Precision measurements at FCC-ee

requirements on theor and experiments

Motivation (well known)

for the precision measurements and associated precision calculations

1. given that the SM is complete with the Higgs discovery, how do we find out:
-- if the Higgs boson is exactly what is foreseen by the standard model, shifting the energy levels of the whole universe to generate particle masses?
-- where/what are the new physics phenomena that must be present to explain:
baryon asymmetry
dark matter,
neutrino masses (and other mysteries we don't understand)

2. one of the most powerful and broadly efficient methods is to perform **precision measurements** at a level that will establish the Higgs boson properties and could be sensitive to new physics:
-- this requires identification of the **observables** that contain sensitivity to new phenomena, either by loops, direct long distance propagator effects, or mixing with known particles.
-- then requires high precision theory both to extract these observables in a precise way from experiment, and high precision calculations to compare with the theory
-- this also requires precise measurements of ancillary quantities (alpha_QED, gHZZ or TTZ couplings) that will be used for other precise measurements
-- and require themselves high precision theory to be extracted from experiment.

-- this requires identification of the **observables**

Theory and experiment communicate by way of observables

or pseudo-observables that are extracted from experimental measurements using well defined and minimally model-dependent prescriptions.

This was possible at LEP Z and W for such things as QED corrected line-shape parameters and cross-sections, ➔ mass, width, peak cross-section, partial widths or branching ratios, polarization or forward-backward cross-section asymmetries

model dependence was that

1) **QED is correct;**
2) **weak interaction is V,A (or L,R)**
3) **final states are e mu tau, invisible, hadrons (including b, c)**
4) **other possible final states had been searched exclusively**

This was well adapted to the problems of the day:

-- what are the masses of top and Higgs

-- is there evidence of new physics in loops? In particular: is there breaking of SU(2) custodial symmetry ($\rho_0 \neq 1$) ?

One very common source of confusion is the **definition of the weak mixing angle**

-- for the sake of calculations it is often practical for theorists to define (rather, note)

(1) $\sin^2\theta_W = 1 - \frac{m_W{}^2}{m_Z{}^2}$

experimenters: at high energy this is a completely useless quantity ,
redundant with the measurements of masses of W and Z. **FORGET THIS, PLEASE.**

The SM lagrangian also introduces the electric charge e and the weak coupling g, and

$\sin\theta_W = \frac{e}{g}$

this is never measured as such, but the following closely related quantity is obtained from the chiral couplings

$g_{R,L} = I^3 - Q \sin^2\theta_W^{eff}$ ➔ for electron : $g_{Re} = - e \sin^2\theta_W$, $g_{Le} = - 1/2 - e \sin^2\theta_W$

observables will be all Z pole asymmetries

$$\mathcal{A}_f = \frac{g_{L,f}^2 - g_{R,f}^2}{g_{L,f}^2 + g_{R,f}^2} = \frac{2 v_f a_f}{a_f^2 + v_f^2}.$$

$$A_{LR} = \mathcal{P}\mathcal{A}_e \,, \quad \text{and} \quad A_{FB,pol}^f = \frac{3}{4}\mathcal{P}\mathcal{A}_f.$$

↑ with beam polarization P

or without→

$$A_{FB}^f = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \,, \quad \langle P_\tau \rangle = -\mathcal{A}_\tau \,, \quad \text{and} \quad A_{FB,pol}^\tau = \frac{3}{4}\mathcal{A}_e \,.$$

Thus at LEP we defined **$\sin^2\theta_W^{eff}$ as the short hand notation for the electron chiral coupling asymetry** or **$\sin^2\theta_W^{eff} = ¼(1-g_{Ve}/g_{Ae})$**

$$A_{FB}^{f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f\,, \quad \langle P_\tau \rangle = -\mathcal{A}_\tau\,, \quad \text{and} \quad A_{FB,pol}^{\tau} = \frac{3}{4}\mathcal{A}_e\,.$$

NB this enters in all A_{FB}s (leptons, b,c,qs) as driving term in heavy physics sensitivity because the Z is initially polarized due to the electron coupling asymmetry.

Theoretial tasks

1. identify observables that contain sensitivity to new phenomena, either by

loops → Universal (in photon, Z, W propagators) → S,T,U

loops → flavour dependent (in boxes and vertices) → δ_b

direct long distance propagator effects, (ex: new Z') flavour, or quark lepton univ. violation

mixing with known particles (Z'-Z mixing , ν-N mixing)

neutrino and flavour dependent violations,

2. high precision SM theory to extract these observables in a precise way from experiment

(precise QED, QCD Monte-Carlo or ISR radiator)

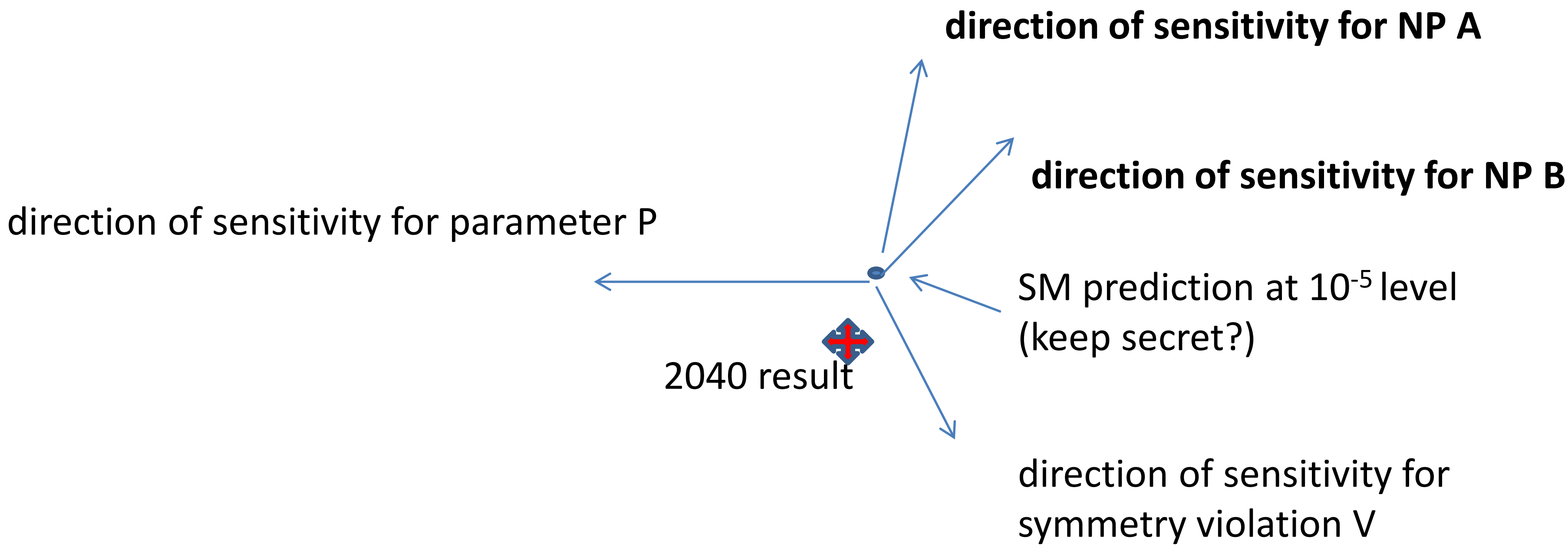
3. high precision calculations of observables in SM to compare with experiment

precise multi-loop SM calculation starting from m_Z , G_F , α_{QED} (mz), α_{QCD} (mz), m_H , m_t $\{m_f\}$

-- this also requires precise measurements of ancillary quantities (alpha_QED, mt, etc) that will be used for other precise measurements

-- and require themselves high precision theory to be extracted from experiment.

please produce this in 2038 for as man observables as possible
(Sensitiities earlier to optimize run plan)



PRECISION

The most solid inputs to this disussion are
-- statistics
-- time scale
see next slides.

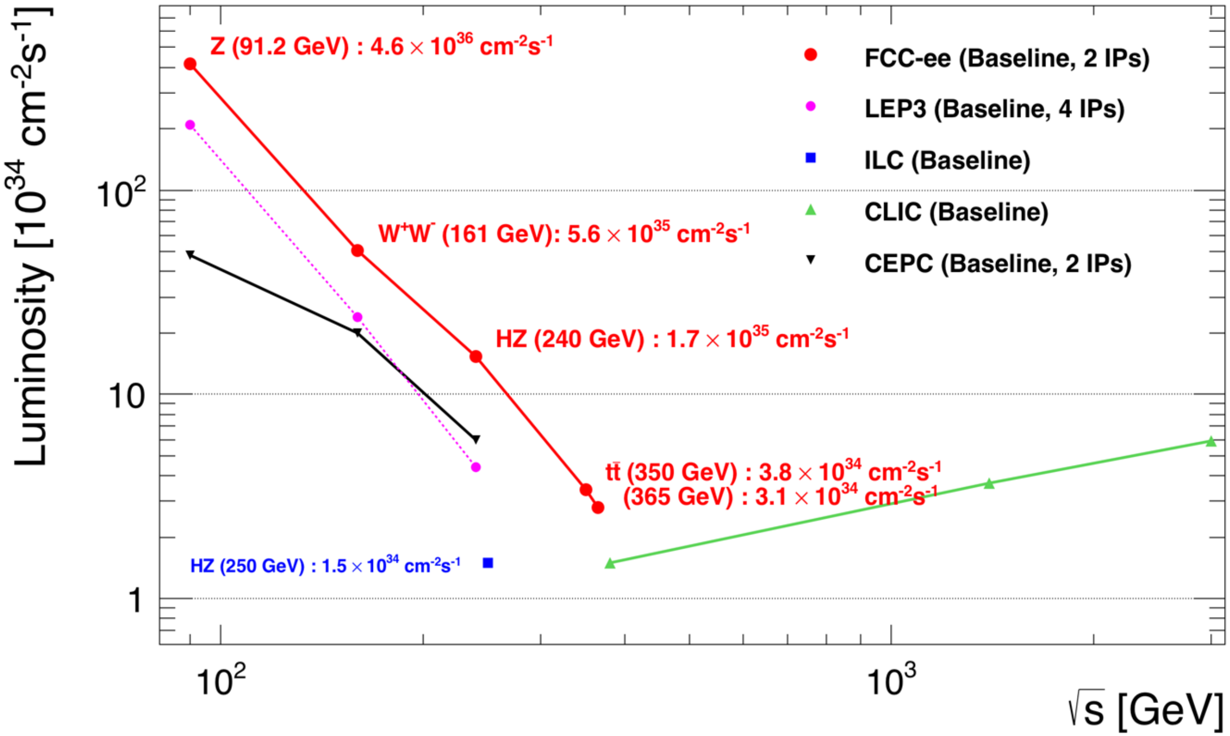
In practice we can give with some confidence the statistical uncertainties, both for experimental observables and ancillary parameters

In the CDR we give a set of 'estimates' for systematics which are (not totally consistently)
-- either 'we are sure we an do better than that'
-- or ' we think it will take some work to go beyond this level and we dont know where we will arrive'.

➔ our goal is to reduce both experimental and theory systematics as far as possible.
➔ <u>'statistics is the limit'</u>

FCC-ee

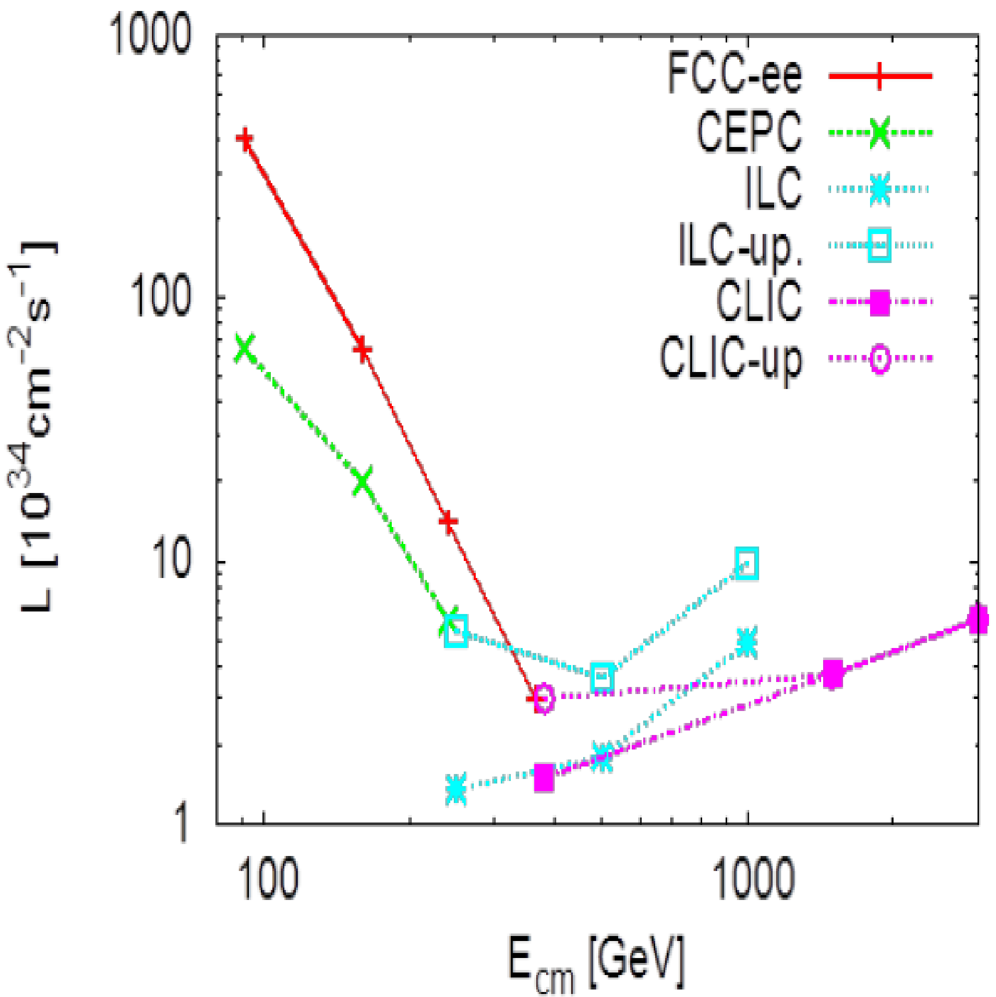
Z WW HZ tt



Event statistics :

					E_{CM} errors:
Z peak	E_{cm} : 91 GeV	$5\ 10^{12}$	e+e- → Z	LEP x 2.10^5	<100 keV
WW threshold	E_{cm} : 161 GeV	10^8	e+e- → WW	LEP x 2.10^3	<300 keV
ZH threshold	E_{cm} : 240 GeV	10^6	e+e- → ZH	Never done	2 MeV
$\overline{t}t$ threshold	E_{cm} : 350 GeV	10^6	e+e- → $\overline{t}t$	Never done	5 MeV

the LEP statistics of 1.6 10^7 hadronic Z's will be rpoduced in 200 seconds at FCC-ee(Z)



Great energy range for the heavy particles of the Standard Model
COMPLEMENTARITY WITH LINEAR COLLIDERS (ILC, CLIC) overlap 300-400 GeV
certainly could imagine a world with 1 circular lab and 1 linear lab!

FCC-ee run plan

Table 2.1: Run plan for FCC-ee in its baseline configuration with two experiments. The number of WW events is given for the entirety of the FCC-ee running at and above the WW threshold.

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events

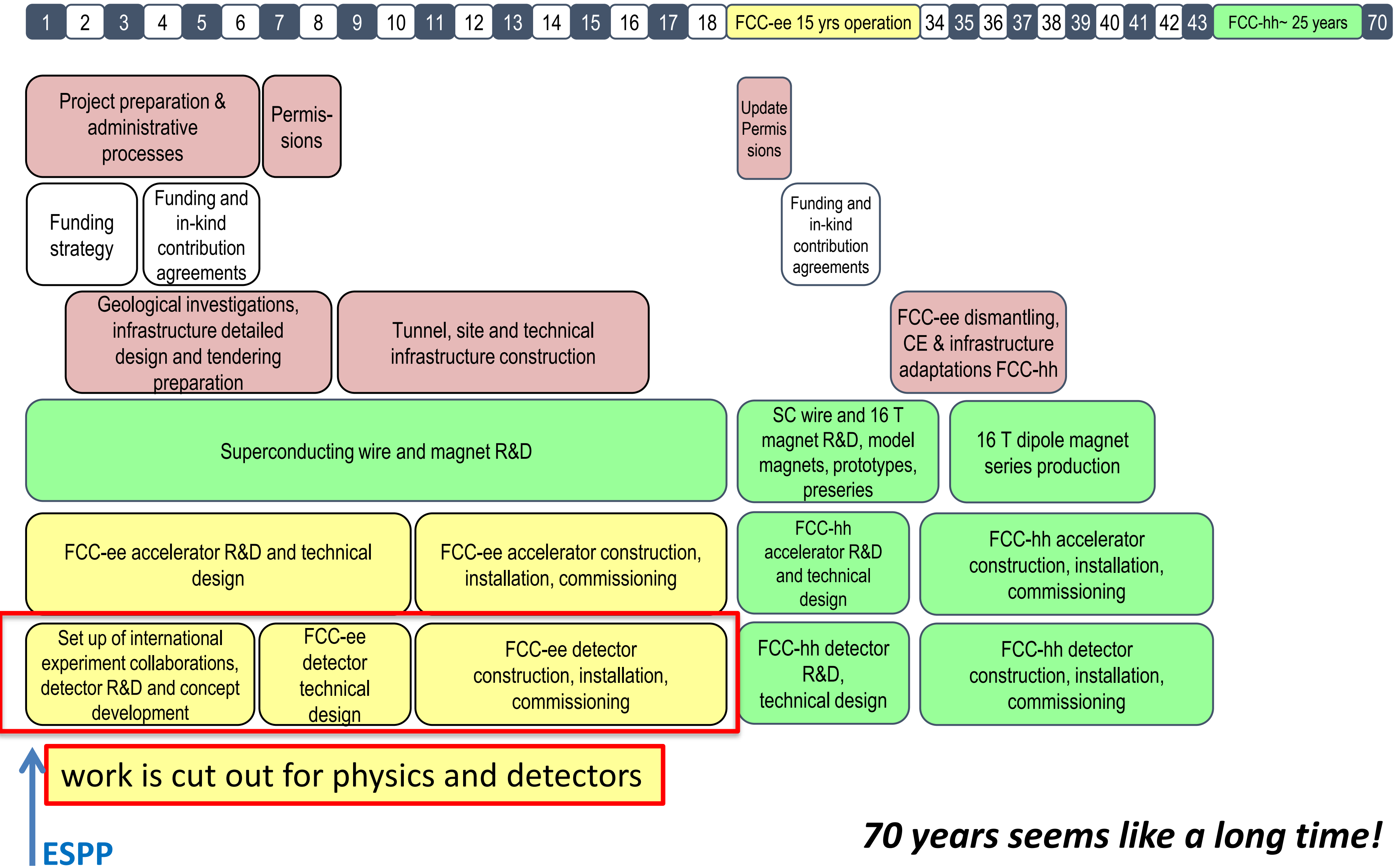
from the CDR

1. Obviously this is a working assumption; order of Z,W and H points can be changed, this will all be decided close to turn on.

2. e+e- → H (ECM = m_H) unique, not in the schedule so far.

3. Transerse polarization → precision beam energy.
Longitudinal possible (for both beams) but not in CDR by choice

FCC integrated project timeline



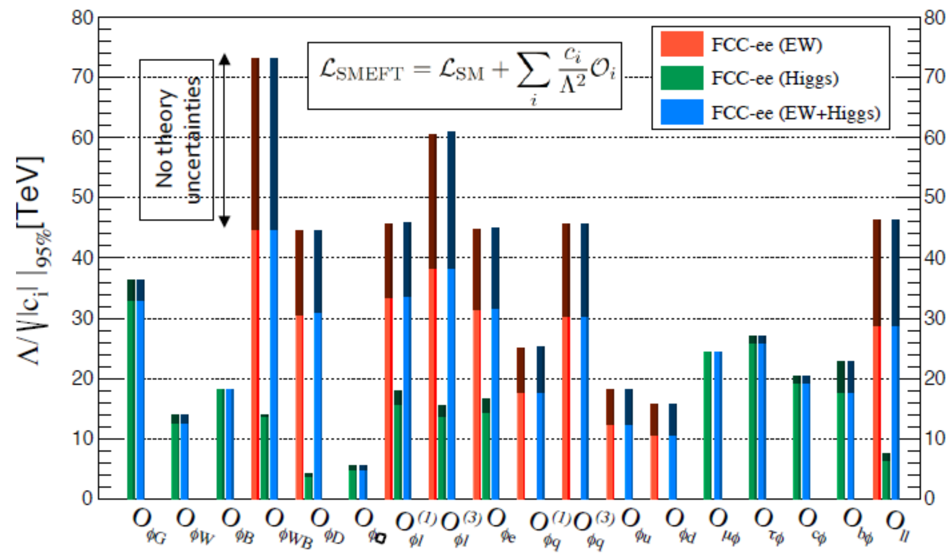
70 years seems like a long time!

Examples

Table 3.1: Measurement of selected electroweak quantities at the FCC-ee, compared with the present precisions.

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV/c^2)	91186700 ± 2200	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	8	100	From Z line shape scan Beam energy calibration
R_ℓ^Z ($\times 10^3$)	20767 ± 25	0.06	0.2-1	ratio of hadrons to leptons acceptance for leptons
$\alpha_s(m_Z)$ ($\times 10^4$)	1196 ± 30	0.1	0.4-1.6	from R_ℓ^Z above [29]
R_b ($\times 10^6$)	216290 ± 660	0.3	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [30]
σ^0_{had} ($\times 10^3$) (nb)	41541 ± 37	0.1	4	peak hadronic cross-section luminosity measurement
N_ν ($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{\mathrm{eff}}$ ($\times 10^6$)	231480 ± 160	3	2 - 5	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\mathrm{QED}}(m_Z)$ ($\times 10^3$)	128952 ± 14	4	small	from $A_{FB}^{\mu\mu}$ off peak [20]
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{\mathrm{pol},\tau}$ ($\times 10^4$)	1498 ± 49	0.15	<2	τ polarisation and charge asymmetry τ decay physics
m_W (keV/c^2)	80350000 ± 15000	600	300	From WW threshold scan Beam energy calibration
Γ_W (keV)	2085000 ± 42000	1500	300	From WW threshold scan Beam energy calibration
$\alpha_s(m_W)$ ($\times 10^4$)	1170 ± 420	3	small	from R_ℓ^W [31]
N_ν ($\times 10^3$)	2920 ± 50	0.8	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	20	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	40	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\mathrm{top}}/\lambda_{\mathrm{top}}^{\mathrm{SM}}$	1.2 ± 0.3	0.08	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	<2%	small	From E_{CM} = 365GeV run

Pecision EW measurements:
is the SM complete?



-^- EFT D6 operators (some assumptions)

-^- Higgs and EWPOs are complementary

-^- top quark mass and couplings essential!

(the 100km circumference is optimal for this)

<-- many systematics are preliminary
and should improve with more work.

<-- tau b and c observables still to be added

<-- complemented by high energy FCC-hh

Theory work is critical and initiated

status as of briefing book
still based on (conservative)
experimental and theory errors:

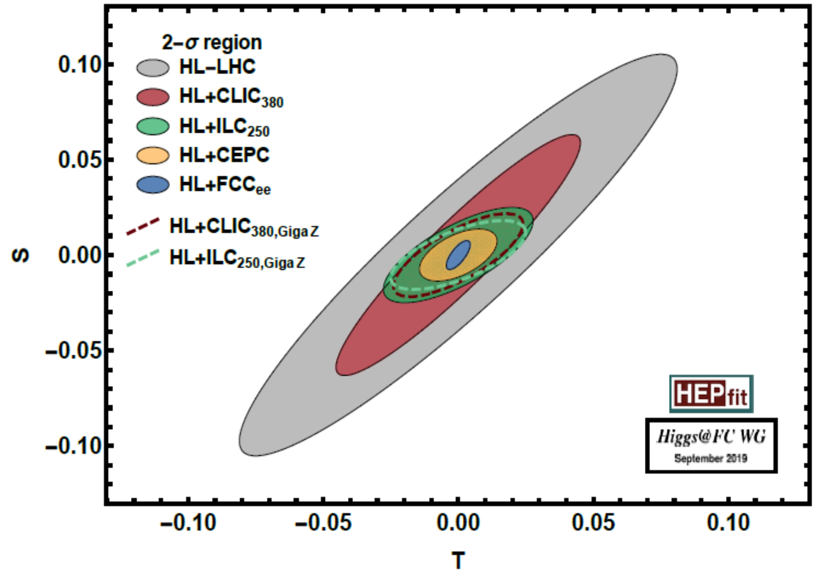
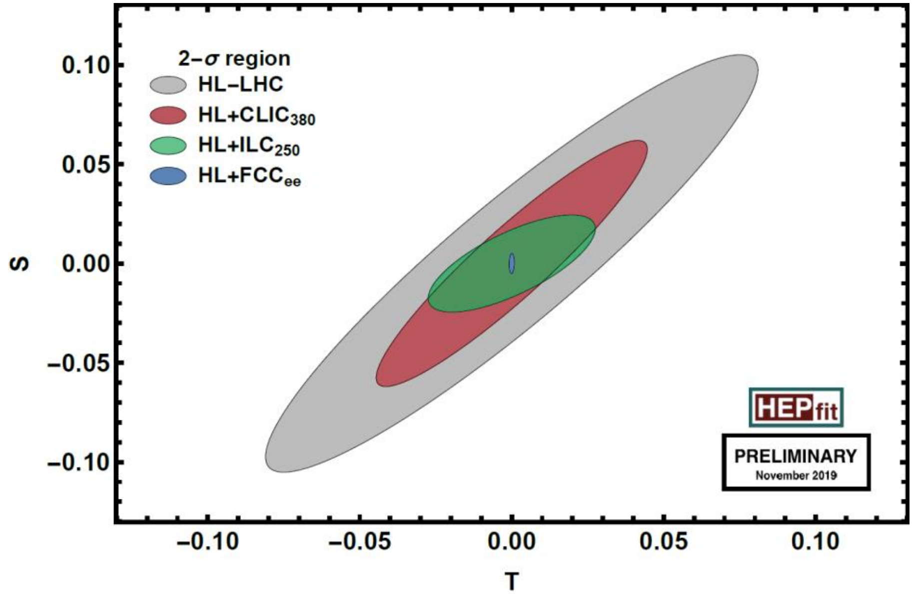


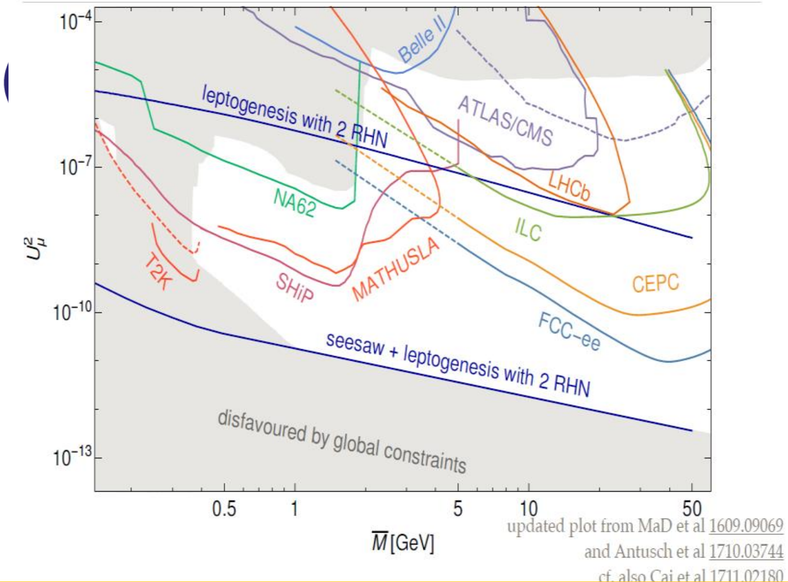
Fig. 3.7: Expected uncertainty contour for the S and T parameters for various colliders in their first energy stage. For ILC and CLIC the projections are shown with and without dedicated running at the Z-pole. All other oblique parameters are set to zero.

our goal: work out systematics
until we reach statistical level:

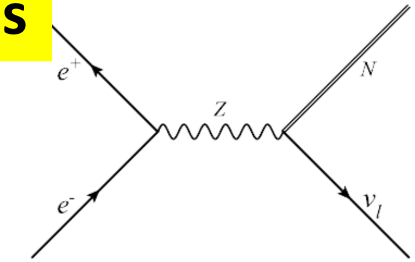
(a lot of work to do!)



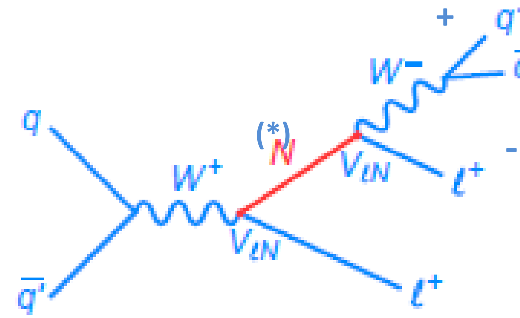
Heavy neutrinos



FCC-ee Z



FCC-hh



or $l^{\pm}\nu$

<u>FCC-ee</u>

-- EWPO : sensitivity 10^{-5} up to very high masses

-- high sensitivity to single N(→ $l_2^{\pm}$W) in Z decay

<u>FCC-hh</u>

-- production in W-> $l_1^{\pm}$ + N(→ $l_2^{\pm}$W)   (LNV+LFV)

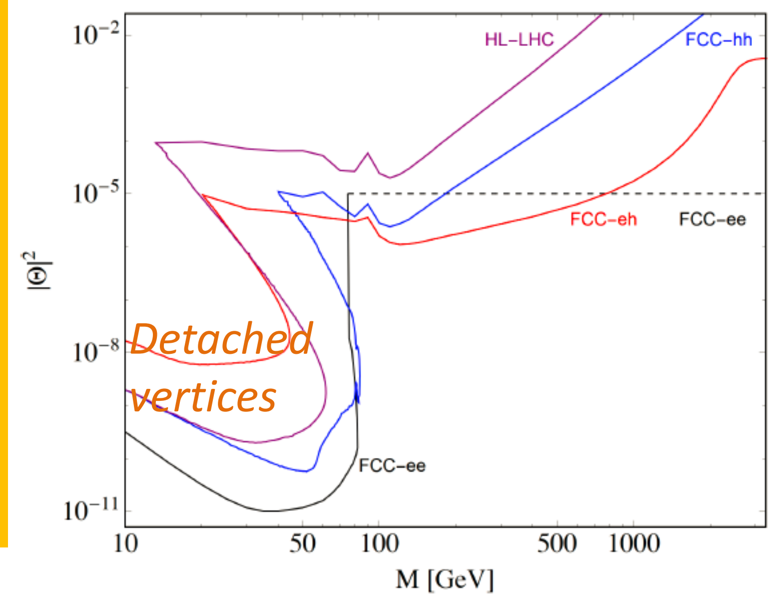
with initial and final lepton charge and flavour

<u>FCC e-p</u>

-- production in CC $e^{\pm}$ p → X N(→ $l^{\pm}$W) high mass

<u>Complementarity:</u>

discovery + studies of FNV and LFV!



Massive neutrino mechanisms for generating the matter-antimatter asymmetry in the Universe should be a central consideration in the selection and design of future colliders. (neutrino town meeting report to ESPP)

(indirect) Effect of right handed neutrinos on EW precision observables

The relationship $|U|^2 \propto \theta^2 \approx \boldsymbol{m_\nu} / m_N$ is valid for one family see-saw.
For two or three families the mixing can be larger (*Shaposhnikov*)
Antush and Fisher have shown that a slight # in Majorana mass can generate larger mixing between the left- and right-handed neutrinos. ***Worth exploring.***

«$\boldsymbol{\nu_L} = \boldsymbol{\nu} \cos\theta + \boldsymbol{N} \sin\theta$» → $(\cos\theta)^2$ becomes parametrized as 1+ $\varepsilon_{\alpha\beta}$ ($\varepsilon_{\alpha\alpha}$ is negative)
the coupling to light neutrinos is typically suppressed.
In the G_F, M_Z α_{QED} scheme, G_F (extracted from $\mu \to e \nu_e \nu_\mu$) and *g* should be increased
This leads to *correlated* variations of all predictions upon e or mu neutrino mixing.
Only the 'number of neutrinos' (R_{inv} and σ_{had}^{peak}) is sensitive to the tau-neutrino mixing.

Prediction in MUV	Prediction in the SM	Experiment
$[R_\ell]_{\rm SM}\,(1-0.15(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	20.744(11)	20.767(25)
$[R_b]_{\rm SM}\,(1+0.03(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.21577(4)	0.21629(66)
$[R_c]_{\rm SM}\,(1-0.06(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.17226(6)	0.1721(30)
$[\sigma^0_{had}]_{\rm SM}\,(1-0.25(\varepsilon_{ee}+\varepsilon_{\mu\mu})-0.27\varepsilon_\tau)$	41.470(15) nb	41.541(37) nb
$[R_{inv}]_{\rm SM}\,(1+0.75(\varepsilon_{ee}+\varepsilon_{\mu\mu})+0.67\varepsilon_\tau)$	5.9723(10)	5.942(16)
$[M_W]_{\rm SM}(1-0.11(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	80.359(11) GeV	80.385(15) GeV
$[\Gamma_{\rm lept}]_{\rm SM}(1-0.59(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	83.966(12) MeV	83.984(86) MeV
$[(s^{\ell,\rm lep}_{W,\rm eff})^2]_{\rm SM}(1+0.71(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.23150(1)	0.23113(21)
$[(s^{\ell,\rm had}_{W,\rm eff})^2]_{\rm SM}(1+0.71(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.23150(1)	0.23222(27)

Table 1: Experimental results and SM predictions for the EWPO, and the modification in the MUV scheme, to first order in the parameters $\varepsilon_{\alpha\beta}$. The theoretical predictions and experimental values are taken from Ref. [16]. The values of $(s^{\ell,\rm lep}_{W,\rm eff})^2$ and $(s^{\ell,\rm had}_{W,\rm eff})^2$ are taken from Ref. [17].

Other quantities that could be sensitive to the light-heavy mixing

1. the tau life time would be sensitive to $\varepsilon_{\tau\tau}$

→ how well can we measure the tau life time with 10^{11} $\tau\tau$?

τ_τ = (290.3 ± 0.5) × 10−15 s $c\tau_\tau$ = 87.03 μm

Mass m = 1776.86 ± 0.12 MeV limits the sensitivity to 0.3 10^{-4}

this must be completed by tau leptonic branching ratios

2. the measurement of the 'number of neutrinos' at the Z or in radiatie returns (see R. Aleksan's talk on thursday)

line shape example

from the work presented yesterday by J Wenninger, we estimated the beam energy related errors on the line shape parameters.

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

Observable	statistics	$\Delta\sqrt{s}_{\mathrm{abs}}$ 100 keV	$\Delta\sqrt{s}_{\mathrm{syst-ptp}}$ **40 keV**	calib. stats. 200 keV / $\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ 85 ± **0.05** MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_W^{\mathrm{eff}} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(m_Z^2)}{\alpha_{QED}(m_Z^2)} \times 10^5$	3	0.1	**0.9**	–	**0.1**

from the three point scan we extract hadron cross-sections and muon forward backward asymmetry as function of ECM.

→ m_Z, Γ_Z, $A_{FB}{}^{\mu}$ (Pole) and α_{QED}(mZ) from the slope of AFB(s)

these are only the beam energ related errors must add lumi errors.

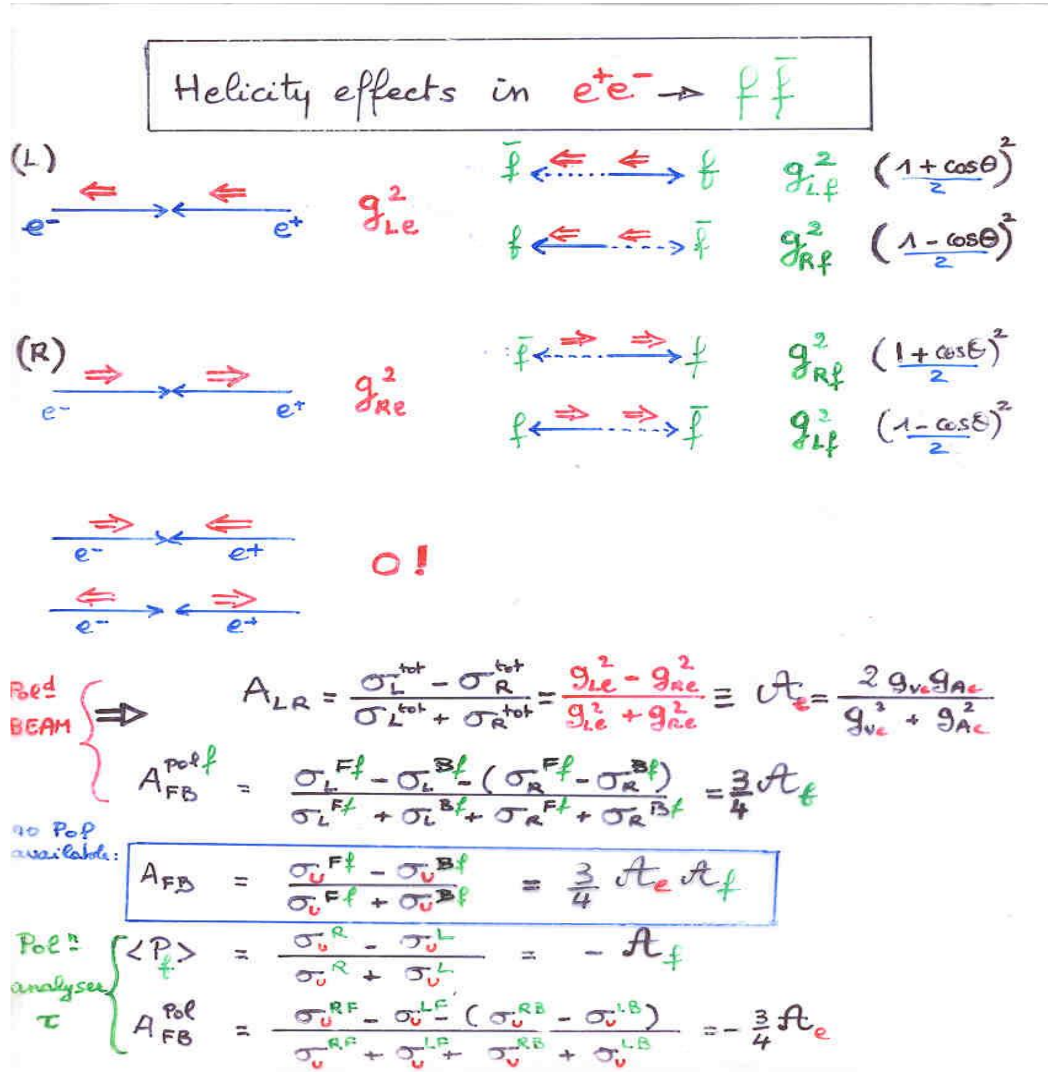
One of the ways to reduce the point to point errors is to use the muon momentum distributior

Polarization effects and left-right coupling asymmetries

This is very old stuff →
(see e.g. A. B.
Beam Polarization in e+e- annihilation,
http://cds.cern.ch/record/252128 ,
1993 pp 30-32)

the main points are
-- with beam helicity the quantity
A_{LR} can be measured with full statistics
of hadrons
-- need both e+ and e- polarization flip
to constrain the otherwise limiting error
on the beam polarization
➔ $\Delta A_e / A_e = 5\ 10^{-4}$ for ILC

-- without beam helicity
the variation of tau polarization
with polar angle allows a determination
of the electron coupling asymmetry
with 1.7 10^{11} tau pairs the $\tau \rightarrow \pi\nu$ and $\rho\nu$ allow
$\Delta A_e / A_e = 10^{-4}$ for FCC-ee



This was very well shown by R. Tenchini at the FCC meeting in Amsterdam
and at the FCC CDR presentation at CERN https://indico.cern.ch/event/789349/

tau polarization plays a central role at FCC-ee

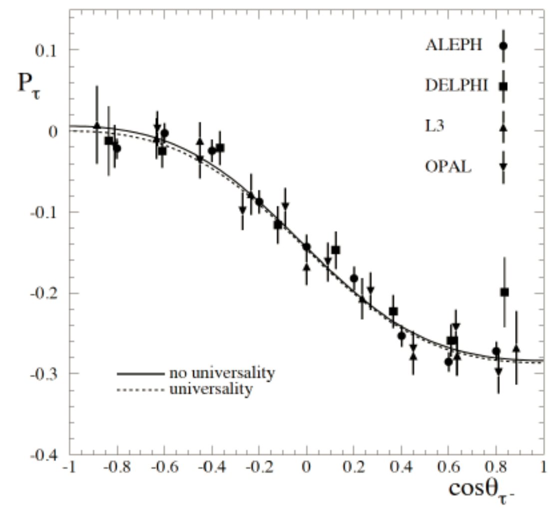
- Separate measurements of A_e and A_τ from

$$P_\tau(\cos\theta) = \frac{A_{pol}(1+\cos^2\theta) + \frac{8}{3}A_{pol}^{FB}\cos\theta}{(1+\cos^2\theta)+\frac{8}{3}A_{FB}\cos\theta}$$

$$A_{pol} = \frac{\sigma_{F,R} + \sigma_{B,R} - \sigma_{F,L} - \sigma_{B,L}}{\sigma_{tot}} = -A_f$$

$$A_{pol}^{FB} = \frac{\sigma_{F,R} - \sigma_{B,R} - \sigma_{F,L} + \sigma_{B,L}}{\sigma_{tot}} = -\frac{3}{4}A_e$$

Measured P_τ vs $\cos\theta_{\tau^-}$



At FCC-ee

- very high statistics: improved knowledge of tau parameters (e.g. branching fraction, tau decay modeling) with FCC-ee data
- use best decay channels (e.g. $\tau \rightarrow \rho\nu_\tau$ decay very clean), note that detector performance for photons / π^0 very relevant

→ **measure $\sin^2\theta_{eff}$ with 6.6 10^{-6} precision**

NB this is a relative precision of $\Delta A_e / A_e = 10^{-4}$
(the purely statistical error is about three times smaller)

Precisions on coupling ratio factors, A_f

$$\mathcal{A}_e = \frac{2g_{Ve}g_{Ae}}{(g_{Ve})^2 + (g_{Ae})^2} = \frac{2g_{Ve}/g_{Ae}}{1 + (g_{Ve}/g_{Ae})^2}$$

	Statistical uncertainty	Systematic uncertainty	improvement w.r.t. LEP
$\mathcal{A}_e$	$5. \times 10^{-5}$	$1. \times 10^{-4}$	50
$\mathcal{A}_\mu$	2.5×10^{-5}	1.5×10^{-4}	30
$\mathcal{A}_\tau$	$4. \times 10^{-5}$	$3. \times 10^{-4}$	15
$\mathcal{A}_b$	2×10^{-4}	30×10^{-4}	5
$\mathcal{A}_c$	3×10^{-4}	80×10^{-4}	4
$\sin^2\theta_{W,eff}$ (from muon FB)	10^{-7}	$5. \times 10^{-6}$	100
$\sin^2\theta_{W,eff}$ (from tau pol)	10^{-7}	6.6×10^{-6}	75

The magic formula appears in the LEP EW paper on the Z pole arXiv:hep-ex/0509008v3

$$\mathcal{P}_\tau(\cos\theta_{\tau^-}) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta_{\tau^-}) + 2\mathcal{A}_e\cos\theta_{\tau^-}}{(1+\cos^2\theta_{\tau^-}) + \frac{8}{3}A_{FB}^{\tau}\cos\theta_{\tau^-}}. \tag{4.2}$$

The τ polarisation measurements allow for the determination of $\mathcal{A}_\tau$ and $\mathcal{A}_e$ and are largely insensitive to A_{FB}^{τ}.

the most extensive publication is the ALEPH tau polarization paper arXiv:hep-ex/0104038v1 20 Apr 2001

It is evident that a combined analysis of $\tau\to\pi\nu$ and $\rho\nu$ is essentially limited (for the angular distribution) by the MC statistics and other data-controlable quantities.

Nevertheless, a dedicated simulation and analysis of this essential channel should be foreseen in the next years to evaluate the requirements on detector to achive this precision. (geometry precision and hermiticity to photons and charged tracks)

Precisions on normalized partial widths $R_f = \sigma_f/\sigma_{had}$

	Statistical uncertainty	Systematic uncertainty	improvement w.r.t. LEP
R_μ (R_ℓ)	10^{-6}	5×10^{-5}	20
R_τ	1.5×10^{-6}	10^{-4}	20
R_e	1.5×10^{-6}	3×10^{-4}	20
R_b	5×10^{-5}	3×10^{-4}	10
R_c	1.5×10^{-4}	15×10^{-4}	10

Relative precisions

We should revisit the relative precisions. Also the measurement of the electron couplin g from the peak coss-section for electron pairs (proportional to Γ_e^2 / Γ_Z^2 should be included as it should provide better precision (0.5 10^{-4} from lumi measurement at 10^{-4} precision)

➔ all ratios of partial widths should be known better than 10^{-4}

$$\sigma_f^0 = \frac{12\pi(\hbar c)^2}{M_Z^2}\frac{\Gamma_e\Gamma_f}{\Gamma_Z^2} =$$

Table 5: Comparisons between the ILC GigaZ and FCC-ee TeraZ for the measurements of left-right coupling asymmetries, tests of lepton universality, and measurements of the effective weak mixing angle at the Z pole. Also indicated is the limiting precision on the effective mixing angle from the precision on $\alpha_{\mathrm{QED}}(m_{\mathrm{Z}}^2)$ taking into account for FCC-ee of the improvement on this quantity from the off-peak measurement of the muon forward-backward asymmetry [63].

Facility	ILC-GigaZ	FCC-ee
Z produced at the peak	10^9	4×10^{12}
Longitudinal polarization $(P_{\mathrm{e}^-}, P_{\mathrm{e}^-})$	$(\pm 0.8, 0.0)$	$(0.0, 0.0)$
$\Delta \mathcal{A}_{\mathrm{e}}$	1.2×10^{-4}	1.5×10^{-5}
$\Delta \mathcal{A}_{\mu}$	3×10^{-4}	5×10^{-5}
$\Delta \mathcal{A}_{\tau}$	3×10^{-4}	5×10^{-5}
$\Delta \frac{\mathcal{A}_{\mu}}{\mathcal{A}_{e}}$	1.6×10^{-3}	2.5 to 4×10^{-4}
$\Delta \frac{\mathcal{A}_{\mu}}{\mathcal{A}_{\tau}}$	2.3×10^{-3}	3.3×10^{-4}
$\Delta \sin^2 \theta_{\mathrm{W}}^{\mathrm{eff}}$	1.5×10^{-5}	6×10^{-6}
Hard limit on SM prediction:		
$\Delta \sin^2 \theta_{\mathrm{W}}^{\mathrm{eff}}$ from $\alpha_{\mathrm{QED}}(m_{\mathrm{Z}}^2)$	1.1×10^{-5}	7×10^{-6}

this table produced for arXiv:1906.02693v1 (FCC-ee your questions asked)
will be extended to include the other results that follow.

CC couplings

present status

The best knowledge of the lepton coupling comes from the measurements of the tau mass / life time and branching ratios

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\left(\frac{m_\mu}{m_\tau}\right)^5 B_e \frac{f(\frac{m_e^2}{m_\mu^2})}{f(\frac{m_e^2}{m_\tau^2})}\Delta_W \Delta_\gamma \ , \qquad (25)$$

$$\left(\frac{g_\tau}{g_e}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\left(\frac{m_\mu}{m_\tau}\right)^5 B_\mu \frac{f(\frac{m_e^2}{m_\mu^2})}{f(\frac{m_\mu^2}{m_\tau^2})}\Delta_W \Delta_\gamma \ , \qquad (26)$$

where $f(\frac{m_e^2}{m_\mu^2}) = 0.9998$, $\Delta_W = \frac{\delta_W^\mu}{\delta_W^\tau} = 1 - 2.9 \times 10^{-4}$, $\Delta_\gamma = \frac{\delta_\gamma^\mu}{\delta_\gamma^\tau} = 1 + 8.5 \times 10^{-5}$, and τ_l is the lepton l lifetime.

The present average is still dominated by LEP results. and stands at a precision of $1.5 10^{-3}$

$$\frac{g_\tau}{g_\mu} = 1.0010 \pm 0.0015 \ ; \frac{g_\tau}{g_e} = 1.0029 \pm 0.0015$$

Improvement of the tau lifetime will come at FCC-ee wrt LEP by improved resolution typically proportional to beam pipe radius x detector resolution.
We should already gain a factor nearly 10 intrinsically and 100 in statistics.

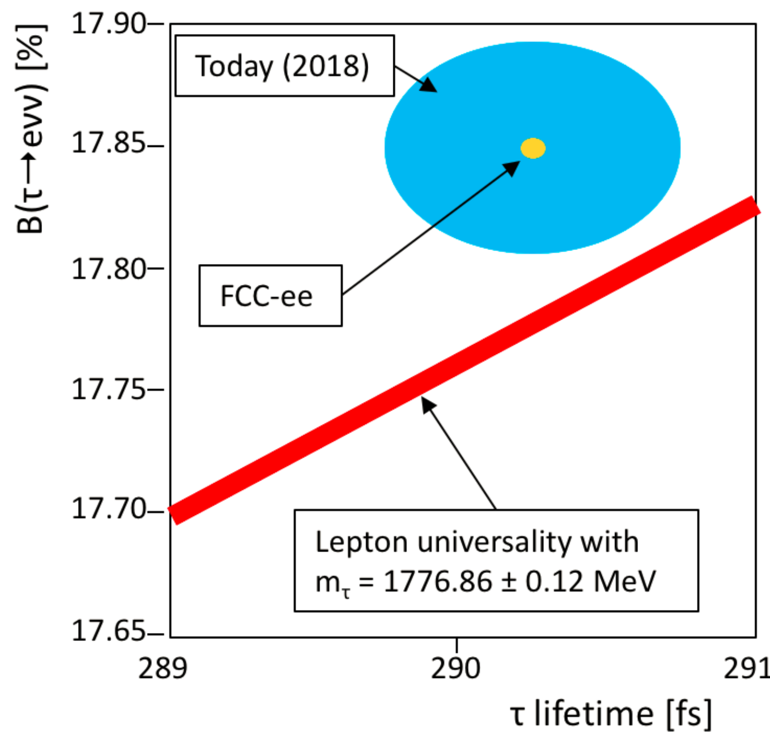
The of 1.7 10^{11} tau pairs should allow to reduce these uncertainties to the 10^{-5} level

τ physics

Improve Lepton flavour violation sensitivity by 3 orders of magnitude

$$\mathcal{B}(Z \to \tau^{\pm}\ell^{\mp}) < 10^{-9} \text{ @ } 95\% \text{ C.L.}$$

tau branching ratios are a good **test of Universality** of the α - ν_{α} CC coupling α= e μ τ
➔ sensitive to light-heavy neutrino mixing
(Can someone re-measure the tau mass better?)

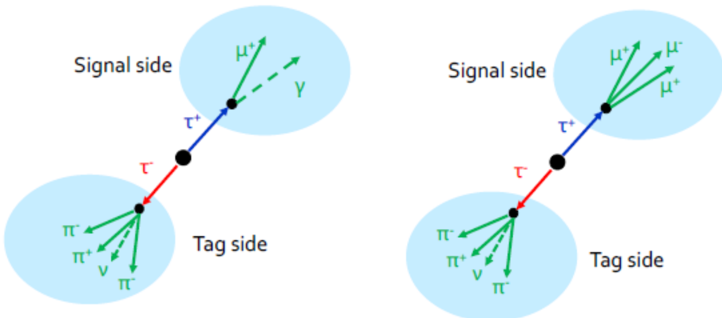


and many more....

Property	Current WA	FCC-ee stat	FCC-ee syst
Mass [MeV]	1776.86 +/- 0.12	0.004	0.1
Electron BF [%]	17.82 +/- 0.05	0.0001	0.003
Muon BF [%]	17.39 +/- 0.05	0.0001	0.003
Lifetime [fs]	290.3 +/- 0.5	0.005	0.04

«systematics will be at least this good»
probably much better → to be studied further!

Lepton Flavour Violating-τ decays



Visible Z decays	3×10^{12}
$Z \rightarrow \tau^+\tau^-$	1.3×10^{11}
1 vs. 3 prongs	3.2×10^{10}
3 vs. 3 prong	2.8×10^{9}
1 vs. 5 prong	2.1×10^{8}
1 vs. 7 prong	< 67,000
1 vs 9 prong	?

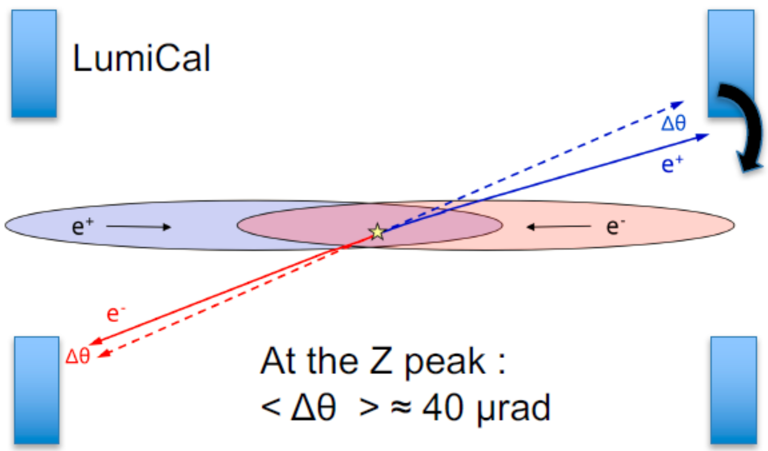
- Benefits from the huge statistics and boosted topologies.
- Calorimetric performance as ILD.
- Main backgrounds are initial and final state radiative events.

Decay	Current bound	FCC-ee sensitivity
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2×10^{-8}	10^{-10}

Beam-induced effects on the luminosity measurement

Precision goal at the Z peak and WW :

- 10^{-4} (absolute), a few 10^{-5} (relative, line-shape scan)



Focusing of the Bhabha e+/- by the beam force :

The # of e+/- that end up in the acceptance of the LumiCal is reduced: L measured < L true

Leads to $\Delta L / L \approx 0.2$ %
i.e. 20x larger than the target !

Needs to be corrected for. The precision on the correction factor should be about 5% to ensure a residual systematic below 10-4.
Correction can be calculated in principle... but desirable to determine it experimentally.

Two methods proposed in JHEP 10 (2019) 225 [arXiv:1908.01698]. Only one is described here.
Numbers refer to the Z peak.

Bhabha electrons at LEP were also affected by the beam-induced focusing !

Voutsinas et al, arXiv:1908.01704

Typical focusing was O (10 μrad)
Leads to a bias on the luminosity of about 0.1 %

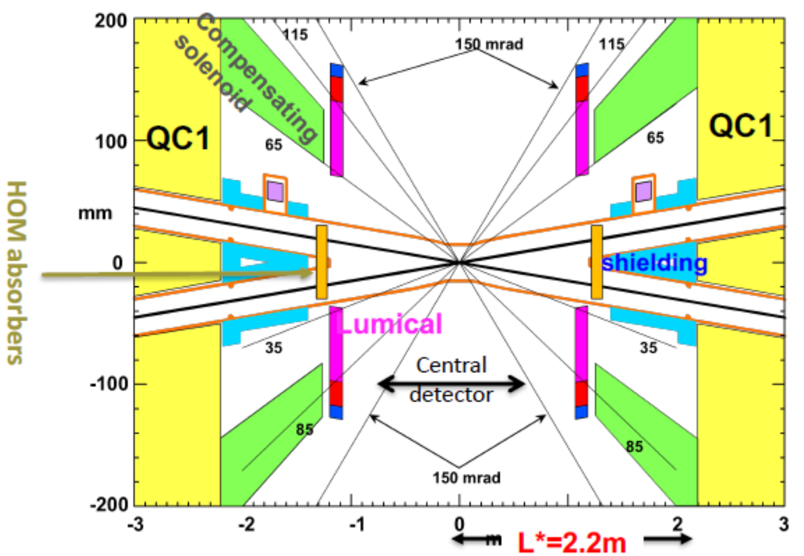
- Not accounted for by the experiments
- large compared to the quoted uncertainties (e.g. OPAL: 0.034% (exp), 0.056% (theo.))

FCC-ee detector challenges…

No pileup, no underlying event, and demonstrated to be feasible but:

- Extremely large statistics / statistical precision
- …need small systematics (10^{-5} !) to match
- Physics event rates up to 100 kHz
- Bunch spacing down to 20 ns
- Continous beams, no power pulsing
- Complex interaction region
- beam pipe ∅ 2-3 cm

2D-top view with expanded x-coordinate



Optimization to be done for extremely rich physics capabilities, **especially at the Z pole**

10^{12} bb, cc, 2 10^{11} $\tau\tau$, etc…

-- search for rare processes → excellent acceptance closure, sensitivity to displaced vertices

-- luminosity measurement at 10^{-5} (rel), 10^{-4} (abs)

-- acceptance definition at $\leq 10^{-5}$

-- optimal b/c/gluon separation

-- PID (TOF, dE/dx, Ckov?)

-- determination of point-to-point scan energies at 10 keV level

NEW challenges in design, technology, metrology, stability, monitoring

FCC-ee Detector Specificities

In general the physics requirements are similar to those of the LC (ILC/CLIC) detectors.
Top energy being smaller the precision on momentum (and strength of magnetic field, depth of calorimeter etc..) can be somewhat relaxed (2T is sufficient).

There are some specific hard challenges at the Z peak run and for extreme precision measurements, as well as for the Flavour physics which is more limited at LC, ATLAS&CMS

1. measurement of the ratio of hadrons to leptons as well as leptonic cross-section.

$R_{lept} = \sigma(e+e- \rightarrow \text{hadrons}) / \sigma(e+e- \rightarrow \ell+ \ell-)$

This measurement is sensitive to α_{QCD} and the b vertex correction.

-- 3 10^{12} e+e-→Z → Hadron events

-- 1.5 10^{11} e+e- → Z→ $\mu\mu$ $\tau\tau$ ee each – 5 10^{11} for all leptons.

aim is systematic error < statistical error of O(2-3 10^{-6})

-- detector acceptance to be defined with precision linked to lepton angular acceptance for an acceptance limit at 15 degrees, this corresponds to an angle known **on average** with a precision of 3.5 microradians (or 7 microns radius at 2m from the interaction point).

→ This is the precision on the position of the detector,

→ this is not the precision of the detector for a track, which can be worse.

→ this can be implemented for the tracker or the EM calorimeter, or a fiducial detector in-between

Detector should be hermetic in acceptance region (no cracks)

FCC-ee Detector Specificities

Some hard physics challenges at the Z peak run:

2. Luminosity measurement there is a similar requirement (at smaller angle) for the luminosity detector where the inner limit of the detector acceptance should be known to 1 micron at 1m from IP.

3. Stability of momentum measurement
this will affect the mass, width, asymmetry measurements which are sensitive to relative values of center-of-mass energies across the Z line shape, W pair threshold
(ZH threshold and top threshold are less critical)
(see http://arxiv.org/abs/arXiv:1909.12245)

The magnetic field in the tracker should be stable, or monitored, with a precision of $\ll 10^{-6}$
Center-of-mass energy will be obtained from resonant depolarization with a precision of 10^{-6}.
Small changes with respect to the common scale affect the measurements and one tries to detect them by measuring the average ECM with muon pairs.

Can one monitor the magnetic field with this precision? The absolute value is not so important, but the value should remain unchanged with that precision when changing (every few days to a week) center-of mass Energy by a few GeV back and forth.

FCC-ee Detector Specificities

4. flavour physics
everything having to do with b/c/gluon jet separation is of great interest for H and top physics.
in addition the tau life time measurement with 1.5 10^{11} $\tau\tau$ events will give a GF measurement equivalent to that with muons (lepton universality test!)

This places a great premium on a **precision vertex detector.**

beam pipe size is 2cm in diameter.

Aim is to improve thickness considerably compared with LHC, radiation hardness is probably much less critical.
Compared with ILC:
1. power pulsing is impossible
2. but occupancy due to beam related backgrounds is enarly one order of magnitude lower.

5. Particle identification is very relevant for flavour physics.
Should cover energies from sub-GeV (TOF) up to ~50 GeV (CKOV, dE/dx)
implementation without perturbing hermiticity is a challenge

CONCLUSIONS

There is a large amount of work trying to find the elusive pointers to new physics by a two order of magnitude improvement in precision measurements

we have a good idea of how to proceed and the interest by the theory community is remarkable, but still patchy.

We need to create the same awareness in the experimental community

One of the upcoming tasks is to write-up the full overall picture and methodology in the EW working group.