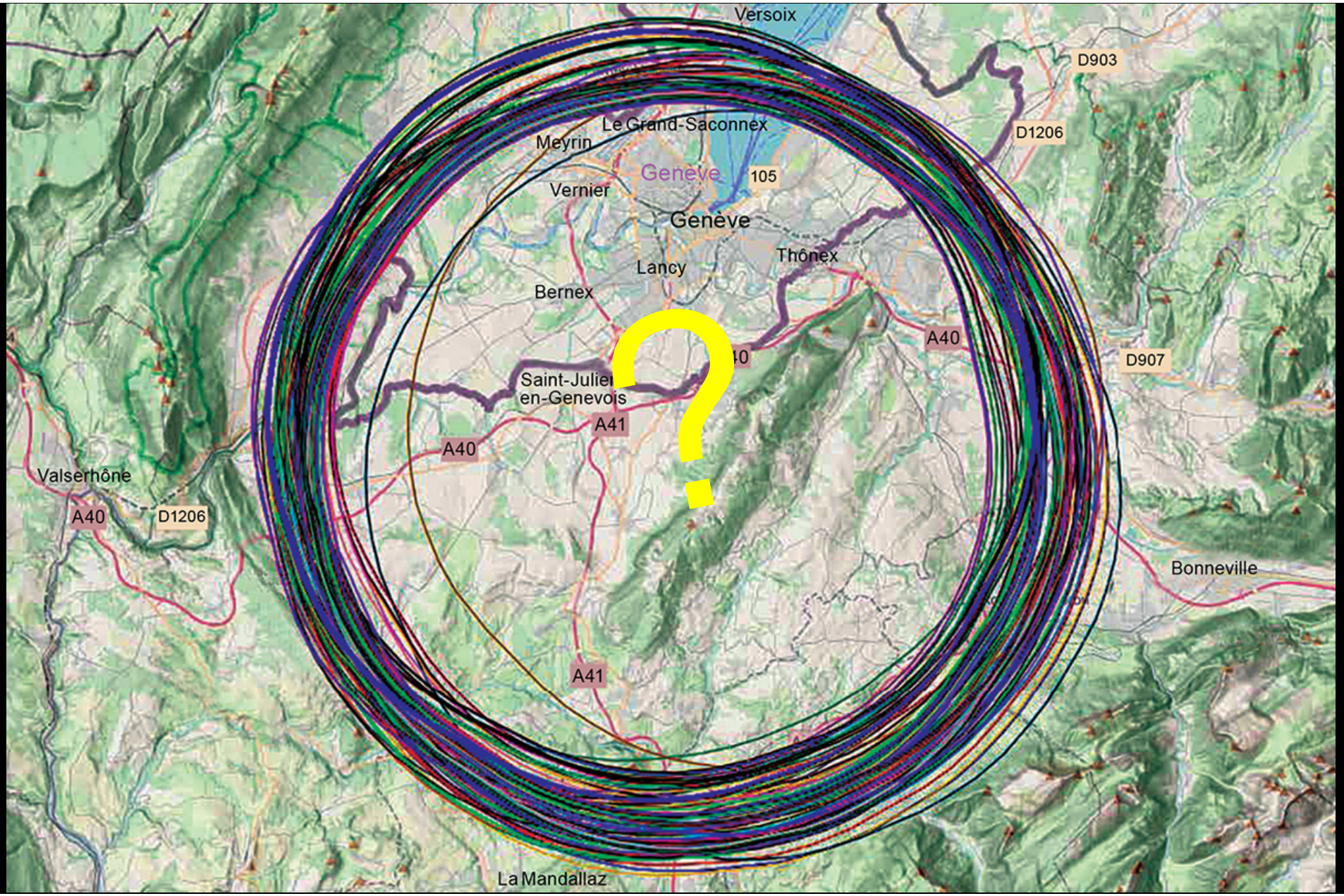
HL-LHC gives 10-few% precision on SM properties of the Higgs boson

Example: Higgs full decay width (and decay to invisible particles, both essential for investigating link to dark matter)

BTW: same is true for many other SM parameters via SMEFT

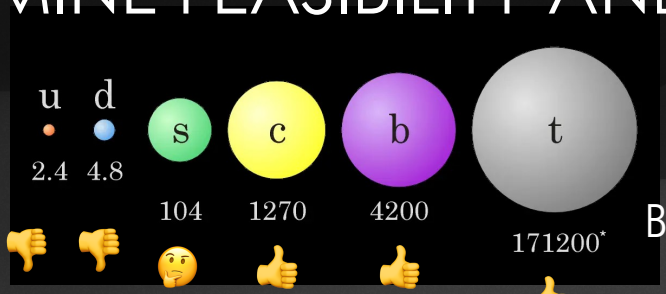
S. Dawson et al, Report of the Topical Group on Higgs Physics for Snowmass 2021: The Case for Precision Higgs Physics, arXiv:2209.07510


LHC
SWITZERLAND
FRANCE
FCC
?


Versoix
D903
Le Grand-Saconnex
Meyrin
D1206
Genève
105
Vernier
Genève
Thônex
Lancy
Bernex
A40
D907
Saint-Julien
en-Genevois
A41
A40
Valserhône
A40
D1206
Bonneville
A41
La Mandallaz

WISHLIST FOR THE FUTURE
TO DETERMINE FEASIBILITY AND NEEDS





?

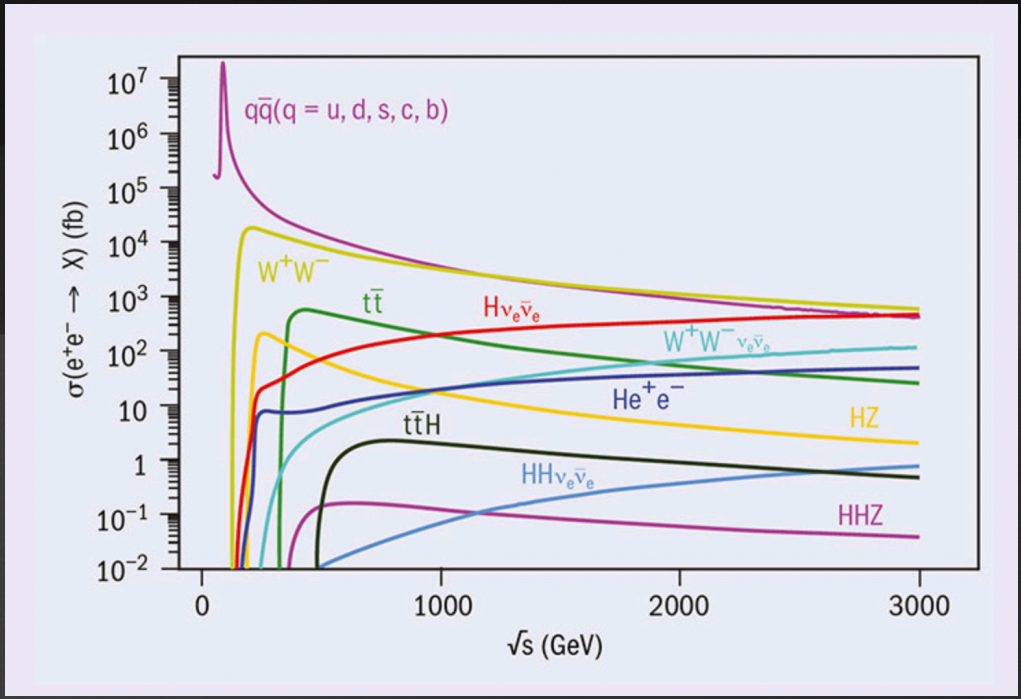
Better than 10%

Measuring Higgs boson and other particles, couplings to quarks and gauge bosons at least one order of magnitude more precisely
(needs also huge theoretical physics advances btw!)

More details: J. List, Open study questions, 1st ECFA workshop on e+e- Higgs/EW/Top factories, https://indico.desy.de/event/33640/

*) Masses not to scale. But they do increase

COLLISION ENERGY DETERMINES WHAT WE CAN STUDY



Higgs factory =

Very high statistics e+e- machine with Z+H at maximum (240-250 GeV)

Run at lower energies like Z pole and WW threshold possible with circular accelerators

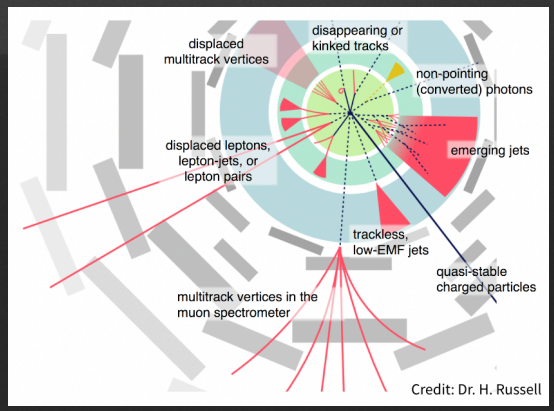
Runs at higher energies (ttbar, higher) most challenging for the accelerator aspect

CERN courier, https://cerncourier.com/a/clic-steps-up-to-the-tev-challenge/

WISHLIST FOR THE FUTURE
TO DETERMINE FEASIBILITY AND NEEDS



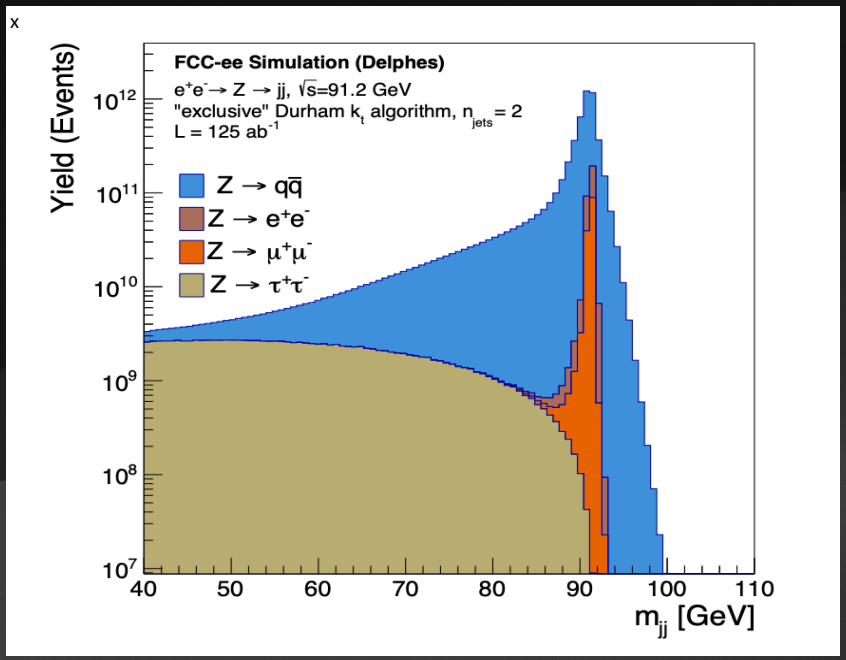
Measure the free parameters of the standard model related to Higgs, Z and W boson with an order of magnitude more accuracy at least

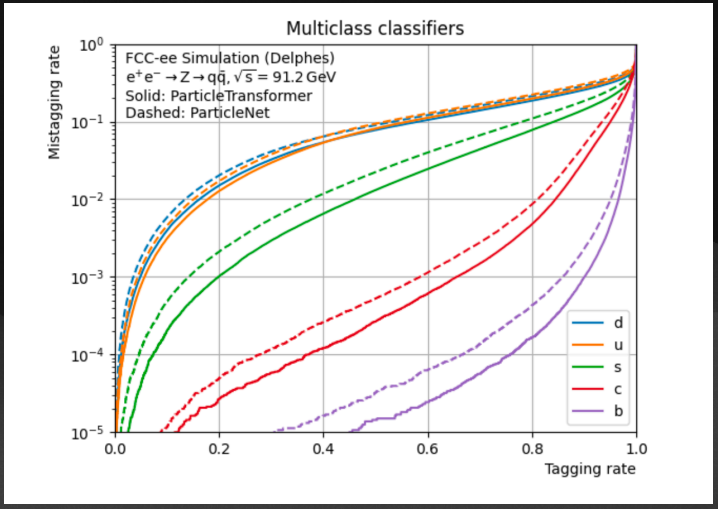


Bonus but not the main goal: search for undiscovered particles. Benchmark: long-lived particles as great for detector design aspirations

More details: J. List, Open study questions, 1st ECFA workshop on e+e- Higgs/EW/Top factories, https://indico.desy.de/event/33640/

COULD WE DO EVEN MORE?





	d	u	s	c	b
ParticleNet	0.878	0.874	0.938	0.978	0.996
ParticleTransformer	0.894	0.888	0.954	0.984	0.997

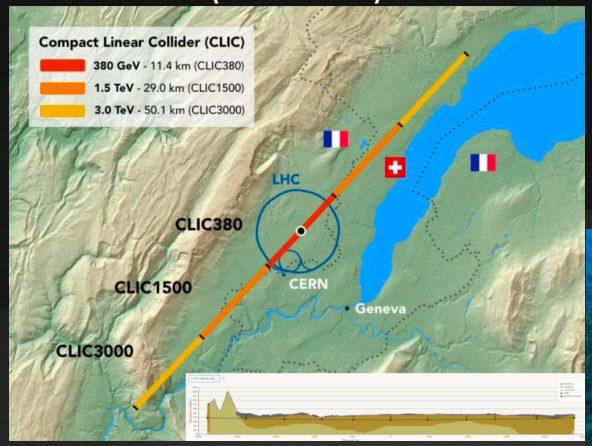
Table 6.4: AUC scores showing the flavour tagging performance of the multiclass models.

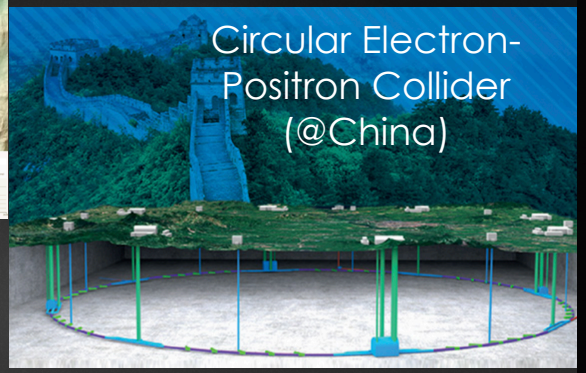
In ten years, it should be possible to fully identify every constituent of every event (also up, down quarks and gluons!)

Plots: K. Gautam, R. Kootz.
Publishedh examples (many more available unpublished): Jet-Origin Identification and Its Application at an Electron-Positron Higgs Factory, H.~Liang, Y.~Zhu et.al. https://arxiv.org/pdf/2310.03440

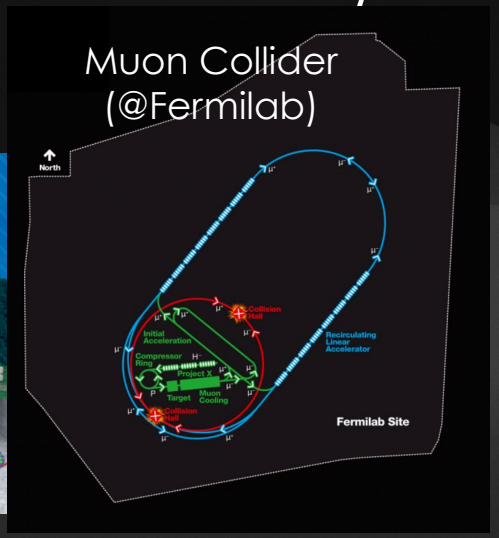
(NOT ALL) EXAMPLES
NOT TO SCALE (OF INTEREST)

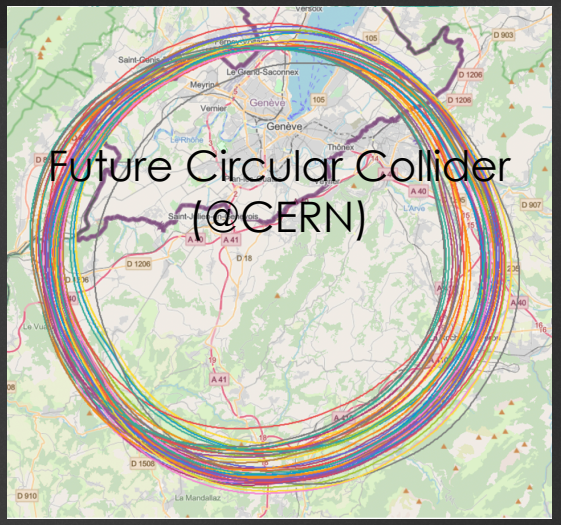
Compact Linear Collider (@CERN)

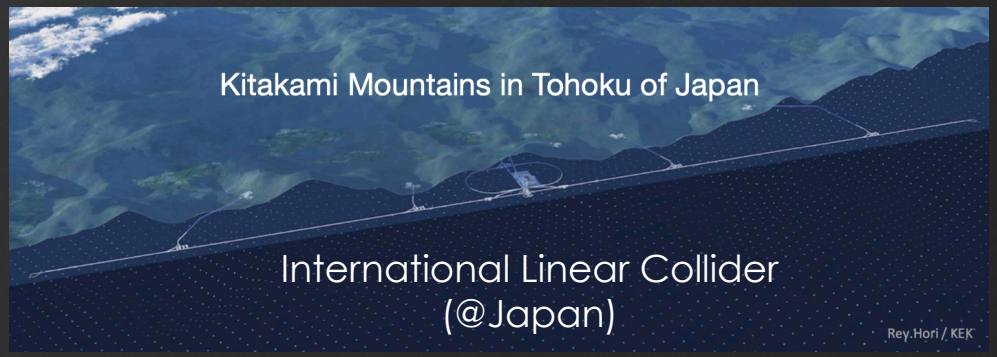




Muon Collider (@Fermilab)







AH, THOSE ORGANISED PARTICLE PHYSICISTS!

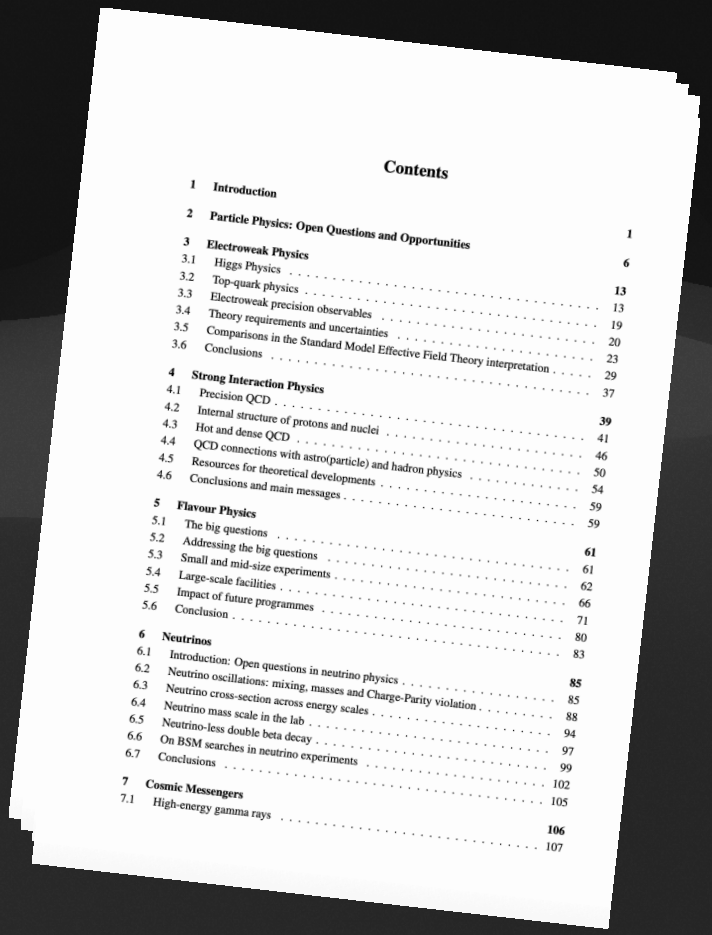
For context, the physics case for the LHC was made in 1984; it then took about 10 years to be approved and 25 years to develop and install the magnets. Colliders are once-in-a-generation endeavours.

Physics Potential:
- Physics Briefing Book (2025)
- Assessment of overall Physics Potential by pan-european panel including adjecent fields, smaller experiments, etc etc.

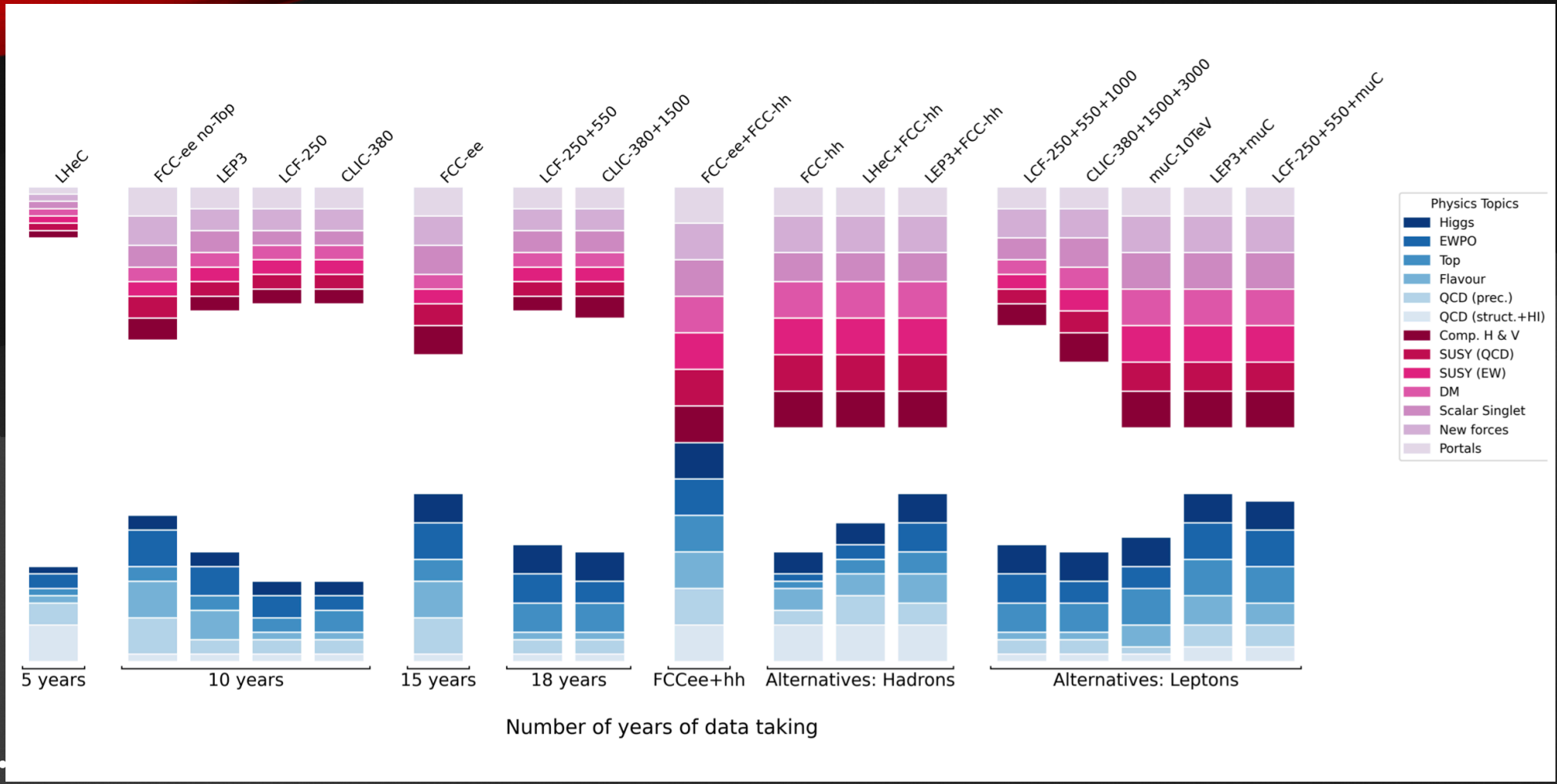
Final input by National HEP communities to the European Strategy (2025-2026)

Public consultation ongoing
Around 2027-2028: Decision by the CERN Member States and international partners
2030s: Start of construction
Mid-2040s: FCC-ee begins operations (15 years)

all the gory detail (and executive summaries): https://cds.cern.ch/record/2944678 = https://arxiv.org/abs/2511.03883

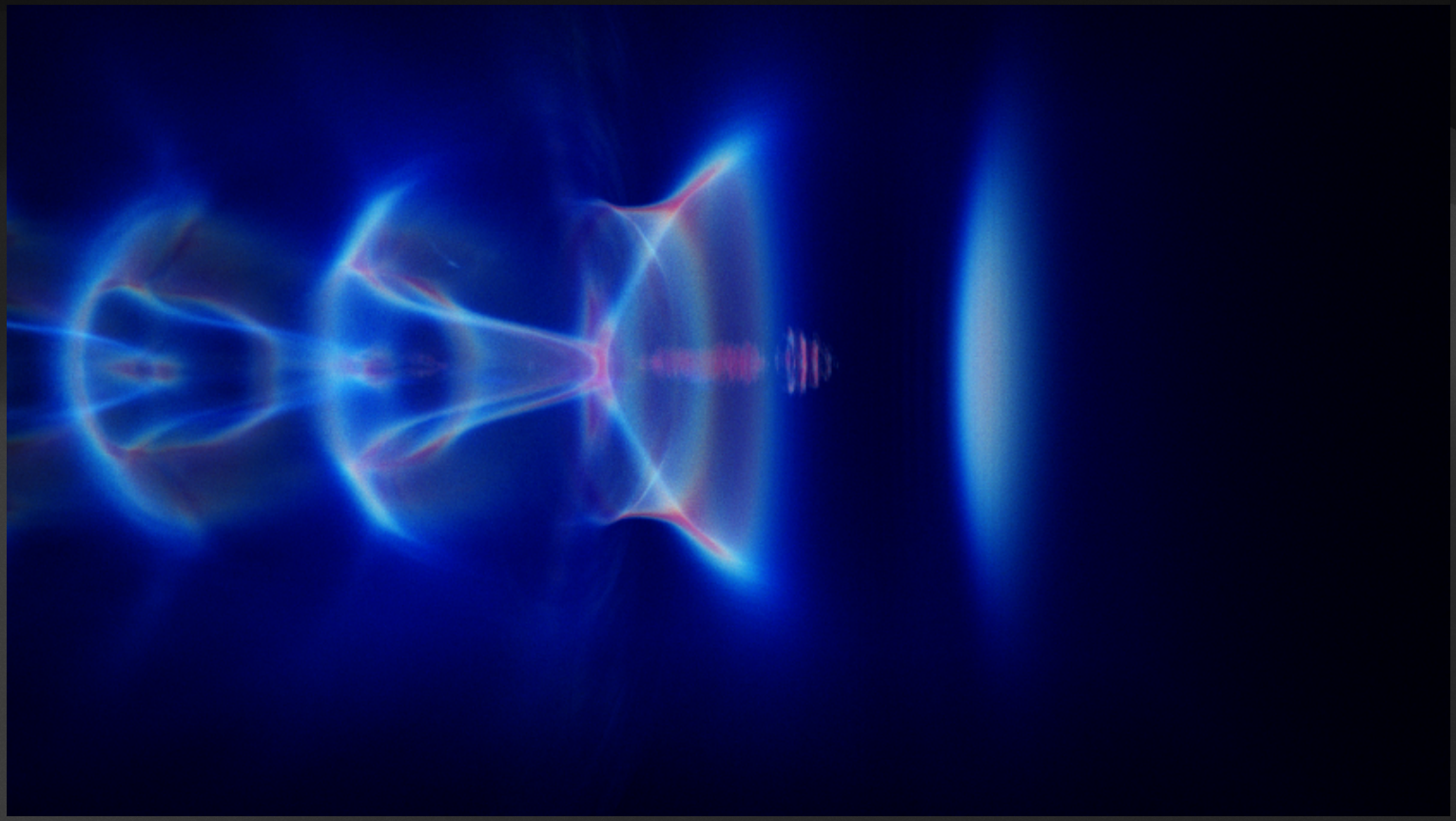


EUROPEAN STRATEGY: APPLES-TO-APPLES COMPARISONS



- all the gory detail (and executive summaries): https://cds.cern.ch/record/2944678 = https://arxiv.org/abs/2511.03883

INNOVATION ON ACCELERATOR SIDE



INNOVATION ON ACCELERATOR SIDE



INNOVATION ON THEORY CALCULATION SIDE



DECISIONS



Highly multidimensional choices

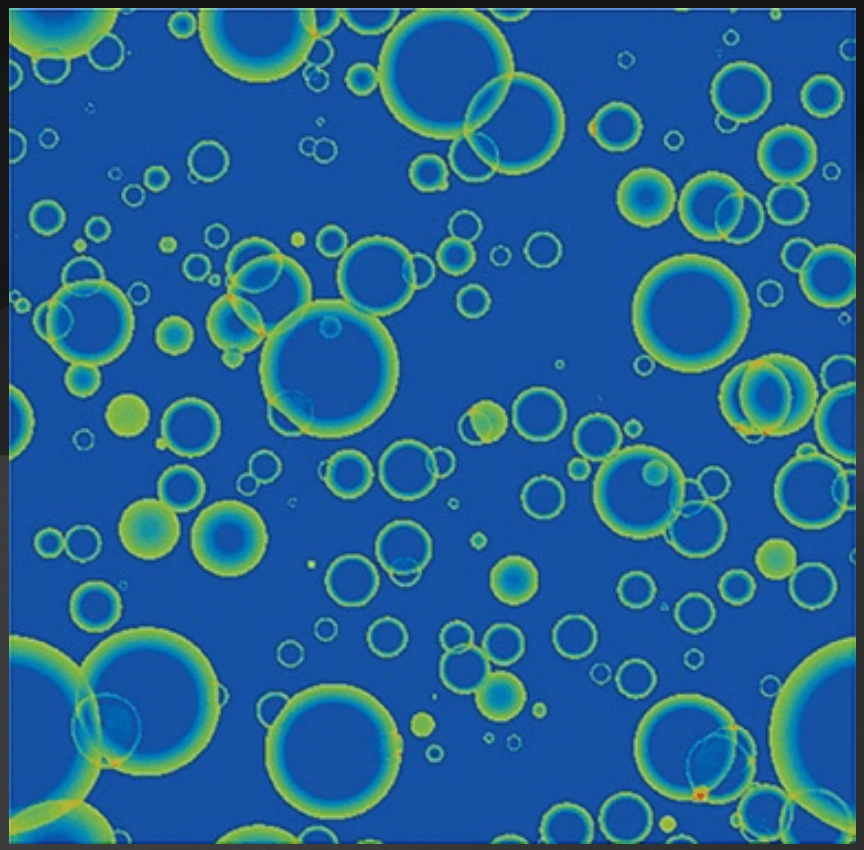
Community has agreed there is a clear need for a Higgs factory

But *what* factory - and part of a bigger plan

Timelines are long. Potential costs are high.

Staying within CERN budget will be a challenge

THE HIGGS BOSON IS THE KEY!

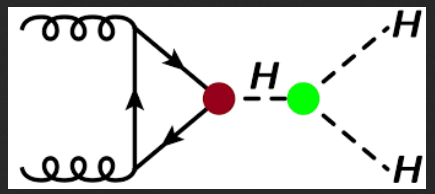


Measuring its couplings and properties better than a few percent accuracies is essential to understand

There is consensus that a Higgs factory is the highest priority

the question is how/what factory exactly?





Bass, S.D., De Roeck, A. & Kado, M. The Higgs boson implications and prospects for future discoveries. *Nat Rev Phys* **3**, 608–624 (2021).



FUTURE
CIRCULAR
COLLIDER

Flagship?