Brookhaven National Laboratory

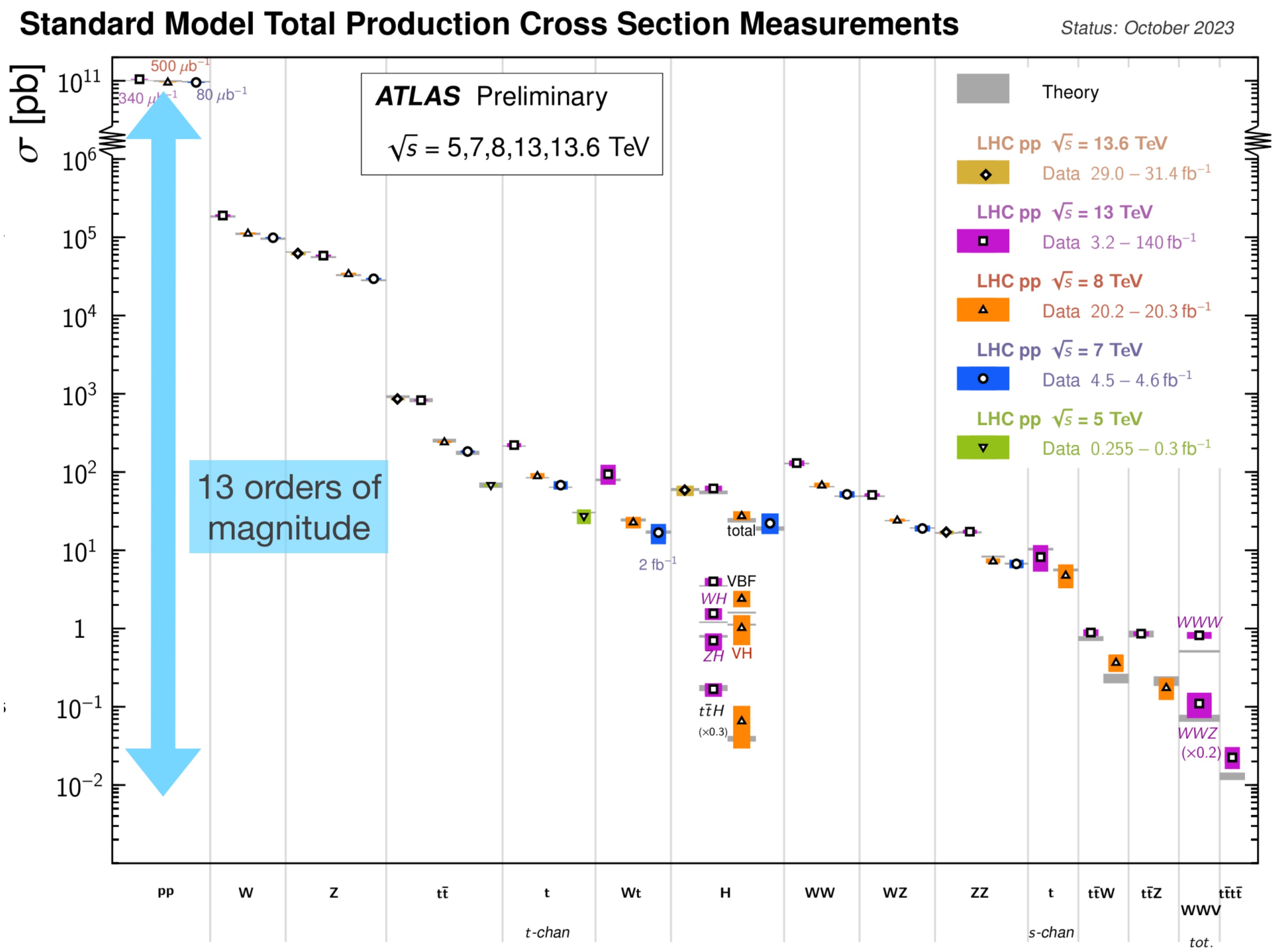
U.S. DEPARTMENT OF ENERGY

FCC Week Keynote

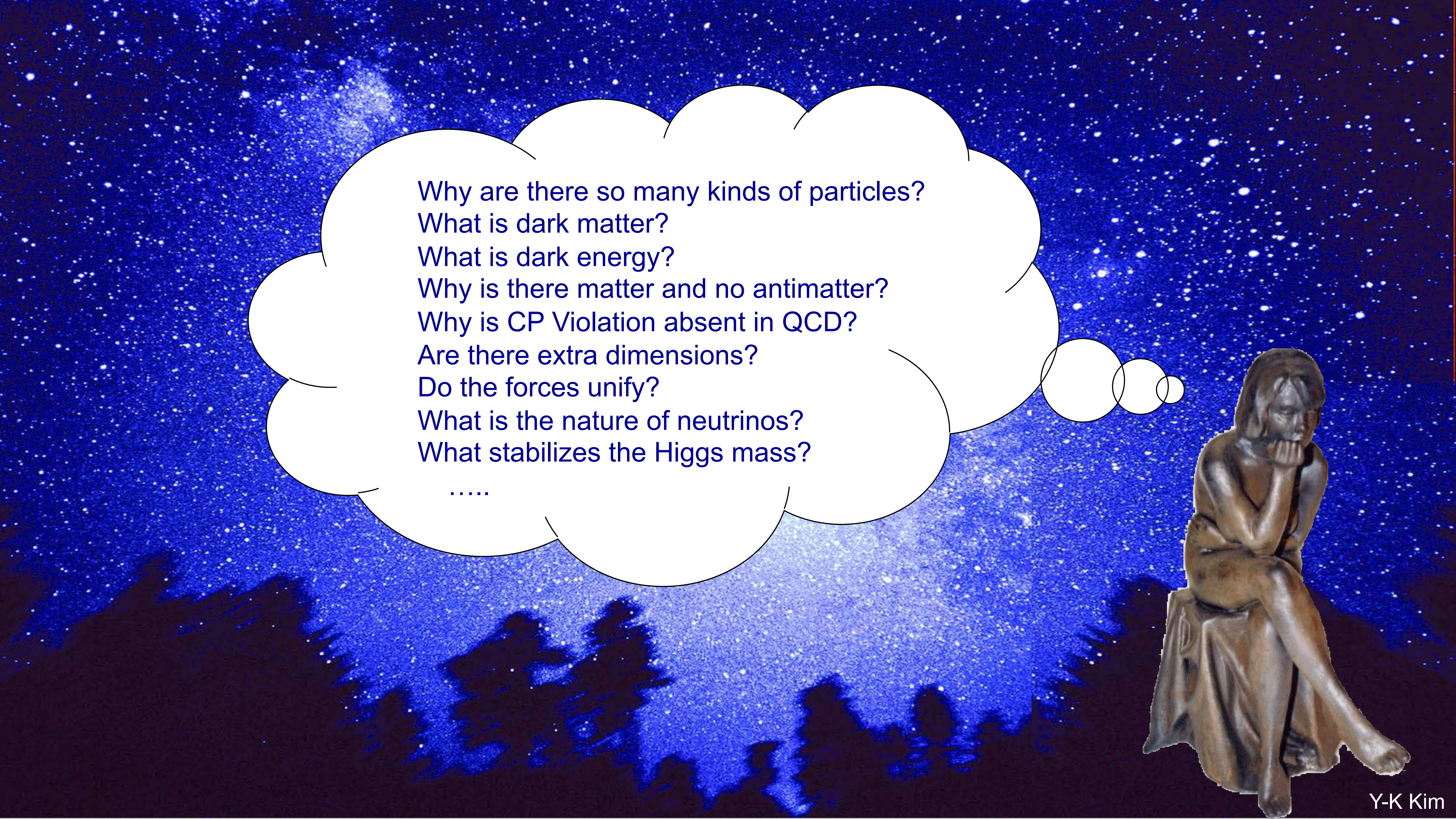
JoAnne Hewett

Brookhaven National Lab

LHC data agree amazingly well with SM predictions



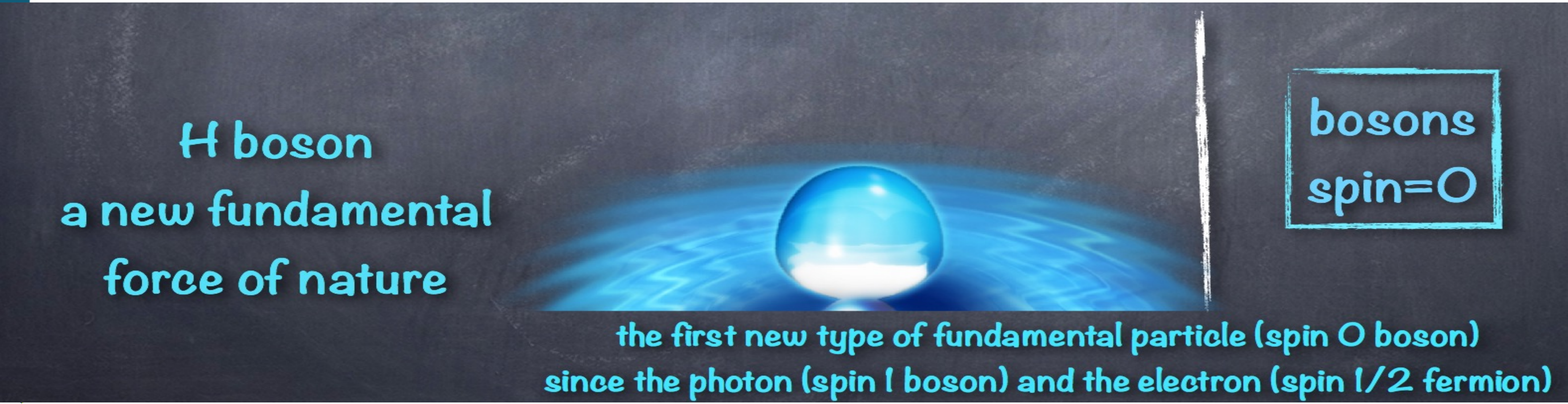
The LHC is a precision measurement machine!


Why are there so many kinds of particles?
What is dark matter?
What is dark energy?
Why is there matter and no antimatter?
Why is CP Violation absent in QCD?
Are there extra dimensions?
Do the forces unify?
What is the nature of neutrinos?
What stabilizes the Higgs mass?
…..
Y-K Kim


Science
BREAKTHROUGH of the YEAR
The HIGGS BOSON
Physicists Find Elusive Particle Seen as Key to Universe
The New York Times
The Economist
In praise of charter schools
Britain's banking scandal spreads
Volkswagen overtakes the rest
A power struggle at the Vatican
When Lonesome George met Noah
A giant leap for science
Finding
International Herald Tribune
LA VANGUARDIA
LA RAZON
Levante
El juez imputa a Rato y 32 consejeros de Bankia
DIE WELT
LA STAMPA
la Repubblica
MK
THE HINDU
The Telegraph
l'Unità
Elusive particle found, looks like Higgs boson
It walks, it quacks but best to...
Rai, colpo di mano di Schifani
The Gazette
AD ALGEMEEN DAGBLAD
THE JERUSALEM POST
Chasing the Higgs Boson
INTRODUCTION
PROMISED FIREBALLS
GAME OF BUMPS
STILL MISSING
OOZING INTO VIEW
OPENING THE BOX
Chasing the Higgs Boson
The first time that the entire NYT Science section is devoted to a single story
TIME
Nº5 PARTICLE PHYSICIST FABIOLA GIANOTTI
FOX NEWS
son Quest Inspires Epic LHC Art
The elusive particle: 5 Implications of finding Higgs Boson
to Universe
THE DAILY BEAST
3 Ways the Higgs Boson Discovery Will Impact Financial
Google
The Higgs discovery

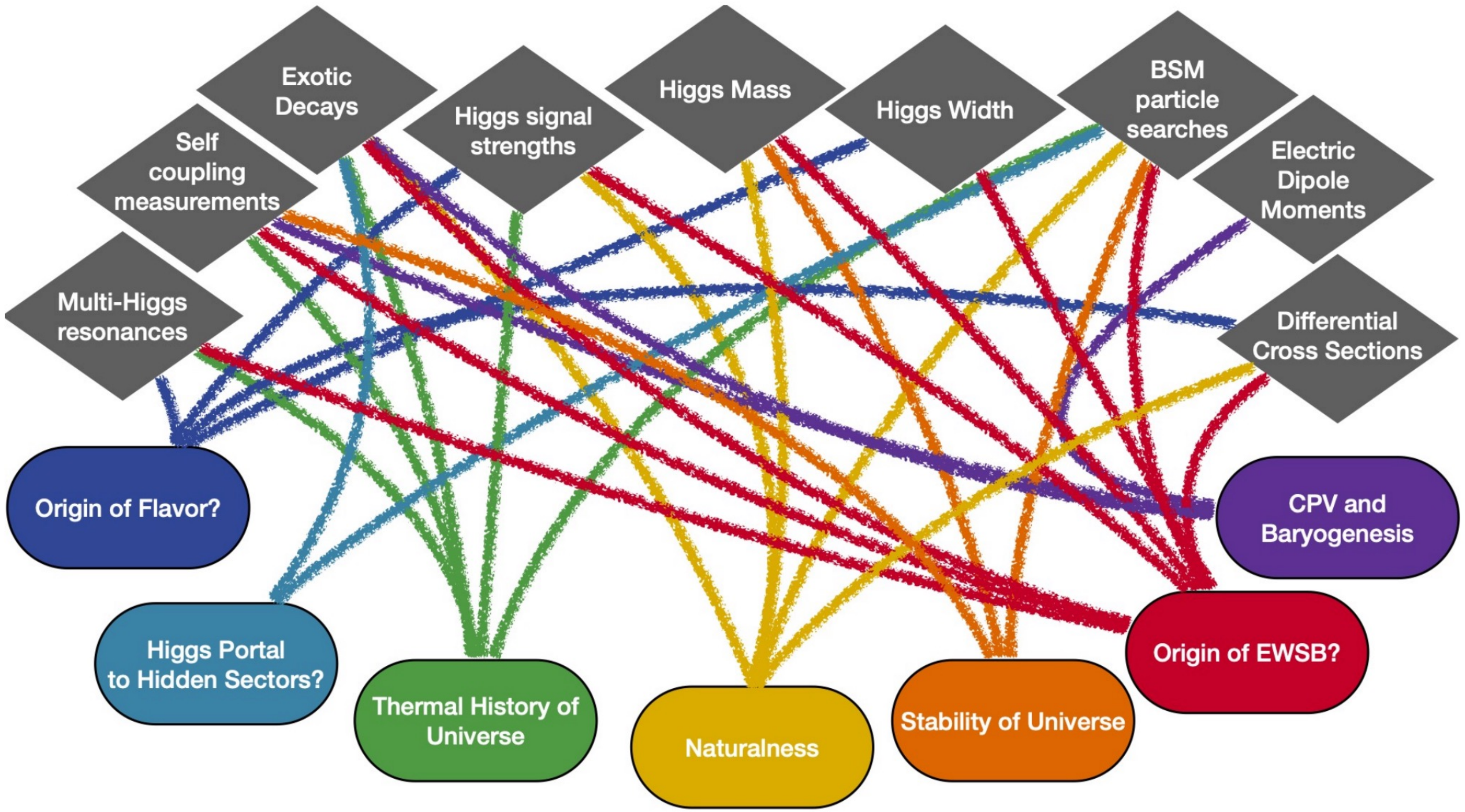
The Higgs Boson is special

The recently discovered Higgs boson is a form of matter never before observed, and it is mysterious. What principles determine its effects on other particles? How does it interact with neutrinos or with dark matter? Is there one Higgs particle or many? Is the new particle really fundamental, or is it composed of others? *2014 P5 Report*

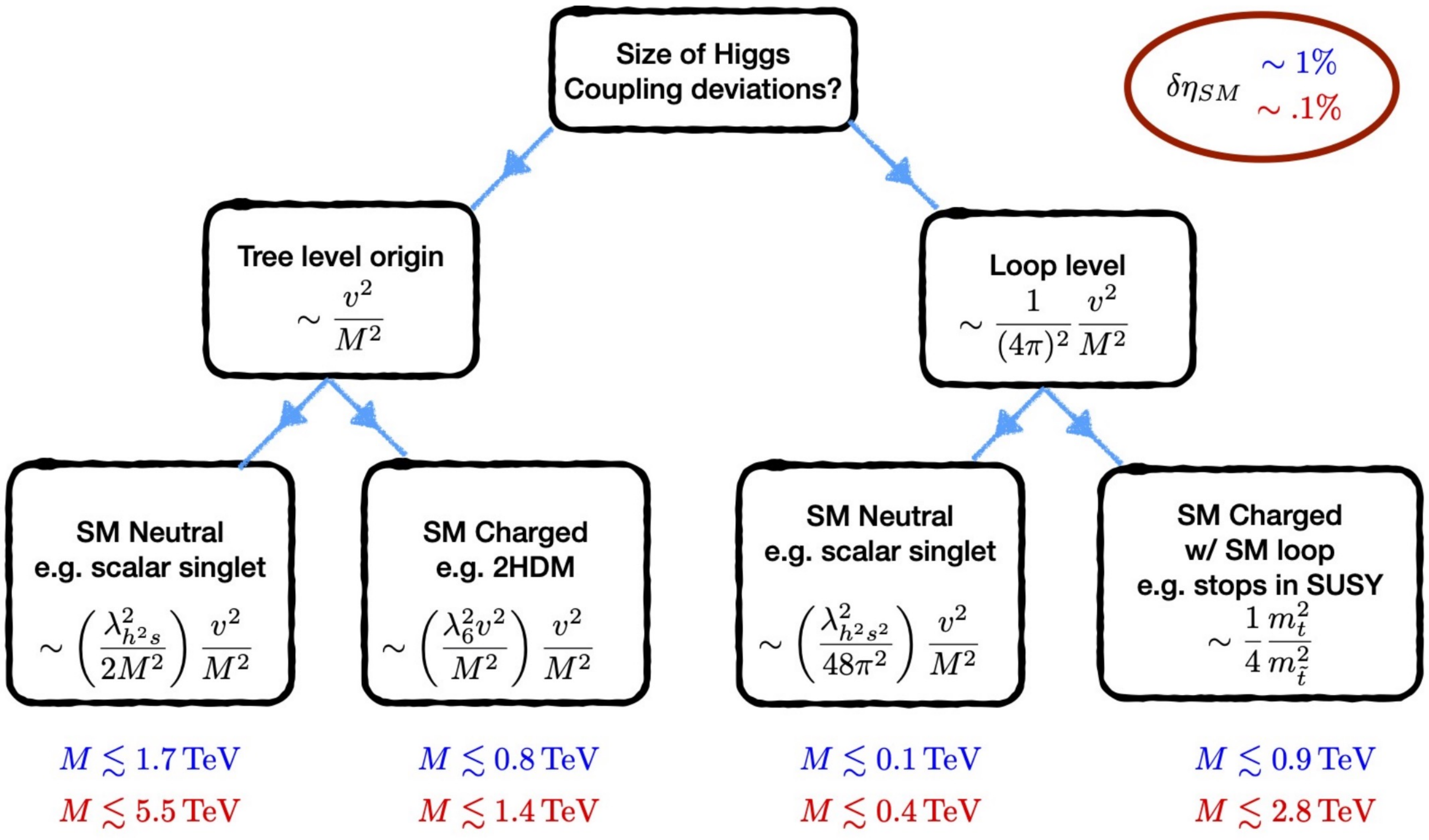


The Higgs Boson as a tool for discovery

Precision Higgs measurements are key for BSM physics



Typical mass scale probed by precision Higgs coupling measurements



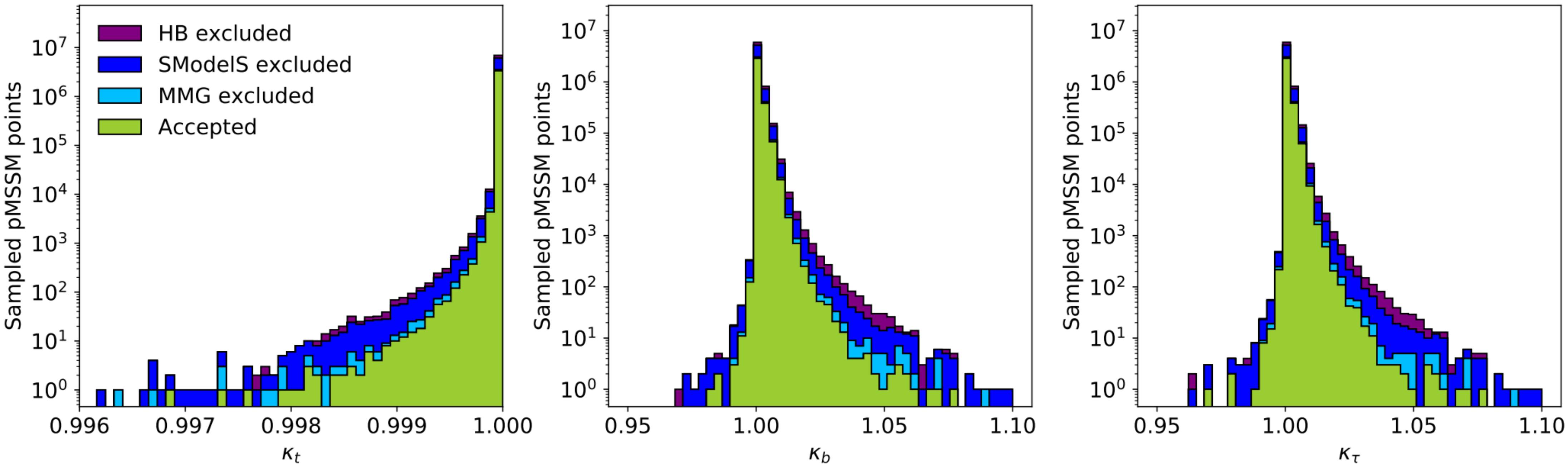
Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

Dawson etal, 2209.07510

Higgs couplings in the phenomenological MSSM

Higgs coupling measurements sensitive to models with masses up to ten's of TeV

pMSSM scan: 0.09-25 TeV for non-colored sparticles and 0.2-50 TeV for sparticles with color

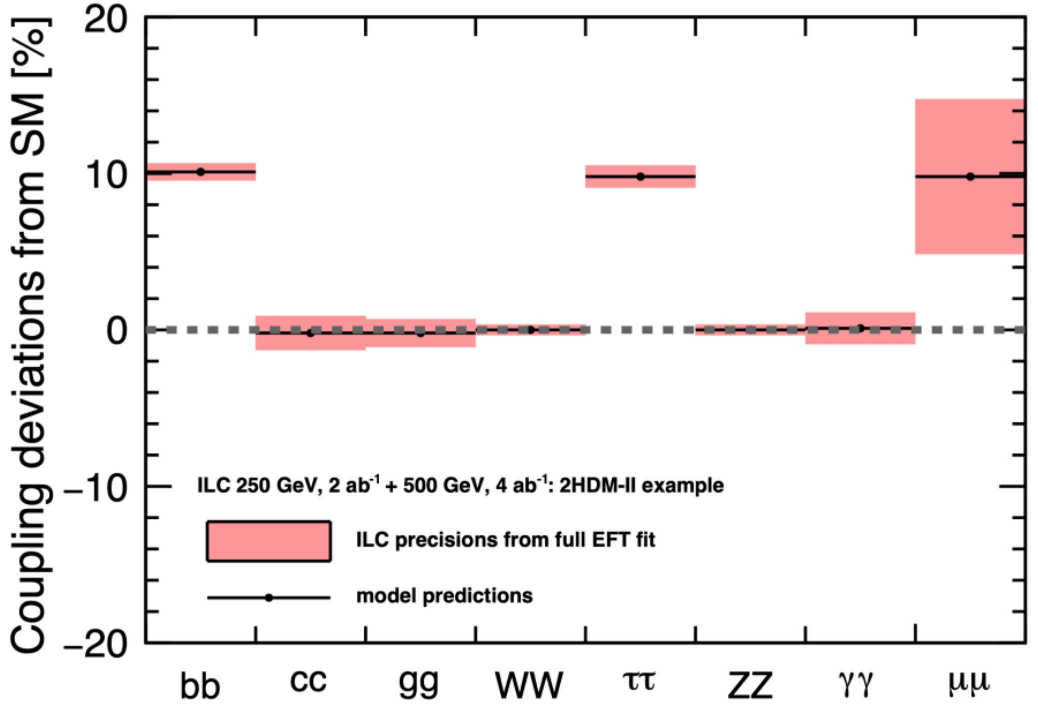


Dickinson etal, 2207.05103

Pattern of Higgs coupling deviations are model dependent

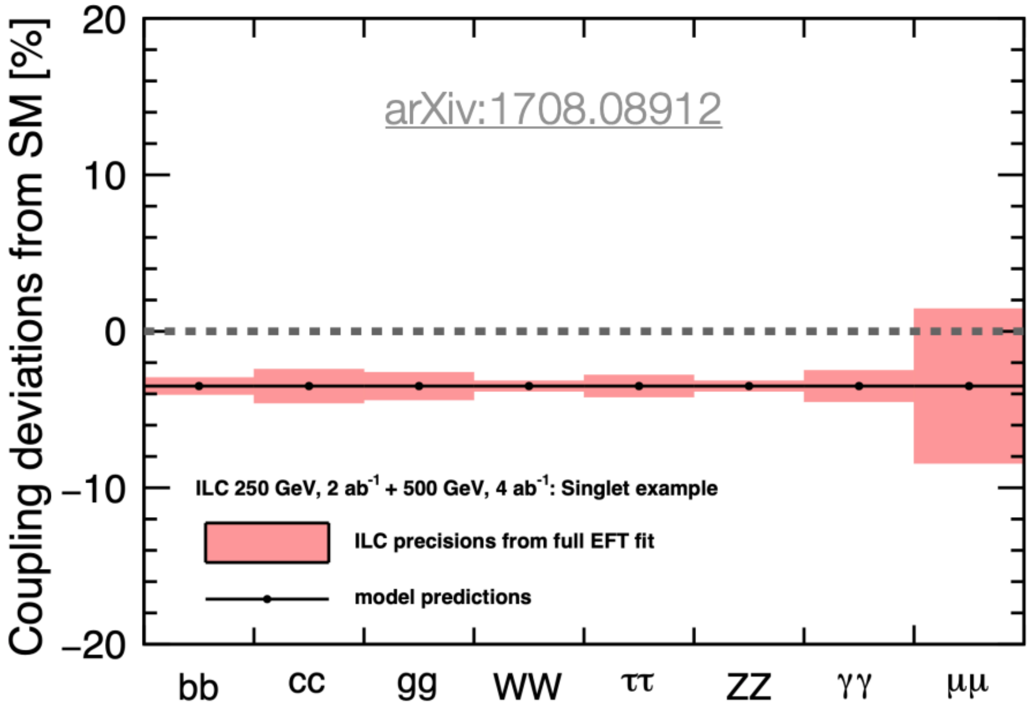
2HDM Type-II

$m_A = 600$ GeV, $\tan\beta = 7$



Extra Higgs singlet

$m_X = 2.8$ TeV, max allowed mixing

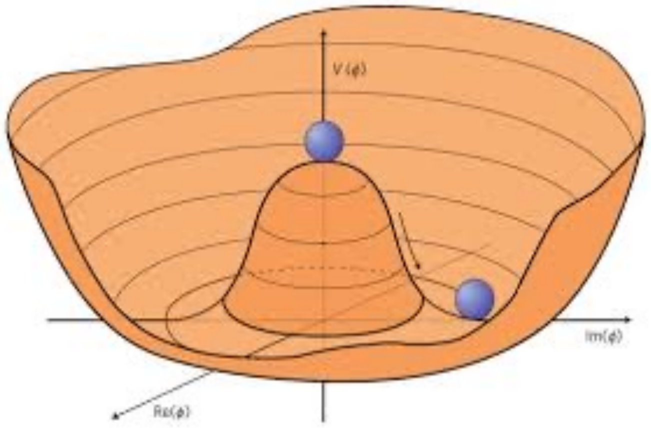


Idachi etal, 2203.07646

Higgs self-coupling

Important to measure shape of the Higgs potential

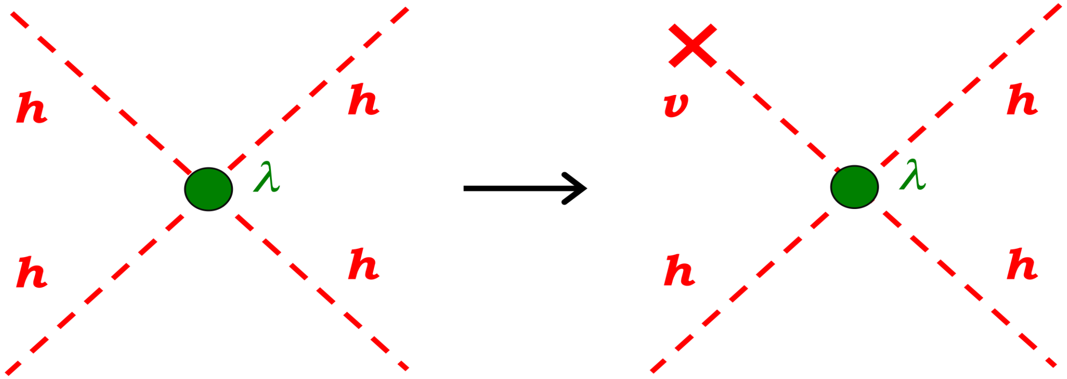
$$V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4/2$$

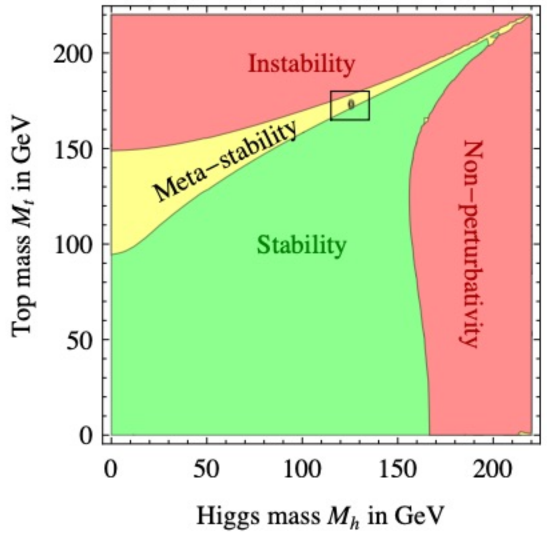


Higgs mass is directly related to dynamics of Higgs sector

$$\lambda_{hhh} = 3\sqrt{2}\,\lambda v = 3m_h^2/\sqrt{2}\,v \qquad \lambda_{hhhh} = 3\lambda = 3m_h^2/2v^2$$

Triple Higgs coupling provides evidence of vacuum condensation

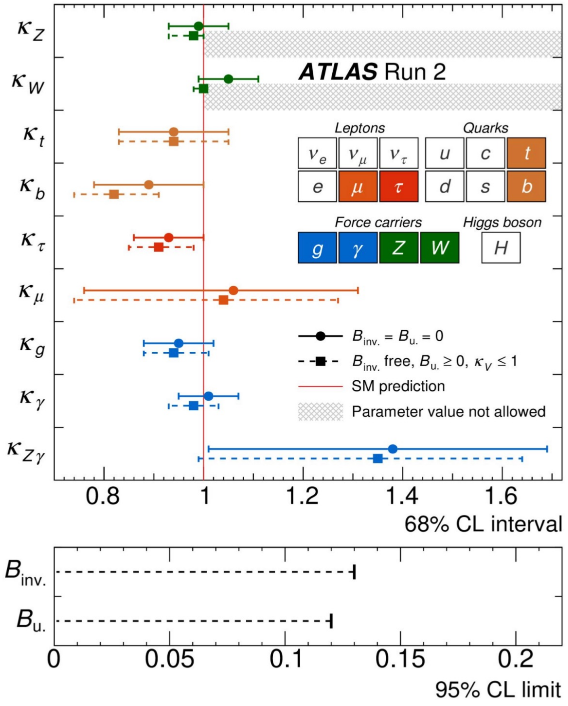


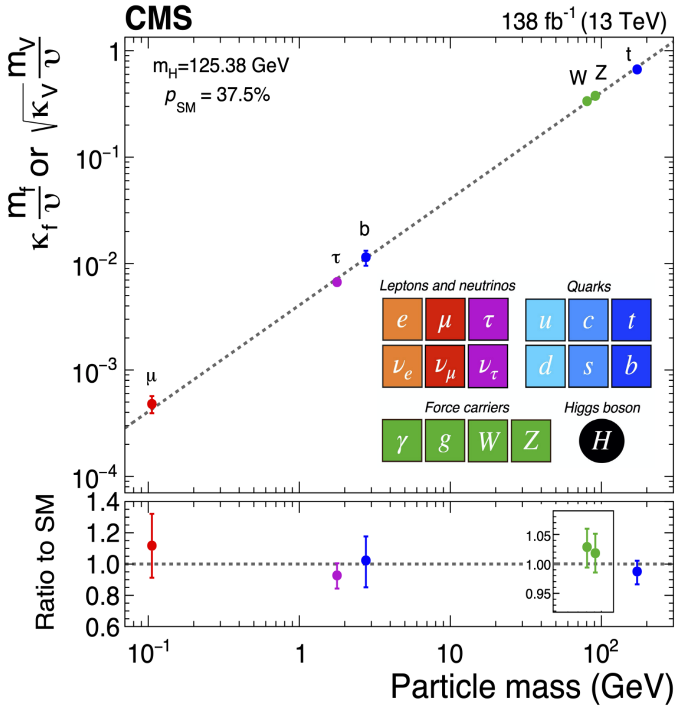


Higgs coupling measurements @LHC

A great achievement!
Provides first portrait of EWSB
Higgs appears to be SM-like

[Nature 607 (2022) 52]

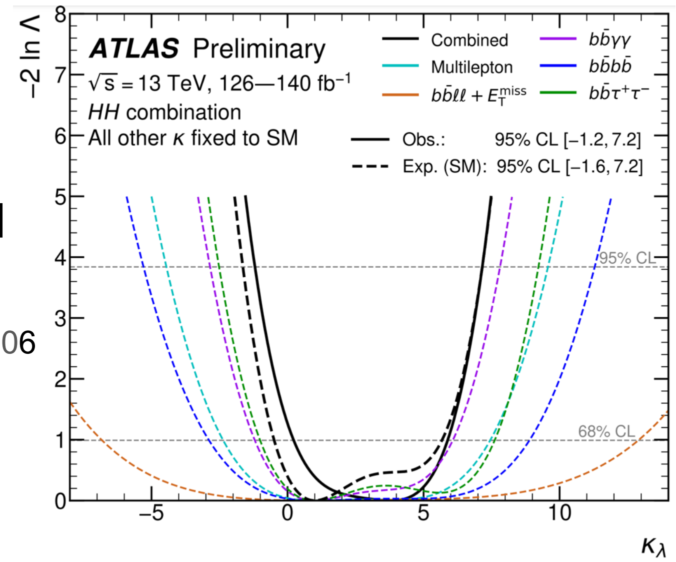




Fermion and Boson couplings measured to ~10% (20% in some cases)

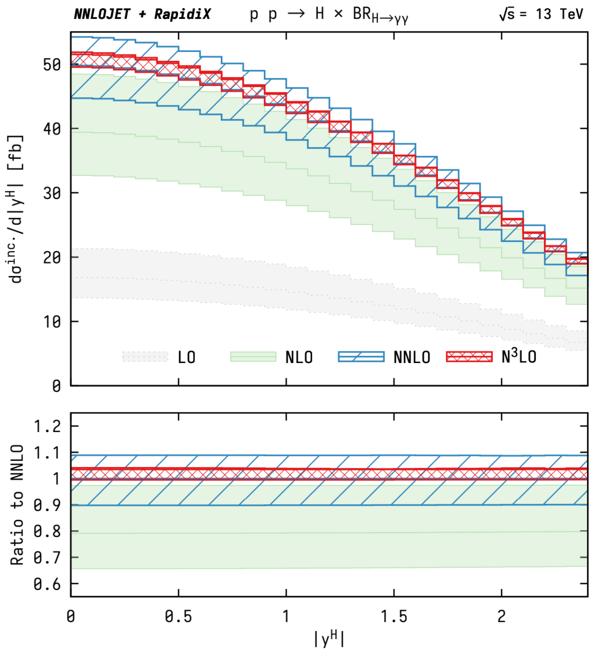
Self-coupling constraints from combined channels

ATLAS-CONF-2024-006



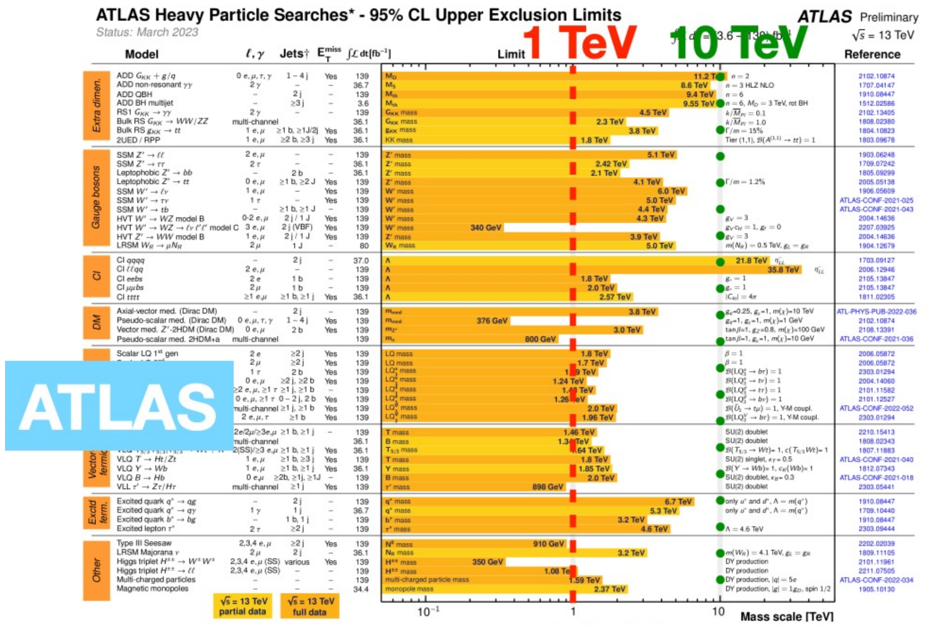
Theory becoming more precise @ N3LO

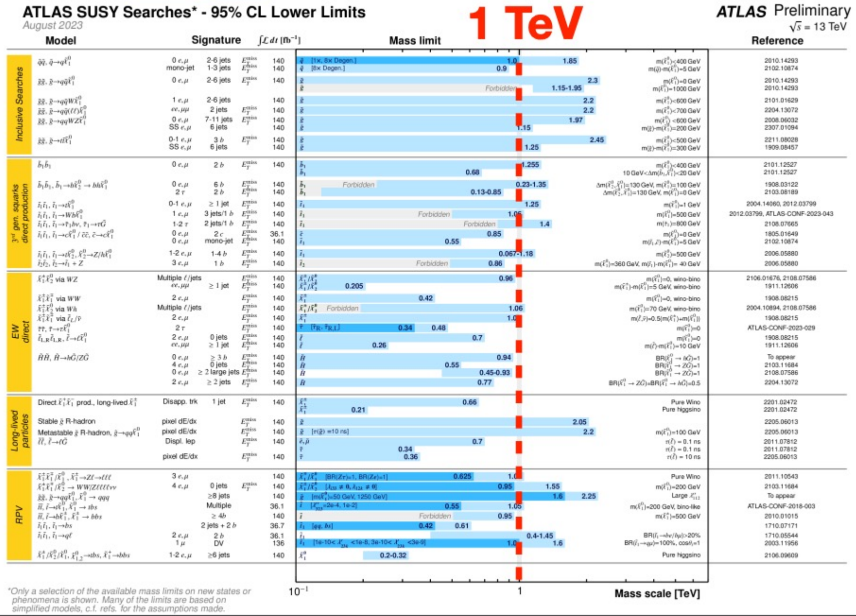
Inclusive cross section for pp → H →γγ

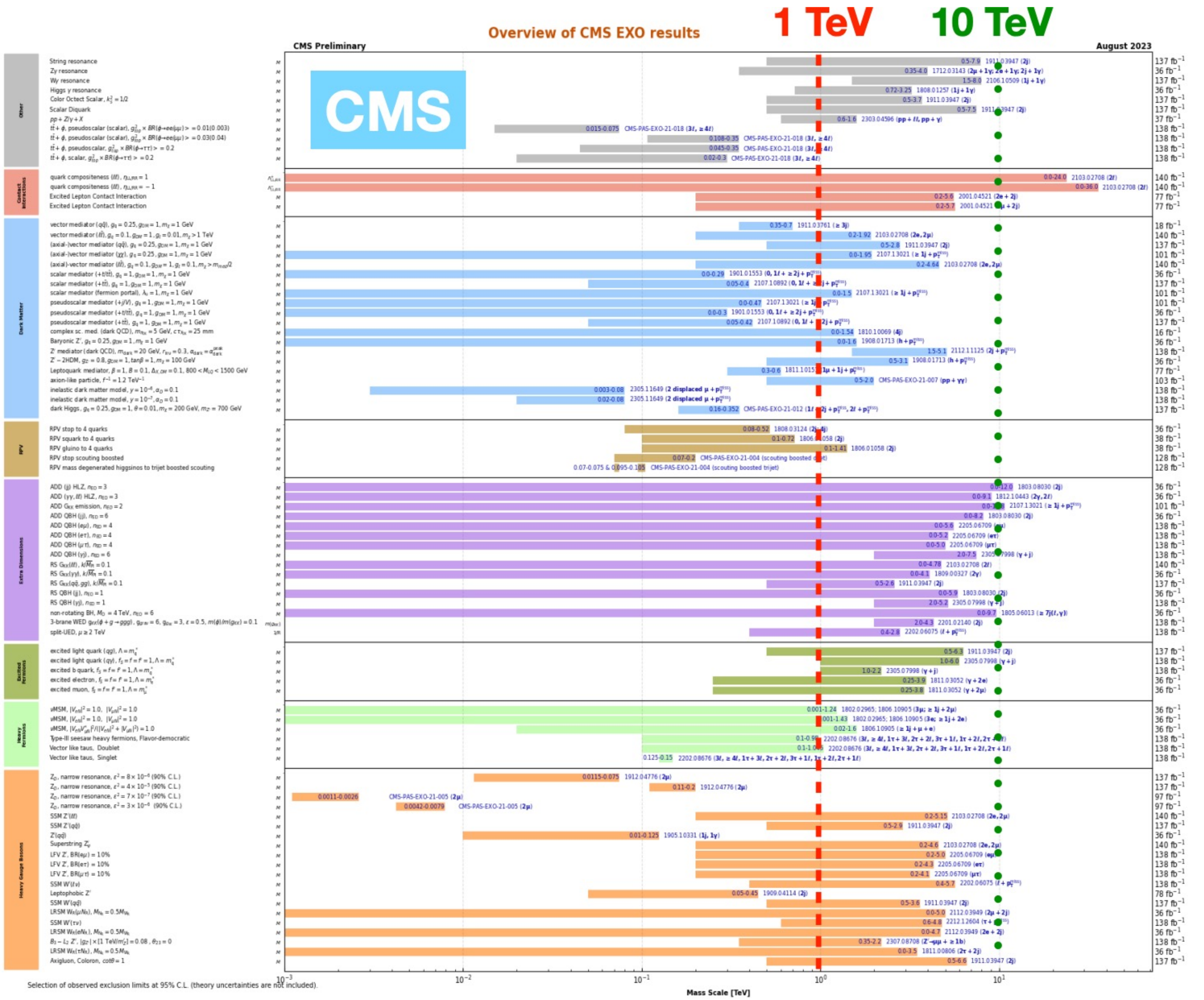


Chen etal, 2102.07607

Direct searches for BSM







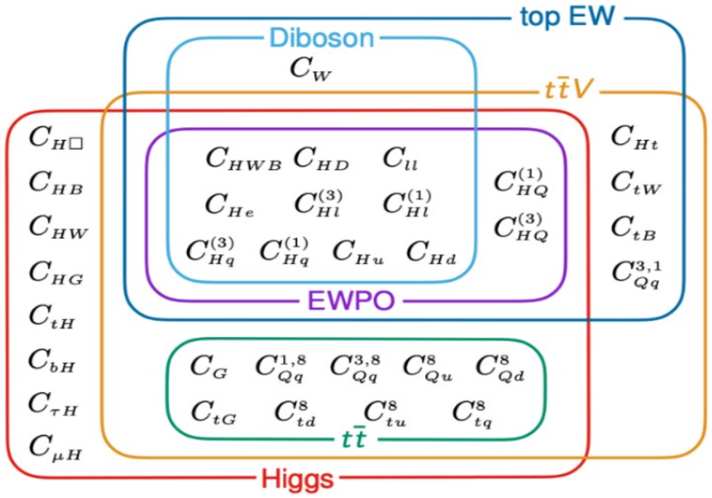
Effective Field Theories: Global fits to new physics

Model independent description of new physics

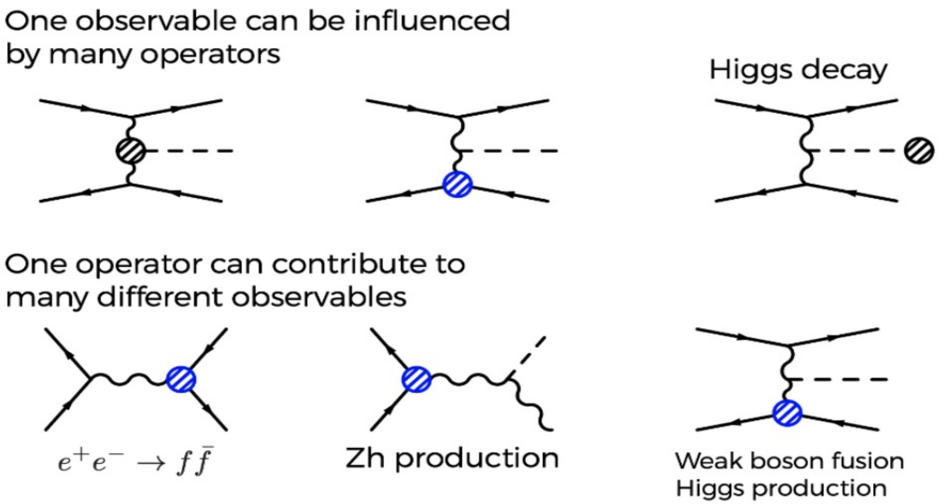
Wilson expansion, in powers of the cut-off scale and new physics encoded in the Wilson coefficients

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d=5}^{\infty} \sum_{i} \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

A complete basis of operators with d=5-8 totals **2499** operators!
84 operators for one generation
59 if CP is also conserved



[2012.02779] Fitmaker collaboration



Anke Biekötter - HET seminar Brookhaven

HL-LHC is around the corner!

Identified as a highest priority in 2013 European Particle Physics Strategy update and 2014 P5 report

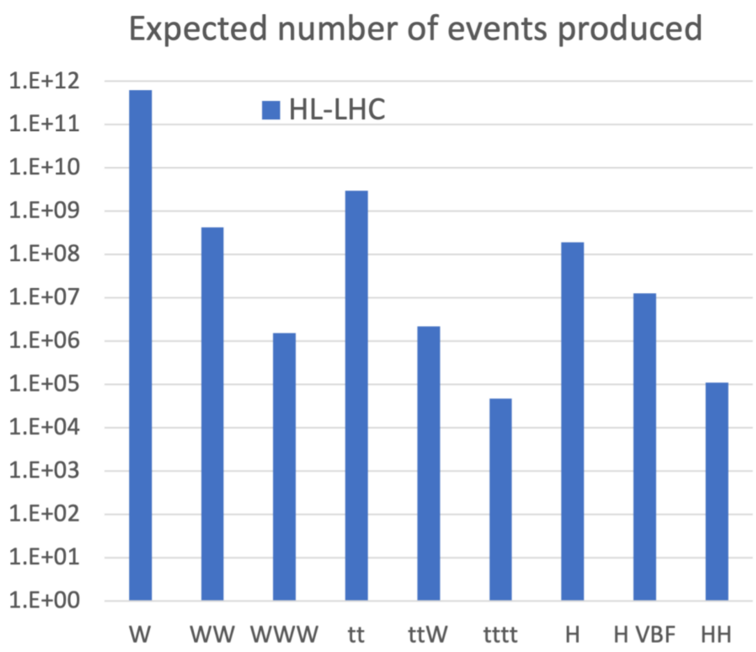
The HL-LHC has a compelling and comprehensive program that includes essential measurements of the Higgs properties

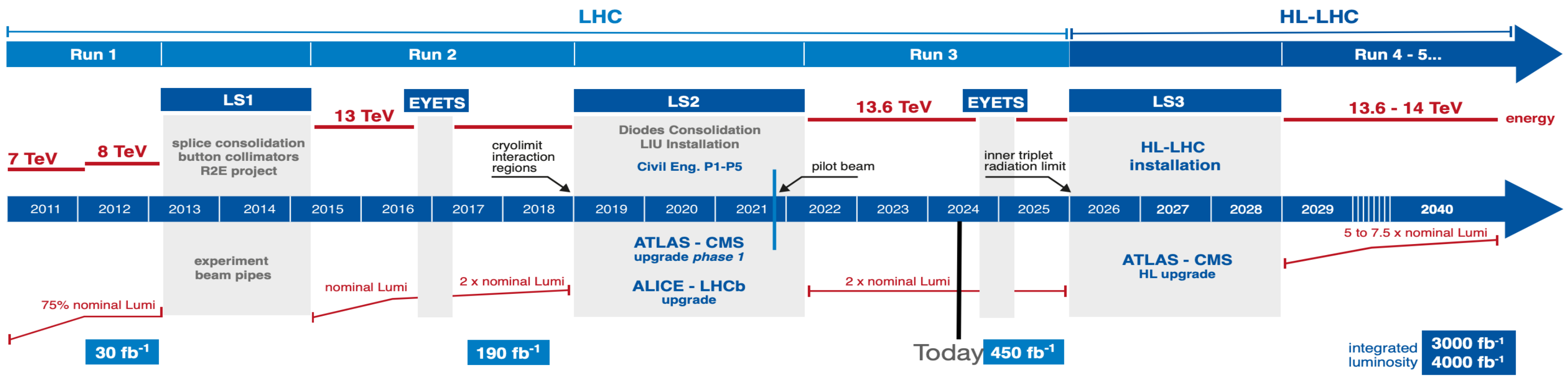
Plan for 3 ab^{-1} of pp collisions at 14 TeV

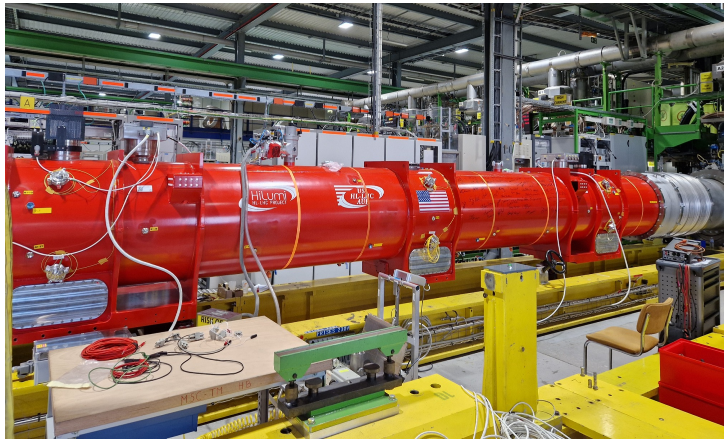
190M Higgs bosons to be produced!

120k Higgs boson pairs produced

Significant upgrades for the detectors and accelerator







Expectations for Higgs Coupling Measurements @HL-LHC

Powerful tool to further explore the Higgs sector

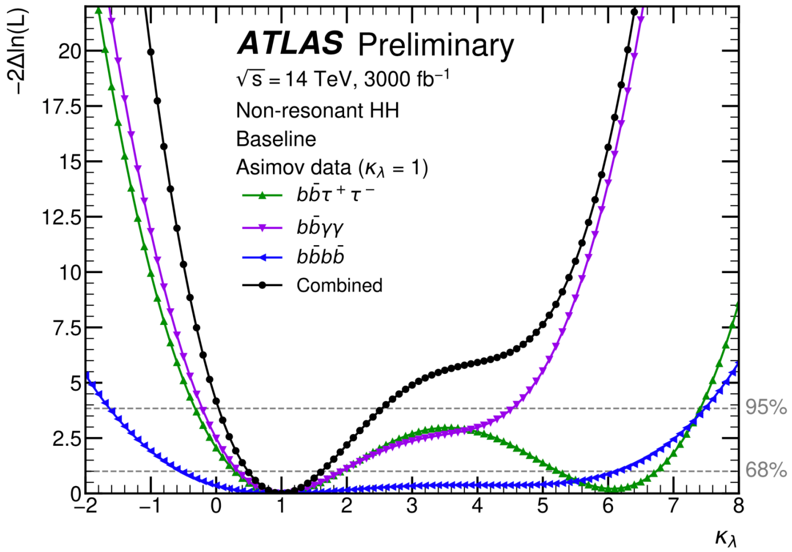
(Pile-up a challenge)

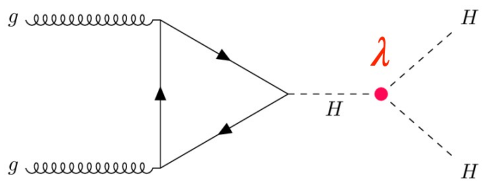
- Bosonic Higgs couplings to ~<2%
- Fermionic Higgs couplings to ~2-4%
- Theory is largest contribution to uncertainties

Tri-linear coupling a science driver

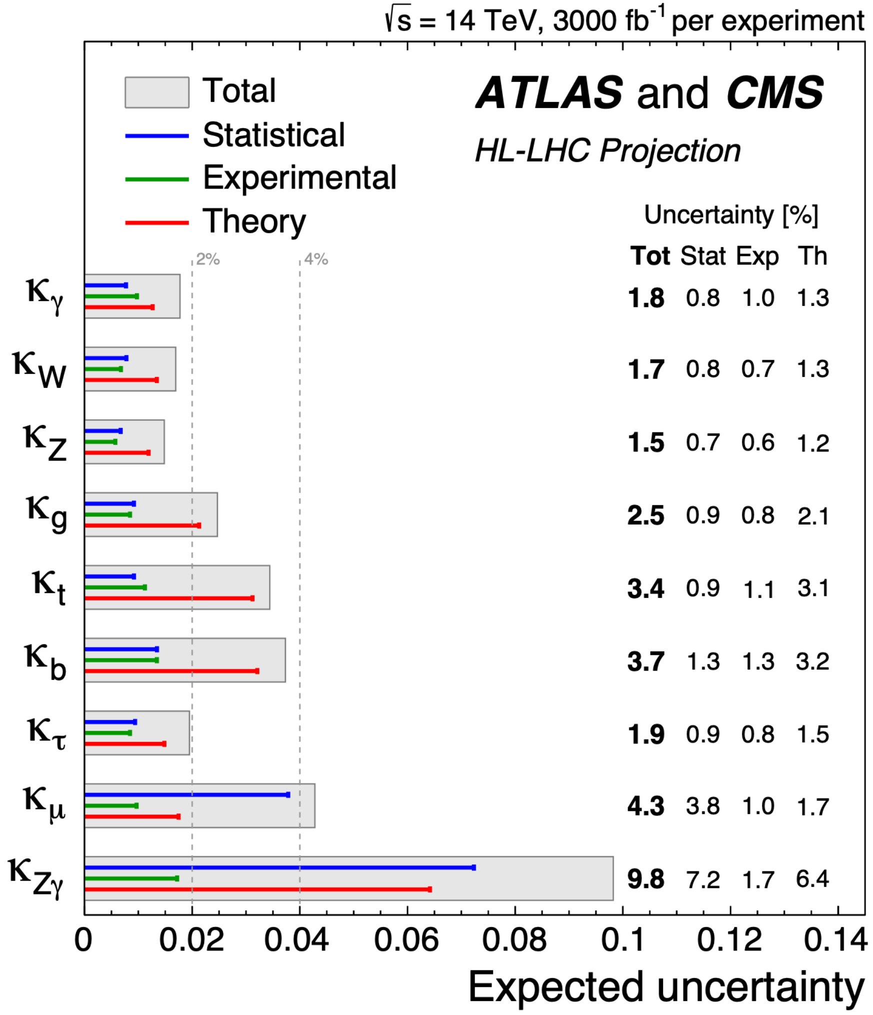
- Observe pp → HH @ 3.4σ

ATLAS-PHYS-PUB-2022-053

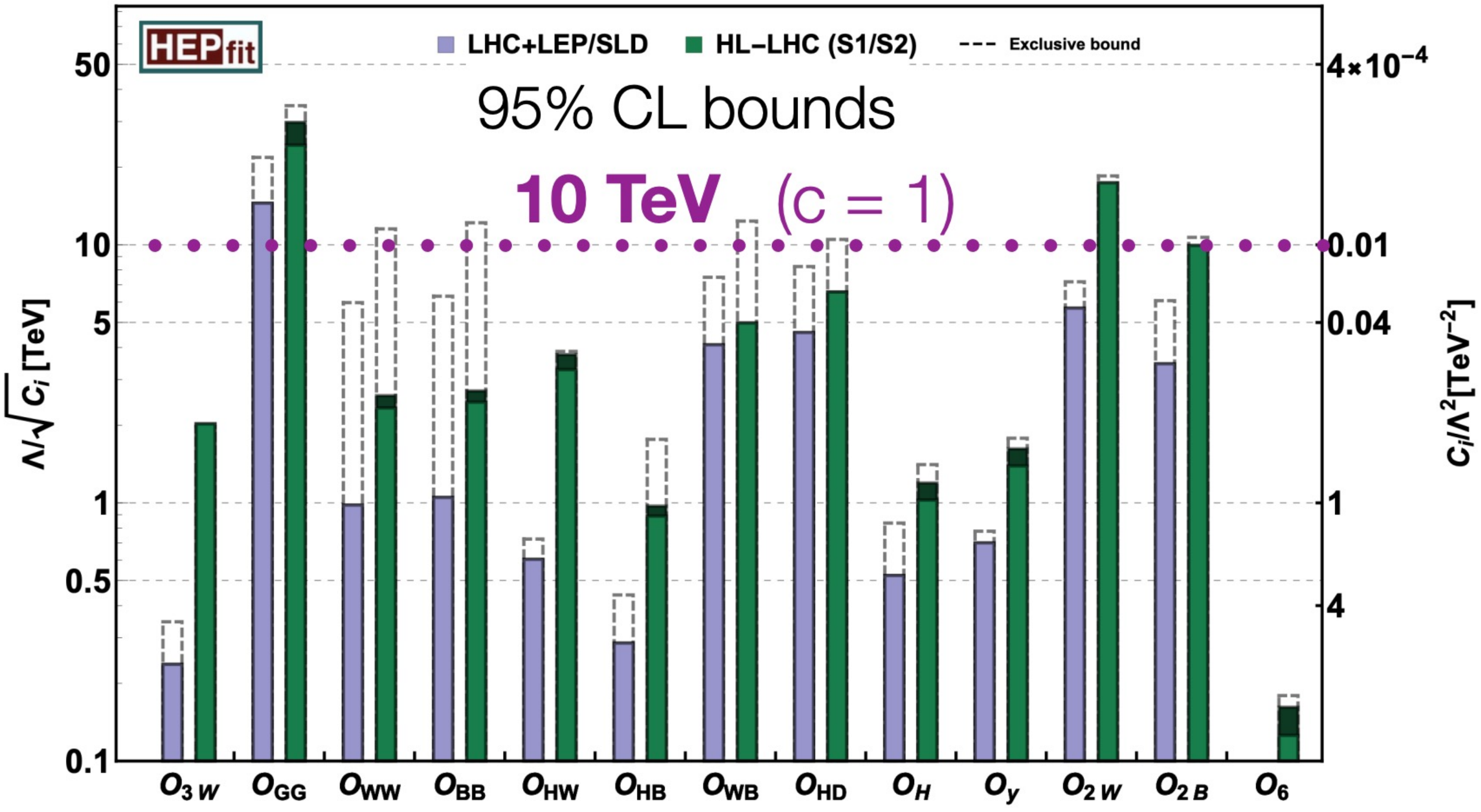




Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]



EFT sensitivity



Next step: a precision Higgs Factory

2020 European Particle Physics update

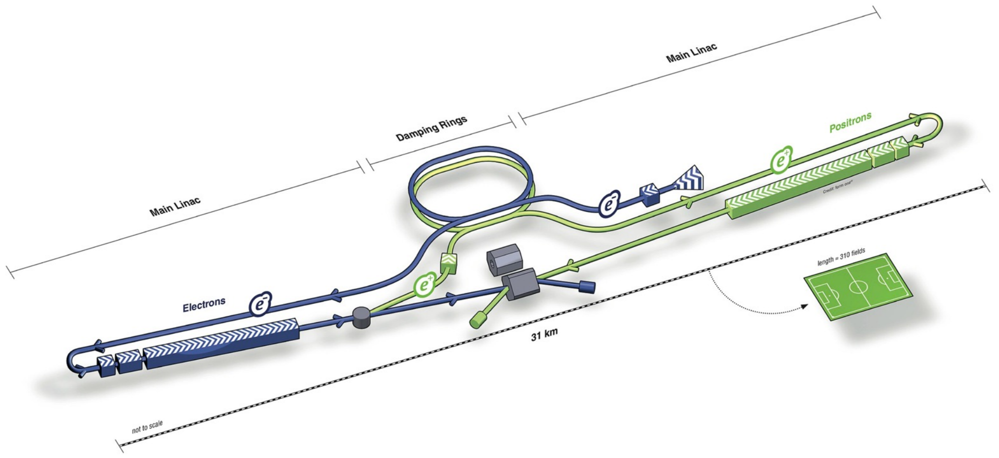
- An electron-positron Higgs factory is the highest priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these goals will require innovation and cutting edge technology.

2023 P5 Report

- Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe.
  - An offshore 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, 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 onshore program in particle physics.

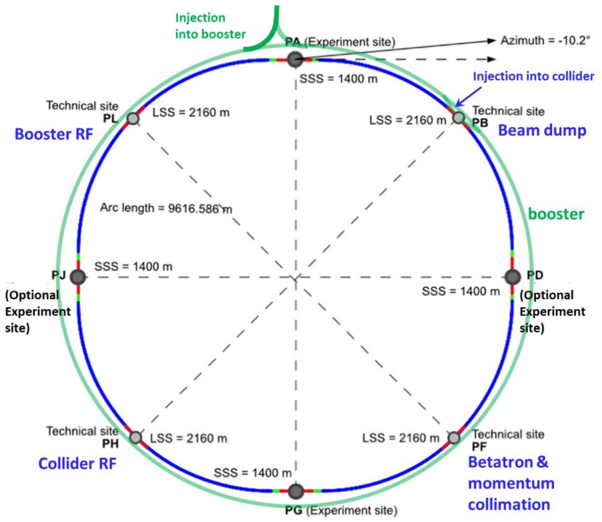
Design features of e^+e^- Higgs Factories

Linear Colliders: ILC/C3/CLIC



- Energy can reach to TeV
- Longitudinal polarization “easy”
- Low radiation
- Energy efficient

Circular Colliders: FCC-ee/CEPC

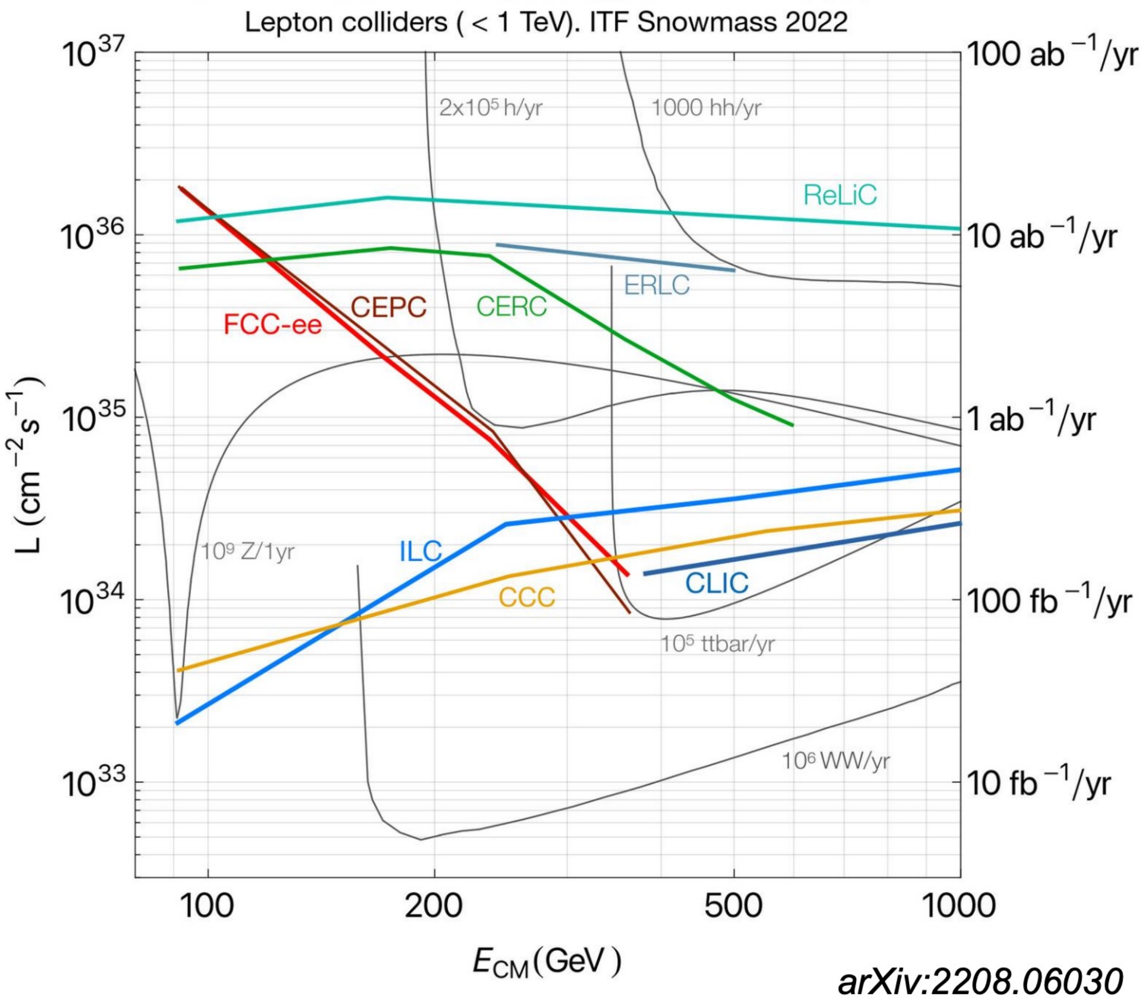


- Beams circulate after collisions
- Highest lumi at Z/WW/ZH
- Energy limited to < 400 GeV
- Less energy efficient

e^+e^- machine comparison: Physics potential

- Roughly equal number of Higgs produced for circular vs linear run plans
- Circular option enables precision EW Z and WW physics program
- Linear option enables extension to higher energies for Higgs self-coupling

Which is best?



arXiv:2208.06030

e^+e^- machine comparison: Physics potential

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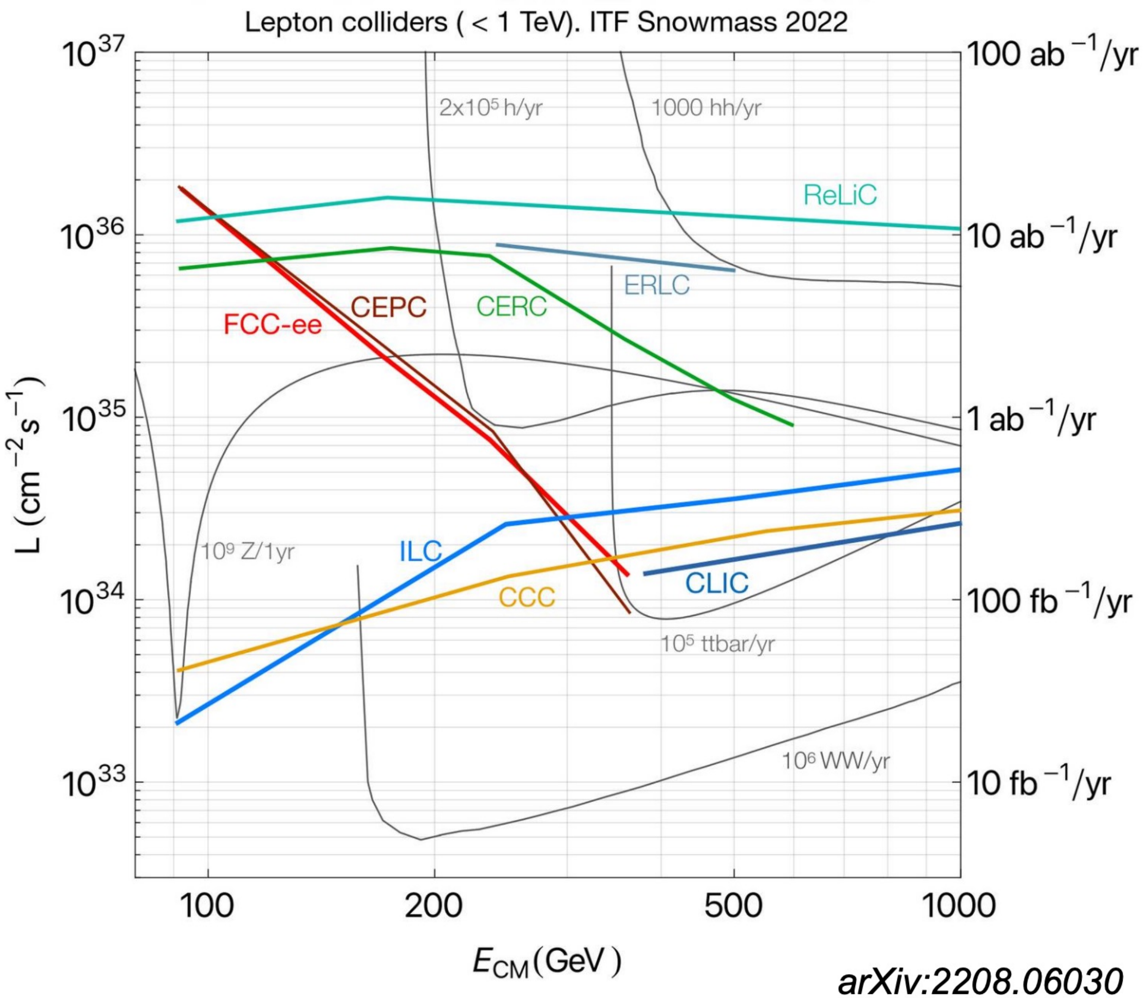
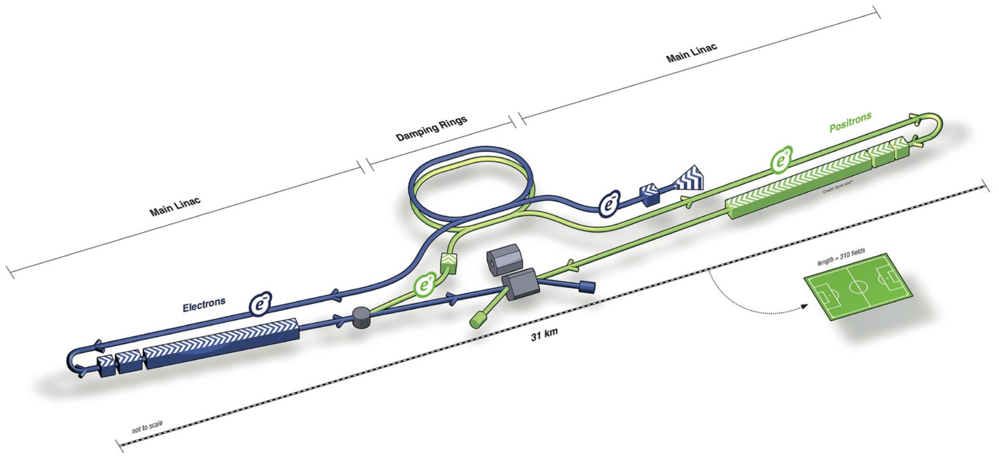


arXiv:2208.06030

Which is best? **Whichever one we can get built!**

Design features of e^+e^- Higgs Factories

Linear Colliders: ILC/C3/CLIC



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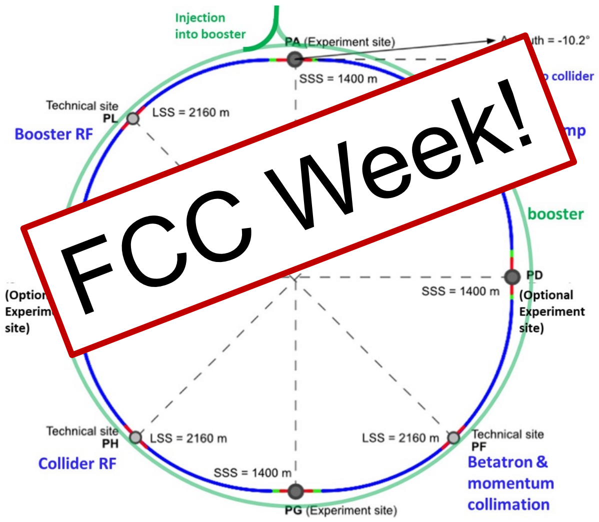
Circular Colliders: FCC-ee/CEPC



- Beams circulate after collisions
- Highest lumi at Z/WW/ZH
- Energy limited to < 400 GeV
- Less energy efficient

Recoil mass technique

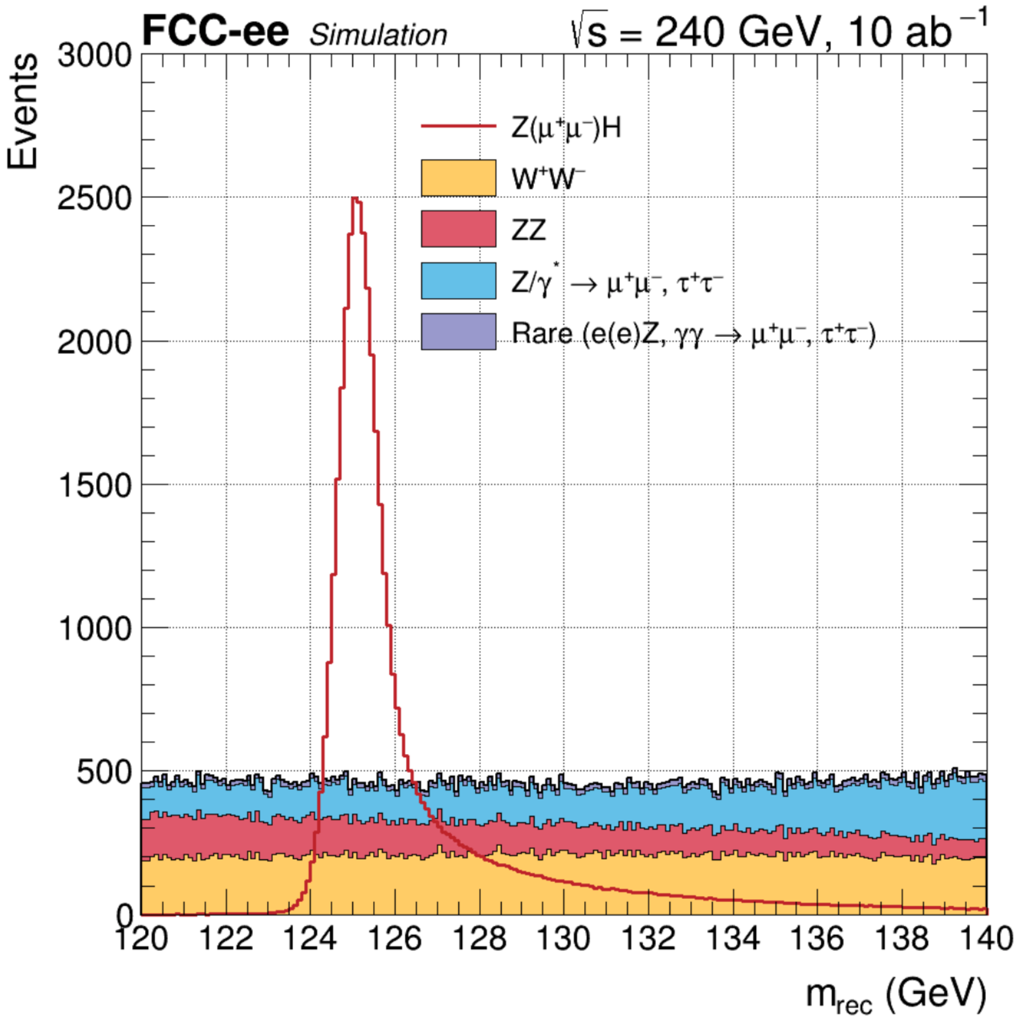
e+e- $\rightarrow$ Z + Anything

- 'Anything' corresponds to a system recoiling against the Z, tagged by leptons/jets
- The mass of this system is determined solely by kinematics and conservation of energy
- Peak in Recoil Mass corresponds to 125 GeV Higgs!

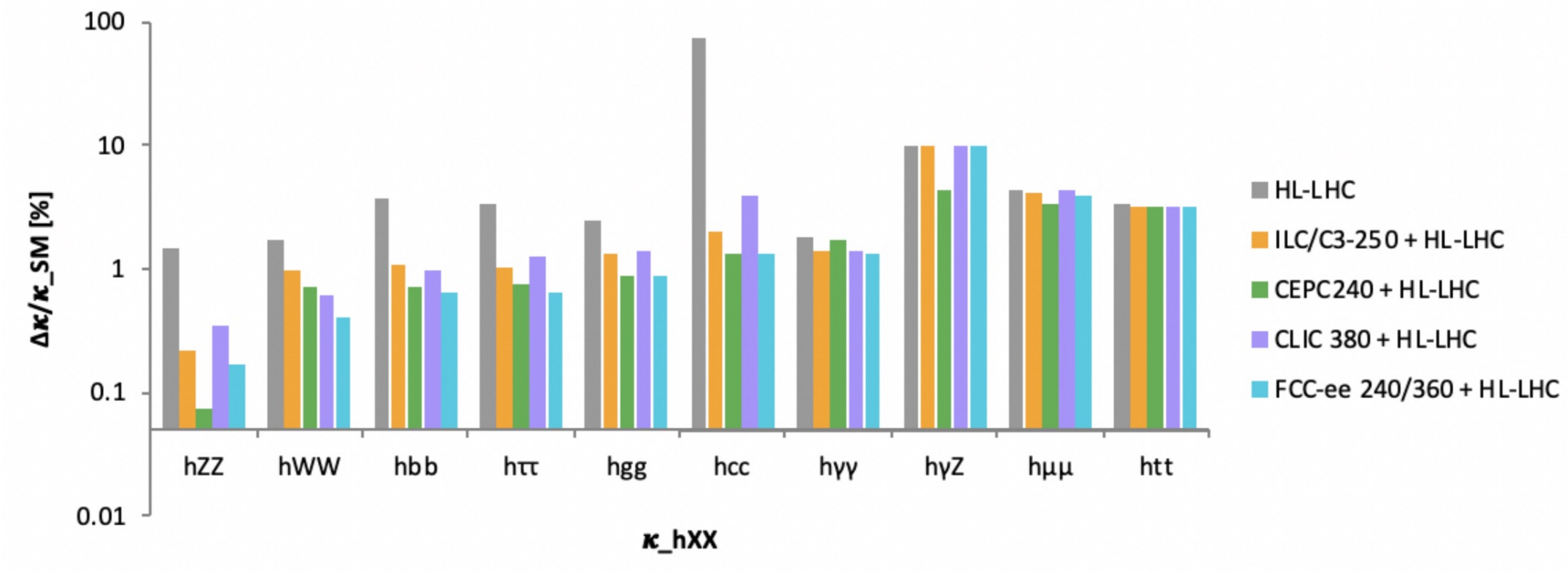
Allows for:

- Δm_h ~ 15-31 MeV (depending on Lumi)
- Model *independent* measurement of σ_{ZH} and Higgs couplings

- Advantage of e^+e^- collisions: initial quantum state is fully known



Precision Higgs measurements at future colliders



Sub-1% measurement of most couplings
H charm coupling measured to %-level

Dawson etal, 2209.07510

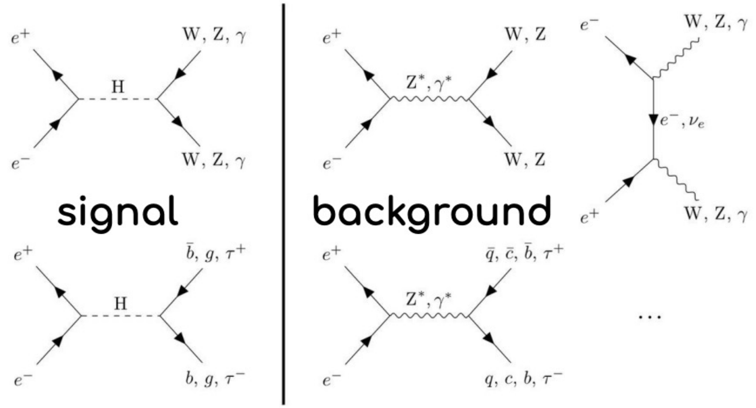
Feasible 1st generation Higgs coupling measurement?

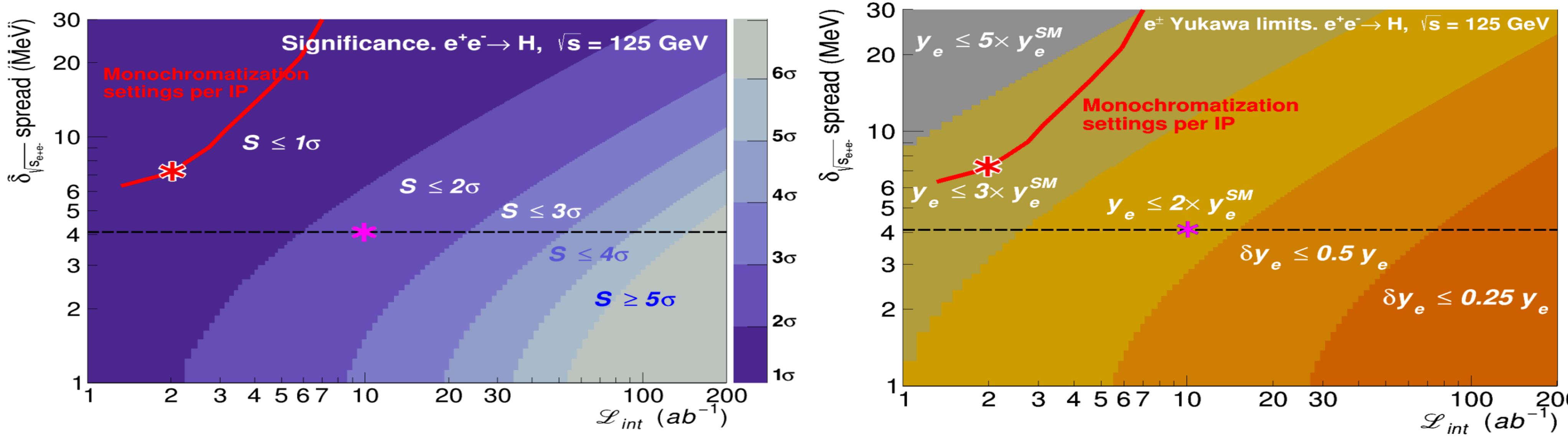
Run at √s = 125 GeV

Require very small beam energy spread ~ 4 MeV

Large background

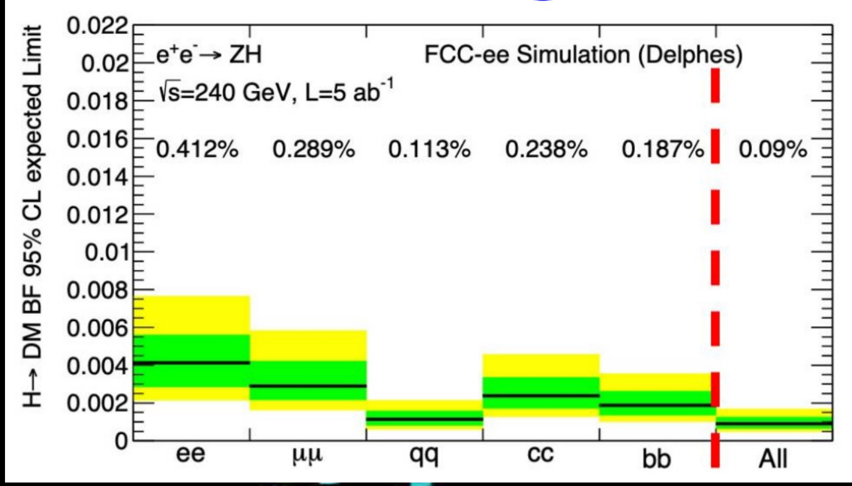
1.3σ significance /IP/yr, combing all Higgs final states

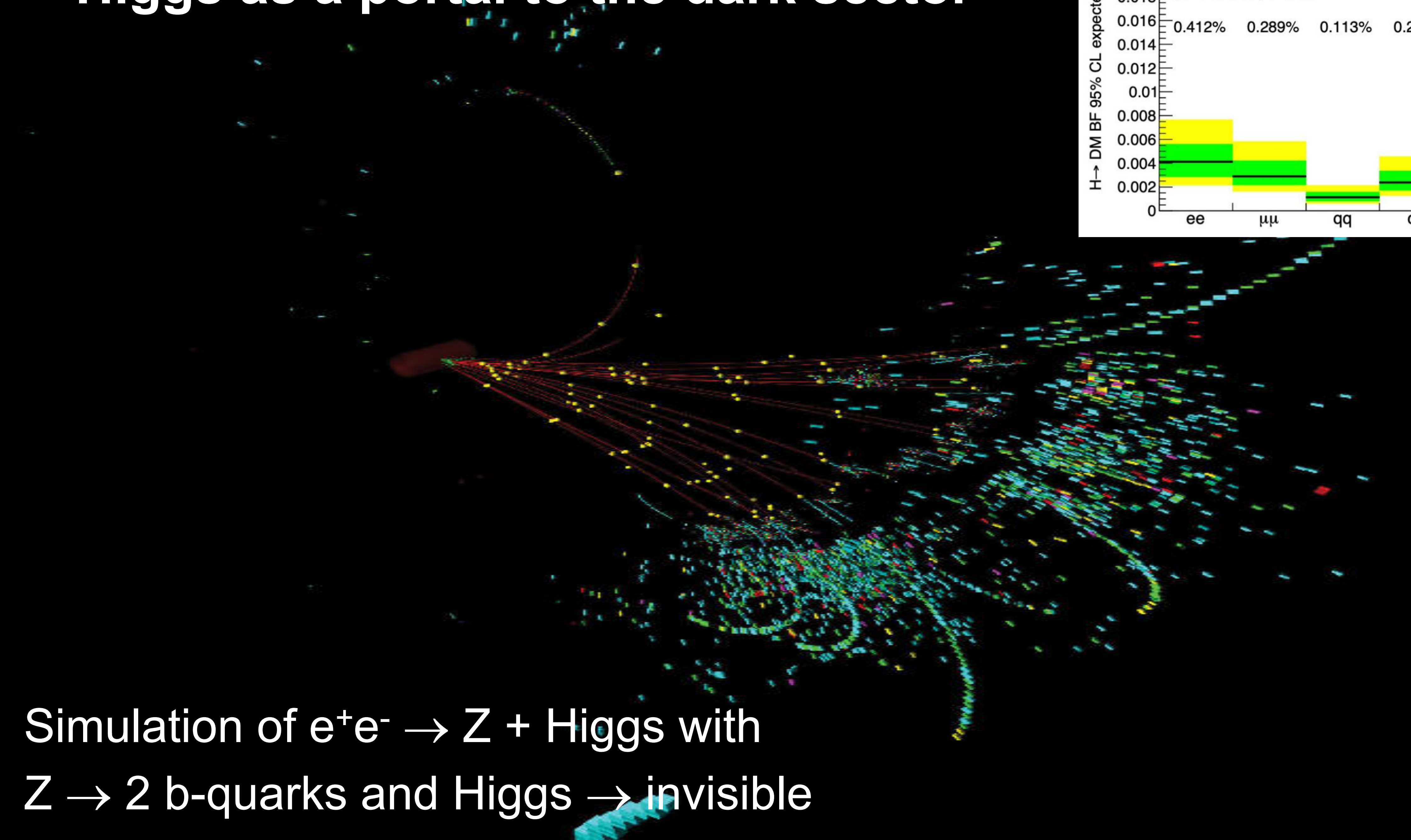




Enterria etal, 2107.02686

Higgs as a portal to the dark sector



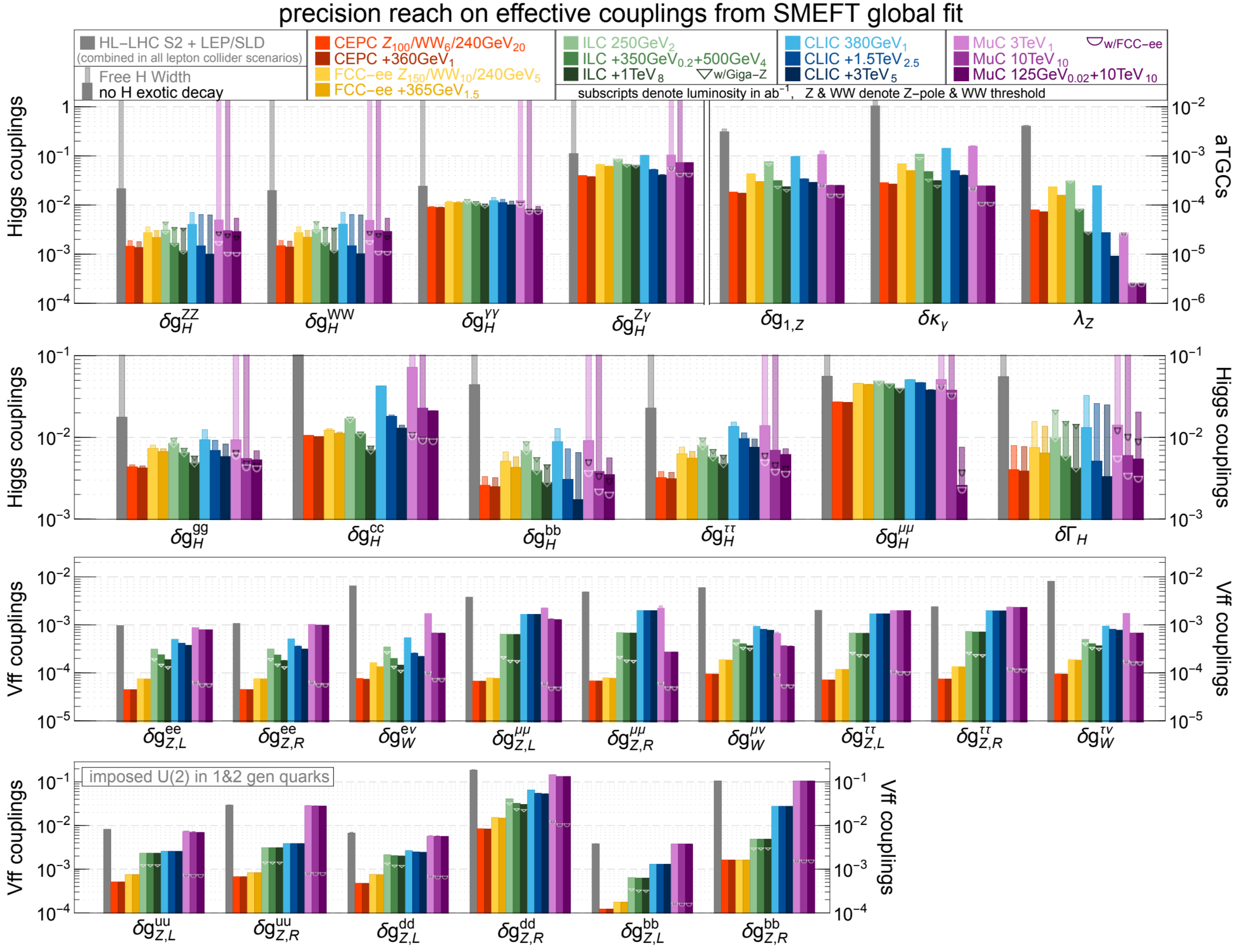


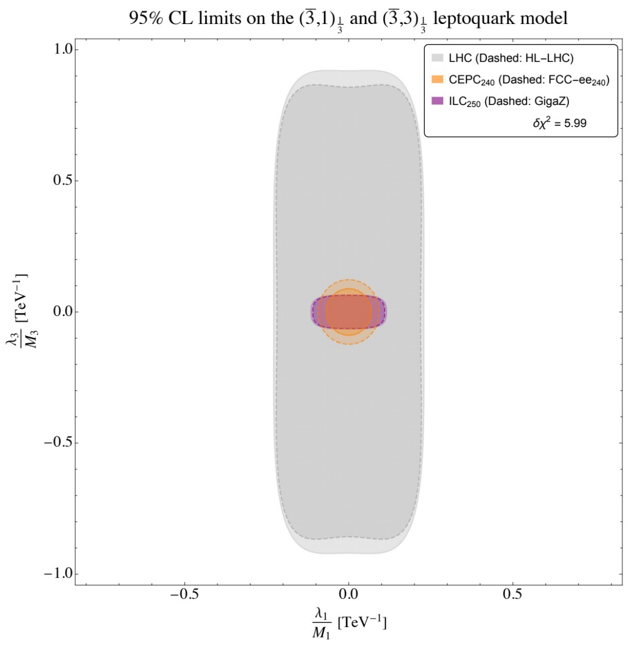
Simulation of $e^+e^- \rightarrow Z$ + Higgs with

$Z \rightarrow 2$ b-quarks and Higgs $\rightarrow$ invisible

N. Graf

Expected precision on effective couplings





Example of the power of this approach
Limits on leptoquark coupling/mass

Belloni etal, 2209.08078

Rare Higgs decays

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not\!\!E_T$
$h \to 2 \to 3$	$h \to \gamma + \not\!\!E_T$ $h \to (b\bar{b}) + \not\!\!E_T$ $h \to (jj) + \not\!\!E_T$ $h \to (\tau^+\tau^-) + \not\!\!E_T$ $h \to (\gamma\gamma) + \not\!\!E_T$ $h \to (\ell^+\ell^-) + \not\!\!E_T$
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not\!\!E_T$ $h \to (jj) + \not\!\!E_T$ $h \to (\tau^+\tau^-) + \not\!\!E_T$ $h \to (\gamma\gamma) + \not\!\!E_T$ $h \to (\ell^+\ell^-) + \not\!\!E_T$ $h \to (\mu^+\mu^-) + \not\!\!E_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not\!\!E_T$ $h \to jj + \not\!\!E_T$ $h \to \tau^+\tau^- + \not\!\!E_T$ $h \to \gamma\gamma + \not\!\!E_T$ $h \to \ell^+\ell^- + \not\!\!E_T$

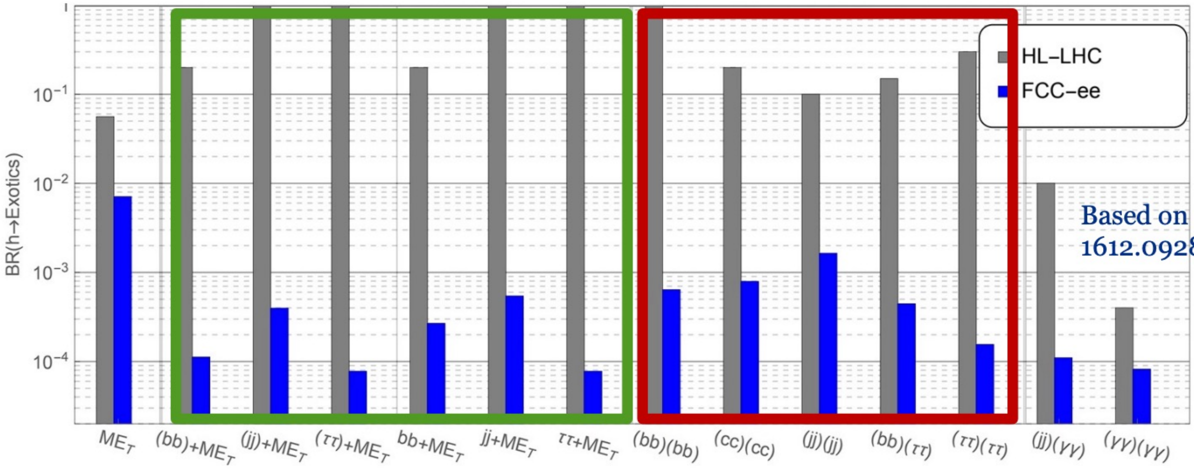
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$ $h \to (\mu^+\mu^-)(\mu^+\mu^-)$ $h \to (\gamma\gamma)(\gamma\gamma)$ $h \to \gamma\gamma + \not\!\!E_T$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not\!\!E_T$ $h \to (\ell^+\ell^-) + \not\!\!E_T + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not\!\!E_T$ $h \to \ell^+\ell^- + \not\!\!E_T + X$

Z. Liu et al. arXiv:1312.4992 ; arXiv:1612.09284

Green boxes denote HL-LHC strength

Rest covered by FCC-ee

95% C.L. upper limit limit on BR(H → exotics)



Precision EW run plan

ZH maximum	$\sqrt{s} \sim 240$ GeV	3 years	10^6	$e^+e^- \to ZH$
$t\bar{t}$ threshold	$\sqrt{s} \sim 365$ GeV	5 years	10^6	$e^+e^- \to t\bar{t}$
Z peak	$\sqrt{s} \sim 91$ GeV	4 years	5×10^{12}	$e^+e^- \to Z$
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	$> 10^8$	$e^+e^- \to W^+W^-$
[s-channel H	$\sqrt{s} = 125$ GeV	5? years	~5000	$e^+e^- \to H_{125}$]

Tera-Z

- 5-6 Trillion Z-bosons
- Reduced stat uncertainty by factor of ~500

WW Threshold

- 200M WW pairs
- 1000 x LEP statistics
- W mass to 0.4 MeV

Enables spectacular EW precision observable science program

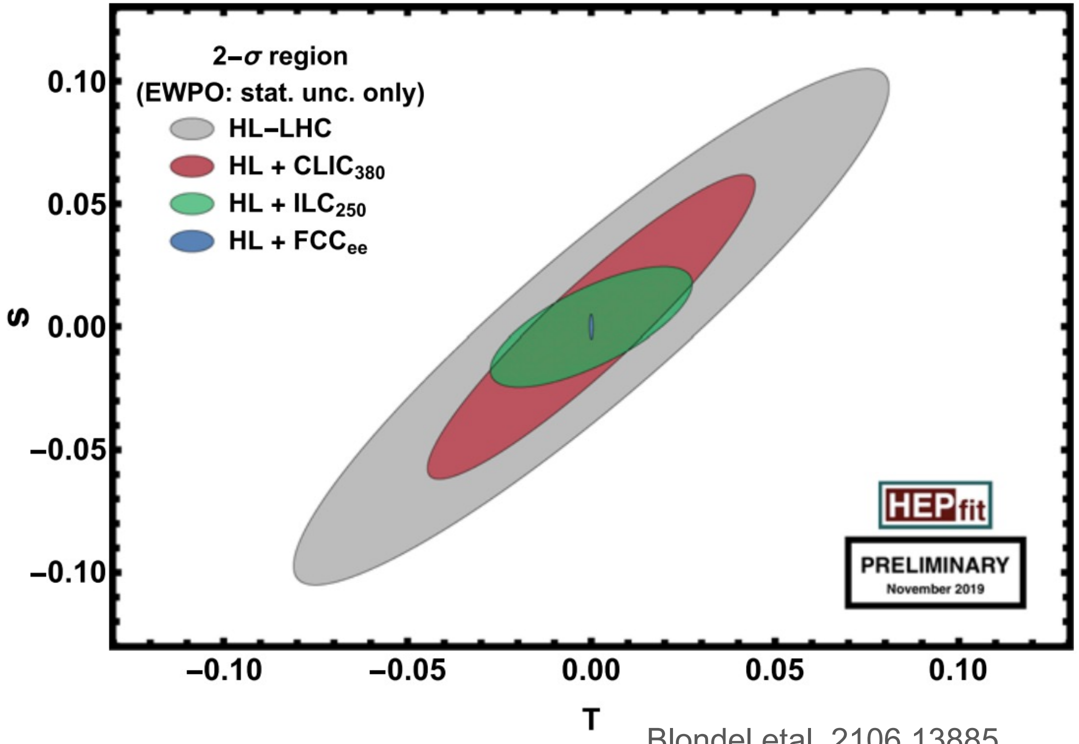
Full LEP1 data set accumulated every minute!

Observable	present value	±	error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu(\times 10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

Enables spectacular EW precision observable science program

Requires theory calculations at next order, or higher!!

Oblique parameters



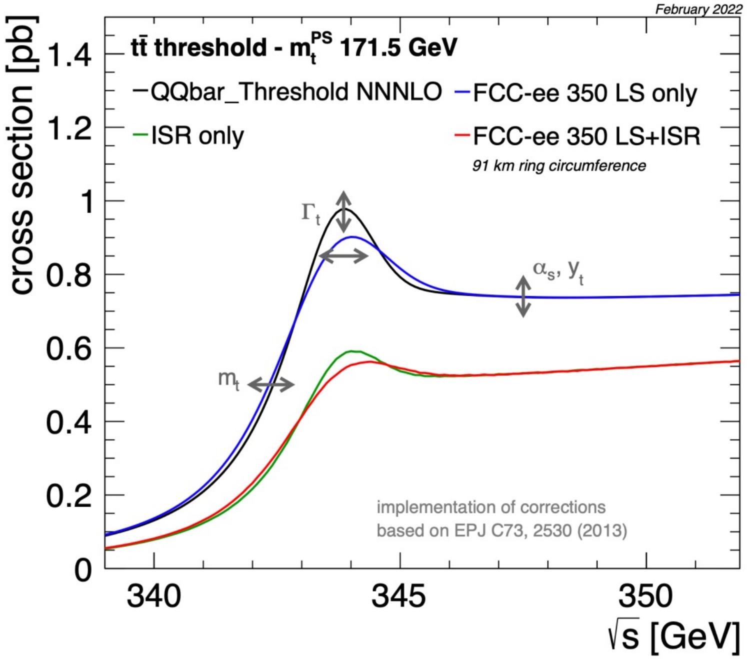
Blondel etal, 2106.13885

Top-quark physics

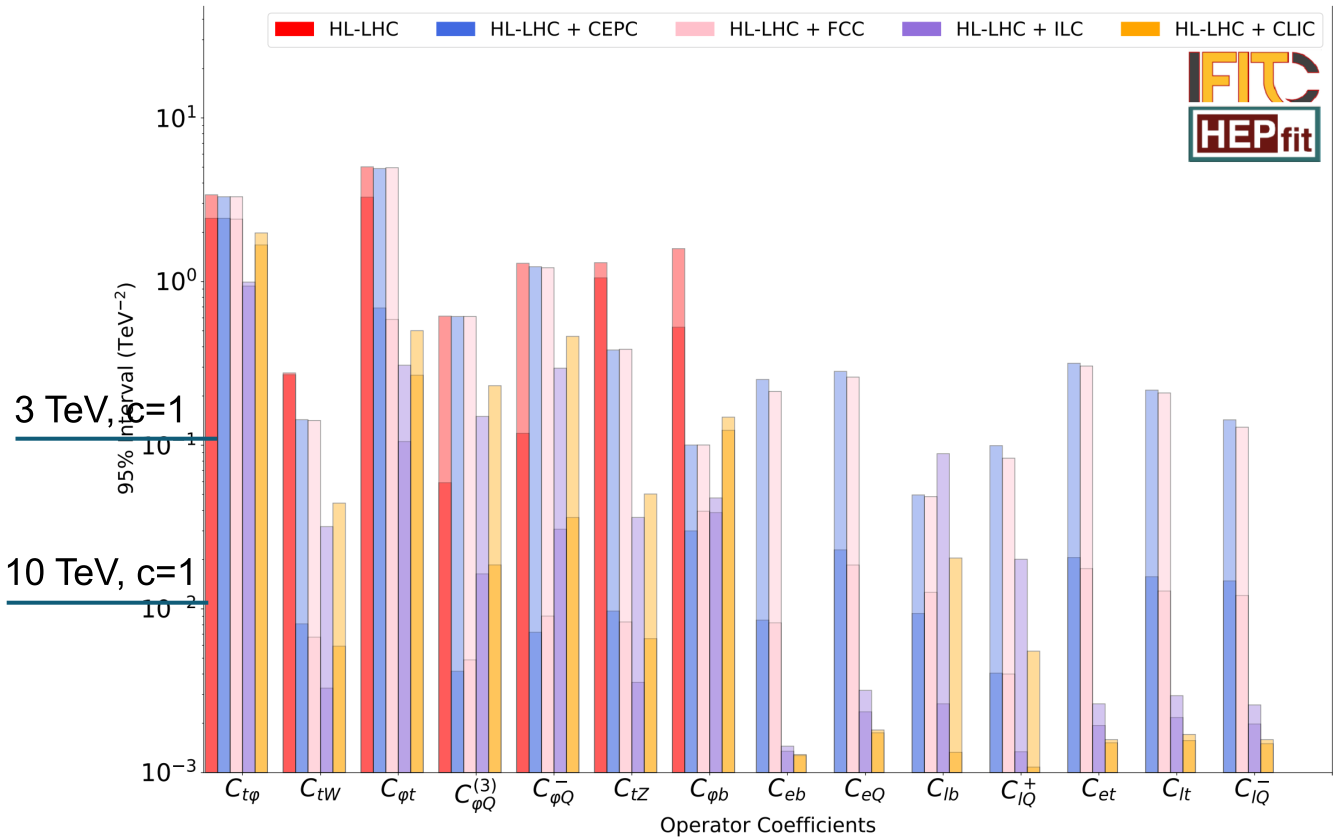
Top-quark mass important input to numerous observables/quantities, including vaccum stability

Vary √s to perform scan at top-quark threshold for precision top mass measurement of 20-70 MeV, factor of 10 improvement over HL-LHC

arXiv:2203.06520



EFT constraints on top-quark couplings



Shaded bars are global fit

Belloni etal, 2209.08078

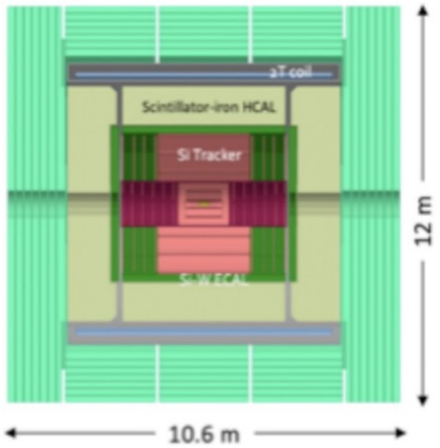
Detector Requirements

Challenges at FCC-ee

- **At the Z pole, high beam currents with bunch spacing 20 ns**
  - Almost continuous beam has implications on power management/cooling, density, readout,…
- **Extremely high luminosities L ~ 1.8 x 10^{36}/cm^{2}s at Z-pole**
  - Require absolute luminosity measurements to 10^{-4} to achieve desired physics sensitivity
  - Online/Offline handling of high data rates/total volume.
- **Physics interaction rate at Z pole ~ 100 kHz**
  - Implications on detector response time, event size, FE electronics and timing
- **Beam dynamics**
  - 30 mrad crossing angle sets constraints on the solenoid field to 2 T → larger tracker volume
  - Backgrounds from incoherent pair production (IPC) and synchrotron radiation (SR) to a lesser extent (tungsten masks significantly reduces SR toward IP)
- **High Luminosities**
  - High statistical precision: Requires control of systematics down to 10^{-6} – 10^{-5} level.
  - Online and Offline data handling O(10^{13}) events
  - Physics events up to 100 kHz imposes requirements on detector response time, FE electronics and DAQ.

Several strawdog FCC-ee detector benchmarks

CLD

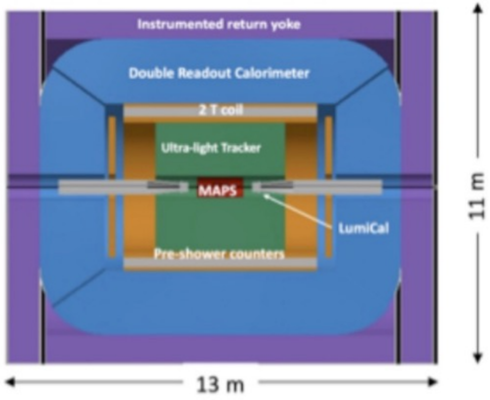


Design (ILC/CLIC/Calice)

- All silicon tracker (pixels + strips)
- Si-W EM calorimeter
  - $22X_0$, 40 long. layers.
- Steel-Scintillator hadronic calo.
  - SiPM readout
- Solenoid outside calorimeter
- RPC based Muon system

https://arxiv.org/pdf/1911.12230.pdf

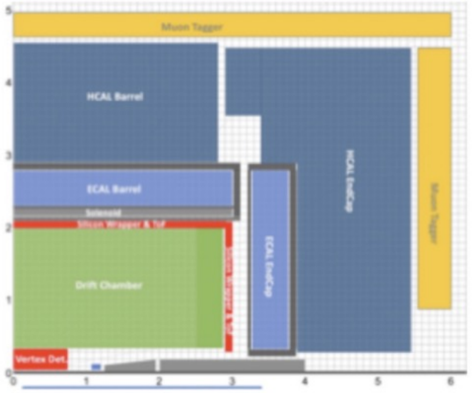
IDEA



- MAPS based vertex detector (1% X_0)
- High-precision low-mass drift chamber with surrounding Si microstrip (t_d < 400 ns).
- pre-shower with MPGD readout
- Lead-Fiber dual readout calorimeter
- Sensitive to both Sci/Cerenkov
  - Hybrid with crystal EM?
- large μ-Rwell muon chambers

https://inspirehep.net/files/49ec726758c422bc454e270a71f6e59f

Allegro



- Includes a highly granular noble liquid calorimeter
- Possible design being explored are lead/steel absorbers (RM ~4 cm), stacked azimuthally inclined at 50° wrt radial axis with LAr as the active medium.
- Other considerations include Tungsten absorbers and/or Liquid Krypton.
- https://arxiv.org/pdf/2109.00391.pdf

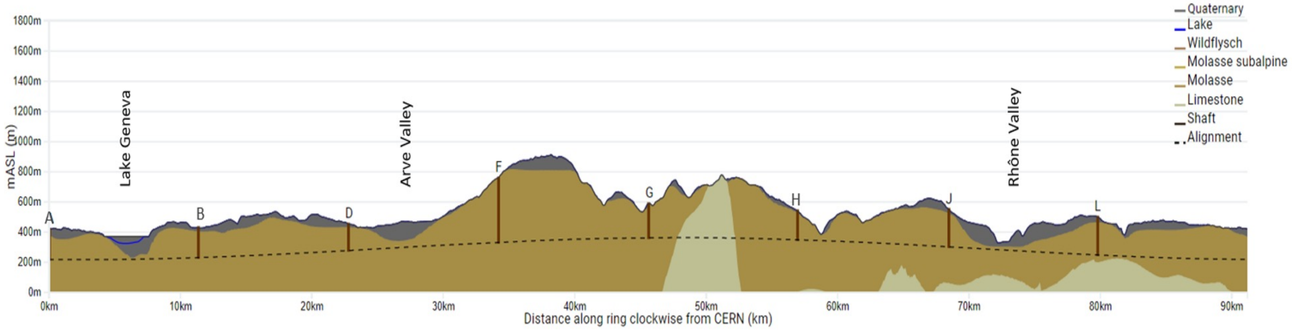
FCC-ee Next Steps

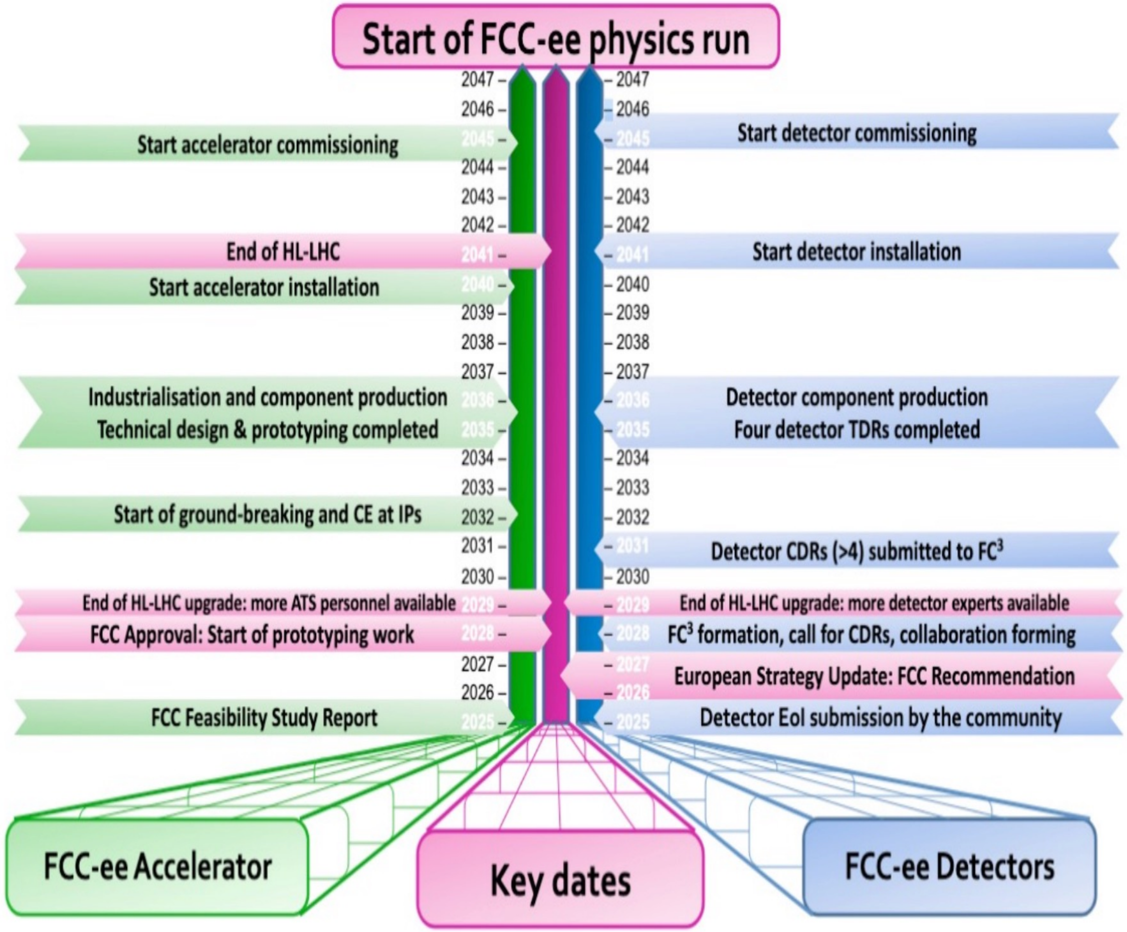
Feasibility study – Launched in 2021

- Consolidation of science program and detector technologies, administrative and financial issues, and significant work on territorial feasibility, including: geological, environmental impact, infrastructures, and civil engineering

CERN Council recently launched next European Particle Physics Strategy update

- Process to begin soon





U.S. statement of intent

Joint Statement of Intent between the US and CERN concerns future planning for large research infrastructures, advanced scientific computing and open science signed in Washington DC April 2024

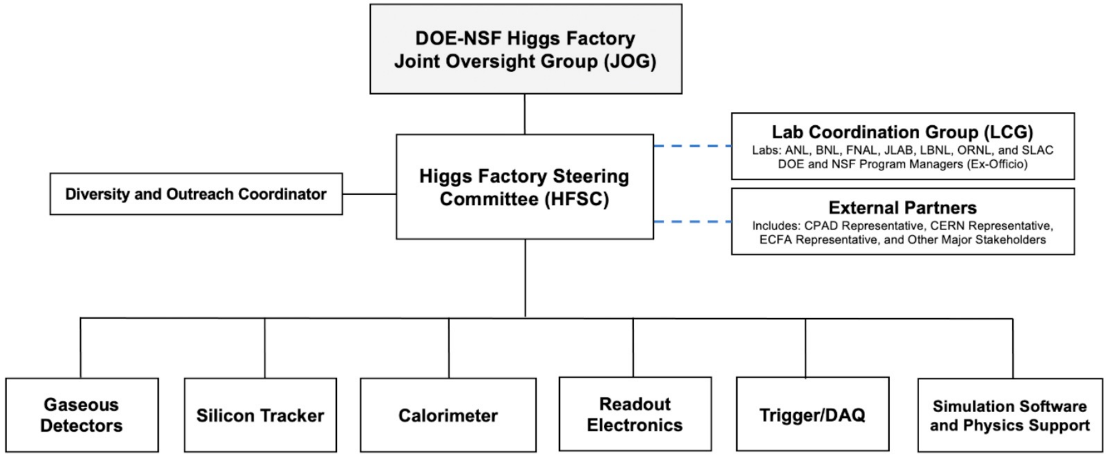
D. Mulligan, OSTP and F. Gianotti, CERN

Concerning the proposed Future Circular Collider, FCC-ee, the text states:

“*Should the CERN Member States determine the FCC-ee is likely to be CERN’s next world-leading research facility following the high-luminosity Large Hadron Collider, the United States intends to collaborate on its construction and physics exploitation, subject to appropriate domestic approvals***.”**

U.S. Higgs Factory Coordination Consortium

Provide strategic direction for the U.S. community to engage, shape, and thereby advance the development of the physics, experiment, and detector program for a potential future Higgs factory



HFSC: S. Rajagopalan, chair, R. Patterson, co-chair, M. Demarteau, S. Eno

U.S. Department of Energy
and the
National Science Foundation

May 28, 2024

SUBJECT: U.S. Higgs Factory Coordination Consortium

Dear Chair and Deputy Chair of the U.S. Higgs Factory Steering Committee:

The 2023 report of the Particle Physics Project Prioritization Panel (P5), developed under the auspices of the High Energy Physics Advisory Panel (HEPAP), laid out a compelling scientific program that recommended world-leading facilities with exciting new capabilities, as well as a robust scientific research program. As part of the efforts to implement the P5 recommendations, the Government of the United States and CERN jointly signed a Statement of Intent (SOI) in April 2024 concerning future planning of large research infrastructures, advanced scientific computing, and open science. Among the topics, the SOI expresses our intention to collaborate in an off-shore internationally driven Higgs factory, where decisions to proceed are subject to appropriate approvals in the U.S. and at CERN including those that are taken following the next update of the European Strategy for Particle Physics. The U.S. is also engaged in feasibility and design studies towards a next-generation future collider. To that end, the U.S. Department of Energy (DOE) and the National Science Foundation (NSF) are hereby forming a nationally coordinated U.S. Higgs Factory Coordination Consortium (HFCC) to provide strategic direction and leadership for the U.S. community to engage, shape, and thereby advance the development of the physics, experiment, and detector (PED) program for a potential future Higgs factory; and to ensure cooperation with our partners in the international program.

The U.S. HFCC is to coordinate efforts in the following areas:

(1) Physics and technical feasibility studies, including any associated design and R&D efforts, to advance various experiment detector concepts at a future Higgs factory;

(2) Prioritization and stewardship of the national R&D efforts should funds be identified by DOE and/or NSF;

(3) Development of the pre-project detector R&D scope that will be required prior to DOE and/or NSF initiating any detector project at a future e^+e^- collider;

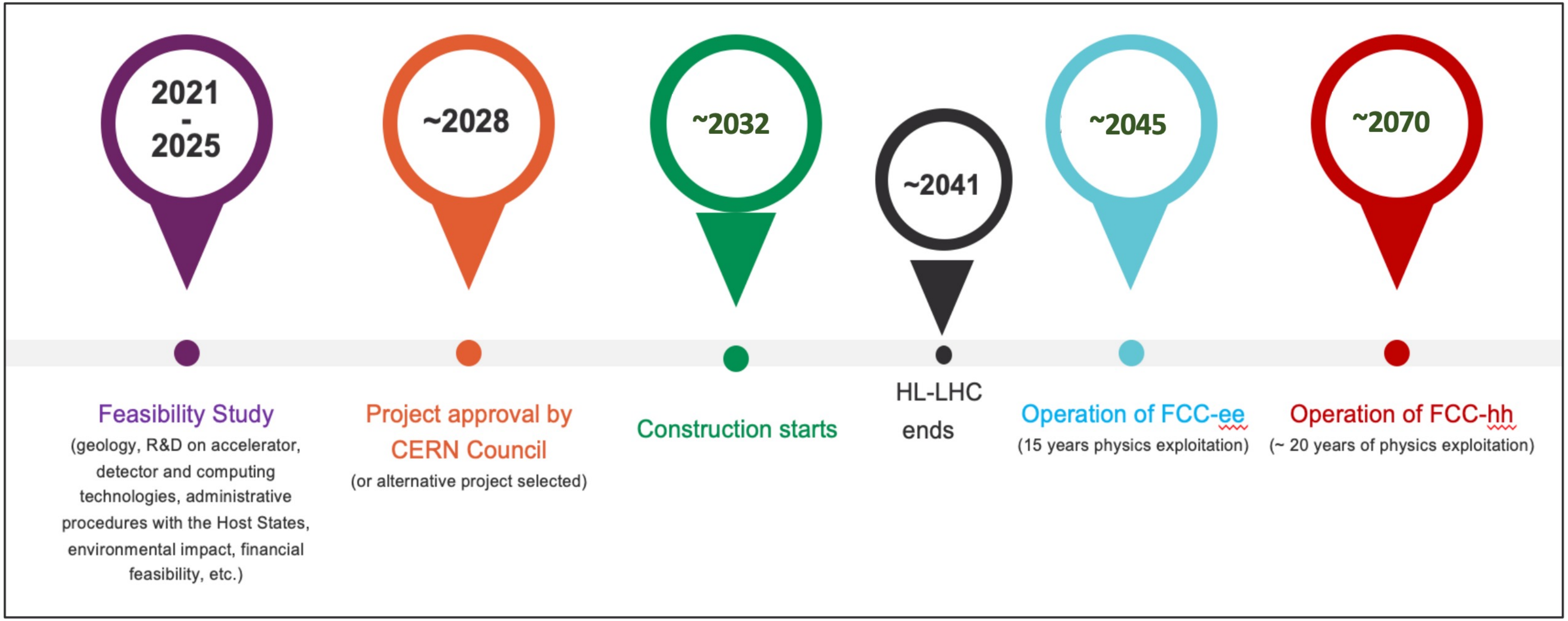
(4) Conceptualization of the software and computing framework that will be needed to advance physics studies and R&D efforts; and to collect, store, and analyze the large volumes of physics data at future collider experiments;

(5) In consultation with DOE and NSF program managers, develop various funding models that will be required to support the R&D efforts described in items (3) and (4) above; and

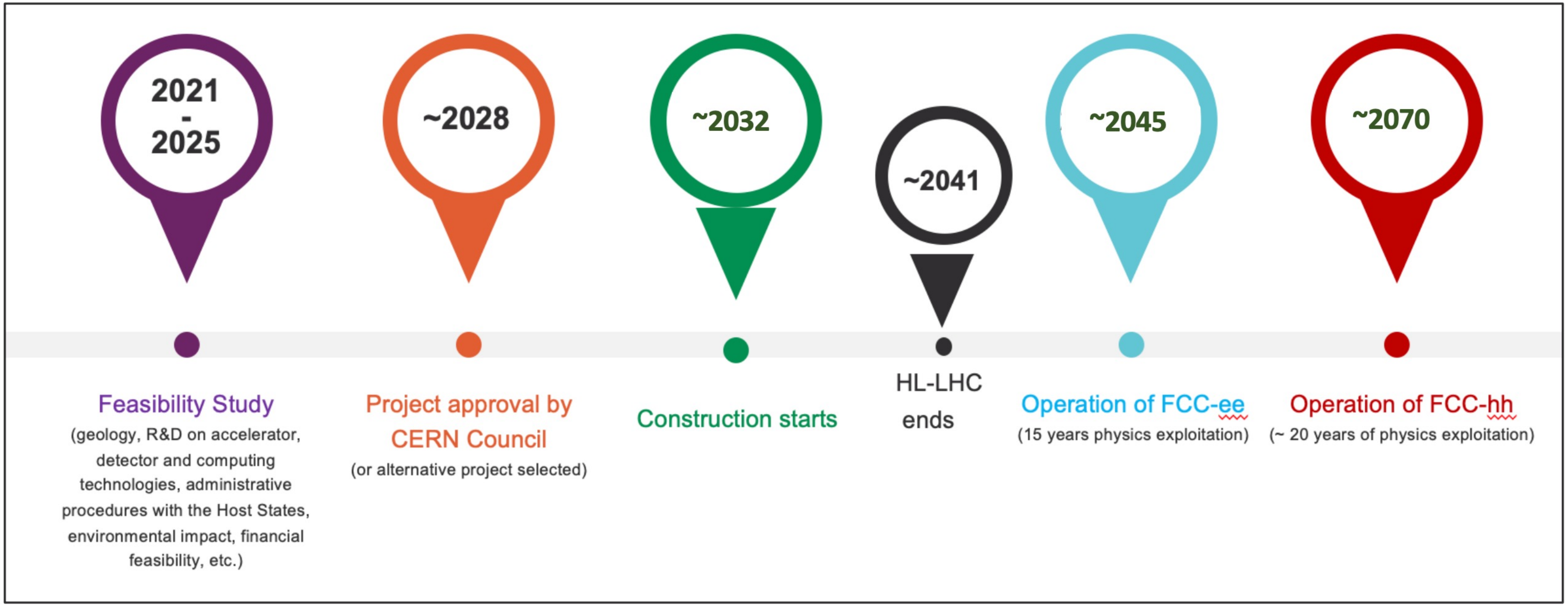
(6) Ensure collaborations by the U.S. with our partners are cost-effectively carried out to advance the future Higgs factory initiatives. Such partner efforts include, but are not limited to, those being undertaken by a) the U.S. Coordinating Panel for Advanced Detectors (CPAD); b) the CERN-hosted Detector R&D (DRD) initiative; c) the European Committee for Future Accelerators (ECFA); and d) other major stakeholders.

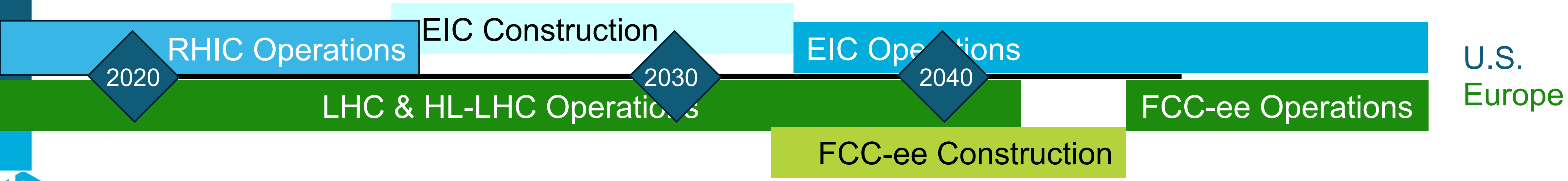
The 2023 P5 strategic plan also recommended that once a specific off-shore Higgs factory project has been deemed feasible, DOE and NSF are to convene a targeted panel to consider the nature and

CERN FCC Timeline



US-Europe Collider Timeline



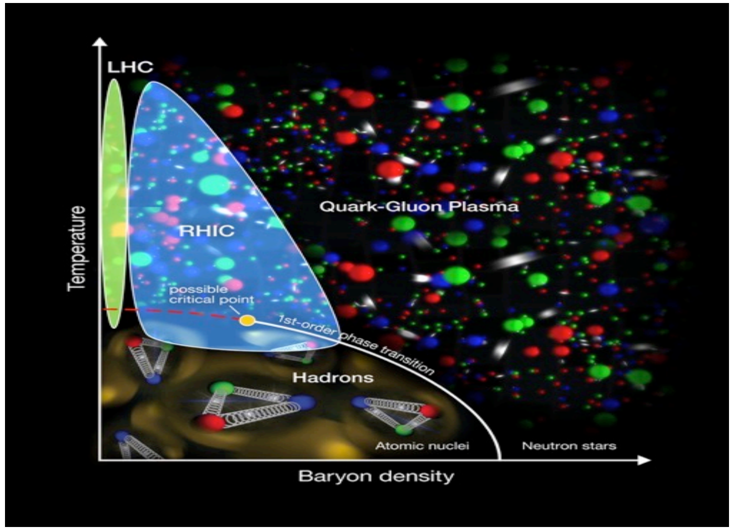


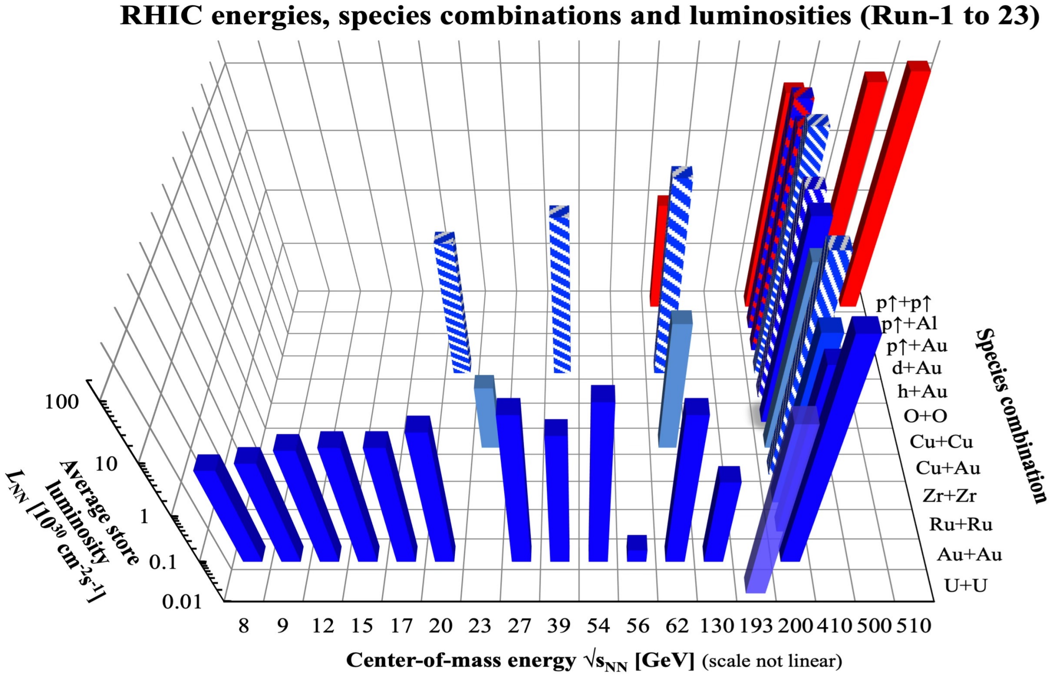
Relativistic Heavy Ion Collider

24 Continuous years of operation

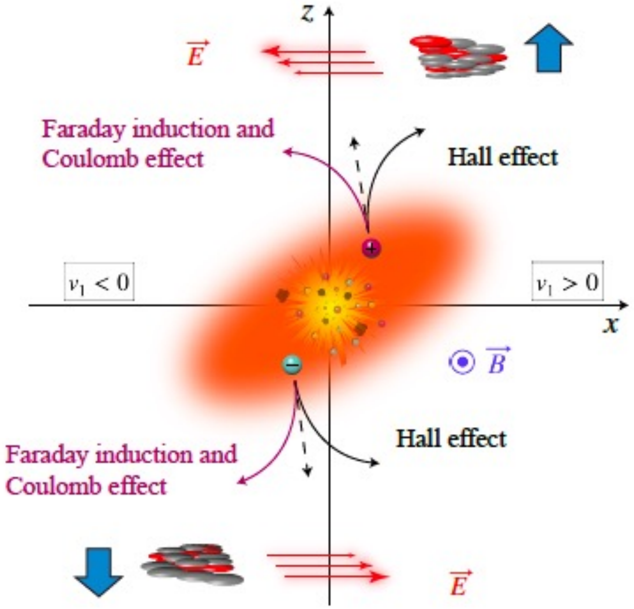
Only operating collider in the U.S.

Will shut down in 2025





Colossal magnetic field observed in Quark-Gluon Plasma with $B = 10^{18}\ B_{Earth}$



STAR, arXiv: 2304.03430, PRX 14, 011028 (2024)

Compelling EIC Science Highlighted by NAS Report

How do quarks, gluons, and orbital angular momentum contribute to proton spin?

Spin: a fundamental property of matter

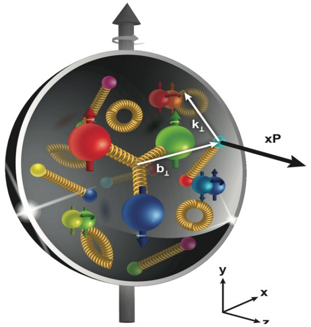
All elementary particles, but the Higgs carry spin

Spin cannot be explained by a static picture, rather the interplay between the properties and interactions of quarks and gluons inside the proton

Does the mass of visible matter emerge from quark-gluon interactions?

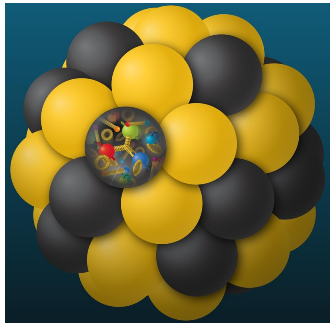
Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100

The EIC will determine an important term contributing to the proton mass, the so-called “QCD trace anomaly.



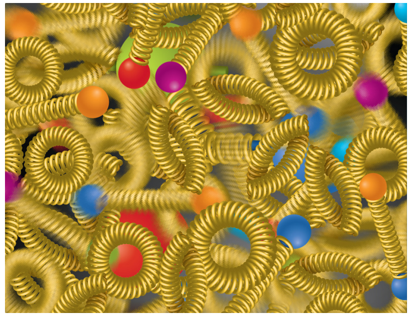
How can we understand the QCD dynamics and the relation to Confinement?

EIC will image quarks and gluons in 3D in space and momentum inside the nucleon & nuclei
Uncover how the nucleon properties emerge from quarks and gluons and their interactions.



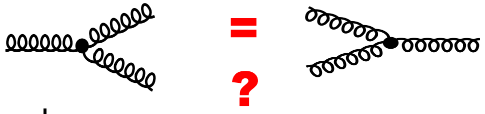
How do the quark-gluon interactions create nuclear binding?

Is the structure of a free and bound nucleon the same?
How do quarks and gluons, interact with a nuclear medium?
How do the confined hadronic states emerge from these quarks and gluons?



Does gluon density in nuclei saturate at high energy?

How many gluons can fit in a proton?
How does a dense nuclear environment affect the quarks and gluons, their correlations and interactions?



gluon splitting

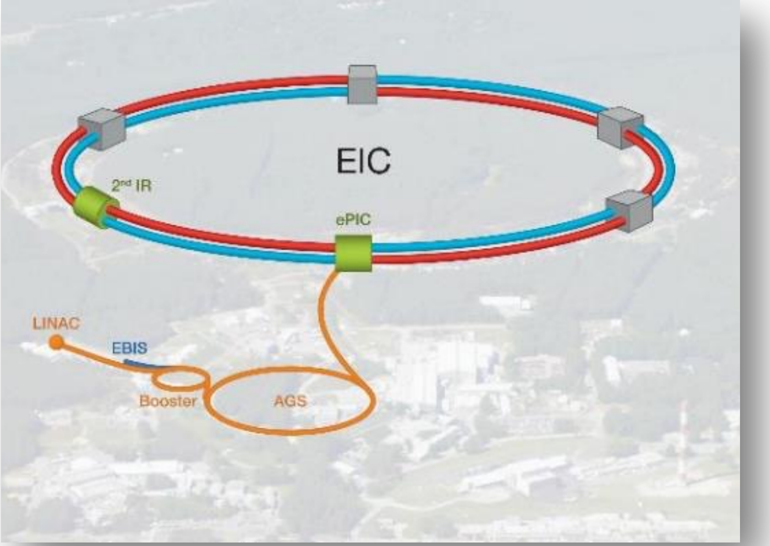
gluon recombination

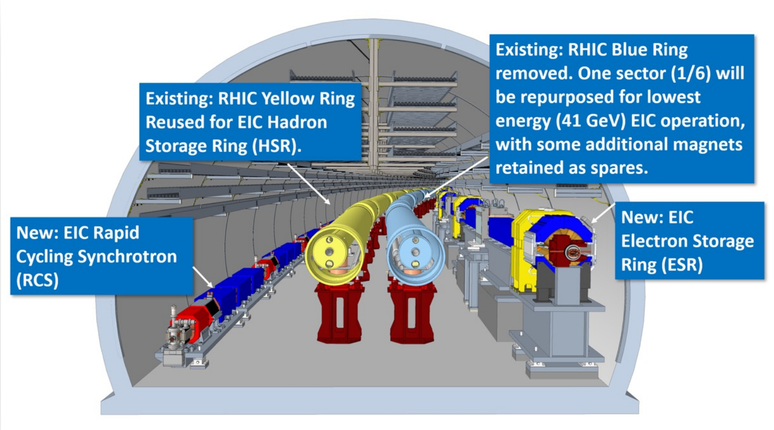
Facility Requirements

EIC Facility Performance Goals

- High Luminosity: L= 10^{33} – 10^{34}cm^{-2}sec^{-1}, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 20 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Ability to Accommodate a Complementary Second Interaction Region (IR) and Detector

Conceptual design scope and expected performance satisfy the U.S. Nuclear Science Advisory Committee (NSAC) Long Range Plans (2015 & 2023) and the requirements endorsed by the U.S. National Academy of Sciences (2018).





Project status

Schedule: CD-3B = March 2025

CD2/3 = End of 2025, CD-4 = 2034

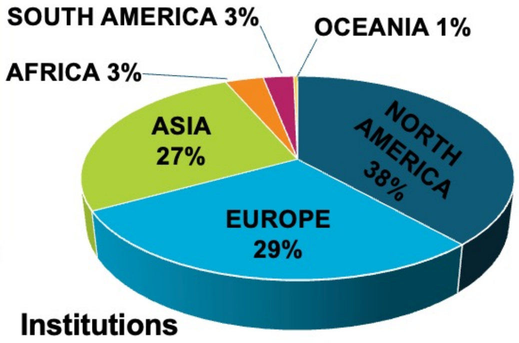
Cost: CD-1 cost range of $1.7-2.8B

Funding: $397M provided from FY20 - FY24

$100M New York State Grant for EIC Buildings Awarded February 2024

UK commits £58 in-kind

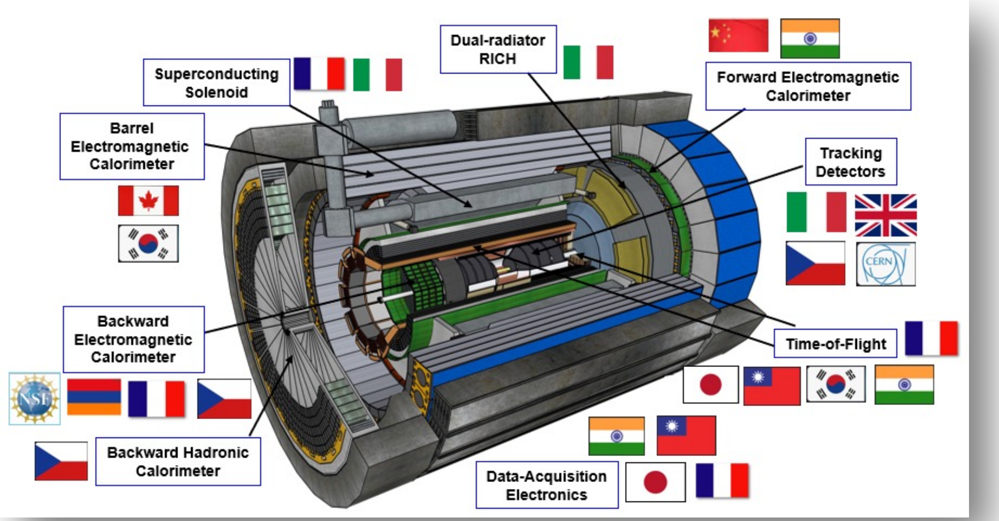
The EIC scientific community is rapidly growing with more than 1,529 members from 294 institutions and 40 countries.



BNL-TJNAF partnership agreement signed in May 2020.

US Labs
1. Argonne National Laboratory
2. Brookhaven National Laboratory
3. Fermi National Accelerator Laboratory
4. Lawrence Berkeley National Laboratory
5. Los Alamos National Laboratory
6. Oak Ridge National Laboratory
7. SLAC National Accelerator Laboratory
8. Thomas Jefferson National Accelerator Facility
US Universities
Over 80 US universities are participating in the EICUG.

EIC Accelerator Collaboration Kick-Off Meeting at IPAC24



Slide from F. Zimmerman

FUTURE CIRCULAR COLLIDER

US Electron Ion Collider (EIC)

Brookhaven National Laboratory

Jefferson Lab

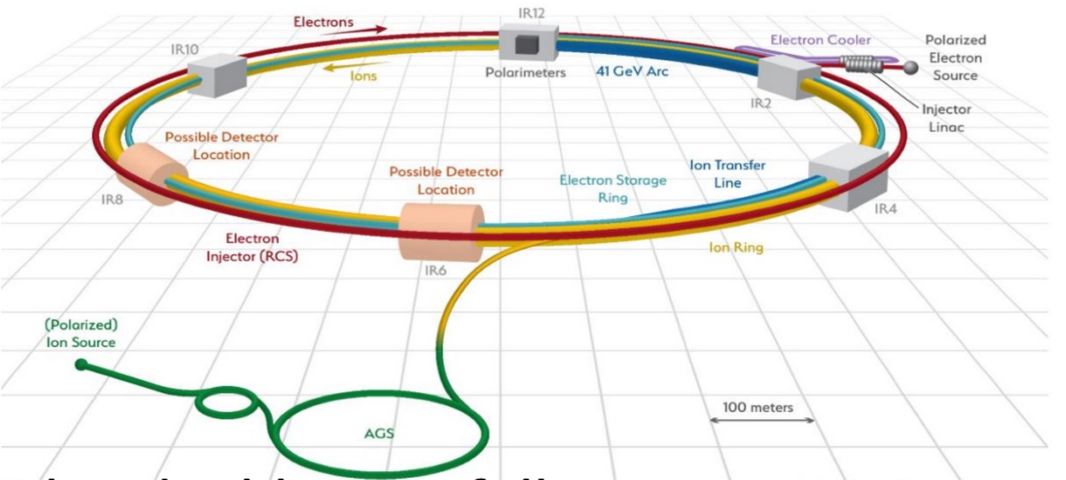
US EIC Electron Storage Ring similar to, but more challenging than, FCC-ee

beam parameters almost identical, but twice the maximum electron beam current, or half the bunch spacing, and lower beam energy

>10 areas of common interest identified by the FCC and EIC design teams, addressed through **joint EIC-FCC working groups**, still evolving

EIC will start beam operation about a decade prior to FCC-ee

The EIC will provide another invaluable opportunity to train next generation of accelerator physicists on an operating collider, to test hardware prototypes, beam control schemes, etc.

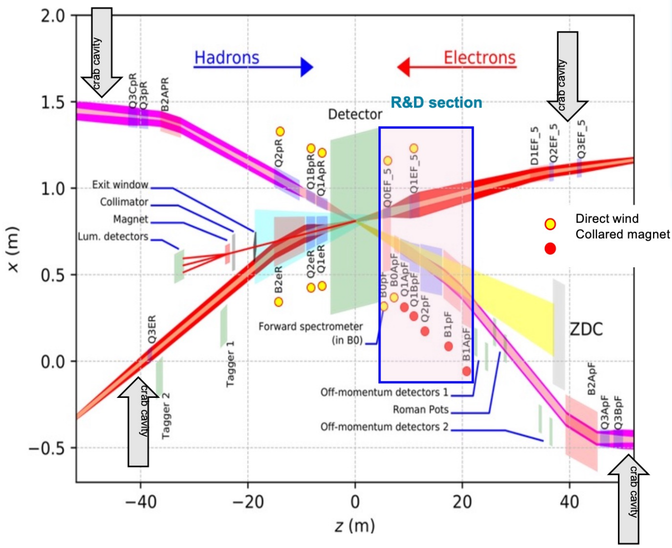


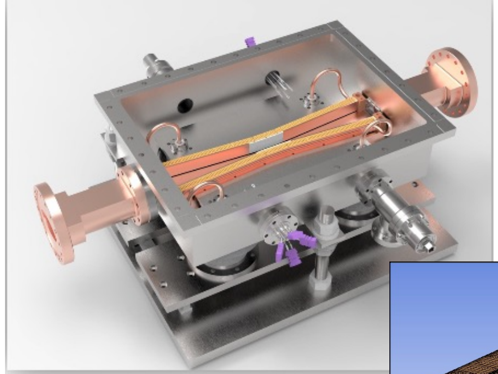
3.83 km double ring, full-energy e^- inj., injection rate 1 Hz, every 2 min into same bucket

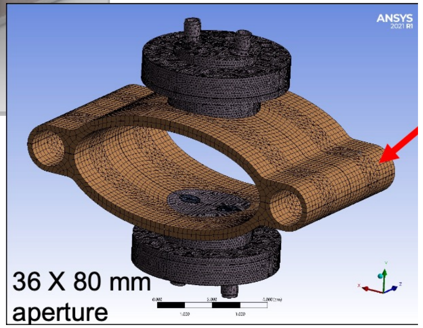
	EIC	FCC-ee-Z
Beam energy [GeV]	10 (18)	45.6 (80)
Bunch population [10^{11}]	1.7	2.1
Bunch spacing [ns]	10	25
Rms bunch length [mm]	7	5.6 (SR)
Beam current [A]	2.5 (0.23)	1.27
RF frequency [MHz]	591	400
SR power/beam/meter [W/m]	3000	650
Critical photon energy [keV]	6.2 (36)	20 (106)

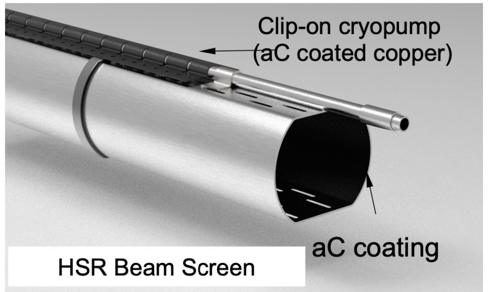
EIC – FCC Synergies

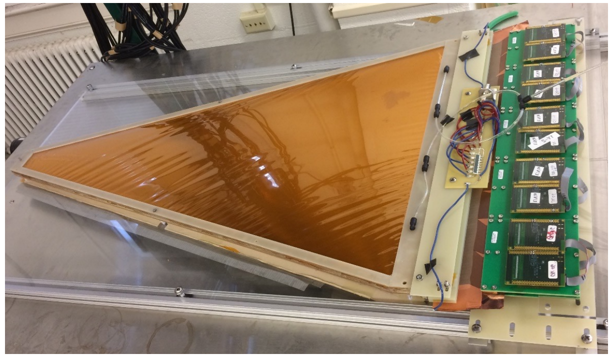
- SRF cavities, electron gun (high current, high brightness beams)
- Beam instrumentation: SR monitors, BLM, BPMs, Beam feedback systems,
- crab angle measurements
- Vacuum systems
- IR region magnets, prototypes, production
- MDI, IR shielding
- Collimation
- Beam-beam interactions, beam-gas interactions
- Impedance model, instabilities, HOM, ion instability
- AC-LGAD Technology
- LAPPD Photon sensors
- MAPS
- ITS3 sensor technology
- Streaming readout
- Common software and tools

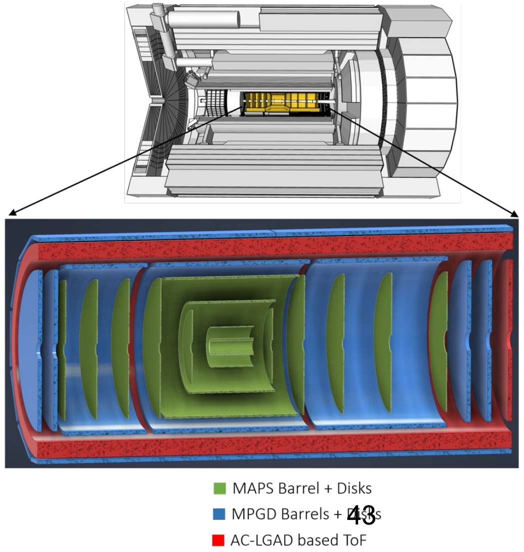












EIC provides accelerator & detector R&D opportunities for FCC- ee

FCC-ee has *outstanding* science potential

Higgs
factory

m_H, σ, Γ_H
self-coupling
$H \to$ bb, cc, ss, gg
$H \to$ inv
$ee \to H$
$H \to$ bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
"boosted" B/D/τ factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \to \tau \nu$
$B_s \to D_s K/\pi$
$B_s \to K^* \tau \tau$
$B \to K^* \nu \nu$
$B_s \to \varphi \nu \nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ, R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

There is much work to do and it will take time

….Discoveries await!!