Future Circular Collider

BCVSPIN Conference

Particle Physics and Cosmology in the Himalayas

9-13 Dec 2024

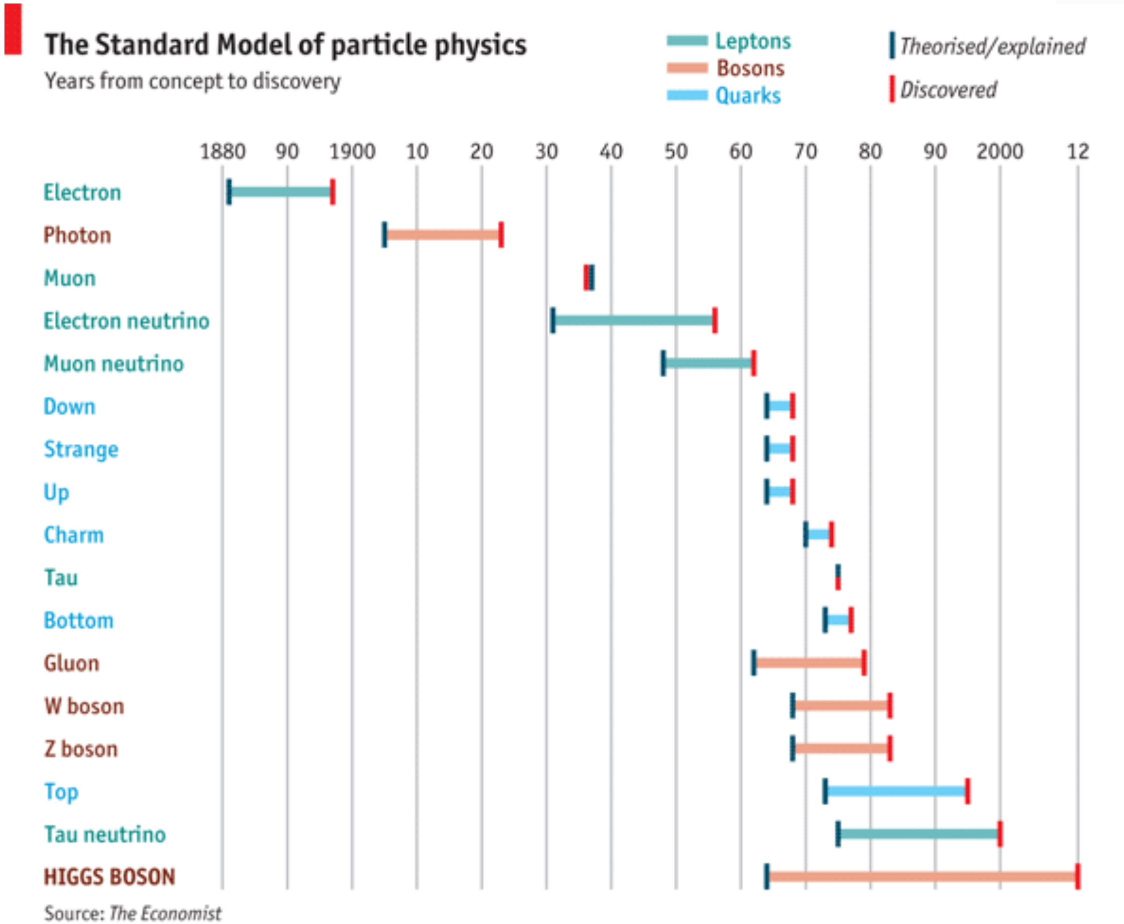
Kathmandu, Nepal

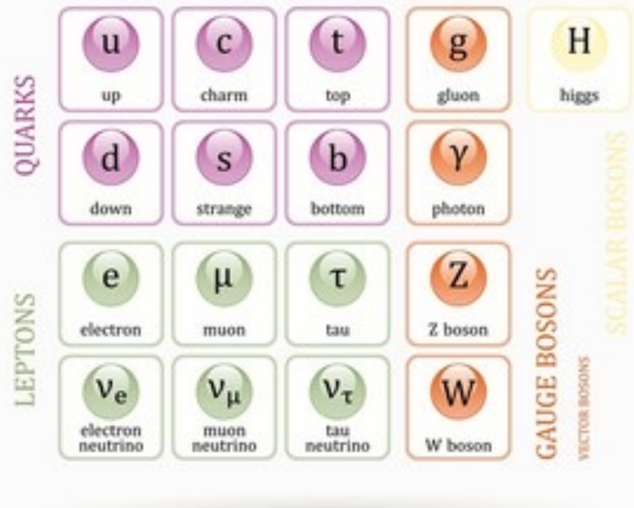
Prolay K. Mal

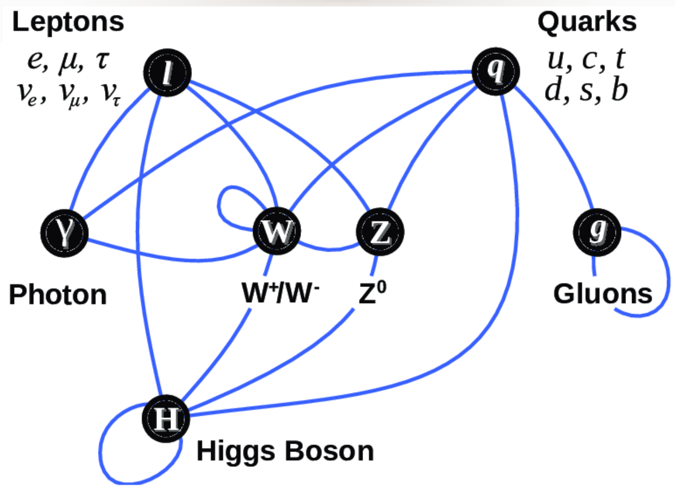
National Institute of Science Education and Research (India)

(on behalf of FCC collaboration)

Standard Model of Particle Physics



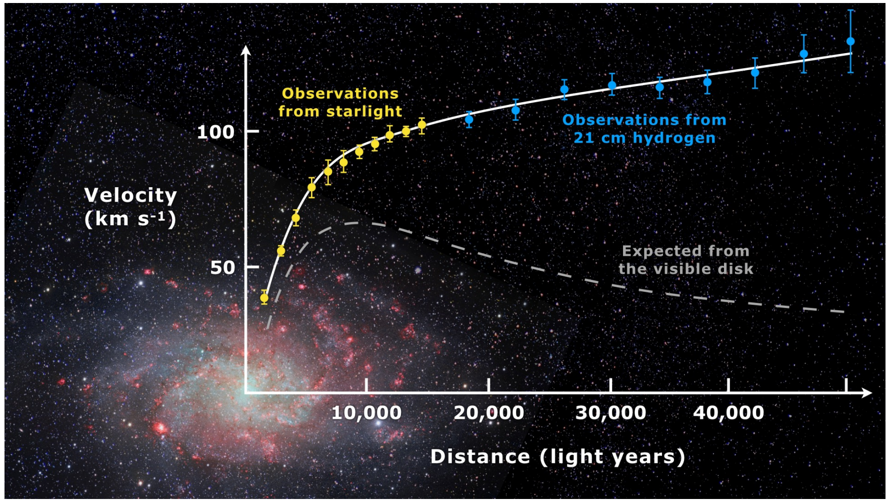




Completeness(?) of the Standard Model

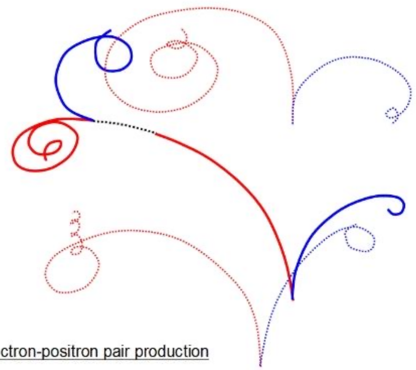
What is Dark Matter?

The visible universe explained by the Standard Model particles is only 5%



Where is the primordial antimatter gone?

-- matter-antimatter asymmetry



Electron-positron pair production

Origin of neutrino masses?

-- No unique explanation within the SM
-- Dirac vs Majorana hypothesis
-- Heavy right-handed neutrinos

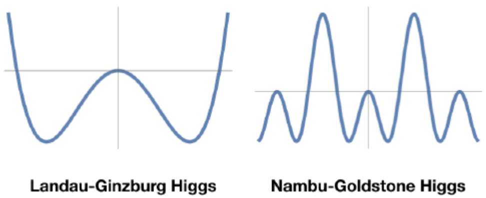
FCC and the deciphering of the Higgs boson….

- → It is a unique object, a scalar particle/field (spin 0), not a matter field, not a boson mediating a gauge interaction, but a field carrying a new type of interaction of the Yukawa type.
- → Many proposals for new accelerators to study it, and to study Beyond SM physics
- → Easier choice now that it has been discovered.

Precise nature of the Higgs boson ?

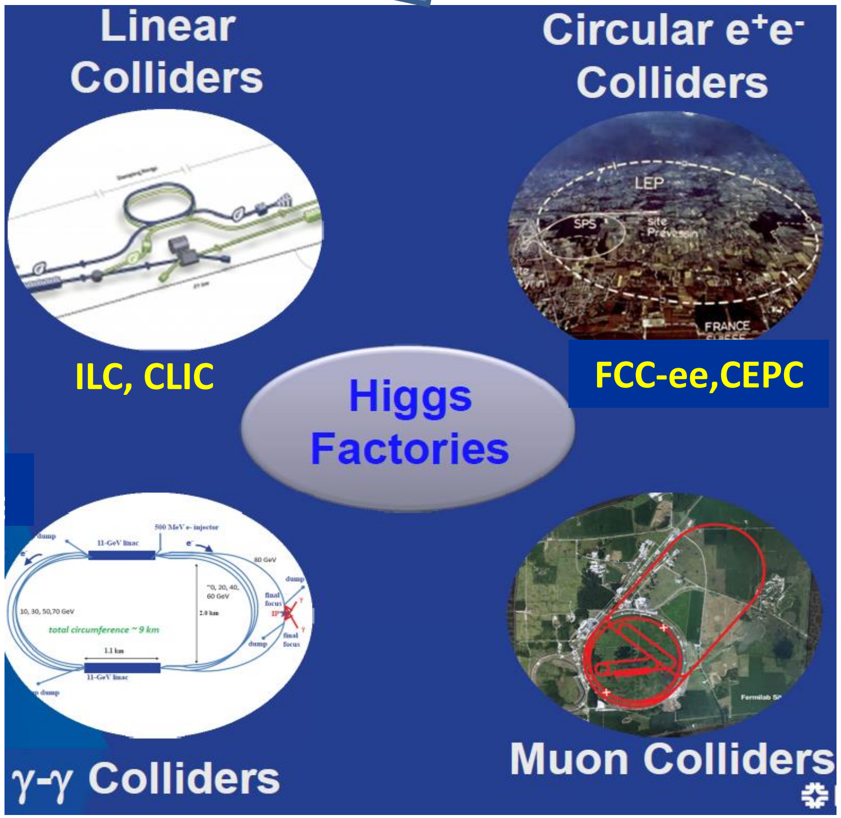
Origin of electroweak symmetry breaking (EWSB) ?

Shape of the Higgs potential ?



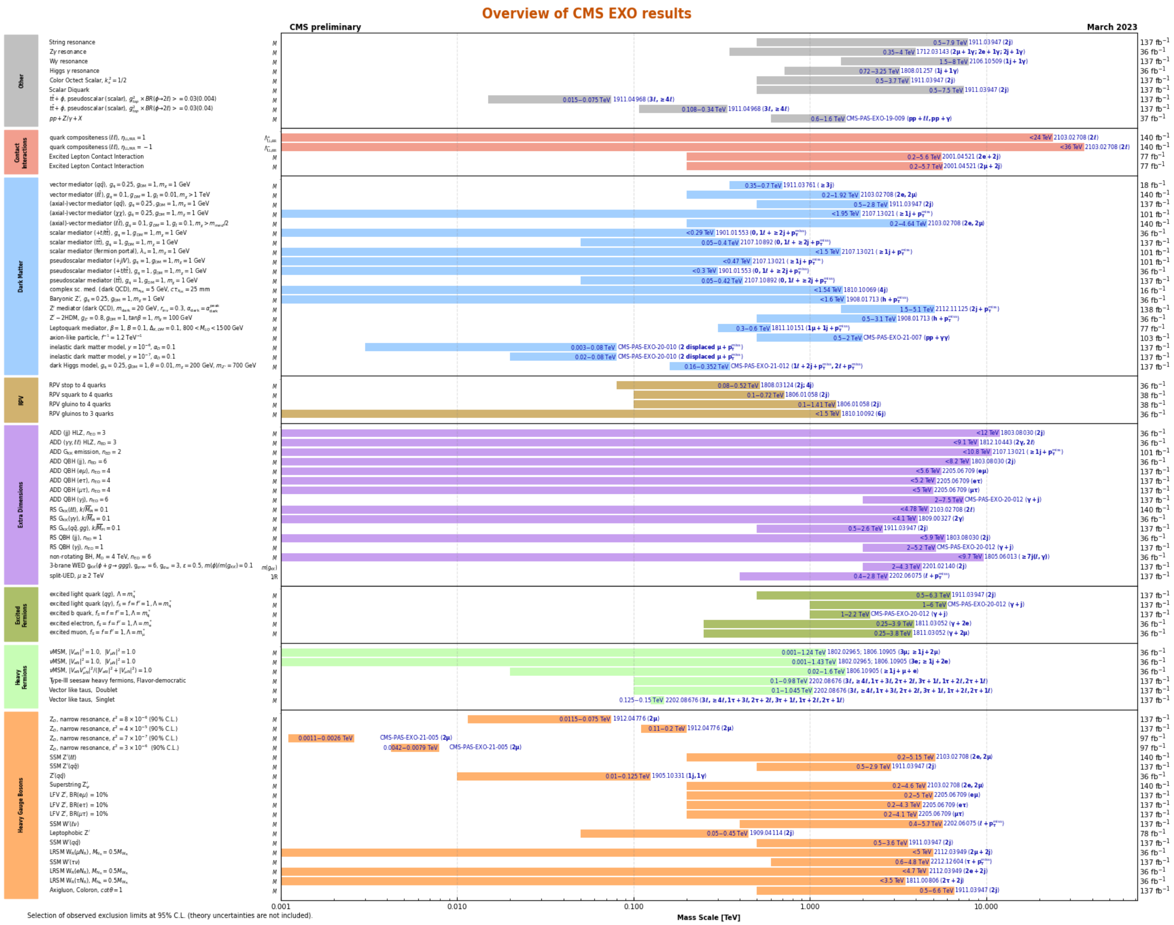
Strength of the electroweak phase transition ? What is its role just after the big bang ? Inflation ?

We need to determine precisely the Higgs couplings and the Higgs self-couplings to answer these questions.



The LHC Legacy (so far)

- LHC turned into a precision machine
  - Precision on the Standard Model measurements are beyond the design sensitivity
  - Both theoretical and experimental systematics are under control
- Higgs boson discovery at the mass (at least for the SM one) predicted by the electroweak measurements performed at LEP experiments
- Absence of any new physics
  - Traditional model-based new physics searches are highly constrained at multi-TeV scale



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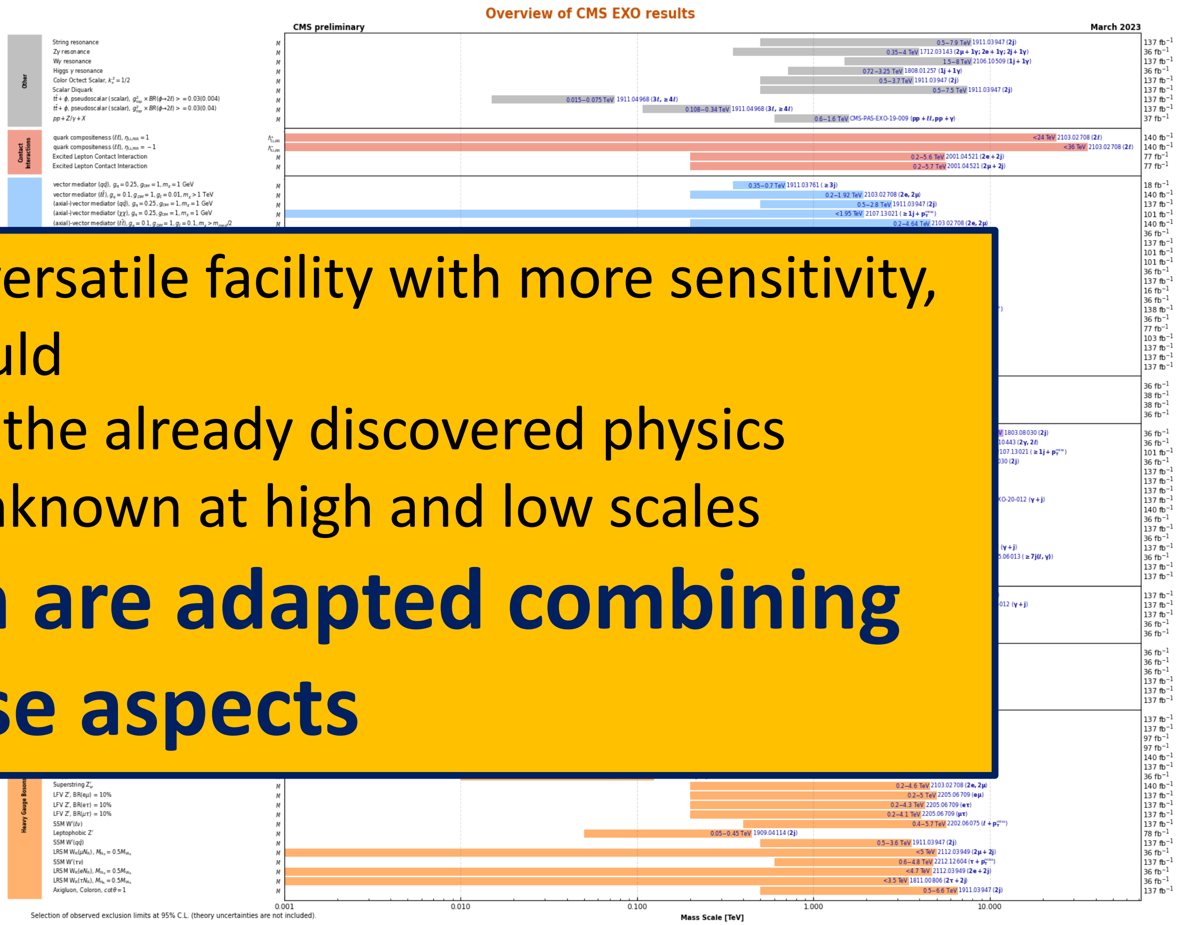


Requirement of a broad and versatile facility with more sensitivity, precision and energy that would

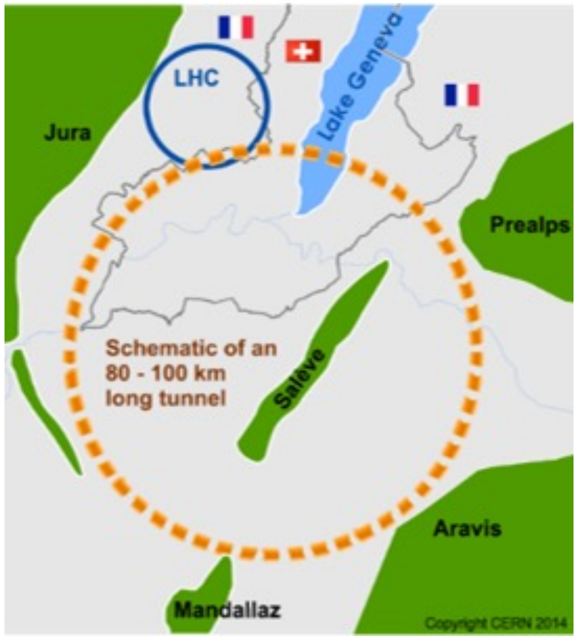
- sharpen our knowledge on the already discovered physics
- push the frontiers of the unknown at high and low scales

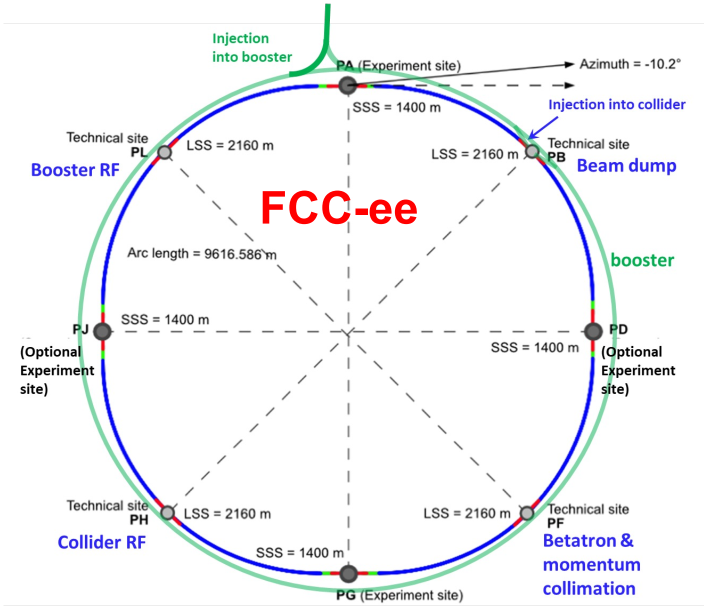
FCC-ee and FCC-hh are adapted combining these aspects

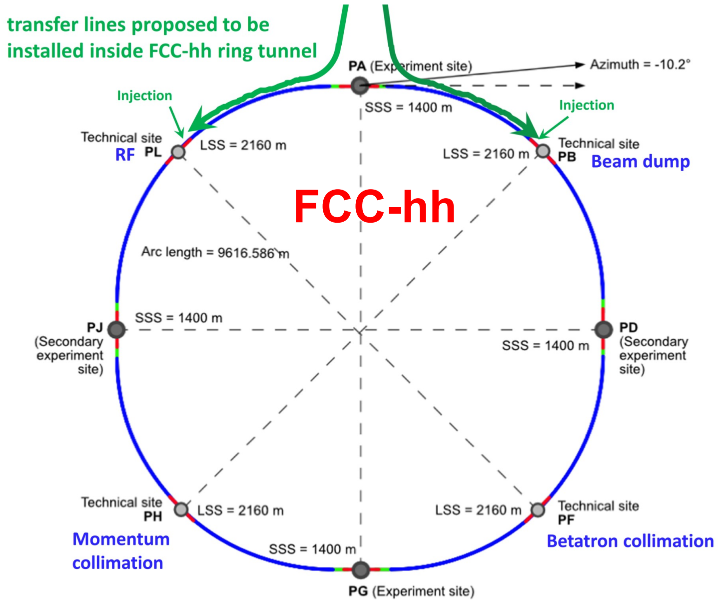
FCC-integrated Program

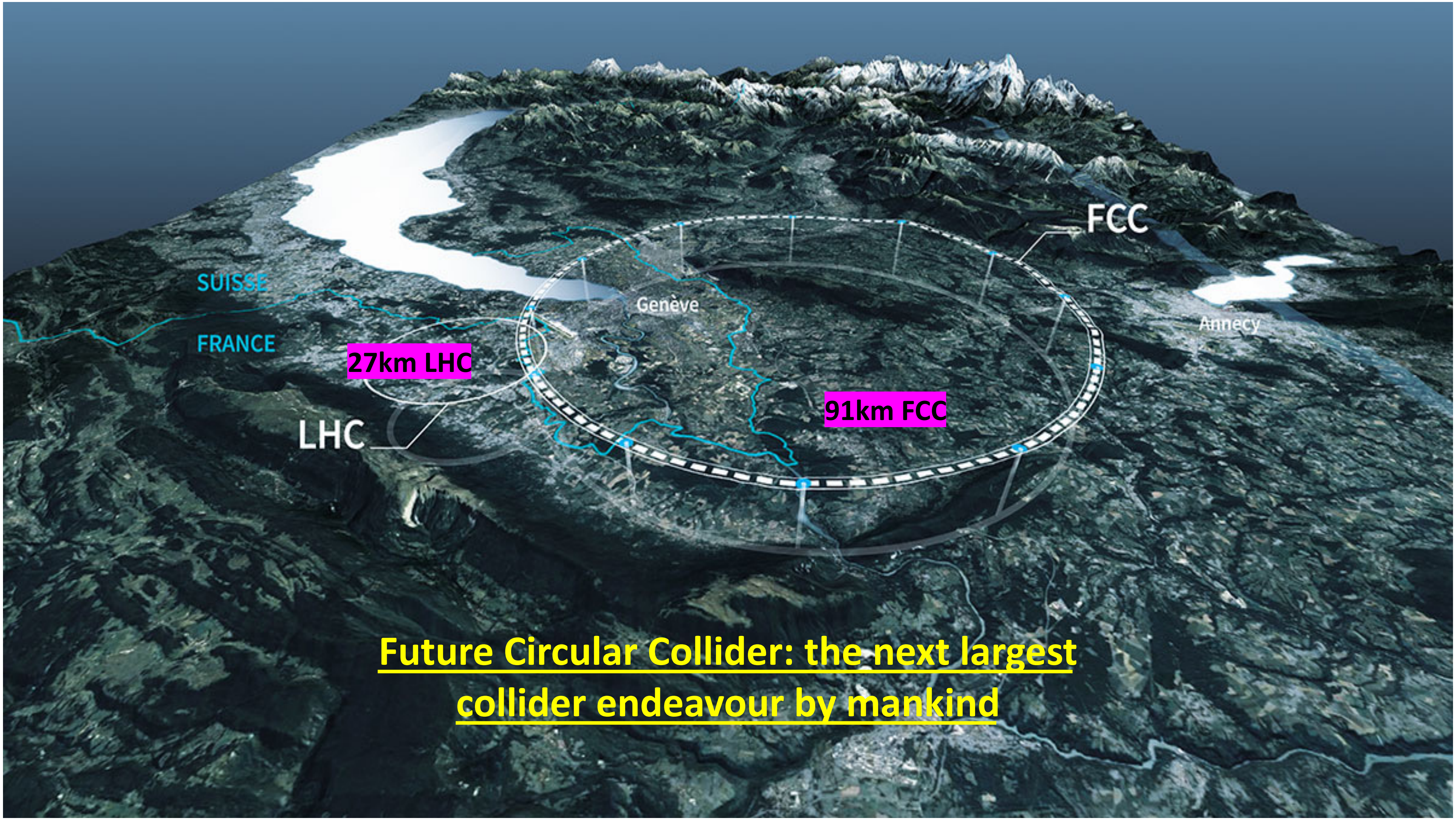
Comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC



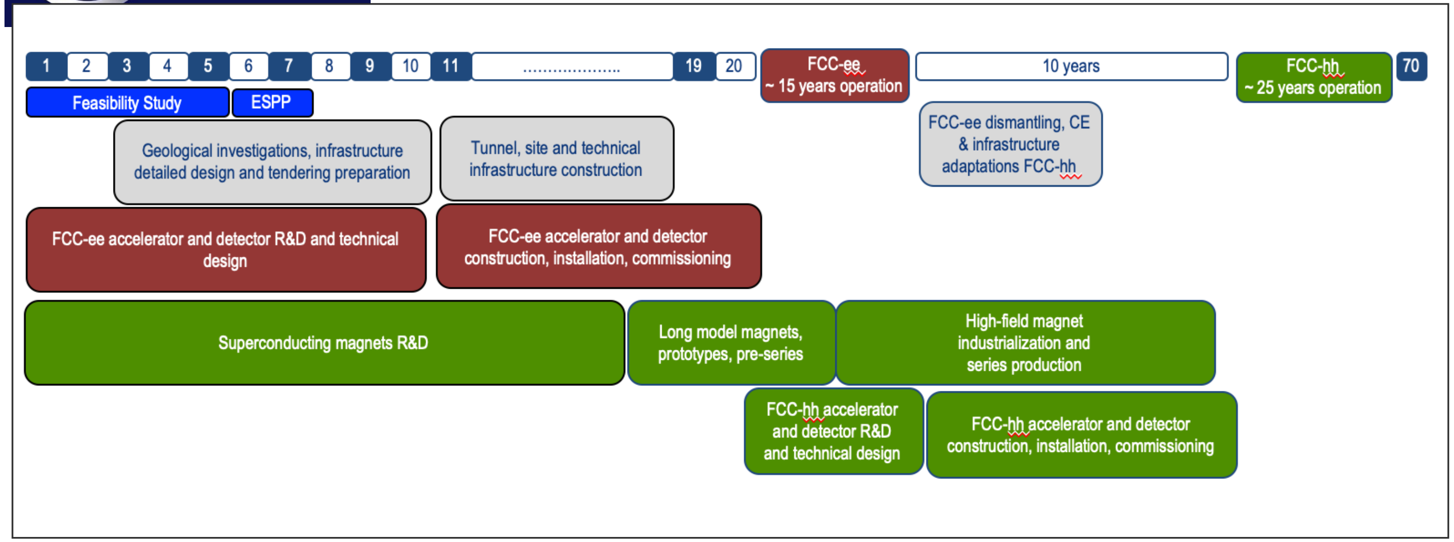




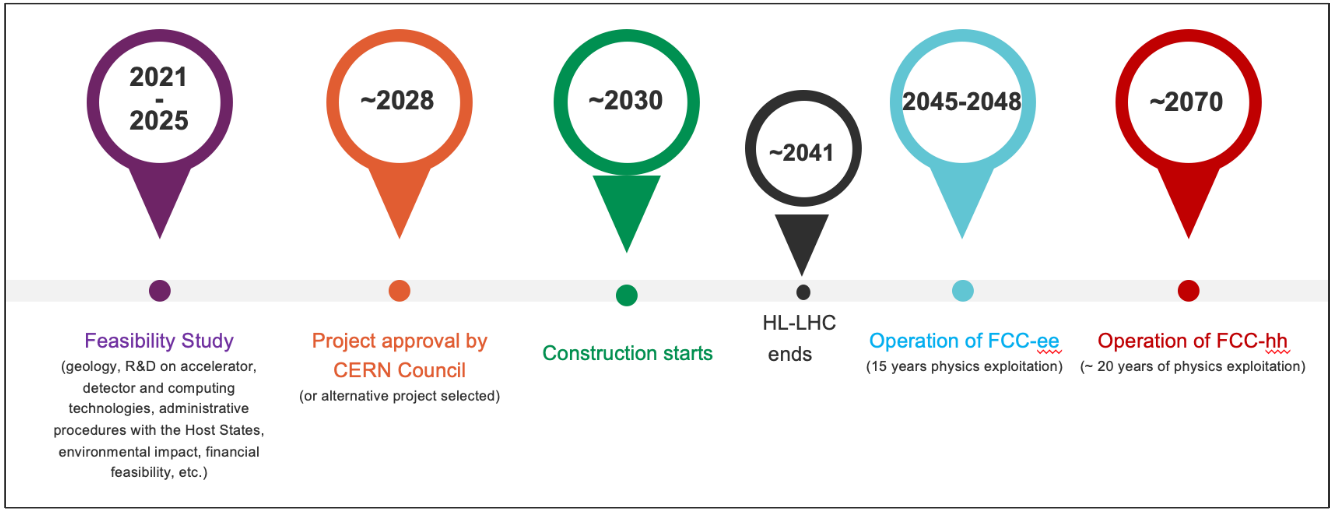


FCC
SUISSE
FRANCE
Genève
Annecy
27km LHC
91km FCC
LHC
Future Circular Collider: the next largest collider endeavour by mankind

FCC-integrated Program - timeline



Note: FCC Conceptual Design Study started in 2014 leading to CDR in 2018



"Realistic" schedule taking into account:
- ❑ past experience in building colliders at CERN
- ❑ approval timeline: ESPP, Council decision
- ❑ that HL-LHC will run until 2041

Can be accelerated if more resources available

European Strategy for Particle Physics

2013 Update of European Strategy for Particle Physics:

"CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines."

→ FCC Conceptual Design Reports (2018/19)

Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC

CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 ,
EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

2020 Update of European Strategy for Particle Physics:

"Europe, together with its international partners, should investigate technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage."

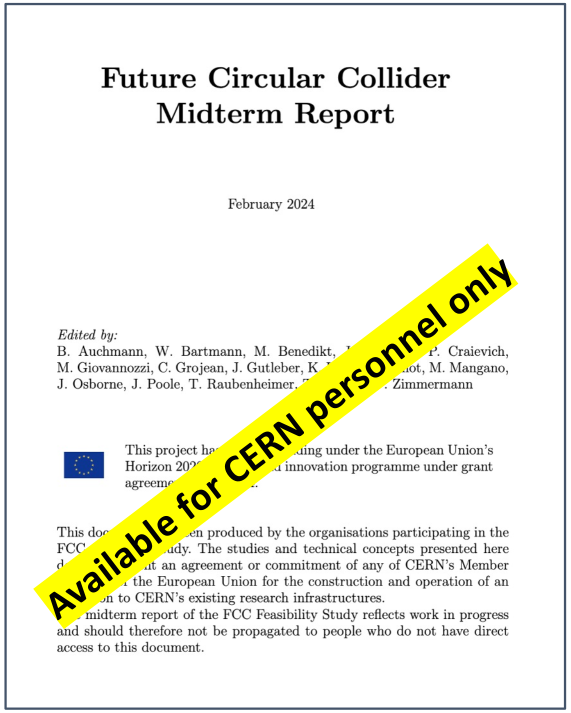
Feasibility Studies Mid-Term Review passed in 2023!

Deliverables:

D1 : Definition of the baseline scenario
D2 : Civil engineering
D3 : Processes and implementation studies with the Host States
D4 : Technical infrastructure
D5 : FCC-ee accelerator
D6: FCC-hh accelerator
D7: Project cost and financial feasibility
D8: Physics, experiments and detectors

Documents:

- Mid-term report (all deliverables except D7)
- Executive Summary of mid-term report
- Updated cost assessment (D7)
- Funding model (D7)



Full Report

8 Chapters/Deliverables

~ 700 pp document

~ 16 editors

~ 500 contributors

Review process:

Oct 2023:
- **FCC Scientific Advisory Committee** chaired by Andrew Parker / Cambridge (sci. and tech. aspects)
- **Cost Review Panel** chaired by Norbert Holtkamp / Stanford (ad hoc committee; cost and financial asp.)

Nov 2023:
- **CERN Scientific Policy Committee** and **CERN Finance Committee**

2 Feb 2024:
- **CERN Council**

Approved deliverables:
https://indico.cern.ch/event/1197445/contributions/5034859/attachments/2510649/4315140/spc-e-1183-Rev2-c-e-3654-Rev2_FCC_Mid_Term_Review.pdf

All deliverables met, no technical showstoppers

→ **70-80 recommendations**

Main goals 2024 / beginning 2025

Complete technical work for Feasibility Study until end 2024

- Implementation of recommendations from the mid-term review
- Focus on "feasibility items" and items with important impact on cost/performance
- Develop a risk register
- Update cost estimate to reach cat 3 level on cost uncertainty.
- Further develop the funding model based on discussions with the Council

Continue work with host states on:

- project definition and responsibilities
- authorization procedures
- excavation material strategy
- regional implementation development

Conclude Feasibility Study by March 2025 as input for ESPP update

Status of FCC global collaboration

Increasing international collaboration as a prerequisite for success:
→links with **science, research & development** and **high-tech industry** will be essential to further advance and prepare the implementation of FCC

FCC Feasibility Study:
Aim is to further increase the collaboration, on all aspects, in particular on Accelerator and Particle/Experiments/Detectors

141 Institutes

32 countries + CERN

FUTURE CIRCULAR COLLIDER
Feasibility Study

Progress on International Collaboration

26 April 2024

White House Office of Science and Technology Policy Principal Deputy U.S. Chief Technology Officer Deirdre Mulligan signed for the United States while Director-General Fabiola Gianotti signed for CERN.

The United States and CERN intend to:

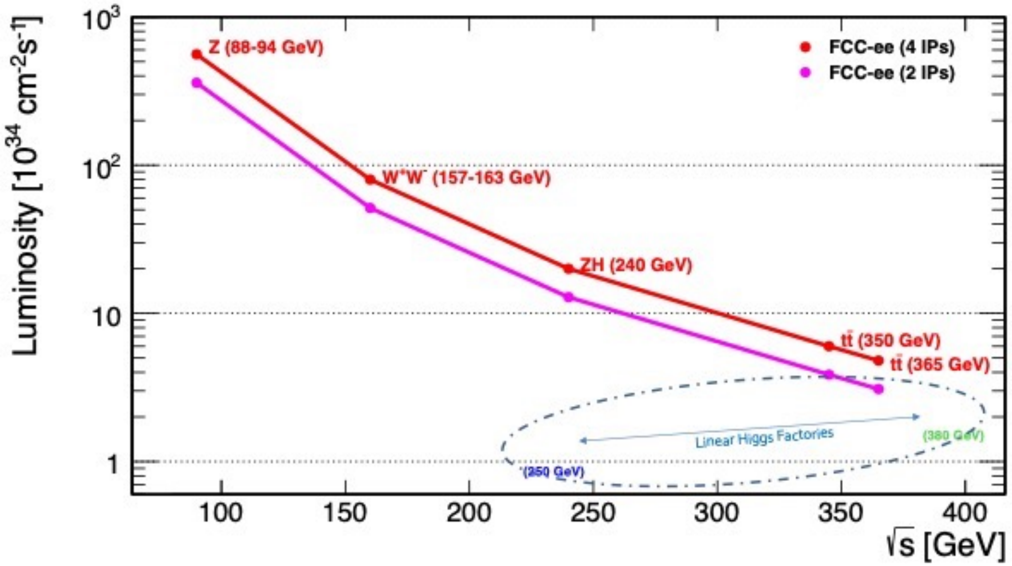
- Enhance collaboration in future planning activities for large-scale, resource-intensive facilities with the goal of providing a sustainable and responsible pathway for the peaceful use of future accelerator technologies;
- Continue to collaborate in the feasibility study of the Future Circular Collider Higgs Factory (FCC-ee), the proposed major research facility planned to be hosted in Europe by CERN with international participation, with the intent of strengthening the global scientific enterprise and providing a clear pathway for future activities in open and trusted research environments; and
- Discuss potential collaboration on pilot projects on incorporating new analytics techniques and tools such as artificial intelligence (AI) into particle physics research at scale.

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.

FCC-ee Run Plan.

LEP1 data accumulated in **every 2 mn**. Exciting & diverse programme with different priorities every few years.

(order of the different stages still subject to discussion/optimisation)



— Superb statistics achieved in only 15 years —

in each detector:
10^5 Z/sec, 10^4 W/hour,
1500 Higgs/day, 1500 top/day

Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW $\rightarrow$ H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW $\rightarrow$ H	

Christophe Grojean

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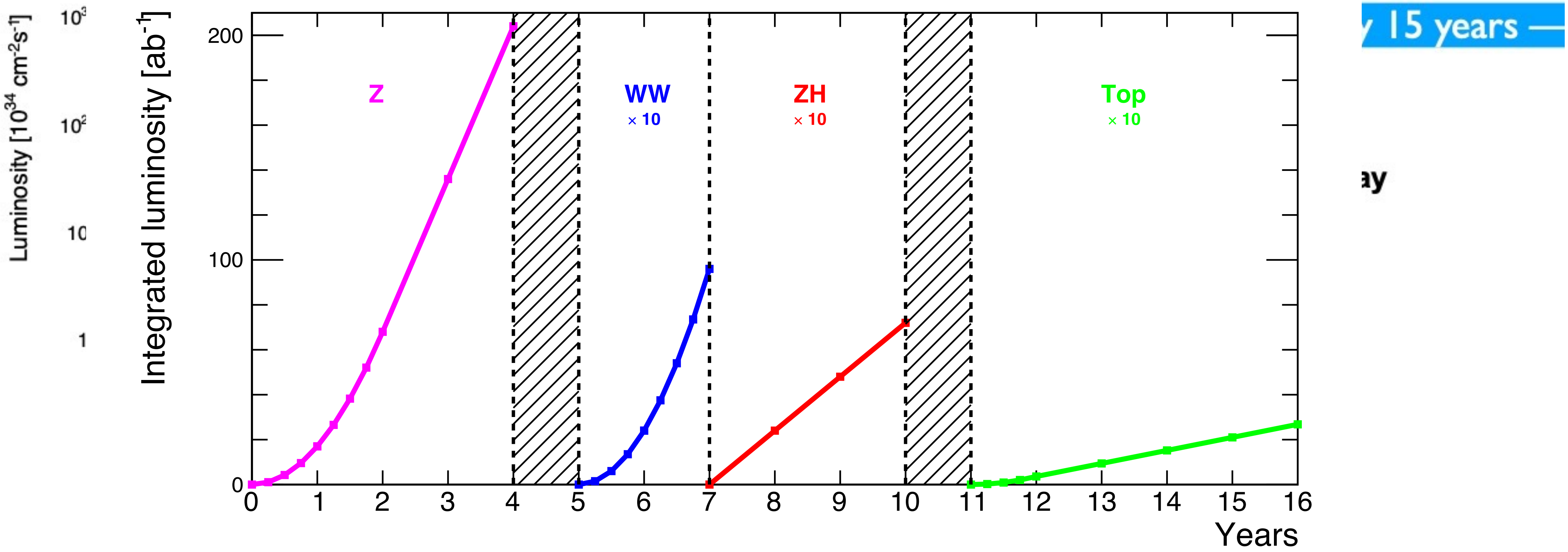

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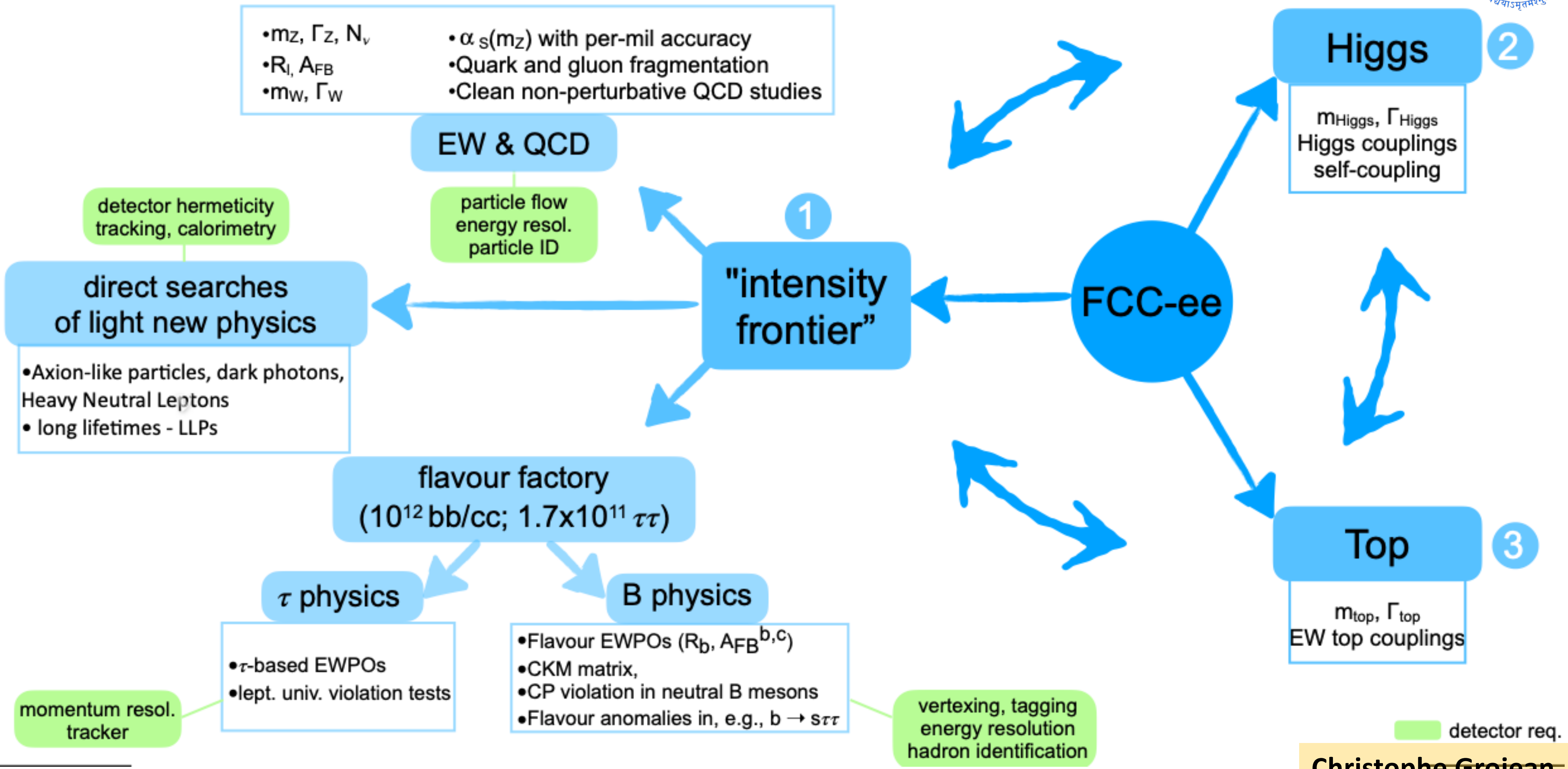
Christophe Grojean

FCC-ee Physics Programme.



Christophe Grojean

FCC-ee Physics Programme.

- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W
- $\alpha_S(m_Z)$ with per-mil accuracy
- Quark and gluon fragmentation
- Clean non-perturbative QCD studies

EW & QCD

Higgs 2

m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

detector herme
tracking, calori

direct sear
of light new p

- Axion-like particles, d
Heavy Neutral Leptons
- long lifetimes - LLPs

baseline FCC-ee detector performance	
track momentum	$\frac{\sigma_p}{p} = 0.02\cdot10^{-3} \cdot p_T(\text{GeV}) \oplus 1\cdot10^{-3}$
track impact parameter	$\sigma_{d_0} = \frac{15\,\mu\text{m}}{\sin^{3/2}\theta} \oplus 5\,\mu\text{m}$
electromagnetic energy	$\frac{\sigma_{E_\gamma}}{E_\gamma} = \frac{15\%}{E_\gamma} \oplus 1\%$
electromagnetic energy xy position	$\sigma_{\gamma,xy} = \frac{6\,\text{mm}}{E(\text{GeV})} \oplus 2\,\text{mm}$

(10^{12} bb/cc; $1.7\text{x}10^{11}$ $\tau\tau$)

Top 3

m_{top}, Γ_{top}
EW top couplings

τ physics

- τ-based EWPOs
- lept. univ. violation tests

momentum resol.
tracker

B physics

- Flavour EWPOs (R_b, $A_{FB}^{b,c}$)
- CKM matrix,
- CP violation in neutral B mesons
- Flavour anomalies in, e.g., $b \to s\tau\tau$

vertexing, tagging
energy resolution
hadron identification

detector req.

Christophe Grojean

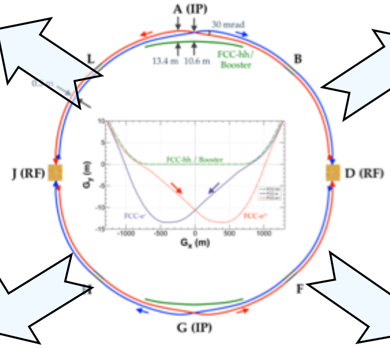
FCC-ee Detector requirements

"Higgs Factory" Programme

- Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{pT}/p_T \simeq 10^{-3}$ commensurate with beam energy spread
- Jet energy resolution of 30%/$\sqrt{E}$ in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme & QCD

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from $\mu\mu$)
- Stability of B-field to 10^{-6} : stability of $\sqrt{s}$ meast.



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ $\sqrt{E}$ level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs

Benchmark signature: $Z \rightarrow \nu N$, with N decaying late

- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Precise timing for velocity (mass) estimate
- Hermeticity

Mogens Dam

FCC-ee Detectors/Challenges

FCC-ee key machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

Design and parameters dominated by the choice to allow for 50 MW synchrotron radiation per beam.

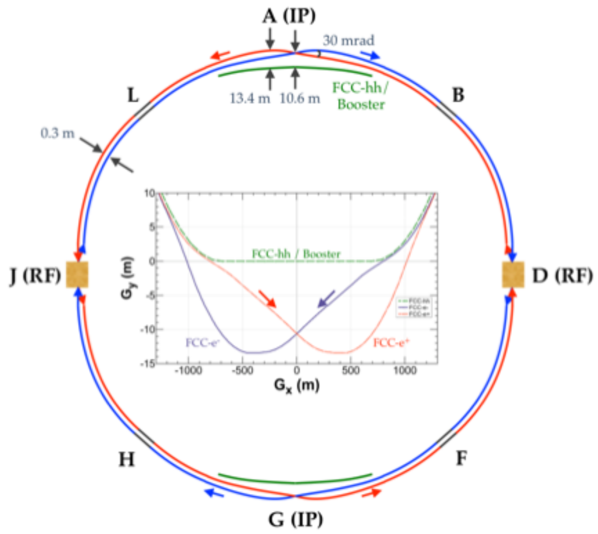
- ❑ x 10-50 improvements on all EW observables
- ❑ up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- ❑ x10 Belle II statistics for b, c, τ
- ❑ indirect discovery potential up to ~ 70 TeV
- ❑ direct discovery potential for feebly-interacting particles over 5-100 GeV mass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

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

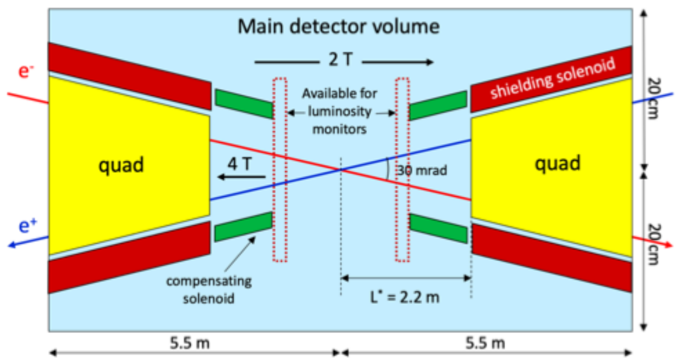
F. Gianotti

FCC-ee Experimental Challenges

- 30 mrad beam crossing angle
  - Detector B-field limited to 2 Tesla (at least at Z-pole energy)
  - Very complex and tightly packed MDI (Machine Detector Interface)
- ”Continuous” beams (no bunch trains); bunch spacing down to 25 ns
  - Power management and cooling (no power pulsing)
- Extremely high luminosities
  - High statistical precision ⇒ control of systematics down to 10^{-5} level
  - Online and offline handling of $\mathcal{O}(10^{13})$ events for precision physics:
    ”Big Data”
- Physics events at up to 100 kHz
  - Fast detector response ($\lesssim$ 1 μs) to minimise dead-time and event overlaps (pile-up)
  - Strong requirements on sub-detector front-end electronics and DAQ systems
    - At the same time, keep low material budget: minimise mass of electronics, cables, cooling, …



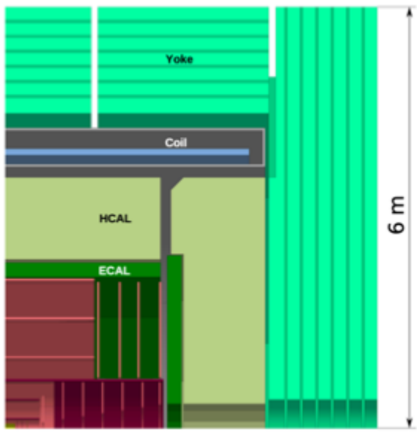
Central part of detector volume – top view



State-of-the-art detector concepts

CDR

CLD



Conceptually extended from CLIC detector design

- Full silicon tracker
- High granularity silicon-tungsten ECAL
- High granularity scintilator-steel HCAL
- Instrumented return-yoke for muon detection
- Large 2 T coil surrounding calorimeter system

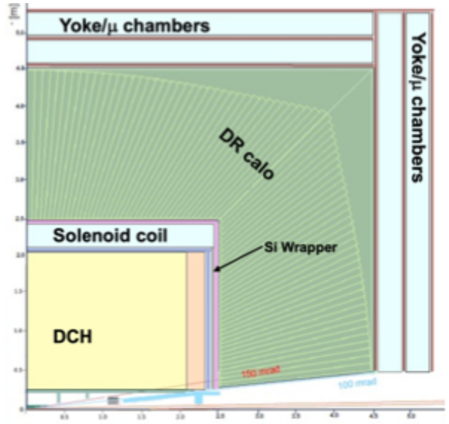
Engineering needed for adaptation to continous beam operation (no power pulsing)

- Cooling of Si-sensors & calorimeters

Possible detector optimisations

- Improved ECAL and momentum resolutions
- Particle identification (TOF and/or RICH)

IDEA



Specifically designed for FCC-ee (and CEPC)

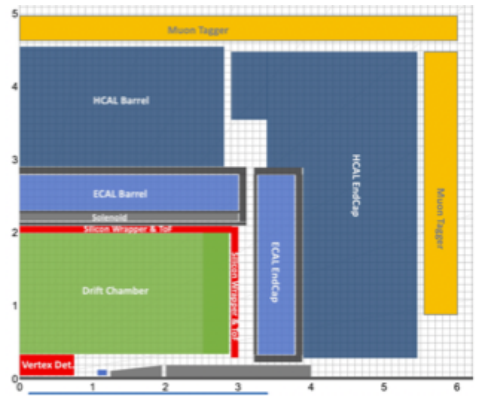
- Silicon vertex detector
- Low X_0 drift chamber with high-resolution particle ID via ionisation measurement
- Silicon wrapper around drift chamber
- Light, thin 2T coil inside calorimeter system
- Pre-shower detector based on MPGC
- Dual-readout calorimeter; copper-scintilating/Cherenkov fibres
- Instrumented yoke with MPGC muon system

Possible detector optimisation

- Much improved EM energy resolution via crystal ECAL in front of coil

Noble-Liquid ECAL based

new



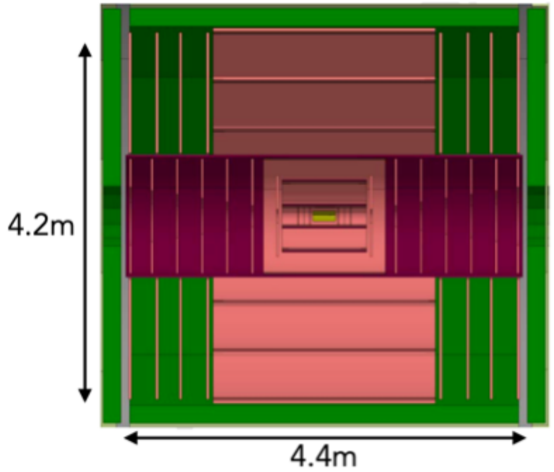
Specifically designed for FCC-ee, recent concept, under development

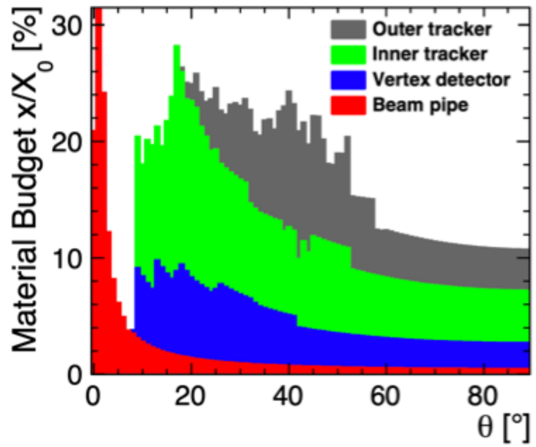
- Silicon vertex detector
- Low X_0 drift chamber with high-resolution particle ID via ionisation measurement
- Light, thin 2T coil inside same cryostat as ECAL
- High granularity Lead/Noble Liquid (LAr, possibly LKr) ECAL
- HCAL and muon systems to be specified

FCC-ee Tracking detectors

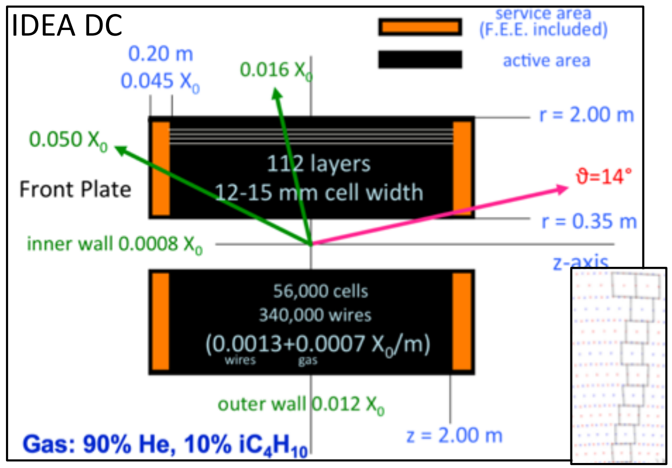
Two solutions under study

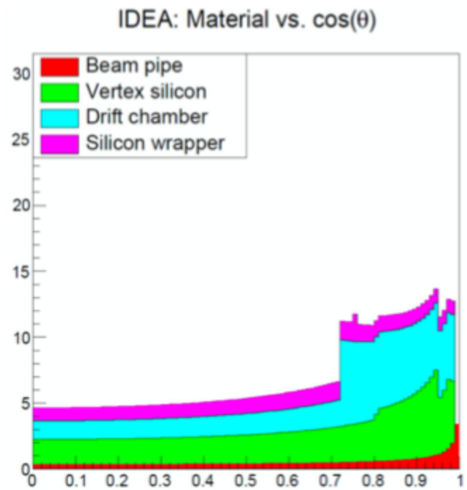
- CLD: All silicon: pixel VTX + strips tracker
  - Inner: 3 (7) barrel (fwd) layers (1% X_0 each)
  - Outer: 3 (4) barrel (fwd) layers (1% X_0 each)
  - Separated by support tube @ r= 675 mm (2.5% X_0)





- IDEA: Extremely transparent Drift Chamber
  - GAS: 90% He – 10% iC_4H_{10}
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of X_0 at 90°
    - Tungsten wires dominant contribution
  - Full system includes Si VXT and Si "wrapper"





FCC-ee calorimeter jet energy resolution

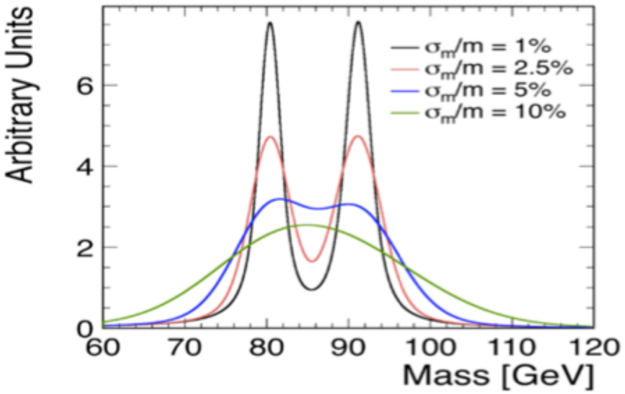
Energy coverage ≲ 180 GeV : 22 X_0, 7λ

Jet energy: $\delta E_{jet}/E_{jet} \simeq 30\% / \sqrt{E}$ [GeV]

⇒ Mass reconstruction from jet pairs

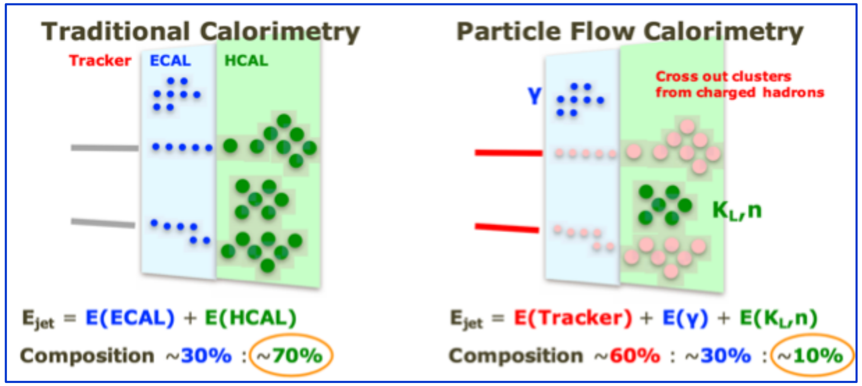
Resolution important for control of (combinatorial) backgrounds in multi-jet final states

- Separation of HZ and WW fusion contribution to ννH
- HZ → 4 jets, $t\bar{t}$ events (6 jets), etc.
- At $\delta E/E \simeq 30\% / \sqrt{E}$ [GeV], detector resolution is comparable to natural widths of W and Z bosons



To reach jet energy resolutions of ~3%, detectors employ

- **highly granular calorimetry**
- **Particle Flow Analysis techniques**



Technologies being pursued

a) **CALICE** like – extremely fine segmentation (ILC, CLIC, **CLD**)
  - ECAL: W/Si or W/scint+SiPM
  - HCAL: steel/scint+SiPM or steel/glass RPC

b) Parallel fiber **dual readout** calorimeter (**IDEA**)
  - Fine transverse segmentation; longitudinal inf. via timing

c) **Noble Liquid** (e.g. **LAr**) ECAL + **CALICE-like** HCAL
  - Fine segmentation, high stability, $\delta E_{EM}/E_{EM} \sim$ 6-9%

FCC-ee ECAL performance

ECAL energy resolutiuon parametrised as

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

with typically

technology	a	b	c
CALICE	15%	-	1%
Fiber DR	10%	-	1%
LAr	8%	-	-
Crystal	3-5%	-	0.5%

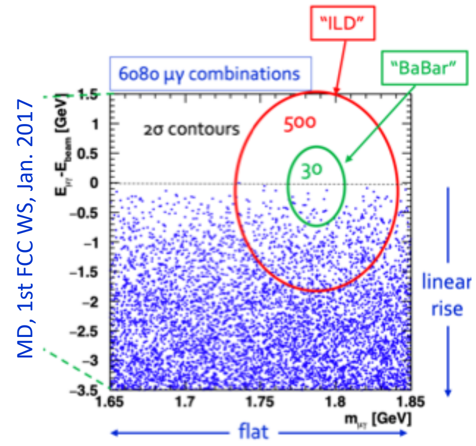
- CALICE-like resolution has been regarded sufficient at linear colliders with emphasis on physics at 250-500GeV
- Improved resolution advantageous for the 90-180 GeV FCC-ee programme

Finely segmented ECAL (transverse and longitudinal) is important for the precise identification of γ's and π^0's in dense topologies, e.g. τ and other heavy flavour physics

Examples:

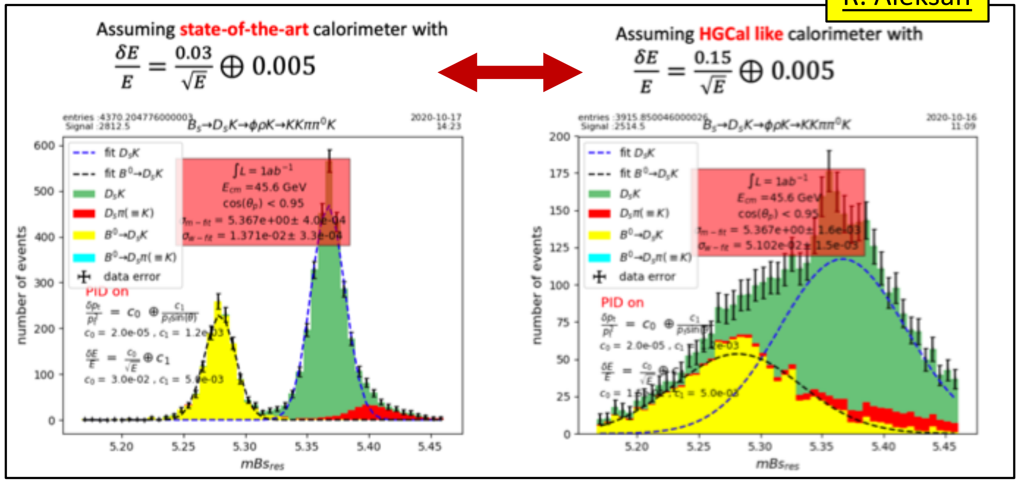
a) Much improved search limits for rare decays involving γ's.

- Here LFV decay $\tau \to \mu\gamma$



b) Much improved b-physics reach by making accesible exclusive channels with π^0's

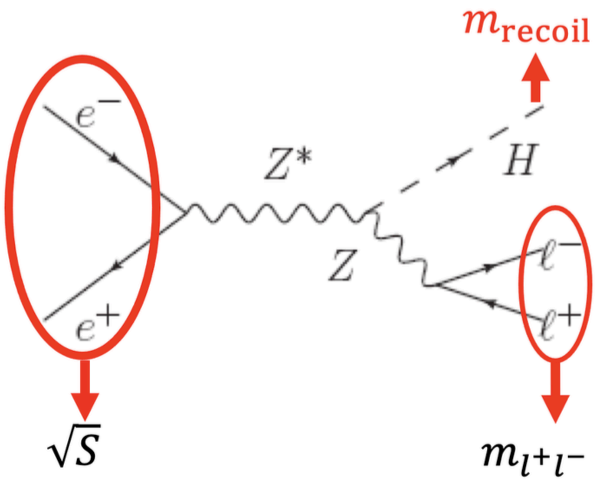
R. Aleksan

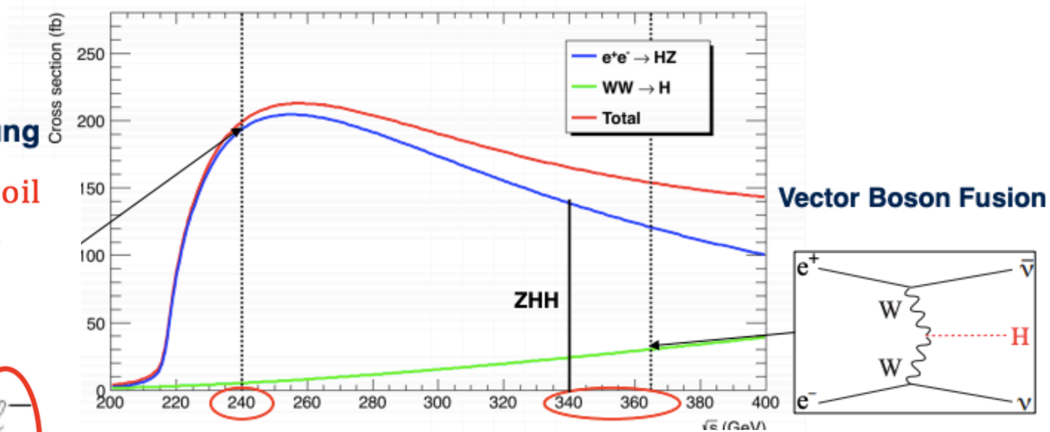


Physics Potential

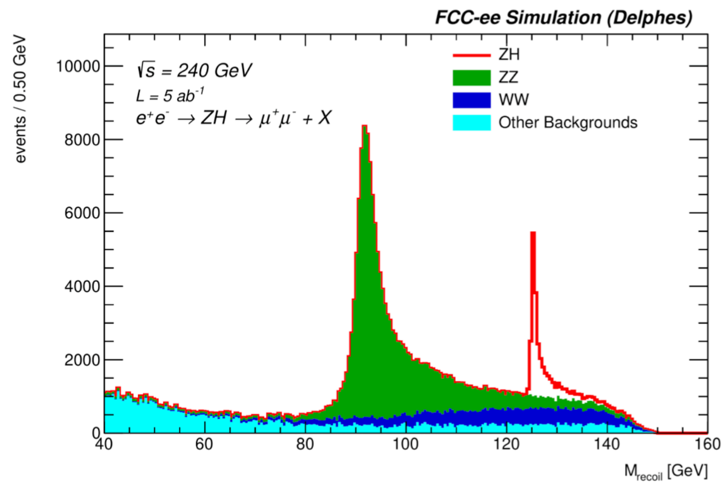
FCC-ee Higgs production & couplings

Higgs strahlung





$$m_{recoil}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2$$



- Allows **model independent** determination of couplings

FCC-ee Higgs couplings precision

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR_{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

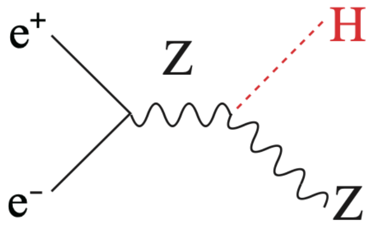
Table from mid-term report

$$\kappa_X = \frac{g_{hXX}}{g_{hXX}^{\mathrm{SM}}}$$

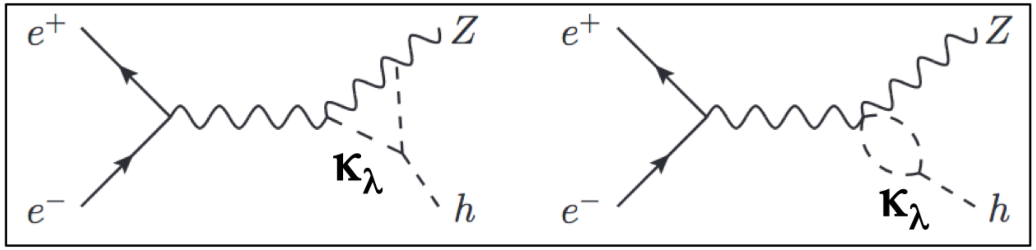
- FCC-ee: Model-independent coupling determination and improvement factor up to 10 compared to LHC
- FCC-hh: produces over 10^{10} Higgs bosons, 10^8 ttH and $2\mathrm{x}10^7$ HH pairs:
  - Improving precision on g_{Htt}, g_{HHH}
  - Access to Rare Decays: $\mu\mu, \gamma\gamma, Z\gamma$
- FCC-ee + FCC-hh is outstanding:
  - All accessible couplings with per-mil precision
  - Self-coupling with few per-cent precision

FCC-ee Higgs self-couplings with single Higgs

σ_{HZ}



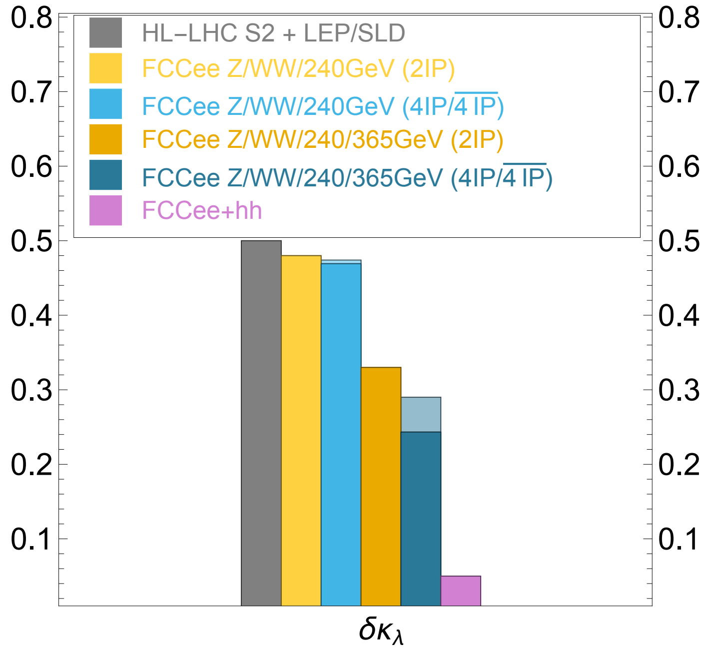
+



$\kappa_\lambda = \lambda / \lambda_{SM}$

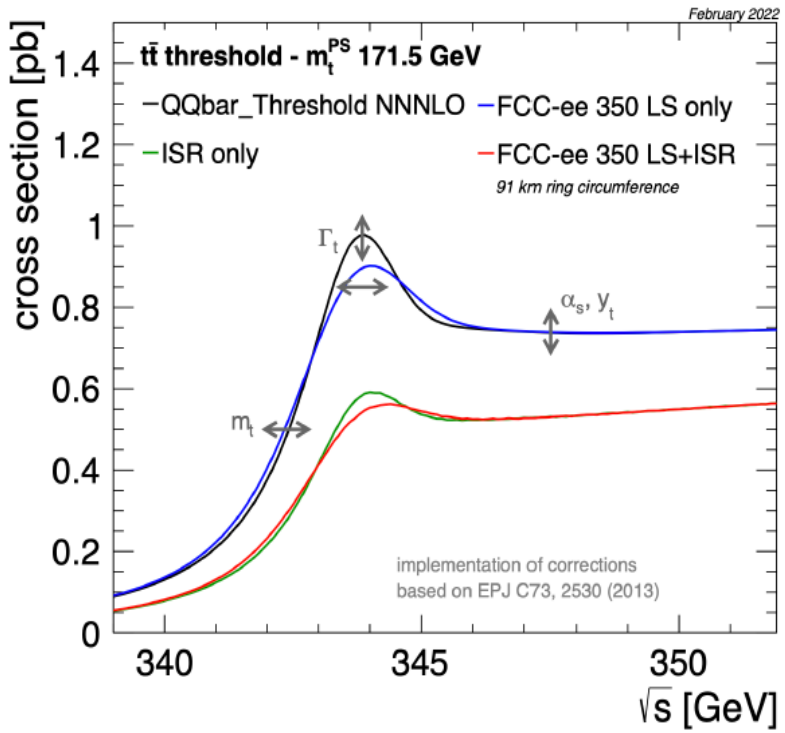
$$\sigma_{\mathrm{i,NLO}} = Z_H \sigma_{\mathrm{i,LO}} (1 + \kappa_\lambda C_{1,i})$$

- The precision of FCC-ee on the ZH cross section measurement (0.1%) allows to exploit the higher order effects from the Higgs self-coupling and have an estimate of $\delta k_\lambda \approx 25\ \%$ with 4IPs (optimised scenario)
- Current estimates suggest that a precise determination with an uncertainty of 3.4 − 7.8% would be within the reach of the 100 TeV pp collider



FCC-ee Top pair-production at 340-365 GeV

- One million ttbar events expected in a clean environment with the ability to scan √s
- Probing the Higgs mechanism through measurement of top mass (m_t) and top Yukawa coupling
  - at FCC-ee, the interpretation of cross-section near threshold would lead to m_t measurement
  - Simultaneous fit of m_t and Γ_t with respective uncertainties of 17 MeV and 45 MeV
  - Scale uncertainty of 45 MeV on m_t at NNNLO
- ttZ coupling extraction from σ ($e^+e^- \rightarrow Z/\gamma^* \rightarrow tt$)
  - Uncertainty ~10 times smaller than at HL-LHC
  - Key input to extract top Yukawa coupling from FCC-ee with reduced theoretical uncertainty



FCC-ee BSM in flavor/tau physics

Particle production (10^9)	B^0	B^-	B_s^0	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	600	170

FCC-ee = 10 x BelleII

Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
EW/H penguins				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu_{mu}$	5%	–	–	3%
$B^+ \to \tau^+\nu_{tau}$	7%	–	–	2%
$B_c^+ \to \tau^+\nu_{tau}$	n/a	–	–	5%
CP / hadronic decays				
$B^0 \to J/\Psi K_S$ ($\sigma_{\sin(2\phi_d)}$)	$\sim 2.*10^6$ (0.008)	41500 (0.04)	$\sim 0.8 \cdot 10^6$ (0.01)	$\sim 35 \cdot 10^6$ (0.006)
$B_s \to D_s^\pm K^\mp$	n/a	6000	~ 200000	$\sim 30 \cdot 10^6$
$B_s(B^0) \to J/\Psi\phi$ (σ_{ϕ_s} rad)	n/a	96000 (0.049)	$\sim 2.10^6$ (0.008)	$16 \cdot 10^6$ (0.003)

boosted b's/τ's at FCC-ee

Makes possible a topological rec. of the decays w/ miss. energy

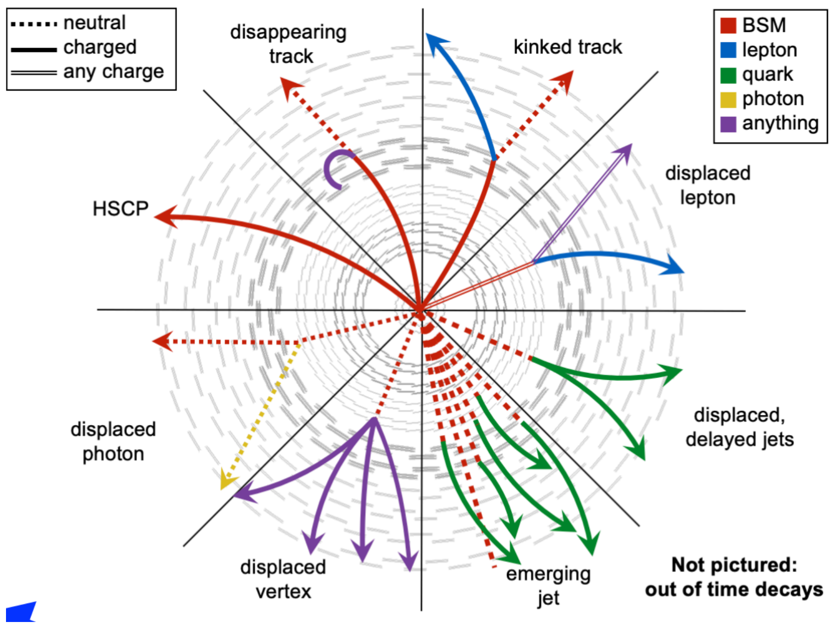
Out of reach at LHCb/Belle

FCC-ee Direct search for feebly interacting particle

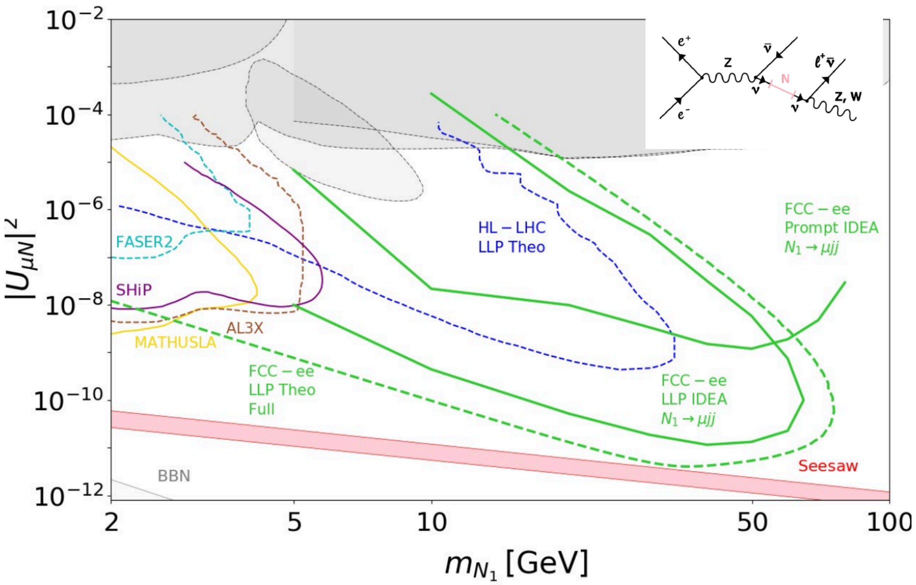
- **Intensity frontier at Tera-Z offers the opportunity to directly observe new feebly interacting particles in a very clean environment**

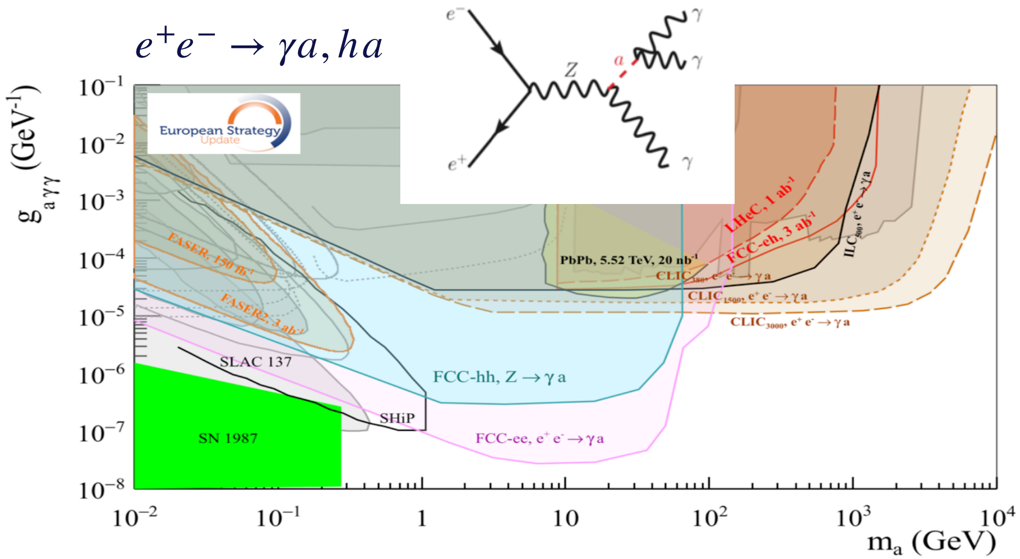
- Design signature driven search for UNUSUAL final states
- Extract novel detector requirement (or additional detectors in the cavern) to fully exploit the possibilities
- Few concrete examples: HNL, ALPS, Dark photons, Higgs exotic decays

Variety of signatures and lifetimes



FCC-ee searches for heavy neutral leptons & ALPS





- **FCC will probe space not constrained by astrophysics or cosmology, complementary to fixed target, neutrino, and 0vbb prospects**

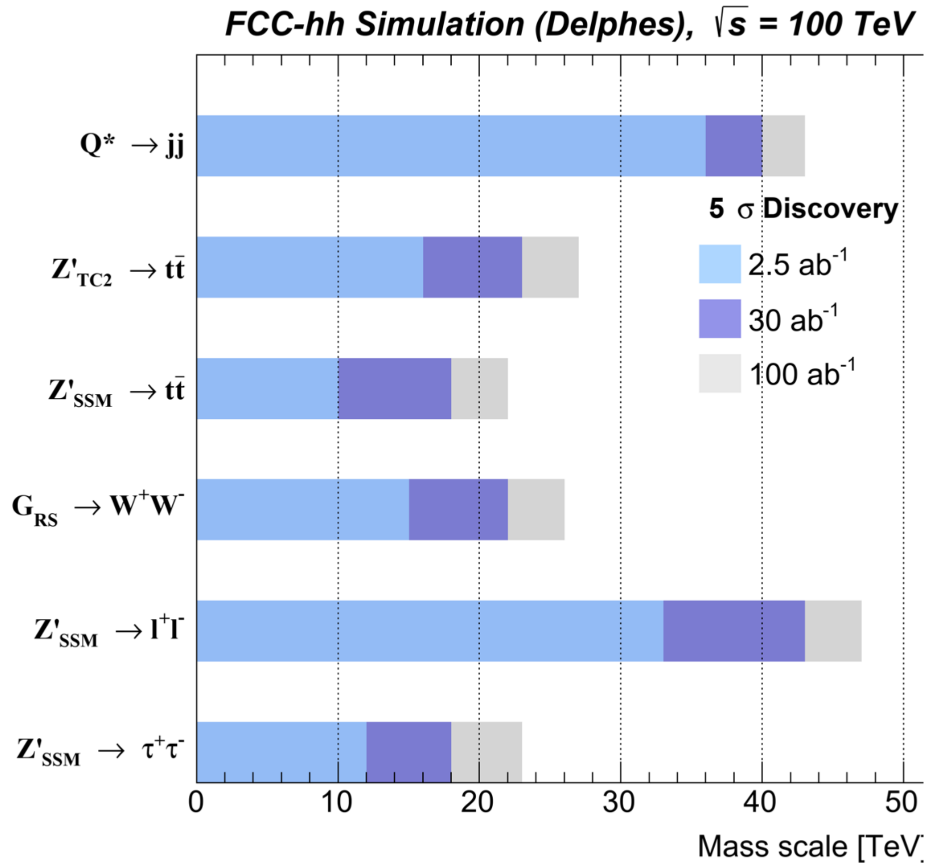
- At the FCC-ee predominantly produced in association with a photon, Z or Higgs boson.
- ALPS might be long-lived when couplings and mass are small

FCC-hh projections

FCC-hh Direct discovery potential

- Higher parton centre-of-mass energy
  ➡ high mass reach:
  - Strongly coupled new particles, new gauge bosons (Z', W'), excited quarks: up to 40 TeV!
  - Extra Higgs bosons: up to 5-20 TeV
  - High sensitivity to high energy phenomena, e.g., WW scattering, DY up to 15 TeV

about x6 LHC mass reach at high mass, well matched to reveal the origin of deviations indirectly detected at the FCC-ee



Summary & Outlook

- FCC-integrated program is well setup and progressing well
- A "Higgs factory" is essential to address the fundamental questions through precision measurement of Higgs couplings
- FCC-ee is an excellent choice here; it also can probe BSM physics directly or indirectly
- Major priority till 2025 is to complete the feasibility study report

Strong collaboration with extended international partners essential for success !

Extras

FCC-hh machine parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} cm^{-2}s^{-1}]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

With FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies

Formidable challenges:

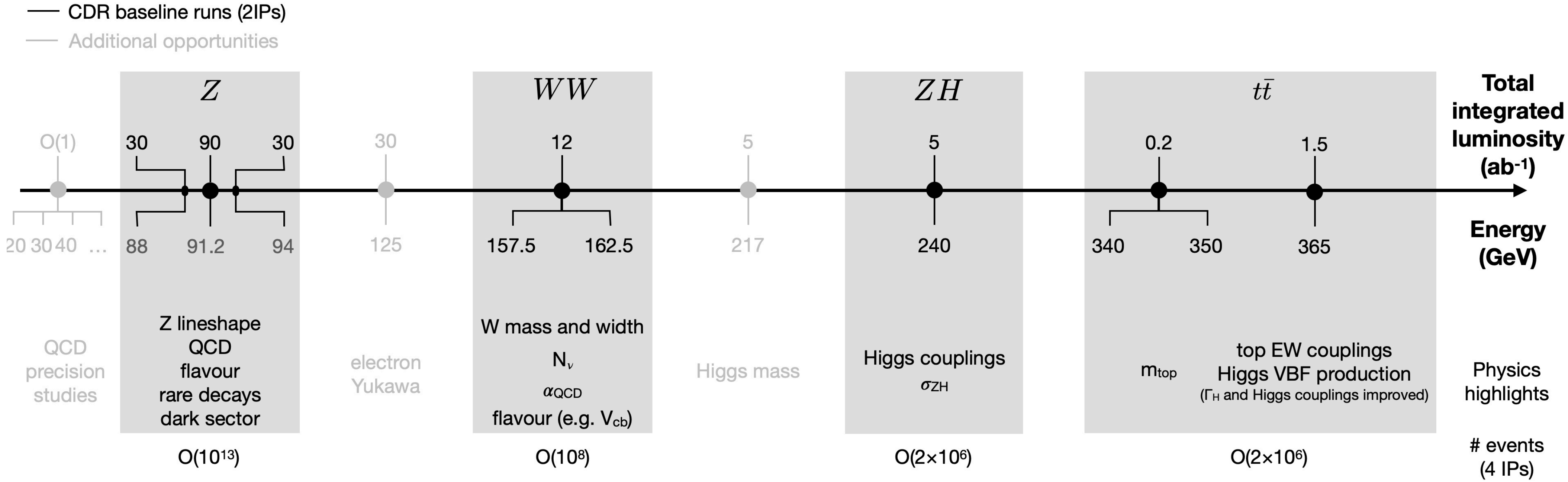
- ❑ high-field superconducting magnets: 14 - 20 T
- ❑ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ❑ stored beam energy: ~ 9 GJ → machine protection
- ❑ pile-up in the detectors: ~1000 events/xing
- ❑ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:

- ❑ Direct discovery potential up to ~ 40 TeV
- ❑ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ❑ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, Zγ, μμ)
- ❑ Final word about WIMP dark matter

F. Gianotti

Collider Programme (and beyond).



- **Opportunities** beyond the baseline plan ($\sqrt{s}$ below Z, 125GeV, 217GeV; larger integrated lumi…)
- **Opportunities** to exploit FCC facility differently (to be studied more carefully):
  - using the electrons from the injectors for beam-dump experiments,
  - extracting electron beams from the booster,
  - reusing the synchrotron radiation photons.

Christophe Grojean