Baseline running scheme with wigglers and systematic errors as they stand RELOADED

Mike Koratzinos,

EPOL workshop,

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Bibliography

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

- This presentation is an update of my talk in Washington (FCC week) of 23/3/2015
- I have corrected/enhanced some parts after fruitful discussions with all involved

Preface

- Accurate beam energy knowledge (and more precisely centre-of-mass energy knowledge) is important for many physics studies
- LEP led the way with very precise energy determination at the Z peak
- We need a strategy for achieving the best possible precision at all energies, but 90 and 160GeV are the most critical (where there resonant depolarization method can be used)

What is new from the LEP times

- Resonant depolarization every ~10 minutes on both e+ and e-
- Measurement of beam spread from the experiments (muon acolinearity)
- Measurement of energy difference from the experiments (muon acolinearity)
- The new super polarimeter can measure polarization levels to 2% every second (this should be our requirement) photons alone if possible also the electrons.
- The new superpolarimeter might also measure (relative and perhaps absolute) LOCAL energy to be demonstrated
- We can only perform limited swing Vernier scans moving off by 0.1 sigma_y. (This last point is disputed by Jorg, who thinks that the scan could be larger without introducing instabilities)

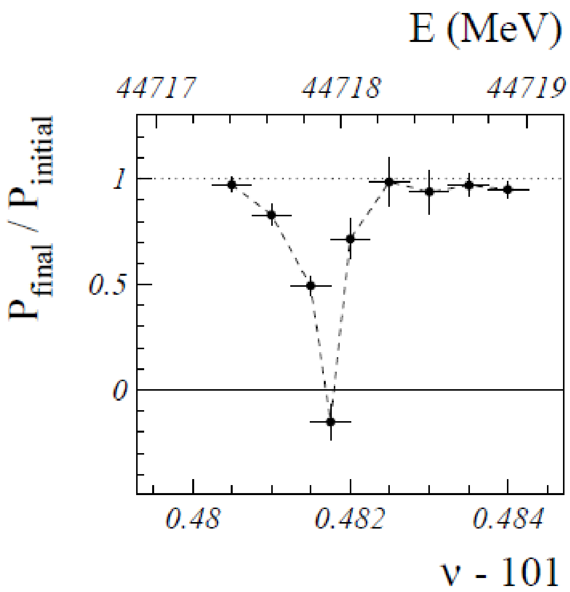
Z peak

- 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 and cannot be matched, due to the very high statistics: 5keV for the Z mass, 8keV for the Z width

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)



Extrapolations needed

- The resonant depolarization method measures the average beam energy of non-colliding bunches of e+ and e-
- From average energy of non-colliding bunches ➔ average energy of colliding bunches
- From average energy of colliding bunches ➔ energy at the IP for e+ and e-
- From the energy at the IP of e+ and e- ➔ ECM energy

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) – arbitrarily choose 52MeV.
  - Switch them on only where necessary

Machine	Energy	No. of wigglers	B+	Polarization time to 10%	Energy spread	Wiggler SR power	Critical energy
TLEP	45	0	0	25 hours	17MeV	0	
TLEP	45	12	0.62T	2.1 hours	52MeV	20MW	830keV
TLEP	45	1	1.35T	2.4 hours	52MeV	9MW	1.8MeV

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

Decision on wiggler number/strength

Optimise the following:

- Polarization time
- Critical energy of SR photons –use 800keV ➔ Bmax ~0.6T
- Power consumption – between 10-20MW! This is no relevant if we only use the wigglers for the pilot bunches
- Eliana's numbers:

numb	B+	tau10%	sigma_e	U/turn	E_critical
8	0.67 T	108 min	59.7 MeV	49 MeV	902keV
12	0.58 T	108 min	58.5 MeV	51 MeV	781keV

➔proposal for the CDR:

- Beam energy spread 60MeV
- 12 wigglers, Bmax ~0.6T, E_critical 780keV
- 8 wigglers, Bmax~0.7T, E_critical 900keV
- Polarization to 10% = 1.8 hours for both suggestions

My recommendation: 12 wigglers

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 direct method (see Patrick's talk) and a dedicated energy spread measuring device, for instance a SR camera at a place of large dispersion.

➔CDR proposed strategy: muon acolinearity method, plus a streak camera

Measuring the energy spread

- Use the acolinearity of muons in each of the two FCC-ee detectors.
- As Patrick has shown:
  - Monitor the beam energy spread to 0.2% every 5 minutes at the Z peak
  - Every 15 minutes at the Z off-peak points
  - No requirement for the W running

Resonant depolarization accuracy at LEP

From [2]

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 vertical 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). 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?

➔Estimate for the CDR:
nq=3200; KL^2=2E-3;
sigma_y=0.1mm ➔ 14keV

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

→need an estimate for the CDR

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)

→for FCC-ee, we are compensating fully the detector solenoid.
If we do not, we will not be able to get the luminosity we expect.
We need to put this in numbers for the CDR.

Quadratic non-linearities

- Small systematic spin tune shifts can occur due to 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

→need an estimate for the CDR

From non-colliding to colliding bunches

- Energies of colliding bunches are modified by the presence of strong BS.
- Simulation shows that the effect of BS on full intensity bunches on collision energy is 7MeV at the Z. This energy loss is taken care of by the RF system, and needs to be modelled like the sawtooth (17MeV per half turn).
- Dedicated MD where we build up a healthy (maximum) polarization with separated bunches, then we let them collide while measuring their energy will not be possible (due to instabilities) with full size bunches. Up to what intensity would it be possible?

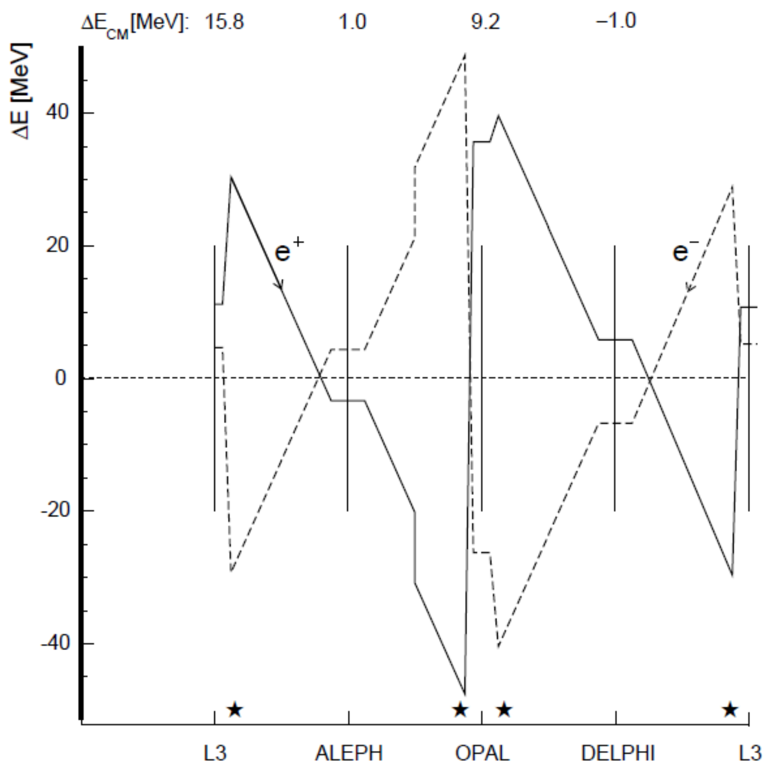
➔proposed strategy for the CDR:

- Investigate the use the super-polarimeter to measure the relative energy of colliding and non-colliding bunches.
- The superpolarimeter becomes an **essential** tool for this, if we do not wish to rely on simulation only

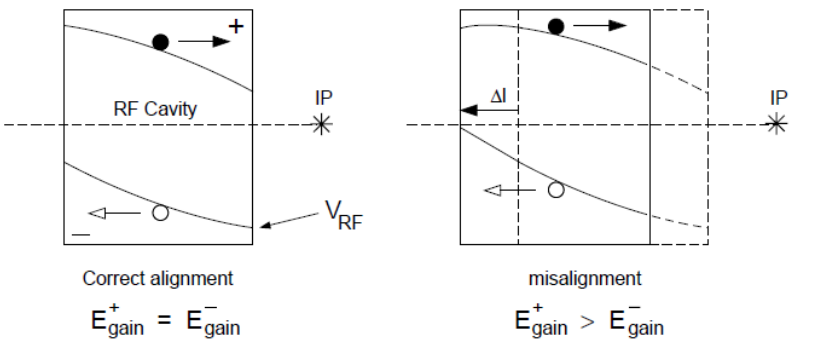
IP-specific corrections plus ECM corrections

- 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

RF corrections

- Number of unknowns:
- E_IP1e+, E_IP1e-, E_IP2e+, E_IP2e-,E_RF1_e+, E_RF2_e+, E_RF1_e-, E_RF2_e-, (8 unknowns)
- What we measure:
- E_average_e+, E_average_e-, (E_IP1e+-E_IP1e-), (E_IP2e+-E_IP2e-) (4 measurements)
- Our unknowns are related through (2 equations):
- E_average_e+ = f(E_IP1e+, E_IP2e+,E_SRloss, E_RF1_e+, E_RF2_e+)
- E_average_e- = f(E_IP1e-, E_IP2e-,E_SRloss, E_RF1_e-, E_RF2_e-)
- Assume that we can model accurately E_SR_loss, we have two more constraints:
- E_SRloss_e+ = (E_RF1_e+ + E_RF2_e+)
- E_SRloss_e+ = (E_RF1_e+ + E_RF2_e+)
- 8 equations, 8 unknowns

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

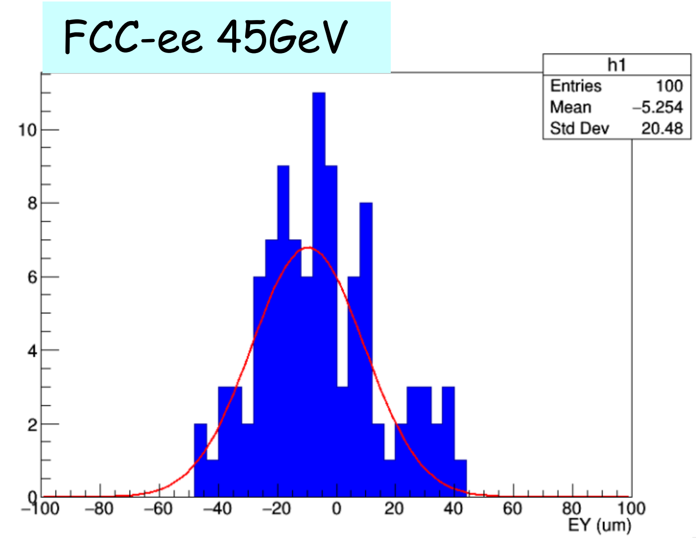
Get numbers for FCC-ee

How big is this effect in FCC-ee?

$$\Delta E_{\mathrm{CM}} = -\frac{1}{2} \cdot \frac{\delta y}{\sigma_y^2} \cdot \frac{\sigma_{E_{\mathrm{b}}^2}}{E_{\mathrm{b}}} \cdot \Delta D_y^*$$

For FCC-ee at the Z we have:

- Dispersion of e+ and e- beams at the IP is 20um (uncorrelated) – only the difference in dispersion matters in this calculation – divide by SQRT(2), so $\Delta D_y^* = 14\mu m$.
- Sigma_y is 30nm
- Sigma_E is 0.132%*45000MeV=60MeV
- Delta_ECM is therefore **2MeV** for a 10% offset
- Note that we cannot perform Vernier scans like at LEP, we can only displace the two beams by ~10%sigma_y
- Assume each Vernier scan accurate to 1% sigma_y
- We need 100 vernier scans to get an accuracy of 20keV – suggestion: vernier scan every hour



Dima El Khechen

→suggestion for CDR: perform a Vernier scan every hour; all colliding bunches at all IPs.

Resonant depolarization accuracy at TLEP/FCCee – wild extrapolation

LEP results

Per beam, not ECM

FCC-ee expected

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	[illegible]
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	3k[illegible]	1keV
Quadratic non-linearities	10^{-7}	5 keV	[illegible]	5keV
Total error	$4.4 \cdot 10^{-6}$	200 keV	~20keV	~12keV
IP specific errors			~40keV	~20keV
total			~45keV	~23keV

Update for CDR

- 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

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.
- Anton has done a carful study. The part of the errors that DO NOT affect the mean energy of the beam (and therefore will be measured accurately with depolarization measurements) need to be propagated to this analysis and the CDR

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

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

➔update the table for the CDR

Baseline running scheme

For a typical fill at 45GeV:

- Inject 250 non-colliding bunches
- Switch wigglers on for 1-2 hours
- Fill the rest of the machine, start physics running (1 hour)
- Switch wigglers off
- Start measuring the energy by depolarizing one non-colliding bunch every 12 minutes
- In 50 hours all bunches would have been depolarized, but natural polarization would have kicked in.

Conclusions

- It seems possible that the error due to the energy determination is kept below the 0.1MeV level for the Z.
- Situation is more relaxed by a factor of ~2 for the W.
- We need to finalise the error estimates, as well as the specs for the hardware needed (wigglers, but also polarimeter).

End

Thank you

BACKUP SLIDES

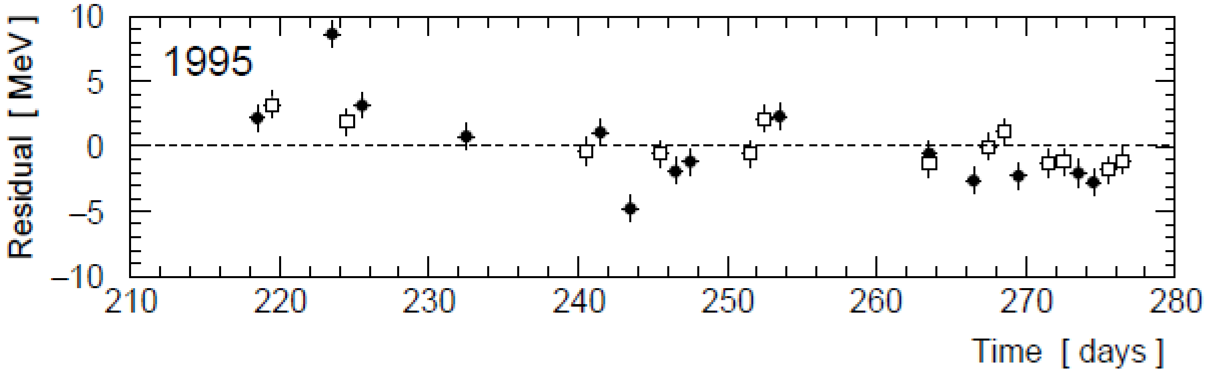
LEP 1993-1995: calibrated fills

- 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)							Energy correlation	Year correlation	Δm_Z (MeV)	$\Delta\Gamma_Z$ (MeV)
	P−2 93	P 93	P+2 93	P 94	P−2 95	P 95	P+2 95				
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

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**	$g \to bb$
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 $e^+e^- \to \gamma Z, Z \to \nu\nu, ll$	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%**	**?**	$\alpha_s(m_Z)$