Karlsruhe Institute of Technology

Collaborative Research Center TRR 257

Particle Physics Phenomenology after the Higgs Discovery

Theory overview and draft for the ESPP input document

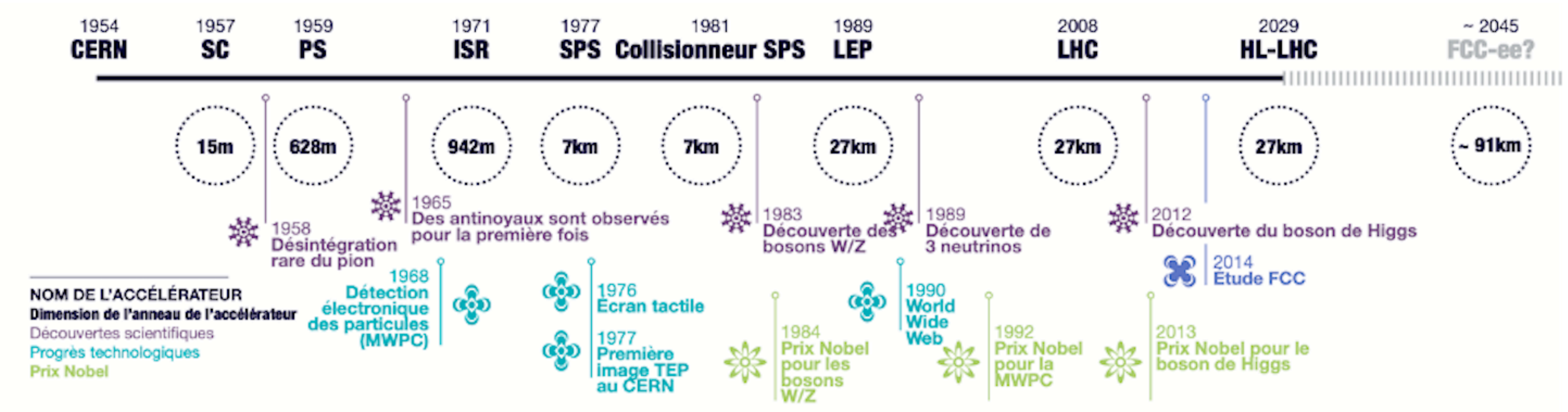


image credit: CERN

Gudrun Heinrich

Institute for Theoretical Physics

Karlsruhe Institute of Technology

Physikzentrum Bad Honnef

European Strategy Update

January 20, 2025

The role of theory

Disclaimer: *not a comprehensive summary of the theory talks given at this workshop series so far*
comparing collider options is not the aim.

Thanks *to Stefan Dittmaier, Michael Krämer, Margarete Mühlleitner, Hans-Christian Schultz-Coulon for comments*

The mission of theoretical particle physics is to

- ask the "Big Questions"
- provide a "vision" and guidance:

➡ construct possible answers to Big Questions ("models")

➡ provide global interpretations of experimental results

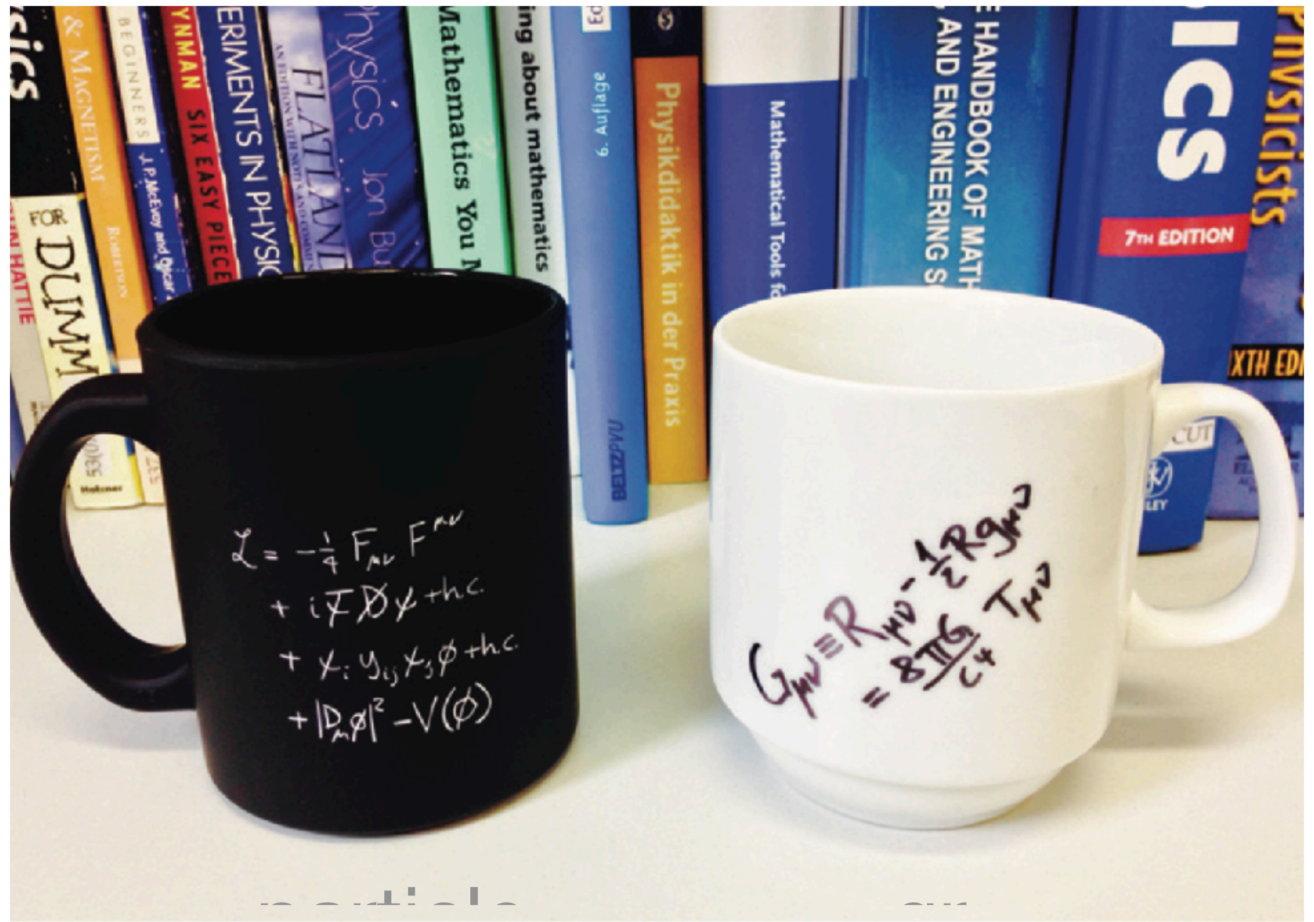
➡ refine/extend the model (or confirm SM or rule out)

- provide tools, simulations,
- new ideas how to measure unphysical objects (e.g. couplings)

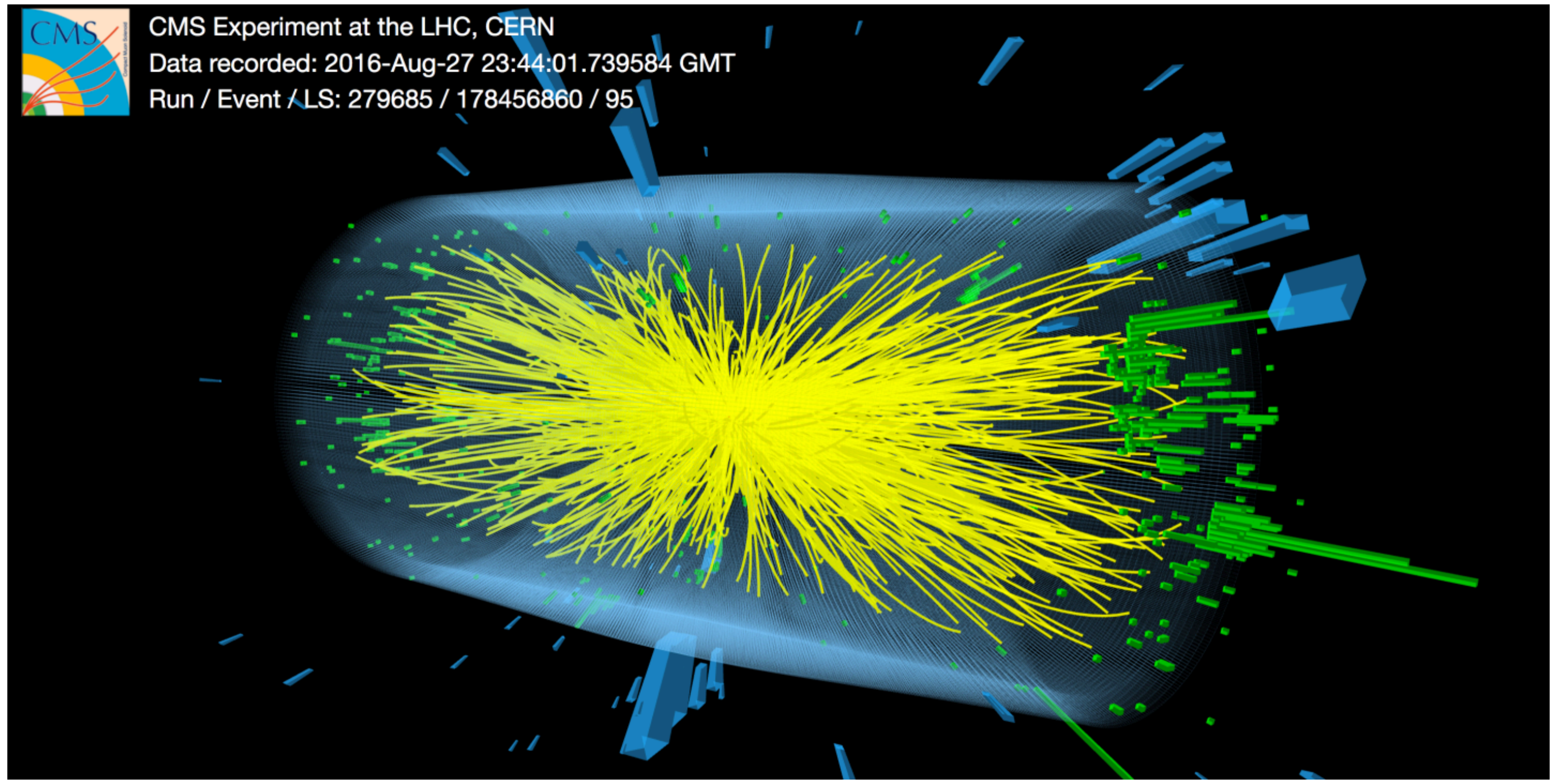
Theory plays a very important role in cornering new physics (scale and type) **indirectly**

New theoretical insights are guaranteed at a next flagship collider project; this does not necessarily mean new particles

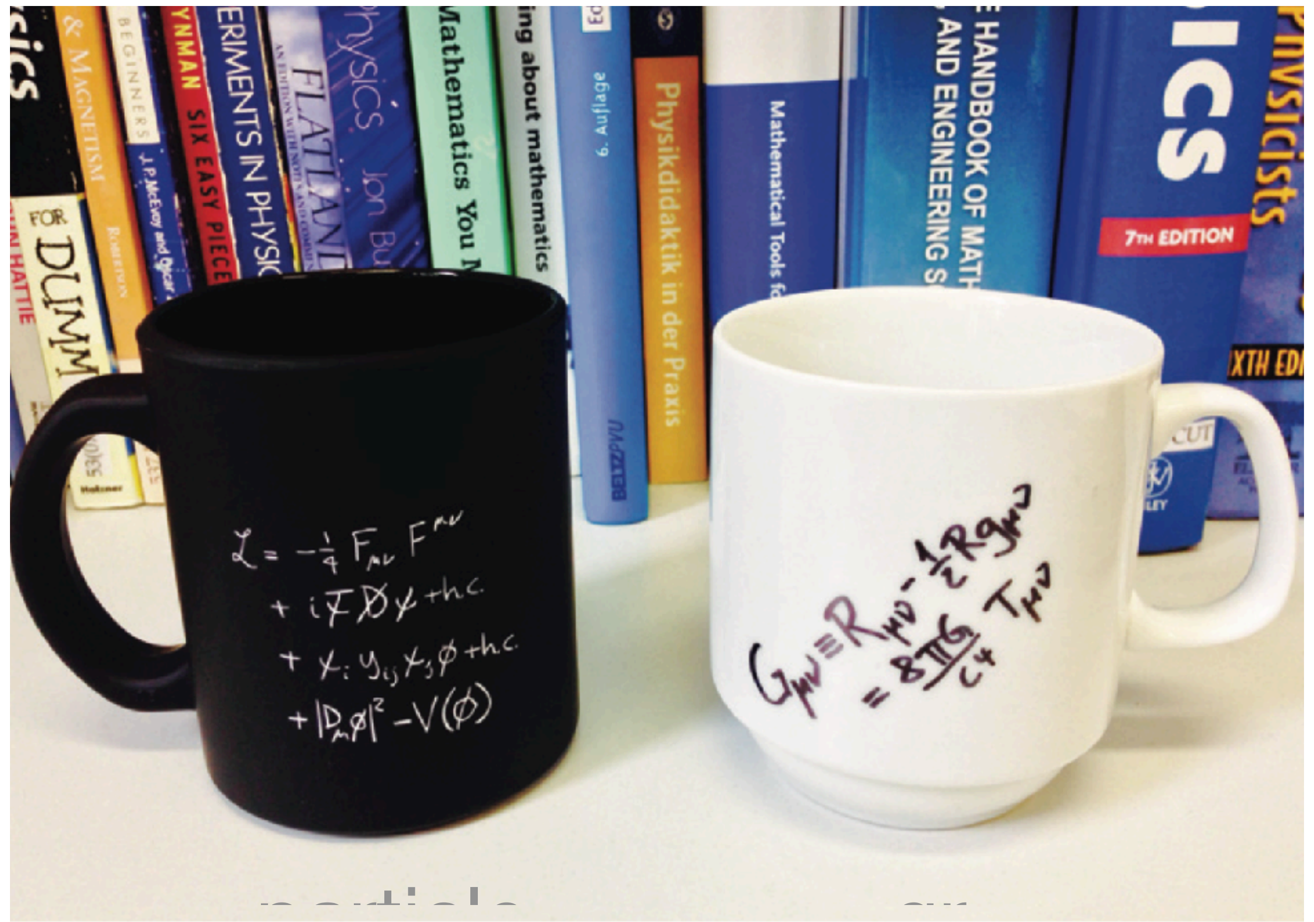
The mission of particle theory



mathematically consistent
models and concepts
(not only!)

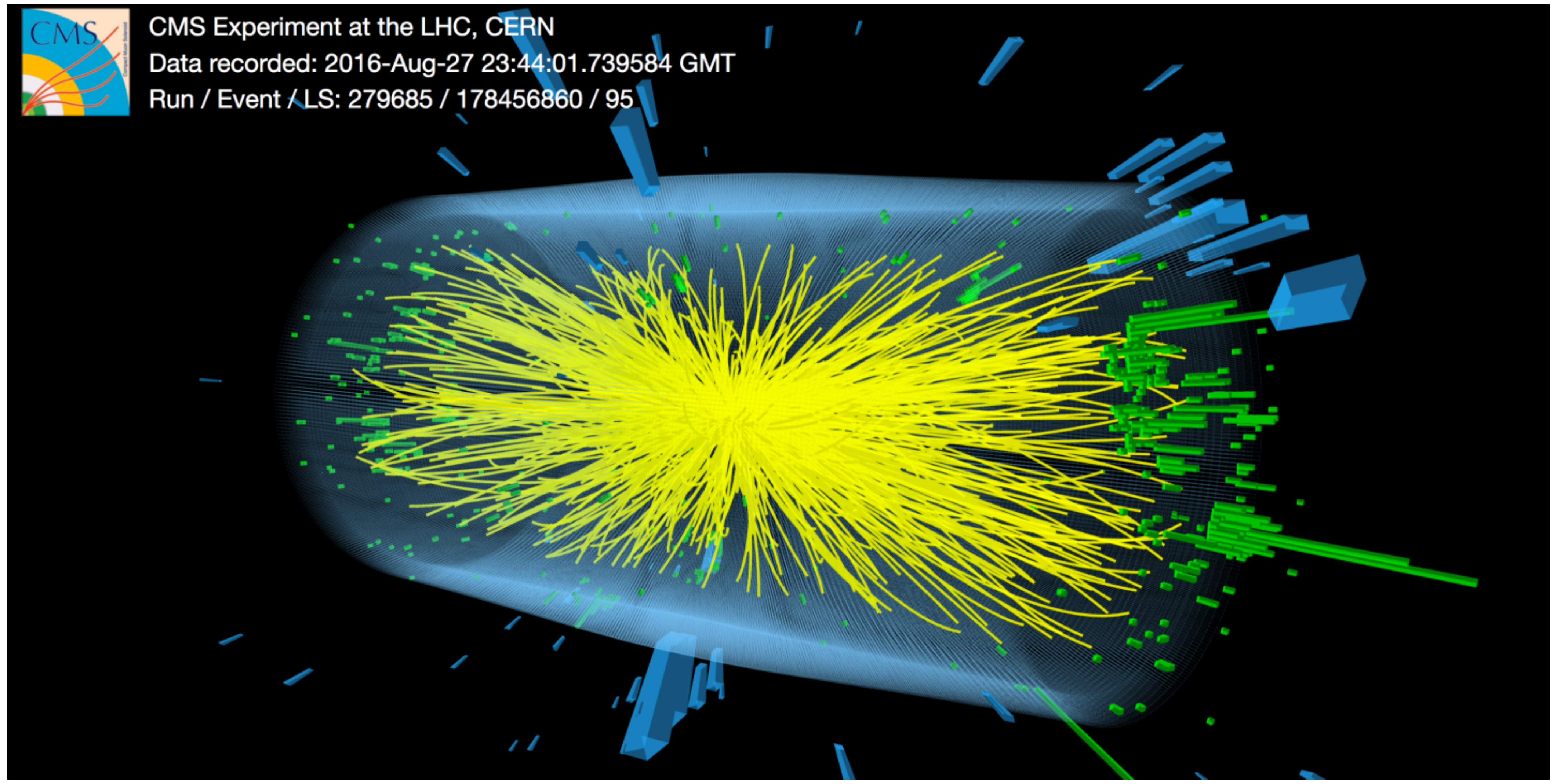


The mission of particle theory

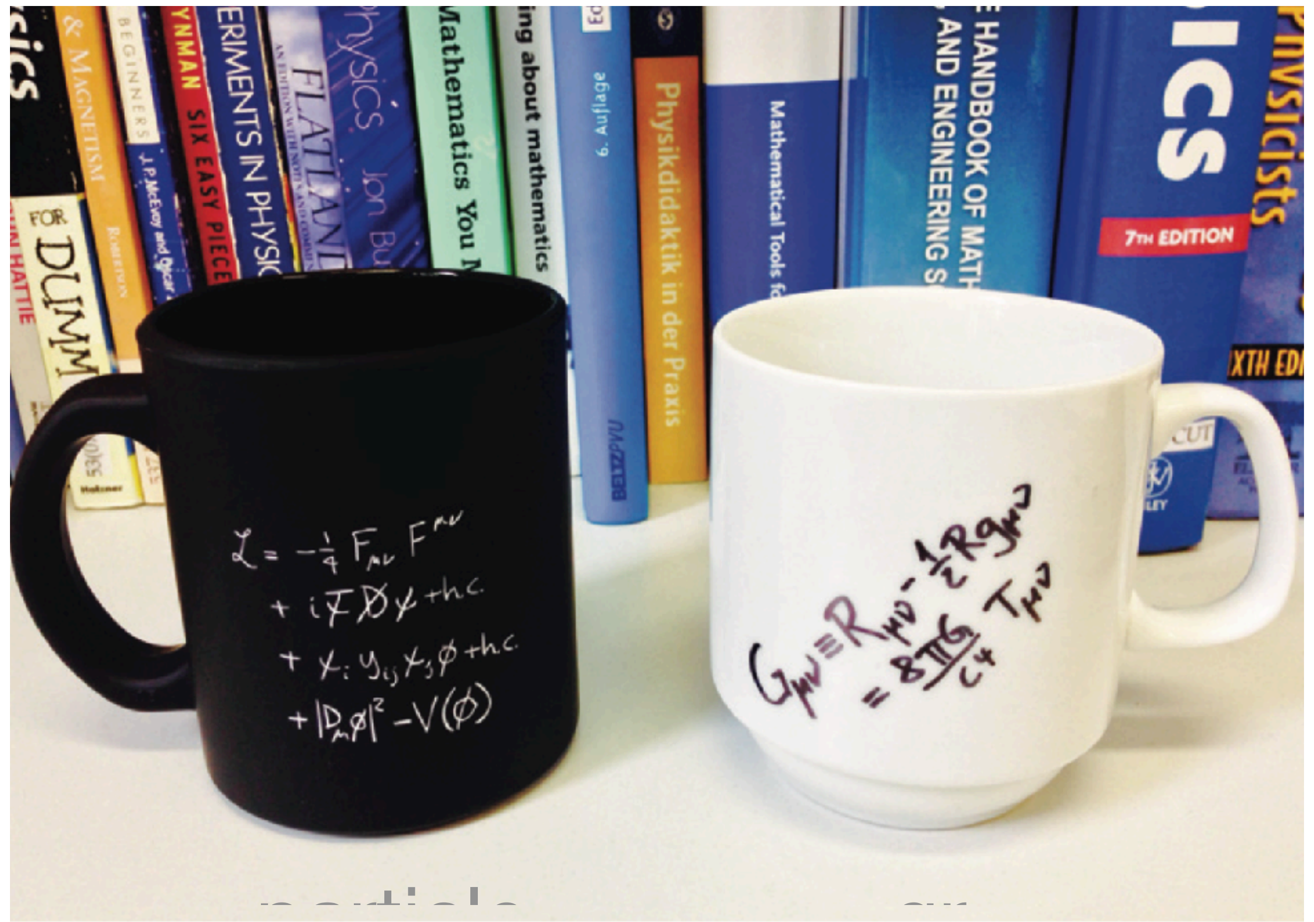


mathematically consistent
models and concepts
(not only!)

theory also needed
at interface:

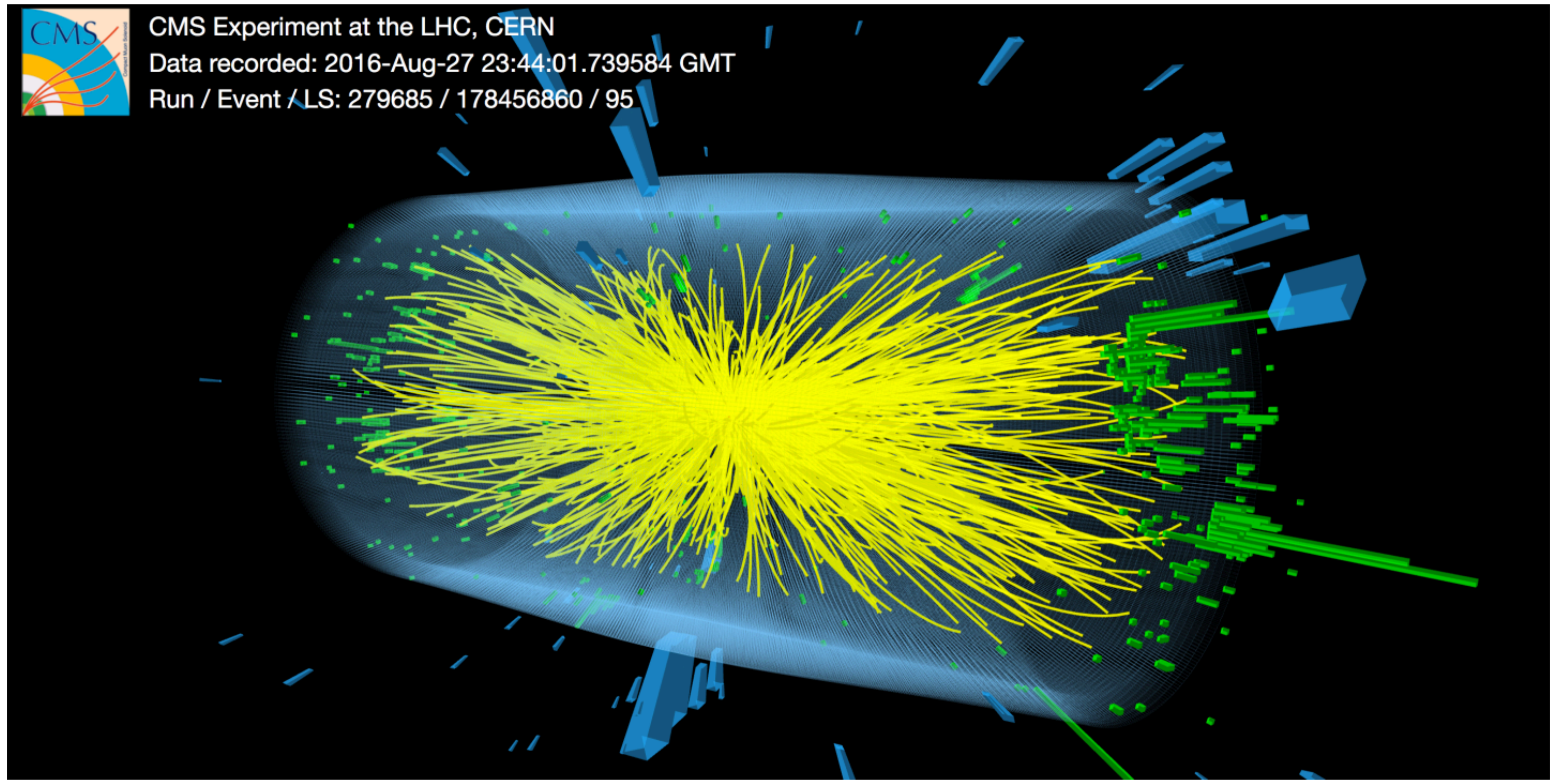


The mission of particle theory



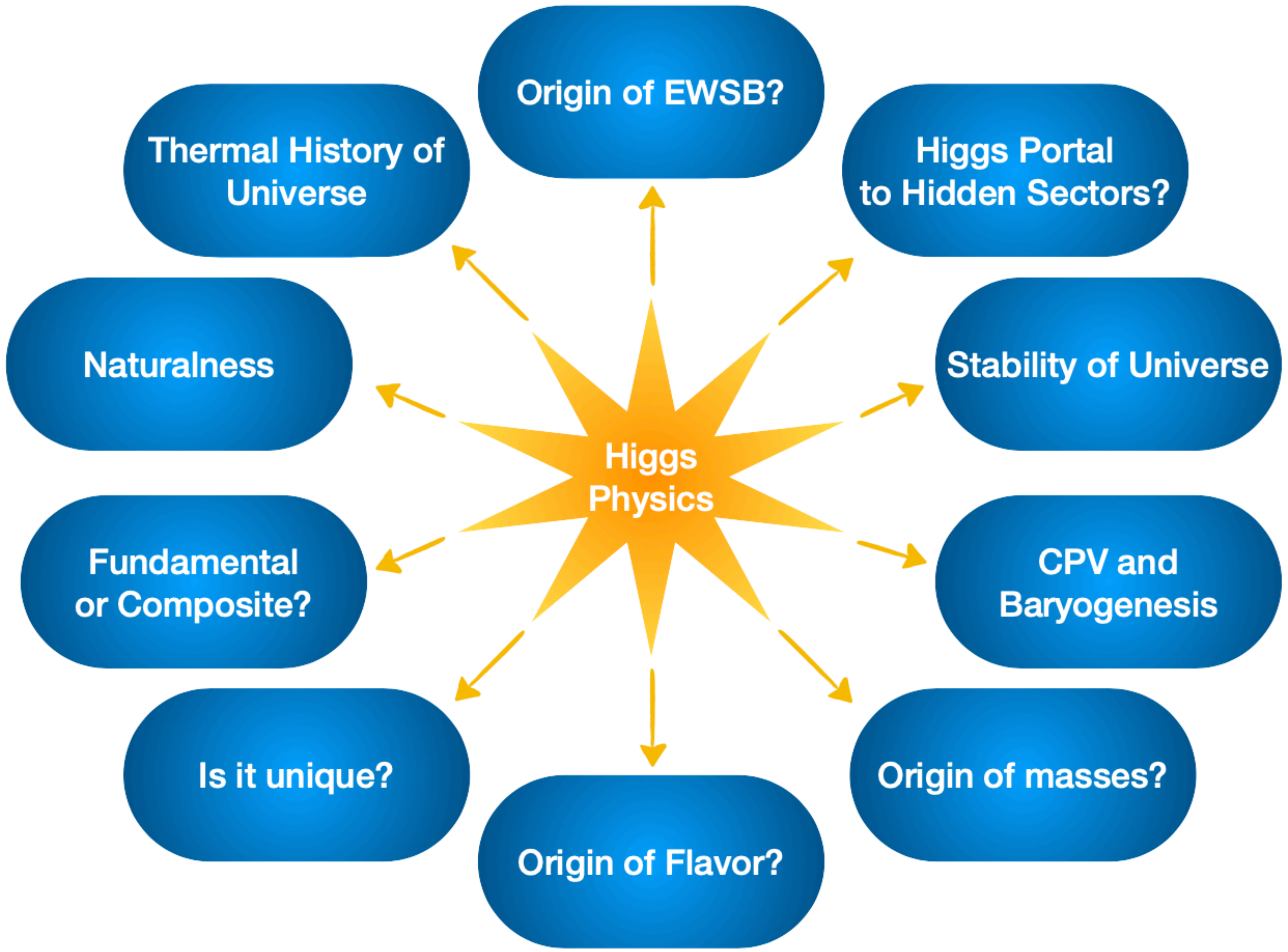
mathematically consistent
models and concepts
(not only!)

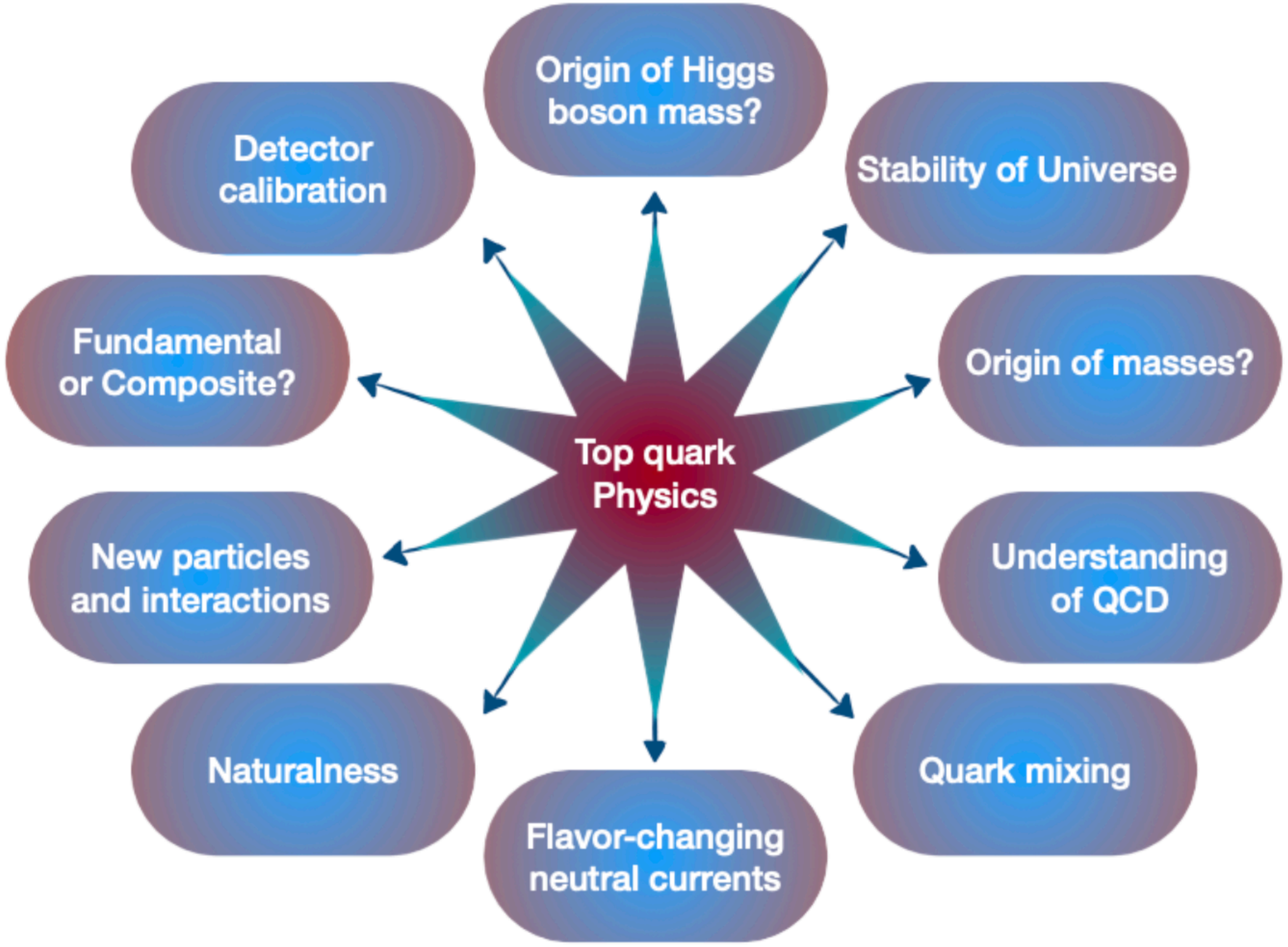
theory also needed
at interface:



- guidance what to look for/where to look
- precise predictions and simulation tools
- couplings, Wilson coefficients, etc. are not observables:
  how to constrain them best and how to interpret the constraints needs theory input
- indirect hints for new physics: quantum corrections indispensable!

The Big Questions

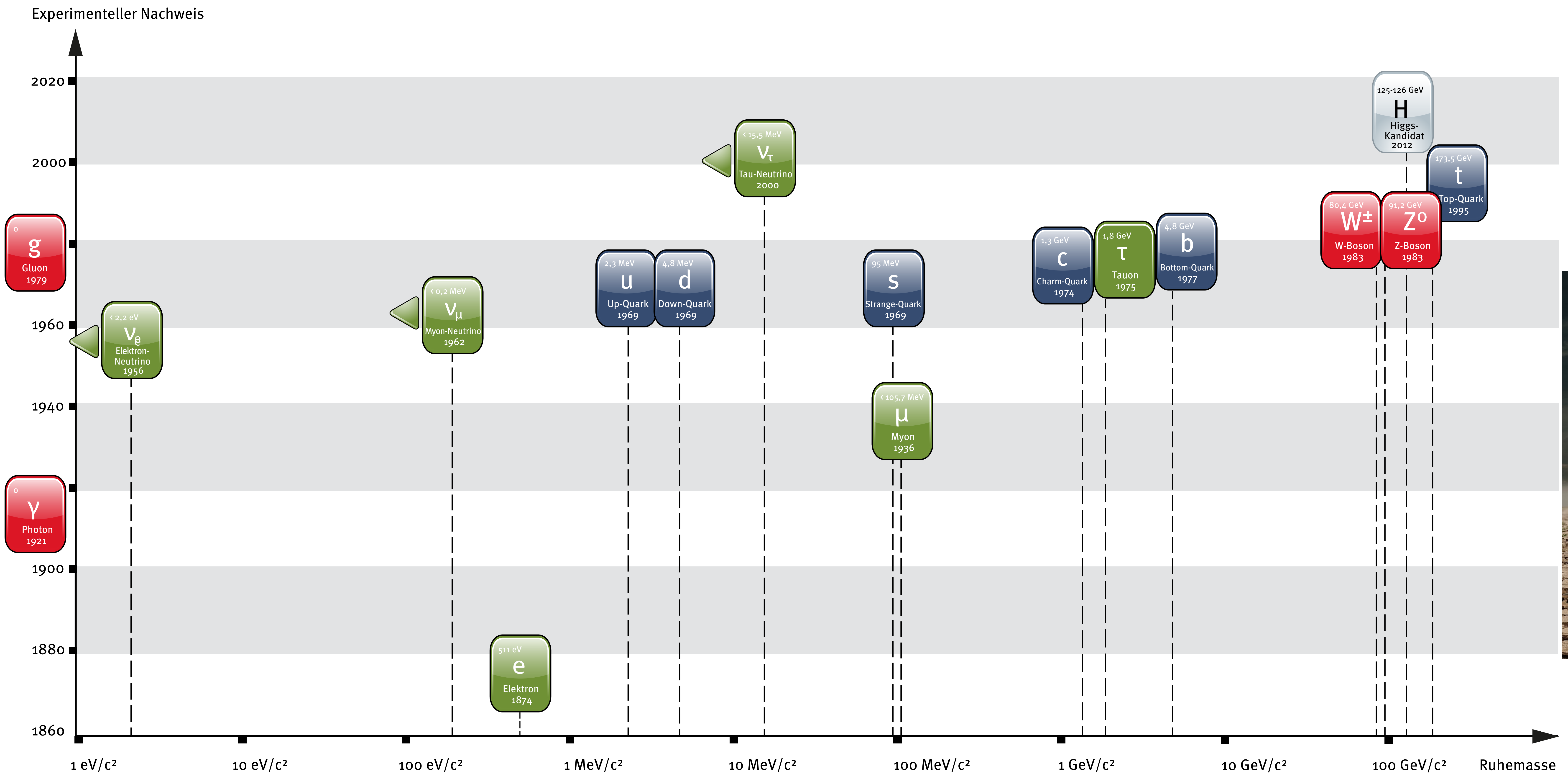




Snowmass Energy Frontier Report 2211.11084

New physics needed to explain this pattern

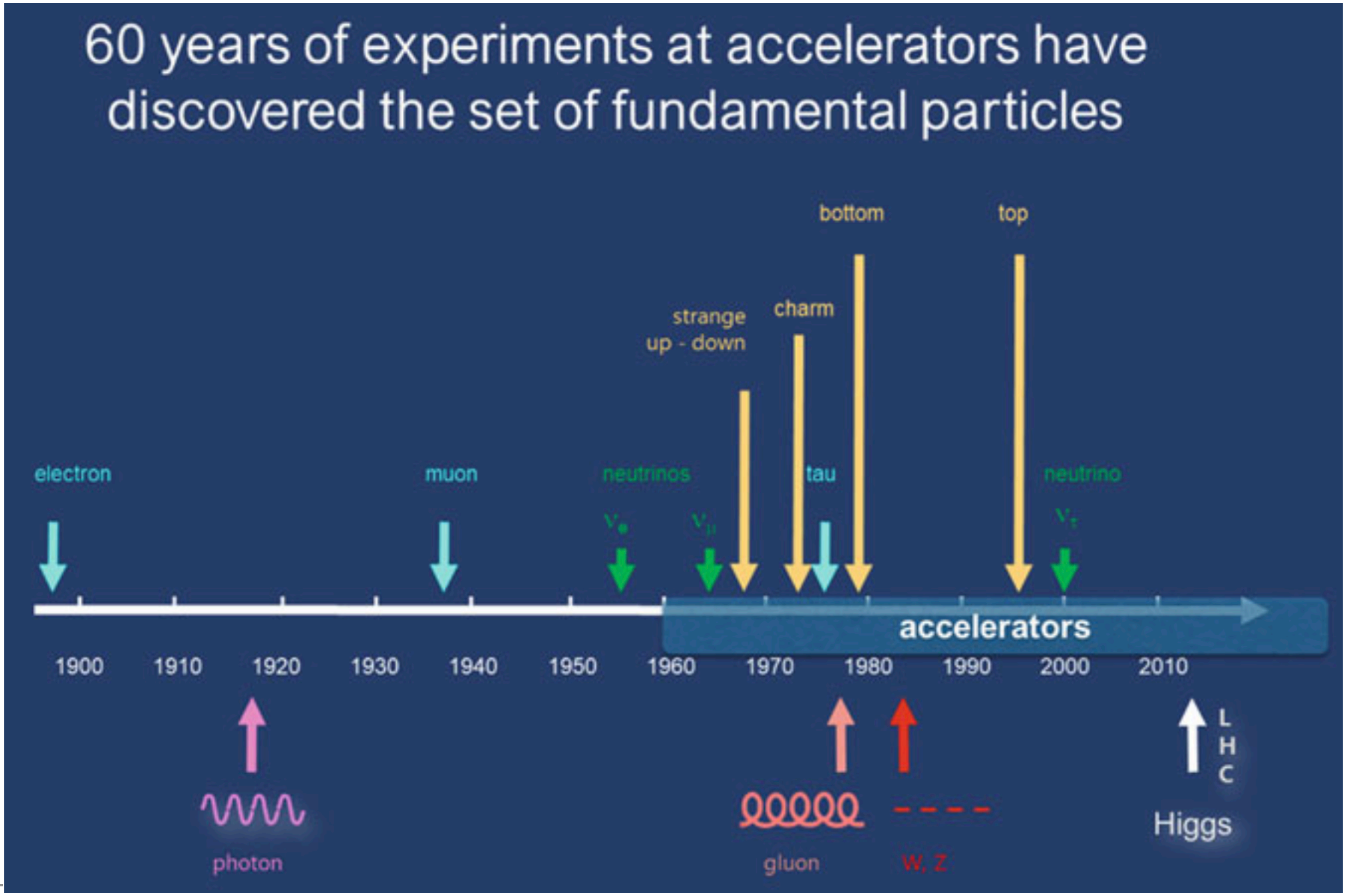
Karlsruhe Institute of Technology



?

10^15 GeV

The era of particle accelerators …



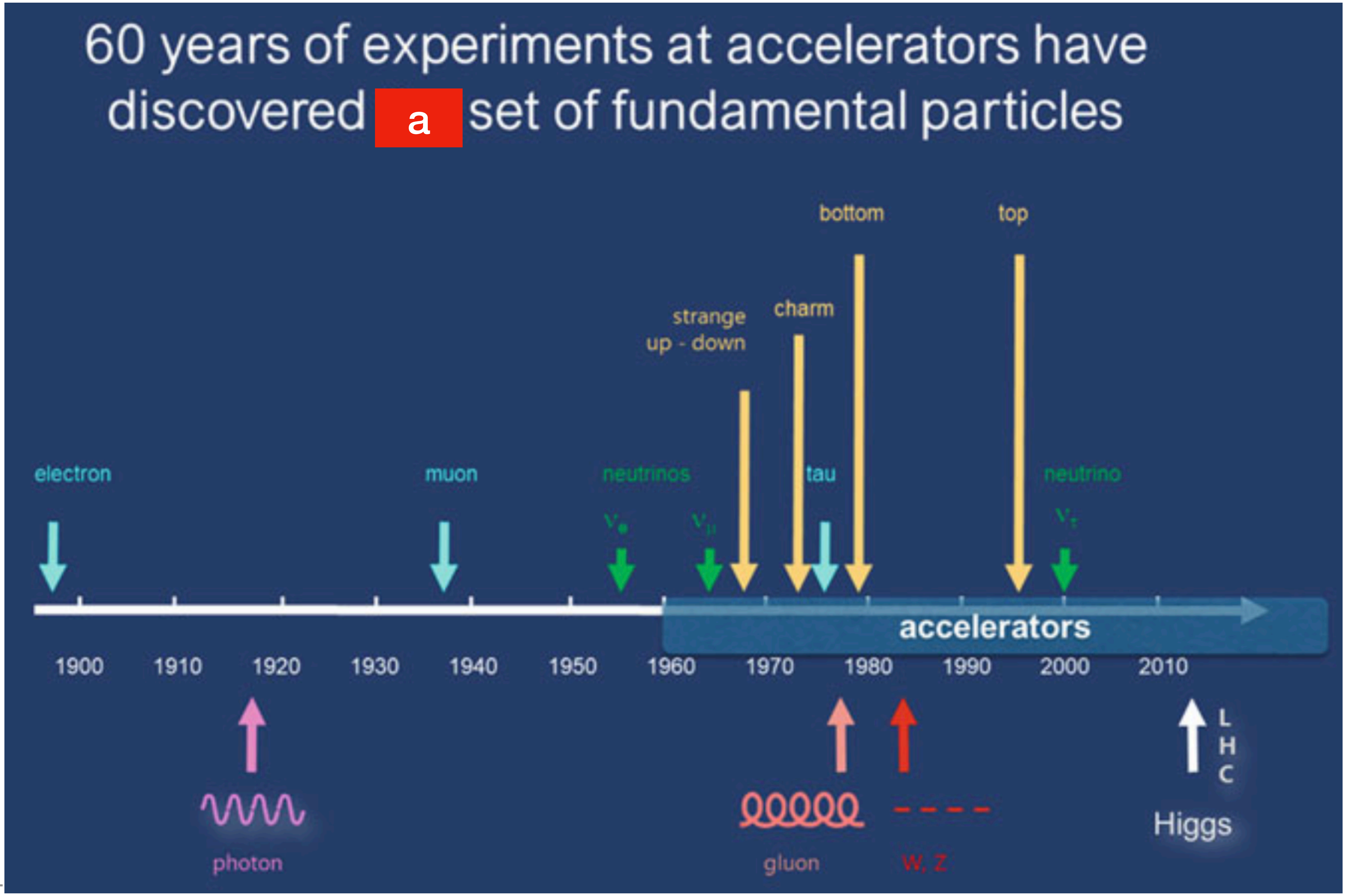
picture: CERN Courier

2070

FCC-hh

SM+?

The era of particle accelerators …



picture: CERN Courier

2070

FCC-hh

SM+?

Theory (or related) talks the Collider Workshop at DESY, November 2024

Karlsruhe Institute of Technology

- Higgs Margarete Mühlleitner
- top Michał Czakon
- EW precision Stefan Dittmaier
- QCD Sven Moch
- Flavour Gudrun Hiller
- Direct searches/BSM Georg Weiglein
- Hadron spectroscopy Misha Mikhasenko
- QCD phase diagram, high density QCD Urs Wiedemann
- Monte Carlo generators Steffen Schumann
- Computing, Tools, AI Lukas Heinrich

Summary Single Higgs

Higgs Factories
(e+e- circ/lin, μ+μ-)

◇ absolute coupling measur. ($\delta\Gamma_H = \mathcal{O}(1\%)$)
◇ perform similar ($\mathcal{L}$ vs. polarisation)
◇ precision: % to ‰ level
◇ running at 2 energies: precision ↑
◇ less sensitive to rare decays

FCC-ee
◇ $\delta m_H = 4$ MeV ◇ $|\delta y_t| \sim 10\,\%$
◇ unique: Hee-coupling measurement

mu-Collider
◇ lineshape: $\delta m_H = 0.21$ MeV, $\delta\Gamma_H = 1.1$-1.4%
◇ $|\delta y_t| \sim 3\,\%$ (<- high prec. Γ_H)

Linear e+e- Colliders
◇ $\delta m_H = 14$ MeV
◇ $|\delta y_t|_{dir} \sim 3/1.5\,\%$ CLIC,ILC500/ILC1000

(HE-)LHeC/FCC-eh
◇ precise measurement of pdf, α_S
◇ input for FCC-hh prec. measur.
◇ LHeC parallel to HL-LHC: synergy

FCC-hh
◇ optimal for rare decays & heavy states
◇ sub-percent on all major couplings
◇ precise measur. of diff. distributions

HE-LHC/FCC-hh<100TeV
◇ precise measurements possible
◇ discovery & precision alternative

M.M. Mühlleitner, KIT „The Future of Collider Physics", DESY, 27-29 Nov 2024 85

Higgs

Summary Single Higgs

Karlsruhe Institute of Technology

Higgs Factories
(e+e- circ/lin, $\mu+\mu$-)

◇ absolute coupling measur. ($\delta\Gamma_H = \mathcal{O}(1\%)$)
◇ perform similar ($\mathcal{L}$ vs. polarisation)
◇ precision: % to ‰ level
◇ running at 2 energies
◇ less sensitiv ... ays

...C-ee
... MeV ◇ $|\delta y_t| \sim 10\,\%$
...unique: Hee-coupling measurement

mu-Collider
◇ lineshape: $\delta m_H = 0.21$ MeV, $\delta\Gamma_H = 1.1$-1.4%
◇ $|\delta y_t| \sim 3\,\%$ (<- high prec. Γ_H)

Linear e+e- Colliders
◇ $\delta m_H = 14$ MeV
◇ $|\delta y_t|_{dir} \sim 3/1.5\,\%$ CLIC,ILC500/ILC1000

(HE-)LHeC/FCC-eh
◇ precise measurement of pdf, α_S
◇ input for FCC-hh prec. measur.
◇ LHeC parallel to HL-LHC: synergy

FCC-hh
◇ optimal for rare decays & heavy states
◇ sub-percent on all major couplings
◇ precise measur. of diff. distributions

HE-LHC/FCC-hh<100TeV
◇ precise measurements possible
◇ discovery & precision alternative

precision is the name of the game

M.M. Mühlleitner, KIT „The Future of Collider Physics", DESY, 27-29 Nov 2024 85

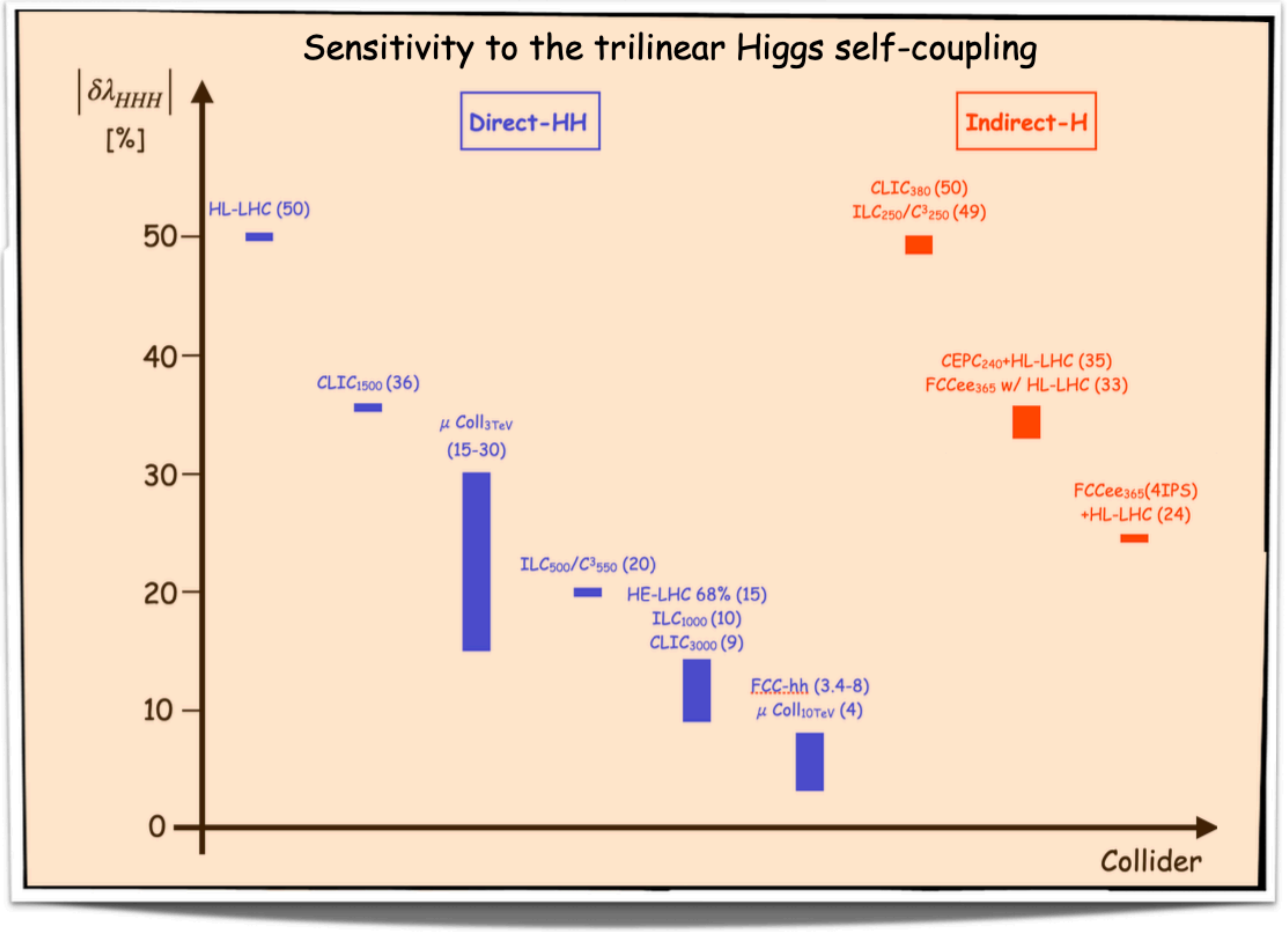
Summary Di-Higgs

Indirect Detection from Single Higgs **Direct Detection from Double Higgs**

- ◊ Single/Di-Higgs: Sensitivity depends on New Physics Scenario and on value of trilinear coupling
- ◊ Single Higgs: EFT analysis taking into account LO and NLO operators crucial
- ◊ Single/Di-Higgs: Challenge ⇝ determination of all input parameters as precisely as possible, exploit different energies, polarization

NLO EW corrections + corresponding operators

see e.g. https://arxiv.org/abs/2409.11466



Note on λ_{HHHH}: first studies show sensitivity @ HL-LHC, LC$_{>1TeV}$, FCC-hh

dependence on EW scheme, operator basis, RGE running, decays, …

… theory effort crucial!

(QCD corrections+(SM)EFT are in a more mature state and easier to automate)

SM theory uncertainty recently reduced see 2501.00587

M.M. Mühlleitner, KIT „The Future of Collider Physics", DESY, 27-29 Nov 2024 85

Trilinear Higgs coupling ("the holy grail")

Karlsruhe Institute of Technology

collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
$\mathrm{ILC}_{250}/\mathrm{C}^3$-250 [51, 52]	49%	—	49%
$\mathrm{ILC}_{500}/\mathrm{C}^3$-550 [51, 52]	38%	20%	20%
CLIC_{380} [54]	50%	—	50%
CLIC_{1500} [54]	49%	36%	29%
CLIC_{3000} [54]	49%	9%	9%
FCC-ee [55]	33%	—	33%
FCC-ee (4 IPs) [55]	24%	—	24%
FCC-hh [79]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [64]	-	15-30%	15-30%
μ(10 TeV) [64]	-	4%	4%

most likely will be better

these numbers are similar, but **direct** vs **indirect**

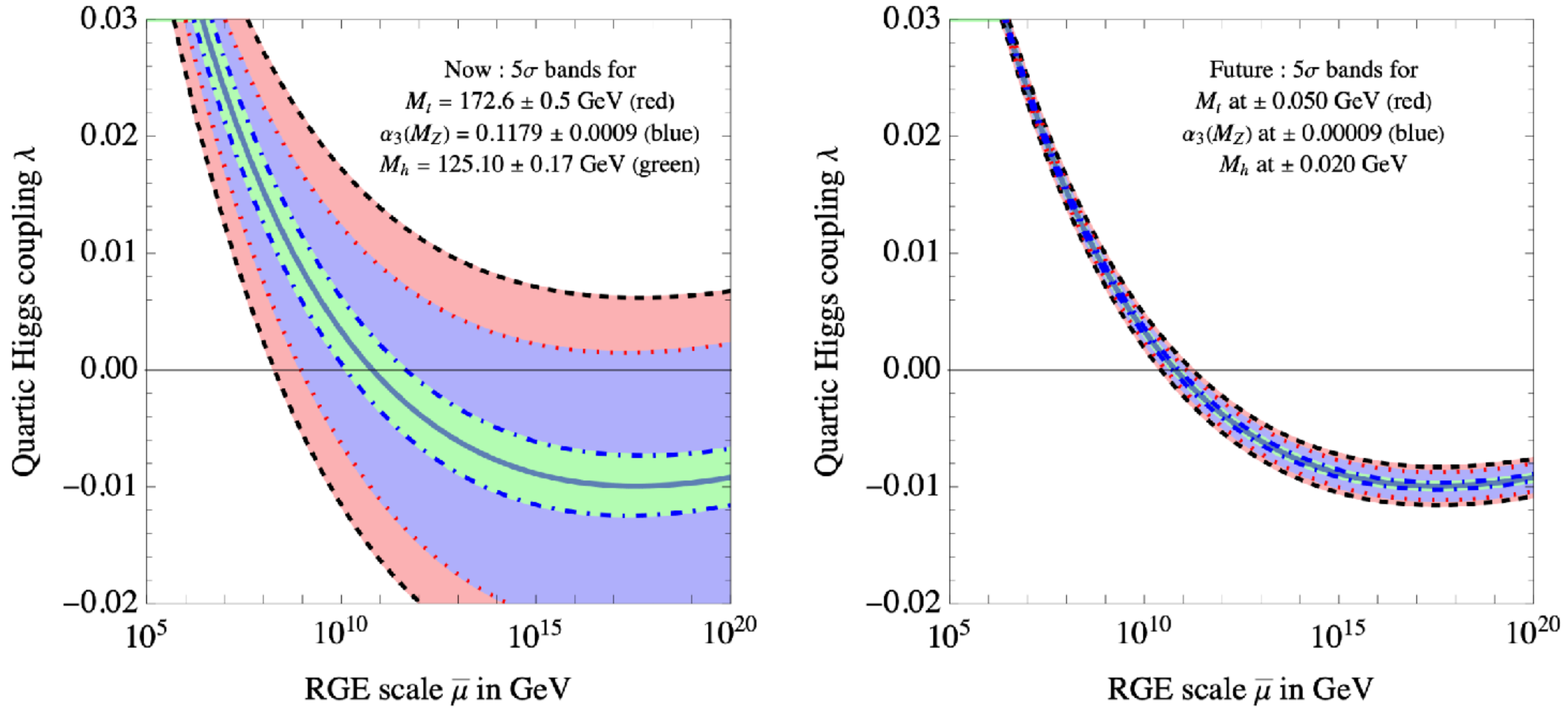
indirect needs more theory effort, control of operators entering at the same (loop) order, EFT truncation uncertainties, running Wilson coefficients, …

Snowmass Higgs Report 2209.07510

top quark physics

Karlsruhe Institute of Technology

heaviest SM particle, many connections to the “big questions”



Franceschini, Strumia, Wulzer ‘22

- vacuum stability to give hints of new physics scales:
  top quark mass plays a crucial role

- EFT operators involving top quarks are ubiquitous,
  global fits and matching to UV models important for interpretation

- FCNC decays of top quarks: FCC-hh can reach model discriminating power

- top quarks are difficult from a modelling perspective
  (off-shell effects, bound state effects, renormalisation scheme dependence, …)

M. Czakon: “*theory will not be the limiting factor* for precision top quark physics at FC-x,
much work to be done, but time scales long”

EW precision physics

- challenging precision calculations! However "**feasible (anticipating progress + support)**" (S. Dittmaier)

	experimental accuracy				intrinsic theory uncertainty		
	current	ILC	CEPC	FCC-ee	current	current source	prospect
ΔM_Z[MeV]	2.1	–	0.1	0.1			
$\Delta\Gamma_Z$[MeV]	2.3	1	0.025	0.1(0.025)	0.4	$\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$	0.15
$\Delta \sin^2\theta^\ell_{\rm eff}[10^{-5}]$	16	1.3	0.4	0.6(0.24)	4.5	$\alpha^3, \alpha^2\alpha_s$	1.5
$\Delta R_b[10^{-5}]$	66	14	4	6	11	$\alpha^3, \alpha^2\alpha_s$	5
$\Delta R_\ell[10^{-3}]$	25	3	2	1	6	$\alpha^3, \alpha^2\alpha_s$	1.5

- M_W from σ_{WW} measurement at threshold: $\delta M_W \lesssim 1\,\mathrm{MeV}$, requires $\delta_{\rm TH} < 0.05\%$

- W/Z dynamics at high energies:
  - window to EW symmetry breaking via off-shell Higgs exchange at high energies, **complementary** to direct analyses of Higgs bosons
  - high sensitivity to **anomalous gauge boson couplings**
  - **EW showers** need to be studied

EW precision physics

Karlsruhe Institute of Technology

- challenging precision calculations! However “**feasible (anticipating progress + support)**” (S. Dittmaier)

	experimental accuracy				intrinsic theory uncertainty		
	current	ILC	CEPC	FCC-ee	current	current source	prospect
$\Delta M_Z[\mathrm{MeV}]$	2.1	–	0.1	0.1			
$\Delta\Gamma_Z[\mathrm{MeV}]$	2.3	1	0.025	0.1(0.025)	0.4	$\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$	0.15
$\Delta \sin^2\theta^{\ell}_{\mathrm{eff}}[10^{-5}]$	16	1.3	0.4	0.6(0.24)	4.5	$\alpha^3, \alpha^2\alpha_s$	1.5
$\Delta R_b[10^{-5}]$	66	14	4	6	11	$\alpha^3, \alpha^2\alpha_s$	5
$\Delta R_\ell[10^{-3}]$	25	3	2	1	6	$\alpha^3, \alpha^2\alpha_s$	[illegible]

- M_W from σ_{WW} measurement at threshold: [illegible], requires $\delta_{\mathrm{TH}} < 0.05\%$

will lead to a “quantum leap” in theory predictions
on both conceptual and computational level

- W/Z dynamics at high energies:
  - window to EW symmetry breaking via off-shell Higgs exchange at high energies, **complementary** to direct analyses of Higgs bosons
  - high sensitivity to **anomalous gauge boson couplings**
  - **EW showers** need to be studied

QCD and parton shower MCs

Karlsruhe Institute of Technology

- potential at FCC-ee: $\alpha_s(M_Z)$ with permil precision

  (so far values from e+e- or EW fits higher than from DIS or hadronic collisions -> resolve this “puzzle”?)

- **PDFs:**
  - EIC @ BNL will be a great opportunity to improve our knowledge on parton kinematics
  - LHeC would enter very small x regime (x~10^-6)
  - FCC-hh: can reach x~10^-7, differences due to different PDF sets ~4% for gluon fusion Higgs@100TeV, consistent PDFs at FCC-hh need much more care (e.g. treatment of charm quarks)

Monte Carlo event generators: **vital for realistic phenomenological and experimental analyses**

- need improved accuracy, quantifiable systematics, resource efficiency
- algorithmic developments are needed and are being worked on
  (higher than log accuracy, QED/EW corrections, NN improved phase space sampling, …)
- readiness for heterogeneous hardware (CPU+GPU, …)

QCD and parton shower MCs

Karlsruhe Institute of Technology

- potential at FCC-ee: $\alpha_s(M_Z)$ with permil precision

(so far values from e+e- or EW fits higher than from DIS or hadronic collisions -> resolve this “puzzle”?)

- **PDFs:**
  - EIC @ BNL will be a great opportunity to improve our knowledge on parton kinematics
  - LHeC would enter very small x regime (x~10^-6)
  - FCC-hh: can reach x~10^-7, differences due to different PDF sets ~4% for gluon fusion [illegible]gs@100TeV, consistent PDFs at FCC-hh need much more care (e.g. treatment of ch[illegible])

Monte Carlo event generators: **vital for realistic phenomenol[illegible]erimental analyses**

- need improved accuracy, quantifiable systematics, resou[illegible]
- algorithmic developments are needed and are be[illegible] (higher than log accuracy, QED/EW corrections, N[illegible]oved phase space sampling, …)
- readiness for heterogeneous hardware (CPU+GPU, …)

progress guaranteed provided enough support and training opportunities

BSM

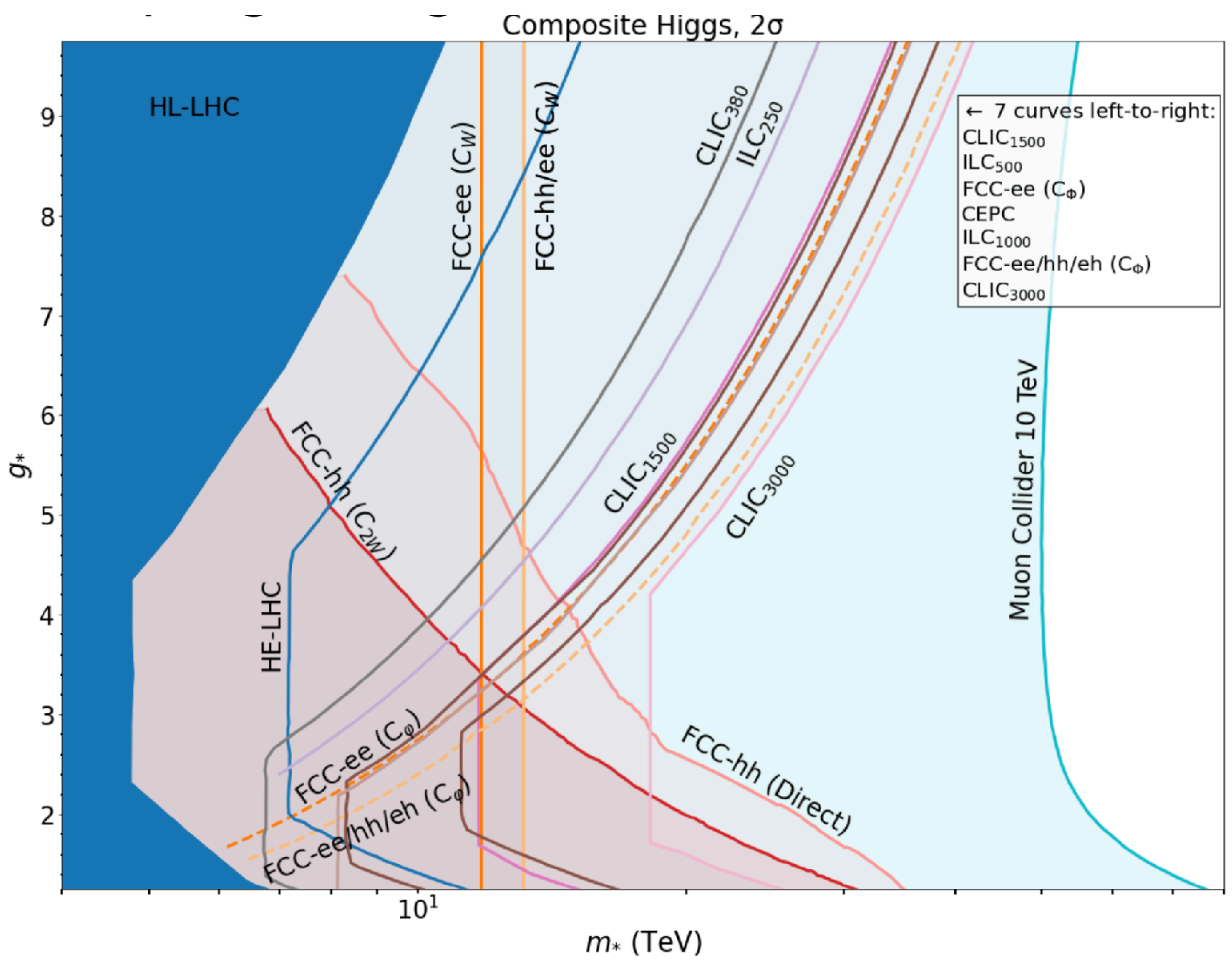
If hints for BSM became substantial in Run 3 or HL-LHC, what would be the best next collider?

- **dedicated searches:**
  - BSM Higgs searches
  - compositeness, top partners, Z', leptoquarks, …
  - Higgs self-coupling

  direct $e^+e^- \to Zhh$ needs at least $\sqrt{s} = 500$ GeV or

  $\gamma\gamma \to hh$ at a 380 GeV photon collider (XFEL)

How compelling can indirect hints for new particles be?



T. Bose et al. 2209.13128

- **searches where the signals can be hidden:**

  dark sector, extra dimensions, superpartners, strings, …

note: for mono-X searches (dark matter) polarised beams help a lot

Flavour

Karlsruhe Institute of Technology

- flavour physics profits more from high luminosity than from high energy

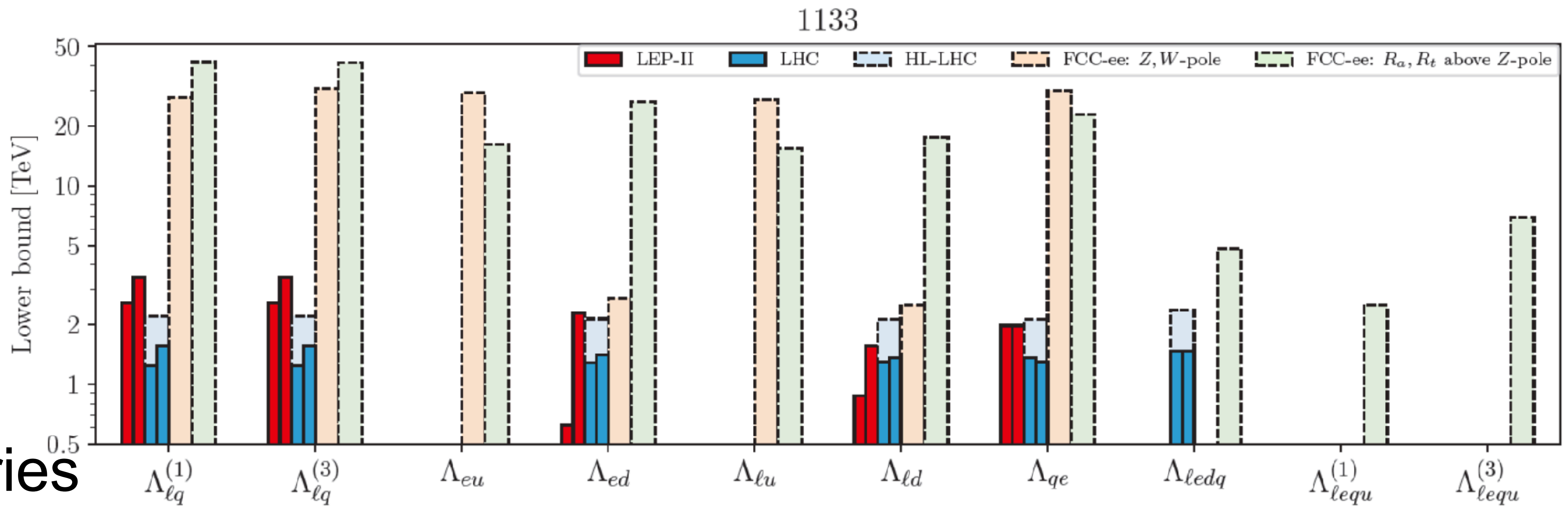
  “FCC-ee, CEPC (”Tera-Z”): More than an order of magnitude than Belle II, plus more species” (G. Hiller)

- the flavour sector is the sector of the SM that cries loudest for new physics!
  - unexplained lepton mass pattern
  - unexplained mixing pattern
  - 3 generations: CP violation yes, but not sufficient for baryon asymmetry of the universe

➡ investigate rare processes, signs for FCNCs

➡ investigate decays to invisible
(e.g. dark matter, axions, sterile neutrinos), …

➡ unprecedented reach into CP violation at Tera-Z factories



2411.02485

Hadron spectroscopy, high density QCD

Karlsruhe Institute of Technology

understanding the QCD vacuum, confinement, bound state formation, tetra- and pentaquarks, …

- at the LHC, 75 new hadrons have been discovered!
- high production rates of heavy quarks and good mass resolution essential
- connections to flavour physics, nuclear physics, astrophysics, …

QCD under extreme conditions:

- many new discoveries at CERN: jet quenching, flow phenomena, strangeness enhancement, …
- more to come with full exploitation of HL-LHC as a Heavy Ion Collider

Heavy ion physics does not inform the ESPPU discussion (apart from obvious FCC-hh opportunities)

(Urs Wiedemann)

Computing, AI

Of increasing importance, also in theoretical particle physics!

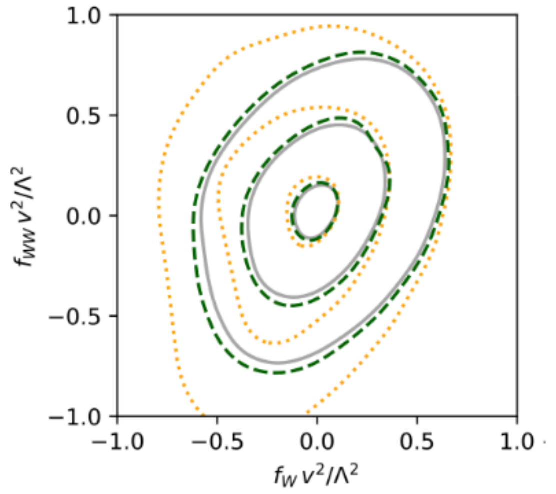
see also https://arxiv.org/abs/2501.05382 and ML living Review

Particle Physics always was and will stay **fundamentally aligned** with AI

High-Level Abstractions

High-dimensional Raw Data

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

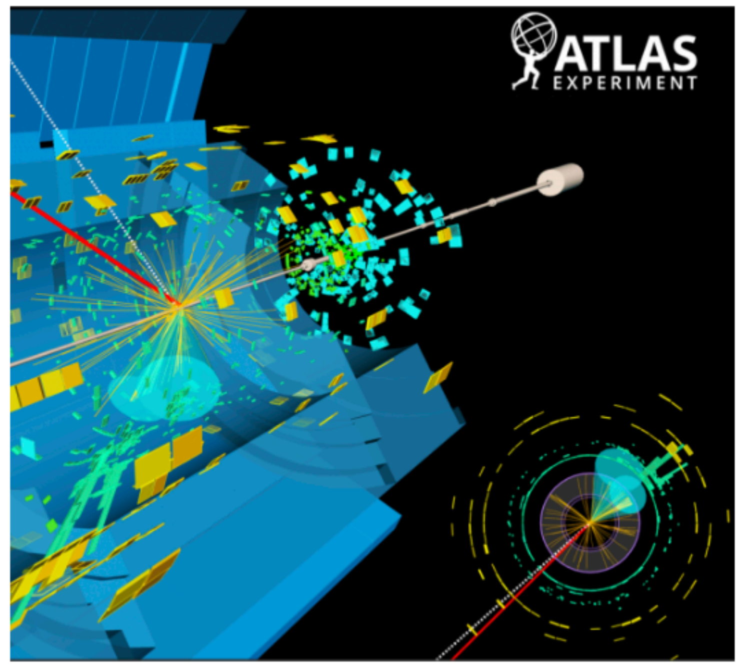


Stochastic Simulation: $x \sim p(x\,|\,\theta)$

Reco & Analysis: $f_\phi(x)$

Conditional Generative AI: $x \sim p(x\,|\,\theta)$

Multi-modal Pattern Recognition : $f_\phi(x)$



"AI is too transformative to not be mentioned in the Update"

(Lukas Heinrich)

Recommendations (Theory)

Karlsruhe Institute of Technology

- Substantial ramp-up in **high precision for SM predictions** for Higgs, top, EW, QCD, MCs:

  *Challenging, but **possible**, **provided** sufficient (human, computing, …, i.e. funding) **resources** are available*

- Need **improved precision of EFT** parametrisations of new physics

  inclusion of QCD and EW corrections, going beyond SMEFT dim-6 or leading HEFT operators, running Wilson coefficients, consistent global fits, combination of high- and low energy observables, input from non-collider experiments, …

- EFTs can only serve as a vehicle to **identify patterns of deviations** from the SM

➡ need **model building**, EFT matching, inference “dictionaries”

➡ need “smart” observables and methods that help discriminating between models

➡ need a **global picture**
(input from astro-particle physics, cosmology, atomic physics, …, mathematical physics, …)

importance of outreach: get the general public excited about a project of the scale of a space mission!

Draft items for strategy document (1)

Karlsruhe Institute of Technology

- Theoretical particle physics provides **possible solutions to big questions** that the Standard Model of particle physics still leaves open, through **models and concepts** that go beyond our current experimentally tested knowledge.

- Theory also **gives guidance** for searches to be carried out at a collider exploring the next energy or intensity frontier and for the **interpretation** of the measurements. This includes a large spectrum, ranging from model building to generic parametrisations of new physics effects through Effective Field Theories. Even completely agnostic anomaly searches (for example based on machine learning) will need substantial theory input for their interpretation.
  For the identification and inference of **indirect effects of new particles** a concerted theory effort is particularly important.

- The anticipated experimental precision at the next high energy collider needs to be matched by highly precise theory predictions. **Precision calculations** to reduce the perturbative uncertainties and an excellent control of non-perturbative uncertainties are therefore an essential part of the activities of the theory community. Electroweak corrections leveraged to a precision level that requires substantial conceptual and computational developments will be particularly important at future lepton colliders.
  Simulation tools (Monte Carlo programs) with high efficiency and quantifiable uncertainties, based on first principles given by quantum field theory and well controlled non-perturbative parameters, are vital to fully exploit experimental results.

Draft items for strategy document (2)

- Calculations of such unprecedented precision are **very challenging and only feasible if supported sufficiently** by corresponding resources.

A diverse program to achieve higher precision in the theoretical predictions, going way beyond just increasing the loop order, is essential for the success of a future collider program.

- The German theory community has expertise in all aspects of such a theory program, ranging from mathematical aspects of scattering amplitudes and model building to phenomenological predictions and event generators.

- The broad range of activities in theoretical particle physics, from formal to phenomenological aspects, fosters **interdisciplinary research,** creating synergies with cosmology, astroparticle physics, nuclear physics, computer science and mathematics. The close **collaboration between the experimental and theoretical communities** that has always been supported by CERN should be invigorated.

- **Importance of outreach:** Striving for a deeper understanding of our universe is deeply rooted in the human mind, and a facility reaching out to uncharted territory that cannot be explored by other means will inspire young researchers and fascinate the public.

Theory paragraph in the 2020 Strategy Document

Theoretical physics is an essential driver of particle physics that opens new, daring lines of research, motivates experimental searches and provides the tools needed to fully exploit experimental results. It also plays an important role in capturing the imagination of the public and inspiring young researchers. The success of the field depends on dedicated theoretical work and intense collaboration between the theoretical and experimental communities.
Europe should continue to vigorously support a broad programme of theoretical research covering the full spectrum of particle physics from abstract to phenomenological topics. The pursuit of new research directions should be encouraged and links with fields such as cosmology, astroparticle physics, and nuclear physics fostered. Both exploratory research and theoretical research with direct impact on experiments should be supported, including recognition for the activity of providing and developing computational tools.