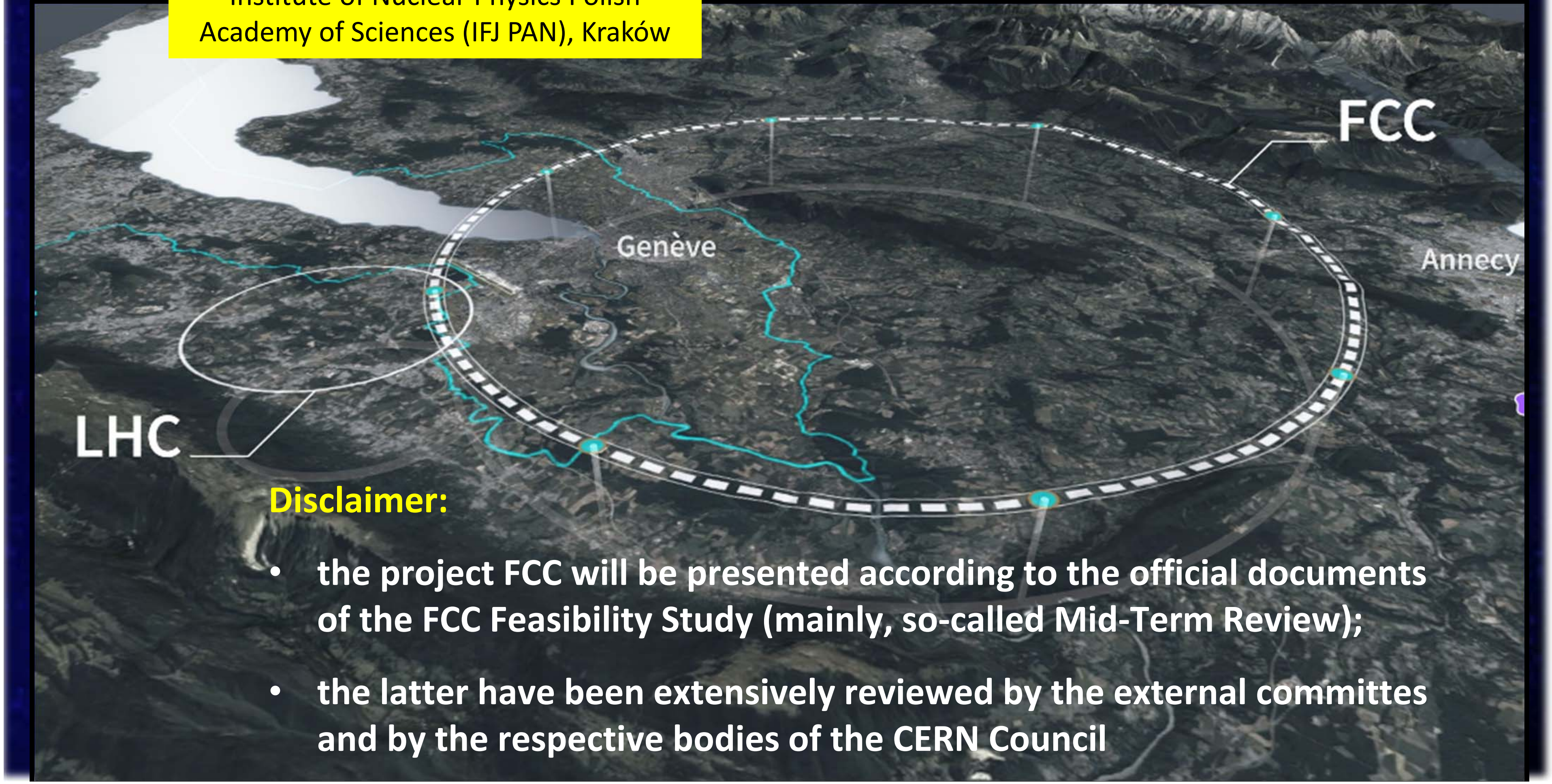
The Future Circular Collider Project: Plans and Physics Program

Tadeusz Lesiak
Institute of Nuclear Physics Polish
Academy of Sciences (IFJ PAN), Kraków

1. FCC project in a nutshell
2. FCC-ee Physics Programme
3. A few words about the FCC-hh



Disclaimer:

- **the project FCC will be presented according to the official documents of the FCC Feasibility Study (mainly, so-called Mid-Term Review);**
- **the latter have been extensively reviewed by the external committes and by the respective bodies of the CERN Council**

FCC and European Strategy for Particle Physics (2020)

"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."

"**Europe,** together with its international partners, **should investigate the 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.** "

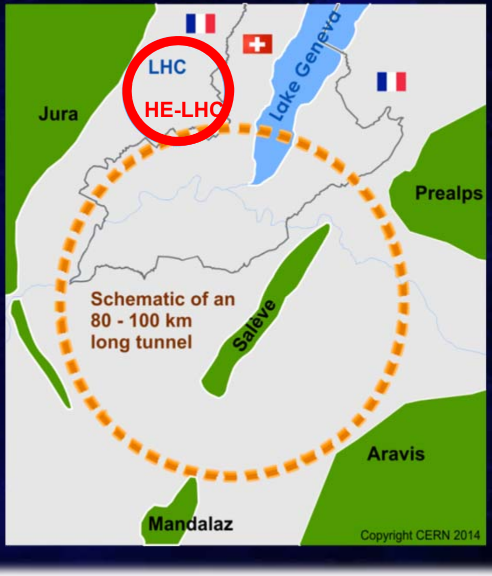
CERN Council, June 2021:
approval of the FCC feasibility study (FCC-FS)
→ Mid term review by the end of 2023
→ Final report by the end 2025

https://cds.cern.ch/record/2721370/files/CERN-ESU-015-2020%20Update%20European%20Strategy.pdf

FCC - global international collaboration hosted at CERN

- ✓ **0th stage:** construction of ~91 km circumference tunnel infrastructure in Geveva area to host:
- ✓ **1st stage – FCC-ee: electron positron collisions (90-360) GeV**
- ✓ **2nd stage – FCC-hh: proton-proton collisions at ~100 TeV**
- ✓ **Options of AA and eh also envisioned**

fcc.web.cern.ch



150
Institutes

32
Companies

34
Countries

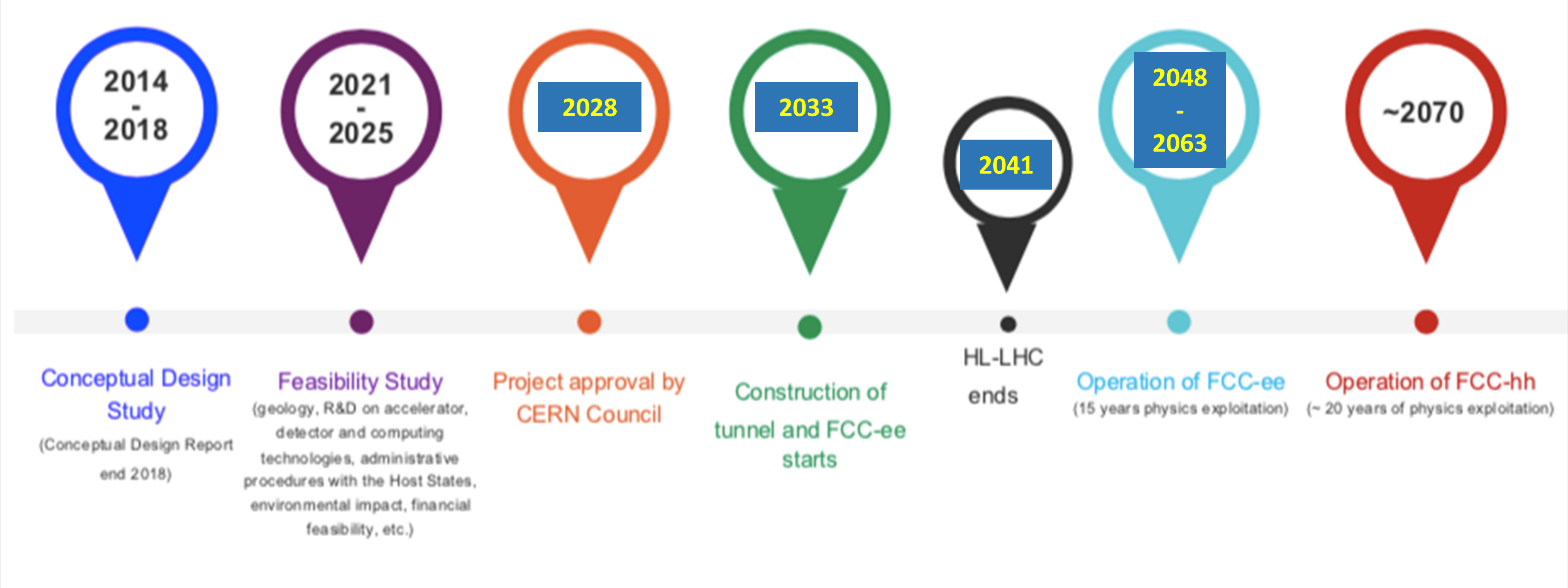
FCC Feasibility Study

EC
H2020

FCC timeline

ANY future collider at CERN cannot start physics operation before ~2045-2048

(but construction will proceed in parallel to HL-LHC operation)



2014 - 2018

Conceptual Design Study

(Conceptual Design Report end 2018)

2021 - 2025

Feasibility Study

(geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)

2028

Project approval by CERN Council

2033

Construction of tunnel and FCC-ee starts

2041

HL-LHC ends

2048 - 2063

Operation of FCC-ee

(15 years physics exploitation)

~2070

Operation of FCC-hh

(~ 20 years of physics exploitation)

2014-2048	2048-2063	2063-2100
Preparation & tunnel	FCC-ee	FCC-hh

Why FCC?

➢ The motivation for FCC-ee: a circular e^+e^- Higgs factory

- Opportunity for precise studies at four (five) energy thresholds - well motivated by physics:

$$\sqrt{s} = M_Z,\ M(WW),\ M(ZH),\ M(t\bar{t}),\ (\text{and } m_H)?$$

- Discovery of a light (m= 125 GeV) Higgs boson – accessible to a circular machine
- Substantial progress in e^+e^- circular collider technology (B factories et al.) → mature technology
- Lack of BSM physics at the LHC → limits the physics case of the 1 TeV scale linear colliders
- The best performance of all proposed Higgs and electroweak factories → see below

➢ The motivation for proton-proton collider FCC-hh:

- Indirect exploration of the next energy frontier (~ 10x LHC)
- Addressing the fundamental aspects of the SM; further significant improvement in its precision tests
- Heavy-ion collisions and, possibly, ep/e-ion collisions
- Excellent playground for the HFM/HTS technology

➢ **Optimization of overall investment: FCC-hh will reuse same civil engineering and large part of FCC-ee technical infrastructure**

➢ **It's the only facility commensurate to the size of the CERN community (at least 4 expts) which would guarantee the leading role of CERN in HEP for the next decades**

Fortuna Varibilis: Linear vs Circular Colliders

CIRCULAR, 20 years ago:

„LEP is the last circular e^+e^- collider"

$$\Delta E_{SR} \propto \frac{(E/m)^4}{R}$$

$\sqrt{s}$ (GeV)	ΔE_{SR} (GeV)
10	0.001
100	2.5
500	156

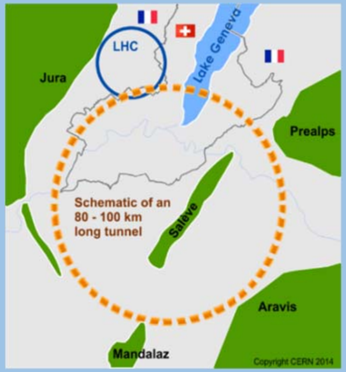
$$\mathcal{L} \propto R\frac{P_{\text{SR}}}{\beta_y^*}$$

$$\mathcal{L} \sim 10^{31}\ \text{cm}^{-2}\text{s}^{-1}$$

$$\beta_y^* \sim 50\ \text{mm}$$

CIRCULAR, Now:

enormous progress



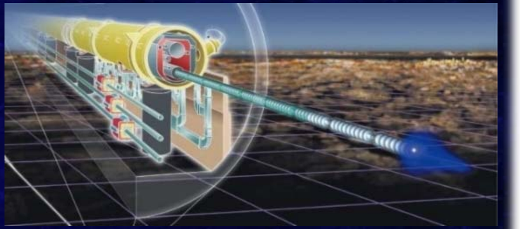
$$\mathcal{L} \leq 10^{36}\ \text{cm}^{-2}\text{s}^{-1}$$

- $\beta_y^* \sim 0.8\ \text{mm}$ x (50-250)
- Continuous injection (x5)
- Increase beam power (x5)
- Increase radius (x4)

Maturing technology; usable up to $t\bar{t}$ threshold

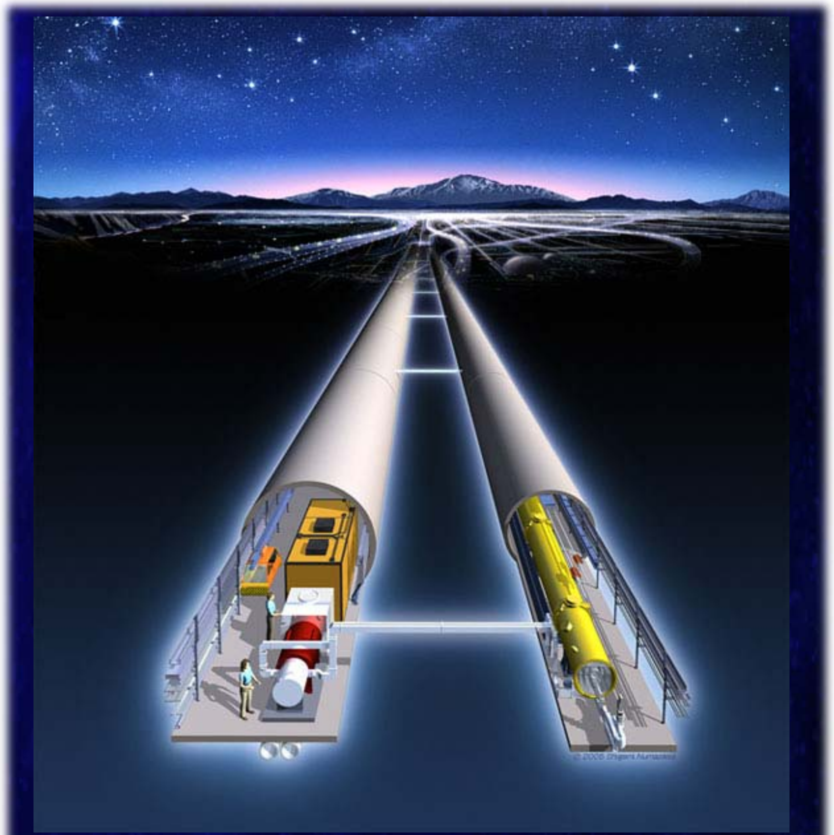
LINEAR, Now:

enormous progress, mature(-ing) technology



- The beams are accelerated and usable only once
- Longitudinal beam polarization
- The only option for E > 400 GeV

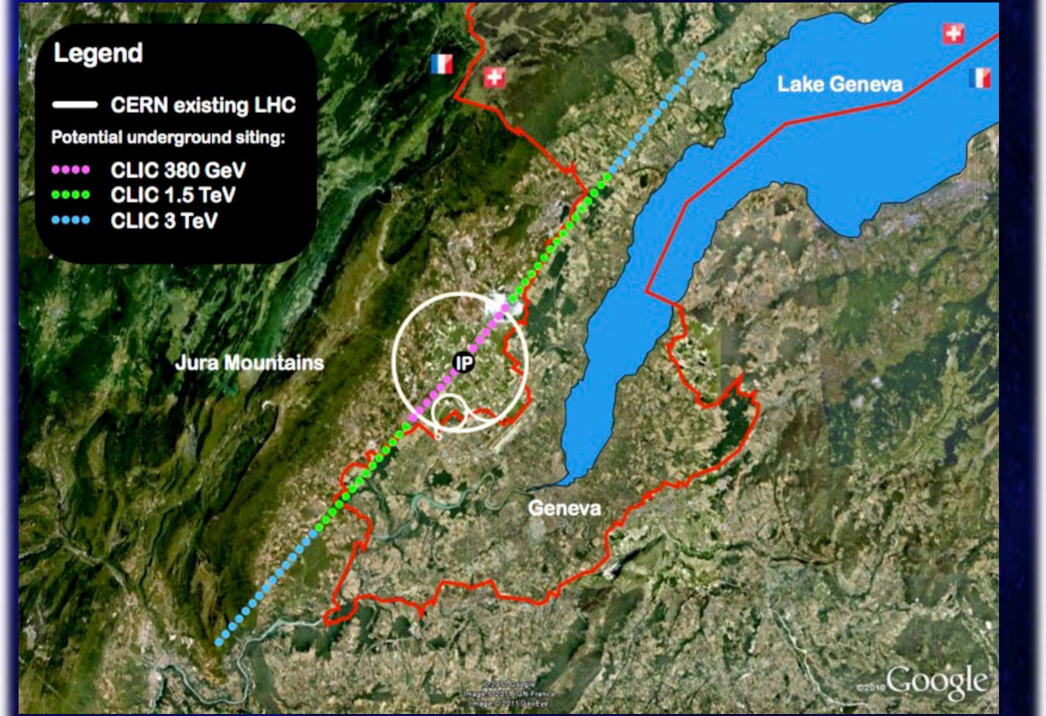
Proposed Linear e^+e^- Colliders



ILC

International Linear Collider,

Kitakami, Japan



CLIC

Compact Linear Collider,

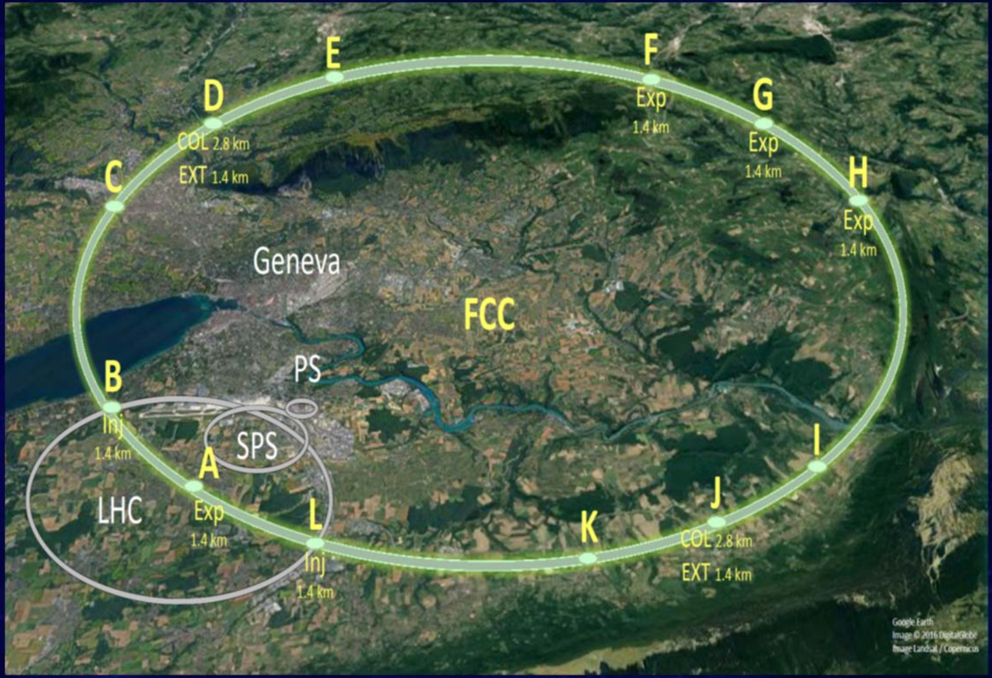
CERN

Proposed Circular e^+e^- Colliders

FCC – ee

Future Circular Collider,

CERN



CEPC

Circular Electron Positron Collider,

China

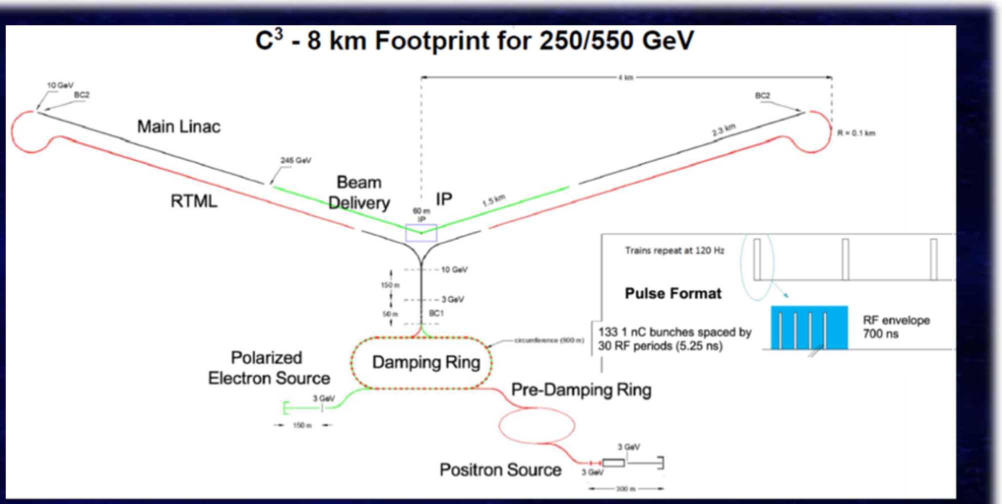
Recently Proposed e$^+$e$^-$ Colliders

C^3

Cool Copper Collider,

US

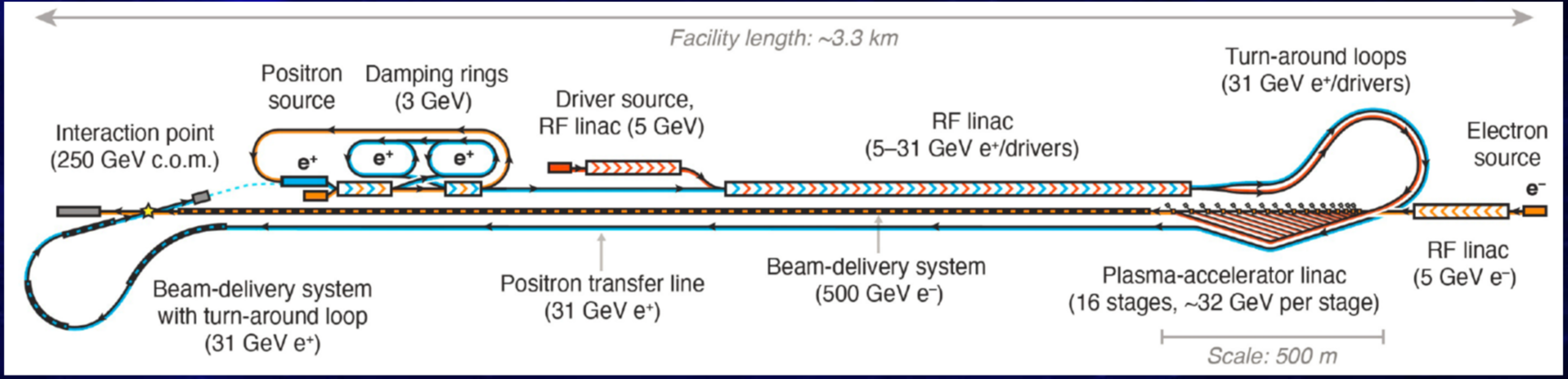
Normal conducting RF



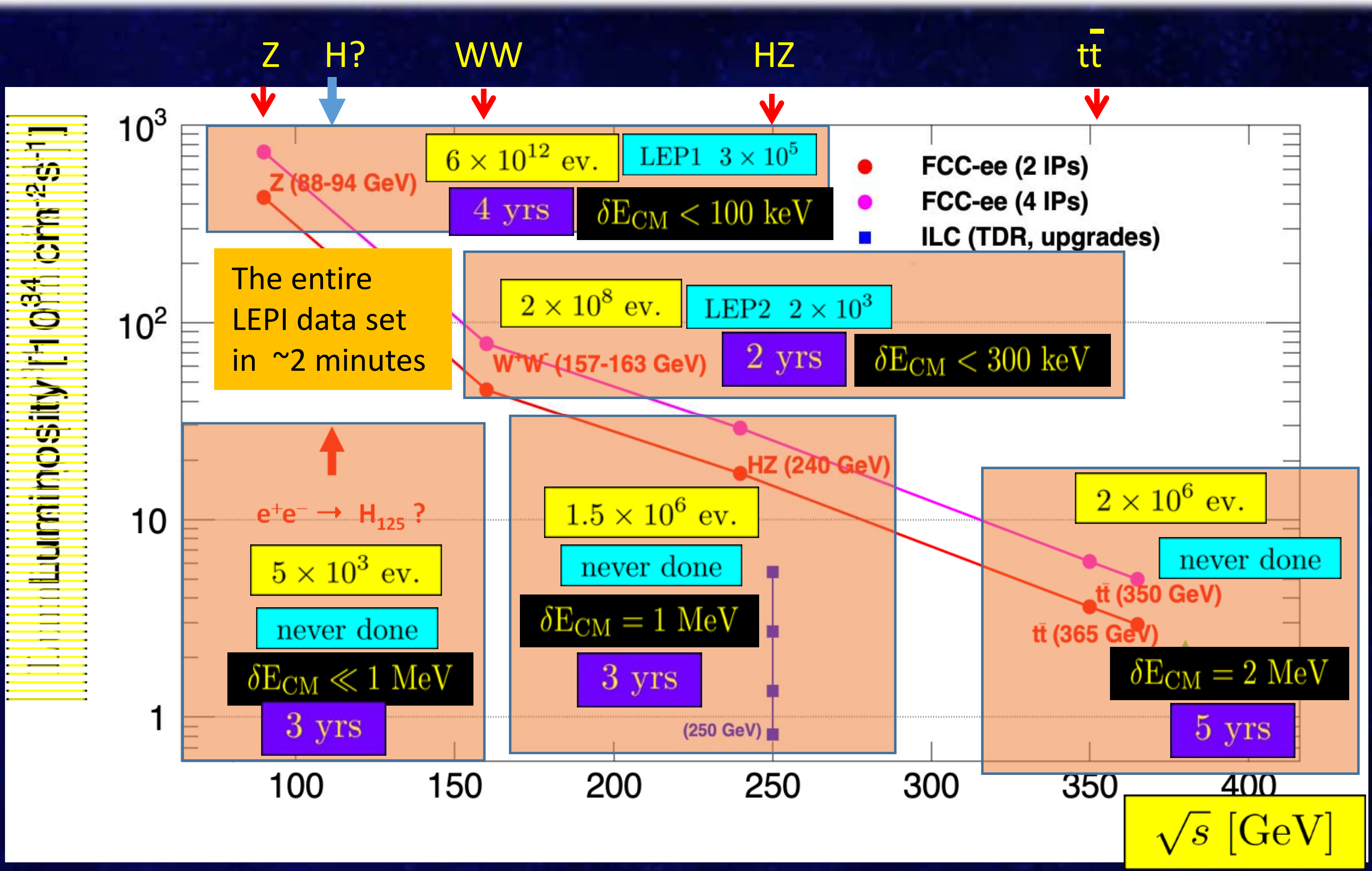
HALHF

Hybrid Asymmetric Linear Higgs Factory

B.Foster, R.D'Arcy, C.A. Lindstroem



FCC Working Points



The entire LEPI data set in ~2 minutes

- Optimal energy range for SM particles!
- HZ and ttbar thresholds never investigated at leptonic colliders !
- Circular colliders can serve up to 4 IPs → increase discovery potential and the community

FCC Mid-Term Report (MTR) Status

The goal of the FCC FS mid-term review is to assess the progress of the Study towards the final report (to be submitted in 2025).

Deliverables (approved by Council in Sept 2022):
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

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

Many thanks to the Host States for their strong support!

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

For feedback
RESTRICTED COUNCIL
2 February 2024

FUTURE CIRCULAR COLLIDER FEASIBILITY STUDY MID-TERM REVIEW
FULL REPORT

The Council is invited to give feedback on the Future Circular Collider Feasibility Study Mid-Term report, as set out in this document.

Documents:
- ☐ Mid-term report (all deliverables except D7; ~ 700 pages)
- ☐ Executive Summary of mid-term report (~ 50 pages)
- ☐ Updated cost assessment (D7)
- ☐ Funding model (D7)

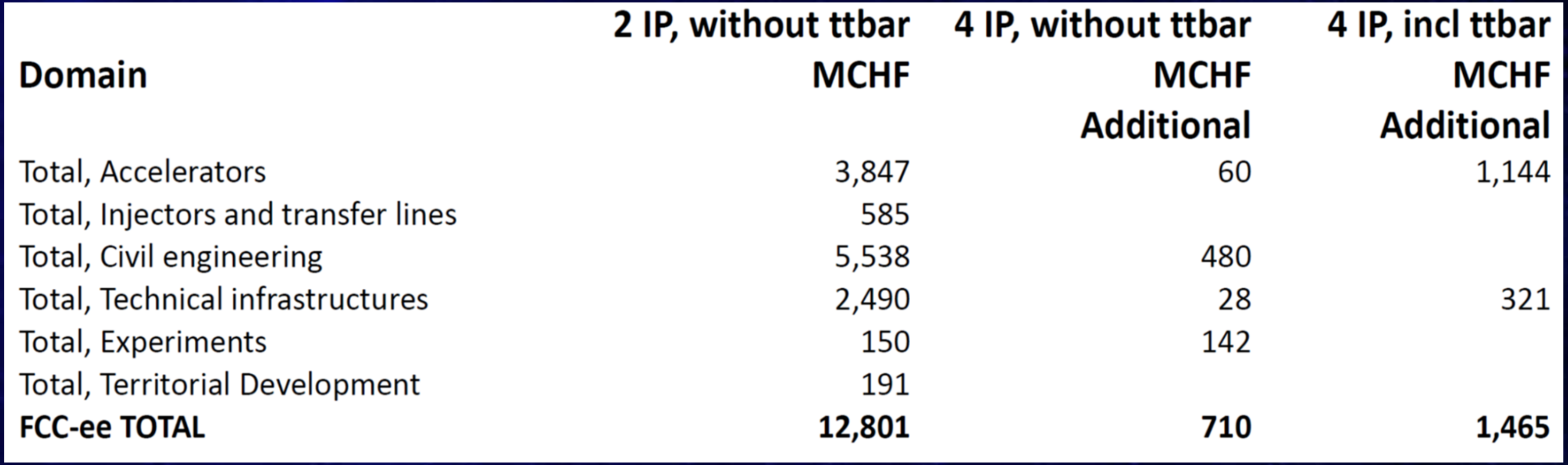
Extremely positive feedback so far.
The huge amount of work and great progress appreciated by the committees.
No show-stopper found at this stage.

Review steps:
- ☐ Oct 2023: FCC Scientific Advisory Ccommittee (scientific and technical aspects) and Cost Review Panel (ad hoc committee; cost and financial aspects)
- ☐ Nov 2023: SPC and FC
- ☐ 2 Feb 2024: Council

Financing:
FCC IS: 100 MCHF (4yrs)
HFM : 20 MCHF (annually)

FCC-ee Cost (as given by the MTR)

COST (tunnel & FCC-ee & 10% expts)



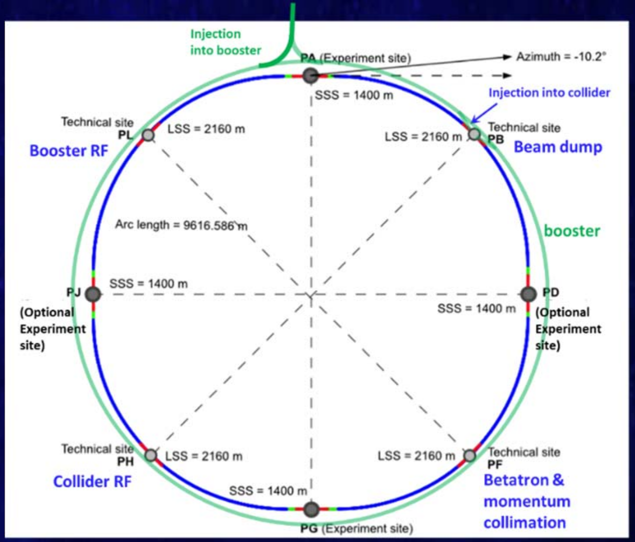
Domain	2 IP, without ttbar MCHF	4 IP, without ttbar MCHF Additional	4 IP, incl ttbar MCHF Additional
Total, Accelerators	3,847	60	1,144
Total, Injectors and transfer lines	585		
Total, Civil engineering	5,538	480	
Total, Technical infrastructures	2,490	28	321
Total, Experiments	150	142	
Total, Territorial Development	191		
FCC-ee TOTAL	**12,801**	**710**	**1,465**

FCC-ee: Design and Placement

- The double ring e^+e^- collider
- **Top-up injection scheme** (for HL) → requires booster synchrotron in the collider tunnel

- SR power of 50 MW/beam at all beam energies
- **Perfect 4-fold super-periodicity allowing 2 or 4 IPs** (robustness, statistics, option for specialised detectors, maximization of physics output)

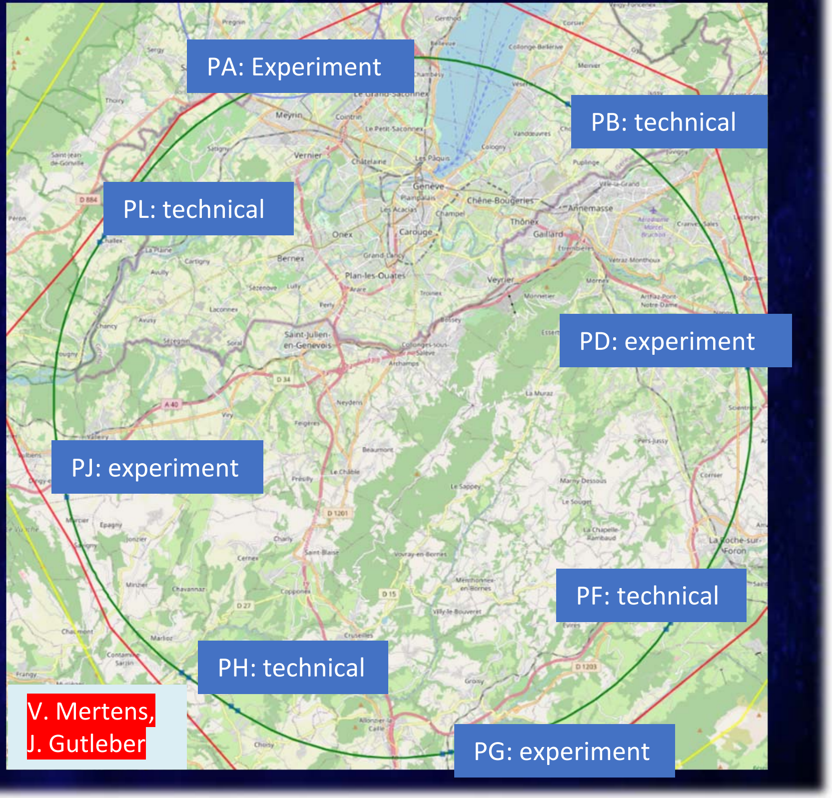
- **Large horizontal crossing angle of 30 mrad**
- **Crab-waist collision optics**



- **The optimized ring placement** chosen out of ~ 100 initial variants (based on geology, surface constraints, environment, infrastructure etc.)

- Total circumference 90.7 km

- Common footprint with FCC-hh (except around IPs)



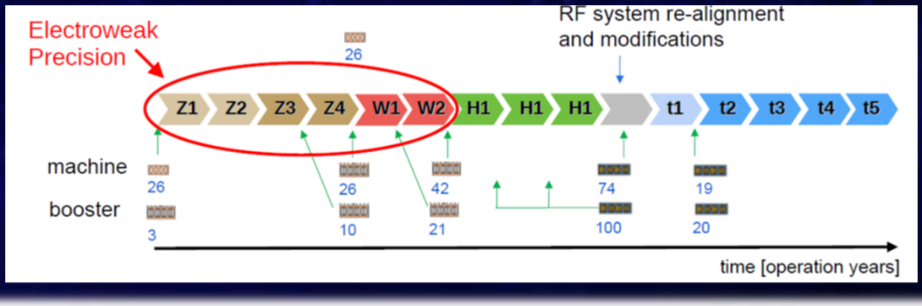
V. Mertens, J. Gutleber

FCC-ee: Collider Parameters & Run Plan

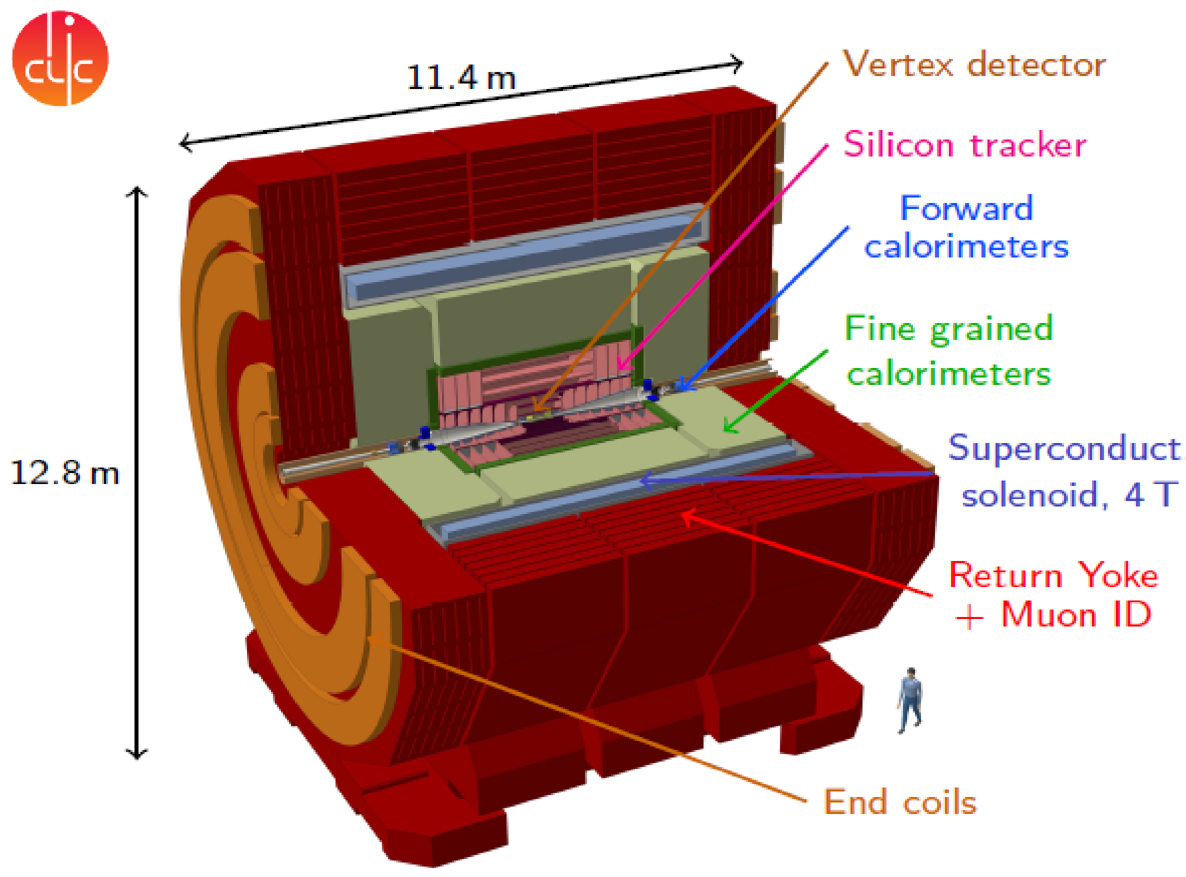
Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
luminosity per IP [10^{34} cm^{-2}s^{-1}]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr] 4 IPs	87	9.3	3.5	0.65
beam lifetime (rad Bhabha + BS+lattice)	8	18	6	10

Z	WW	H (ZH)	ttbar
4 years 5 x 10^{12} Z LEP x 10^5	2 years 2 x 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

- Z run produces most events followed by the WW run
- Z run the most demanding a.f.a. accelerator and detector are concerned
- Accelerator upgrade in stages



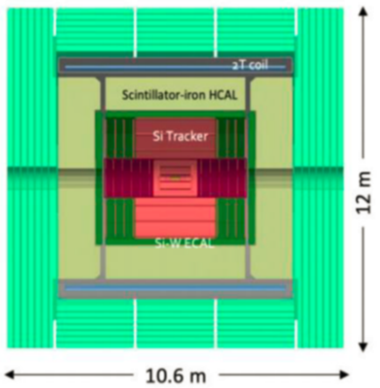
FCC-ee Detectors in a nutshell



- **Low material budget**
- **Hermeticity (forward region)**
- **Precision vertex and tracking detectors**
- **High granularity calorimeters (Particle Flow Algorithm PFA)**
- **Cost 500-700 MEUR**
- **Technology fully mature**
- **Number of electronic channels: >10^9**
- **Most of the machine induced limitations are imposed by the Z pole run (large collision rates (33 MHz) and continuous beams, large event rates (100 kHz), beamstrahlung**

FCC-ee Detector Concepts

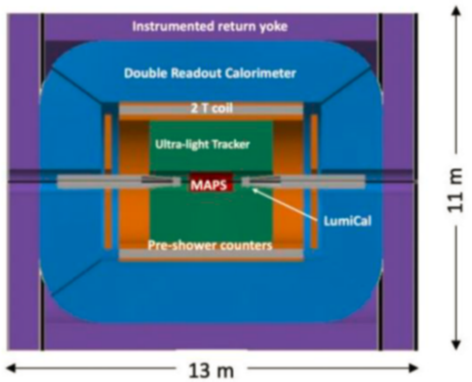
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …

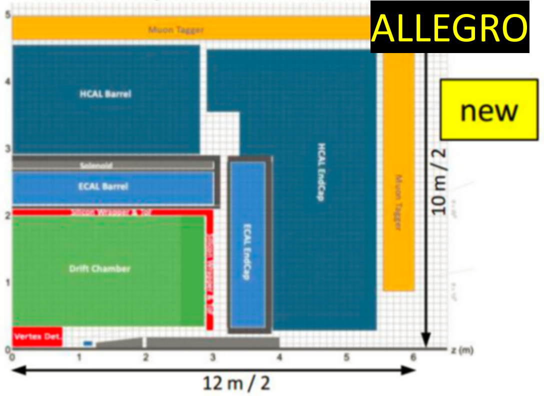
CDR

IDEA



- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

Noble Liquid ECAL based



- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

FCC-ee CDR: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

https://arxiv.org/abs/1911.12230, https://arxiv.org/abs/1905.02520 https://pos.sissa.it/390/

Full Si vtx

&

tracker

Si vtx

&

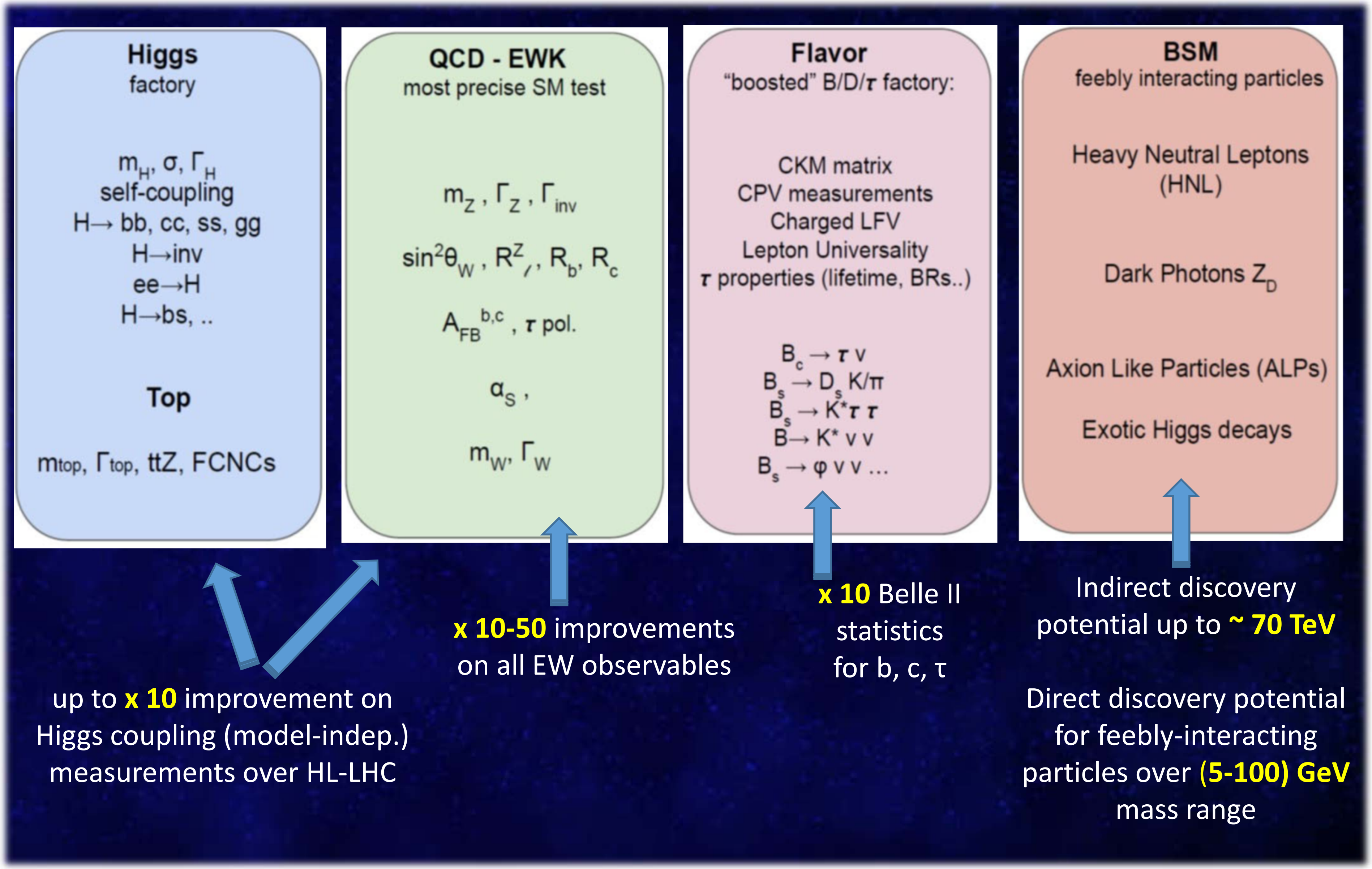
ultra light drift chamber

Si vtx &

ultra light drift chamber (or Si)

High granularity noble Liquid ECAL

FCC-ee: Physics Landscape



Higgs
factory

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

Top

m_{top}, Γ_{top}, ttZ, FCNCs

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

Flavor
"boosted" B/D/τ factory:

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

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

BSM
feebly interacting particles

Heavy Neutral Leptons
(HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

up to **x 10** improvement on
Higgs coupling (model-indep.)
measurements over HL-LHC

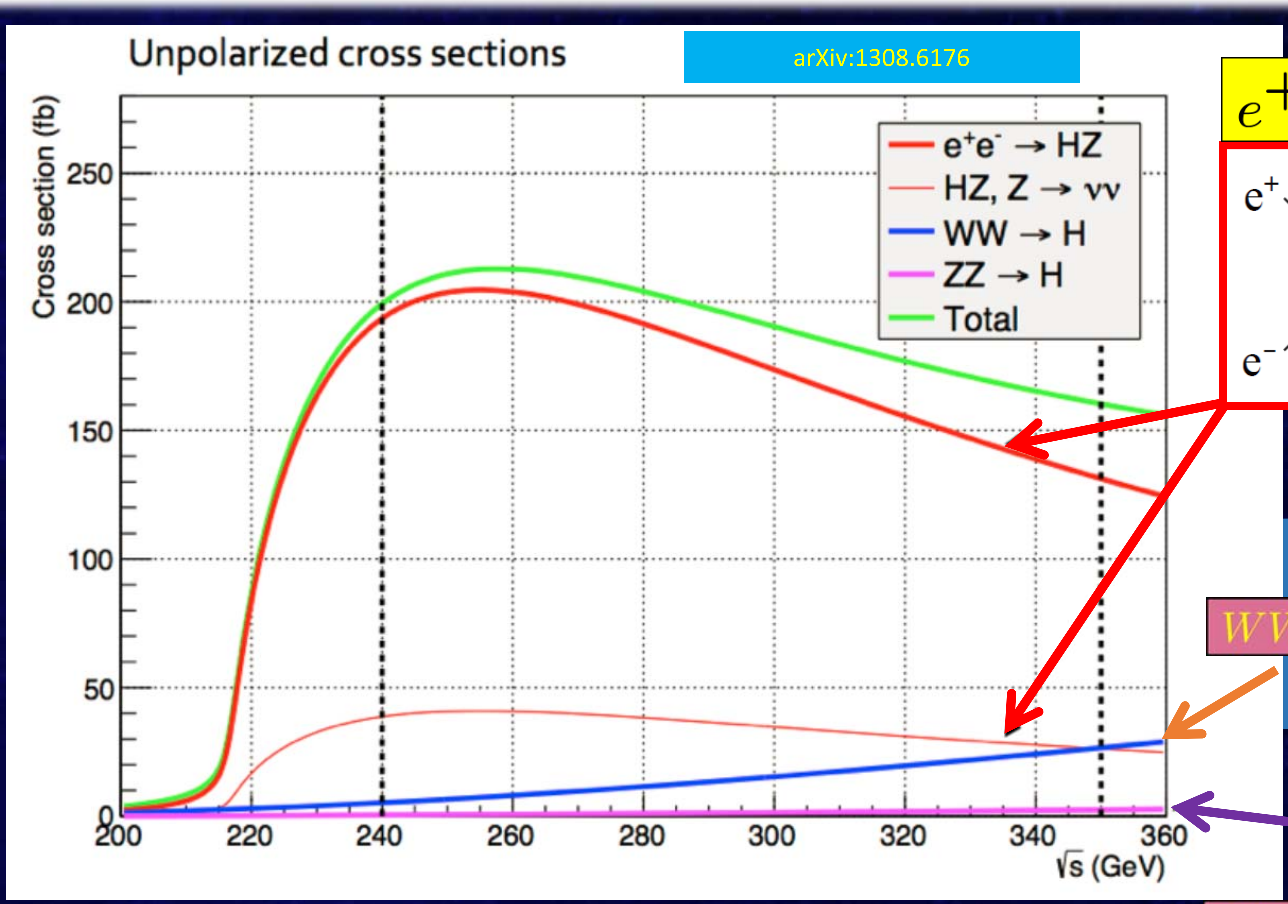
x 10-50 improvements
on all EW observables

x 10 Belle II
statistics
for b, c, τ

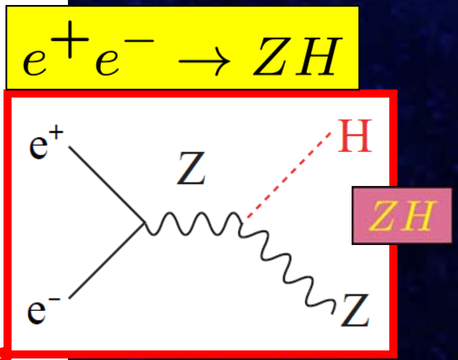
Indirect discovery
potential up to **~ 70 TeV**

Direct discovery potential
for feebly-interacting
particles over **(5-100) GeV**
mass range

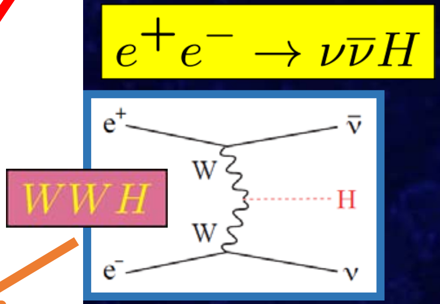
Higgs Boson Production at e^+e^- Collider



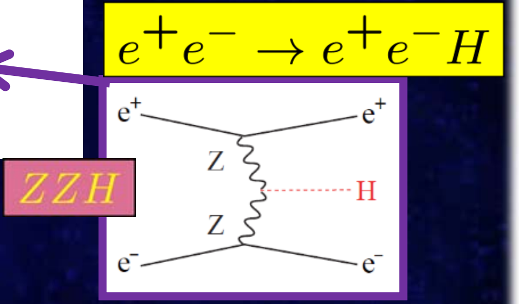
$e^+e^- \to ZH$



$e^+e^- \to \nu\bar{\nu}H$



$e^+e^- \to e^+e^-H$



With 2 IPs:

Phase / threshold	$\sqrt{s}$ [GeV]	int. lumi. [ab^{-1}]	Run duration [years]	No. of Higgs bosons
ZH	240	5.0	3	10^6
$t\bar{t}$	345-365	1.5	5	2×10^5 ZH 5×10^4 VBF
		$VBF = WWH + ZZH$		

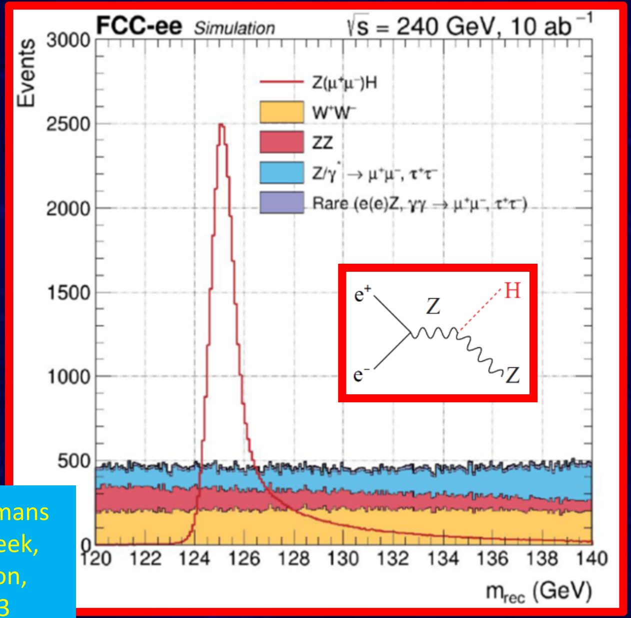
With 4 IPs:

- **Total integrated luminosity x 1.7**
- **Statistical precision increase x 1.3**

Higgs Mass Determination

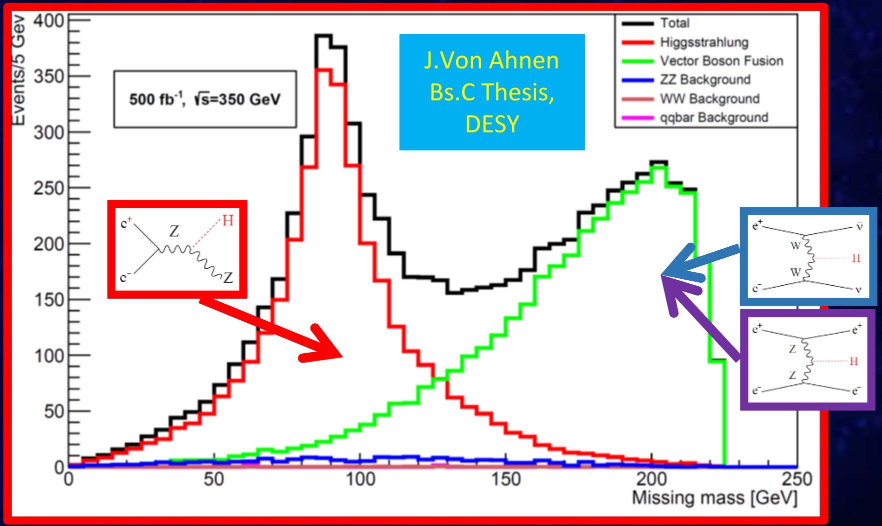
➢ The recoil technique in $e^+e^- \rightarrow ZH$ - unique for lepton colliders:

- Look just at the Z and reconstruct its decay products
- ZH events are tagged independently of Higgs decay mode (include invisible decay modes)
- Very clean Higgs mass determination: $\mathbf{m^2_{recoil} = (\sqrt{s} - E_Z)^2 - |p_Z|^2}$ $\Delta m_H \sim 10$ MeV
- Precise determination of the ZH cross-section: $\Delta\sigma(ZH)/\sigma(ZH) \sim 0.5\%$



J.Eysermans FCC week, London, 2023

$e^+e^- \rightarrow \nu\bar{\nu}H(\rightarrow b\bar{b})$ (both HZ and VBF)



J.Von Ahnen Bs.C Thesis, DESY

Higgs Total Width and Couplings

$\sqrt{s} = 240$ GeV

$$\sigma(HZ) \propto g^2_{HZZ}$$

g_{HZZ} measured (0.1%)

$\sqrt{s} = 240$ GeV

$\sqrt{s} = 365$ GeV

$$\frac{\sigma(e^+e^- \to H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})}{\sigma(e^+e^- \to HZ) \times BR(H \to b\bar{b})} \propto \frac{g^2_{HWW}}{g^2_{HZZ}}$$

g_{HWW} measured

$\sqrt{s} = 240$ GeV

$$\sigma(e^+e^- \to HZ) \times BR(H \to ZZ^*) \propto \frac{g^4_{HZZ}}{\Gamma_H}$$

Γ_H measured (1%)

Higgs couplings to $b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$, $\mu^+\mu^-$, gg, γγ …

can be determined through the tagging of the respective Higgs decay final states:

$\sqrt{s} = 240$ GeV

$$\sigma(e^+e^- \to HZ) \times \mathrm{BR}(H \to X\bar{X}) \propto \frac{g^2_{HZZ}g^2_{HXX}}{\Gamma_H}$$

$\sqrt{s} = 365$ GeV

$$\sigma(e^+e^- \to \nu\bar{\nu}H) \times \mathrm{BR}(H \to X\bar{X}) \propto \frac{g^2_{HWW}g^2_{HXX}}{\Gamma_H}$$

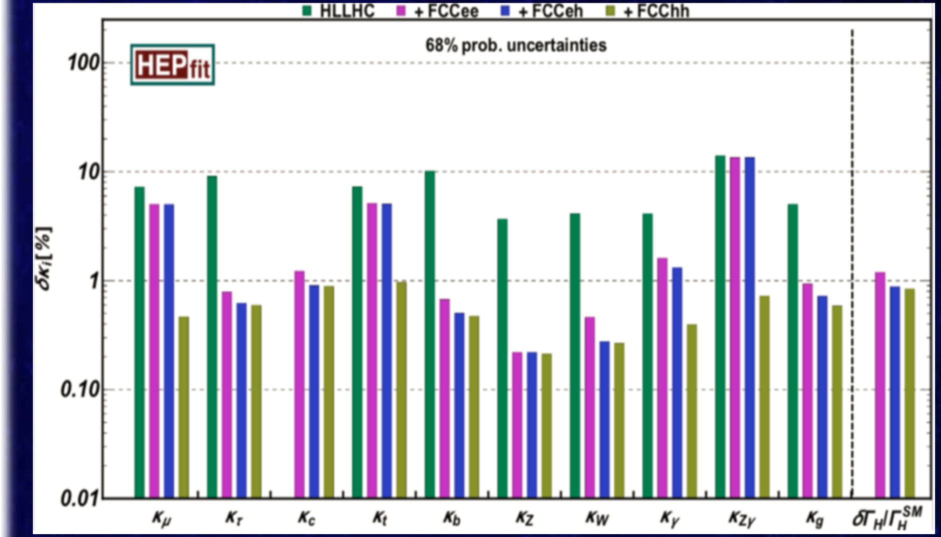
g_{HXX} measured

Higgs Couplings: Post FCC-ee

- **Higgs couplings normalized to the Standard Model predictions:**

$$k_f = \frac{g_{Hff}}{g_{Hff}^{SM}}, \quad f = b, c, \tau$$

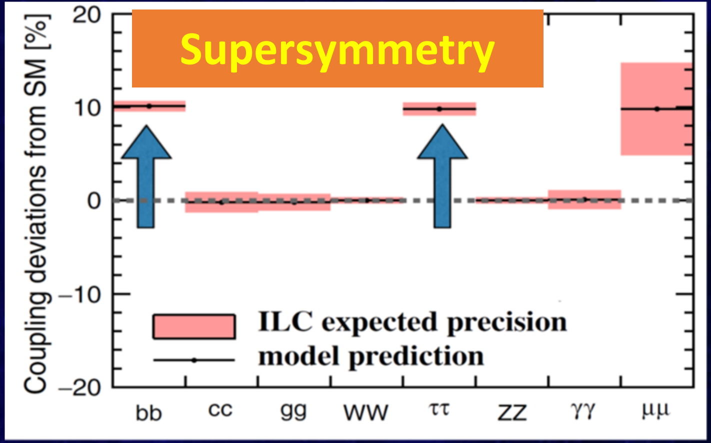
$$k_V = \frac{g_{HVV}}{g_{HVV}^{SM}}, \quad V = W, Z, \gamma, g$$

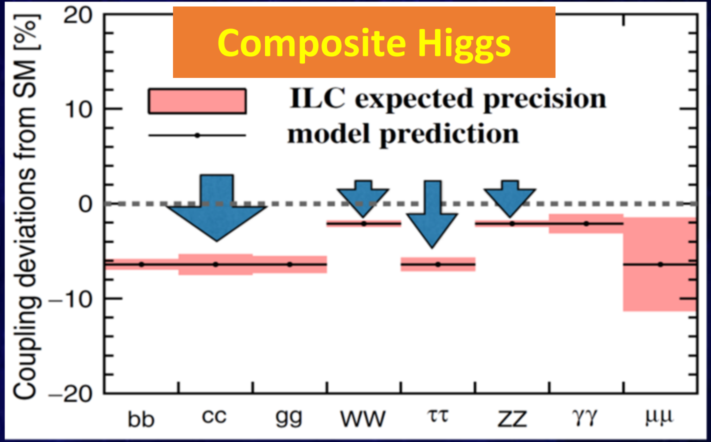


Eur. Phys. J. Plus (2022) 137:92

FCC: Factor of (4-10)x improvement for most couplings (w.r.t. HL-LHC)

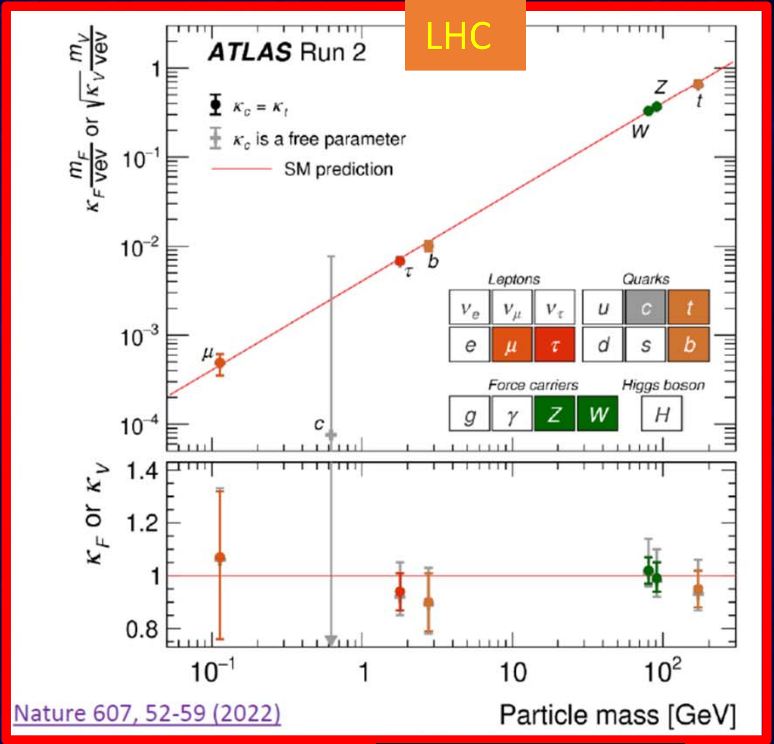
- **Fingerprinting NP:** different BSM models predict different pattern of deviations from the SM:



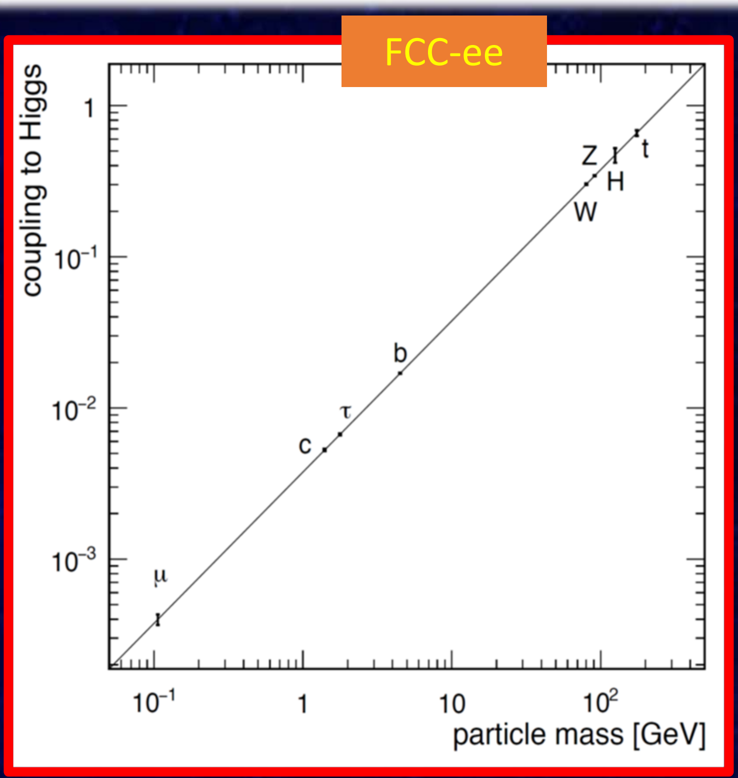


Phys Rev. D 97, 053003 (2018)

Higgs Couplings: Post FCC-ee



Nature 607, 52-59 (2022)



$\Delta k_f \sim 15\%$

$\Delta k_f \sim 1\%$

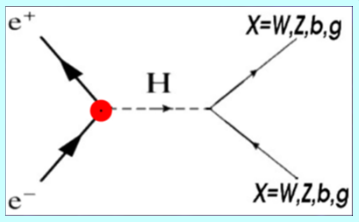
3rd and 2nd fermion generations only (qualitative precision level for the latter)

3rd AND 2nd generations precise measurements

Other Higgs topics: Higgs self-coupling

Direct Higgs Production in s-channel

- FCC-ee: potential for direct measurement of the H-e-e Yukawa coupling $BR(H \to e^+e^-) \approx 5 \times 10^{-9}$



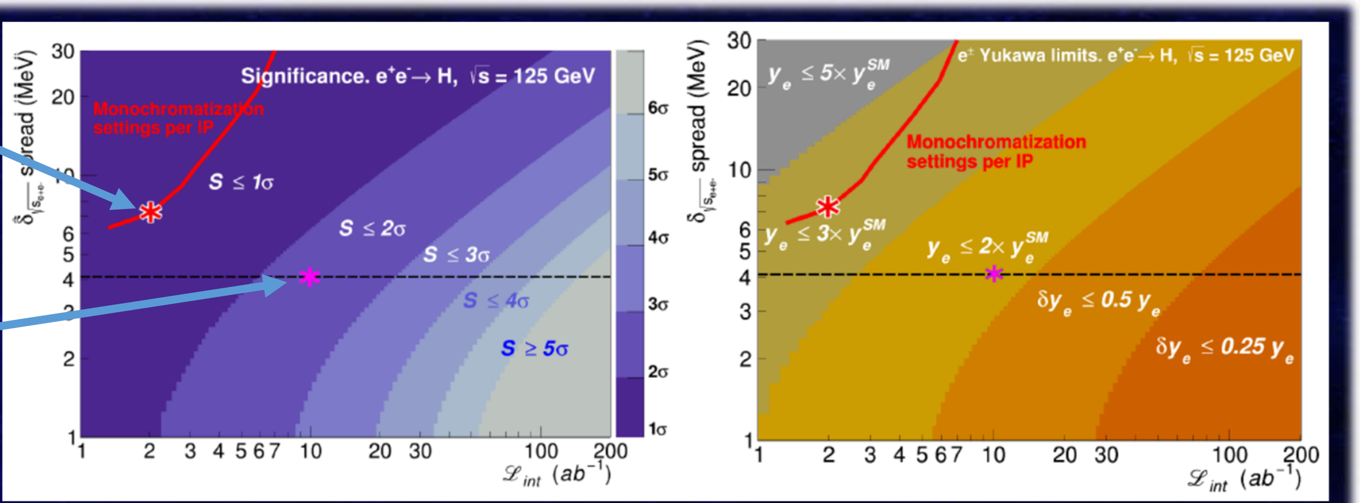
- $\sigma(e^+e^- \to H) = 1.64\ \text{fb}$ - very small $(m_H = 125\ \text{GeV},\ \Gamma_H = 4.2\ \text{MeV})$
  (several (≈10) final states can be studied)
- Calls for a high-luminosity run precisely at $\sqrt{s} = M_H = 125\ \text{GeV}$
- Since Γ_H = 4.1 MeV, it requires beam energy spread monochromatization from the natural spread of ~46 MeV down to ~4.1 MeV (and a prior knowledge of the Higgs mass to a few MeV)
- Other problems: ISR+FSR, big backgrounds

Currently reached monochromatization

$\mathrm{C} = (\delta_{\sqrt{s}}, \mathcal{L}_{\rm int}) = (7\ \mathrm{MeV}, 2\ \mathrm{ab}^{-1})$

Best signal strength monochromatization

$\mathrm{B} = (\delta_{\sqrt{s}}, \mathcal{L}_{\rm int}) = (4.1\ \mathrm{MeV}, 10\ \mathrm{ab}^{-1})$



- The signal significance at C

  $S \approx 0.4\sigma/\text{year}/IP$

- Assuming B and two years of running with 4 IPs (~12k eeH events) ➡ $|\mathrm{y_e}| < 1.6|\mathrm{y_e^{SM}}|\ (1.3\sigma)$

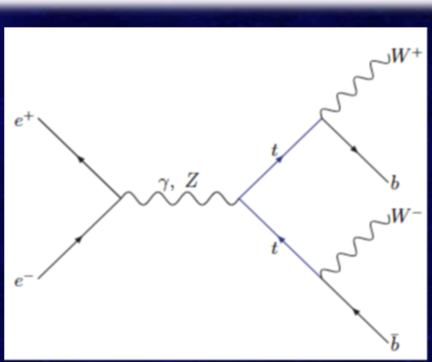
Not yet in the baseline

arXiv:2107.0268

$t\bar{t}$ Pair Production at Threshold

- **Any next e^+e^- collider:**

for the 1st time the top quark to be studied using a precisely defined leptonic initial state



$$e^+e^- \to Z/\gamma \to t\bar{t} \to (bW^+)(\bar{b}W^-)$$

Final state	BR [%]	signature
Fully hadronic	46.2	6 jets
Semi leptonic	43.5	4 jets, 1 $l^{\pm}$, 1 ν
Fully leptonic	10.3	2 jets, 2 $l^{\pm}$, 2 ν

- The shape of the $t\bar{t}$ production cross-section at the threshold **is computable to high precision and depends on m_t, Γ_t, α_s, y_t, (and luminosity** spectrum)

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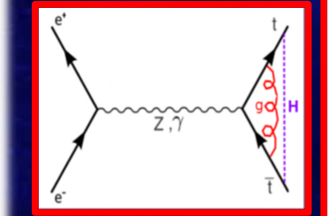
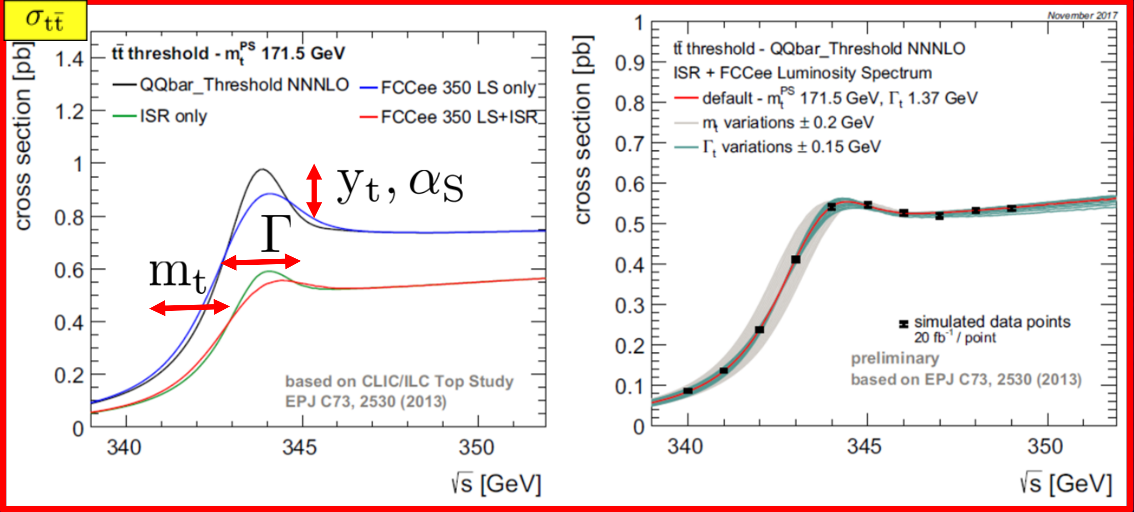




- **Other top topics:**

Single top production,
top quark FCNC,
$e^+e^- \to t\bar{t}\gamma$,
top-quark EW couplings
…

PDG:

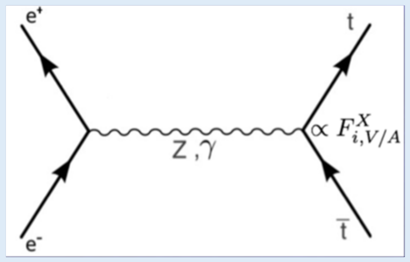
$$\text{PDG}: \quad m_t = (172.69 \pm 0.30)\ \text{GeV}$$

FCC-ee

$$\Delta m_t \geq 10\ \text{MeV}$$

EW Couplings of the Top Quark

$e^+e^- \to \gamma^*/Z^* \to t\bar{t}$



Clean EW process; parametrisation of the current at $t\bar{t}X, \; X = Z, \gamma$ vertex

$$\Gamma^{ttX}_{\mu}(k^2, q, \bar{q}) = -ie\left\{\underbrace{\gamma_\mu \left(F^X_{1V}(k^2)}_{\text{Vector}} + \underbrace{\gamma_5 F^X_{1A}(k^2)\right)}_{\text{Axial}} + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu \left(\underbrace{iF^X_{2V}(k^2)}_{\text{Tensorial}} + \underbrace{\gamma_5 \cancel{F^X_{2A}(k^2)}}_{\text{CPV}}\right)\right\}$$

$q \; (\bar{q})$ - four-vector of the t (tbar) quark $k^2 = (q+\bar{q})^2$

Sensitivity of the V and A couplings to NP

Linear Collider: **profit from the initial-state longitudinal polarisation of the incoming e⁺, e⁻ beam**

- Determination of the cross-section and the A_{FB} of two configurations:

$\mathcal{P}_{e^-} = \pm 0.8$ $\mathcal{P}_{e^+} = \mp 0.3$

Measure: $\sigma^+, \sigma^-, A^+_{FB}, A^-_{FB}$

$+ = e^-_R$

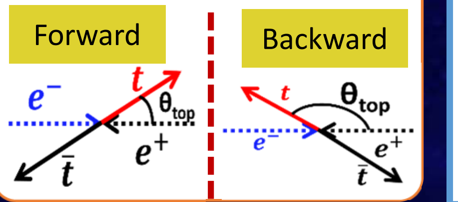
$- = e^-_L$

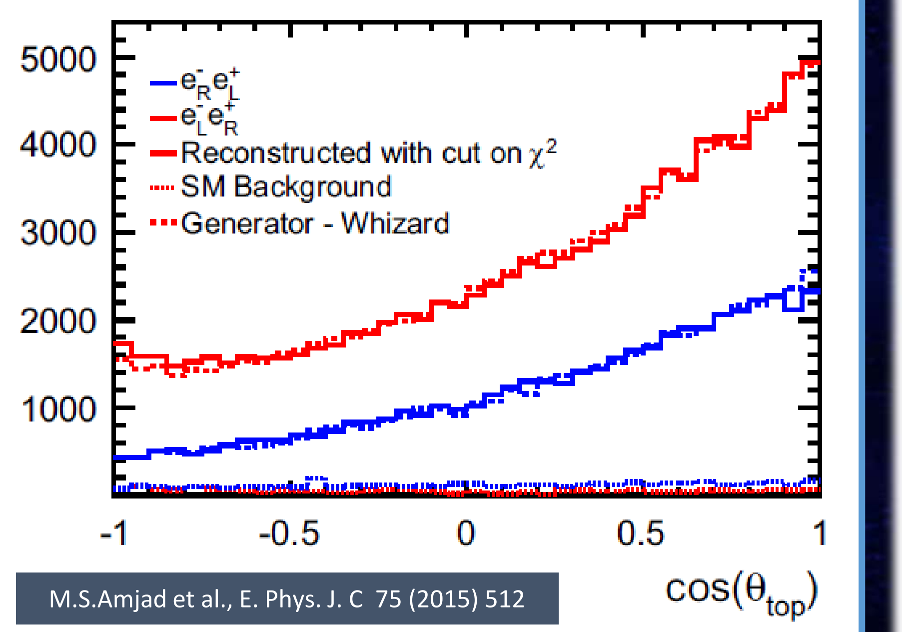
Extract:

$F^Z_{1V}, F^Z_{2V}, F^Z_A$

$F^\gamma_{1V} \cdot F^\gamma_{2V}, F^\gamma_A \equiv 0$

$$A_{FB} \equiv \frac{N(cos\theta_{top} > 0) - N(cos\theta_{top} < 0)}{N(cos\theta_{top} > 0) + N(cos\theta_{top} < 0)}$$





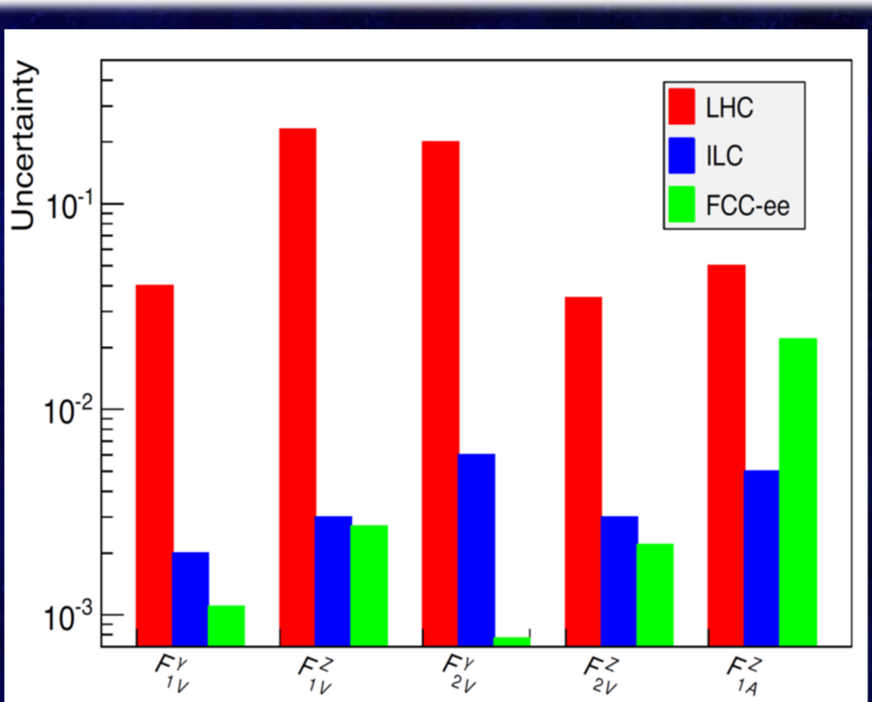
M.S.Amjad et al., E. Phys. J. C 75 (2015) 512

EW Couplings of the Top Quark

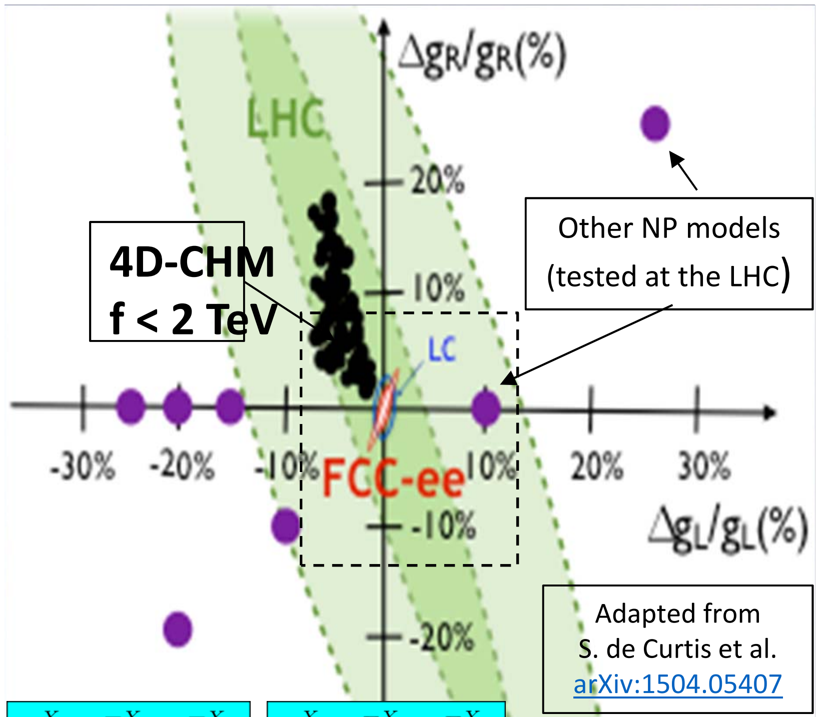
Circular Collider: **lack of initial-state polarization → profit from the final-state polarisation, which is maximally transferred to the top decay products (t→ Wb)**

Any anomalous ttZ, ttγ coupling would lead to a **modification** of the final kinematics, in particular **of the angular and energy distributions of the leptons from the W decays.** (analogy to τ polarisation in Z → τ τ decays at LEP)

P. Janot JHEP 04 (2015) 182



$\Delta F \sim (10^{-2} - 10^{-3})$



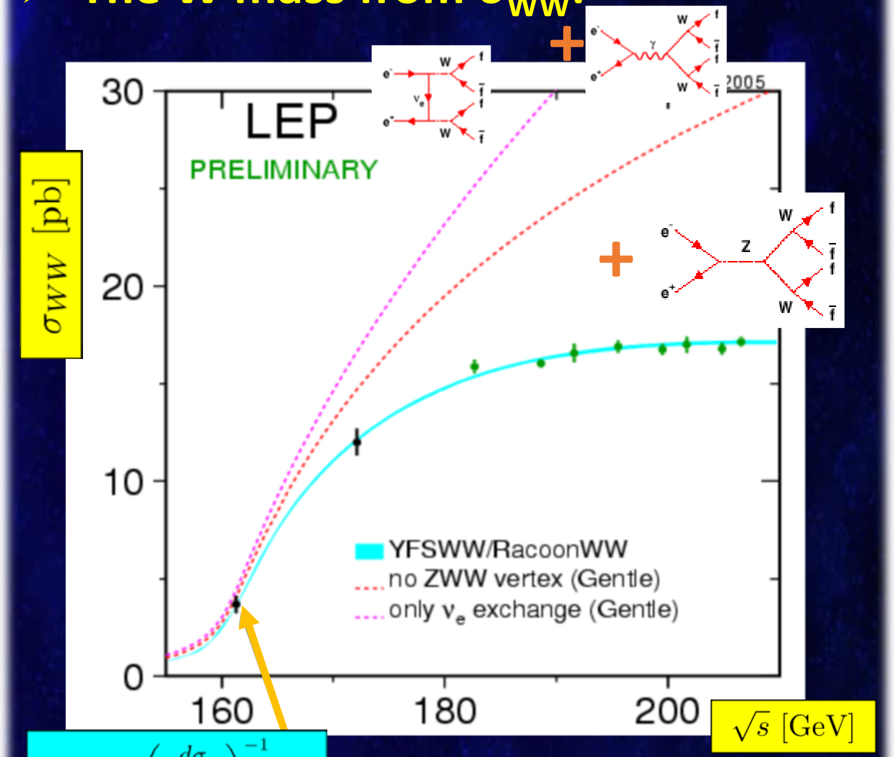
Adapted from
S. de Curtis et al.
arXiv:1504.05407

$g_R^X = F_{1V}^X + F_{1A}^X$ $g_L^X = F_{1V}^X - F_{1A}^X$

(courtesy R.Poeschl)

WW Pair Production at Threshold

➢ The W mass from σ_{WW}:



$$\Delta m_W = \left(\frac{d\sigma}{dm_W}\right)^{-1} \Delta\sigma$$

	LEP2 Stat./Prec.	FCC – ee stat (syst)
N_{WW}	4×10^4	3×10^7
M_W [MeV]	$80376 \pm 33 \pm 4$	$0.3\ (< \pm 1)$

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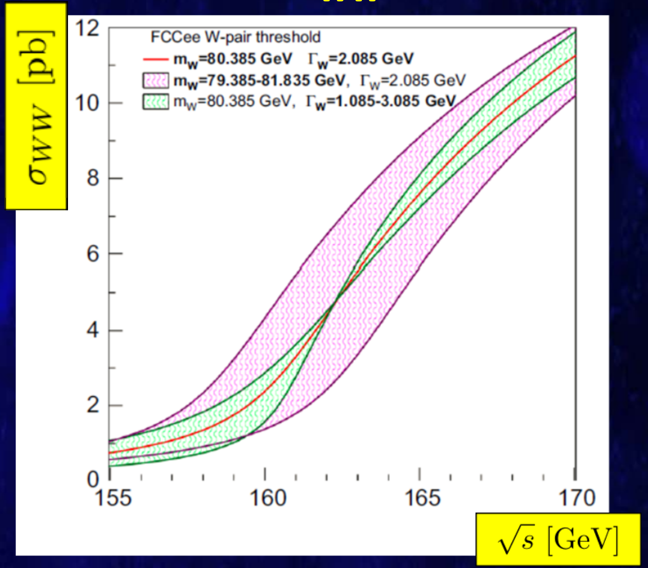
Other W topics:

W branching ratios (universality), TGCs, α_s …

➢ The W width from σ_{WW}:



- Measure σ_{WW} in two energy points E_1 and E_2, with the fractions of luminosity f and (1-f) ➔ evaluation of both m_W and Γ_W

- Choose the parameters E_1, E_2, and f in order to minimize the errors: $\Delta\Gamma_W$ an Δm_W:

$E_1 = 157.5$ GeV $E_1 = 162.5$ GeV $f = 0.4$ 12 ab^{-1}

➡ $\Delta m_W = 0.5$ MeV $\Delta\Gamma_W = 1.2$ MeV

W Physics: Branching Ratios, TGCs…

➢ WW samples (FCC-ee)

$\sqrt{s}$ [GeV]	161	240	350
$N_{WW}[\times 10^6]$	30	80	15

➢ W Branching ratios (%)

LEP2

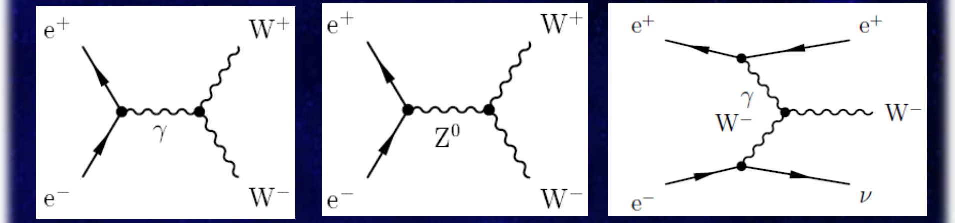
$\mathrm{BR}(W \to e\nu)$	10.65 ± 0.17
$\mathrm{BR}(W \to \mu\nu)$	10.59 ± 0.15
$\mathrm{BR}(W \to \tau\nu)$	11.44 ± 0.22
$\mathrm{BR}(W \to l\nu)$	10.84 ± 0.09
$\mathrm{BR}(W \to \text{hadrons})$	67.48 ± 0.28

- Lepton universality tested at 2% level (2.7σ discrepancy between τ and μ/e)
- Quark-lepton universality tested at 0.6%

FCC-ee

- Lepton universality test at 0.04% level
- Quark-lepton universality test at 0.01%
- Flavour tagging → V_{cs} V_{cb}…

➢ Triple Gauge Couplings



- Selected LEP limits (95% C.L.)

Δk_γ	$[-9.9, 6.6] \times 10^{-2}$
λ_γ	$[-5.9, 1.7] \times 10^{-2}$
Δk_Z	$[-7.4, 5.1] \times 10^{-2}$
λ_z	$[-5.9, 1.7] \times 10^{-2}$
Δg_1^Z	$[-5.4, 2.1] \times 10^{-2}$

- FCC-ee: overall improvements by a factor of 50 to compare with LEP

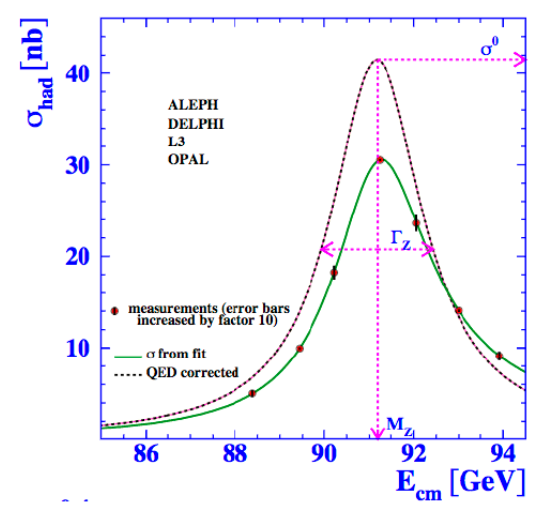
➢ The strong coupling constant:

- FCC-ee: $\Delta_{\mathrm{rel}}\alpha_S(m_W^2) = 3 \times 10^{-3}$
  from hadronic W decays (Γ_W and $\mathrm{BR}_{W,had}$)
- LEP2 precision: 37%

Electroweak Physics at the Z pole

LEP $N_Z = 1.7 \times 10^7$ → **FCC-ee** $N_Z \sim 5 \times 10^{12}$ → **Extreme precision of EW observables**

➢ Z mass and width (from Z pole scan):



The crucial factor: continuous E_{CM} calibration (resonant depolarization)

$$\Delta E_{\rm CM} \approx (10\ ({\rm stat}) + 100\ ({\rm syst}))\ {\rm keV}$$

	Δ_{rel} (LEP)	Improvement factor
Z mass	1×10^{-6}	~ 20
Z width	5×10^{-5}	~ 20

$(\sim 300\ ({\rm stat}) \oplus \sim 10\ ({\rm syst}))$

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$2.1\ {\rm MeV} \to 100\ {\rm keV}$

$2.3\ {\rm MeV} \to 100\ {\rm keV}$

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➢ Normalized partial widths:

$$R_l = \frac{\Gamma_{\rm had}}{\Gamma_{l\bar{l}}},\ l = e, \mu, \tau \qquad \Gamma_{f\bar{f}} \propto (g_V^f)^2 + (g_A^f)^2$$

$$R_q = \frac{\Gamma_{q\bar{q}}}{\Gamma_{\rm had}},\ q = b, c \qquad f = l,\ q$$

	PDG (LEP) value	PDG (LEP) rel. precision	FCC – ee Improvement factor
R_e	20.804 ± 0.050	2.4×10^{-3}	~ 20
R_μ	20.785 ± 0.033	1.6×10^{-3}	~ 20
R_τ	20.764 ± 0.045	2.2×10^{-3}	~ 20
R_b	0.21629 ± 0.00066	3.1×10^{-3}	~ 10
R_c	0.1721 ± 0.0030	1.7×10^{-2}	~ 10

necessary input for a precise measurement of EW couplings (next slide)

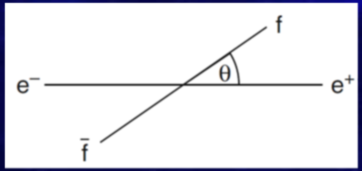
and $\alpha_S(m^2_Z)$ (from hadronic Z decays). FCC-ee precision: $\Delta_{\rm rel}\alpha_S(m_Z^2) = 2 \times 10^{-3}$ LEP: 2.5%

Electroweak Physics at the Z pole

- **Z asymmetries:**

$$\frac{d\sigma_{f\bar{f}}}{d\cos\theta} = \frac{3}{8}\sigma^{\mathrm{tot}}_{f\bar{f}}\left[(1-\mathcal{P}_e\mathcal{A}_e)(1+\cos^2\theta) + 2(\mathcal{A}_e - \mathcal{P}_e)\mathcal{A}_f\cos\theta\right]$$

$\mathcal{P}_e$ - polarization of the initial state e^-



The forward-backward asymmetry: $A^f_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$

The left-right asymmetry: $A^f_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \mathcal{A}_e$

$$\mathcal{A}_f = \frac{2g^f_V g^f_A}{(g^f_V)^2 + (g^f_A)^2}$$

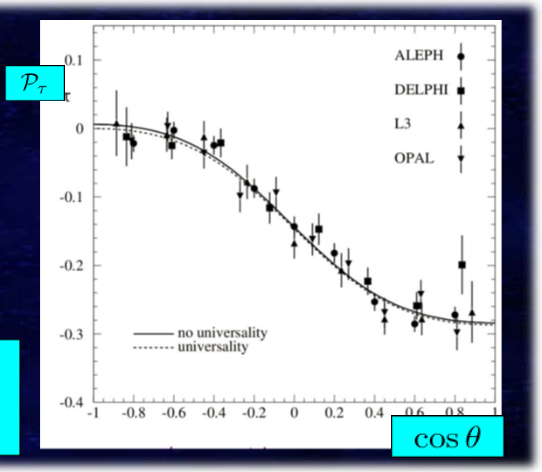
LEP & SLC: longstanding discrepancies between different asymmetry measurements; uncertainties dominated by statistics

tau lepton case:
the final state helicity can be measured

$$\mathcal{P}_\tau(\cos\theta) = \frac{d(\sigma_r - \sigma_l)}{d\cos\theta}\cdot\left(\frac{d(\sigma_r + \sigma_l)}{d\cos\theta}\right)^{-1}$$

$$\mathcal{P}_\tau(\cos\theta) = \frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta) + \mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

$$A^\tau_{FB} = \frac{(\sigma_r - \sigma_l)_F - (\sigma_r - \sigma_l)_B}{(\sigma_r + \sigma_l)_F + (\sigma_r + \sigma_l)_B}$$



Experimentally accessible observables: $\langle\mathcal{P}_\tau\rangle = -\mathcal{A}_\tau$ $\quad A^\tau_{FB} = -\frac{3}{4}\mathcal{A}_e$

$\mathcal{A}_f$ measured (f = e, μ, τ, b, c) → $g_V^f\, g_A^f$ extracted → $\sin^2\theta^f_{\mathrm{W,eff}} = \frac{1}{4}\left(1 - \frac{g^f_V}{g^f_A}\right)$

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	$\Delta^{\mathrm{stat}}_{\mathrm{rel}}$ (FCC − ee)	$\Delta^{\mathrm{syst}}_{\mathrm{rel}}$ (FCC − ee)	Improvement factor w.r.t. LEP
$\mathcal{A}_e$	5.0×10^{-5}	1.0×10^{-4}	~ 50
$\mathcal{A}_\mu$	2.5×10^{-5}	1.5×10^{-4}	~ 30
$\mathcal{A}_\tau$	4.0×10^{-5}	3.0×10^{-4}	~ 15
$\mathcal{A}_b$	2.0×10^{-4}	3.0×10^{-3}	~ 5
$\mathcal{A}_c$	3.0×10^{-4}	8.0×10^{-3}	~ 4

Systematic uncertainties dominate

Precision on vector and axial couplings from R_f and A_f :

Improvement w.r.t. LEP: (10-100)x

fermion	Δg_V	Δg_A
e	2.5×10^{-4}	1.5×10^{-4}
μ	2.0×10^{-4}	2.5×10^{-5}
τ	3.5×10^{-4}	0.5×10^{-4}
b	1.0×10^{-2}	1.5×10^{-3}
c	1.0×10^{-2}	2.0×10^{-3}

Electroweak Physics at the Z pole

$\sin^2\theta_{\mathrm{W,eff}}$ (absolute) uncertainties:

	stat	syst	Improvement w.r.t. LEP
from muon FB	10^{-7}	5.0×10^{-6}	~ 100
from tau pol	10^{-7}	6.6×10^{-6}	~ 75

➢ Measurement of $\alpha_{QED}(m_Z^2)$ - better precision necessary for future precision SM tests !

- **Current uncertainty:** $\Delta\alpha_{\mathrm{QED}}(m_Z^2) = 10^{-4}$ from running coupling constant formula: $\alpha_{\mathrm{QED}}(m_Z^2) = \dfrac{\alpha_{\mathrm{QED}}(0)}{1 - \Delta\alpha_l(m_Z^2) - \Delta\alpha^{(5)}_{\mathrm{had}}(m_Z^2)}$

dominated by the experimental determination of the hadronic vacuum polarization, obtained from dispersion integral with expt. input from low energies (KLOE, Belle, BaBar, CLEO, BES CMD-2…)

➢ Alternative: the direct measurement of $\alpha_{QED}(m_Z^2)$ from the muon FB asymmetry just below and just above the Z pole (as part of Z resonance scan) – no need of extrapolation from $\alpha_{\mathrm{QED}}(0)$

- **The $A_{FB}^{\mu\mu}$ - self normalized quantity** $A^{\mu\mu}_{FB} = \dfrac{\sigma^F_{\mu\mu} - \sigma^B_{\mu\mu}}{\sigma^F_{\mu\mu} + \sigma^B_{\mu\mu}}$

(no need for measurement of L_{int};
most uncertainties (sel. efficiency, det. accceptance) cancel in the ratio

$$\frac{\Delta\alpha_{\mathrm{QED}}}{\alpha_{\mathrm{QED}}} \simeq \frac{\Delta A^{\mu\mu}_{\mathrm{FB}}}{A^{\mu\mu}_{\mathrm{FB}}} \times \frac{\mathcal{Z}+\mathcal{G}}{\mathcal{Z}-\mathcal{G}}$$

2x 6 months of FCC-ee running:

$\mathcal{Z}(\mathcal{G})$ - Z(photon)–exchange terms

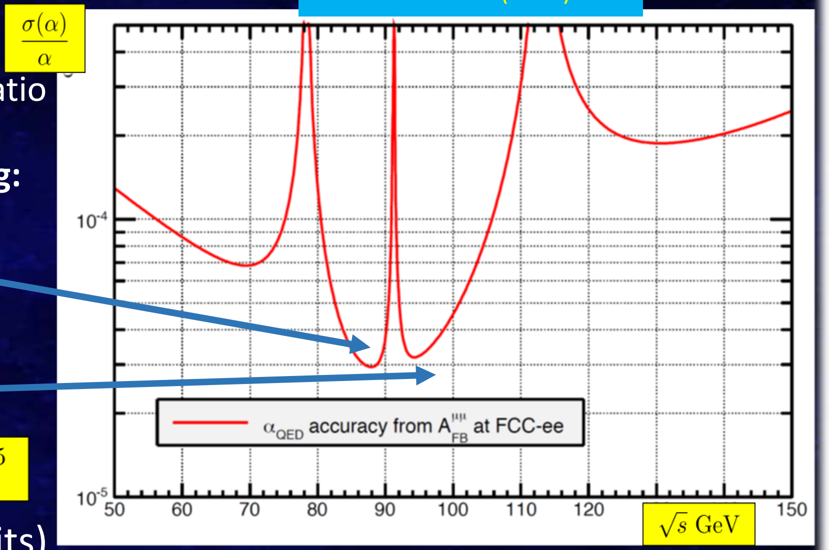
Optimal CMS energies: $\sqrt{s_-} = 87.9\ \mathrm{GeV}$ $\sqrt{s_+} = 94.3\ \mathrm{GeV}$

$$\frac{1}{\alpha_{\mathrm{QED}}(m_Z^2)} = \frac{1}{\alpha_\pm} + \beta_{\mathrm{QED}} \log\frac{s_\pm}{m_Z^2}$$

$\Rightarrow$ $\Delta\alpha_{\mathrm{QED}}(m_Z^2) = 3 \times 10^{-5}$

(adequate for future precision EW fits)

P.Janot JHEP 02 (2016) 053



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The Z Invisible Width – Number of Light Neutrino Species

1) N$_\nu$ determined at LEP1 from the Z line-shape scan:

$$\boxed{N_\nu = 2.991 \pm 0.007}$$

$$N_\nu \cdot \Gamma_\nu = \Gamma_Z - \Gamma_h - 3\Gamma_l$$

$$N_\nu = \left(\frac{\Gamma_l}{\Gamma_\nu}\right)_{\mathrm{SM}} \cdot \left(\sqrt{\frac{12\pi R_l}{M_Z^2 \sigma_{\mathrm{had}}^{\mathrm{peak},0}}} - R_l - 3\right)$$

theory

all measured at the peak

Only small room for improvements:
precision limited mainly by the theoretical uncertainty on luminosity determination
i.e. on small angle Bhabha cross section
(LEP1: ΔL/L = 0.00061, ΔN$_\nu^{\mathrm{lumi}}$ = 0.0046 ➔ ΔN$_\nu^{\mathrm{lumi}}$ = 0.0001 @FCC-ee). $\Delta N_\nu^{\mathrm{FCC-ee}} = 0.00008(\mathrm{stat}) \ \pm 0.0001(\mathrm{syst})$

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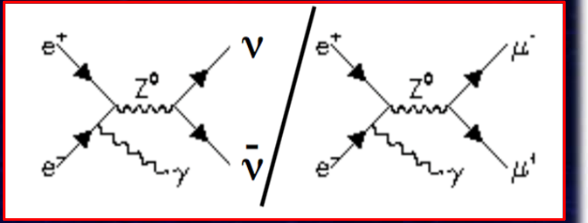
2) N$_\nu$ from the radiative return process $e^+e^- \to Z\gamma, \quad Z \to \nu\bar{\nu}$ from the higher masses than the Z resonance

Monophoton events (normalized to photon-lepton-lepton events):

$$N_\nu = \left(\frac{e^+e^- \to \gamma Z_{\mathrm{inv}}}{e^+e^- \to \gamma Z_{\mathrm{lept}}}\right)^{\mathrm{meas}} / \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{\mathrm{lept}}}\right)^{\mathrm{SM}}$$



- LEP1: $N_\nu = 2.92 \pm 0.05$ (statistics too scarce).

- Photon selection common for both final states ➔ cancellations of systematics.
- N$_\nu$ can be measured vs sqrt(s) ➔ sensitivity to NP at high energy scales.
- FCC-ee sensitivity:

$\sqrt{s}$ [GeV]	years of running	ΔN_ν (stat)
161	1	0.0011
240 & 340	5	0.0008
125	1	0.0004

$3 \times 10^7 \gamma Z(\mathrm{inv})$ ev.

(running parasitically)

$\Delta N_\nu \leq 4 \times 10^{-4}$

Electroweak Observables: Instead of Summary

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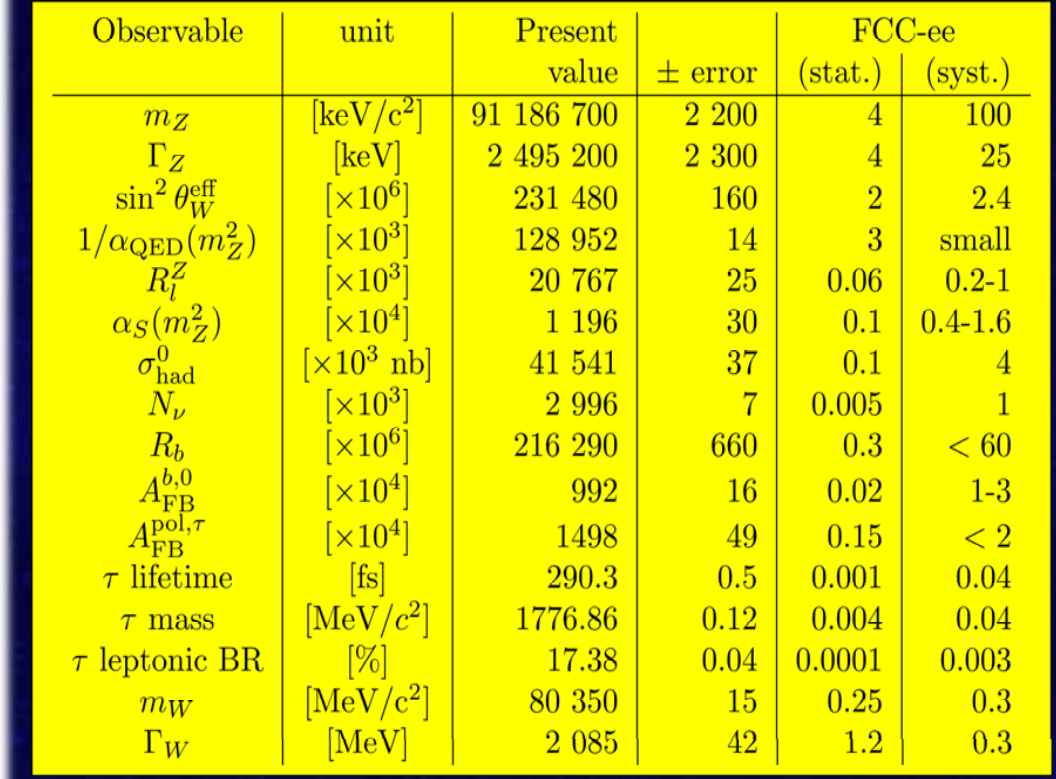
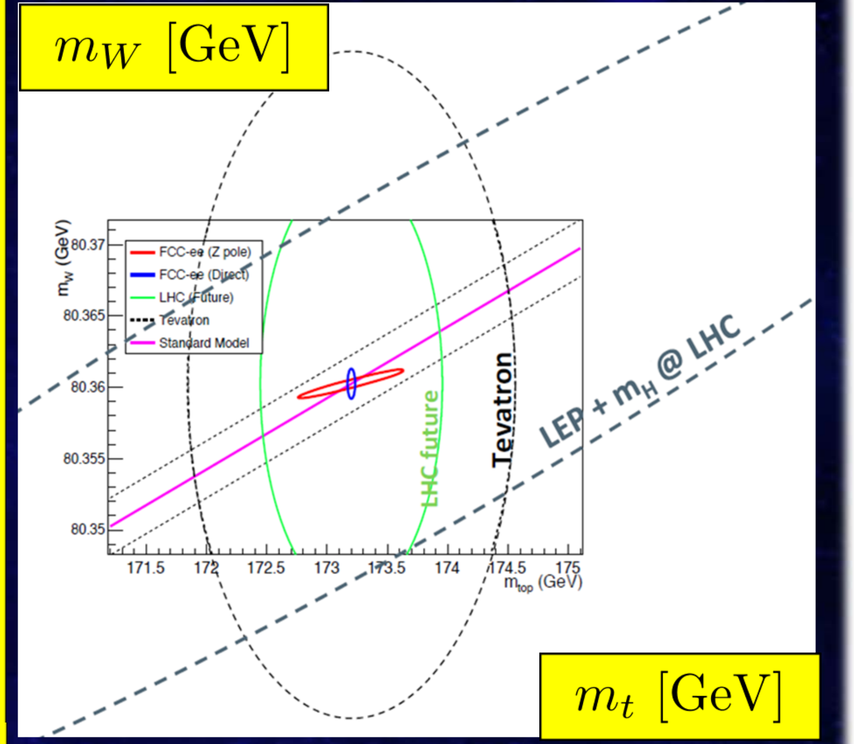


Observable	unit	Present value	± error	FCC-ee (stat.)	FCC-ee (syst.)
m_Z	[keV/c^2]	91 186 700	2 200	4	100
Γ_Z	[keV]	2 495 200	2 300	4	25
$\sin^2\theta_W^{\rm eff}$	[$\times10^6$]	231 480	160	2	2.4
$1/\alpha_{\rm QED}(m_Z^2)$	[$\times10^3$]	128 952	14	3	small
R_l^Z	[$\times10^3$]	20 767	25	0.06	0.2-1
$\alpha_S(m_Z^2)$	[$\times10^4$]	1 196	30	0.1	0.4-1.6
$\sigma^0_{\rm had}$	[$\times10^3$ nb]	41 541	37	0.1	4
N_ν	[$\times10^3$]	2 996	7	0.005	1
R_b	[$\times10^6$]	216 290	660	0.3	< 60
$A_{\rm FB}^{b,0}$	[$\times10^4$]	992	16	0.02	1-3
$A_{\rm FB}^{{\rm pol},\tau}$	[$\times10^4$]	1498	49	0.15	< 2
τ lifetime	[fs]	290.3	0.5	0.001	0.04
τ mass	[MeV/c^2]	1776.86	0.12	0.004	0.04
τ leptonic BR	[%]	17.38	0.04	0.0001	0.003
m_W	[MeV/c^2]	80 350	15	0.25	0.3
Γ_W	[MeV]	2 085	42	1.2	0.3



Flavour Physics

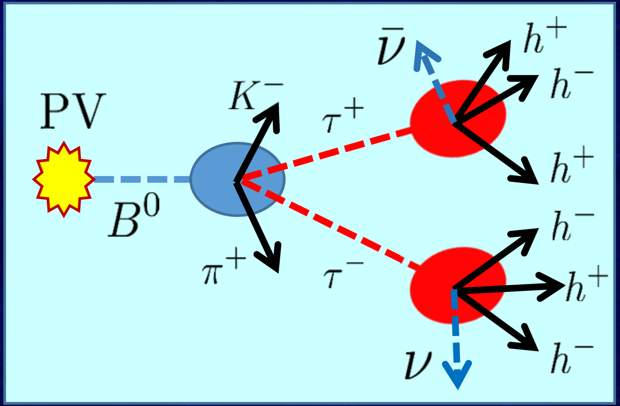
- **The sheer power of statistics:**

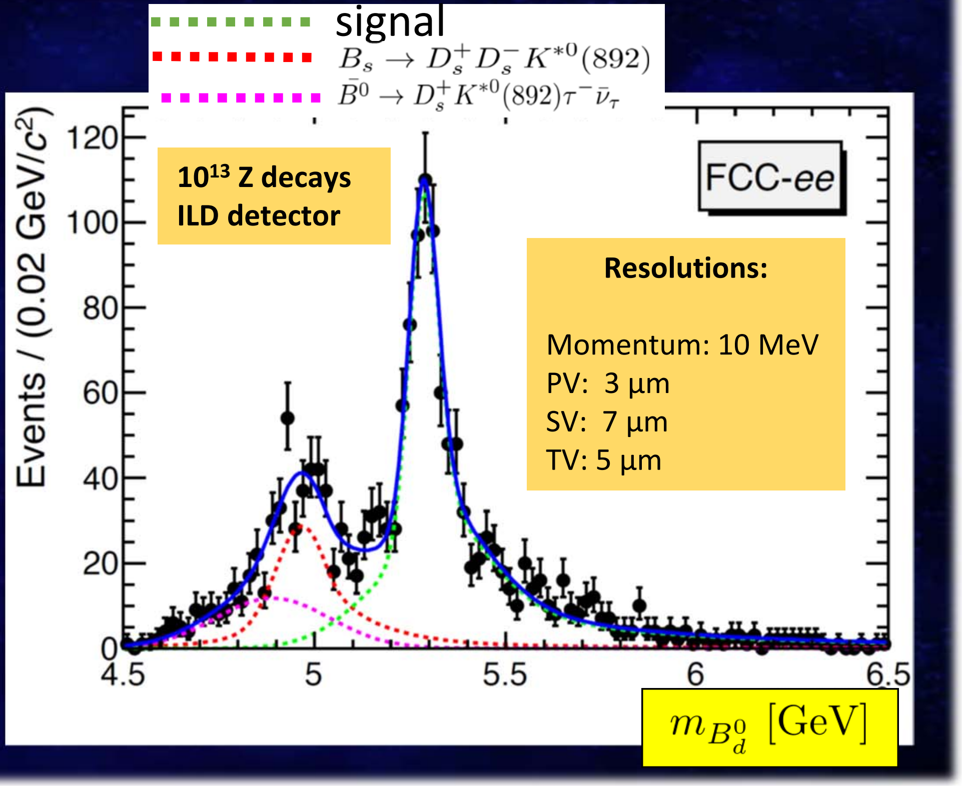
Particles	B^0/B^+	B^0_s	Λ_b	B_c	$Z \to \tau^+\tau^-$
Yields (FCC-*ee* 150 ab^{-1})	10^{12}	$2.5\ 10^{11}$	$2.5\ 10^{11}$	$2.5\ 10^{9}$	$5.\ 10^{11}$
Yields (Belle II 50 ab^{-1})	10^{11}	10^{7-8}	–	–	$5.\ 10^{10}$

LEP : $\sim 6 \times 10^6$

S.Monteil. 2nd FCC Physics Workshop

- **Example: $B \to K^*(892)\tau^+\tau^-$ decay**
  - Excellent vtx reconstruction ($\tau \to$ 3 prongs)





10^{13} Z decays
ILD detector

Resolutions:

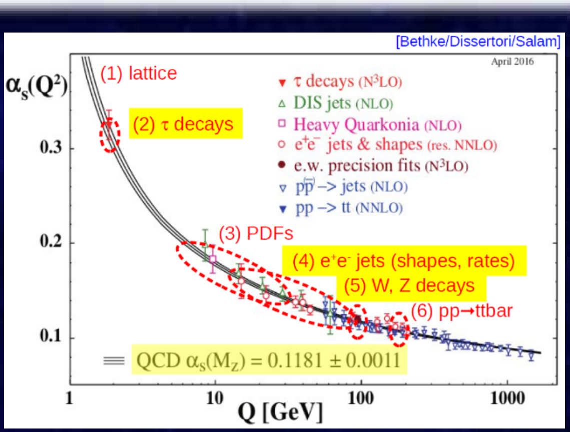
Momentum: 10 MeV
PV: 3 µm
SV: 7 µm
TV: 5 µm

  - FCC-ee: 1000 signal events expected, Belle2: 10 events expected
  - The angular analysis feasible

Other flavour topics: CKM parameters, UT angles, tau physics, lepton universality, heavy quark spectroscopy, rare decays…

QCD Measurements

- **High precision α_S determination** (with the accuracy at the ‰ level) **from:**
  - hadronic τ decays
  - Jet rates, event shapes
  - hadronic Z decays
  - hadronic W decays



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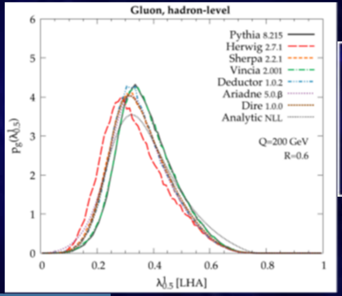
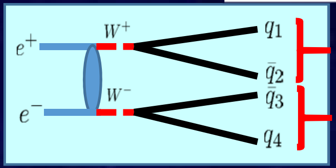
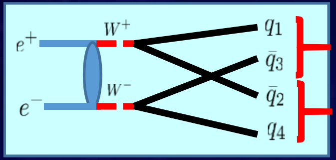
- **High precision studies of perturbative parton radiation including:**
  - jet rates and event shapes
  - jet substructure
  - quark/gluon/heavy-quark discrimination
  - g,q,b,c parton-to-hadron fragmentation functions



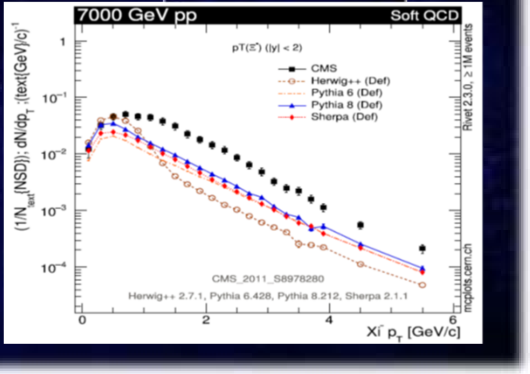
Gluon radiation & fragmentain poorly known

- **High precision non-perturbative QCD studies including:**
  - colour reconnection (<1% control)
  - final-state multiparticle correlations





Ξ⁻ spectrum

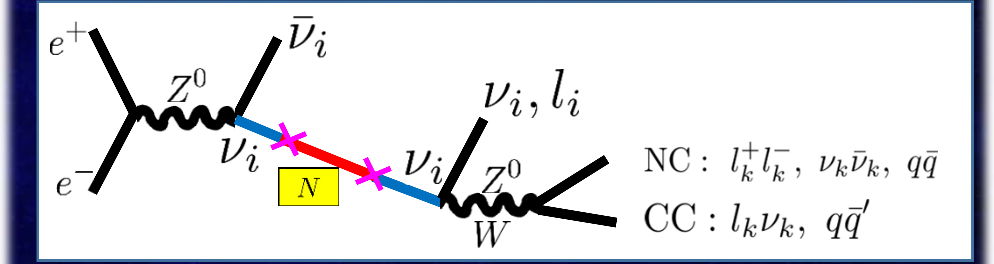


- **High precision hadronization studies**
  - very rare hadron production and decays

Heavy Neutral Leptons (HNL) Searches

- Sterile, right-handed neutrinos (N) are common in extensions of the SM; they couple to Higss and SM ν
- Substantial part of them are HNLs: very massive and characterised by macroscopic decay length

- The HNL production and decay at the $\sqrt{s} = M_Z$



$\mathrm{NC}: \ l_k^+ l_k^-, \ \nu_k \bar{\nu}_k, \ q\bar{q}$

$\mathrm{CC}: \ l_k \nu_k, \ q\bar{q}'$

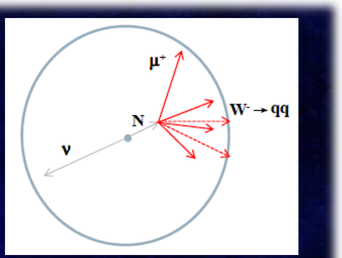
$\nu_L = \nu \cos\theta + N \sin\theta$

$\theta \approx m_\nu / m_N$

- Experimental signatures

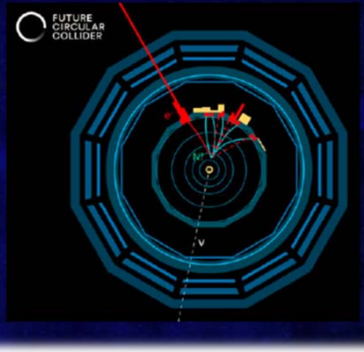
NC: 2 leptons/jets + E_{miss}

CC: 2 jets + lepton/E_{miss}



Search for (highly) displaced vertices;

very clean events



- FCC-ee sensitivity

  to HNLs up to 10^{-11}

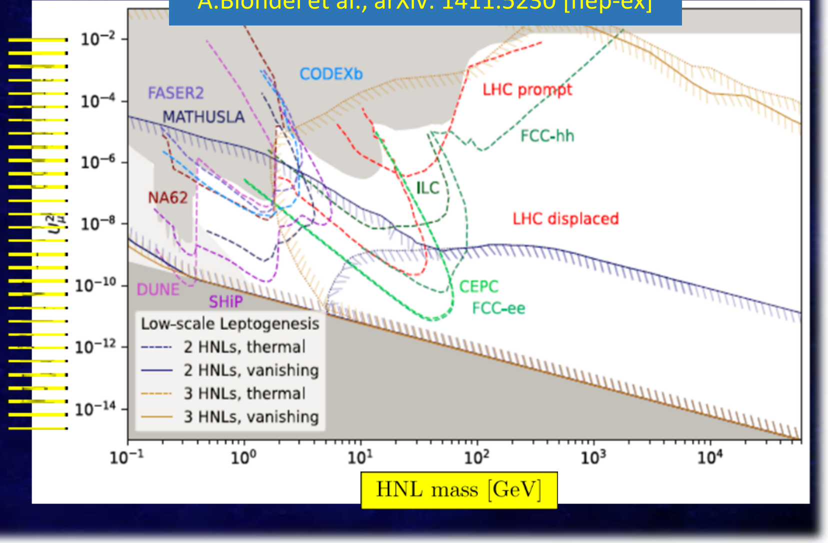
- Complementary to

  beam dump facilities

- The upper limits of LEP

  searches: 10^{-4}

A.Blondel et al., arXiv: 1411.5230 [hep-ex]



Other topics:

axion-like particles, exotic Higgs decays,…

Sensitivity to NP

- **New Physics** → **new interactions of SM particles:**

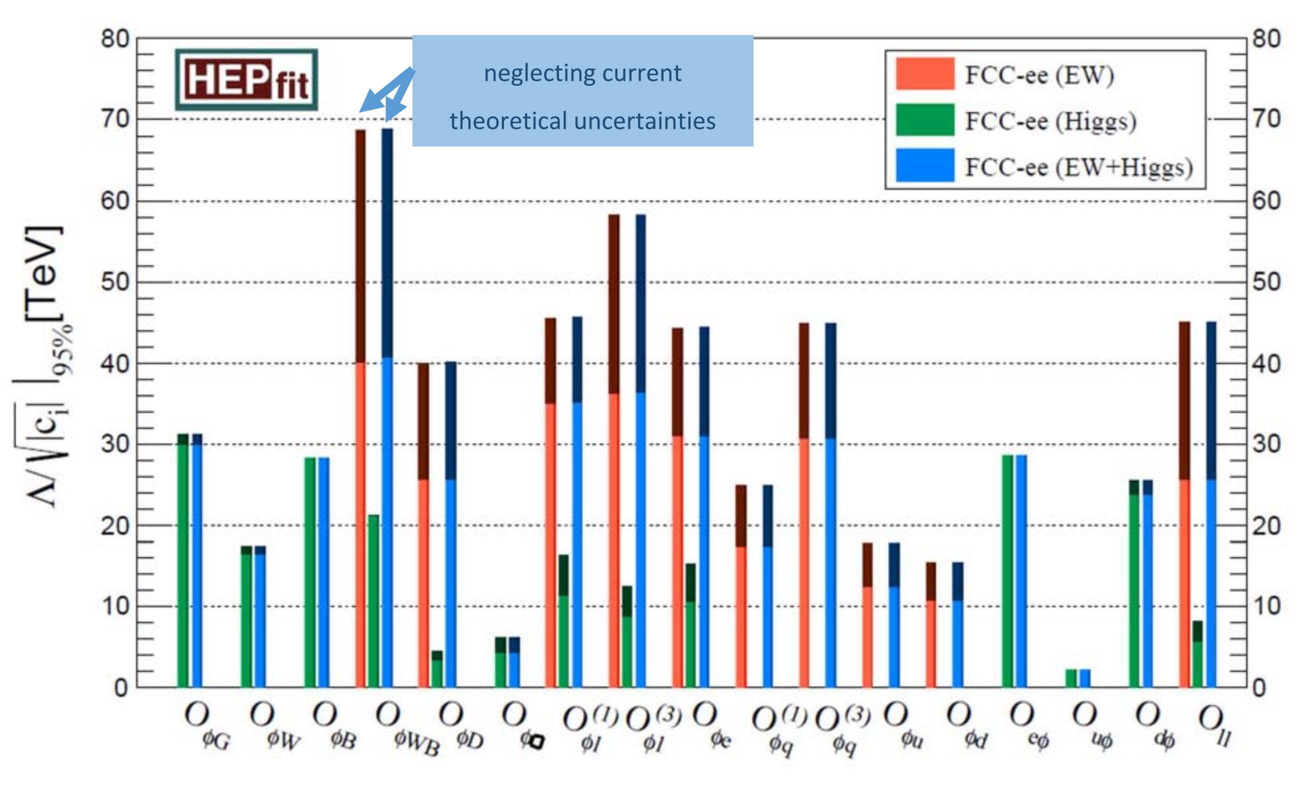
$$\mathcal{L}_{\mathrm{rmEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{\mathrm{i}} \frac{\mathrm{C}_{\mathrm{i}}^{(6)}\mathrm{O}_{\mathrm{i}}^{(6)}}{\Lambda^2} + \mathrm{o}(\Lambda^{-4})$$

Λ - mass scale

$\mathrm{C}_{\mathrm{i}}^{(6)}$ - dimensionless coefficients

$\mathrm{O}_{\mathrm{i}}^{(6)}$ - operators of dimension d

95% probability bounds on the interaction scale $\Lambda/(c_i)^{1/2}$



neglecting current theoretical uncertainties

Nucl. Phys. B268 (1986) 621

arXiv 1008.4884

Eur Phys. J. C. (2019) 79, 474

Sensitivity exceeding 50 TeV for several EFTs

Motivation for FCC-hh

➢ Opportunities of ~100 TeV pp collider:

- Exploration of scenarios that could emerge from a FCC-ee
- The next qualitative leap in precision of crucial measurements, providing hope to answer nagging questions (shortages of SM, BSM…)

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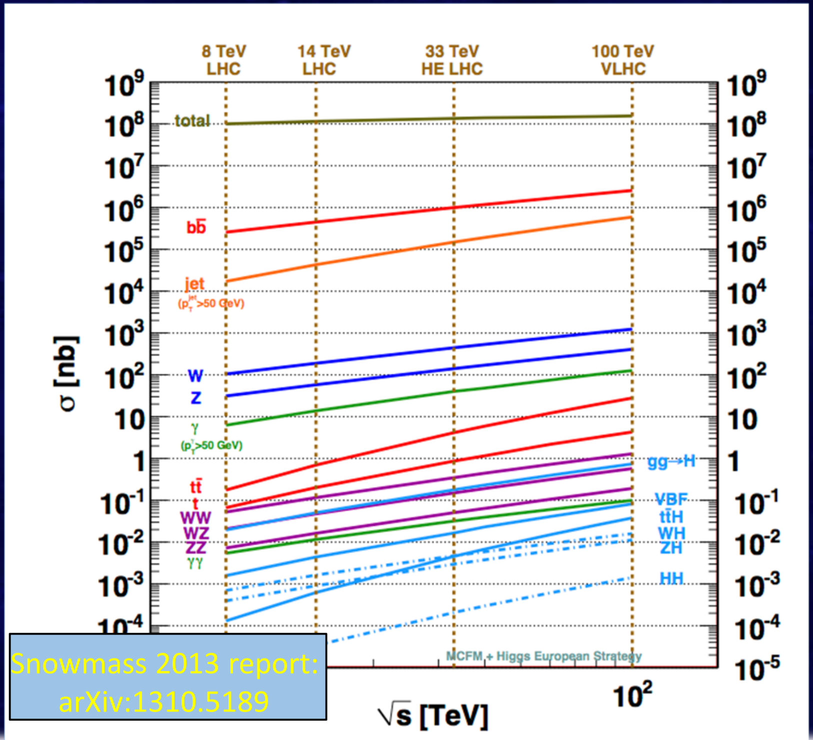
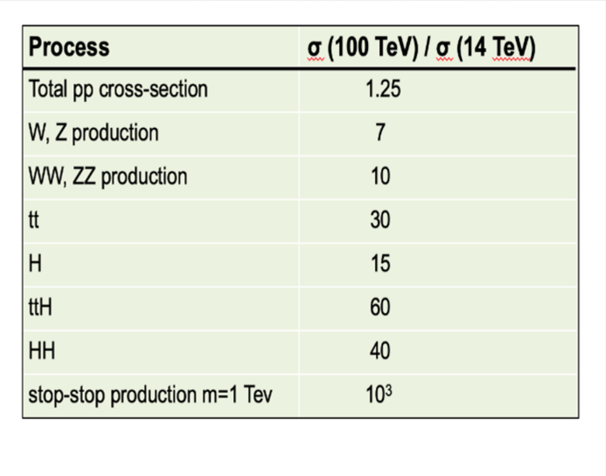
➢ Big gain (x10) in production cross sections of many relevant processes

→ Impressive precision of the SM measurements

→ Reach of terra incognita in the energy frontier



Snowmass 2013 report: arXiv:1310.5189

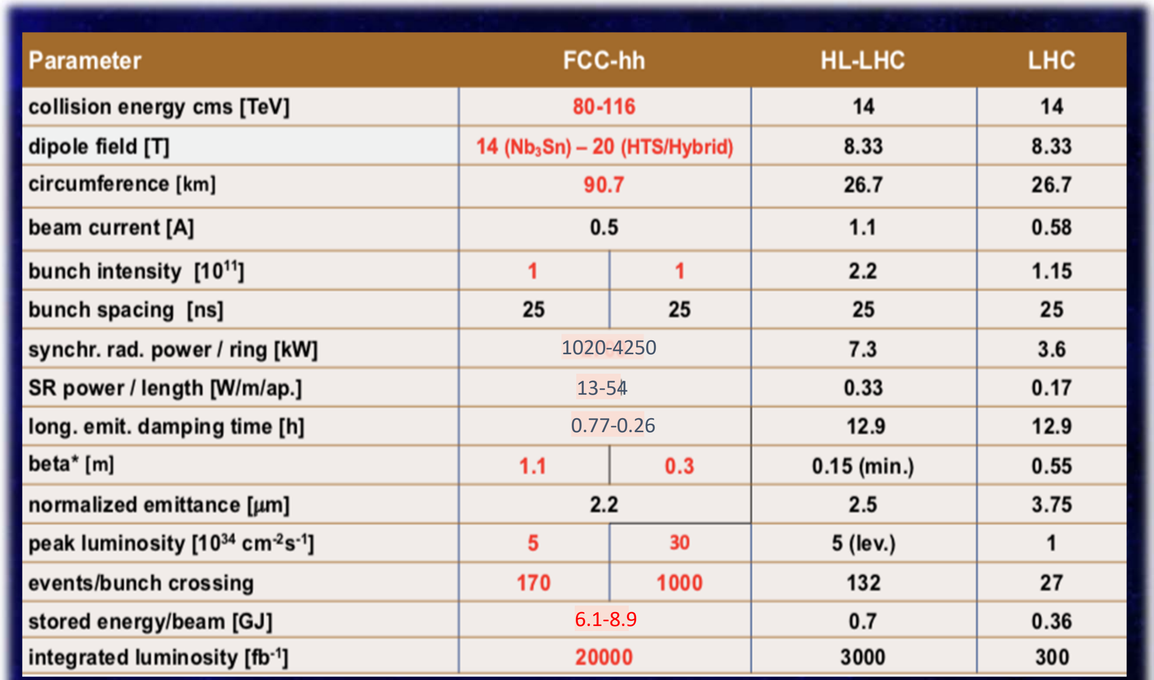


Process	σ (100 TeV) / σ (14 TeV)
Total pp cross-section	1.25
W, Z production	7
WW, ZZ production	10
tt	30
H	15
ttH	60
HH	40
stop-stop production m=1 Tev	10^3

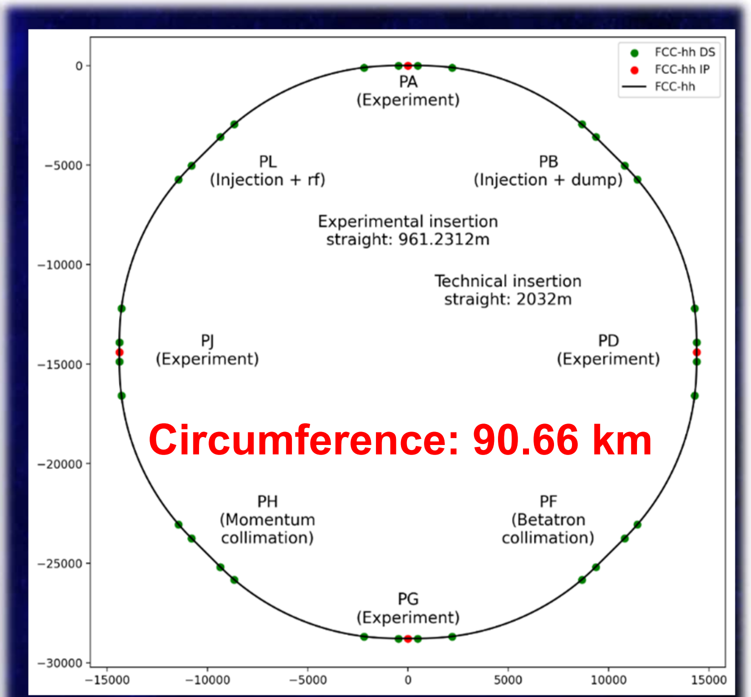
With 20 ab^{-1} at √s=100 TeV expect:

~ 10^{13}	W	~ 10^9	ttH
~ 10^{12}	Z	~ 10^7	HH
~ 10^{11}	tt	~ 10^5	gluino pairs m=8 TeV
~ 10^{10}	H		

FCC-hh Accelerator



Parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	80-116		14	14
dipole field [T]	14 (Nb_3Sn) – 20 (HTS/Hybrid)		8.33	8.33
circumference [km]	90.7		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	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	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [µm]	2.2		2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	6.1-8.9		0.7	0.36
integrated luminosity [fb^{-1}]	20000		3000	300



Circumference: 90.66 km

- **Formidable challenges:**

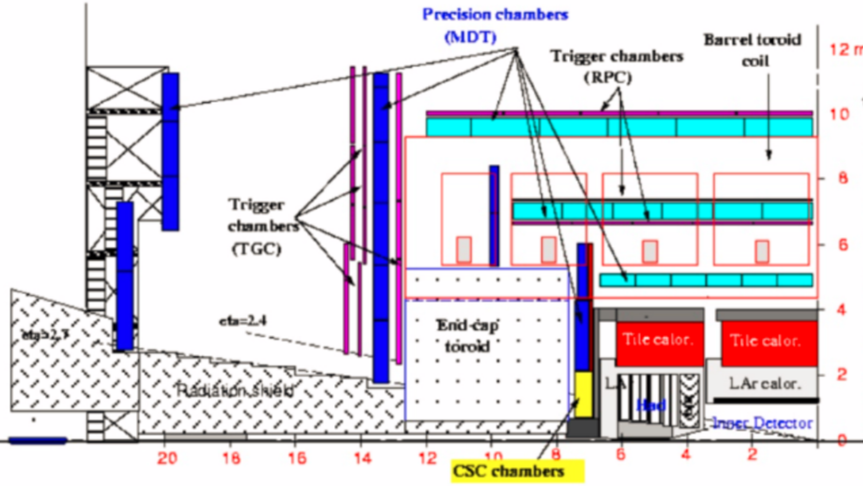
arXiv:2203.07804

- High-field SC magnets: (14 – 20) T; current setup with 16T dipoles → beam energy 48GeV
- 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/crossing
- Energy consumption: 4 TWh/year
- …

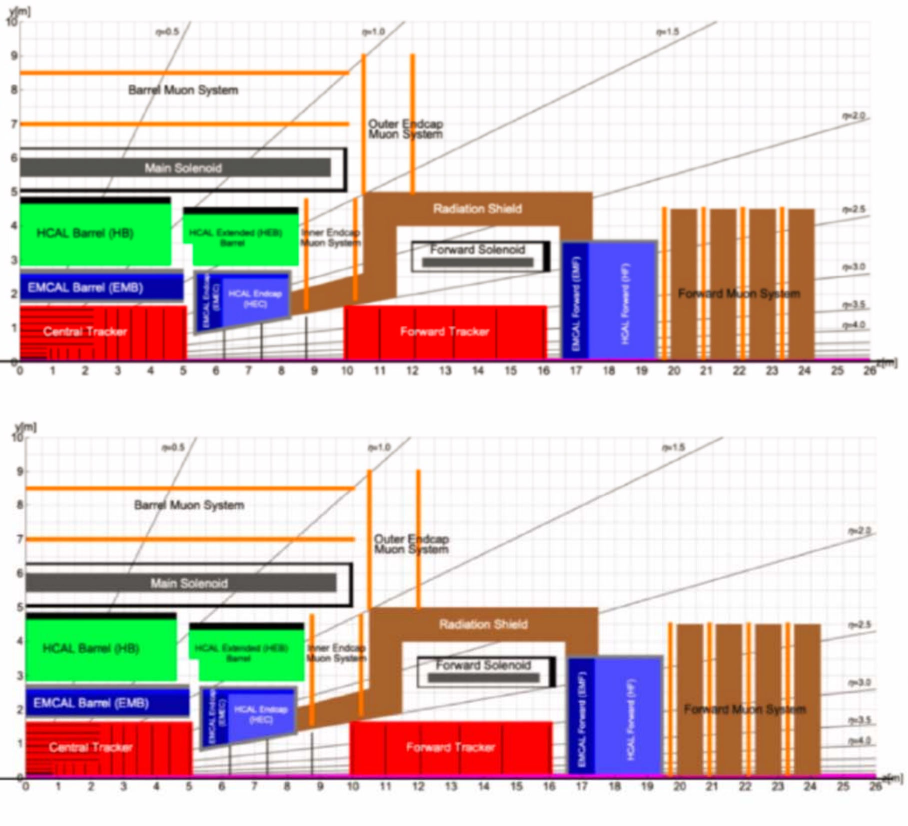
→ R&D on cryogenics, HTS, beam current…

FCC-hh Detectors

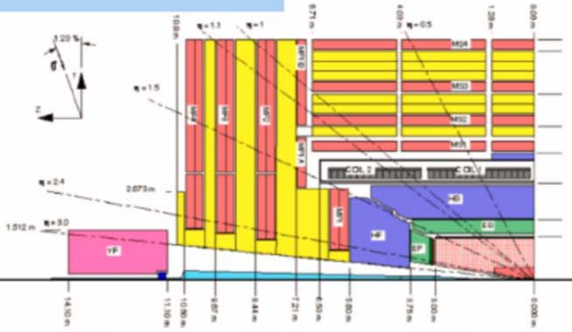
ATLAS



FCC-hh



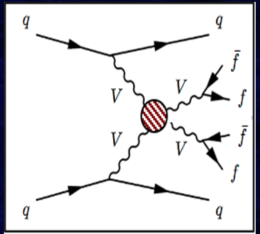
CMS



FCC-hh Physics Potential Examples

➢ Direct discovery potential up to ~40 TeV

➢ Conclusive elucidation of EWSB by probing SM in regime where EW symmetry is restored (√ŝ >> v=246 GeV)



Without H: V_LV_L scattering violates unitarity at m_{VV} ~TeV

- H regularizes the theory fully → a crucial "closure test" of the SM
- Else: new physics: anomalous quartic couplings (VVVV, VVhh) and/or new heavy resonances
- FCC-hh: direct discovery potential of new resonances in the o(10 TeV) range

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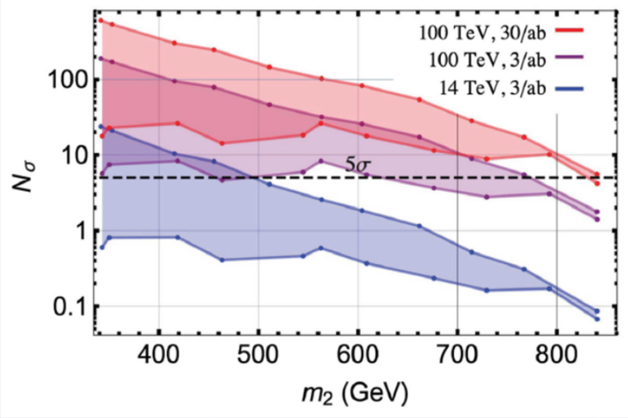
➢ Determination of nature of EW phase transition

(is it 1st order transition, faster than in SM, as required for EW baryogenesis ? → modification to Higgs potential)



Additional Higgs singlet with mass m_2 decaying into HH

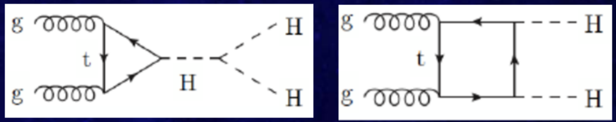
Constraints also from self-coupling (5% precision of FCC-hh, 50% @HL-LHC), and from HZZ at FCC-ee.

➢ Higgs Self Coupling (HSC λ_{3H})

$$V(h) = \frac{m_H^2}{2}h^2 + \lambda_{3H}\nu h^3 + \lambda_{4H}\nu h^4$$

$$\nu = 246 \text{ GeV}$$

- Issues of EWPT and HSC are tightly connected – their aswer depends on the parameters of V(h)
- Di-Higgs production (destructive interference of the box and triangle diagrams):



$$\sigma_{HH}^{LHC} \approx 37 \text{ fb}$$

$$\sigma_{HH}^{FCC-hh} \approx 50 \times \sigma_{HH}^{LHC}$$

- Main decay channels: $b\bar{b}\gamma\gamma, b\bar{b}\tau\tau, b\bar{b}b\bar{b}$
- Expected precision:

$$\delta\lambda_{3H}/\lambda_{3H} \sim 5~\%$$

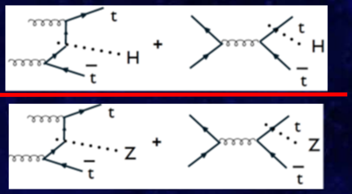
arXiv:2203.08042

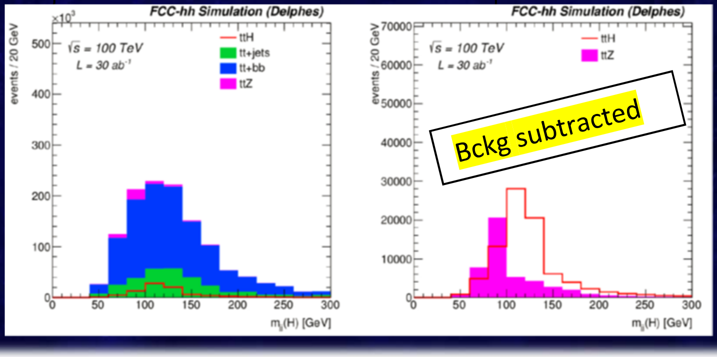
FUTURE
CIRCULAR
COLLIDER

FCC-hh Physics Potential Examples

➢ Top - Higgs Yukawa Coupling (k_t)

- Measurement of $\sigma_{\mathrm{ttH}}/\sigma_{\mathrm{ttZ}}$
  - identical production dynamics
  - substantial reduction of theoretical uncertainties)



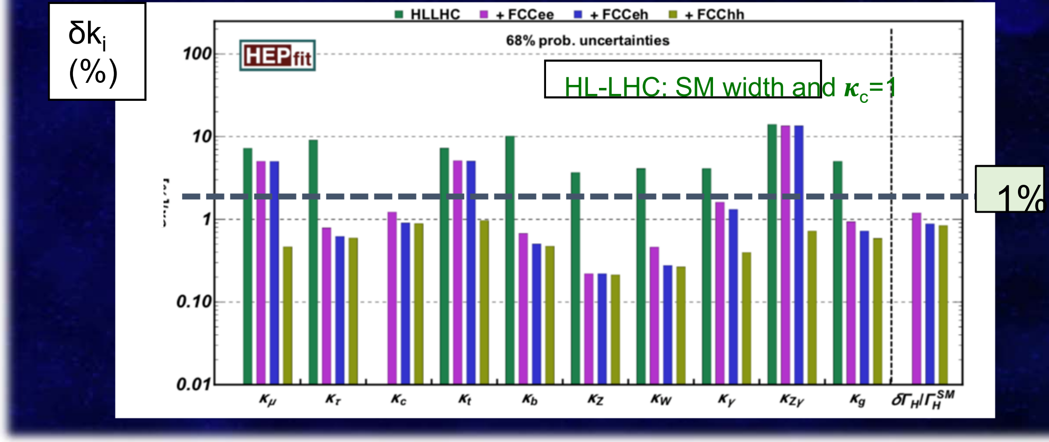


Bckg subtracted

arXiv:1507.08169

$\delta k_t/k_t \sim 1\ \%$

➢ Precise measurement of SM couplings with precision ~ 1%



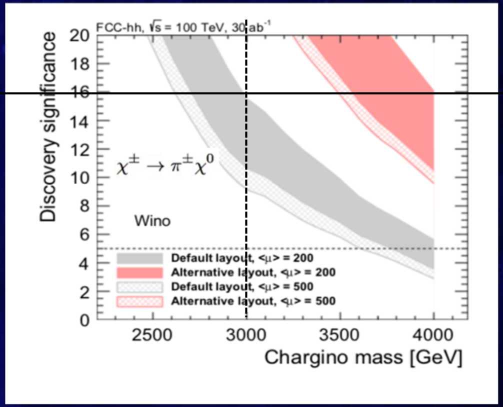
δk_i (%)

HL-LHC: SM width and κ_c=1

1%

➢ Final word about thermal WIMP dark matter (DM)

- Thermal WIMP dark cannot be too heavy: (1- 3) TeV upper mass limit from observed relic abundance
- The conclusive affirmation/rejection of WIMPs by accelerator expts is of paramount importance
- LHC: can exclude only a fraction of the range (1-3) TeV
- FCC-hh is necessary and just sufficient with this respect



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Summary

- ✓ The FCC project offers a complete, coherent and exciting option for the particle physics for the next decades – in agreement with ESPP
- ✓ Both electron-positron and proton-proton machines have a complementary physics programme
- ✓ The exploitation of two (or more) subsequent colliders in the same tunnel maximizes the outcome
- ✓ The project is progressing well and gaining momentum