Future Circular e^+e^- and pp Colliders

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MelFest, UChicago

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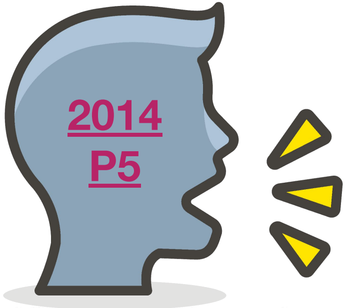
Big Questions in HEP

- **What's up with the Higgs?**
- **What is dark matter?**
- **What else IS there?**
    - Unknown unknowns
    - Look for the impacts of well-motivated theoretical models
    - Simplified models
    - Small deviations from the SM in properties of SM particles



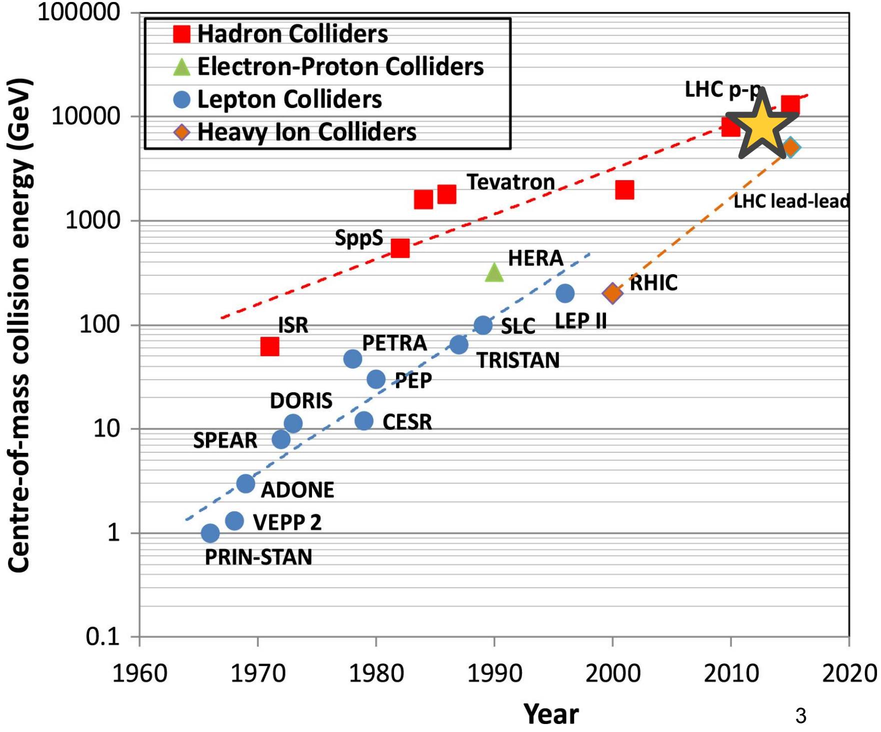
A vast number of scientific opportunities were investigated, discussed, and summarized in Snowmass reports. We distilled those essential inputs into five intertwined science Drivers for the field:

- **Use the Higgs boson as a new tool for discovery**
- **Pursue the physics associated with neutrino mass**
- **Identify the new physics of dark matter**
- **Understand cosmic acceleration: dark energy and inflation**
- **Explore the unknown: new particles, interactions, and physical principles.**

Timeline (“previous ~50 years”)

- We’ve made lots of lepton colliders, less hadron colliders
- Discovery, then precision measurements
  - ⭐ The Higgs boson
  - Agreement in EF & AF Snowmass reports re: next ten years
    - Strong finish: HL-LHC program
    - Construction: Higgs factory
    - R&D: multi-TeV collider

[Frank Zimmermann, 2018]



Now

Currently, there are two operational high-energy hadron colliders - RHIC at BNL and LHC at CERN. The Large Hadron Collider now represents the "accelerator frontier" with its 6.8 TeV energy per beam, $2.1 \cdot 10^{34}$ $cm^{-2}s^{-1}$ luminosity and some 1 TWh of annual total site electric energy consumption. Since the start of operation in 2009, the LHC has delivered 190 fb^{-1}/IP in *pp* collisions – mostly over the past few years at 13 TeV c.m.e., exceeding its design luminosity goal by a factor of two. The High-Luminosity LHC upgrade will be completed by 2028 with the goal of reaching 250 fb^{-1}/yr at 14 TeV c.m.e. via doubling the beam current, lower beta-function at the IPs with new Nb_3Sn SC IR magnets, and using *beam crabbing* and *luminosity leveling* techniques [43]. The upgrade will be followed by a decade of operation to obtain a total integrated luminosity of 3-4 ab^{-1}.

Two colliders are under construction - and both will serve the nuclear physics research community - the NICA pp/ion-ion collider in Russia with $\sqrt{s}$=4-11 GeV with expected first collisions ca 2024 and the Electron-Ion Collider (EIC) in the US (BNL) that will collide 10-18 GeV electrons with ions/protons up to 275 GeV energies. The later will be an excellent test bed for HEP colliders. Many topics, including polarization, ERLs, cooling, etc. will be developed for this machine and will benefit future high energy colliders.

Charged particle colliders – arguably the most complex and advanced scientific instruments – have been at the forefront of scientific discoveries in high-energy and nuclear physics since the 1960s [20]. There are five electron-positron colliders in operation at present: DAΦNE in Frascati, Italy, VEPP-4M and VEPP-2000 in Novosibirsk, Russia, BEPC-II at IHEP, Bejing, and SuperKEKB at KEK, Japan. The SuperKEKB is an asymmetric e^+e^- B-factory with 4 and 7 GeV beam energies, respectively. Since the startup in 2018, SuperKEKB is pushing the frontiers of accelerator physics with crab-waist collisions, a world-record

Snowmass Accelerator Frontier Report

What we have now

+ B-factories, which are not the focus of this talk

What did we expect?

On observing H→bb:

resonance observed in this mass region. Since the direct production, $gg \rightarrow H$ with $H \rightarrow b\bar{b}$, cannot be efficiently triggered nor extracted as a signal above the huge QCD two-jet background, the associated production with a W or Z boson or a $t\bar{t}$ pair remains as the only possible process to observe a signal from $H \rightarrow b\bar{b}$ decays. The leptonic decays of the W boson or semi-leptonic

- ATLAS TDR

On studies of Higgs pair production:

In total, inclusive dihiggs production with decay to four b quarks has a signal-over-background ratio S/B which is too bad to be a suitable search channel, al-

- theory friends, 10 years ago

The small signal cross section combined with the huge QCD $4b$ background make it essentially impossible to determine the Higgs boson self-coupling in $pp \rightarrow 4b$. We quantify

- theory friends, 20 years ago

Studies of di-Higgs boson production in the $bb\gamma\gamma$ and $bb\tau\tau$ final states are ongoing. The measurement of this process is very challenging, but is nevertheless anticipated to be accessible at some level at the HL-LHC.

- ATLAS Higgs prospects at the HL-LHC, ten years ago

What did we expect?

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- ATLAS TDR

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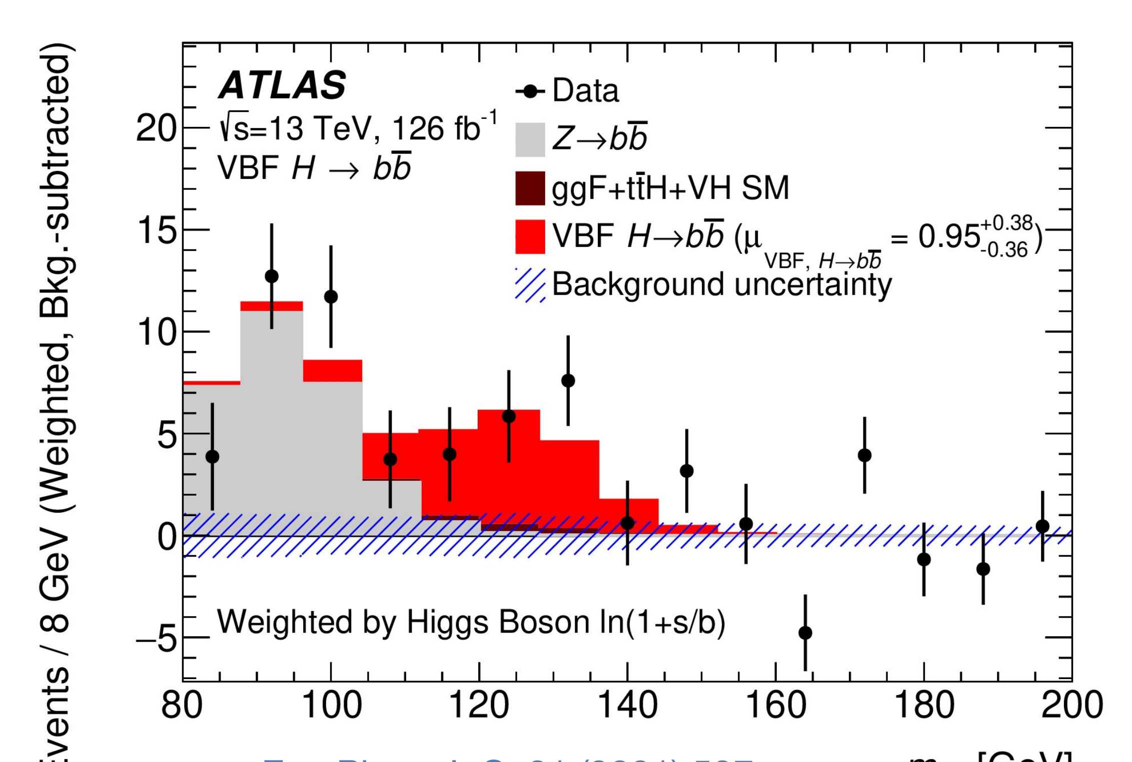

Eur. Phys. J. C. 81 (2021) 537

Studies of di-Hig… g. The measure-
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- ATLAS Higgs prospects at the HL-LHC, ten years ago

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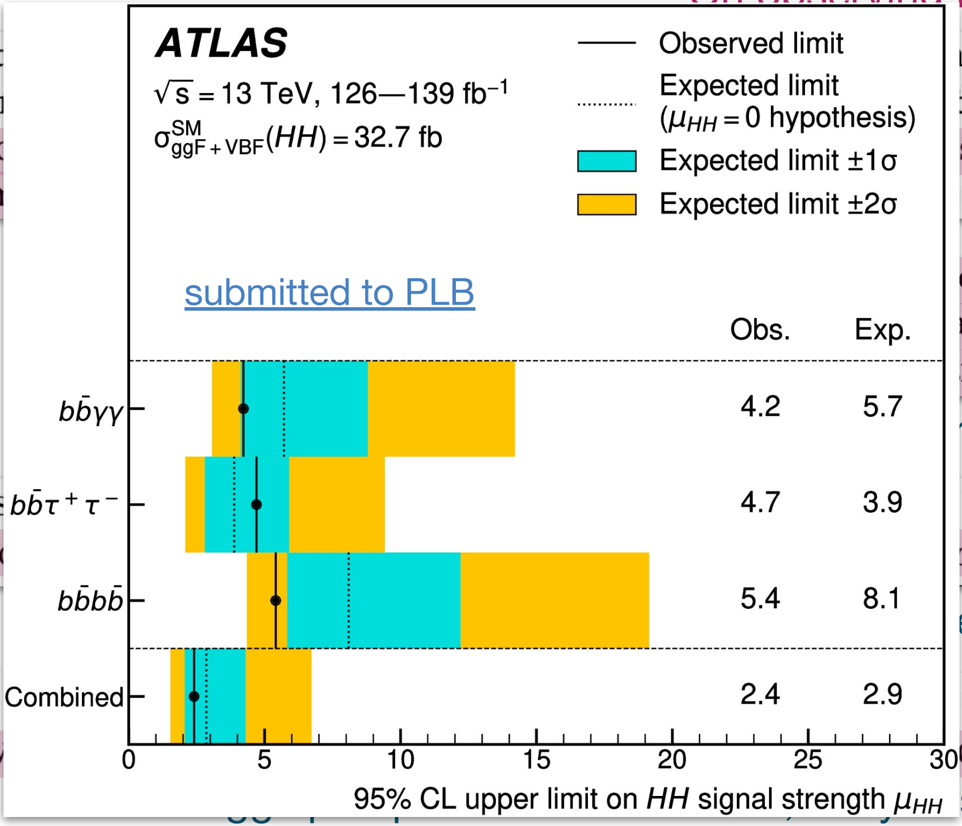
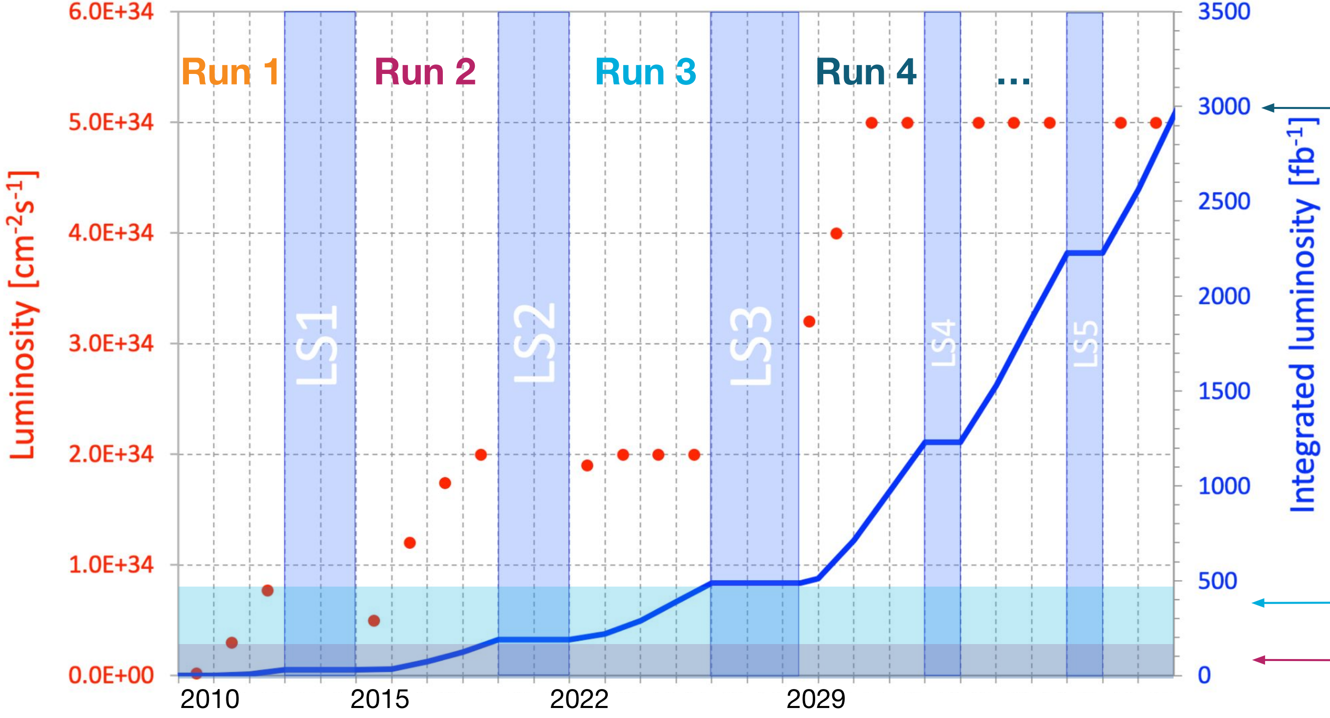


LHC proton-proton dataset



Total HL-LHC dataset (3000 fb^{-1})

Run 3: ~10% of total dataset collected

Run 2: ~5% of total dataset collected

↑ Higgs discovery

↑ Start of HL-LHC operations

lhc-commissioning.web.cern.ch

Why am I talking about the HL-LHC?

- **This session is on "future" colliders -- the HL-LHC doesn't start until 2029**
    - "We have a perfectly good collider at home"
    - We have large upgrades to build and commission
- **The HL-LHC will operate for the next twenty years**
    - How can we make the best possible use of the full LHC dataset?
    - How can we make sure to collect the best possible data?
- **The eventual HL-LHC reach will inform what the next machine will need to do**
    - We've seen huge improvements already in our analysis techniques and data collection methods

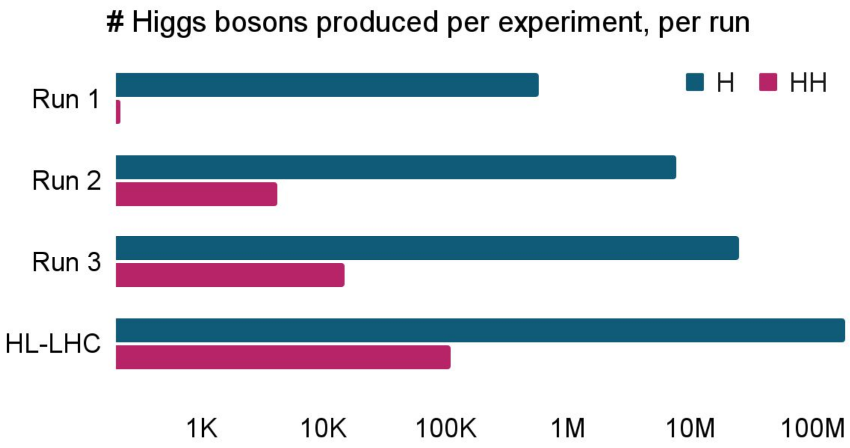
What do we want to learn at the HL-LHC?

- A detailed exploration of the mechanism of electroweak symmetry breaking through the properties of the Higgs boson
- Extend Standard Model Measurements
- Searches for New Physics
- Measurements of the properties of any newly-discovered particles

We found the Higgs, what now?

A detailed exploration of the mechanism of electroweak symmetry breaking through the properties of the Higgs boson, including:

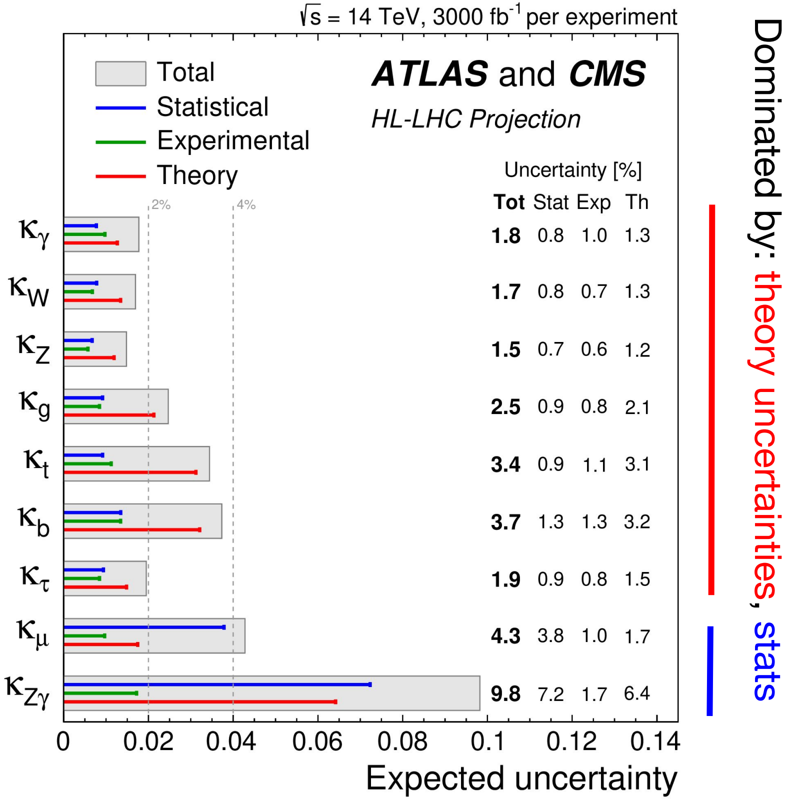
- Couplings to other SM particles, mass, and width
- Rare decays
- HH cross section and trilinear self-coupling
- Connections to new physics through Higgs sector?



Cross sections from the LHC Higgs Working Group

Higgs couplings @ HL-LHC

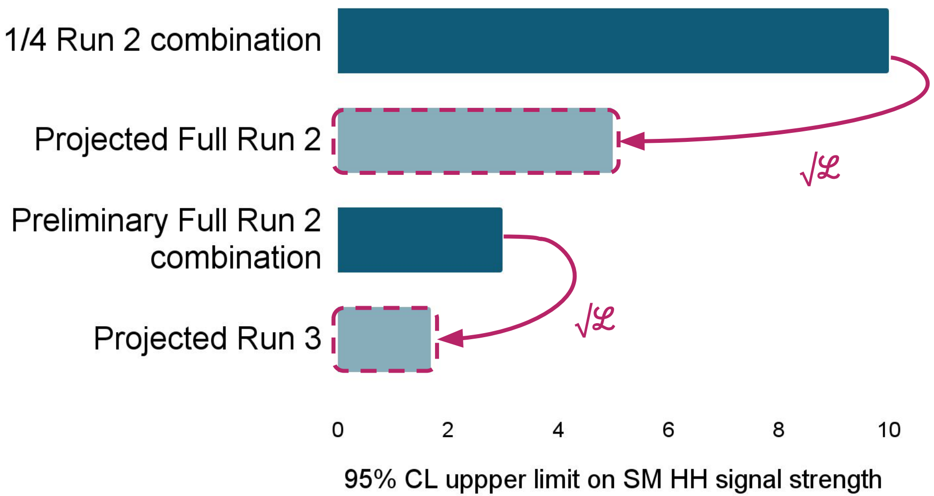
- **Higgs couplings move into precision regime**
  - those not dominated by statistical uncertainty will be known at few-% level
  - most dominated by theory uncertainties
- **More difficult to access at the HL-LHC:**
  - Higgs coupling to charm
  - Higgs coupling to invisible
  - Higgs self-coupling
  - Higgs coupling to BSM particles?



CERN-2019-007

Higgs pair production is rare at the LHC...

...1000x more rare than single Higgs production. HH searches are stats-limited.



We've already seen a factor of ~1.7 improvement due to improved reconstruction and analysis techniques in full Run 2 dataset (compared to simple projection based on √ℒ)

SM expectation within reach for Run 3 limits if we:

- Continue the same pace of analysis improvements, or
- Combine ATLAS+CMS results

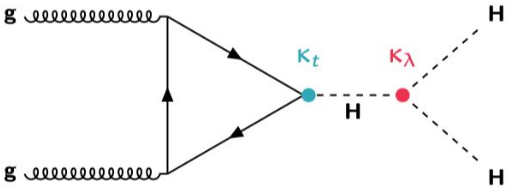
HH projections for the HL-LHC

Latest public projection: “We will need the full HL-LHC dataset (20x more data than we have now!) to measure the HH cross section”

- The 2019 Yellow Report projects that we’ll get to **~4.0σ** on the HH cross section with the HL-LHC dataset

  (we believe now this is conservative, based on more recent HH results !)

- Implies the need for a new, combined projection



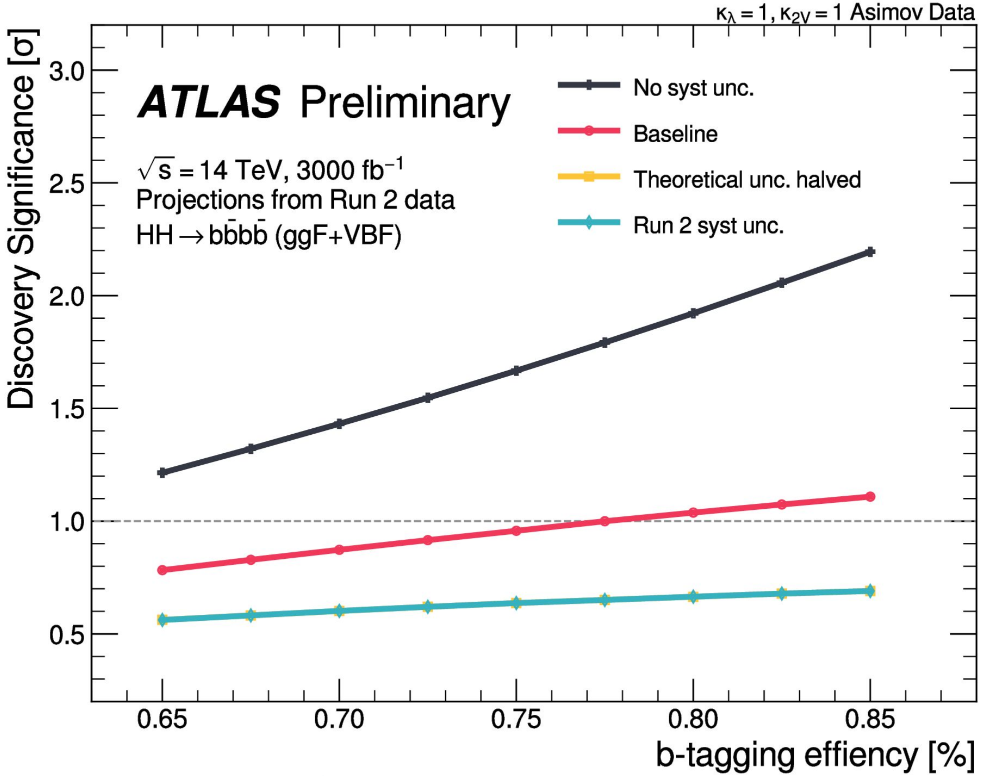
Uncertainty on the value of the self-coupling: 50%

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

[CERN Yellow Report: Higgs physics at the HL-LHC and HE-LHC]

How can we continue to improve?

- **We need to continue to improve:**
  - **Detectors themselves**
  - **Trigger menu and hardware**
  - **Event reconstruction**
  - **Software & computing**
  - **Physics analysis techniques**

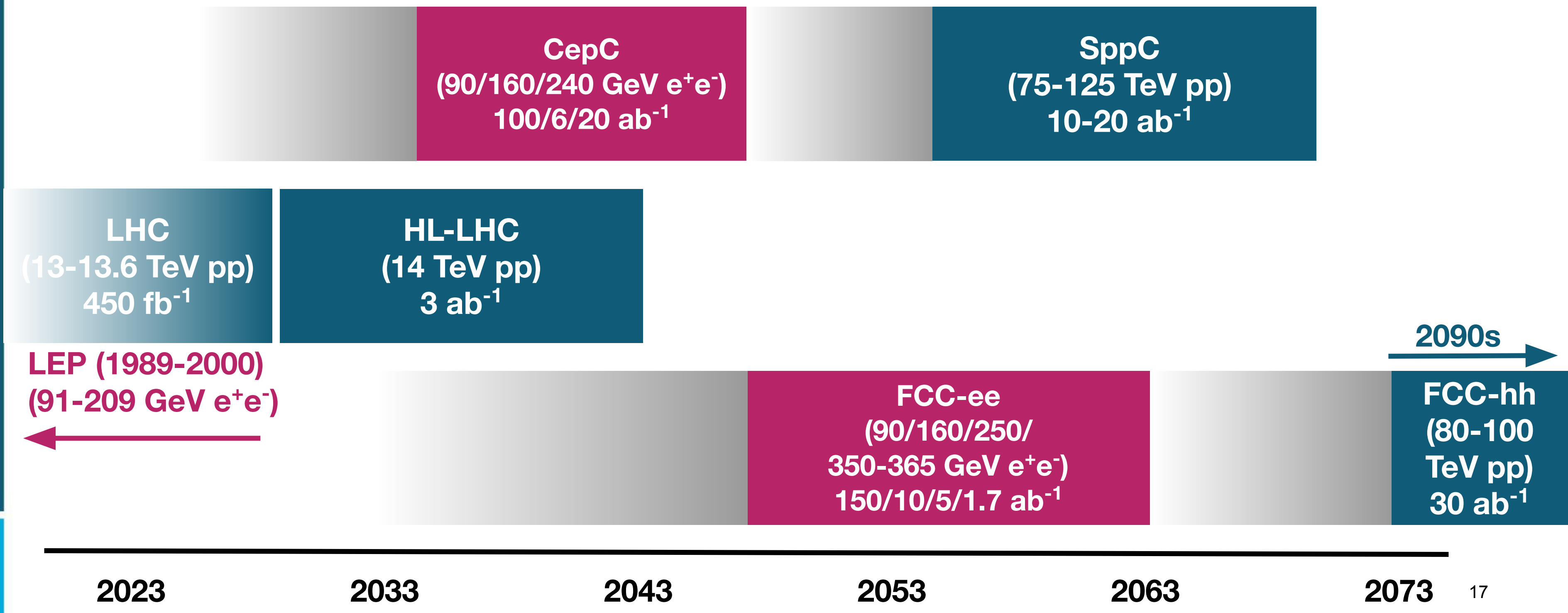


ATL-PHYS-PUB-2022-053

Timeline (“next 50 years”)

Adapted from the [Snowmass Energy Frontier Report]

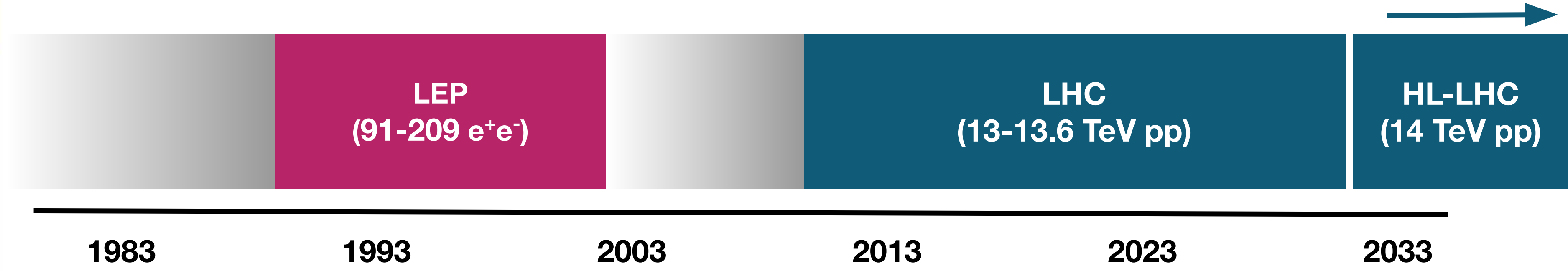
Collider-In-The-Sea
(500 TeV pp)



Circular colliders in the next 50 years

“had so much fun let’s do it again”

LEP→LHC



- Six years at the Z mass (4.5 million Zs per experiment)
- Five years at WW
- Highest center-of-mass energy achieved: 209 GeV
  - Just missed the Higgs
- LHC continues to follow up on open questions
  - Found the Higgs at the LHC!
  - Excesses

LEP ... LHC

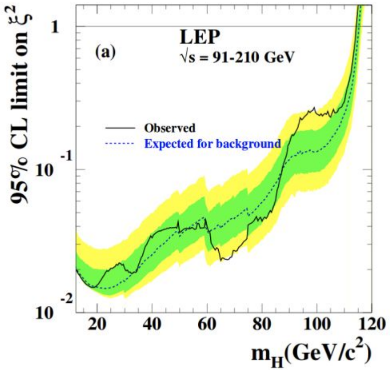
1983 ... 2033

HL-LHC (14 TeV pp)

- Si...
- Fi...
- Hi...
  - ○ ...
- LH...
  - ○ ...

The 95GeV excesses

Karlsruher Institut für Technologie

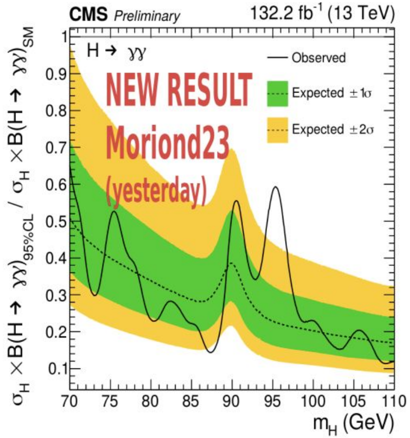


[LEP: hep-ex/0306033]

Local significance: 2.3σ

Extracted signal strength:
$\mu_{bb}\left(e^+e^- \to Zh \to Zb\bar{b}\right) = 0.117 \pm 0.057$

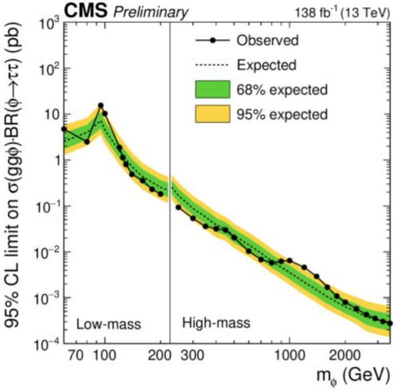
[Cao, Guo, He, Wu, Zhang: 1612.08522]



[CMS HIG-20-002]

Local significance: 2.9σ

Extracted signal strength:
$\mu_{\gamma\gamma}\left(gg \to h \to \gamma\gamma\right) \approx 0.35$



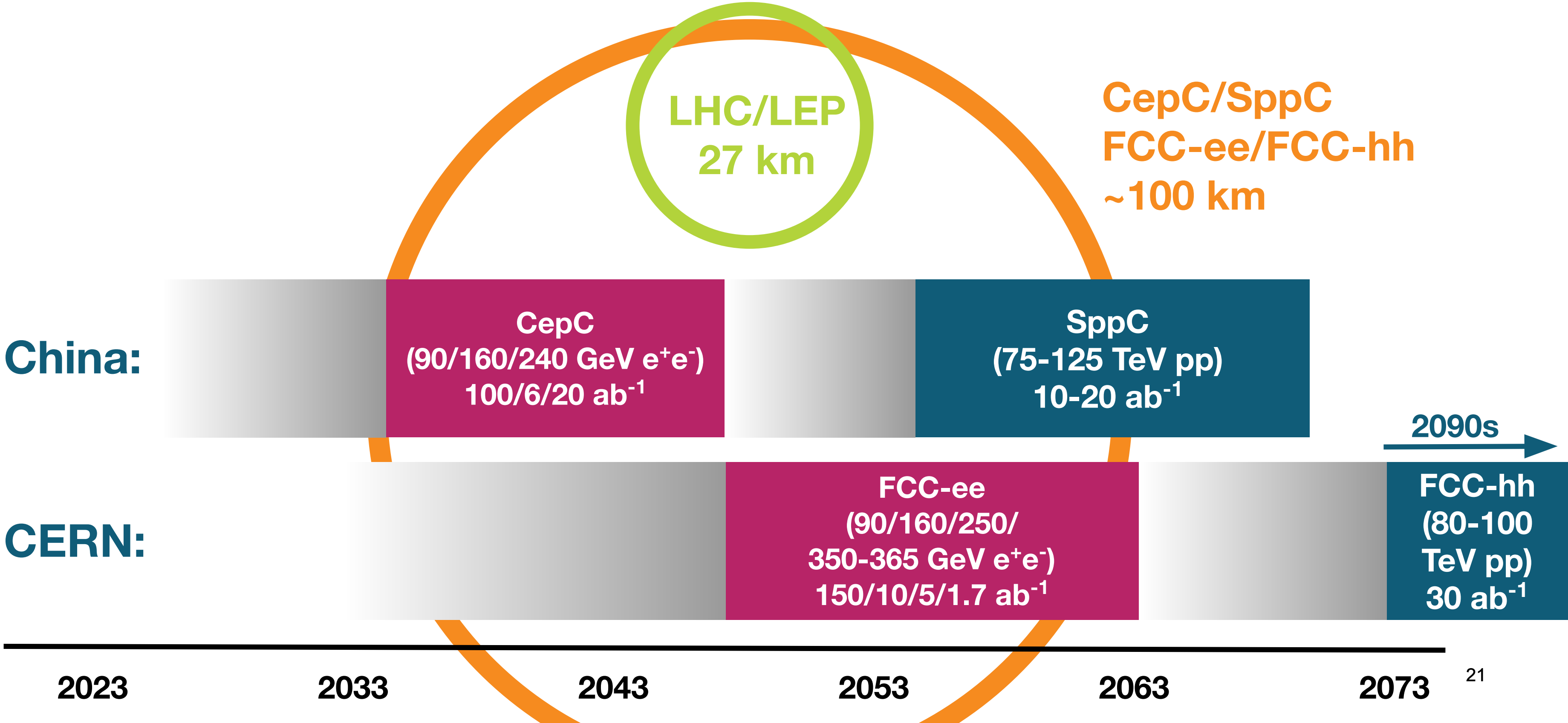
[CMS: 2208.02717]

Local significance: 3.1σ

Extracted signal strength:
$\mu_{\tau\tau}\left(gg \to h \to \tau^+\tau^-\right) = 1.2 \pm 0.5$

[CMS: 2208.02717]

“had so much fun let’s do it again”



Can we have a e^+e^- Higgs factory?

The Higgs/EW factories centered on 240-250 GeV energy are not very challenging from the point of view of energy, but they are high-precision machines and luminosity will be the main figure of merit. Therefore, the focus of the R&D effort should be on how to make these colliders more compact, reducing the cost, and to assure the highest possible integrated luminosity within reasonable site power limits and duration of operation.

Snowmass Accelerator Frontier Report

Detector challenges:

- Jet energy resolution for W/Z separation
- Impact parameter resolution for b/c-tagging
- Momentum resolution "as good as possible" for EW precision
- Particle ID (for example, π^0/γ separation) for flavor physics

FCC-ee (4 IPs)

Z (88-95 GeV) $150\ ab^{-1}$	W (158-162 GeV) $12\ ab^{-1}$	H (240 GeV) $5\ ab^{-1}$	ttbar (345-365 GeV) $1.5\ ab^{-1}$

- **4 yrs @ Z (LEP1 data accumulated every 2 minutes - 10^{13} Z)**
  - Z mass, width, electroweak precision measurements, flavor
- **2 yrs @ WW (10^8 W)**
  - W mass, W width, electroweak precision measurements
- **3 yrs @ H (10^6 $e^+e^- \rightarrow ZH$)**
  - Model-independent Higgs xs, Higgs couplings, Higgs self-coupling input
- **5 yrs @ ttbar (10^6 ttbar pairs)**
  - Top mass, top width, WW→H, Higgs self-coupling input
- **s-channel H? (5000 $e^+e^- \rightarrow$ H in 5? years)**

CepC (2 IPs)

- 7 yrs @ H (10^6 $e^+e^- \to ZH$)
- 2 yrs @ Z (10^{12} Z)
- 1 yr @ WW (10^8 W)

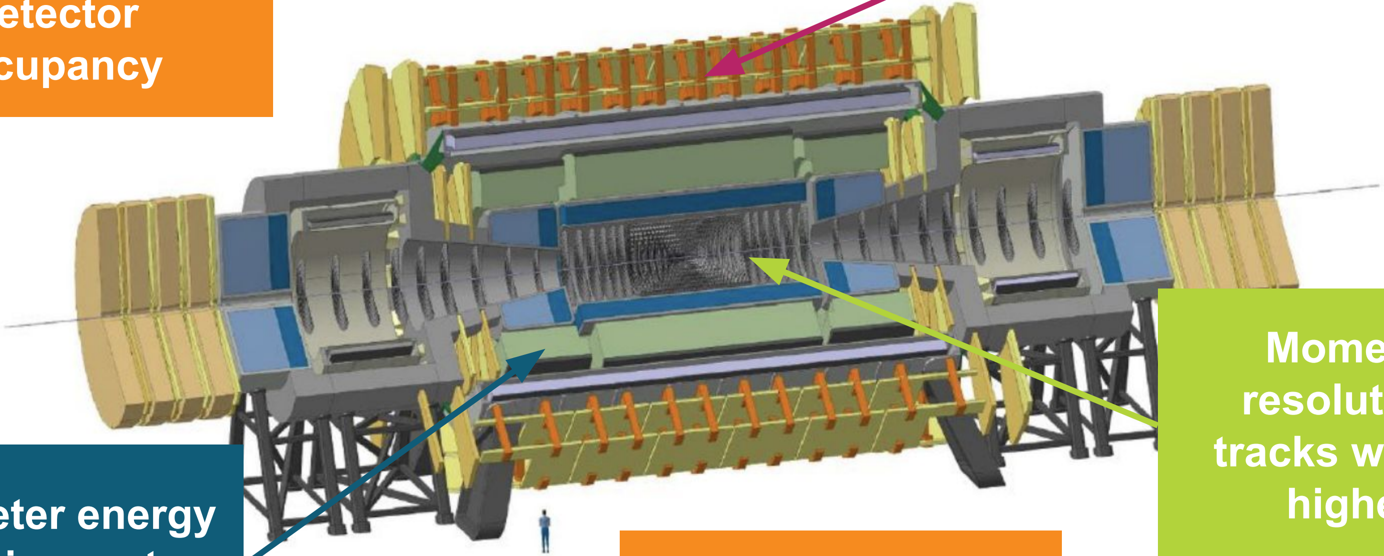
Next step: High-energy pp colliders

- **FCC-hh (~100 TeV, 30*10^{34} $cm^{-2}s^{-1}$)**
  - Reuse FCC-ee tunnel
  - Needs: 16-17T superconducting magnets → 20 years dev needed
    - Note: getting all the way to 100 TeV in the currently-planned 91km ring requires nearly 18T
  - 14T/80 TeV-- an easier plan (citation: AF summary, SLAC P5 town hall)
- **SppC (75-125 TeV)**
  - Reuse CepC tunnel
  - Needs: 12T (75 TeV), 20T (125 TeV) magnets
  - Proposed iron-based high temperature superconductor magnets for first stage

100 TeV pp colliders: detector challenges

Muon resolution

Detector occupancy



Momentum resolution for tracks with ~10x higher p_T

Calorimeter energy resolution: gets better with energy

4π coverage

100 TeV pp colliders: detector challenges

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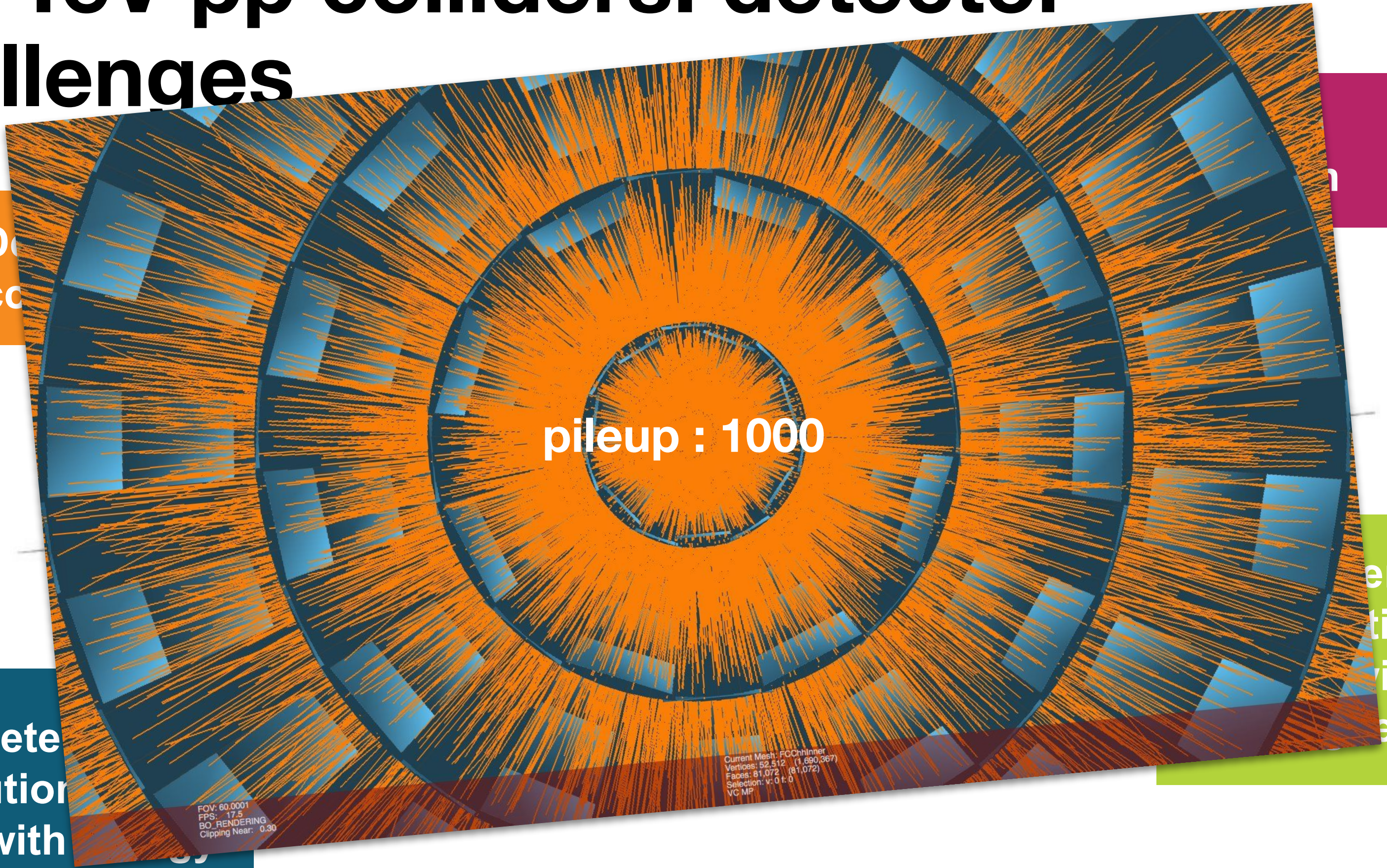
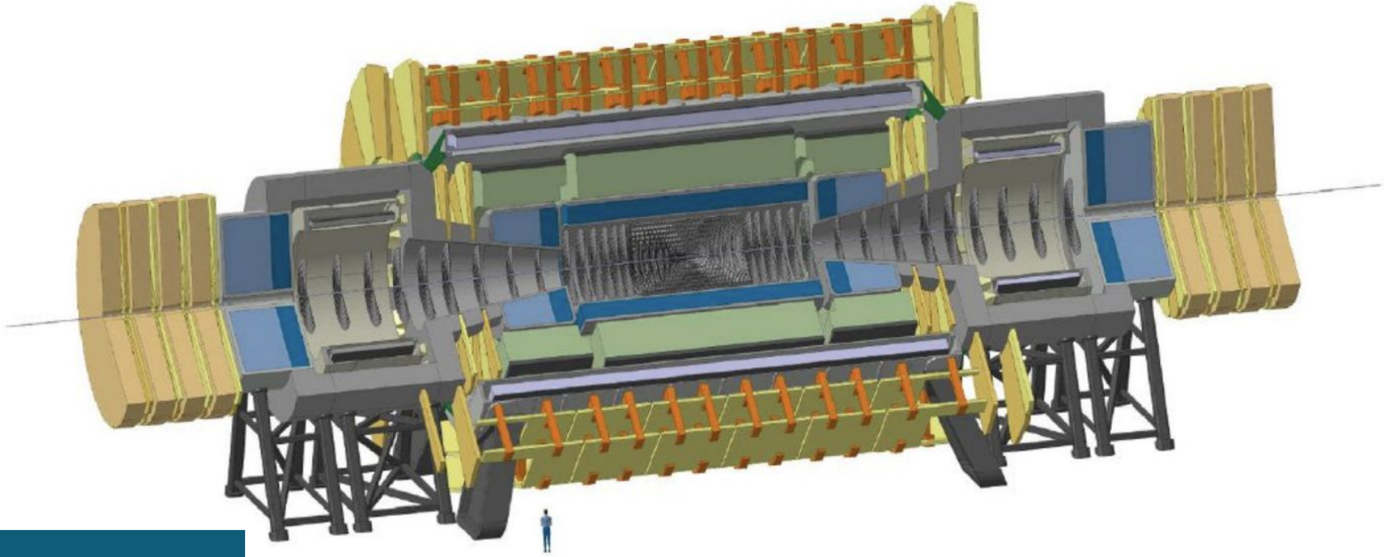


100 TeV pp colliders: detector challenges

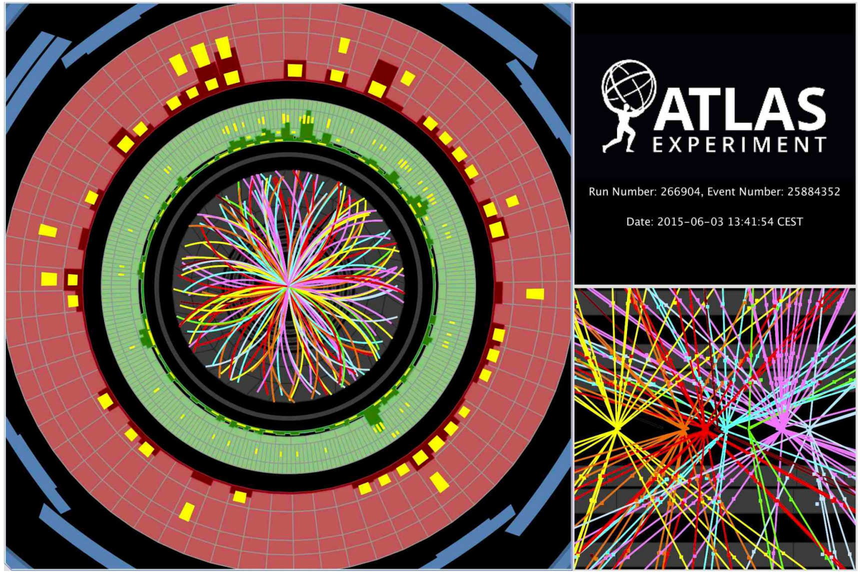
Radiation tolerant

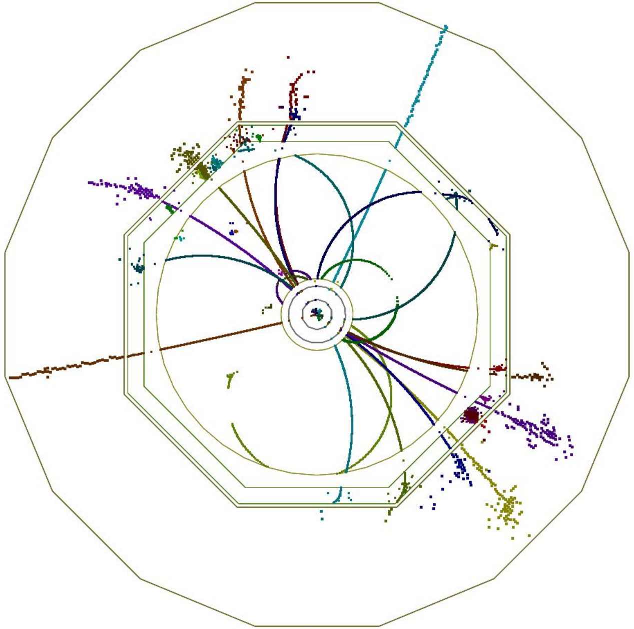


Excellent pileup discrimination

Physics at colliders in the next 50 years

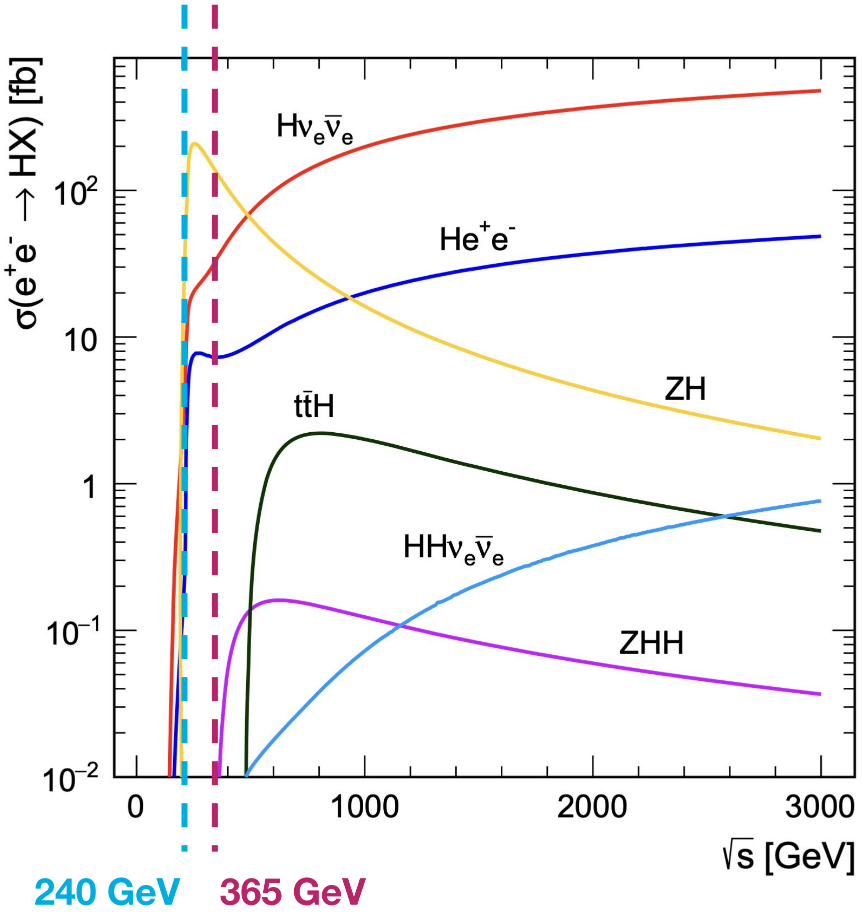
proton-proton vs electron-positron collisions





Higgs @ e^+e^-

- **Major goals of the Higgs Factory physics programs:**
  - model-independent measurement of the Higgs width
  - Higgs couplings to sub-percent precision
- **Higgs pair production:**
  - Only above ~500 GeV

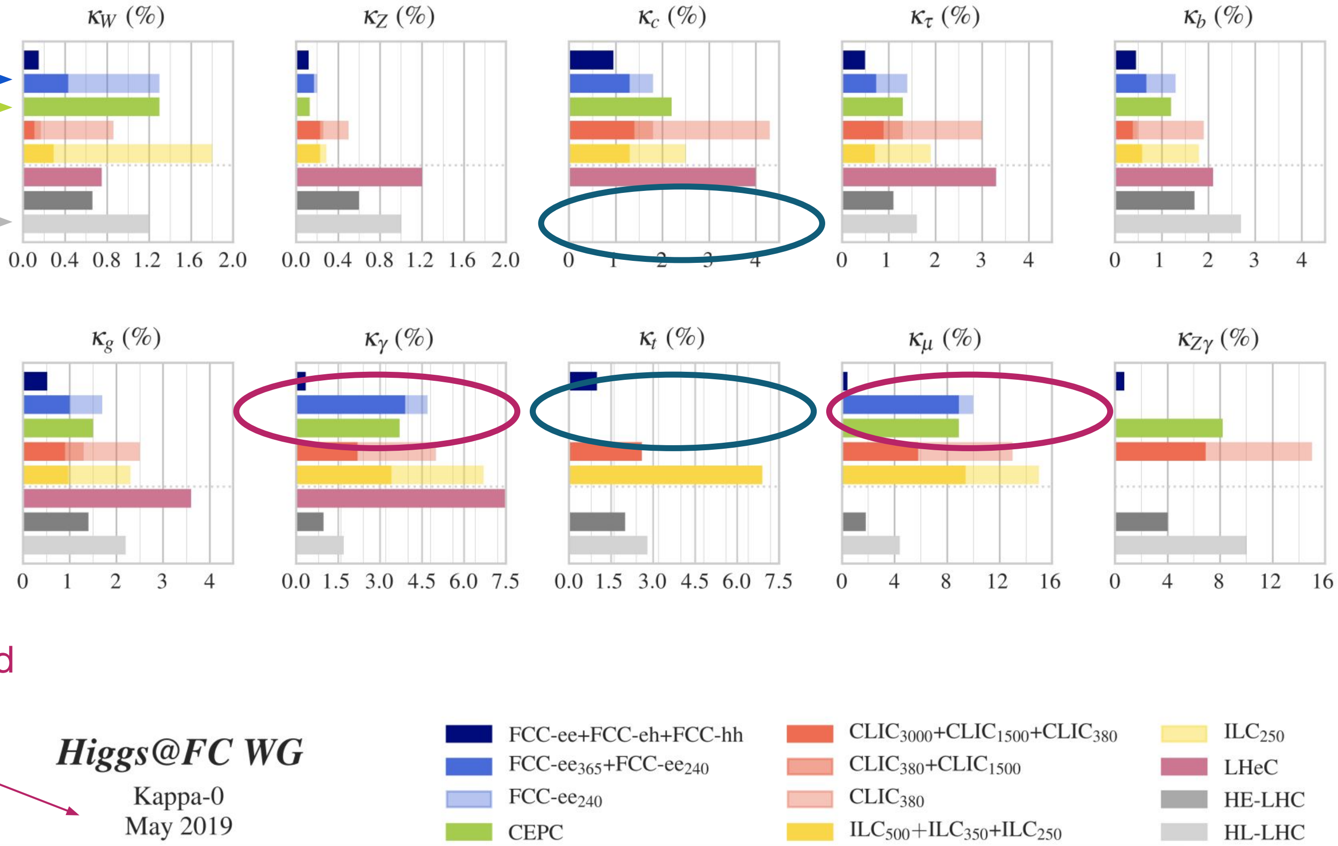


Higgs couplings at future colliders

FCC-ee

CepC

HL-LHC



kappa-0 = not combined with HL-LHC

Higgs Boson studies at future particle colliders, 2019

What precision do we *need* on the Higgs self-coupling?

- **Is 50% at the HL-LHC enough?**
  - Depends which models you would like to study
- **Motivates future colliders**
  - “**The goal for future machines beyond the HL-LHC should be to probe the Higgs potential quantitatively. This requires at least gold quality precision for the self-coupling parameter.** … achievable … at the highest energy lepton machines (ILC_{1000} or $CLIC_{3000}$) and hadron machines (FCC-hh)”

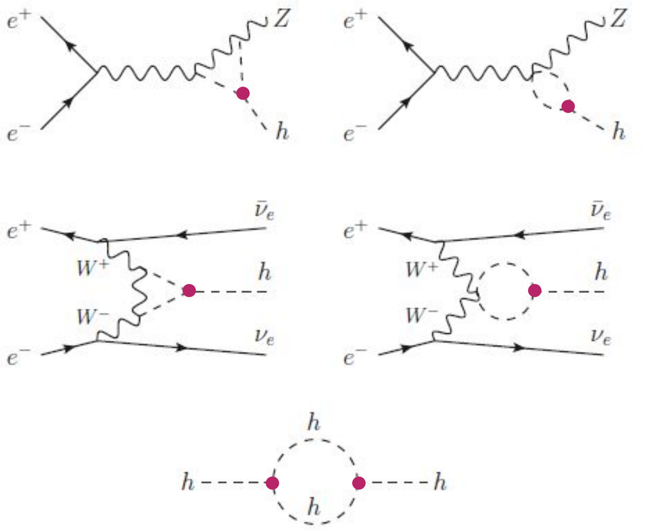
- **Bronze (100%):** sensitive to models with the largest new physics effects
- **Silver (25-50%):** can exclude a physical hypothesis with realistic deviations in the Higgs self-coupling
- **Gold (5-10%):** sensitive to a broad class of loop diagram effects… could complement measurements on new particles that could be discovered at the HL-LHC.
- **Platinum (1%):** sensitive to typical quantum corrections to the Higgs self-coupling generated by loop diagrams.

HH White Paper 2018 arXiv:1910.00012

Brookhaven National Laboratory

How to indirectly measure the self-coupling at a 240 GeV Higgs Factory?

- The FCC-ee self-coupling measurement depends mainly on measurements of the ZH and WW→H production cross sections and Higgs decays to boson pairs (ZZ and WW)
    - For example, if $\kappa_\lambda = 0$, ZH cross section increases by ~1.5% at 240 GeV
- The ZH cross section, which will be measured at an energy of ~240 GeV, is most sensitive to changes in the self-coupling, but reductions in uncertainties on other parameters, from a ~350 GeV energy run, are necessary for achieving the final precision



How to indirectly measure the self-coupling at a 240 GeV Higgs Factory?

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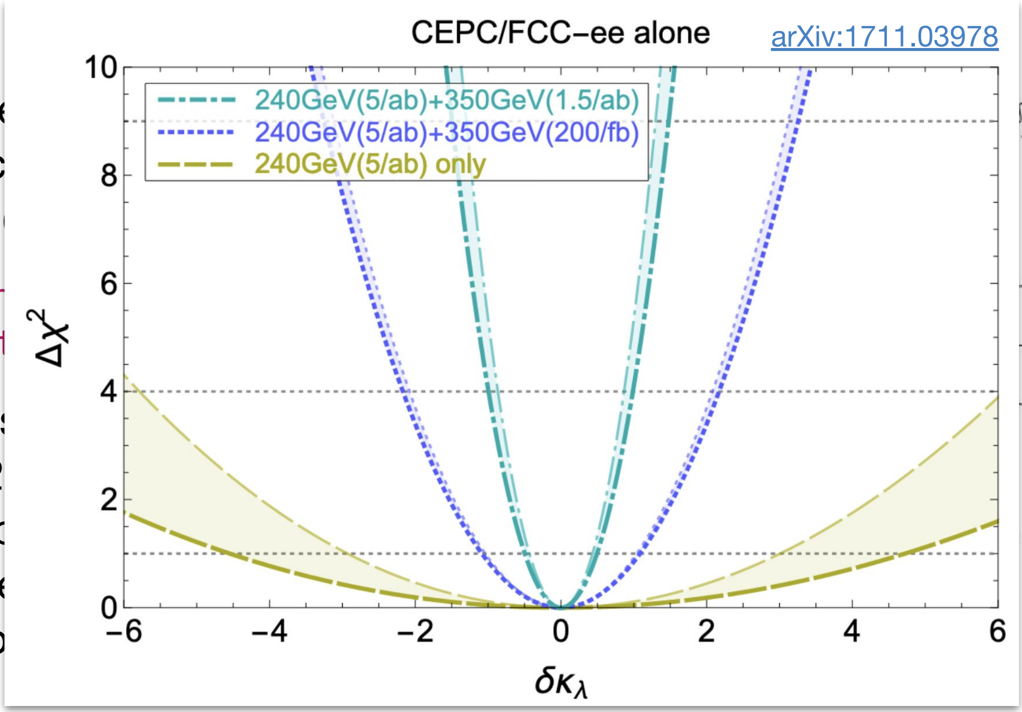

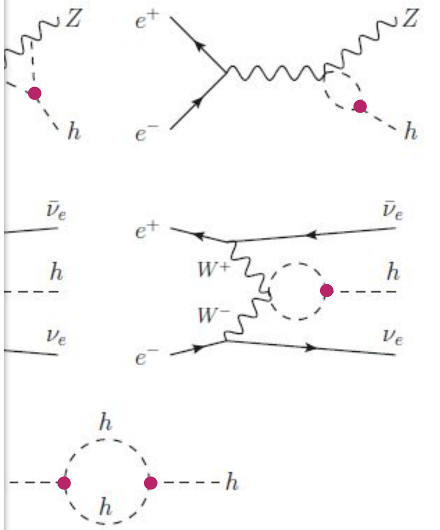

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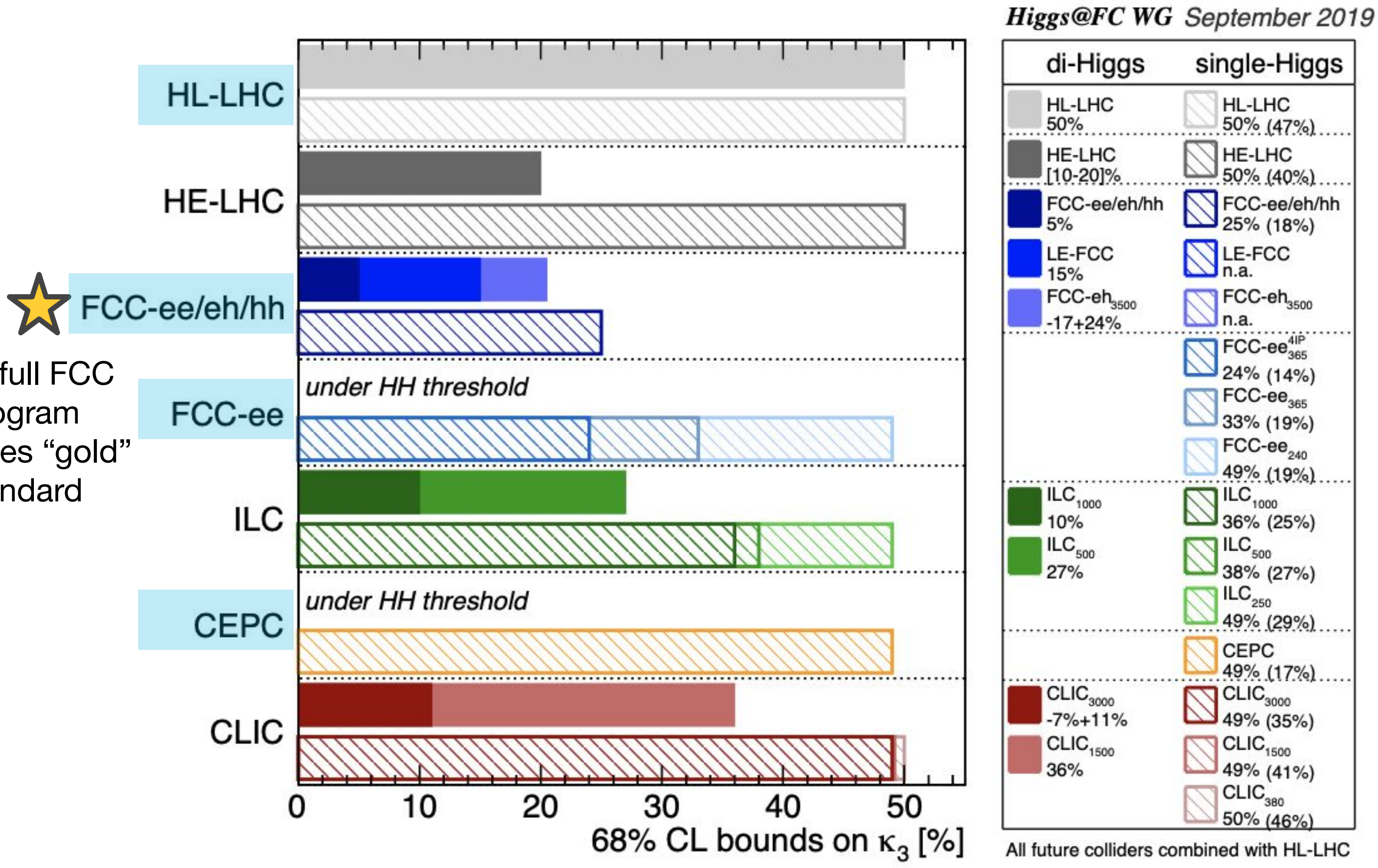
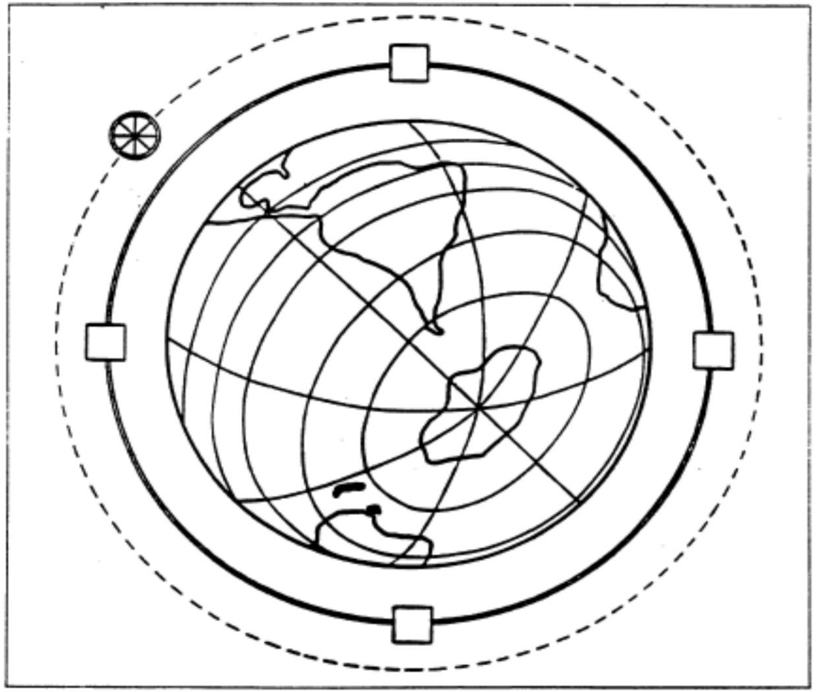
Only full FCC program achieves "gold" standard



Conclusions

- **Wrap up HL-LHC physics program**
- **Circular Higgs factories:**
  - + Rate of lumi accumulation
  - - Large footprint, power consumption
- **Strengthen and expand education and training programs**
  - Improve US participation
- **Study environmental impact of future collider choices**

Globaltron (3-5 PeV pp), 40,000 km



From a 1954 Slide by Enrico Fermi, University of Chicago Special Collections.

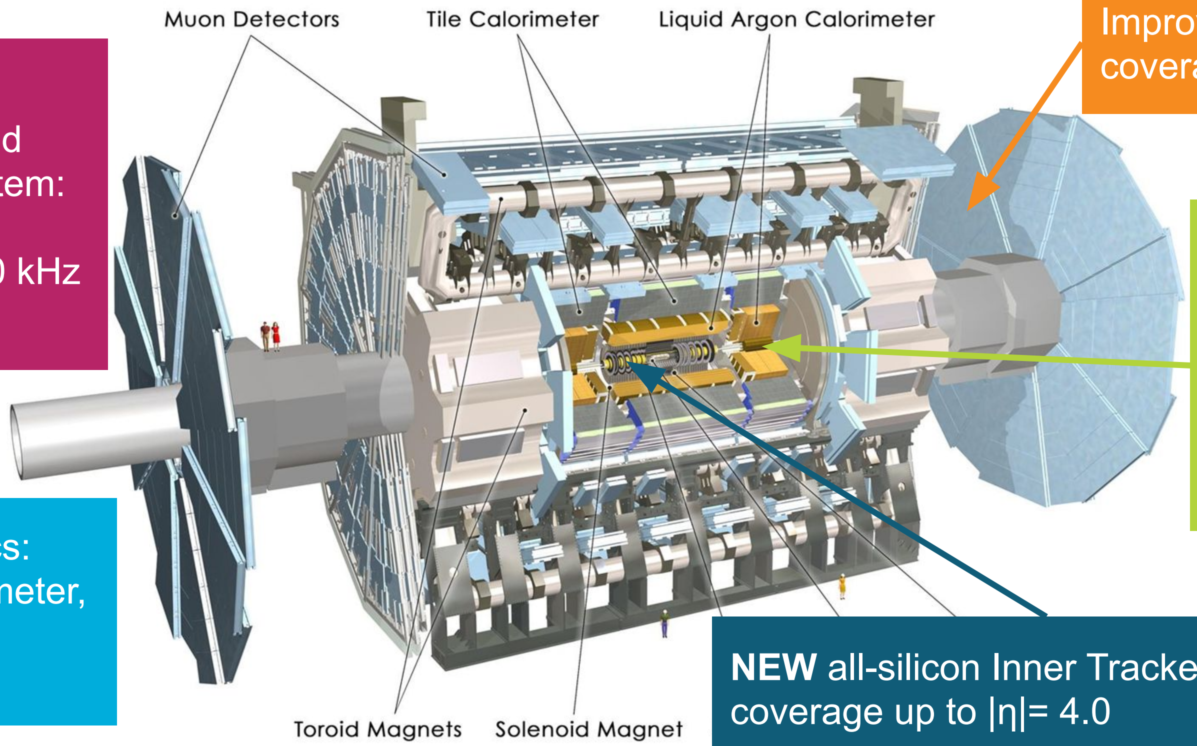
Backup

ATLAS Detector Upgrade

Upgraded Trigger and Data Acquisition system:

- L0 rate: 1 MHz
- Event Filter: 10 kHz

Upgraded electronics:
Liquid Argon Calorimeter,
Tile Calorimeter,
Muon system



Improved muon coverage and trigger

NEW endcap high - granularity timing detector

NEW all-silicon Inner Tracker, coverage up to $|\eta|= 4.0$

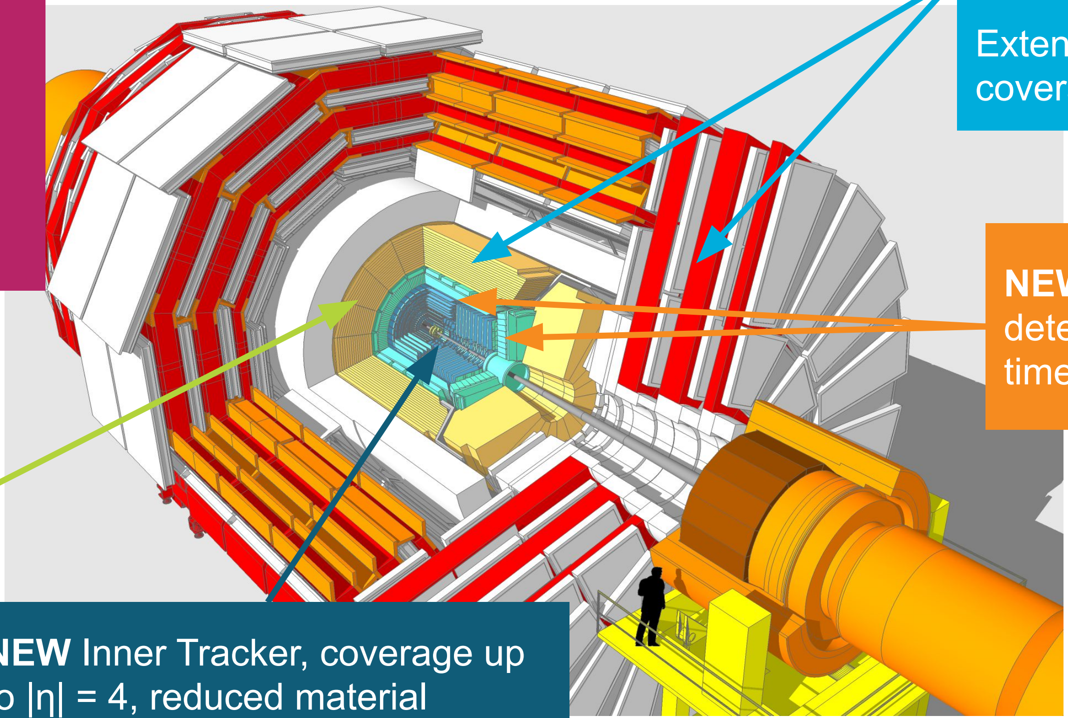
CMS Detector Upgrade

Upgraded Trigger and Data Acquisition system:

- Add tracks at L1 (1 MHz)
- High Level Trigger output 7.5 kHz

Electronics upgrade: barrel calorimeters and muon system

Extended muon coverage to |η| ~ 2.8



NEW MIP timing detector with 30 - 50 ps time resolution

NEW
High-granularity calorimeter endcap

NEW Inner Tracker, coverage up to |η| = 4, reduced material

ERL

Energy Recovery and Recirculating Linacs (ERLs and RLAs). Linac-based and circular colliders with energy recovery are an alternative approach to high energy electron-positron colliders with the aim to significantly reduce beam energy losses and consequently, power consumption. There are two proposed configurations. A circular e^+e^- collider with two 100 km storage rings using Energy-Recovery Linacs (CERC) [36] [37] or two large linear colliders with damping rings, a Linear Energy Recovery Linac Collider (ReLiC) [38] and an ERL-based linear e^+e^- collider ERLC [39]. Starting as a Higgs factory they have the capability of achieving c.m. energies up to 600 GeV. The energy as well as the particles are recycled in this scheme and make fully polarized electron and positron beams possible. A large fraction of the energy of the used beams is recovered by decelerating them. The beams are then reinjected into a damping ring where they are cooled and reused. Beam that is lost during the recovery process is replaced via a linear injector into the damping rings.

ERL's are currently in a process of technological development. A number of compact ERL facilities and demonstrators have been constructed. The highest circulating Continuous Wave (CW) power was achieved in the IR FEL ERL at Jefferson Laboratory that operated with 8.5 mA at 150 MeV. A global development program for the ERL technology is discussed in [40].

Snowmass Accelerator Frontier Report

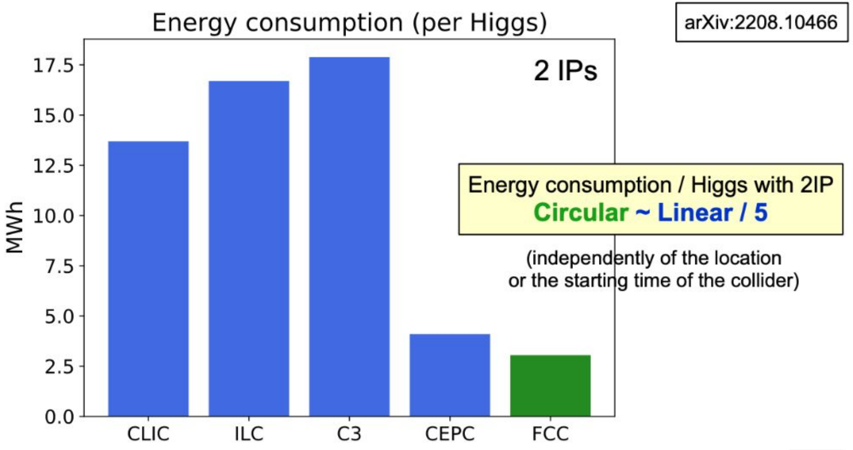
Power?

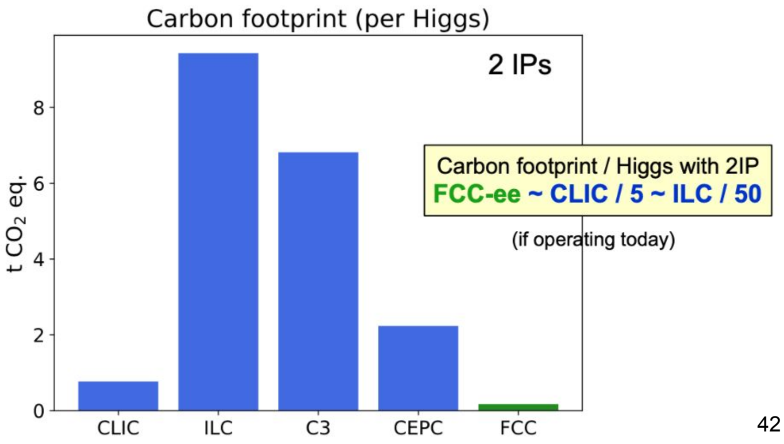
(see also FACT2022-FRXAS0101)

Higgs factory $\sqrt{s}$ (GeV)	CLIC 380	ILC 250	C^3 250	CEPC 240	FCC-ee 240
Instantaneous power P (MW)	110	140	150	340	290
Annual collision time T (10^7 s)	1.20	1.60	1.60	1.30	1.08
Operational efficiency ϵ (%)	75	75	75	60	75
Annual energy consumption E (TWh)	0.4	0.7	0.8	1.6	1.0

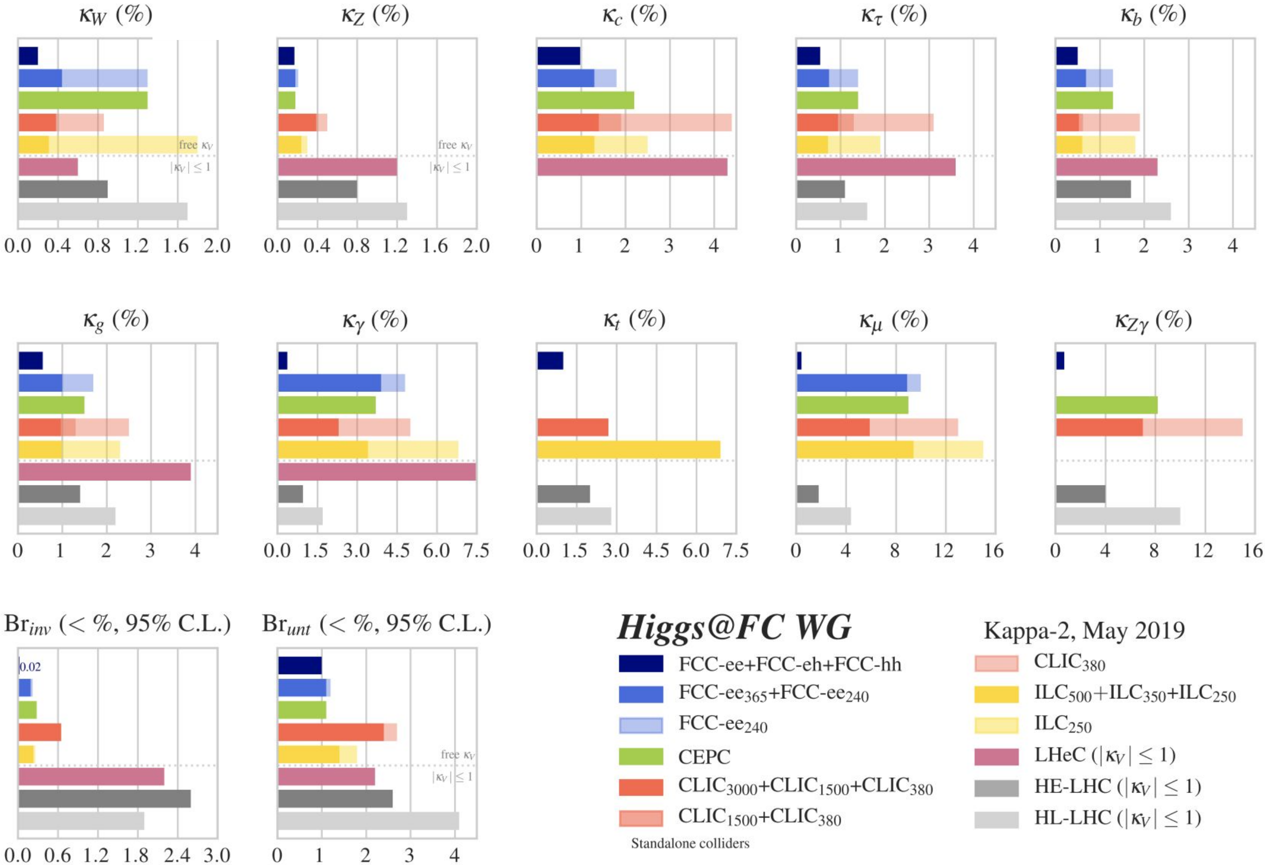
The Snowmass'21 Implementation Task Force collected the power (in MW) of each Higgs factory (arXiv:2208.06030) …

… from which the annual energy consumption during operation as a Higgs factory can be inferred consistently (arXiv:2208.10466)





Higgs couplings at future colliders



Higgs Boson studies at future particle colliders, 2019