FCC-ee: the benefits of a layout with 4 IPs

Alain BLONDEL Patrick JANOT

05.03.2021

With many contributions from the FCC PED SG and coordination group

Motivation

One of the great advantages of the circular e+ e- colliders is:
-- The possibility of serving several interaction points with net overall gain
both in integrated luminosity **and** luminosity/MW.

The FCC-ee is a machine with a very rich menu of physics possibilities
-- this leads to many detector requirements, which cannot be simultaneously satisfied by only two detectors. example: EM calorimeter
(high E precision vs high granularity vs high stability vs geometric accuracy vs PID vs cost)

Furthermore
-- many measurements will serve as input to future programmes in particular FCC-hh
-- many are statistically limited
-- redundancy provided by 4IPs is essential for high precision measurements
-- and different detector solutions will be invaluable in uncovering hidden systematic biases.

Last but not least
-- some key physics capabilities are nearly missed with the present run plan and 2 IPs.

FCC-ee physics programme

M. Dam ECFA R&D road map input
https://indico.cern.ch/event/994685/

"Higgs Factory" Programme

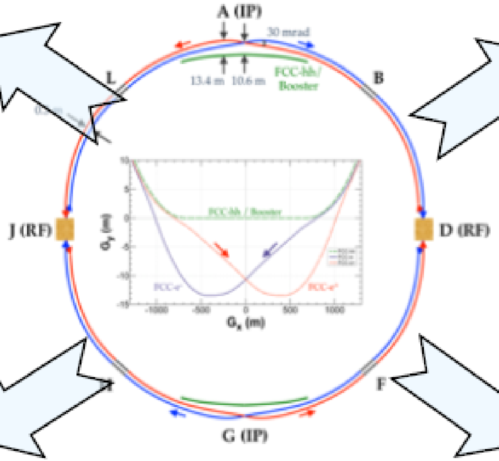
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- 5×10^{12} Z and 10^{8} WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W...
- 10^{6} tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale



Heavy Flavour Programme

- Enormous statistics: 10^{12} bb, cc; 1.7×10^{11} ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays

- CKM matrix, CP measurements, "flavour anomaly" studies, e.g. b → sττ, rare decays, cLFV searches, lepton universality, PNMS matrix unitarity

Feebly Coupled Particles - LLPs

Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z :

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

Detector requirements (present status)

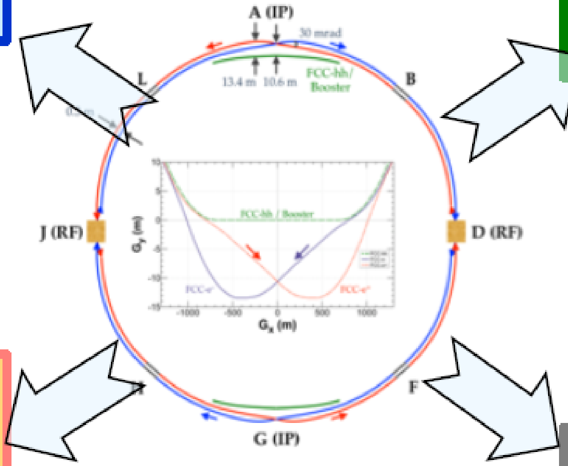
M. Dam ECFA R&D road map input
https://indico.cern.ch/event/994685/

"Higgs Factory" Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$ commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of $30\%/\sqrt{E}$ in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme

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



Heavy Flavour Programme

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

Feebly Coupled Particles - LLPs

Benchmark signature: Z → νN, with N decaying late

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

Physics of the Higgs boson

Baseline (2IP): at 240 and 365 GeV, collect in total 1.2MHZ events and 75k WW →H events

Statistics-limited:

-- Higgs couplings to fermions & bosons; model-independent, normalized to e+e- →ZH cross-section
→ fixed candle for past (HL-LHC) and future (FCC-hh) studies at hadron colliders (H→ ZZ)
-- Higgs properties: CP violation, H→ gg … …

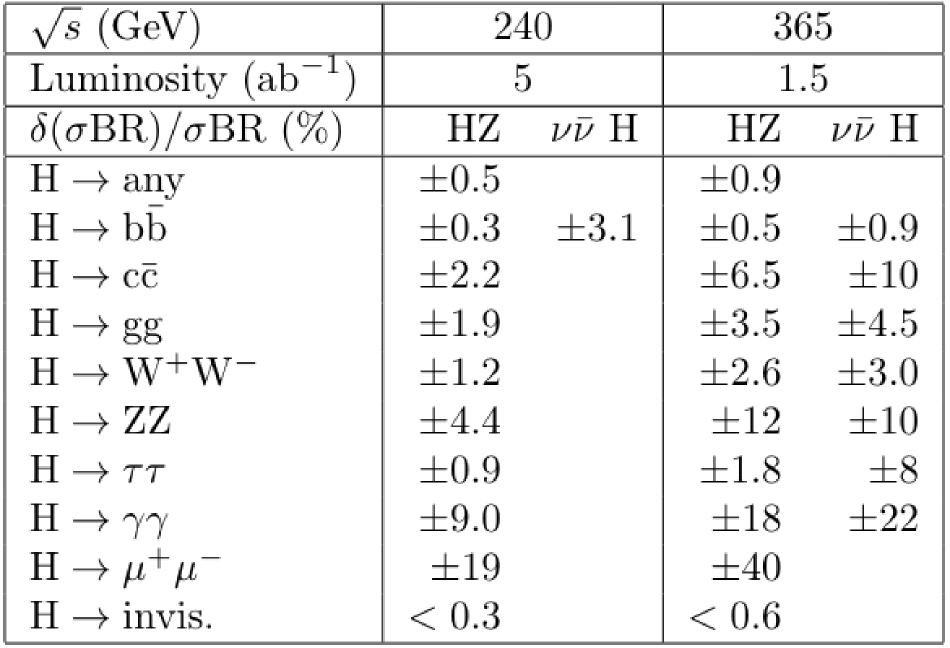
Close to discovery level

-- Higgs self-coupling (2-5? σ) via loop diagrams : a very fundamental question!
complementary w.r.t. HH production at higher energy machines (CLIC3000(9%) , FCC-hh (2-3%))

-- Unique possibility: measure electron coupling in s-channel production e+e-→H @ √s = 125 GeV
highly demanding on luminosity, monochromatization with 1, 2 or 4 IPs?

Higgs couplings and properties

- Baseline scenario with 2 IP
  - 5 ab^{-1} at 240 GeV in 3 yrs
  - 0.2 ab^{-1} at 340-350 GeV in 1 yr
  - 1.5 ab^{-1} at 365 GeV in 4 yrs

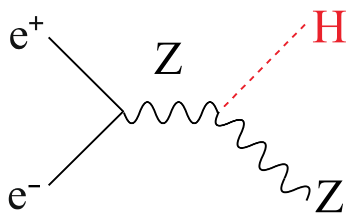


$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma\mathrm{BR})/\sigma\mathrm{BR}$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$\mathrm{H} \rightarrow$ any	±0.5		±0.9	
$\mathrm{H} \rightarrow \mathrm{b\bar{b}}$	±0.3	±3.1	±0.5	±0.9
$\mathrm{H} \rightarrow \mathrm{c\bar{c}}$	±2.2		±6.5	±10
$\mathrm{H} \rightarrow \mathrm{gg}$	±1.9		±3.5	±4.5
$\mathrm{H} \rightarrow \mathrm{W^+W^-}$	±1.2		±2.6	±3.0
$\mathrm{H} \rightarrow \mathrm{ZZ}$	±4.4		±12	±10
$\mathrm{H} \rightarrow \tau\tau$	±0.9		±1.8	±8
$\mathrm{H} \rightarrow \gamma\gamma$	±9.0		±18	±22
$\mathrm{H} \rightarrow \mu^+\mu^-$	±19		±40	
$\mathrm{H} \rightarrow$ invis.	< 0.3		< 0.6	

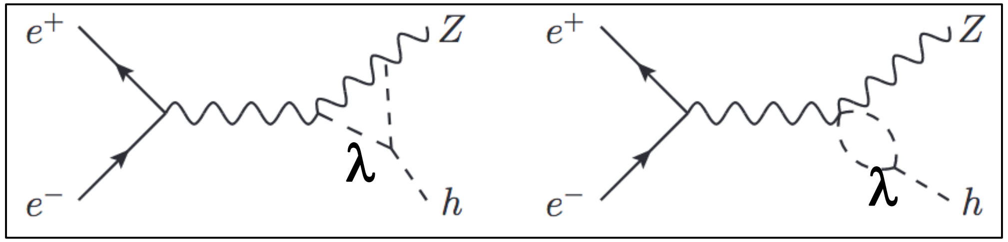
- Precision obtained on $\boldsymbol{\sigma} \times \boldsymbol{BR}$
  - Typically, a few per mil to a few per cent
- Experimental uncertainties
  - Will be controlled to much better than a per mil (use regular Z data for calibration/alignment)
- Theoretical uncertainties
  - Are not expected to be a concern for Higgs measurements (in the future)
- **Take-home message : more data will improve Higgs measurements precision as 1/√L**
- **NB: probability of an nσ deviation scales as exp(- ½ (nσ)^2)**

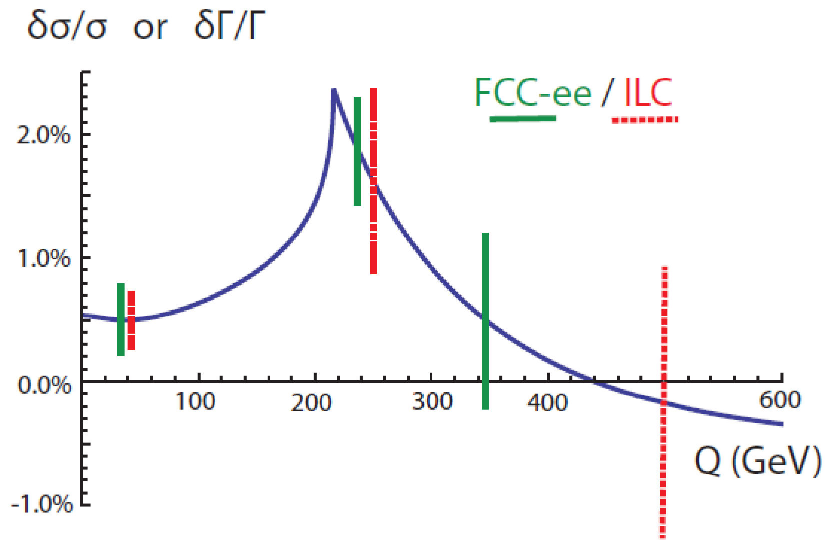
Higgs self-coupling λ

Sensitivity comes from loop corrections to the e+e- → ZH production x-section
... and the resulting change as function of Q.



+





present estimate → ≥2σ from 0 with 2 IPs and present run plan

-- dominated by the Z → leptons channel (mostly Z→ μ μ (e e) + Higgs)

-- hope for improvements from

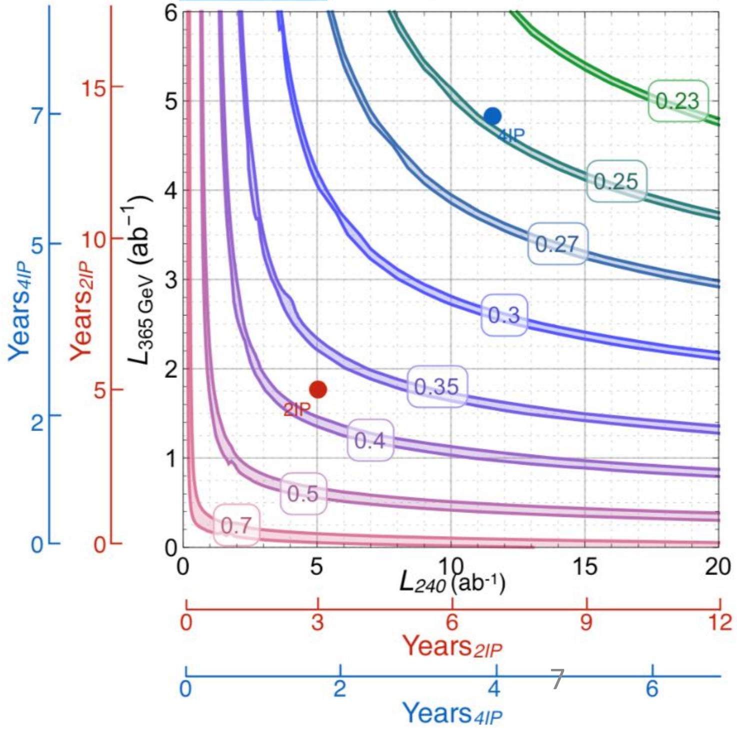
-- better use of Z --> $\bar{q}q$ and other channels, optimization of data taking and analysis synergetic with precision Higgs mass measurement required before ee --> H

-- increase of statistics and optimization of run plan (see 1809.10041 & next slide*→) (increase duration of 240 and 365 runs, reduce Z and WW runs @constant statistics)

-- or better: increase overall running time *(if its worth doing, its worth doing well)*

Target: increase to 5σ (discovery) the separation between λ= 0 vs 1 vs 2 seems possible only with 4IP!

Precision on λ FCC-ee + HL-LHC



Improvement with 4IP, (as of arxiv 1809.10041)

AB,P. Janot 1809.10041

- First scenario: keep the same operation model as with 2 IP
  - Total luminosity increases by a factor 1.7
    - Precision on Higgs couplings and Higgs width improves by a factor 1.3
- Second scenario: optimize the operation model towards the Higgs
  - For example, maximize the sensitivity to the Higgs self-coupling

    spend 10 years at 240 and 365 GeV, instead of the baseline 7 years

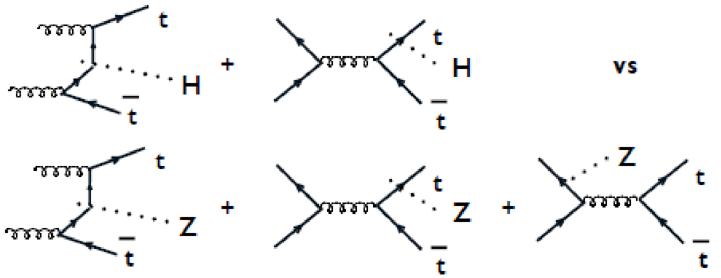
    Say 3.5 years at 240 GeV and 6.5 years at 365 GeV (plus 0.5 yr at 340-350 GeV)

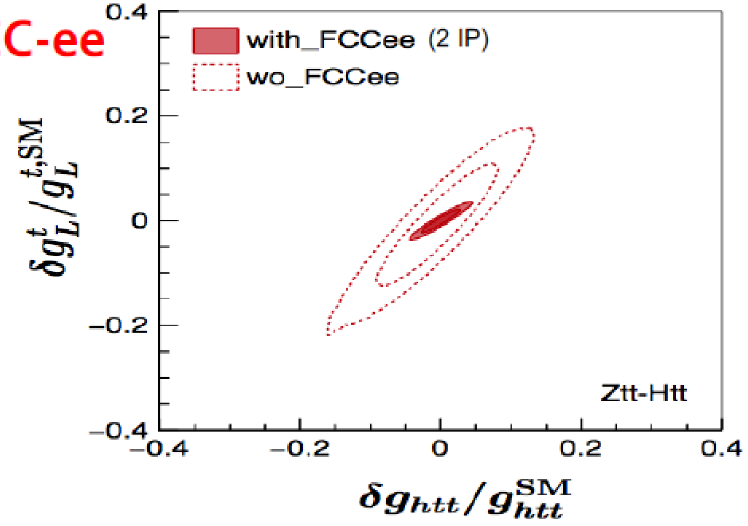
    With a total luminosity / year ~1.7 larger than in the baseline

	κ_Z	κ_W	κ_b	κ_c	κ_g	κ_τ	κ_μ	κ_γ	BR_{inv}	Γ_H
2 IP	0.17%	0.43%	0.61%	1.21%	1.01%	0.74%	9.0%	3.9%	< 0.3%	1.3%
4 IP	0.10%	0.24%	0.36%	0.73%	0.60%	0.43%	5.5%	3.0%	<0.2%	0.77%

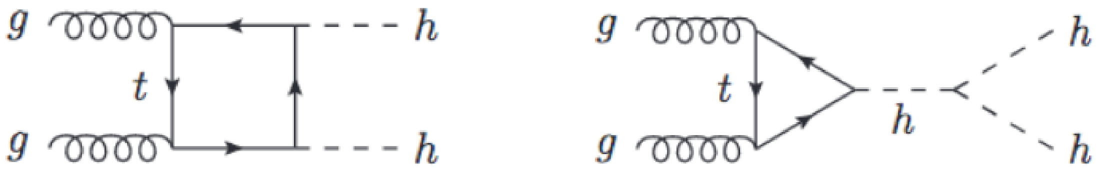
Top electroweak couplings @ 365 GeV

- Top Yukawa coupling@FCC-hh: dominated by top EW couplings@FCC-ee
  - Measure σ(ttH) / σ(ttZ) at FCC-hh
    - Similar production mechanism
    - Most theory uncertainties cancel
      - → <1% precision possible
  - Information needed from FCC-ee
    - Measure t_Lt_LZ couplings to fix the denominator (precision ~1.5%)
    - Measure Higgs branching ratios to fix the numerator (precision ~0.5%)
  - Top EW precision@FCC-ee is statistically limited: 4IP reduce FCC-hh precision by a factor $\sqrt{4.5/1.5}$ ~ 1.7

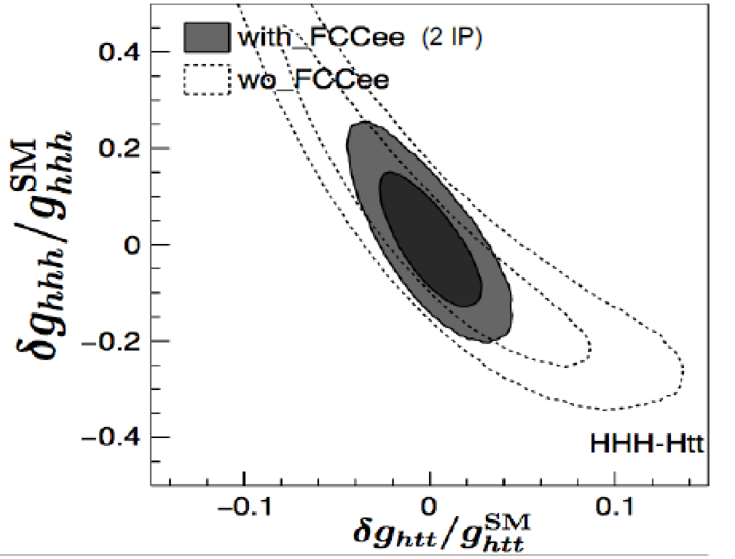




- Help in turn the precision of the Higgs self-coupling @ FCC-hh
  - The top Yukawa coupling is needed to predict HH production cross section



  - The aforementioned factor 1.7 is precious to reach the ultimate κ_λ precision



Precision measurements

Precision tests of the SM = relations between observables

$$m_Z \xrightarrow{\alpha_{QED}(m_Z),\ m_{top},\ S,T,U} \sin^2\theta_W^{eff}$$

$$m_Z \xrightarrow{\alpha_{QED}(m_Z),\ m_{top},\ S,T,U} m_W$$

$$m_Z \xrightarrow{\alpha_s(m_Z),\ m_{top},\ T,\ N_\nu,\ \delta_{vb}} \Gamma_Z$$

$$m_W \xrightarrow{m_{top},\ S,T,U} \sin^2\theta_W^{eff}$$

Rb → δ_{vb} ; R_ℓ (Z) & R_ℓ (W) → $\alpha_s(m_Z)$,
350GeV top scan + $\alpha_s(m_Z)$ → m_{top} etc, etc.
new physics (NP) ‘parameters’ in red

1. **many interconnected measurements →**
2. **All FCC-ee run plan on Z, W and top is essential**
3. **Huge statistics → precision, real chance of discovery**
4. **Most of work will be on systematic errors**
5. **To spot and evaluate systematics having >2 experiments is essential**

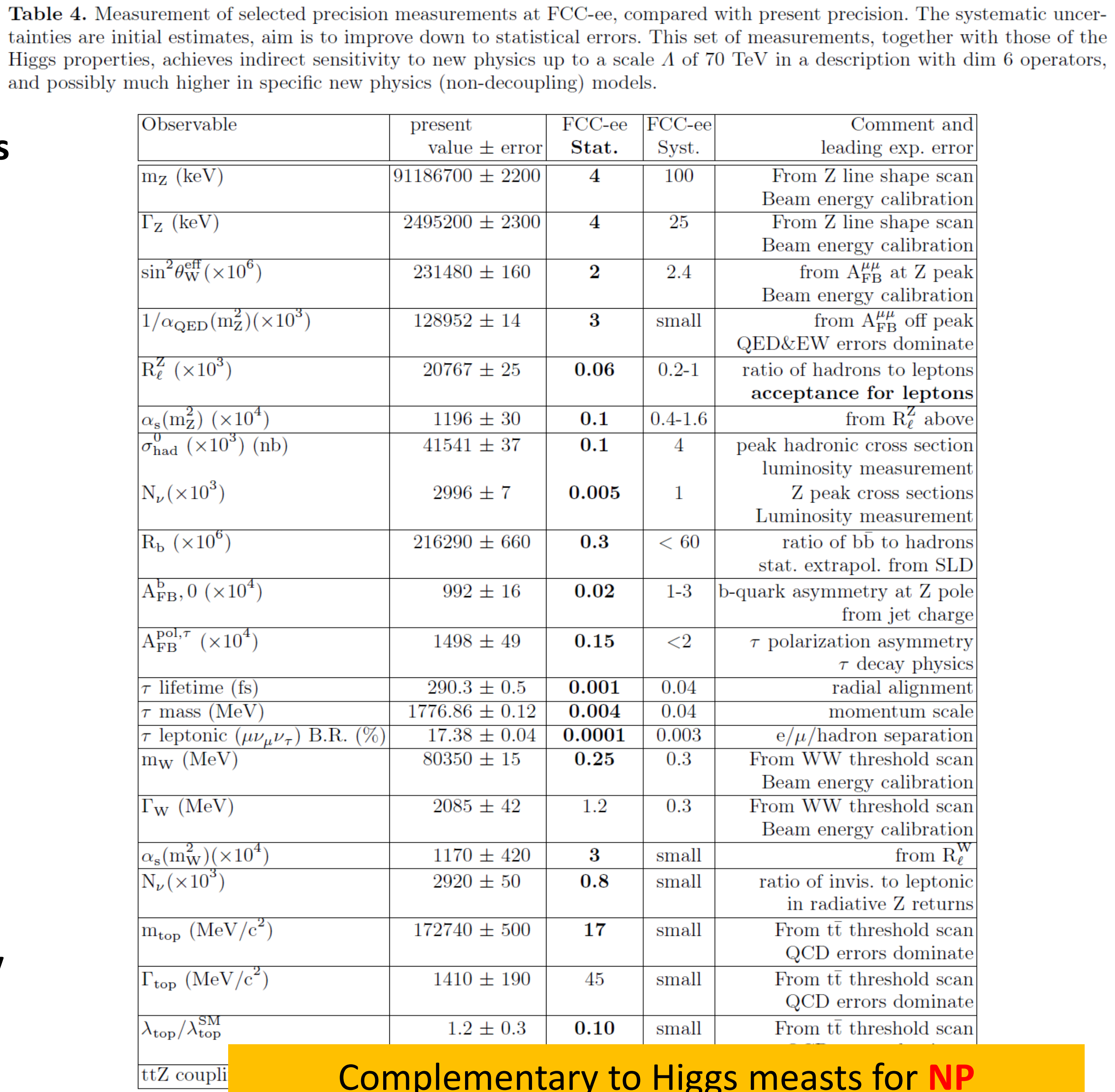


Table 4. Measurement of selected precision measurements at FCC-ee, compared with present precision. The systematic uncertainties are initial estimates, aim is to improve down to statistical errors. This set of measurements, together with those of the Higgs properties, achieves indirect sensitivity to new physics up to a scale Λ of 70 TeV in a description with dim 6 operators, and possibly much higher in specific new physics (non-decoupling) models.

Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan
ttZ coupli				

Complementary to Higgs measts for **NP**
Will rebaseline the whole field of HEP for decades

Statistics/systematics-limited precision measurements

Take the line shape:
arXiv:1909.12245v1

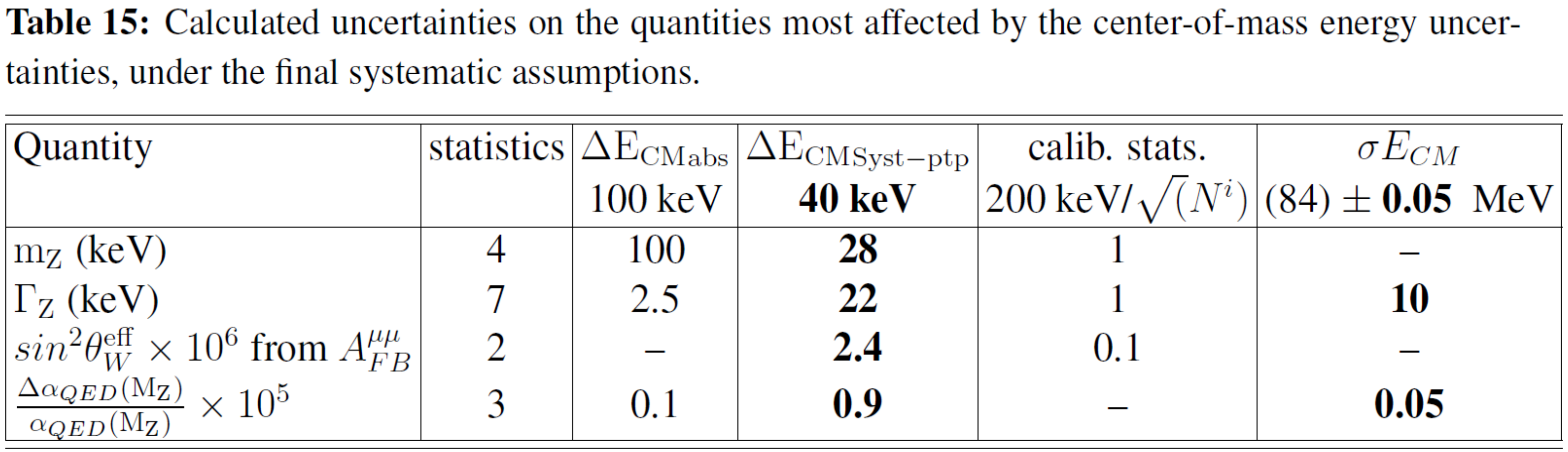


Table 15: Calculated uncertainties on the quantities most affected by the center-of-mass energy uncertainties, under the final systematic assumptions.

Quantity	statistics	$\Delta E_{\mathrm{CMabs}}$ 100 keV	$\Delta E_{\mathrm{CMSyst-ptp}}$ **40 keV**	calib. stats. 200 keV/$\sqrt(N^i)$	σE_{CM} (84) ± **0.05** MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	7	2.5	**22**	1	**10**
$sin^2\theta_W^{\mathrm{eff}} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(\mathrm{M_Z})}{\alpha_{QED}(\mathrm{M_Z})} \times 10^5$	3	0.1	**0.9**	–	**0.05**

$\alpha_{QED}(m_Z)$

FCC special

Traditionally obtained from calculation using the cross-sections γ, $\gamma^*/Z^* \rightarrow$ hadrons cross-sections at various smaller centre-of-mass energies → systematic error subject to debate.
Here for the first time a *direct* measurement of this important quantity itself is made (game-changer)
Enters as a limiting ‘parametric’ uncertainty in the NP interpretation of many past and future measurements.
Is statistics limited (off-peak asymmetries) and will directly benefit from more luminosity with 4 IP

$\sin^2\theta_W^{\mathrm{eff}}$ & Γ_Z
(also m_W vs m_Z)

appear systematics limited by point-to-point energy uncertainties. However these are based on error in the comparison btw ECM(exp from mu pairs) and spin-tune, **obtained each day of running** (100 times)
➔ At the end it boils down to statitics and to detector systematics.
This contains systematics such as stability in the magnetic field or tracker alignment etc.
➔ **these are uncorrelated between experiments and will scale down as 1/√N(exp)**

Statistics/systematics-limited precision measurements

A. We often hear that more Z pole statistics is useless because the measurements are limited by systematics

this is a « passive » attitude and has always led to overly pessimistic expectations → wrong conclusions.

-- experience shows that a careful systematics analysis boils down to a statistical problem

-- if well prepared, 'theory' will go as far as useful (i.e at level of combined stats and systematics)

B. Precision measurements are all about redundancy

-- as seen in the following example, measuring the same quantity in several experiments can reveal overlooked sources of errors. →

-- in this context a given amount of luminosity is better used in four detectors than in one or even two.

(and even better of course if more experiments means more statistics!)

  -- a single experiment is quite vulnerable to unforeseen effects

  -- comparison between two experiments can detect inconsistencies at level of > (exp. error *√2)

  consistency can still happen 'by chance'. → comparison is poor measurement of systematics.

  -- such bad luck is much less likely in the case of four experiments

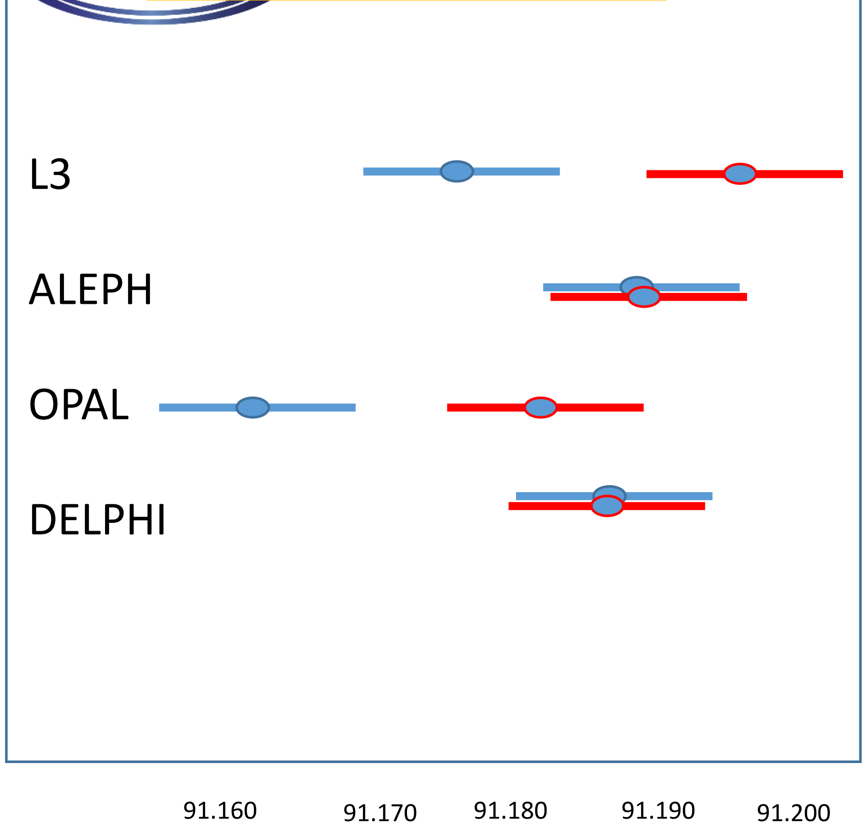
C. Detector requirements for the precision measurements are new wrt those at Higgs and top energies

-- fiducials must be known to O(10^{-5}) level

-- magnetic field and energy calibrations must be very stable

-- ... ...

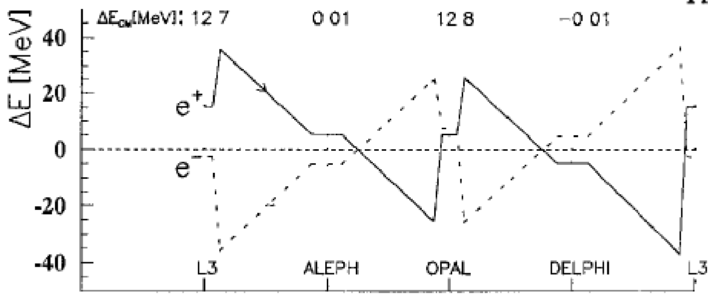
Z mass from 1991 Z scan



??.... ... . ??

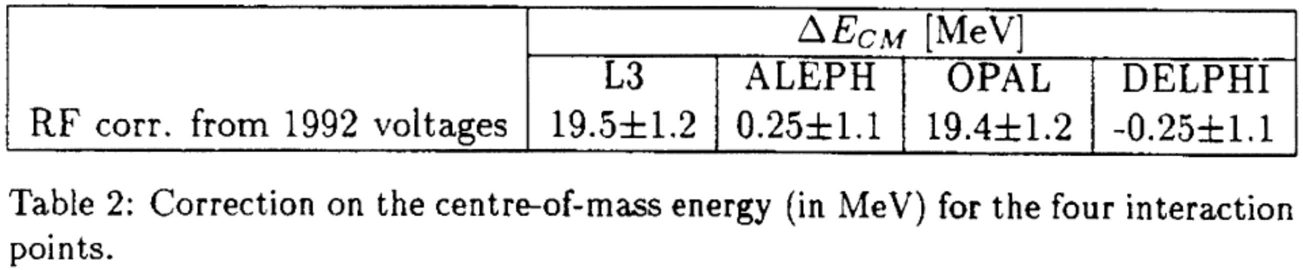
preparing the 1991 scan results for Moriond 1992
G. Quast from OPAL (+M. Hildreth & others)
noticed this discrepancy and started investigation
within the LEP energy calibration WG.

Effect of RF phases and voltages discovered after the fact!



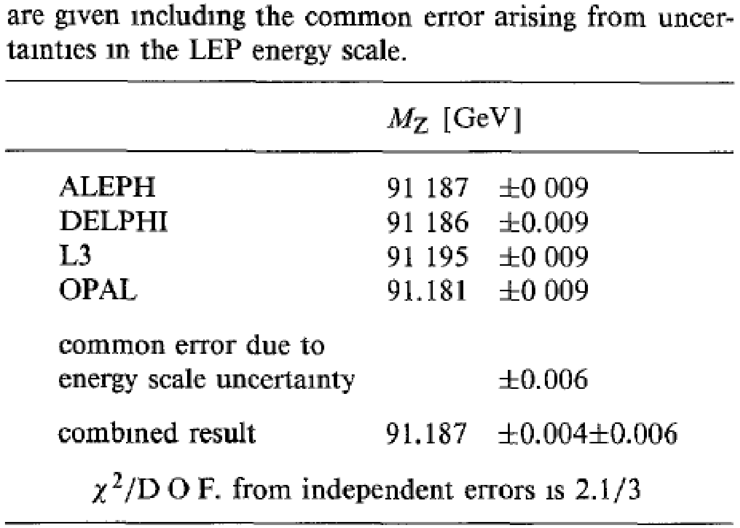
Physics Letters B 307 (1993) 187–193

CERN SL/93-21 (DI)



	ΔE_{CM} [MeV]			
	L3	ALEPH	OPAL	DELPHI
RF corr. from 1992 voltages	19.5±1.2	0.25±1.1	19.4±1.2	-0.25±1.1

Table 2: Correction on the centre-of-mass energy (in MeV) for the four interaction points.



are given including the common error arising from uncertainties in the LEP energy scale.

	M_Z [GeV]	
ALEPH	91.187	±0.009
DELPHI	91.186	±0.009
L3	91.195	±0.009
OPAL	91.181	±0.009
common error due to energy scale uncertainty		±0.006
combined result	91.187	±0.004±0.006

χ^2/D.O.F. from independent errors is 2.1/3

THIS could have remained unnoticed for a long time (or forever)
if there had been only

ALEPH and DELPHI
-- or –
OPAL and L3

around the ring!

Similar issues could occur in a 2IP machine in case of unexpected energy loss (impedance) in one of the rings.

This illustrates the competitive collaboration between the four LEP experiments and collaboration with the accelerator team

Precision measurements -- examples

Many key measurements lead to new detector systematics. Three examples:

-- **R_ℓ (Z) $\equiv \Gamma_{Z\to had} / \Gamma_{Z\to leptons}$** : dominated by knowledge of acceptance boundary at 10 μm level → $\alpha_s(m_Z)$

-- **σ^0_{had}** (peak hadronic cross-section); dominated by luminosity meast (acceptance boundary at 1 μm) → N_ν

-- **tau life-time, tau mass & tau branching ratios** –> G_F from taus at O(10^{-5}) precision (heavy neutrino mixing etc..)
Errors dominated by life-time scale error (few nm), detector momentum scale (10^{-6}), lepton separation

For all of these, detector systematics will scale as 1/√N(exp) *AND* 4 exp will be instrumental in finding ‘unexpected effects’

Accelerator monitoring

NEW wrt LEP!

70kHz of events in each detector will allow very quick and high quality *measurement* of beam parameters

-- IR position in x,y,z and size in x,z (indirectly in y from intensity and luminosity)

-- CM boost → energy spread and (E_{e+}-E_{e-}) with high precision (2 MeV every second, 30 keV every hr)
at four IR points

-- crossing angle of *colliding particles* in x,z plane (in y, if any) and possible deflection in y,z.

-- measurement of these parameters within bunch in x and z directions

-- others we haven't thought about.

Huge amount of information on energy model and beam properties.
Will be enriched further with four detectors and four experimental teams

see arxiv:1909.12245

At the limit of sensitivity: feebly coupled particles and forbidden processes

Heavy Neutrinos

Massive Neutrinos is today the construction zone of the Standard Model

The search for Heavy neutrinos, motivated by the see-saw model (Dirac *and* Majorana mass terms) has become an active branch of the Energy Frontier. We noted this already in 2013 (see FCC Kick-off meeting!)

The main region of interest is for couplings of magnitude $m_\nu/m_N = O(10^{-12})$.

Complementary with FCC-hh where Lepton Number Violation is "easier" to see...

➔ potentially of great impact on the design of FCC-hh detectors.

Dark Sector

The heavy neutrinos are almost sterile and constitute the poster child of a generic type of dark sector solutions to SM puzzles invoking feebly coupled particles. These have the added benefit of not affecting the SM radiative corrections and running of coupling constants thus avoiding associated hierarchy problem and Stability of the Universe

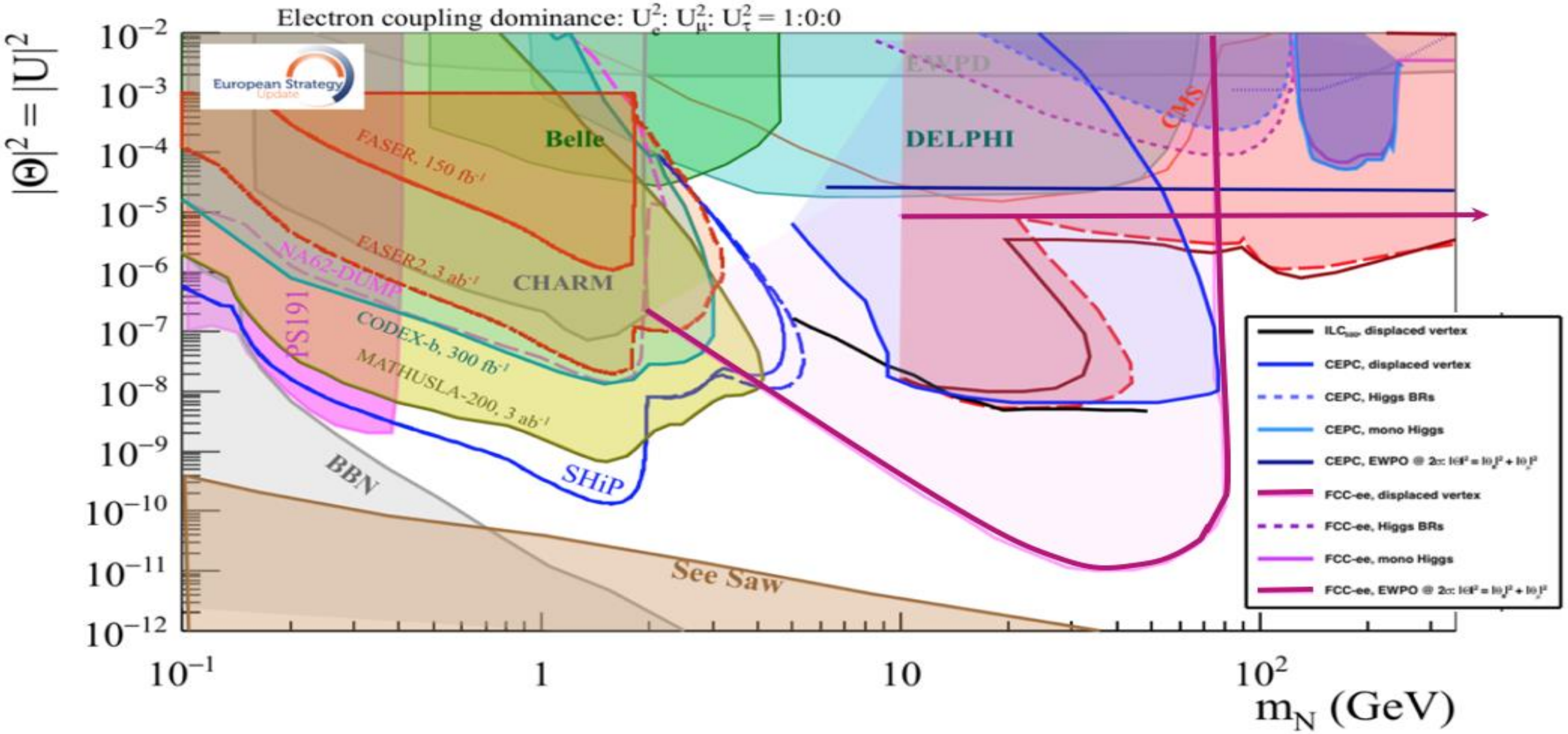
A good example is given by Axion-Like Particles (ALPs).

Any increase of luminosity is welcome!

This picture from the briefing book is relevant to Neutrino, Dark sectors and High Energy Frontiers.

FCC-ee (Z) compared to the other machines for right-handed (sterile) neutrinos

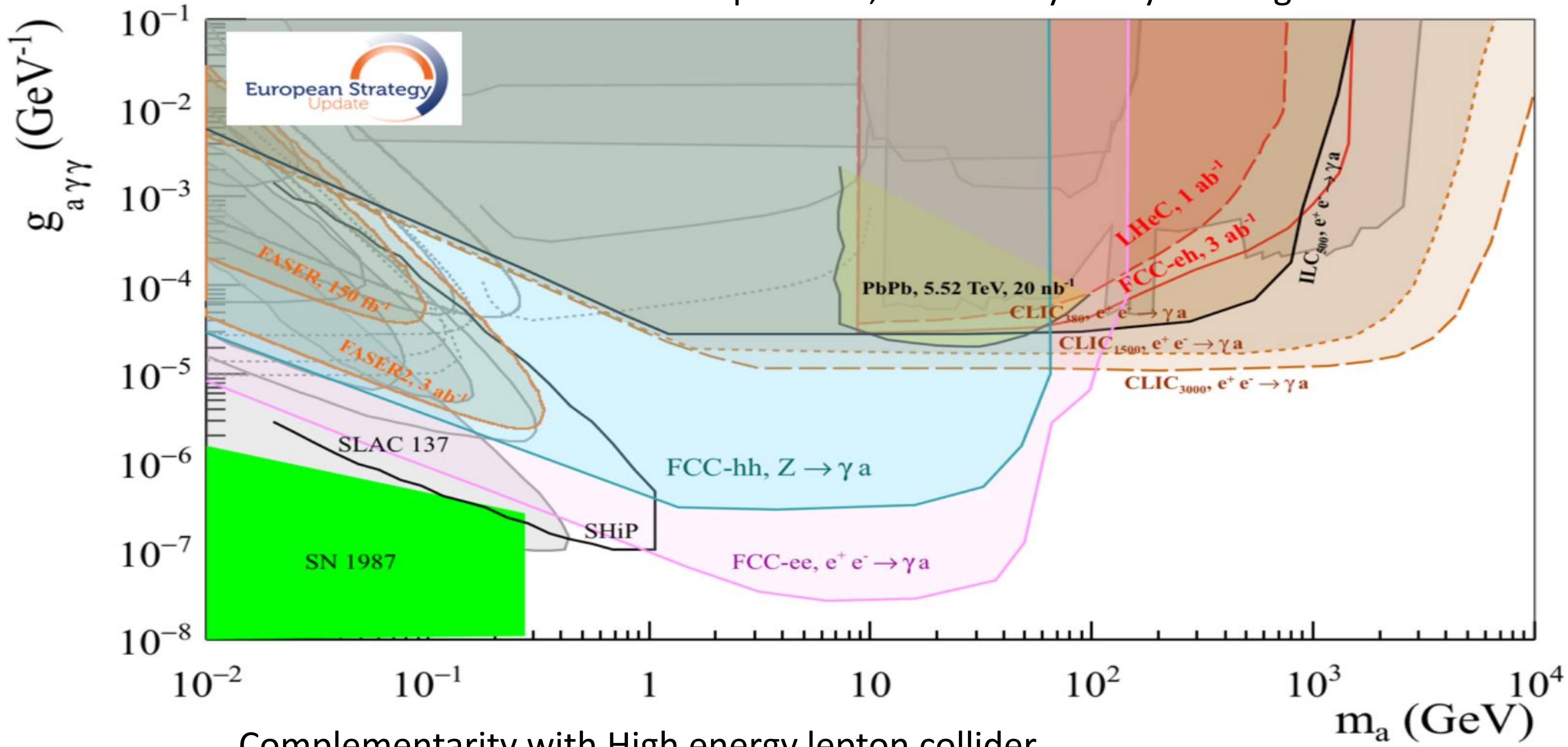
How close can we get to the 'see-saw limit'? can we improve acceptance and reach?



-- the purple line shows the reach for observing **heavy neutrino decays** (here for 2.10^{12} Z)

-- the horizontal line represents the sensitivity to **mixing of neutrinos** to the dark sector, using EWPOs (G_F vs $\sin^2\theta_W^{eff}$ and m_Z, m_W, tau decays) which extends sensitivity to 10^{-5} mixing all the way to very high energies (500-1000 TeV at least). arxiv:2011.04725

Similar situation for Axion-like-particles; Luminosity is key to the game



Complementarity with High energy lepton collider,
much to explore at FCC-ee-Z and FCC-hh!

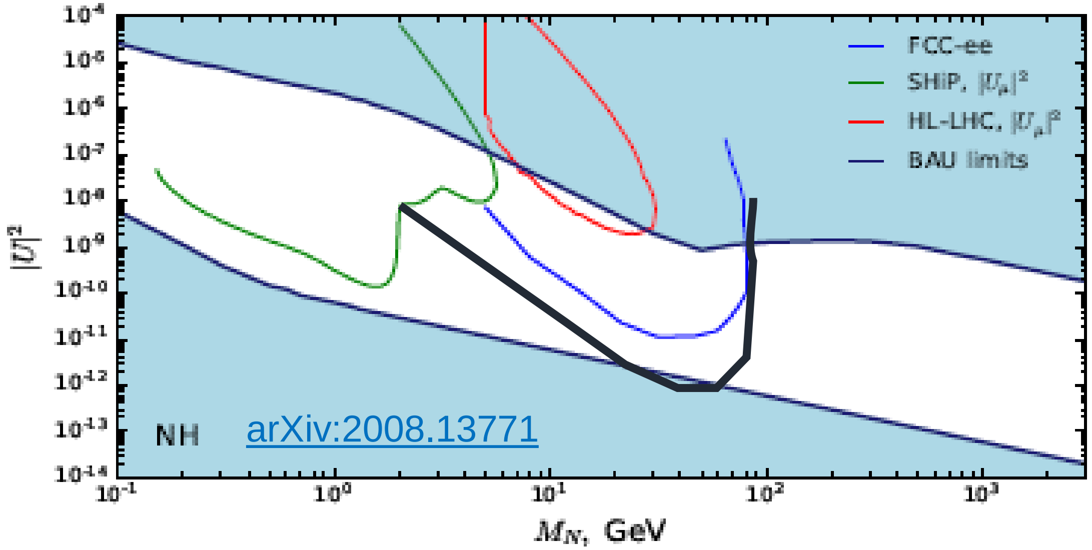
For right-handed-neutrino HNLs, the region of greatest interest is the parameter set which is consistent with the see-saw mechanism and with the leptogenesis over the largest possible range of Rhnu mass.

FCC-ee study from 2014 show that the see-saw line can be reached with a Z run of **10^{13}Z.** Z→ νν is 20%, N→ $\ell^{\pm}$ W* is 50%. (1/(10^{13} x 0.2 x2 x0.5 (x$0.5_{\mathrm{acc,kin}}$) = 10^{-12})

1. for Long Lived Particles, no significant source of background identified at this point

2. It may take of $\mathcal{O}$(100) evts to establish the Fermion Number Violating nature of the discovered HNL. (work in progress, probably in central detector only)

3. This search might have large impact on the design of the FCC-hh detectors!

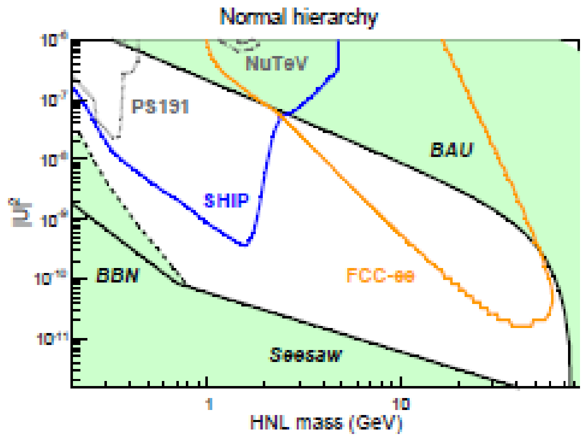


These 'common plots' only refer to 2.10^{12} Z

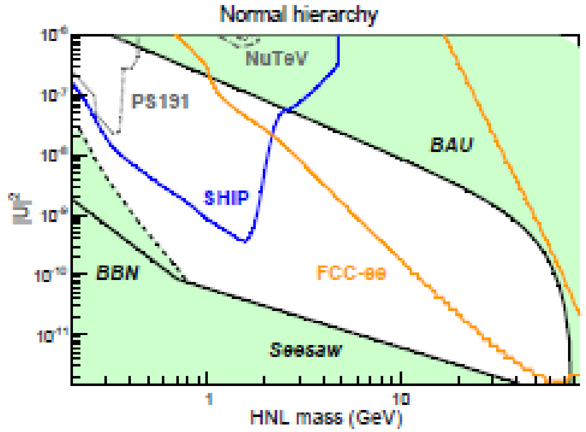
.

-- Approx 4IP line 1 evt (M. Drewes, J. Hijer)

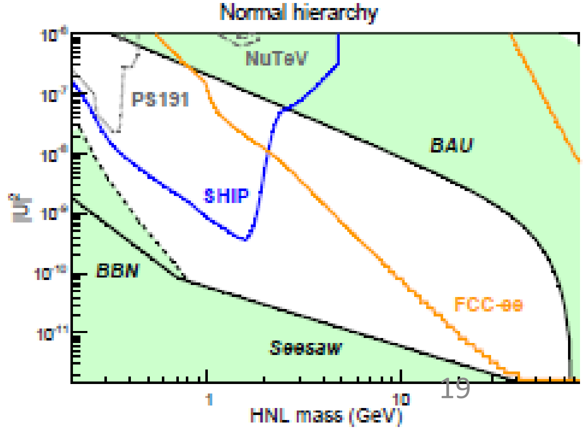
More integrated luminosity → more chance of discovery of HNL and LNV!!!



(a) Decay length 10-100 cm, 10^{12} Z^0



(b) Decay length 10-100 cm, 10^{13} Z^0



Heavy Flavour Physics

Flavour (number of families, spectrum, quark-lepton correspondance etc...) is a great mystery for HEP.

FCC-ee is of special relevance for b and t quark as well as τ lepton physics (unique among ‘Higgs Factories’)

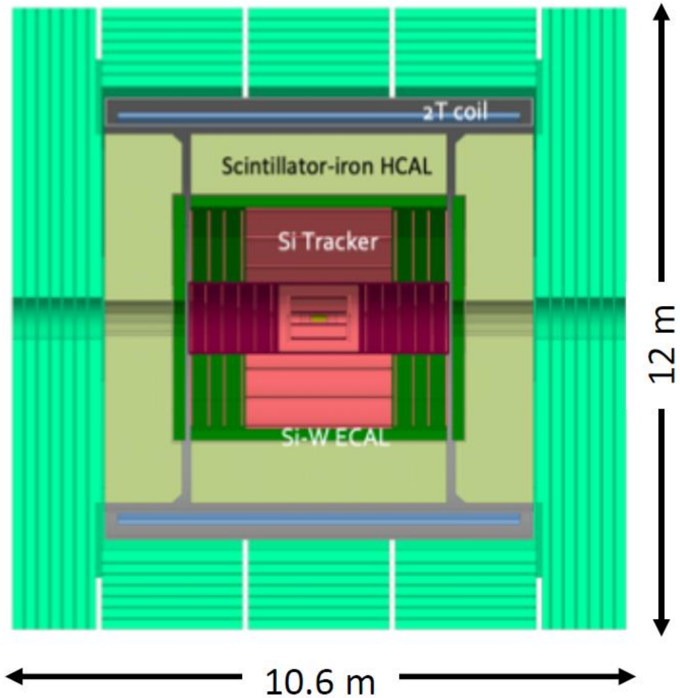
at the Z very large samples of highly boosted:
B hadrons of all type (10^{12})
tau leptons (1.510^{11})
at the W and above: 310^{8} W decays for direct measurements of V_{cb} and V_{cs}

Many analyses are statistics limited
-- *CP* violation, b, c and tau rare decays, will benefit of an increase of statistics.
-- and τ precision measurements will benefit both from statistics and of the increased number of detectors
-- One of the repeated conclusion of Flavours discussion in Granada ESPP was “**at least** 5 10^{12} Z” desirable (more = better)

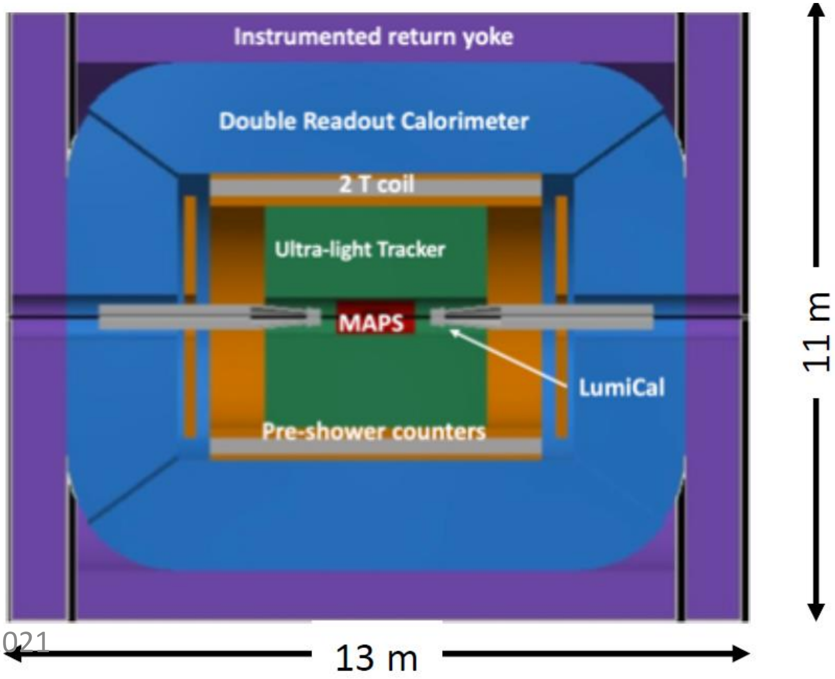
Detector requirements are varied with many new things w.r.t. ‘Higgs Factory’ and precision measurements
hadron particle ID, high resolution e/γ calorimeter etc. (top physics likely to change « color » with these added features)
Some incompatibility with each other or with EW precision measurements or particle flow
➔ **need several different detectors to explore the full physics program**

The heavy flavor community is both
-- numerous (2000 members between BELLE II and LHCb)
-- highly competent ... and with high expectations

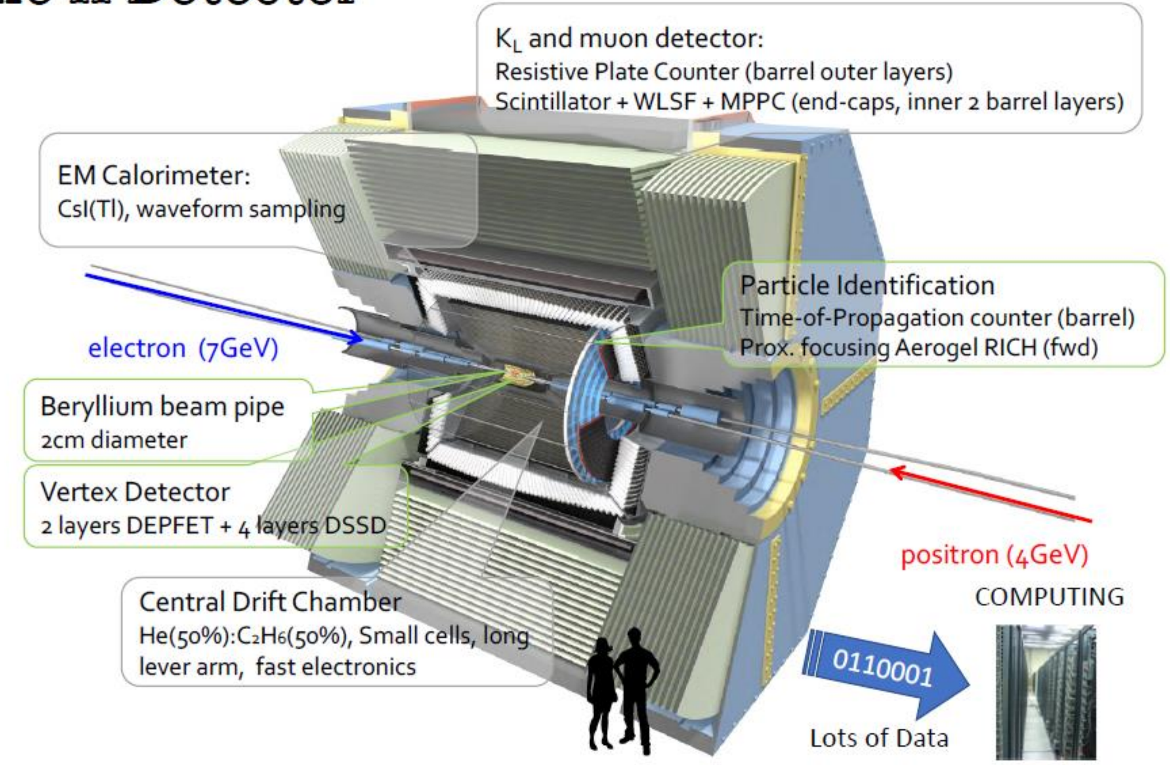
CLD



IDEA



Belle II Detector



These detectors look similar at first sight BUT

-- different coil location

-- different tracker (silicon vs drift chamber)

-- dedicated PID (TOP CKOV, TOF, dE/dx)

-- EM calorimeter

High Energy resolution vs high granularity vs Energy flow

-- Hadron calorimeter (scintillator vs RPC vs...)

Intense studies in the next ~5 years!

CP violation / CKM program:

Two categories of the most important statistically limited observables :

-- The CP-violating phases γ and the ϕ_s phase.
Determined at the *Z* pole, the precision w/ 5 10^{12} Z is commensurate w/ LHCb upgrade II.

-- The Vcb CKM matrix element magnitude: a critical element of the CKM profile (normalisation) but also a key element of the New Physics energy scale one can set from *B* mixing observables.

FCCee is unique here with the on-shell W decays (FCC-ee at W threshold and higher energies)
Any statistical gain translates into a higher NP energy scale.

Rare decays

Taking an increasingly important role in the BSM model buildings (following LHCb anomalies):

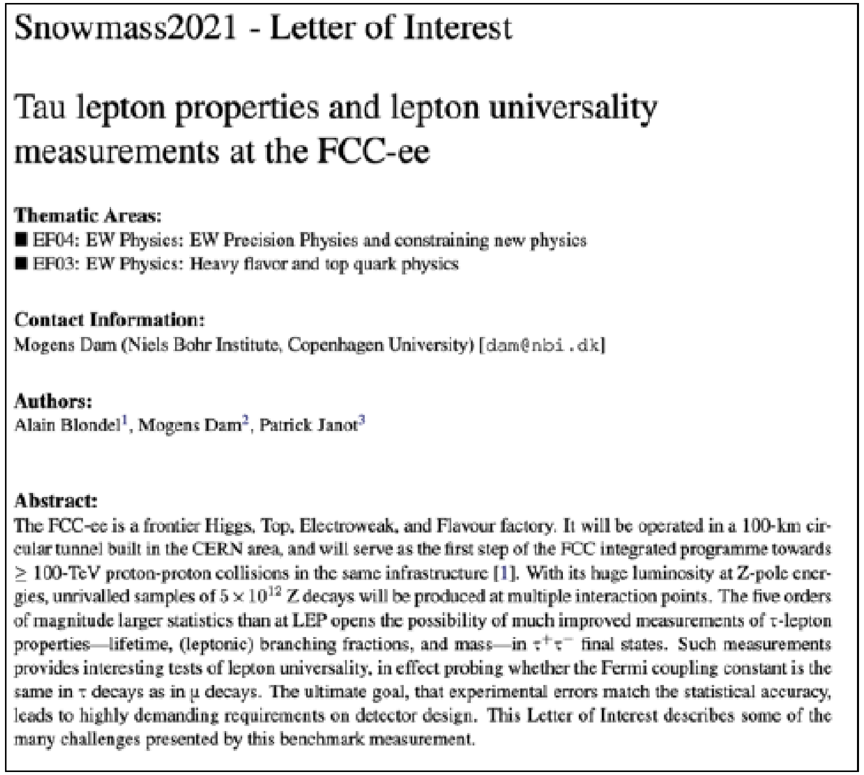
The helicity-suppressed leptonic decays $B^0 \rightarrow \mu^+\mu^-$ and $B_s \rightarrow \tau^+\tau^-$ are SUSY-killers (drivers). Both benefit from the luminosity increase.

The semileptonic $b \rightarrow s\ell\ell$: the transitions with tau leptons benefit most from the luminosity increase. They are instrumental in exploration of Lepton-Flavour-Universality violating (LFV) models and a motivation per se of any Flavour program.

The rare many-bodies tau decays are also directly limited by statistics.

The tau rare/forbidden decay modes are all benefitting from 4 IPs **LFV $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow 3\ell$ (critical on tracking)**

τ-lepton properties and Lepton Universality



Snowmass2021 - Letter of Interest

Tau lepton properties and lepton universality measurements at the FCC-ee

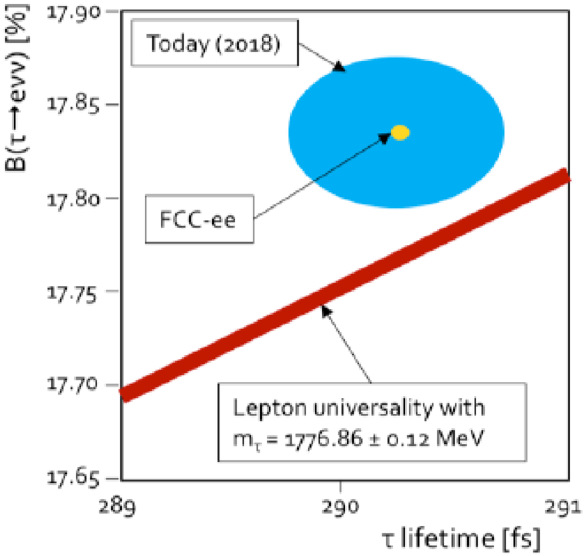
Thematic Areas:
■ EF04: EW Physics: EW Precision Physics and constraining new physics
■ EF03: EW Physics: Heavy flavor and top quark physics

Contact Information:
Mogens Dam (Niels Bohr Institute, Copenhagen University) [`dam@nbi.dk`]

Authors:
Alain Blondel[1], Mogens Dam[2], Patrick Janot[3]

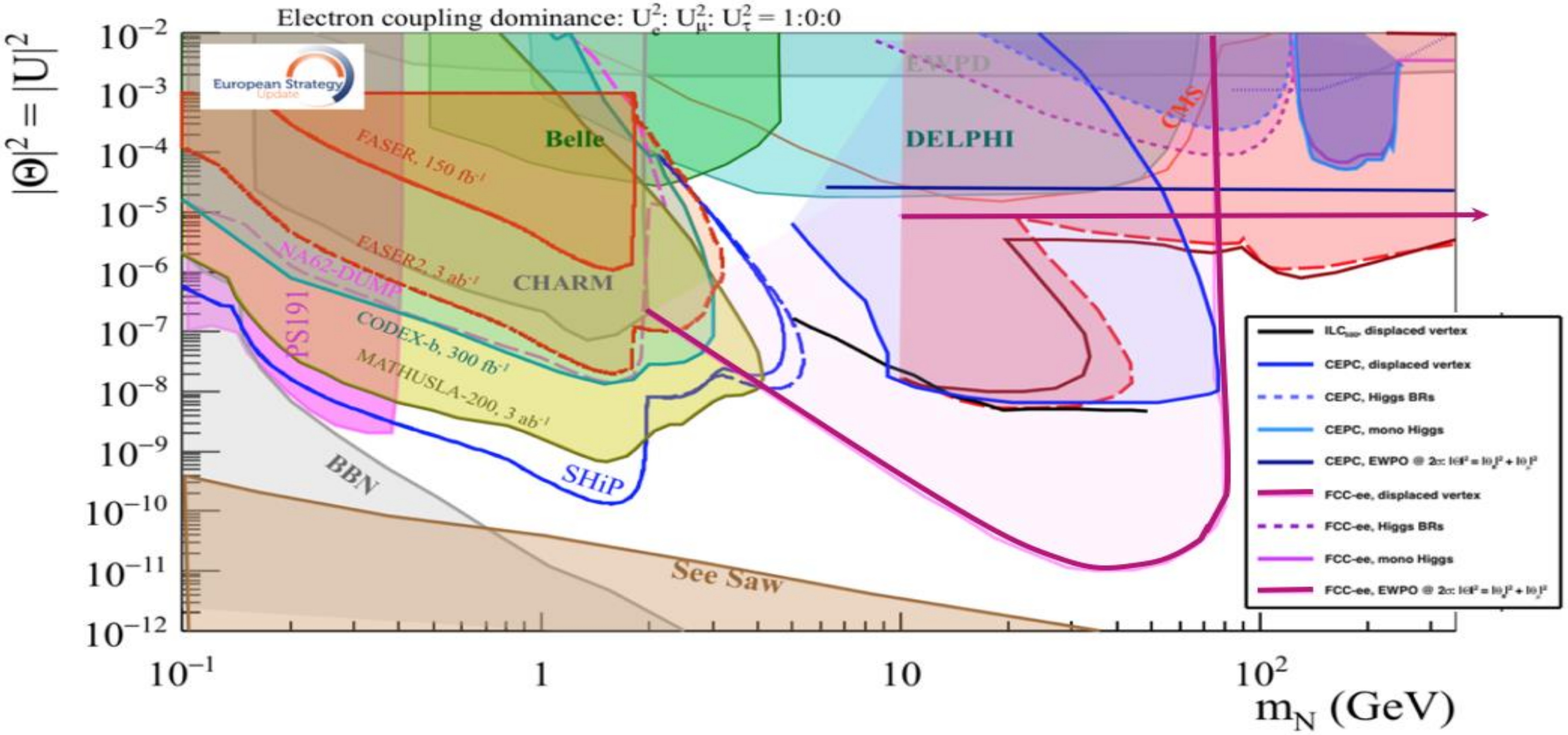
Abstract:
The FCC-ee is a frontier Higgs, Top, Electroweak, and Flavour factory. It will be operated in a 100-km circular tunnel built in the CERN area, and will serve as the first step of the FCC integrated programme towards ≥ 100-TeV proton-proton collisions in the same infrastructure [1]. With its huge luminosity at Z-pole energies, unrivalled samples of 5×10^{12} Z decays will be produced at multiple interaction points. The five orders of magnitude larger statistics than at LEP opens the possibility of much improved measurements of τ-lepton properties—lifetime, (leptonic) branching fractions, and mass—in $\tau^+\tau^-$ final states. Such measurements provides interesting tests of lepton universality, in effect probing whether the Fermi coupling constant is the same in τ decays as in μ decays. The ultimate goal, that experimental errors match the statistical accuracy, leads to highly demanding requirements on detector design. This Letter of Interest describes some of the many challenges presented by this benchmark measurement.

a) Mass
b) Lifetime
c) Leptonic branching fractions



The ultimate e/mu/tau universality test: targets G_F from taus at $O(10^{-5})$ precision
extremely demanding on lifetime meast, momentum scale precision and e/mu separation $(1/\sqrt{N_{exp}})$
→ sensitive to heavy neutrino mixing with the ν_τ up to very high mass scale (>> 50 TeV)

This picture from the briefing book is relevant to Neutrino, Dark sectors and High Energy Frontiers.
FCC-ee (Z) compared to the other machines for right-handed (sterile) neutrinos
How close can we get to the 'see-saw limit'? can we improve acceptance and reach?



-- the purple line shows the reach for observing **heavy neutrino decays** (here for 2.10^{12} Z)
-- the horizontal line represents the sensitivity to **mixing of neutrinos** to the dark sector, using EWPOs (G_F vs $\sin^2\theta_W^{eff}$ and m_Z, m_W, tau decays) which extends sensitivity to 10^{-5} mixing all the way to very high energies (500-1000 TeV at least). arxiv:2011.04725

Conclusion(I): FCC-ee really calls for four interaction points

One of the great advantages of the circular e+ e- colliders is:
-- The possibility of serving several interaction points with net overall gain
both in integrated luminosity **and** luminosity/MW.

The FCC-ee is a machine with a very rich menu of physics possibilities
-- precision measurements that will rebaseline particle physics for many years
on Higgs, top, Electroweak, QCD and Flavour Physics
-- significant chances of discovery from precision, rare processes and high sensitivity to feebly coupled particles
-- several will impact FCC-hh physics results and detector design
-- High luminosity, redundancy and careful preparation of detector set-ups will be key to success
-- many measurements are statistics limited and will immediately benefit from four Interaction points.
-- several key physics targets are tantalizingly close (but missed) with the present set-up

Having four IPs will allow for a range of detector solutions to cover FCC-ee all physics potential opportunities
-- example: EM calorimeter requirements (high precision vs high granularity vs high stability vs geometric accuracy vs PID vs cost)
unlikely to be all satisfied with only two detector concepts.
-- different solutions will be invaluable in uncovering hidden systematic biases and avoid conspiracy of errors.
-- and provide an attractive challenge for all skills (detector design and R&D, software, analysis, theory...)

Conclusion(II): FCC-ee should be fully designed for 4IP

After review with the FCC Physics Experiments and Detectors coordination group
we have concluded emphatically that FCC-ee should be designed for four interaction points.

--- It will always be time to revert to two if absolutely necessary – the reverse is not true

so as to be able to
-- adapt to the guidelines resulting of the full exploration of the physics potential taking place in the next ~5 years
-- increase the interest of the community for the FCC;
eventually adapt to its resouces and size, and the quality of its proposals

➔THIS SHOULD NOT PRECLUDE CONSTANT EFFORTS TO INCREASE THE LUMINOSITY per IP