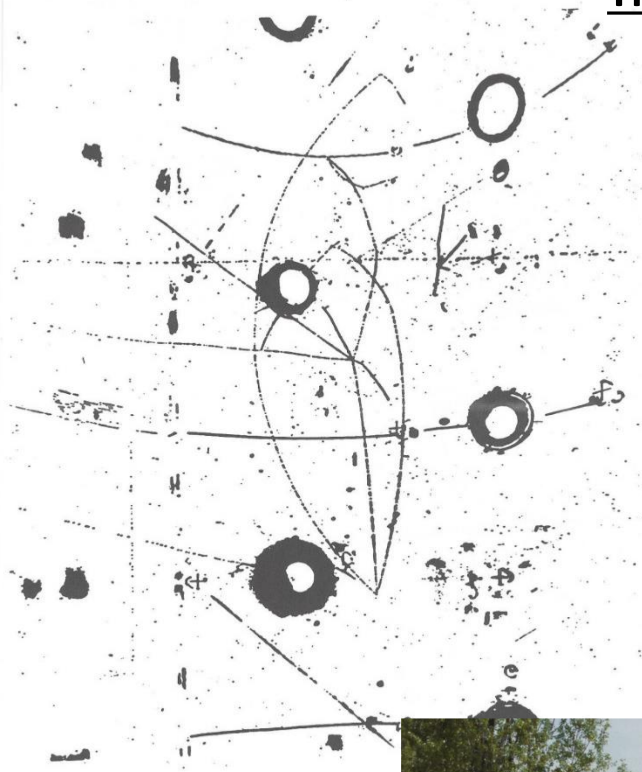
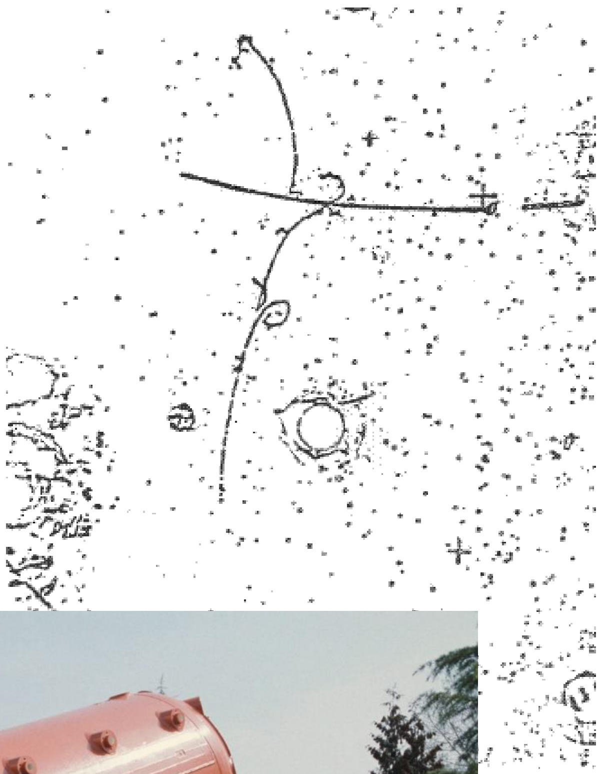
Electroweak Precision Measurements at LEP and FCCee

In 1973 – 50 years ago: Gargamelle discovery of Neutral currents,
The Standard Model (unified electro-weak theory) was born to the experimental world

F.J. Hasert et al., Neutrino-like interactions



ig. 3. An NC event showing identification of all seconda
eposited is about 6 GeV.



The Nobel Prize in Physics 1979

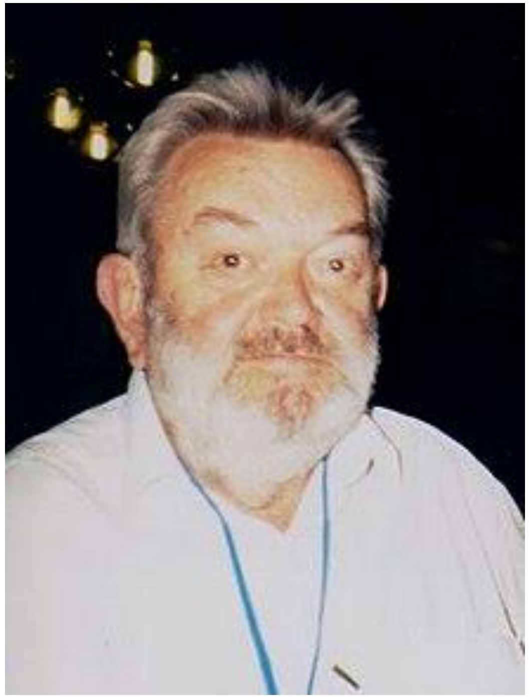
Photo from the Nobel Foundation archive.
Sheldon Lee Glashow
Prize share: 1/3

Photo from the Nobel Foundation archive.
Abdus Salam
Prize share: 1/3

Photo from the Nobel Foundation archive.
Steven Weinberg
Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"

The measurement of the NC/CC ratio led to the determination of $\sin^2\theta_W$ and immediately, with G_F and α_{QED} predicted the mass of W and Z (within ± 10 GeV)



Veltman in 1975 (w. D. Ross),1977 explained that relationship bw G_F, $\sin^2\theta_W$ m_Z m_W would be modified by heavy physics if it violates the $SU(2)_L$ symmetry

$$\rho = \left(\frac{m_W}{m_Z \cos\theta_W}\right)^2 = 1 + \alpha/\pi \left(\frac{m_{top}}{m_W}\right)^2$$

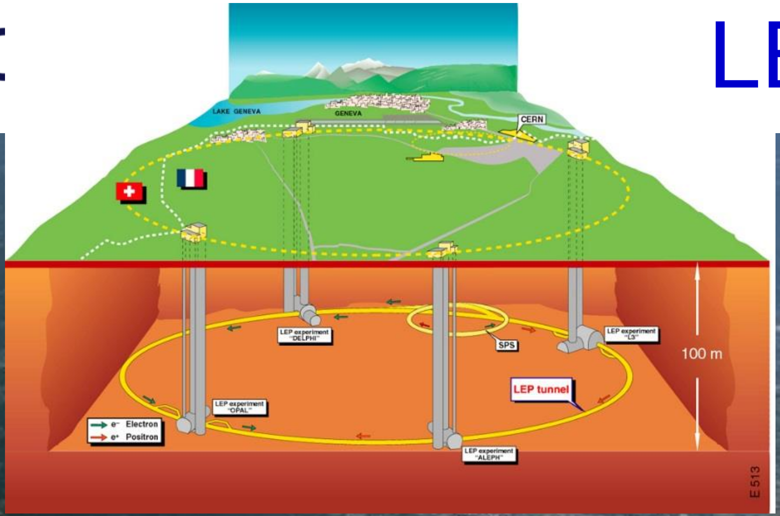
➔ **EW precision measurements as a way to investigate the existence of heavy physics inaccessible directly at contemporary accelerators**

This is **not** why the 26.7 km circumference LEP was built.
Veltman *lui-même* who was part of the committee, insisted that it should be large enough to verify that W pair production was not divergent. (TGC)

The construction of LEP was (pushed since 1976)decided by CERN council in 1981, before the W and Z were observed at the proton-antiproton collider! Construction started in 1983.

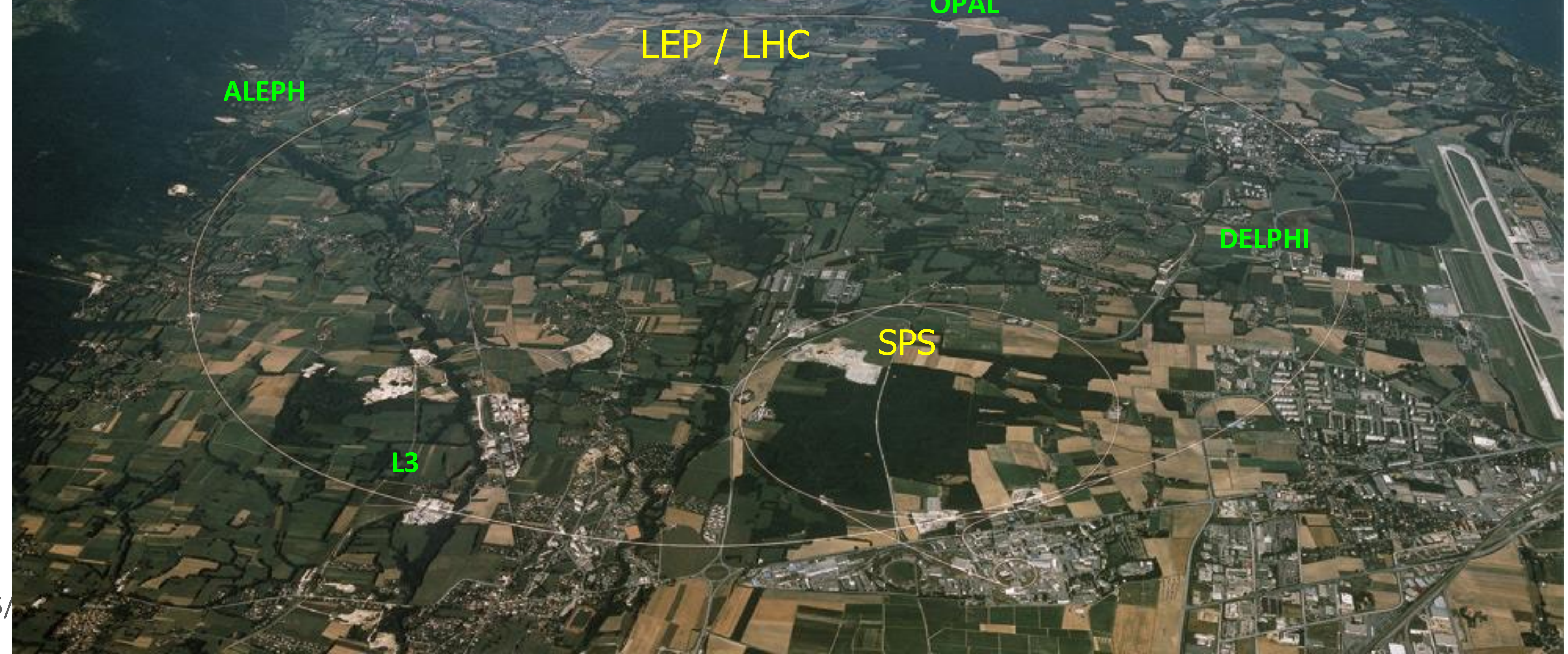
A big scare of the time was the unknown **number of neutrinos**
too many neutrinos would wash out the Z peak (J. Ellis)

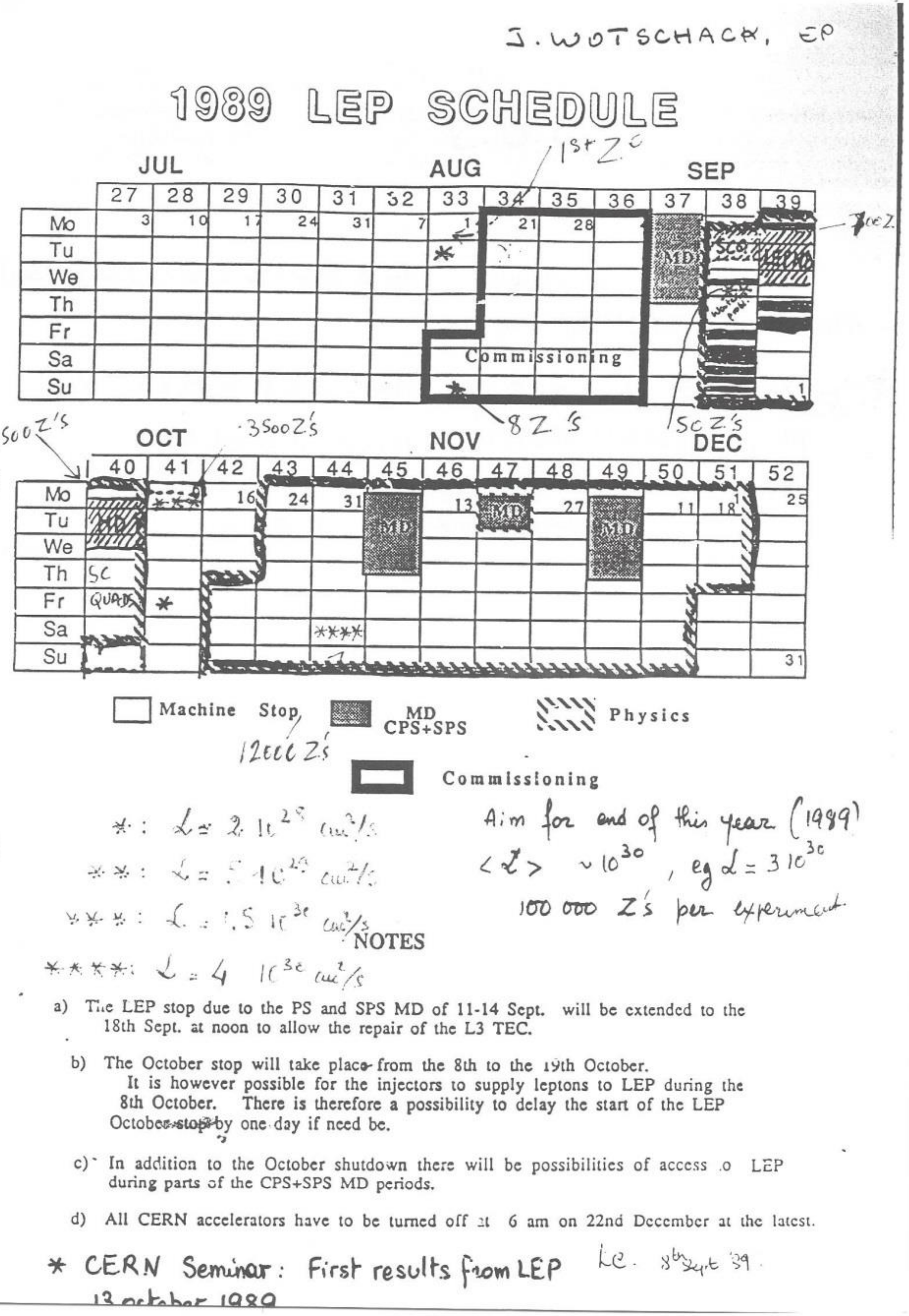
LEP / LHC Layout



The 26.7 km LEP tunnel

Depth: 40-140 m





J. WOTSCHACK, EP

1989 LEP SCHEDULE

	JUL					AUG					SEP		
	27	28	29	30	31	32	33	34	35	36	37	38	39
Mo	3	10	17	24	31	7	14	21	28				
Tu							*				MD		
We													
Th													
Fr													
Sa							Commissioning						
Su							*						1

1st Z° — 8 Z's — 50 Z's — 300 Z

	OCT				NOV					DEC			
	40	41	42	43	44	45	46	47	48	49	50	51	52
Mo		**	16	24	31		13		27		11	18	25
Tu	MD					MD		MD		MD			
We													
Th	SC												
Fr	QUADS	*											
Sa					****								
Su													31

1500 Z's — 3500 Z's — 12000 Z's

Machine Stop — MD CPS+SPS — Physics — Commissioning

*: $\mathcal{L} = 2\ 10^{29}\ cm^2/s$
**: $\mathcal{L} = 5\ 10^{29}\ cm^2/s$
***: $\mathcal{L} = 1.5\ 10^{30}\ cm^2/s$
****: $\mathcal{L} = 4\ 10^{30}\ cm^2/s$

Aim for end of this year (1989)
$\langle \mathcal{L} \rangle \sim 10^{30}$, eg $\mathcal{L} = 3\ 10^{30}$
100 000 Z's per experiment

NOTES

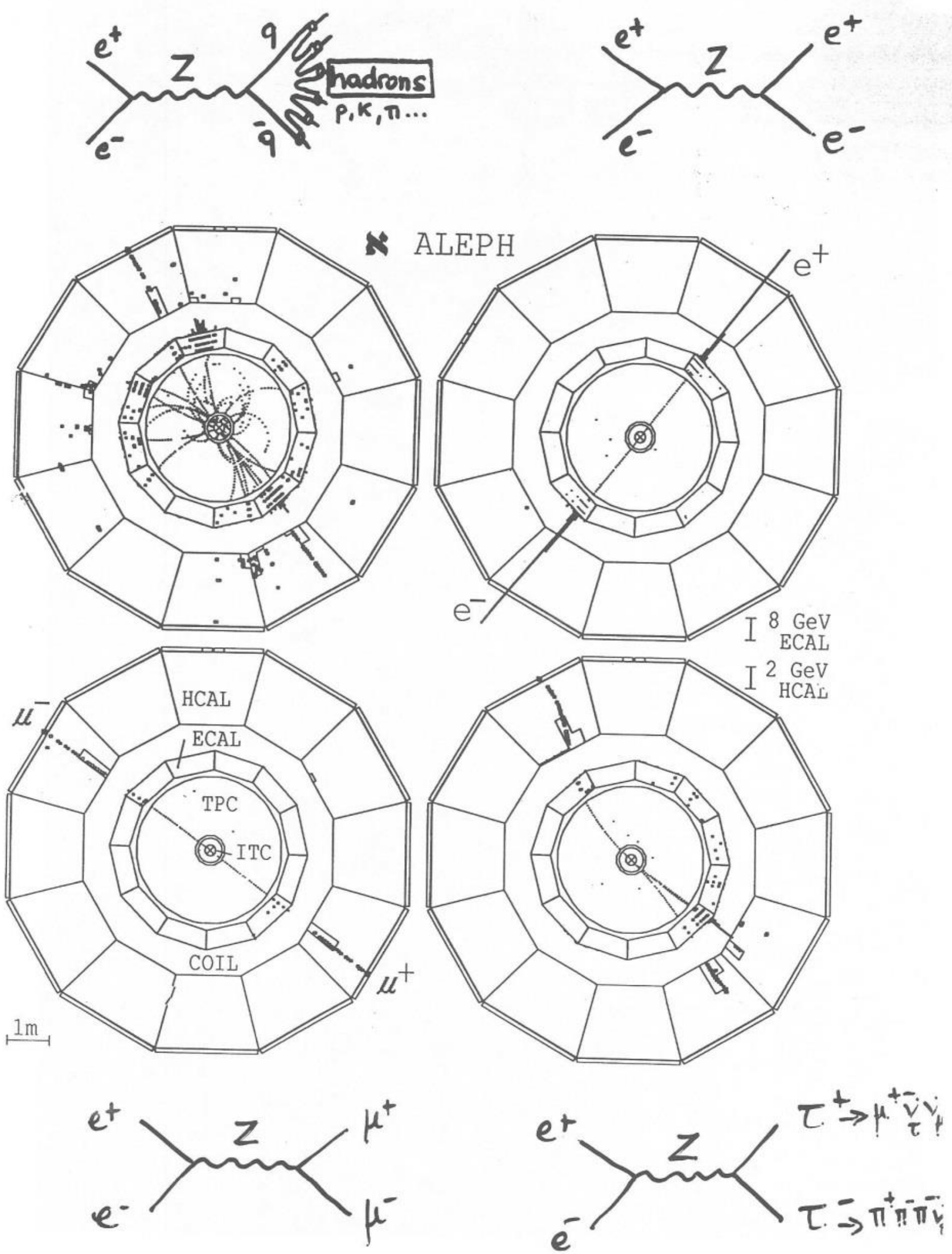
a) The LEP stop due to the PS and SPS MD of 11-14 Sept. will be extended to the 18th Sept. at noon to allow the repair of the L3 TEC.

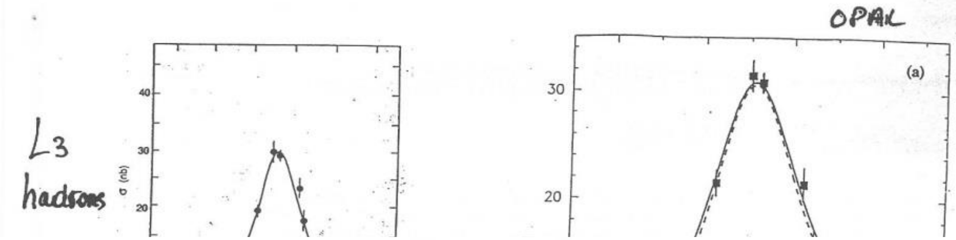
b) The October stop will take place from the 8th to the 19th October. It is however possible for the injectors to supply leptons to LEP during the 8th October. There is therefore a possibility to delay the start of the LEP October stop by one day if need be.

c) In addition to the October shutdown there will be possibilities of access to LEP during parts of the CPS+SPS MD periods.

d) All CERN accelerators have to be turned off at 6 am on 22nd December at the latest.

* CERN Seminar: First results from LEP i.e. 8th Sept 89
13 october 1989





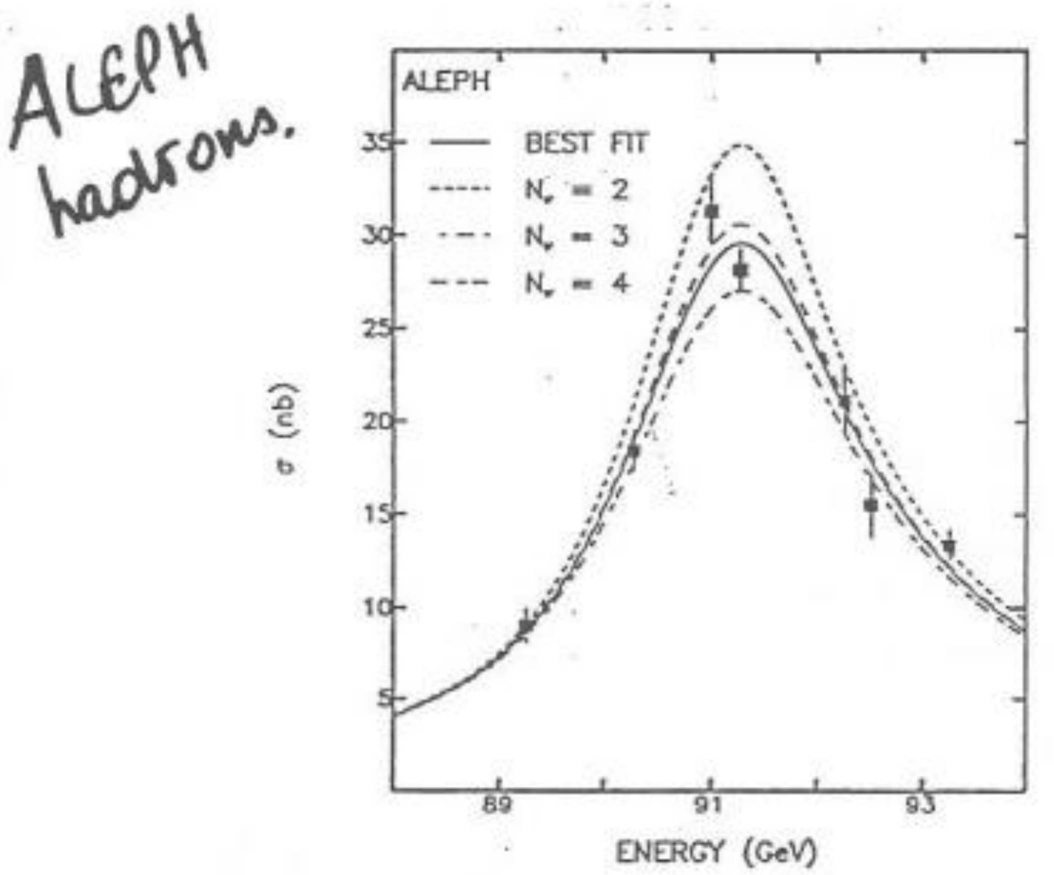


Fig. 5. The cross-section for $e^+e^- \to$ hadrons as a function of centre-of-mass energy and result of the three parameter fit.

me 231, number 4 PHYSICS LETTERS B 16 November 1989

A DETERMINATION OF THE PROPERTIES OF THE NEUTRAL INTERMEDIATE VECTOR BOSON Z^0

L3 Collaboration

Received 12 October 1989

We report the results of first physics runs of the L3 detector at LEP. Based on 2538 hadron events, we determined the mass m_{Z^0} and the width Γ_{Z^0} of the intermediate vector boson Z^0 to be $m_{Z^0}=91.132\pm0.057$ GeV (not including the 46 MeV LEP machine energy uncertainty) and $\Gamma_{Z^0}=2.588\pm0.137$ GeV. We also determined $\Gamma_{invisible}=0.567\pm0.080$ GeV, corresponding to 3.42 ± 0.48 number of neutrino flavors. We also measured the muon pair cross section and determined the branching ratio $\Gamma_{\mu\mu}=\Gamma_h=0.056\pm0.006$. The partial width of $Z^0\to e^+e^-$ is $\Gamma_{ee}=88\pm9\pm7$ MeV.

2538 $Z\to q\bar{q}$
95 e^+e^- 97 $\mu^+\mu^-$

$N_\nu = 3.42 \pm 0.48$
$M_Z = 91.132 \pm 0.057 \pm 0.046$ LEP
$\Gamma_Z = 2.588 \pm 0.137$

DETERMINATION OF THE NUMBER OF LIGHT NEUTRINO SPECIES

ALEPH Collaboration

Received 12 October 1989

The cross-section for $e^+e^-\to$ hadrons in the vicinity of the Z boson peak has been measured with the ALEPH detector at the CERN Large Electron Positron collider, LEP. Measurements of the Z mass, $M_Z=(91.174\pm0.070)$ GeV, the Z width $\Gamma_Z=(2.68\pm0.15)$ GeV, and of the peak hadronic cross-section, $\sigma^{peak}_{had}=(29.3\pm1.2)$ nb, are presented. Within the constraints of the standard electroweak model, the number of light neutrino species is found to be $N_\nu=3.27\pm0.30$. This result rules out the possibility of a fourth type of light neutrino at 98% CL.

3112 $Z\to q\bar{q}$

$N_\nu = 3.27 \pm 0.30$
$M_Z = 91.174 \pm 0.055 \pm 0.045$
$\Gamma_Z = 2.68 \pm 0.15$

MEASUREMENT OF THE Z^0 MASS AND WIDTH WITH THE OPAL DETECTOR AT LEP

OPAL Collaboration

Received 13 October 1989

1350 $Z\to q\bar{q}$

We report an experimental determination of the cross section for $e^+e^-\to$hadrons from a scan around the Z^0 pole. On the basis of [redacted] hadronic events collected over seven energy points between 89.26 GeV and 93.26 GeV we obtain a mass of $m_Z=91.01\pm0.05\pm0.05$ GeV, and a total decay width of $\Gamma_Z=2.60\pm0.13$ GeV. In the context of the standard model these results imply 3.1 ± 0.4 neutrino generations.

$N_\nu = 3.1 \pm 0.4$
$M_Z = 91.01 \pm 0.05 \pm 0.05$
$\Gamma_Z = 2.60 \pm 0.13$

MEASUREMENT OF THE MASS AND WIDTH OF THE Z^0-PARTICLE ...NAL STATES PRODUCED IN e^+e^- ANNIHILATIONS

W.A. : 3.11±0.16

ed 16 October 1989

Three weeks of data at LEP…
and there were only three neutrinos

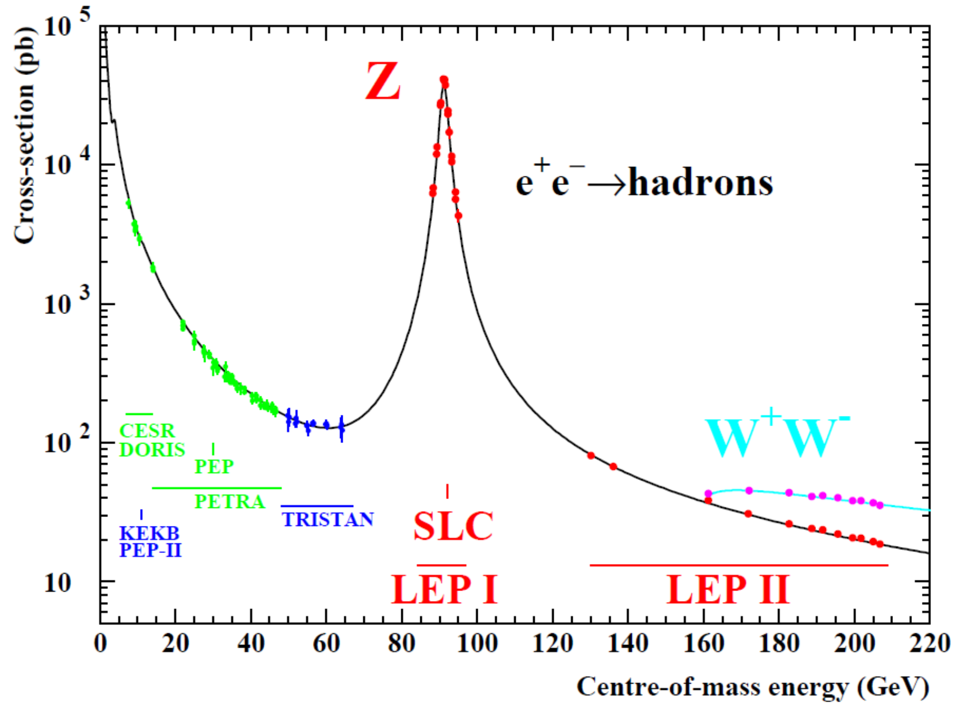
...of the Z^0 performed at the newly commissioned LEP Collider by the DELPHI ...s are derived from the study of multihadronic final states produced in e^+e^- anni- ... The values found for the mass and width are $M(Z^0)=91.06\pm0.09$ (stat.) ±0.045 ...V respectively, from a three-parameter fit to the line shape. A two-parameter fit ...or the number of light neutrino species $N_\nu=2.4\pm0.4$ (stat.) ±0.5 (syst.).

13 October 1989 :

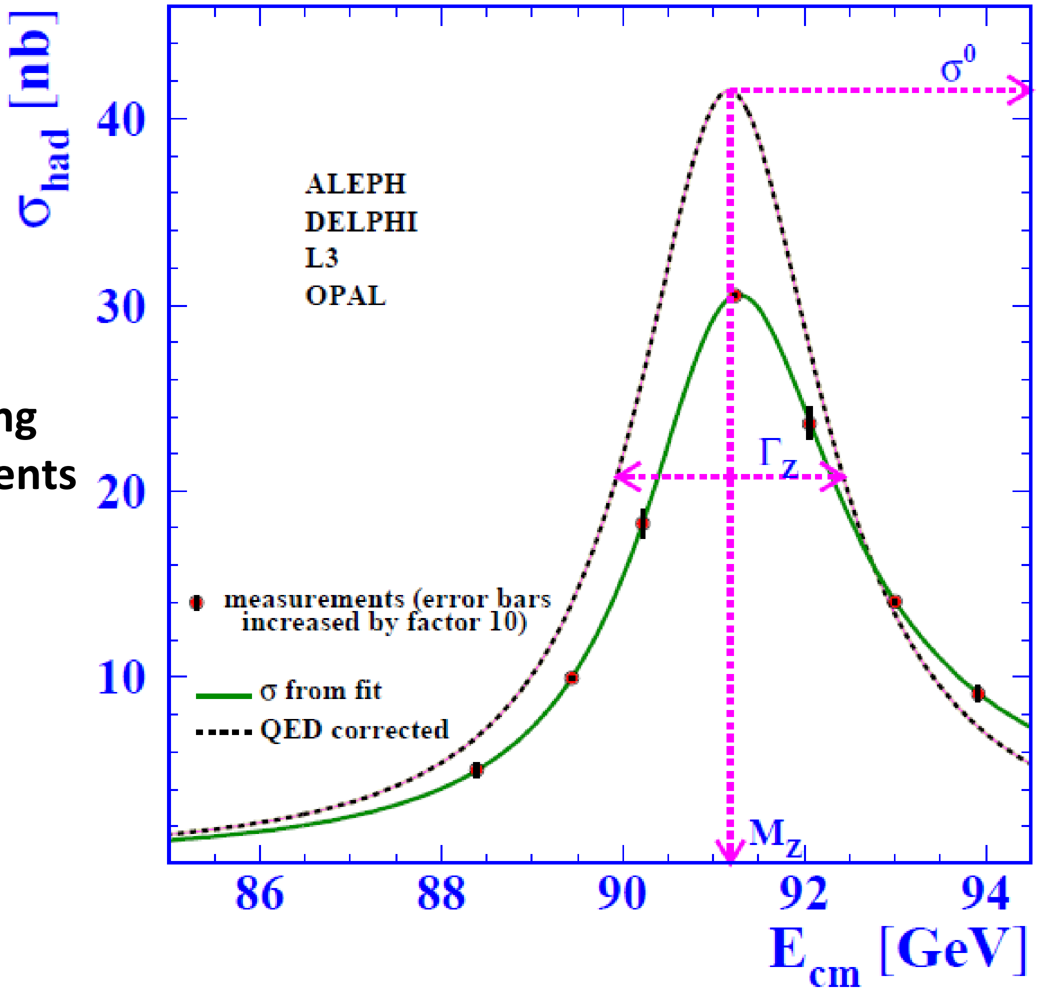
$N_\nu = 3.16 \pm 0.20$ $\chi^2 = 1.8/3$
$M_Z = 91.094 \pm 0.029 \pm 0.045$ $\chi^2 = 5.5/3$

$N_\nu = 2.4 \pm 0.4 \pm 0.5$
$M_Z = 91.06 \pm 0.09 \pm 0.045$
$\Gamma_Z = 2.42 \pm (6)21$

Measuring the Z line shape



Luminosity normalization using low angle e+e- events

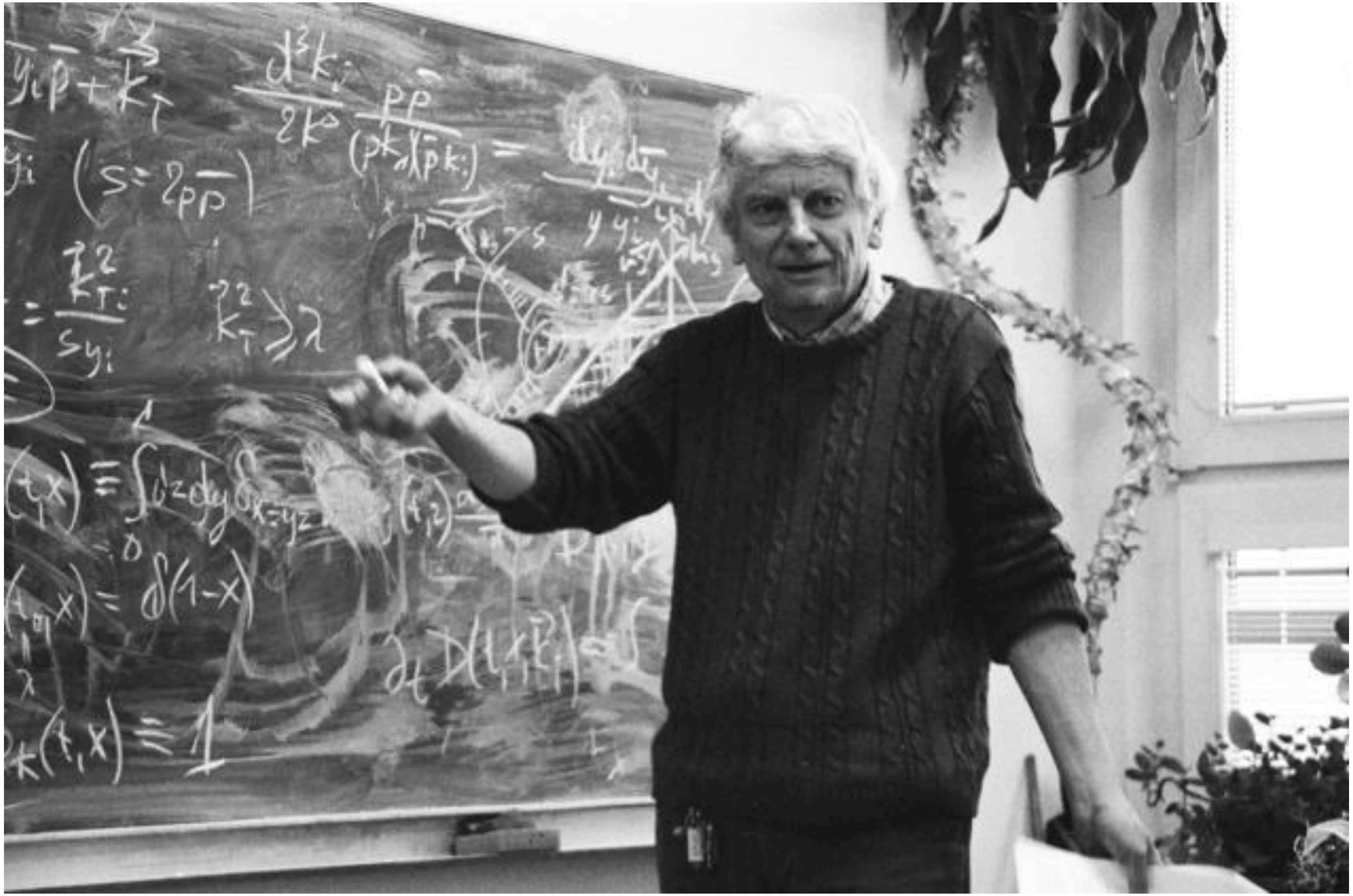


Number of Events										
	$Z \to q\bar{q}$					$Z \to \ell^+\ell^-$				
Year	A	D	L	O	LEP	A	D	L	O	LEP
1990/91	433	357	416	454	1660	53	36	39	58	186
1992	633	697	678	733	2741	77	70	59	88	294
1993	630	682	646	649	2607	78	75	64	79	296
1994	1640	1310	1359	1601	5910	202	137	127	191	657
1995	735	659	526	659	2579	90	66	54	81	291
Total	4071	3705	3625	4096	15497	500	384	343	497	1724

Table 1.2: The $q\bar{q}$ and $\ell^+\ell^-$ event statistics, in units of 10^3, used for Z analyses by the experiments ALEPH (A), DELPHI (D), L3 (L) and OPAL (O).

O(10^6) statistics ➔ permil precisions
a challenge for theory community!
Also for beam energy calibration...

GENRAP (1975)
MUSTRAHL(1982)
....
KKMC
KORALZ
TAULA
BHLUMI
KORALWW
...



Staszek Jadach

... All collaborations use BHLUMI 4.04 [23],
the best available Monte-Carlo generator for small angle Bhabha scattering,
to calculate the acceptance of their low angle luminosity counters....
... All collaborations use TAULA, KORALZ

LEP Collaborations Phys.Rept.427:257-454,2006

[20] S. Jadach, B.F.L. Ward and Z. Wąs, Comput. Phys. Commun. **79** (1994) 503, (KORALZ 4.0).

[21] S. Jadach, B.F.L. Ward and Z. Wąs, Comput. Phys. Commun. **130** (2000) 260, (KK Monte Carlo).

[22] F.A. Berends, R. Kleiss and W. Hollik, Nucl. Phys. **B304** (1988) 712, (BABAMC).

[23] S. Jadach, W. Placzek, E. Richter-Wąs, B.F.L. Ward and Z. Wąs, Comput. Phys. Commun. **102** (1997) 229, (BHLUMI 4.04).

FCC

from S. Jadach list of 500+ papers

The Monte Carlo program KORALZ, version 4.0, for the lepton or quark pair production at LEP / SLC energies #7

S. Jadach (CERN and Cracow, INP), B.F.L. Ward (Tennessee U. and SLAC), Z. Was (CERN and Cracow, INP) (Nov, 1993)

Published in: *Comput.Phys.Commun.* 79 (1994) 503-522

DOI cite claim reference search 739 citations

The tau decay library TAUOLA: Version 2.4 #8

S. Jadach (CERN and Cracow, INP), Z. Was (CERN and Cracow, INP), R. Decker (Karlsruhe U.), Johann H. Kuhn (Karlsruhe U.) (Feb, 1993)

Published in: *Comput.Phys.Commun.* 76 (1993) 361-380

DOI cite claim reference search 1,108 citations

Toward a model independent analysis of electroweak data #9

Guido Altarelli (CERN), Riccardo Barbieri (Pisa U.), S. Jadach (CERN) (Jun, 1991)

Published in: *Nucl.Phys.B* 369 (1992) 3-32, *Nucl.Phys.B* 376 (1992) 444 (erratum)

DOI cite claim reference search 536 citations

TAUOLA: A Library of Monte Carlo programs to simulate decays of polarized tau leptons #10

ELECTROWEAK RADIATIVE CORRECTIONS

relation between observables and $\{ G_F , \alpha(M_Z), M_Z \}$

Altarelli, Barbieri, Jadach 91

DEFINITIONS

$$\sin^2\theta_W^{eff} \cdot \cos^2\theta_W^{eff} = \frac{\pi \alpha(M_Z)}{\sqrt{2}\, G_F M_Z^2 (1+\Delta\rho)(1-\varepsilon_3/\cos^2\theta_W)}$$

$$\Gamma_\ell = \frac{G_F M_Z^3}{24\sqrt{2}\,\pi}(1+\Delta\rho)\left(1+\frac{3}{4}\frac{\alpha}{\pi}\right)$$

$$m_W^2 = \frac{\pi\, \alpha(M_Z)}{\sqrt{2}\, G_F \left(1-\frac{m_W^2}{m_Z^2}\right)\left(1-\Delta_r^{ew}\right)}$$

$$\Gamma_b = \Gamma_d (1+\delta_{vb})$$

$$\Delta\rho \simeq \frac{\alpha}{\pi}\frac{m_t^2}{M_Z^2} - \frac{\alpha}{4\pi}\ln\frac{m_H^2}{m_Z^2}$$

this is $\varepsilon_1 \propto \alpha T$

$$\varepsilon_3 \simeq + \frac{\alpha}{12\pi}\ln\frac{m_H^2}{m_Z^2}$$

and this is $\propto \alpha S$

$$\varepsilon_2 \simeq + \frac{\alpha}{9\pi}\ln\frac{m_H^2}{m_Z^2}$$

$$\delta_{vb} \simeq -\frac{20\alpha}{13\pi}\frac{m_t^2}{m_Z^2}$$

this is ε_b (too often forgotten!)

$$\Delta_r^{ew} = -\frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho + 2\varepsilon_3 - \frac{\cos^2\sin^2}{\cos^2-\sin^2}\varepsilon_2$$

this is (part of) Marciano's Δr

$\sin^2\theta^{eff}_W \equiv 1/4\,(1-g_v/g_a)_{electron}$

1. in principle using different observables, it is possible to disentangle the effects of top, Higgs and even something else. (3 most elevant parameters ε_1, ε_3, ε_b + more in BSM)
2. the Z mass and width are measured using all Z decays and thus faster statistically and very easy systematically rather than asymmetries or partial widths that require final state selection
3. QED corrections constitute a gauge inv. set that factorizes out and has little sensitivity to heavy physics

Polarization at LEP

As a side effect of synchrotron radiation emission, e^+/e^- beams polarize spontaneously (align their spins) in the transverse (vertical) direction, i.e. along the direction of the bending field.

Polarization is however a slow and delicate process which requires a lot of care in machine setup and special conditions.

Ideal machine :

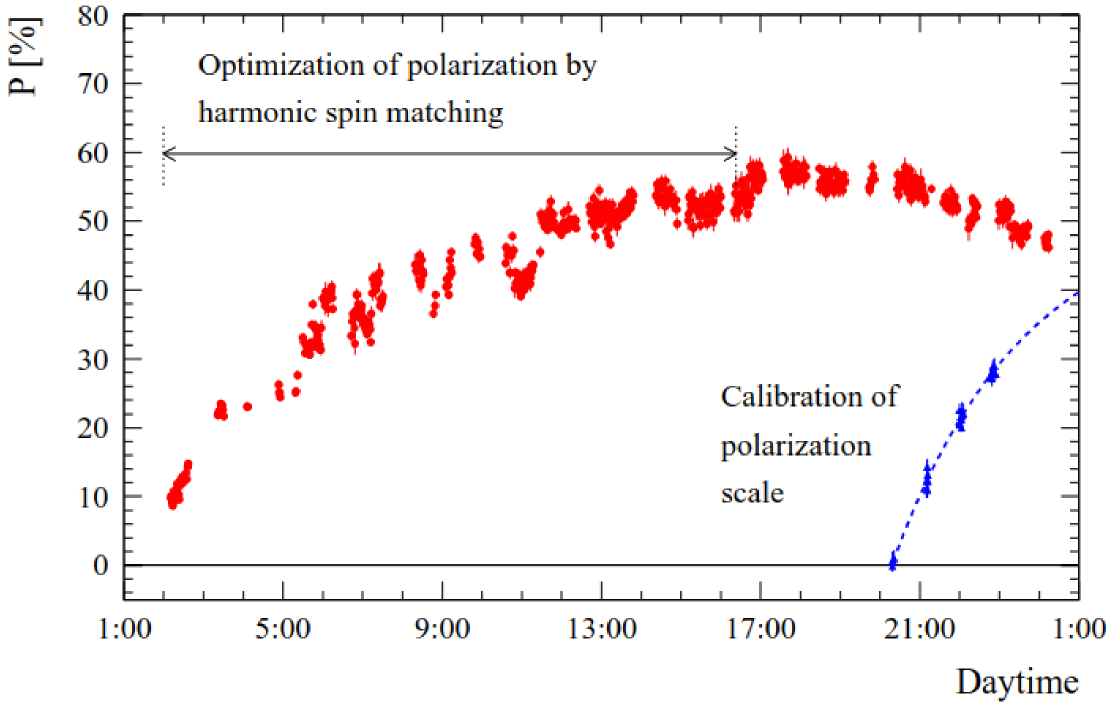
$P_T^{max} = 92.4\%$

At LEP :

record $P_T = 57\%$

routine $P_T = 5$ -10%

Up to 60.6 GeV



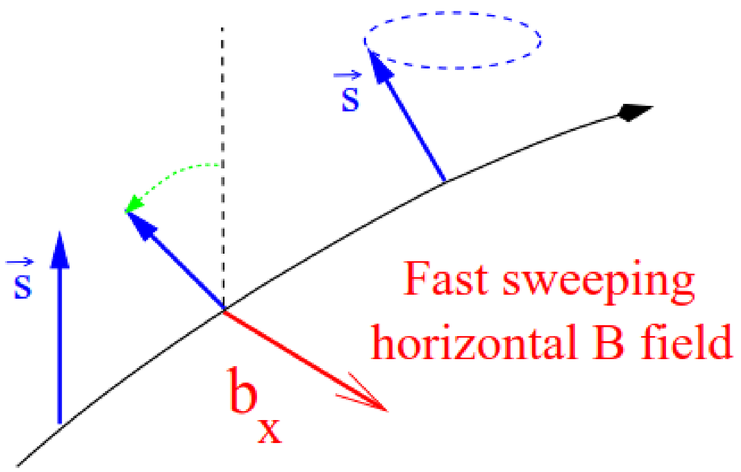
Resonant Depolarization

The interest of P_T : magnetic moments precess in B-fields

The **number of precessions/turn** ν, called **the spin tune**, is **proportional to the energy** :

$$\nu = \frac{g_e - 2}{2}\frac{E}{mc^2} = \frac{E[\mathrm{MeV}]}{440.6486(1)[\mathrm{MeV}]}$$

To determine the energy → **Measure ν**



Principle :

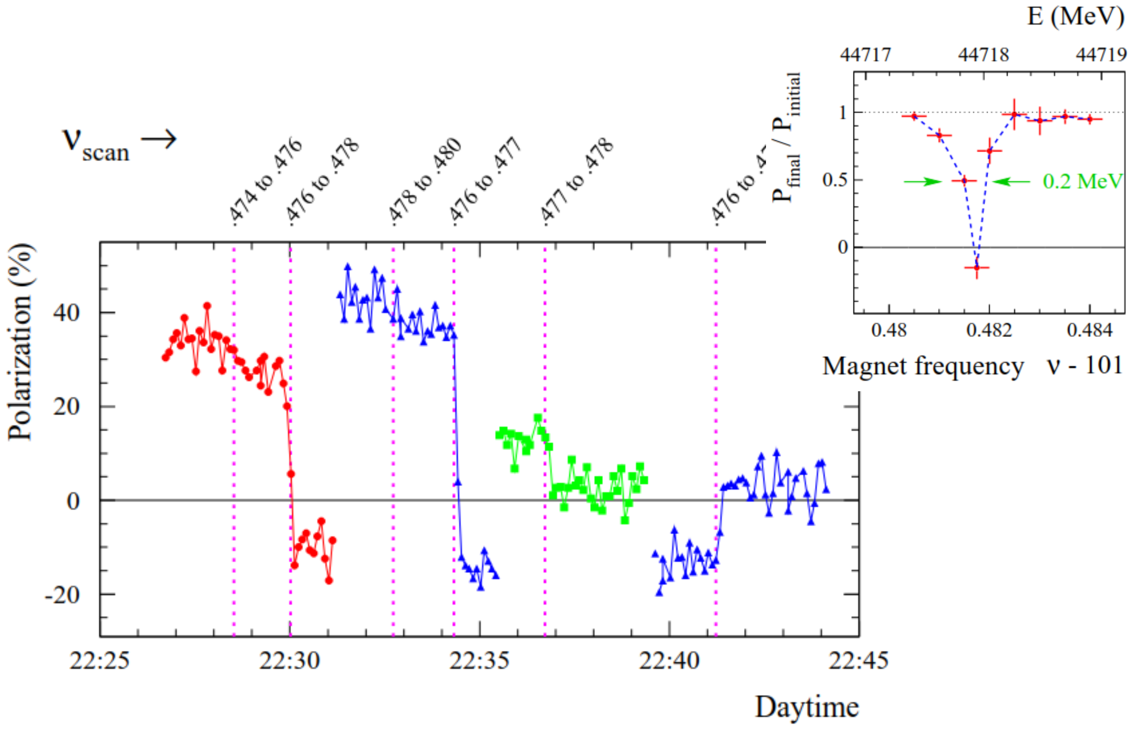
- Sweep the B-field of a fast pulsing magnet ("kicker") in frequency and observe P_T,
- If kicker frequency and ν match, P_T is rotated away from the vertical axis.

Resonant depolarization

Resonant Depolarization II

In practice :

- The kicker frequency is swept over a selected interval (~ 22 Hz).
- P_T can be destroyed or flipped when the kicker is in resonance.



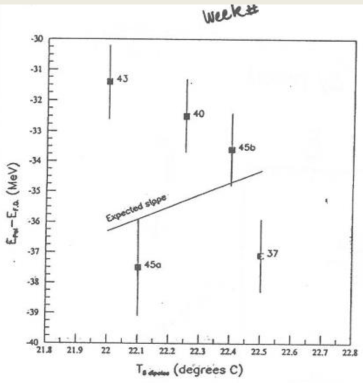
Intrinsic accuracy at LEP :

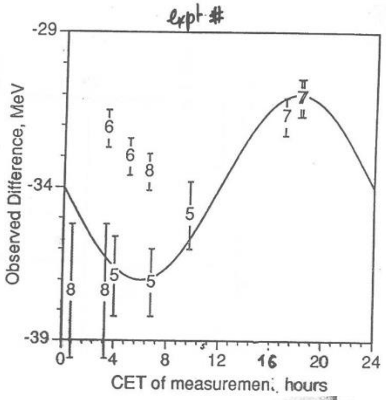
ΔE < 0.4 MeV
$\Delta E/E < 10^{-5}$

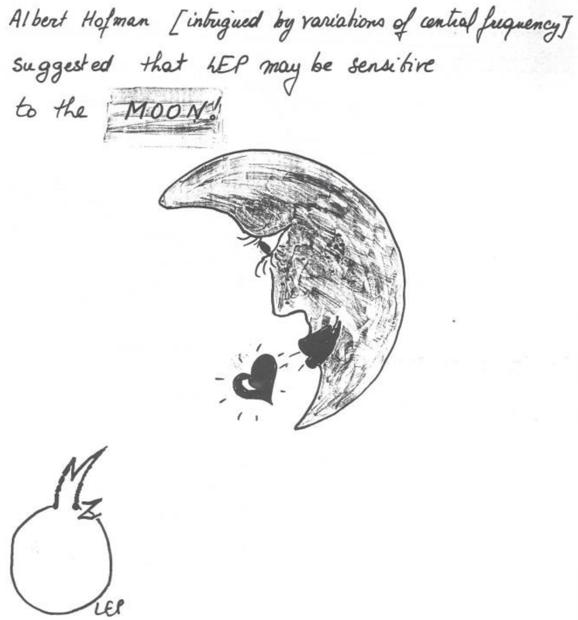
This technique is over an order of magnitude more accurate than any other method !

But it required a large amount of DEDICATED beam time as polarization was not considered compatible with physics data taking. Done at end of physics fills → bias
For instance, solenoids were not spin-compensated
Only e- (not e+) was measured
(AB: in hindsight this was a big mistake)
➔ in the future need pilot bunches, compensation, and both e+ and e- polarimeters

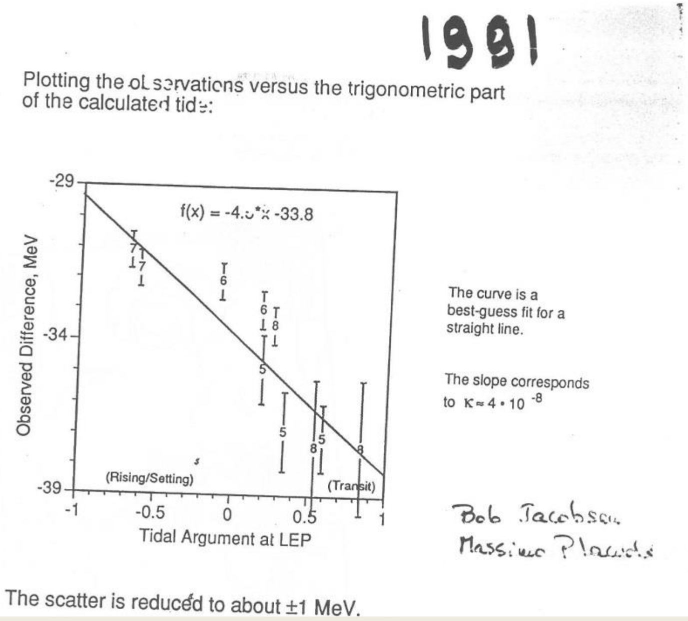
The measurements were very precise but not reproducible! no correlation with temperature or time of day.





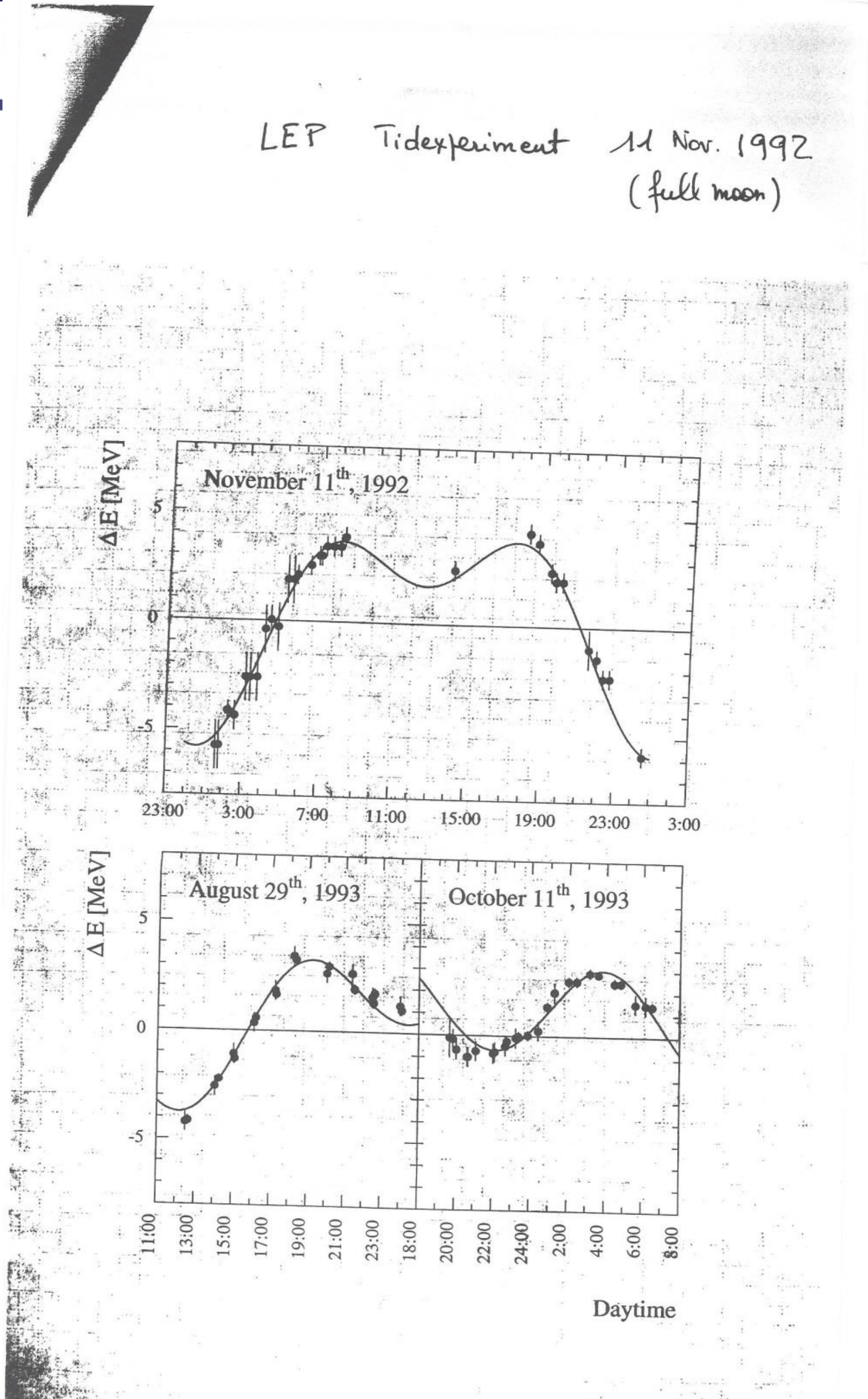


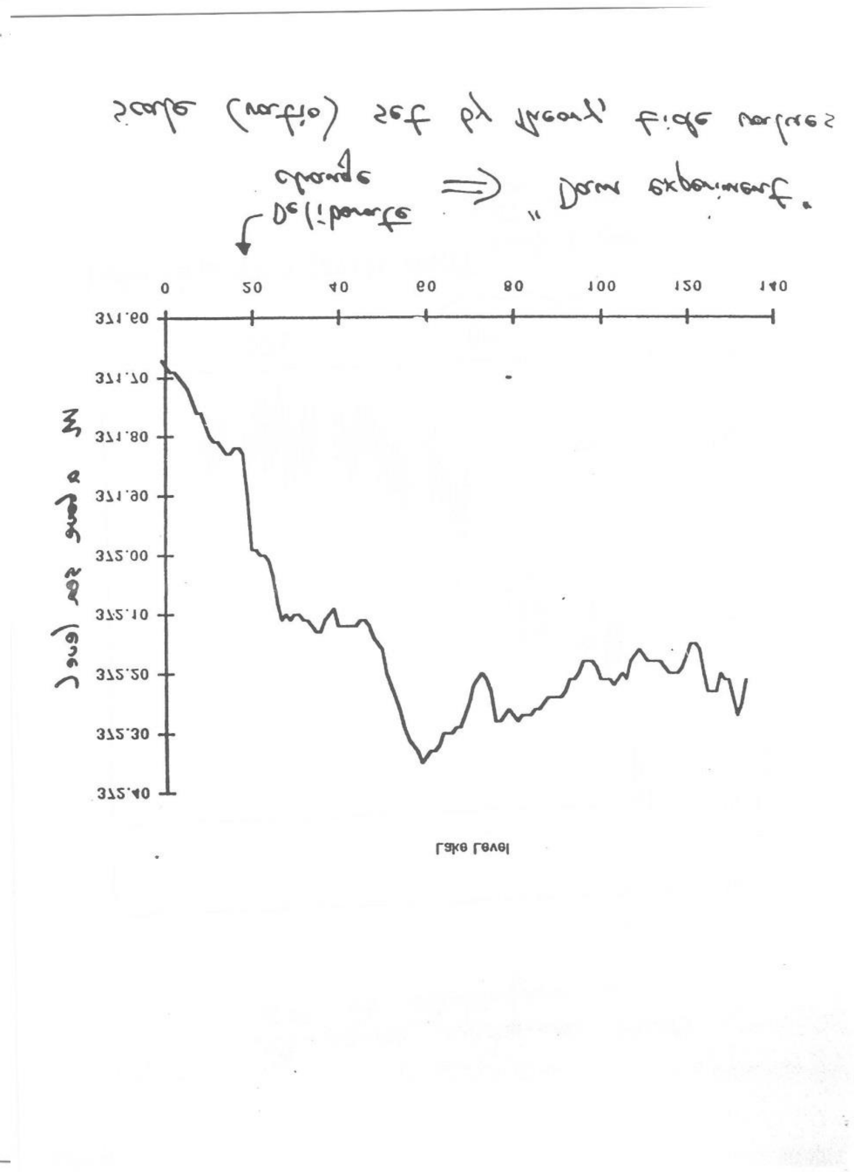
and indeed the measurements correlated nicely with the calculated amplitude of the earth tides.

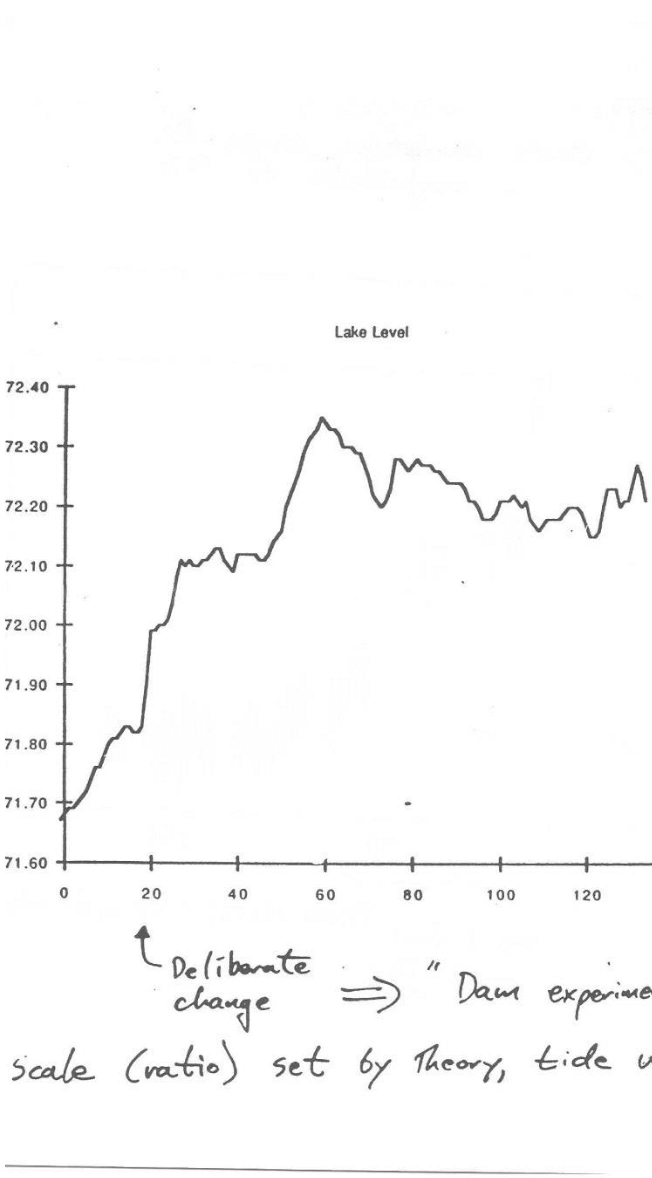


in 1992 we stopped scanning and spent some time understanding things better…

beginning.







Al

Success in the Press !

Moon Found Behind Particle-Accelerator Puzzle

By MALCOLM W. BROWNE

In Physics, the Moon Factor

GENEVA (IHT) — Scientists at the European Laboratory for Particle Physics will have to consult the phase of the moon in future before calibrating instruments on the Large Electron Positron collider outside Geneva.

Long puzzled by variations in the energy of the circulating beam made up of hundreds of millions of subatomic particles, physicists have now discovered that these correspond exactly to minute deformations in the Earth's crust caused by lunar attraction. Over the 27 kilome-

SCIENCES

Au LEP, près de Genève

Les effets de Lune dévoilés par les physiciens

Dans le grand accélérateur européen de particules, les mesures étai... parfois ...le.

Physicists look to the moon for atomic answers

PHYSIQUE DES PARTICULES Mystère élucidé

Comment la lune a trompé le CERN : les physiciens expliquent

Les scientifiques ont enfin trouvé l'origine d'une imprécision qui entachait leurs expériences : des « marées terrestres » provoquées par la lun...

La lune trouble le CERN

L'énergie des particules circulant dans l'anneau du LEP se modifie en fonction des phases lunaires.

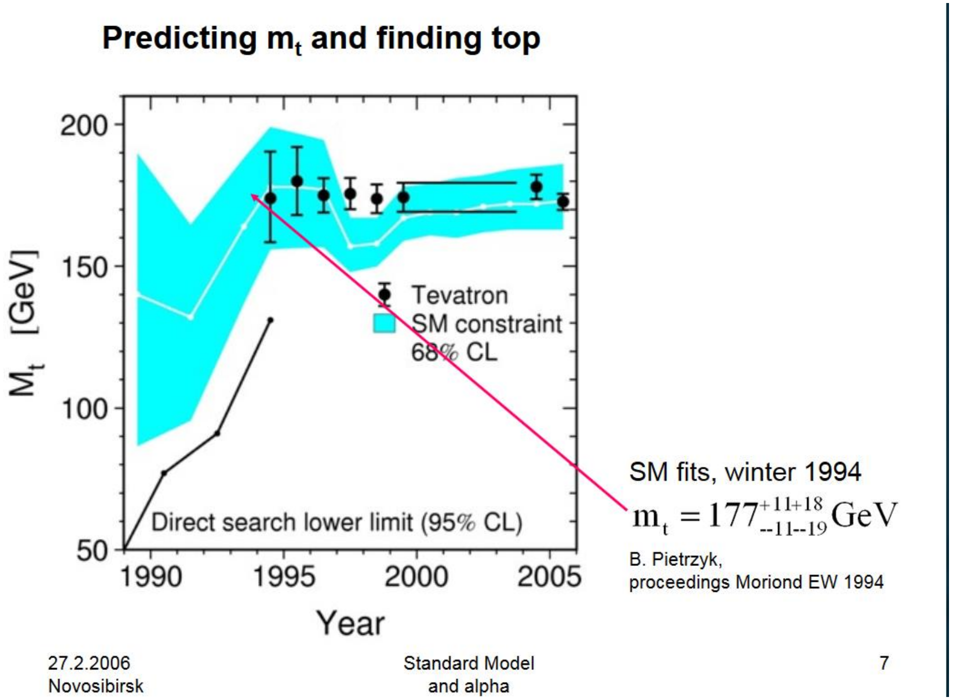
In 1993 the Z peak was scanned very thoroughly with a sequence of data points at spin tunes of 101.5 (peak '-2') , 103.5 (peak) , 105.5 (peak'+2')
Nature was kind because these points were both ar away from spin resonances, and very near optimal for the Z width determination with precision of $\pm$3 MeV.
At the same time the muon forward-backward asymmetries (this also depends strongly on energy) were measured as well as tau polarization and all things that measure $\sin^2\theta_w^{eff}$.

At the end of year the cross-section and asymmetry data were analysed and put together by the LEP electroweak working group to obtain a prediction for the top quark mass of

m_{top} = 177 $\pm$11 (+18-19 for m_H =1000,100, 30),
as kindly referred to in the CDF paper of April 1994 who reported an excess of 2.8 σ in that same mass range with best mass of 176$\pm$16 GeV.

CDF and D0 went on to discover the top in 1995, and LEP and SLC went on to predicting the Higgs mass using the top quark mass from the Tevatron.

....LHC discoverd the Higgs boson with m=125 GeV



The Nobel Prize in Physics 1999

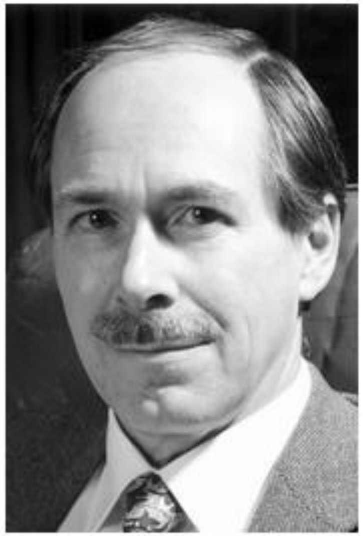


Photo from the Nobel Foundation archive.

Gerardus 't Hooft

Prize share: 1/2

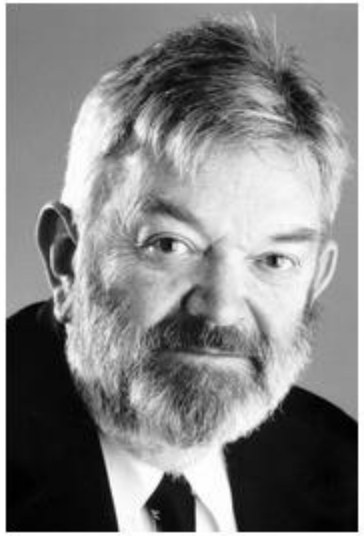


Photo from the Nobel Foundation archive.

Martinus J.G. Veltman

Prize share: 1/2

The Nobel Prize in Physics 1999 was awarded jointly to Gerardus 't Hooft and Martinus J.G. Veltman "for elucidating the quantum structure of electroweak interactions in physics"

in the 'advanced information'...written by C. Jarlskog

For example, the mass of the top quark could be predicted, using high precision data from the accelerator LEP (Large Electron Positron) at the Laboratory CERN, Switzerland, several years before it was discovered, in 1995 at the Fermi National Laboratory in USA. The top quark, in spite of being too heavy to be produced at the LEP accelerator, contributed through quantum corrections by a measurable amount to several quantities that could be measured at LEP. Similarly, comparison of theoretical values of quantum corrections involving the Higgs Boson with precision measurements at LEP gives information on the mass of this as yet undiscovered particle.

FCC

The final LEPI and SLC and Tevatron results can be found in **arXiv:hep-ex/0509008**
providing spectacular agreement of data with the Standard Model

and a prediction for the Higgs boson mass of 129 +74-69 GeV.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
STANFORD LINEAR ACCELERATOR CENTER

CERN-PH-EP/2005-041
SLAC-R-774
hep-ex/0509008
7 September 2005

Precision Electroweak Measurements on the Z Resonance

The ALEPH, DELPHI, L3, OPAL, SLD Collaborations,[1]
the LEP Electroweak Working Group,[2]
the SLD Electroweak and Heavy Flavour Groups

Parameter	Value	Correlations				
		$\Delta\alpha^{(5)}_{\rm had}(m^2_Z)$	$\alpha_S(m^2_Z)$	m_Z	m_t	$\log_{10}(m_H/\mathrm{GeV})$
$\Delta\alpha^{(5)}_{\rm had}(m^2_Z)$	0.02767 ± 0.00034	1.00				
$\alpha_S(m^2_Z)$	0.1188 ± 0.0027	−0.02	1.00			
m_Z [GeV]	91.1874 ± 0.0021	−0.01	−0.02	1.00		
m_t [GeV]	178.5 ± 3.9	−0.05	0.11	−0.03	1.00	
$\log_{10}(m_H/\mathrm{GeV})$	2.11 ± 0.20	−0.46	0.18	0.06	0.67	1.00
m_H [GeV]	$129\pm^{74}_{49}$	−0.46	0.18	0.06	0.67	1.00

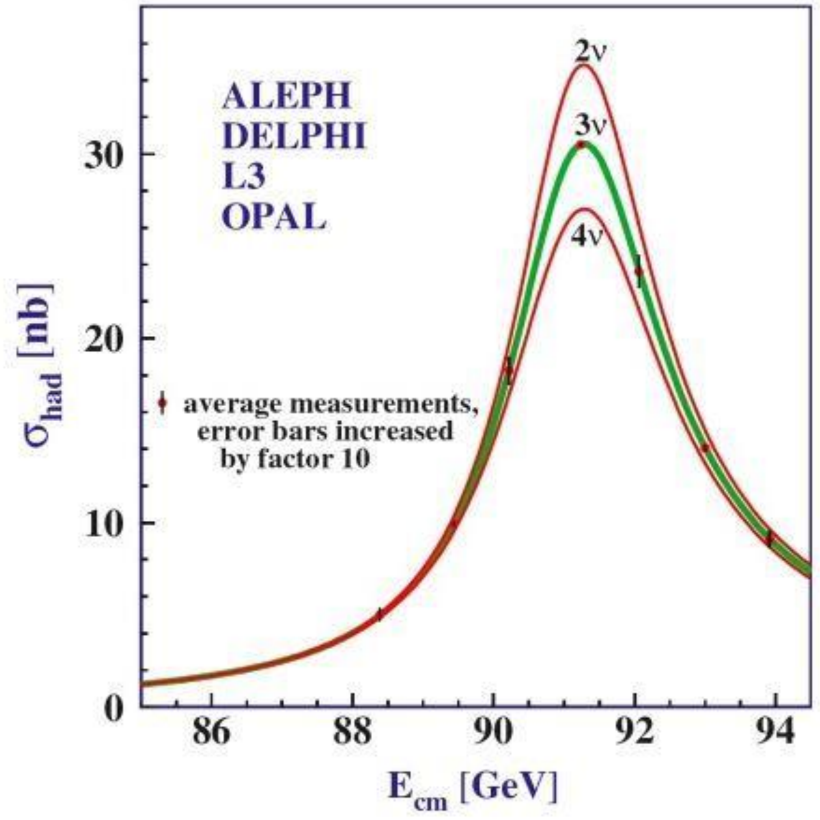
Table 8.3: Results for the five SM input parameters derived from a fit to the Z-pole results and $\Delta\alpha^{(5)}_{\rm had}(m^2_Z)$, plus m_t, m_W, and Γ_W from Tevatron Run-I and LEP-II. The fit has a χ^2/dof of 18.3/13, corresponding to a probability of 15%. See Section 8.4 for a discussion of the theoretical uncertainties not included here. The results on m_H, obtained by exponentiating the fit results on $\log_{10}(m_H/\mathrm{GeV})$, are also shown. The direct measurements of m_W and Γ_W used here are preliminary.

At the end of LEP:

Phys.Rept.427:257-454,2006

$N_\nu = 2.984 \pm 0.008$

This is determined from the Z line shape scan and dominated by the measurement of the hadronic cross-section at the Z peak maximum ➔



The dominant systematic error is the theoretical uncertainty on the Bhabha cross-section (0.06%) which represents an error of $\pm$0.0046 on N_ν

Improving on N_ν by more than a factor 10 would require a large effort to improve on the Bhabha cross-section calculation!

See Patrick's talk for a further avatar on this important measurement.

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Lessons from LEP -- many!

Verified a number of fundamentals of the SM at the 10^{-3} level

-- universality of e/μ/τ/ν couplings @10^{-3} for NC (Z p. widths and asymetries)
as well as CC (using tau decays)

-- lepton quark universality (from ratio of hadron to lepton decay width)

-- Measured essential input (Z mass at 10^{-5} level)

-- observed effect of top mass and predicted the mass
before and independently of first direct observations

-- constrained the Higgs boson mass [114.7(direct) → 285 GeV(Rad.Cor.)]

-- measured W mass, WW production and gauge couplings

→ Assuming **NO** BSM physics modifies the SM predictions

More lessons learned...

1. LEP exceeded expectations in almost every aspect that involved « systematics-dominated » measurements!

   examples of precisions: Z mass and width (exp:20-50 MeV, achieved 2 MeV) (EPOL)

   luminosity measurement (exp ~2%, achieved ~6 10^{-4}) ➔ N_ν

   $\sin^2\theta^{eff}_w$ (exp 0.001, achieved 0.00016)

   R_b (exp 2-5%? achieved 0.3%) etc etc

   + corresponding improvements in theory calulations and superb MC codes

2. also realized that things could have been better if better prepared

   difficulty in measuring the leptonic B.R. (end-cap design)

   did not expect all the difficulties in beam energy calibration

   still some measurements limited by th. unertainties

Partly because spelled out 'expectations' were too conservative!

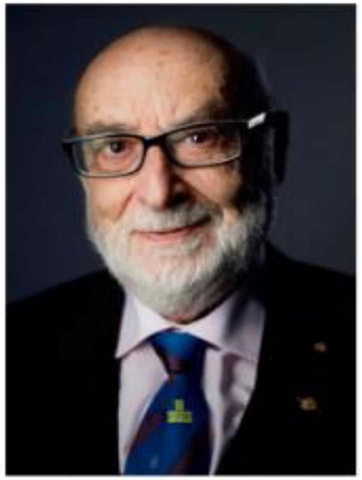
its not because things are difficult that we dont dare...

its because we dont dare that things are difficult

What happened since LEP?

LHC of course, and much more

The Nobel Prize in Physics 2013



© Nobel Media AB. Photo: A. Mahmoud

François Englert

Prize share: 1/2

© Nobel Media AB. Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

Share this: 951

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Particle physics after the discovery of the Higgs boson

Two facets:

The Higgs boson is very special

It generates (couples to) mass. Alone?

-- W,Z masses ⇔ Higgs coupling to WW, ZZ? FCC-ee

-- (all) fermion masses ⇔ Higgs couplings? FCC-ee

FCC-hh(+ee) -- decays ($\gamma\gamma$, gg, Zγ) ⇔ SM particle content?

-- are all elementary particles given mass this way?

FCC-ee(?) even electrons? and even the neutrinos?

Yukawa (→ ν_R , sterile → Majorana HNL) FCC-ee

Higgs couples to itself!

-- Spontaneous Symmetry Breaking

-- What is the value of the self-coupling?

-- impact on σ_{HZ} near threshold FCC-ee

-- HH production

FCC-hh, high energy lepton colliders

FCC-hh

The SM is « complete »

-- Higgs and top masses predicted from EWPOs

assuming no new SM coupled particles exist

-- $m_H \approx$ 125GeV → SM extrapolates to the Plank scale

assuming no new SM coupled particles exist

-- SM works wonderfully... **So why continue?**

-- SM does not explain everything

Baryon Asymmetry of the Universe

Dark Matter

Neutrino masses

and more.... ➔ require new particles!

nature and **mass scale is unknown**

FCC-ee: EWPO Flavour

Are there any further SM-coupled particles?

FCC-hh

-- no guarantee or exp. indication that any exist

-- but many BSM solutions include them...

-- DARK SECTOR → possibly light, sterile particles

FCC-ee: LLP EWPO Flavour

Particle physics after the discovery that neutrinos have mass

« Beyond the Standard Model » because SM is defined as having massless neutrinos

Neutrinos oscillate

3x3 oscillation → possibility of CP violation
➔ T2K, HyperK, DUNE

'near future' (2030-2040..) and after that?

New degrees of freedom

Fermion number is no longer a conserved quantity
Neutrino coupling with Higgs boson
➔ right handed neutrinos
minimal see-saw (see slides 44-51)
➔ Heavy Majorana, sterile, Neutral Leptons

Sakharov condition for generation of the **Baryon Asymmetry of the Universe:**
-- Fermion number violation
-- CP or T violation and
-- out-of-equilibrium universe (Big Bang)

➔ Baryogenesis or Leptogenesis + sphalerons

Massive neutrinos are THE natural candidate to explain the dominance of matter over antimatter in the universe.

a hard look at the situation...

Since the NC discovery we have been relying on increasing collider energies for the next SM particle to show up...
... or else a drama would happen (t-less models, no-lose theorem, etc...)

This is no longer necessarily the case.
The SM-coupled particles predicted by the SM have all been found, yet unexplained phenomena are observed. (DM. BAU)
It is quite possible that no more SM-coupled particle exist!
The question 'are there any more particles with SM couplings?' must be tested by all possible means!
➔ **Any solid set of SM deviations would be a big discovery**
➔ EW+Flavours at colliders and high precision facilities with several orders of magnitude increase of precision.

The new physics there is : Higgs boson and massive neutrinos.
What is predicted are sterile particles with couplings many many orders of magnitude smaller than SM and whose mass can vary between few keV and 10^{10} GeV... still must look for them wherever we can!
➔ **High precision, huge intensities and more energy are required.**

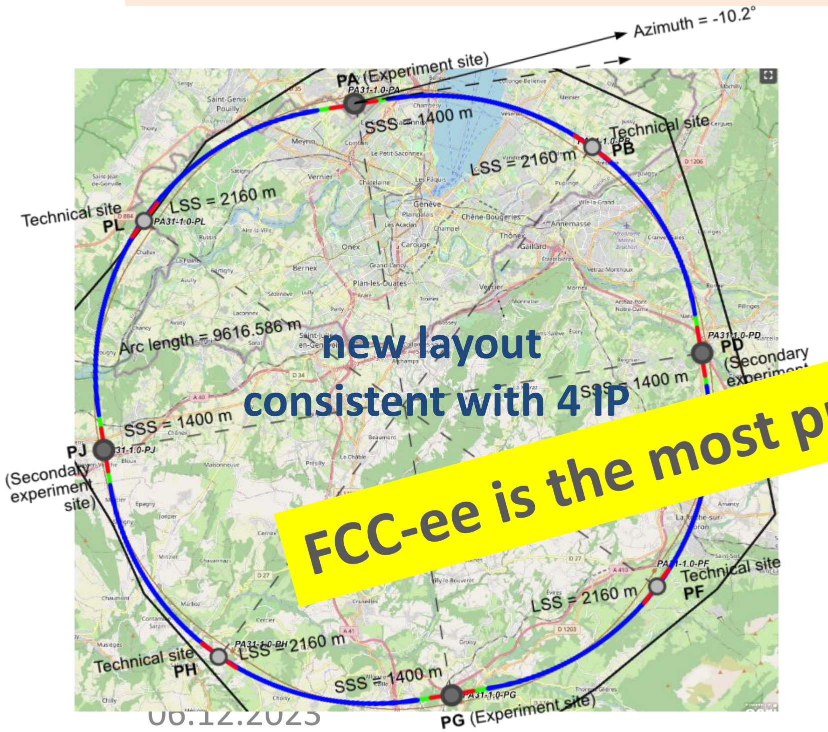
A NEW ERA OF EXPLORATION

The FCC integrated program at CERN

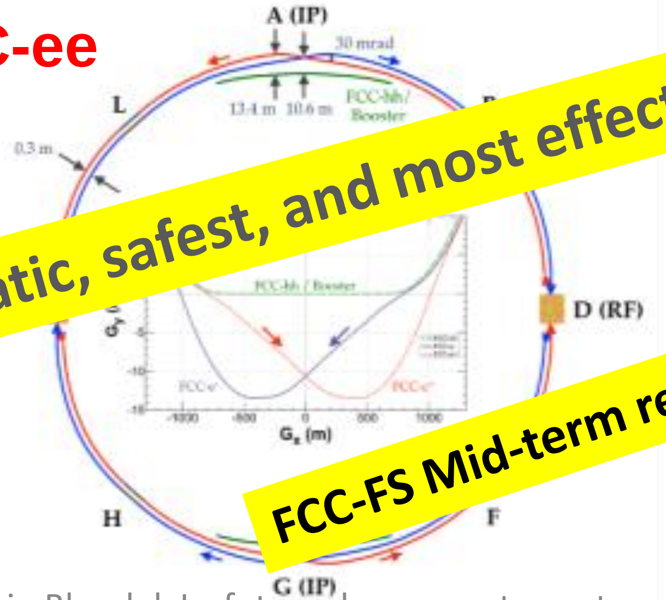
Comprehensive cost-effective program inspired by successful LEP – LHC success story

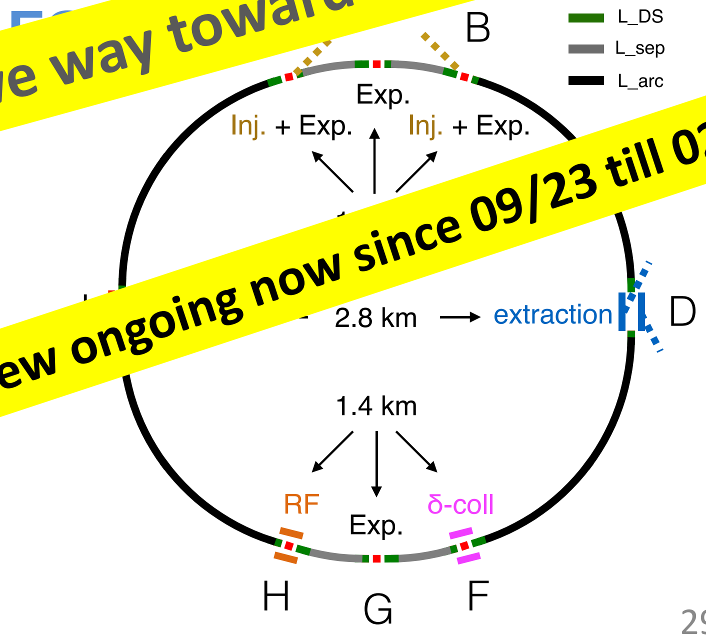
- **Stage 1: FCC-ee (Z, W, H, tt) as first generation Higgs EW and top factory at highest luminosities.**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options.**
- **Maximizes physics output with strong complementarity**
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure.
- **FCC-INT project plan is fully integrated with HL-LHC exploitation ➔ seamless continuation of HEP**
- **Feasibility study approved and funded at CERN (100MCHF/5yrs) + magnet R&D (120 MCHF/6yrs)**

***** GLOBAL COLLABORATION *****



FCC-ee





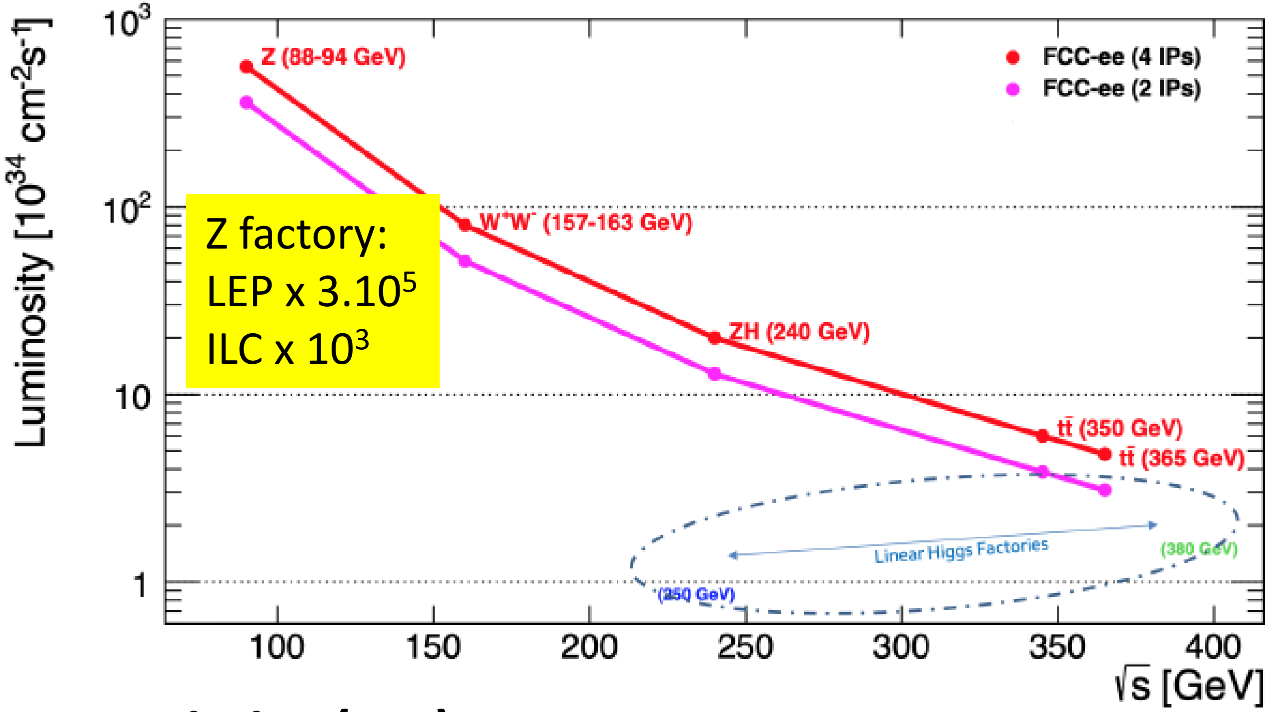
FCC-ee is the most pragmatic, safest, and most effective way toward FCC-hh

FCC-FS Mid-term review ongoing now since 09/23 till 02/24

FCC

FCC-ee

Great energy range for the heavy particles of the Standard Model



Z factory:
LEP x 3.10^5
ILC x 10^3

notes:

-- 4IP increases Total Lumi by ~ 1.5 x2IP
-- order and duration of Z/WW/ZH can be decided at a later stage
-- if ee→ H possible it must be after both Z and ZH and before tt

The entire LEPI data set in ~2 minutes

Event statistics (4IP)

						E_{CM} errors:
Z peak	**E_{cm} : 91 GeV**	**4yrs**	**$6.\ 10^{12}$**	**e+e- → Z (qq)**	**LEP x 3.10^5**	<100 keV
WW threshold	**$E_{cm} \geq$ 157-161**	**2yrs**	**$2.\ 10^8$**	**e+e- → WW**	**LEP x 2.10^3**	<300 keV
ZH maximum	**E_{cm} : 240 GeV**	**3yrs**	**$1.5\ 10^6$**	**e+e- → ZH**	**Never done**	1 MeV
s-channel H	***E_{cm} : m_H***	***(3yrs?)***	***O(5000)***	***e+e- → H***	***Never done***	<< 1 MeV
$t\bar{t}$	**E_{cm} : 340-365 GeV**	**5yrs**	**$2.\ 10^6$**	**e+e- → $t\bar{t}$**	**Never done**	2 MeV

FCC-ee: main machine parameters

« FCC is the best project for CERN »

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 [illegible]	[illegible]	2.08/0	4.0/7.25
long. damping time [turns]	[illegible]	[illegible]	64.5	18.5
horizontal beta* [m]	[illegible]	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal g[illegible]	0.71	2.17	0.64	1.49
vertical geom[illegible] [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

F. Gianotti,
P5 meeting
2023-04-15

- x 10-50 improvements on all EW observables
- up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 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

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

Physics at FCC

1. HIGGS FACTORY

→ Higgs provides a very good reason why we need e+e- (or $\mu\mu$) collider

→ **2. ELECTROWEAK PRECISION (10^{-3} today → $10^{-5/6}$)**

Z + WW + top required!

CHALLENGES

3. Z FACTORY

($6\ 10^{12}$ Z i.e. $1.5\ 10^{11}$ ee, $\mu\mu$, $\tau\tau$; ~$0.7\ 10^{12}$ uu,dd,ss,cc,bb ; 10^{12} $\nu\nu$)

High statistics for Heavy Flavours, QCD

→ Search for Feebly-Coupled/sterile Particles (HNL, ALPS, etc) “Dark Sector”

Place for ‘direct discovery’

4. {90-120} TeV FCC-hh

The most powerful high energy exploration machine esp for any gluon-mediated process including W (>> 10^{13} from top decay) and Higgs ($2\ 10^{10}$ from gg-> H) and direct searches in the multi TeV region (up to 50 TeV)

<u>Motivation</u> for the precision measurements *and* precision calculations

1. Given that the minimal 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? (→ Higgs Factory)
-- 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) (→ EW/top factory)

2. A powerful and broadly efficient method is to perform **<u>precision EW measurements</u>**
-- many **<u>observables</u>** contain sensitivity to new phenomena, either by loops, direct long distance propagator effects, or mixing with SM coupled particles. Having many observables is essential to provide redundancy and point to the origin.

→ are there any more weakly coupled particles?

Veltman: $\Delta\rho = \Delta T.\alpha = \alpha/\pi \, . \, \mathbf{(m^2_{top} - m^2_b)/m^2_W}$

«T» The top quark effect at LEP was 10σ! (→ there is *not* another t-b quark system)
any custodial SU(2)-violating effect appears <u>regardless of mass scale</u>

«ν» -- is there mixing ? Z-Z' **active-sterile neutrino mixing**

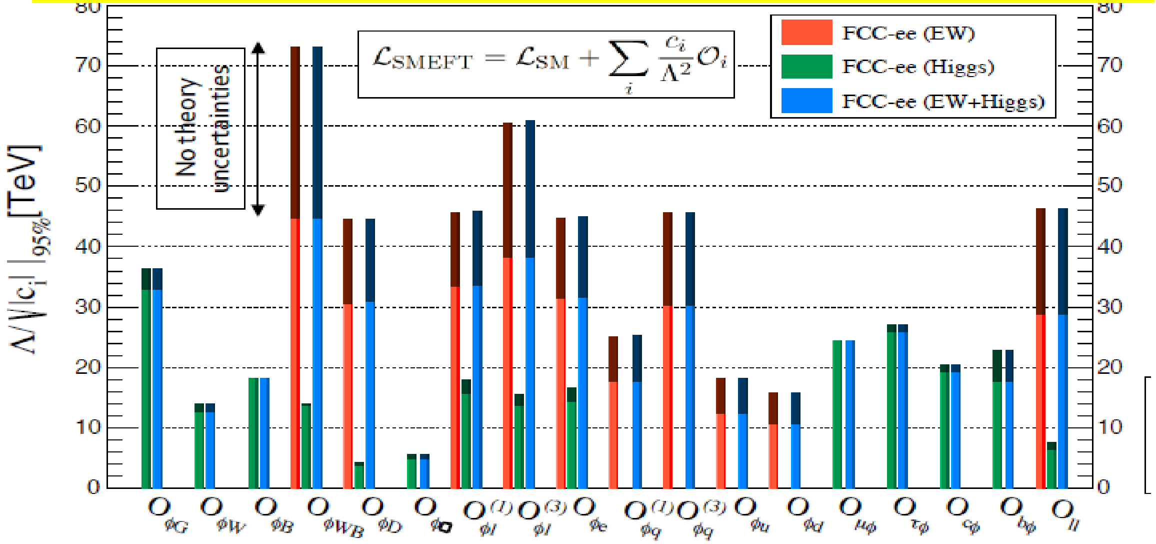
«S» -- high mass SM-coupled and custodial SU(2)-respecting → (ex: Z' or degenerate SuSy)

not to forget:
QCD
Lepton-quark
lepton and quark family
Universality

<u>Emphasis on different observables depending on the question asked → different patterns of effects</u>

Precision EW measurements: is the SM complete?

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 QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run



- ***Higgs and EWPOs are complementary***
- top quark mass and couplings essential!

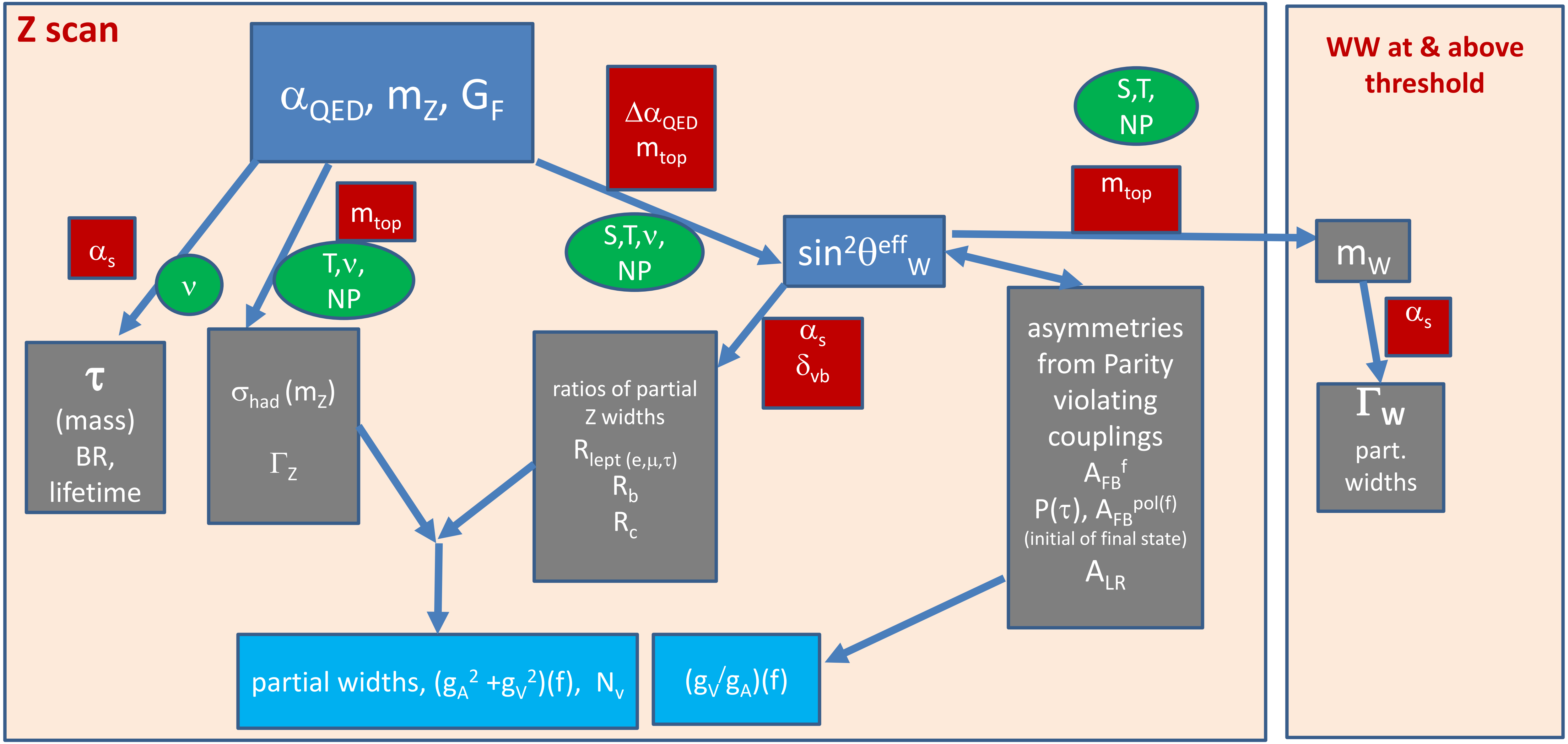
(the 100km circumference is optimal for this)

- preliminary systematics!

aim at reducing to the level of systematics

- many observables still to be added (flavours)
- complemented by high energy FCC-hh
- ***Theory work is critical and initiated***
- *1809.01830 and several follow ups*
- Target precision is statistics column

FCC Overview of loop correction relationships and examples of new physics effects

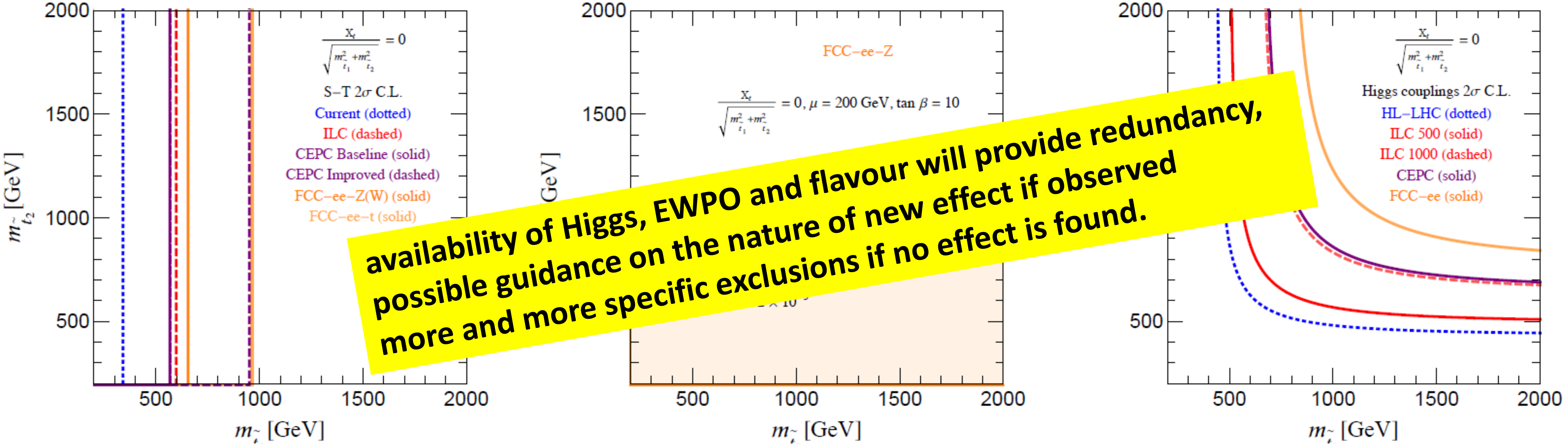


uncertainty on $\Delta\alpha_{QED}$ impacts $\sin^2\theta^{eff}_W$ sensitivity. **Direct measurement of $\Delta\alpha_{QED}$ by FCCee from $A_{FB}{}^{\mu\mu}$ (s) is UNIQUE**

Higgs, EWPOs and flavours are complementary

Precision Natural SUSY at CEPC, FCC-ee, and ILC, JJ Fan, M. Rees and Liantao Wang

arXiv:1412.3107v2 figure 5 (top row)



availability of Higgs, EWPO and flavour will provide redundancy, possible guidance on the nature of new effect if observed more and more specific exclusions if no effect is found.

Figure 5. Regions in the stop physical mass plane that are/will be excluded at 2σ by EWPT with oblique corrections (left column), R_b at FCC-ee (mid column) and Higgs couplings (right column) for different choices of $X_t/\sqrt{m_{\tilde t_1}^2+m_{\tilde t_2}^2}$: 0 (first row), 0.6 (2nd row), 1.0 (3rd row) and 1.4 (last row). We chose the mass eigenstate with $m_{\tilde t_1}$ to be mostly left-handed while the mass eigenstate with $m_{\tilde t_2}$ to be mostly right-handed. For non-zero choices of X_t, there are regions along the diagonal line which cannot be attained by diagonalizing a Hermitian mass matrix [32]. Also notice that the vacuum instability bound constrains $X_t/\sqrt{m_{\tilde t_1}^2+m_{\tilde t_2}^2} \lesssim \sqrt{3}$ [76].

" also, b→ sγ could be useful"

FCC

Huge statistics will help with systematics....
but detectors must be designed for this!

With statistics 300 000 times those of LEP ➔ statistical precision improves by 500
even more for b, tau and charm observables because of improvement of vertex detector and smaller beam pipe

Target: improve systematics to the level of the statistical precision

Examples(all work in progress, or to be done)

-- monitor luminosity with 10^{10} $\gamma\gamma$ events in addition to low angle Bhabha.

→ 1.5 10^{-5} precision provided fiducial volume limit (10-20 degrees) can be known to 10-15 microns at 2.5m.

-- perform beam energy calibration continuously with pilot polarized bunches RDP and solenoid compensation

-- use several tags (inclusive double tag, exclusive B decay modes tag, etc. etc.) for b-jet efficiency for R_b

-- use huge samples of muon pairs (1.5 10^{11}) to perform exquisite detector alignment (for tau life time, luminosity etc...

--- etc etc

Success requires to be proactive and design detectors with these precision targets in mind.

➔ a new era of detector design!

➔ Considerable opportunities in physics studies during phase towards preparation of detector collaborations!

FCC

Huge statistics will help with systematics....
and theory must be ready for it!

Staszek Jadach got interested early in TLEP/FCCee

attracted by the physics potential of the electroweak measurements .

- ➔ **Made many contributions at FCC weeks and physics workshops/meetings + publications**
- ➔ **worked with/attracted many collaborators to follow on his pioneering ideas and the huge challenges**

just one example:

Eur. Phys. J. C (2019) 79:756
https://doi.org/10.1140/epjc/s10052-019-7255-9

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Theoretical Physics

QED challenges at FCC-ee precision measurements

S. Jadach[a], M. Skrzypek
Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Kraków, Poland

arbores serit, quorum poma non viderit

He plants trees, the fruits of which he will not see.

FCC

Snapsot of ongoing efforts on theory side

Precision calculations for the Z line shape at the FCC-ee

S. Jadach et al, FCC week 2018 (Amsterdam)

+ I.Dubovyk A. Freitas, J. Gluza K. Grzankac T. Riemann J. Usovitsch

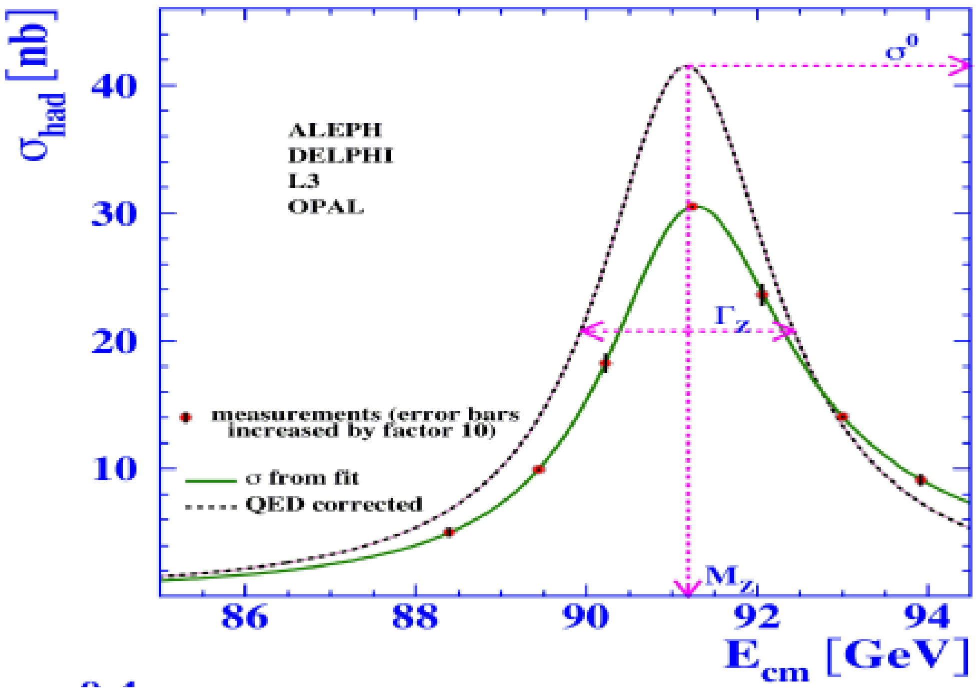
Next decade: complete 3-loop calculations [3]

$Z \to e^+ e^-, \ldots$			
Number of topologies	1 loop	2 loops	3 loops
	1	$14 \to^{(A)} 7 \to^{(B)} 5$	$211 \to^{(A)} 84 \to^{(B)} 51$
Number of diagrams	14	$2012 \to^{(A,B)} 880$	$397690 \to^{(A,B)} 91472$
Fermionic loops	0	114	13104
Bosonic loops	14	766	78368
Planar / Non-planar	14 / 0	782 / 98	65487 / 25985
QCD / EW	0 / 14	0 / 880	144 / 91328

Table 3: Presents the number of Z decay Feynman diagrams needed to be calculated for TH3 of Table 2. Tadpoles, products of lower loop diagrams (A) and symmetrical diagrams (B) are not included.

A first tackle might concentrate on the 13,104 electroweak 2-loop diagrams with closed internal fermionic loops, to be determined with a net accuracy of two relevant digits.

ment



Needs for substantially improved theoretical analysis software:

- QED Monte Carlo code of the KKMC-type [S. Jadach et al.]
- Unfolding code of the SMATASY type [M. Grünewald et al.]
- Electroweak library of the ZFITTER type [T. Riemann et al.]

$$\sigma^{meas} \xrightarrow{\text{KKMC},\cdots} \sigma^{real} \xrightarrow[\text{ZFITTER},\cdots]{\text{SMATASY},\cdots} \begin{cases} \sigma_0 \equiv \sigma^{eff,f} \\ M_Z, \Gamma_Z, \Gamma_f \\ A_{FB}^{eff,f}, A_{LR}^{eff,f} \\ R_b, R_\ell, R_{had} \\ \cdots \end{cases}$$

first thing: **accept that**

the target precision is the statistical error!

Centre of mass Energy Calibration: the cornerstone of the precision programme

Large ring→transverse polarization of $e^{\pm}$ up to $E_{beam} > 80$ GeV $\sigma_E \propto E^2/\sqrt{\rho}$

Resonant depolarization provides high precision E_{beam} $\nu_s = \frac{g-2}{2}\frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)}$

Unique to circular machines (ee or μμ)

Improve over LEP by using pilot bunches + both e- and e+ polarimeter

Relationship between ν_s and E_{CM}

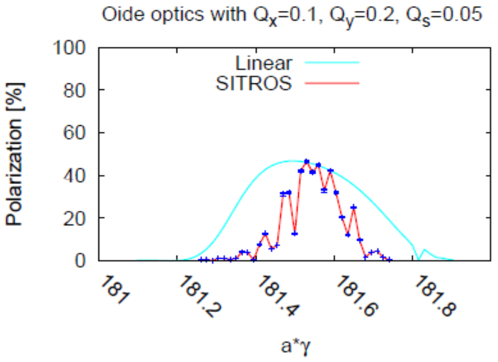
- ➔ **CM boost, σ_{ECM}, α_{coll} determined from 10^6 μμ /5min**
- ➔ **Beamstahlung monitor under study etc...**

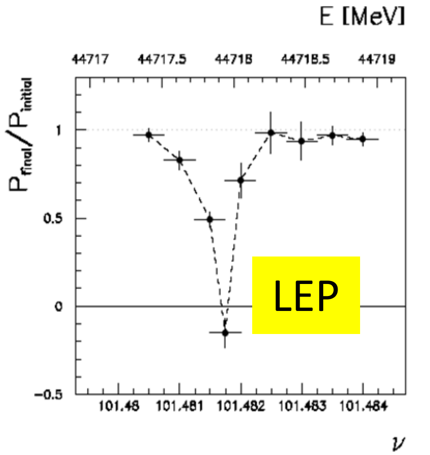
First round of studies (arxiv 1909.12245)

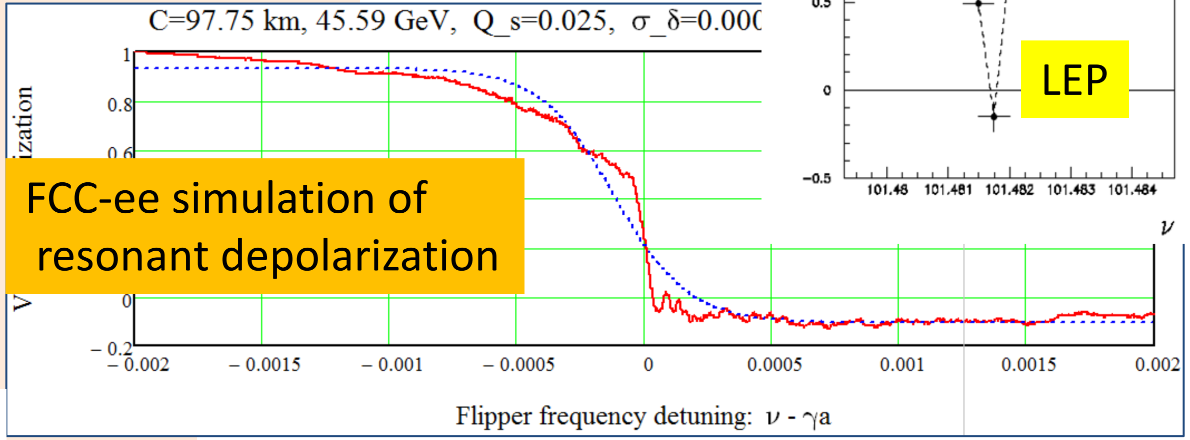
m_Z, Γ_Z, $\sin^2\theta_W^{eff}$, $\alpha_{QED}(m_Z)$, m_W

next target: bring syst. closer to stat. errors, esp. pt-to-pt errors

E. Gianfelice

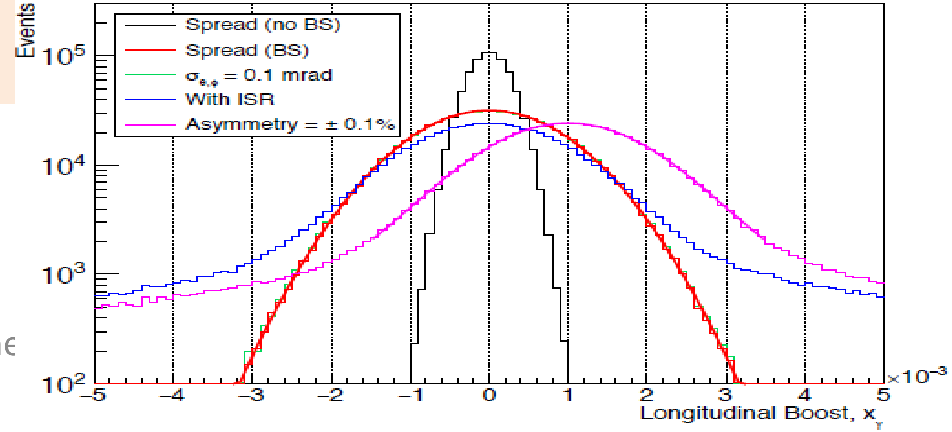






FCC-ee simulation of resonant depolarization

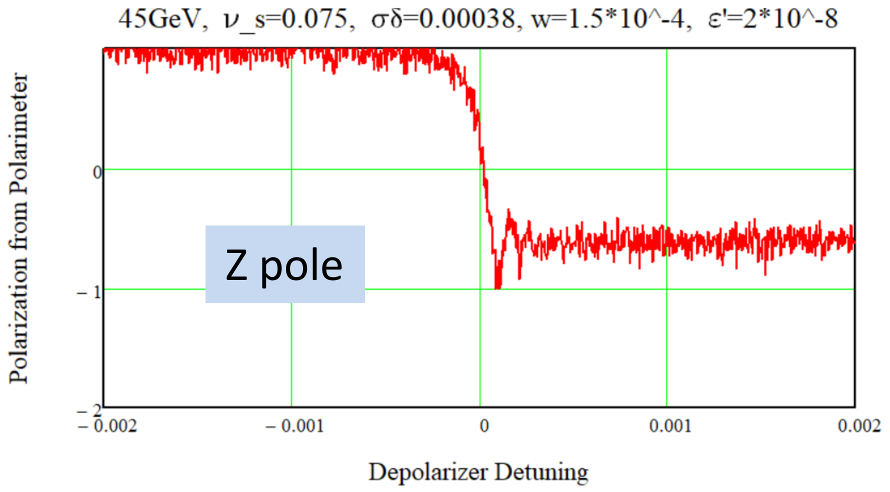
Quantity	statistics	ΔE_{CMabs} 100 keV	$\Delta E_{CMSyst-ptp}$ **40 keV**	calib. stats. 200 keV/$\sqrt{(N^i)}$	σE_{CM} (84) ± **0.05** MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	7	2.5	**22**	1	**10**
$sin^2\theta_W^{eff} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(M_Z)}{\alpha_{QED}(M_Z)}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

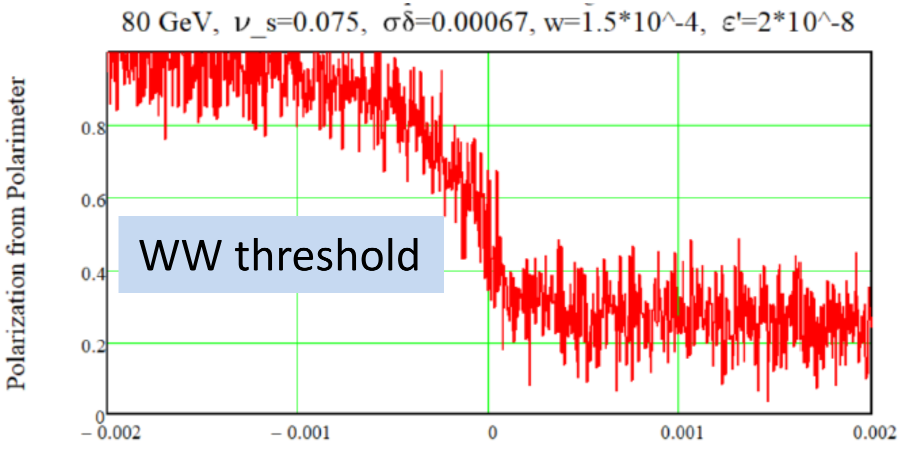


At our luminosity level, longitudinal polarization brings nothing that cannot be done otherwise.

Progress in FCC-ee energy calibration

From FCC week 2022 and FCC EPOL workshop:





-- Resonant depolarization measures energy every 15 minutes at < 50 keV/beam level at Z, 100 keV/beam at W

➔ syst will be reduced to < 100keV on m_W
at Z point to point uncertainties remain to be understood

-- Only one RF station around the ring, + the Energy losses of the two beams are strongly constrained from the direct measurement of boost at the IPs O(5 keV level) every 8hrs shift in 2/4 experiments

-- beam-beam deflection measurement is extremely sensitive to beam beam offset and local opposite-sign dispersion (previously large point-to-point error):
still lots to do but O(20 keV) per measurement every 3 second

➔ targeting to match or go below statistical errors of 4 keV
EPOL working group (Keintzel, Wilkinson, et al) establishing requirements

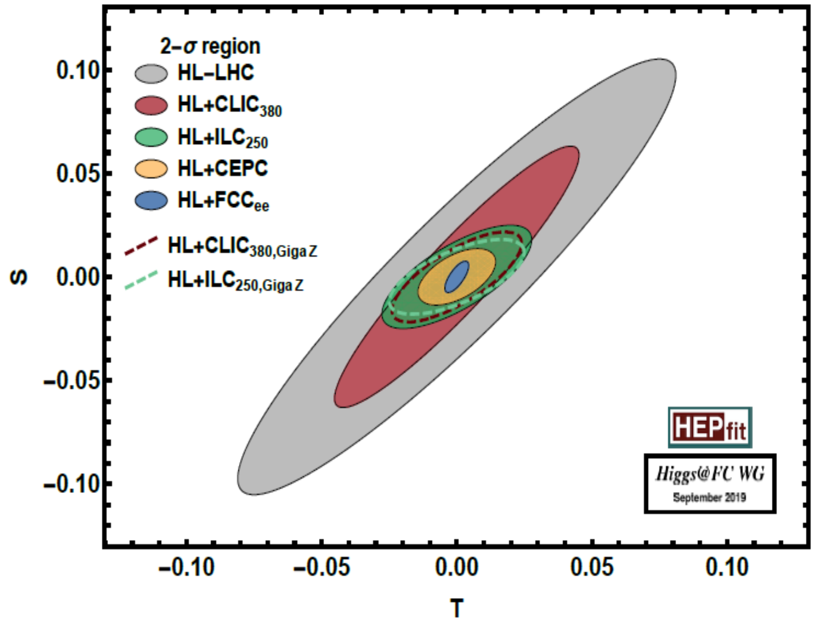
FCC

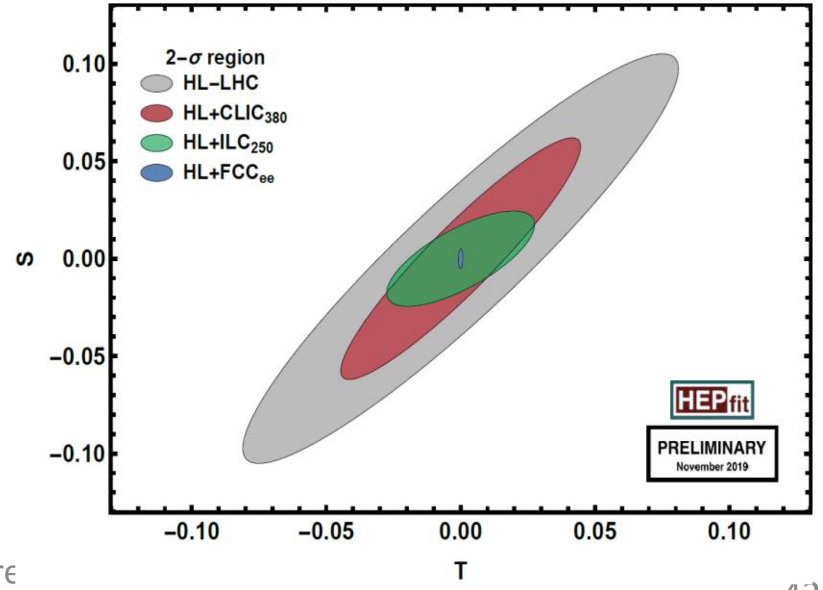
Electroweak Physics

Z factory + WW + top The realm of FCC-ee

Highest luminosities at 91, 160 and 350 GeV
Transverse pol. at 91 and 160 GeV → Ecm calibration
m_Z (100 keV) Γ_Z (25 keV), m_W (<500 keV), $\alpha_{QED}(m_Z)$ (3.10^{-5}) and $\sin^2\theta_W^{eff}$ ($1.5\ 10^{-6}$)

Complete set of EW observables can be measured
Precision unique to FCC-ee + new physics sensitivity
→ a lot more potential to exploit with detector design than present treatment suggests





The reach for new physics depends on the new physics:
-- new non-degenerate SU(2) doublet should not have mass splitting greater than ~5 GeV
-- Heavy Neutrino mixing limit ~ 10^{-5} mixing up to 500-1000 TeV
-- $1/\Lambda^2$ new physics → 30-70 TeV

FCC

The Flavour Factory

More on TeraZ

Progress in flavour physics wrt SuperKEKb/BELLEII requires > 10^{11} b pair events,

FCC-ee(Z): will provide ~10^{12} b pairs. "**Want at least 5 10^{12} Z…"**

- precision of CKM matrix elements
- Push forward searches for FCNC, CP violation and mixing
- Study rare penguin EW transitions such as $b \rightarrow s\, \tau^+ \tau^-$, spectroscopy (produce b-baryons, B_s …)
- **Test lepton universality with 10^{11} τ decays (with τ lifetime, mass, BRs) at 10^{-5} level, LFV to 10^{-10}**

-- all very important to constrain / (provide hints of) new BSM physics.

need special detectors (PID); a story to be written!

The 5 × 10^{12} hadronic Z decays also provide precious input for QCD studies

High-precision measurement of $\alpha_s(m_Z)$ with R_ℓ in Z and W decay, jet rates, τ decays, etc. : $10^{-3} \rightarrow 10^{-4}$

huge $\sqrt{s}$ lever-arm between 30 GeV and 365 GeV, fragmentation, baryon production ….

Testing running of α_s to excellent precision with hadron production from low energy ($\gamma^*/Z^* + \gamma$) to 365 GeV

And… H→gg is a pure gluon factory (100'000 H→ gg events)!

Fermion number conservation

Is *not* in itself a law or a symmetry of the Standard Model

For charged fermions (e/mu/tau and the quarks) it is not possible to transform a fermion into an antifermion **because of charge conservation**

For neutrinos, which are neutral, the SM assumes they are massless.
neutrino is left-handed (identical if massless to negative helicity)
and the antineutrino has positive helicity
neutrino <-> antineutrino transition is forbidden by **angular momentum conservation**

This results in practice in apparent, accidental, conservation of fermion number

The existence of massive neutrinos allows for spin flip and thus in principle a neutrino-antineutrino transition
since a left-handed field (EW eigenstate) has a component of the opposite helicity (EW state $\neq$ physical state)
$\nu_L \approx \nu_- + \nu_+ \, m/E$ (mass is what allows to flip the helicity)

for the allowed masses of light neutrinos this is very, very small: for m_ν =50 meV and P^*_π =30 MeV ➔ $(m/E)^2 = 10^{-18}$

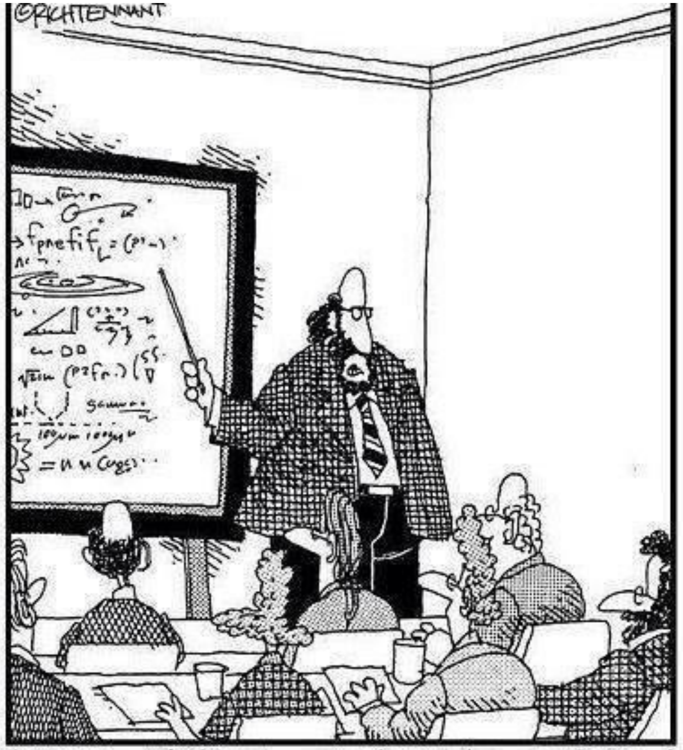
This can be observed in neutrino less double beta decay or by searching directly for the right-handed neutrinos

my SM training in 1976

NEUTRINO MASSES

Electroweak eigenstates

$I = 1/2$	$I = 0$	
$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R \; (\mu)_R \; (\tau)_R$	Q= -1
	$(\nu_e)_R \; (\nu_\mu)_R \; (\nu_\tau)_R$	Q= 0



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

Right handed neutrinos
are singlets
no weak interaction
no EM interaction
no strong interaction

can't produce them
can't detect them
-- so why bother? –
Also called 'sterile'

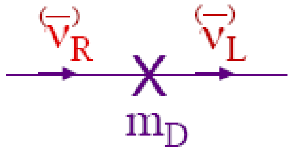
NB unlike for ν_L, no interaction distinguishes particle and antiparticle of ν_R which is a singlet (no 'charge')
→ naturally a Majorana particle

Neutrino masses occur via processes which are intimately related to the Higgs boson what are the couplings of the H(125) to neutrinos?

Let us follow the steps of the Standard Model to construct a minimal neutrino mass model

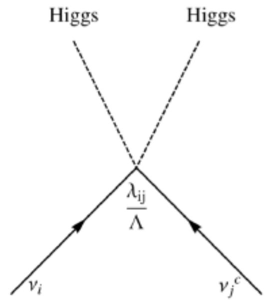
Adding neutrino masses to the Standard model 'simply' by adding a Dirac mass ➔ right-handed neutrino

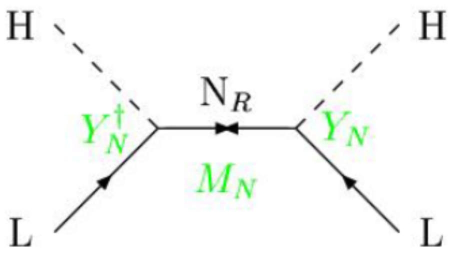
$m_D \overline{\nu_L} \nu_R$



m_D is the Higgs **Yukawa coupling** (like everybody else). Then the right handed neutrinos are sterile, (**except** that they couple to both the Higgs boson and gravitation).
Things become more interesting: **a Majorana mass term** arises (So-called **Weinberg Operator**) using the Higgs boson and the neutrino Yukawa coupling:

Origin of neutrino mass:





Pilar Hernandez, Granada 2019-05

Majorana mass term is extremely interesting as this is the **particle-to-antiparticle transition** that we want in order to explain **the Baryon asymmetry of the Universe** (+ CP violation in e.g. neutrinos)

$\mathbf{M_R}\ \overline{\nu_R^{\ c}}\ \nu_R$

B. Kayser 1989)

Having two mass terms per family , neutrinos undergo level splitting ➔ Mass eigenstates

See-saw type I :

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L, \bar{N}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana mass terms

$$\tan 2\theta = \frac{2\, m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \tfrac{1}{2}\left[(0 + M_R) - \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \tfrac{1}{2}\left[(0 + M_R) + \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

$M_R = 0$
$m_D \neq 0$
Dirac only, (like e- vs e+):

m ↑

	ν_L	ν_R	$\bar{\nu}_L$	$\bar{\nu}_R$
I_{weak}=	½	0	½	0

4 states of equal masses

Some have I=1/2 (active)
Some have I=0 (sterile)

$M_R \neq 0$
$m_D = 0$
Majorana only

m ↑

	ν_L	$\bar{\nu}_R$
I_{weak}=	½	½

2 states of equal masses

All have I=1/2 (active)

$M_R > m_D \neq 0$ — see-saw

Dirac + Majorana

m ↑

dominantly:	ν	N	$\bar{\nu}$	N
I_{weak}=	½	0	½	0

4 states , 2 mass levels

m_1 have ~I=1/2 (~active)
m_2 have ~I=0 (~sterile)

Manifestations of right handed neutrinos

one family see-saw :
$\theta \approx (m_D/M)$
$m_\nu \approx \frac{m_D^2}{M}$
$m_N \approx M$
$|U|^2 \propto \theta^2 \approx m_\nu / m_N$

$$\nu = \nu_L \cos\theta - N^c_R \sin\theta$$

$$N = N_R \cos\theta + \nu_L^{\ c} \sin\theta$$

what is produced in W, Z decays is:

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

ν = light mass eigenstate
N = heavy mass eigenstate HNL
$\neq \nu_L$, active neutrino
which couples to weak inter.
and $\neq N_R$, which does'nt.

-- mixing with active neutrinos leads to various observable consequences

-- if very light (eV) , possible effect on neutrino oscillations ('eV sterile neutrino' (LSND/miniBooNE/reactor anomalies etc... but ruled out since PLANCK mission MINOS/ICECUBE/DAYABAY/microBooNE. Search still ongoing in broader region)

-- if in 5-100 keV region (dark matter), monochromatic photons from galaxies with $E=m_N/2$, KATRIN

-- possibly measurable effects at High Energy

➔ If N is heavy it will decay in the detector ➔ spectacular

➔ Higgs, Z, W visible exotic decays H➔ $\nu_i \bar{N}_i$ and Z➔ $\nu_i \bar{N}_i$, W-> $l_i \bar{N}_i$

➔ also in K, charm and b decays via W*-> $l_i^{\pm} \bar{N}$, N ➔ $l_j^{\pm}$
with any of six sign and lepton flavour combination

➔ violation of unitarity and lepton universality in Z, W or τ decays

➔ PMNS matrix unitarity violation and deficit in Z «invisible» width $N_\nu < 3$ (C. Jarlskog 1990)

-- etc... etc...

-- Couplings are very small ($|U|^2 = m_\nu / m_N$) for one family. For three families they can be somewhat larger
but most interesting region is near the one-family see-saw limit

Heavy Neutral Leptons -- recent litterature

The Present and Future Status of Heavy Neutral Leptons

Asli M. Abdullahi, Pablo Barham Alzas, Brian Batell, Alexey Boyarsky, Saneli Carbajal, Animesh Chatterjee, Jose I. Crespo-Anadon, Frank F. Deppisch, Albert De Roeck, Marco Drewes, Alberto Martin Gago, Rebeca Gonzalez Suarez, Evgueni Goudzovski, Athanasios Hatzikoutelis, Marco Hufnagel, Philip Ilten, Alexander Izmaylov, Kevin J. Kelly, Juraj Klaric, Joachim Kopp, Suchita Kulkarni, Mathieu Lamoureux, Gaia Lanfranchi, Jacobo Lopez-Pavon, Oleksii Mikulenko, Michael Mooney, Miha Nemevsek, Maksym Ovchynnikov, Silvia Pascoli, Ryan Plestid, Mohamed Rashad Darwish, Federico Leo Redi, Oleg Ruchayskiy, Richard Ruiz, Mikhail Shaposhnikov, Ian M. Shoemaker, Robert Shrock, Alex Sousa, Nick Van Remortel, Vsevolod Syvolap, Volodymyr Takhistov, Jean-Loup Tastet, Inar Timiryasov, Aaron C. Vincent, Jaehoon Yu

777 references!

The existence of non-zero neutrino masses points to the likely existence of multiple SM neutral fermions. When such states are heavy enough that they cannot be produced in oscillations, they are referred to as Heavy Neutral Leptons (HNLs). In this white paper we discuss the present experimental status of HNLs including colliders, beta decay, accelerators, as well as astrophysical and cosmological impacts. We discuss the importance of continuing to search for HNLs, and its potential impact on our understanding on key fundamental questions, and additionally we outline the future prospects for next-generation future experiments or upcoming accelerator run scenarios.

Comments: 82 pages, 34 figures. Contribution to Snowmass 2021
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - E
Cite as: arXiv:2203.08039 **[hep-ph]**
(or arXiv:2203.08039v1 **[hep-ph]** for this version)
https://doi.org/10.48550/arXiv.2203.08039

High Energy Physics - Experiment

[Submitted on 10 Mar 2022 (v1), last revised 11 Mar 2022 (this version, v2)]

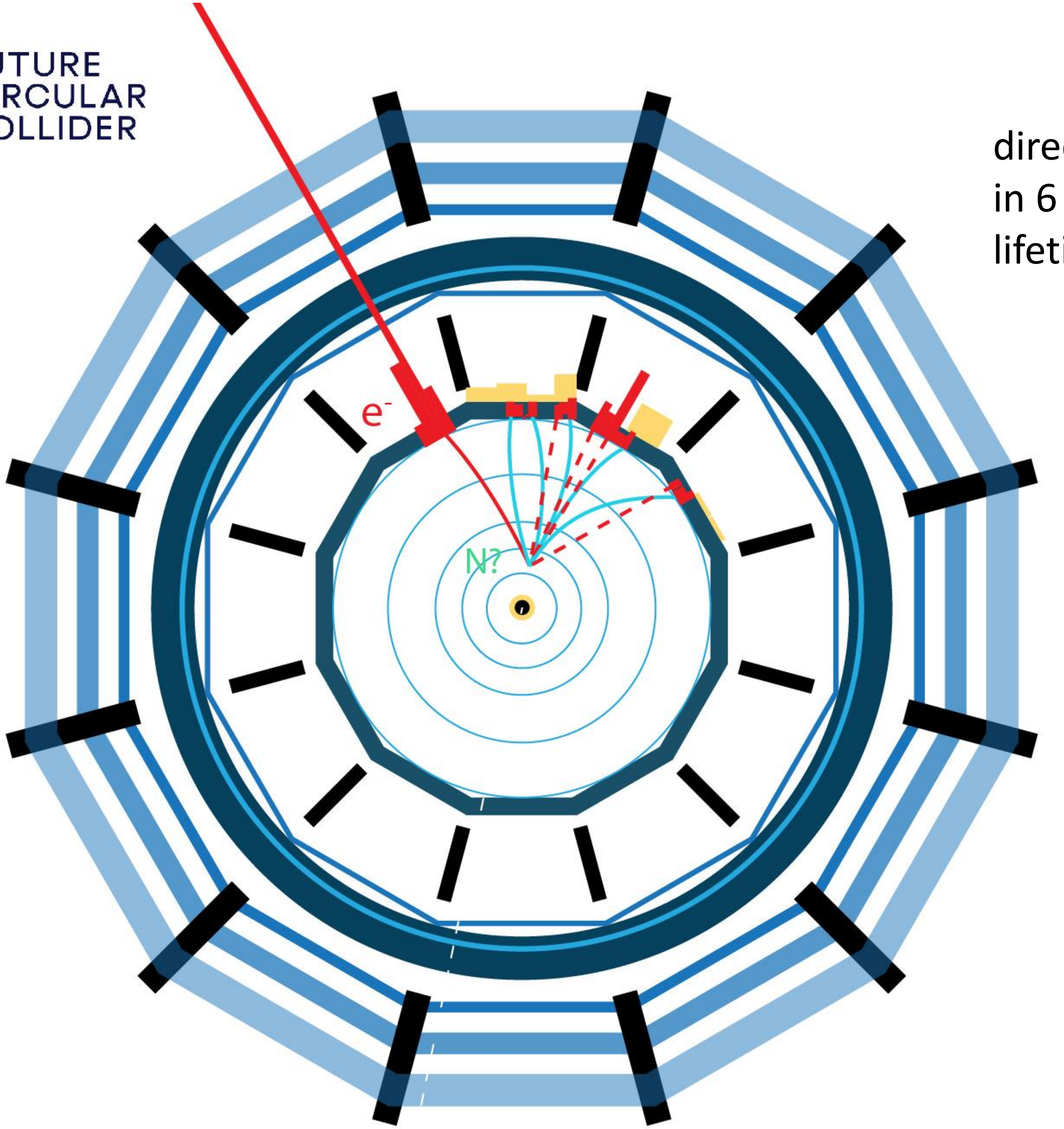
Searches for Long-Lived Particles at the Future FCC-ee

J. Alimena, P. Azzi, M. Bauer, A. Blondel, M. Drewes, R. Gonzalez Suarez, J. Klaric, S. Kulkarni, M. Neubert, C. Rizzi, R. Ruiz, L. Rygaard, A. Sfyrla, T. Sharma, A. Thamm, C. B. Verhaaren

The electron-positron stage of the Future Circular Collider, FCC-ee, is a frontier factory for Higgs, top, electroweak, and flavour physics. It is designed to operate in a 100 km circular tunnel built at CERN, and will serve as the first step towards $\geq$ 100 TeV proton-proton collisions. In addition to an essential and unique Higgs program, it offers powerful opportunities to discover direct or indirect evidence of physics beyond the Standard Model.
Direct searches for long-lived particles at FCC-ee could be particularly fertile in the high-luminosity Z run, where 5×10^{12} Z bosons are anticipated to be produced for the configuration with two interaction points. The high statistics of Higgs bosons, W bosons and top quarks in very clean experimental conditions could offer additional opportunities at other collision energies. Three physics cases producing long-lived signatures at FCC-ee are highlighted and studied in this paper: heavy neutral leptons (HNLs), axion-like particles (ALPs), and exotic decays of the Higgs boson. These searches motivate out-of-the-box optimization of experimental conditions and analysis techniques, that could lead to improvements in other physics searches.

Comments: Contribution to Snowmass 2021
Subjects: **High Energy Physics - Experiment (hep-ex)**; High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Theory (hep-th)
Cite as: arXiv:2203.05502 **[hep-ex]**
(or arXiv:2203.05502v2 **[hep-ex]** for this version)
https://doi.org/10.48550/arXiv.2203.05502

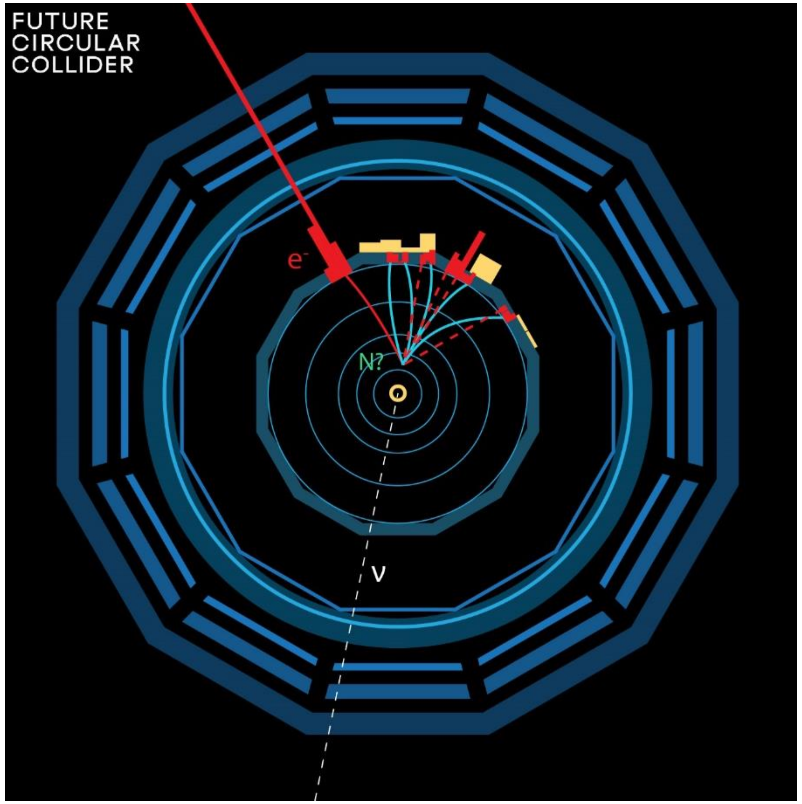
Heavy Neutral Leptons at the Z factory

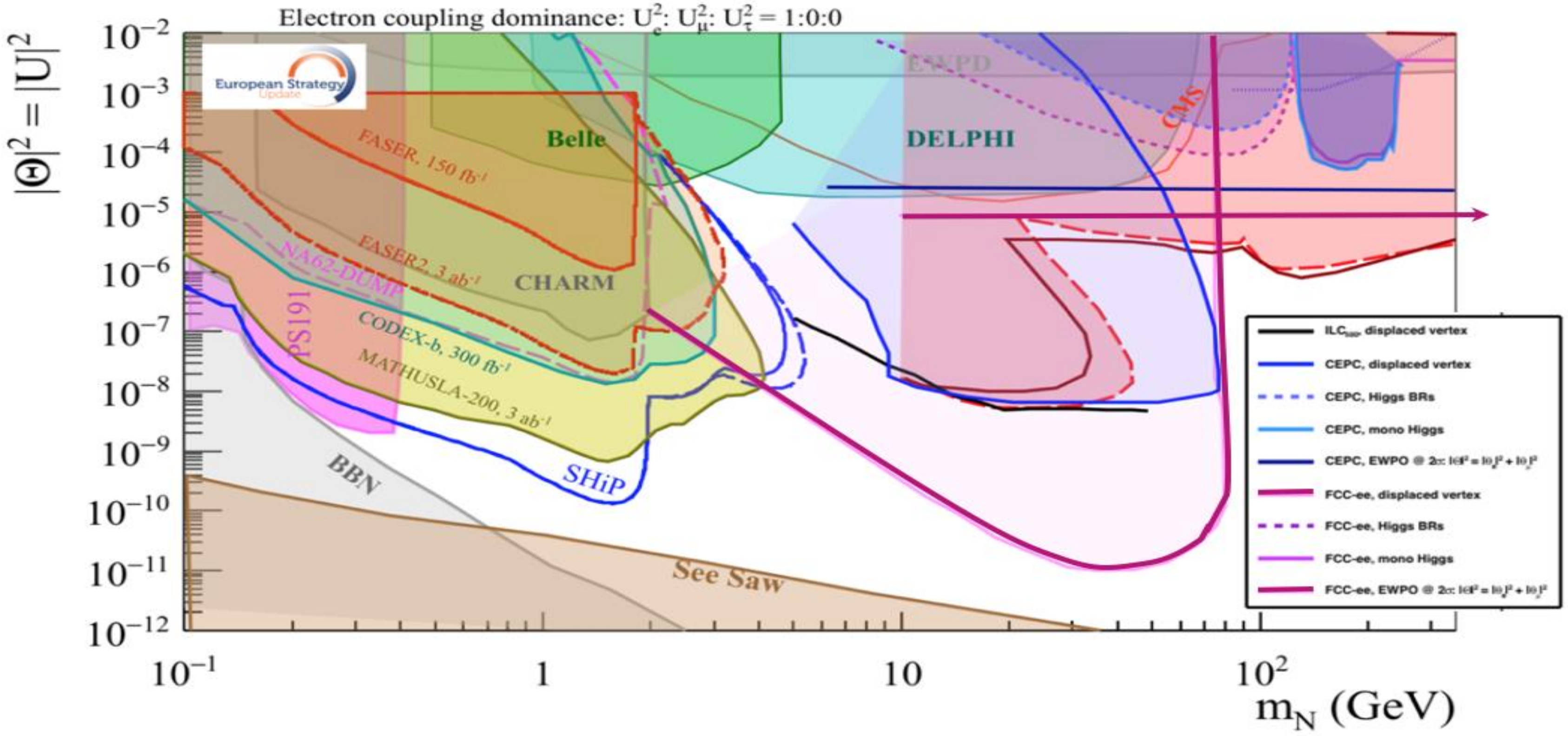


direct production of a few events in 6 10^{12} Z decays with long lifetimes

courtesy
Panos Charitos

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'?





-- the purple line shows the 95% CL limit if no HNL is observed. (here for 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

Why do we need a new accelerator after the LHC?

We absolutely need a next accelerator but the next facility must be versatile (and feasible!) with as broad and powerful reach as possible, as there is no precise target

→ more Sensitivity, more Precision, more Energy

FCC@CERN, thanks to local synergies and internal complementarities, offers the most versatile and adapted response to today's physics landscape

The huge step in statistics (and precision) is extremely challenging on all accounts Accelerator, Detectors, Theory must plan proactively to match the challenges!

THANK YOU STASZEK!

for your immense contributions and insight for the extraction of physics from LEP data
For your irreplaceable enthusiasm and pragmatism in planning the FCCee ‘impossible’ precision
For your vision!

arbores serit, quorum poma non viderit
He plants trees, the fruits of which he will not see.