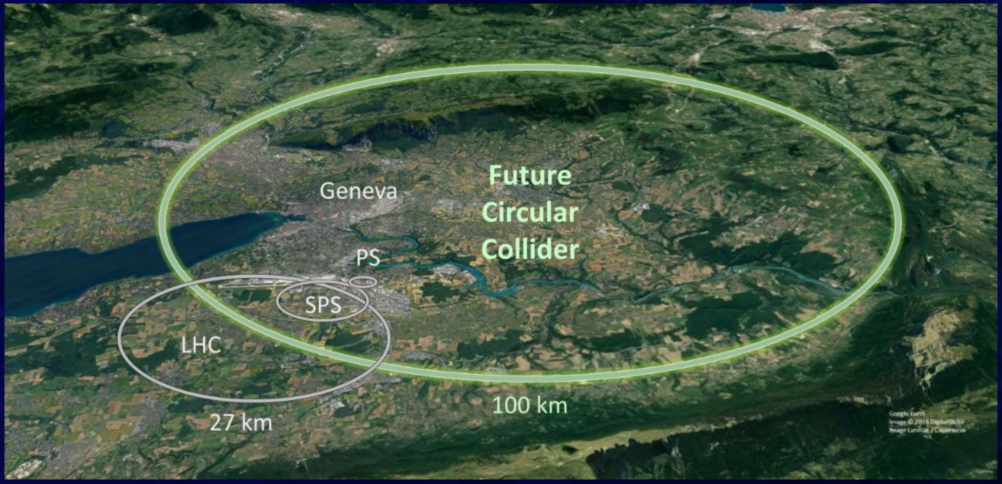
The Future Circular Collider Project: Plans and Physics Programme

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

FCC Detectors:
the talk by Paolo Giacomelli



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.** ”

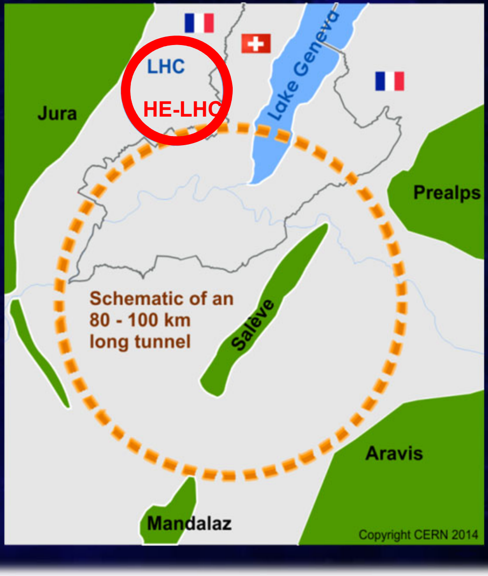
CERN Council, June 2021:
approval of the FCC feasibility study (FCC-FS)
→ Mid term review by the end of 2023
→ Final report by the end 2025

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

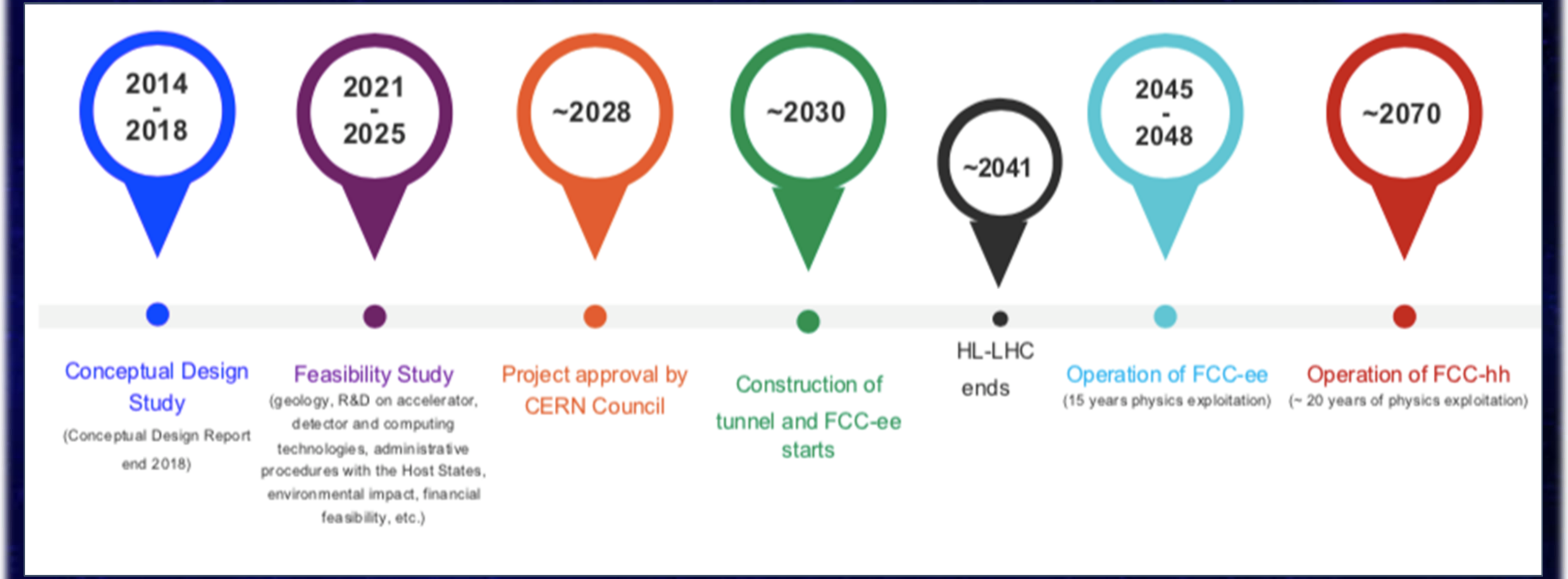
FCC Feasibility Study

EC
H2020

FCC timeline

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

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



2014-2045	2045-2070	2070-2100
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:

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

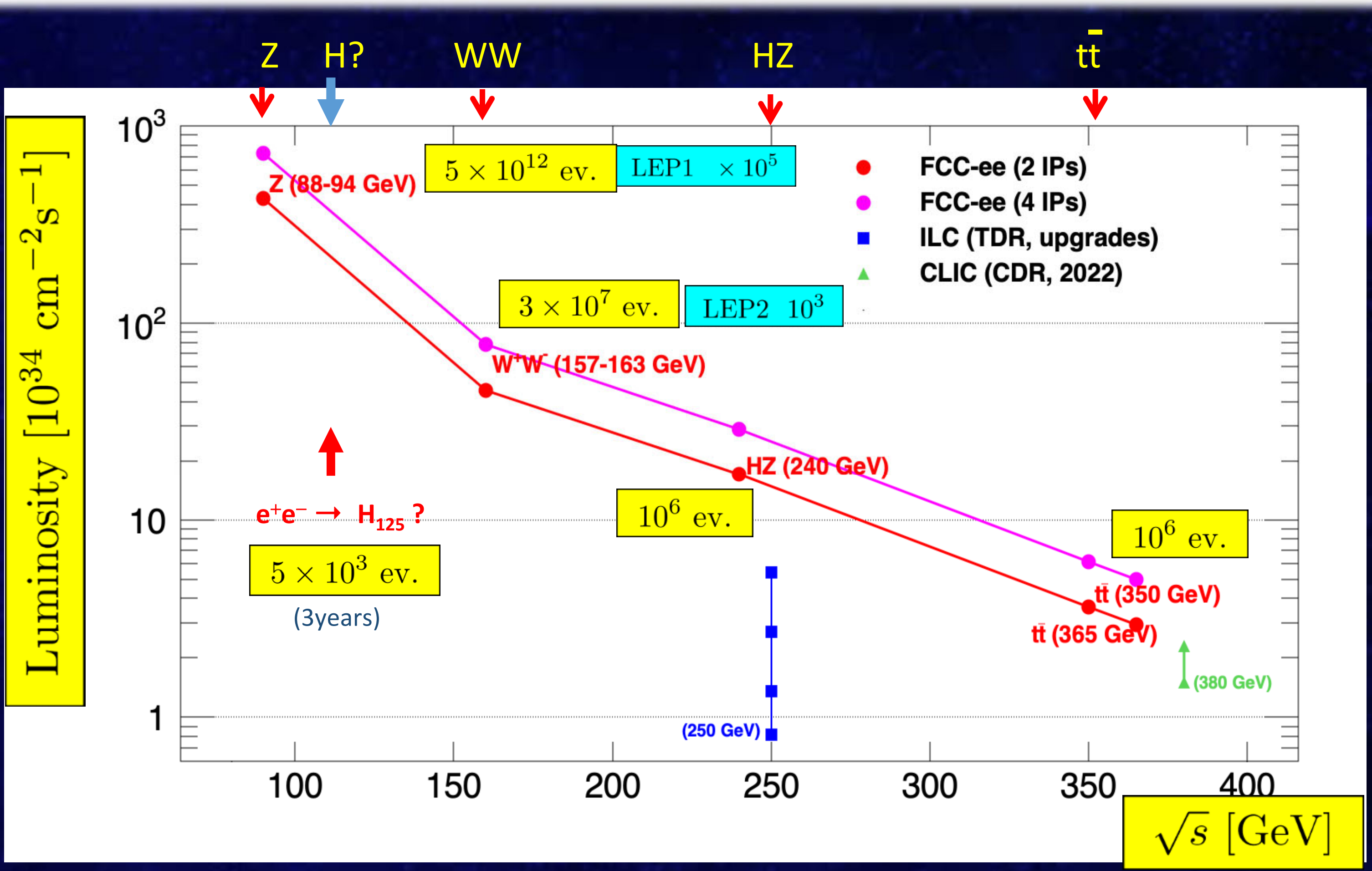
- Discovery of a light (m= 125 GeV) Higgs boson – accessible to a circular machine
- Substantial progress in e^+e^- circular collider technology (B factories et al.) → mature technology
- Lack of BSM physics at the LHC → limits the physics case of the 1 TeV scale linear colliders
- The best performance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

Proposed New e^+e^- Colliders



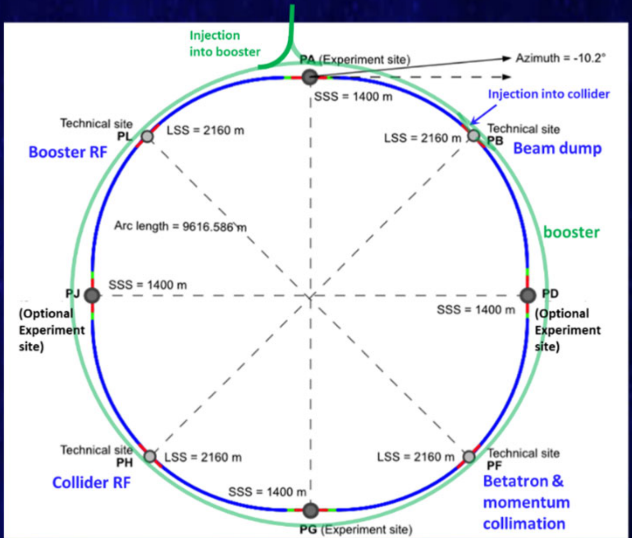
- **Optimal energy range for SM particles!**
- **HZ and ttbar thresholds never investigated at leptonic colliders !**
- **Circular colliders can serve up to 4 IPs → increase discovery potential and the community**

FCC-ee: Design and Placement

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

- 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)

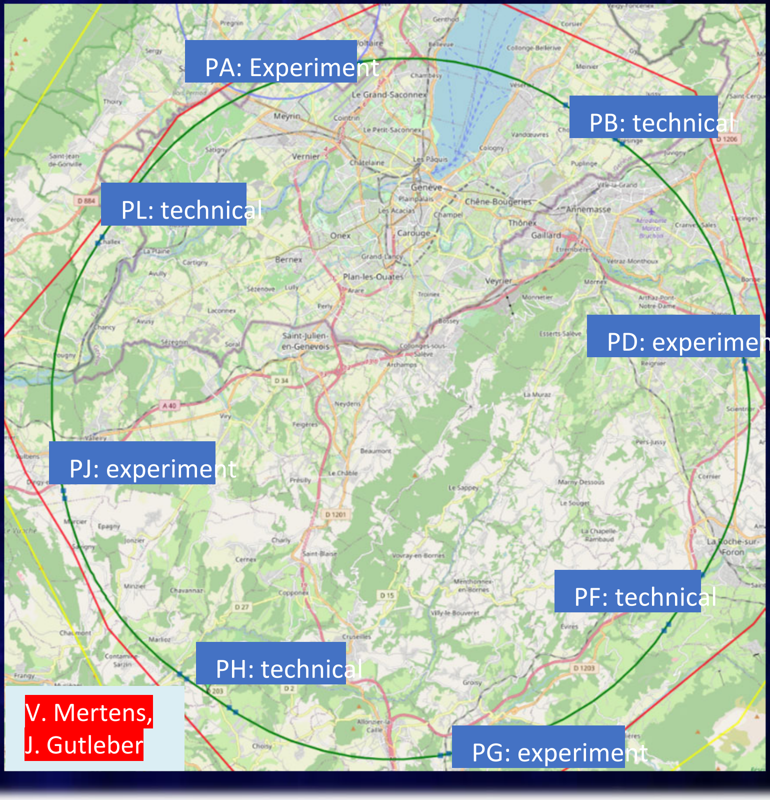
- **Large horizontal crossing angle of 30 mrad**
- **Crab-waist collision optics**



- **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

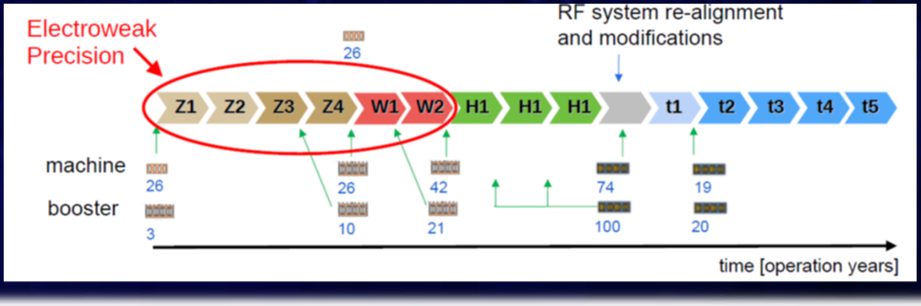
4 years
5 x 10^{12} Z
LEP x 10^5

2 years
> 10^8 WW
LEP x 10^4

3 years
2 x 10^6 H

5 years
2 x 10^6 tt pairs

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



FUTURE
CIRCULAR
COLLIDER

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..)

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

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

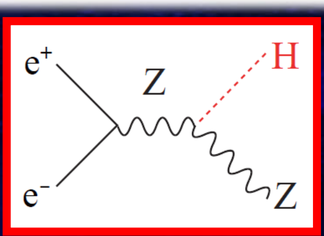
x 10 Belle II
statistics
for b, c, τ

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

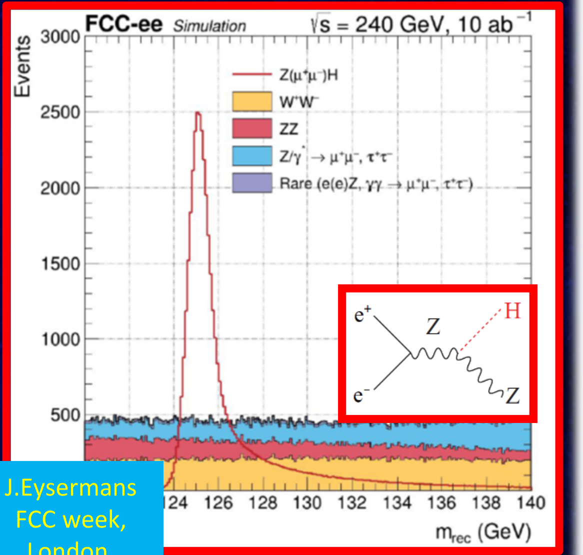
Direct discovery potential
for feebly-interacting
particles over **(5-100) GeV**
mass range

Higgs Physics

➢ 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 (includes invisible decay modes)
- Very clean Higgs mass determination: $\mathbf{m^2_{recoil} = (\sqrt{s} - E_{ll})^2 - |\tilde{p}_{ll}|^2}$ ➡ $\Delta m_H \sim 10$ MeV
- Precise determination of the ZH cross-section: $\Delta\sigma(ZH)/\sigma(ZH) \sim 0.5\%$



J.Eysermans FCC week, London, 2023

➢ Higgs couplings normalized to the SM predictions:

$$\mathbf{k_f = \frac{g_{Hff}}{g^{SM}_{Hff}},\ f = b, c, \tau, \mu}$$

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

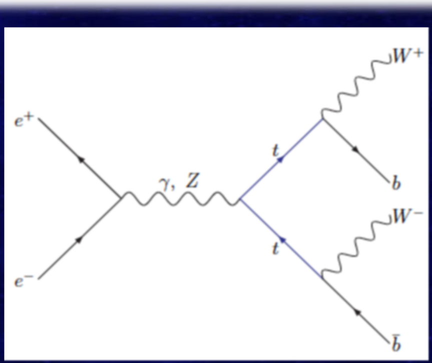
Coupling	HL-LHC	+ FCC 240 GeV	+FCC 265 GeV	+FCC-hh
k_Z	1.5	0.18	0.17	0.16
k_W	1.7	0.44	0.41	0.19
k_b	5.1	0.69	0.64	0.48
k_c	SM	1.3	1.3	0.96
k_g	2.5	1.0	0.89	0.50
k_τ	1.9	0.74	0.66	0.46
k_μ	4.4	8.9	3.9	0.43
k_γ	1.8	3.9	1.2	0.32
$k_{Z\gamma}$	11	–	10	0.70
k_t	3.4	10	3.1	0.95
k_H	50	44	33	3-4

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

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

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

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

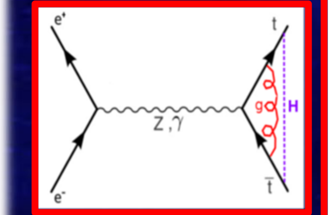


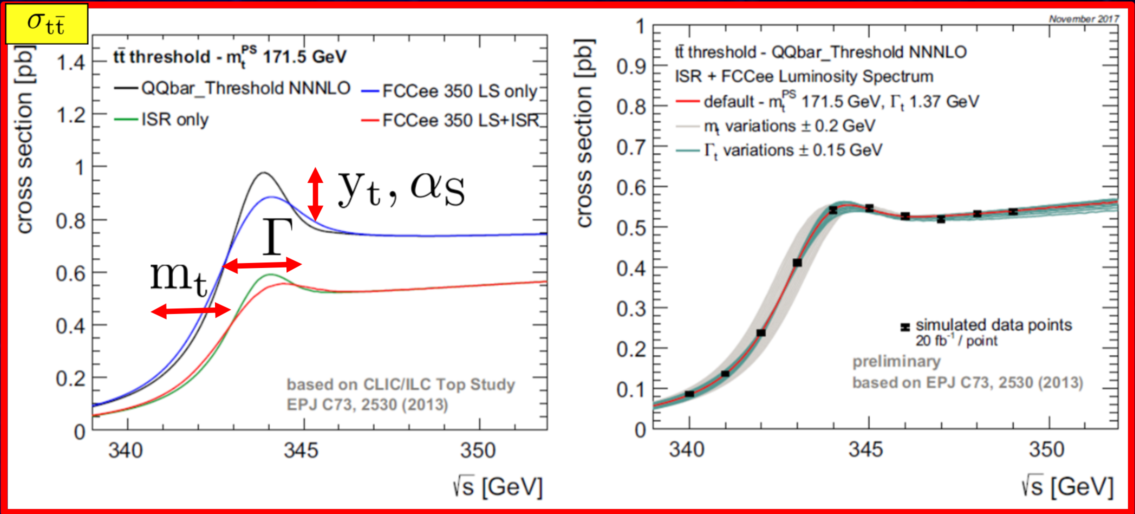
$$e^+e^- \to Z/\gamma \to t\bar{t} \to (bW^+)(\bar{b}W^-)$$

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)

Eur. Phys. J. C (2019) 79





PDG:

- **Other top topics:**

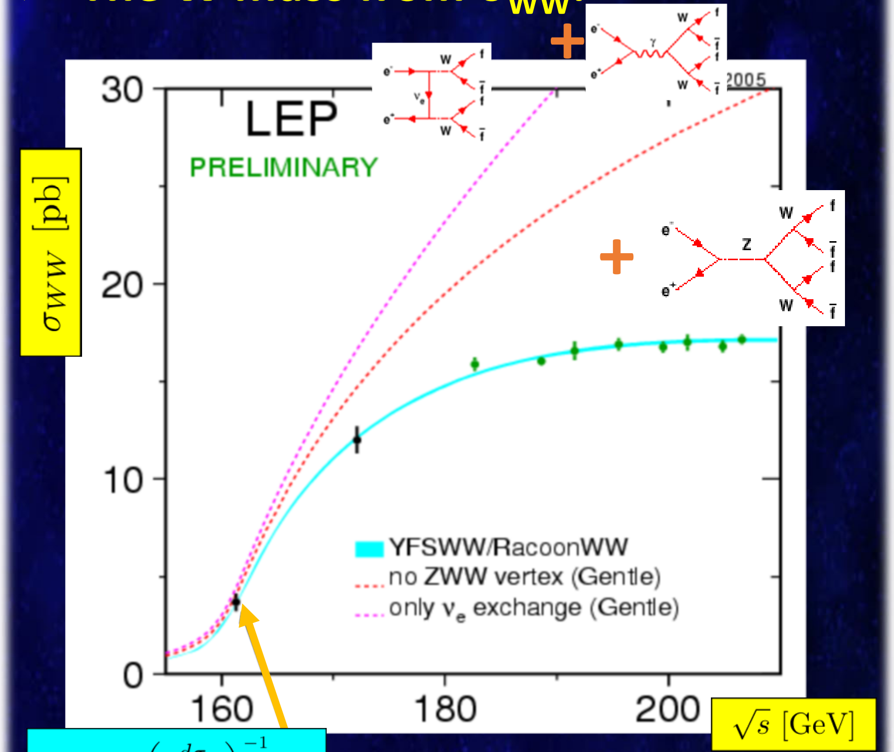
  Single top production,
  Top quark FCNC,
  $e^+e^- \to t\bar{t}\gamma$,
  Top-quark EW couplings
  …

$\text{PDG}: \quad m_t = (172.69 \pm 0.30)\ \text{GeV}$ → FCC-ee $\Delta m_t \geq 10\ \text{MeV}$

FUTURE CIRCULAR COLLIDER

WW Pair Production at Threshold

➢ The W mass from σ_{WW}:



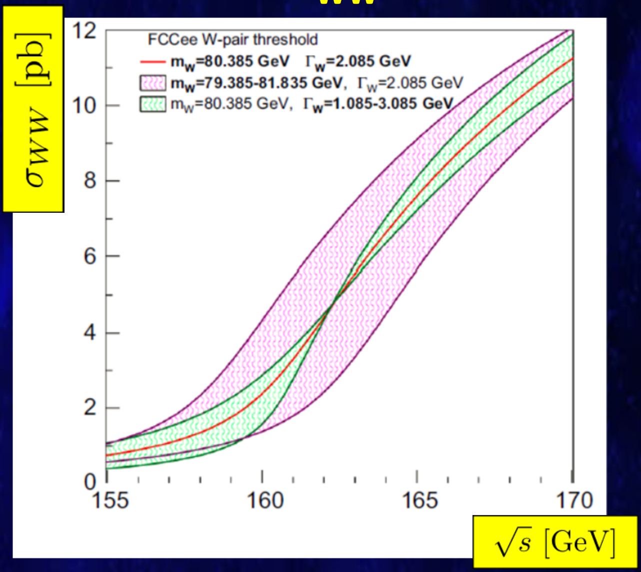
$$\Delta m_W = \left(\frac{d\sigma}{dm_W}\right)^{-1} \Delta\sigma$$

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

Eur. Phys. J. C (2019) 79

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:

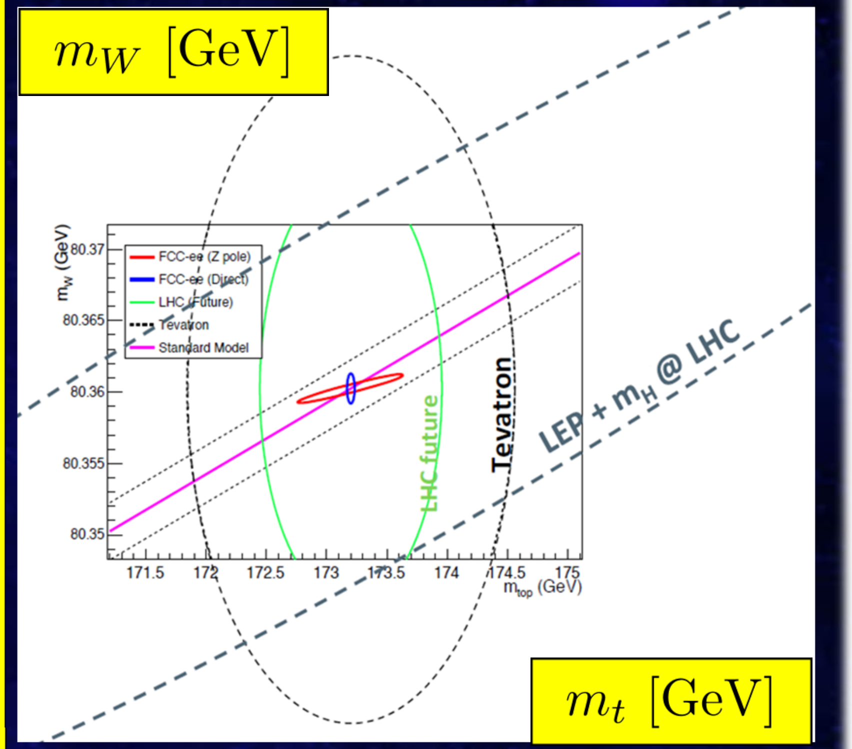
$E_1 = 157.5$ GeV $E_1 = 162.5$ GeV $f = 0.4$ $12\ \mathrm{ab}^{-1}$

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

Electroweak Observables: Instead of Summary

Eur. Phys. J. Plus (2022) 137

Observable	unit	Present		FCC-ee	
		value	± error	(stat.)	(syst.)
m_Z	[keV/c^2]	91 186 700	2 200	4	100
Γ_Z	[keV]	2 495 200	2 300	4	25
$\sin^2\theta_W^{\text{eff}}$	[$\times 10^6$]	231 480	160	2	2.4
$1/\alpha_{\text{QED}}(m_Z^2)$	[$\times 10^3$]	128 952	14	3	small
R_l^Z	[$\times 10^3$]	20 767	25	0.06	0.2-1
$\alpha_S(m_Z^2)$	[$\times 10^4$]	1 196	30	0.1	0.4-1.6
σ_{had}^0	[$\times 10^3$ nb]	41 541	37	0.1	4
N_ν	[$\times 10^3$]	2 996	7	0.005	1
R_b	[$\times 10^6$]	216 290	660	0.3	< 60
$A_{\text{FB}}^{b,0}$	[$\times 10^4$]	992	16	0.02	1-3
$A_{\text{FB}}^{\text{pol},\tau}$	[$\times 10^4$]	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:**

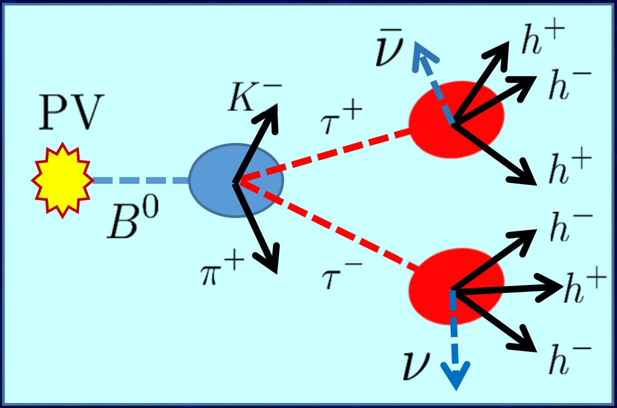
Particles	B^0/B^+	B^0_s	Λ_b	B_c	$Z \to \tau^+\tau^-$
Yields (FCC-*ee* 150 ab^{-1})	10^{12}	2.5 10^{11}	2.5 10^{11}	2.5 10^{9}	5. 10^{11}
Yields (Belle II 50 ab^{-1})	10^{11}	10^{7-8}	–	–	5. 10^{10}

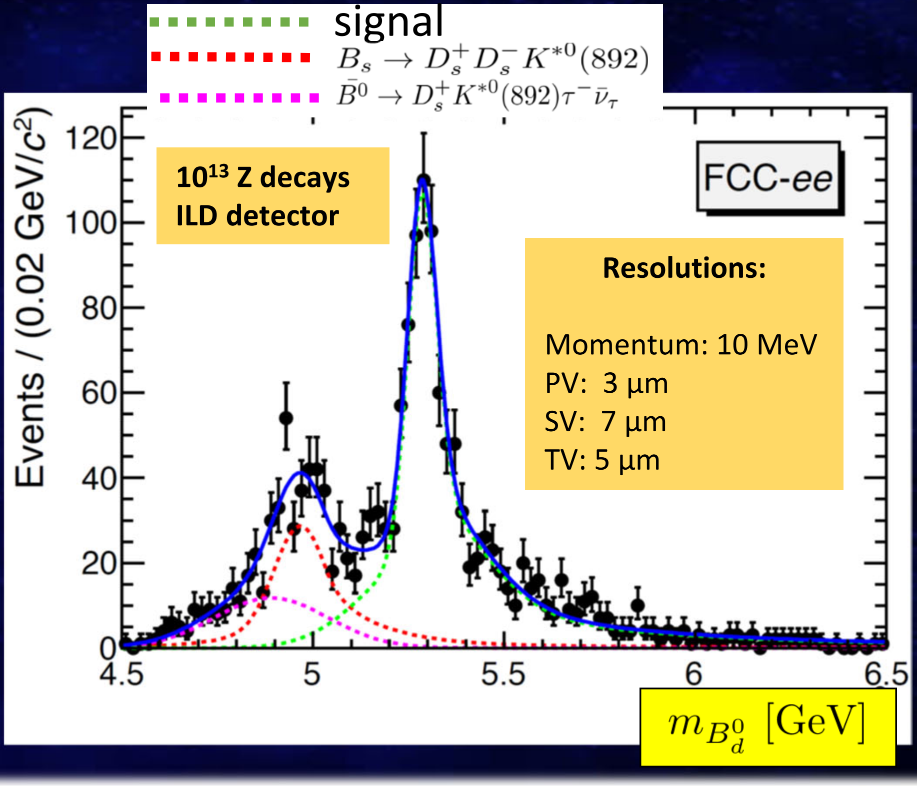
LEP : $\sim 6 \times 10^6$

S.Monteil. 2nd FCC Physics Workshop

Example: B→K*(892)$\tau^+\tau^-$ decay

- Excellent vtx reconstruction (τ → 3 prongs)





**10^{13} Z decays
ILD detector**

Resolutions:

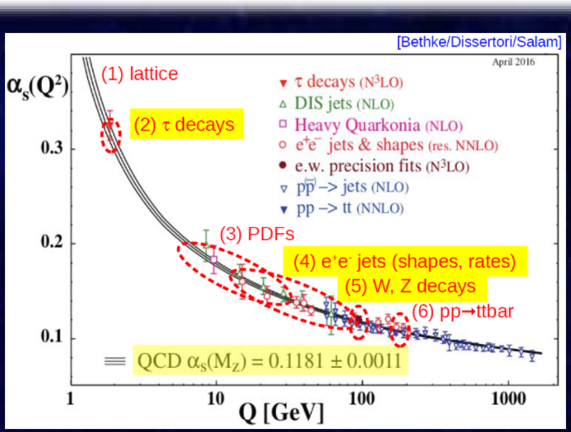
Momentum: 10 MeV
PV: 3 µm
SV: 7 µm
TV: 5 µm

- **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…

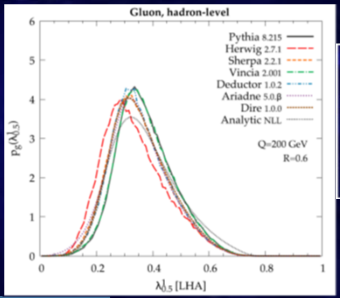
QCD Measurements

- **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



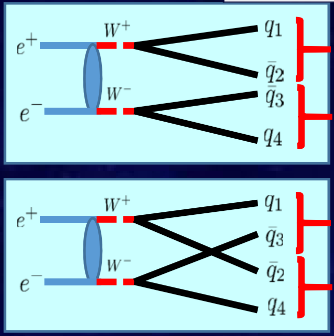
Eur. Phys. J. Plus (2022) 137:92

- **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



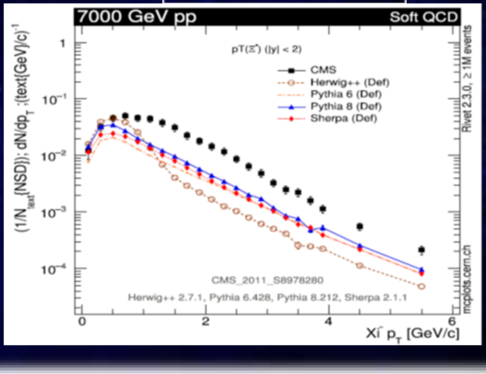
Gluon radiation
& fragmentaion
poorly known

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



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

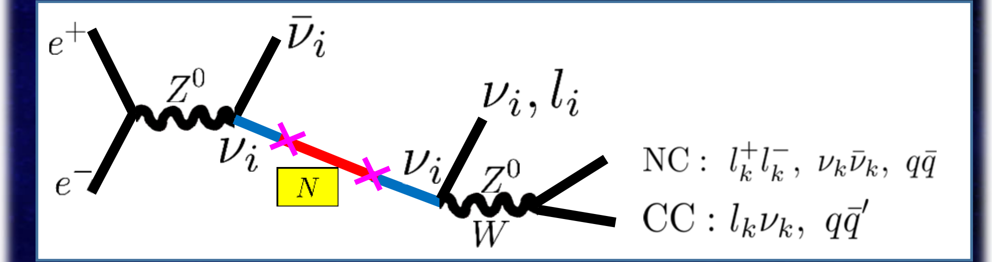
Ξ⁻ spectrum



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 $\sqrt{s} = M_Z$

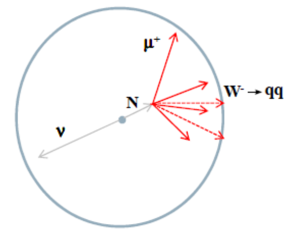


$\nu_L = \nu \cos\theta + N \sin\theta$ $\theta \approx m_\nu / m_N$

- Experimental signatures

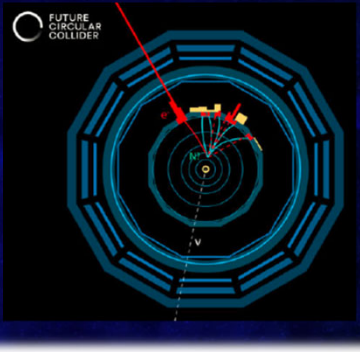
  NC: 2 leptons/jets + E_{miss}

  CC: 2 jets + lepton/E_{miss}



Search for (highly) displaced vertices;

very clean events



- FCC-ee sensitivity

  to HNLs up to 10^{-11}

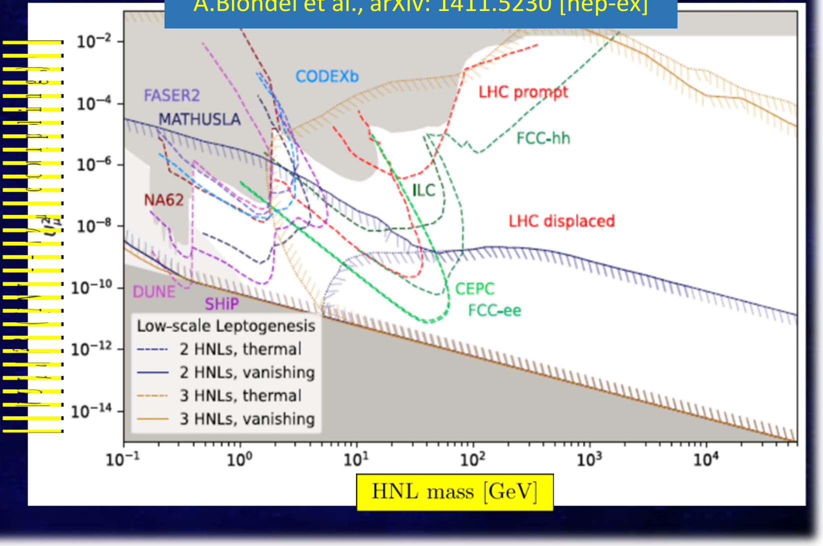
- Complementary to

  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:**

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

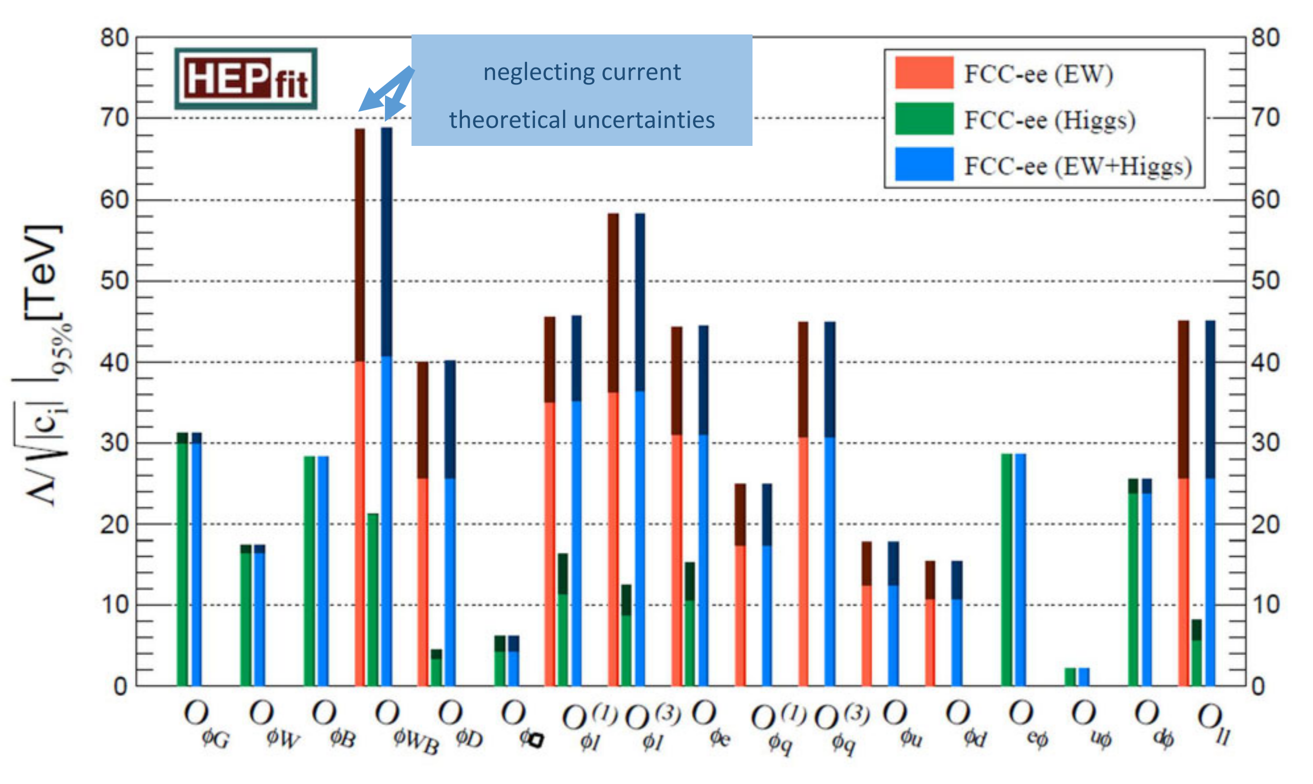
Λ - mass scale
$\mathrm{C}_{\mathrm{i}}^{(6)}$ - dimensionless coefficients
$\mathrm{O}_{\mathrm{i}}^{(6)}$ - operators of dimension d

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

Nucl. Phys. B268 (1986) 621

arXiv 1008.4884

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



neglecting current theoretical uncertainties

Sensitivity exceeding 50 TeV for several EFTs

Motivation for FCC-hh

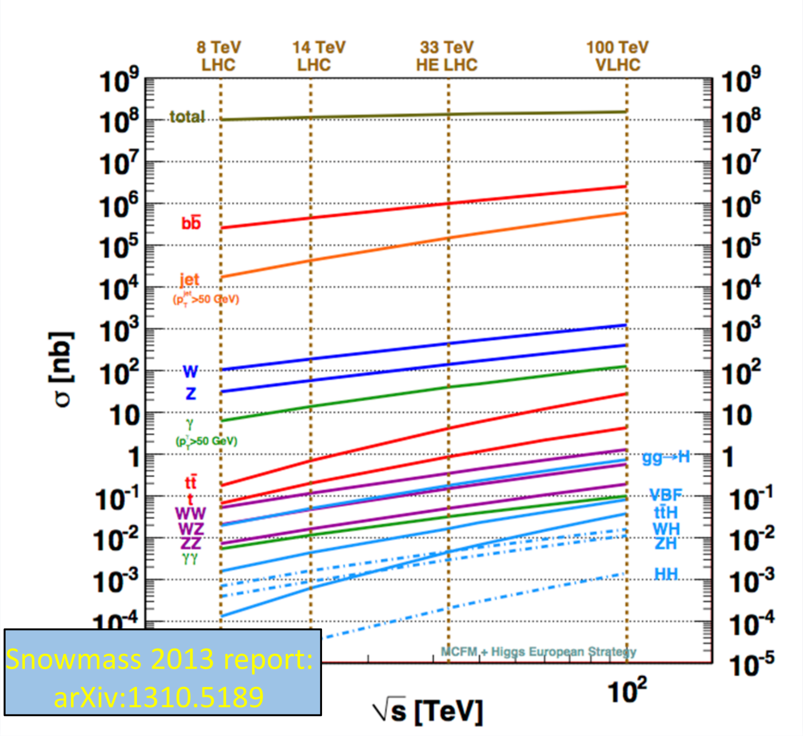
- **Big opportunities of ~100 TeV pp collider:**
  - Exploration of scenarios that could emerge from a FCC-ee
  - The next qualitative leap in precision of crucial measurements, providing hope to answer nagging questions (shortages of SM, BSM…)

Eur. Phys. J. Special Topics (2019) 228; 755

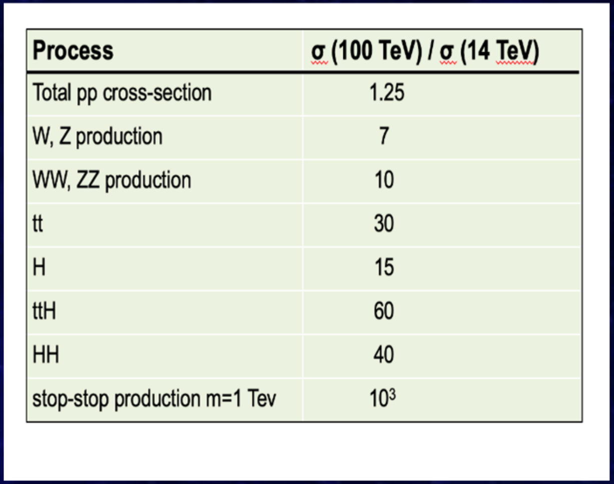
- **Big gain (x10) in production cross sections of many relevant processes**

→ Impressive precision of the SM measurements

→ Reach of terra incognita in the energy frontier



Snowmass 2013 report: arXiv:1310.5189



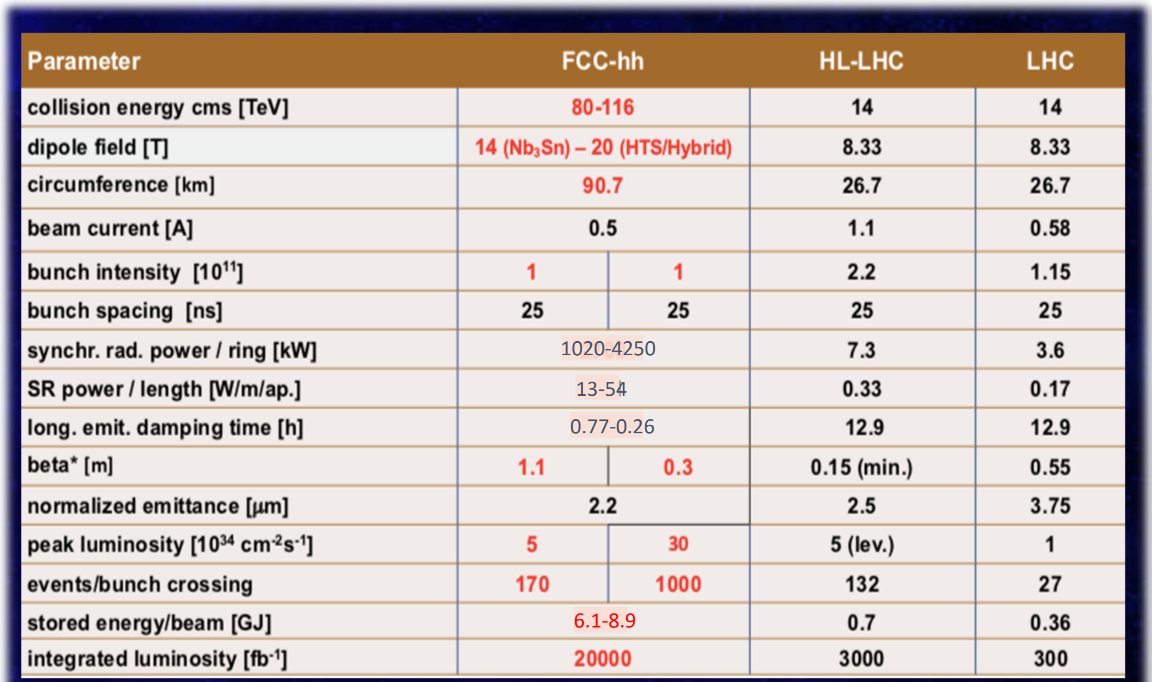
Process	σ (100 TeV) / σ (14 TeV)
Total pp cross-section	1.25
W, Z production	7
WW, ZZ production	10
tt	30
H	15
ttH	60
HH	40
stop-stop production m=1 Tev	10^3

With 20 ab^{-1} at √s=100 TeV expect:

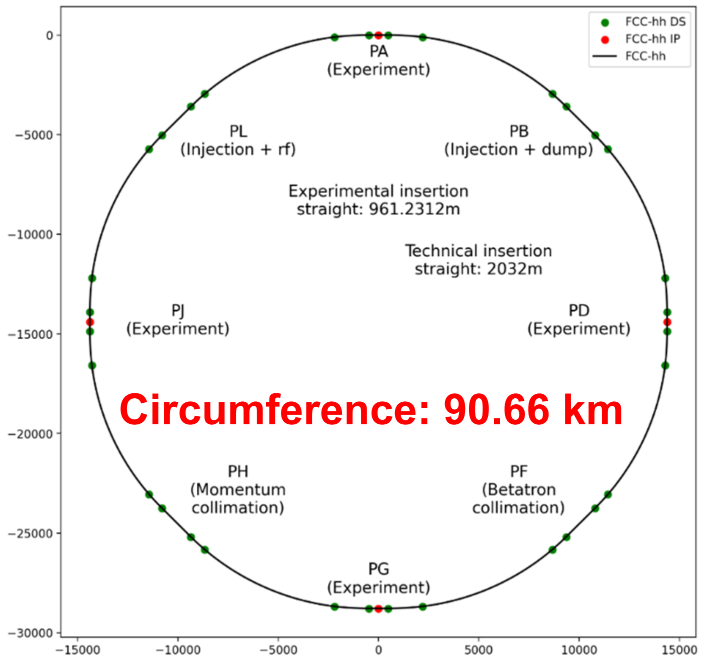
~ 10^{13} W
~ 10^{12} Z
~ 10^{11} tt
~ 10^{10} H

~ 10^9 ttH
~ 10^7 HH
~ 10^5 gluino pairs m=8 TeV

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

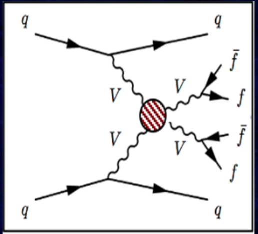
- High-field superconducting magnets: (14 – 20) T;
  current setup with 16T dipoles → beam energy 48GeV
- Power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- Stored beam energy: ~ 9 GJ → machine protection
- Pile-up in the detectors: ~1000 events/crossing
- Energy consumption: 4 TWh/year → R&D on cryogenics, HTS, beam current
- …

FCC-hh Physics Potential Examples

- ➢ **Direct discovery potential up to ~40 TeV**

- ➢ **Conclusive elucidation of EWSB by probing SM in regime where EW symmetry is restored** ($\sqrt{\hat{s}} >> v$=246 GeV)

  Without H: $V_L V_L$ 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

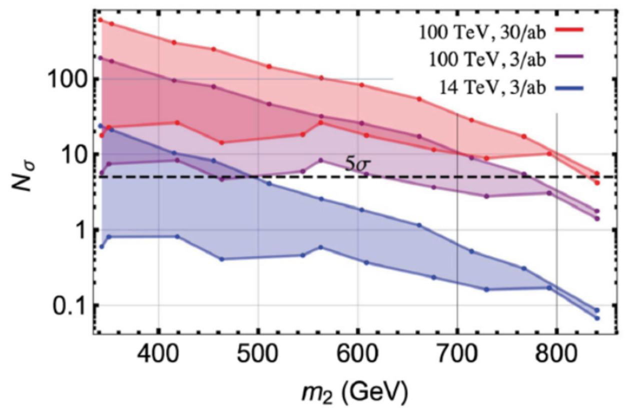


Eur. Phys. J. Special Topics (2019) 228; 755

Eur. Phys. J. C (2019) 79

- ➢ **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

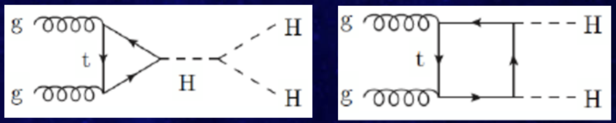
Constraints also from self-coupling (5% precision of FCC-hh, 50% @HL-LHC), and from HZZ at FCC-ee.

- ➢ **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:

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

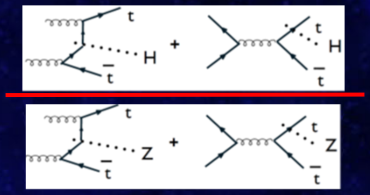
arXiv:2203.08042

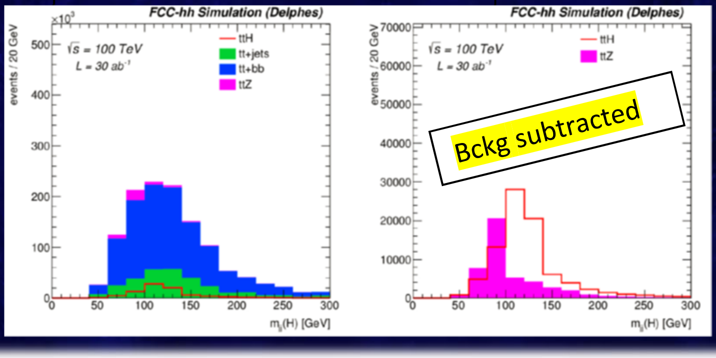
FUTURE CIRCULAR COLLIDER

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)

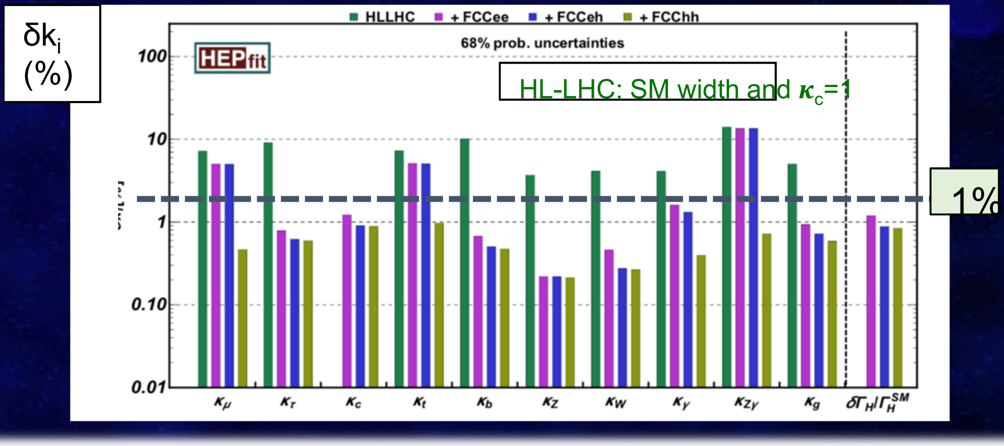




arXiv:1507.08169

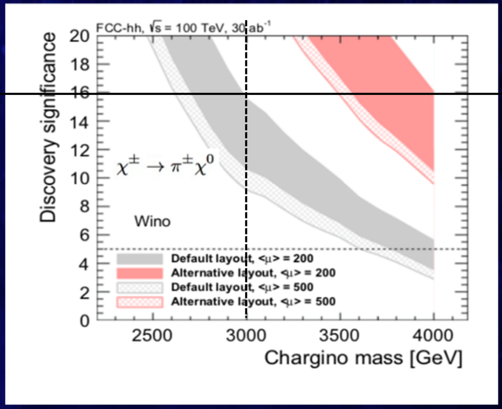
$\delta k_t/k_t \sim 1\ \%$

➢ Precise measurement of SM couplings with precision ~ 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



Eur. Phys. J. Special Topics (2019) 228; 755

FUTURE
CIRCULAR
COLLIDER

Summary

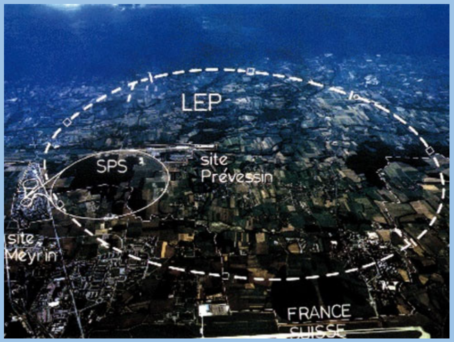
- ✓ The FCC project offers a complete, coherent and exciting option for the particle physics for the next decades – in agreement with ESPP
- ✓ Both electron-positron and proton-proton machines have a complementary physics programme
- ✓ The exploitation of two (or more) subsequent colliders in the same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

Spare Slides

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

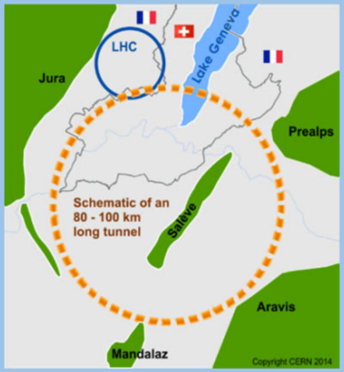
$$\mathcal{L} \propto R\frac{P_{\text{SR}}}{\beta_y^*}$$

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

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

CIRCULAR, Now:

enormous progress



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

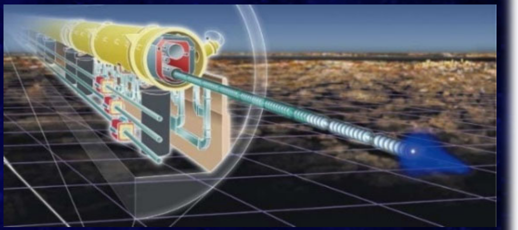
- $\beta_y^* \sim 0.8\ \text{mm}$ x (50-250)
- Continuous injection (x5)
- Increase beam power (x5)
- Increase radius (x4)

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

LINEAR, Now:

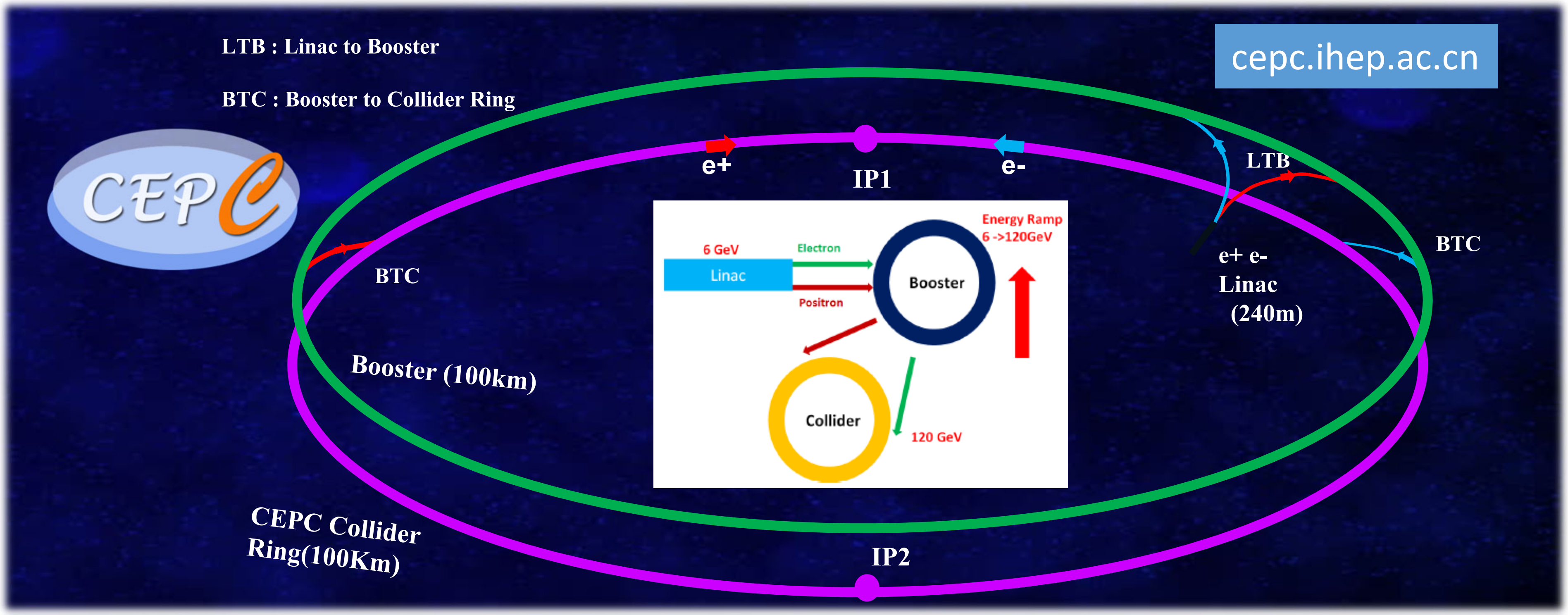
enormous progress, mature(-ing) technology

- The beams are accelerated and usable only once



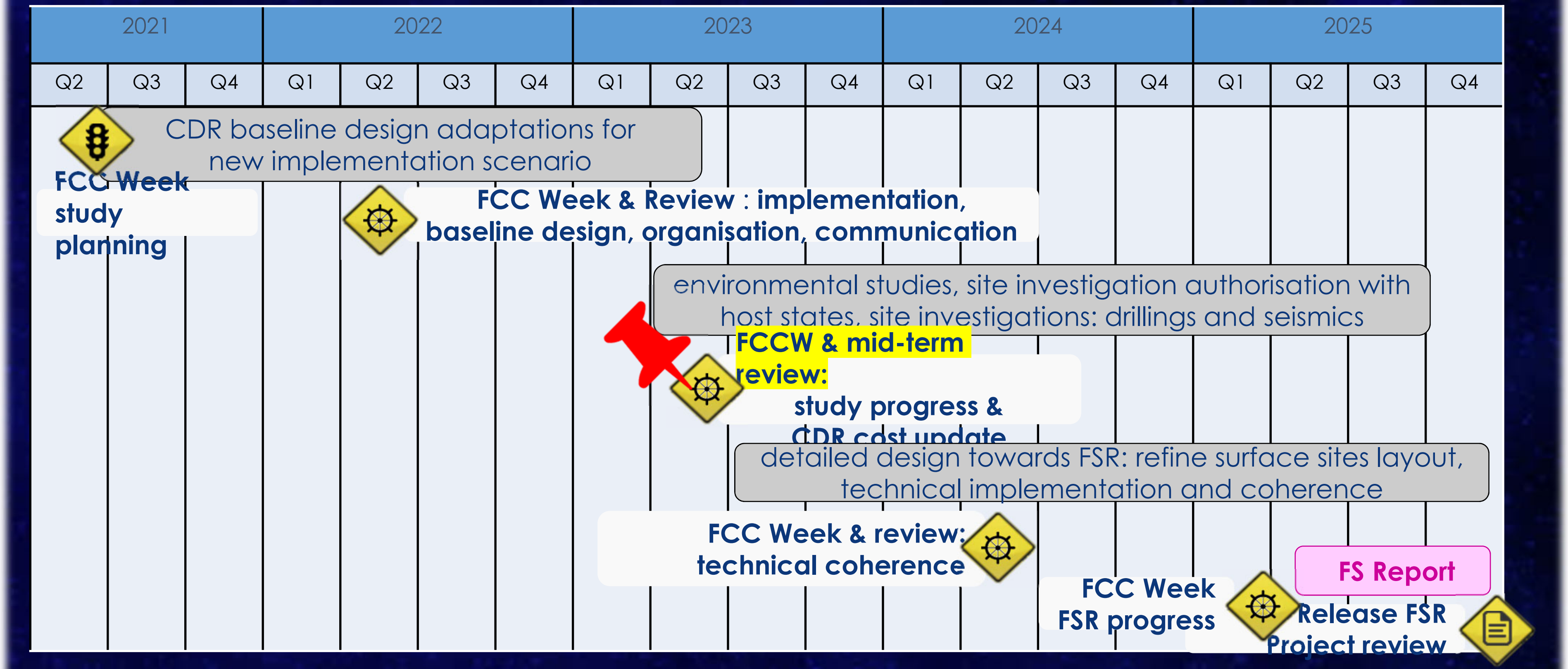
- Longitudinal beam polarization
- The only option for E > 400 GeV

CEPC – Circular Electron Positron Collider



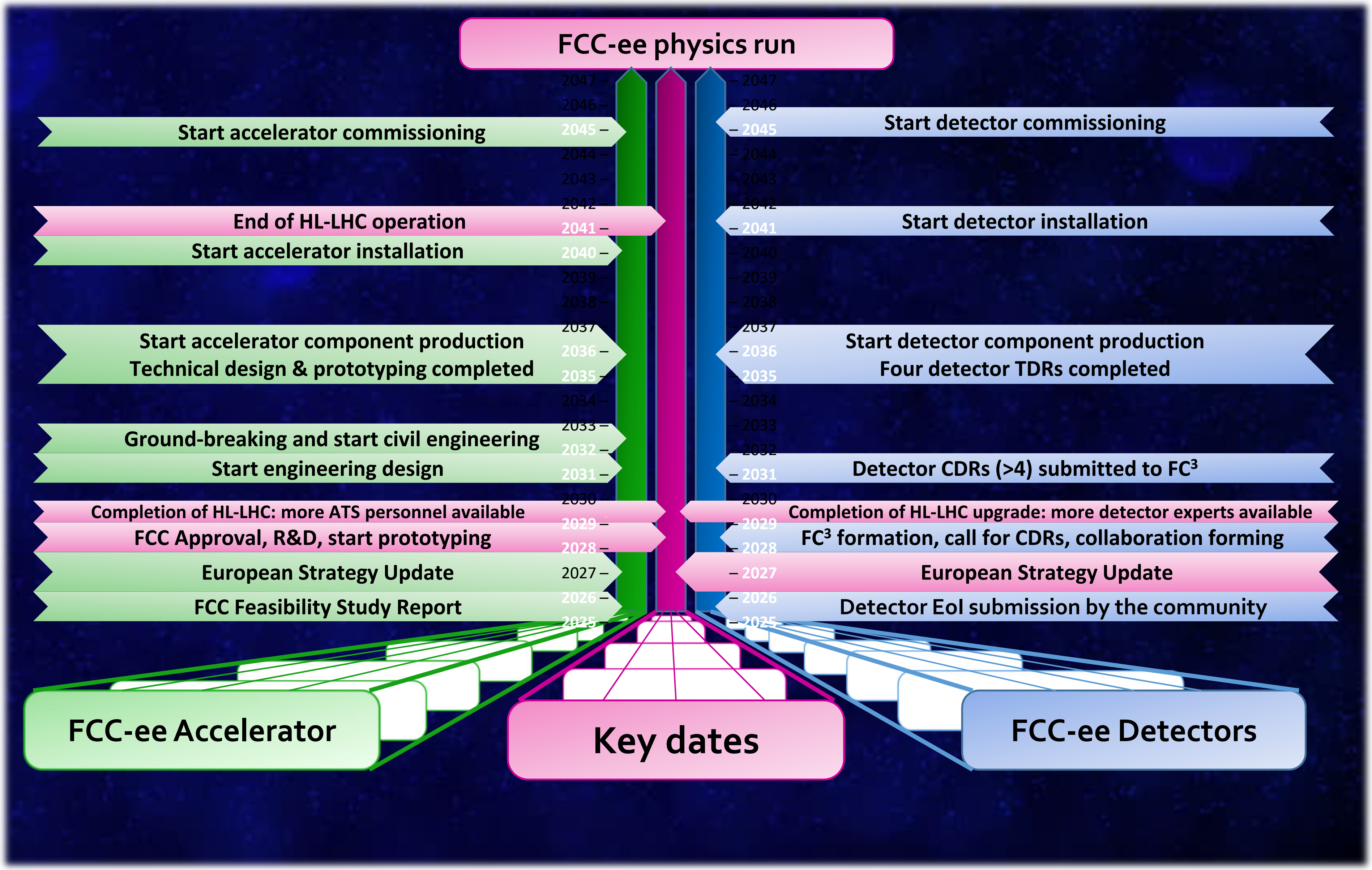
- **Collider:** two rings; two interaction points; flat beams; non-zero crossing angle
- Luminosity ≈ 1.5 x 10^{34} cm^{-2}s^{-1} ; working points: $\sqrt{s} = M_Z,\ M(WW),\ M(ZH)$
- Circumference ≈ 100 km; tunnel's diameter 6m (LHC: 3.6m) → can host also the pp machine (SppC)
- CDR (accelerator) issued in July 2018
- Site(s): six potential locations considered

FCC IS Timeline and Main Activities



FUTURE
CIRCULAR
COLLIDER

FCC-ee Timeline



FCC-ee physics run

Start accelerator commissioning

End of HL-LHC operation

Start accelerator installation

Start accelerator component production

Technical design & prototyping completed

Ground-breaking and start civil engineering

Start engineering design

Completion of HL-LHC: more ATS personnel available

FCC Approval, R&D, start prototyping

European Strategy Update

FCC Feasibility Study Report

Start detector commissioning

Start detector installation

Start detector component production

Four detector TDRs completed

Detector CDRs (>4) submitted to FC^3

Completion of HL-LHC upgrade: more detector experts available

FC^3 formation, call for CDRs, collaboration forming

European Strategy Update

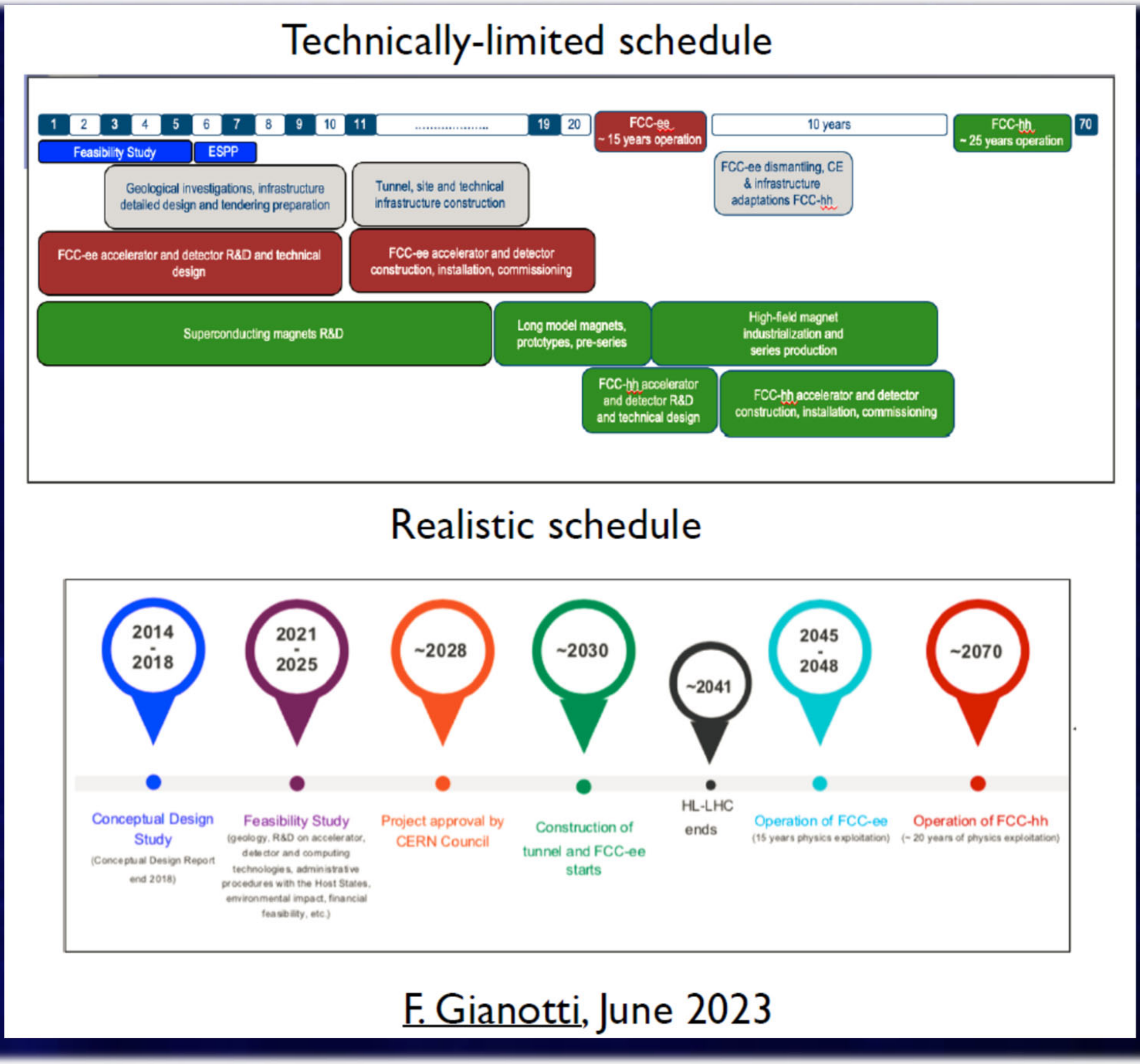
Detector EoI submission by the community

FCC-ee Accelerator

Key dates

FCC-ee Detectors

FCC schedule



Technically-limited schedule

1 2 3 4 5 6 7 8 9 10 11 .... 19 20

Feasibility Study

ESPP

FCC-ee
~ 15 years operation

10 years

FCC-hh
~ 25 years operation

70

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator and detector R&D and technical design

FCC-ee accelerator and detector construction, installation, commissioning

Superconducting magnets R&D

Long model magnets, prototypes, pre-series

High-field magnet industrialization and series production

FCC-hh accelerator and detector R&D and technical design

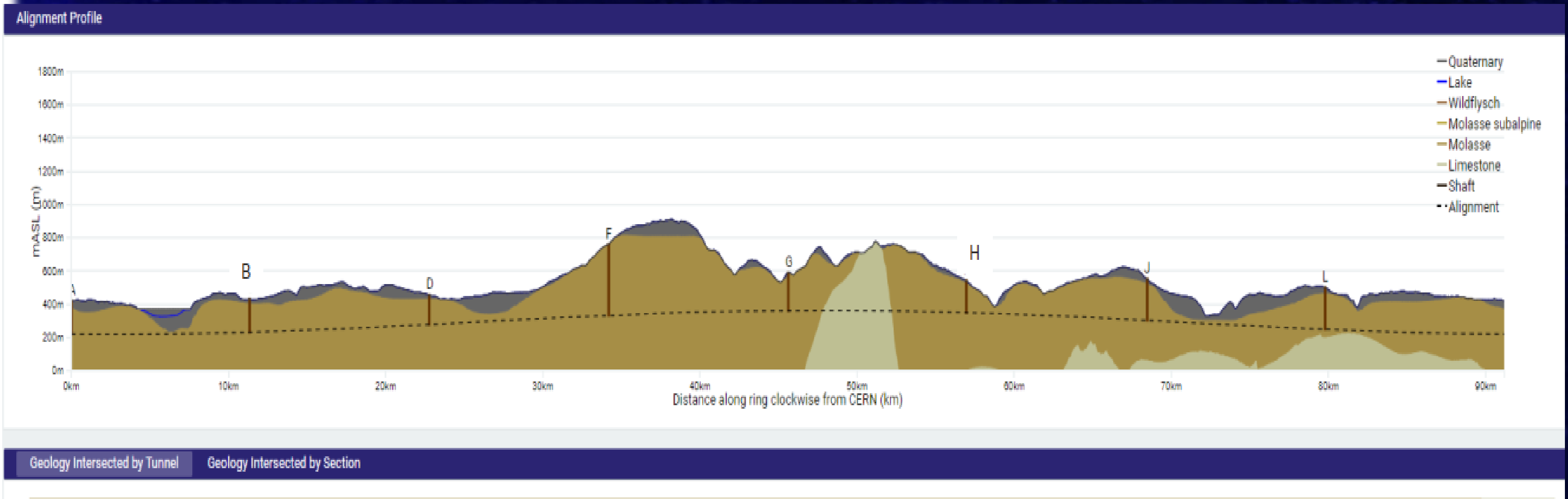
FCC-hh accelerator and detector construction, installation, commissioning

Realistic schedule

- 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
- ~2030: Construction of tunnel and FCC-ee starts
- ~2041: HL-LHC ends
- 2045 - 2048: Operation of FCC-ee (15 years physics exploitation)
- ~2070: Operation of FCC-hh (~ 20 years of physics exploitation)

F. Gianotti, June 2023

FCC-ee: Optimized Placement



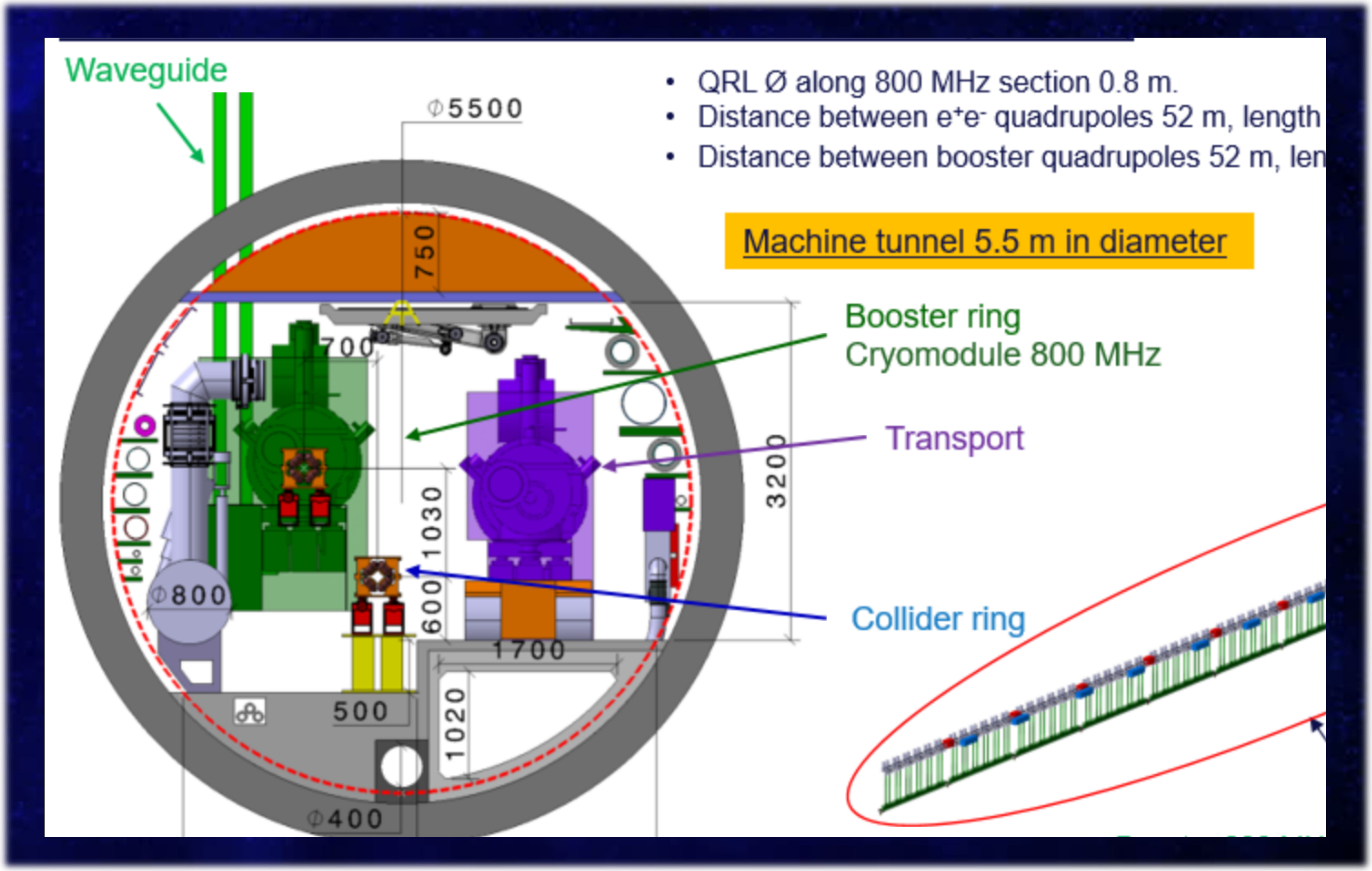
present baseline implementation

- Layout chosen out of ~ 50 initial variants
- 95% in molasse geology for minimising tunnel construction risk
- Well matched to existing electrical power distribution
- <4 km of new roads in total to connect the surface sites to existing roads and other networks

site investigations planned for 2024 and 2025 to verify geological conditions:

- limestone-molasse border, karstification, water pressure, moraine properties, etc.
- ~40-50 drillings, 100 km of seismic lines

FCC Tunnel



- QRL Ø along 800 MHz section 0.8 m.
- Distance between e^+e^- quadrupoles 52 m, length
- Distance between booster quadrupoles 52 m, len

Machine tunnel 5.5 m in diameter

Civil Engineering

Tunnel Circumference: 91 km

Excavated vol: 6.2M m3 (In the ground)

Access shafts: 12

Construction shafts: 1

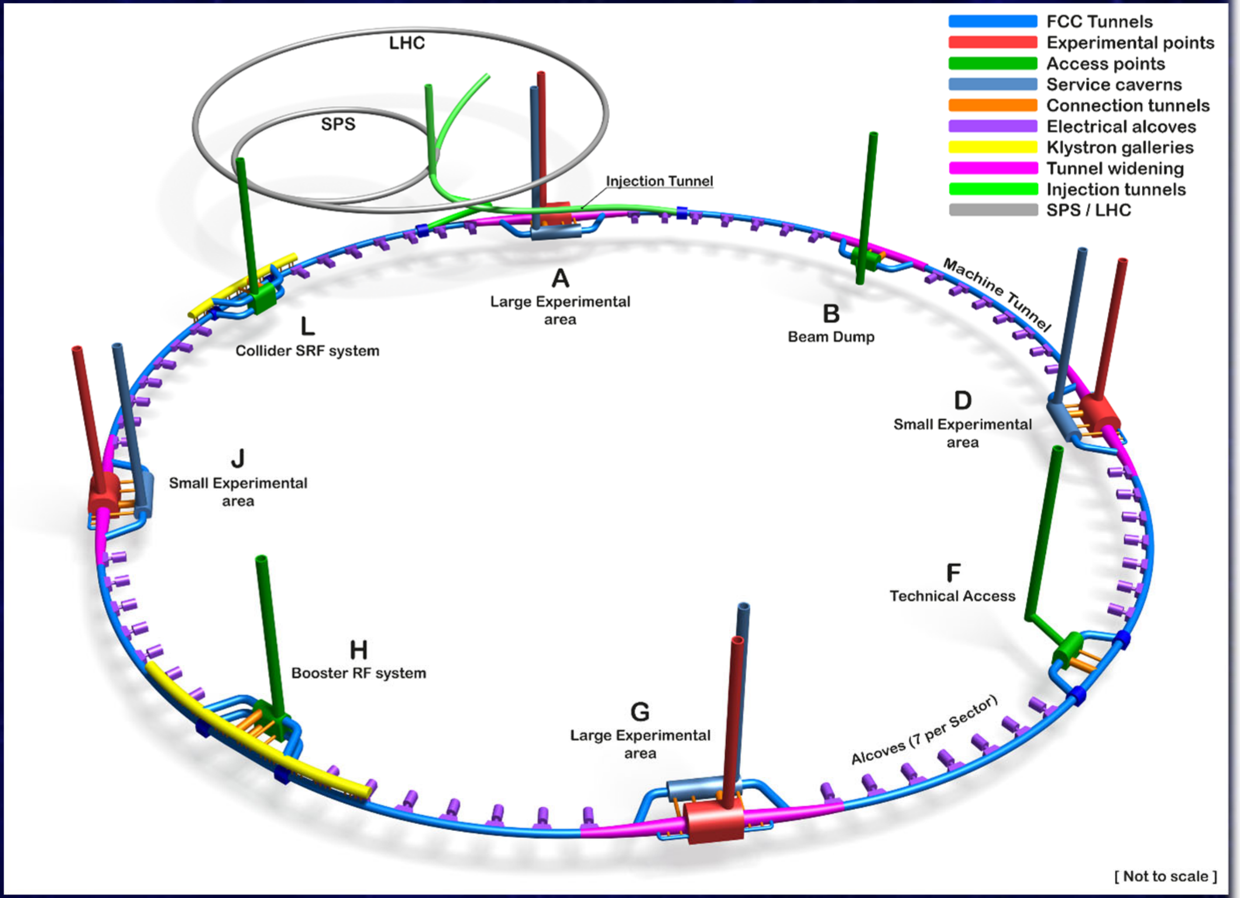
Large experiment areas: 2

Small experiment areas: 2

Technical points: 4

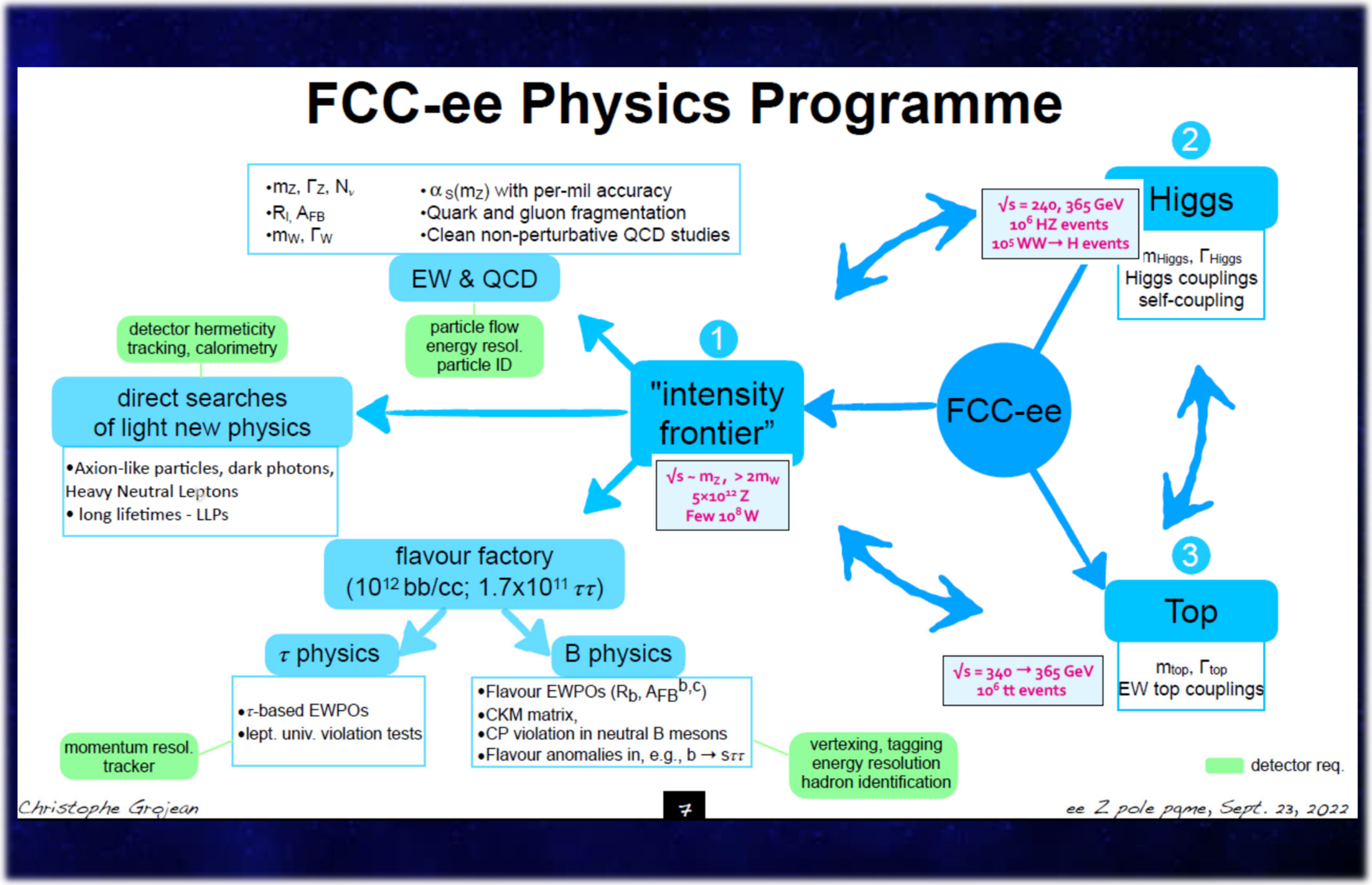
Deepest shaft: 400m

Average shaft depth: 243m



Schematic of the Underground Civil Engineering

FCC Physics Programme



FCC-ee Physics Programme

FCC-ee

"intensity frontier"

①

$\sqrt{s} \sim m_Z$, $> 2m_W$
5×10^{12} Z
Few 10^8 W

EW & QCD

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

particle flow
energy resol.
particle ID

direct searches of light new physics

- Axion-like particles, dark photons, Heavy Neutral Leptons
- long lifetimes - LLPs

detector hermeticity
tracking, calorimetry

flavour factory
(10^{12} bb/cc; 1.7x10^{11} $\tau\tau$)

τ physics

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

momentum resol.
tracker

B physics

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

vertexing, tagging
energy resolution
hadron identification

②

Higgs

$\sqrt{s}$ = 240, 365 GeV
10^6 HZ events
10^5 WW→ H events

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

③

Top

$\sqrt{s}$ = 340 → 365 GeV
10^6 tt events

m_{top}, Γ_{top}
EW top couplings

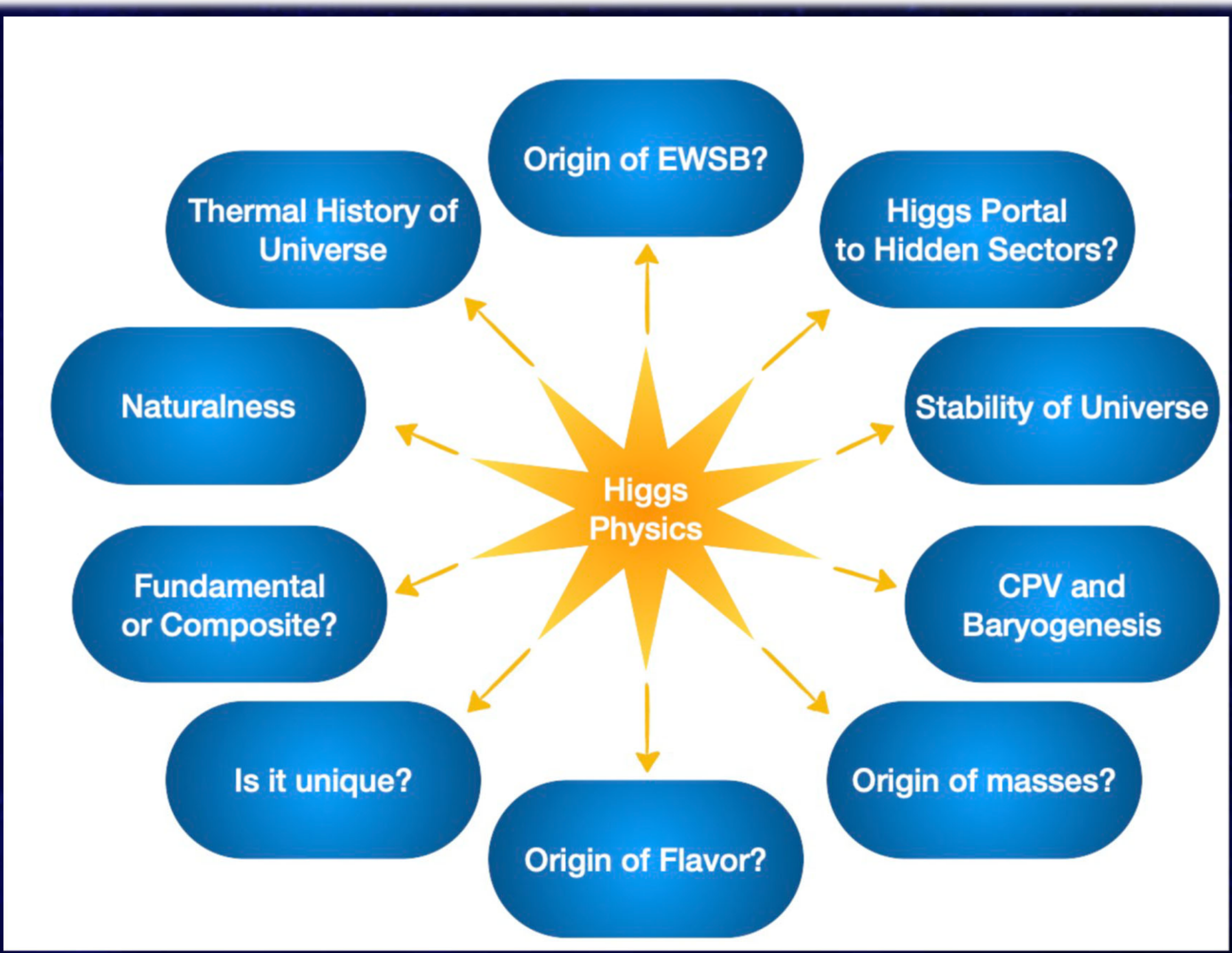
🟩 detector req.

Christophe Grojean

7

ee Z pole pgme, Sept. 23, 2022

Higgs Physics



Higgs Physics

Origin of EWSB?

Higgs Portal to Hidden Sectors?

Stability of Universe

CPV and Baryogenesis

Origin of masses?

Origin of Flavor?

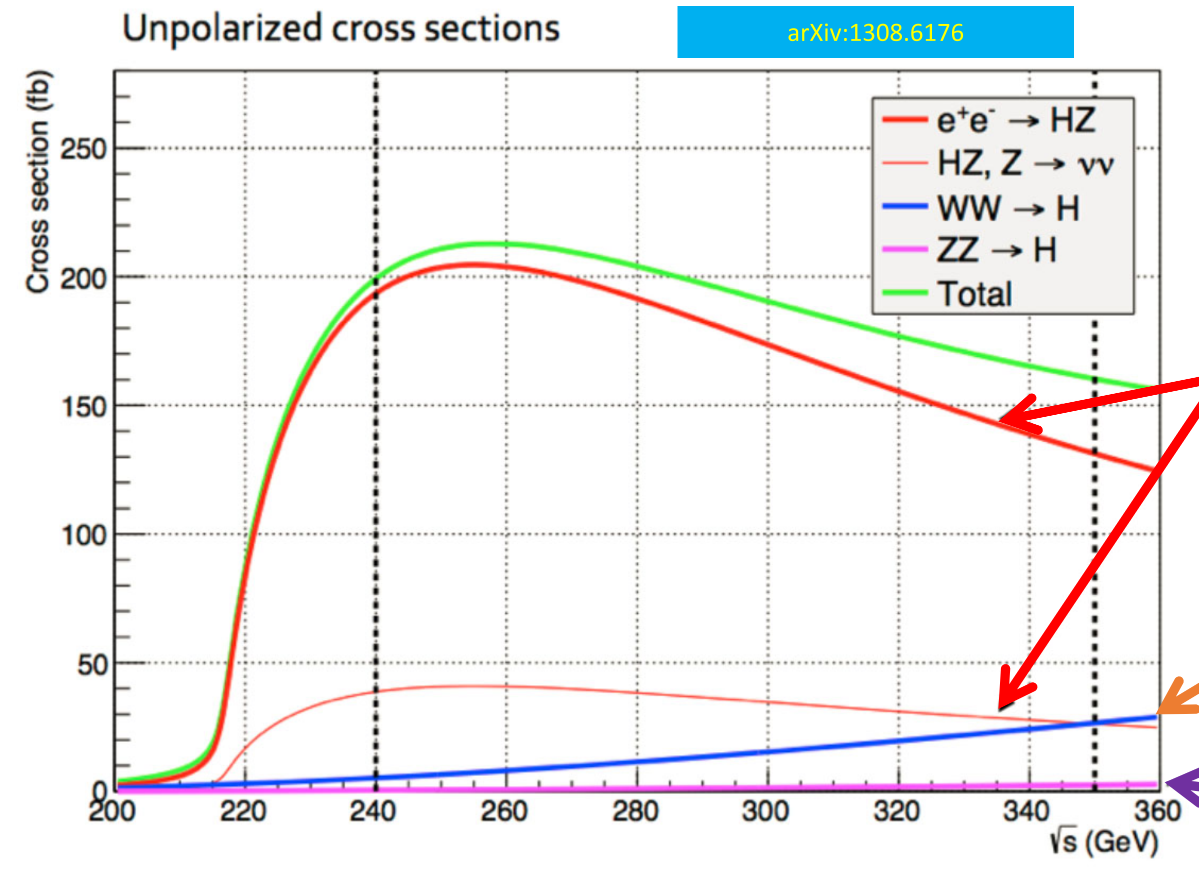
Is it unique?

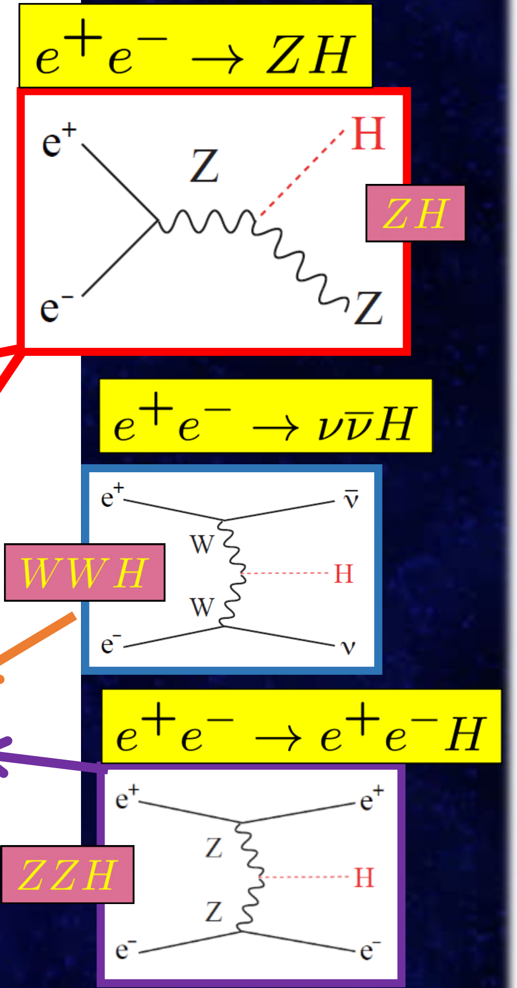
Fundamental or Composite?

Naturalness

Thermal History of Universe

Higgs Boson Production at e^+e^- Collider





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 $VBF = WWH + ZZH$	5	$2 \times 10^5\ ZH$ $5 \times 10^4\ VBF$

With 4 IPs:

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

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 detemined through the tagging of the respective Higgs decay final states:

$\sqrt{s} = 240$ GeV

(X = b, c, τ, μ, g, γ,…)

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

$\sqrt{s} = 365$ 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 normalized to the SM predictions:

$$k_f = \frac{g_{Hff}}{g^{SM}_{Hff}}, \ f = b, c, \tau, \mu \qquad k_V = \frac{g_{HVV}}{g^{SM}_{HVV}}, \ V = W, Z, \gamma, g$$

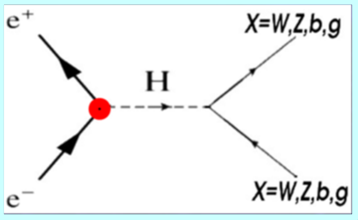
Eur. Phys. J. Plus (2022) 137:92

Coupling	HL-LHC	+ FCC 240 GeV	+FCC 265 GeV	+FCC-hh
k_Z	1.5	0.18	0.17	0.16
k_W	1.7	0.44	0.41	0.19
k_b	5.1	0.69	0.64	0.48
k_c	SM	1.3	1.3	0.96
k_g	2.5	1.0	0.89	0.50
k_τ	1.9	0.74	0.66	0.46
k_μ	4.4	8.9	3.9	0.43
k_γ	1.8	3.9	1.2	0.32
$k_{Z\gamma}$	11	–	10	0.70
k_t	3.4	10	3.1	0.95
k_H	50	44	33	3-4

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

Direct Higgs Production in s-channel

- FCC-ee: potential for direct measurement of the H-e-e Yukawa coupling $BR(H \to e^+e^-) \approx 5 \times 10^{-9}$
- But $\sigma(e^+e^- \to H) = 1.64\ \text{fb}$ - 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 $\sqrt{s} = M_H = 125\ \text{GeV}$



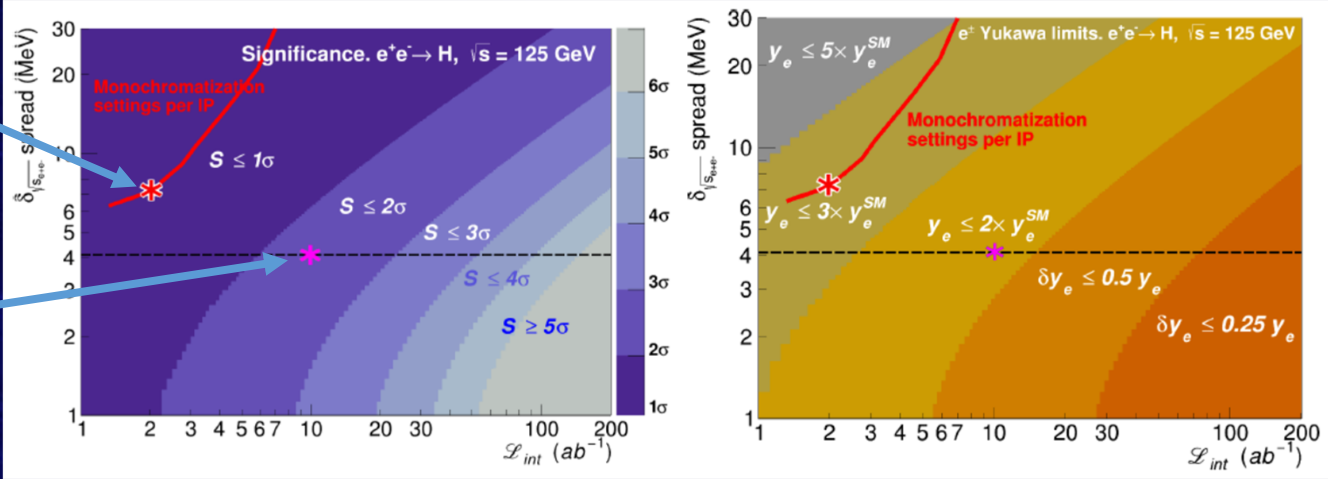
- Since Γ_H = 4.1 MeV, it requires beam energy spread monochromatization from the natural spread of ~46 MeV down to ~4.1 MeV (and a prior knowledge of the Higgs mass to a few MeV)
- Other problems: ISR+FSR, big backgrounds

Currently reached monochromatization

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

Best signal strength monochromatization

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

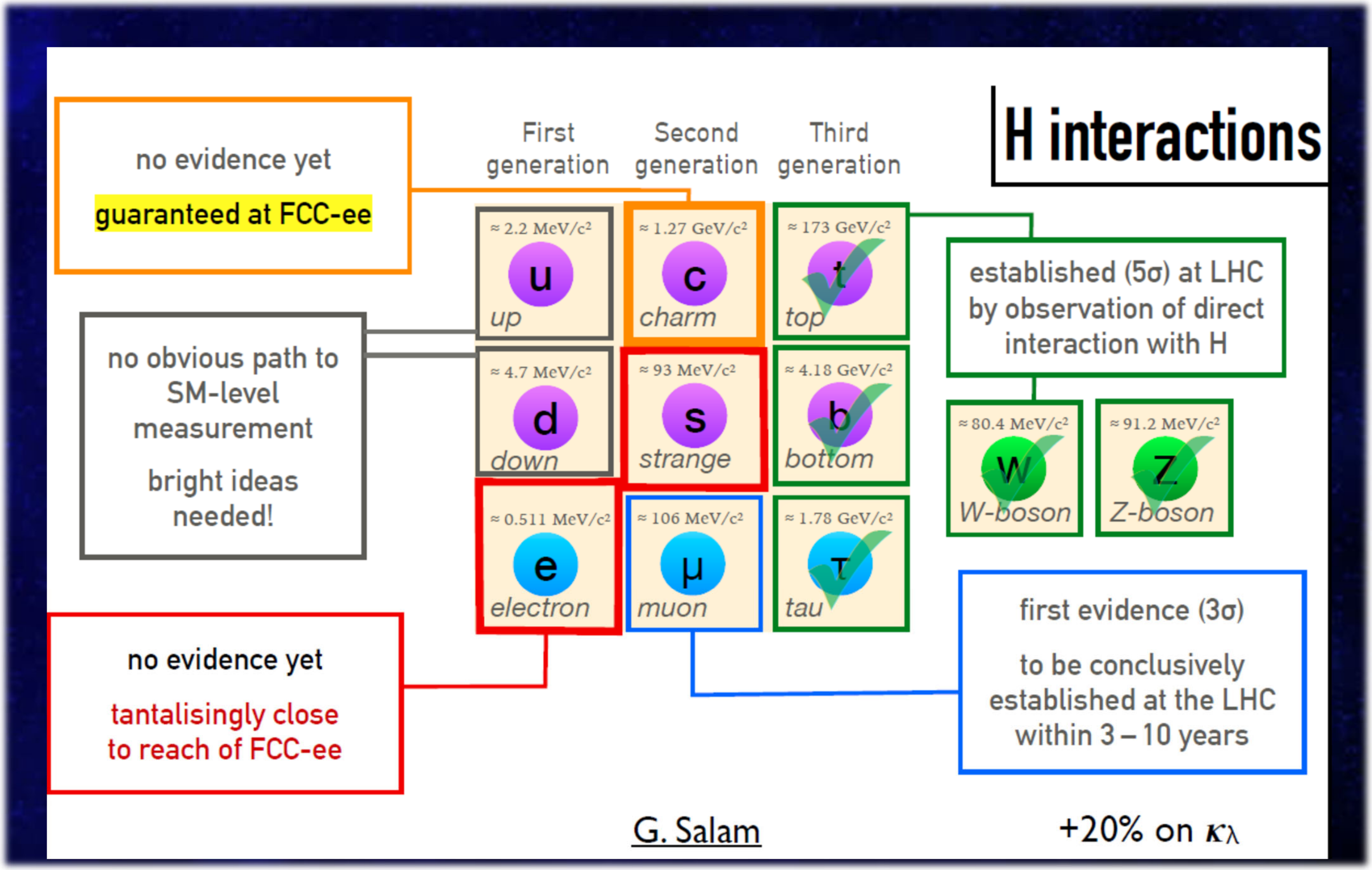


- The signal significance at C $S \approx 0.4\sigma/\text{year}/IP$
- Assuming B and two years of running with 4 IPs (~12k eeH events) $|\mathrm{y_e}| < 1.6|\mathrm{y_e^{SM}}|\ (1.3\sigma)$

Not yet in the baseline

arXiv:2107.0268

Higgs Couplings at FCC-ee



H interactions

no evidence yet

guaranteed at FCC-ee

	First generation	Second generation	Third generation
	≈ 2.2 MeV/c^2 u up	≈ 1.27 GeV/c^2 c charm	≈ 173 GeV/c^2 t ✓ top
	≈ 4.7 MeV/c^2 d down	≈ 93 MeV/c^2 s strange	≈ 4.18 GeV/c^2 b ✓ bottom
	≈ 0.511 MeV/c^2 e electron	≈ 106 MeV/c^2 μ muon	≈ 1.78 GeV/c^2 τ ✓ tau

≈ 80.4 MeV/c^2 W ✓ W-boson

≈ 91.2 MeV/c^2 Z ✓ Z-boson

established (5σ) at LHC by observation of direct interaction with H

no obvious path to SM-level measurement

bright ideas needed!

no evidence yet

tantalisingly close to reach of FCC-ee

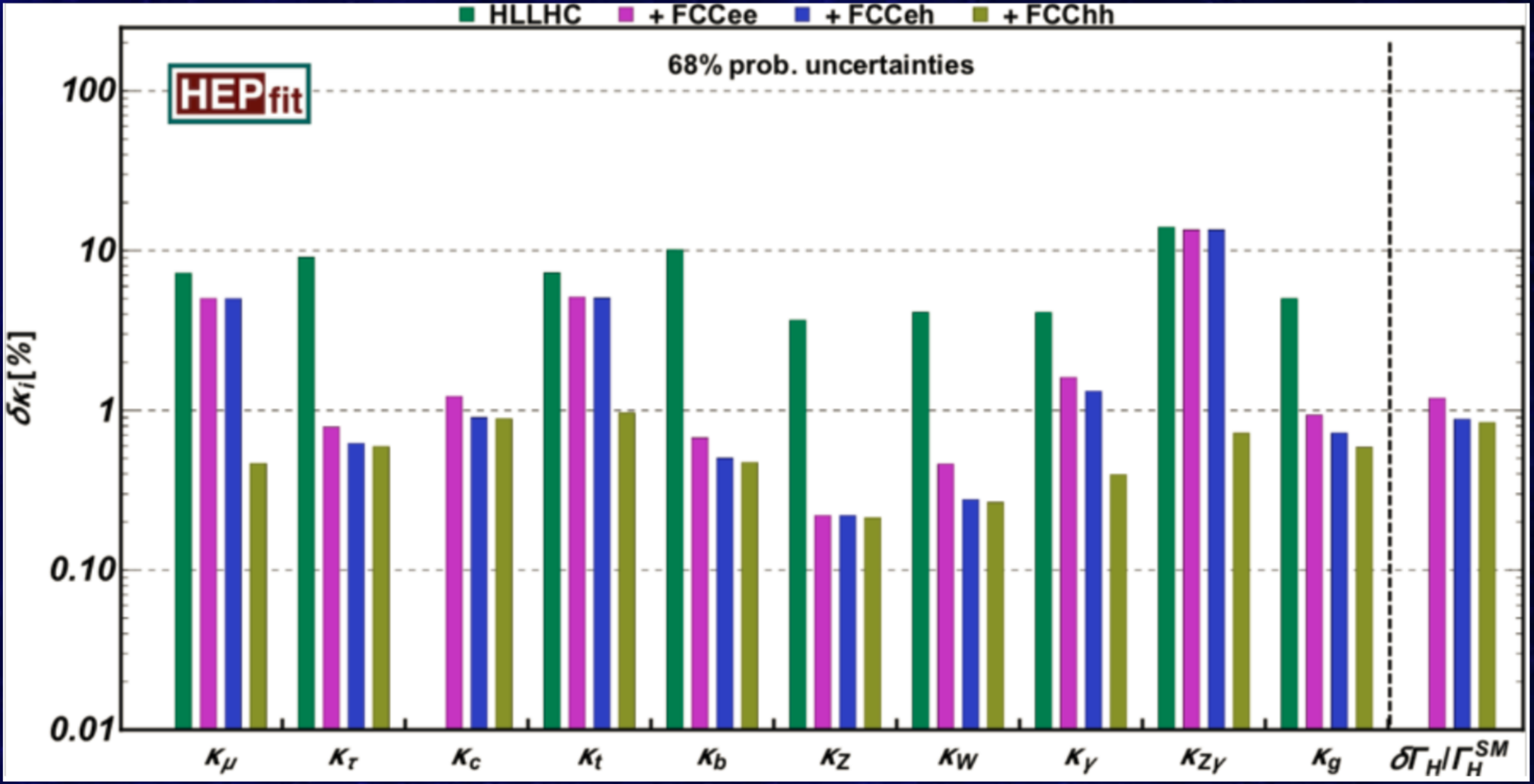
first evidence (3σ)

to be conclusively established at the LHC within 3 – 10 years

G. Salam

+20% on κ_λ

Higgs Couplings: Post FCC-ee



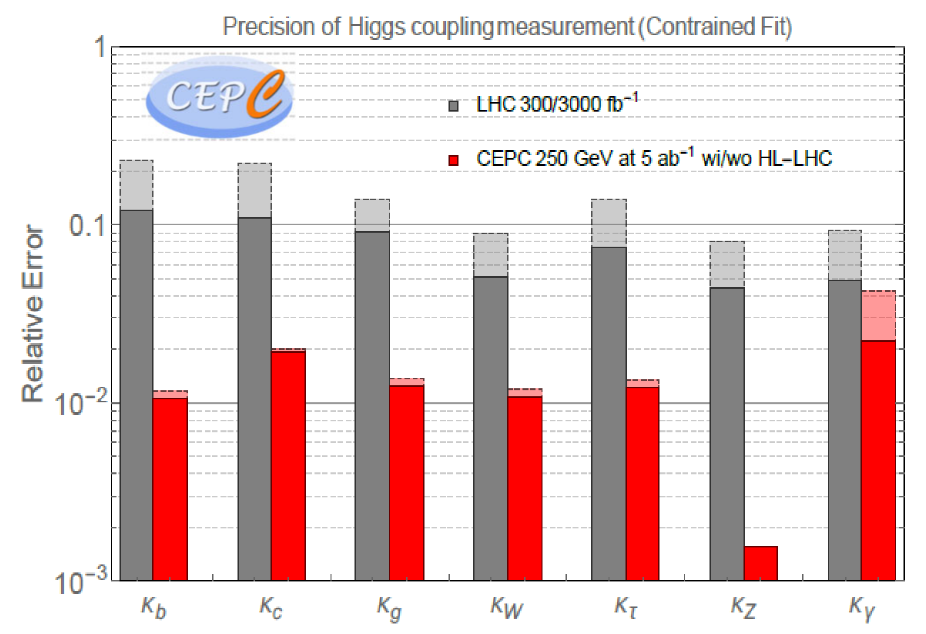
Other Higgs topics: Higgs self-coupling

Normalized Higgs Couplings

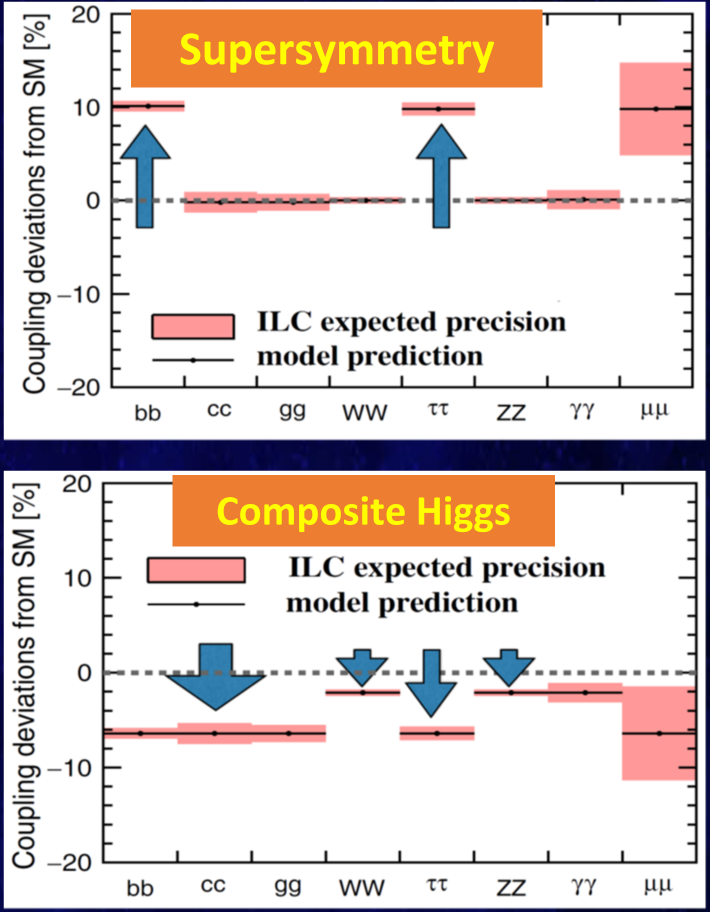
- **Higgs couplings normalized to the Standard Model predictions:**

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

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

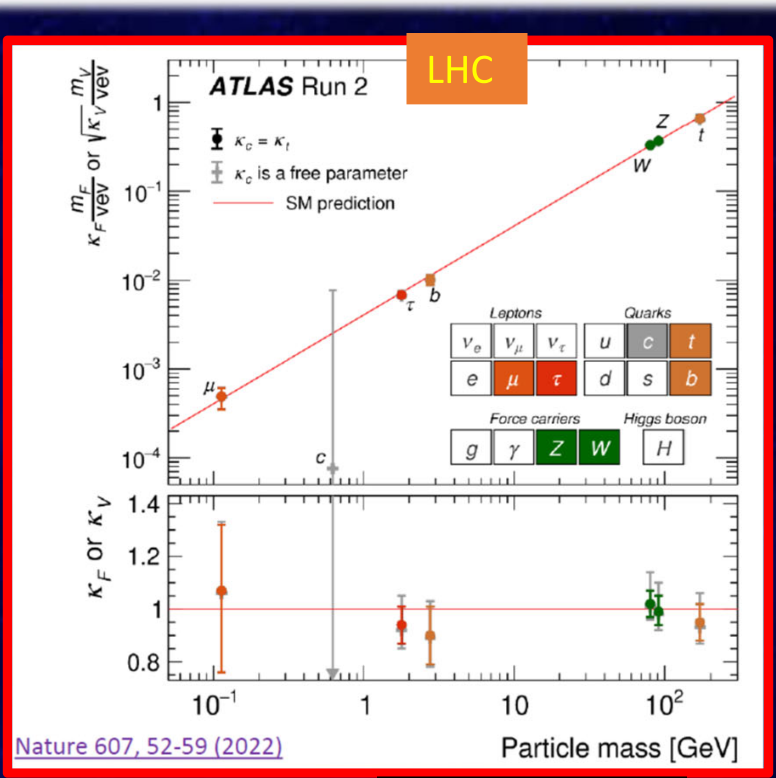


- **Fingerprinting NP:** different BSM models predict different pattern of deviations from the SM:

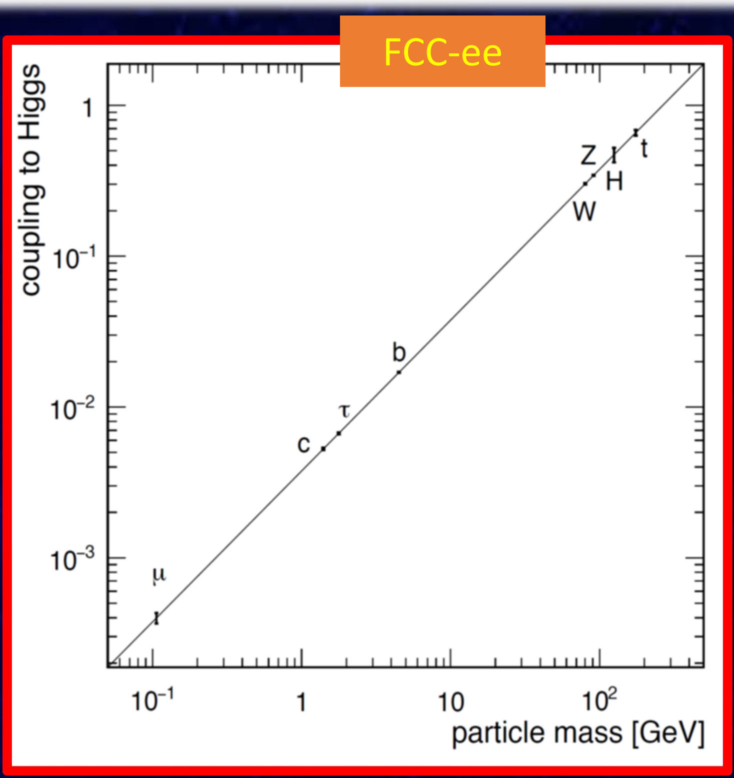


Phys Rev. D 97, 053003 (2018)

Higgs Couplings: Post FCC-ee



Nature 607, 52-59 (2022)

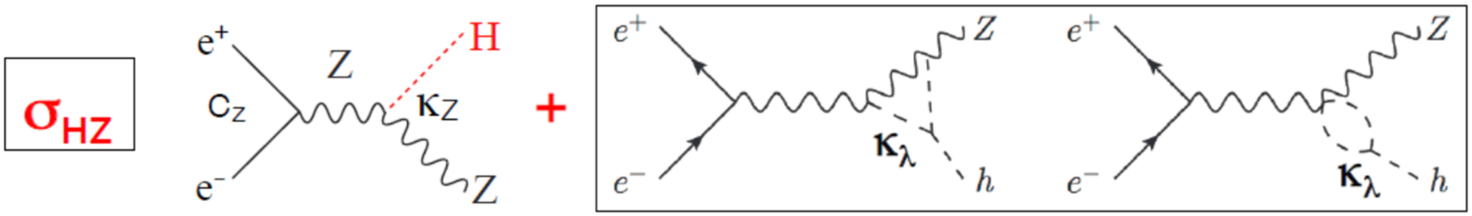


$\Delta k_f \sim 15\%$ → $\Delta k_f \sim 1\%$

3rd and 2nd fermion generations only (qualitative precision level) → 3rd AND 2nd generations precise measurements

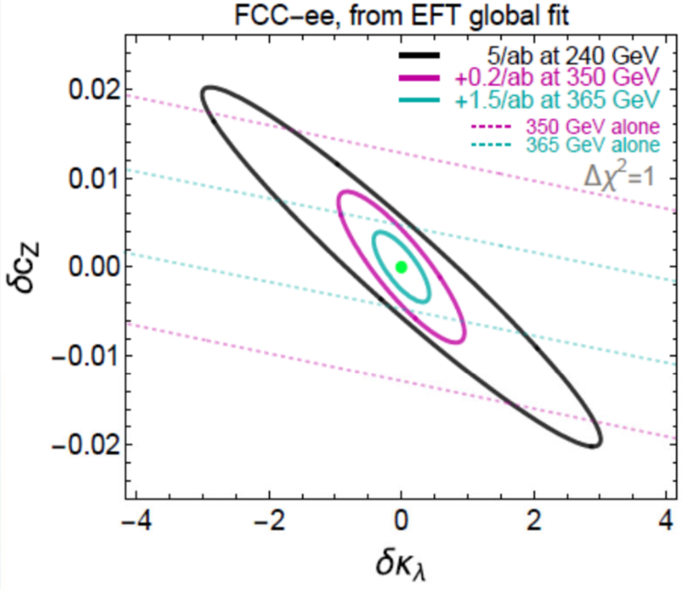
Other Higgs topics: Higgs self-coupling

Higgs Boson Self-coupling

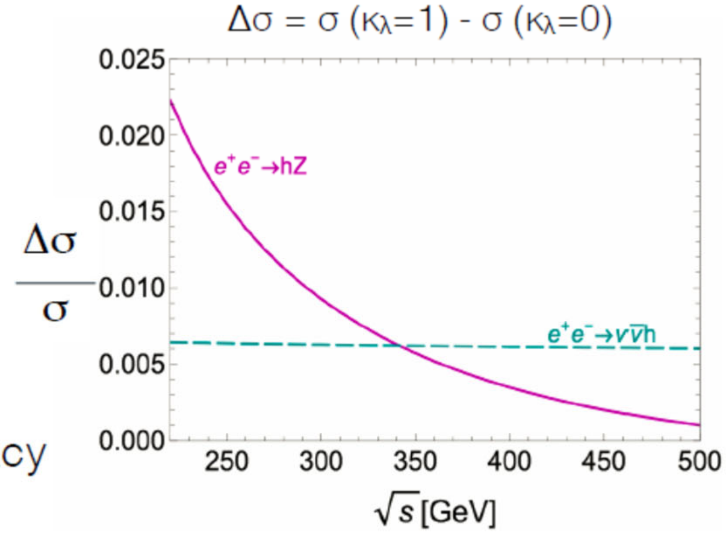


$\kappa = g/g_{\mathrm{SM}}$

M. McCullough
arXiv:1312.3322



- setting all other SM paramters to the SM, $\Delta\kappa_\lambda/\kappa_\lambda$ ~ 9%
- using a global EFT fit $\Delta\kappa_\lambda/\kappa_\lambda$ ~ 25% with 4 IP.

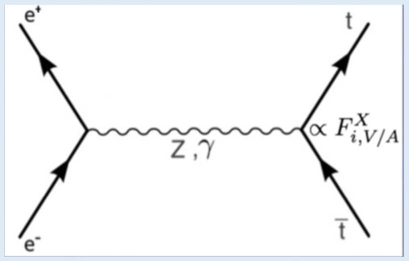


varying √s removes partially cZ, κ_λ degeneracy

FUTURE CIRCULAR COLLIDER

EW Couplings of the Top Quark

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



Clean EW proces; 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 $\quad k^2 = (q+\bar{q})^2$

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:

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

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

$+ = e^-_R$

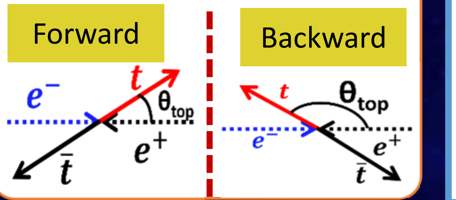
$- = e^-_L$

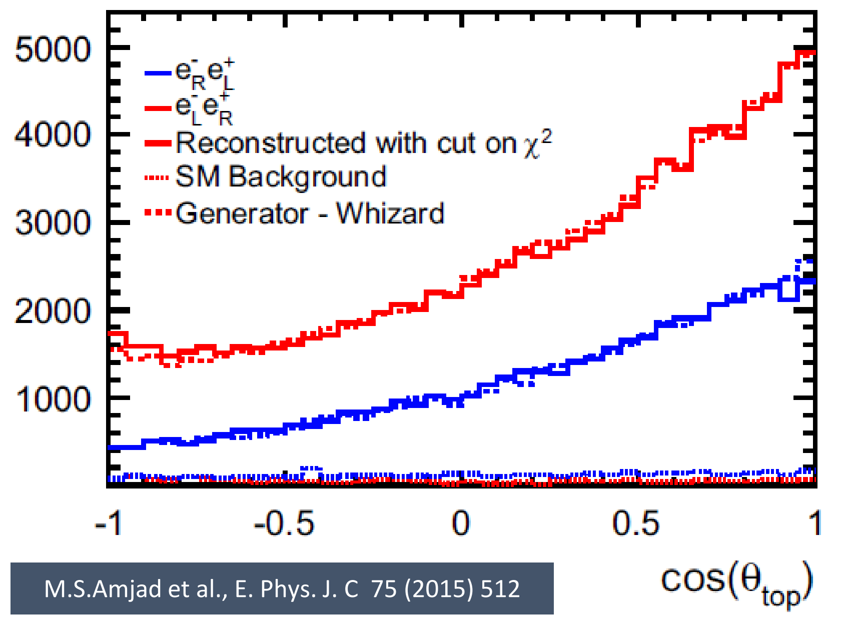
Extract:

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

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

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





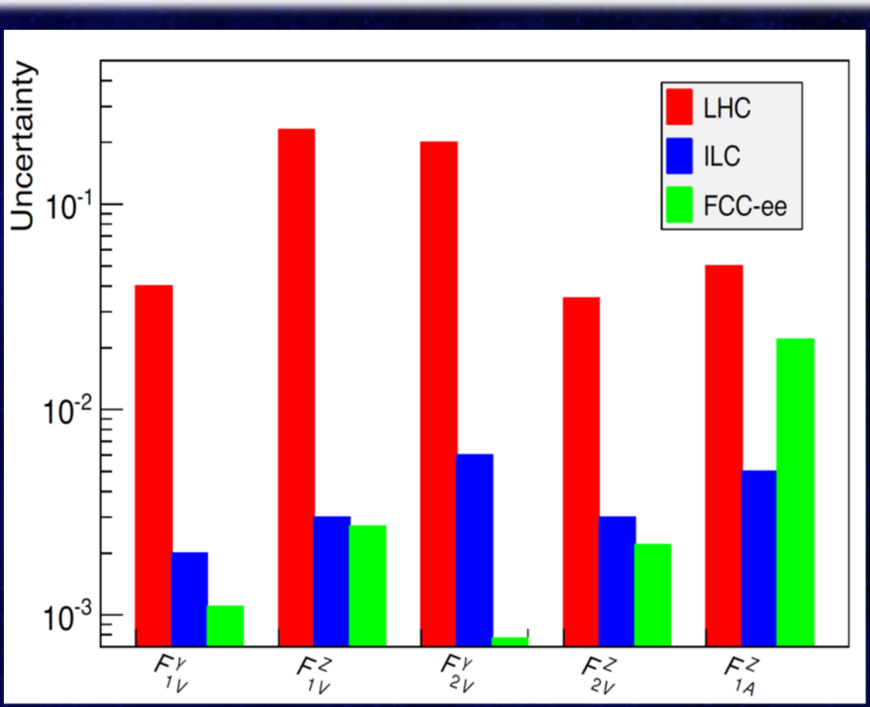
M.S.Amjad et al., E. Phys. J. C 75 (2015) 512

EW Couplings of the Top Quark

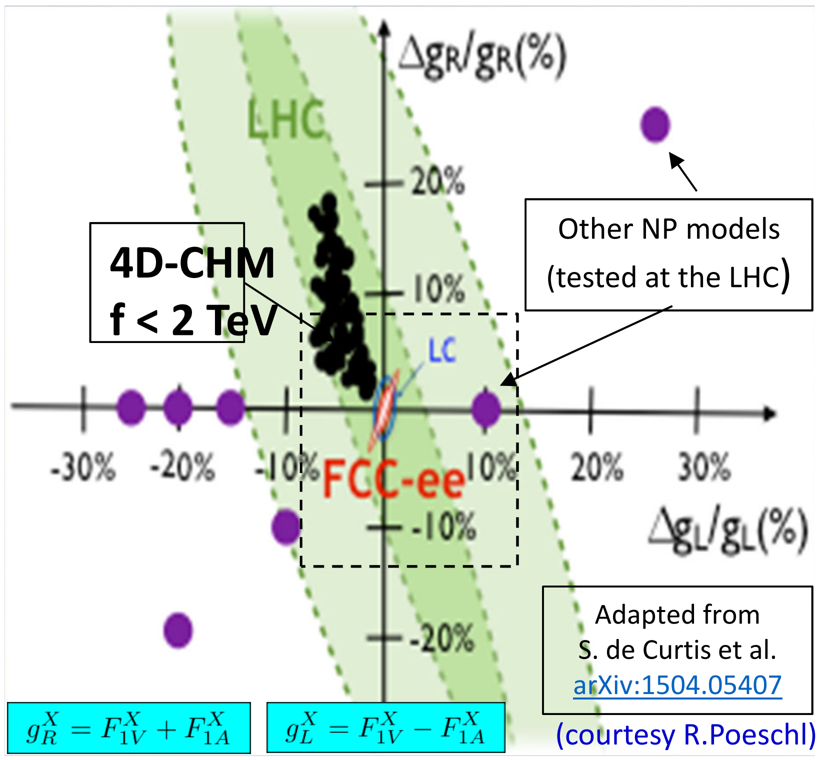
Circular Collider: **lack of initial-state polarization ➔ profit from the final-state polarisation, which is maximally transferred to the top decay products (t➔ Wb)**

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



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



$g^X_R = F^X_{1V} + F^X_{1A}$

$g^X_L = F^X_{1V} - F^X_{1A}$

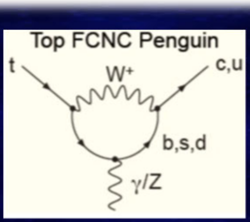
Adapted from
S. de Curtis et al.
arXiv:1504.05407

(courtesy R.Poeschl)

FCNC Top Decays; $Ht\bar{t}$ Yukawa Coupling (y_t)

➢ FCNC top decays

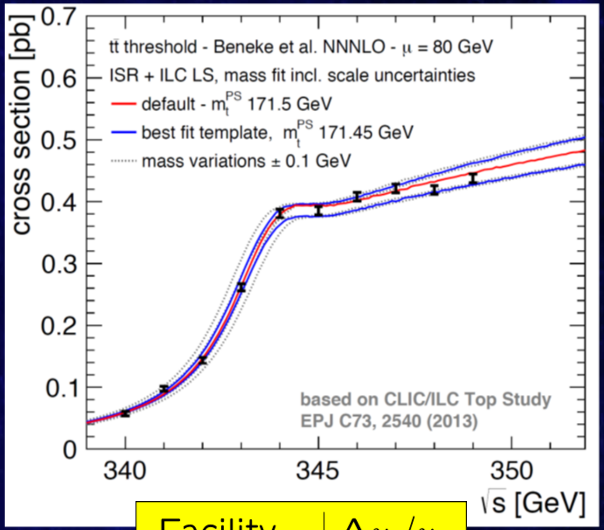
- Strongly suppressed in the SM (GIM & CKM)
- Significantly enhanced in many NP scenarios


Top FCNC Penguin

Process	BR (SM)
$t \to cZ$	1×10^{-14}
$t \to c\gamma$	5×10^{-14}
$t \to cH$	3×10^{-14}

Facility	$\mathrm{BR}(t \to cH)$
LHC Run2	$< 4.6 \times 10^{-3}$
HL – LHC	$< 2.0 \times 10^{-4}$
CLIC, FCC – ee	$< 1.0 \times 10^{-5}$

➢ Top Yukawa coupling via threshold scan

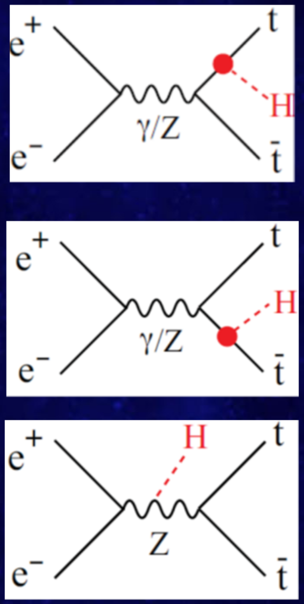


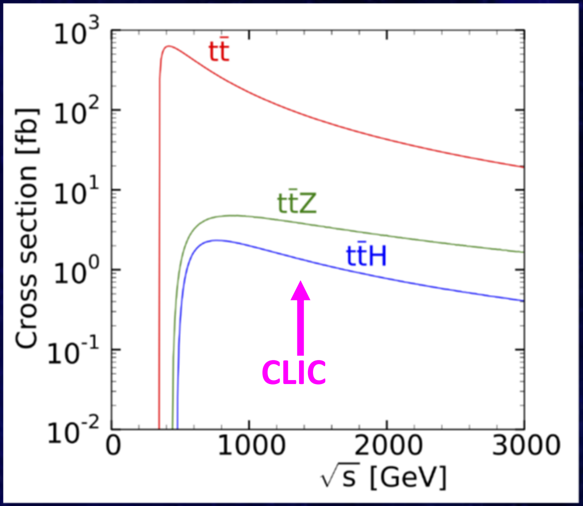
Facility	$\Delta y_t/y_t$
ILC	0.067
CLIC	0.067
FCC – ee	0.057

(fixed m_t Γ_t and α_s; statistical uncertainties only)

➢ Direct measurement of y_t (for E > 500 GeV)

- Measurement of the $e^+e^- \to t\bar{t}H$ cross-section
  ➔ extraction of y_t





- troublesome: scarse statistics, large backgrounds…

CLIC at $\sqrt{s} = 1.4$ TeV : $\Delta y_t/y_t \sim 0.038$

FUTURE CIRCULAR COLLIDER

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

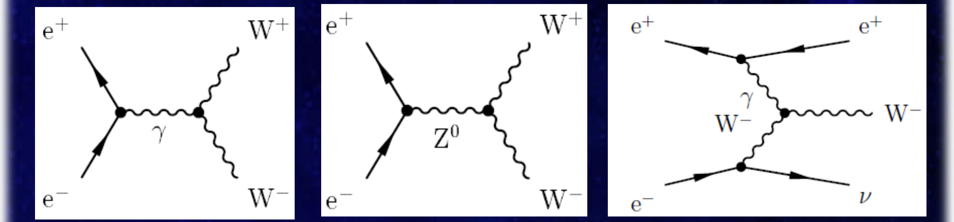
$\mathrm{BR}(W \to e\nu)$	10.65 ± 0.17
$\mathrm{BR}(W \to \mu\nu)$	10.59 ± 0.15
$\mathrm{BR}(W \to \tau\nu)$	11.44 ± 0.22
$\mathrm{BR}(W \to l\nu)$	10.84 ± 0.09
$\mathrm{BR}(W \to \mathrm{hadrons})$	67.48 ± 0.28

- Lepton universality tested at 2% level (2.7σ discrepancy between τand 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

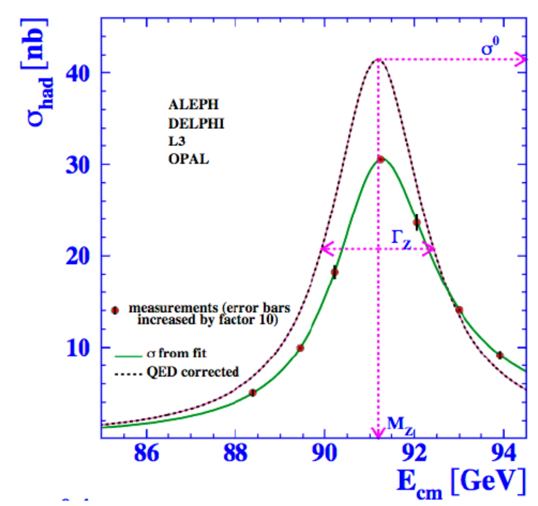
➢ The strong coupling constant:

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

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

FUTURE CIRCULAR COLLIDER

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

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

Eur. Phys. J. C (2019) 79

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%

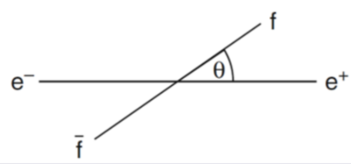
FUTURE CIRCULAR COLLIDER

Electroweak Physics at the Z pole

- **Z asymmetries:**

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

$\mathcal{P}_e$ - 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

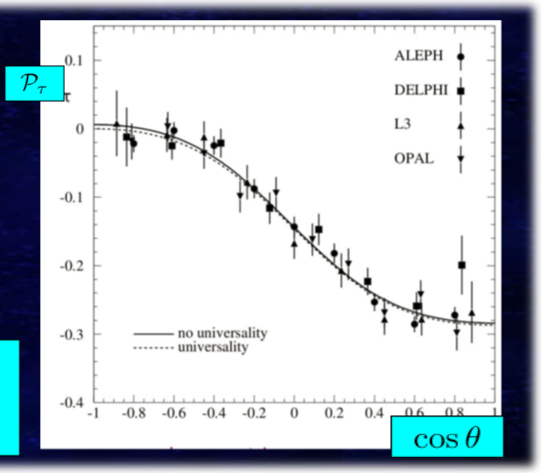
tau lepton case:
the final state helicity can be measured

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

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

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

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



$\mathcal{A}_f$ measured (f = e, μ, τ, b, c)

$g_V^f\ g_A^f$ extracted

$$\sin^2\theta^f_{\text{W,eff}} = \frac{1}{4}\left(1-\frac{g^f_V}{g^f_A}\right)$$

Eur. Phys. J. C (2019) 79

	$\Delta^{\text{stat}}_{\text{rel}}$ (FCC – ee)	$\Delta^{\text{syst}}_{\text{rel}}$ (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

$\sin^2\theta_{W,\mathrm{eff}}$ (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: $\alpha_{\mathrm{QED}}(m_Z^2) = \frac{\alpha_{\mathrm{QED}}(0)}{1 - \Delta\alpha_l(m_Z^2) - \Delta\alpha^{(5)}_{\mathrm{had}}(m_Z^2)}$

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** $A^{\mu\mu}_{FB} = \frac{\sigma^F_{\mu\mu} - \sigma^B_{\mu\mu}}{\sigma^F_{\mu\mu} + \sigma^B_{\mu\mu}}$

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

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

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

2x 6 months of FCC-ee running:

Optimal CMS energies:

$$\sqrt{s_-} = 87.9\ \mathrm{GeV}$$

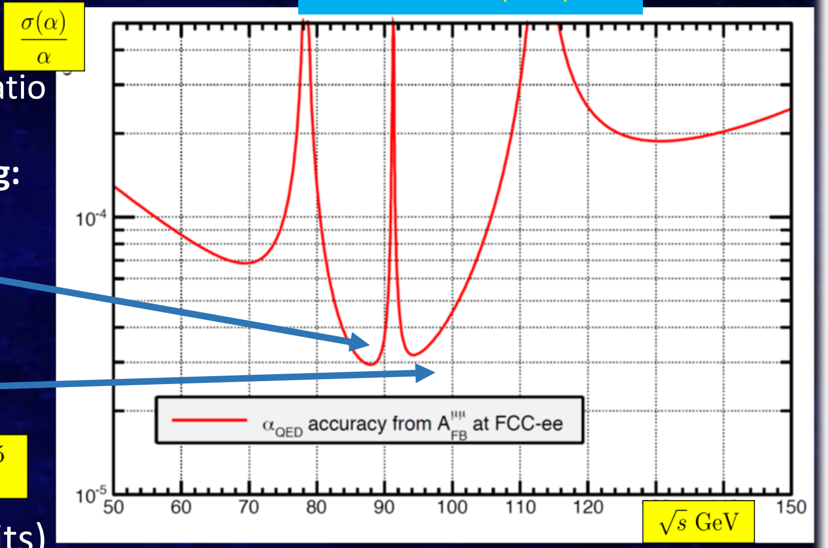
$$\sqrt{s_+} = 94.3\ \mathrm{GeV}$$

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

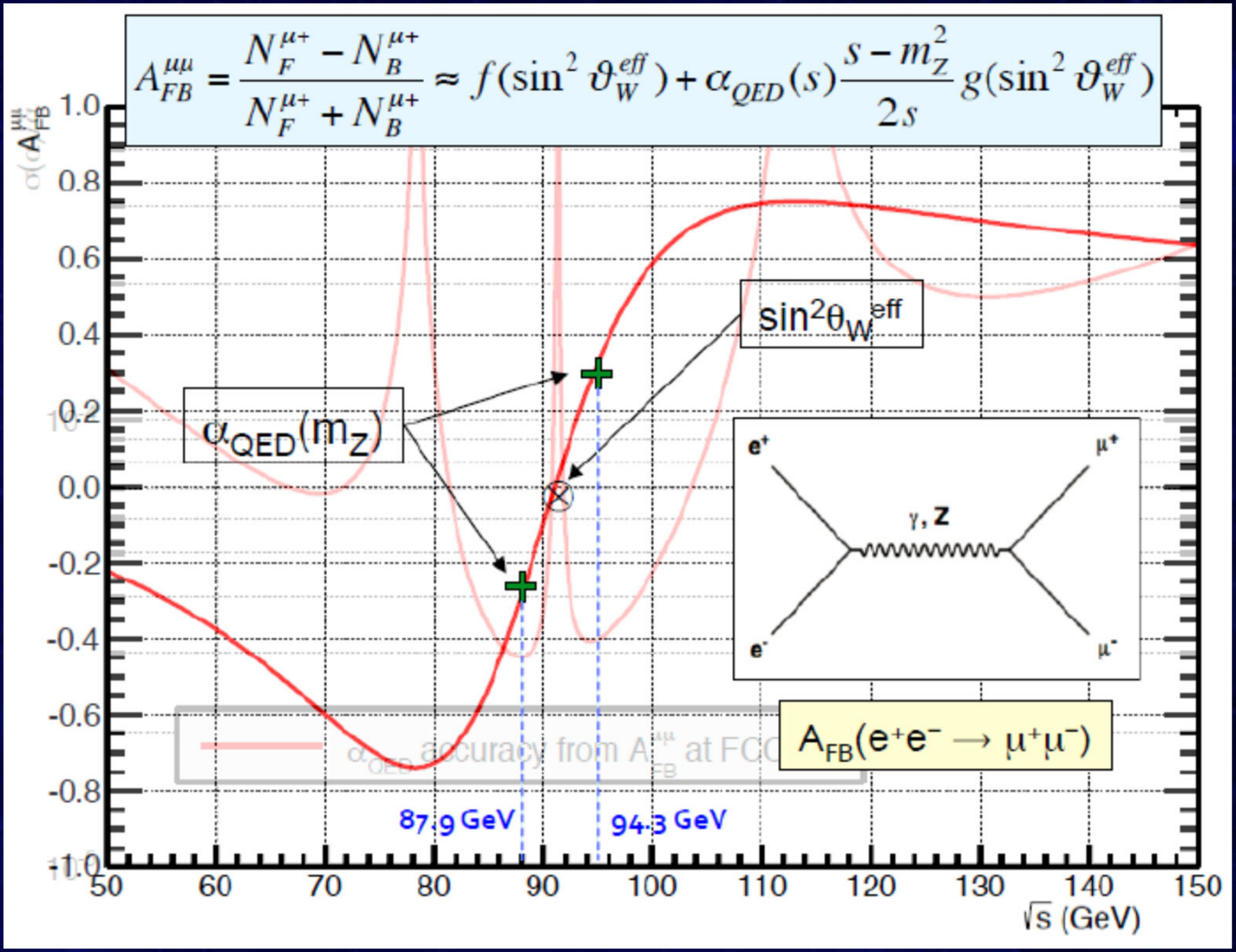
$$\Delta\alpha_{\mathrm{QED}}(m_Z^2) = 3 \times 10^{-5}$$

(adequate for future precision EW fits)

P.Janot JHEP 02 (2016) 053



Electroweak Physics at the Z pole



$$A_{FB}^{\mu\mu} = \frac{N_F^{\mu+} - N_B^{\mu+}}{N_F^{\mu+} + N_B^{\mu+}} \approx f(\sin^2\vartheta_W^{eff}) + \alpha_{QED}(s)\frac{s-m_Z^2}{2s}\,g(\sin^2\vartheta_W^{eff})$$

The Z Invisible Width – Number of Light Neutrino Species

1) N_ν 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, $\Delta N_\nu^{\mathrm{lumi}}$ = 0.0046 ➔ $\Delta N_\nu^{\mathrm{lumi}}$ = 0.0001 @FCC-ee).

$$\Delta N_\nu^{\mathrm{FCC-ee}} = 0.00008(\mathrm{stat}) \pm 0.0001(\mathrm{syst})$$

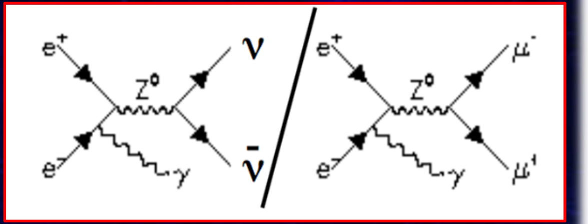
Eur. Phys. J. C (2019) 79

2) N_ν 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 scarse).

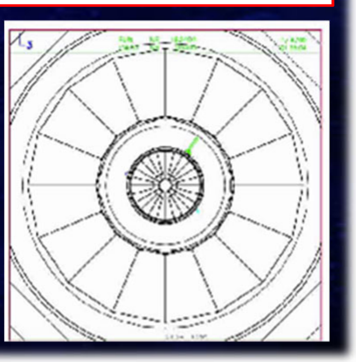
- Photon selection common for both final states ➔ cancellations of systematics.
- N_ν can be measured vs sqrt(s) ➔ sensitivity to NP at high energy scales.
- FCC-ee sensitivity:

$\sqrt{s}$ [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)

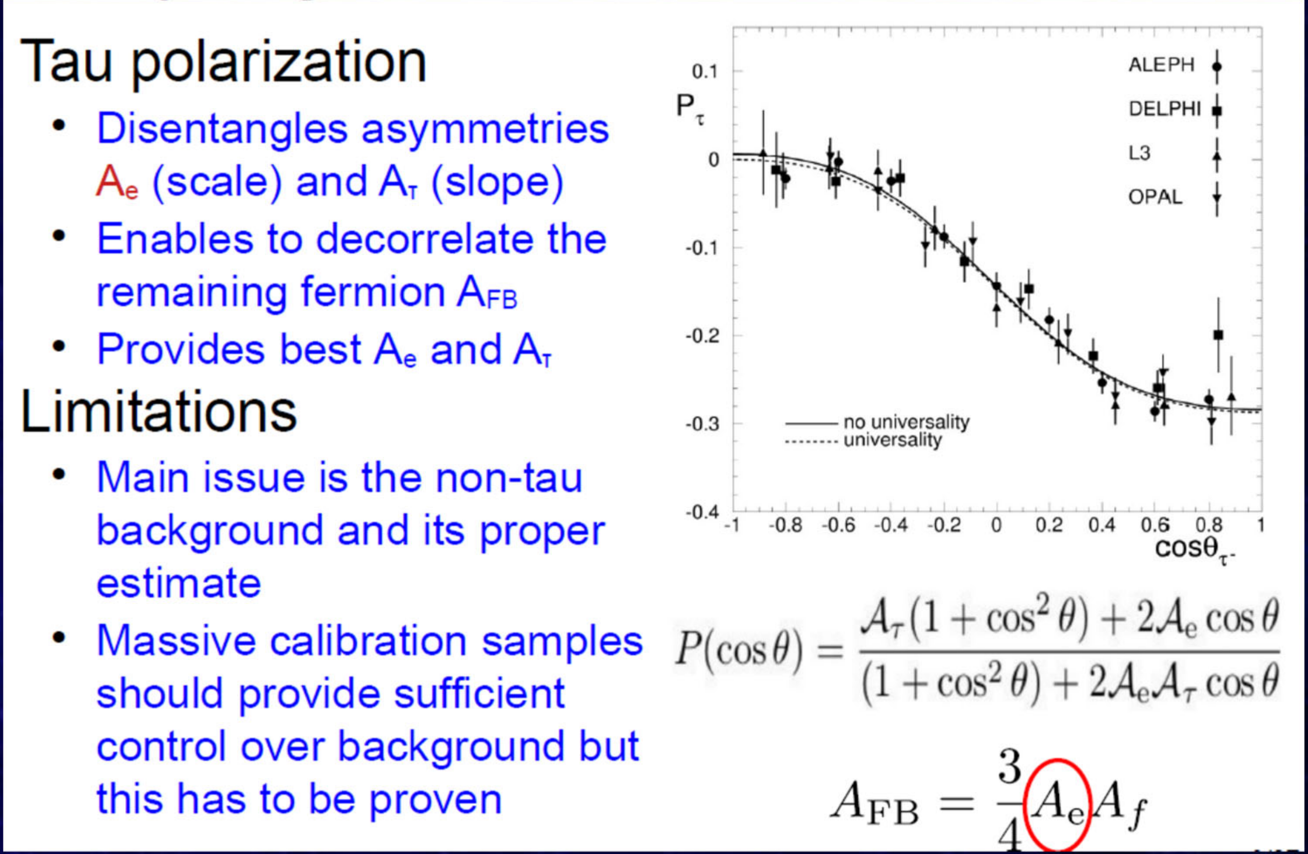
$$\Delta N_\nu \lesssim 4 \times 10^{-4}$$



Electroweak Physics at the Z pole

$$\mathcal{A}_\tau = < \mathcal{P}_\tau >$$

→ A_tau can be measured from the distribution of the hadron helicity angle of tau→ h nu in the tau rest frame



Tau polarization

- Disentangles asymmetries A_e (scale) and A_τ (slope)
- Enables to decorrelate the remaining fermion A_{FB}
- Provides best A_e and A_τ

Limitations

- Main issue is the non-tau background and its proper estimate
- Massive calibration samples should provide sufficient control over background but this has to be proven

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

$$A_{\mathrm{FB}} = \frac{3}{4} A_{\mathrm{e}} A_f$$

$$\frac{1}{\mathrm{N}}\frac{\mathrm{dN}}{\mathrm{d}\cos\theta_{\mathrm{h}}} = 1/2(1+\alpha \mathrm{P}_\tau \cos\theta_{\mathrm{h}})$$

$$\alpha = 1$$

Theta – angle tau- e- in the CMS

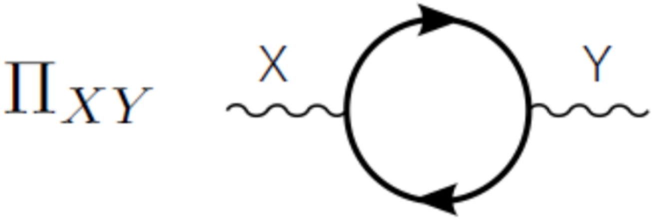
A_tau known → from here A_e only

FUTURE
CIRCULAR
COLLIDER

Electroweak Physics at the Z pole

$$\hat{\alpha}(M_Z)T \equiv \frac{\Pi^{\rm new}_{WW}(0)}{M_W^2} - \frac{\Pi^{\rm new}_{ZZ}(0)}{M_Z^2} ,$$

$$\frac{\hat{\alpha}(M_Z)}{4\,\hat{s}^2_Z\hat{c}^2_Z}S \equiv \frac{\Pi^{\rm new}_{ZZ}(M_Z^2) - \Pi^{\rm new}_{ZZ}(0)}{M_Z^2} - \frac{\hat{c}^2_Z - \hat{s}^2_Z}{\hat{c}_Z\hat{s}_Z}\frac{\Pi^{\rm new}_{Z\gamma}(M_Z^2)}{M_Z^2} - \frac{\Pi^{\rm new}_{\gamma\gamma}(M_Z^2)}{M_Z^2}$$



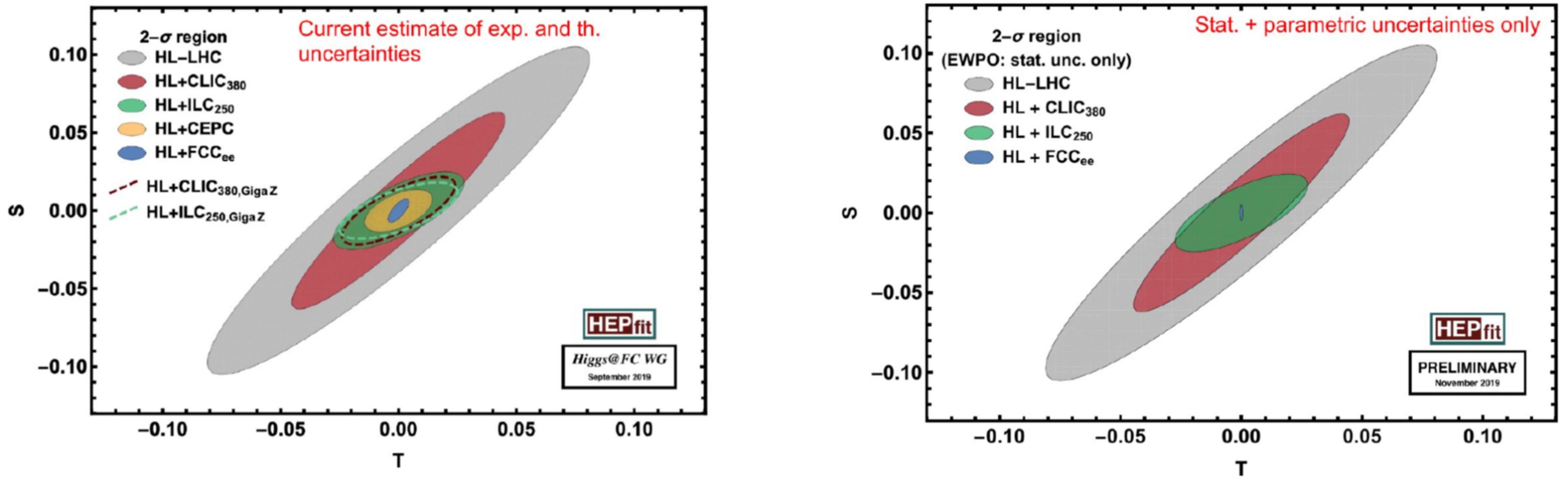
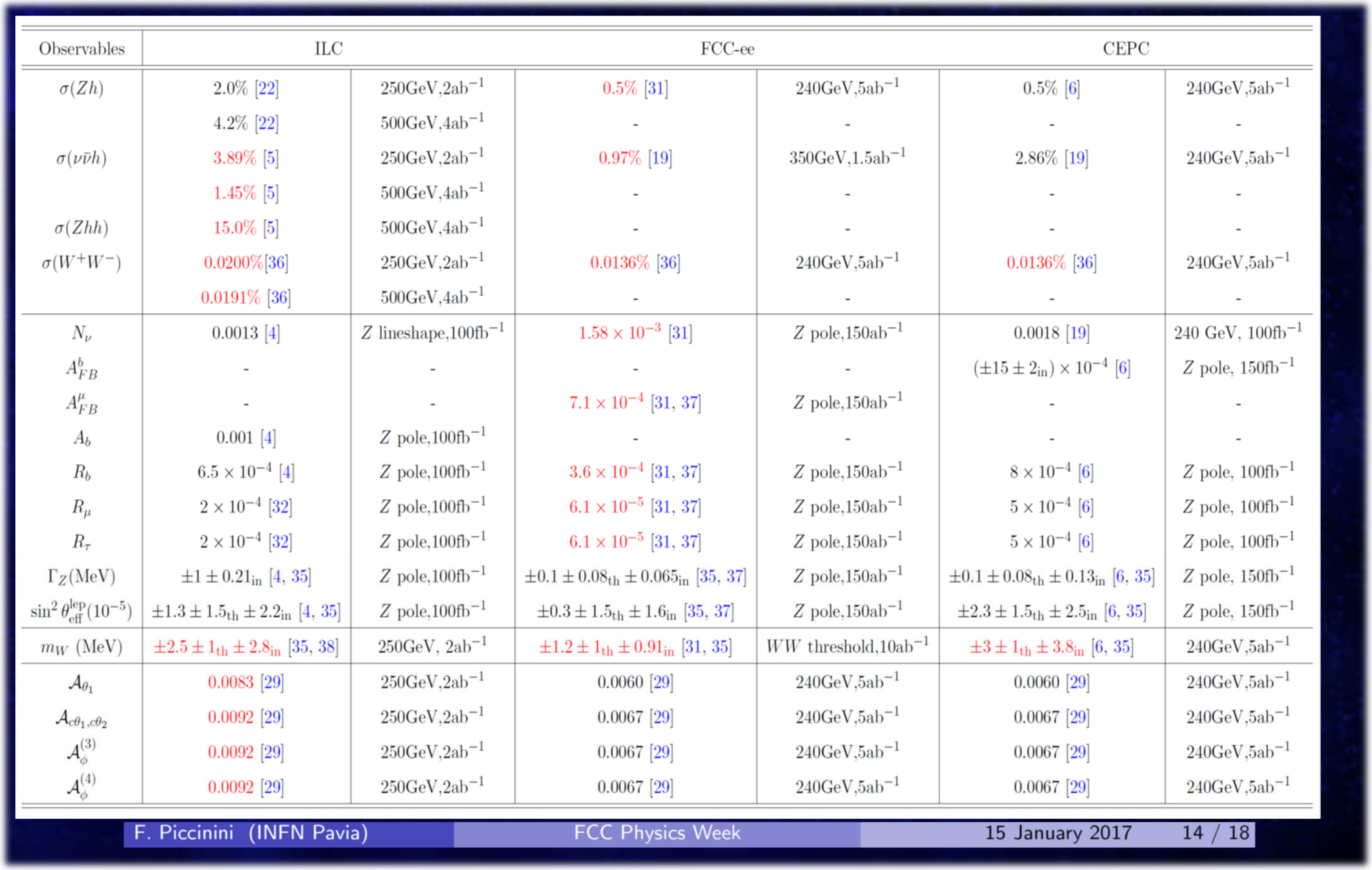


Fig. 4 Expected uncertainty contour for the S and T parameters for various colliders in their first energy stage. For ILC and CLIC, the projections are shown with and without dedicated running at the Z pole, with the current (somewhat arbitrary) estimate of future experimental and theoretical systematic uncertainty (left, from Ref. [36]); and with only statistical and parametric uncertainties (right, from Ref. [48])

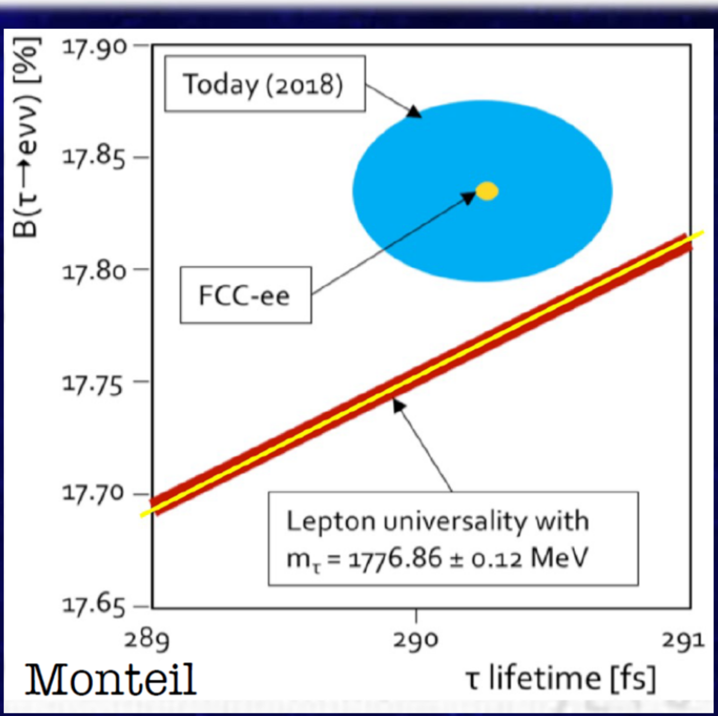
EW Observables



Observables	ILC		FCC-ee		CEPC	
$\sigma(Zh)$	2.0% [22]	250GeV,2ab^{-1}	0.5% [31]	240GeV,5ab^{-1}	0.5% [6]	240GeV,5ab^{-1}
	4.2% [22]	500GeV,4ab^{-1}	-	-	-	-
$\sigma(\nu\bar{\nu}h)$	3.89% [5]	250GeV,2ab^{-1}	0.97% [19]	350GeV,1.5ab^{-1}	2.86% [19]	240GeV,5ab^{-1}
	1.45% [5]	500GeV,4ab^{-1}	-	-	-	-
$\sigma(Zhh)$	15.0% [5]	500GeV,4ab^{-1}	-	-	-	-
$\sigma(W^+W^-)$	0.0200%[36]	250GeV,2ab^{-1}	0.0136% [36]	240GeV,5ab^{-1}	0.0136% [36]	240GeV,5ab^{-1}
	0.0191% [36]	500GeV,4ab^{-1}	-	-	-	-
N_ν	0.0013 [4]	Z lineshape,100fb^{-1}	1.58×10^{-3} [31]	Z pole,150ab^{-1}	0.0018 [19]	240 GeV, 100fb^{-1}
A^b_{FB}	-	-	-	-	$(\pm 15 \pm 2_{\text{in}}) \times 10^{-4}$ [6]	Z pole, 150fb^{-1}
A^μ_{FB}	-	-	7.1×10^{-4} [31, 37]	Z pole,150ab^{-1}	-	-
A_b	0.001 [4]	Z pole,100fb^{-1}	-	-	-	-
R_b	6.5×10^{-4} [4]	Z pole,100fb^{-1}	3.6×10^{-4} [31, 37]	Z pole,150ab^{-1}	8×10^{-4} [6]	Z pole, 100fb^{-1}
R_μ	2×10^{-4} [32]	Z pole,100fb^{-1}	6.1×10^{-5} [31, 37]	Z pole,150ab^{-1}	5×10^{-4} [6]	Z pole, 100fb^{-1}
R_τ	2×10^{-4} [32]	Z pole,100fb^{-1}	6.1×10^{-5} [31, 37]	Z pole,150ab^{-1}	5×10^{-4} [6]	Z pole, 100fb^{-1}
Γ_Z(MeV)	$\pm 1 \pm 0.21_{\text{in}}$ [4, 35]	Z pole,100fb^{-1}	$\pm 0.1 \pm 0.08_{\text{th}} \pm 0.065_{\text{in}}$ [35, 37]	Z pole,150ab^{-1}	$\pm 0.1 \pm 0.08_{\text{th}} \pm 0.13_{\text{in}}$ [6, 35]	Z pole, 150fb^{-1}
$\sin^2 \theta^{\text{lep}}_{\text{eff}} (10^{-5})$	$\pm 1.3 \pm 1.5_{\text{th}} \pm 2.2_{\text{in}}$ [4, 35]	Z pole,100fb^{-1}	$\pm 0.3 \pm 1.5_{\text{th}} \pm 1.6_{\text{in}}$ [35, 37]	Z pole,150ab^{-1}	$\pm 2.3 \pm 1.5_{\text{th}} \pm 2.5_{\text{in}}$ [6, 35]	Z pole, 150fb^{-1}
m_W (MeV)	$\pm 2.5 \pm 1_{\text{th}} \pm 2.8_{\text{in}}$ [35, 38]	250GeV, 2ab^{-1}	$\pm 1.2 \pm 1_{\text{th}} \pm 0.91_{\text{in}}$ [31, 35]	WW threshold,10ab^{-1}	$\pm 3 \pm 1_{\text{th}} \pm 3.8_{\text{in}}$ [6, 35]	240GeV,5ab^{-1}
$\mathcal{A}_{\theta_1}$	0.0083 [29]	250GeV,2ab^{-1}	0.0060 [29]	240GeV,5ab^{-1}	0.0060 [29]	240GeV,5ab^{-1}
$\mathcal{A}_{c\theta_1,c\theta_2}$	0.0092 [29]	250GeV,2ab^{-1}	0.0067 [29]	240GeV,5ab^{-1}	0.0067 [29]	240GeV,5ab^{-1}
$\mathcal{A}^{(3)}_\phi$	0.0092 [29]	250GeV,2ab^{-1}	0.0067 [29]	240GeV,5ab^{-1}	0.0067 [29]	240GeV,5ab^{-1}
$\mathcal{A}^{(4)}_\phi$	0.0092 [29]	250GeV,2ab^{-1}	0.0067 [29]	240GeV,5ab^{-1}	0.0067 [29]	240GeV,5ab^{-1}

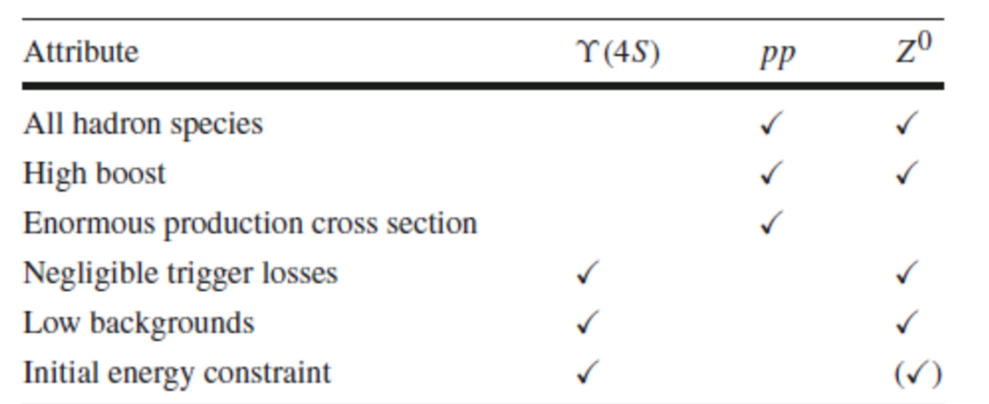
F. Piccinini (INFN Pavia) FCC Physics Week 15 January 2017 14 / 18

Flavour Physics



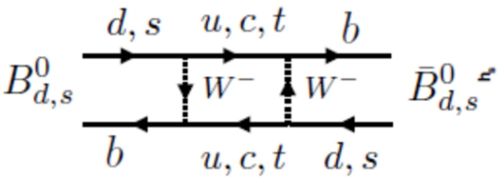
Lepton universality with $m_\tau = 1776.86 \pm 0.12$ MeV

Monteil

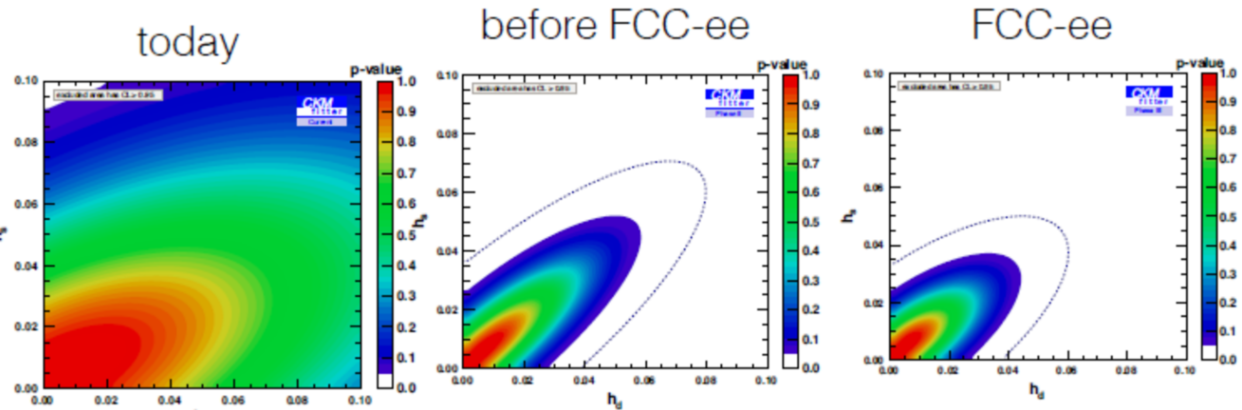


Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

- New physics can be parametrised as contribution to the B⁰ mixing matrix element M_{12}



$$M_{12} = (M_{12})_{\rm SM} \times (1 + h e^{2i\sigma})$$



today

before FCC-ee

FCC-ee

Flavour Physics

P. Janot FCC Week 30.5.22

- **FCC-ee combines advantages from LHCb and Belle2, with 10 × larger stat than Belle II**

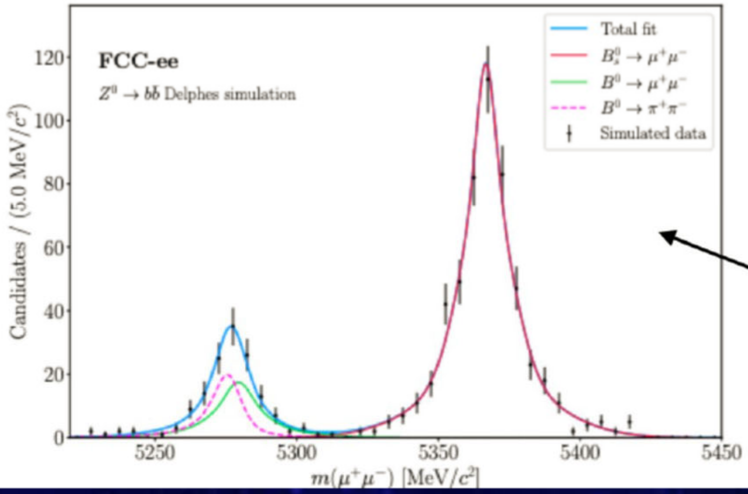
Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

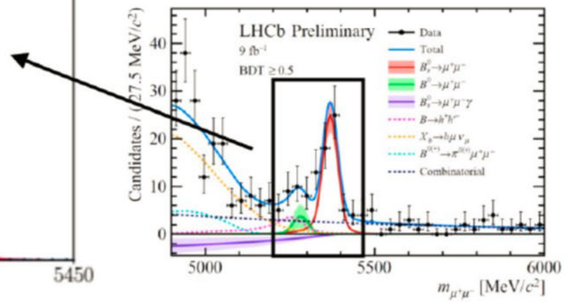
Make CP violation studies possible for very rare B decays?

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	300	300	80	80	600	150

Much higher rate and better separation for $B^0_d/B^0_s \to \mu^+\mu^-$

Complete case study required





Heavy Neutral Leptons Searches

- The see-saw mechanism: efficient generation of masses of ν upon the inclusion of sterile RH neutrinos

- Example: Neutrino Minimal Standard Model (νMSM)

L.Canetti, M.Drewes, T.Frosard, M.Shaposhnikov,
Phys. Rev. D87 (9) (2013) 093006

$I = \frac{1}{2}$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$$

$I = 0$

$$(e)_R \qquad (\mu)_R \qquad (\tau)_R \qquad Q = -1$$

$$(\nu_e)_R \equiv N_1 \qquad (\nu_\mu)_R \equiv N_2 \qquad (\nu_\tau)_R \equiv N_3 \qquad Q = 0$$

„sterile”, HNL – Heavy Neutral Leptons

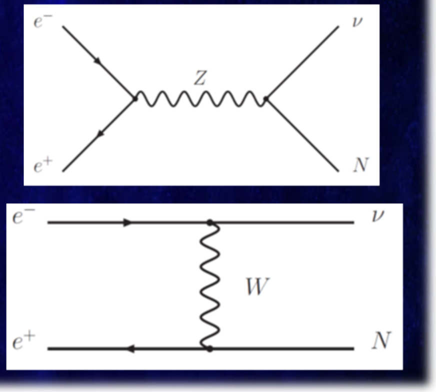
N_1 - DM candidate ($N_1 \to \nu\gamma$)

N_2, N_3 - can generate Baryon Asymmetry of the Universe (BAU)

A ”physical left-handed neutrino” produced e.g. in the Z^0 decay is a mixture of the light and heavy state $\nu_L = \nu \cos\theta + N \sin\theta$ with the mixing angle $\theta \approx m_\nu / m_N$

- **The HNL production**

$$e^+ e^- \to N\nu$$

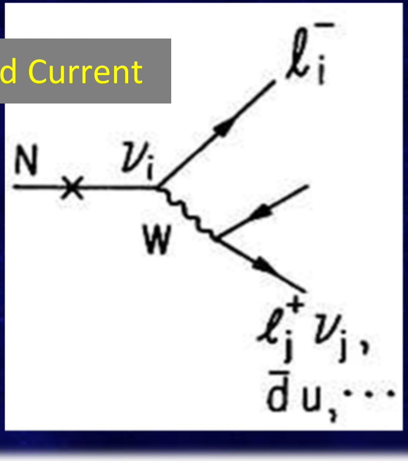


- The HNL decay

The Charged Current

$l_i^- l_j^+ \nu_j$

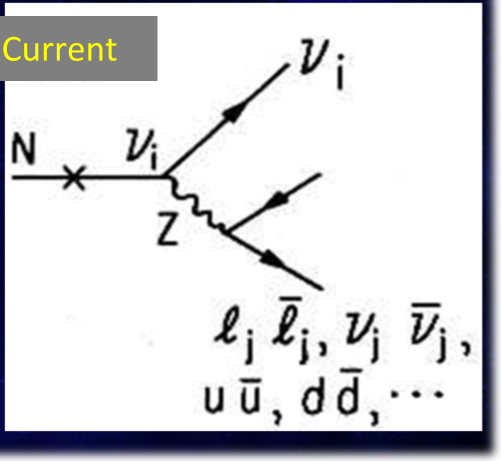
$l_i^- \bar{d}u, \ldots$



The Neutral Current

$\nu_i l_j^+ l_j^-$

$\nu_i u\bar{u}, \ldots$



SMEFT Basics

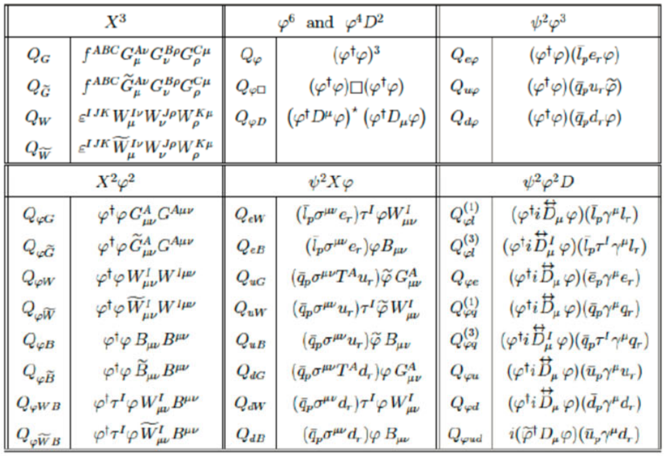
SMEFT@dim-6

New Physics: → New Interactions of SM particles

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

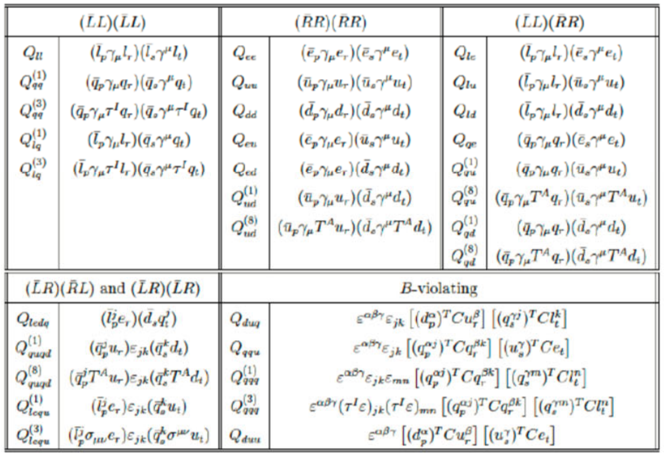
Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

Grzadkowski et al arXiv:1008.4884



X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu \varphi\right)^\star \left(\varphi^\dagger D_\mu \varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

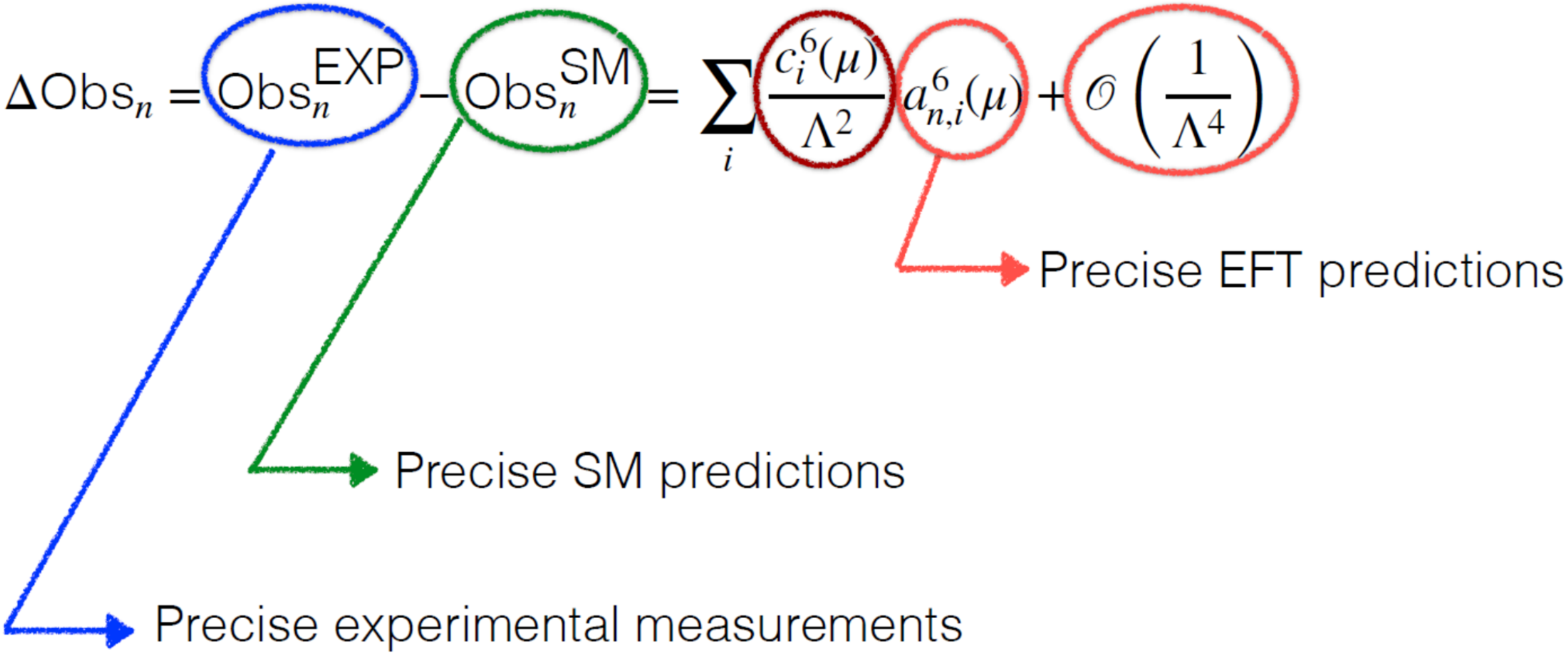


$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

SMEFT Basics

SMEFT@colliders in practice

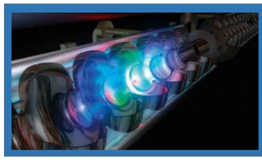


$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \sum_i \frac{c_i^6(\mu)}{\Lambda^2} a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Precise EFT predictions

Precise SM predictions

Precise experimental measurements



FCC-ee: Detector Requirements

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

BSM
feebly interacting particles

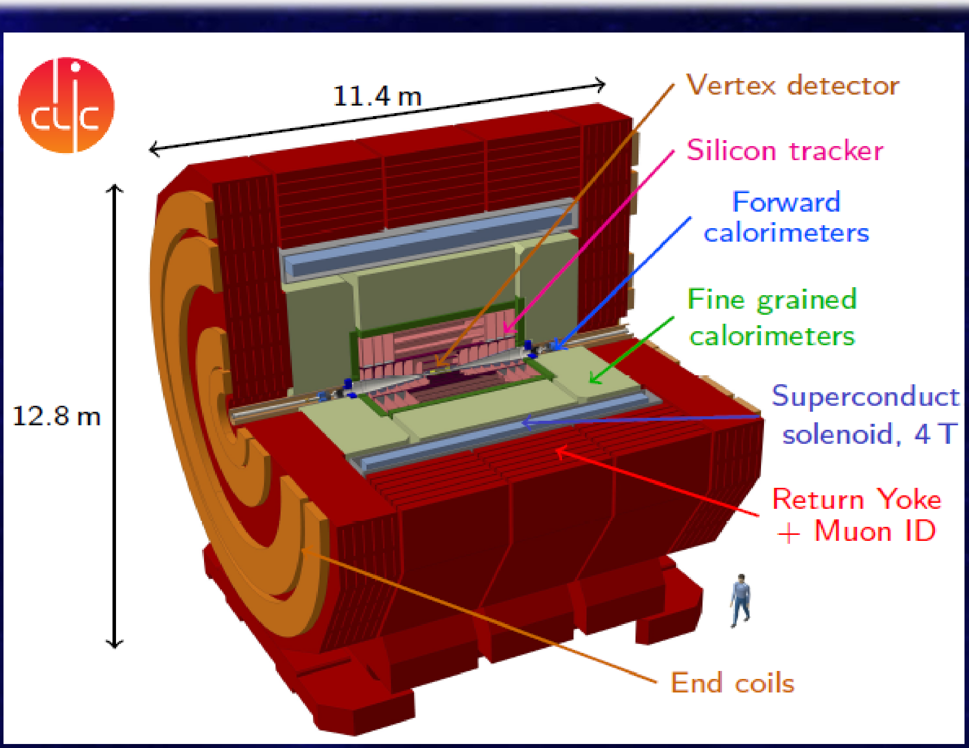
Large decay volume

High radial segmentation
- tracker
- calorimetry
- muon

impact parameter resolution for large displacement

triggerless

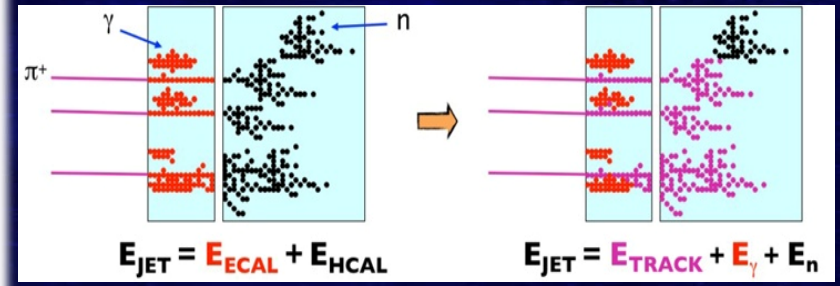
FCC-ee Detectors in a nutshell



- **Low material budget**
- **Hermeticity (forward region)**
- **Precision vertex and tracking detectors**
- **High granularity calorimeters (PFA)**

- **Technology fully mature**
- **Cost < 500 k EUR**
- **Number of electronic channels: >10^9**

Particle Flow Algorithm (PFA)



$E_{JET} = E_{ECAL} + E_{HCAL}$

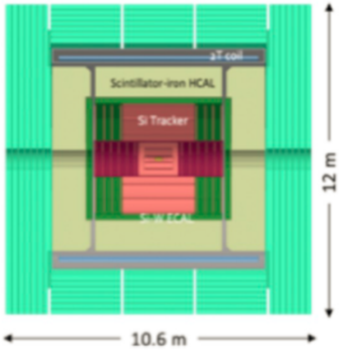
$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

- Chase individual particles cradle → grave
- Separate and reconstruct each individual particle in a jet: combined tracking and calorimetric measurements
- 4-momenta of charged hadrons measured by trackers
- gammas and neutral hadrons recovered from calorimeters

FUTURE
CIRCULAR
COLLIDER

FCC-ee Detector Concepts

CLD

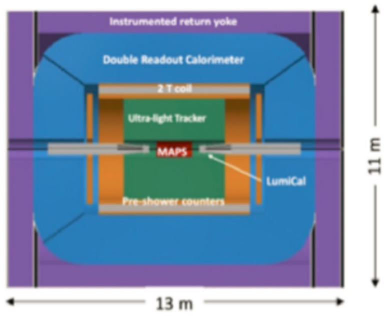


Design (ILC/CLIC/Calice)

- All silicon tracker (pixels + strips)
- Si-W EM calorimeter
    - ○ $22X_0$, 40 long. layers.
- Steel-Scintillator hadronic calo.
    - ○ SiPM readout
- Solenoid outside calorimeter
- RPC based Muon system

https://arxiv.org/pdf/1911.12230.pdf

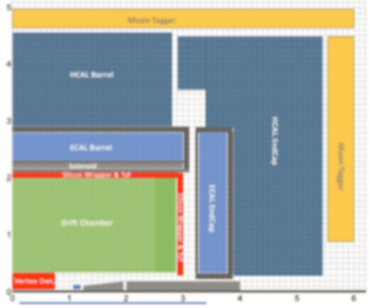
IDEA



- MAPS based vertex detector (1% X_0)
- High-precision low-mass drift chamber with surrounding Si microstrip ($t_d < 400$ ns).
- pre-shower with MPGD readout
- Lead-Fiber dual readout calorimeter
- Sensitive to both Sci/Cerenkov
    - ○ Hybrid with crystal EM?
- large μ-Rwell muon chambers

https://inspirehep.net/files/49ec726758c422bc454e270a71f6e59f

Noble Liquid

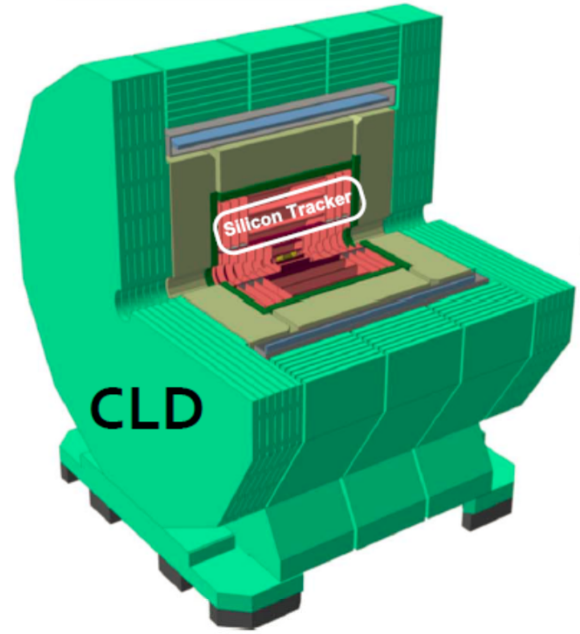


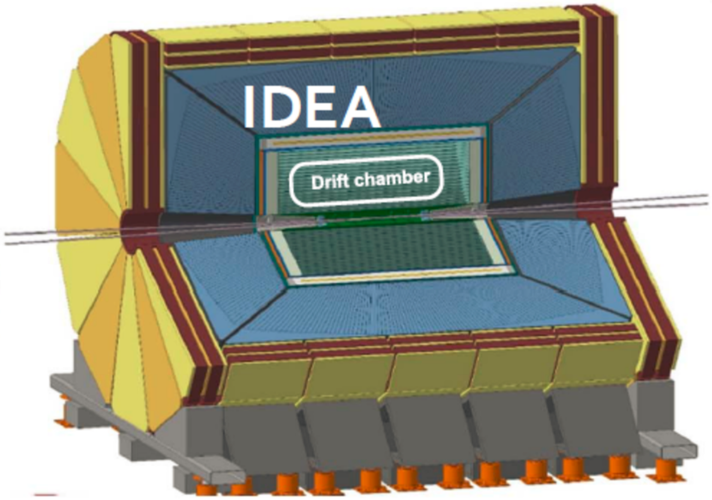
- Includes a highly granular noble liquid calorimeter
- Possible design being explored are lead/steel absorbers (RM ~4 cm), stacked azimuthally inclined at 50° wrt radial axis with LAr as the active medium.
- Other considerations include Tungsten absorbers and/or Liquid Krypton.
- https://arxiv.org/pdf/2109.00391.pdf

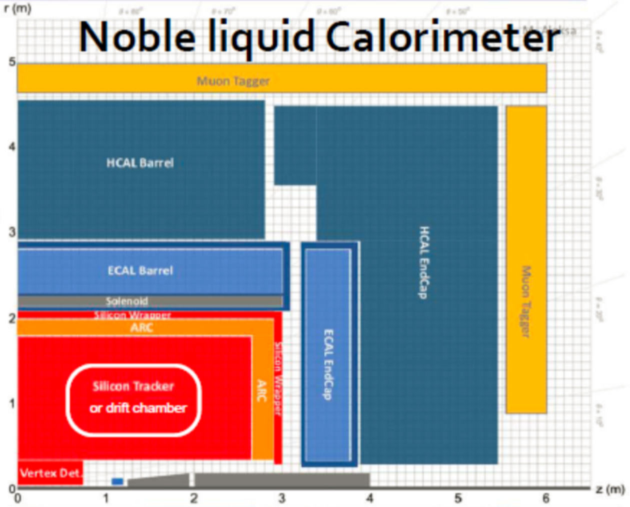
FUTURE CIRCULAR COLLIDER

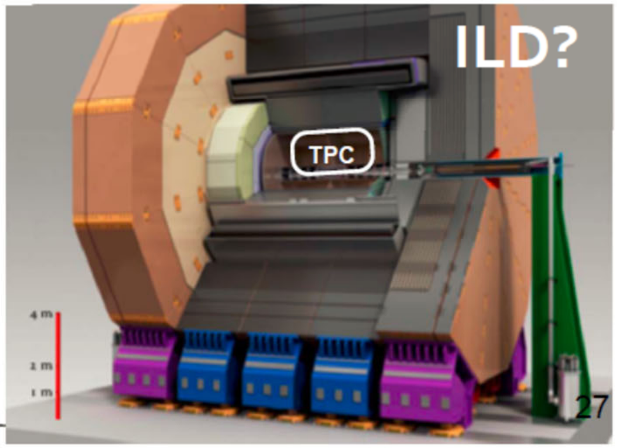
FCC-ee Detector Concepts

Proto-detectors: A basis towards detector concepts







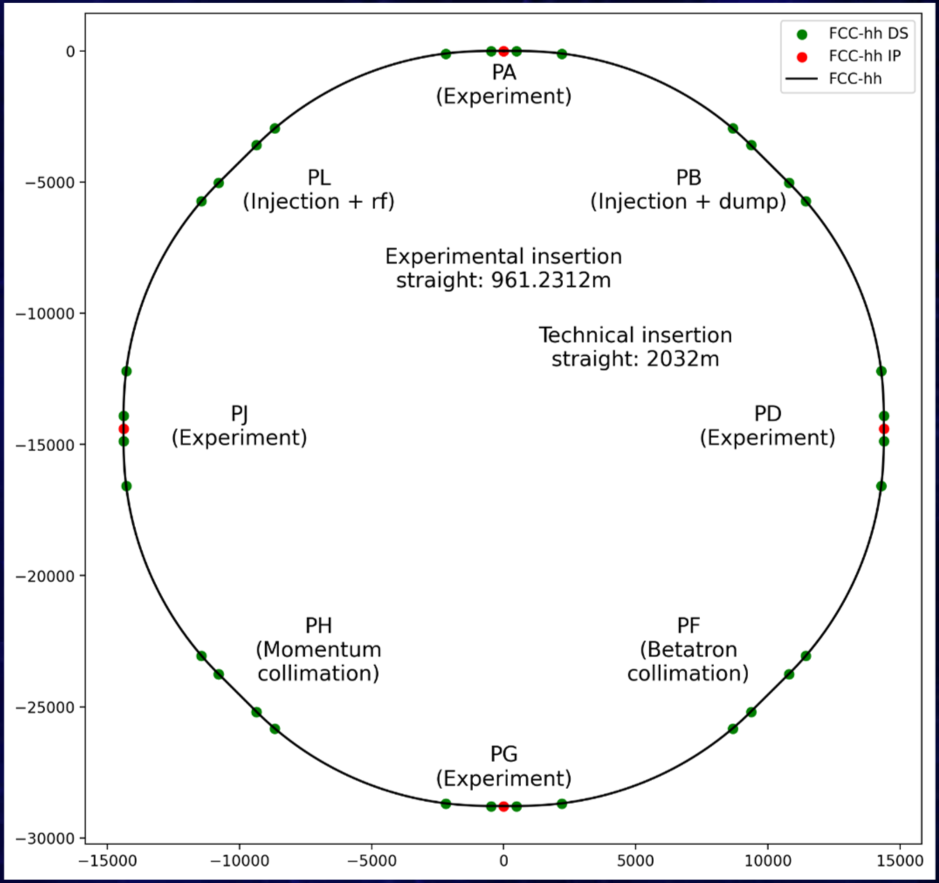


- ❑ Three tracker concepts to test for synchrotron radiation
  - ◆ Si Tracker, Drift Chamber, Time Projection Chamber
    - Only existing simulation so far : CLD Si Tracker
      - → IDEA Drift Chamber will follow soon

Layout of the FCC-hh Ring

New beam energy (for 16 T dipoles): 48 TeV

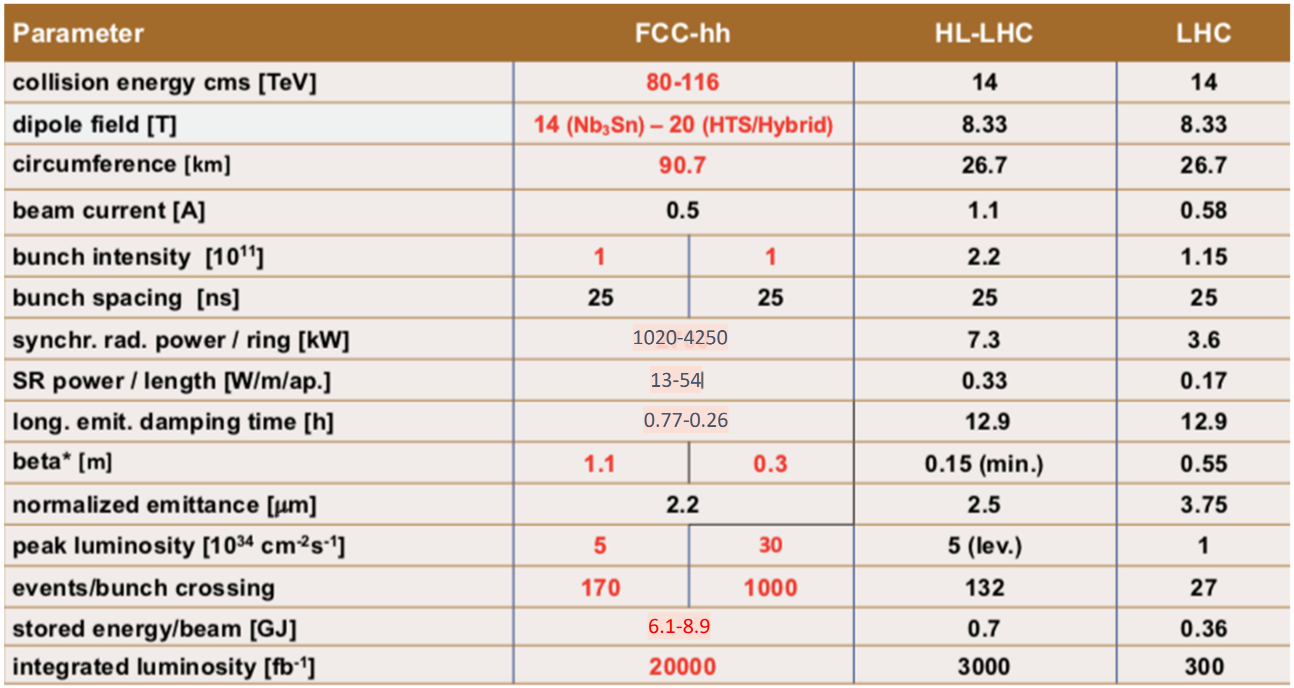
- Following the outcome of placement studies, a new FCC-hh layout has been designed.
- IPA, IPD, IPG, IPJ: experimental insertions
- Compatible with LHC or a superconducting SPS as injector



Circumference: 90.66 km

FUTURE CIRCULAR COLLIDER

FCC-hh Machine Parameters



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

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

Formidable challenges:

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

Formidable physics reach, including:

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

F. Gianotti

FCC-hh Stored Beam Energy

- Circular proton-(anti)proton colliders - the main (unique) tool to explore the scale of tens (hundreds) of TeV
- $p \approx 0.3eB\rho$ ➔ increase the magnetic field of the bending magnets (B) AND/OR the ring circumference (ρ)
- Intense magnet R&D

	B[T]	SC material
(HL-) LHC	8.3	Nb-Ti
HE-LHC	16	Nb_3Sn
FCC-pp	16 / 45	Nb_3Sn / HTS

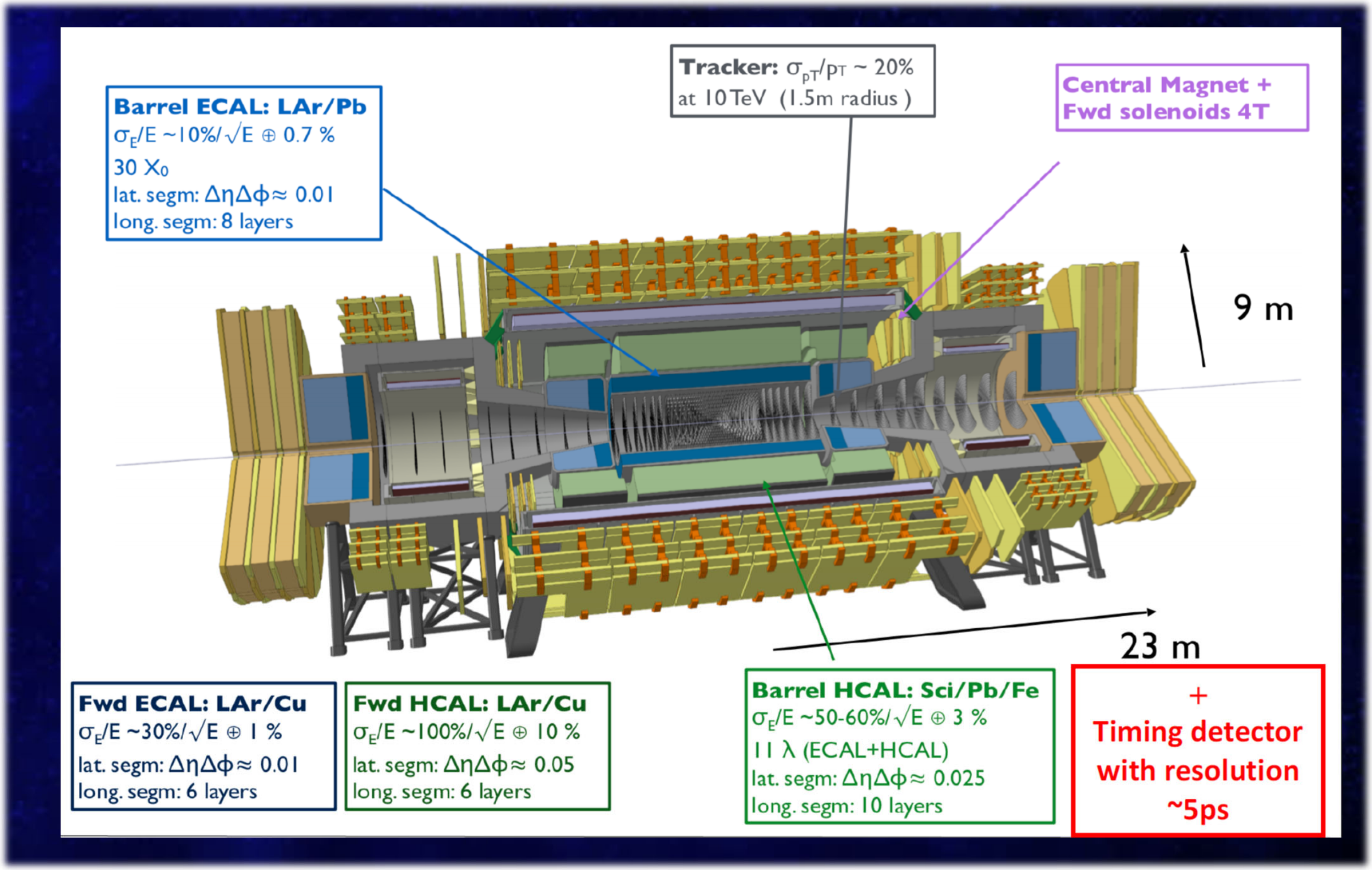
HTS – High Temperature Superconductor

- Stored beam energy: 8 GJ/beam (0.4 GJ LHC) = 2 tons of TNT ➔ equivalent to an Airbus A380 (560 t) at full speed (850 km/h).

- Enormous pile-up (~1000)
- At the scale of 100 TeV the SR radiation will NOT be negligible for the first time in pp collisions

- Cross-sections for most interesting processes grow significantly from 14 TeV to 100 TeV
- With the luminosity of 30 ab^{-1} @100 TeV most measurements will be limited by systematic uncertainties
- Physics program: LHC on strong steroids.

FCC-hh Detector



Tracker: $\sigma_{p_T}/p_T \sim 20\%$ at 10TeV (1.5m radius)

Central Magnet + Fwd solenoids 4T

Barrel ECAL: LAr/Pb
$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.7\ \%$
$30\ X_0$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 8 layers

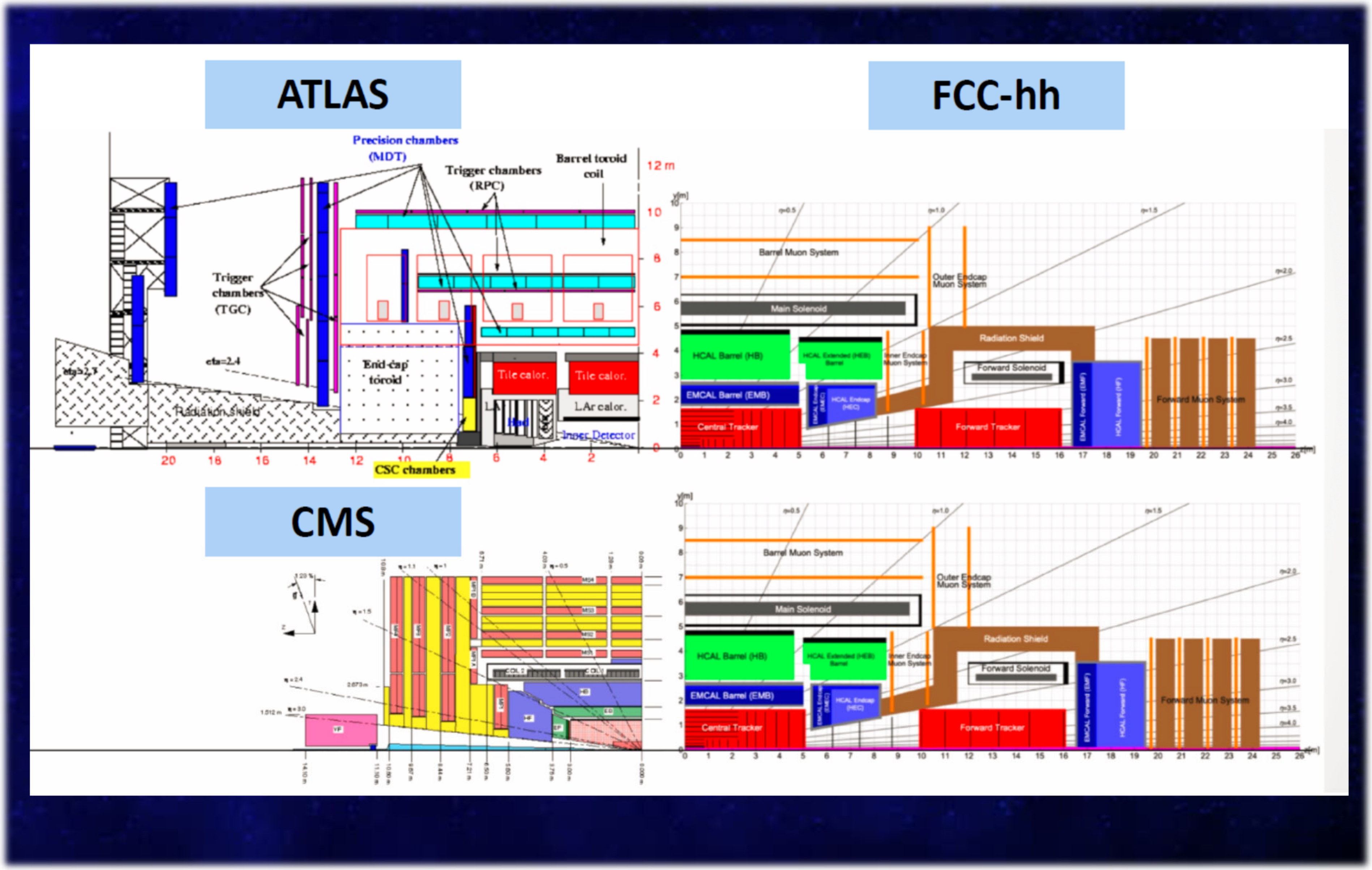
Fwd ECAL: LAr/Cu
$\sigma_E/E \sim 30\%/\sqrt{E} \oplus 1\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 6 layers

Fwd HCAL: LAr/Cu
$\sigma_E/E \sim 100\%/\sqrt{E} \oplus 10\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.05$
long. segm: 6 layers

Barrel HCAL: Sci/Pb/Fe
$\sigma_E/E \sim 50\text{-}60\%/\sqrt{E} \oplus 3\ \%$
$11\ \lambda$ (ECAL+HCAL)
lat. segm: $\Delta\eta\Delta\phi \approx 0.025$
long. segm: 10 layers

+
Timing detector with resolution ~5ps

FCC-hh Detectors



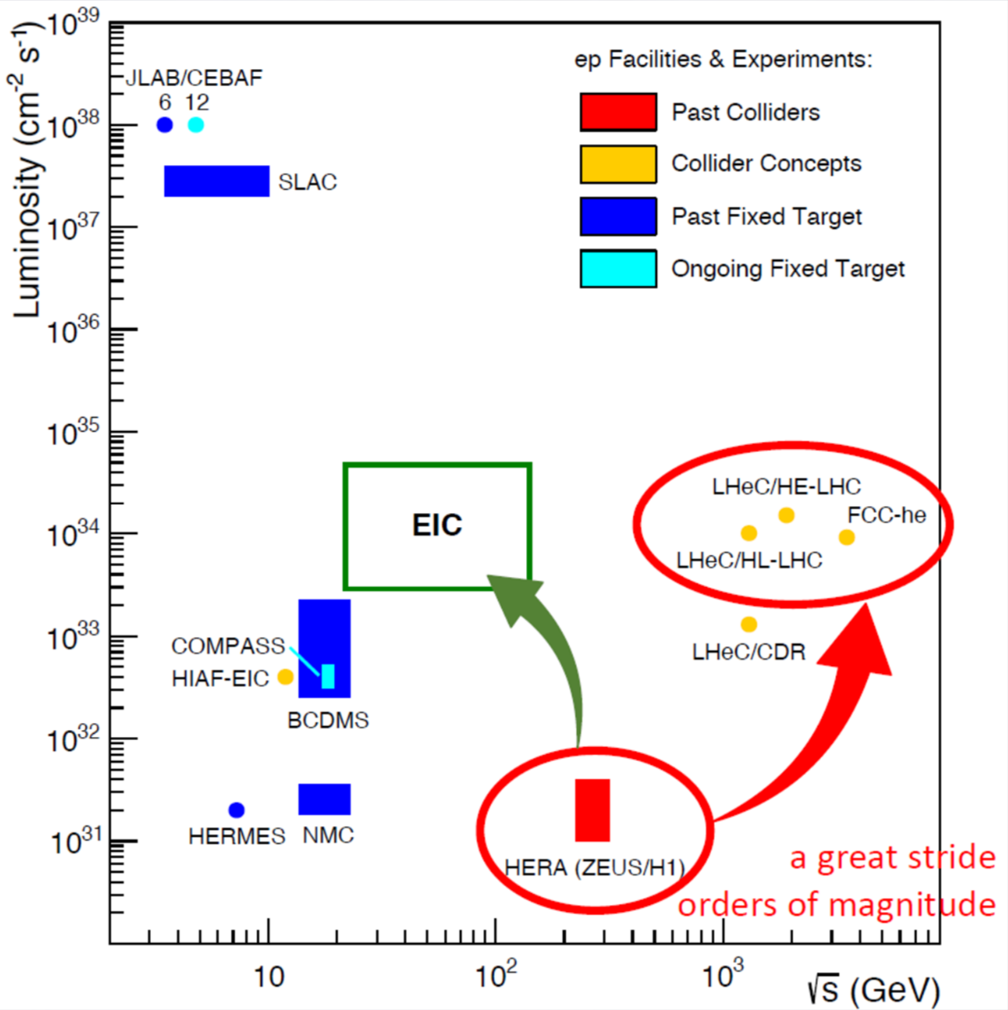
FCC-eh: ep/A Landscape

The EIC will dominate ep/eh physics in the next decade

BUT, expanding ep/eA physics both for higher luminosities and bigger energies is highly desirable

That’s why LHeC and FCC-eh are being proposed

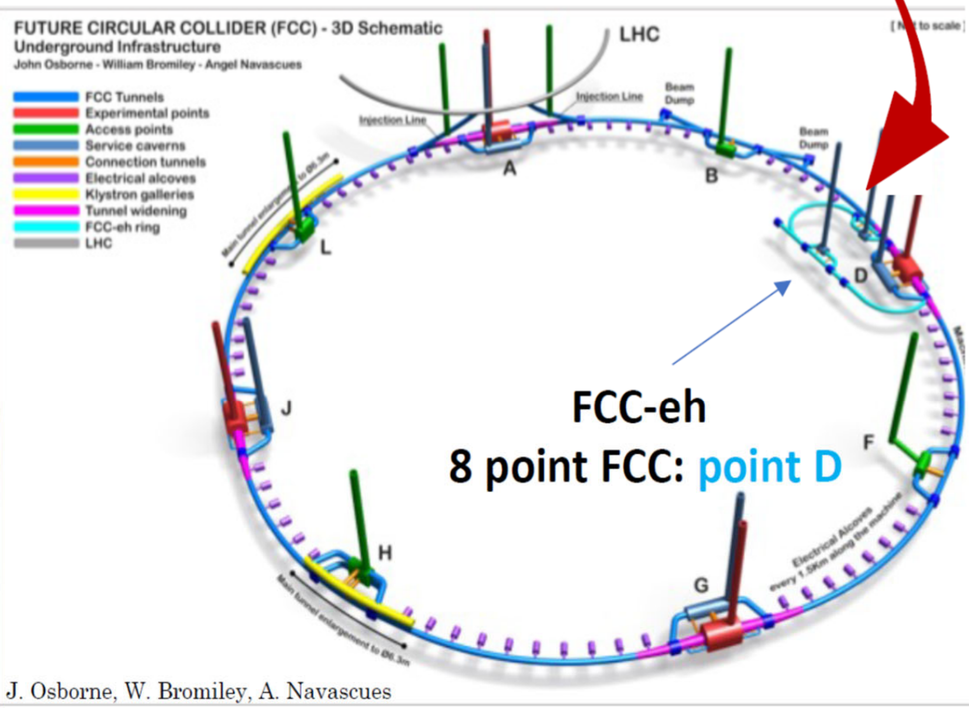
At high energies e-p colliders provide a General-Purpose experiment



a great stride
orders of magnitude

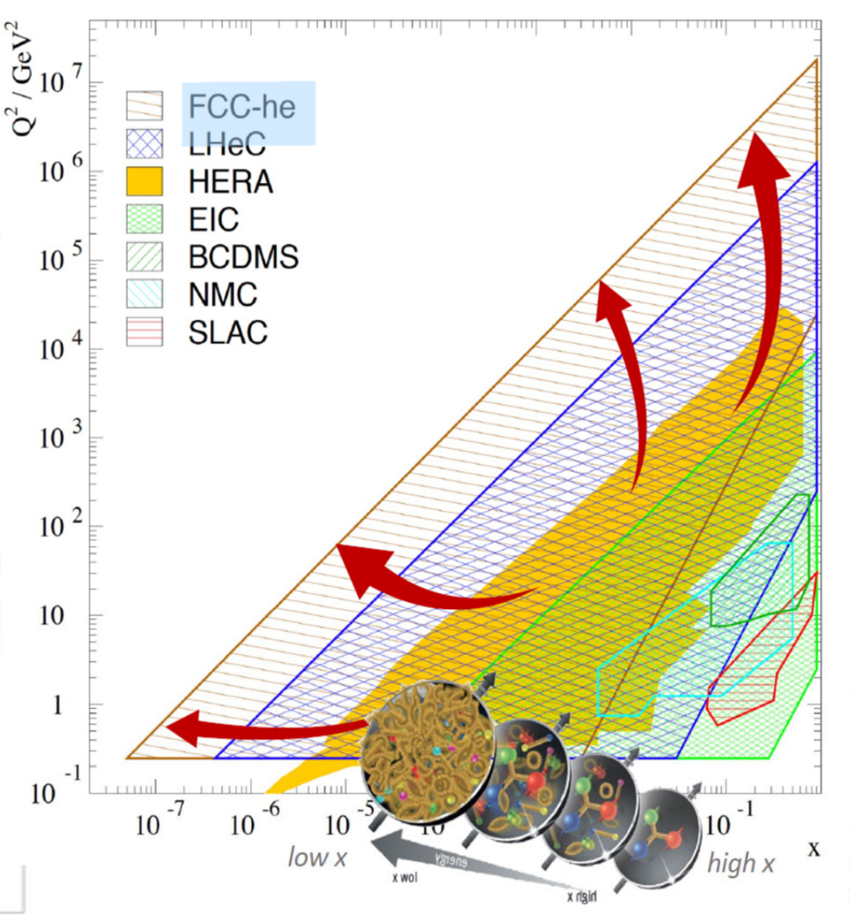
FCC-eh Programme

FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh



FCC-eh
8 point FCC: point D

J. Osborne, W. Bromiley, A. Navascues

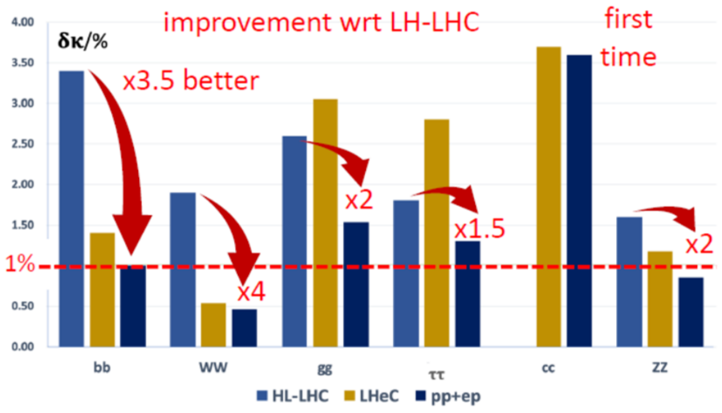


The challenge: high intensity electron beam

The Energy Recovery Linac proposed as a solution (beam power 1 GW → 100 MW)

Physics Highlights of the LHeC (FCC-eh

Higgs physics



EW physics

- ○ Δm_W down to 2 MeV (today at ~10 MeV)
- ○ $\Delta \sin^2\theta_W^{eff}$ to 0.00015 (same as LEP)

Top quark physics

- ○ $|V_{tb}|$ precision better than 1% (today ~5%)
- ○ top quark FCNC and γ, W, Z couplings

DIS scattering cross sections

- ○ PDFs extended in (Q^2,x) by orders of magnitude

Strong interaction physics

- ○ α_s precision of 0.1%
- ○ low-x: a new discovery frontier

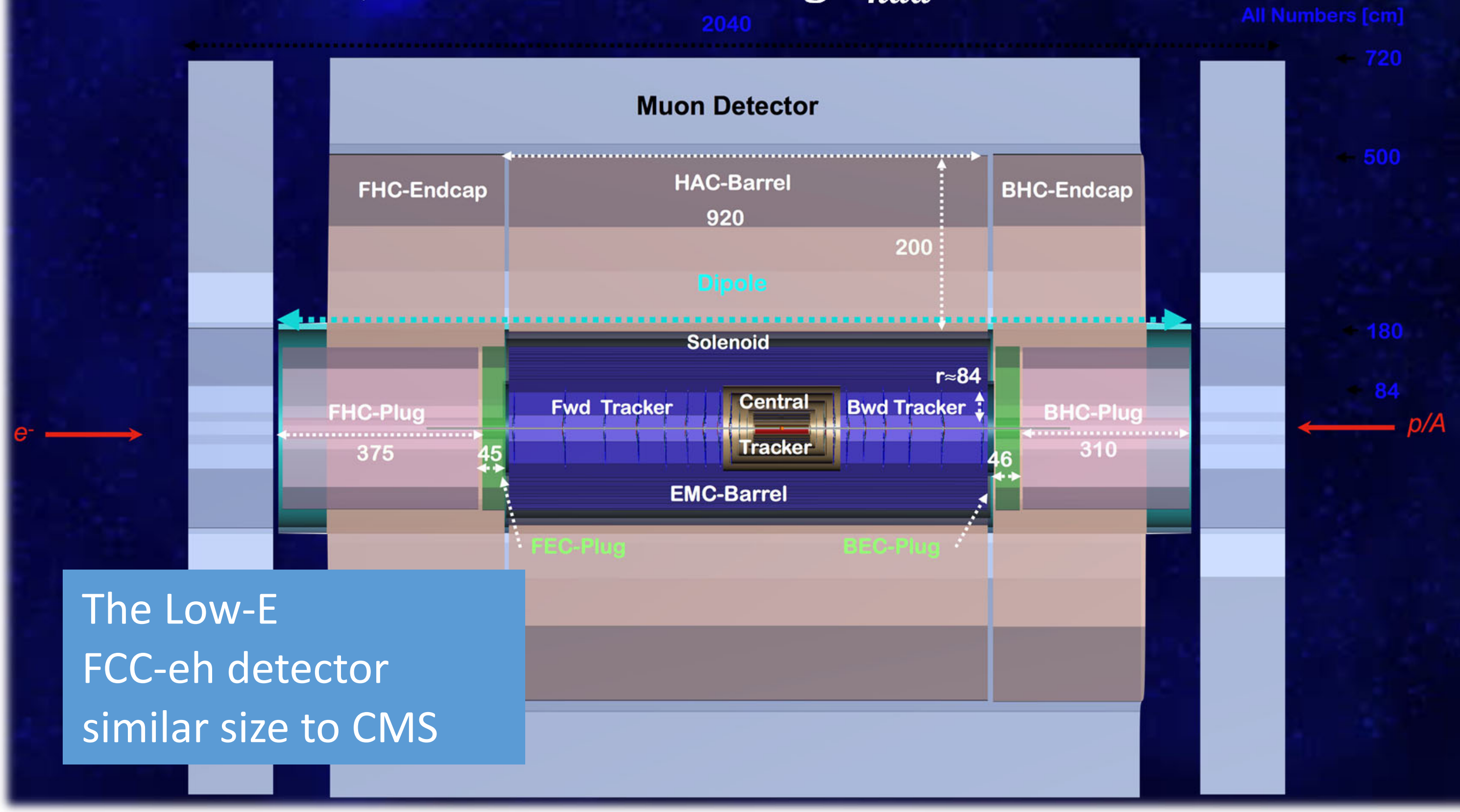
For EW/Higgs/top physics: similar improvement factor: LHC→ HL-LHC, HL-LHC→ LHeC →FCC-eh

A joint ep/pp interaction region with the same detector would correlate results and reach the ultimate precision (e.g. Δm_W = 1 MeV)

In addtion, the FEE-eh would offer a unique potential to search for new physics phenomena

FCC-eh Detector

- Proton 20 and 50 TeV, electron 60 GeV
  - Almost no change in low-mass event propertlies (e.g. Higgs) while new high-mass objects would be detected in **very forward rapidities**
- Design for LHeC with extended volume / layers will serve also for FCC-eh
  - **Forward/Central: scales in $\sim \log E_{had}$ for calo**



The Low-E
FCC-eh detector
similar size to CMS

Total length
20.4m
Radius 7.2m

Central tracker also with (possibly tilted) wheels

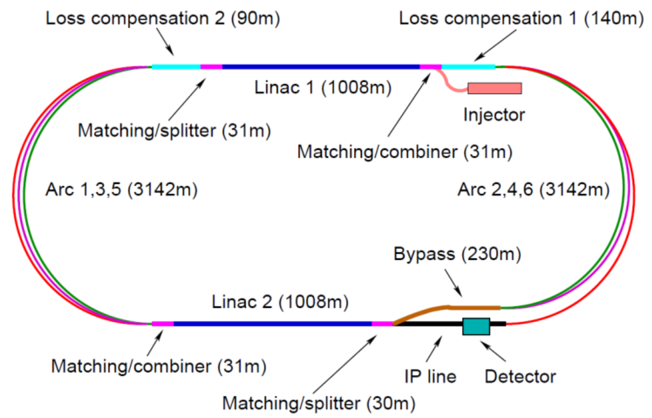
Fwd tracker 8 disks
Bwd 6 disks

HadCal:
12-15 interaction lengths

Most demanding:
forward detectors

FCC-eh and LHeC

- DIS e-p (e-nucleus) – a noble method to study matter
- Idea: use a proton (heavy ion) beam from a hadron collider and collide it with a (polarizable) electron beam from a newly built electron machine:



The e- accelerator:

an energy recovery liniac (ERL) with a horserace-track ring with two LINACs (10 GeV each)

Ring circumference: 9 km

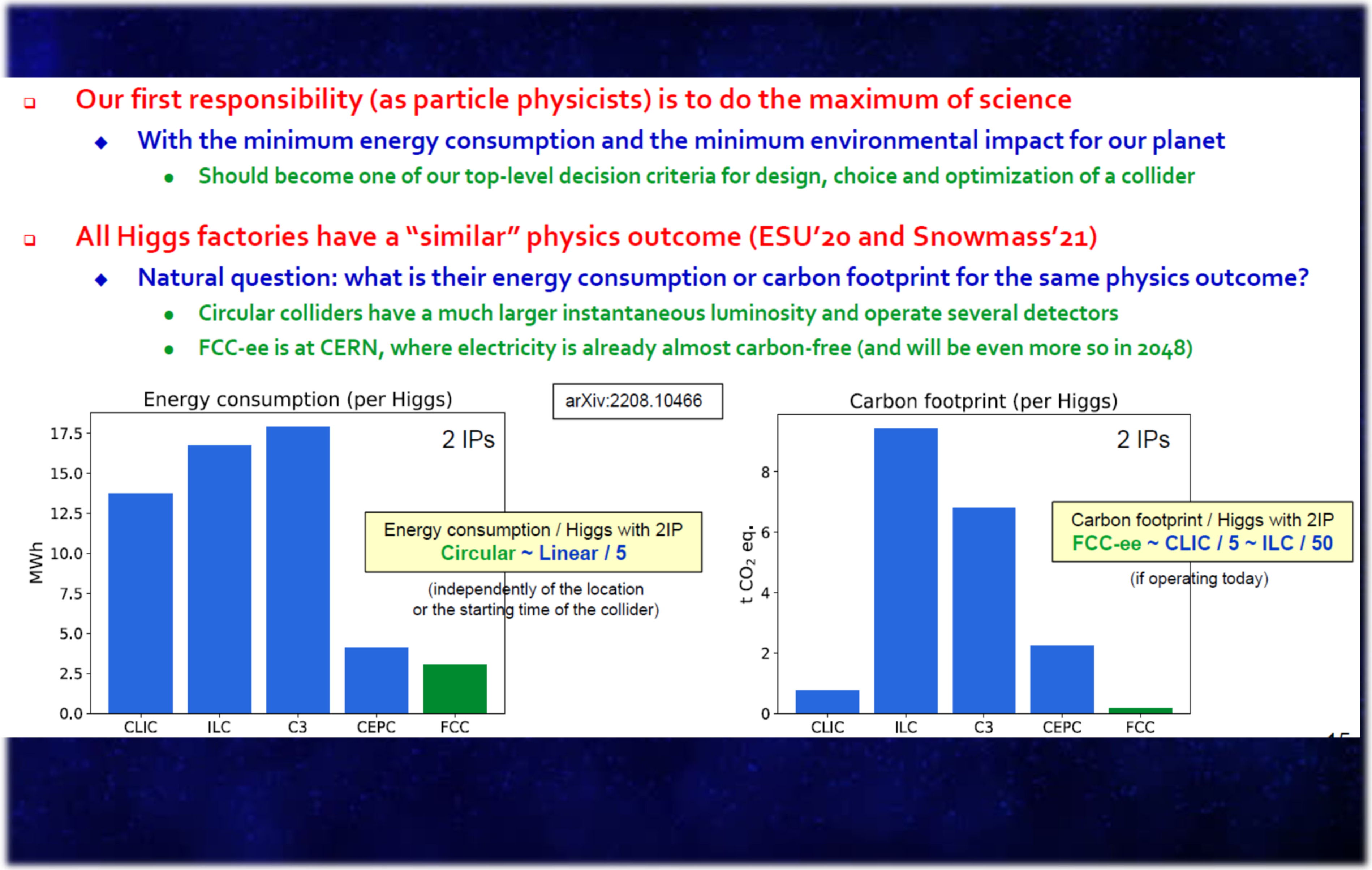
RF power recycling: after the collision the beam runs in the same LINAC at an opposite phaseto the accelerated beam – is decelerated and giving back the power for acceleration

PERLE – small scale demonstrator at LAL Orsay

	Electron beam [GeV]	Proton beam [TeV]	CMS energy [TeV]	Q^2 [GeV^2]	x
HERA	27	0.92	0.3	10^4	10^{-5}
LHeC	60	7	1.3	106	10^{-7}
FCC-eh	60	50	3.5	107	10^{-8}

- The e-h machine can run concurently with p-p collisions
- Rich physics program!

Energy Consumption and Carbon Footprint



- **Our first responsibility (as particle physicists) is to do the maximum of science**
  - With the minimum energy consumption and the minimum environmental impact for our planet
    - Should become one of our top-level decision criteria for design, choice and optimization of a collider
- **All Higgs factories have a "similar" physics outcome (ESU'20 and Snowmass'21)**
  - Natural question: what is their energy consumption or carbon footprint for the same physics outcome?
    - Circular colliders have a much larger instantaneous luminosity and operate several detectors
    - FCC-ee is at CERN, where electricity is already almost carbon-free (and will be even more so in 2048)

Energy consumption (per Higgs)

arXiv:2208.10466

Carbon footprint (per Higgs)

Energy consumption / Higgs with 2IP
Circular ~ Linear / 5

(independently of the location
or the starting time of the collider)

Carbon footprint / Higgs with 2IP
FCC-ee ~ CLIC / 5 ~ ILC / 50

(if operating today)