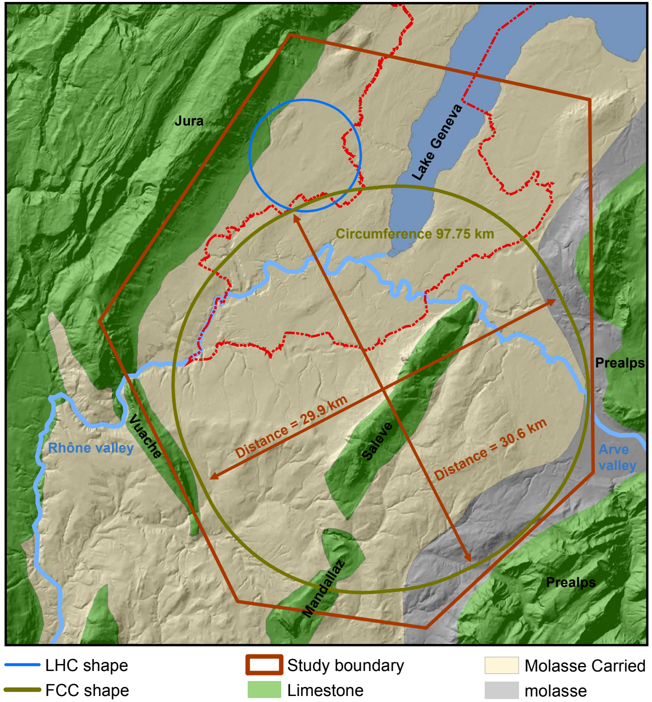
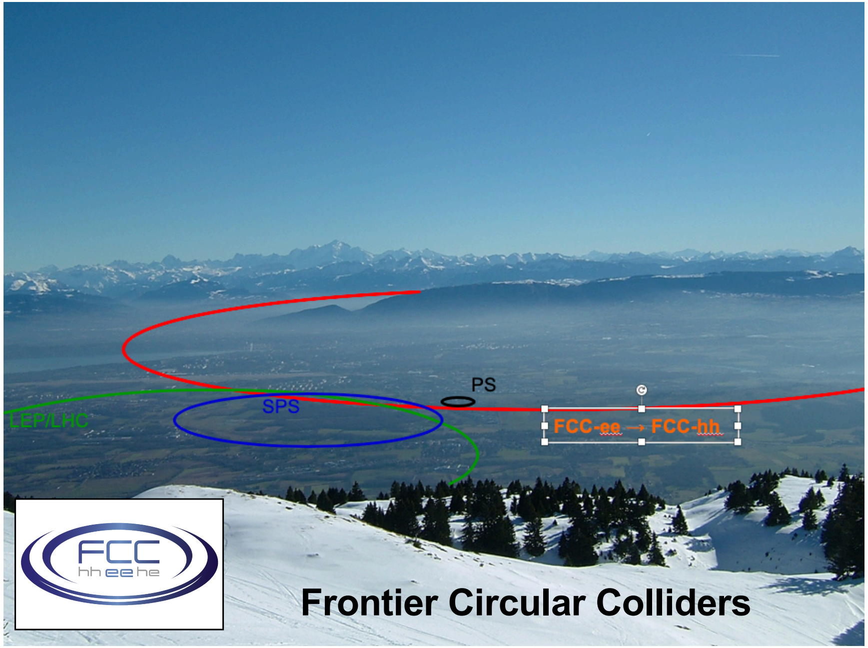
FCC : Physics and Experiments



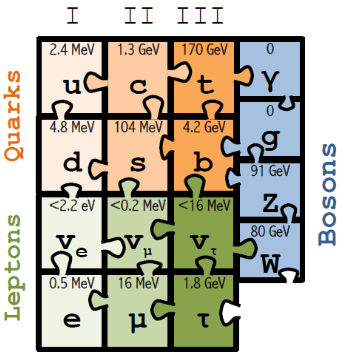


See F. Zimmermann's presentation for the colliders' description

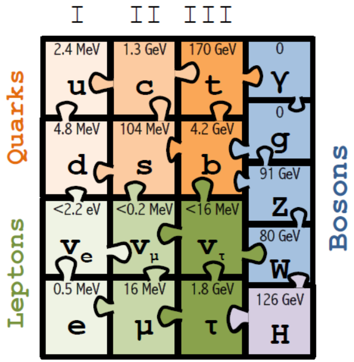
The Physics Landscape

- **Particle Physics has arrived at an important moment of its History**

1989-1999:
- Top mass predicted
  (LEP m_Z and Γ_Z)
- Top quark observed
  at the right mass
  (Tevatron, 1995)
- Nobel Prize 1999
  (t'Hooft & Veltman)



1997-2013:
- Higgs mass cornered
  (LEP EW + Tevatron m_{top}, m_W)
- Higgs boson observed
  at the right mass
  (LHC 2012)
- Nobel Prize 2013
  (Englert & Higgs)



- **It looks like the Standard Model is complete and consistent theory**
- **It describes all observed collider phenomena – and actually all particle physics (except neutrino masses)**
  - **Was beautifully verified in a complementary manner at LEP, SLC, Tevatron, and LHC**
  - **EWPO radiative corrections predicted top and Higgs masses assuming SM and nothing else**
- **With m_H = 125 GeV, it can even be extrapolated to the Plank scale without the need of New Physics.**

- **Is it the END ?**

Why new collider(s) / experiments?

- We need to extend mass & interaction reach for phenomena that SM cannot explain
  - Dark matter
    - SM particles constitute only 5% of the energy of the Universe
  - Baryon Asymmetry of the Universe
    - Where is anti-matter gone?
  - Neutrino Masses
    - Why so small? Dirac/Majorana? Heavier right-handed neutrinos? At what mass?

These facts require Particle Physics explanations

We must continue our quest, but HOW ?

- Efficient experimental ways include
  - Direct search for and observation of new particles (with any mass and any coupling to SM particles)
  - Observation of new phenomena (such as neutrino oscillations, CP violation …)
  - Measurements of small deviations from precise predictions (such as top and Higgs mass predictions from loops)

What collider?

- We are in a fascinating situation
  - There is no experimental hints as to the origin of these observed (unexplained) phenomena
  - There is no theoretical hints that would point to one direction more than another

For the first time since Fermi theory

We have no clear energy scale for new physics

We don't know its coupling strength to SM particles

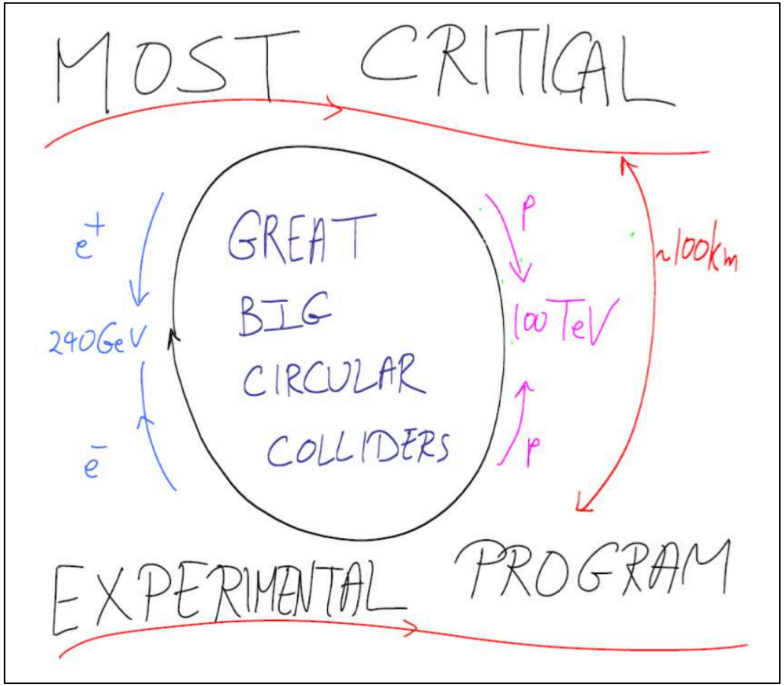
- The next facility must be versatile
  - With a reach as broad and as powerful as possible – as there is no specific target

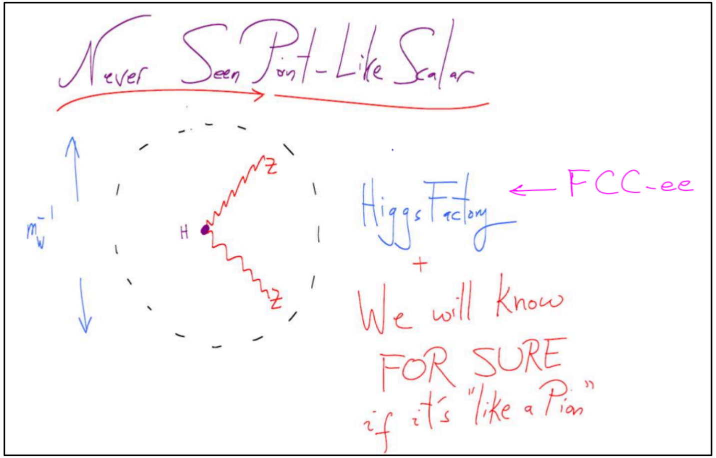
More SENSITIVITY, more PRECISION, more ENERGY

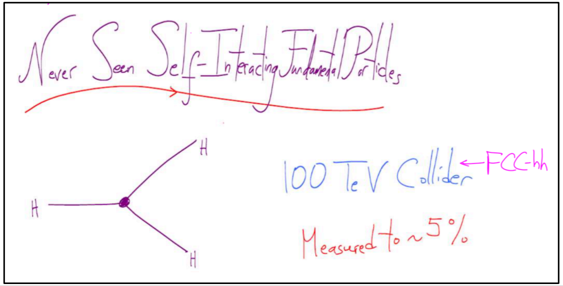
- Frontier Circular Colliders (FCC) offer the most adapted response to this situation
  - Largest luminosity, highest parton energy, synergies and complementarities between ee and pp, etc.

A concrete target: The Higgs boson

- Nima's vision (FCC week 2019)

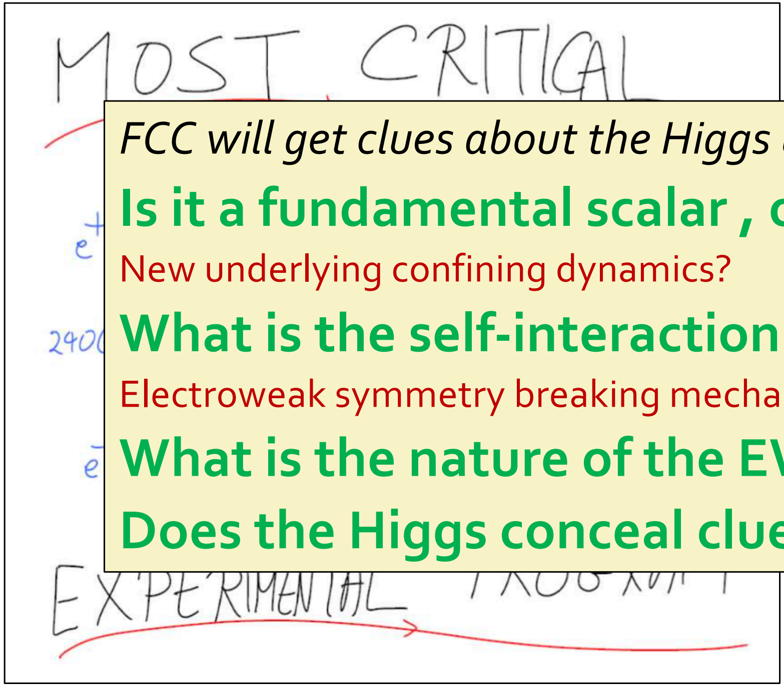


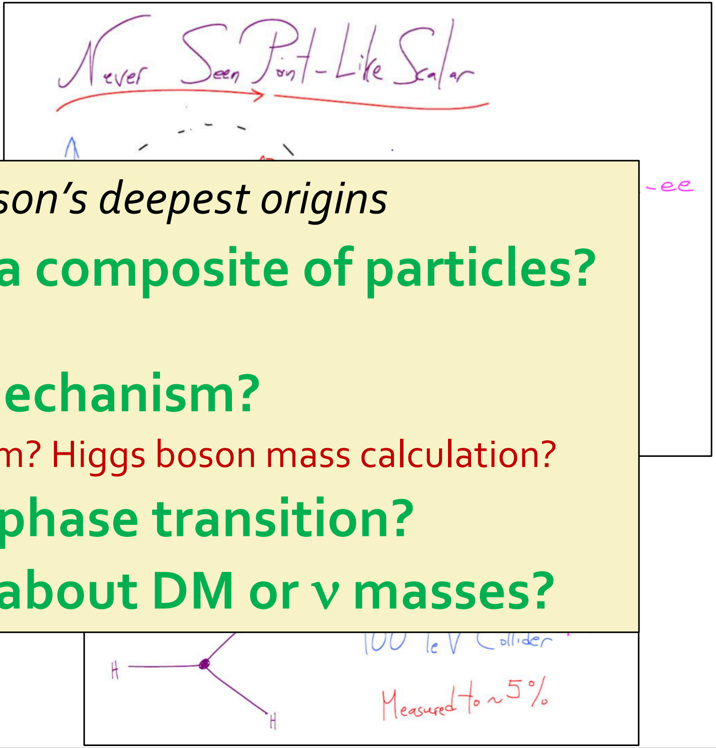




A concrete target: The Higgs boson

- **Nima's vision (FCC week 2019)**





FCC will get clues about the Higgs boson's deepest origins

Is it a fundamental scalar , or a composite of particles?

New underlying confining dynamics?

What is the self-interaction mechanism?

Electroweak symmetry breaking mechanism? Higgs boson mass calculation?

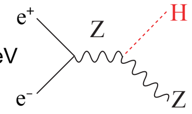
What is the nature of the EW phase transition?

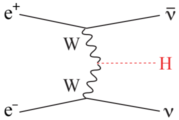
Does the Higgs conceal clues about DM or ν masses?

The Higgs boson: FCC synergies

- The FCC integrated program (ee, hh, eh) has built-in synergies and complementarities
  - It will provide the most complete and model-independent studies of the Higgs boson

√s = 240 GeV





√s = 365 GeV

FCC-ee provides 10^6 HZ + 10^5 WW → H events

Absolute determination of g_{HZZ} to ±0.17%

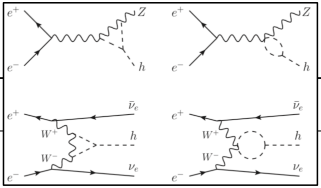
Model-independent determination of Γ_H to ±1%

→ Fixed « candle » for all other measurements including those made at HL-LHC or FCC-hh

→ Measure couplings to WW, bb, ττ, cc, gg, …

Even possibly the Hee coupling!

→ First sensitivity to g_{HHH} to ±34% (±21% with 4IP)



FCC-hh provides 3×10^{10} Higgs bosons

With this huge sample and using the FCC-ee candle

→ Model-independent ttH coupling to < 1%

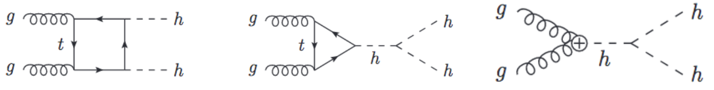
(HL-LHC and FCC-ee give ±2.6%)

Use ±1% ttZ measurement at FCC-ee

→ Rare decays: couplings to μμ, γγ, Zγ …

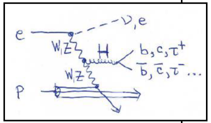
→ Higgs self coupling g_{HHH} to ±5%

With double-Higgs production



FCC-eh provides 2.5 10^6 Higgs bosons

With the FCC-ee candle, further improves on several measurements (e.g., g_{HWW})



See C. Grojean's presentation

Comparisons with other scenarios

❑ Low-energy Higgs factories

# Higgs bosons:		500k	175k	1.1M	1.3M

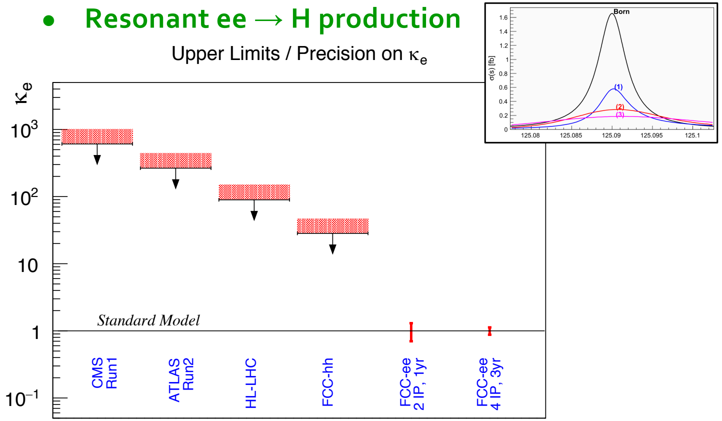
Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	$FCC\text{-}ee_{240\to365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years		11.5 [5]	8	7	3 + 1 + 4
g_{HZZ} (%)	1.5 / 3.6	0.29 / 0.47	0.44 / 0.66	0.18 / 0.52	**0.17 / 0.26**
g_{HWW} (%)	1.7 / 3.2	1.1 / 0.48	0.75 / 0.65	0.95 / 0.51	**0.41 / 0.27**
g_{Hbb} (%)	3.7 / 5.1	1.2 / 0.83	1.2 / 1.0	0.92 / 0.67	**0.64 / 0.56**
g_{Hcc} (%)	SM / SM	2.0 / 1.8	4.1 / 4.0	2.0 / 1.9	**1.3 / 1.3**
g_{Hgg} (%)	2.5 / 2.2	1.4 / 1.1	1.5 / 1.3	1.1 / 0.79	**0.89 / 0.82**
$g_{H\tau\tau}$ (%)	1.9 / 3.5	1.1 / 0.85	1.4 / 1.3	1.0 / 0.70	**0.66 / 0.57**
$g_{H\mu\mu}$ (%)	4.3 / 5.5	4.2 / 4.1	4.4 / 4.3	3.9 / 3.8	**3.9 / 3.8**
$g_{H\gamma\gamma}$ (%)	1.8 / 3.7	1.3 / 1.3	1.5 / 1.4	1.2 / 1.2	**1.2 / 1.2**
$g_{HZ\gamma}$ (%)	11. / 11.	11. / 10.	11. / 9.8	6.3 / 6.3	**10. / 9.4**
g_{Htt} (%)	3.4 / 2.9	2.7 / 2.6	2.7 / 2.7	2.6 / 2.6	**2.6 / 2.6**
g_{HHH} (%)	50. / 52.	28. / 49.	45. / 50.	17. / 49.	**19. / 34.**
Γ_H (%)	SM	2.4	2.6	1.9	**1.2**
BR_{inv} (%)	1.9	0.26	0.63	0.27	**0.19**
BR_{EXO} (%)	SM (0.0)	1.8	2.7	1.1	**1.0**

First number: kappa fit / Second number: EFT fit

- **One million Higgs in three years at FCC-ee**
- **g_{HZZ} and Γ_H: typically twice better at FCC-ee**
- **Higgs self-coupling sensitivity only at FCC-ee**

❑ Unique to FCC-ee: Hee coupling

- **20 ab^{-1} / year at $\sqrt{s}$ = 125 GeV** *(not in baseline FCC-ee)*
- **Monochromatization $\sigma_{\sqrt{s}}$ ~ 1-2 × Γ_H ~ 6 to 10 MeV**
  - **Resonant ee → H production**

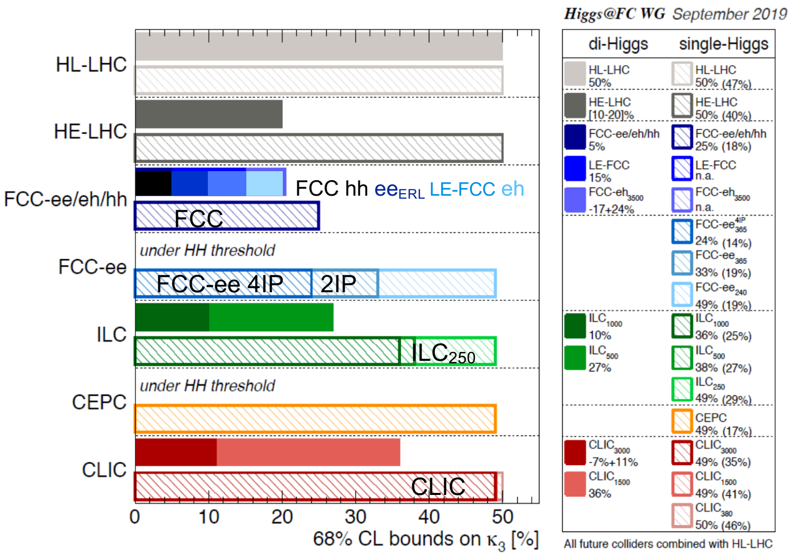


- **2σ excess in one year with 2 IP**
- **±15% precion on κ_e in 3 years with 4 IP**
  - ➔ **Not feasible at ILC or CLIC**

Comparisons with other scenarios

- **High-energy stages: ILC_{500}, $CLIC_{3TeV}$, FCC-hh (using FCC-ee candle)**
  - ZZ, WW, bb, cc, gg, ττ couplings, and Γ_H (FCC-ee)
    - Still 50% better than ILC_{500} / $CLIC_{3TeV}$
  - Rare decays (μμ, γγ, Zγ)
    - Typically 5-10 times better than ILC/CLIC
  - ttH coupling, Higgs self coupling
    - Typically twice better than ILC/CLIC

Collider	$ILC_{250+500}$	$CLIC_{3\ TeV}$	FCC	Years
g_{HZZ} (%)	0.23 / 0.22	0.39 / 0.20	**0.17 / 0.13**	< 1
g_{HWW} (%)	0.29 / 0.23	0.38 / 0.18	**0.20 / 0.13**	< 1
g_{Hbb} (%)	0.57 / 0.52	0.53 / 0.38	**0.48 / 0.44**	< 1
g_{Hcc} (%)	1.2 / 1.2	1.4 / 1.4	**0.97 / 0.95**	< 1
g_{Hgg} (%)	0.84 / 0.79	0.86 / 0.75	**0.53 / 0.49**	< 1
$g_{H\tau\tau}$ (%)	0.64 / 0.60	0.82 / 0.73	**0.49 / 0.45**	< 1
$g_{H\mu\mu}$ (%)	3.9 / 3.9	3.5 / 3.4	**0.44 / 0.42**	< 1
$g_{H\gamma\gamma}$ (%)	1.2 / 1.1	1.1 / 1.1	**0.36 / 0.34**	< 1
$g_{HZ\gamma}$ (%)	11. / 6.7	5.7 / 3.7	**0.70 / 0.70**	< 1
g_{Htt} (%)	2.4 / 2.4	1.9 / 2.0	**0.95 / 1.6**	< 1
g_{HHH} (%)	27./27.	11./n.a.	**5./6.**	1–7
Γ_H (%)	1.4	1.6	**0.91**	< 1
BR_{inv} (%)	0.22	0.61	**0.024**	< 1
BR_{EXO} (%)	1.4	2.4	**1.0**	< 1

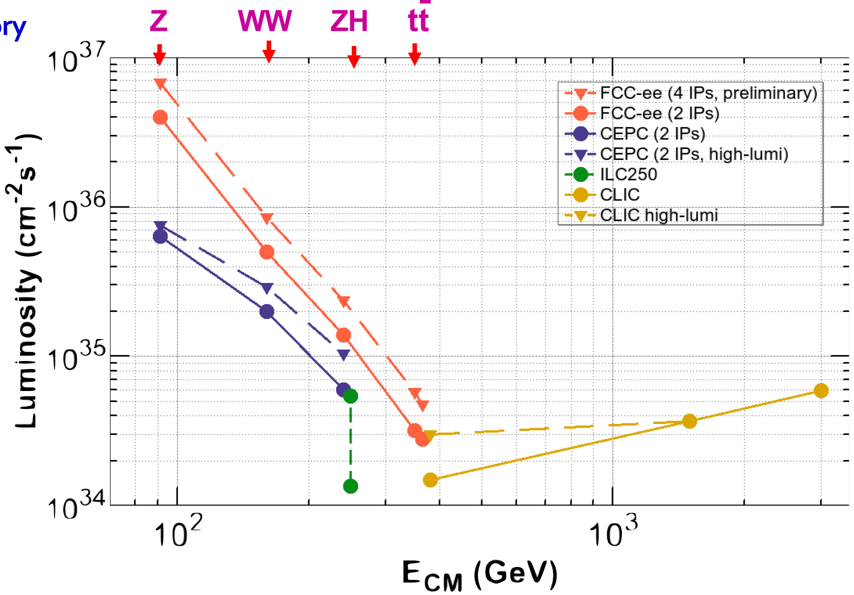


Few 100's HH events at ILC_{500}; Few 1000's at $CLIC_{3TeV}$; 36 millions HH events at FCC-hh

FCC is much more than the best Higgs factory

- **FCC-ee offers the largest luminosities in the 88 → 365 GeV range**
  - Ultimate « Higgs, Electroweak & Flavour » factory
    - 100 000 Z / second
    - 10 000 W / hour
    - 1 500 Higgs / day
    - 1 500 top / day
  - Cleanest environment
    - No pileup
    - Beam backgrounds under control
    - E, p constraints
  - PRECISION
    - Gives access to high energy scales
  - SENSITIVITY
    - To rare and elusive phenomena
  - CONTROL of systematic uncertainties
    - Huge event samples / Runs at the Z

in each detector



- **Discovery potential multiplied by the four heaviest SM particles present in its energy range**

FCC-ee discovery potential (highlights)

- **EXPLORE the 10-100 TeV energy scale with precision measurements**
  - Up to 20-100-fold improved precision on all EW observables (equivalent to a factor 5-10 in mass)
    - m_Z, m_W, m_{top}, Γ_Z, $\sin^2\theta_W^{eff}$, R_b, $\alpha_{QED}(m_Z)$, $\alpha_s(m_Z\, m_W\, m_\tau)$, top EW couplings …
  - Up to 10-fold more precise and *model-independent* Higgs couplings
    - Providing a fixed candle for Higgs measurements
- **DISCOVER that the Standard model does not fit**
  - NEW PHYSICS ! Pattern of deviations may point to the source.
- **DISCOVER a violation of flavour conservation / universality**
  - Example: τ BR / lifetime in 2×10^{11} τ decays; FCNC ($Z\rightarrow\tau\mu$, τe) in 5×10^{12} Z decays
  - Flavour physics in 10^{12} bb events ($B^0\rightarrow K^{*0}\tau^+\tau^-$, $B_S\rightarrow\tau^+\tau^-$, …)
- **DISCOVER dark matter in invisible decays of Higgs or Z**
- **DISCOVER feebly interacting particles in the 5-100 GeV mass range**
  - Such as Right-Handed neutrinos, ALPs, Dark photons …
- **… and many other opportunities**
  - e.g. QCD (α_S to 10^{-4}, $H\rightarrow gg$, fragmentation…)

Energy calibration to 25-100 keV
Unique to FCC-ee

See A. Blondel's presentation

Complete set of EW observables
Unique to FCC-ee

Tera Z
Unique to FCC-ee

FCC-hh discovery potential (highlights)

- FCC-hh physics potential is dominated by three features
  - Highest parton centre-of-mass energy → A BIG STEP IN HIGH MASS REACH
    - Strongly coupled new particles : up to 40 TeV
    - New gauge bosons (Z′, W′), excited quarks: up to 40 TeV
    - Extra Higgs bosons: up to 5-20 TeV
    - May give the final word on natural SUSY and WIMPS
    - High sensitivity to high energy phenomena, e.g., WW scattering, DY up to 15 TeV
    - Direct New Physics production at FCC-hh complemented with quantum effects at FCC-ee
  - Huge rates of SM particles (H, W, Z, t, b, …) in single/multiple production
    - Higgs precision tests using ratios: almost free of systematic uncertainties
    - Precise determination of triple Higgs coupling; Access to quartic coupling.
    - Detection of rare decays e.g., H → ργ, ϕγ, J/ψγ (Higgs coupling to 1^{st} / 2^{nd} generations)
    - Rich top and heavy-flavour programme: 10^{12} top quarks and 10^{17} b quarks produced
    - Search for invisibles (invisible Higgs decay [→ 10^{-4}], RH neutrinos in W decays, DM searches)
    - Long-lived particles
  - SM particles produced at high p_T with large statistics
    - Allows cleaner signals for channels that are currently difficult at LHC

High-mass reach
Unique to FCC-hh

New Physics identification
Unique to FCC-ee+hh

Huge event samples
Unique to FCC-hh

FCC-eh potential (highlights)

- **Explores untouched domain of (x,Q^2) DIS plane**
  - Extremely precise structure function determination: important input for FCC-hh
  - Higs precision on α_S ($\sim 10^{-4}$) – similar to FCC-ee but from totally different source
  - Discovery in QCD: non-linear parton evolution, instantons?
- **Copious production of heavy SM particles**
  - 2.5×10^6 Higgs bosons produced in WW and ZZ fusion: Precise couplings complementary to FCC-ee (esp. g_{HWW})
  - 2×10^7 top quarks: FCNC, V_{tb} at % level, …
- **Searches for new particles**
  - Leptoquarks, right-handed neutrinos, …

Other opportunities unique to FCC

- **Heavy ions**
  - Ion-ion, ion-proton, or electron-ion collisions: QGP physics with top-quark observables
- **Injectors**
  - Fixed target physics with protons and heavy ions

arXiv:1906.02693, FCC-ee: Your questions answered

	e^+e^- collisions							pp collisions		
$\sqrt{s}$ → / Physics ↓	m_Z	$2m_W$	HZ max. 240-250 GeV	$2m_{top}$ 340-380 GeV	500 GeV	1.5 TeV	3 TeV	28 TeV 37 TeV 48 TeV	100 TeV	Leading Physics Questions
Precision EW (Z, W, top)	Transverse polarization	Transverse polarization		m_W, α_S						Existence of more SM-Interacting particles
QCD (α_S) QED (α_{QED})	5×10^{12} Z	3×10^{8} W	10^5 H→gg							Fundamental constants and tests of QED/QCD
Model-independent Higgs couplings	ee → H $\sqrt{s} = m_H$		1.2×10^6 HZ and 75k WW→H at two energies						<1% precision (*)	Test Higgs nature
Higgs rare decays									<1% precision (*)	Portal to new physics
Higgs invisible decays									10^{-4} BR sensitivity	Portal to dark matter
Higgs self-coupling			3 to 5σ from loop corrections to Higgs cross sections						5% (HH prod) (*)	Key to EWSB
Flavours (b, τ)	5×10^{12} Z									Portal to new physics Test of symmetries
RH ν's, Feebly interacting particles	5×10^{12} Z								10^{11} W	Direct NP discovery At low couplings
Direct search at high scales					M_χ<250GeV Small ΔM	M_χ<750GeV Small ΔM	M_χ<1.5TeV Small ΔM		Up to 40 TeV	Direct NP discovery At high mass
Precision EW at high energy							*Y*		*W, Z*	Indirect Sensitivity to Nearby new physics
Quark-gluon plasma Physics w/ injectors										QCD at origins

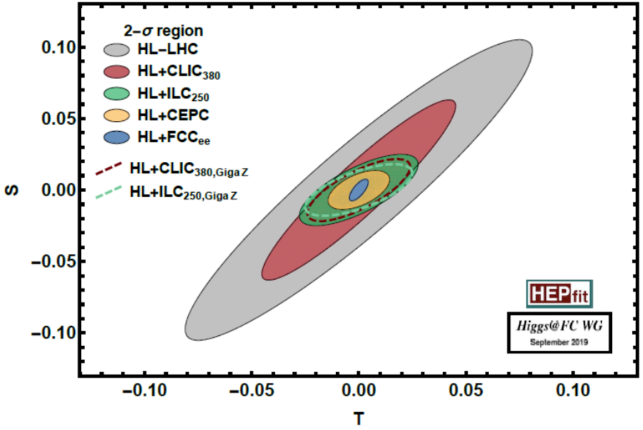
Green = Unique to FCC; **Blue = Best with FCC**; **(*) = if FCC-hh is combined with FCC-ee**; **Pink = Best with other colliders**

Example 1: Unique set of EW precision measurements

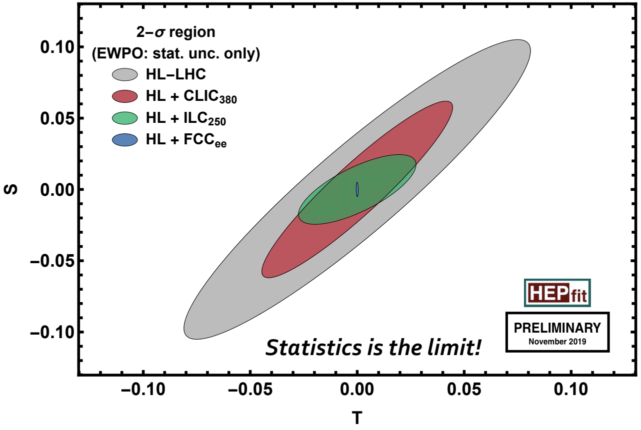
- **Fit of S and T parameters** (representing loop corrections to Z and W propagators)

See E. Locci's presentation

- **Current estimate of theory/systematic uncertainties:**



- **True potential (only stat + parametric errors):**



- Precise measurement of m_Z (100 keV) , Γ_Z (25 keV), m_W (<500 keV), $\alpha_{QED}(m_Z)$ (3.10^{-5}) (all unique to FCC-ee) make the difference
- True potential of FCC-ee is an order of magnitude better

See A. Blondel's presentation

  - Next step of the study is to devise the experimental and theoretical methods allowing systematic uncertainties to match the available statistics – *These are huge challenges for all of us to solve with new ideas. That's FUN!*

→ Effort is being organized and has just started – Lots of work ahead for the next 10-20 years.

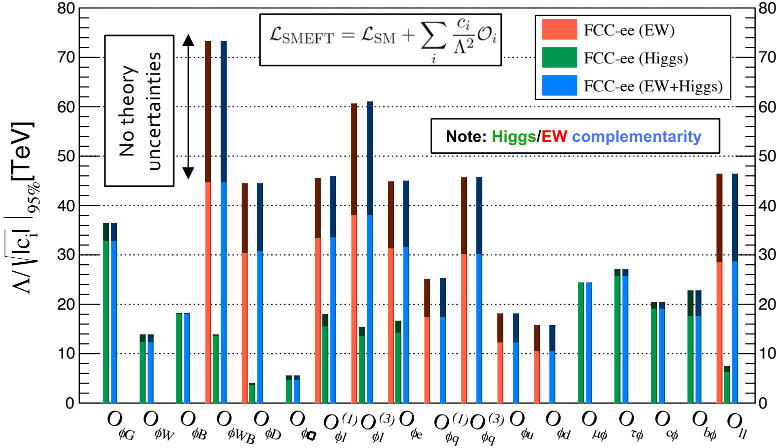
Theory: Precision calculations

- **Series of FCC-ee workshops on "Methods and Tools" has started**
  - Rapidly growing community of theorists: 38 contributors in Jan. 18, 86 contributors in Jan. 19
    - Next workshop at CERN, 13-17 January 2020

10. **Standard model theory for the FCC-ee Tera-Z stage**
A. Blondel (Geneva U.) *et al.*. Sep 6, 2018. 243 pp.
Published in **CERN Yellow Rep.Monogr. 3 (2019)**
CERN-2019-003, BU-HEPP-18-04, CERN-TH-2018-145, IFJ-PAN-IV-2018-09, KW 18-003, MITP/18-052, MPP-2018-143, SI-HEP-2018-21
DOI: 10.23731/CYRM-2019-003
Conference: C18-01-12
e-Print: arXiv:1809.01830 **[hep-ph]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service
Detailed record - Cited by 31 records

4. **Theory report on the 11th FCC-ee workshop**
A. Blondel (ed.) (Geneva U.) *et al.*. May 13, 2019.
BU-HEPP-19-03, CERN-TH-2019-061, CP3-19-22, DESY-19-072, FR-PHENO-2019-005, IFIC/19-23, IFT-UAM-CSIC-19-058, IPhT-19-050, IPPP/19/32, KW 19-003, MPP-2019-84, LTH 1203, ZU-TH-22-19, TUM-HEP-1200-19, TTP19-008, TTK-19-19
Conference: C19-01-08.1
e-Print: arXiv:1905.05078 **[hep-ph]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service
Detailed record - Cited by 8 records

Improving precision has discovery potential



"We anticipate that, at the beginning of the FCC-ee campaign of precision measurements, the theory will be precise enough not to limit their physics interpretation. This statement is however conditional to sufficiently strong support by the physics community and the funding agencies, including strong training programmes".

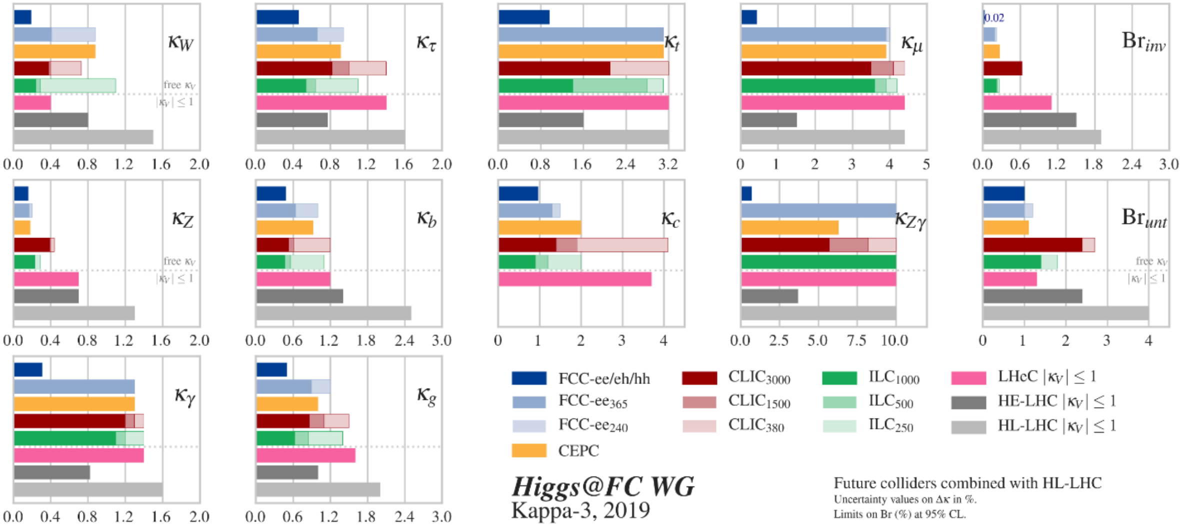
Recognized as strategic priority

Example 2: Complete set of Higgs measurements

- **Precision (%) on the Higgs couplings**

See C. Grojean's presentation

  - Combination FCC-ee + FCC-hh + FCC-eh (dark blue) best everywhere, by large factors.



- **Reminder: Hadron collider results require add'l assumption, and can be compared to e^+e^- collider results only when they are combined with e^+e^- measurements.**

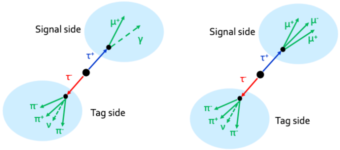
Example 3: Heavy-Flavour physics@TeraZ

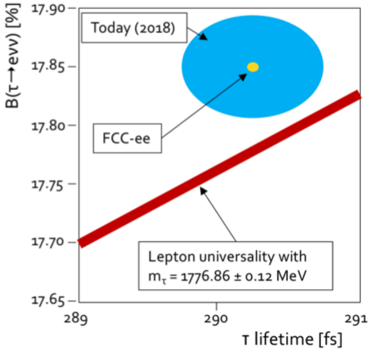
- **Test of lepton-flavour universality**

See G. Isidori's presentation

- **In the τ sector:**

Property	Current WA	FCC-ee stat	FCC-ee syst
Mass [MeV]	1776.86 +/- 0.12	0.004	0.1
Electron BF [%]	17.82 +/- 0.05	0.0001	0.003
Muon BF	17.39 +/- 0.05	0.0001	0.003
Lifetime [fs]	290.3 +/- 0.5	0.005	0.04

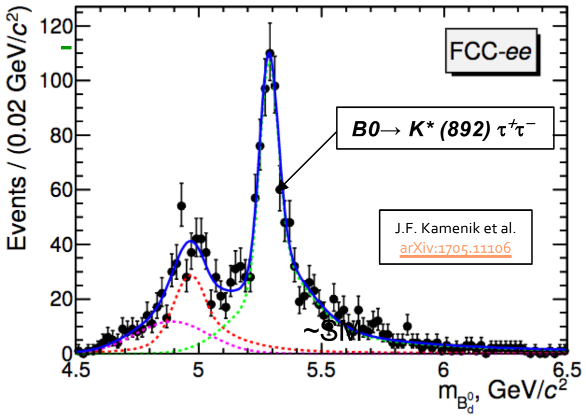




Decay	Current bound	FCC-ee sensitivity
Z -> eμ	0.75 x -6	10-8
Z -> μτ	12 x 10-6	10-9
Z -> eτ	9.8 x 10-6	10-9

Decay	Current bound	FCC-ee sensitivity
τ -> μγ	4.4 x 10-8	2 x 10-9
τ -> 3μ	2 x 10-8	10-10

In $b \to s\, \ell^+\ell^-$ transitions:



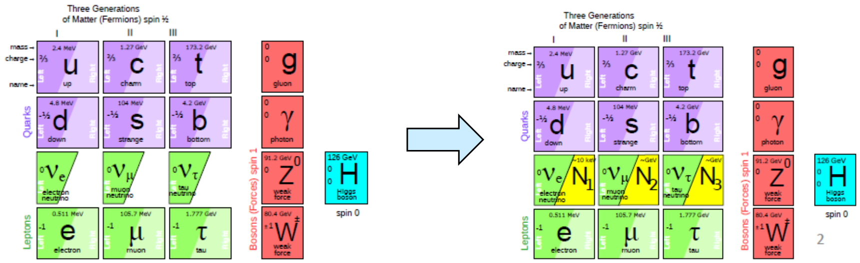
More than 10^3 events. Angular analysis possible

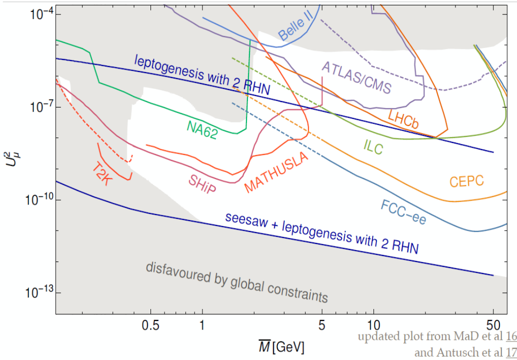
(to be done with full sim)

- **Briefing book unambiguous: FCC-ee is beyond any foreseeable competition**
  - **Study still at very early stages – *Much more will emerge with a systematic study and even better ideas***

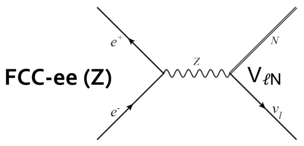
Example 4: Feebly interacting particles

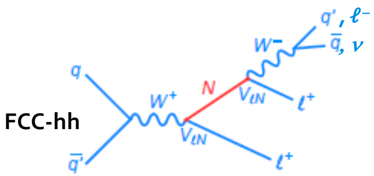
- **Heavy Right-Handed Neutrinos**
  - Complete SM spectrum – and perhaps explain DM, BAU, ν masses



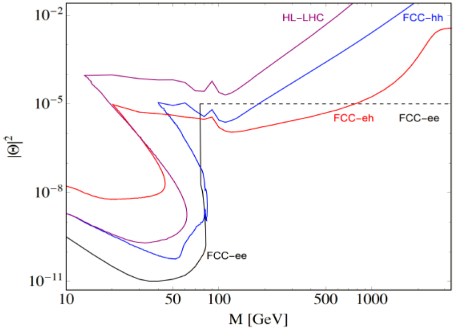


updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180



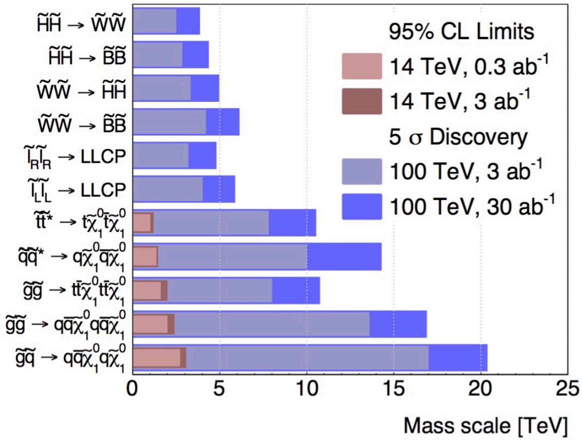


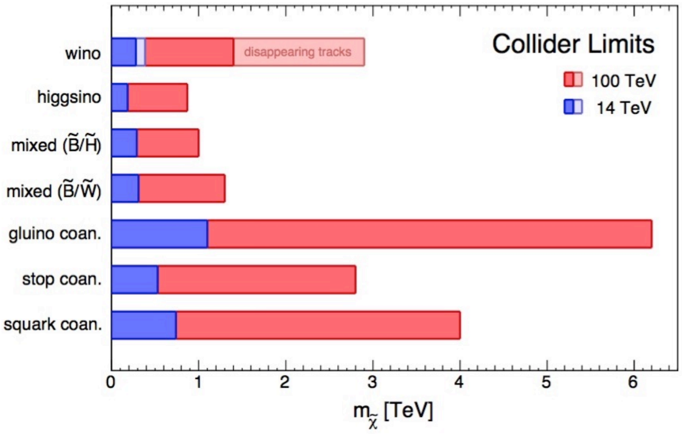
- **FCC-ee sensitivity** (to mixing angle with LH ν)
  - EWPO: ~10^{-5} up to very high masses
  - Best, flavour-blind, sensitivity to $\Sigma_\ell |V_{\ell N}|^2$ below 100 GeV
- **FCC-hh sensitivity**
  - Sensitivity to $V_{\ell_1 N} V_{\ell_2 N}$ with lepton charge and flavour
- **FCC-eh sensitivity**
  - Production in charge currents ep → XN (→ℓW)
  - Sensitivity to $V_{eN} V_{\ell N}$
- **Complementarity**
  - Discovery + complementary studies in overlap regions



Example 5: High energy reach

- **SUSY and WIMP Dark Matter at FCC-hh**





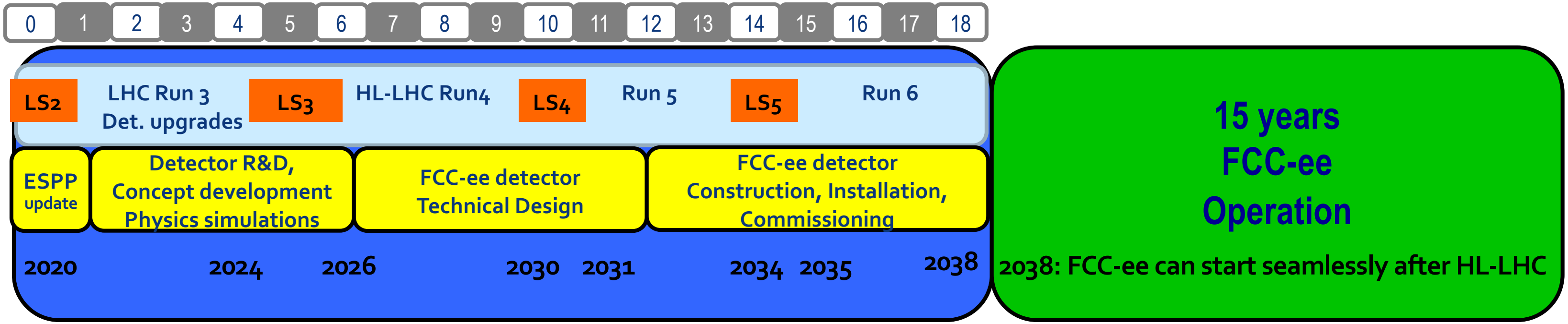
- **From DM relic abundance :** $M_{\mathrm{WIMP}} \leq 1.8\ \mathrm{TeV} \left(\frac{g^2}{0.3}\right)$

  - **FCC-hh can find (or rule out) lot's of weakly interacting massive DM candidates.**

Coming next (Assuming ESPP greenlight)

The BIG challenge:
Creation of a world-wide consortium of scientific contributors who reliably commit resources to the development and preparation of the FCC-ee science project from 2020 onwards

- **Until 2026: Focus on FCC-ee Detector concept development + R&D + Physics simulations**



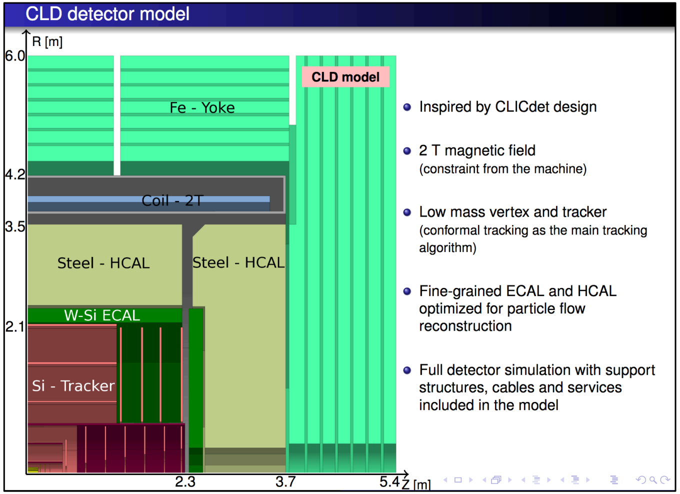
- **2026-2031: FCC-ee Detector Technical Design Study, with collaboration set-up**
  - **When detector experts are more available**
    - **FCC-ee schedule well integrated with HL-LHC experiments schedule**

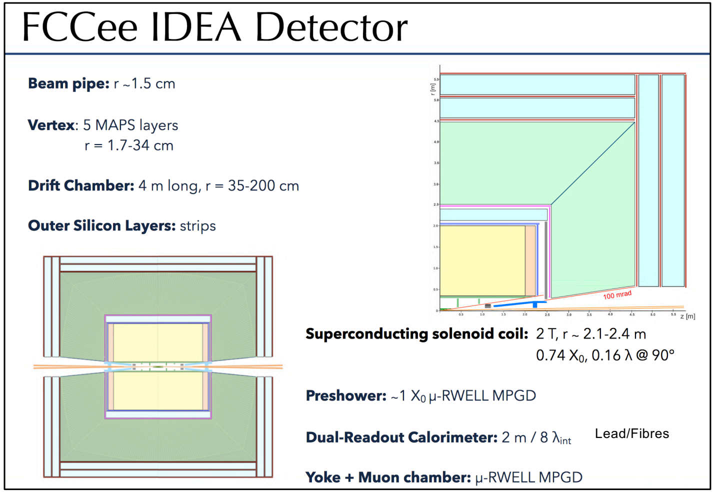
So far: Two detector concepts for the CDR

- It was demonstrated that detectors satisfying requirements are feasible

See P. Giacomelli's presentation

  - Physics performance, beam backgrounds, invasive MDI, event rates, …
    - With two rather complementary designs (tracker / calo technologies, magnets, cost, …)





- It is quite likely that these two concepts will not be the final answer
  - And we might need detectors for four IP, with newest technologies – lots of R&D and fun work ahead.

We now have to go beyond "feasibility"

- **Optimize existing designs (cost, performance)**
  - Transverse & longitudinal segmentation
  - Beam-pipe radius
  - Efficiency for close-by tracks
  - Robustness to beam backgrounds
  - Solenoid inside or outside calorimetry
  - Trigger for 100 kHz event rate at the Z pole
  - …

- **Examine other technologies**
  - Liquid-Argon Calorimetry, Crystals, …
  - Multiple-readout tile calorimetry
  - Time projection chamber
  - Wireless readout and powering
  - Particle-ID detectors (RICH, TORCH, …)
  - Lighter Si detectors (CMOS, …)
  - … go beyond the state of the art

- **Refine physics requirements with case studies**
  - Tracker: Angular and momentum resolutions
  - Calos: Angular and energy resolutions
  - Particle identification, flavour tagging
  - Need for timing
  - Particle-flow reconstruction compatibility
  - Detached vertices
  - Measurement of acceptance to 10^{-5} ! …

- **Study engineering and integration issues**
  - Powering
  - Cabling
  - Cooling
  - Mechanical integration (e.g., LumiCal)
  - Mechanical support (e.g., Tracker)
  - Machine-Detector Interface
  - …

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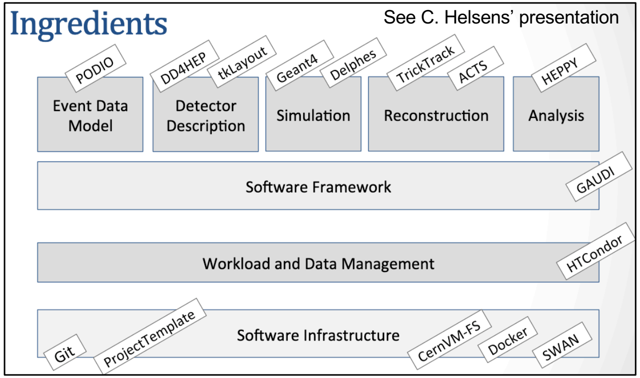
  - …

Innovative and ambitious ideas are most welcome

Dedicated workshop at CERN: 13-17 Jan. 2020

Practically: FCC Physics Software

- **Strategic CERN/EP R&D: Key4HEP and FCCSW**
  - Key4HEP: Common Software Stack for future experiments
  - FCCSW: Set of software, tools and standards for FCC studies
    - Priority is now to expand towards FCC-ee



- **You can participate in many useful(*) ways**
  - Implement your favourite detector geometry
    - And perform full simulations / performance studies
  - Include your favourite reconstruction algorithms
    - E.g., flavour tagging with machine learning
  - Develop your own physics case study, and interface the required event generators
    - And get essential conclusions on detector requirements for FCC-ee
  - …

(*) Useful for the FCC project, and useful for your project

- **Next hands-on tutorial during the FCC physics workshop at CERN, 13-17 Jan. 2020**
  - Register !

Final words

- The FCC design study has established the feasibility of an ambitious set of colliders
  - At the cutting edge of knowledge and technology

See F. Zimmermann's presentation

<u>FCC can be done!</u>

- It has demonstrated outstanding phyiscs cases for FCC-ee and FCC-hh
  - Each in the own right (e^+e^- Higgs, Electroweak & Flavour Factory and pp @ Energy Frontier)
  - The sequential implementation of FCC-ee and FCC-hh offers the broadest physics reach proposed today

<u>Big jumps in Sensitivity, Precision, Energy</u>

  - The other routes to 100 TeV (CLIC 380, LE-FCC, …) are less precise, less complete, more expensive.
- An attractive staging scenario can serve Particle Physics throughout the 21st century
  - With multiple experiments, and taking full advantage of

<u>Multiple Synergies and Complementarities</u>

- The true work towards the FCC experiment realization starts now, from a clean sheet
  - Don't hesitate to join and commit, your contribution will make a difference

Alternatives to FCC-ee en route to FCC-hh

LE-FCC, then FCC-hh

- Not complementary nor synergetic with FCC-hh
  - Brings no additional measurement wrt FCC-hh
  - Kills all FCC-ee synergies/complementarities
- Weakens the physics case of FCC-hh
  - Reduces the CM energy increment (HIGH RISK!)
  - No more guidance from FCC-ee
- Reduces CERN attractiveness (only pp physics)
- More expensive than FCC-INT

CLIC-380, then FCC-hh

- Higgs + Top physics programme ~ FCC-ee (365)
- Measurements less precise than FCC-ee
  - Only 175,000 Higgs boson (vs 1.3×10^6)
  - m_H precision ~ 80 MeV: affects g_{HWW}, g_{HZZ} precision
  - Γ_H precision ~ 2.6% → inferior standard candle
  - No ee → H possibility (too small luminosity)
- CLIC GigaZ: Poor E_{beam} determination, ⋘ $5\ 10^{12}$ Z
- More expensive than FCC-INT

CLIC 3 TeV, no FCC-hh: ONE Experiment

- Similar shortcomings as CLIC-380 + GigaZ
  - Lack of precision of EW measurements (stat, E_{beam})
  - ⋘ $5\ 10^{12}$ Z (no ALPs, no RHνs, no flavours, …)
  - No ee → H possibility
- Short of statistics with respect to FCC-hh
  - Higgs rare decays, g_{HHH}, W's, b's and top's
- Limited high energy exploration
- Cost (~FCC-hh) incompatible with hadron program

ILC in Japan

- Not incompatible/complementary with FCC-ee
  - Many FCC-ee measurements are unique (Z, W, H)
  - Added value of ILC in the higher energy range
    - ➔ 350 GeV and above, with long. Polarization
    - ➔ Complementary to FCC-ee (350/365)
  - Remember LEP vs SLC
- FCC-ee remains the richest/fastest way to FCC-hh
- ILC cost to be supported by Japan