FCC-ee: Energy Calibration Options

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But better ask Alain Blondel, the real expert in this field

Opportunities in EW precision physics

Observable	Measurement	Current precision	TLEP stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \rightarrow bb$
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meas.
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.00001	0.0001	New Physics
m_w (MeV)	Threshold scan	80385 ± 15	0.3	< 0.5	QED Corr.
N_ν	Radiative returns $e^+e^- \rightarrow \gamma Z$, $Z \rightarrow \nu\nu$, ll	2.92 ± 0.05 2.984 ± 0.008	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	173200 ± 900	10	10	QCD (~40 MeV)
Γ_{top} (MeV)	Threshold scan	?	12	?	$\alpha_s(m_Z)$
λ_{top}	Threshold scan	μ = 2.5 ± 1.05	13%	?	$\alpha_s(m_Z)$

Preface

- Accurate beam energy knowledge (and more precisely centre-of-mass energy knowledge) is important form many physics studies
- LEP led the way with very precise energy determination at the Z peak (and at the WW threshold with less precision)
- We need a strategy for achieving the best possible precision at all energies: 90GeV, 160GeV, 240GeV, 350GeV

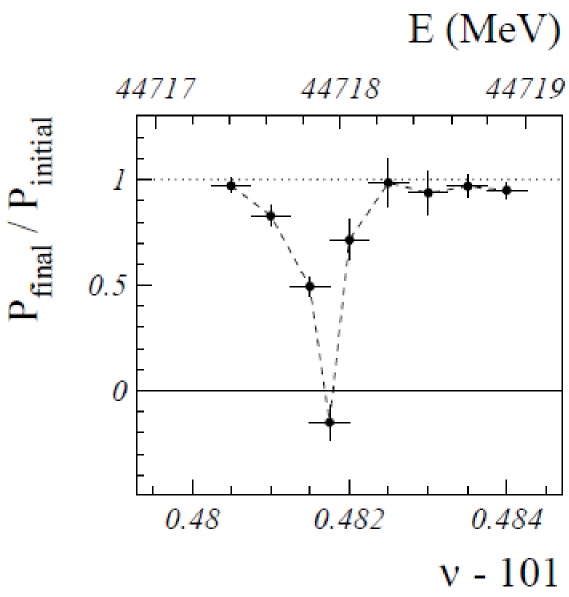
Z peak

- At the Z we will use the resonant depolarization method that gives excellent instantaneous accuracy. This technique is unique to circular colliders.
- Since the statistical precision achievable at the Z is O(10^2) better than what was achieved a LEP, an effort should be made to also improve the accuracy of the collision energy.
- The expected statistical accuracy is fantastic due to the very high statistics: 5keV for the Z mass, 8keV for the Z width (baseline scheme)

The resonant depolarization method

$$\nu = a\gamma = \frac{aE}{mc^2} = \frac{E[MeV]}{440.6486(1)[MeV]}$$

- The spin tune of an electron in a storage ring, ν, is proportional to its energy.
- For a bunch of electrons their polarization vector precesses with the average energy of the bunch. This energy can be measured to ~100keV per beam
- We then need to apply IP specific corrections (due to RF)
- Finally, we need to apply corrections when deriving the ECM energy from the beam energies (if dispersion and offsets are present)



Resonant depolarization measurement

- The measurement consists of measuring the spin precession frequency by introducing a resonance in a 'random walk' fashion.
  - Failure: nothing observed, the frequency used not the correct one
  - Success: the bunch depolarizes, the frequency corresponds to the exact energy at that moment
- For the measurement one needs levels of polarization of 5-10% (the better the polarimeter, the smaller the value) – I hope we will have a good polarimeter!
- One bunch is targeted at a time and one bunch depolarizes per success

Differences from LEP

- During the LEP era the prevailing error was due to the extrapolation from the (few) resonant depolarization calibrations.
- This error will become negligible at the FCC-ee (from 60 measurements → 10,000 measurements)
- A dedicated polarimeter will measure the energy of positrons (we have two beam pipes!!) – no error from extrapolating to positrons from electrons
- Polarization times at the FCC-ee are extremely long and beam lifetimes short → use non-colliding bunches (different tune shift!) and use polarization wigglers

Wigglers

- Wigglers are essential since natural polarization time is long but have two undesired effects:
- They increase the energy spread
- They contribute to the SR power budget of your machine
- Strategy is to use them is such a way that
  - The energy spread is less than some manageable number (so that no resonances are encountered).
  - Switch them on only where necessary

Machine	Energy	No. of wigglers	B+	Polarization time to 10%	Energy spread	Wiggler SR power
TLEP	45	0	0	25 hours	17MeV	0
TLEP	45	12	0.62T	2.1 hours	52MeV	20MW
TLEP	45	1	1.35T	2.4 hours	52MeV	9MW

Lose ~2h at the beginning of (hopefully) very long fills – can reduce this if lower polarization levels could be distinguished by the polarimeter

Energy spread

- The energy spread should also be measured as it contributes to the Z width uncertainty.
- The LEP method of measuring the beam interaction footprint at all IPs will not work (crab waist)
- We need a dedicated energy spread measuring device, for instance a SR camera at a place of large dispersion.

Resonant depolarization accuracy at LEP

Source	$\Delta E/E$	ΔE (E=45.6 GeV)	Nature of the error
Electron mass	$3 \cdot 10^{-7}$	15 keV	systematic
Revolution frequency	10^{-10}	0 keV	
Frequency of the RF magnet	$2 \cdot 10^{-8}$	1 keV	systematic
Width of excited resonance	$2 \cdot 10^{-6}$	90 keV	statistical
Interference of resonances	$2 \cdot 10^{-6}$	90 keV	Stat/syst
Spin tune shifts from long. fields	$1.1 \cdot 10^{-7}$	5 keV	systematic
Spin tune shifts from hor. fields	$2 \cdot 10^{-6}$	100 keV	systematic
Quadratic non-linearities	10^{-7}	5 keV	systematic
Total error	$4.4 \cdot 10^{-6}$	200 keV	

Table 1: The accuracy of the beam energy calibration method by resonant depolarization is summarized for LEP. A standard energy calibration with a well corrected vertical closed orbit is assumed. All errors are understood to be RMS errors.

- Total error was given as 200keV per beam
- Some of these numbers are upper bounds
- Some of these numbers are theoretical estimations which could not be verified experimentally

Resonant depolarization accuracy – spin tune shifts

- The systematic error of resonant depolarization at LEP was dominated by spin tune shifts due to radial magnetic fields (due to quad misalignement).

$$\sigma(\delta\nu) \approx 0.04\, \nu^2 n_Q (KL)^2 \sigma_y^2$$

nq: number of quads
KL: quad strength
σy : RMS orbit distortion

- The spread was estimated to be 30keV for $\sigma_y = 0.5mm$
- The paper finally quotes an error smaller than 100keV
- TLEP needs to do a factor of 30-100 better than LEP in the ratio of quad. strength/misalignment (to be verified if optimistic or pessimistic). Then the error on the energy would be 3keV
- Harmonic spin matching (vertical π bumps): its effect was negligible at LEP – will this be the case in TLEP?

Interference between depolarizing resonances

- The resonance interference error is the shift of an (artificially excited) spin resonance due to a nearby natural spin resonance
- It is actually stated in the text (but not the table) of the paper that the effect is smaller than 90keV.
- it has a statistical and systematic component depending on if the excited spin resonance on the right or on the left of the natural resonance.
- I will have to assume that most of this error contribution would become statistical (why should we always approach a resonance from the same side?) (to be worked on!)
- My assumption: 9keV systematic, 90keV statistical

Spin tune shifts due to longitudinal fields

- These arise from the experimental solenoids, for instance.
- They can be reduced by accurate spin matching of the solenoids
- At LEP this effect was smaller than $\delta\nu < 10^{-5}$ (5keV)

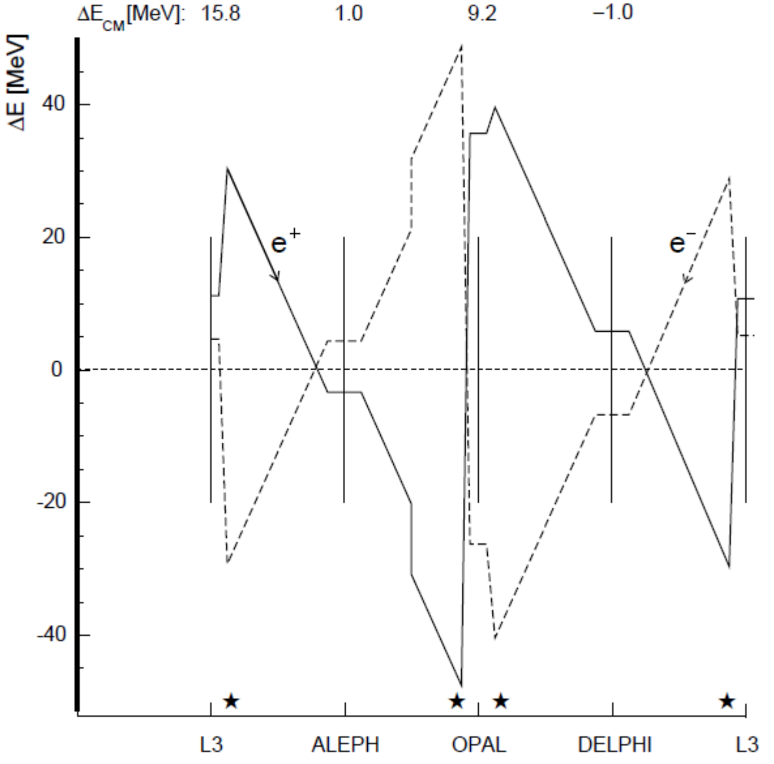
Quadratic non-linearities

- Small systematic spin tune shifts can occur due to the spin tune spread related to synchrotron oscillations of the individual particles.
- For LEP this shift produces a relative error of $\Delta E/E < 1 \cdot 10^{-7}$ (~5keV). This was not measured/estimated at LEP, but chromaticity was increased by a factor 10 with no effect in energy.
- A study for FCC-ee should be done. In absence of a study, I will use the LEP number

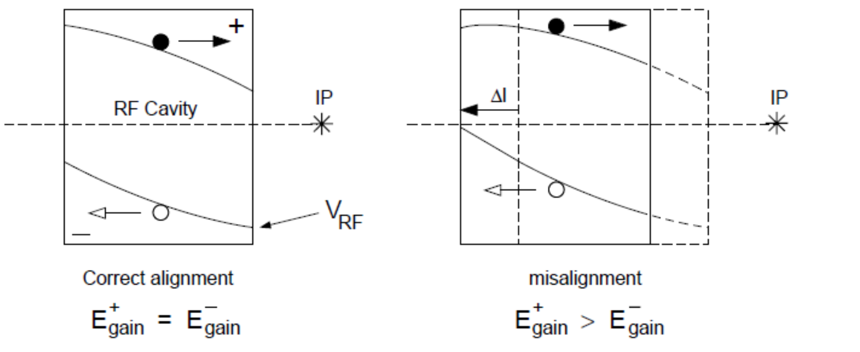
IP-specific corrections plus ECM corrections

- Resonant depolarization gives the average energy of the beam through the ring
- What we need is the ECM energy per experiment
- There are IP specific corrections (due to RF)
- There are also corrections when computing ECM from the beam energy (in some specific dispersion scheme)

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!

This might be the dominant error at FCC-ee

Opposite side vertical dispersion

- OSVD introduced a correlation between ECM energy and bunch collision offset
- Dispersion difference at the IP was ~2mm

$$\Delta E_{\mathrm{CM}} = -\frac{1}{2} \cdot \frac{\delta y}{\sigma_y^2} \cdot \frac{\sigma_{E_b^2}}{E_b} \cdot \Delta D_y^* \qquad (18)$$

Table 15. The centre-of-mass energy correction ΔE_{CM} due to dispersion effects. The error is due to the error on the determination of the collision offset δy

	ΔE_{CM} (MeV) IP2	IP4	IP6	IP8
P−2	−0.99±0.39	0.69±0.24	−0.48±0.33	0.29±0.25
P+2	0.12±0.39	−0.47±0.24	−0.21±0.41	−0.26±0.38

Collision offsets were sub-micron!

Table 13. The luminosity-weighted collision offsets $\langle \delta y \rangle_{\mathrm{lum}}$

	$\langle \delta y \rangle_{\mathrm{lum}}$ (μm) IP2	IP4	IP6	IP8
P−2	0.43±0.17	0.53±0.19	0.34±0.24	0.18±0.16
P+2	−0.05±0.17	−0.36±0.19	0.15±0.30	−0.16±0.24

To avoid the problem, we should run with zero OSVD!

LEP error (ECM) ~400keV

Resonant depolarization accuracy at TLEP/FCCee - wild 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

Energy spread

- Total error at LEP was 1000keV translating to 200keV for the Z width
- The method used at LEP (which was measuring the bunch length at the IP) cannot be used at the FCC-ee if the crab waist scheme is used
- another method should be used: for instance an SR camera at a place of large known dispersion (in the arcs)
- Energy spread at the Z is 17MeV. We need a system that can measure this to 0.1% (not the accuracy of individual measurements, but the accuracy of the method) → 20keV per beam translating to 7keV for the Z width

Other effects

- If we are planning to reduce the error of resonant depolarization measurements by a large amount compared to LEP, new effects that were negligible back then will make their appearance.
- A careful study is called for.

W physics

$$\sigma_E \propto \frac{E^2}{\sqrt{\rho}}$$

- In contrast to LEP, adequate polarization levels are expected to exist at the FCC-ee since the energy spread decreases in a larger ring (to be verified)
- Analysis will be similar to the Z, and resulting error much smaller than what was achieved at LEP (that had to rely on large extrapolation)
- The statistical error is expected to be 0.3MeV (which is much larger than what can be achieved at the Z), so we can be fairly confident that the systematic error due to the energy uncertainty will not be a limiting factor

Higgs and top running

- Here we need to use a reconstruction method (G. Wilson, TLEP7) of γZ events
- Reachable accuracy is ~10ppm (2.4MeV ECM at 240GeV, 3.5MeV ECM at 350GeV)

Summary: What accuracies could we aim at?

	LEP		TLEP	
measurement	Contribution energy error	Contribution energy spread	Contribution energy error	Contribution energy spread
Z mass	2MeV		~0.09MeV	
Z width	2MeV	0.2MeV	~0.05MeV	~0.007MeV
W measurements	25MeV		~0.09MeV	
120GeV running	-	-	~2MeV	
Top physics 175GeV	-	-	~4MeV	

All errors at the Z and W are below the 0.1MeV level (but keep in mind that these numbers are not verified by solid measurements/simulations – more like "back of the envelope" calculations

Conclusions

- A first attempt to quantify the possible errors due the uncertainty of the energy and energy spread of the machine.
- In these “back of the envelope” calculations, errors due to energy on the mass and width of the Z and the mass of the W are below the 0.1MeV level.
- This needs to be substantiated by solid work in the field, to be done over the next couple of years.
- I hope that we will be able to improve on some of these errors!

End

Thank you

BACKUP SLIDES

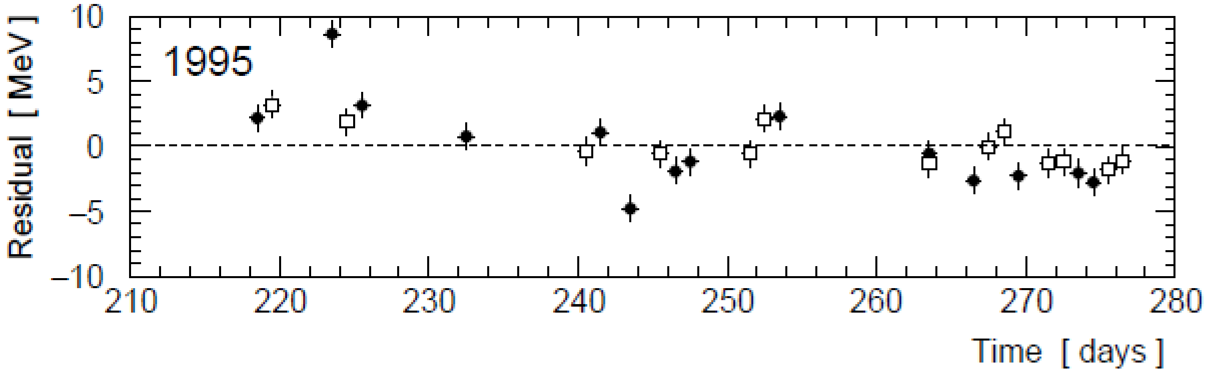
LEP 1993-1995: calibrated fills

- Some proportion of fills was calibrated at the end of a fill (64/352)
- 6 fills had measurements at the beginning and at the end of the fill

	P−2		P		P+2	
Year	$\int$ Ldt	cal. fills	$\int$ Ldt	cal. fills	$\int$ Ldt	cal. fills
1993	$\sim 10\,\mathrm{pb}^{-1}$	13/38(35%)	$\sim 20\,\mathrm{pb}^{-1}$	1/57(2%)	$\sim 10\,\mathrm{pb}^{-1}$	11/31(45%)
1994			$\sim 60\,\mathrm{pb}^{-1}$	11/167(8%)		
1995	$\sim 10\,\mathrm{pb}^{-1}$	14/22(69%)	$\sim 20\,\mathrm{pb}^{-1}$	1/14(6%)	$\sim 10\,\mathrm{pb}^{-1}$	13/23(65%)

How good was the energy model?

- Plot the model prediction versus the real resonant depolarization values. RMS was ~few MeV



LEP error table (simplified)

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

- Can be reduced by measuring the energy continuously during physics
- Can be reduced by measuring the energy of positrons as well