Overview and status of CM energy uncertainties

M. Koratzinos

FCC Week 2019, Brussels

25/6/2019

Acknowledgements

- Based on a 100-page paper almost ready to be published with many authors:

FCC-ee Polarization and Centre-of-mass Energy Calibration

The FCC-ee energy and polarization Working group – we need list of authors and institutes
CERN, Geneva, Switzerland

Abstract
A significant part of the FCC-ee physics program lays in the precise (ppm) measurements of the W and Z masses and widths, as well as forward backward asymmetries. To this effect the centre-of-mass energy

- Special thanks to A. Blondel and J. Wenninger

The disclaimers

- This is work in progress!
- There are certainly omissions and mistakes, but I wanted to give you an idea apout the state of the art in this exciting topic

Prior art

- We have done this before! At LEP (and Novosibirsk)
- BUT this is a completely new ball game (error at LEP ~2MeV, error aimed at FCC ~100keV→10keV)
- We have learned from the LEP experience, and errors that dominated then will be completely negligible
- At this level of accuracy, systematic errors that could be neglected at LEP give important contributions
- Effectively these errors are introduced when we go from measuring the AVERAGE energy of the NON COLLIDING e+ and e- beams to the ECM energy at the different IPs

New tools!

- We now have at our disposal monitoring and measurement tools that we did not have (did not need) at LEP
- Polarization measurements (Eliana’s talk)
  a) Measure e+ and e- separately
  b) Measure them continuously
  c) BUT can only measure non-colliding pilot bunches
- Dimuons provide a powerful tool to measure (Patrick's talk):
  a) The angle of the beams (as a function of beam intensity)
  b) The difference between the energy of e+ and e-
  c) Beam energy spread and variation of ECM over time
- Polarimeter that also measures the energy can be very useful!

At LEP…

- Energy was given off-line for each IP every 15 minutes. A model was used to evolve the energy between accurate resonant depolarization measurements
- A similar approach will be done at FCC. But at FCC we will have a resonant depolarization measurement every fifteen minutes for both e+ and e-.

Energy measurement using the resonant depolarization method

Energy, E of an electron in a synchrotron, is proportional to spin tune, ν (number of times the average spin vector precesses in one revolution in a synchrotron), the electron rest mass and the ratio of anomalous to normal parts of the gyromagnetic ratio:

$$E = \nu \frac{mc^2}{q'/q_0} \, .$$

The ratio of anomalous and normal parts of gyromagnetic ratio is $q'/q_0 = 1.15965218091 \cdot 10^{-3} \pm 0.26 \cdot 10^{-12}$, the electron rest mass is $mc^2 = 0.5109989461 \pm 0.31 \cdot 10^{-8}$ MeV [57]. Hence, beam energy is given by

$$E[MeV] = 440.64846 \cdot \nu \, , \tag{52}$$

with an accuracy of

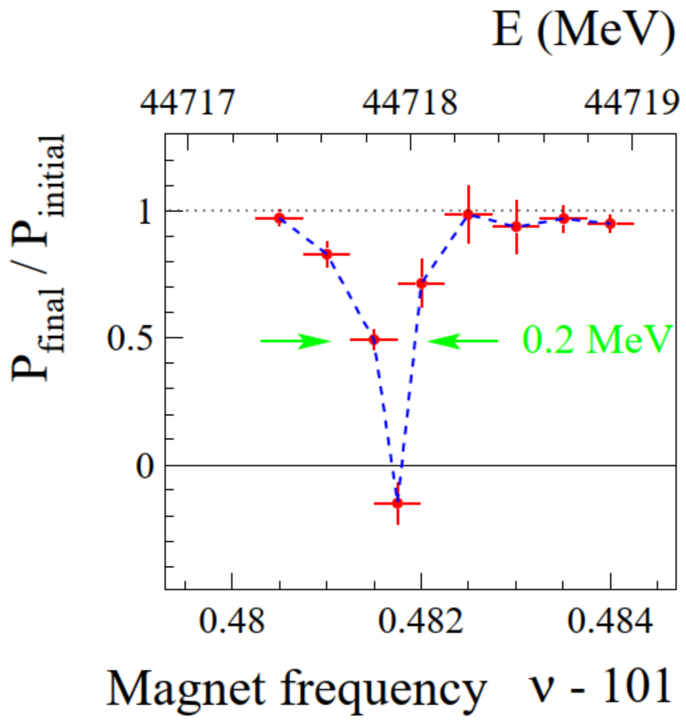
$$\frac{\Delta E}{E} = \sqrt{\left(\frac{\Delta(mc^2)}{mc^2}\right)^2 + \left(\frac{\Delta(q'/q_0)}{q'/q_0}\right)^2} \simeq \frac{\Delta(mc^2)}{mc^2} = 7.8 \cdot 10^{-8} \, .$$

Assumptions: absence of electric and longitudinal magnetic fields, perfectly flat orbit
Uncertainty is essentially the uncertainty in the electron mass, corresponding to 7keV on the Z mass…

The resonant depol. method – instantaneous accuracy

- In an accelerator, we need to deal with bunches of electrons, so their collective spin tune relates to the average energy of the whole bunch.
- By depolarizing a previously polarized bunch (using a resonance) we can measure the (non-integer) part of the spin tune
- Instantaneous accuracy is exquisite: 200keV

Measurement over many turns, over the ensemble of particles

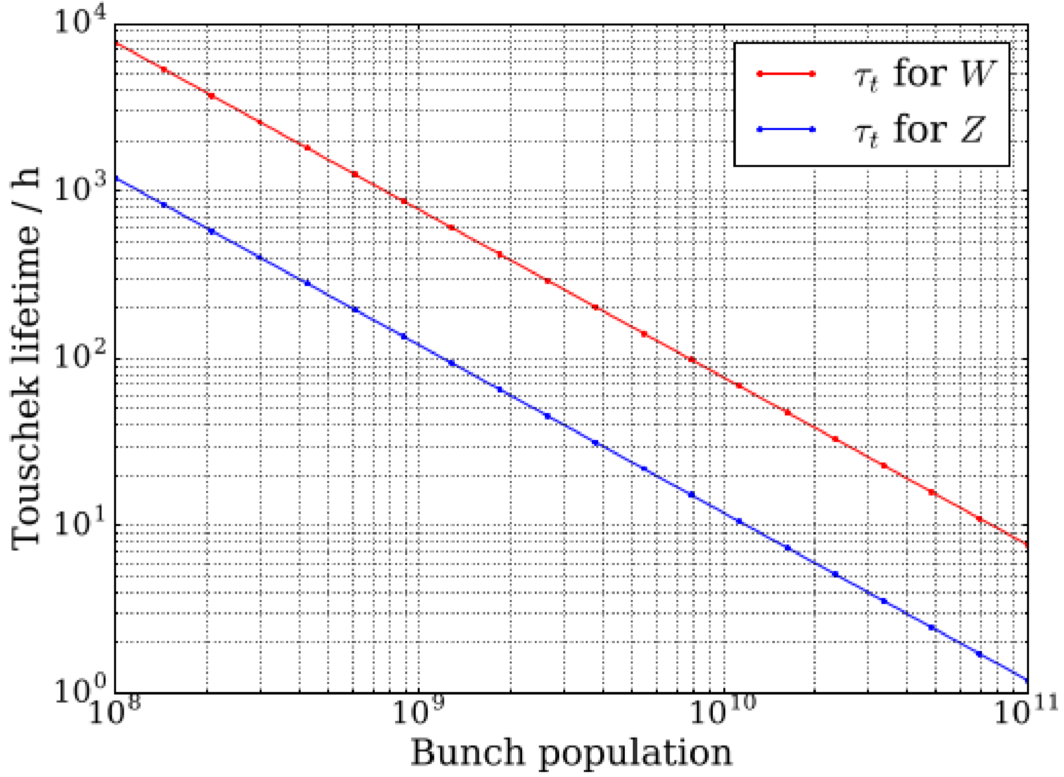


From the LEP campaign: 200 keV instantaneous accuracy

The strategy

- For 5% polarization we need 15 hours with no wigglers at the Z…
- …or a couple of hours with full wigglers and pilot bunches
- One depolarization measurement every 15 minutes
- 100 pilot bunches would take 25 hours to use up
- BUT pilot bunches, although not colliding, have relatively short Toucheck lifetime (next slide).
- A possible strategy: assume that 5% polarization is sufficient for a measurement and that 1E9 electrons in a bunch is adequate.
- Then we need about 100 pilot bunches; after each measurement we replace the bunch with 1E10 electrons and let it polarize naturally. 15 hours later, it is ready to be measured (its intensity is now ~1E9)

Pilot bunches



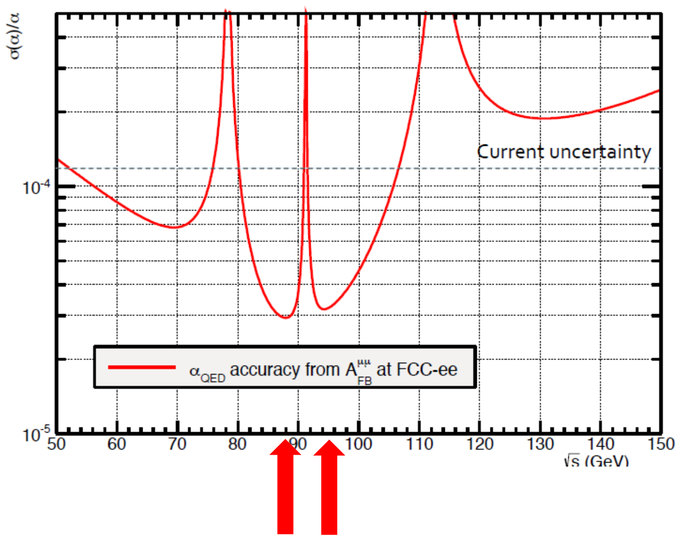
- Severely affected by Toucheck lifetime
- Pilot bunch with 1E10 electrons has a lifetime of 10 hours at the Z
- To go to 20 hours lifetime, the bunch intensity should be less than 6E9
- Problem six times less important at W energies
- Gas scattering lifetime: 20h
- Question is, what bunch intensity is adequate for a depol measurement?

Scan energies at FCC-ee

- Slightly different than the energies at LEP, dictated by the alpha_QED measurement
- Scan energies need to be close to half spin tune – by chance this is the case for the central point

Table 3: Center-of-mass energies for the proposed Z scan. The points noted A and B are half integer spin tune points with energies closest to the requested energies.

Scan point	Centre-of-mass Energy	Beam Energy	Spin tune
E^{-}_{CM} A	87.69	43.85	99.5
E^{-}_{CM} Request	87.9	43.95	99.7
E^{-}_{CM} B	88.57	44.28	100.5
E^{0}_{CM}	91.21	45.61	103.5
E^{+}_{CM} A	93.86	46.93	106.5
E^{+}_{CM} Request	94.3	47.15	107.0
E^{+}_{CM} B	94.74	47.37	107.5



Statistical error of alpha_QED is minimum at 87.4 and 94.3GeV

Analysis of errors due to energy for major observables

$$\frac{\Delta \mathrm{M_Z}}{\mathrm{M_Z}} = \left\{\frac{\Delta \mathrm{E_{CM}}}{\mathrm{E_{CM}}}\right\}_{\mathrm{abs}} \oplus \left\{\frac{\Delta(\mathrm{E^+_{CM}} + \mathrm{E^-_{CM}})}{\mathrm{E^+_{CM}} + \mathrm{E^-_{CM}}}\right\}_{\mathrm{ptp-syst}} \oplus \left\{\frac{\Delta \mathrm{E^{\pm,i}_{CM}}}{\mathrm{E^{\pm,i}_{CM}}\sqrt{\mathrm{N^{\pm,i}}}}\right\}_{\mathrm{sampling}}$$

$$\frac{\Delta \Gamma_\mathrm{Z}}{\Gamma_\mathrm{Z}} = \left\{\frac{\Delta \mathrm{E_{CM}}}{\mathrm{E_{CM}}}\right\}_{\mathrm{abs}} \oplus \left\{\frac{\Delta(\mathrm{E^+_{CM}} - \mathrm{E^-_{CM}})}{\mathrm{E^+_{CM}} - \mathrm{E^-_{CM}}}\right\}_{\mathrm{ptp-syst}} \oplus \left\{\frac{\Delta \mathrm{E^{\pm,i}_{CM}}}{\mathrm{E^{\pm,i}_{CM}}\sqrt{\mathrm{N^{\pm,i}}}}\right\}_{\mathrm{sampling}}$$

$$\Delta A^{\mu\mu}_{FB}(\mathrm{pole}) = \frac{\partial A^{\mu\mu}_{FB}}{\partial \mathrm{E_{CM}}}\left\{\Delta(\mathrm{E^0_{CM}} - 0.5(\mathrm{E^+_{CM}} + \mathrm{E^-_{CM}}))\right\}_{ptp-syst} \oplus \frac{\partial A^{\mu\mu}_{FB}}{\partial \mathrm{E_{CM}}}\left\{\frac{\Delta \mathrm{E^{0,\pm i}_{CM}}}{\sqrt{\mathrm{N^{0,\pm i}}}}\right\}_{\mathrm{sampling}}$$

$$\frac{\Delta \alpha_{QED}(\mathrm{M_Z})}{\alpha_{QED}(\mathrm{M_Z})} = \left\{\frac{\Delta \mathrm{E_{CM}}}{\mathrm{E_{CM}}}\right\}_{\mathrm{abs}} \oplus \left\{\frac{\Delta(\mathrm{E^+_{CM}} - \mathrm{E^-_{CM}})}{\mathrm{E^+_{CM}} - \mathrm{E^-_{CM}}}\right\}_{\mathrm{ptp-syst}} \oplus \left\{\frac{\Delta \mathrm{E^{\pm,i}_{CM}}}{\mathrm{E^{\pm,i}_{CM}}\sqrt{\mathrm{N^{\pm,i}}}}\right\}_{\mathrm{sampling}}$$

Three categories:
- Absolute
- Point to point (correlated and anti-correlated)
- Due to sampling

What can be achieved?

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

Quantity	statistics	ΔE_{CMabs} 100 keV	$\Delta E_{CMSyst-ptp}$ **40 keV**	calib. stats. 200 keV/$\sqrt{(N^i)}$	σE_{CM} (84) $\pm$ **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**

Here we assume

- 100keV for the absolute calibration and
- 40keV for the relative point to point error.
- 200keV for each depol measurement
- One depol measurement every 1000 seconds

Muons can reduce this

W energies

- Optimal points 157.1 GeV and 162.3 GeV
- Closest points 157.3 and 162.6 GeV
- 12 ab-1
- Statistical error on the W mass is 0.45MeV and on the W width 1.3MeV, degradation of 10% from non-optimal points
- Uncertainty on energy translates to ½ uncertainty in W mass. So we need to aim to 200keV to make sure that E_{CM} error is small compared to statistics
- 10% determination on energy spread gives 56keV on mass error 410keV on width error
- Take home message: energy uncertainty needed is 200keV or better, energy spread needs to be known to 10%

Higher energies

- No resonant depolarization possible
- Statistical accuracy for the mass of the Higgs: 8 MeV
- Statistical accuracy for the mass of the top 17MeV
- Energy spread at top should be known to 35%
- What comes in handy (as at LEP) is the radiative fermion pair events $e+e- \to Z\gamma$ with $Z \to \bar{f}f$. The photon escapes undetected but the system is over-constrained by the precise measurement of the fermion angles, the knowledge of the Z boson mass and momentum conservation. E_{CM} can be measured with a statistical precision of few tens of MeV.
- Systematics: the angle scale. Determine it from the W run.
- At 240GeV, 1.7MeV H mass error from E_{CM}, much smaller than the stat. precision of 8MeV.
- Top: the above method is not as efficient, error increases to 30MeV. But there is a viable alternative coming from $e+e- \to W+W-$. At 350GeV the E_{CM} error would be 5MeV and at 365GeV 2MeV, again, smaller than the statistical precision.
- Take home message: there is no need for resonant depolarization at higher energies. E_{CM} can be known to much better accuracy than the statistical precision

Systematic errors of the depolarization method

- Categories of errors: statistical
  - Errors of interpolation of the model
  - Statistical sampling error
- systematic
  - Exactness of formula $E = \nu \frac{mc^2}{q'/q_0}$.
  - Going from pilot bunches to colliding bunches
  - Going from average energy to energy at the IP
  - Going from beam energies to E_{CM}

Machine misalignments

- To depolarize you must first polarize. To be able to polarize you need a good machine
- Misalignment needs to be small to be able to get a good machine (low emittance). My feeling is that polarization requirements will eventually be less stringent than optics requirements.
- No systematic error from horizontal misalignments – any energy shifts are exactly measured. For vertical orbit distortions see slide 22
- Next stage: take a few simulated machines from the optics group and estimate if polarization is adequate – work under way (Eliana’s talk).

Statistical errors: The model

- As in LEP, a model should be used to interpolate between depolarization measurements, although these measurements will be frequent.
- To estimate the resulting error, lets assume that we do not interpolate at all
- Largest shift is due to tides, about 1MeV between successful depol. measurements
- In a year (10^7seconds) we will have 10^4 measurements
- Interpolation error is then 10keV, if we can model tides to 10%, error will be 1keV

Effects that change the energy but also are measured with depol. measurements

- Dipole field drifts
- Circumference drifts (tides etc.)
- Horizontal Orbit distortions
- Sextupoles, betatron oscillations

- All absorbed in the resonant depolarization measurements.

Exactness of formula: Effect of solenoids

- Thanks to compensating and screening solenoids, the effect has been estimated to be only 0.71keV, and can be measured with solenoids on /off
- Negligible error

Effects that break the relationship: α chromaticity

- Momentum compaction factor α dependent on energy. This breaks the relationship and for non-colliding bunches changes the measured energy and the average energy by 2E-12.
- BUT for colliding bunches this number is -9E-7 (80keV at the Z)
- We need to measure the chromaticity of α either with some clever MD or by modelling.
- A reasonable assumption is that we will know that to at least 30%

Vertical orbit distortions

- They break the relationship between beam energy and spin precession frequency
- Machine simulations give a typical vertical orbit RMS of 200um
- This leads to a shift in energy of -3keV and an uncertainty of 5keV at the Z.
- For the W the uncertainty is 40keV

Shift and increase of width of spin distribution

- Synchrotron oscillations increase the width of the spin distribution, but the systematic error introduced is negligible
- However, it is possible to get a shift of an (artificially excited) spin resonance due to a nearby natural spin resonance
- It is stated in the LEP paper that the effect is smaller than 90keV.
- it has mainly a statistical component depending on if the excited spin resonance is on the right or on the left of the natural resonance.
- I will have to assume that most of this error contribution would reduce with the square root of the number of measurements (why should we always approach a resonance from the same side?) (to be worked on!)
- My assumption (this error is not included in the paper): ~9keV systematic error, uncorrelated between energy points

Going from average energy to IP energy: RF

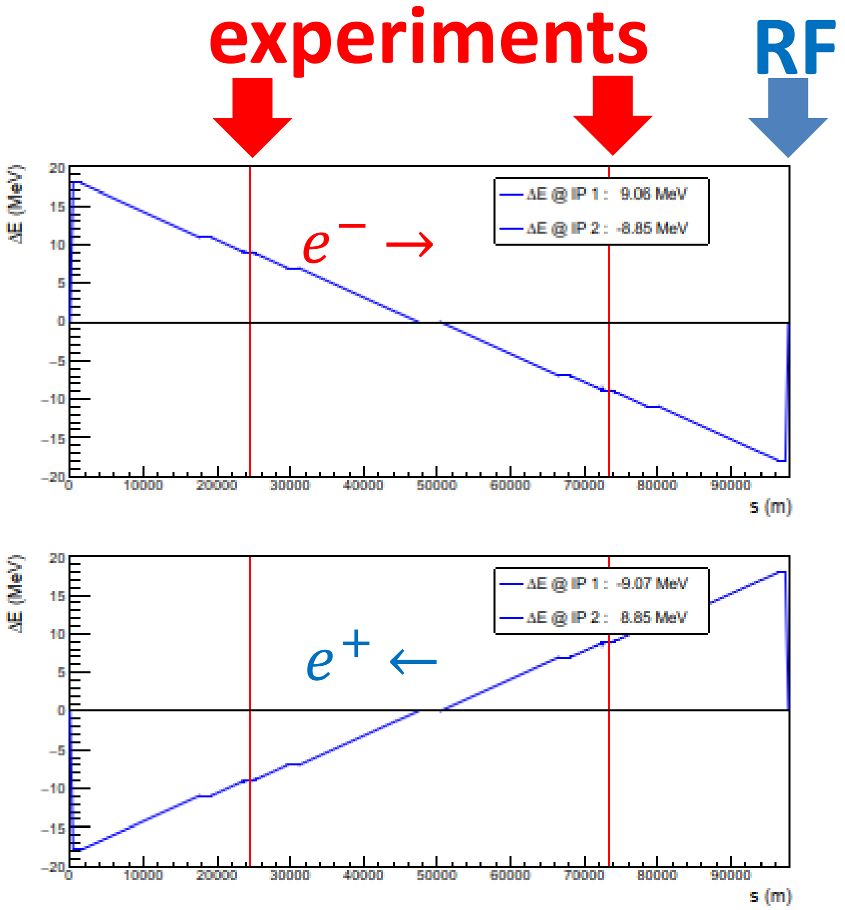


Fig. 41: Energy sawtooth at the Z pole for the two beams with a single RF station per beam in the same location (top: beam direction left to right, bottom: beam direction right to left), the vertical axis corresponds to the relative energy offset and the horizontal axis to the longitudinal coordinate. The two IPs are indicated by the red vertical lines.

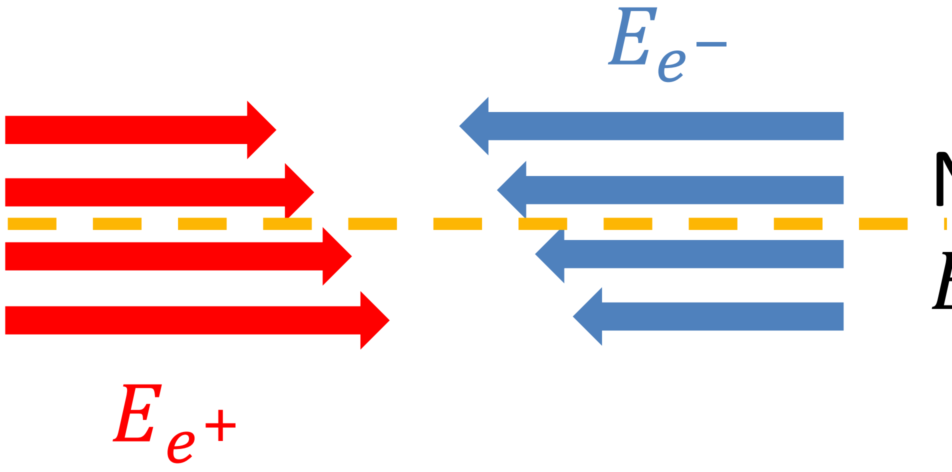
- Depol measurement gives average energy, IP sees local energy
- Distributed energy loss replenished to the RF system (36MeV loss per turn at the Z)
  - We need a model. Typical energy difference between RF and IP is 10MeV. If magnetic field is known to 5E-4, then uncertainty is 10keV
  - Two RF stations: imperfect phasing leads to completely anticorrelated energy shifts in the two experiments.
  - One RF system (left plot): phase automatically adjusts to exactly compensate energy loss. RF configuration errors are thus avoided.
  - The BPM system can be used to monitor energy gain variations. If BPMs are accurate to 3um it is possible to observe relative energy gains of 1e-5. This can be used in controlled experiments to calibrate the effective RF voltage distribution, like at LEP

From average energy to IP energy: impedance

- Due to its large size and high number of accelerator components the longitudinal impedance budget is rather high.
- It is 9MeV per turn for non-colliding bunches and 2-3MeV for colliding bunches (compared to 34MeV due to SR)
- longitudinal impedance budget and the associate power loss is dominated (by about 2/3), by resistive wall.
- The longitudinal power loss can be measured by injecting bunches of different intensities (colliding or non-colliding) and measuring their orbit differences. The intensity or bunch length dependent power loss will induce orbit shifts between the different bunches that can in principle be measured rather accurately as it was done at LEP –to 1%?

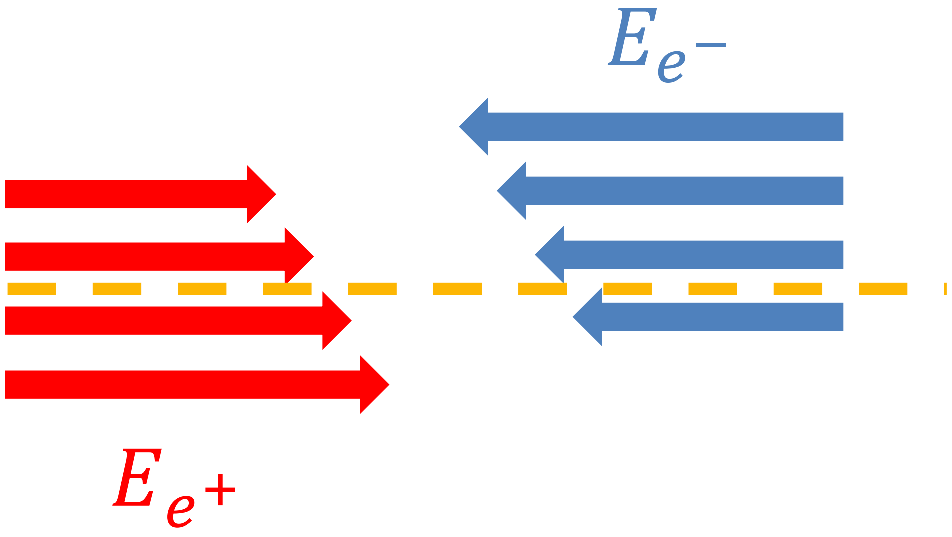
From beams to centre-of-mass: Dispersion (opposite sign) at the IP

Experience from LEP – Vernier scans



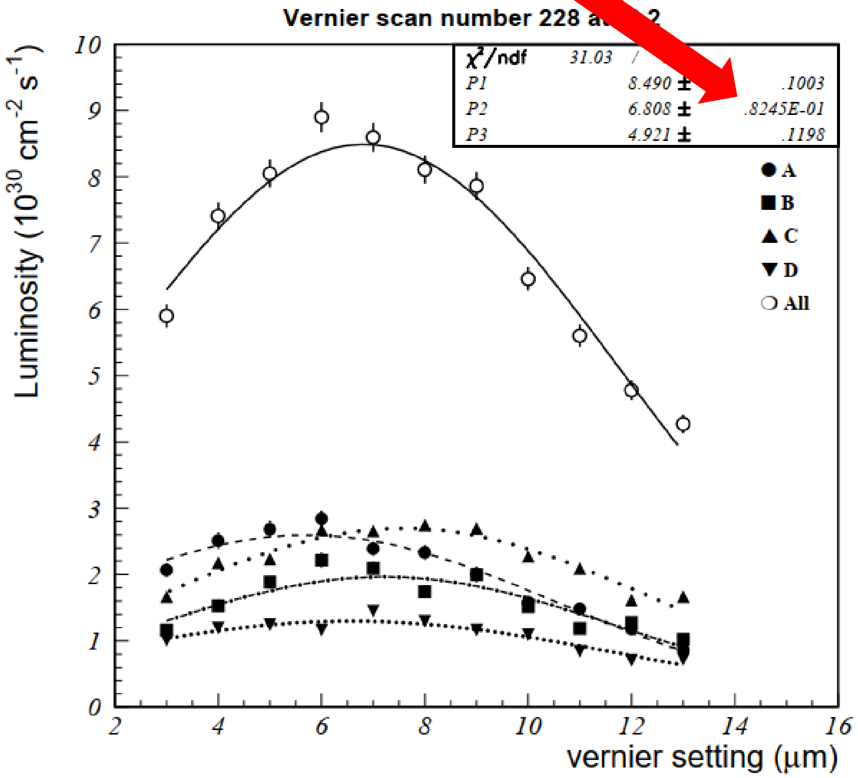
No effect.

$ECM = (E_{e^+} + E_{e^-})$



ECM lower than $(E_{e^+} + E_{e^-})$

Relative position of beams measured to 80 nanometers from one scan



From beams to centre-of-mass: Dispersion at the IP

- Big problem at LEP, but opposite sign vertical dispersion (OSVD) was 2mm. Now OSVD is 10um (the width of the distribution of many simulations); extreme values as large as 30um
- Shift is 960keV per nm of displacement (5% of the width)
- [Horizontal plane Dx=0.2mm max requiring control of beam offsets to 300nm or 5% of horizontal size. This has not been looked at yet – Vernier scans cannot be performed in x]
- Imperative to do Vernier scans! Like at LEP, but cannot go as far off the peaks as at LEP (beams might become unstable).
- Assume each Vernier scan accurate to 1% sigma_y
- We need 4000 vernier scans to get an accuracy of 10keV – a vernier scan every hour. But we might be left with subtle systematic effects!
- There is an alternative to classical Vernier scans: modulate the beam position at a high frequency -- O(100Hz) but small amplitude
- To measure dispersion, need to change RF frequency by 0.1%. For 10um dispersion, this will generate a beam separation of 10nm (half a width), easily measured. Delta D will be known to better than 1um.
- Average dispersion (not only difference) can also be measured by measuring IP position shift
- Another handle: operate at lower beamstrahlung to gain factor 3 in energy spread which gives a factor 10 in the sensitivity to delta_D

From beam energy to ECM: Chromaticity of betatron function

- The chromaticity of β∗ results in different particle densities as a function of the particle energies. As a consequence the luminosity distribution over the CM energy is not symmetric which introduces a bias to the CM energy

Table 11: Beta function chromaticity and corresponding bias of the invariant mass

$\frac{1}{\beta_x}\frac{d\beta_x}{d\delta}$	$\frac{1}{\beta_y}\frac{d\beta_y}{d\delta}$	$\Delta\sqrt{s}$ (keV)	$\frac{\Delta\sqrt{s}}{\sqrt{s}}$
0	15	-49 ± 2.4	$-1.1 \cdot 10^{-6} \pm 5 \cdot 10^{-8}$
200	0	-26 ± 2.4	$-5.7 \cdot 10^{-7} \pm 5 \cdot 10^{-8}$
200	15	-75 ± 2.4	$-1.6 \cdot 10^{-6} \pm 5 \cdot 10^{-8}$

Significant shifts but only 2.4keV error

Collective effects of bunches

- Part of the energy of the electrons is trapped in the potential energy of a bunch
- Effect is estimated to be 1E-5
- To what level will this be known to?
- This effect is still under investigation
- It is bunch intensity dependent

Differences between colliding and non-colliding bunches: Effects from interaction with opposite beam

- Dmitry’s talk
- Beamstrahlung actually makes no difference: average energy loss due to beamstrahlung is 310keV on average at the Z but it is exactly compensated by the RF (the bunch is displaced in the RF by about 1mm)
- Second order effects are investigated
- Energy kick induced by the crossing angle: Effect is 60keV at the Z but the energy kick can be measured by measuring the crossing angle.
- Can be measured with muons at different bunch intensities (Patrick’s talk).

Determination of energy spread

- Cannot use the same technique as LEP (which was to measure the physical length of the interaction region) due to crab waist operation
- But we do have 1E6 di-muon events every 5 minutes!
- Dimuons can measure with excuisite presision and per IP relative changes in:
  - Energy spread
  - Angle of beams
  - Energy of electrons minus energy of positrons

Error table (Z running)

Very preliminary

source	type	Size of correction (keV)	Error on correction-absolute	Error on correction – point to point	comment
Electron mass			7	0	Slide 7
model	statistical	1000	1	0.7	Slide 18
measurement	statistical	200	2	1.4	Slide 78
solenoids	ν formula deviation	0.7	-	-	Slide 20
α chromaticity	ν formula deviation	80	<25	2.5 (?)	Slide 21
Vertical orbit	ν formula deviation	-3	5	3 (?)	Slide 22
Spin shift	ν formula deviation	90	9	6	Slide 23
RF	Average to IP	10000	-	-	Slide 24
impedance	Average to IP	3000	30	-	Slide 25
dispersion	Beam to ECM	960	10	6	Slide 27
β* chromaticity	Beam to ECM	75	2.4	1.7	Slide 28
Energy kick	Colliding → non-colliding	60	dimuons	dimuons	Slide 30
Energy spread		100	dimuons	dimuons	Slide 31

Final words: the power of numbers

- FCC-ee will produce a lot of Z particles!
- We can/should split our dataset to ~10 to 100 subsets and test that there are no undocumented systematics
- This should be a powerful method and help us gain confidence at our results

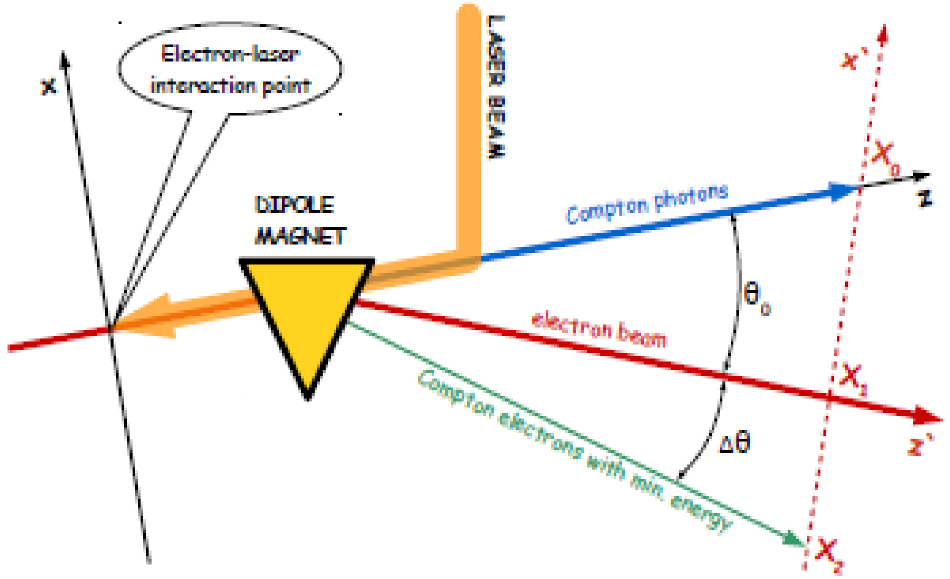
Conclusions

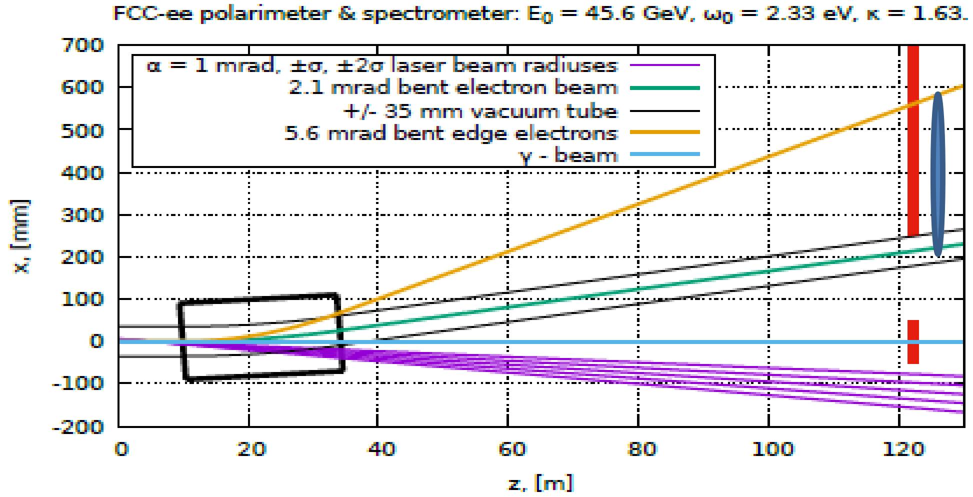
- Measuring the E_{CM} energy at FCC-ee is mind-bogglingly complex but can be done
- Extremely rewarding
- The aim is to achieve 100keV error at the Z mass and 40keV for the Z width.
- I am convinced we can do better than that.
- Many theses to be written on this subject!

THANK YOU

Extra slides

Polarimeter





electron ellipic spot

photon spot

Fig. 27: Sketch of the polarimeter with the lattice dipole (L = 24.12 m, θ_0 = 2.13 mrad, B = 0.0135 T, R_0 = 11302 m), the vacuum chamber and the particle trajectories. Red vertical bars on the right side indicate the location of the scattered particles detectors 100 m away from the center of the dipole.

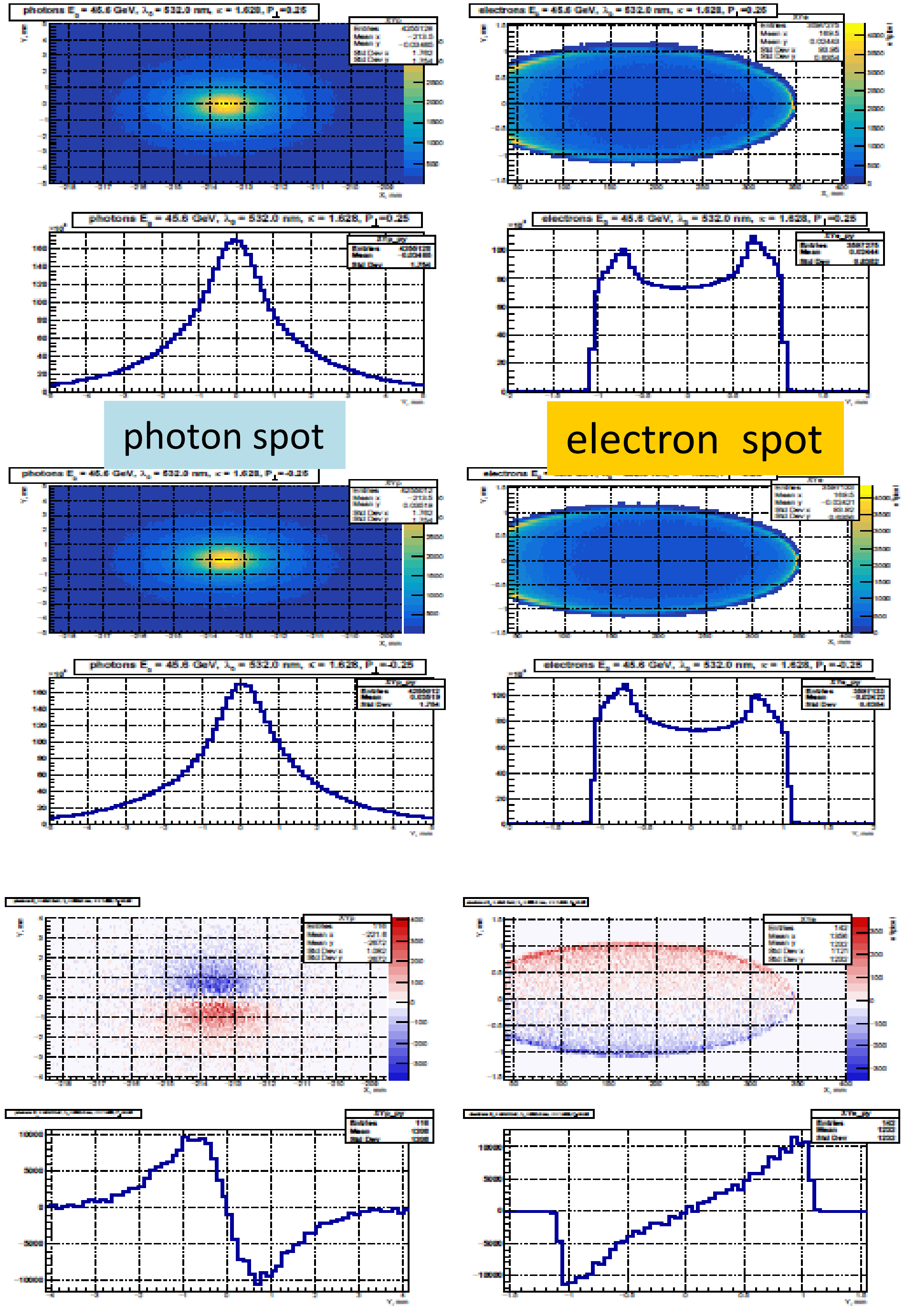


Fig. 30: The difference between corresponding distributions in Fig. 28 and Fig. 29.

for 10^{10} e/bunch

5.3.12 *Polarimeter Summary*

A e+e- polarimeter based on inverse Compton scattering with simultaneous detection of the scattered e+/e- and of the Compton photons provides a powerful and redundant way to measure the transverse polarization with an accuracy of 1% every second. The suggested apparatus will be able to measure in addition the beam energy, the longitudinal polarization and the beam size at the location of the laser-beam interaction.

The statistical accuracy of direct beam energy determination from the e+/e- distribution is at the level of $\Delta E/E < 100$ ppm within a 10 s measurement time. Sources of systematic errors however require additional studies.

Once the resonant depolarization (RDP) is performed regularly, frequent cross-calibrations of the spectrometer can be made by comparison with the RDP result; this, combined with the measurements of energy differences between e+ and e- at the interaction points would provide

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for a beam polarization of 5% and complete depolarization , 10 s measurement before and after the depolarization sweep is more than enough to see the depolarization even with 10^9 electrons per bunch.

How do we measure vertical dispersion at the IP?

- Use BPMs at the high beta points on both sides of the IP
- If we assume a resolution of 1 um, then the resolution on the dispersion is 1um/(dp/p)
- (dp/p) (achieved through change of RF frequency) cannot be more than 1% to avoid non-linearities leading to a resolution of 100um on both sides of the IP
- The dispersion at the IP is the sum of the dispersions on both sides of the IP, which have opposite signs as they are about 180 degrees apart.
- Thus the dispersion at the IP is the subtraction of two big numbers, so relative cross calibration of the two BPMs is also important
- More work is needed here. The required resolution (around 5um) is not yet there.

K. Oide