FUTURE
CIRCULAR
COLLIDER

The FCC project

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Ecole de GIF 2025

The Big questions

- What is the origin of Dark Matter / Energy ?
- What is the origin of matter/anti-matter asymmetry ?
- What is the origin on neutrino masses — the flavour puzzle ?
- What is the origin of the Electro-weak symmetry breaking ?
- What is the solution to hierarchy problem ?

The Standard Model does not provide answers to these questions

There is new physics out there (beyond the Standard Model)

New facilities goals

What we cannot deliver:

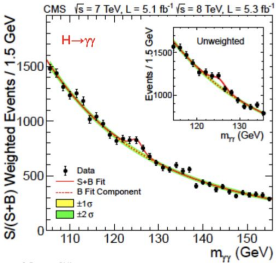
- explore all new physics directions/mass couplings scale
- guarantee discovery

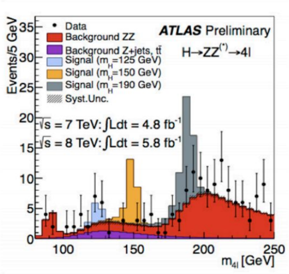
What we can deliver:

- precision
- sensitivity to new as many as possible scenarios of new physics
    - clear yes/no answers to concrete scenarios

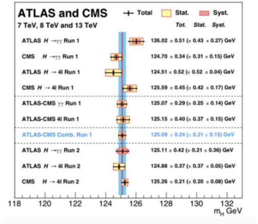
What do we know

- The Higgs boson has been discovered in 2012
    - we have entered the realm of precision!





Higgs mass

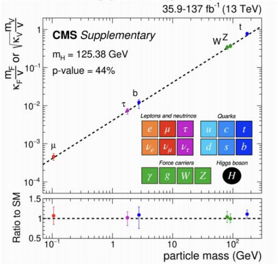


2012 — Discovery

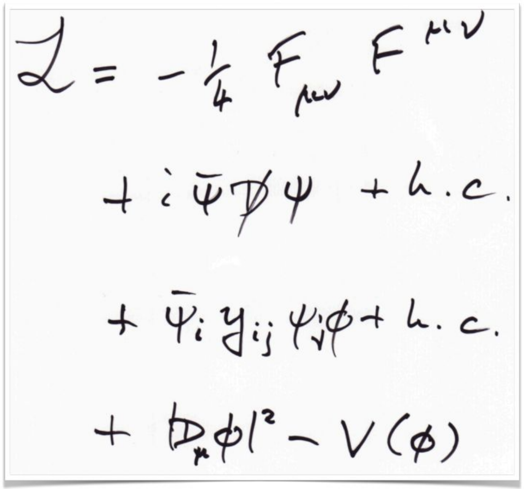
↓

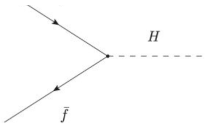
> 2023 — Precision

Higgs couplings



The Higgs Sector

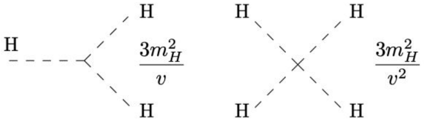




$$\mathcal{L}_{H-f} = -\sum_f \frac{m_f}{v} \bar{f} f H$$

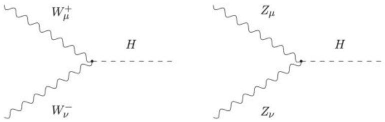
fermion couplings

Higgs potential

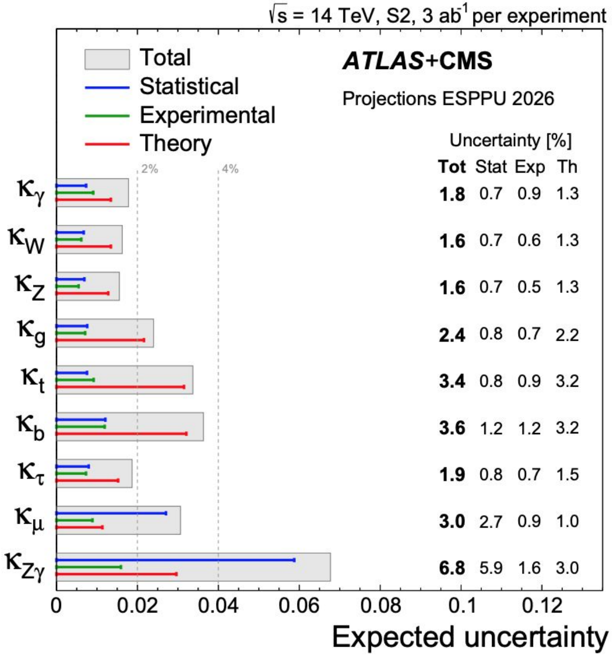


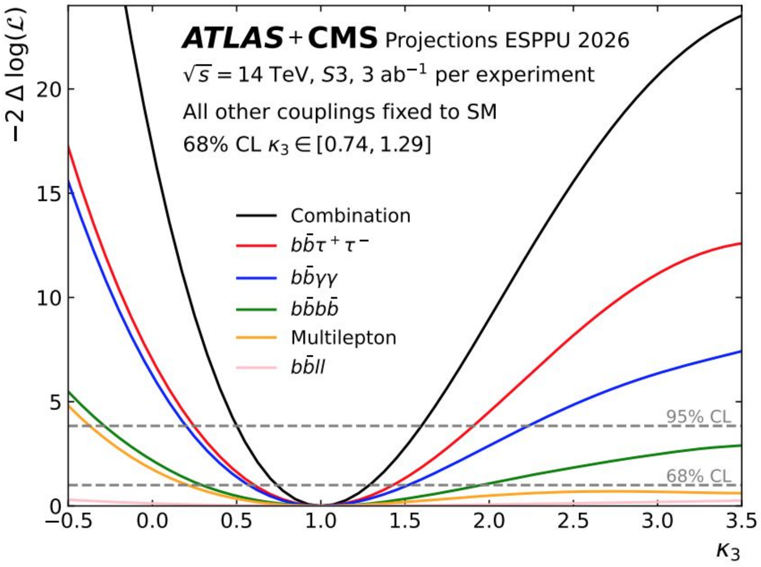
gauge couplings:

$$\frac{2M_W^2}{v}$$



The HL-LHC legacy: Higgs





self-coupling: 30 % precision

Need to go beyond the LHC precision measurements:

$\delta\kappa_X < 1\%$?

- vector boson couplings and 3rd gen III yukawa to ~ 2%
- gen II yukawa ? (except for muons) ~ 100%
- self-coupling ~ 30% (evidence for HH production)
- m_H ~ 30 MeV, Γ_H ~ 25%
- differential measurement in production

What do we know

- The Higgs boson has been discovered in 2012
  - we have entered the realm of precision!

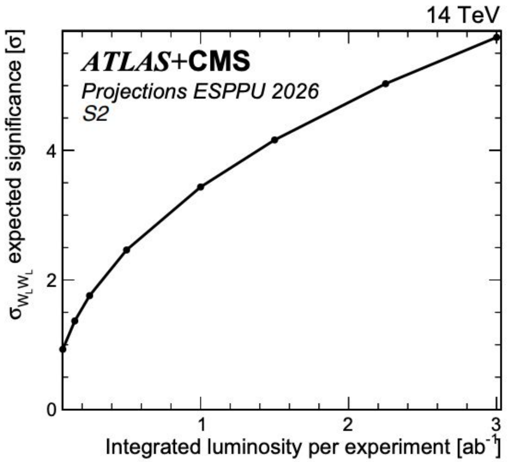
- It is light enough to be abundantly produced in a circular e+e- machine

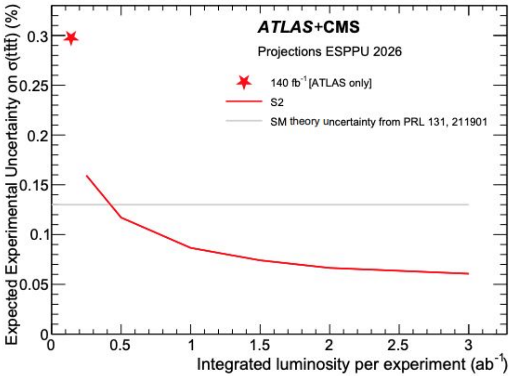
- No new electro-weak NP states found in the 100 GeV-1 TeV range

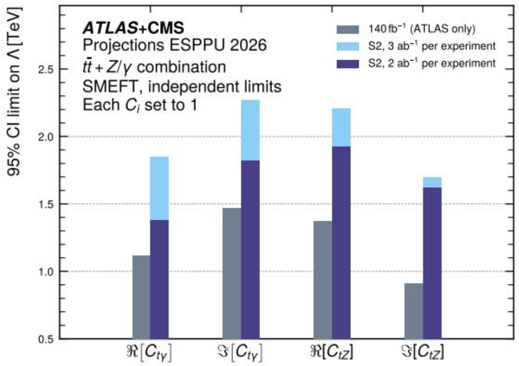
- No strong theoretical guidance on new physics

- The Higgs and EWSB is new physics, it plays a central role in the SM, ought to be measured at permil level precision (as W, Z boson at LEP)

The HL-LHC legacy: EWK and Top







- High Q2 probes
  - Di-boson production ($W_L W_L$ scattering)
  - Precise 4t production (5%)
  - Top EWK couplings (ttZ, tt)
- Precision measurements
  - W mass ~ 5 MeV ? (possibly Z mass, sin θ_W)
  - Top mass ~ 200 MeV ?

Careful! only 5-10% of full LHC dataset analysed so far …

ESPPU 2020

2020 Update of the European Strategy for Particle Physics (link)

> *"**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**."*

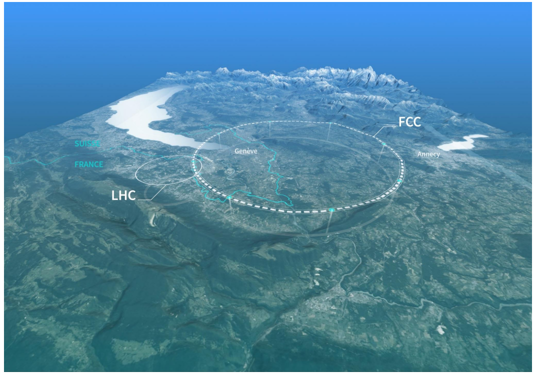
Exactly what the FCC project is addressing

- FCC-ee is an electron positron **Higgs factory (and much more)**
- FCC-hh is a **proton-proton collider** at the highest achievable energy, **using the same tunnel**

The FCC Project

FCC is the proposed post-LHC CERN's flagship 2-stage project (e+e- , pp) to experimentally push the frontiers of the unknown

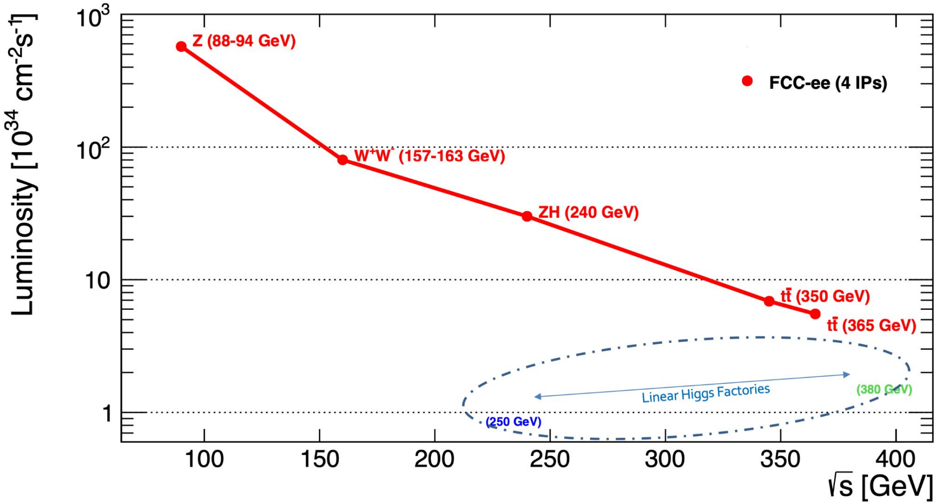
- Baseline accelerator design: 90.7 km, 8 surface points, **4 interaction points**



Possible FCC project timeline. From the perspective of the technical schedule alone, FCC-ee operation could start in 2040 or earlier.

Domain	Cost [MCHF]
Civil engineering	6160
Technical infrastructures	2840
Injectors and transfer lines	590
Booster and collider	4140
CERN contribution to four experiments	290
FCC-ee total	**14 020**
+ Four experiments (non-CERN part)	1300
FCC-ee total, including four experiments	**15 320**

The FCC-ee programme



Exquisite luminosity allows for ultimate precision:

- 10^5 larger dataset than LEP at the Z-pole, enables:
  - 300x improvement in statistical precision in EWPO
  - 10x larger statistics vs. planned flavor factories
  - ultra-feebly interactive particle searches up to m_Z
- ~ millions of extremely clean H and Top, allow:
  - [0.1-1%] H, top couplings precision
  - mass and width 10x better precision than LHC

Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^8 WW	2.2×10^6 ZH + 65k WW $\to$ H	2×10^6 $t\bar{t}$ + 370k ZH + 92k WW $\to$ H	

Flexible running sequence

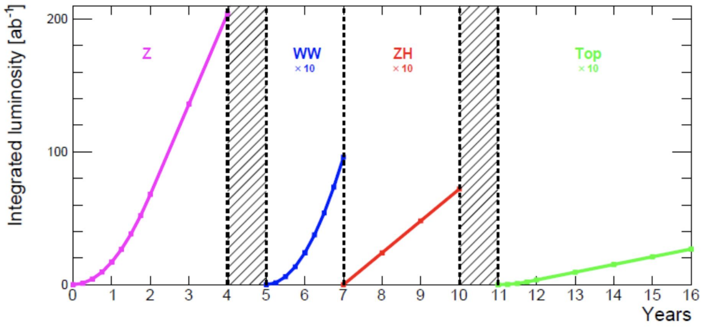
Previous situation: different RF configurations for Z and WW/ZH

- ❑ Hard choices about which run come first
- ❑ 1 year shut down between runs…

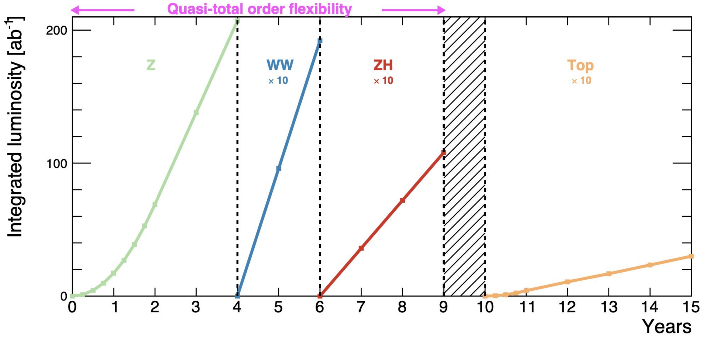
Recent developments enabled **flexible running sequences of Z/WW/ZH, without shut down**

- ❑ Very short run (weeks) at the Z for commissioning/calibration (most challenging mode), go straight for the full ZH run, come back to the Z after

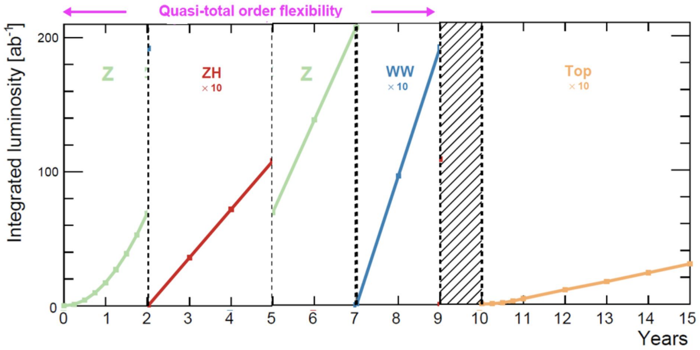
Before



Now



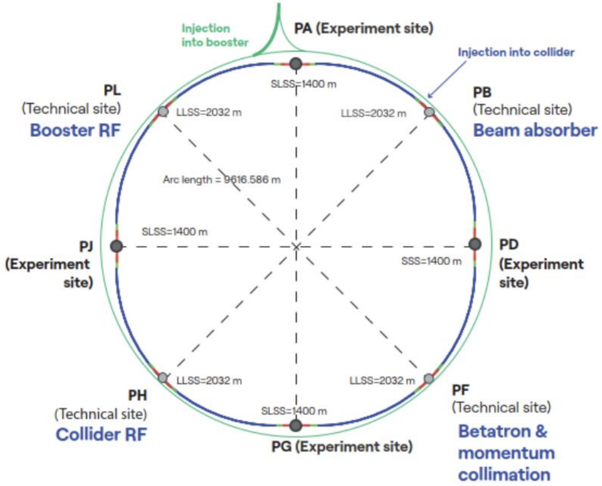
Or



Or …

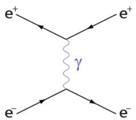
FCC-ee accelerator complex

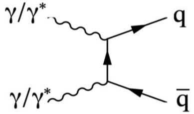
parameter	Z	WW	H (ZH)	$t\bar{t}$
beam energy [GeV]	45.6	80	120	182.5
synchrotron radiation/beam [MW]	50	50	50	50
beam current [mA]	1294	135	26.8	5.1
number bunches / beam	11200	1852	300	64
total RF voltage 400/800 MHz [GV]	0.08 / 0	1.0 / 0	2.09 / 0	2.1 / 9.2
luminosity / IP [10^{34} cm^{-2}s^{-1}]	145	20	7.5	1.4
total integrated luminosity / IP / year [ab^{-1} / yr]	17	2.4	0.9	0.17
beam lifetime [min]	21	13	9	10



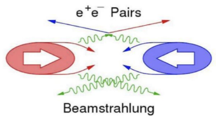
- ❑ Double ring (Top-up injection scheme), many bunches (x200 vs LEP) , larger radius → higher current
- ❑ Strong focusing optics with Crab-waist collision scheme (DAFNE, SuperKEKB)
- ❑ Flexible RF (2 cell 400 MHz) that allows to run with same collider between Z and ZH threshold

Detector requirements - general considerations



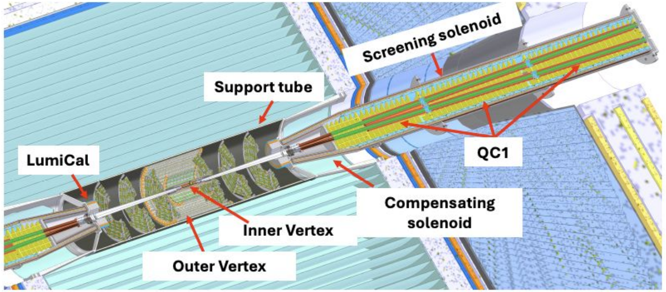


- Requirements for Higgs and above have been studied to some extent by LC:
    - we want a detector that is able to withstand a **large dynamic range**:
        - in energy ($\sqrt{s}$ = 90 - 365 GeV)
        - in luminosity (L = 10^{34} - 10^{36} cm^2/s)



- most of the **machine induced limitations are imposed by the Z pole run**:
    - large collision rates ~ 33 MHz and continuous beams
        - no power pulsing possible
    - large event rates ~ 100 kHz
        - **fast detector response / triggerless** design challenging (but rewarding)
        - **high occupancy** in the inner layers/forward region (Bhabha scattering/incoherent pair production/ γγ hadrons)
    - beamstrahlung

- **complex MDI:** last focusing quadrupole is ~ 2.2m from the IP
    - magnetic field limited to B = 2T at the Z peak (to avoid disrupting vertical e SR)
        - **limits the achievable track momentum resolution**
    - “anti”-solenoid
        - limits the acceptance to ~ 100 mrad



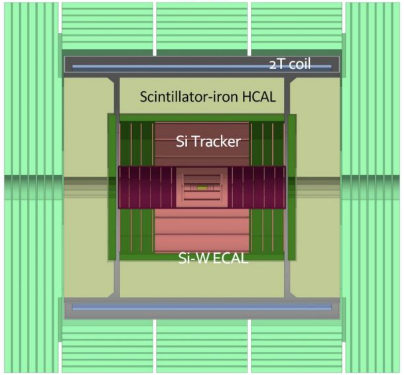
→ mostly affect Z pole, measurements, in principle 3T field is possible at $\sqrt{s}$ = 240 GeV

FCC-ee Detectors Embryos

Several detectors are being designed, more to come (software plug-and-play)

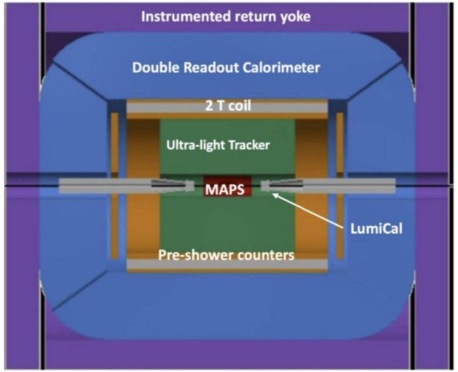
- A lot of detector R&D targeting FCC-ee detectors, organised by DRD's (more in this talk)

CLD



- Full silicon vertex + strip tracker
- CALICE-like 3D-imaging high-granular calorimetry with Si-W for ECAL and Sci-iron for HCAL
- Muon system with RPCs
- Coil outside of calorimeters

IDEA

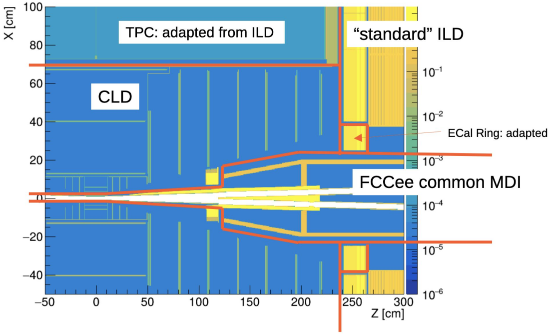


- Silicon vertex + ultra-light tracker
- Monolithic dual readout calorimeter with Cu-fibers (possibly augmented by dual-readout crystal ECAL)
- Muon system with µ-RWELL
- Coil inside calorimeters

ALLEGRO

- Silicon vertex + ultra-light tracker
- High granularity noble liquid ECAL (LAr or LKr with Pb or W absorbers)
- CALICE-like or TileCal-like HCAL
- Muon system
- Coil outside of ECAL

ILD for FCC-ee



ILC baseline of ILD: TPC, inner Si-Tracking, SET, SiW Ecal, SciFeHCal

ILD for FCCee - v01: TPC, inner and fwd tracking from CLD (squeezed), standard FCC-MDI region

FCC-ee Physics Potential

ESPPU submissions / feasibility Study

PED group also submitted 7 documents (10 pages) as input to the strategy discussions:

Manifesto: https://doi.org/10.17181/3kaxg-ejn91

EW, Higgs, Top: https://doi.org/10.17181/n78xk-qcv56

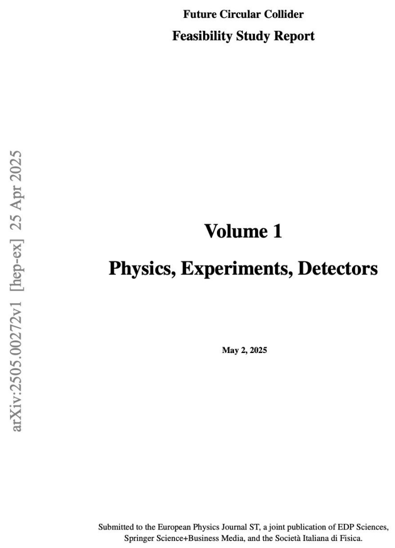
BSM: https://doi.org/10.17181/69m03-zzb95

QCD: https://doi.org/10.17181/nfcpy-vns54

Flavour: https://doi.org/10.17181/jnzpp-1fw39

FCC-hh: https://doi.org/10.17181/bzhc2-mem17

Detector EoIs: http://dx.doi.org/10.17181/wr1sy-dbk95



Future Circular Collider

Feasibility Study Report

Volume 1

Physics, Experiments, Detectors

May 2, 2025

Submitted to the European Physics Journal ST, a joint publication of EDP Sciences, Springer Science+Business Media, and the Società Italiana di Fisica.

arXiv:2505.00272v1 [hep-ex] 25 Apr 2025

I will cover mostly (and partially) Physics and Detectors in this talk …

[CDS, arXiv:2505.00272]

Physics landscape at the FCC-ee

FUTURE CIRCULAR COLLIDER

Higgs
factory

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

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

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

Detector requirements at the FCC-ee

FUTURE CIRCULAR COLLIDER

Higgs
factory

track momentum resolution (low X_0)

IP/vertex resolution for flavor tagging

PID capabilities for flavor tagging

jet energy/angular resolution (stochastic and noise) and PF

Flavor
"boosted" B/D/τ factory:

track momentum resolution (low X_0)

IP/vertex resolution

PID capabilities

Photon resolution, pi0 reconstruction

QCD - EWK
most precise SM test

acceptance/alignment knowledge to 10 μm

luminosity

Momentum resolution

BSM
feebly interacting particles

Large decay volume

High radial segmentation
- tracker
- calorimetry
- muon

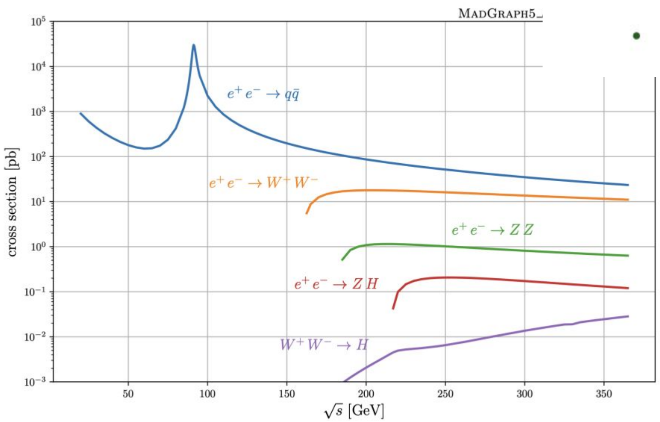
impact parameter resolution for large displacement

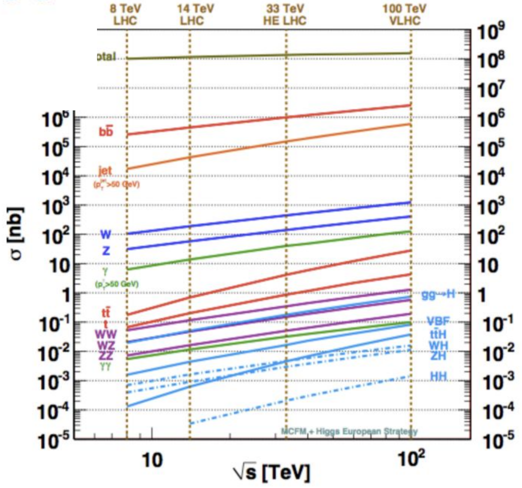
timing

triggerless

collisions e$^+$e$^-$ vs. pp

- Physics background are "small" in e$^+$e$^-$
  - s-channel ~ 1/s
  - t-channel ~ log s





S/B 10^{-2} at e$^+$e$^-$

10^{-10} at hadron colliders

- FCC-ee offers ideal environment for Higgs physics
- large rates (> 10^6)
  - allows to access "abundant" decay modes
- clean exp. environment
  - (no UE, Pile-up, low event rate - trigger less)
- Large S/B (no QCD background)
- Energy, momentum constraints
- small PDFs, QCD theory uncertainties
- Luminosity uncertainties can be neglected (< 10^{-3})

- FCC-hh very large rate , > 10^{10} Higgs bosons produced
  - allows to access rare decays, rare production modes (eg ttH, HH)
- Large backgrounds
- In some cases Higgs physics can be studied in the boosted regime to limit impact of systematics, backgrounds
- Exploit ratios to cancel correlated systematics

Precision Physics at the Tera Z

FCC-ee **Z-pole run**: **a gigantic leap towards the unknown**

- The whole LEP dataset is produced every ~ 30 seconds!
- 10^5 x LEP dataset in total
  - > 100 x reduction in stat. uncertainty
  - **10 x increase in physics reach**
    - $\Lambda \sim \delta O^{-½} \sim \mathcal{L}^{-1/4}$ for dim-6

Precise measurements are discovery tools:

- Loop corrections from heavy particles
- LEP/SLC hinted at the existence of the top and Higgs, and estimated their mass
  - $M_t \sim 170 \pm 10$ GeV, (114 <) M_H < 200 GeV

Main Challenge:

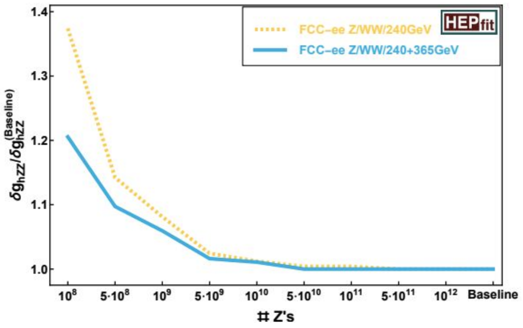
- bring systematics down to stat. level
- designing accelerator with required specifications

Observable	present value	±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}$ ($\times10^6$)	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times10^3$)	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate
R_ℓ^Z ($\times10^3$)	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2)$ ($\times10^4$)	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit
σ_{had}^0 ($\times10^3$) (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement
N_ν($\times10^3$)	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement
R_b ($\times10^6$)	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{FB}^{b,0}$ ($\times10^4$)	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ ($\times10^4$)	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	±	0.09	**0.002**	0.02	estimator bias, ISR, FSR
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	±	0.04	**0.00007**	0.003	PID, π^0 efficiency
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2)$ ($\times10^4$)	1 010	±	270	**2**	2	Combined R_ℓ^W, Γ_{tot}^W fit
N_ν ($\times10^3$)	2 920	±	50	**0.5**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172 570	±	290	**4.2**	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	±	190	**10**	6	From $t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.015**	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
ttZ couplings		±	30%	**0.5–1.5 %**	small	From $\sqrt{s} = 365$ GeV run

Why EWK precision at intensity frontier?

- Potential to test the consistency of the SM via loop corrections
  - $\sin^2\vartheta_W^{eff}$, m_W and other EWPOs parametrically depend on:
    - $\alpha_{QED}(m_Z)$, m_{top}, m_Z, $\alpha_S(m_Z)$, …
      - great precision is needed on these parameters to interpret potential deviations in terms of new physics
      - impacts Higgs precision physics
      - best to have many EWPOs to explore nature of BSM 'signals'
- Programmes
  - Z lineshape:
    - m_Z, Γ_Z, $A_f(\sin\vartheta_W^{eff})$, $R_\ell = \Gamma_{had}/\Gamma_\ell$, $R_q = \Gamma_{qq}/\Gamma_{had}$, σ^0_{had}
    - $\alpha_{QED}(m_Z)$, $\alpha_S(m_Z)$
      - LCF: from lattice
      - FCC-ee, LEP3: direct measurement + Lattice
  - WW threshold (and above)
    - m_W, Γ_W, BR($W \to \ell\nu$), $\alpha_S(m_Z)$, triple/quartic gauge couplings

[2505.00272]



Luminosity/acceptance

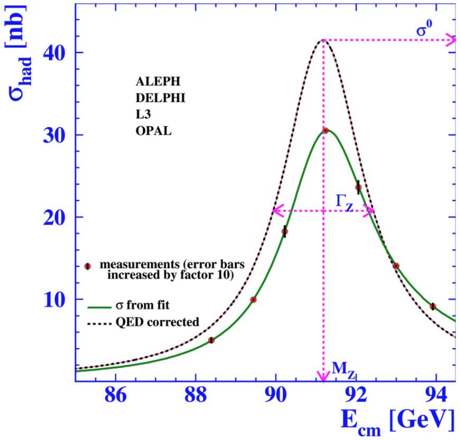
- All **absolute cross-section measurements** rely on precise determination of the **luminosity** uncertainty
  - the ultimate statistical precision
    - 10^{-6} (Z pole) -- 10^{-3} (ZH, top threshold)

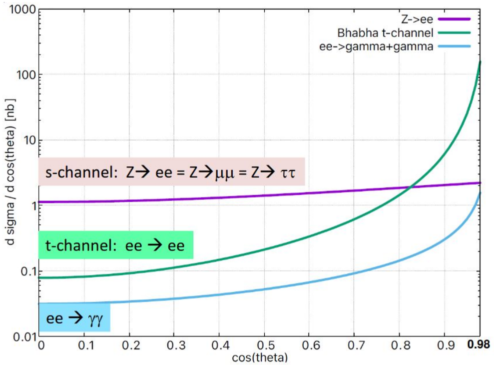
- Contrary to pp, can measured in situ via well (very) known processes
  - di-photon : $e^+e^- \to \gamma\gamma$ ($\delta\sigma_{stat}/\sigma \backsim 10^{-5}$)
    - di-photon: pure QED corrections up to 3-loops

- Theory Challenges:
  - bhabha : $e^+e^- \to e^+ e^-$ ($\delta\sigma_{TH}/\sigma \backsim 10^{-4}$)
    - large systematics from higher order corrections: low energy vacuum polarisation, EW, QED

- Experimental Challenges:
  - require exquisite **control of acceptance**:
    - detector components positioning to 1-10 μm
    - alignment and monitoring to ensure stability
      - physics μμ, e+e-, γγ events using kinematic from well known **initial state and beam constraints (crossing angle)** will be extremely valuable
      - **full potential to be established!**

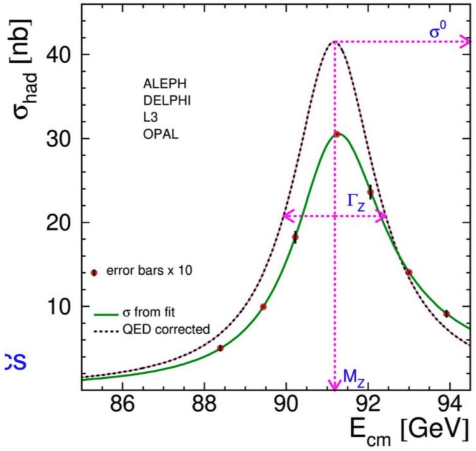
[ADLO+S, Phys. Rept. 427 (2006) 257]

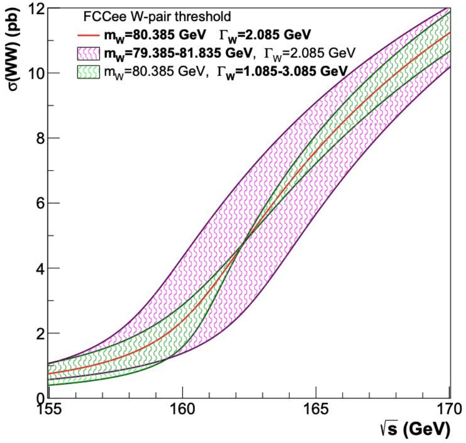




Challenges for precision masses and widths

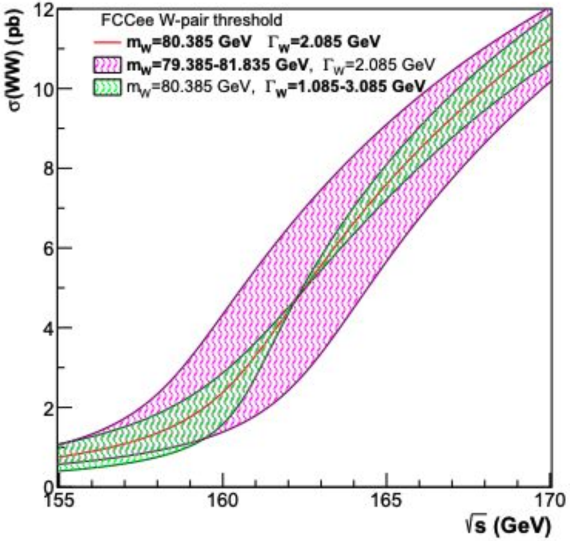
- The statistical precision for precise mass and width determination of Z, W and top is **20-50x better than LHC** (and LEP)
    - e.g **δm_W ~ 200 keV** (reminder: latest CMS δm_W ~ 9.9 MeV)
- Matching such precision requires extraordinary knowledge of beam related parameters
- **Mass** precision determination (m_Z, m_W, m_H, m_t)
    - dominant uncertainty is **absolute knowledge of √s**
        - √s <= $2m_W$ → resonant depolarisation (unique to e+e- colliders)
        - √s > $2m_W$ → monitor using in situ physics events
            - from physics Z(μμ)ɣ events, WW?
                - dominant systematics for m_H,m_t
- **Width** precision determination (Γ_Z), dominant systematics can be constrained in situ with μμ pairs
    - **beam energy spread/ relative "point-to-point" √s** uncertainty
        - Impose **tight requirements** on
            - Tracking momentum resolution (single point, B field, material budget)
            - Momentum scale stability (to monitor with B probes or low mass resonances)
            - Optimal analysis techniques still to be developed





WW threshold mass (and width)

arXiv:2107.04444



- Mass (I) Measure WW production as a function of sqrt(s)

$$\Delta m_{\mathrm{W}}(\mathrm{T}) = \left(\frac{d\sigma_{\mathrm{WW}}}{dm_{\mathrm{W}}}\right)^{-1} \Delta\sigma_{\mathrm{WW}}(\mathrm{T}).$$

$$\Delta m_{\mathrm{W}}(\mathrm{E}) = \left(\frac{d\sigma_{\mathrm{WW}}}{dm_{\mathrm{W}}}\right)^{-1} \left(\frac{d\sigma_{\mathrm{WW}}}{dE_{\mathrm{CM}}}\right) \Delta E_{\mathrm{CM}},$$

THEORY CHALLENGES
(full NNLO EWK calculation)

Δm_W ~ 200 keV (x50)

- Mass (II)
  - Kinematic fit above threshold (using qqlv events)
    - requires also excellent knowledge of sqrt(s) res.depol
    - lepton momentum scale (calibrated also via radiative return Z events)

- Many more opportunities:
  - V_{cb}, V_{cs}, etc …
  - Leptonic BRs > 100x better than today

Observable	present value	±	uncertainty	FCC-ee **Stat.**	FCC-ee syst.	Comment and leading uncertainty
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	WW threshold scan Beam energy calibration
$\mathcal{B}(W \to e\nu_e) \times 10^4$	1071	±	16	**0.13**	0.10	From WW and ZH threshold luminosity
$\mathcal{B}(W \to \mu\nu_\mu) \times 10^4$	1063	±	15	**0.13**	0.10	From WW and ZH threshold luminosity
$\mathcal{B}(W \to \tau\nu_\tau) \times 10^4$	1138	±	21	**0.13**	0.15	From WW scan ZH threshold luminosity
$g_Z^{\nu_e}$	1.06	±	0.18	**0.007**	small	From WW threshold

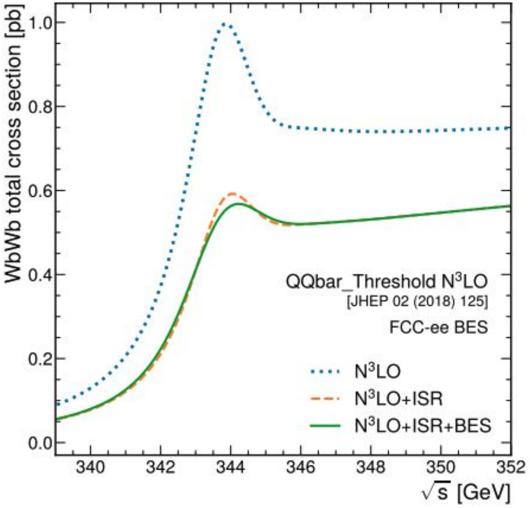
Top quark physics

THEORY CHALLENGES
(full N4LO needed)

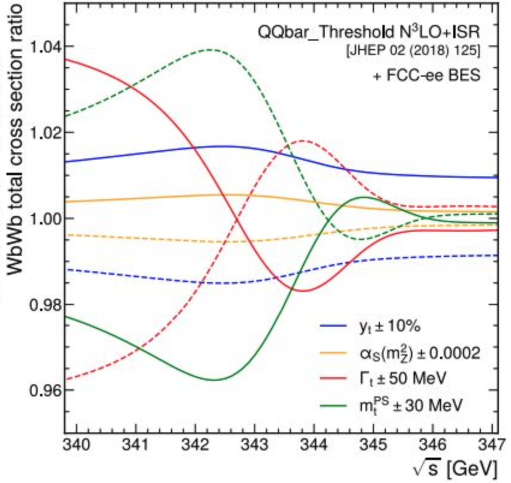
- Similar to WW threshold (and Z pole), top mass, width, and top yukawa can simultaneously determined by measuring the WbWb production cross section as a function of sqrt(s)

- Additional (TH) difficulty: top bound state (~ toponium)

arXiv:2503.18713



Observable	present value	±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_{top} (MeV)	172 570	±	290	**4.2**	4.9*	From $t\bar{t}$ threshold scan parametric, beam calibration
Γ_{top} (MeV)	1 420	±	190	**10.0**	6.0*	From $t\bar{t}$ threshold scan parametric, beam calibration
y_{top}		±	10%	**1.5%**	1.5%*	From $\sqrt{s} = 365$ GeV run paramteric, beam calibration
g_{ttZ} (L-R)		±	10-30%	**0.5–1.5 %**	small	From $\sqrt{s} = 365$ GeV run



- Much more can be done at 365 GeV, notably gL, gR ttZ coupling to 1% level precision
  - Required for ttH interpretation at the FCC-hh (see later)
- Vts to few percent

QCD

Z-pole run: Perfect lab to **study QCD** (fragmentation, jet substructure)

- α_S standard model prediction:

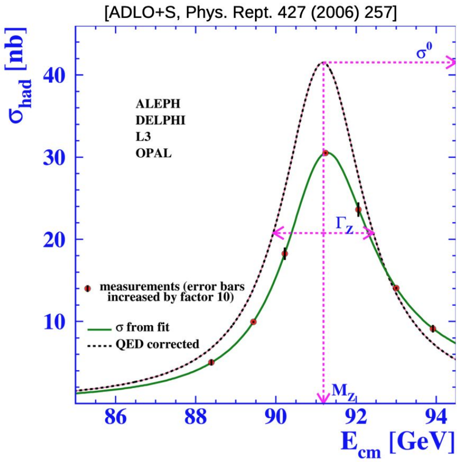
$$R_{W,Z}(Q) = \frac{\Gamma^{had}_{W,Z}(Q)}{\Gamma^{lep}_{W,Z}(Q)} = R^{EW}_{W,Z}\left(1 + \sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{mix} + \delta_{np}\right)$$

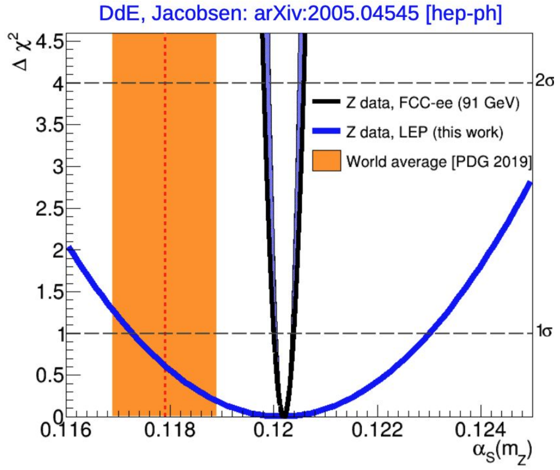
  - Known at N3LO QCD, 2-loop EW corrections
  - Experimentally, expected precision on α_S at permil level

$\alpha_s(m_z) = 0.12030 \pm 0.00028$ **(±0.2%)**

10x improvement

- High order NNLL tuning of shower (q vs gluon discrimination)
- Fragmentation functions
- Jet shapes …





Flavor

Z-pole run: Perfect lab to **study Flavor**

Large abundance of B, D, tau production

Particle species	B^0	B^-	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield (10^9)	740	740	180	160	3.6	720	200

Also LHC(b) produces large amounts of heavy flavors, but at FCC-ee:

- Large (central) boost
- Large geometrical acceptance (favours final states with neutrinos)
- Clean environment (favors final states with π^0)

Attribute	$\Upsilon(4S)$	pp	Z
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
High geometrical acceptance	✓		✓
Low backgrounds	✓		✓
Flavour-tagging power	✓		✓
Initial-energy constraint	✓		(✓)

about 15x anticipated Belle II statistics

Flavor

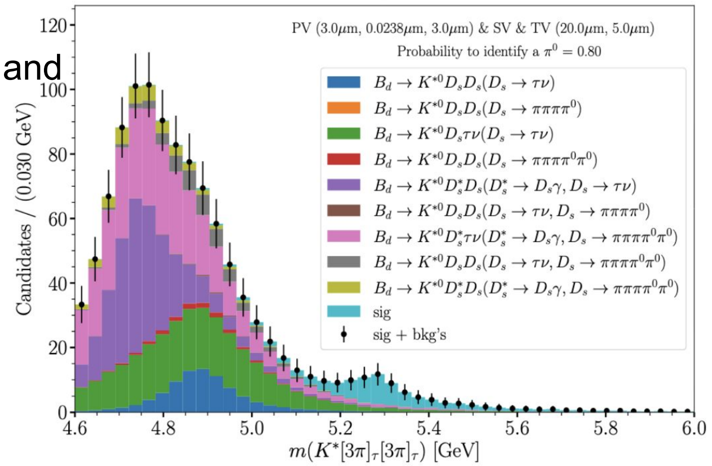
Observation of B → K* **ττ** possible at FCC-ee (impossible at Belle II and LHCb)

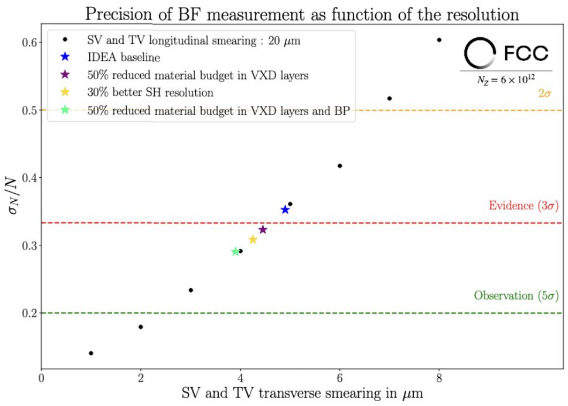
Requires 2-3 μm impact parameter resolution (e.g ALICE - ITS3) and excellent PID capabilities

- allows for clean secondary and tertiary vertex reconstruction

Much more to study:

- other b → s transitions (LFU test)
  - B → K* ee (**$\mu\mu$**)
  - B → K* νν
  - B_s → **ττ**, νν ..
- CP violation in D0 → π^0 π^0 , charm mixing
- **τ** physics (10x or more)
  - Mass, lifetime
  - LFU, LFV

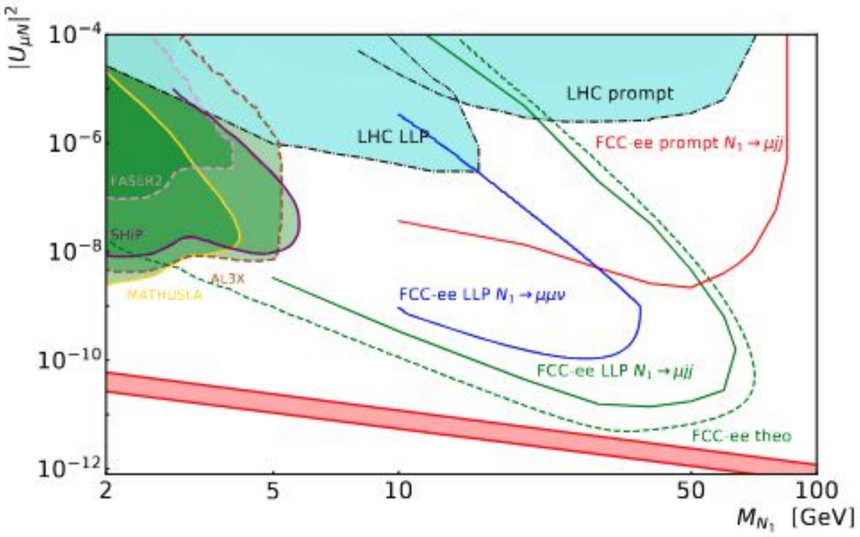




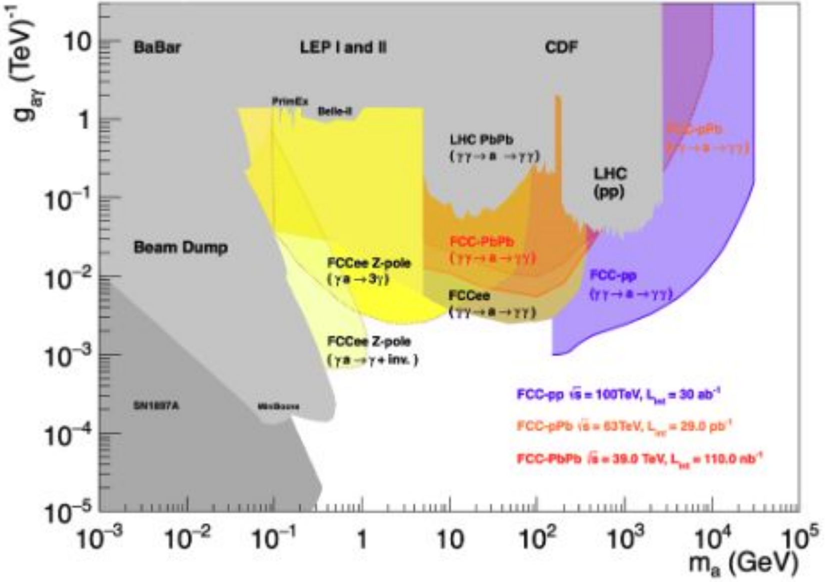
Feebly interacting particles

At the Tera Z can discover light states (possibly feebly coupled and long-lived)

- Highly segmented tracking/calorimetry (pointing needed)



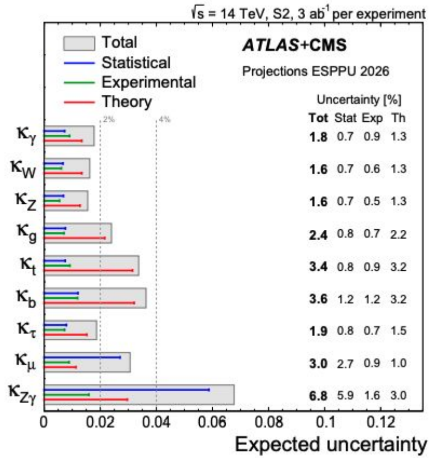
Heavy Neutral leptons (HNL)



Axion-like particles (ALPs)

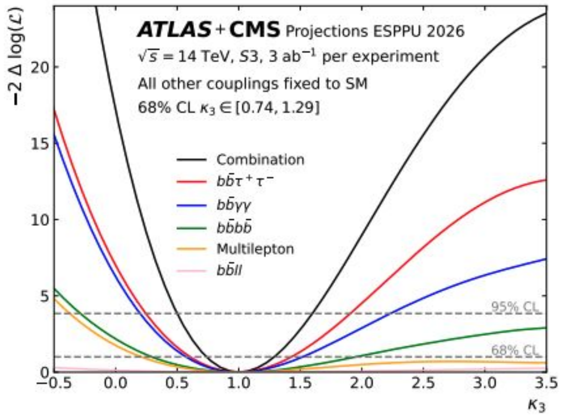
Higgs Physics at FCC-ee

- The Higgs is unique: connected to many of the SM open questions, and possibly to cosmology
- It is also the least known…
  - ❑ (HL-)LHC will improve the situation, but a lot of room for improvement will remain
    - ❑ And (HL-)LHC results are model-dependent



Need to go beyond the LHC precision measurements

$\delta\kappa_X < 1\%$?



- vector boson couplings and 3rd gen III yukawa to ~ 2%
- gen II yukawa ? (except for muons) ~ 100%
- self-coupling ~ 50%
- m_H ~ 30 MeV, Γ_H ~ 25%

Higgs Physics at FCC-ee

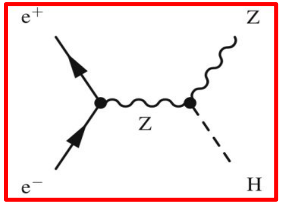
FCC-ee offers broad potential for precision Higgs measurements

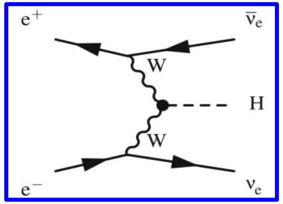
- Higgs factory: production of 2 million Higgs bosons
- Clean environment
- Relative small backgrounds, high S/B

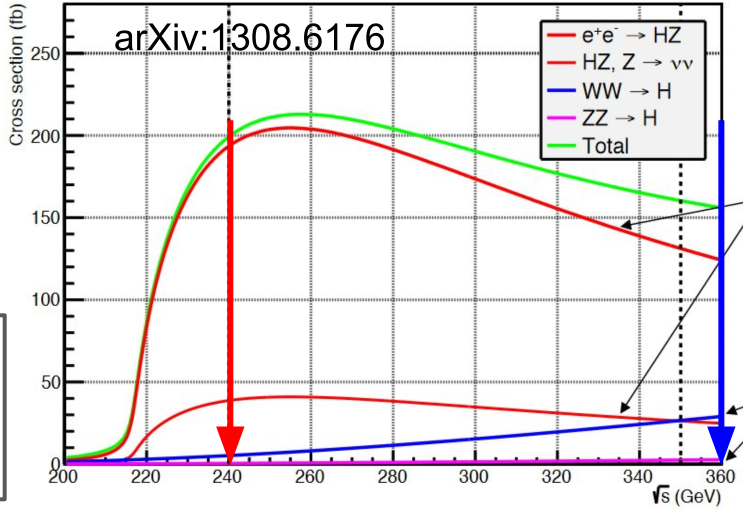
Total Higgs production @ FCC-ee (baseline – 4 IP)		
Threshold	ZH production	VBF production
240 GeV / 10.8 ab^{-1}	2.2 M	65 k
365 GeV / 3.1 ab^{-1}	0.37 M	0.92 M

Main production mechanisms

- **ZH production** "Higgs–strahlung"
- **Vector boson fusion** (VBF), WW dominant

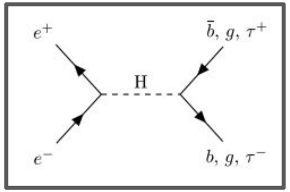




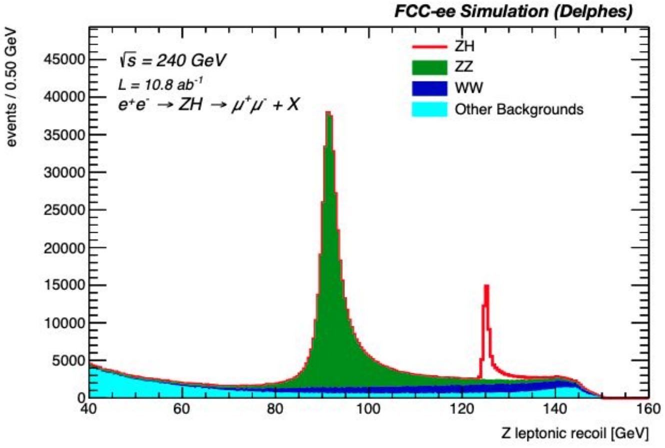


Not in baseline run, but optional $e^+e^- \to H$ at 125 GeV

- Probe directly electron-Yukawa coupling
- Requires beam monochromatisation

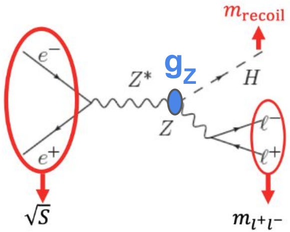


FCC-ee recoil method: total cross-section



$$\Gamma_H \propto \frac{\sigma\left(e^+e^- \to ZH, H \to ZZ\right)^2}{\sigma\left(e^+e^- \to ZH\right)}$$

$$\Gamma_H \propto \frac{\sigma\left(e^+e^- \to \nu\bar{\nu}H, H \to bb\right)\sigma\left(e^+e^- \to ZH\right)^2}{\sigma\left(e^+e^- \to ZH, H \to bb\right)\sigma\left(e^+e^- \to ZH, H \to WW\right)}$$



Higgs recoil mass measurement
→ ZH total production cross-section

- 10^6 Higgs produced at FCC-ee
  - rate ~ $\mathbf{g_Z}^2$ → $\delta g_Z/g_Z$ ~ 0.2%
- Then measure ZH → ZZZ
  - rate ~ $\mathbf{g_Z}^4$ / Γ_H → $\delta\Gamma_H/\Gamma_H$ ~ 1%
- Then measure ZH → ZXX
  - rate ~ $\mathbf{g_Z}^2$ $\mathbf{g_Z}^2$/ Γ_H → $\delta g_X/g_X$ ~ 1%

Precise knowledge of center-of-mass allows for:

- tag the Z by reconstructing pair of leptons
- Reconstruct the **recoil mass**

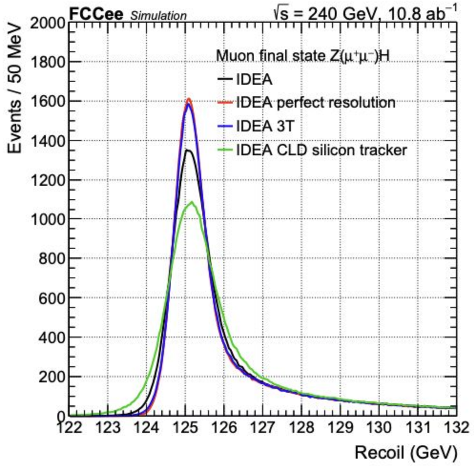
$$m^2_{\text{rec}} = (\sqrt{s} - E_{\ell^+\ell^-})^2 - p^2_{\ell^+\ell^-} = s - 2E_{\ell^+\ell^-}\sqrt{s} + m^2_{\ell^+\ell^-}$$

Provides **absolute** and **model independent** measurement of the g_Z coupling at the FCC-ee

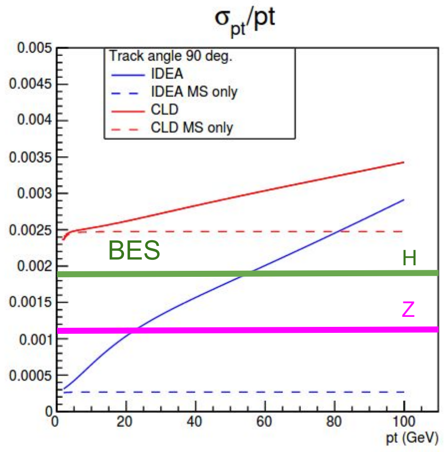
Higgs mass

- Higgs needs to be precisely measured < 10 MeV
  - As parametric uncertainty in several quantity (BRs, cross-section
  - In order to measure electron Yukawa (see later)

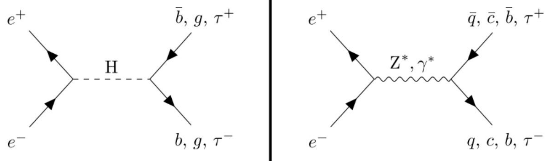
- **Higgs mass** and **ZH production cross-section** can be extracted from the **recoil mass distribution**



- sensitivity dominated by the Z(μμ) final state
  - superior momentum resolution, driven by **tracking**
- track momentum resolution limits sensitivity if larger than beam energy spread (BES = 0.176% at 240 GeV, i.e 211 MeV per beam)
  - requirement: multiple-scattering limit < BES
    - for CLD ~ 30% above
      - **transparent** tracker is key



Electron-Yukawa

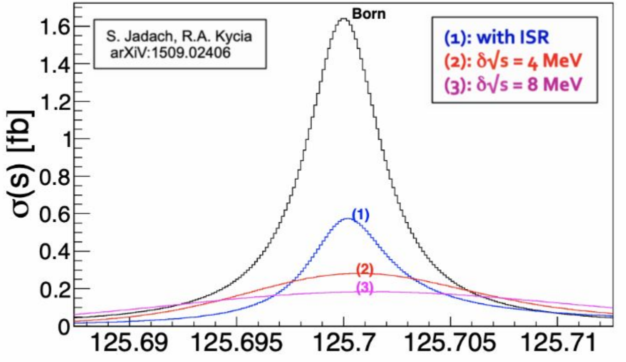


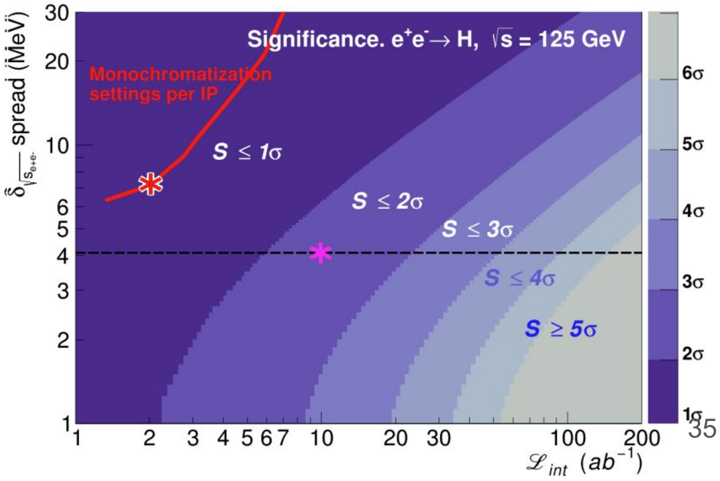
Probe electron-Yukawa coupling

- Direct measurement with coupling too small to be measured
- Using s-channel and beam monochromotization at √s = 125 GeV
  - ISR+FSR → 40 % reduction
  - Beam energy spread ~ Γ_H: δE = 4.2 MeV → 45 % reduction
  - Potential uncertainty on the Higgs mass
  - Total convoluted cross section ~ 280 ab^{-1}: large lumi needed
- Cope with large backgrounds (Z→XX)
  - H→gg most significant (absence of Z→gg)
  - Efficient reduction using BDT/MVA (bkg reduction 17x, sig 2x)
  - Many channels to explore

Expectations

- 4IP / 4years → **4σ (possible evidence)**



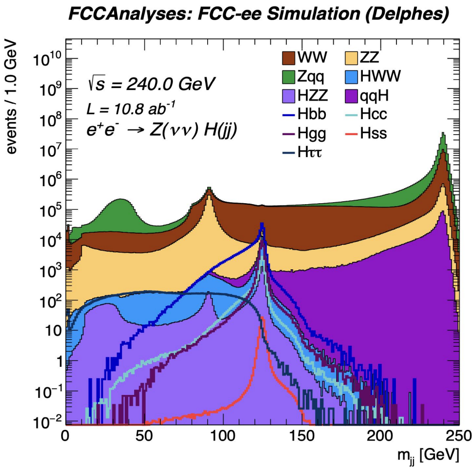


arXiv:2107.02686

Requires breakthrough in mono-chromatisation and gluon tagging

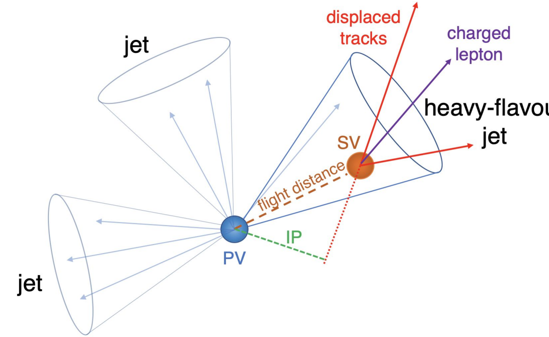
Higgs hadronic modes (bb/cc/ss/gg)

- **bb/cc/gg: workhorse channels for the FCC-ee**
  - "Abundant", clean large S/B (dominant backgrounds are ZZ, WW)
  - Excellent visible mass (jet resolution) needed
  - Light precise vertex detector allow high efficiency x purity jet flavor taggers
- **H→ss** could be measured for the first time (impossible at the LHC)
  - Gives access to strange quark Yukawa coupling (**$\delta\kappa_S$ ~ 50%**)
  - Requires excellent PID
- Complex analysis:
  - Fit simultaneously all the σ x BRs in VBF and ZH modes

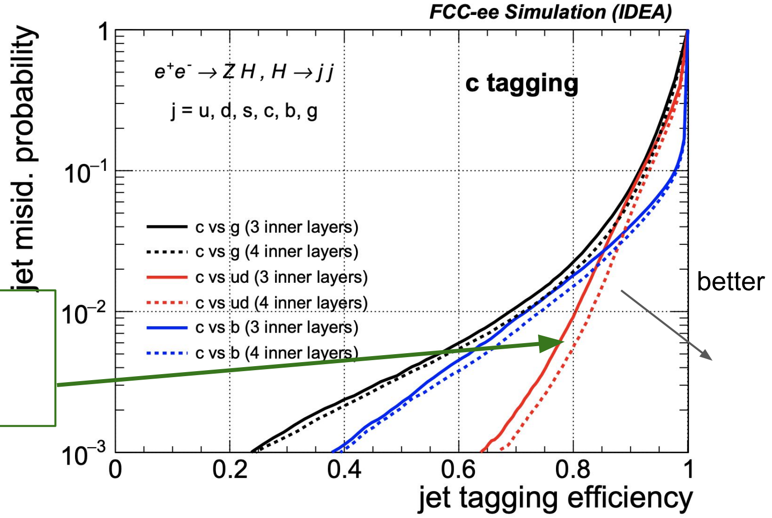


Track impact parameter resolution and vertexing

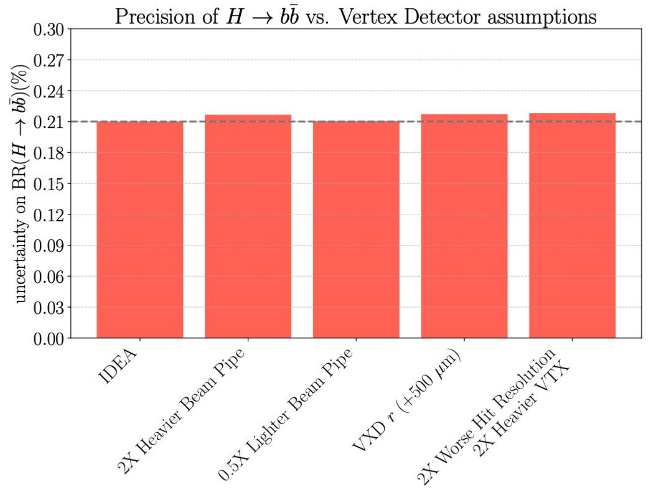
- **Impact parameter resolution** major driver of jet **charm** and **bottom** jet identification
  - B (D) mesons travel a finite decay length 500 (150) μm
- precise IP determination driven by:
  - single point resolution
  - **radial distance of first tracking layer** from the interaction point (at large momentum)
    - need small radius beam-pipe
  - material budget X/X_0 (at low p)



very marginal impact on Hbb/Hcc
(high efficiency/low purity)



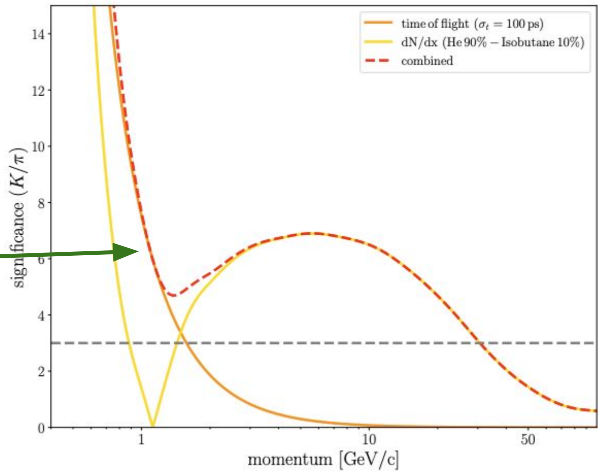
30-40% improvement in bkg rej using :
1st layer at 1 cm

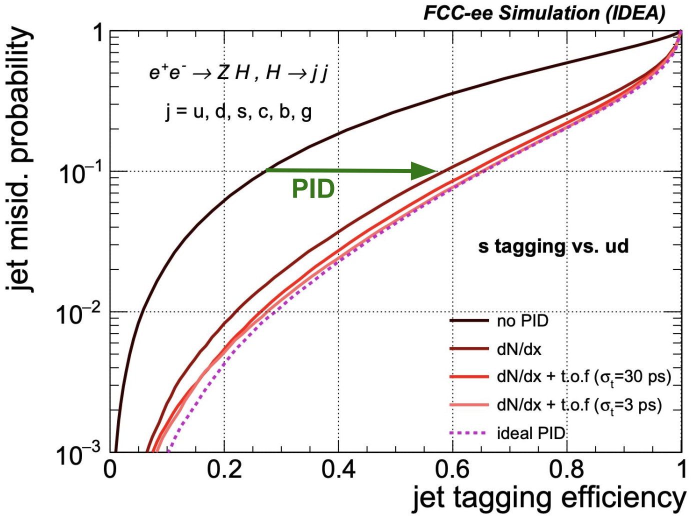


Charged hadron particle identification (K/π/p discrimination)

- PID crucial ingredient of
  - **strange quark** jet identification (H→ss, H→bs, …)
- Toolbox:
  - High momentum dE/dx (**dN/dx**) - Cherenkov detectors (**RICH**)
  - Low momentum: **Time of flight** (what about t_0?)

ToF + dNdx/Cherekov = PID for p < 30 GeV

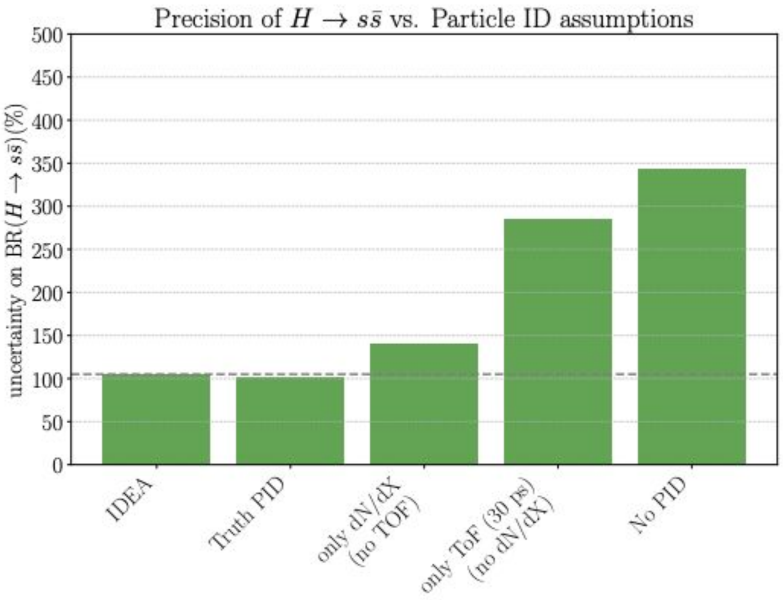


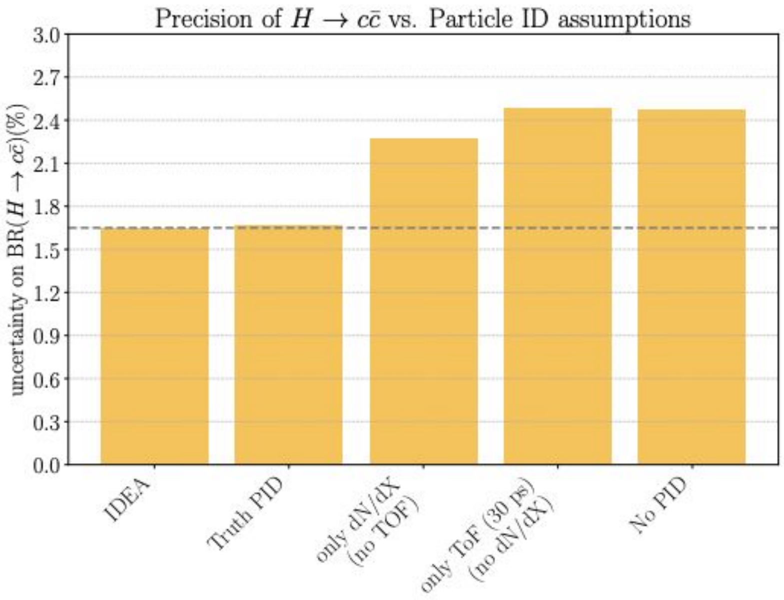


Charged hadron particle identification (K/π/p discrimination)

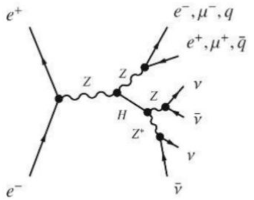
expected precision on BR(H→ss) ~100%
PID performance: **dN/dx > timing** resolution

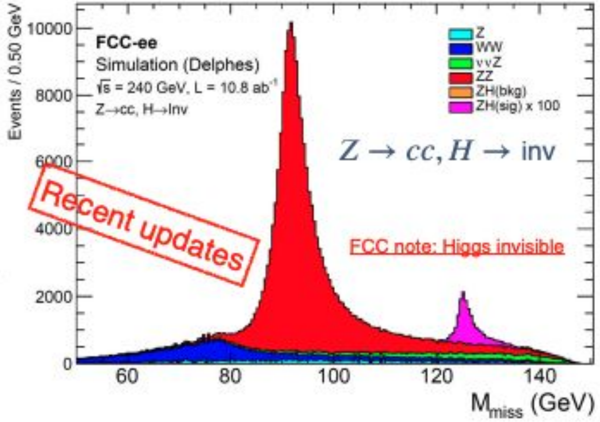
PID improves substantially expected precision on both **Hss** and **Hcc**



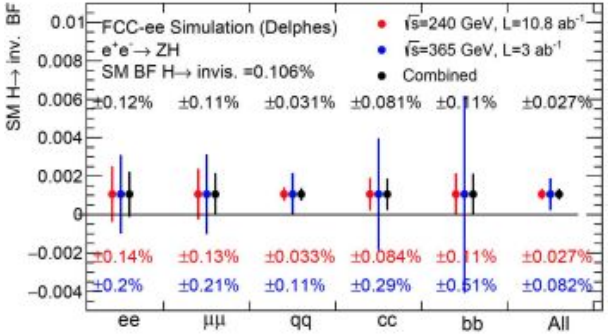


Higgs to invisible, rare

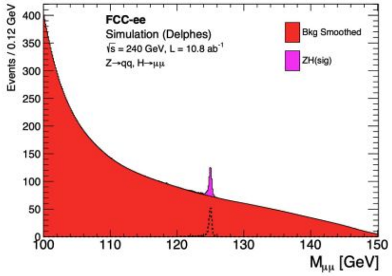




- Higgs to invisible in SM → BR = 10^{-3}
- Tag the Z with lepton or tagger bb/cc jets
  - Reconstruct recoil mass peak
  - Hadron resolution (PFlow) is crucial
    - 2-3 % resolution required
- Can be measured directly at 25% precision at FCC-ee
  - 50x better than LHC



- Higgs rare ɣɣ, μμ, Zɣ challenging at the FCC-ee
  - High statistically limited at the FCC-ee



Higgs couplings, kappa fit

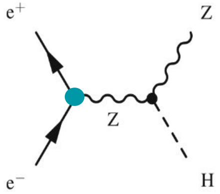
$\sqrt{s}$	240 GeV		365 GeV	
channel	**ZH**	**WW → H**	**ZH**	**WW → H**
ZH → any	±0.31		±0.52	
γH → any	±150			
H → bb	±0.21	±1.9	±0.38	±0.66
H → cc	±1.6	±19	±2.9	±3.4
H → ss	±120	±990	±350	±280
H → gg	±0.80	±5.5	±2.1	±2.6
$H \to \tau\tau$	±0.58		±1.2	±5.6 (*)
$H \to \mu\mu$	±11		±25	
$H \to WW^*$	±0.80		±1.8 (*)	±2.1 (*)
$H \to ZZ^*$	±2.5		±8.3 (*)	±4.6 (*)
$H \to \gamma\gamma$	±3.6		±13	±15
$H \to Z\gamma$	±11.8		±22	±23
$H \to \nu\nu\nu\nu$	±25		±77	
H → inv.	$< 5.5 \times 10^{-4}$		$< 1.6 \times 10^{-3}$	
H → dd	$< 1.2 \times 10^{-3}$			
H → uu	$< 1.2 \times 10^{-3}$			
H → bs	$< 3.1 \times 10^{-4}$			
H → bu	$< 2.2 \times 10^{-4}$			
H → sd	$< 2.0 \times 10^{-4}$			
H → cu	$< 6.5 \times 10^{-4}$			

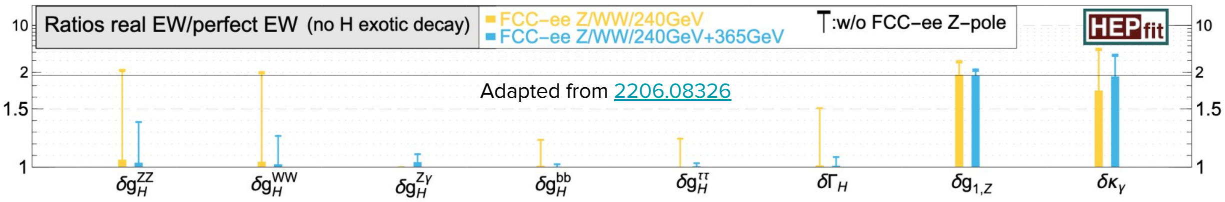
→

Coupling	HL-LHC	FCC-ee
κ_Z (%)	1.3*	0.10
κ_W (%)	1.5*	0.29
κ_b (%)	2.5*	0.38 / 0.49
κ_g (%)	2*	0.49 / 0.54
κ_τ (%)	1.6*	0.46
κ_c (%)	–	0.70 / 0.87
κ_γ (%)	1.6*	1.1
$\kappa_{Z\gamma}$ (%)	10*	4.3
κ_t (%)	3.2*	3.1
κ_μ (%)	4.4*	3.3
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$
Γ_H (%)	–	0.78
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}

10-100x improvement vs HL-LHC for “abundant” or hadronic modes

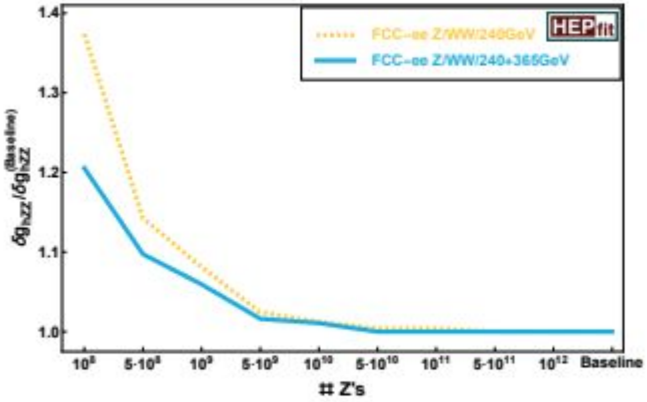
A Holistic Physics Program

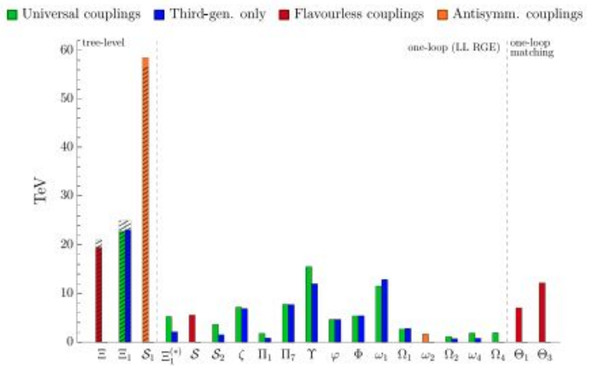




"**Perfect EW**" = resolution on the Higgs coupling if Z couplings were perfectly known
"**Real EW**" = resolution on the Higgs coupling with actual knowledge of Z couplings, from FCC (thick) or LEP (thin)

- Higgs measurements greatly benefit from the Z-pole measurements (Zee coupling)





All runs 'talk' to each other and are needed to have a fully constrained global fit

FCC-hh Physics Potential

W mass / width (threshold scan) - Circular

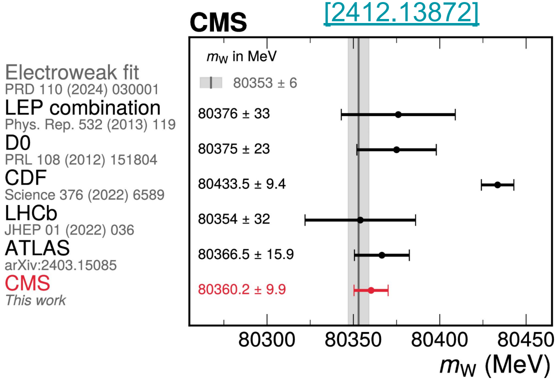
- **W mass** is a a crucial input to test SM consistency
  - Current uncertainty Δm_W **~ 10 MeV (LHC)**
- At lepton colliders, the simplest way is to measure it, is via a threshold scan, i.e cross-section vs. beam energy:
- With 2 or more energy points, m_W and Γ_W can be extracted simultaneously

$$\Delta m_{\mathrm{W}}(\mathrm{stat}) = \left(\frac{d\sigma_{\mathrm{WW}}}{dm_{\mathrm{W}}}\right)^{-1} \frac{\sqrt{\sigma_{\mathrm{WW}}}}{\sqrt{\mathcal{L}}}$$

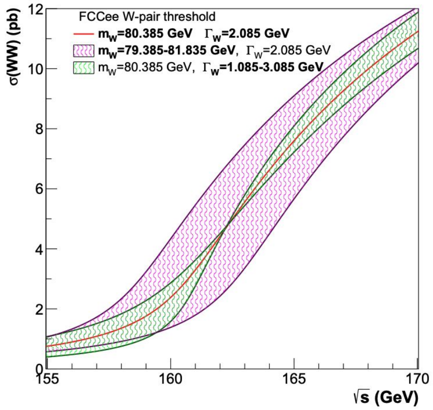
- Δm_W^{scan}(stat) **~ 400 keV** (FCC-ee)
- $\Delta \Gamma_W^{scan}$(stat) **~ 1MeV** (FCC-ee)

- Dominant systematics, beam energy calibration
  - Absolute energy calibration
    - Δm_W (syst) ~ 150 keV (FCC-ee) (300 keV on $\sqrt{s}$)
      - via resonant depolarisation (**only at FCC-ee**)
    - Δm_W (syst) ~ 700 keV (LEP3)
      - via radiative return Z **(at LEP3)**
- Through polarized scan, Δm_W (LCF) ~ 2 MeV (not in official run plan)

[2412.13872]

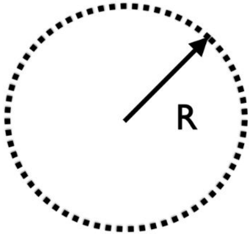


[2107.04444]



High energy hadron machines

p [TeV/c] = 0.3 B [T] R [km]



Pros:

- relatively democratic initial states, strong and electro-weak force
- high center of mass, thanks to ~ small synchrotron power loss $(m_e/m_p)^4$
  - caveat: at 100 TeV it becomes significant!
- high luminosity up to high energy

Cons:

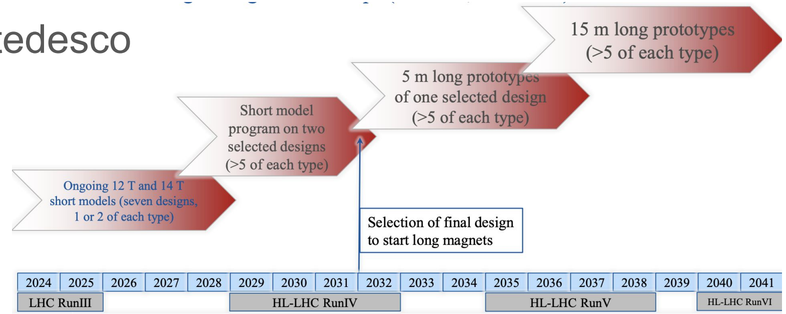
- large backgrounds compared to lepton machines ($\alpha_S > \alpha_{EM,W}$), from
  - high Q2 physics (di-jet, ttbar …)
  - “simultaneous” p-p collision (pile-up)

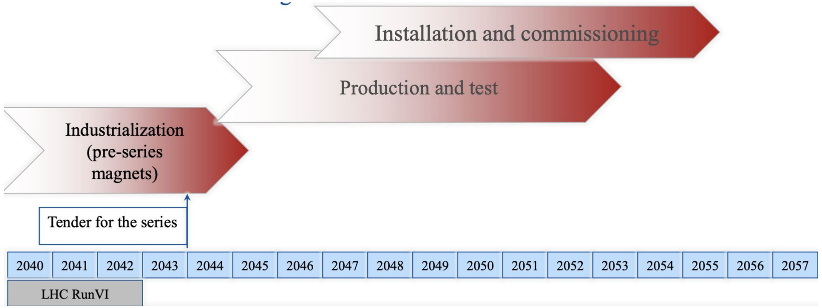
- Discovery machines for heavy new states
- Also suited for precision (thanks to high rates)

Magnet challenge

- Baseline FCC-hh design: B = 14 T ($\sqrt{s}$ = 84 TeV)
- New conductor Nb_3Sn supports higher fields due to its larger critical current density and critical field
  - HTS ? far from required specs still … → needed for higher energy (120 TeV)
- Wider coils (50–55 mm vs. 30 mm in LHC dipoles) are needed to maintain a conservative 400 A/mm² overall current density.
- This design demands 2–2.5 times more conductor material than in LHC dipoles.
  - 4.7k magnets (cost will be addressed in the ESPPU ~ 10 BCHF)
- Still intense R&D required to reach 15-16 T (including safety margin)

Ezio tedesco





Scenarios

name	F12LL	F12HL	F12PU	F14	F17	F20
Dipole Field (T)	12	12	12	14	17	20
√s (TeV)	72	72	72	84	102	120
current (A)	0.5	1.12	1.12	0.5	0.5	0.2
PU	600	3000	1000	600	700	150
SR power (MW) 2 beams	1.3	2.9	2.9	2.4	5.2	4.0
Lumi/yr (ab-1)	1	2	1.3	0.9	0.9	0.35

Limiting factor: 5MW synchrotron power ~ $\sqrt{s}^{\,4}$

Mass reach scaling

How does the reach for observing a a new state of mass M (e.g BSM Higgs, …) **scale** from 14 TeV to 100 TeV ?

Assume we need the same number of events at 14 TeV and 100 TeV to claim discovery:

$$\#\ \text{events}\ (\sqrt{s_2} = 100\ \text{TeV}) \approx \#\ \text{events}\ (\sqrt{s_1} = 14\ \text{TeV})$$

$$(M_2 / M_1) \sim (s_2 / s_1)^{1/2}\ [(s_1/s_2)(\mathscr{L}_2/\mathscr{L}_1)]^{1/(2a+1)}$$

$$M_{100\,\text{TeV}} / M_{14\,\text{TeV}} \approx 7$$

≈ 1

assumes:
- large a
- large luminosity

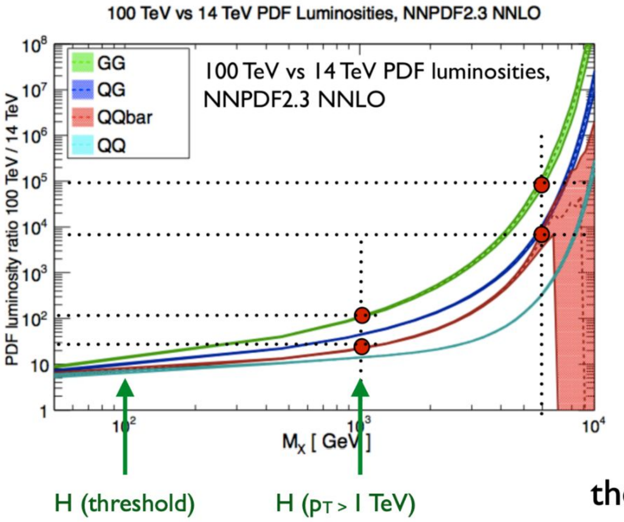
As expected, mass reach scales linearly with $\sqrt{s}$

Cross section scaling

How does the rate of a **given process** (e.g. single Higgs production) scale from 14 TeV to 100 TeV

parton luminosities

$$\frac{\text{cross-section } (\sqrt{s} = 100\text{ TeV})}{\text{cross-section } (\sqrt{s} = 14\text{ TeV})} \approx L_1 / L_2$$

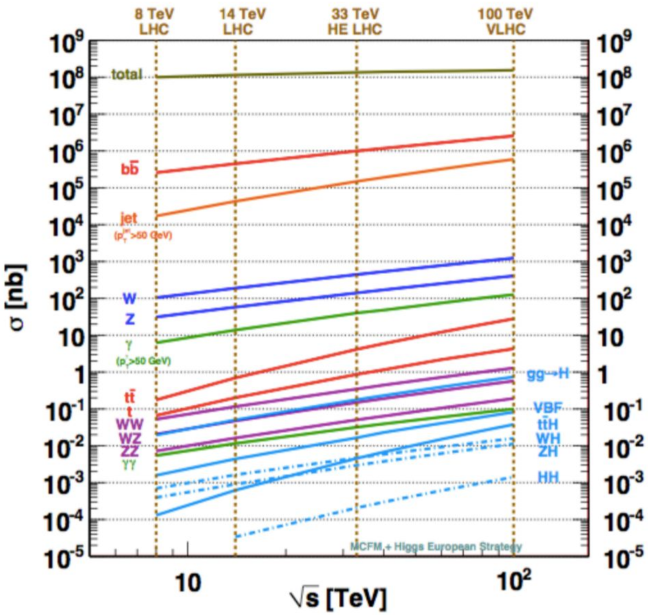


	σ(100)/σ(14)
ggH	15
HH	40
ttH	55
H (p_T > 1 TeV)	400

Very large rate increase by increasing center of mass energy

NB: this improvement only comes from the cross-section (neglects integrated luminosity)

High energy hadron machines



- Total pp cross-section and Minimum bias multiplicity show a modest increase from 14 TeV to 100 TeV

→ Levels of pile-up will scale basically as the instantaneous luminosity.

- Cross-section for relevant processes shows a significant increase.

→ interesting physics sticks out more !

Rate of increase from 14 TeV to 100 TeV:
- ggH x15
- HH x40
- ttH x55

⟶ reduction of **x10-20** statistical uncertainties

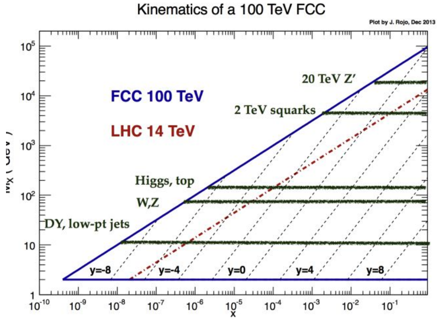
Physics at threshold

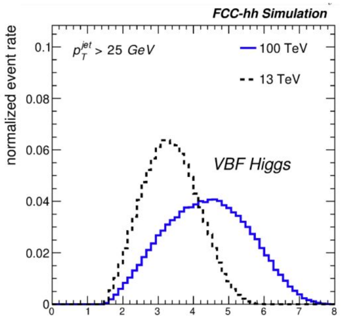
$$x_1 * x_2 * s = M^2$$

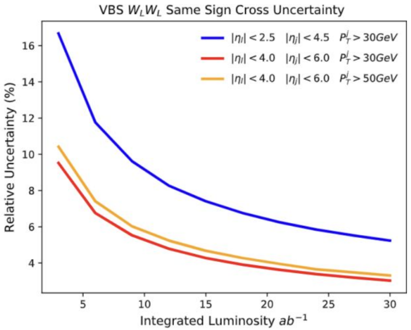
SM Physics is more forward @100TeV

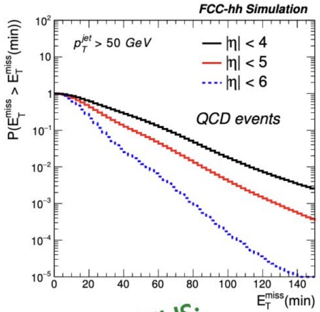
- If we want to maintain **high efficiency in states produced at threshold** need **large rapidity** (with tracking) and **low p_T** coverage

→ highly challenging levels of radiation at large rapidities









Tracking and calorimetry needed up to |η| < 6 for ~. VBF signatures

BONUS: Hermeticity E_T^{miss} resolution

Boosted topologies at multi-TeV energies

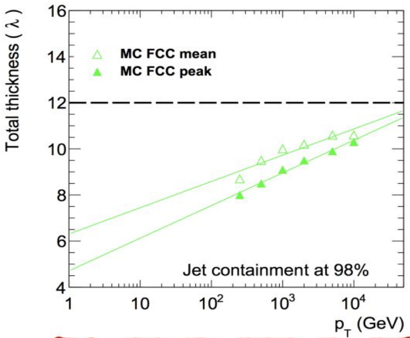
The boosted regime:

→ measure leptons, jets, photons, muons originating ~ 40-50 TeV resonances

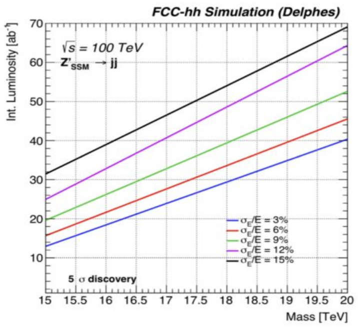
Tracking: $\frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2}$

Calorimeters: $\frac{\sigma(E)}{E} \approx \frac{A}{\sqrt{E}} \bigoplus B$

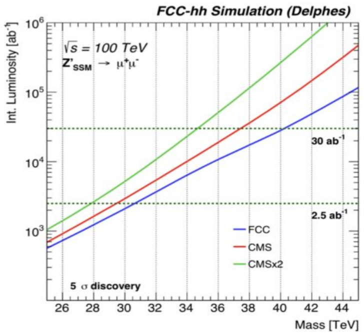
- Tracking target : **σ / p = 20% @10 TeV**
- Muons target: **σ / p = 10% @20 TeV**
- Calorimeters target: containment of p_T = 20 TeV jets



≳11 λ_I for EM + Had



high p_T jets

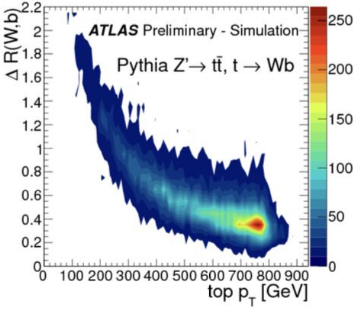


high p_T muons

Boosted topologies at multi-TeV energies

min. distance to resolve two partons

$\Delta R \approx 2\, m / p_T$



ex for top:

p_T = 200 GeV → R ~ 2

p_T = 1 TeV → R ~ 0.4

p_T = 10 TeV → R ~ 0.05

- At 10 TeV whole jet core within 1 calo cell
  - neutrals possibly un-resolvable
    - B field "helps" with charged
  - PF reconstruction will be severely affected
    - Total jet energy OK, calo does good job
    - reed to be studied and rethought for

- Naive approach:
  - use calo for energy measurement
  - tracking for substructure identification

in CMS:

Tracking → ΔR ~ 0.002

ECAL → ΔR ~ 0.02

HCAL → ΔR ~ 0.1

High p_T flavor tagging

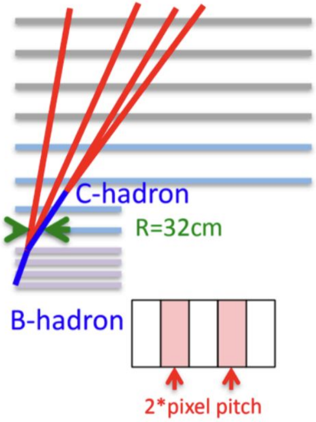
- **The boosted regime:**
  → measure b-jets, taus from multi-TeV resonances

- Long-lived particles live **longer**:

  ex: 5 TeV **b-Hadron** travels **50 cm** before decaying
  5 TeV **tau lepton** travels **10 cm** before decaying

  → extend pixel detector further?
  - useful also for exotic topologies (disappearing tracks and generic BSM Long-lived charged particles)
  - number of channels over large area can get too high

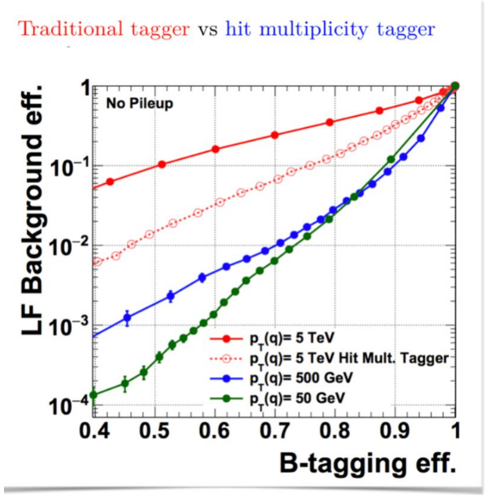
  → re-think reconstruction algorithms:
  - hard to reconstruct displaced vertices
  - **exploit hit multiplicity discontinuity**



Only 71% 5 TeV b-hadrons decay < 5th layer.

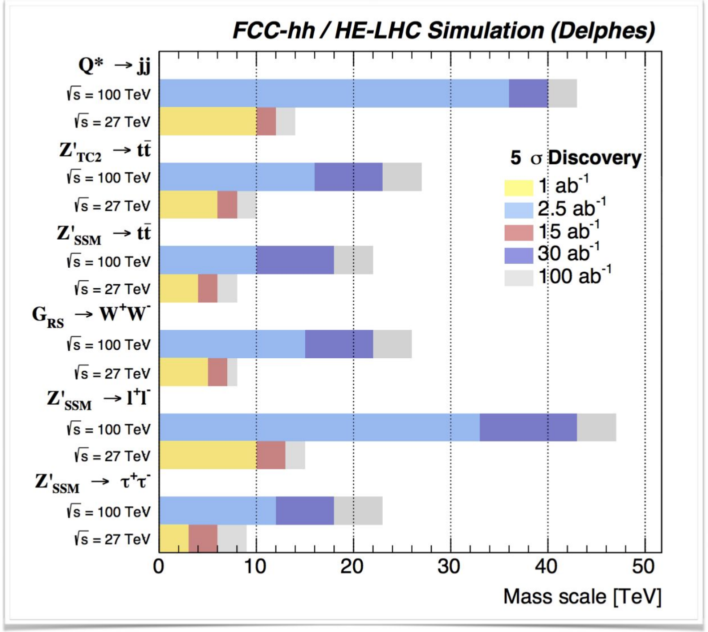
- displaced vertices

Perez Codina, Roloff [CERN-ACC-2018-0023]

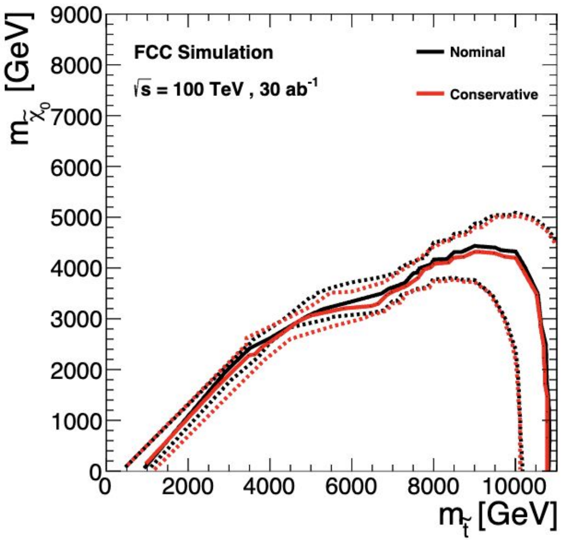


The energy frontier

High mass resonances



stops

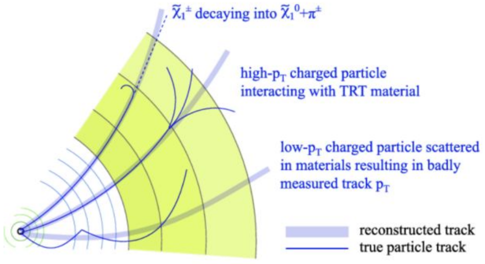


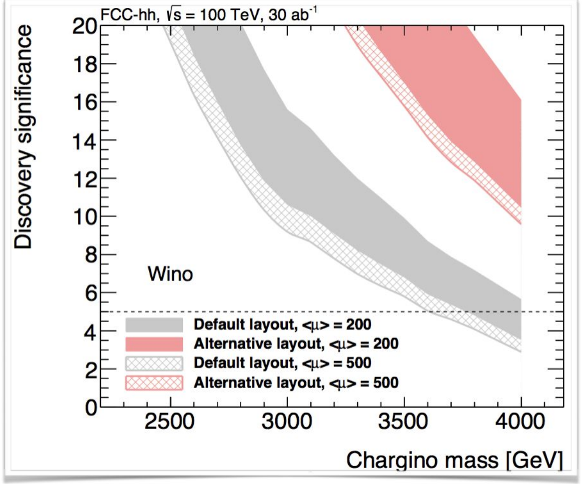
Challenges: multi-TeV collimated top, W, τ highly collimated.

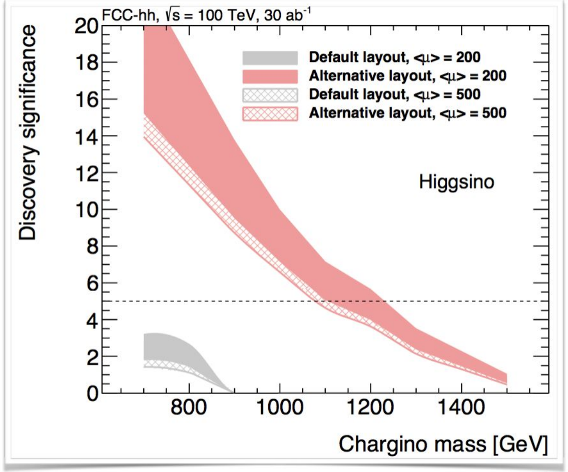
Tracking is the key highly segmented calorimetry

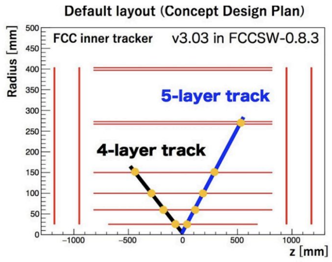
WIMP dark matter - disappearing track analysis

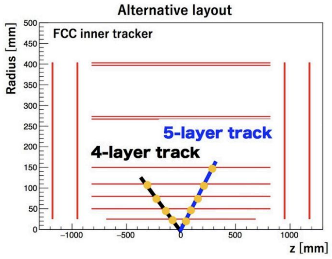
Nearly degenerate chargino-LSP











observed relic density

- M = 1 TeV Higgsino can be discovered
- M = 3 TeV Wino can be discovered

Higgs at 100 TeV vs HL-LHC and FCC-ee

- 100 TeV provides **unique and complementary measurements** to ee colliders:
  - Higgs **self-coupling**
  - **top Yukawa**
  - **Higgs → invisible**
  - **rare decays** (BR(μμ), BR(Zɣ), ratios, ..) measurements will be **statistically limited** at FCC-ee

Coupling	HL-LHC	FCC-ee
κ_Z (%)	1.3*	0.10
κ_W (%)	1.5*	0.29
κ_b (%)	2.5*	0.38 / 0.49
κ_g (%)	2*	0.49 / 0.54
κ_τ (%)	1.6*	0.46
κ_c (%)	–	0.70 / 0.87
κ_γ (%)	1.6*	1.1
$\kappa_{Z\gamma}$ (%)	10*	4.3
κ_t (%)	3.2*	3.1
κ_μ (%)	4.4*	3.3
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$
Γ_H (%)	–	0.78
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}

Need to improve

Large rates for rare modes and HH production at FCC-hh

→ complementary to e^+e^-

Higgs complementarity with lepton machines

At pp colliders we can only measure:

$$\sigma_{prod}\, BR(i) = \sigma_{prod}\, \Gamma_i / \Gamma_H$$

→ we do not know the total width.

In order to perform global fits, we have to make **model-dependent assumptions**

Instead, by performing measurements of ratios of BRs at hadron colliders:

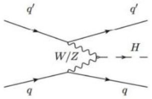
$$BR(H \rightarrow XX) / BR(H \rightarrow ZZ) \approx g_X{}^2 / g_Z{}^2$$

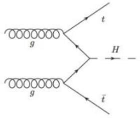
from e^+e^-

We can "convert" **relative measurements into absolute** via g_Z thanks to e^+e^- measurement

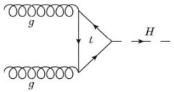
→ synergy between lepton and hadron colliders

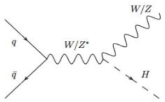
Higgs production in hadron machines





	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N^3LO)	49 pb	803 pb	16
VBF (N^2LO)	3.8 pb	69 pb	16
VH (N^2LO)	2.3 pb	27 pb	11
ttH (N^2LO)	0.5 pb	34 pb	55
HH (NNLO)	40 fb	1.2 pb	30





30M Higgs pairs

Expected improvement at FCC-hh:

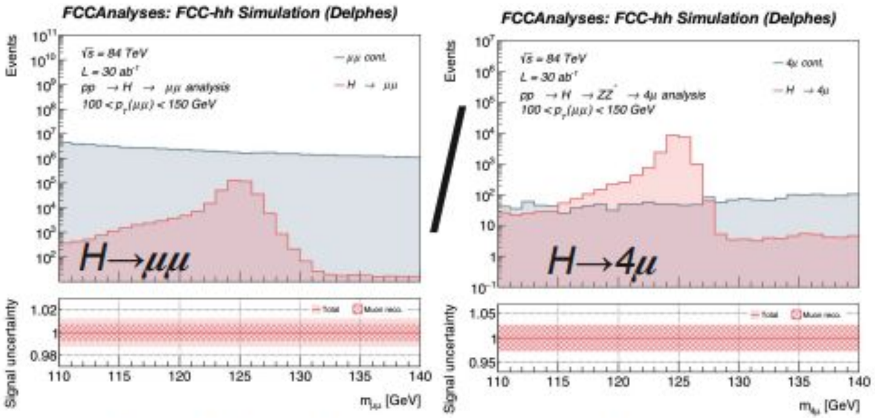
- **20 billion Higgses** produced at FCC-hh
- **factor 10-50** in cross sections (and Lx10)
- reduction of a **factor 10-20 in statistical** uncertainties

Large statistics will allow:

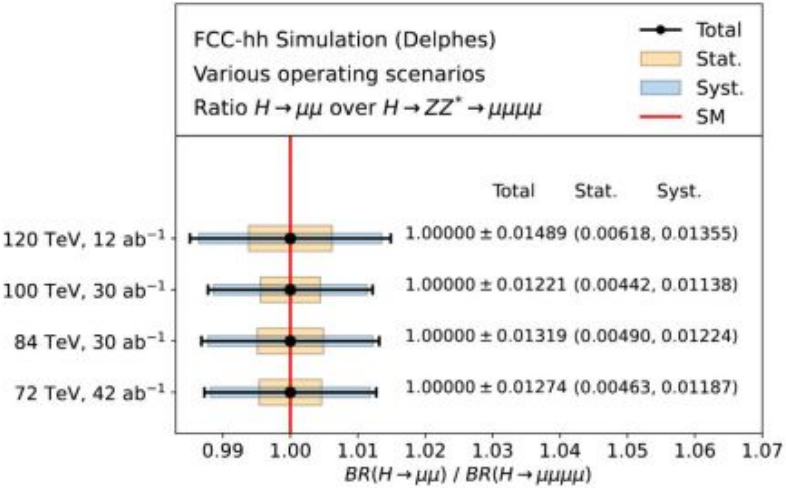
- for **% - level precision in statistically limited** rare channels (μμ, Zɣ)
- in **systematics limited** channel, to isolate **cleaner samples** in regions (e.g. @large Higgs p_T) with :
  - higher S/B
  - smaller (relative) impact of systematic uncertainties

> 10M Higgs boson with pT(H) > 500 GeV

BR ($\mu\mu$,γγ,Zγ) / BR(H→ZZ)

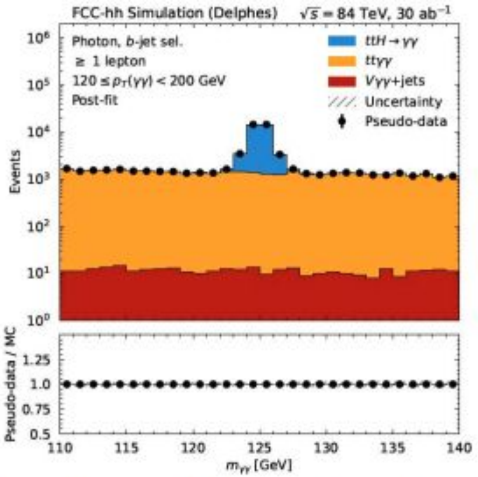


- Benefit from large statistics at high $p_T(H)$, where experimental efficiency systematics are smaller, furthermore focus on ratios of signal strengths to cancel (theory) systematic uncertainties

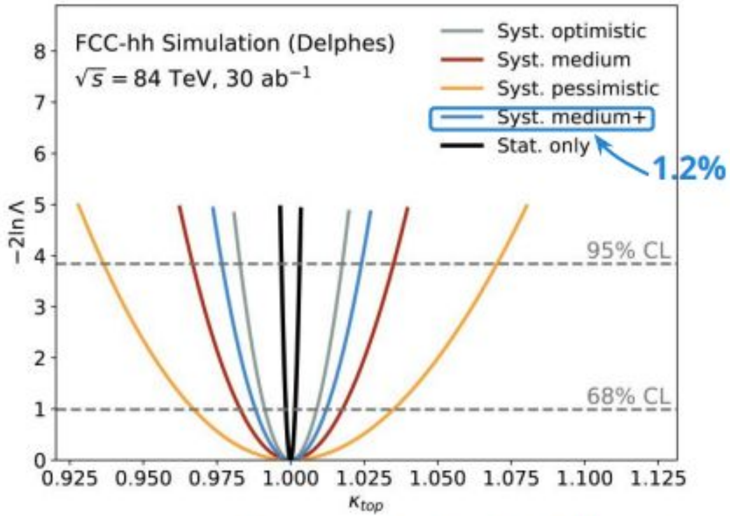


- Updated results from differential fit in $p_T(H)$ bins, for the different operating scenarios

ttH (top Yukawa)



- New channel for precision measurement of top Yukawa coupling κ_{top}
- Extract from fits to invariant di-photon mass in $p_T(H)$ bins

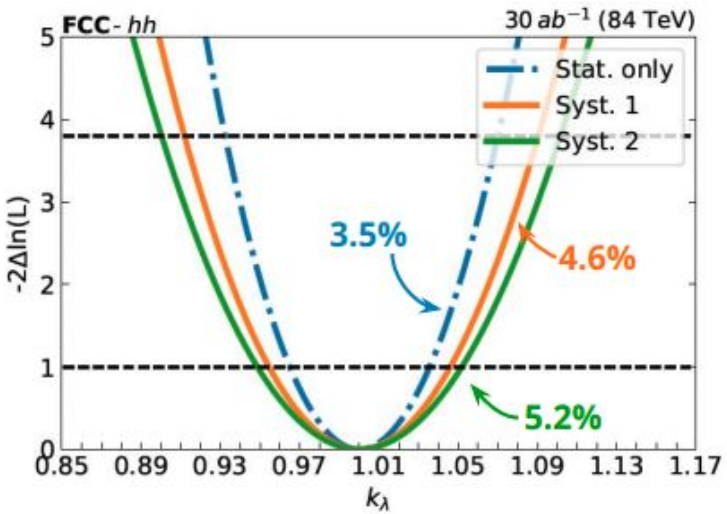


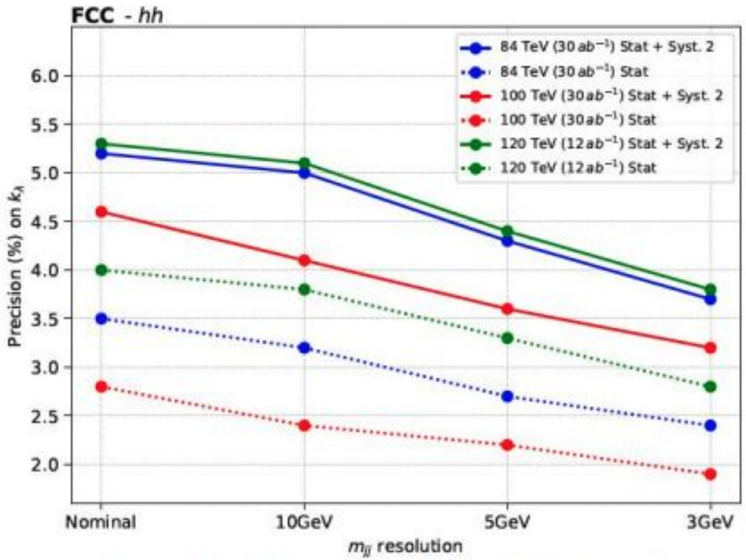
- Expected precision for 84 TeV and different assumptions on systematics
- Differential results also provided

Next: study ttH(γγ) / ttZ(ee) , to benefit from FCC-ee ttZ coupling measurement

Higgs self-coupling

- σ(100 TeV)/σ(14 TeV) ≈ 40 (and Lx10)
- x400 in event yields and x20 in precision





- Re-optimized strategy: Event selection with Deep Neural Network
- Fit invariant di-photon mass in bins of invariant di-jet mass, with different assumptions

- Consider different energies & resolutions of invariant d-jet mass

➡ Impact of di-jet resolution is critical

Higgs combined FCC-ee and hh

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	–	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$	$^{+29}_{-67}$
Γ_H (%)	–	0.78	0.69
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}	6.7×10^{-3}

FCC-ee and FCC-hh Integrated Programme is complementary and provides ~ order of magnitude improvement of all Higgs couplings w.r.t HL-LHC

Outlook (I)

- Road to understanding the fundamental laws of Nature has not come to an end
- Colliders are, and will remain, (the main) tools of choice to study fundamental physics
- Europe is the current world leader in this field, and has delivered many discoveries (neutral currents, W, Z bosons, the Higgs)
- CERN’s scientific vision is based on:
    - A flagship project
    - A diverse scientific program complementary to the flagship project

Outlook (II)

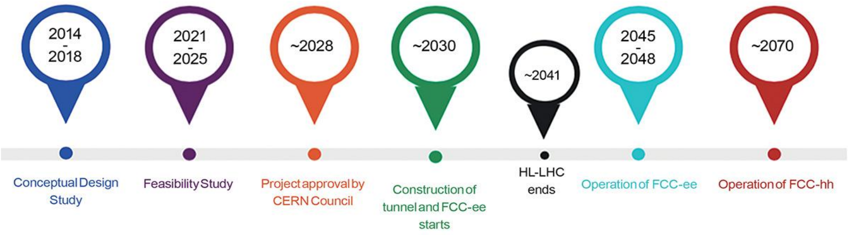
- The FCC project has matured a lot in recent years
  - ❏ The Feasibility Study Report has been completed, no show stopper identified
  - ❏ Physics reach will increase by 1 order of magnitude the new physics scale
    - ❏ Through precision
    - ❏ Direct searches
  - ❏ Still much more to come, still understanding the power of the FCC-ee datasets
    - ❏ A lot of room for new studies, and detector concept proposals
      - ❏ Including re-analysing LEP data with current state-of-the-art analysis and reconstruction techniques
- The FCC integrated program is the option with the broadest scientific outcome
  - ❏ **FCC-ee** allows the **characterisation of the Higgs with a tremendous sensitivity and provides a uniquely diverse physics reach in EW/QCD/Flavor/Top/BSM**
  - ❏ It **paves the way for next generation of hadron colliders, FCC-hh**
    - ❏ Bringing complementary physics output

Backup material

What if China goes ahead with CEPC?

- Do we want to give China the possibility to “veto” CERN projects?
- How likely is it that they start in 2035?
- What if the project fails or is cancelled?
- What about the future of CERN?
- What will be the impact on Early Career Researcher?
- Will it be a real international collaboration?
- …

Possible FCC project timeline. From the perspective of the technical schedule alone, FCC-ee operation could start in 2040 or earlier.



Possible CEPC timeline

The Z-lineshape

Measuring cross-section at peak and off-peak

$$\sigma(\sqrt{s}) = \frac{N_{\text{signal}}}{\mathcal{L}} = \frac{N_{\text{selected}} - N_{\text{background}}}{\varepsilon A \mathcal{L}}$$

What can be extracted

- Z mass (m_Z), Z width (Γ_Z)
- Hadronic peak cross section ($\sigma_{0,\text{ hadr}}$)
- Ratio of leptons (R_ℓ)
- number of light neutrinos, α_s, …

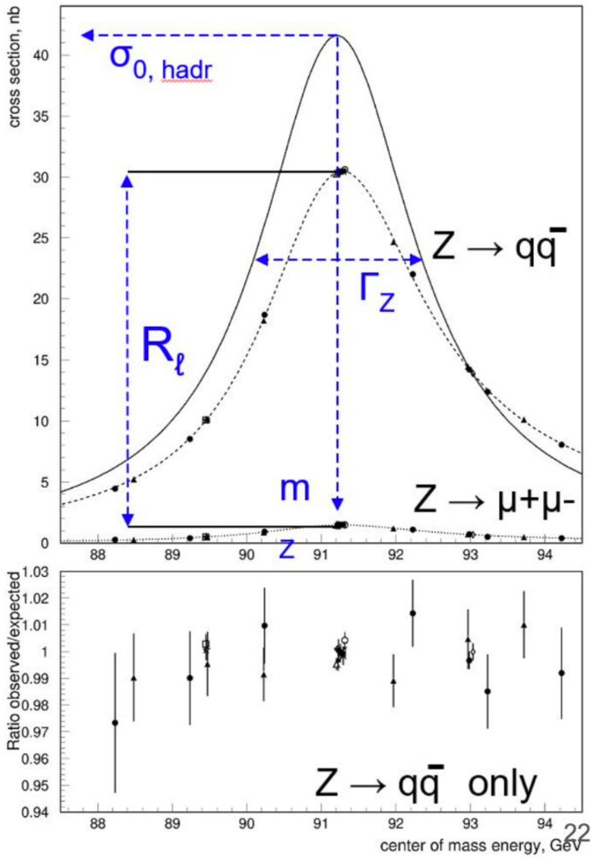
Largest statistics in hadronic final state

- Mass, width and σ_0

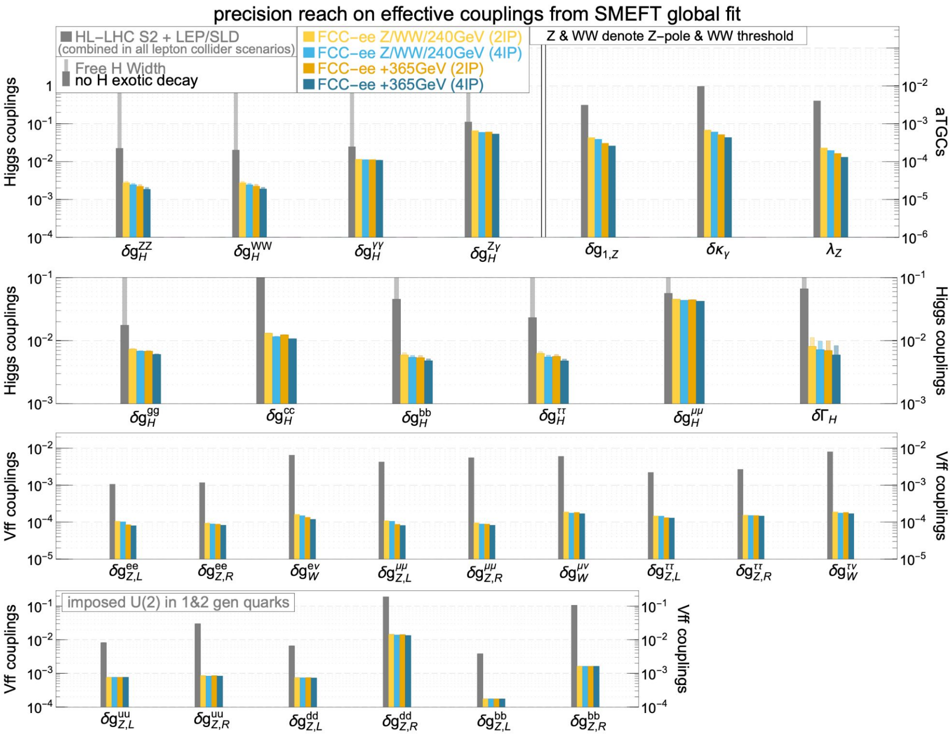
Theory needed

- Deconvolute QED and the EW/QCD corrections
- Precise predictions and Monte Carlo

Jan Eysermans



FCC-ee and SMEFT



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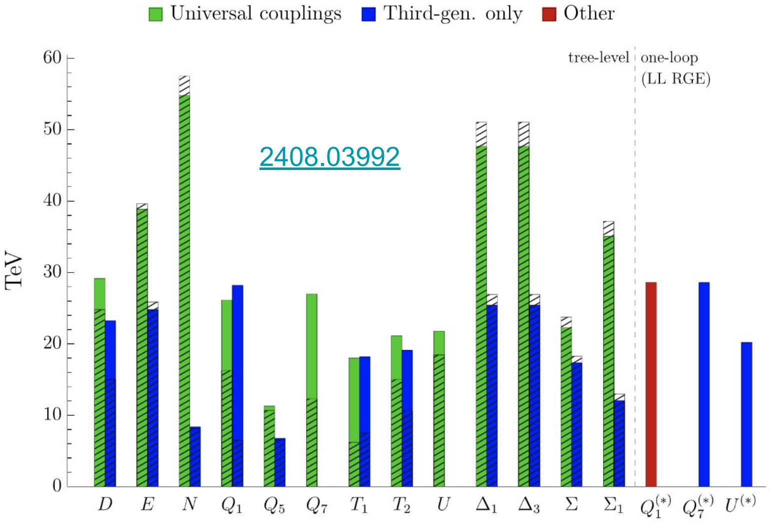


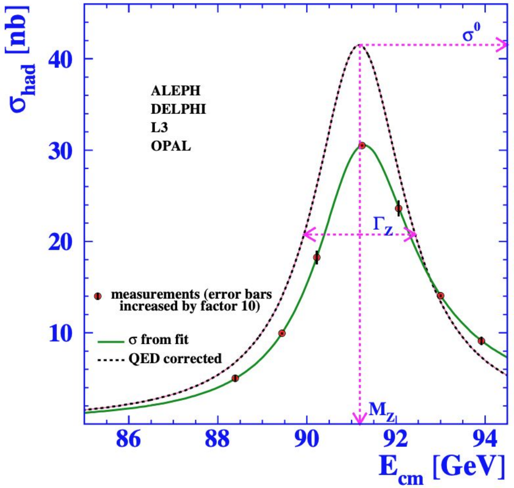
Figure 5: Projected bounds on the masses of new fermion fields. The vertical dashed line separates fields which contribute to EWPOs at tree level (left) and via one-loop RG evolution (right). The green and blue bars correspond to different assumptions for the coupling to SM fermions, as described near the start of Sec. 4, while the red bar for $Q_1^{(*)}$ corresponds to the exceptional case where Q_1 couples only to right-handed top quarks, as noted in Table 4. Fields indicated with a $^{(*)}$ correspond to cases where the tree-level contribution has been set to zero by forbidding a specific coupling (see Table 4). Hatched bars correspond to pure tree-level limits, without RG running.

Z mass / Width

[0509008]

- **Z Mass** is a parametric input to xsec, width, BR, …
  - Current uncertainty **Δm_Z ~ 2 MeV (LEP)**
  - Statistical uncertainty scales as ~ $\Gamma_Z / 2\sqrt{N_Z}^{\text{off-peak}}$
    - 4 (7) keV at FCC-ee (LEP3)
    - 20 keV at LCF
  - Dominant systematic:
    - FCC-ee (LEP3): absolute beam energy calibration:
      - resonant depolarisation $\Delta\sqrt{s}$ ~ **Δm_Z ~ 100 keV**
        - achieved at LEP, ongoing effort to improve
    - LCF: absolute momentum scale
      - Δp ~ **Δm_Z ~ 200 keV** using J/ψ mass (or $K_S \to \pi\pi$)
        - absolute limit 2 ppm (is 10 ppm more feasible?)

- **Z total width** is sensitive to fermion couplings and to BSM
  - Current **$\Delta\Gamma_Z$ ~ 2 MeV**
  - Dominant systematic:
    - relative absolute beam energy calibration
      - point-to-point $\Delta\sqrt{s}_{\text{p.t.p}}$ (uncorrelated component)
        - can be measured in-situ with μμ events
          - **$\Delta\Gamma_Z$ ~ 12 (25) (125) keV** at FCC-ee (LEP3) (LCF)



$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + \Gamma_{inv}.$$

$$\sigma^0_{had} \equiv \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}$$

$$R^0_\ell \equiv \Gamma_{had}/\Gamma_{\ell\ell}$$

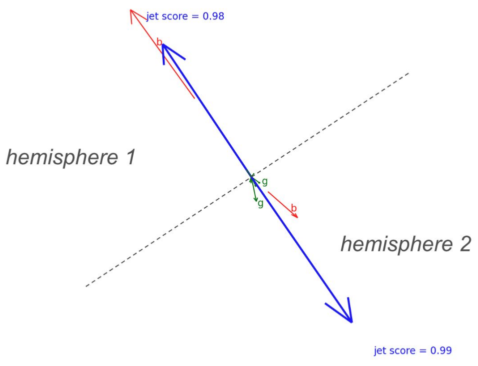
lepton universality:

$$R^0_{inv} = \left(\frac{12\pi R^0_\ell}{\sigma^0_{had} m_Z^2}\right)^{\frac{1}{2}} - R^0_\ell - (3+\delta_\tau)$$

$$R^0_{inv} = N_\nu \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{\ell\ell}}\right)_{SM}$$

Hadronic Branching Ratios

- Defined as $\mathbf{R_q = \Gamma_q / \Gamma_{had}}$ with q = b, c, s measure individual chiral couplings to the Z → $(\sim g_L^2 + g_R^2)$
- Current (relative) uncertainties ~ $\mathbf{10^{-3}}$
- Dramatic improvements compared to LEP are expected, driven by:
  - Reduced beam-spot sizes, light beam-pipe
  - Light and precise vertex detectors (few μm single point resolution)
  - Particle ID allowing strange tagging (K+ identification up to 30-40 GeV)
    - and NEW measurement of R_s
  - Advanced AI flavor tagging algorithms
    - pure b, c and strange jets → background contamination negligible
- Dominant systematics:
  - Hemisphere correlations
    - mainly driven by QCD (gluon emissions, g→bb/cc, etc ..)
      - can be positive (negative) for hard (soft) emissions
    - can be reduced with (acoplanarity) cuts
    - measured directly in data
      - 10^9 (10^6) gluon splitting samples in FCC-ee (LCF)
- Projections:
  - **2(b) - 10(s) (4-10) x 10^{-6}** for **FCC-ee (LEP3)** and **50-200x 10^{-6}** for **LCF**



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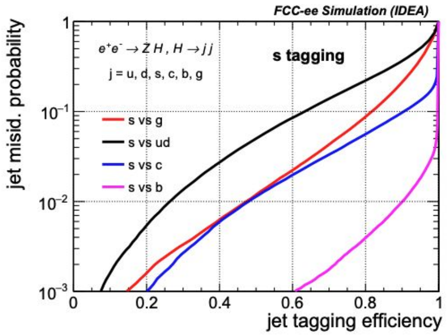


Asymmetries (LCF)

- $\mathbf{A_f}$ measures the asymmetry between Left (L) and Right (R) handed **Zff** couplings ($\sin^2\theta_W$):

$$\mathcal{A}_\mathrm{f} = \frac{g_\mathrm{Lf}^2 - g_\mathrm{Rf}^2}{g_\mathrm{Lf}^2 + g_\mathrm{Rf}^2}$$

- Linear colliders can measure $\mathbf{A_e}$ directly via LR asymmetry, using longitudinal beam polarisation combinations
  - very clean experimentally (measure total hadronic cross-section)
    - independent of Z decay mode
  - requires excellent control of initial state polarisation
    - determined by Blondel scheme
  - provided best measurement of $\mathbf{\sin^2\theta_W}$ at SLC

$$P_{e^-} \approx \pm 0.80,\ P_{e^+} \approx \pm 0.30$$

$$P_\mathrm{eff} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^-}P_{e^+}} \approx 0.89$$

$$A_\mathrm{LR} = \frac{1}{P_\mathrm{eff}} \frac{N_L - N_R}{N_L + N_R} \approx A_e$$

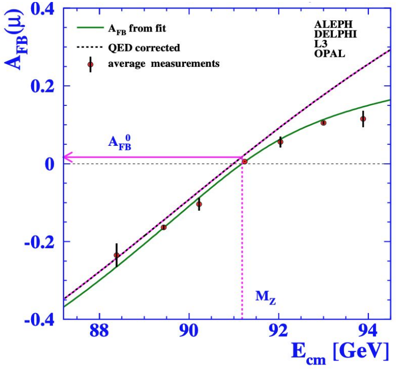
  - provides a measurement of $\Delta A_e/A_e \sim 2 \times 10^{-4}$
    - $\Delta\sin^2\theta_W \sim 4 \times 10^{-6}$ (**100x** vs. today world average)

Fermion asymmetries (FCC-ee/LEP3)

$$A_{FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

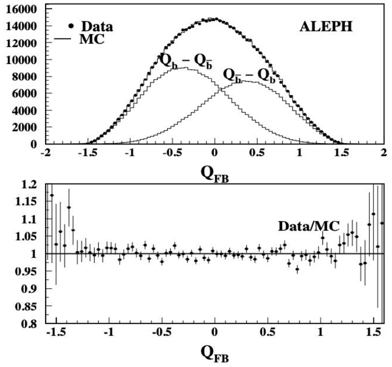
- Once $\mathbf{A_e}$ is known, $\mathbf{A_f}$ can then be measured from Forward-Backward asymmetries
  - dominant systematics:
    - $A_{FB}^{\mu,\tau}$: point-to-point energy calibration
      - $\Delta A_{FB}^{\mu} \approx 2.3$ [2.4] x 10^{-6} → $\Delta A_\mu/A_\mu \sim 3(6) \times 10^{-5}$
      - $\Delta A_{FB}^{\tau} \approx 2.7$ [2.4] x 10^{-6} → $\Delta A_\tau/A_\tau \sim 4(7) \times 10^{-5}$

[0509008]



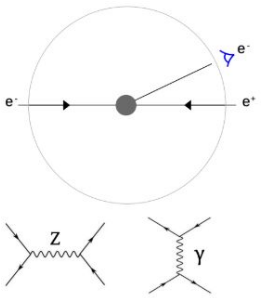
- $\mathbf{A_q}$ for heavy flavors (q=b,c,s) requires the determination of the jet (hemisphere) charge
  - Measure simultaneously:
    - average FB hemisphere charge difference AND sum
    - Measure charge separation
    - → $\Delta A_{FB}^{q} \sim 5 \times 10^{-6}$ → $\Delta A_q \sim 2 \times 10^{-4}$
  - dominant systematics:
    - Asymmetry in detector material (nuclear interactions produce excess of positive charge)
      - can be monitored with conversions
    - Background contamination
      - tagger purities much larger than LEP

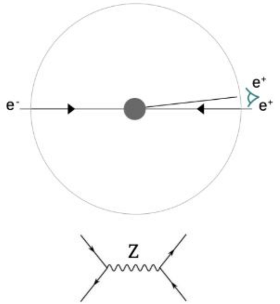
[0107033]



$\alpha_{QED}(m_Z)$

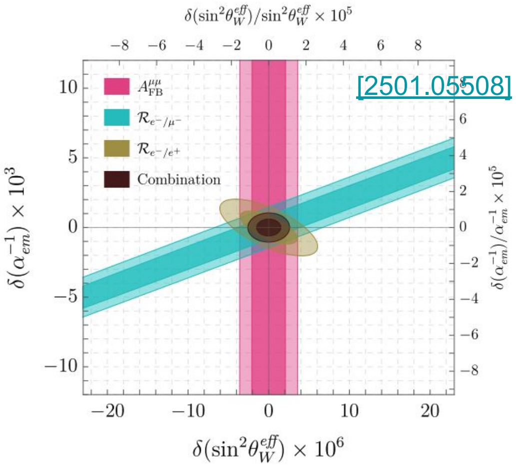
Riembau





$$\mathcal{R}_{e^-/e^+}(\theta) = \frac{\sigma(e^-e^+ \to e^-(\theta) + X)}{\sigma(e^-e^+ \to e^+(\theta) + X)}$$

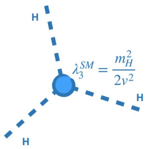
- Dominant parametric uncertainty in EW precision ($\sin \vartheta_W^{eff}$ and m_W) fit:
  - Current uncertainty $\delta\alpha/\alpha$ = 1.4 x 10^{-4}
- LCF has to assume required precision from Lattice
- FCC-ee (LEP3) can directly measure it :
  - from off-peak FB asymmetry (interference with γ*) in $\mu\mu$ events ($\delta\alpha/\alpha$ = 3x10^{-5})
    - small experimental uncertainty, stat dominated
    - Z-pole energy points chosen to optimize measurement !
  - from $R_{e+/e-}$, $R_{e-/\mu-}$ ($\delta\alpha/\alpha$ = 0.6x10^{-5})
    - e^+/e^- efficiency control (charge mis-id), material budget
    - e^-/μ^- acceptance difference (to be determined from 10^{11} lepton pairs)
  - Can then provide comparison with Lattice calculation

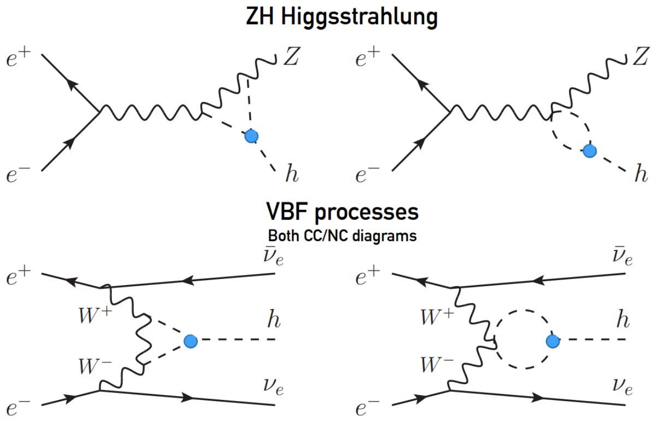


Higgs self coupling

Probe *indirectly* trilinear Higgs self coupling λ_3 through single Higgs boson cross section

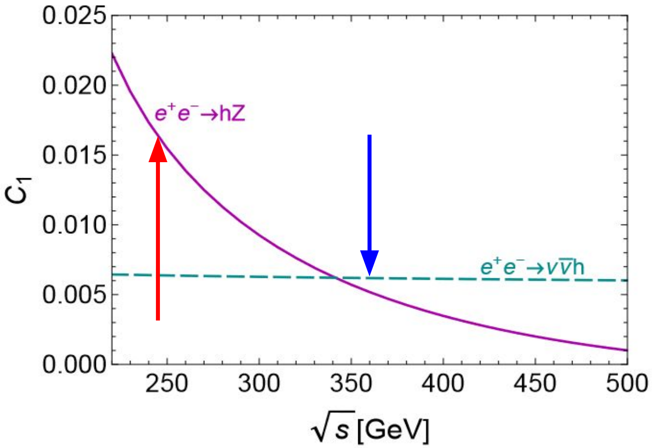
$$\Sigma_{\mathrm{NLO}} = Z_H \Sigma_{\mathrm{LO}}(1+\kappa_\lambda C_1) \qquad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\mathrm{SM}}}$$





Total cross section can be measured O(1%) at FCC-ee

- Higgs decay-mode independent → challenge for Z(qq)
- Probing NLO deviations from SM: $\delta\kappa_\lambda = \kappa_\lambda - 1$
- C_1 sensitive to √s: exploit different sensitivities at both energies



27% precision standalone on the self-coupling
18% if combined with HL-LHC

Detector Requirements

Table 14: Summary of detector requirements

	Aggressive	Conservative	Comments
Beam-pipe	$\frac{X}{X_0} < 0.5\%$	$\frac{X}{X_0} < 1\%$	$\mathrm{B} \to \mathrm{K}^* \tau\tau$
Vertex	$\sigma(d_0) = 3 \oplus 15\,/\,(p \sin^{3/2}\theta)$ µm $\frac{X}{X_0} < 1\%$	–	$\mathrm{B} \to \mathrm{K}^* \tau\tau$ R_c
	$\delta L = 5\,\mathrm{ppm}$	–	$\delta\tau_\tau < 10\,\mathrm{ppm}$
Tracking	$\frac{\sigma_p}{p} < 0.1\%$ for $\mathcal{O}(50)$ GeV tracks	$\frac{\sigma_p}{p} < 0.2\%$ for $\mathcal{O}(50)$ GeV tracks	$\delta M_H = 4\,\mathrm{MeV}$ $\delta\Gamma_Z = 15\,\mathrm{keV}$ $\mathrm{Z} \to \tau\mu$
	t.b.d.	$\sigma_\theta < 0.1$ mrad	$\delta\Gamma_\mathrm{Z}(\mathrm{BES}) < 10\,\mathrm{keV}$
ECAL	$\frac{\sigma_E}{E} = \frac{3\%}{\sqrt{E}}$	$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}}$	$\mathrm{Z} \to \nu_e\bar{\nu}_e$ coupling, B physics, ALPs
	$\Delta x \times \Delta y = 2 \times 2\ \mathrm{mm}^2$	$\Delta x \times \Delta y = 5 \times 5\ \mathrm{mm}^2$	τ polarization boosted π^0 decays bremsstrahlung recovery
	$\delta z = 100$ µm, $\delta R_{\mathrm{min}} = 10$ µm ($\theta = 20°$)	–	alignment tolerance for $\delta\mathcal{L} = 10^{-4}$ with $\gamma\gamma$ events
HCAL	$\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E}}$	$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}}$	$\mathrm{H} \to \mathrm{s\bar{s}},\ \mathrm{c\bar{c}}$, gg, invisible HNLs
	$\Delta x \times \Delta y = 2 \times 2\ \mathrm{mm}^2$	$\Delta x \times \Delta y = 20 \times 20\ \mathrm{mm}^2$	$\mathrm{H} \to \mathrm{s\bar{s}},\ \mathrm{c\bar{c}}$, gg
Muons	low momentum ($p < 1\,\mathrm{GeV}$) ID	–	$\mathrm{B_s} \to \nu\bar{\nu}$
Particle ID	3σ K/π $p < 40$ GeV	3σ K/π $p < 30$ GeV	$\mathrm{H} \to \mathrm{s\bar{s}}$ $b \to s\nu\bar{\nu}, \ldots$
LumiCal	tolerance $\delta z = 100$ µm, $\delta R_{\mathrm{min}} = 1$ µm acceptance 50-100 mrad	–	$\delta\mathcal{L} = 10^{-4}$ target (Bhabha)
Acceptance	100 mrad	–	$\mathrm{e^+e^-} \to \gamma\gamma$ $\mathrm{e^+e^-} \to \mathrm{e^+e^-}\tau^+\tau^-(\mathrm{c\bar{c}})$

Longer Term Storage Needs (FCC-ee)

- Estimated FCC-ee **storage** need during the **Z run, for data only**, is **comparable** to what will be needed by the end of **HL-LHC**
- To fit the MC budget, an **increase of the HL-LHC resources** will likely be **needed**
  - +20% each year after HL-LHC would likely be required to simulate ~10 times the int. lumi.
- We **need to understand the statistical power that will be required** for the analyses and plan accordingly

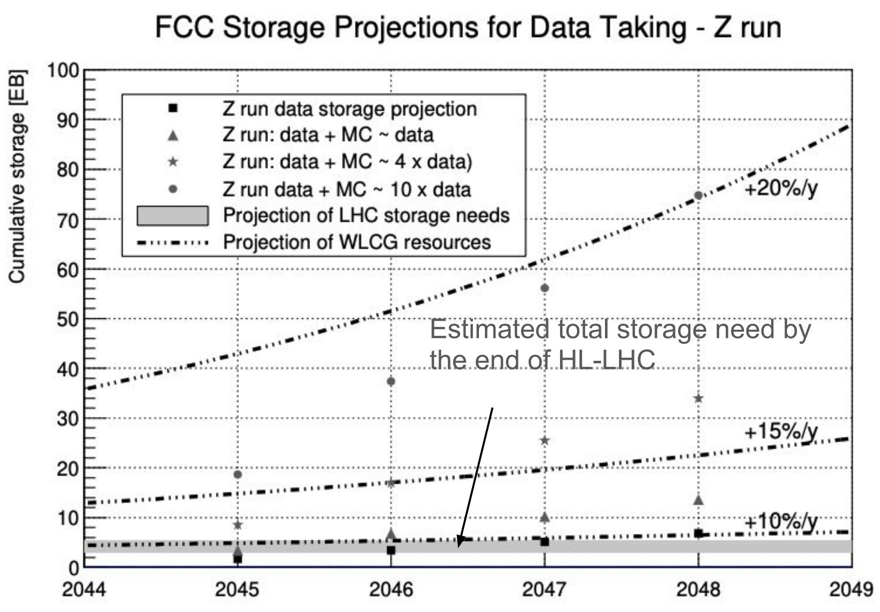


Fig. 131: Projection of the current resources to Z run based on the assumptions of four experiments, four equal runs in 2045, 2046, 2047, and 2048, and varying amounts of Monte Carlo data. The figure also includes the projected resource needs of the LHC and a hypothetical evolution of WLCG resources under different scenarios for sustained annual budget increases. See text for details.

More details in [this talk]

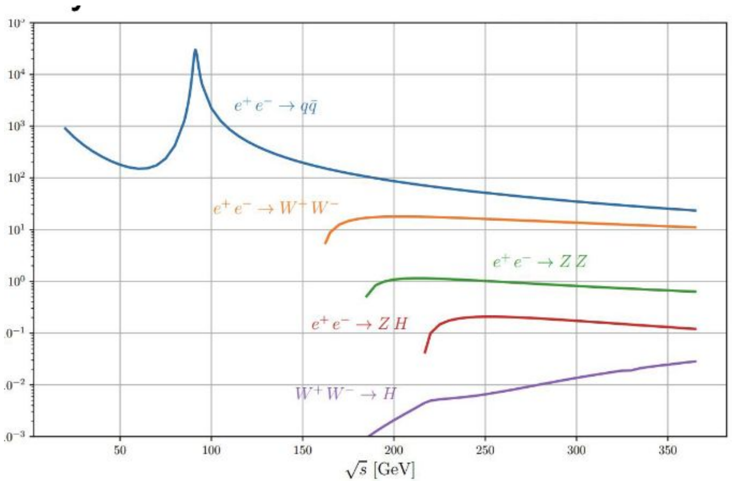
Computing needs per event

Process $e^+e^- \to$	E_{CMS} (GeV)	Event Sizes /evt		Processing time /evt	
		`Delphes` (kB)	`Full` (MB)	`Delphes` (ms)	`Full` (s)
$Z \to \bar{q}q, \ell^+\ell^-$	91.18	8.3, 1.2	1.1, 0.16	14, 0.5	11, 1.6
$W^+W^- \to$ all, $\nu\bar{\nu}\ell^+\ell^-$	157-163	9.5, 1.2	1.3, 0.16	16, 0.5	13, 1.6
$HZ \to \nu\bar{\nu}b\bar{b}, b\bar{b}b\bar{b}$	240	8.9, 13	1.2, 1.8	15, 23	12, 18
$ZZ \to$ all	240	10	1.4	17	13
$\bar{t}t \to$ all	365	18	2.3	30	23

Computing needs for 100xLEP

Table 23: Baseline projected needs per detector concept for the scenario with nominal integrated luminosity samples for the W, HZ and top runs, and event samples 100 times larger than the LEP samples for the Z run (see text for details). The total corresponds to 4 experiments requiring the same resources. Amount of HS06 is shown for a reference period of 3 years, i.e., roughly the pre-TDR duration. In bold are the figures beyond today's availability.

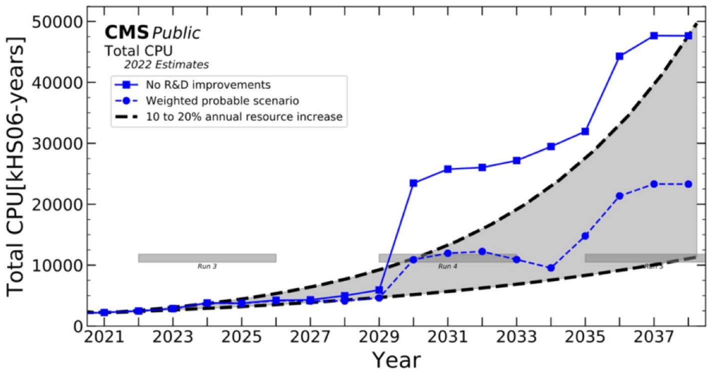
Run	Process	N evts	Delphes		Full	
			Storage (TB)	CPU (HS06)	Storage (TB)	CPU (HS06)
Z (100xLEP)	$\bar{q}q$	400 M	3.25	~ 1	440	475
	$\ell^+\ell^-$	42.5 M	0.05		6.5	7
W	W^+W^-	60 M	0.6		75	72
HZ	HZ	500 k	0.0065		1	~ 1
	VBFH	16 k	~0.001		0.25	
Top	$\bar{t}t$	500 k	0.009		9	~ 1
	HZ	90 k	~0.001		0.2	
	VBFH	23 k	~0.001		0.25	
Total		500 M	4	~ 1	**530**	**550**
4 exp		2000 M	16	~ 4	**2100**	**2200**

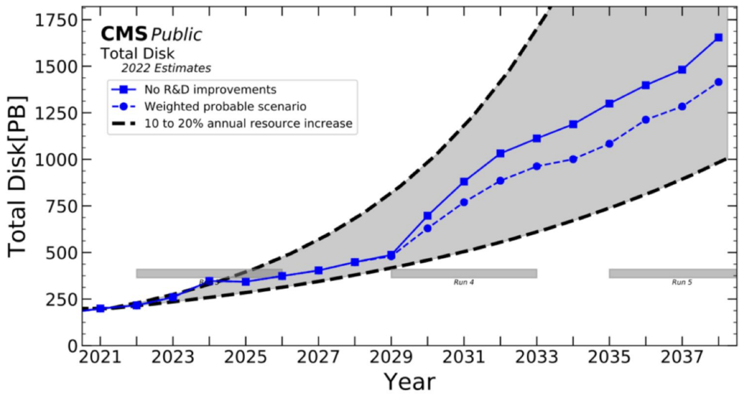


Longer Term Resource Needs (FCC-ee)

Table 22: Baseline needs for the nominal integrated luminosity and per detector concept. Amount of HS06 is shown for a reference period of 3 years, i.e., roughly the pre-TDR duration.

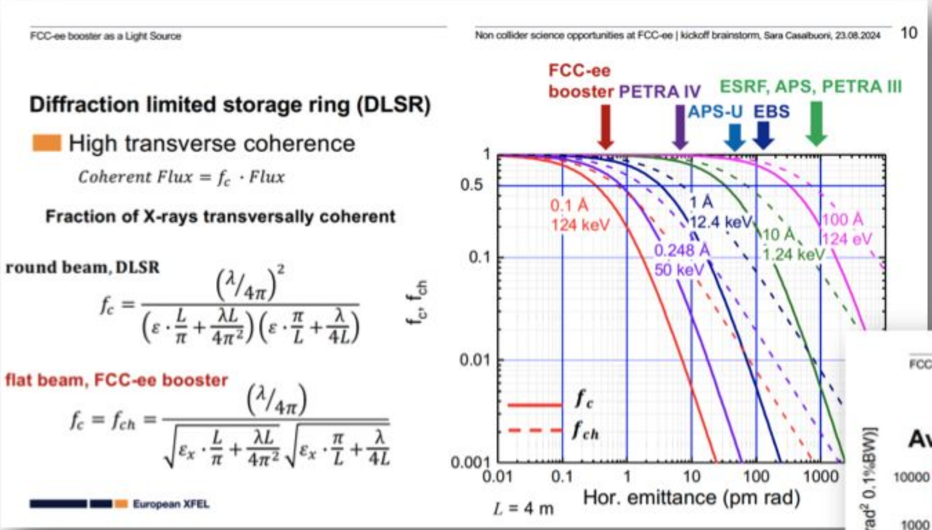
Run	Process	N evts	Delphes Storage (PB)	Delphes CPU (HS06)	Full Storage (PB)	Full CPU (HS06)
Z	$\bar{q}q$	1500 G	12.5	2.2 k	1650	2 M
	$\ell^+\ell^-$	225 G	0.275	12	40	40 k
W	W^+W^-	60 M	$\sim 10^{-3}$		0.075	72
HZ	HZ	500 k	$\sim 10^{-5}$		$\sim 10^{-3}$	~ 1
	VBFH	16 k	$\sim 10^{-6}$		$\leq 10^{-3}$	
Top	$\bar{t}t$	500 k	$\sim 10^{-5}$		$\sim 10^{-2}$	~ 1
	HZ	90 k	$\sim 10^{-6}$		$\leq 10^{-3}$	
	VBFH	23 k	$\sim 10^{-6}$		$\leq 10^{-3}$	
Total		1725 G	**13**	2.2	**1690**	**2 M**





Imaging on FCC-ee?

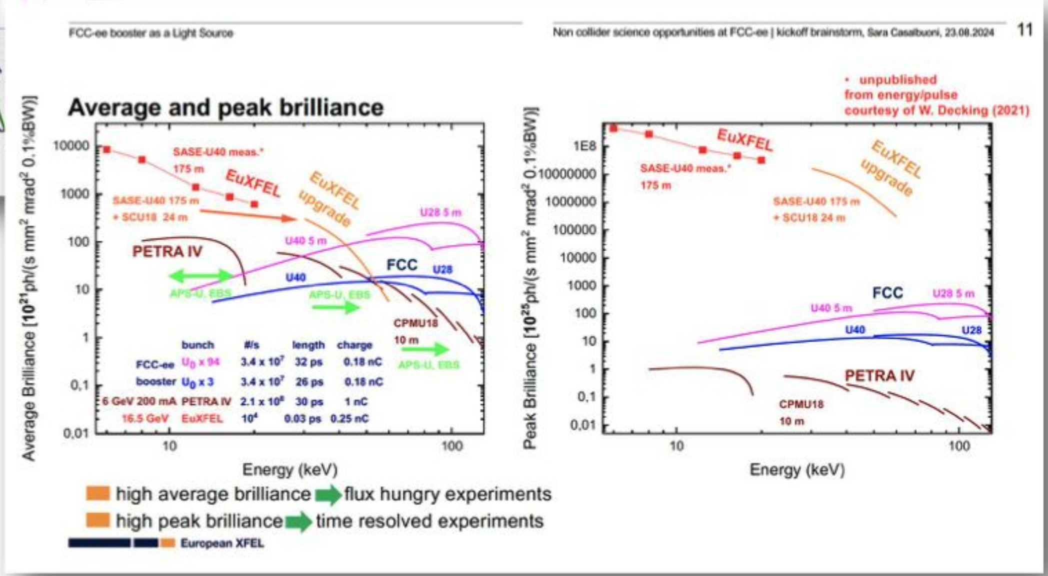
PSI



From August 2024 "Kick-off brainstorm" in Hamburg…

Compared to PETRA IV, at 50-100 keV the FCC-ee booster could produce:

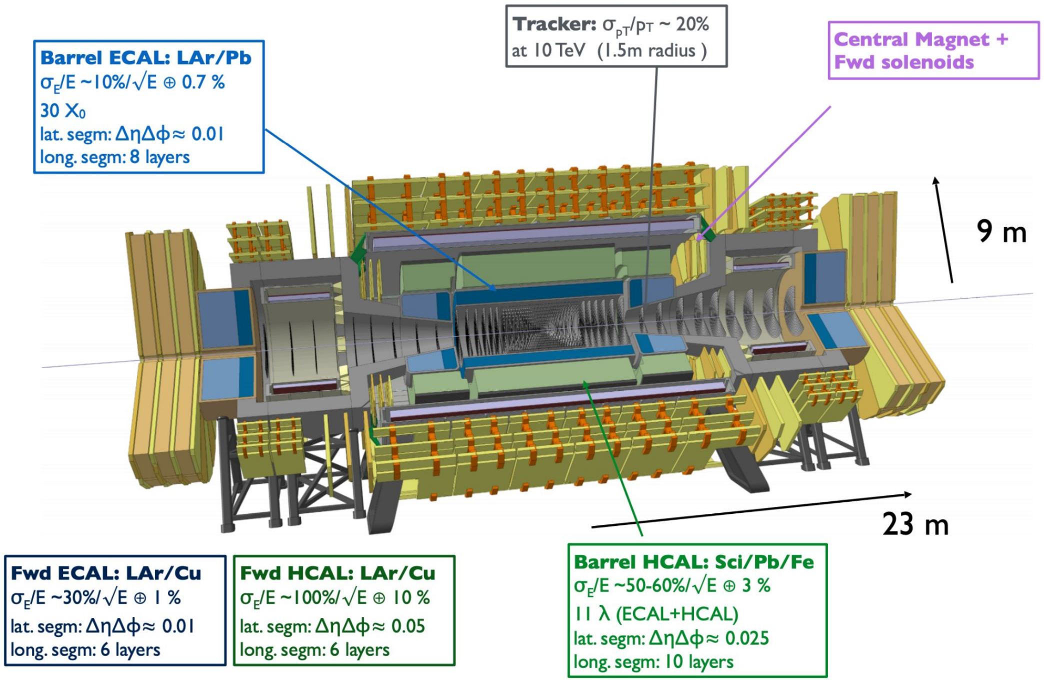
- a fraction of coherent X-rays larger by one order of magnitude
- an average brilliance larger by up to two orders of magnitude
- a peak brilliance larger by up to four orders of magnitudes



FCC-ee might boost imaging to unprecedented levels:

- Exceptional peak-brilliance and coherent fraction will enable high-energy time-resolved ptychographic imaging (larger samples, heavier materials, *in-situ/operando)*
- Exceptional average brilliance will push dynamic imaging beyond all currently achievable capabilities and eventually make scanning Compton X-ray Microscopy a valuable tool

A detector concept that does the job …



Challenges

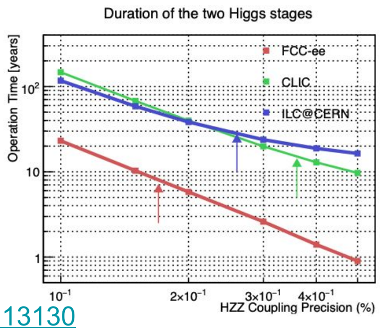
- Large dynamic range
- High occupancy (1000 PU)
  - Timing (3 ps resolution)
- High data rates
  - 10x data vs HL-LHC
- High radiation
  - 3e18 1MeV neq / cm2

R&D should continue after HL-LHC

Implantation and Societal Impact

Sustainability

- Studying techno-economic feasibility of **waste heat distribution**
  - Adaptation of operation schedule when more heat is required
  - Reduces cooling water needs and partially compensate carbon footprint
- **Reducing land consumption**: 12 → 8 surface sites
  - 100 to 45 ha, with **4.5 ha/year over 10 years** of construction
  - Comparison: **France artificializes 66 ha/day**, Switzerland 13 ha/day
- Electricity needs: on average **1.3 TWh/year** (equivalent to one large “Meta” company data center)
  - Working on an operational model leveraging renewable energy
  - To be **integrated over** a **short period thanks to high inst. Lumi. and 4 IPs**
- Tunnel construction carbon footprint: **530 ktCO_2e**
  - **0.11 kgCO_2e per capita** in Member States **per year** of construction
  - Paris Agreement goal for 2050: **2 000 kg per person per year**
  - This **tunnel will serve HEP for the whole 21st century**, without the need for extension
  - **Other tunnels**: Lyon-Turin ~ 10 MtCO_2e, **Gotthard 24 MtCO_2e**
- **Valorisation of excavated material e.g. make molasse fertile**



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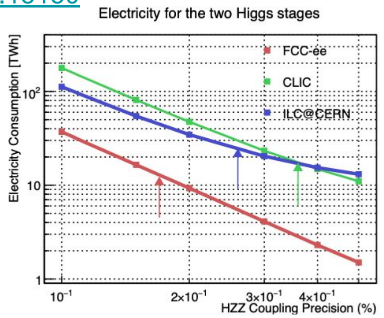
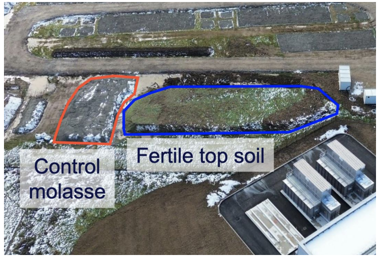
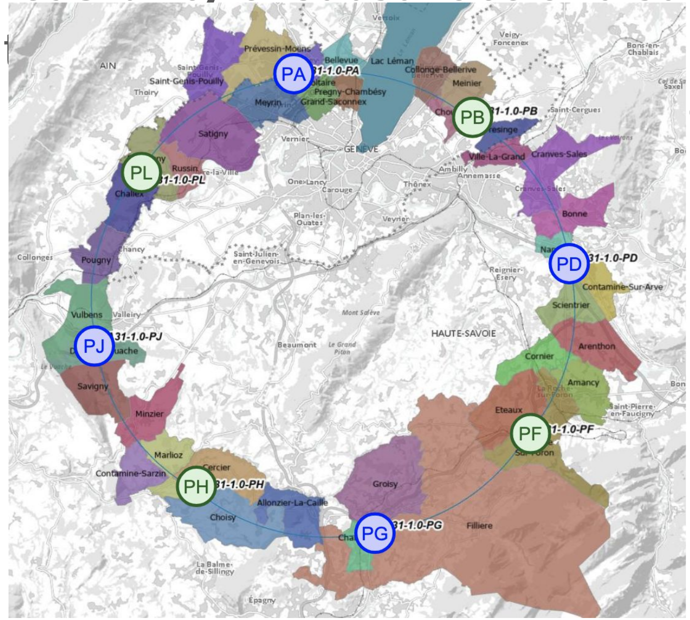


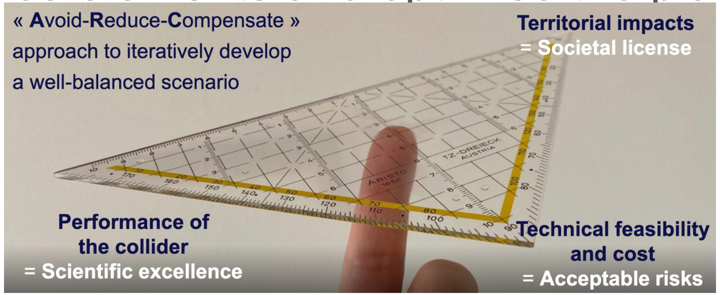


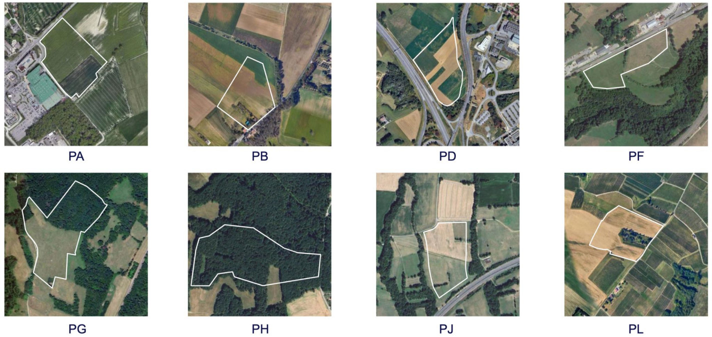
More details also here

Implantation Study

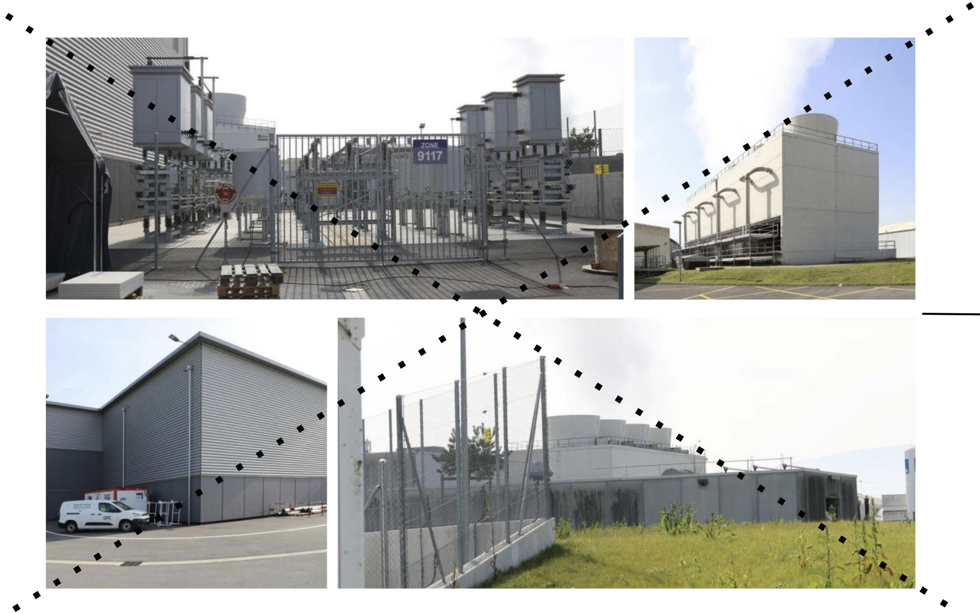
- **Demonstrate geological, technical, environmental, and administrative feasibility** of subsurface and surface elements and optimise the placement of t… ce

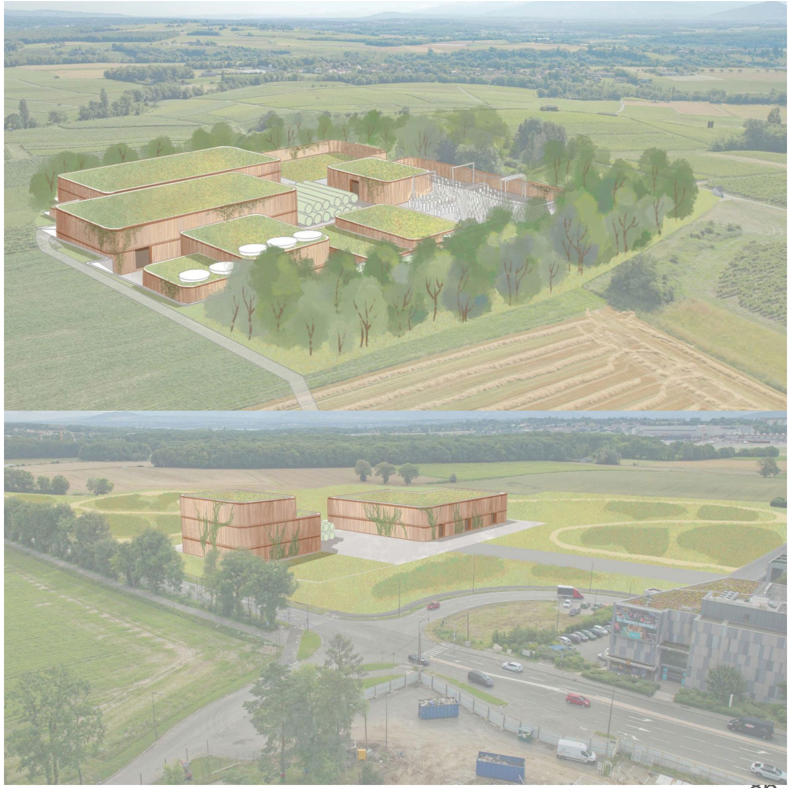






Societal acceptance is different than in the past

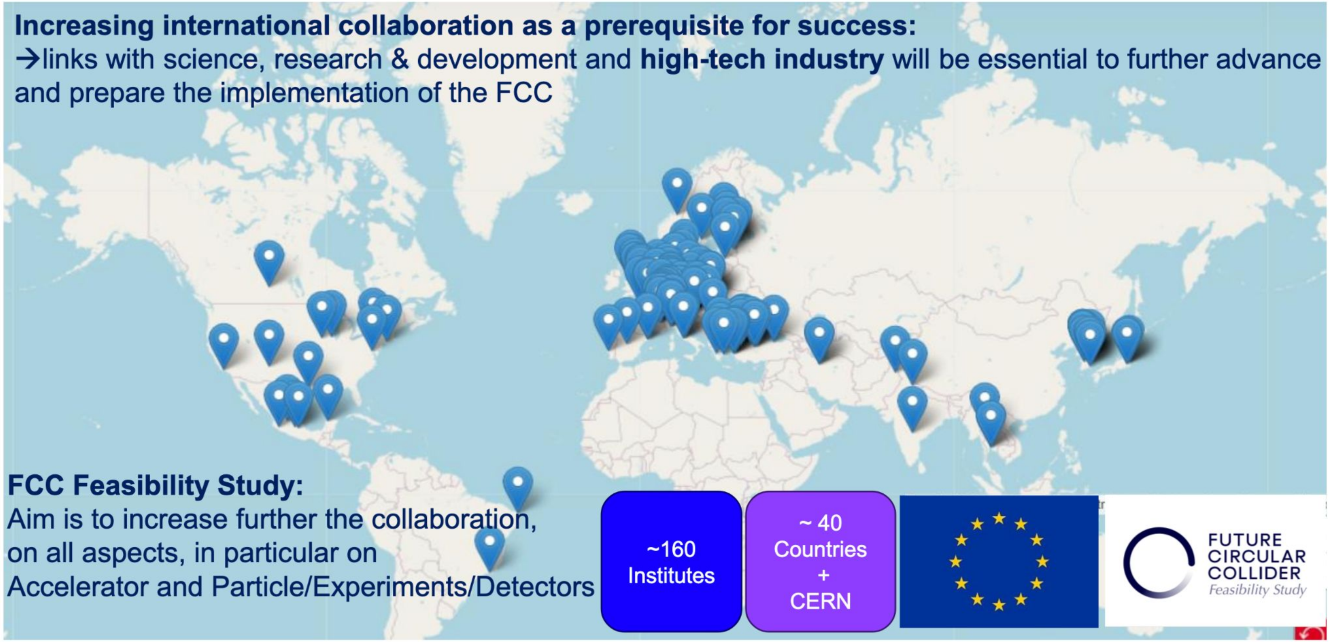




Community Building

International Collaboration

As for the LHC, we have to engage the whole community



Statement of intent CERN & USA, April 2024, White House

Support from the US

“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 Week, June 2024, San Francisco, 449 participants

Second Annual US FCC Workshop, MIT, March 2024, 209 participants

Support Within Europe

CERN 70's anniversary

"….No European country alone could have built the world's largest particle collider. CERN has become a global hub because it rallied Europe and this is even more crucial today.

I am proud that we have financed the feasibility study for CERN's Future Circular Collider (FCC). This could preserve Europe's scientific edge and could push the boundaries of human knowledge even further. *And as the global science race is on, I want Europe to switch gears. To do so, European unity is our greatest asset. …."*

Ursula von der Leyen, President of the European Commis*sion*

Support Within Europe

“The future of European competitiveness”, Sep 2024, Mario Draghi (for the European Commission)

The CERN success story

The Large Hadron Collider has propelled CERN to global leadership in particle physics – a mantle that has shifted from the US to Europe – and it stands as CERN’s flagship facility. One of CERN’s most promising current projects, with significant scientific potential, is the construction of the Future Circular Collider (FCC): a 90-km ring designed initially for an electron collider and later for a hadron collider. Chinese authorities are also considering constructing a similar accelerator in China, recognising its scientific potential and its role in advancing cutting-edge technologies. If China were to win this race and its circular collider were to start working before CERN’s, Europe would risk losing its leadership in particle physics, potentially jeopardising CERN’s future.

Invest in world-leading research and technological infrastructure

We have already discussed the remarkable returns from the creation of the European Organization for Nuclear Research (CERN) and emphasised that the future of CERN is at risk due to China’s progress in emulating one of CERN’s most promising current projects, the Future Circular Collider (FCC). Refinancing CERN and ensuring its continued global leadership in frontier research should be regarded as a top EU priority, given the objective of maintaining European prominence in this critical area of fundamental research, which is expected to generate significant business spillovers in the coming years.

Support from the new CERN DG

"From the perspective of today's European strategy, the **Future Circular Collider (FCC) is an extremely appealing project** that would map out an **exciting future for CERN for many decades**. I think we'll see this come through strongly in an open and science-driven European strategy process."

"**Scientifically, the FCC provides everything you want from a Higgs factory**, both in terms of luminosity and the opportunity to support multiple experiments.
Second, investment in the FCC tunnel will provide a **route to hadron–hadron collisions at the 100TeV** scale. I find it **difficult to foresee a future where we will not want this capability.**
These two aspects make the FCC a very attractive proposition."

"The scale of the **FCC will provide a huge number of opportunities for young scientists and engineers.**"

Mark Thomson in "A word with CERN's next Director-General", CERN Courrier, 27th of January 2025