Beam Polarization and E_{CM} Calibration at FCC-ee

The FCC-ee Energy and Polarization Working Group

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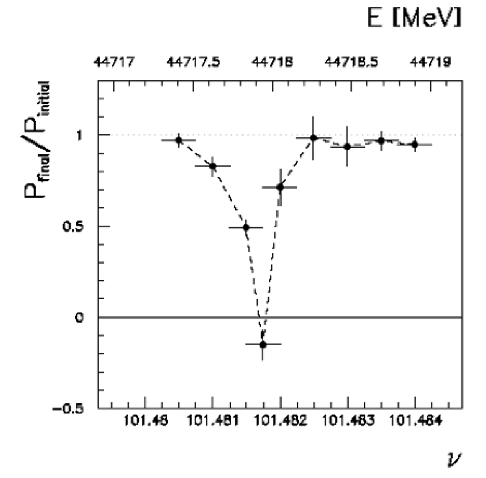
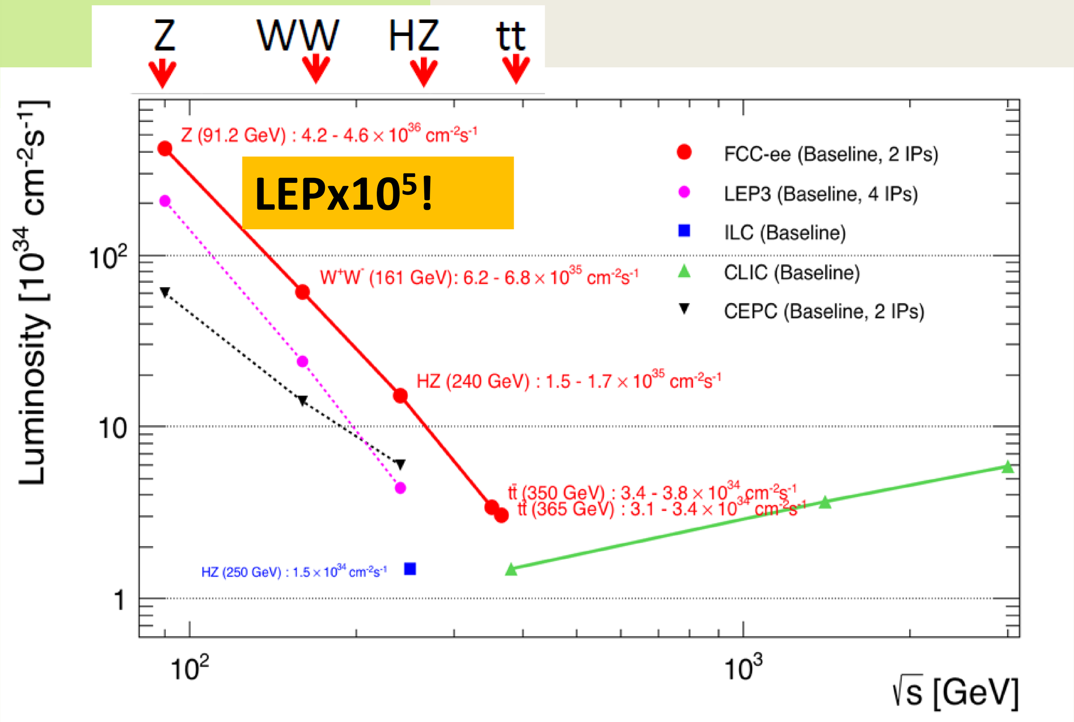


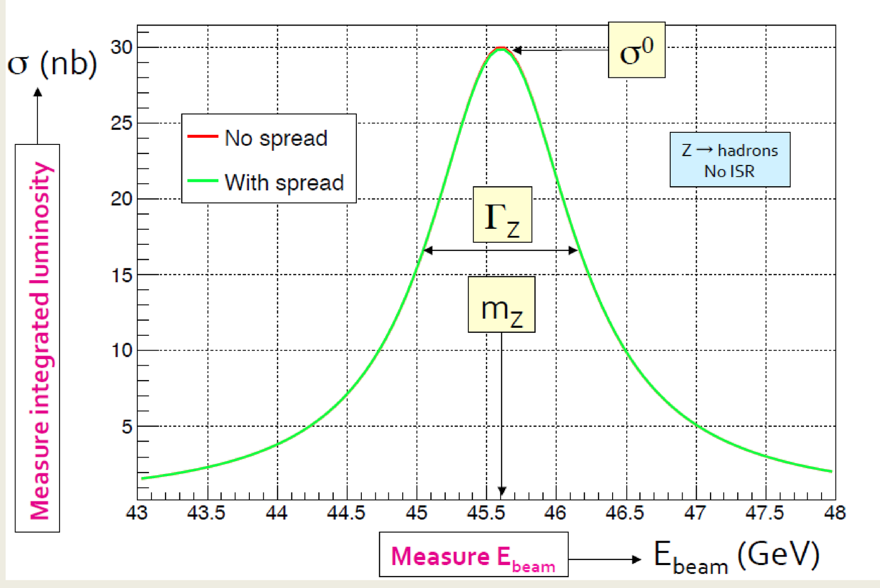
Electroweak Factory

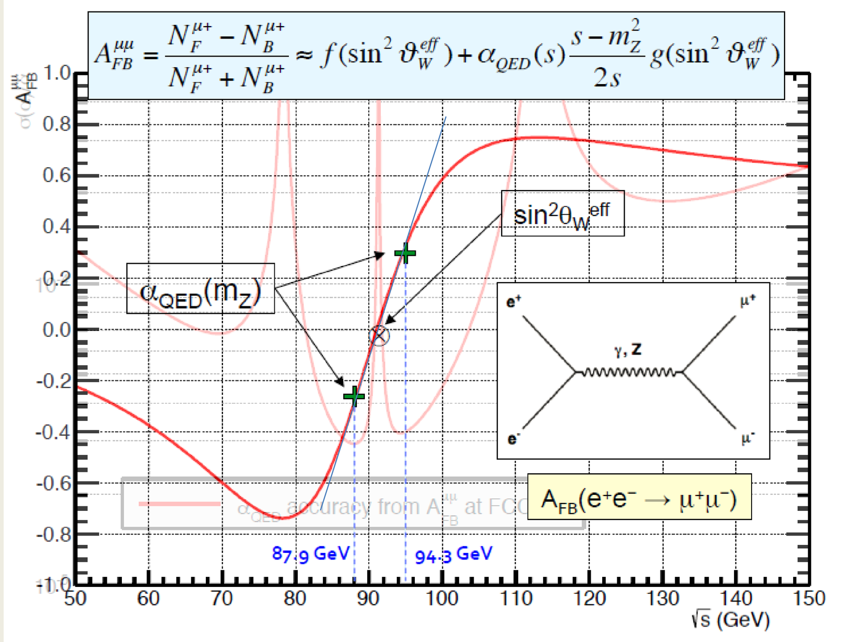


$5\ 10^{12}$ Z
$3\ 10^{8}$ WW
10^{6} ZH
10^{6} t t

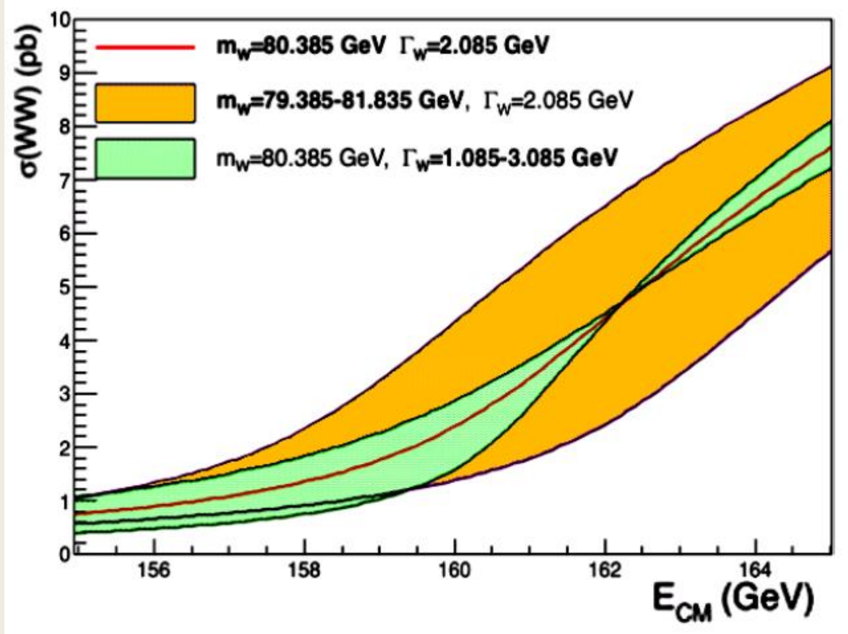
FCC-ee will produce huge statistics of Z and Ws and millions of Higgs and tops.
This is an opportunity to perform extremely precise measurements of many electroweak observables, such as mass and width of the Z, Z pole asymmetries, the W, & top quark masses, and Higgs mass and width. These quantities are **sensitive to new physics up to 10-100 TeV** (decoupling) or possibly much more (non decoupling).
This also enables to perform e+e- → H s-channel production measure the electron Yukawa couling.

This requires high luminosity and an extremely precise knowledge of the beam energy, UNIQUE TO THE MODERN CIRCULAR e+ e- and COLLIDERS





Physics priorities scan points



Scans using the half integer spin tunes can be used.
for Z line shape ν= 99.5, 103.5, 106.5/107.5
and W W threshold ν= 178.5, 184.5
In order to avoid extrapolation errors, a set of 200 'pilot' bunches – having no colliding counterpart -- will be stored at the beginning of fills with polarization wigglers ON, for about 1.5 hour to develop about 5-10% transverse polarization, then, after a first energy calibration is performed, the full luminosity run will comprise regular calibrations (1/10 min) on the pilot bunches.

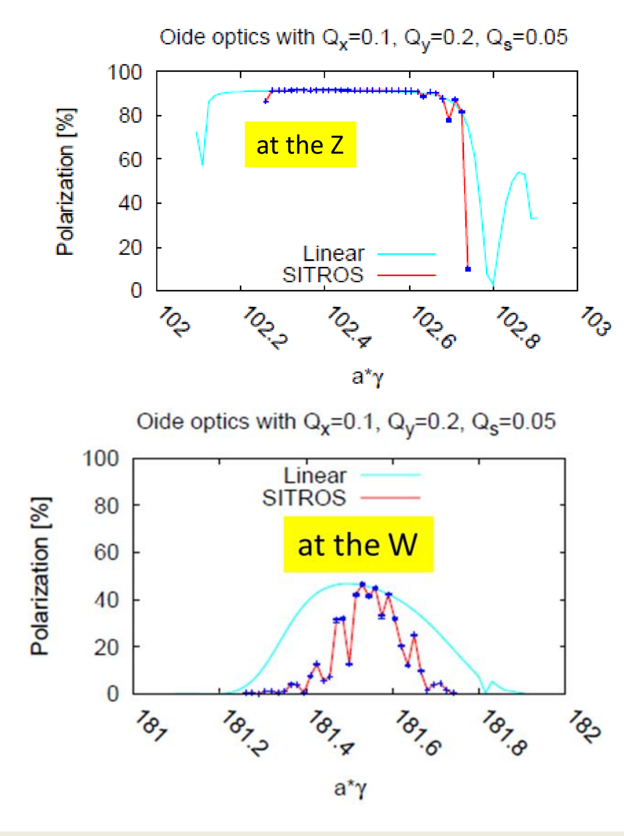
Goal precisions; uncertainties on
m_Z , Γ_Z : ±100 keV , m_W : ±300 keV – or better.

Beam Energy measurement by Resonant depolarization

This is a well known method, which has been used to measure particle masses such as the J/ψ à Novosibirsk, the τ mass at IHEP Beijing, the ϒ mass at Doris (DESY), the Z mass at LEP. It requires transverse polarization of the beams

Beam polarization

In FCC-ee the e+ and e- beams polarize naturally along the magnetic field by Sokolov-Ternov effect. Excellent levels of asymptotic polarization are expected in FCC-ee at the Z, and sufficient at the W.

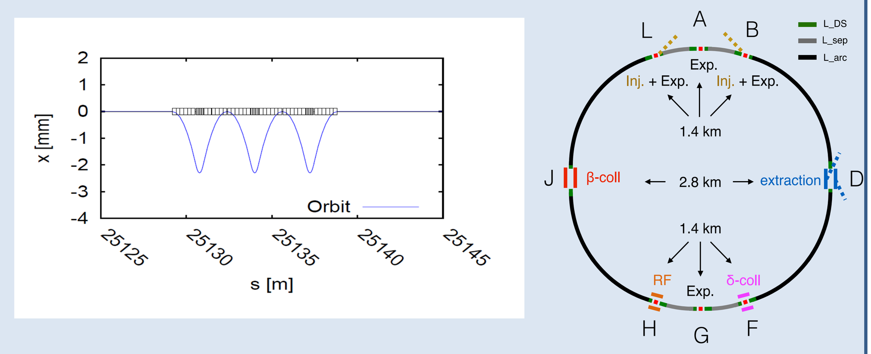


Polarization Wigglers

The polarization time at the Z is slow, (250 hrs)

$$\tau_p = \left(\frac{5\sqrt{3}}{8}\frac{\hbar r_e E_{beam}{}^5}{m_e^6 \rho^3}\right)^{-1}$$

It can reduced using asymmetric **Polarization wigglers** placed in dispersion-free regions (H,F)



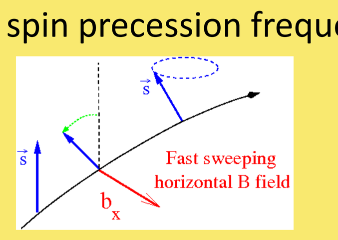
8 such units per beam with

B+=0.7 T L+ = 43cm L-/L+ = B+/B- = 6
at Eb= 45.6 GeV and B+= 0.67 T (E_{crit}=902 keV)

will provide a polarization level of P=10% in 1.8H while increasing the energy spread within a reasonable value of σ_{Eb} = 60 MeV

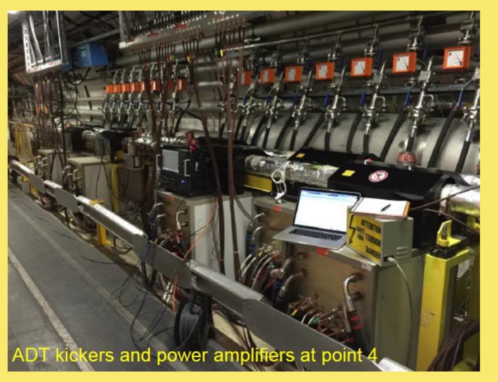
Resonant depolarization

A visible depolarization can be realized with a transverse kicker excited at a frequency in resonance with the spin precession frequency a.k.a. spin tune ν



$$\nu = a_e\gamma = \frac{g_e - 2}{2}\frac{E_{Beam}}{m_e c^2} = \frac{E_{Beam}}{0.4406486(1)}$$

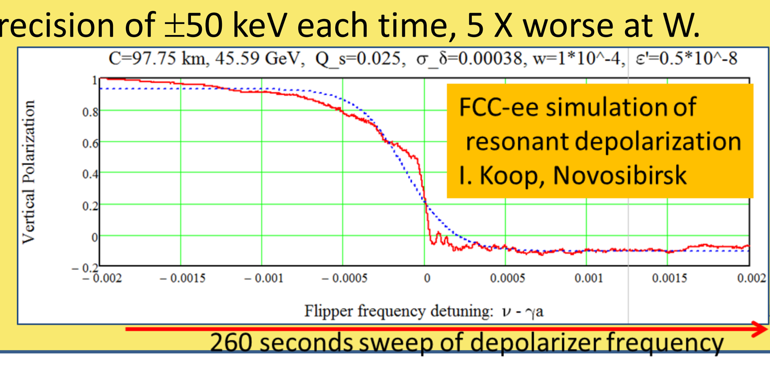
The spin tune is proportional to the beam energy



The bunch crossing rate at the Z is 1/10ns.

The LHC TF system works essentially on a bunch by bunch basis for 25ns. They would provide a transverse kick of up to ~20 mrad at the Z peak with ~10 MHz bandwidth. This is 10x more than what we may need-
→ a priori OK !

The well known plot shown in banner of this poster shows the location of the resonance at LEP (in that case ±100keV) The process has been simulated by I. Koop for FCC-Z with a precision of ±50 keV each time, 5 X worse at W.



Beam energy uncertainties

Absolute: The proportionality between spin tune and beam energy is rigourously true only if the ring is perfectly planar. A certain number of effects resulting from imperfections in the ring can affect this relation and bias the beam energy calibration. Other effects such as opposite sign dispersion at the IRs also need to be considered.

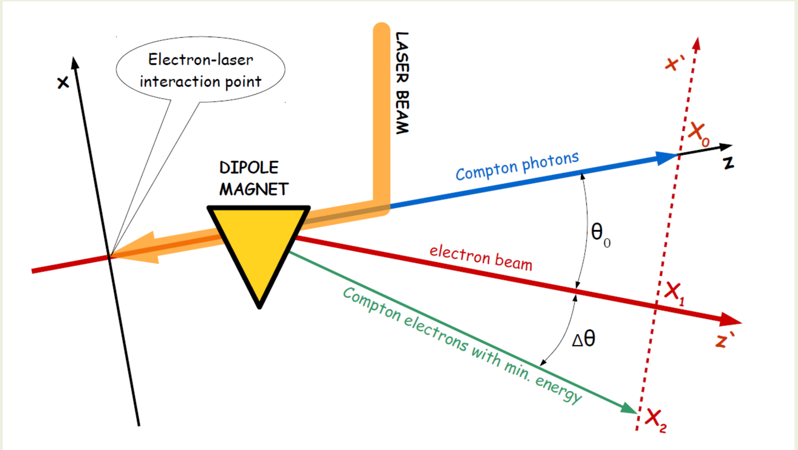
Source	$\Delta\sqrt{s}/\sqrt{s}$ (10^{-6})	RDP	$\delta\sqrt{s}/\sqrt{s}$ (10^{-6})	Error control
Dipole field drifts	100	Y		Tunnel T, PC control
Circumference drifts	2000	Y		Radial feedback
Hor. orbit distortions	100	Y		Orbit feedback
Sextupoles, β-tron oscil.	3	Y		Orbit feedback, machine model
Energy dependence of χ	2	N	< 0.2	Machine model
Vert. orbit distortions	0.3	N	0.3	Orbit control, alignment
Longitudinal fields	1	N	< 0.3	Magnetic model
SR losses	200	N	0.2	Magnetic model, one RF station
Collective effects	100	N	0.2	Machine model
IP dispersion (vertical)	100	N	1	Beam overlap, D^* measurement
IP dispersion (horizontal)	100	N	NE	Beam overlap
β^* chromaticity	1-5	N	NE	Machine model, Beam-beam
Collective field	10	N		Real?
Crossing angle		N		Muon measurements

A summary of possible uncertainties on E_{CM}.

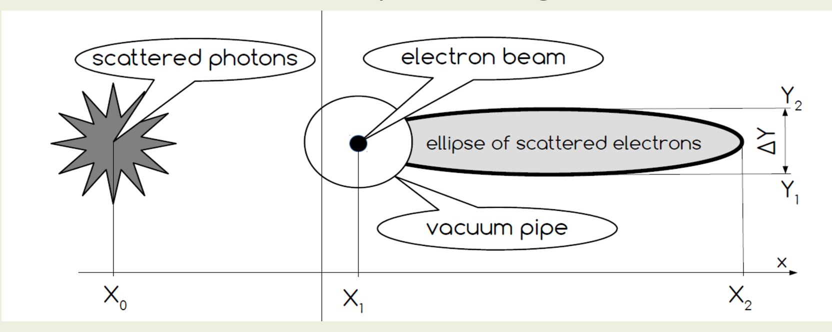
Point-to-point (ptp) :The Z width, and the A_{FB} depend on relative uncertainties between the scan points. When considering only errors that can be different between scan points a relative error of ~±20keV at the Z is inferred. Experimental verification either with the polarimeter-spectrometer or using muon pairs can be made at **±40 keV** on a daily basis.

Polarization measurement

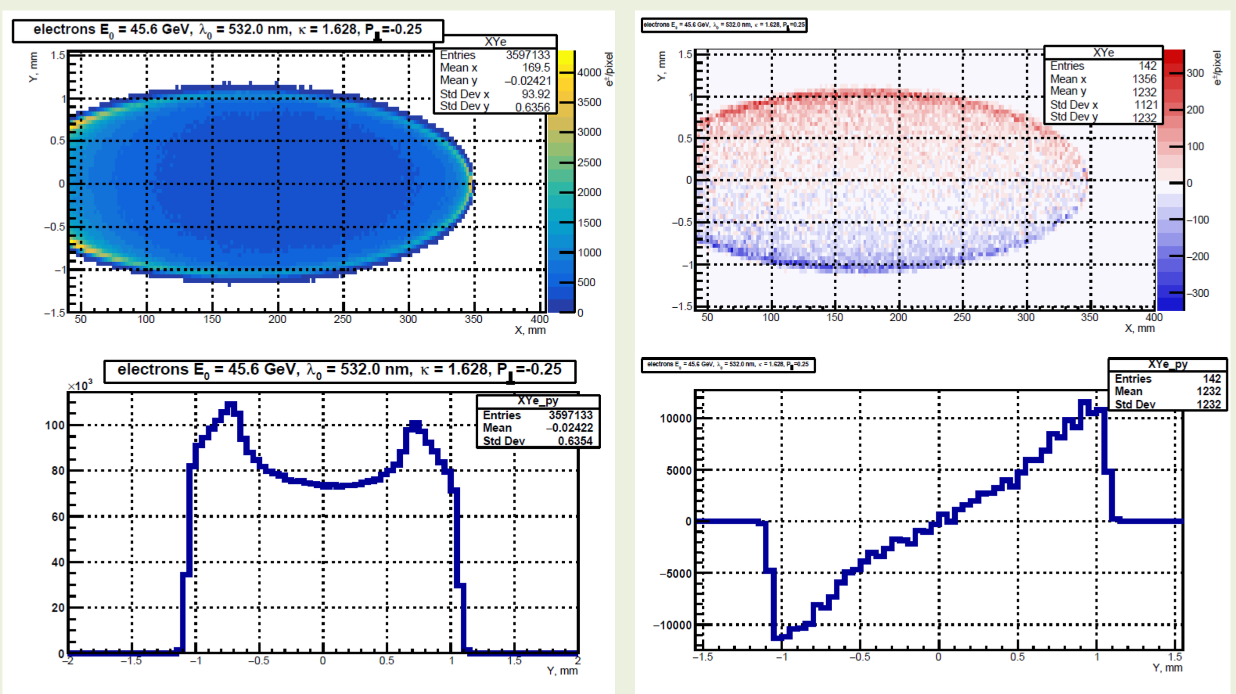
The electron or positron beam polarization can be measured with a compton backscattering polarimeter. This technique was already used at LEP, where only the backscattered photons were detected. The FCC-ee polarimeter, designed by Muchnoy, proposes to make use also of the recoil electron to increase the sensitivity.



There will be two polarimeters, for e+ and e-, using the dispersion suppressor magnet, as the beam enters points H and F on the locally outer ring.



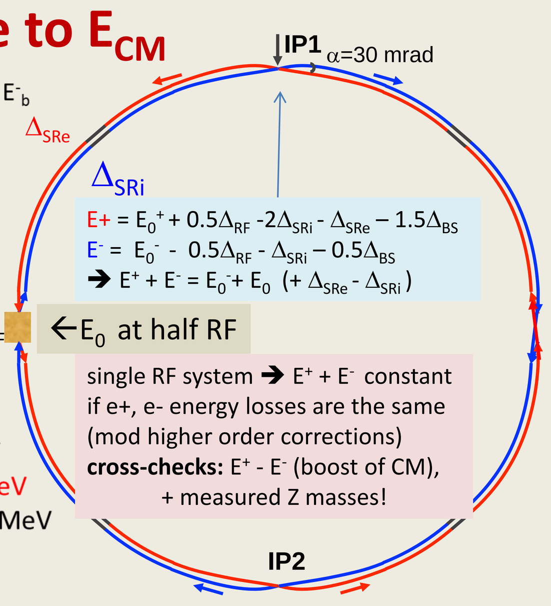
The polarimeter is sketched above. The e-γ IP is situated upstream of a ring magnet with suitable optics, so that the backscattered photon beam is centered on X_o, in the direction of the original beam, while the recoiling electrons are defelected by the magnet and measured between X_1 (the unscattered beam) and X_2 (for the slowest electrons). For a 45 GeV beam and a distance of the detection plane of 100m from the e-γ IP, $X_2 - X_o$ = 638 mm. The end point moves by 2.4 microns for a variation of energy of 10^{-5}. **The polarimeter thus acts as a spectrometer, capable of constantly monitoring the beam energy with a sensitivity of a few 10^{-5} every second.**



The measurement of polarization will be made, as in LEP, by observing changes in the recoil electron and photons, upon reversing the circular polarization of the incoming laser beam. The beam spot of the photon beam will move by about ± ***P** x1.4 mm* at a distance of100 m. If the polarization is small this movement can be mistaken with a movement of the beam. The change for the electron recoil is more distinctive: the change in the relative population of the outer ring of the electron recoil spot is unmistakable.
The beam (transverse or longitudinal) polarization can be measured with a precision of ±1% every second.

From spin tune to E_{CM}

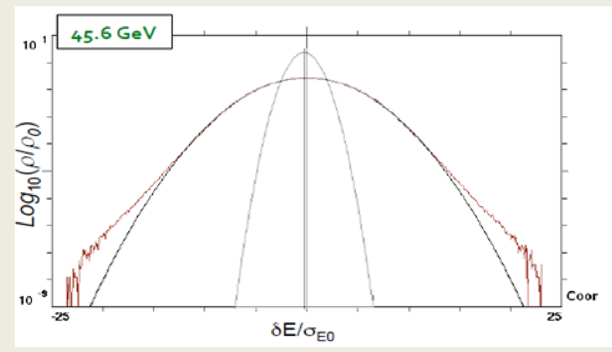
$\sqrt{s} = 2\sqrt{E_b^+ E_b^-}\cos\alpha/2$, $\approx E^+_b + E^-_b$



$\Delta_{RF} = 2\Delta_{SRi} + 2\Delta_{SRe} + 2\Delta_{BS}$

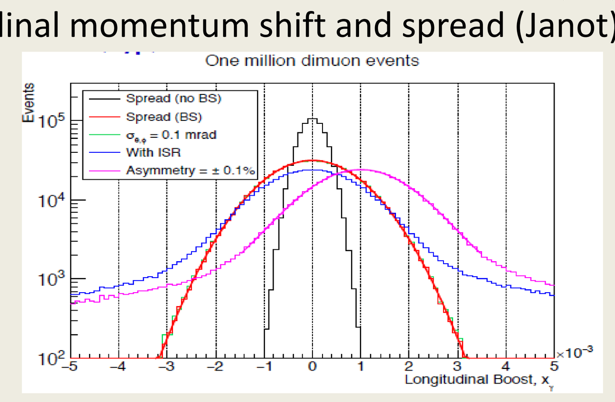
at the Z (O of mag.):
$\Delta_{SR} = 2\Delta_{SRi} + 2\Delta_{SRe}$ =36 MeV
$\Delta_{SRe} - \Delta_{SRi} \approx \alpha/2\pi\ \Delta_{SR}$ = 0.17 MeV
Δ_{BS} = 0 up to 0.62 MeV

energy E_0 around ring is determined by magnetic fields
➔*same for colliding or non-colliding beams*
-- measured by resonant depolarization
-- *can be different for e^+ and e^-*



Beam energy spectrum without/with beamstrahlung

-- layout of accelerator with one RF station
➔ 0.5 ($E_{CM}{}^A$ + $E_{CM}{}^G$) = ($E_b{}^+$ +$E_b{}^-$) cos($\alpha_{crossing}$ /2)
-- $E_b{}^+$ vs $E_b{}^-$ asymmetries and energy spread can be measured/monitored in expt, using e+e- → μ+ μ- events longitudinal momentum shift and spread (Janot)



In 5 min at the Z the energy spread and ($E_b{}^+$ - $E_b{}^-$) can be measured to ± 40 keV.

Opposite sign dispersion

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

Since the two beams circulate in two independent rings it is unavoidable that there will be a residual opposite sign dispersion in both x and y planes. This can bias the center-of-mass energy, by up to 4 MeV. This requires beam collision scans every hour to reduce the total error to <40 keV. It is expected to be largely correlated between the scan points .

RESULTS and CONCLUSIONS

The impact on the energy calibration systematics on the key line shape measurements are as follows.

Quantity (unit)	stat. error	ΔE_{CM} (abs) 100 keV	ΔE_{CM} (ptp) 40 keV	Energy spread 50 keV
m_Z (keV)	**4**	100	28	--
Γ_Z (keV)	**4**	2.5	22	10
$\sin^2\theta_W{}^{eff}$ from $A_{FB}{}^{\mu\mu}$	**$2\ 10^{-6}$**	**--**	**$2.4\ 10^{-6}$**	**--**
$\frac{\Delta\alpha_{QED}(mz)}{\alpha_{QED}(mz)}$	**$3\ 10^{-5}$**	**$0.1\ 10^{-5}$**	**$0.9\ 10^{-5}$**	**$0.05\ 10^{-5}$**

We are well on track to achieve center-of-mass energy calibration systematics at the level of 100 keV (abs.) 40 keV (rel.) at the Z and 300 keV at the W – or better.

There remains much to do:

- -- integration of spin code in optics codes
- -- diagnostics to measure directly beam-beam offsets and local dispersion to control Opp. Sign Vert. Dispersion
- -- improve precision at the W threshold to match 200keV stat.
- -- Wiggler implementation
- -- further reduction of point to point errors
  - -- energy model, logging and diagnostics
  - -- spectrometer stability
  - -- expt magnet and momentum scale stability
- -- automatization and logging of all procedures!

JOIN US!