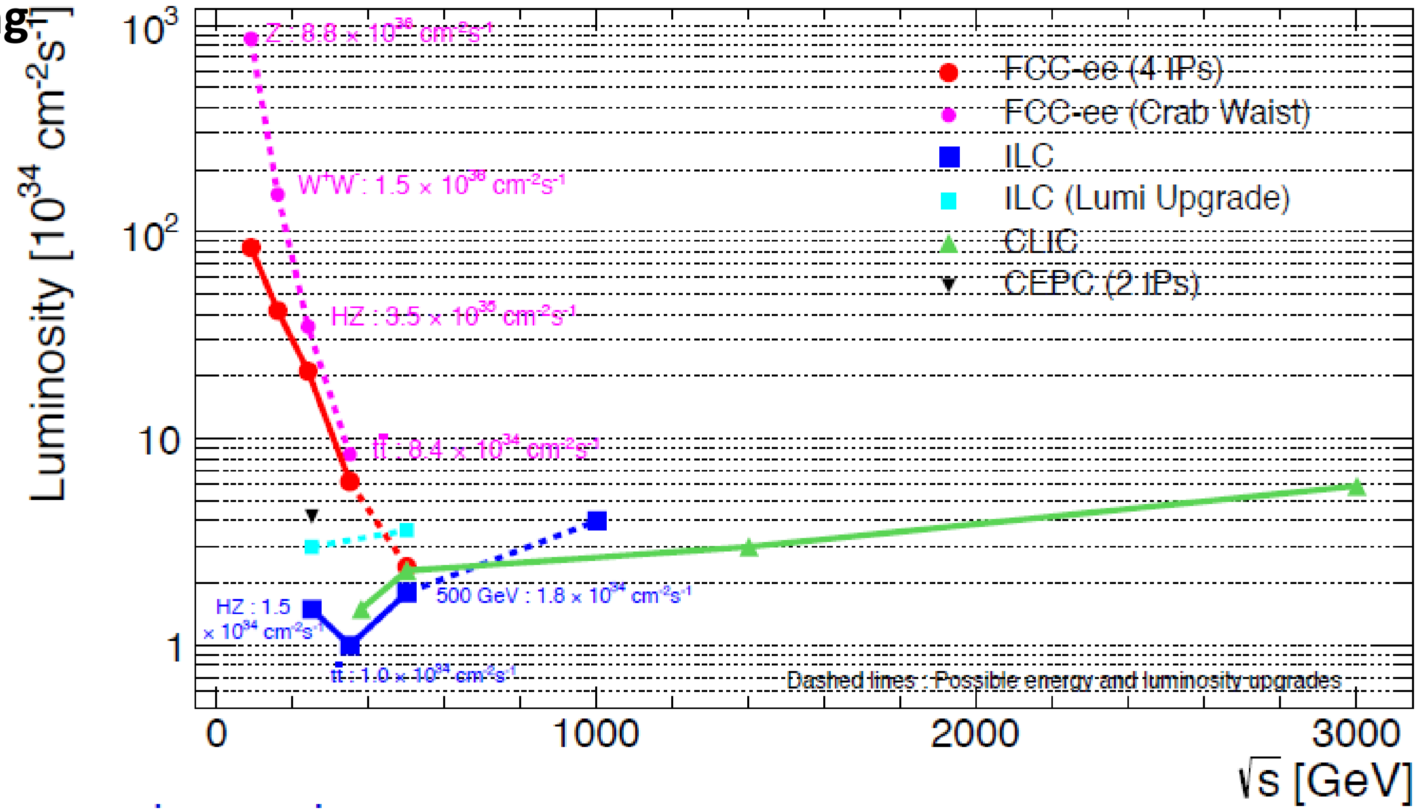
FCC-ee: Precision measurements

references: talks by AB, Koratzinos, Piccinini, Tenchini, and many others

Provide highest possible luminosity from Z to tt by exploiting b-factory technologies:

- **separate e- and e+ storage rings**
- **very strong focussing: β*y = 1mm**
- **top-up injection**
- **crab-waist crossing**



Overlap in Higgs/top region, but differences and complementarities between linear and circular machines:
Circ: High luminosity, experimental environment (2 to 4 IP), E_{CM} calibration
Linear: higher energy reach, longitudinal beam polarization

CERN Circular Colliders and FCC

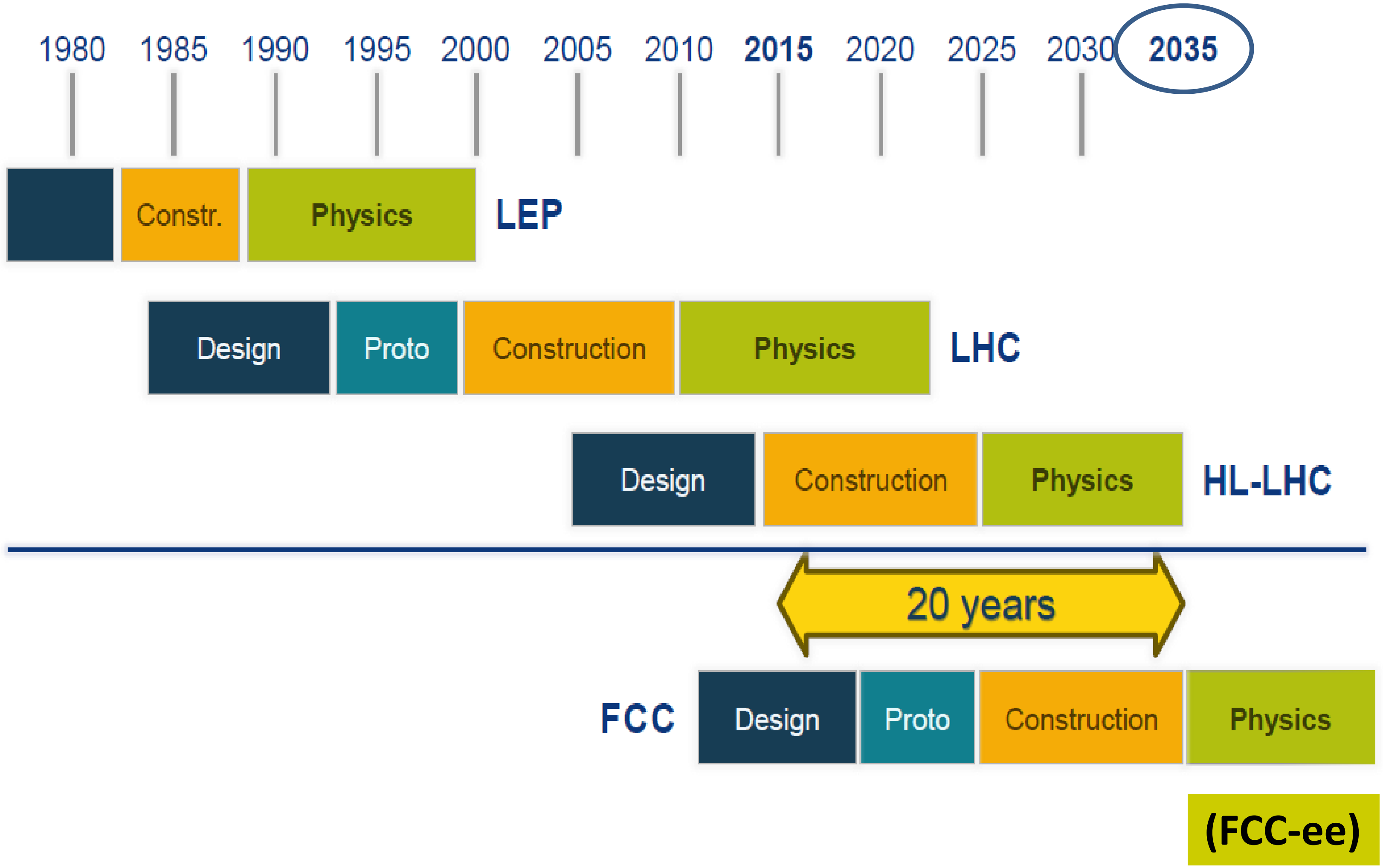


Table 1: Key parameters for FCC-ee, at three beam energies, compared with LEP2. The parameter ranges indicated reflect a sensitivity to the number of IPs and to the choice of collision scheme (“baseline” [3] with varying arc cell length and small crossing angle, or a crab-waist scheme based on a larger crossing angle and constant cell length [4]).

Parameter	FCC-ee			LEP2
energy/beam [GeV]	45	120	175	105
bunches/beam	13000- 60000	500- 1400	51- 98	4
beam current [mA]	1450	30	6.6	3
luminosity/IP x 10^{34}cm^{-2}s^{-1}	21 - 280	5 - 11	1.5 - 2.6	0.0012
vertical IP β^* [mm]	1	1	1	50
geom. hor. emittance [nm]	0.1-30	1	2	22
energy loss/turn [GeV]	0.03	1.67	7.55	3.34
synchrotron power [MW]	100			22
RF voltage [GV]	0.2-2.5	3.6-5.5	11	3.5

Physics > Accelerator Physics

Status and Challenges for FCC-ee

Michael Benedikt, Katsunobu Oide, Frank Zimmermann, Anton Wienands

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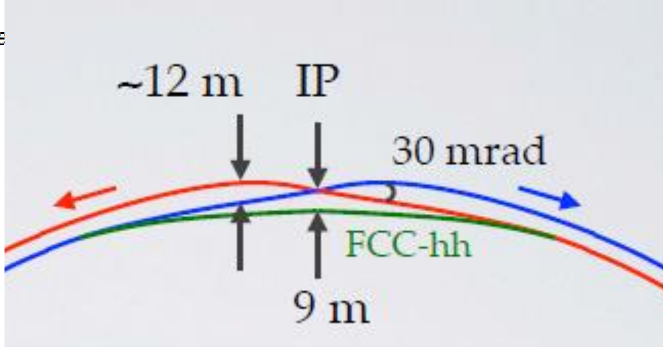
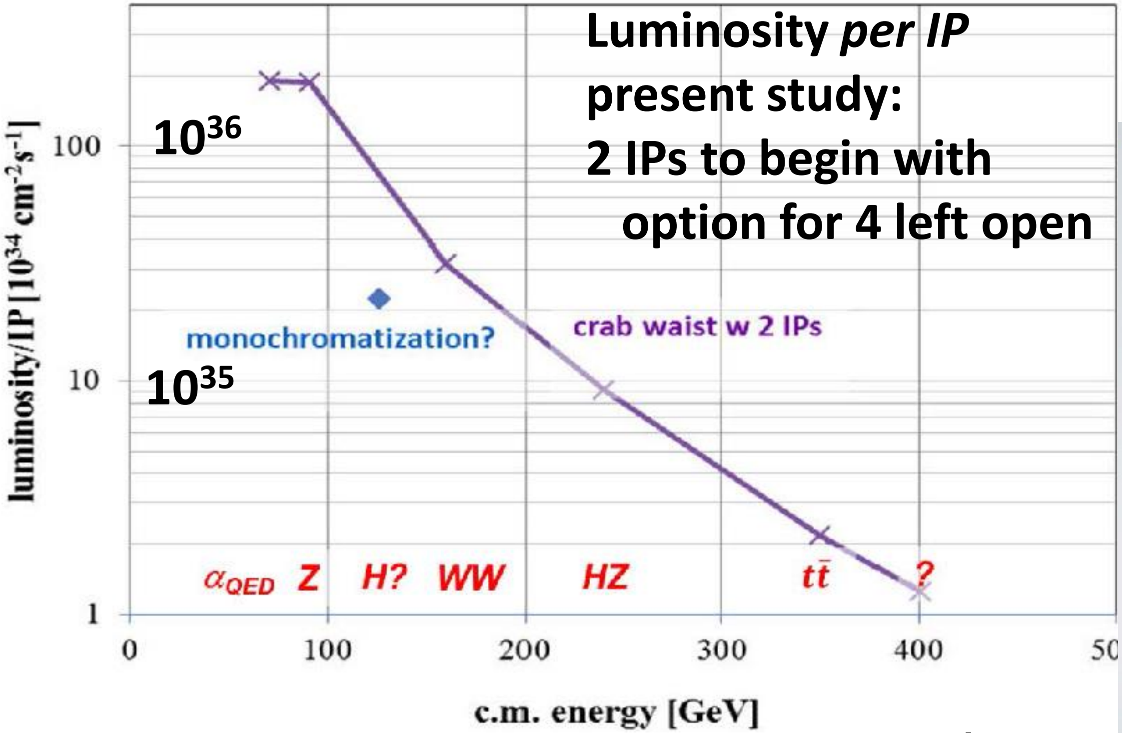
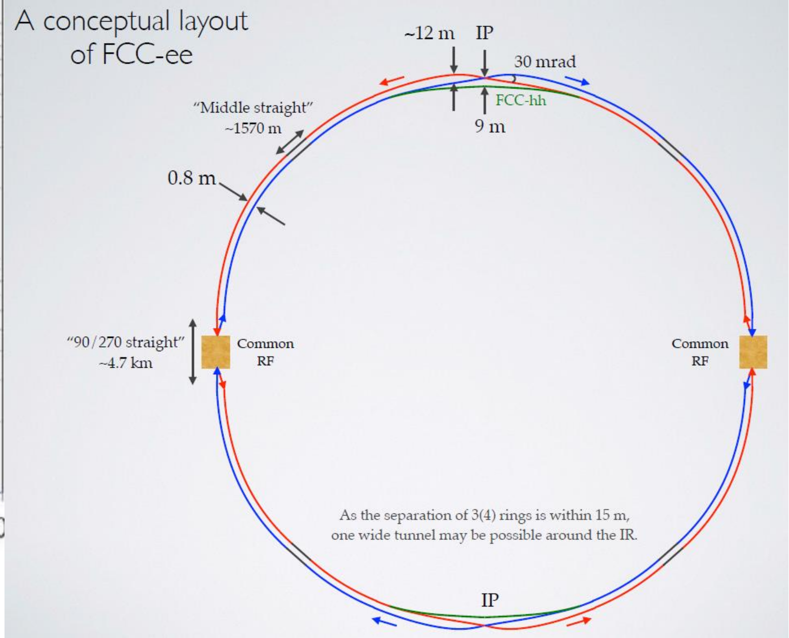




Luminosity *per IP*
present study:
2 IPs to begin with
option for 4 left open

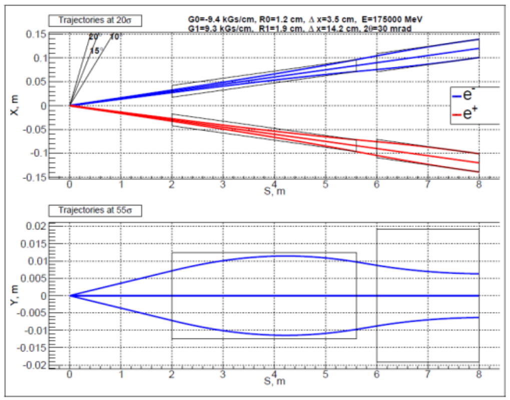
new: asymmetric crossing to minimize SR to IP



SynRad bend cones for TLEP_V14_IR_6-13-2 BINP IR

MDISIM/root/ 3d-OGL display

Final Focus layout

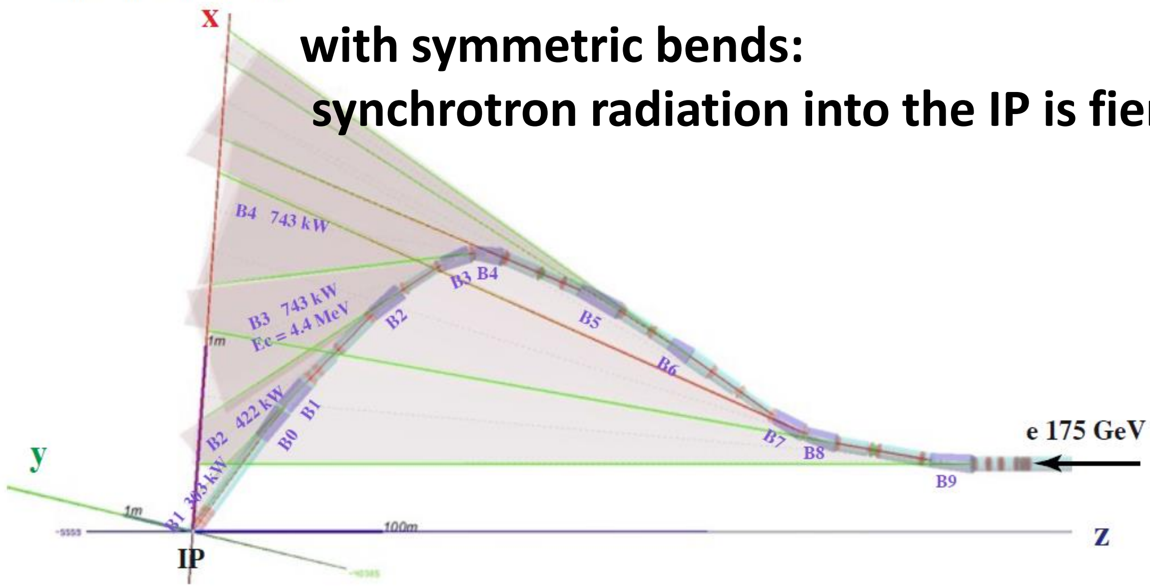


Rectangles represent bare apertures.

	L [m]
Q0	3.6
Q1	2

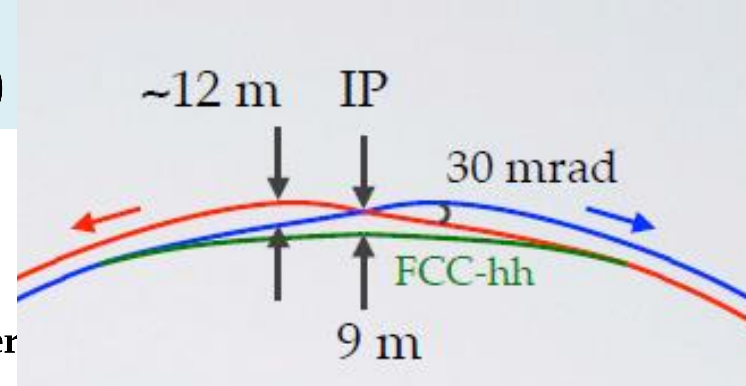
	R [m]
Q0	0.012
Q1	0.019

with symmetric bends: synchrotron radiation into the IP is fierce



Synchrotron radiation into IR major challenge : 2.3 MW / beam of MeV γ's into detector region

Asymmetric configuration (straight from the arcs to the IP and bend afterwards) reduce this problem to backscattered photons by eliminating the incoming bend
NB this also saves magnets and energy loss
and allows a layout consistent with FCC-hh (K. Oide)



crab waist optics is being developed by BINP

Parameters for crab waist

	Z	W	H	tt
Energy [GeV]	45	80	120	175
Perimeter [km]	100			
Crossing angle [mrad]	30			
Particles per bunch [10^{11}]	1	4	4.7	4
Number of bunches	29791	739	127	33
Energy spread [10^{-3}]	1.1	2.1	2.4	2.6
Emittance hor. [nm]	0.14	0.44	1	2.1
Emittance ver. [pm]	1	2	2	4.3
β_x^* / β_y^* [m]	0.5 / 0.001			
Luminosity / IP [$10^{34}\ cm^{-2}s^{-1}$]	212	36	9	1.3
Energy loss / turn [GeV]	0.03	0.3	1.7	7.7
Gain w.r.t. 'baseline optics'	**8**	**3**	**1.5**	**~1**

note very high
-- and variable --
number of bunches

PHYS. REV. S.T. - AB 17, 041004 (2014)

A. Bogomyagkov (BINP) FCC-ee crab waist IR and the arc

AMBITIOUS and CHALLENGING: Excellent luminosity prospects, E aperture OK,
<u>but IR region is a great challenge</u> ! Aim at decision in fall 2015

FCC-ee PHYSICS PROGRAM

-- Z and W Electroweak physics (10^{13}Z, 10^{8} WW)

precision energy calibration (100 KeV) → m_Z, Γ_Z, m_W, $\sin^2\theta_W$

new possibly precision measurement of α_{QED} (m_Z)

high luminosity search for rare Z decays

neutrino counting and search for RH neutrinos

-- Higgs Physics at E_{CM}= 240 GeV (ZH) and 350 GeV, 2 10^6 ZH events

unique determination of ZH coupling and H width,

all fermion and boson couplings (except ttH and HHH)

rare decays

-- top quark physics at 350 -370 GeV

top quark mass (essential for precision EW tests) to exp. precision of 10 MeV

new top quark couplings (no need for beam polarization)

-- investigating run at E_{CM}= m_H to determine Hee coupling

Run Plan

Assuming 4 IP

P. Janot

- Time needed to achieve this ambitious programme
  - Number of events expected for each year of running at the FCC-ee

Top couplings

√s (GeV)	90 (Z)	160 (WW)	240 (HZ)	350 (tt)	350+ (WW→H)
Lumi (ab^{-1}/yr)	86.0	15.2	3.5	1.0	1.0
Events/year	3.7×10^{12}	6.1×10^{7}	7.0×10^{5}	4.2×10^{5}	2.5×10^{4}

  - Number of years needed to complete the core programme $N_Z=10^{(12)13}$

1 year = 10^7 s

# years	(0.3) 2.5	1	3	0.5	3

With 4 IP can execute Z,W,H,t program in 10 years of full luminosity operation (10^7 s/year)
Commissioning etc, to be added -- but as usual, hard to guess

Staging is foreseen for RF:

1. low RF (5 GV/beam , 12 MW): begin with Z scan, develop crab waist, energy calibration + HZ at low luminosity

2. Complete power for High lumi ZH (and WW)

3. arrange RF to reach 10 GV/beam, run 350+ GeV E_{CM}

4. run high statistics Z pole

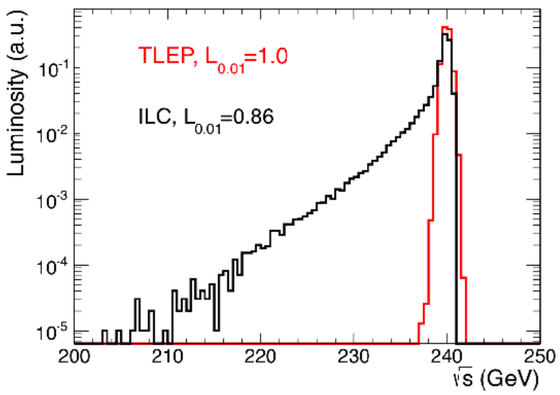
Experimental conditions

-- 2-4 IPs L^{*}~2m

-- bunch crossing spacing from 2-5 ns (Z) up to 3μs (top)

-- no pile-up (<0.001 at FCC-Z/CrabWaist)

-- beamstrahlung is mild for experiments



	FCCZ	FCCZ, c.w	CEPC	FCC ZH	ILC500
Npairs / BX	200	9900	3260	640	165000
Leading process	96% LL	65% LL	80% LL	90% LL	60% BH
Epairs / BX (GeV)	86	2940	2600	570	400000
Leading process	100% LL	100% LL	98% LL	96% LL	70% BH

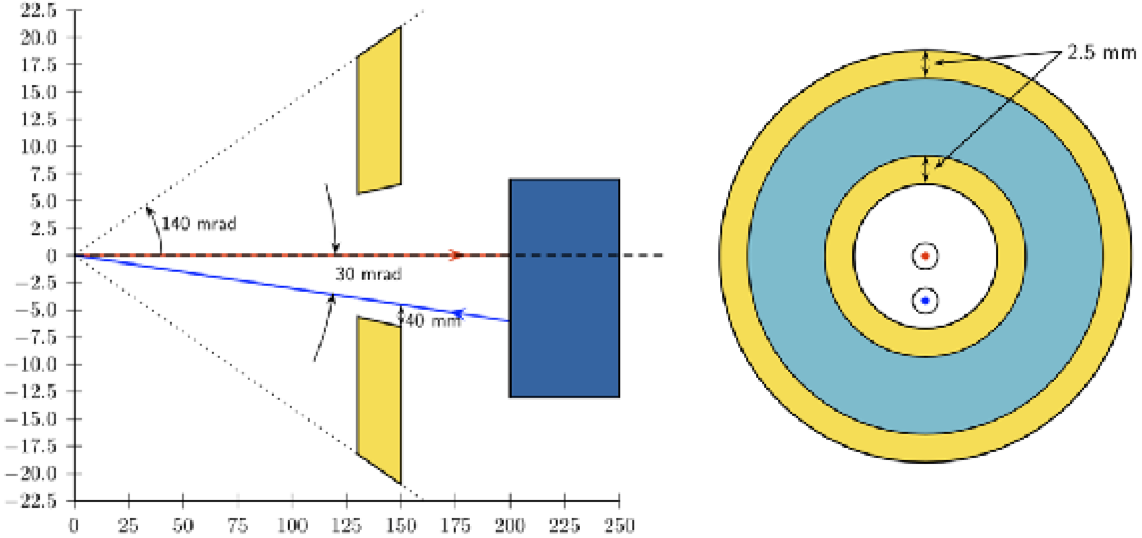
E. Perez,
C. Leonidopoulos

-- Beam energy calibration for Z and W running

-- IR design with crossing angle is not trivial

➔ a challenging magnet design issue.

Of particular importance: luminosity monitors



M. Dam

Requirements dominated by Z line shape and peak cross-section measurements

Shift in parameter for a shift of $+10^{-4}$ in acceptance

z_{front} [mm]	r_{min} [mm]	r_{max} [mm]	θ_{min} [mrad]	θ_{max} [mrad]	σ [nb]	δz_{front} [μm]	δr_{min} [μm]	δr_{max} [μm]
1000	80	115	80	115	10	50	−2.1	6.1
1300	89	157	68	121	18	65	−3.0	17
1500	95	185	63	123	23	75	−3.5	26

Input from Physics to the accelerator design

0. Nobody complains that the luminosity is too high (the more you get, the more you want)

no pile up, even at the Z: at most 1ev /300bx

1. Do we need polarized beams?

-1- transverse polarization:

continuous beam Energy calibration with resonant depolarization

central to the precision measurements of m_Z , m_W , Γ_Z

requires 'single bunches' and calibration of both e+ and e-

a priori doable up to W energies -- workarounds exist above (e.g. γZ events)

large ring with small emittance excellent. Saw-tooth smaller than LEP for Z

<u>need wigglers</u> (or else inject polarized e- and e+) to polarize 'singles';

simulations ongoing (E. Gianfelice, M. Koratzinos, I.Kopp)

-2- longitudinal polarization requires spin rotators and is very difficult at high energies

-- We recently found that it is not necessary to extract top couplings (Janot)

-- improves Z peak measurements *if loss in luminosity is not too strong*

but brings no information that is not otherwise accessible

2. What energies are necessary?

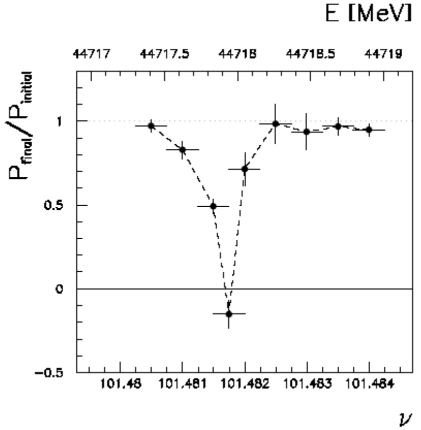
-- in addition to Z, W, H and top listed the following are being considered

-- e+e- → H(125.2) (requires monochromatization A. Faus) (under study)

-- e+e- at top threshold ~20 GeV for top couplings (E_max up to 180 -185 GeV)

-- no obvious case for going to 500 GeV

Beam polarization and E-calibration @ FCC-ee



Precise meast of E_{beam} by resonant depolarization
~100 keV each time the meast is made *LEP →*

At LEP transverse polarization was achieved routinely at Z peak.
instrumental in 10^{-3} measurement of the Z width in 1993
led to prediction of top quark mass (179+- 20 GeV) in Mar'94

Polarization in collisions was observed *(40% at BBTS = 0.04) →*

At LEP beam energy spread destroyed polarization above 61 GeV
$\sigma_E \propto E^2/\sqrt{\rho}$ ➔ *At TLEP transverse polarization up to at least 81 GeV (WW threshold)*
to go to higher energies requires spin rotators and siberian snake (see spares)

FCC-ee: use 'single' bunches to measure the beam energy continuously
→ *no interpolation errors due to tides, ground motion or trains etc…*

<< 100 keV beam energy calibration around Z peak and W pair threshold.
Δm_Z ~0.1 MeV, $\Delta\Gamma_Z$ ~0.1 MeV, Δm_W ~ 0.5 MeV

EUROPEAN ORGANIZATION FOR PARTICLE PHYSICS

CERN–EP/98–40
CERN–SL/98–12
March 11, 1998

Calibration of centre-of-mass energies at LEP1 for precise measurements of Z properties

The LEP Energy Working Group

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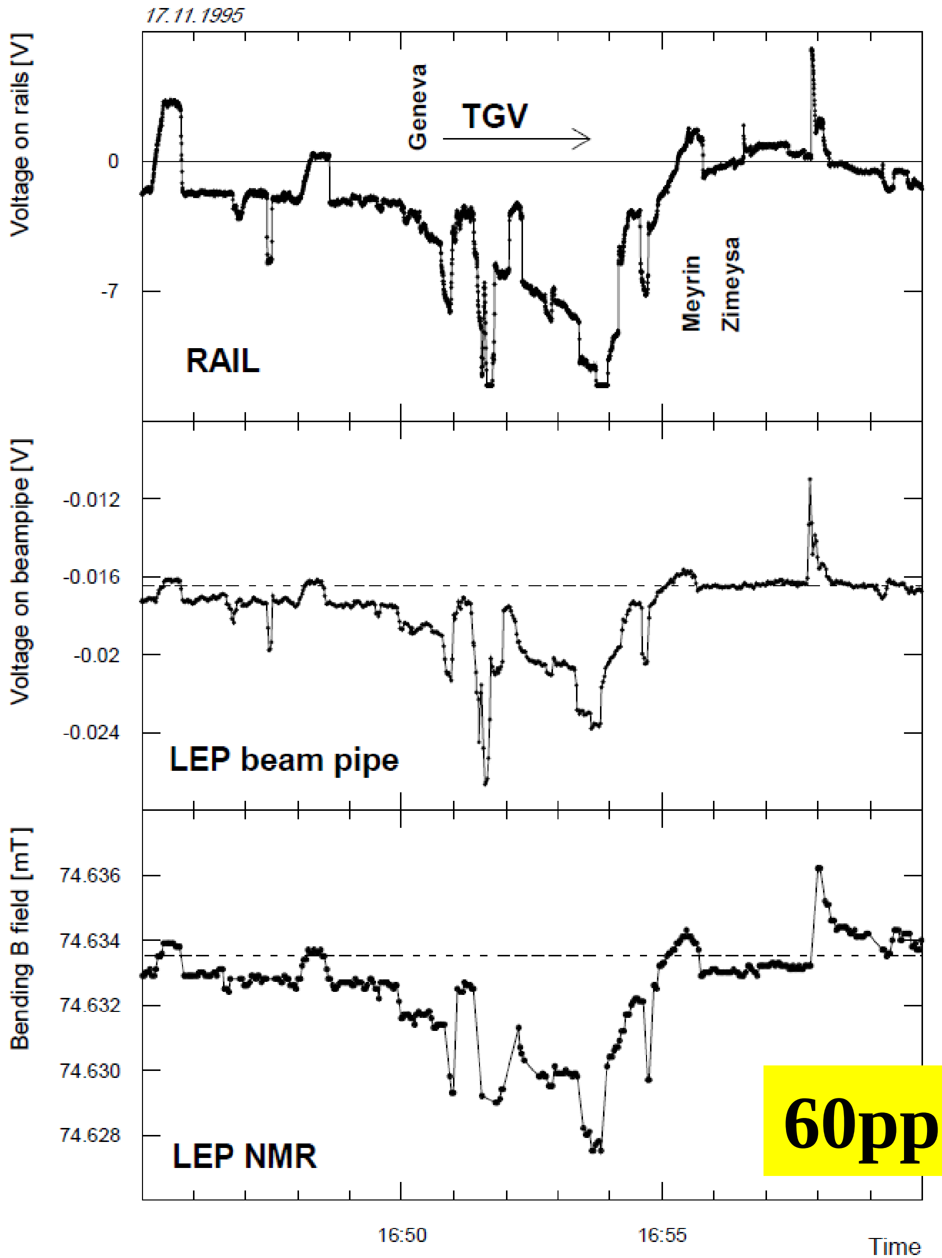


60ppm in 5 minutes!

Tide correction...

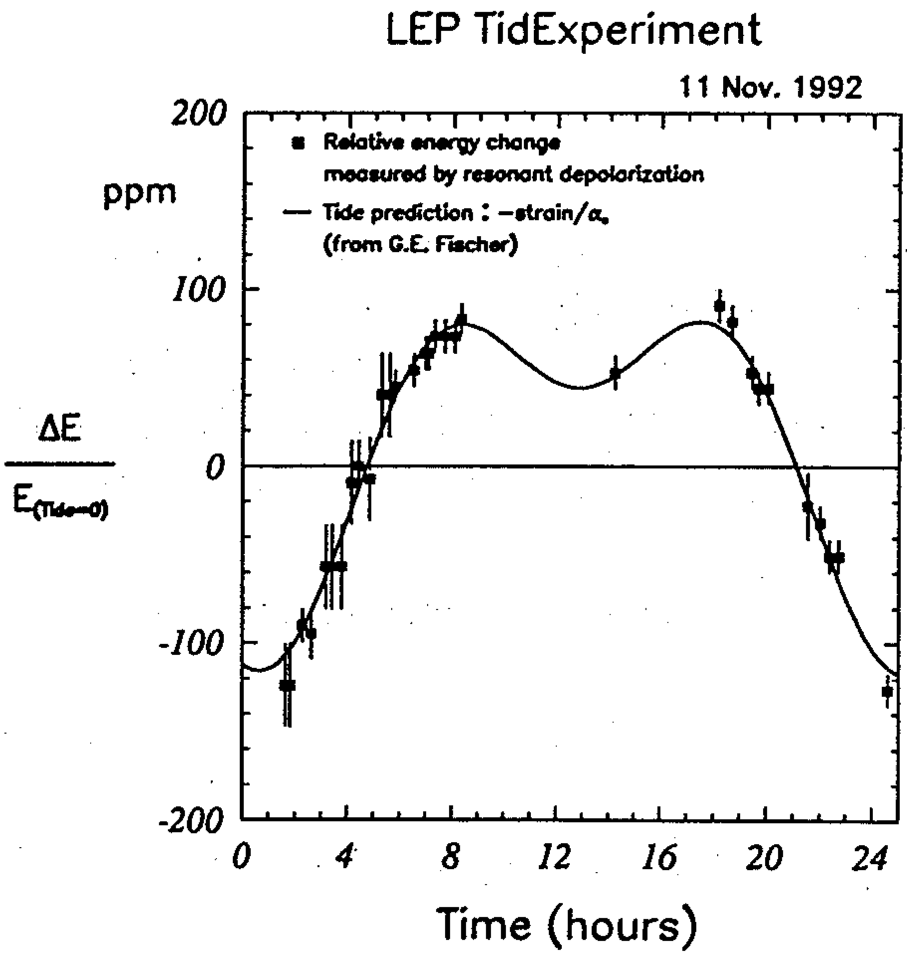
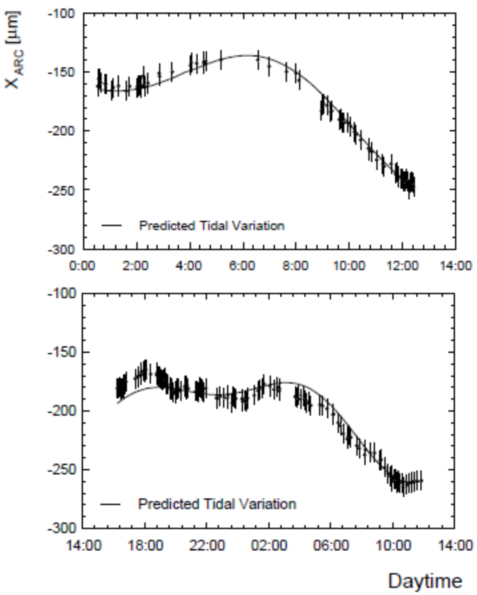


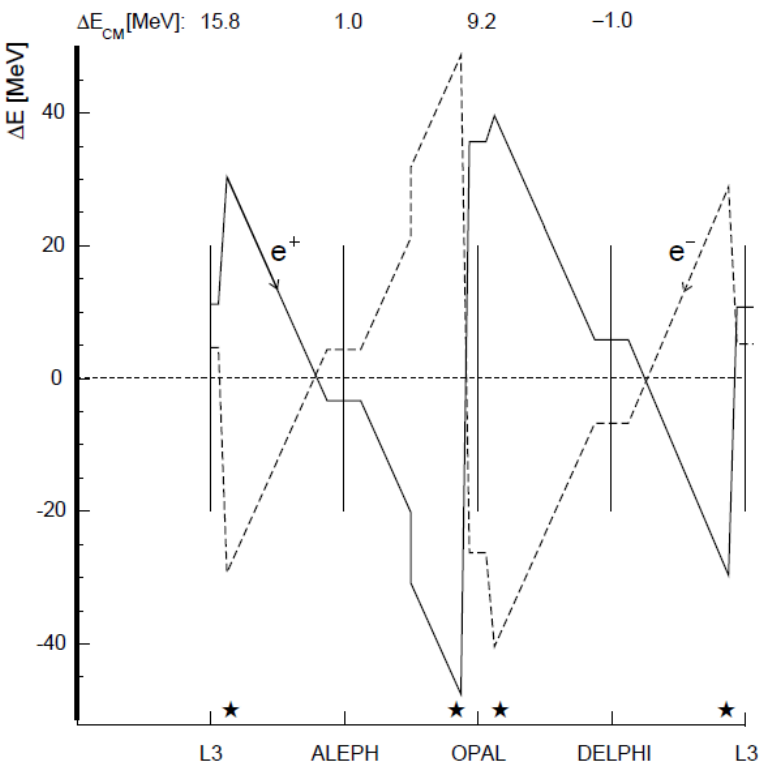
Figure 23: Beam energy variations measured over 24 hours compared to the expectation from the tidal LEP deformation.



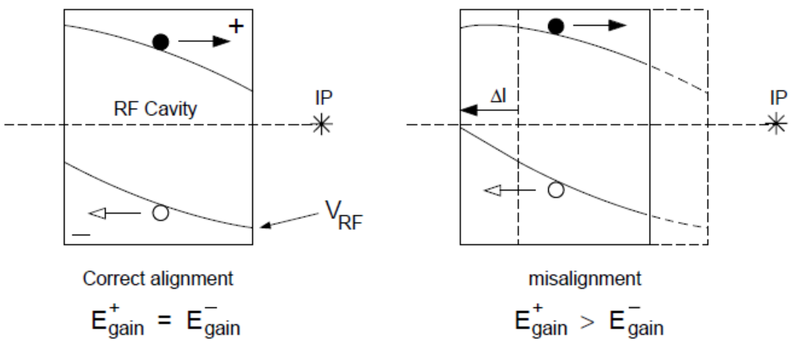
orizontal orbit position for two LEP fills. The predicted tidal variations are indicated figure (fill 1694) the agreement is excellent. In the bottom figure (fill 2260) the tidal orbit movements. The errors on each point are estimates.

are orbit measurements enough?

RF corrections



Errors arise due to cavity misalignments primarily:



- At LEP cavity misalignment was assumed to be 1.4mm in 1995

Work is needed to reduce this error. For LEP the error was of the order of 500keV (leading to an error of 400/200keV for the mass/width of the Z. Need to reduce this error by (more than) a factor of 10! NB The effect smaller at FCC-ee (smaller E_loss)

Most of these systematics, but not all, vanish with ‘single’ bunches calib.

Source	ΔE_{CM} (MeV) P−2 93	P 93	P+2 93	P 94	P−2 95	P 95	P+2 95	Energy correlation	Year correlation	Δm_Z (MeV)	$\Delta\Gamma_Z$ (MeV)
Normalization error	1.7	5.9	0.9	1.1	0.8	5.0	0.4	0.	0.	0.5	0.8
RD energy measurement	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.04	0.04	0.4	0.5
QFQD correction	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.75	[0., 0.75]	0.1	0.1
Horizontal correctors	0.0	0.4	−0.4	0.2	−0.2	−0.5	−0.2	±0.75	±0.75	0.2	0.1
Tide amplitude	0.0	−0.3	0.2	−0.1	−0.0	−0.0	−0.0	±1.	1.	0.0	0.1
Tide phase	0.0	0.0	−0.1	0.1	−0.2	−0.0	0.0	±1.	0.50	0.0	0.1
Ring temperature	0.1	0.4	0.4	0.2	0.4	0.3	0.4	0.75	0.75	0.3	0.2
B rise scatter+model	2.8	3.0	2.5	3.3	0.6	0.6	0.6	[0.47, 0.86]	0.50	1.5	0.5
B rise NMR48 T-coeff	0.6	0.3	0.6	0.5	1.0	1.0	1.1	0.75	0.75	0.8	0.3
Bending modulation jump	0.	0.	0.	0.	0.0	1.4	0.3	0.75	0.	0.1	0.1
e^+ Energy uncertainty	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.5	[0., 0.50]	0.2	0.1
RF corrections (Comb.)	0.5	0.5	0.5	0.6	0.7	0.7	0.7	[0.63, 0.96]	[0.18, 0.70]	0.4	0.2
Dispersion corr. (Comb.)	0.4	0.4	0.4	0.7	0.3	0.3	0.3	[0.50, 0.75]	[0., 0.50]	0.2	0.1
Energy spread											0.2

Table 19: Summary of errors (MeV) on the centre-of-mass energy determination. These are selected numbers shown for illustration, the exact errors are determined using the correlation matrix formalism. The energy correlation coefficients between energy points and between years are shown. Whenever the year-to-year or the energy-to-energy correlation coefficient is not fixed the range is indicated. The relative sign of the energy correlation coefficient is given by the relative sign of the error. The last two rows give average errors due to RF and dispersion effects when combining the 4 IPs with the respective correlation coefficients. The last two columns give estimates of the error contributions to the determination of m_Z and Γ_Z in MeV: the actual errors depend on the details of experimental samples.

Resonant depolarization accuracy at TLEP/FCCee – extrapolation

Per beam, not ECM

Source	$\Delta E/E$	ΔE (E=45.6 GeV)	Correlated/Z mass	Uncorrelated / Z width
Electron mass	$3 \cdot 10^{-7}$	15 keV	15keV	0keV
Revolution frequency	10^{-10}	0 keV	0keV	0keV
Frequency of the RF magnet	$2 \cdot 10^{-8}$	1 keV	1keV	0keV
Width of excited resonance	$2 \cdot 10^{-6}$	90 keV	1keV	1keV
Interference of resonances	$2 \cdot 10^{-6}$	90 keV	9keV	9keV
Spin tune shifts from long. fields	$1.1 \cdot 10^{-7}$	5 keV	5keV	5keV
Spin tune shifts from hor. fields	$2 \cdot 10^{-6}$	100 keV	3keV	1keV
Quadratic non-linearities	10^{-7}	5 keV	5keV	5keV
Total error	$4.4 \cdot 10^{-6}$	200 keV	~20keV	~12keV
IP specific errors			~40keV	~20keV
total			~45keV	~23keV

- Statistical errors are divided by sqrt(10,000) - negligible
- This is a zeroth order working hypothesis
- The table should eventually also include effects that were negligible at the time of LEP

1. ELECTROWEAK PRECISION TESTS (EWPT)

Test of the ‘closure’ of the SM:

test the existence of electroweakly coupled new particles ...

-- if they are nearby in Energy scale

or

-- if they violate symmetries of the Standard Model (in which case, no «decoupling»)

e.g. Higgs boson $\propto \alpha/\pi \log (mH/mZ)^2$ and top-bottom mass splitting $\propto \alpha/\pi \, (m_t/m_Z)^2$

2. TESTS OF ELECTROWEAK SYMMETRY BREAKING (EWSB)

Is the H(125) a Higgs boson?

→ couplings proportional to mass?

if not could be more complicated EWSB e.g. more Higgses

→ Higgs supposed to cancel WW scattering anomalies at TeV scale

does this work?

EWRCs

relations to the well measured

G_F m_Z α_{QED}

at first order:

$\Delta\rho$: $\equiv \varepsilon_1$

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

ε_3

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

δ_{vb}

$$\Gamma_b = (1+\delta_{vb})\;\Gamma_d\left(1-\underset{\alpha\, m_b^2/M_Z^2}{\text{mass corrections}}\right)$$

ε_2

$$M_W^2 = \frac{\pi\,\alpha(M_Z^2)}{\sqrt{2}\;G_F \sin^2\theta_W^{eff}}\cdot\frac{1}{(1-\varepsilon_3+\varepsilon_2)}$$

$\sin^2\theta_W^{eff}$ is defined from

$$\sin^2\theta_W^{eff} = \frac{1}{4}\left(1-\frac{g_{V\ell}}{\underbrace{g_{A\ell}}}\right) = \sin^2\theta_W{}^{eff}_{lept}$$

obtained from asymmetries at the Z.

also

Δr

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\,G_F}\cdot\frac{1}{\left(1-\frac{M_W^2}{M_Z^2}\right)}\;\frac{1}{(1-\Delta r)}$$

$$\Delta r = \Delta\alpha - \frac{\cos^2\theta_W}{\sin^2\theta_W}\,\Delta\rho + 2\,\frac{\cos^2\theta_W}{\sin^2\theta_W}\,\varepsilon_3 + \frac{c^2-s^2}{s^2}\,\varepsilon_2$$

$\Delta\rho = \alpha/\pi\;(m_{top}/m_Z)^2$

$-\;\alpha/4\pi\;\log(m_h/m_Z)^2$

$\varepsilon_3 = \cos^2\theta_w\;\alpha/9\pi\;\log(m_h/m_Z)^2$

$\delta_{vb} = 20/13\;\alpha/\pi\;(m_{top}/m_Z)^2$

complete formulae at 2d order including strong corrections are available in fitting codes

e.g. ZFITTER , GFITTER

The main players

Inputs:

$G_F = 1.1663787(6) \times 10^{-5}$ /GeV^2	from muon life time	**6 10^{-7}**
$M_Z = 91.1876 \pm 0.0021$ GeV	Z line shape	**2 10^{-5}**
$\alpha = 1/137.035999074(44)$	electron g-2	**3 10^{-10}**

EW observables sensitive to new physics:

$M_W = 80.385 \pm 0.015$	LEP, Tevatron	**2 10^{-4}**
$\sin^2\theta_W^{eff} = 0.23153 \pm 0.00016$	WA Z pole asymmetries	**7 10^{-4}**
$+ \Gamma$ Rb etc...		

Nuisance parameters:

$\alpha\ (M_Z) = 1/127.944(14)$	**hadronic corrections** to running alpha	**1.1 10^{-4}**
$\alpha_S\ (M_Z) = 0.1187(17)$	strong coupling constant	**1.7 10^{-2}**
m_{top} $= 173.34 \pm 0.76$ GeV	from LHC+Tevatron combination	**4 10^{-3}**

m_H = 125.09±0.21 (stat.)±0.11 (syst.) GeV/c^2 (CMS+ATLAS) **2 10^{-3}**

Example (from Langacker, Erler PDG 2014)

$\Delta\rho = \varepsilon_1 = \alpha(M_Z)\ .\ T$
$\varepsilon_3 = 4 \sin^2\theta_W\ \alpha(M_Z)\ .\ S$

From the EW fit

$$\rho_0 = 1.00040 \pm 0.00024\ ,$$

$\Delta\rho$ = 0. 0004 +- 0.00024

-- is consistent with 0 at 1.7σ (0= SM)
-- is sensitive to non conventional Higgs bosons (e.g. in SU(2) triplet with 'funny v.e.v.s)
-- is sensitive to Isospin violation such as $m_t \neq m_b$

$$\rho_0 = 1 + \frac{3\,G_F}{8\sqrt{2}\pi^2} \sum_i \frac{C_i}{3}\,\Delta m_i^2\ , \tag{10.63}$$

where the sum includes fourth-family quark or lepton doublets, $\binom{t'}{b'}$ or $\binom{E^0}{E^-}$, right-handed (mirror) doublets, non-degenerate vector-like fermion doublets (with an extra factor of 2), and scalar doublets such as $\binom{\tilde{t}}{\tilde{b}}$ in Supersymmetry (in the absence of L–R mixing).

Measurement implies

$$\sum_i \frac{C_i}{3}\,\Delta m_i^2 \leq (50\ \mathrm{GeV})^2.$$

The larger possible mass splitting of an SU(2) doublet is 50 GeV

no matter what its mass is.

Similarly $$S = \frac{C}{3\pi}\sum_i \Big(t_{3L}(i) - t_{3R}(i)\Big)^2,$$

Would be sensitive to a doublet of new fermions where Left and Right have different masses etc… (neutrinos are already included)

Note that often EW radiative corrections do not decouple with mass => a very powerful tool of investigation

$$\Delta\rho = \alpha/\pi\ (m_{top}/m_Z)^2 - \alpha/4\pi\ \log(m_h/m_Z)^2$$

$$\varepsilon_3 = \cos^2\theta_w\ \alpha/9\pi\ \log(m_h/m_Z)^2$$

$$\delta_{\nu b} = 20/13\ \alpha/\pi\ (m_{top}/m_Z)^2$$

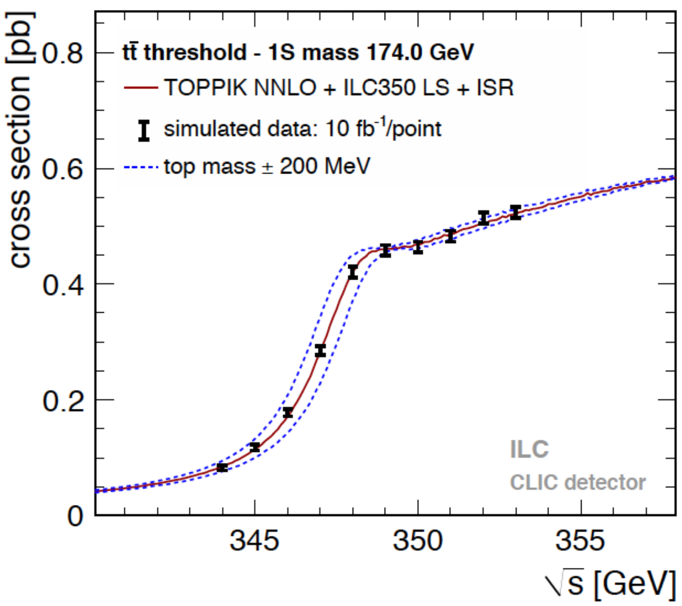
A Sample of Essential Quantities:

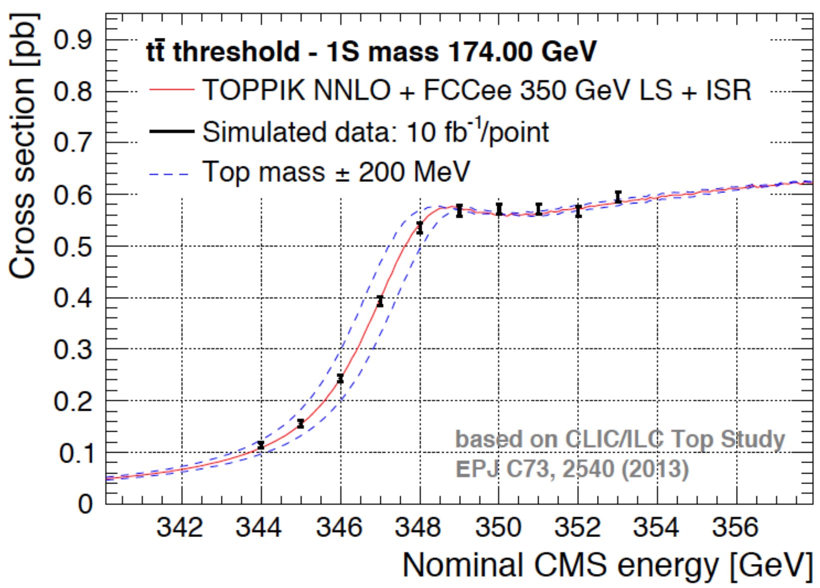
X	Physics	Present precision		TLEP stat Syst Precision	TLEP key	Challenge
M_Z MeV/c2	**Input**	91187.5 ±2.1	Z Line shape scan	**0.005 MeV** **<±0.1 MeV**	E_cal	QED corrections
Γ_Z MeV/c2	**$\Delta\rho$ (T)** **(no $\Delta\alpha$!)**	2495.2 ±2.3	Z Line shape scan	**0.008 MeV** **<±0.1 MeV**	E_cal	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	**0.0001** **± 0.002** **- 0.0002**	Statistics	QED corrections
N_ν	**Unitarity of PMNS, sterile ν's**	2.984 ±0.008	Z Peak Z+γ(161 GeV)	**0.00008** **±0.004** **0.0004-0.001**	->lumi meast Statistics	**QED corrections to Bhabha scat.**
R_b	δ_b	0.21629 ±0.00066	Z Peak	**0.000003** **±0.000020 - 60**	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho$, ε_3 ,$\Delta\alpha$ **(T, S)**	0.1514 ±0.0022	Z peak, polarized	**±0.000015**	4 bunch scheme	Design experiment
M_W MeV/c2	$\Delta\rho$, ε_3 , ε_2, $\Delta\alpha$ **(T, S, U)**	80385 ± 15	Threshold (161 GeV)	**0.3 MeV** **<1 MeV**	E_cal & Statistics	QED corections
m_{top} MeV/c2	**Input**	173200 ± 900	Threshold scan	**10 MeV**	E_cal & Statistics	Theory limit at 100 MeV?

350 GeV: the top mass

- **Advantage of a very low level of beamstrahlung in circular machines**
- **Could potentially reach 10 MeV uncertainty (stat) on m_{top}**
- **The main issue is relation ship between tt threshold and the loop corrections**

- Comparing ILC and FCCee - assuming identical detector performance





Simulated data points - same integrated luminosity

NB: Assuming unpolarized beams - LC beams can be polarized, increasing cross-sections / reducing backgrounds

From Frank Simon, presented at 7th TLEP-FCC-ee workshop, CERN, June 2014

Potential of $\alpha_{QED}(m_Z)$ measurement (1)

For exploitation of precision EW measurements, need precise knowledge of $\alpha_{QED}(m_Z)$

- Standard method involves extrapolation from $\alpha_{QED}(0)$ to $\alpha_{QED}(m_Z)$
  - Dispersion integral over hadronic cross section – low energy resonances: **$\delta\alpha/\alpha$ = 1.1 x 10^{-4}**

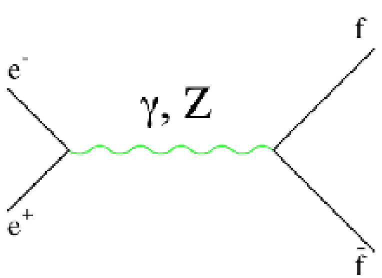
$$\boxed{\alpha_{QED}^{-1}(m_Z) = 128.952 \pm 0.014}$$

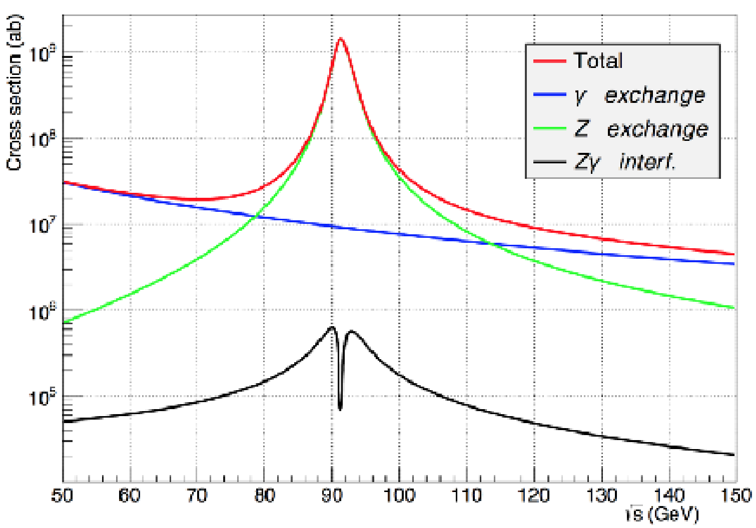
New idea: exploit large statistics of FCC-ee to measure $\alpha_{QED}(m_Z)$ directly **close to m_Z**

- Extrapolation error becomes negligible!

Two methods considered: Meast. of cross section, $\sigma(e^+e^- \to \mu^+\mu^-)$, and asymmetry, $A_{FB}^{\mu\mu}$

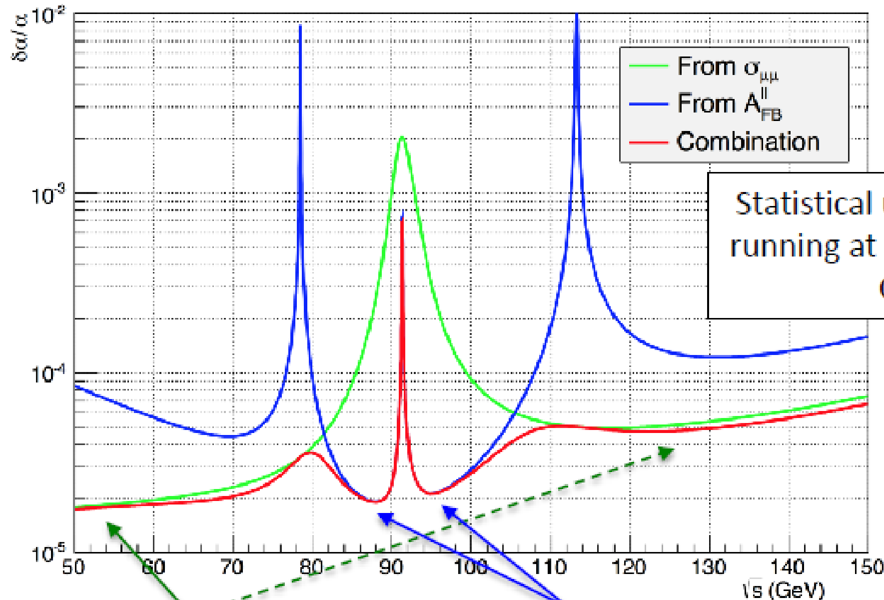
- γ exchange proportional to $\alpha^2_{QED}(\sqrt{s})$
- Z exchange independent of $\alpha_{QED}(\sqrt{s})$
- γZ interference proportional to $\alpha_{QED}(\sqrt{s})$





P. Janot: [FCC-ee Physics Vidyo Meeting, June 29th 2015]

Potential of $\alpha_{QED}(m_Z)$ measurement (2)



Statistical uncertainty for one year of running at any centre-of-mass energy. Crab-waiste, 4 IP.

From $\sigma_{\mu\mu}$ measurement
- Sensitivity best "far" away from Z peak, particularly at the low side
- Systematics (normalisation) probably a killer

From $A_{FB}^{\mu\mu}$ measurement
- Sensitivity best at 88 and 95 GeV
- Experimental systs. looks controlable; further studies needed
- Theoretical systs. to large degree cancel by "averaging" over 88 and 95 GeV point

By running six months at each of 88 and 95 GeV points:
➢ Could potentially reach a precision of : $\delta\alpha/\alpha = 2 \times 10^{-5}$

Strong coupling constant, $\alpha_s(m_Z)$

At LEP, a precise $\alpha_s(m_Z)$ measurement was derived from the Z decay ratio $R_l = \Gamma_{had}/\Gamma_l$. Reinterpreting this measurement in light of: i) new N_3LO calculations; ii) improved m_{top} ; and iii) knowledge of the m_{Higgs}, the uncertainty is now something like:

$$\boxed{\delta(\alpha_s(m_Z))_{LEP} = \pm 0.0038 \text{ (exp.)} \pm 0.0002 \text{ (others)}}$$

R_l measurement was statistics dominated: Foresee a factor ≥25 improvement at FCC-ee. From the Z-pole, therefore a resonable experimental target is

$$\boxed{\delta(\alpha_s(m_Z))_{FCC\text{-}ee} = \pm 0.00015}$$

Similarly, from the WW threshold, $\alpha_s(m_W)$ can be derived from the high stats measurement of $B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$

$$\boxed{\delta(\alpha_s(m_W))_{FCC\text{-}ee} = \pm 0.00015}$$

Combining the two above, a realistic target precision would be

$$\boxed{\delta(\alpha_s(m_Z))_{FCC\text{-}ee} = \pm 0.0001}$$

stats as of TLEP paper
might improve with Crab Waist

	$A_{FB}^{\mu\mu}$ @ FCC-ee		A_{LR} @ ILC
visible Z decays	10^{12}	visible Z decays	10^{9}
muon pairs	$5\ 10^{10}$	beam polarization	90%
$\Delta A_{FB}^{\mu\mu}$ (stat)	$4.6\ 10^{-6}$	ΔA_{LR} (stat)	$4.2\ 10^{-5}$
$\Delta\ E_{cm}$ (MeV)	0.1		2.2
$\Delta A_{FB}^{\mu\mu}$ (E_{CM})	$9.2\ 10^{-6}$	ΔA_{LR} (E_{CM})	$4.1\ 10^{-5}$
$\Delta A_{FB}^{\mu\mu}$	$1.0\ 10^{-5}$	ΔA_{LR}	$5.9\ 10^{-5}$
$\Delta \sin^2\theta^{lept}_W$	**$5.9\ 10^{-6}$**		**$7.5\ 10^{-6}$**

PRESENT:

	from $A_{FB}^{\mu\mu}$ LEP 2.10^7Z	SLC, 5.10^5 Z	W.A.	$\Delta\alpha$
$\Delta \sin^2\theta^{lept}_W$	$5.3\ 10^{-4}$	$2.6\ 10^{-4}$	$1.6\ 10^{-4}$	$3.5\ 10^{-5}$

from α_{QED} (mZ) $\Delta\alpha = 0.00002$

➔ $\Delta \sin^2\theta^{lept}_W = 7\ 10^{-6}$

Theoretical limitations

FCC-ee

R. Kogler, Moriond EW 2013

SM predictions (using other input)

0.000'2 0.000'1 0.000'3

$$M_W = 80.3593 \pm 0.0056_{m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}}$$

0.0005

$$\pm 0.0017_{\alpha_S} \pm 0.0002_{M_H} \pm 0.0040_{\rm theo}$$

0.000'25 0.000'0

$$= 80.359 \pm 0.011_{\rm tot}$$

0.000'0015 0.000'001 0.000'007

$$\sin^2\theta^\ell_{\rm eff} = 0.231496 \pm 0.000030_{m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{\rm had}}$$

0.000'006

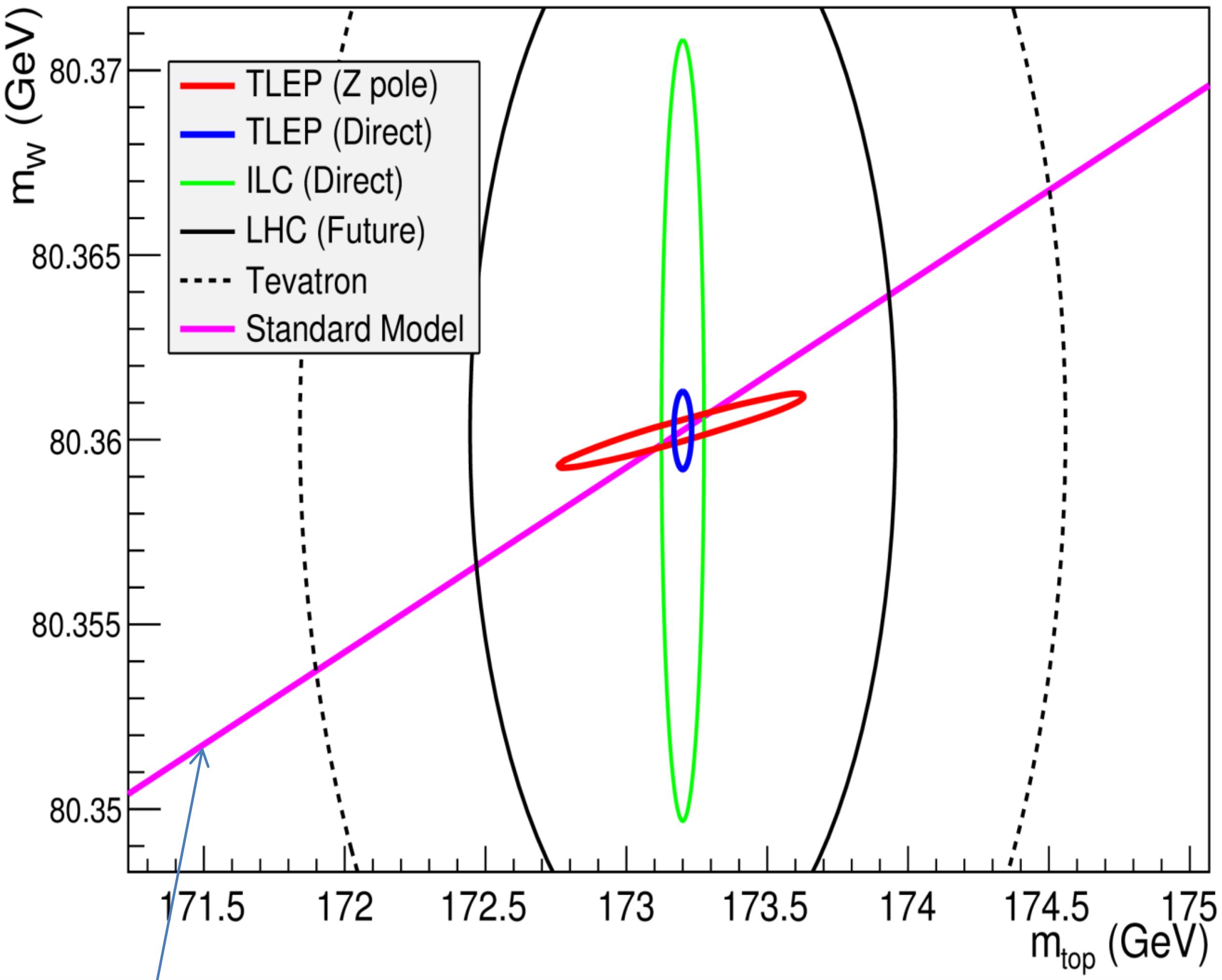
$$\pm 0.000010_{\alpha_S} \pm 0.000002_{M_H} \pm 0.000047_{\rm theo}$$

0.000'0014 0.000'000

$$= 0.23150 \pm 0.00010_{\rm tot}$$

Experimental errors at FCC-ee will be 20-100 times smaller than the present errors.
BUT can be typically 10 -30 times smaller than present level of theory errors
Will require significant theoretical effort and additional measurements!

Radiative correction workshop 13-14 July 2015 stressed the need for 3 loop calculations for the future!
Suggest including manpower for theoretical calculations in the project cost.

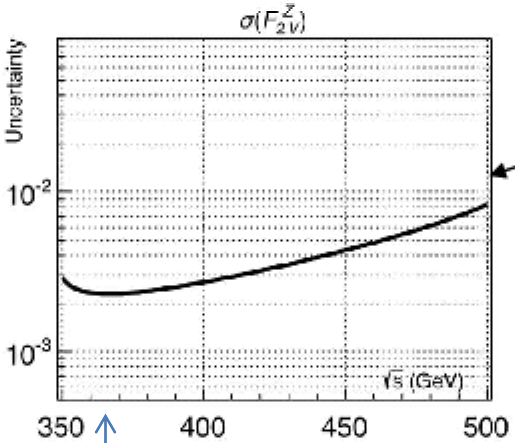


NB width of this line : Z mass error. Without FCC-ee its 2.2 MeV!

in other words .... $\Delta(\Delta\rho) = \pm 10^{-5}$ + several tests of same precision

NEW

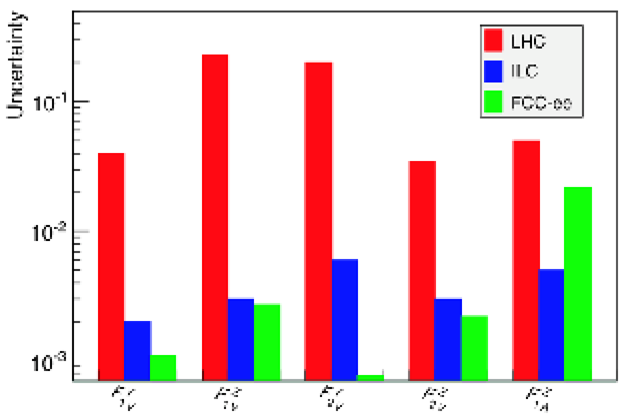
Determination of top-quark EW couplings via measurement of top-quark polarization.
In semileptonic decays, fit to lepton momentum vs scattering angle

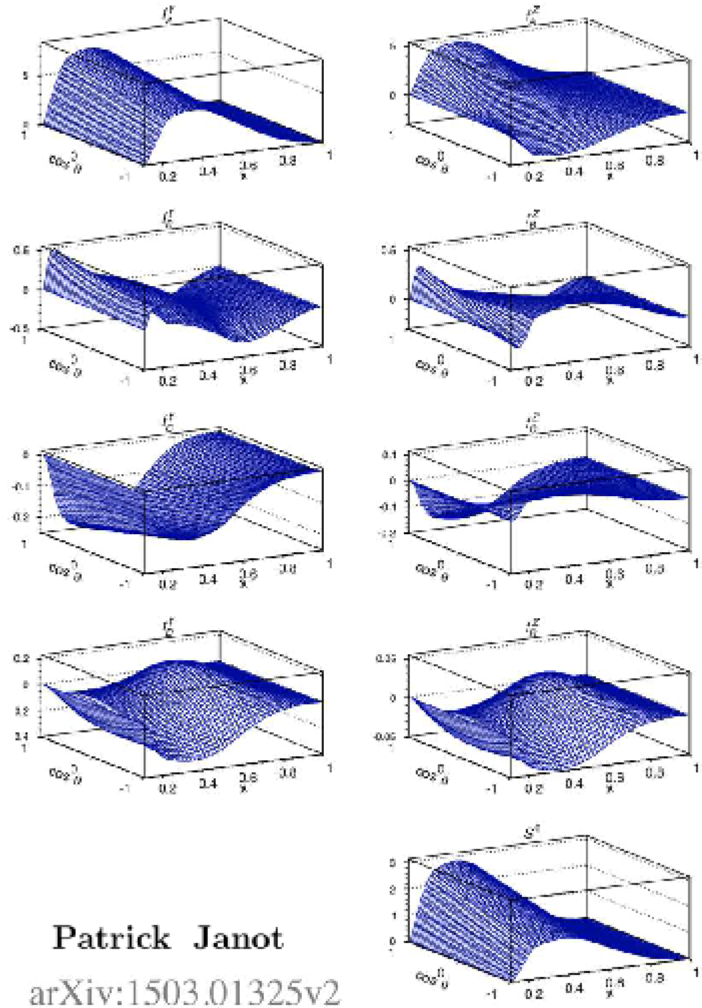


Typically best sensitivity just above production threshold

Momenta up to: 175 GeV

no need for High Energy or beam polarization





Patrick Janot
arXiv:1503.01325v2

Conclusions

FCC-ee offers a coherent program of EW precision measts on 'all fronts'

In view of the accelerator design:

-- energy calibration is essential

-- Jury is still open on longitudinal polarization

-- no obvious need except perhaps at the Z peak

-- nobody complains about too much luminosity (pile-up < 0.001)

-- for the EW fits, we need to cover Z,W, and top.

In view of the design study report:

-- unprecedented precisions can be achieved on all fronts

-- All parametric errors can be considerably reduced to below the exprimental uncertainties and reveal the

absolute need to improve the theoretical accuracies

==> a plan for this has to be included in the design report.

more observables to investigate (A_{FB}^{b}, R_b, etc...)

-- the resulting precision in terms of reach for new physics can be quantified in various ways -- we need to work on this.