Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

Physics Vision

Exploring the Quantum Universe

2023p5report.org

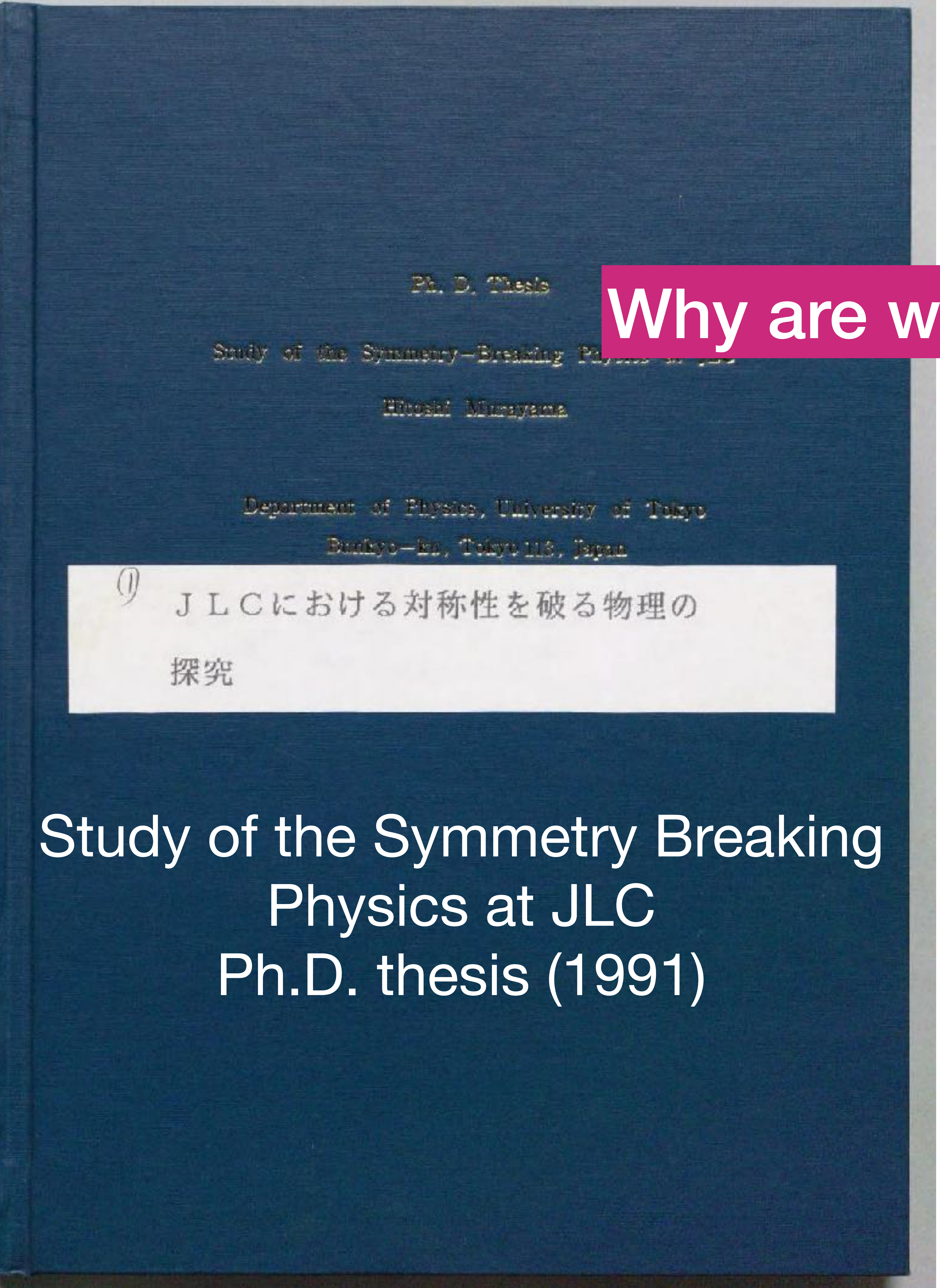
U.S. DEPARTMENT OF ENERGY

NSF

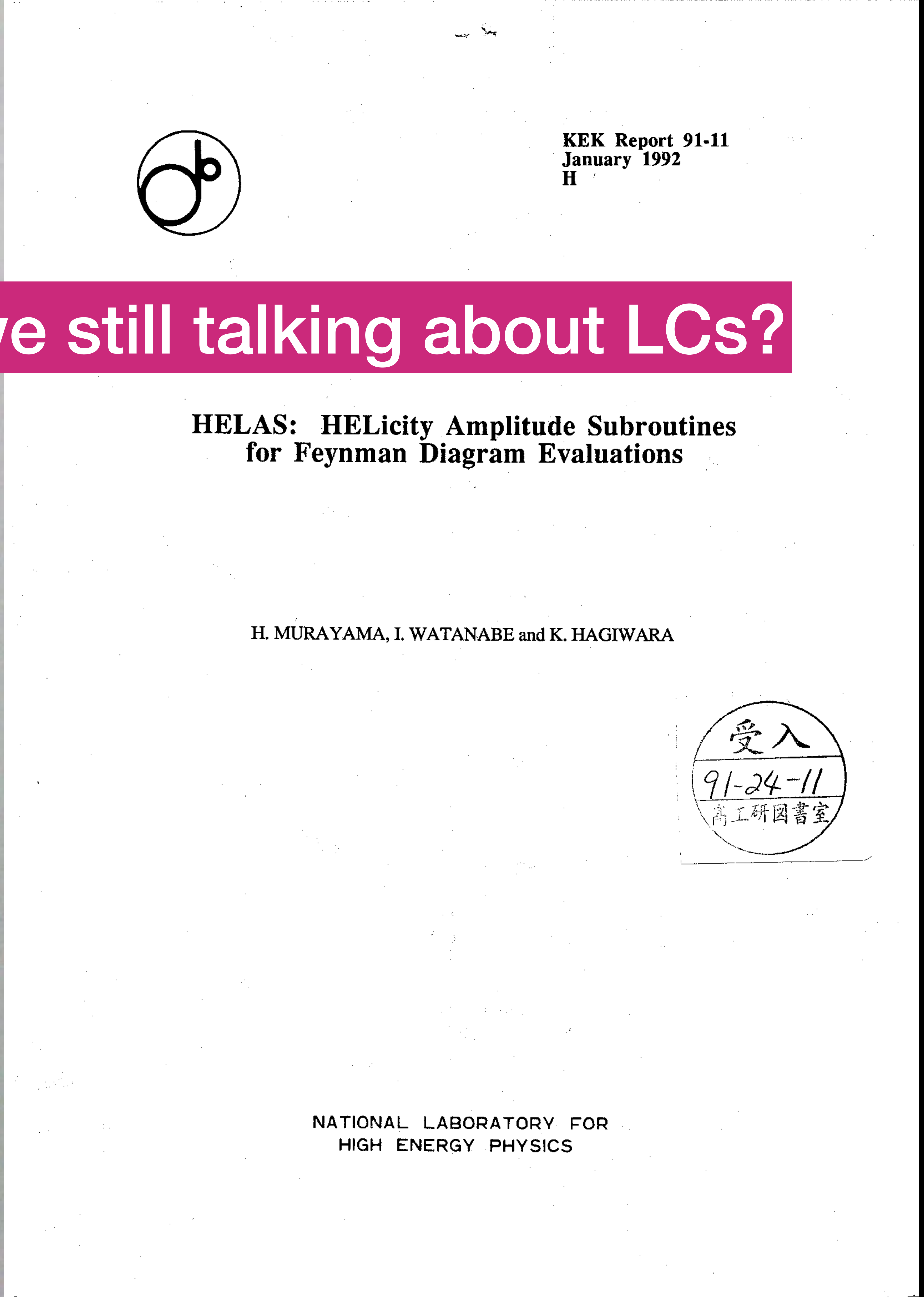
LCWS2024 Tokyo July 11, 2024

Hitoshi Murayama (Berkeley, Kavli IPMU Tokyo)

Why are we still talking about LCs?



Study of the Symmetry Breaking Physics at JLC
Ph.D. thesis (1991)



KEK Report 91-11
January 1992
H

HELAS: HELicity Amplitude Subroutines for Feynman Diagram Evaluations

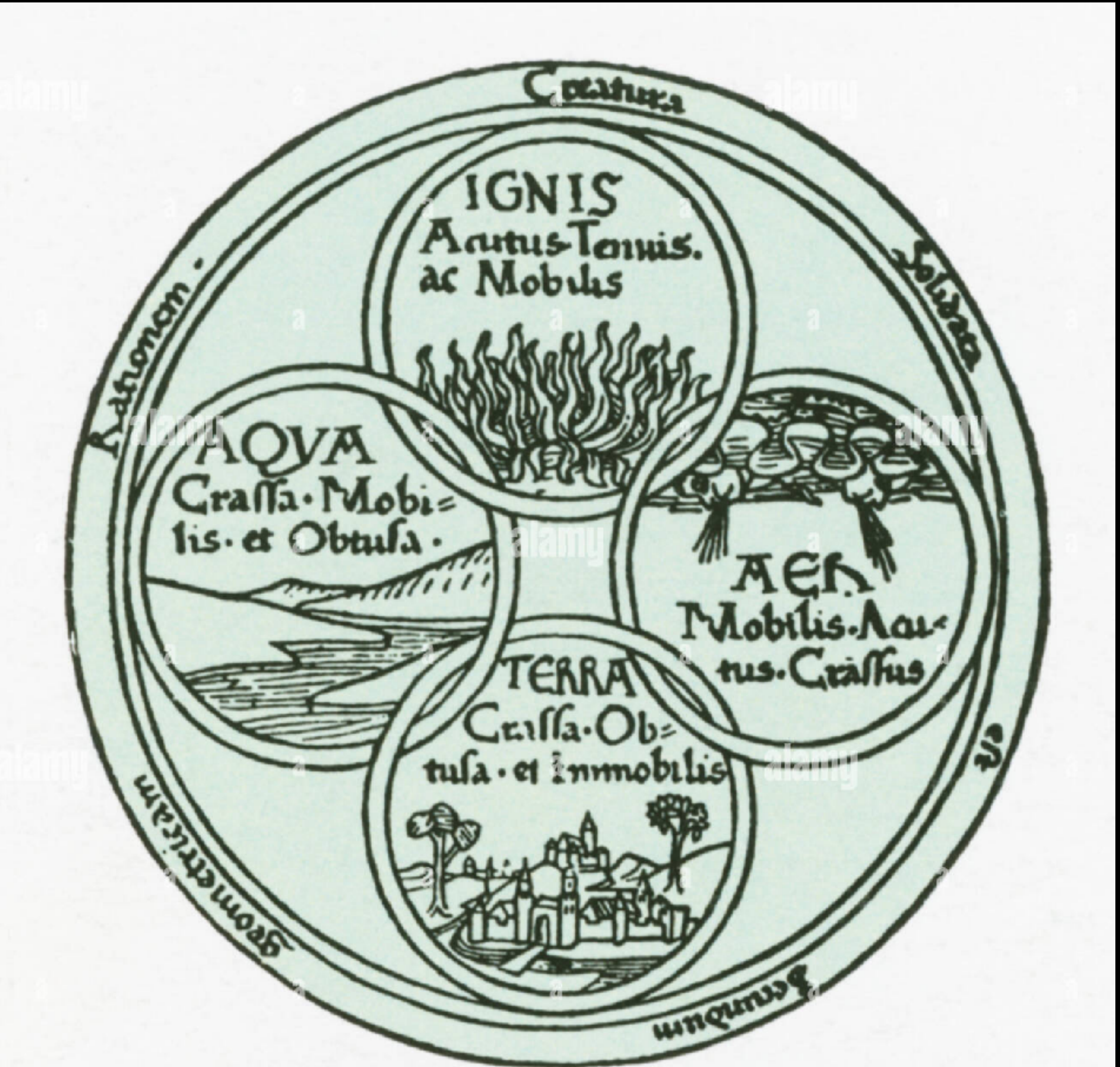
H. MURAYAMA, I. WATANABE and K. HAGIWARA

受入
91-24-11
高工研図書室

NATIONAL LABORATORY FOR
HIGH ENERGY PHYSICS

→ MadGraph

Ancient Greeks: Elements



This periodic table depicts the primary source on Earth for each element. In cases where two sources contribute fairly equally, both appear.

Credit: NASA

It’s A ~~Small~~ Wo
Messy

Who ordered that?

top 1995

tau 1975

bottom 1978

muon

strange

charm 1974

electron

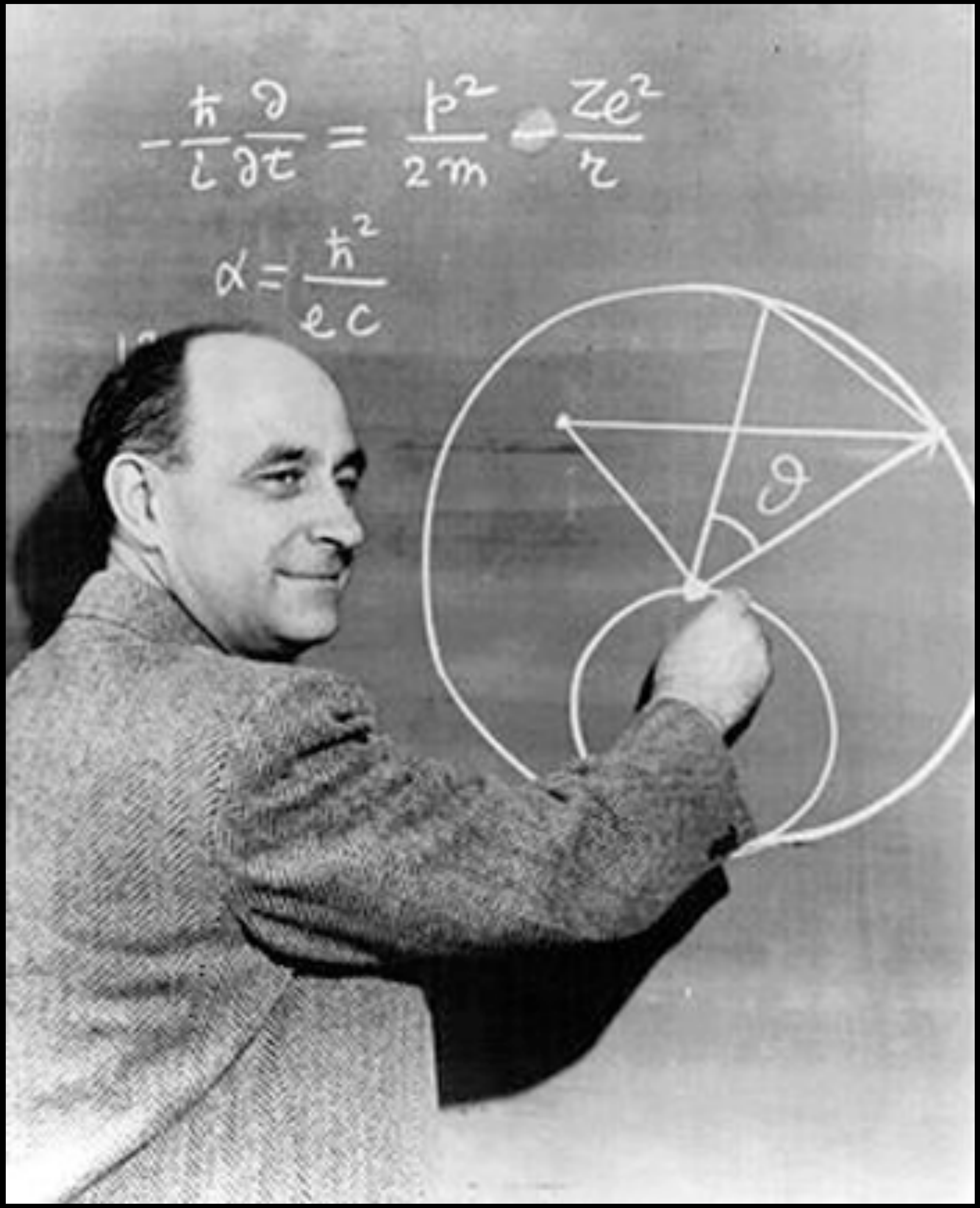
down

up

All you need to build atoms

Fermi's dream era

- Fermi formulated the first theory of the weak interaction (1932)
- *The required energy scale to study the problem known since then:* ~TeV
- We are finally got there with LHC!




early cyclotron

Redo the Big Bang!

fixed target vs collider

- fixed target experiment:

$$\sqrt{s} = \sqrt{2E_{\text{beam}}M_{\text{target}}}$$

$$\simeq \text{GeV}\left(\frac{E_{\text{beam}}}{\text{GeV}}\right)^{1/2}$$

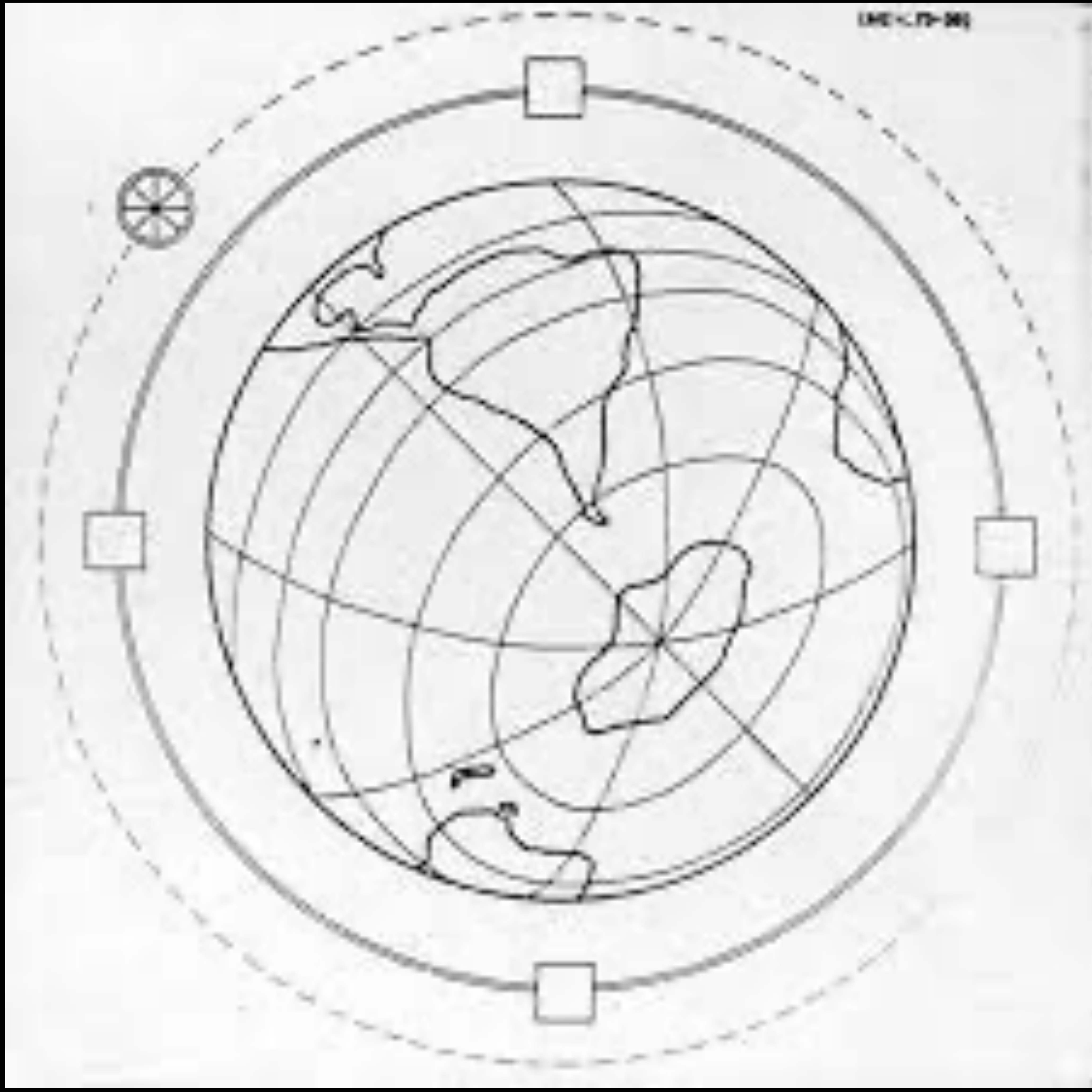
$$\sqrt{s} \simeq 14 \text{ TeV}$$

$$\Rightarrow E_{\text{beam}} \simeq 100,000\text{TeV}$$

- need R~400,000km with 8T magnets
- collider: R=27km

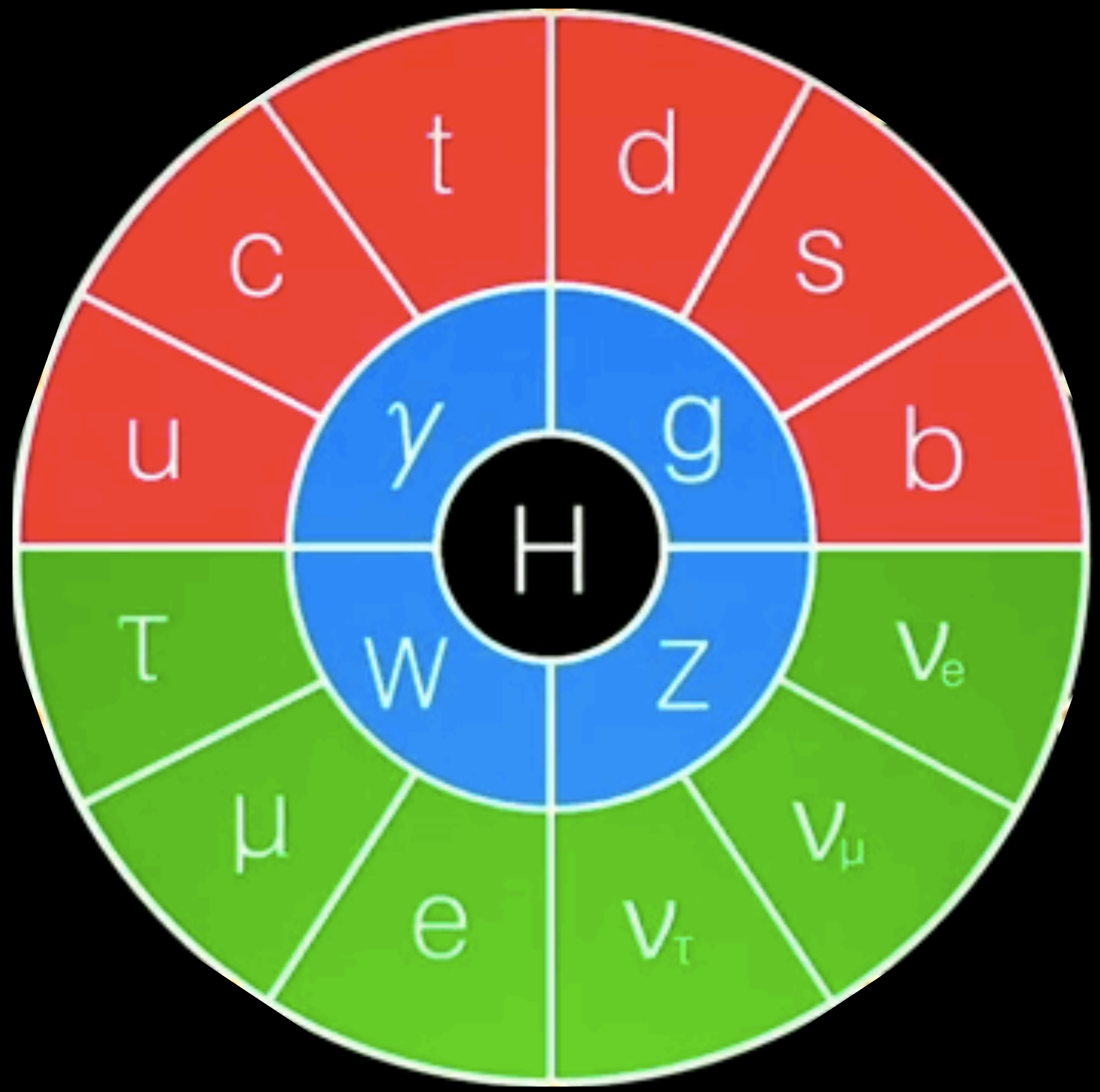
$$\sqrt{s} = 2E_{\text{beam}} = 2 \times 7 \text{ TeV}$$

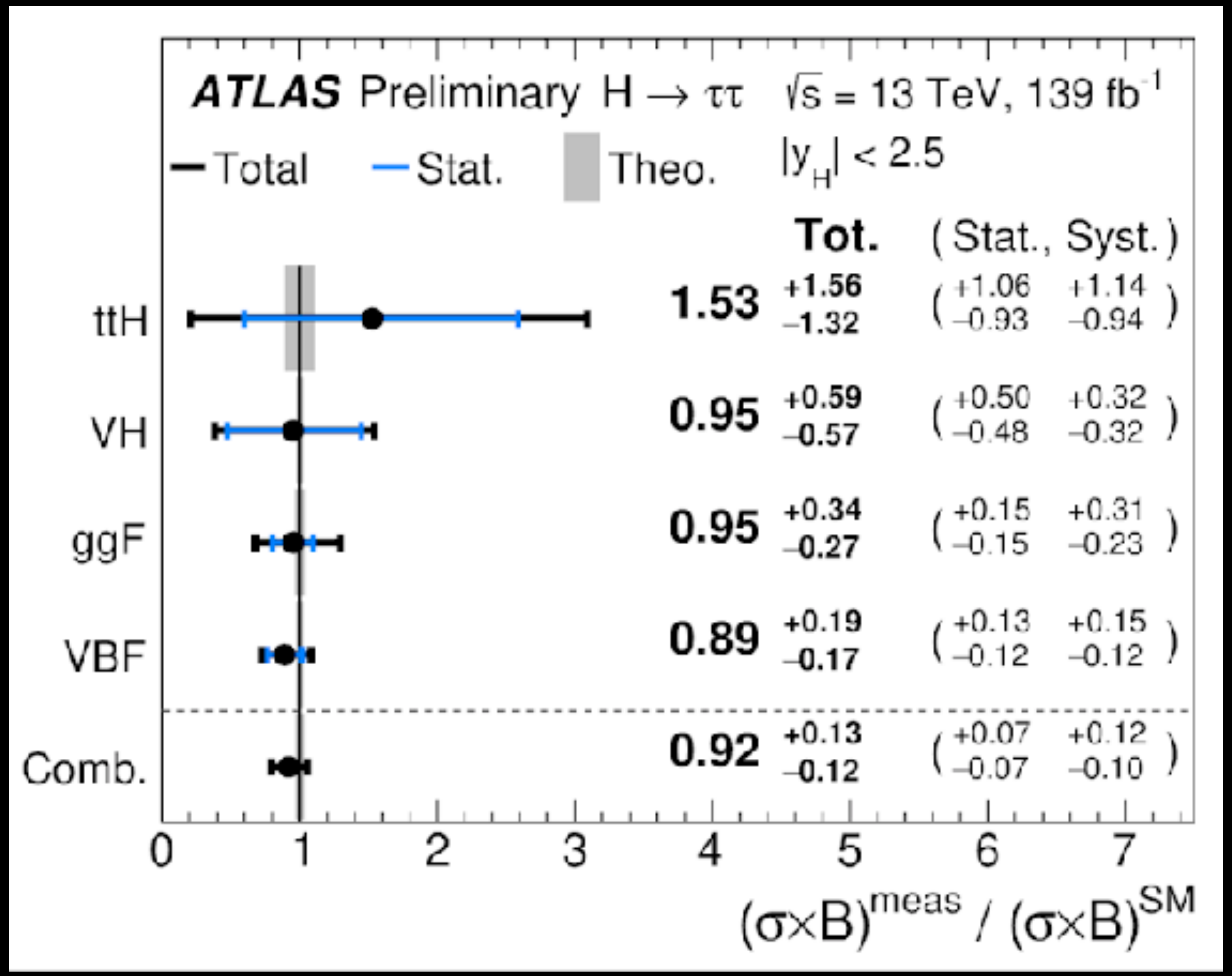
kudos to our accelerator friends who make unthinkable a reality

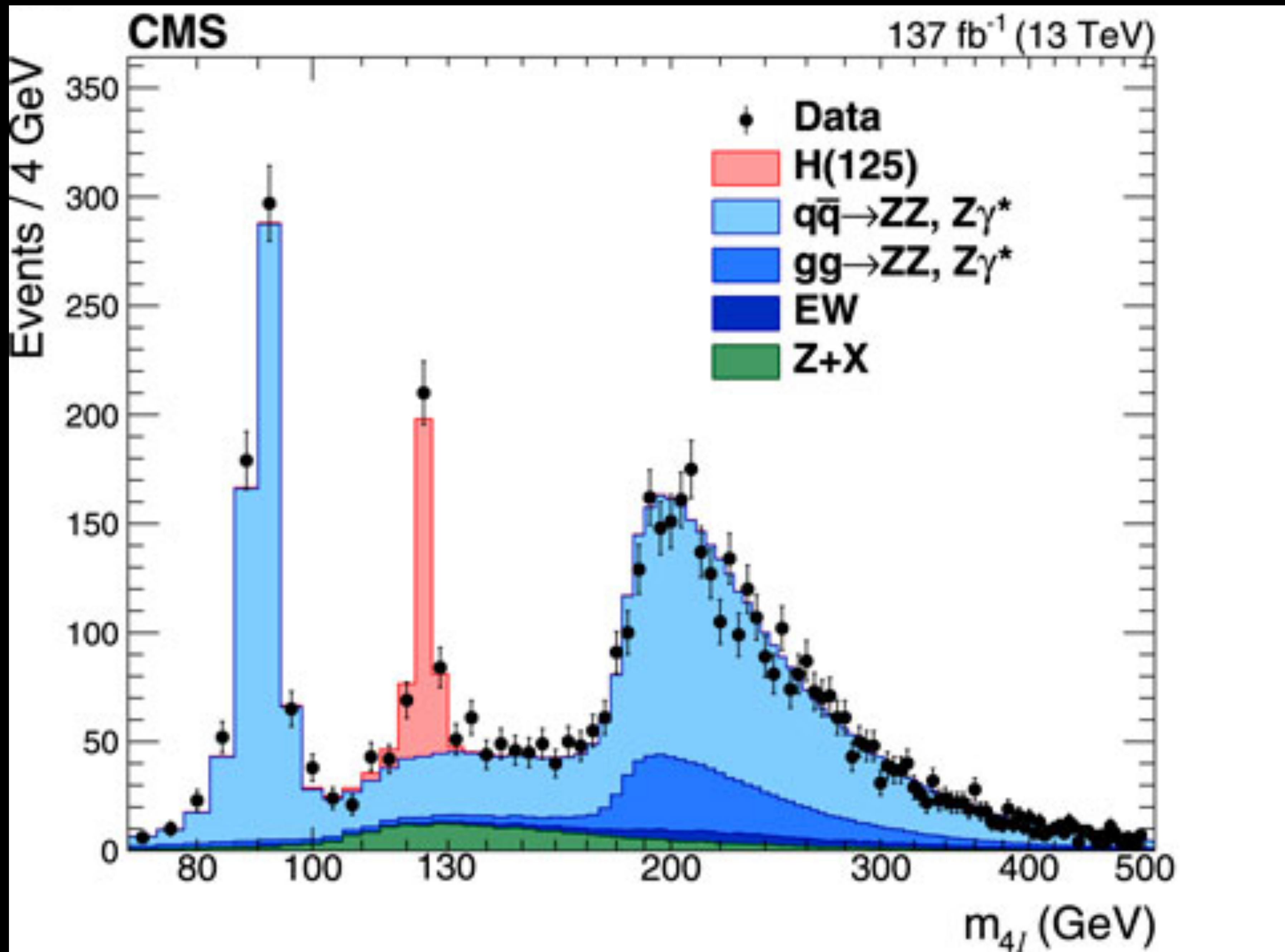


Globatron 40000km

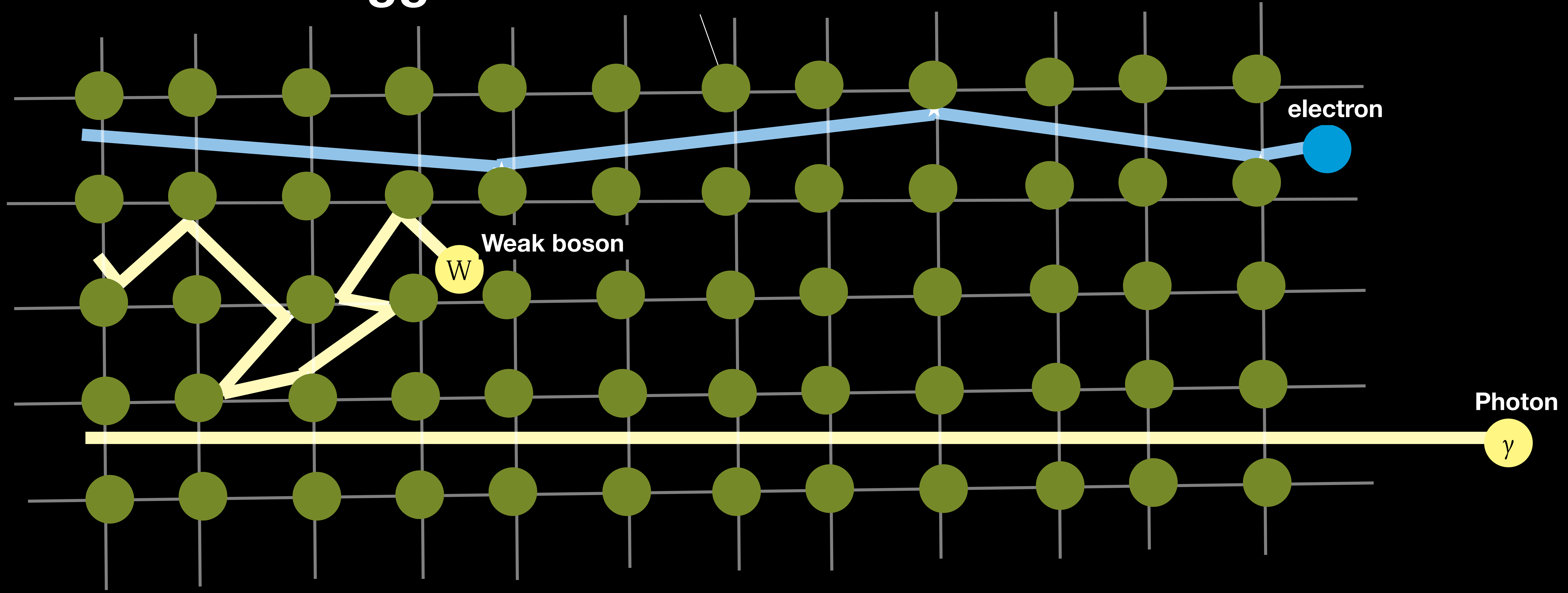
Standard Model





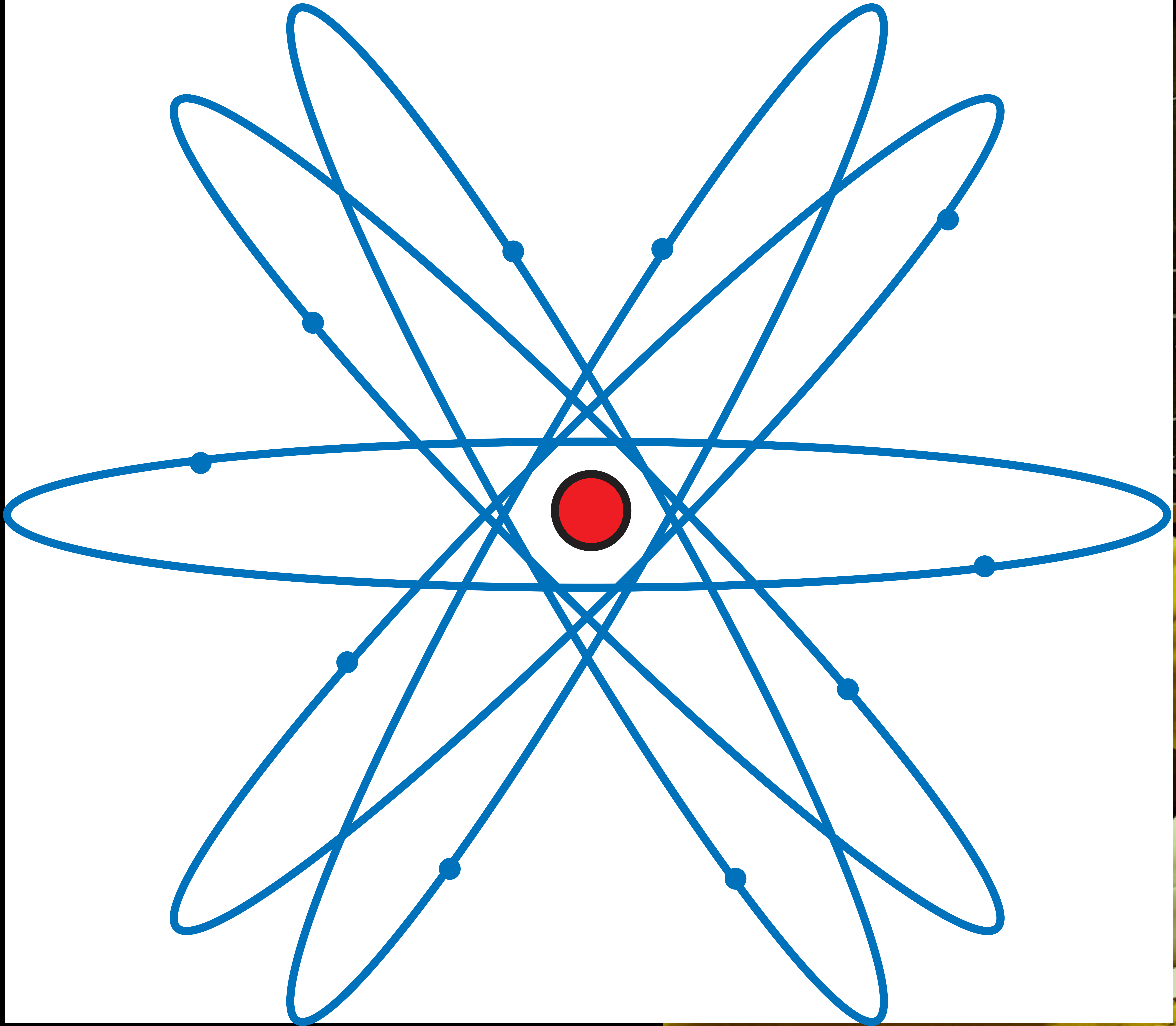


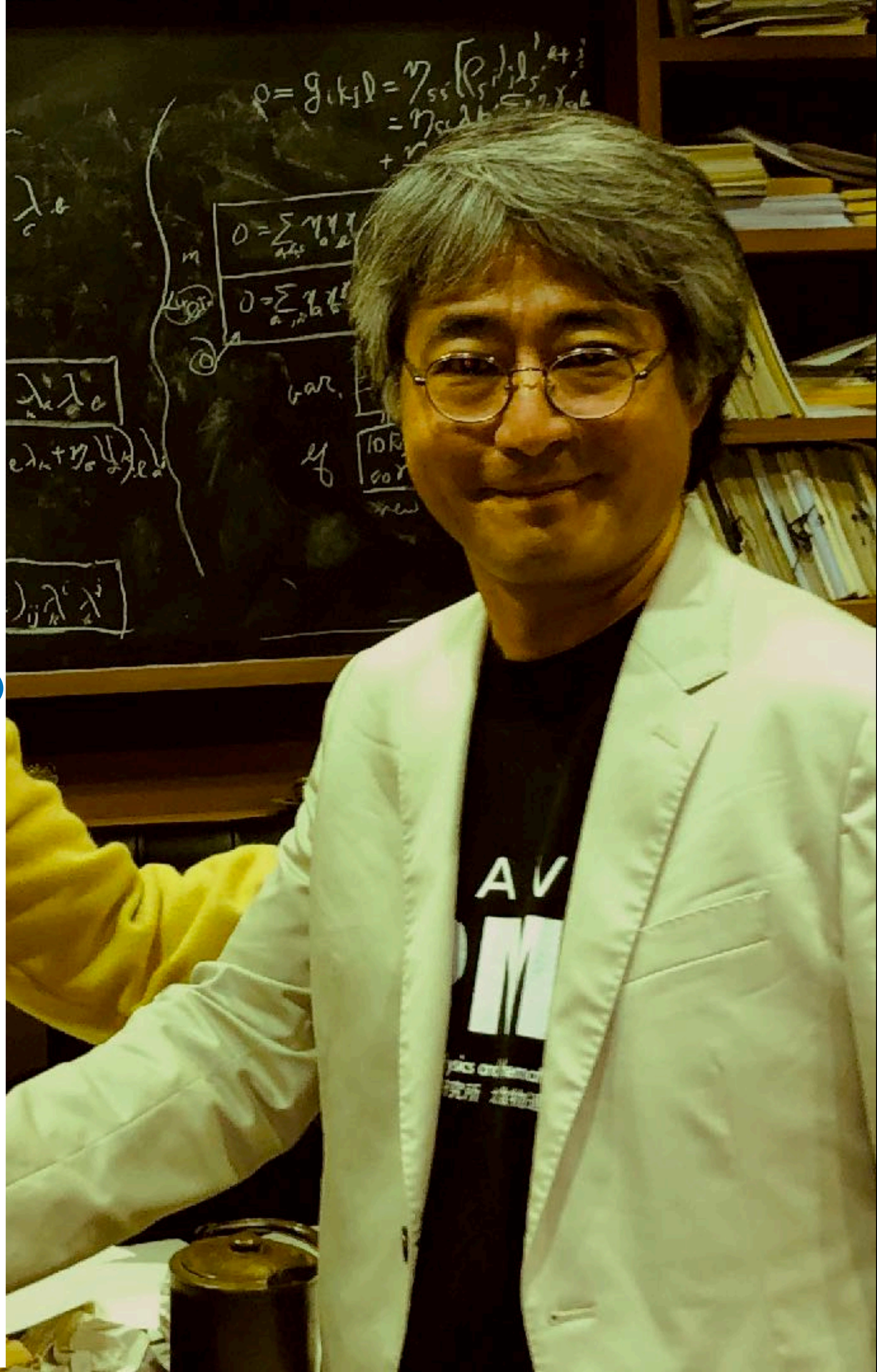
Higgs boson frozen in the Universe



Just the right amount of Higgs boson for us to exist!

Credit: Newton Japan





Who are they?
Why are they frozen?
Why do we exist?

Higgs filling up the space keeping us in one piece

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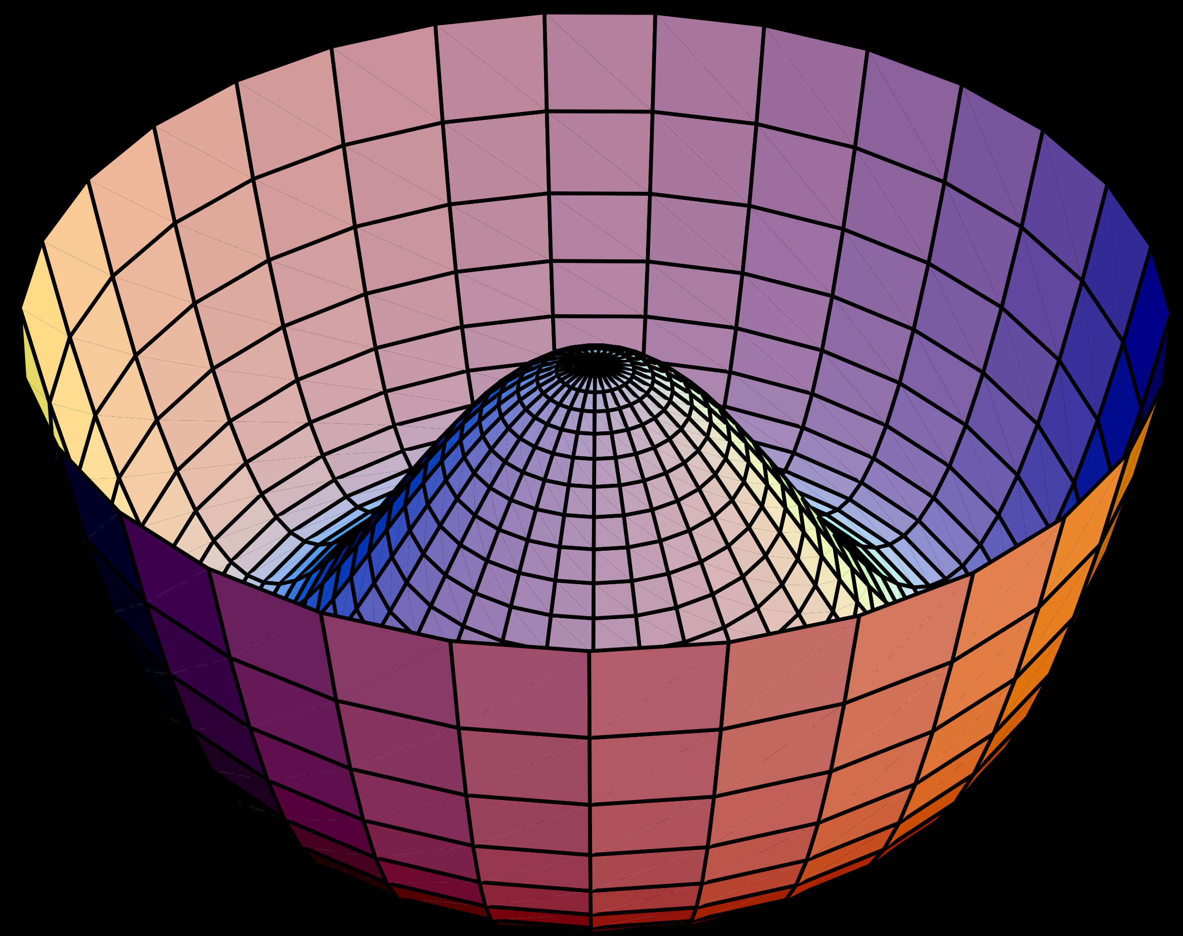
What is Higgs?
Is it alone?
Any siblings?
Any relatives?
Why frozen?

I didn't believe it

- Higgs boson is the *only spin 0 particle* in the standard model
  - it is *faceless*
  - one of its kind, no context
  - but does the most important job
- looks very artificial
- we still don't know *dynamics* behind the Higgs condensate
- *Higgsless theories*: now dead

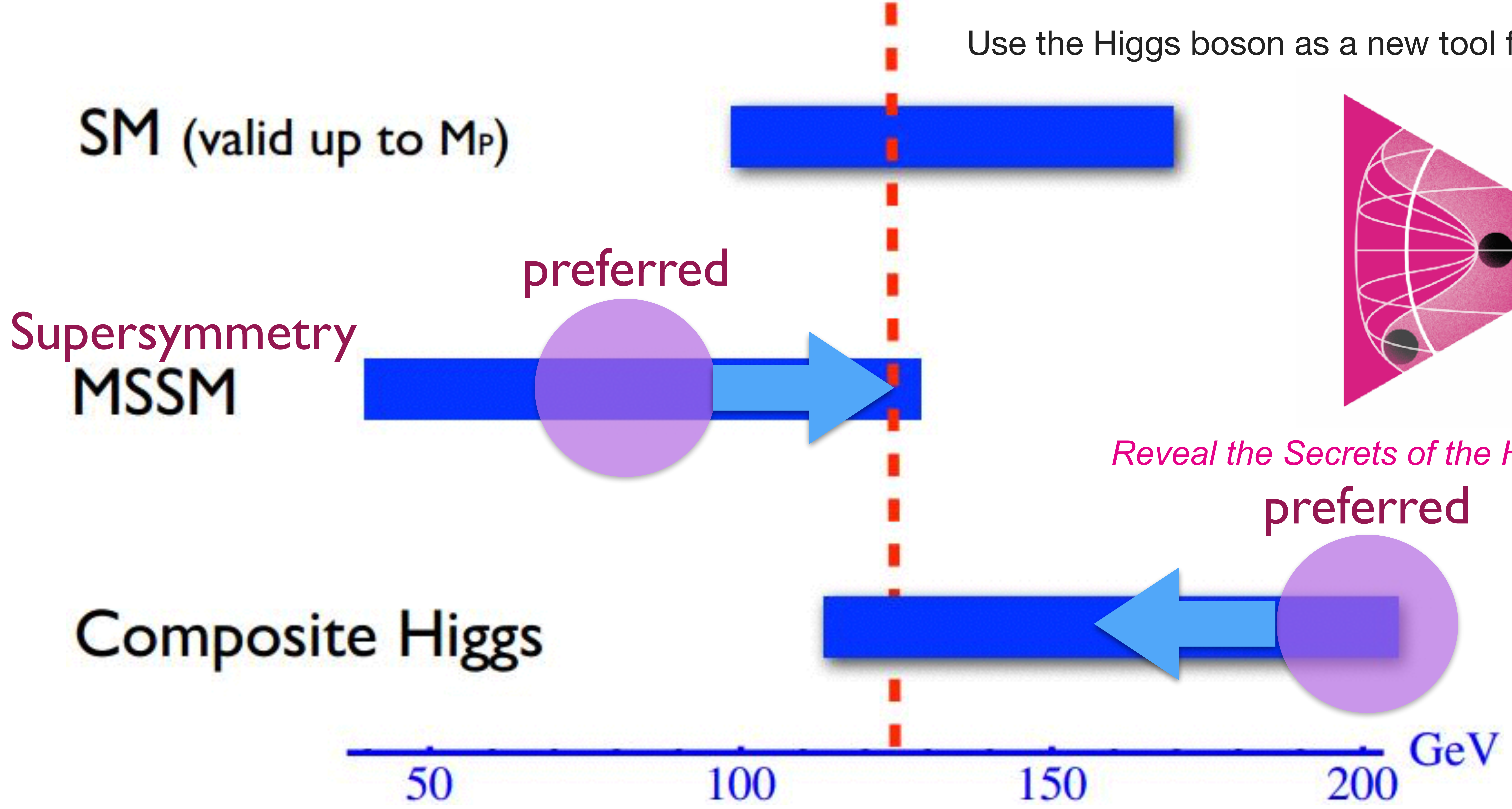


Nima's anguish

m_H=125 GeV seems almost maliciously designed
to prolong the agony of BSM theorists….

Higgs mass range

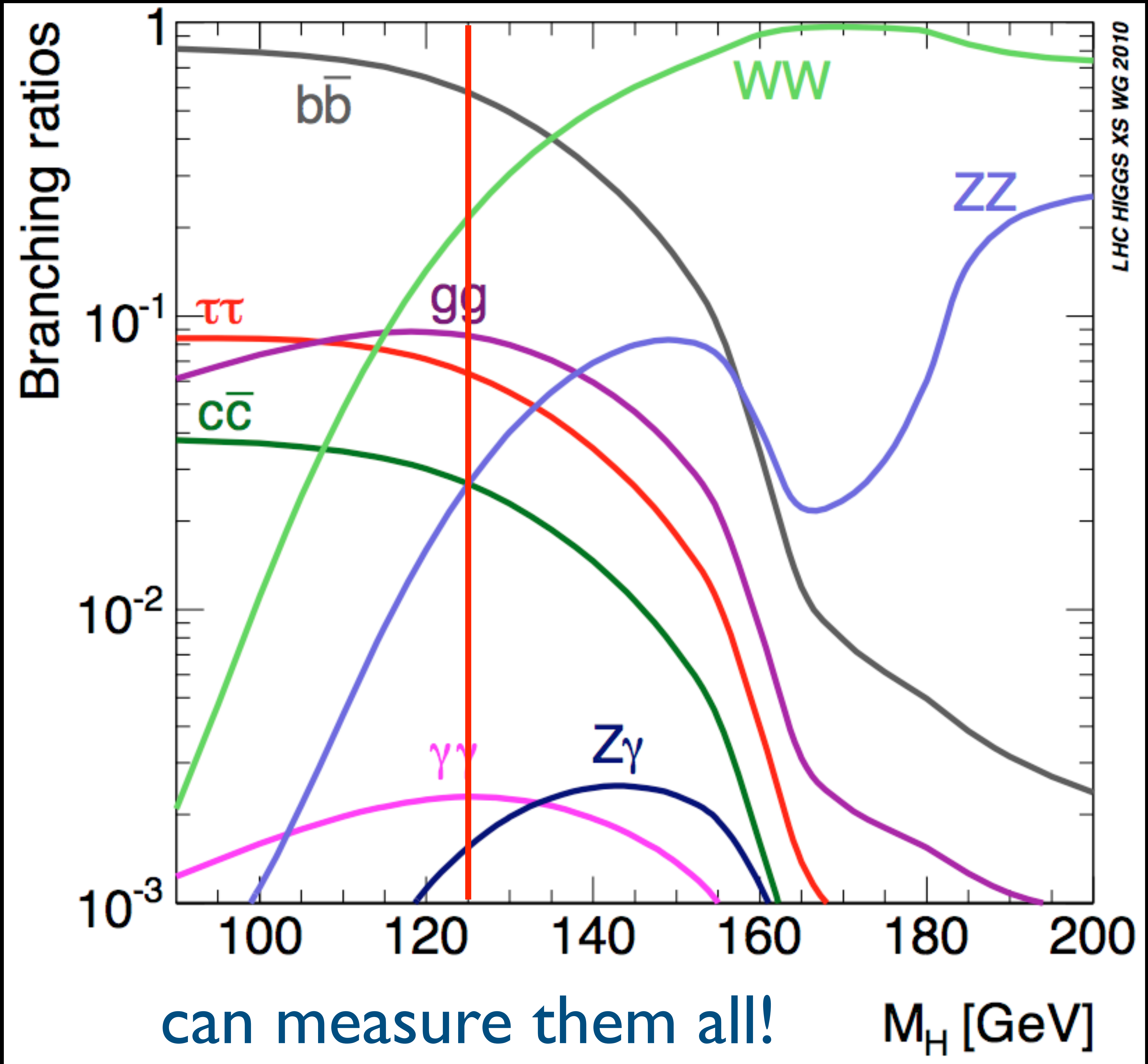
Use the Higgs boson as a new tool for discovery



Reveal the Secrets of the Higgs Boson

Alex Pomarol

dream case for experiments



can measure them all!

Exploring the Quantum Universe

Recommendation 2

Rank-Ordered

New exciting initiatives

a. **CMB-S4**, which looks back at the earliest moments of the universe to probe physics at the highest energy scales. It is critical to install telescopes at and observe from both the South Pole and Chile sites to achieve the science goals (section 4.2).

b. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).

c. **An off-shore Higgs factory**, realized in collaboration with **international partners**, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined (see also Recommendation 6), the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US on-shore program in particle physics (section 3.2).

d. **An ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog, in coordination with international partners and preferably sited in the US (section 4.1).

e. **IceCube-Gen2** for study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter covering higher mass ranges using neutrinos as a tool (section 4.1).

Exploring the Quantum Universe

Difficult Choices

Figure 2 – Construction in Various Budget Scenarios

Index: Y: Yes N: No R&D: Recommend R&D only C: Conditional yes based on review P: Primary S: Secondary

Delayed: Recommend construction but delayed to the next decade

† Recommend infrastructure support to enable international contributions

Can be considered as part of ASTAE with reduced scope

US Construction Cost	Scenarios: Less	Baseline	More	Science Drivers: Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
>$3B										
onshore Higgs factory	N	N	N		P	S		P	P	
$1–3B										
offshore Higgs factory	Delayed	Y	Y		P	S		P	P	
ACE-BR	R&D	R&D	C	P				P	P	
$400–1000M										
CMB-S4	Y	Y	Y	S		S	P			P
Spec-S5	R&D	R&D	Y	S		S	P			P
$100–400M										
IceCube-Gen2	Y	Y	Y	P		S				P
G3 Dark Matter 1	Y	Y	Y	S		P				
DUNE FD3	Y	Y	Y	P				S	S	S
test facilities & demonstrator(s)	C	C	C		P	P		P	P	
ACE-MIRT	R&D	Y	Y	P						
DUNE FD4	R&D	R&D	Y	P				S	S	S
G3 Dark Matter 2	N	N	Y	S		P				
Mu2e-II	R&D	R&D	R&D						P	
srEDM	N	N	N						P	
$60–100M										
SURF expansion	N	Y	Y	P		P				
DUNE MCND	N†	Y	Y	P				S	S	
MATHUSLA	N#	N#	N#			P		P		
FPF trio	N#	N#	N#	P		P		P		

2014 P5

Table 1
Summary of Scenarios

Project/Activity	Scenarios: Scenario A (low)	Scenario B (medium)	Scenario C (unlimited)	Science Drivers: Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contri-butions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

TABLE 1 Summary of Scenarios A, B, and C. Each major project considered by P5 is shown, grouped by project size and listed in time order based on year of peak construction. Project sizes are: Large (>$200M), Medium ($50M-$200M), and Small (<$50M). The science Drivers primarily addressed by each project are also indicated, along with the Frontier technique area (E=Energy, I=Intensity, C=Cosmic) defined in the 2008 P5 report.


Exploring
the
Quantum
Universe
The University of TOKYO

Federal Ministry
of Education
and Research

Future of CERN = FCC?

“The cost estimates in the feasibility study are subject to a large number of ***uncertainties****, the effects of which are still largely unknown.* ***The financing plan is extremely vague*** *and requires a high level of* ***commitment from external partners****, which is neither assured nor even in prospect at the present time.*

Under the current economic conditions, ***Germany is not in a position to provide the planned funding****. In view of all these points, the* ***FCC has to be considered as not affordable****.*

Hence, CERN has to ***diversify its efforts and prepare for different scenarios*** *including one without the FCC-ee.”*

BMBF Statement in CERN Council Meeting 02/2024

European Strategy Group (ESG) remit

Approved by Council in June

The remit of the European Strategy Group (ESG), established in June 2024, is to develop an update of the European Strategy for Particle Physics and submit it for approval by the Council. The aim of the Strategy update should be to develop a visionary and concrete plan that greatly advances human knowledge in fundamental physics through the realisation of the next flagship project at CERN. This plan should attract and value international collaboration and should allow Europe to continue to play a leading role in the field.

The ESG should take into consideration:

- the input of the particle physics community;
- the status of implementation of the 2020 Strategy update;
- the accomplishments over recent years, including the results from the LHC and other experiments and facilities worldwide, the progress in the construction of the High-Luminosity LHC, the outcome of the Future Circular Collider Feasibility Study, and recent technological developments in accelerator, detector and computing; the international landscape of the field.

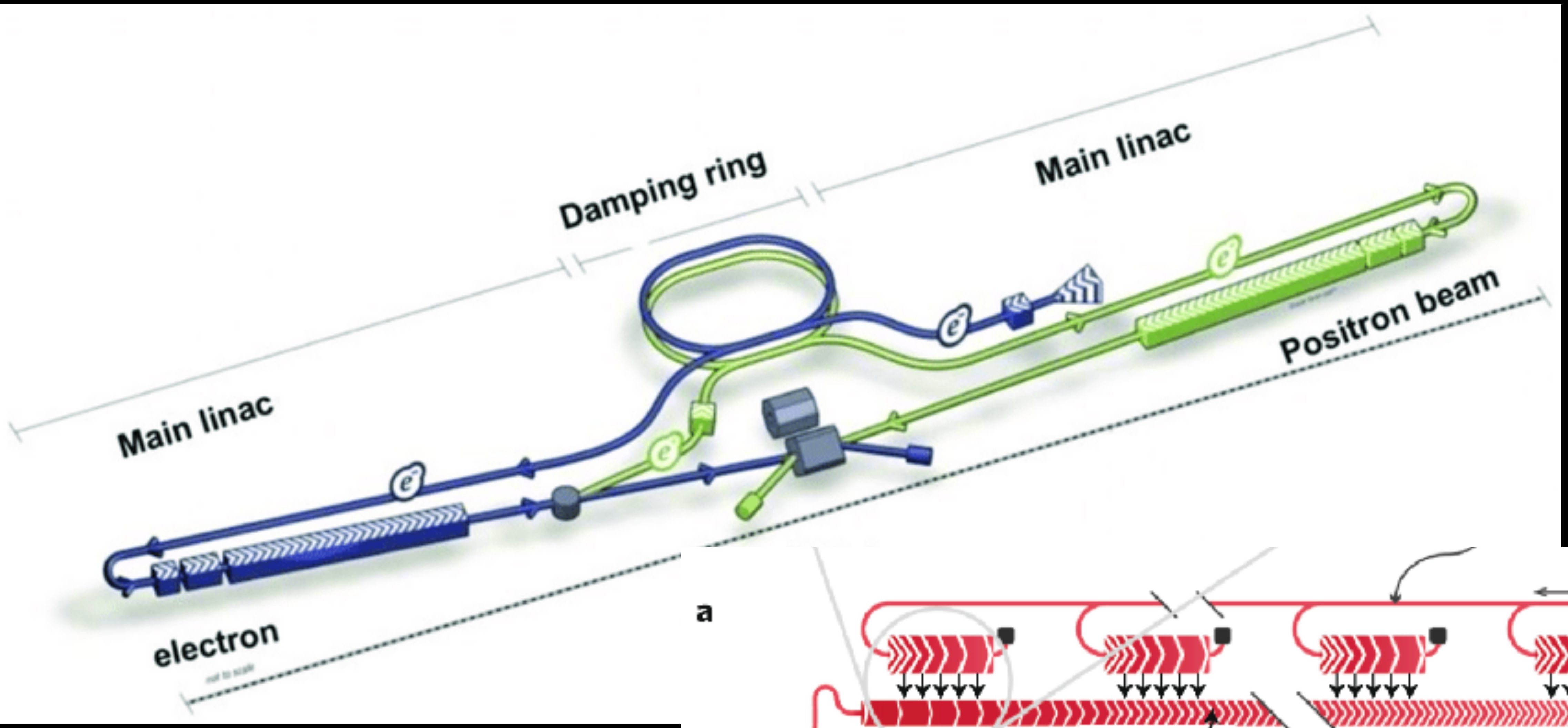
The Strategy update should include the preferred option for the next collider at CERN and prioritised alternative options to be pursued if the chosen preferred plan turns out not to be feasible or competitive. The Strategy update should also indicate areas of priority for exploration complementary to colliders and for other experiments to be considered at CERN and at other laboratories in Europe, as well as for participation in projects outside Europe.

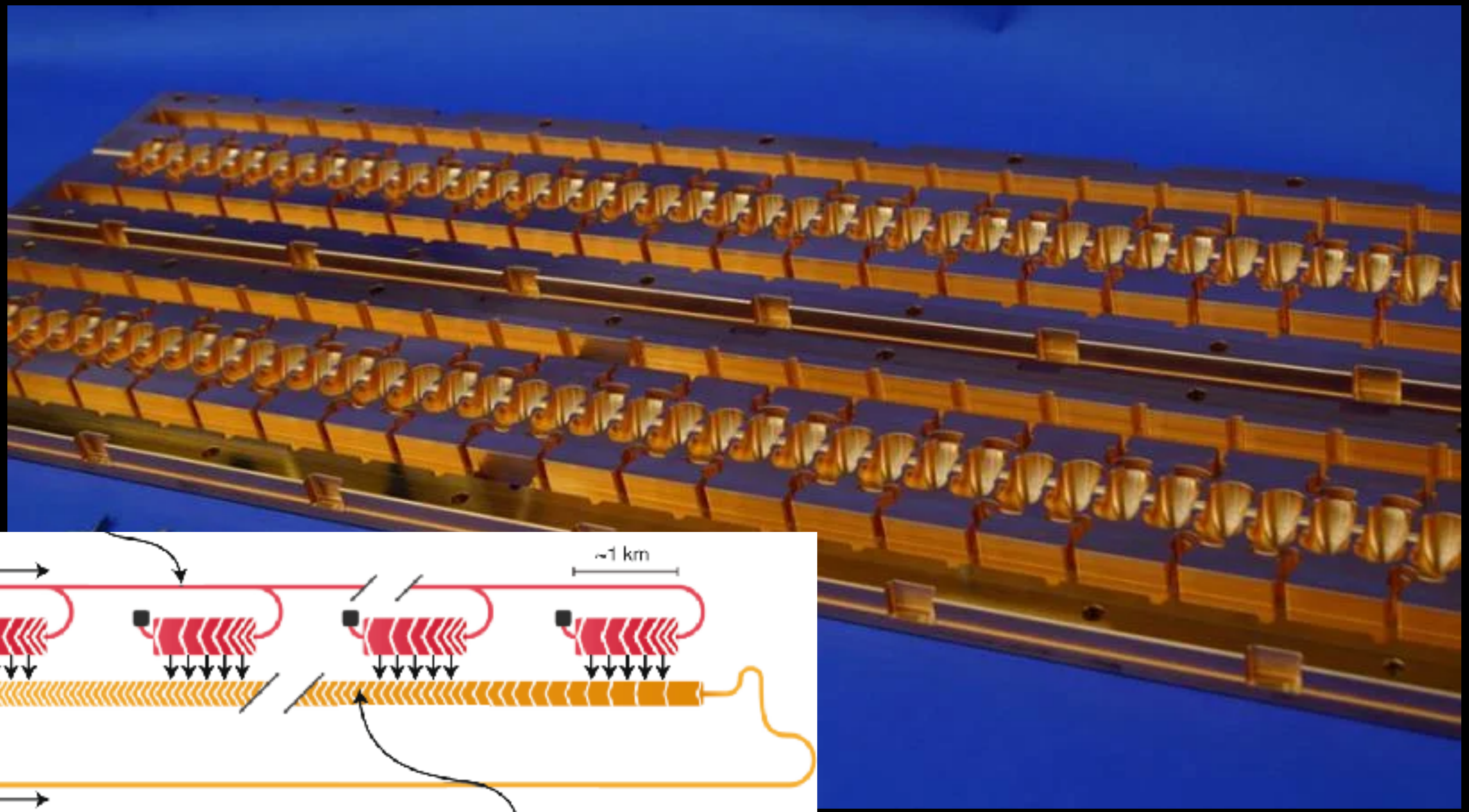
The ESG should review and update the Strategy and add other items identified as relevant to the field, including accelerator, detector and computing R&D, the theory frontier, actions to minimise the environmental impact and to improve the sustainability of accelerator-based particle physics, the strategy and initiatives to attract, train and retain the young generations, public engagement and outreach.

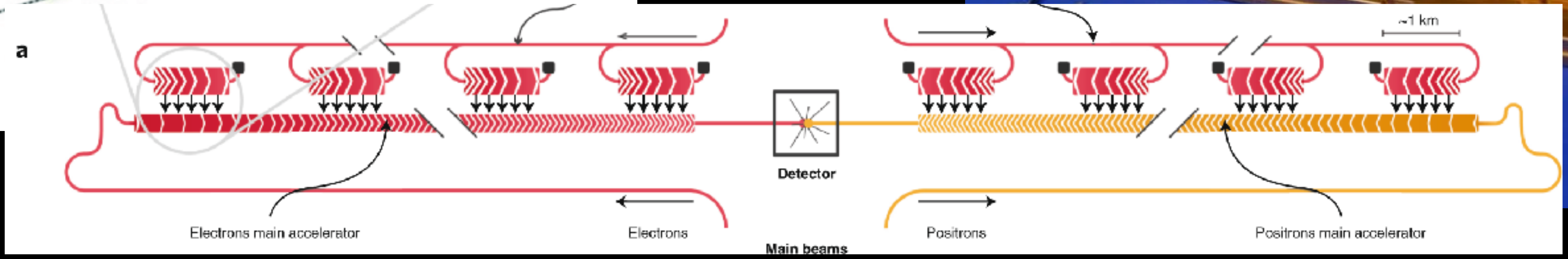
The ESG should submit the proposed Strategy update to the Council by the end of January 2026.

Power of Linear Colliders

- can reach higher energies with higher luminosities
- flexible science program as science evolves with many upgrade options
- (nearly) affordable
- smaller CO_2 footprint
- tighter beam
- beam polarization: four colliders at a single facility
- the right machine for the world at the right time
- won't tie the community for the next hundred years

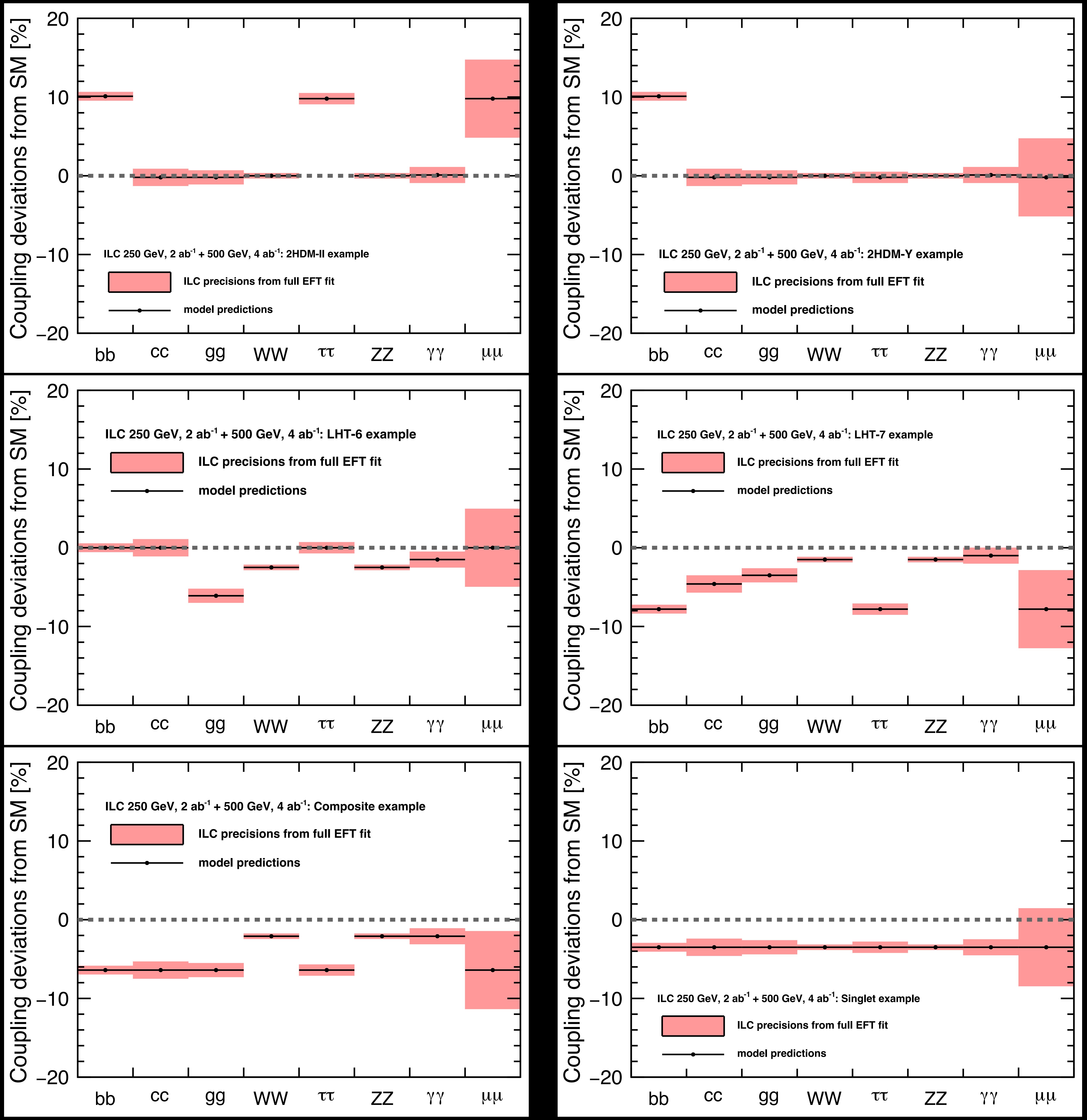




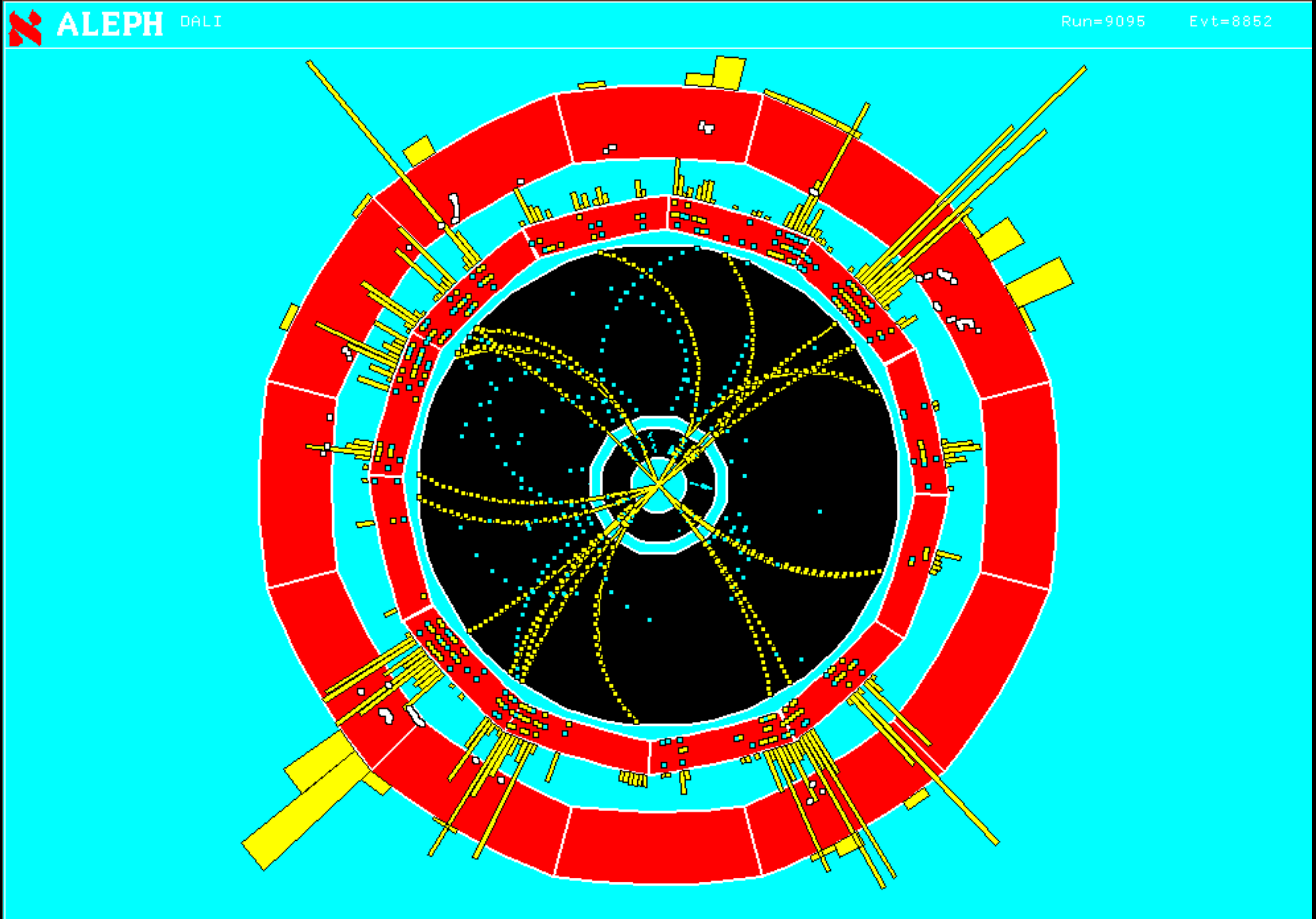


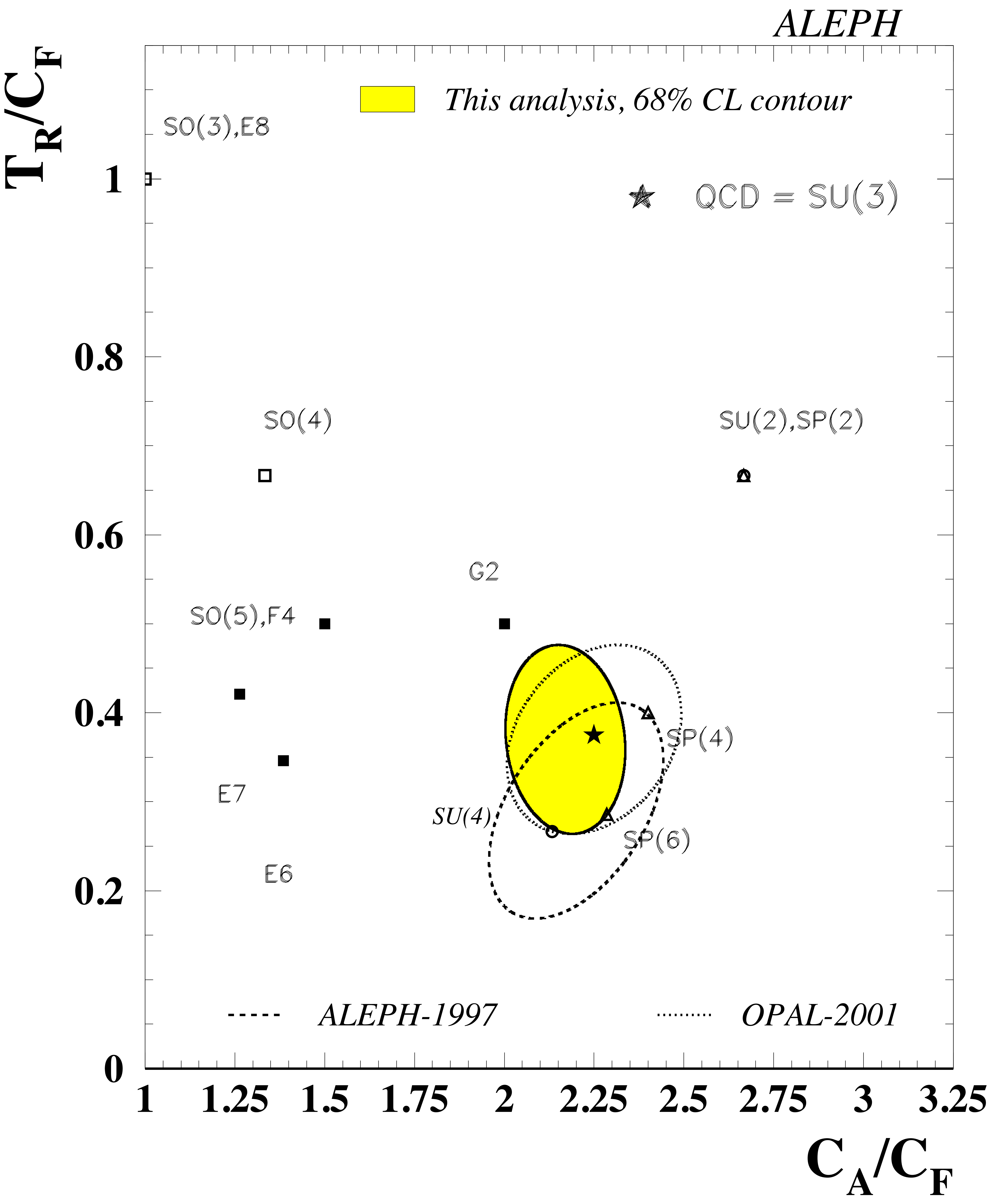
Who is he?

We will finally know who Higgs boson is with linear colliders




Accelerators
LHC heavy ions
is visible
TODAY
LHC protons
High-energy cosmic rays
Size of visible universe
Infla
Big Bang
Higgs
telescopes
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
Credit: Particle Data Group
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)

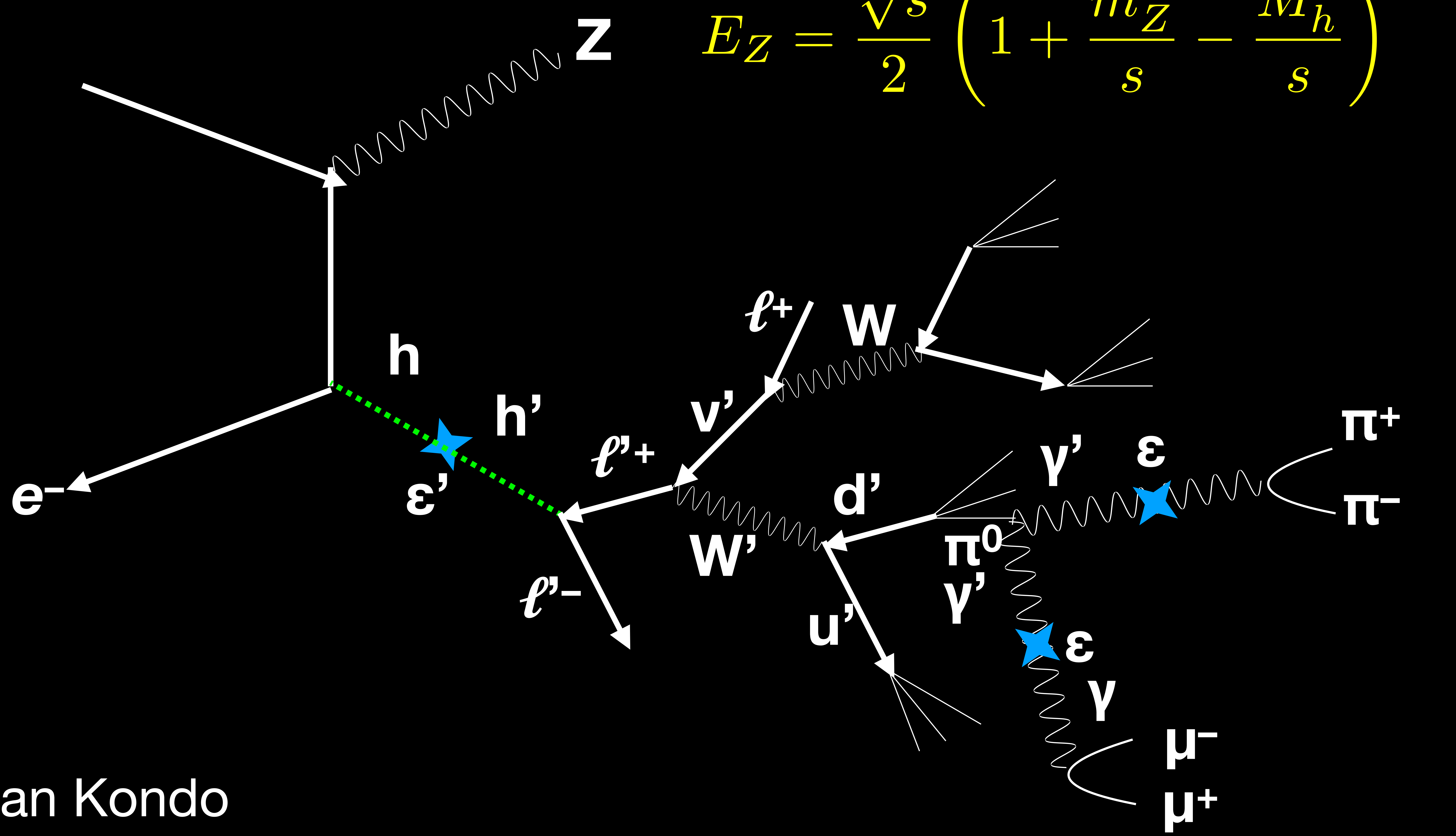

ALEPH
DALI
Run=9095
Evt=8852


ALEPH
This analysis, 68% CL contour
QCD = SU(3)
SO(3),E8
SO(4)
SU(2),SP(2)
G2
SO(5),F4
SP(4)
E7
SU(4)
SP(6)
E6
ALEPH-1997
OPAL-2001
T_R/C_F
C_A/C_F
1
0.8
0.6
0.4
0.2
0
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3
3.25

and it’s SU(3)!

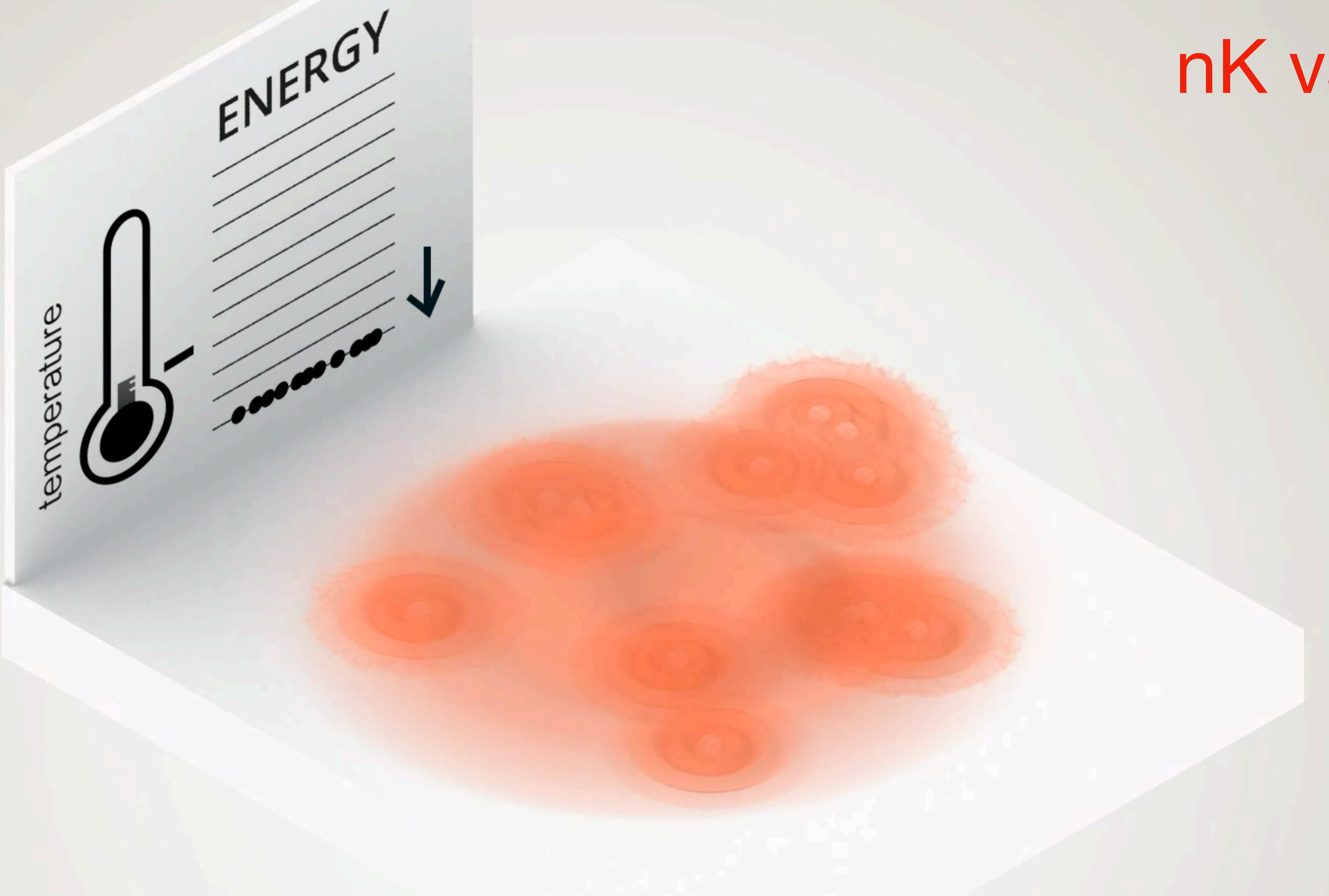
Higgs portal

$$E_Z = \frac{\sqrt{s}}{2}\left(1 + \frac{m_Z^2}{s} - \frac{M_h^2}{s}\right)$$



e.g. poster by Dan Kondo

nK vs PK



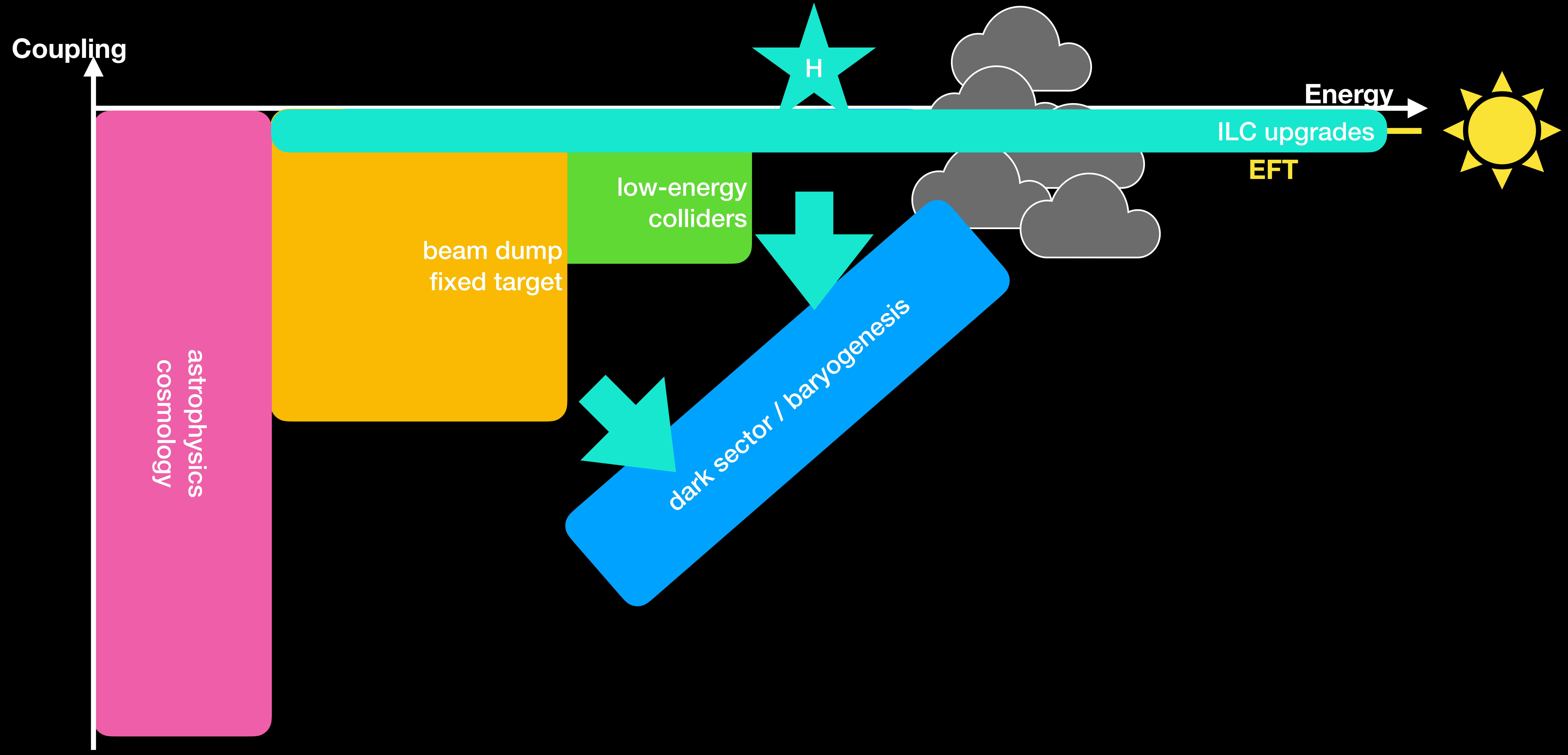
Then, at this very low temperature, all of the bosons are able to be at the very same energy in the same quantum state.

https://en.wikipedia.org/wiki/File:Bose-Einstein_Condensation.ogv

History of Colliders

1. precision measurements of neutral current (*i.e.* polarized *e*+*d*) predicted m_W, m_Z
2. UA1/UA2 discovered *W*/*Z* particles
3. LEP *nailed* the gauge sector
1. precision measurements of *W* and *Z* (*i.e.* LEP + Tevatron) predicted m_H
2. LHC discovered *a Higgs particle*
3. LC *nails* the Higgs sector?
1. precision measurements at LC predict ???

ILC++



Coupling
Energy
H
ILC upgrades
EFT
low-energy
colliders
beam dump
fixed target
astrophysics
cosmology
dark sector / baryogenesis


MAKE ILC
GREAT AGAIN