From Inspirations to Futures!

Chris Quigg

Fermilab Users Meeting · July 12, 2024

ca. 2000: **In a decade or two, we can hope to . . .**

- Understand electroweak symmetry breaking
- Observe the Higgs boson
- Measure neutrino masses and mixings
- Establish Majorana neutrinos ($\beta\beta_{0\nu}$)
- Thoroughly explore CP violation in B decays
- Exploit rare decays (K, D, . . .)
- Observe neutron EDM, pursue electron EDM
- Use top as a tool
- Observe new phases of matter
- Understand hadron structure quantitatively
- Uncover the full implications of QCD
- Observe proton decay
- Understand the baryon excess
- Catalogue matter and energy of the universe
- Measure dark energy equation of state
- Search for new macroscopic forces
- Determine GUT symmetry
- Detect neutrinos from the universe
- Learn how to quantize gravity
- Learn why empty space is nearly weightless
- Test the inflation hypothesis
- Understand discrete symmetry violation
- Resolve the hierarchy problem
- Discover new gauge forces
- Directly detect dark-matter particles
- Explore extra spatial dimensions
- Understand the origin of large-scale structure
- Observe gravitational radiation
- Solve the strong CP problem
- Learn whether supersymmetry is TeV-scale
- Seek TeV-scale dynamical symmetry breaking
- Search for new strong dynamics
- Explain the highest-energy cosmic rays
- Formulate the problem of identity

. . . and learn the right questions to ask

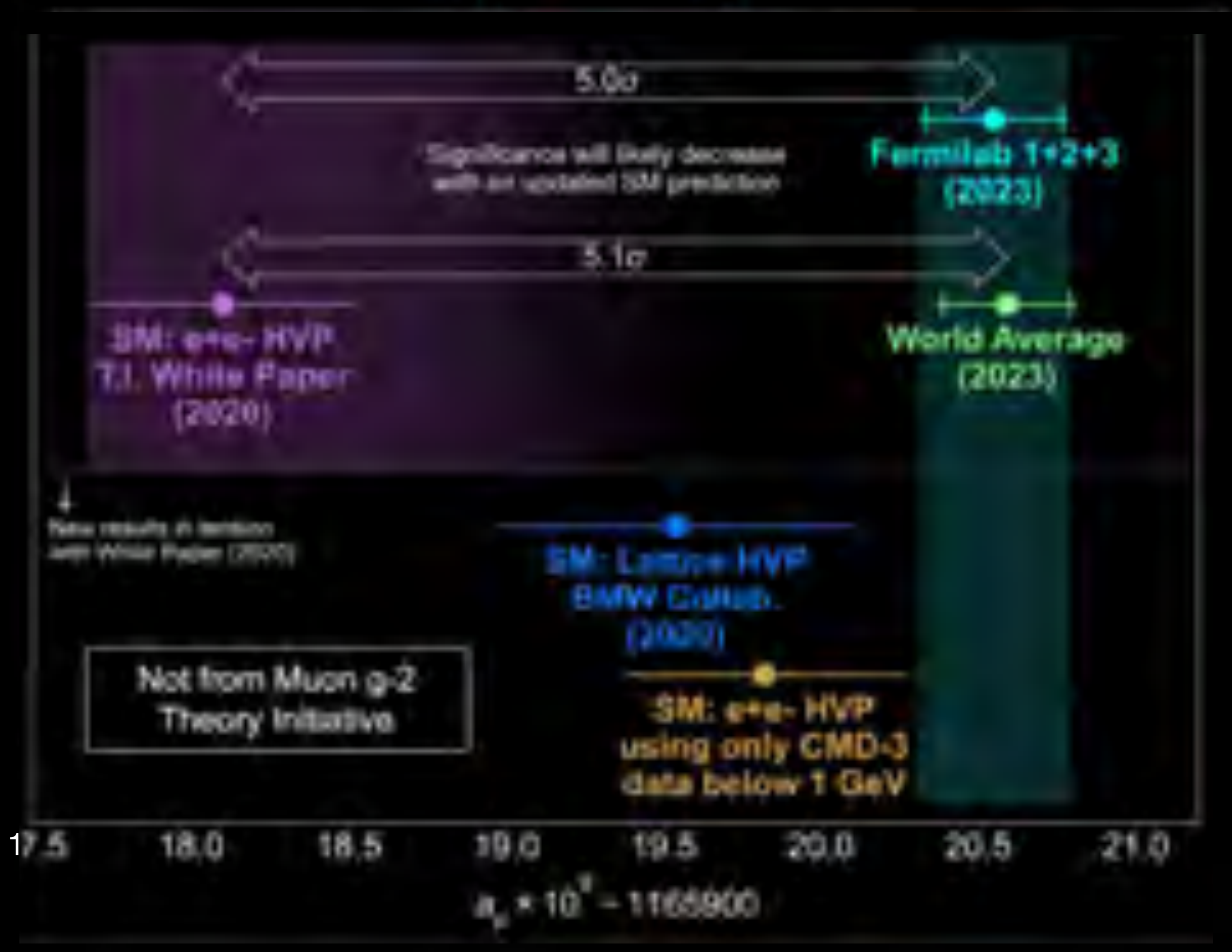
Current list: → 120 Questions

“sixth place of the decimal” and beyond …

ATLAS M_W (2024): 80.3665 ± 0.0159 MeV

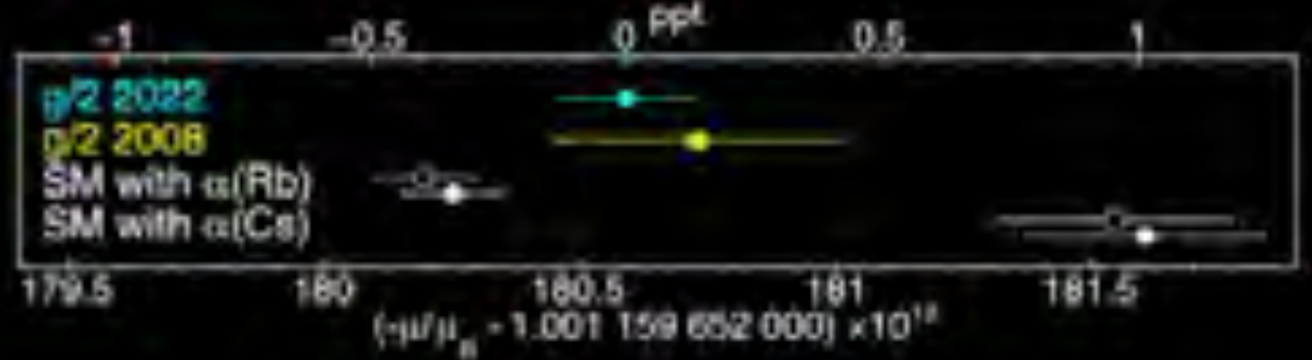
CMS (2024): $a_\tau = 0.0009^{+0.0032}_{-0.0031}$

$(g-2)_\mu$



e magnetic dipole moment measured to 0.13 ppt

$-\mu_e/\mu_B =$ 1.00115965218059(13)



Harvard–NU

fine structure constant

Berkeley: $\alpha^{-1}(\mathrm{Cs}) =$ 137.035 999 046(27)

Paris: $\alpha^{-1}(\mathrm{Rb}) =$ 137.035 999 206(11)

(differ by 5.4 s.d.)

(Anti)proton magnetic moments: CPT test

$$\mu_{\bar{p}} = -2.792\,847\,344\,1(42)\ \mu_N$$

vs.

$$\mu_p = +2.792\,847\,344\,62(82)\ \mu_N$$

BASE Collaboration @CERN Antiproton Decelerator

UNIVERSITIES RESEARCH ASSOCIATION

Tollestrup Award For Postdoctoral Research

(virtual)

Ana Martina Botti

Fermi National Accelerator Laboratory

"For highly impactful contributions to detector R&D and operations of the SENSEI(Sub-Electron-Noise Skipper-CCD Experimental Instrument)/OSCURA(Observatory of Skipper CCDs Unveiling Recoiling Atoms) Experiment, including an order of magnitude reduction in dark current which has been critical to the experimental sensitivity."

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UNIVERSITIES RESEARCH ASSOCIATION

Doctoral Thesis Award

Brynn Kristin MacCoy

University of Washington

"Dr. MacCoy's thesis asks significant questions: 'What is the measurement, really?' 'What could affect the answer?' 'How well do we really know these assumptions?' The answers serve as reference to the physics community, especially the clear and approachable introduction to beam dynamics. The conclusions give a clear sense of the impact of this work on the wider physics community and clearly describe future experimental and theoretical work."

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UNIVERSITIES RESEARCH ASSOCIATION

Early Career Award

Kevin Pedro

Fermi National Accelerator Laboratory

"For groundbreaking searches for dark matter arising from strongly coupled dark sectors with the CMS detector, pioneering work in ML-based model-independent anomaly detection for collider and astrophysics experiments, and leadership in the development of new AI/ML techniques to improve event reconstruction and detector simulation in particle physics, as well as novel strategies to accelerate AI inference and throughput with heterogeneous computing using coprocessors as a service."

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UNIVERSITIES RESEARCH ASSOCIATION

Engineering Award

William Pellico

Fermi National Accelerator Laboratory

"Bill Pellico has led the development of innovative Power-over-Fiber (PoF) readout electronics for the Photon Detection System of the DUNE Far Detector. The challenge of delivering power to the photon detectors placed on the -300 kV cathode surface of the liquid argon time projection chamber (LArTPC) has been met thanks to his foresight and creativity, and this development underpins the expanded neutrino physics reach of the DUNE Far Detector (FD2). This achievement is a highlight among many throughout Bill Pellico's career, including his multiple engineering and leadership contributions to increasing the proton throughput of the accelerator complex that have been crucial to the successes of the Fermilab neutrino program, and his recent pursuit of the development of robotic systems to enable safer and more efficient maintenance of detectors and accelerators."

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Robert R. Wilson: “to create a paradise for users"

In Leon's company, it seemed that anything might be possible

Paradise?

Paradise?

Huge thanks to Doug Glenzinski and Site Access Steering Committee


CMS / LPC
HL-LHC to come

$$13.6\ \text{TeV} = 10^{12}\ \text{Rydberg}$$

Neutrinos . . .

Neutrinos oscillate among the three known species, ν_e, ν_μ, ν_τ
(discovered with neutrinos from natural sources)

Accelerator-based long-baseline experiments NOνA and T2K
$\rightsquigarrow$ DUNE and Hyper-Kamiokande + new short-baseline experiments

Kinematics: ^{3}H β-decay experiment KATRIN; ^{163}Ho $\rightarrow^{163}$ Dy
experiments that rely on reactors (JUNO)
or natural sources (IceCube and KM3Net)

Puzzling results: LSND–MiniBooNE, "Reactor anomaly"
$\rightsquigarrow$ MicroBooNE, . . .

Some outstanding questions about neutrino physics

64 What is the order of levels of the mass eigenstates ν_1, ν_2, ν_3? It is known that the ν_e-rich ν_1 is the lighter of the "solar pair," with the more massive ν_2. Does the ν_e-poor ν_3 lie above or below the other two (normal or inverted mass ordering)?

65 What is the absolute scale of neutrino masses? KATRIN vs. Cosmo?

66 What is the flavor composition of ν_3? Is it richer in ν_μ or ν_τ?

67 Is CP violated in neutrino oscillations? To what degree?

68 Are neutrinos Majorana particles? While this issue is primarily addressed by searches for neutrinoless double-β decay, collider searches for same-sign lepton pairs also speak to it.

69 Do three light (left-handed) neutrinos suffice?

70 What is the nature of right-handed neutrinos?

More outstanding questions about neutrino physics

71. Are there light sterile neutrinos? If so, how could they arise?
72. Do neutrinos have nonstandard interactions, beyond those mediated by $W^{\pm}$ and Z?
73. How can we detect the cosmic neutrino background?
    Each species, now: $\approx 56\ \text{cm}^{-3}$ $\quad T_\nu \approx 2\ \text{K} \approx 1.7 \times 10^{-4}\ \text{eV}$
74. Are all the neutrinos stable?
75. Do neutrinos contribute appreciably to the dark matter of the Universe?
76. How is neutrino mass a sign of physics beyond the standard model?
77. Will neutrinos give us insight into the matter excess in the Universe (through leptogenesis)?

Why so little attention to a neutrino factory?

A Neutrino Factory based on a muon storage ring could provide a very strong second act for the coming generation of accelerator-based neutrino experiments.

Beyond its application to oscillation experiments as an intense source with known composition, an instrument that delivered 10^{20} ν per year could be a highly valuable resource for on-campus experiments.

Neutrino interactions on thin targets, polarized targets, or active targets could complement the nucleon-structure programs carried out in electron scattering at Jefferson Lab and elsewhere.

Gomez-Cadenas & Harris (2002)

Toward Future Machines

Refine *e*, *p* technologies

Develop exotic technologies

Accelerate exotic particles

Past Innovations

Cyclic acceleration

Phase stability

Strong focusing

Colliding beams

Active optics

Superconducting magnets

Ultrahigh vacuum technology

Superconducting RF

. . .

Memos for the Next Millennium

Chris Quigg
Theoretical Physics Department
quigg@fnal.gov

- Opening remarks
- Expectations for Run II
- Aspirations for Run III
- Fermilab and the LHC
- e^+e^- linear collider
- The path to a $\mu^+\mu^-$ collider
- Beyond the LHC
- Strengthening Our Institutions

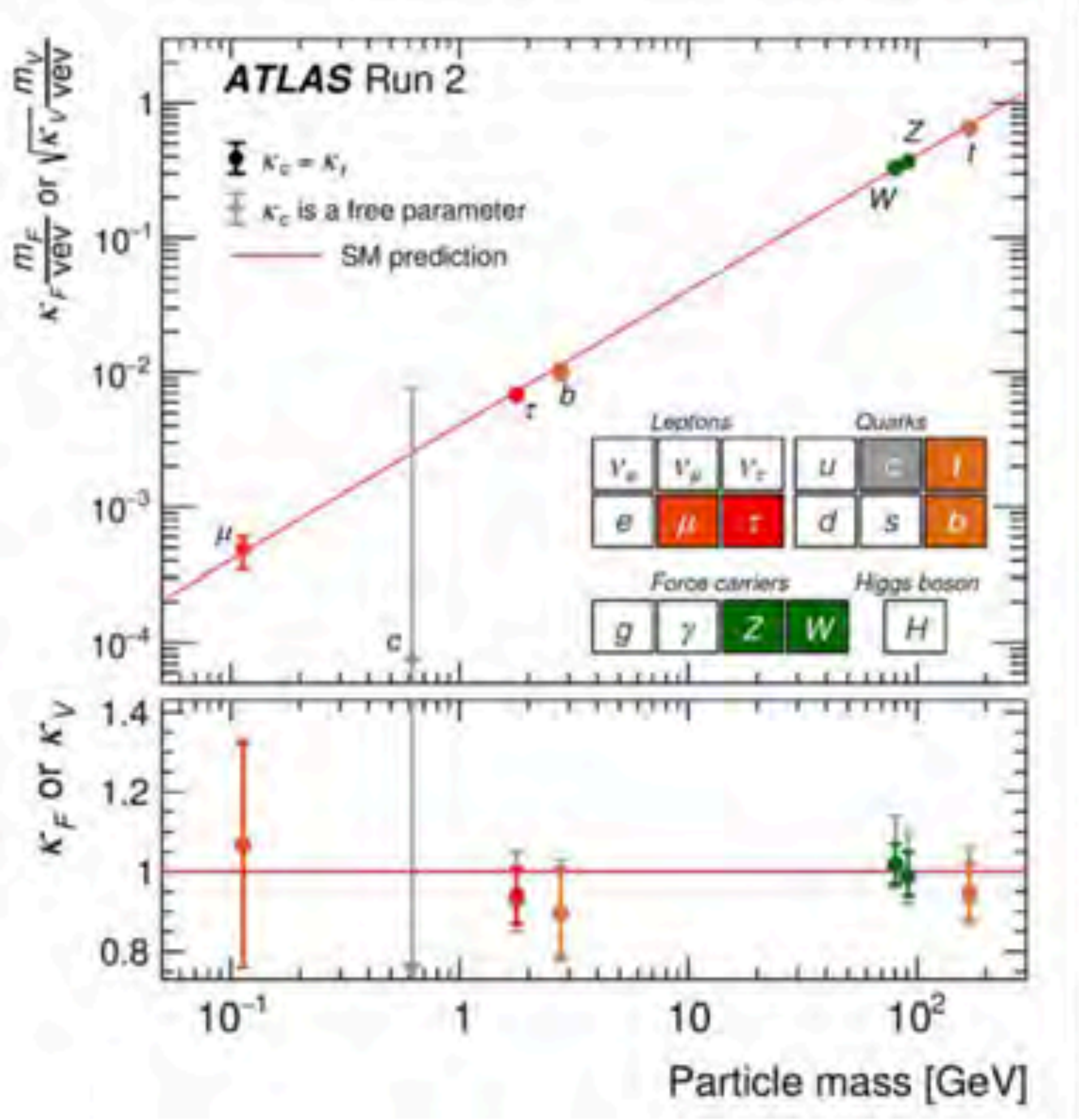
Gilman subpanel recommendation: 1999

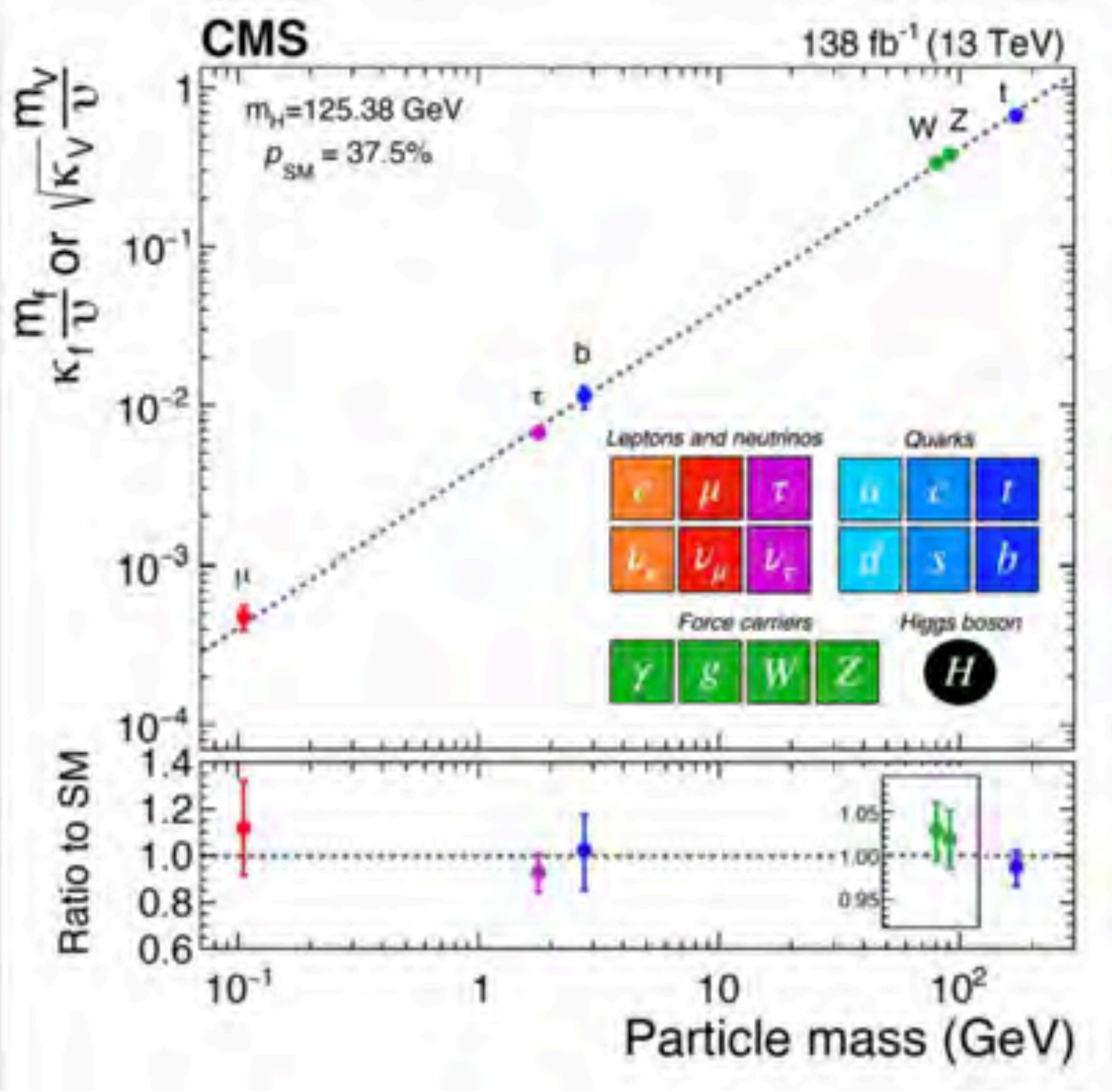
The Subpanel recommends that SLAC continue R&D with Japan's KEK toward a common design for an electron-positron linear collider with a luminosity of at least 10^{34} cm^{-2} s^{-1} and an initial capability of 1 TeV in the center of mass, extendible to 1.5 TeV. The Subpanel recommends that SLAC be authorized to produce a Conceptual Design Report for this machine in close collaboration with KEK.

This is not a recommendation to proceed with construction. A decision on whether to construct a linear collider should only follow the recommendation of a future subpanel convened after the CDR is complete. The decision will depend on what is known about the technology of linear colliders and other potential facilities, costs, international support, and advances in our physics understanding.

Do we still need a Higgs Factory?

Higgs Coupling Strengths





Snowmass 2021–22 Higgs Report, arXiv:2209.07510

"An offshore Higgs factory, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson."

Essential reading: FCC Week 2024

Far away vision

C. Paus

FCC-ee Specs

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
luminosity per IP [10^{34} cm^{-2}s^{-1}]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr] 4 IPs	87	9.3	3.5	0.65
beam lifetime (rad Bhabha + BS+lattice)	8	18	6	10
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

From Fabiola's talk

Currently assessing technical feasibility of changing operation sequence (e.g. starting at ZH energy)

C. Paus

- x 10-50 improvements on all EW observables
- up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

See Also Sam Posen

Exp. precision estimates for electroweak parameters:

	Current exp.	ILC250	CEPC	FCC-ee
M_W [MeV]	11–12	2.4	0.5	0.4
Γ_Z [MeV]	2.3	1.5	0.025	0.025
$R_\ell = \Gamma_Z^{had}/\Gamma_Z^\ell$ [10^{-3}]	25	20	2	1
$R_b = \Gamma_Z^b/\Gamma_Z^{had}$ [10^{-5}]	66	23	4.3	6
$\sin^2\theta^\ell_{eff}$ [10^{-5}]	13	2	0.3	0.4

Exp. precision estimates for Higgs couplings:

	ILC250	CEPC	FCC-ee
hbb	1.1%	0.7%	0.6%
hcc	2.0%	1.3%	1.3%
$h\tau\tau$	1.0%	0.8%	0.7%
hWW	0.98%	0.73%	0.41%
hZZ	0.22%	0.07%	0.17%
$h\gamma\gamma$	1.4%	1.7%	1.3%
hgg	1.3%	0.9%	0.9%

Ayres Freitas

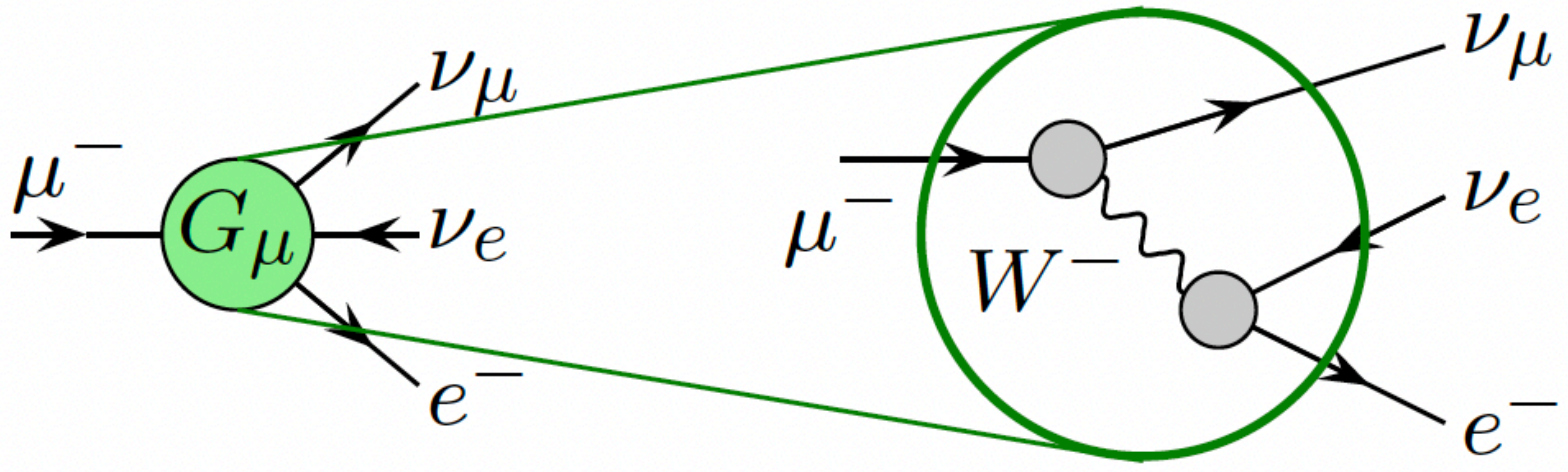
Snowmass '21/22

Comparison of EWPOs with theory

- To probe new physics, compare EWPOs with SM theory predictions
- Need to take theory error into account:

	Current exp.	Current th.	CEPC	FCC-ee
M_{W} [MeV]	11–12	4*	0.5*	0.4*
Γ_Z [MeV]	2.3	0.4	0.025	0.025
$R_\ell = \Gamma_Z^{\text{had}}/\Gamma_Z^\ell$ [10^{-3}]	25	5	2	1
$R_b = \Gamma_Z^b/\Gamma_Z^{\text{had}}$ [10^{-5}]	66	10	4.3	6
$\sin^2\theta^\ell_{\text{eff}}$ [10^{-5}]	13	4.5	0.3	0.4

* computed from G_μ



Strong points of FCC-ee are evident

and so are liabilities:

size, cost, time scale;

e^+e^- machine addresses topics sequentially

Fermilab + US Community must engage now

Help define machine and detectors,
conceive improvements

Validate cost estimates and technical risks

Develop the community that will use Higgs Factory

Prepare theoretical advances, analysis techniques

A modest proposal: *Higgs Factory Fellows*

Show our commitment to the enterprise
and to young people
by emulating the SSC Fellowship Program
(compare also Neutrino Theory Initiative
and LHC Theory Fellowships)

Texas funding supported
ten postdocs + ten junior-faculty members
(theory + experiment)
with a year's salary plus research funds

Gilman subpanel recommendation: 1999

> The Subpanel recommends that an expanded program of R&D be carried out on a muon collider, involving both simulation and experiments. This R&D program should have central project management, involve both laboratory and university groups, and have the aim of resolving the question of whether this machine is feasible to build and operate for exploring the high-energy frontier. The scale and progress of this R&D program should be subject to additional review in about two years.

European interest:

- Report to ECFA, "Prospective Study of Muon Storage Rings in Europe"
- CERN–SPSC/98-30, "Physics Opportunities at a CERN-based Neutrino Factory"

A 10-TeV μ+μ- Collider for My 101st Birthday?

16.5 km

10 km

Be ambitious.

Be optimistic.

Don’t be delusional.

Fermi National Accelerator Laboratory

FERMILAB-Conf-98/073-T

Physics with a Millimole of Muons

Chris Quigg

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

March 1998

Published Proceedings of the *Workshop on Physics at the First Muon Collider and at the Front End of a Muon Collider*, Fermilab, Batavia, Illinois, November 6-9, 1997

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

"It is worth keeping in mind Bob Palmer's estimate that a First Muon Collider might be in operation around the year 2010."

Recommended reading for aspiring project builders

Learn from others

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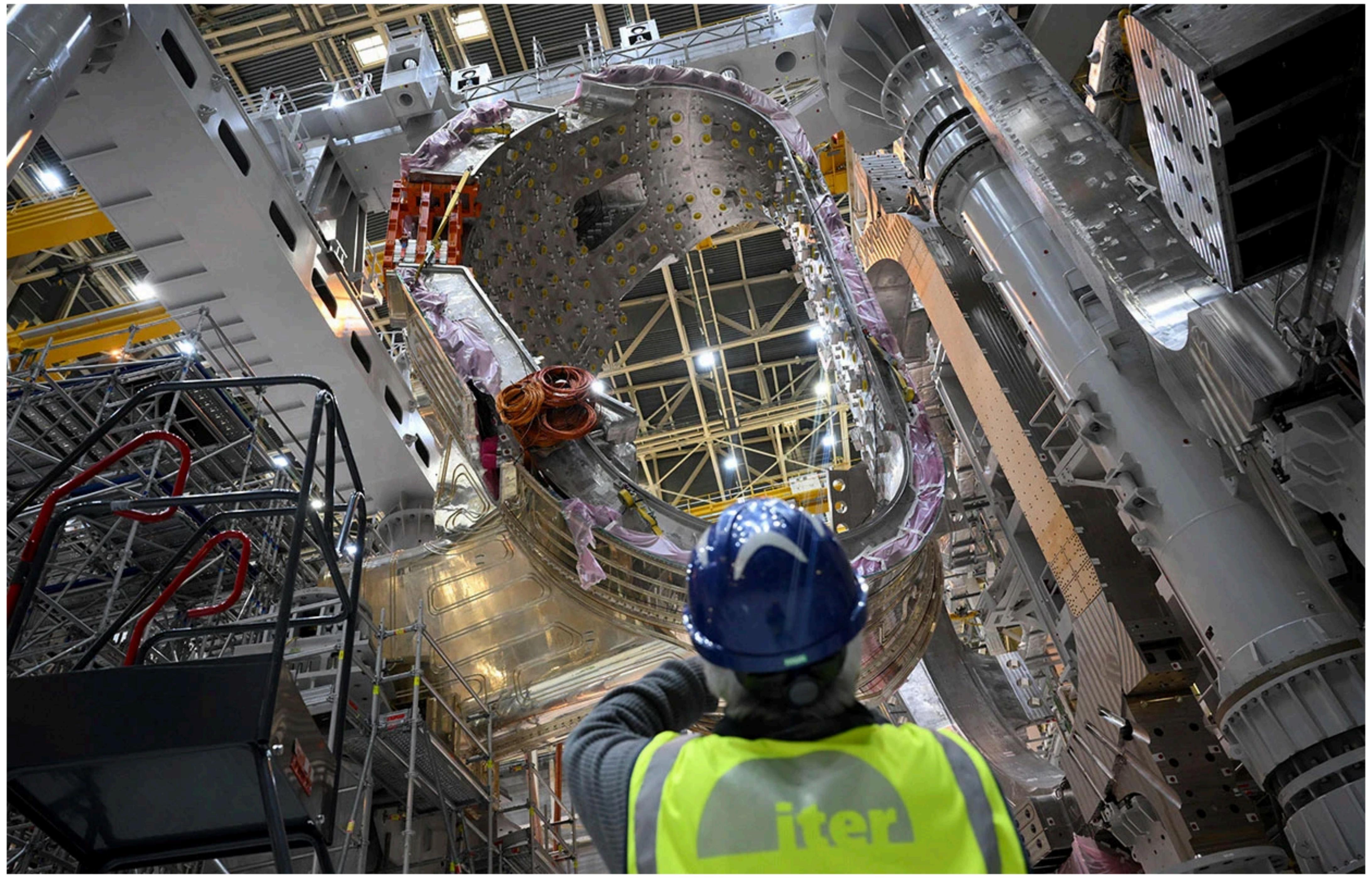
nature › news › article

NEWS | 08 July 2024

ITER delay: what it means for nuclear fusion

The world's biggest fusion-energy experiment is likely to be beaten to its goals by other projects — but the massive reactor still has value, say scientists.

By Elizabeth Gibney



Lessons Learned from my SSC Adventure

We could have done it.
The story is more intricate than you will even know.
Many “lessons learned” are incorrect or incomplete.
Don’t rely on any single source.

Leadership matters!
It will take time.
Take advantage of available talent.
Labs can accomplish hard things. You need at least one.
Develop allies. Be a reliable ally.
Do not rely on 9-to-5ers.
Some aging heroes will lose nerve.
There will be surprises and dislocations (High-T_C)
You will deal with many imperfect people. Some lie.
Bad-faith actors exist.

Lessons Learned from my SSC Adventure (II)

Well-meaning people can do foolish things.
Psychos exist—some ascend to power.
Never cut corners.
Some are short-sighted, will act in misguided self-interest.
Do not put in authority Washington insiders not absolutely committed.
Our field (especially experimental) is under-represented in powerful institutions
Political appointees may lack political judgment.
Senators and representatives keep score on a very broad canvas
Continuously engage international partners.
Never lose your idealism. (You will need it!)

Lessons Learned from my SSC Adventure (II)

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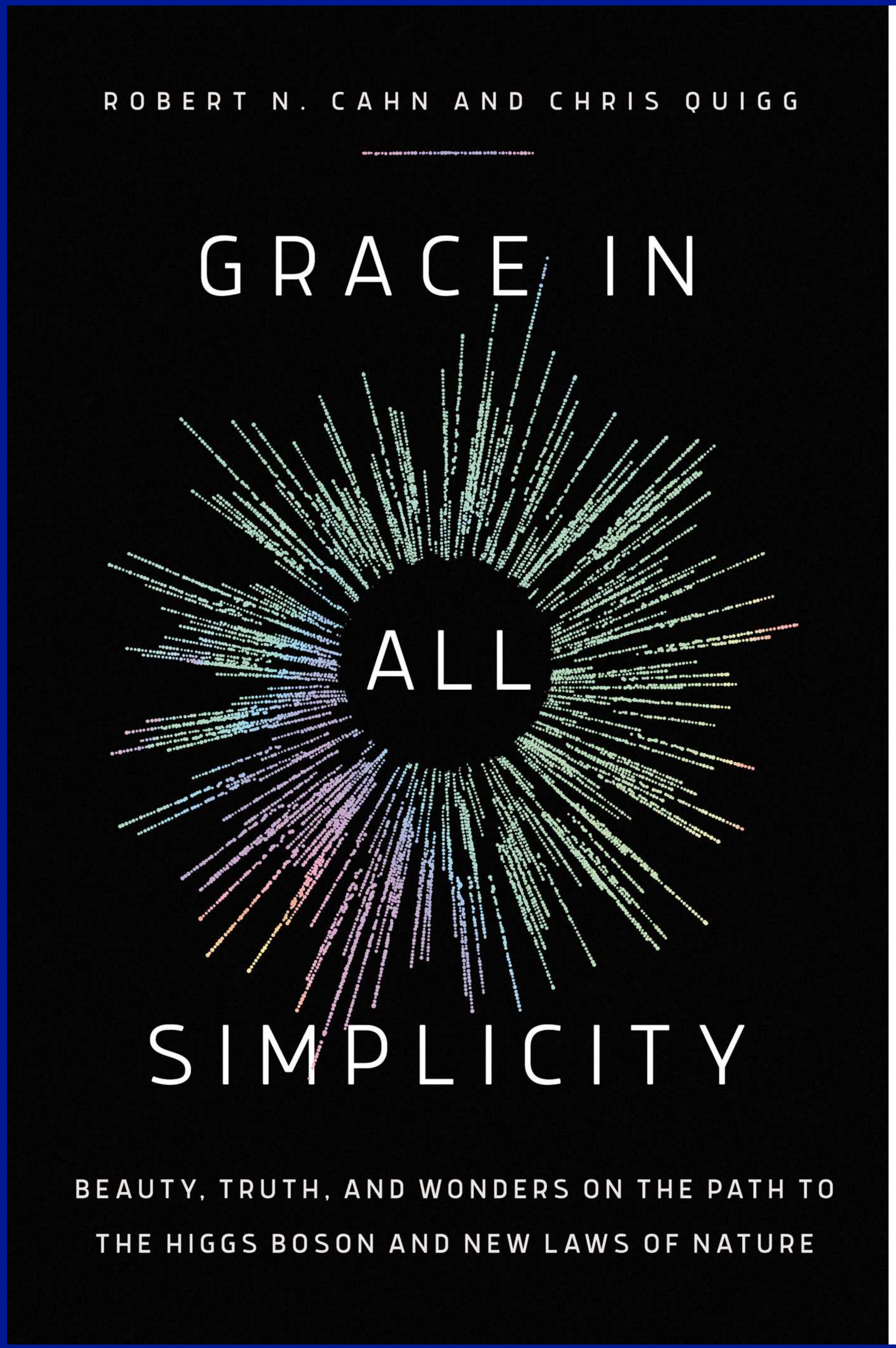
Don’t trust anyone over 30!

The Blank Regions on the Collaboration Maps



Particle physics is a planetary undertaking. It brings together people of different backgrounds and diverse styles who are curious about nature and driven to explore. Professional and personal lives are enriched by teachers and students, colleagues and friends, from many countries and cultures. Together, we elevate experimental test over attachment to received truths. We welcome uncertainty not as motivation to be cynical, but as incentive to open our minds and investigate. As individuals and as teams, we compete and collaborate. Our science thrives in a culture in which standing is measured by knowledge shared, not secrets withheld. For that tradition of openness, we thank the citizens of the world, who provide material support and active encouragement for the explorations we undertake together. What we discover is for all to share.