FCC-ee beam polarization and centre-of-mass energy calibration

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

The FCC-ee Energy and Polarization Working Group:
Alain Blondel,[1,2,3] Patrick Janot,[2] Jörg Wenninger[2] (Editors)
Ralf Aßmann,[4] Sandra Aumon,[2] Paolo Azzurri,[5] Desmond P. Barber,[4]
Michael Benedikt,[2] Anton V. Bogomyagkov,[6] Eliana Gianfelice-Wendt,[7]
Dima El Kerchen,[2] Ivan A. Koop,[6] Mike Koratzinos,[8] Evgeni Levitchev,[6]
Thibaut Lefevre,[2] Attilio Milanese,[2] Nickolai Muchnoi,[6] Sergey A. Nikitin,[6]
Katsunobu Oide,[2] Emmanuel Perez,[2] Robert Rossmanith,[4] David C. Sagan,[9]
Roberto Tenchini,[5] Tobias Tydecks,[2] Dmitry Shatilov,[6] Georgios Voutsinas,[2]
Guy Wilkinson,[10] Frank Zimmermann.[2]

arXiv:1909.12245

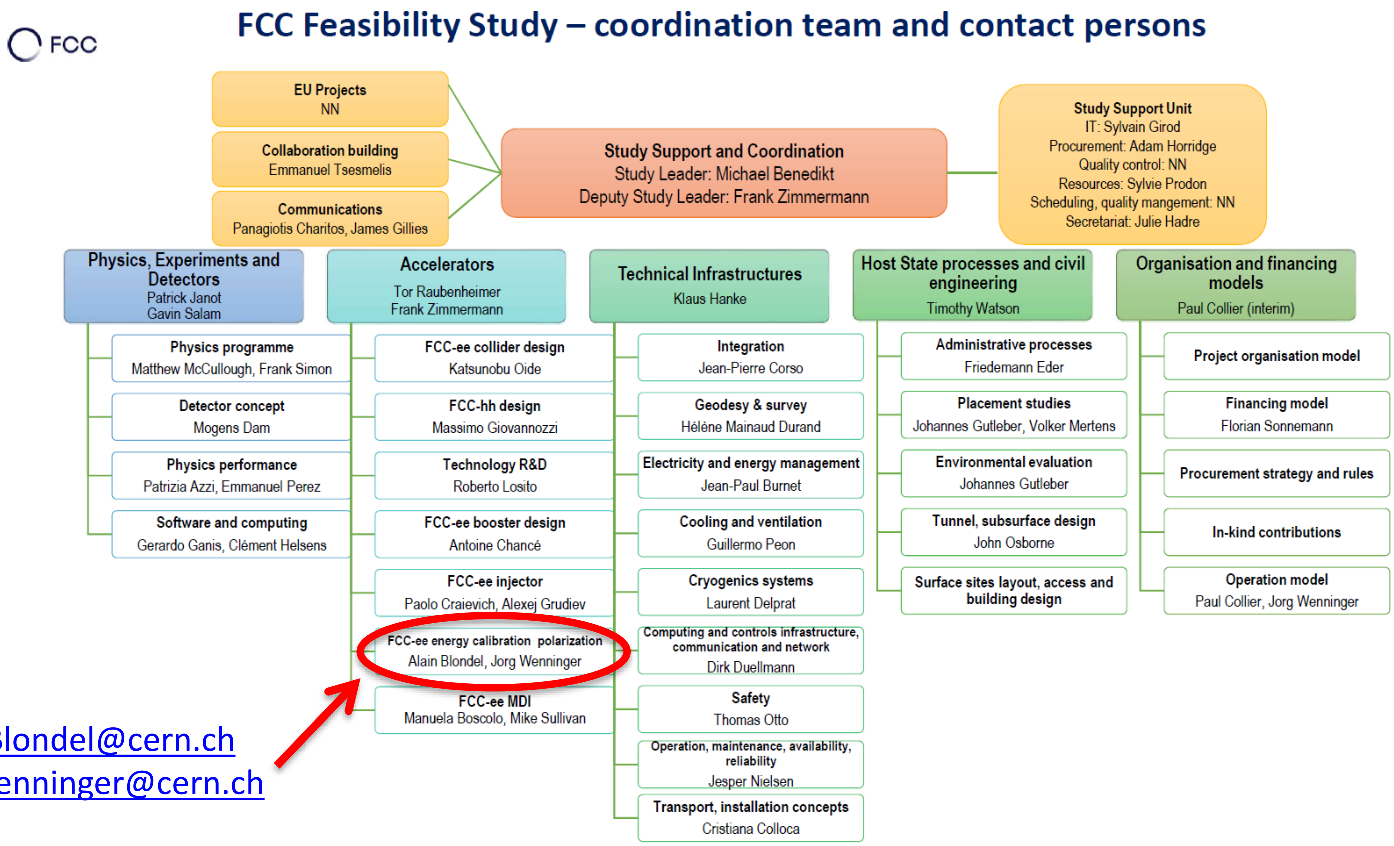
FCC

Some references (not a complete set!):

B. Montague, Phys.Rept. 113 (1984) 1-96;
Polarization at LEP, CERN Yellow Report *88-02;*
Beam Polarization in e+e-, AB, CERN-PPE-93-125 Adv.Ser.Direct.High Energy Phys. 14 (1995) 277-324;
L. Arnaudon et al., Accurate Determination of the LEP Beam Energy by resonant depolarization,
Z. Phys. C 66, 45-62 (1995).
Spin Dynamics in LEP http://dx.doi.org/10.1063/1.1384062
Precision EW Measts on the Z Phys.Rept.427:257-454,2006 arXiv:0509008v3
D.P. Barber and G. Ripken ``Handbook of Accelerator Physics and Engineering” World Scientific (2006), (2013)
D.P. Barber and G. Ripken, Radiative Polarization, Computer Algorithms and Spin Matching in Electron Storage Rings
arXiv:physics/9907034
for FCC-ee:
First look at the physics case of TLEP arXiv:1308.6176, **JHEP 1401 (2014) 164** DOI: 10.1007/JHEP01(2014)164
M. Koratzinos FCC-ee: Energy calibration IPAC'15 arXiv:1506.00933
E. Gianfelice-Wendt: Investigation of beam self-polarization in the FCC-ee arXiv:1705.03003
October 2017 EPOL workshop: https://indico.cern.ch/event/669194/
AB, P. Janot, J. Wenninger et al Polarization & Centre-of-mass Energy Calibration @ FCC-ee **arXiv:1909.12245**
AB, E. Gianfelice **The challenges of beam polarization and keV-scale centre-of-mass energy calibration at the FCC-ee**
https://inspirehep.net/literature/1959346 (new: addresses ee→ H)

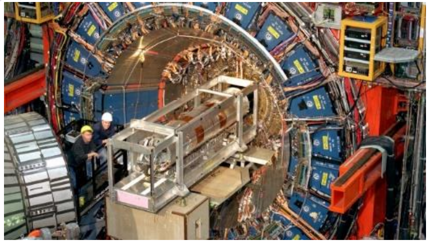
EPOL group indico thread: https://indico.cern.ch/category/8678/

FCC-ee feasibility study



Alain.Blondel@cern.ch
Jorg.wenninger@cern.ch

FCC-ee Energy Calibration and Polarization

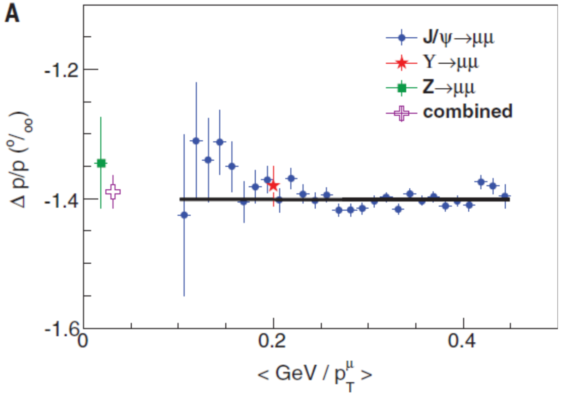


Recent CDF: m_W (MeV)= 80'433.5 $\pm$ 6.4 $_{stat}$ $\pm$ 6.9$_{syst}$ (10^{-4} precision)
-- « could hint at new physics » and surely created a buzz!
-- precision measurements as broad exploration of new physics in quantum corrections, or mixing (SUSY, Heavy neutrinos, etc..)
(-- questions because inconsistent with previous measurements)

CDF measurement is remarkable in two ways:

1. (after 10 years of work)
systematic errors similar to statistical precision

2. relies for the precise calibration on J/ψ, Υ, Z masses
all measured in e+e- colliders...
using resonant depolarization!



Resonant depolarization is the cornerstone of the precision programme of FCC-ee

~40 times more precise than CDF

➔ Improvement by factor 10-1000 on a long list of precision measurements.
e.g. W mass down to ±250 keV, Z mass and width ±4 keV, $\sin^2\theta_W$ ^{eff} ± 2.10^{-6} etc..
➔ explore new physics at 10-100 TeV scale, or 10^{-5} mixing with known particles.

factor 500 more precise than LEP

Methods

based on spin precession frequency measurement

1. **Establish e-, e+ beam polarization on machine in ‘collision mode’**
   -- constraints on machine set-up, energy, (wigglers), corrections etc...
   -- measure beam polarization (polarimeters)
2. **measure spin precession frequency**
   -- resonant depolarization
   -- or/and measure spin precession
3. **relation between spin precession and average beam energy**
4. **relation between average e+e- beam energies and beam energies at IP**
   -- Synchrotron radiation losses
   -- beamstrahlung losses
   -- measurement of center-of-mass energy spread
5. **relation between beam energies and E_{cm}**

Beam Polarization can provide two main ingredients to Physics Measurements

1. **Transverse beam polarization provides beam energy calibration by resonant depolarization**

→ low level of polarization is required (~10% is sufficient)

→ at Z & W pair threshold comes naturally $\sigma_E \propto E^2/\sqrt{\rho}$

→ at Z use of asymmetric wigglers at beginning of fills since polarization time is otherwise very long (250h→ ~1h)

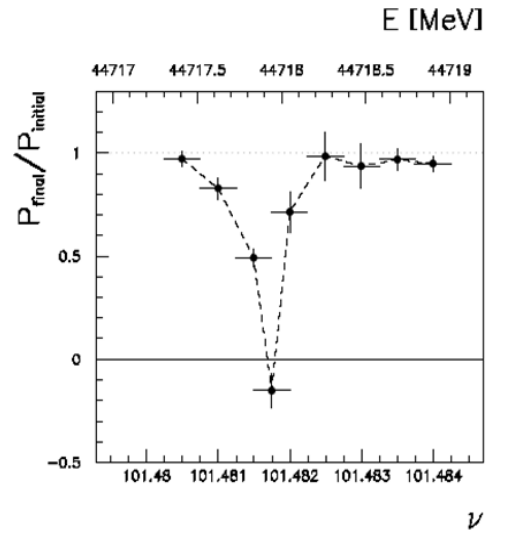
→ should be used also at ee → H(126)

→ use 'single' non-colliding bunches and calibrate continuously during physics fills to avoid issues encountered at LEP

→ Compton polarimeter for both e+ and e-

→ should calibrate at energies corresponding to half-integer spin tune

→ must be complemented by analysis of «average E_beam-to-E_CM» relationship



For beam energies higher than ~90 GeV can use ee → Z γ or ee → WW events to calibrate E_{CM} at ±1-5 MeV level: m_H (5 MeV) and m_{top} (20 MeV) measts

Beam Polarization can provide two main ingredients to Physics Measurements

2. Longitudinal beam polarization provides chiral e+e- system

-- High level of polarization is required (>40%)

-- Must compare with natural e+e- polarization due to chiral co… …trons (15%)
or with final state polarization analysis for CC weak dec… …rized) (tau and top)

-- **Physics case** for Z peak is very well studied and mo…

$A_{LR} = A_e$, $A_{FB}^{Pol}(f)$ etc… (CERN Y.R. 8…

figure of merit is L.P² --> must not los… …factor ~10 in lumi.

self calibrating polarization measu… …es controlled e+ and e- polarization

at high statistics A_{FB}^{Pol} = A … of A_{LR} (Tenchini)

-- enhance Higgs cross se… …o ~30%)

top quark … …al state analysis does as well (Janot **arXiv:1503.01325)**

enha… …btract/monitor backgrounds, for ee→WW , ee →H

-- requir… …ation level and often both e- and e+ polarization

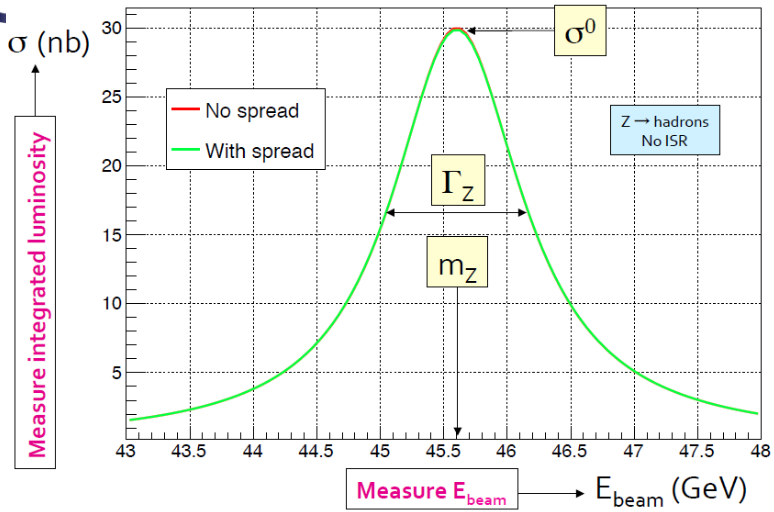
→ … …ing If loss of luminosity is too high

… high level of polarization in high luminosity collisions is delicate in top-up mode

…CIDED to FOCUS ON TRANSERSE POLARIZATION FOR ENERGY CALIBRATION

As far as we could check, there is no physics that can be done with longitudinal polarization that cannot be done without, given enough luminosity

scan points for m_Z and m_W



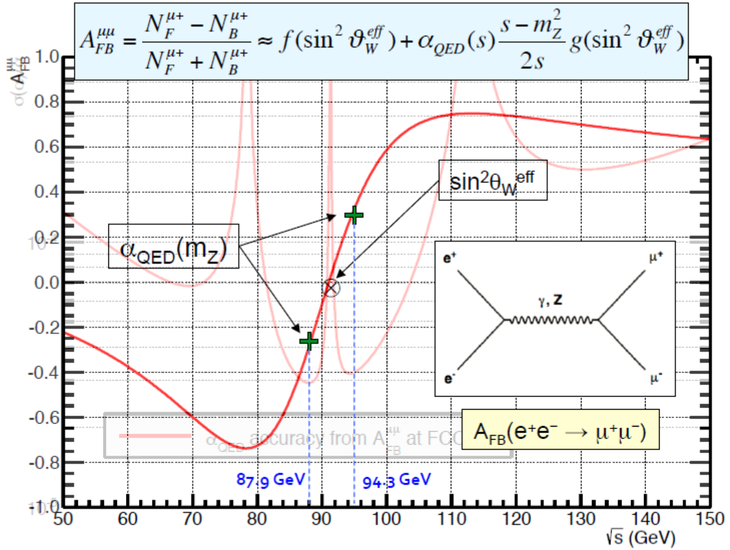
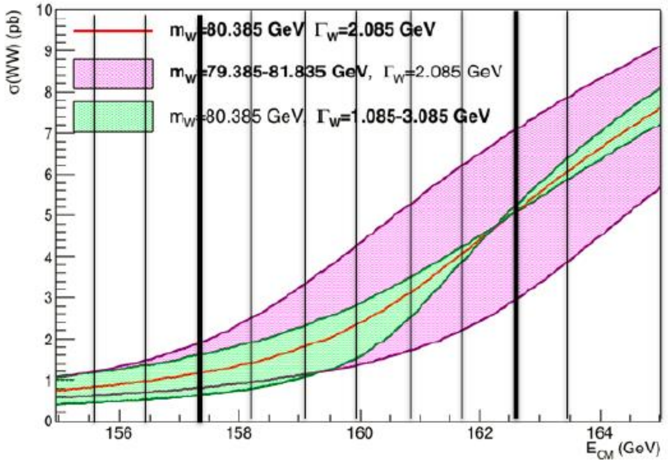


Table 3: Center-of-mass energies for the proposed Z scan. The points noted A and B are half integer spin tune points with energies closest to the requested energies.

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_{CM}^{0}	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 precision at the Z

centre-of-mass energy errors:

$$\frac{\Delta m_Z}{m_Z} = \left\{\frac{\Delta\sqrt{s}}{\sqrt{s}}\right\}_{\rm abs} \oplus \left\{\frac{\Delta(\sqrt{s_+}+\sqrt{s_-})}{\sqrt{s_+}+\sqrt{s_-}}\right\}_{\rm ptp-syst} \oplus_i \left\{\frac{\Delta\sqrt{s^i_\pm}}{\sqrt{s^i_\pm N^i_\pm}}\right\}_{\rm sampling},$$

$$\frac{\Delta\Gamma_Z}{\Gamma_Z} = \left\{\frac{\Delta\sqrt{s}}{\sqrt{s}}\right\}_{\rm abs} \oplus \left\{\frac{\Delta(\sqrt{s_+}-\sqrt{s_-})}{\sqrt{s_+}-\sqrt{s_-}}\right\}_{\rm ptp-syst} \oplus_i \left\{\frac{\Delta\sqrt{s^i_\pm}}{\sqrt{s^i_\pm N^i_\pm}}\right\}_{\rm sampling},$$

$$\Delta A_{\rm FB}^{\mu\mu}({\rm pole}) = \frac{\partial A_{\rm FB}^{\mu\mu}}{\partial\sqrt{s}}\left\{\Delta(\sqrt{s_0}-0.5(\sqrt{s_+}+\sqrt{s_-}))\right\}_{\rm ptp-syst} \oplus_i \frac{\partial A_{\rm FB}^{\mu\mu}}{\partial\sqrt{s}}\left\{\frac{\Delta\sqrt{s^i_{0,\pm}}}{\sqrt{N^i_{0,\pm}}}\right\}_{\rm sampling}, \quad (3.1)$$

$$\frac{\Delta\alpha_{\rm QED}(m_Z^2)}{\alpha_{\rm QED}(m_Z^2)} = \left\{\frac{\Delta\sqrt{s}}{\sqrt{s}}\right\}_{\rm abs} \oplus \left\{\frac{\Delta(\sqrt{s_+}-\sqrt{s_-})}{\sqrt{s_+}-\sqrt{s_-}}\right\}_{\rm ptp-syst} \oplus_i \left\{\frac{\Delta\sqrt{s^i_\pm}}{\sqrt{s^i_\pm N^i_\pm}}\right\}_{\rm sampling},$$

with $\frac{\partial A_{\rm FB}^{\mu\mu}}{\partial\sqrt{s}} \simeq 0.09/{\rm GeV}$.

Three categories:

- **Abs**olute dominate for Z and W mass
- **ptp** Point-to-point dominate for Γ_Z & $A_{FB}^{\mu\mu}$ (peak and off-peak)
- Due to **sampling** – turns out to be negligible for 1meast /(15 min= 1000s) → 10^4 measts

What happens for a typical Z line shape scan

Table 4. Calculated uncertainties on the quantities most affected by the centre-of-mass energy uncertainties, under the initial systematic assumptions.

Observable	statistics	$\Delta\sqrt{s}_{\text{abs}}$ 100 keV	$\Delta\sqrt{s}_{\text{syst-ptp}}$ 100 keV	calib. stats. 200 keV $/\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ 85 $\pm$ 0.5 MeV
m_Z (keV)	4	100	70	1	–
Γ_Z (keV)	4	2.5	55	1	100
$\sin^2\theta_W^{\text{eff}} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	6	0.1	–
$\frac{\Delta\alpha_{QED}(m_Z^2)}{\alpha_{QED}(m_Z^2)} \times 10^5$	3	0.1	2.2	–	1

First set of results obtained in the FCC Design Study:

Polarization and Centre-of-mass Energy Calibration at FCC-ee, arXiv:1909.12245

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	stat/present
m_Z (keV)	**4**	100	**28**	1	–	500
Γ_Z (keV)	**4**	2.5	**22**	1	**10**	400
$sin^2\theta_W^{eff} \times 10^6$ from $A_{FB}^{\mu\mu}$	**2**	–	**2.4**	0.1	–	75
$\frac{\Delta\alpha_{QED}(M_Z)}{\alpha_{QED}(M_Z)} \times 10^5$	**3**	0.1	**0.9**	–	**0.05**	15 (qualitiative!)
m_W(MeV)	**0.250**	-- **0.300** --				40

Next challenges for the feasibility study:

-- Ascertain the above with integrated simulations (simulation of polarization and depolarization on real machine)

-- Match systematic errors with statistics.

most relevant targets : **the point-to-point systematics, improve the WW energy**

– these are effects that would lead to a deviation from relation between

-- the spin tune as measured by resonant depolarization

-- and the center-of-mass energy.

-- examples: 1. interference between depolarizing resonances and the induced depolarizing resonance because the spin tune varies with energy.

2. effects due to collision offsets folded by opposite sign dispersion

-- designevaluate performance and cost the polarimeter at conceptual level

-- finalize implementation in the realistic machine, study operational aspects

Requirements from physics (feasibility study): match statistical precision!

1. Center-of-mass energy determination with precision of <= $\pm$ 4 keV around the Z peak
2. Center-of-mass energy determination with precision of <= 200 keV at W pair threshold
3. For the Z peak-cross-section and width, require energy spread uncertainty $\Delta\sigma_E/\sigma_E$ =0.1%

NB: at 2.3 10^{36}/cm^2/s/IP : **full LEP statistics** 10^6 $\mu\mu$ & 2.10^7 qq in **6 minutes** in each expt

-- use resonant depolarization as main measuring method
-- use pilot bunches to calibrate during physics data taking: 100 calibrations per day each 10^{-6} rel.
-- long lifetime at Z requires the use of wigglers at beginning of fills
➔ take data at points where self polarization is expected

$$\nu_s = \frac{g-2}{2}\frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)} \approx N + (0.5\pm0.1)$$

$$E_{CM} = \left(N + (0.5\pm0.1)\right) \text{ x } 0.8812972 \text{ GeV}$$

Given the Z and W widths of 2 GeV, this is easy to accommodate with little loss of statistics.
It might be more difficult for the Higgs 125.09+-0.2 corresponds to ν_s *= 141.94+-022*

Simulations of self-polarization level with SITROS

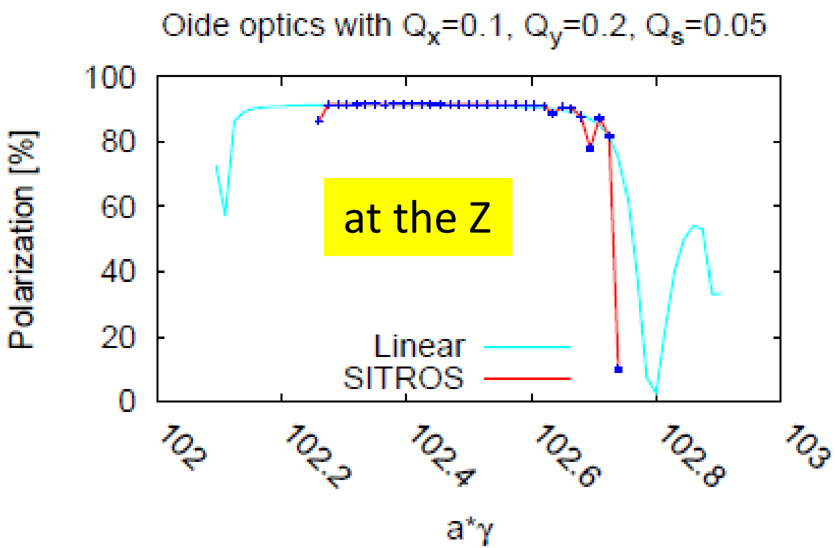
Some results of coupling/dispersion correction

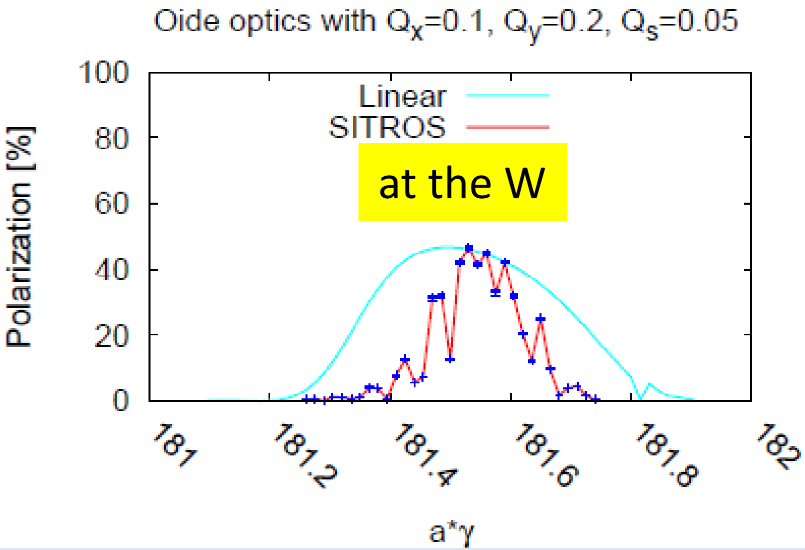
E. Gianfelice

- δy^{Q}_{rms}=200 μm (including doublets)
- 250 μrad quadrupole roll angle (including doublets)
- 1086 BPMs w/o errors
- orbit corrected with 1086 CVs down to y_{rms}=0.05 mm
- coupling/dispersion correction with 289 skew quadrupoles

1. orbit and emittance corrections needed for the FCC-ee luminosity seem sufficient to ensure useful levels of polarization

2. HOWEVER: same simulation does not produce luminosity and polarization,
➔ effect of simultaneous optimization could not be simulated



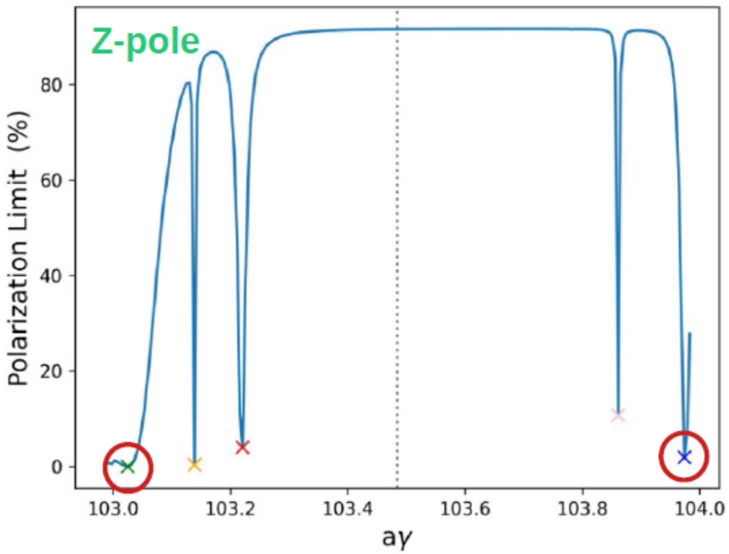


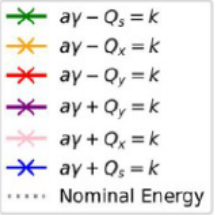
Excellent level of polarization at the Z (even with wigglers) and sufficient at the W $\sigma_E \propto E^2/\rho$

recent progress: Implementation of FCC-ee machine lattice in BMAD
-- Cornell code incl. imprefections luminosity and polarization (+ resonant depolarization)
implementation in MADx in progress (T. Persson, CERN)

- Resonances enhanced with increasing closed orbit
- More misalignments can reduce maximum polarization → orbit corrections essential

$(\Delta y)_{rms}$ = 42.2 μm





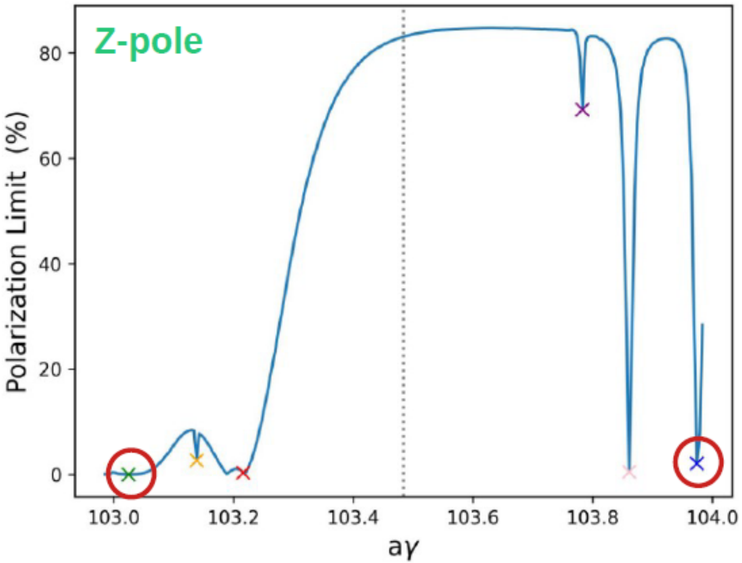
Misalignment errors in Dipoles, quadrupoles Sextupoles

Q_x = .139 Q_y = .219

Q_s = 0.025

Small emittances and large Q_s –> Resonances with the longitudinal plane dominating and symmetric ± Q_s

$(\Delta y)_{rms}$ = 148 μm

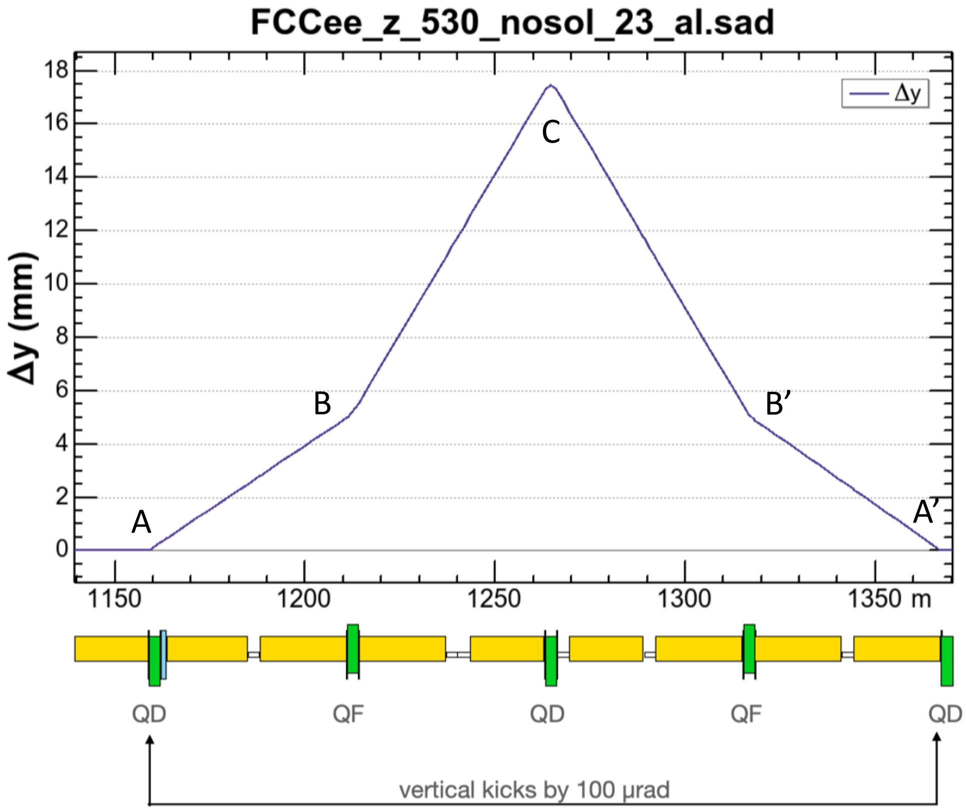


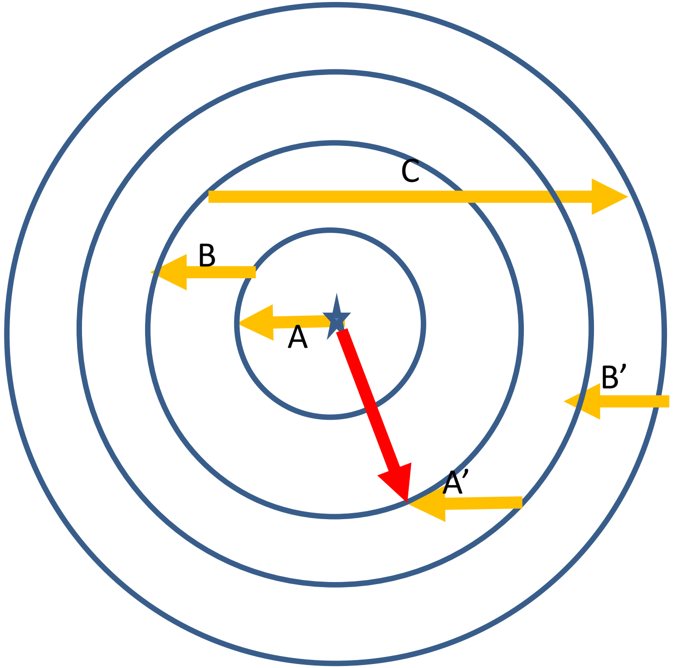
Y. Wu: indico.cern.ch/event/1119730/

FCC

Effect of a pi bump on spin at the Z

'spin knobs'



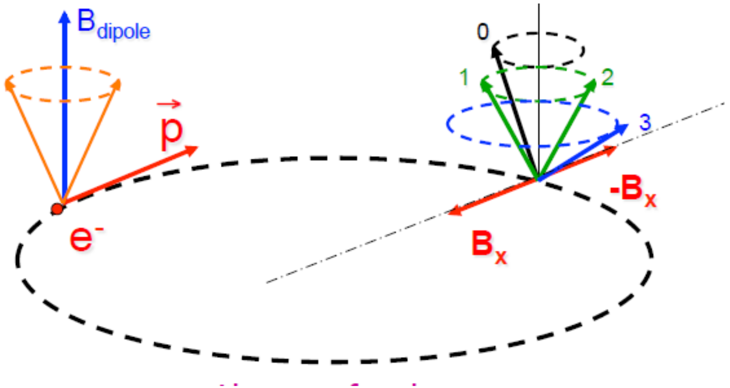


the pi bump generates a spin component rotation of the spin in the x-z direction. The largest rotation is created by the QD quadrupole (focus in vertical plane)

100 microrad orbit kick gets compensated by the pi bump but generates a lasting **25 mrad spin kick**

FCC

RESONANT DEPOLARIZATION



Once the beams are polarized,
an RF kicker at the spin precession frequencv will provoke a spin flip and complete depolarization
Simulation of FCC-ee by I. Kopp:

spin precession (ν is the *spin tune*)

$$\delta\theta_{spin} = (g-2)/2 \ . \ E/m \ \delta\theta_{trajectory}$$
$$= \nu \ . \ \delta\theta_{trajectory}$$
$$\nu = E_{beam} / 0.4406486$$
$$= 103.5 \text{ at the Z peak}$$

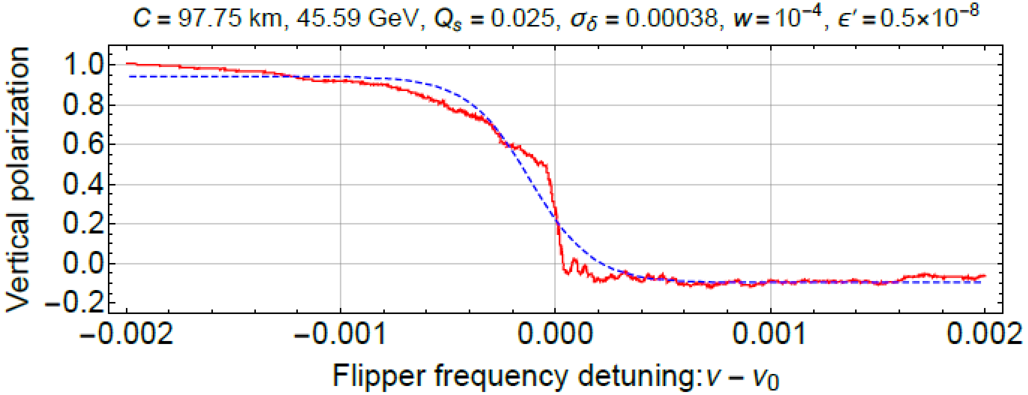
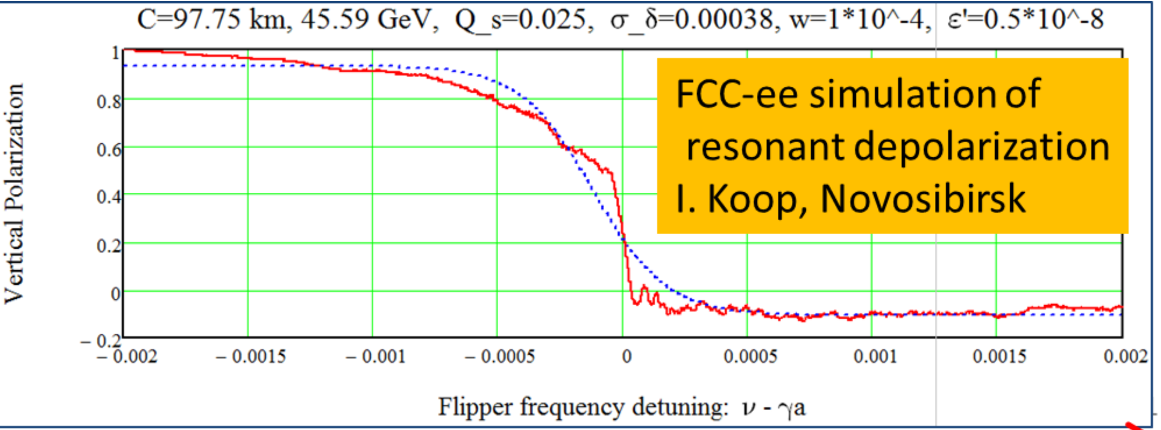
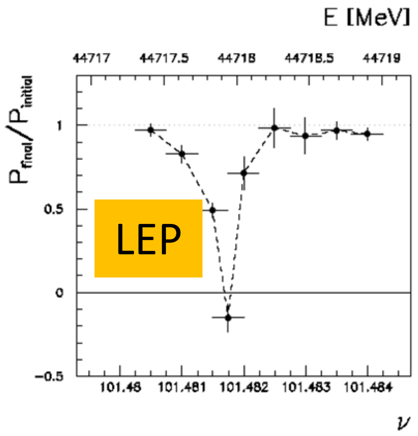


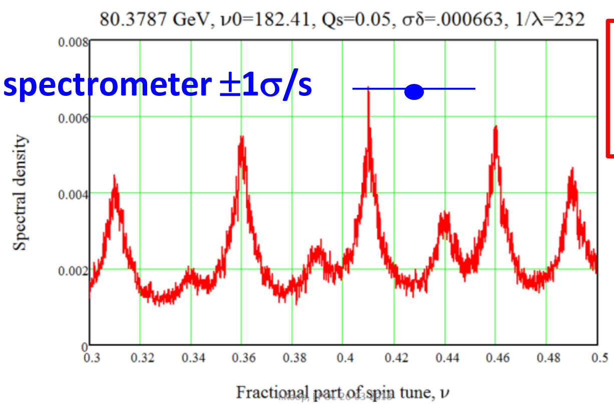
Figure 39. Simulation of a frequency sweep with the depolarizer on the Z pole showing a very sharp depolarization at the exact spin tune value.





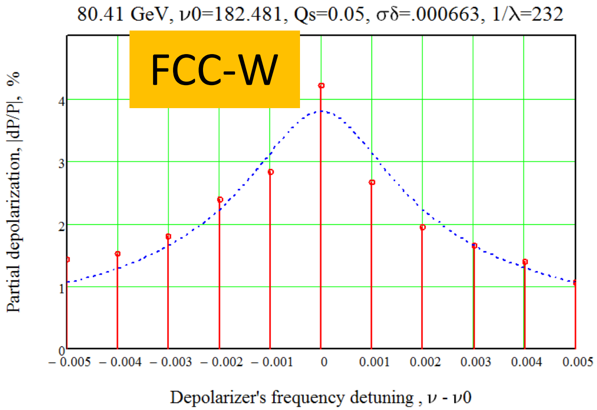
260 seconds sweep of depolarizer frequency

long sweep works well at the Z. Several depolarizations needed: eliminate Qs side band and 0.5 ambiguity
Less well at the W: the Qs side bands are much more excited because of energy spread, need iterations with smaller and smaller sweeps – work in progress. see *I. Koop* presentations at FCC weeks.



← Fourier analysis shows the side band situation at W.

First attempt at 'LEP' multiple sweep technique →



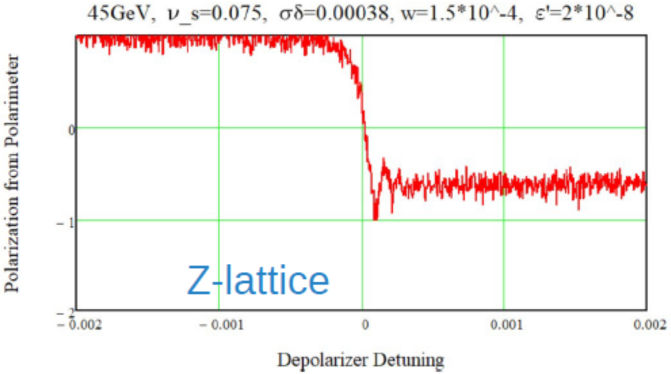
Recent progress: resonant depolarization a the WW threshold (should allow 100 keV or better Ecm calibbration)

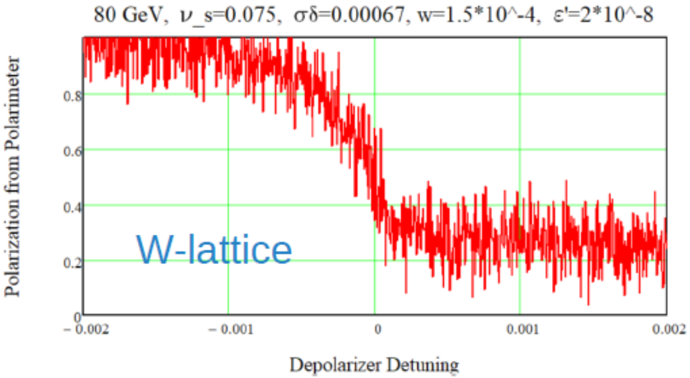
Depolarization Process

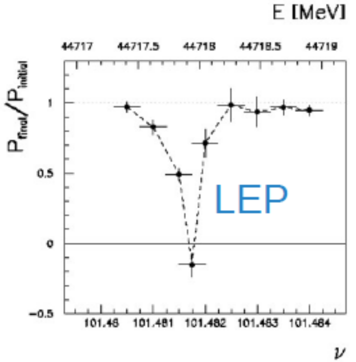
I. Koop

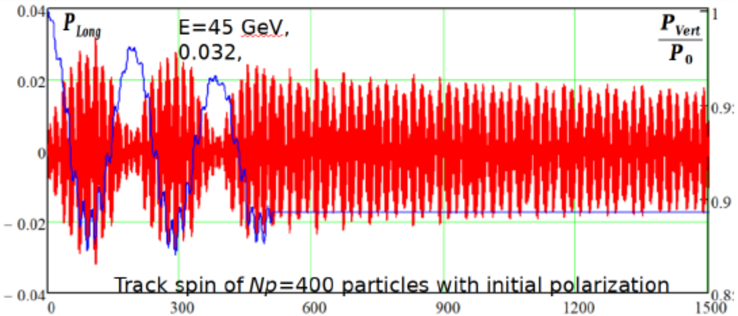
At W Qs too large, step-wise depolariozation required

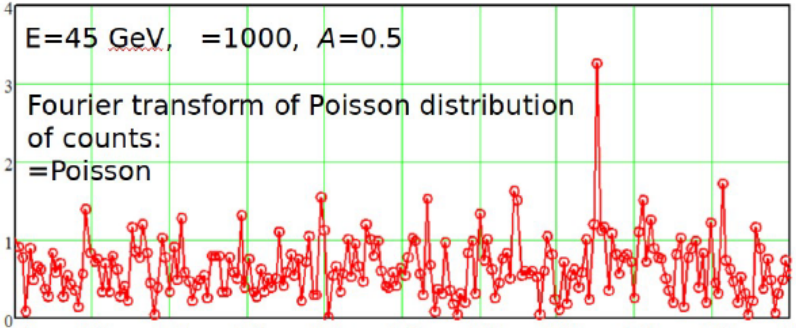
- Resonant depolarization allows to determine spin tune and thus energy











FT of spin coherent spin motion gives spin tune

From beam energy to E_{CM}

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

Energy gain (RF) = losses in the storage ring
Synchrotron radiation (SR)
beamstrahlung (BS)

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

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

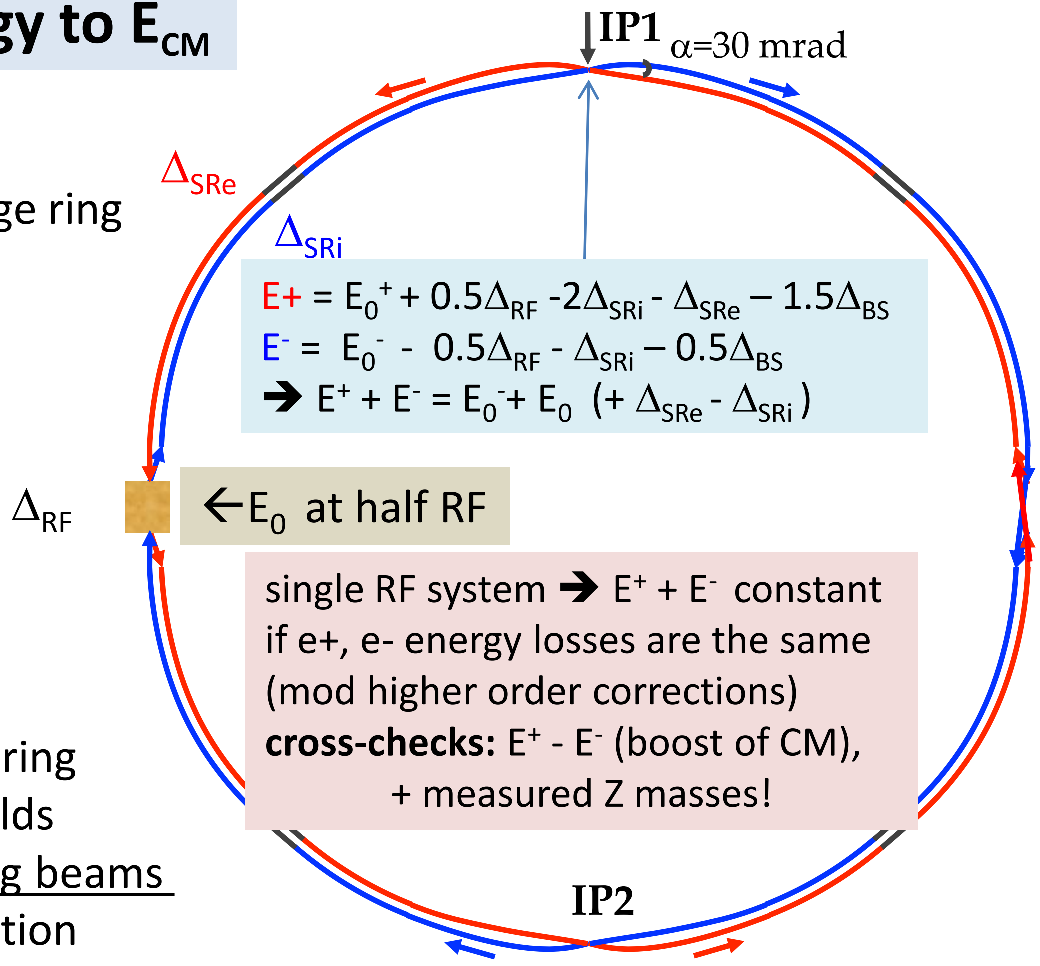
Δ_{BS} = 0 up to 0.62 MeV

the average energies E_0 around the ring are determined by the magnetic fields

➔ same for colliding or non-colliding beams

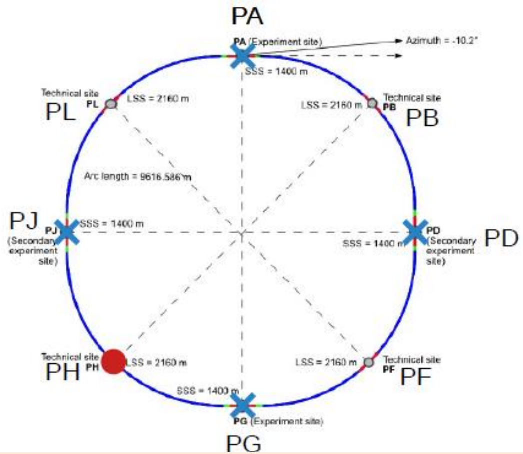
-- measured by resonant depolarization

-- can be different for e^+ and e^-



Resonant depolarization frequency vs average beam energy?

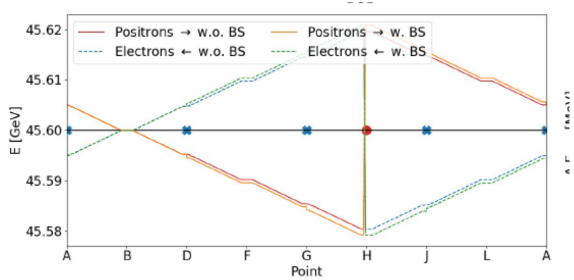
Jacqueline Keintzel



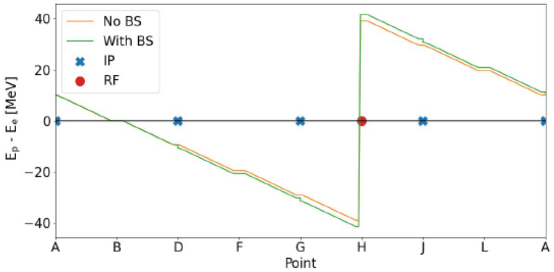
(just because particles have to stay in the ring)
effect of energy losses and gains cancel...

IF there is only one RF section for both e+ and e-

➔ a strong requirement for the Z, W (and ee➔ H) machines



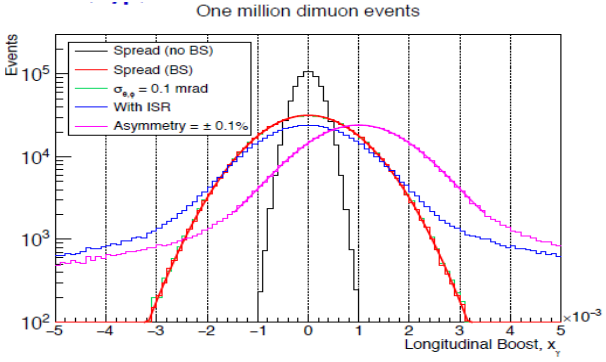
Boost: + for e+; - for e-



The boosts can be verified with great precision, using muon pairs in the experiments, (±40 keV in 5 minutes). Also, the energy spread can be measured

small (8keV) effect comes from $\Delta E \propto \gamma_{\mathrm{rel}}^4$

IP	ΔECM [keV]	Boost [MeV]
PA	- 7.851	10.665
PD	- 7.931	- 10.108
PG	0.570	- 30.883
PJ	0.844	31.439



FCC-ee Beam Polarization and Energy Calibration

3. **From spin tune measurement to center-of-mass determination** $\nu_s = \frac{g-2}{2}\frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)}$

3.1 Synchrotron Radiation energy loss (9 MeV @Z in 4 'arcs') calculable to < permil accuracy

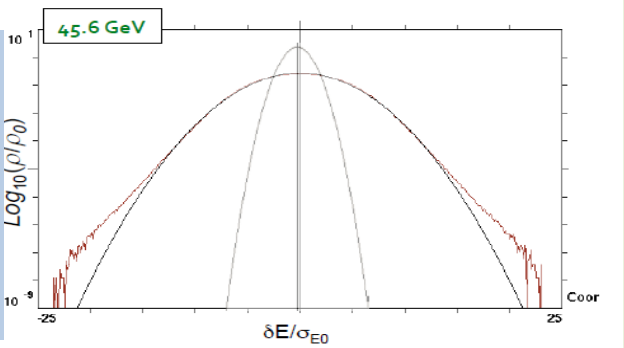
3.3 Beamstrahlung energy loss (0.62 MeV per beam at Z pole), compensated by RF (Shatilov)

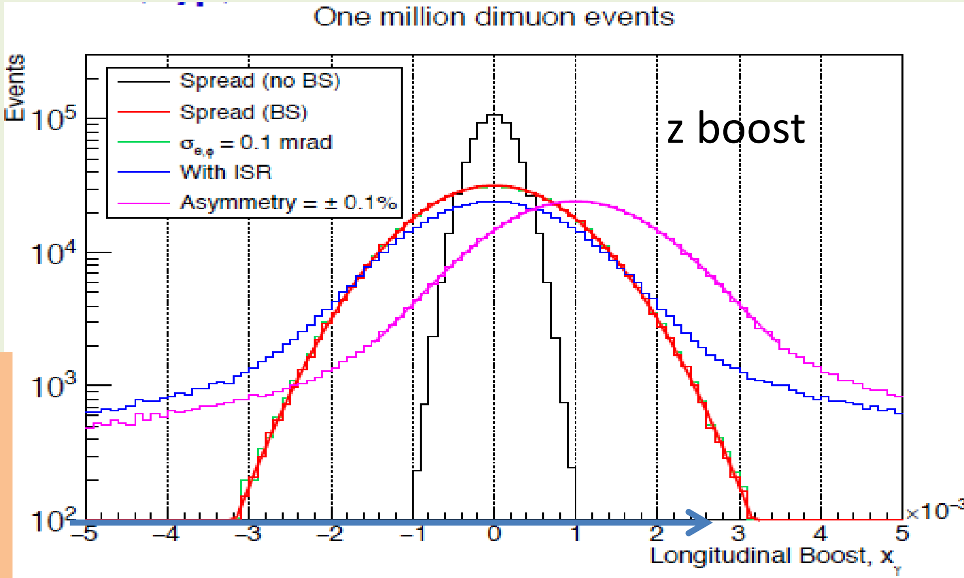
3.4 layout of accelerator with IPs between two arcs well separated from single RF section

3.5 E_b^+ vs E_b^- asymmetries and energy spread can be measured/monitored in expt:

e+e- → μ+ μ- longitudinal momentum shift and spread (Janot)

D. Shatilov: beam energy spectrum without/with beamstrahlung





P. Janot: 5 min/exp @Z ➔ 10^6 μ+ μ- /expt →

→ 50 keV meast both on σ_{ECM} and E^+ - E^-

→ and beam crossing angle α (error negl.)

→ also monitor relative ECM (p-t-p!)

Hardware requirements: wigglers

Given the long polarization time at Z, wigglers will be necessary.

An agreement was reached on a set of **8 wiggler units per beam**

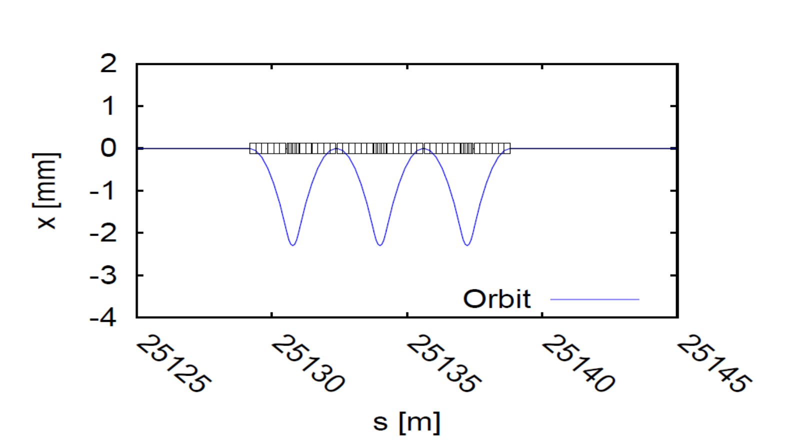
Polarization wigglers

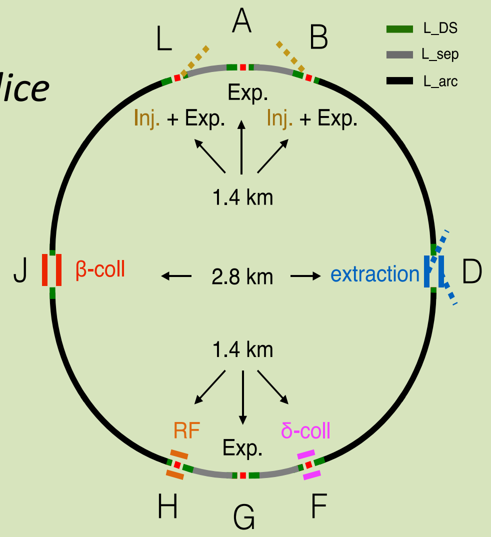
8 units per beam, as specified by *Eliana Gianfelice*

B+=0.7 T L+ = 43cm L-/L+ = B+/B- = 6

at Eb= 45.6 GeV and B+= 0.67 T

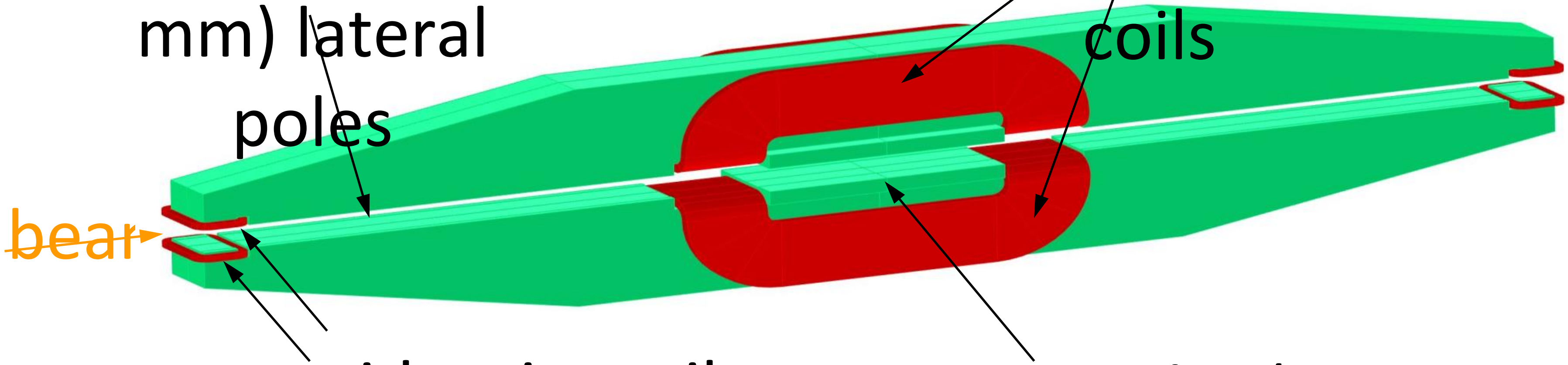
=> P=10% in 1.8H σ_{Eb} = 60 MeV E_{crit}=902 keV





placed e.g. in dispersion-free straight section H and/or F

First single pole magnetic concept, keeps some of the ideas of the LEP design, in particular the “floating” poles



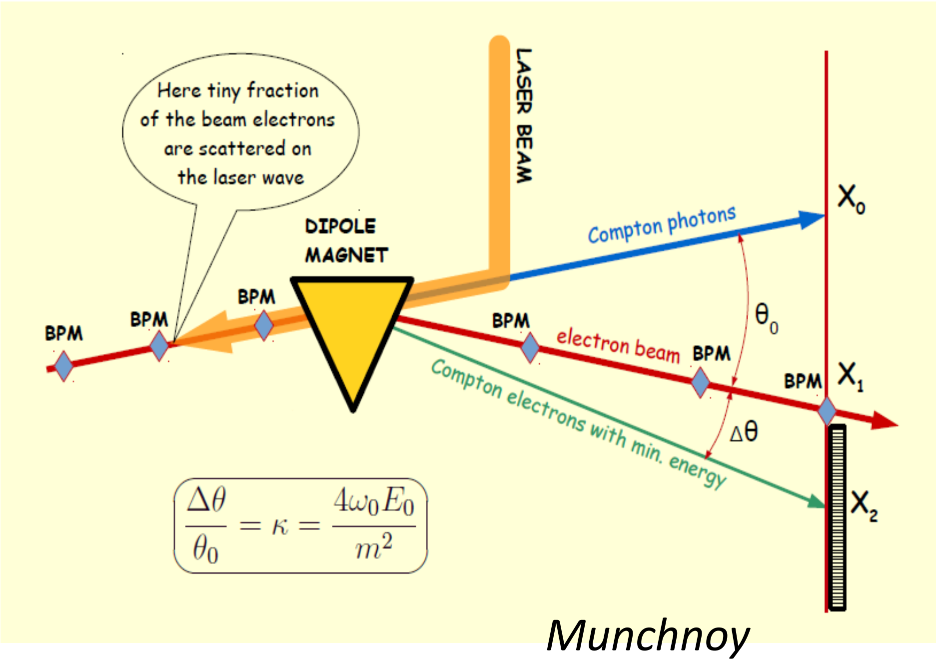
polarimeters

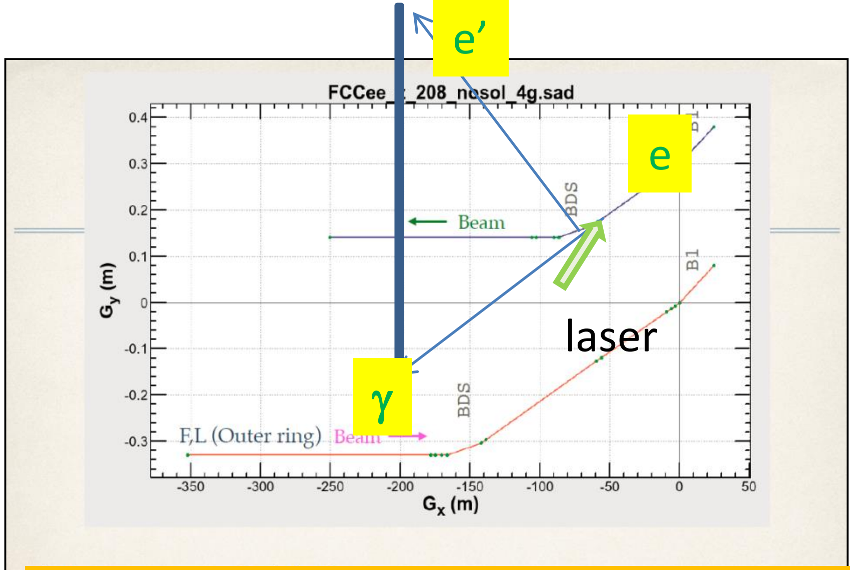
2 Polarimeters, for e+ and e-   Use of both electron and photons recoil → measurement of 3D beam polarization

Backscattered Compton γ +e → γ + e 532 nm (2.33 eV) laser; detection of photon and electron.

Change upon flip of laser circular polarization → beam Polarization ±0.01 per second

End point of recoil electron → beam energy monitoring ± 4 MeV per second (Muchnoi, Aurelien Martens)





install photon-electron IP on inner ring in RF straights *(Oide)*

polarimeter-spectrometer situated 100m from end of dipole.

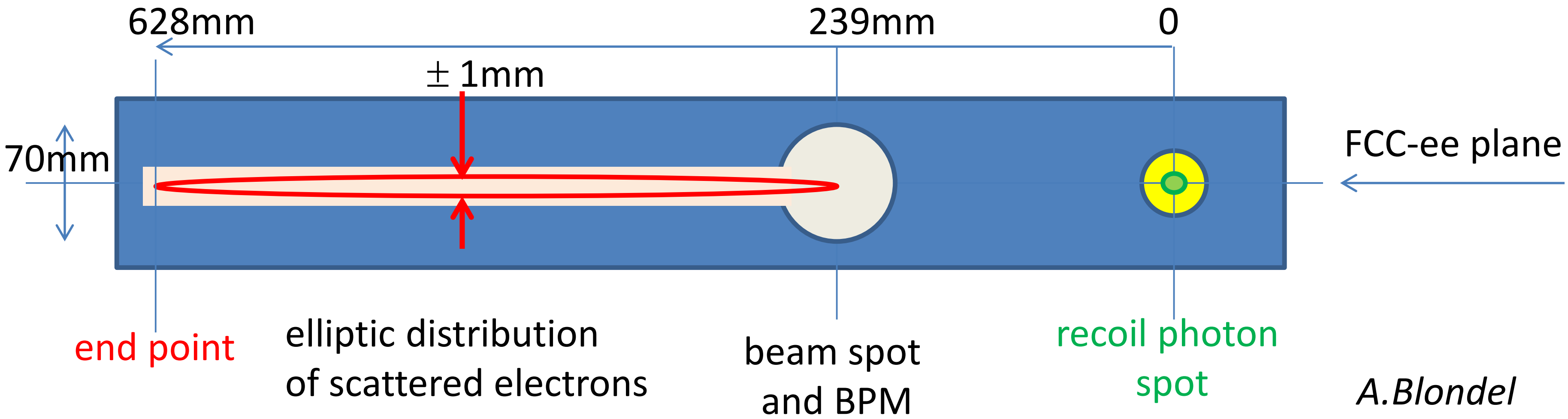
Using the dispersion suppressor dipole with a lever-arm of **100m** from the end of the dipole, one finds

-- minimum compton scattering energy at 45.6 GeV is 17.354 GeV

-- distance from photon recoil to Emin electron is 0.628m

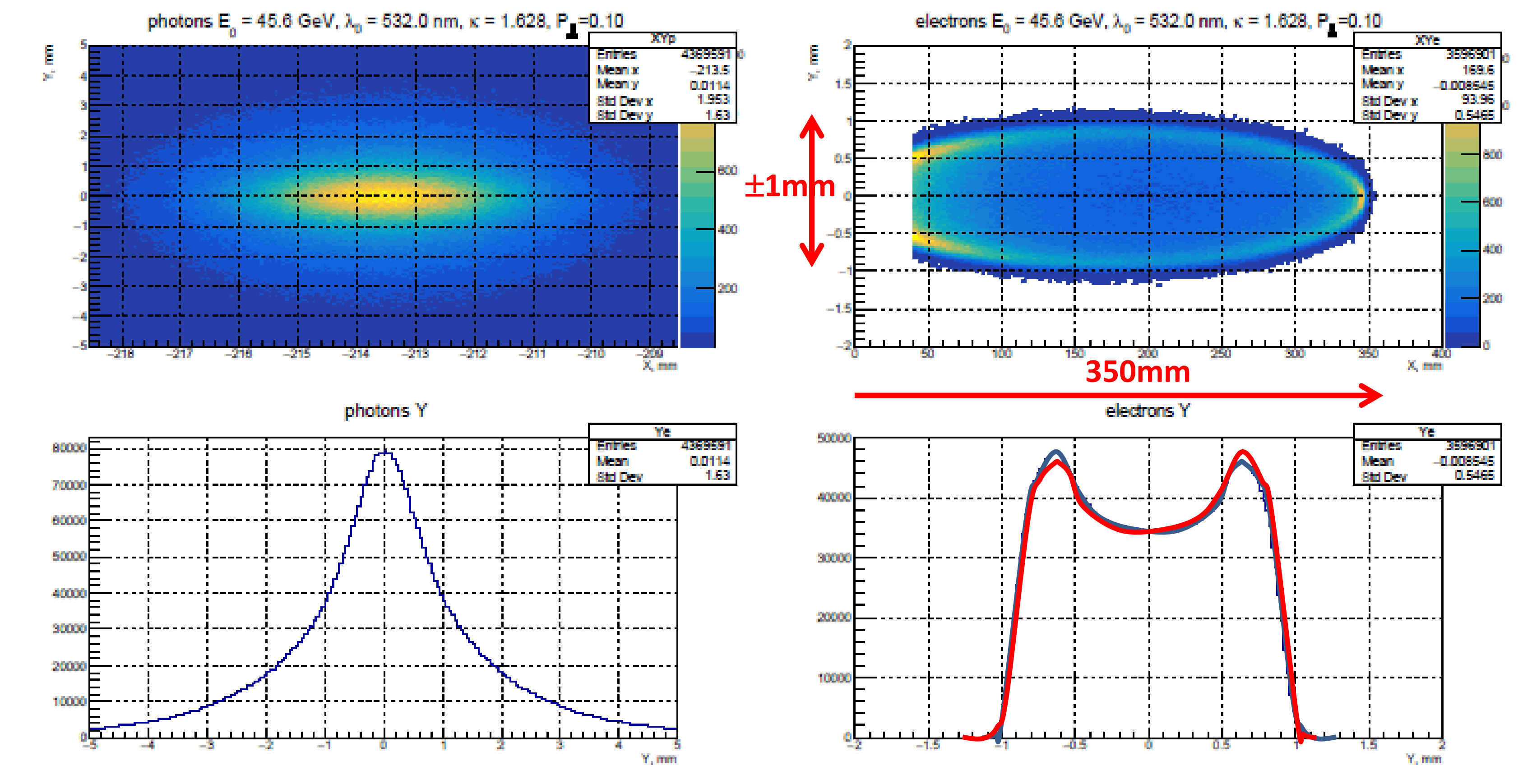
	laser (eV)	beam (GeV)	mc2(MeV)	B field	R	LM	theta	L	true beam
	2.33	45.6	0.511	0.013451	11300	24.119	0.002134	100	45.60005
nominal kappa = 4. E_laser.Ebeam_nom/mc2	1.627567296								
true kappa = 4. E_laser.Ebeam_true/mc2	1.627568924								
nominal Emin	17.35445561								
true Emin	17.35446221								
position of photons	0								
nominal position of beam (m)	0.239182573								
true position of beam (m)	0.239182334	2.39182E-07							
nominal position of min (m)	0.628468308								
true position of min (m)	0.628468069	2.39182E-07							

mouvement of beam and end point are the same:
0.24microns for $\delta Eb/Eb=10^{-6}$ (δEb=45keV)



A.Blondel

measurement of recoil e and



Munchnoi

Compton Polarimeter: Rates

- Laser wavelength $\lambda = 532$ nm.
- Waist size $\sigma_0 = 0.250$ mm. Rayleigh length $z_R = 148$ cm.
- Far field divergence $\theta = 0.169$ mrad
- Interaction angle $\alpha = 1.000$ mrad
- Compton cross section correction 0.5
- Pulse energy: $E_L = 1$ [mJ]; τ_L=5 [ns] (sigma)
- Pulse power: $P_L = 80$ [kW]
- Ratio of angles $R_a = 5.905249$
- Ratio of lengths $R_l = 0.984208$
- $P_L/P_c = 1.1 \cdot 10^{-6}$
- "efficiency" $= 0.13$
- Scattering probability $W \simeq 7 \cdot 10^{-8}$

- With 10^{10} electrons and 3 kHz rep. rate: $\dot{N}_\gamma \simeq 2 \cdot 10^6$

Depolarization

This is not-so trivial in FCC-ee!
16700 bunches circulate
time-between-bunches = 19ns,
depolarize one-and-only-one
of them.
Kicker must have fast (<9ns) rise.

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 !**

LHC transverse feedback system

- Four kickers per beam, per plane, located in RF zone (UX451) at point 4
  - **Electrostatic kicker**, length 1.5 m.
  - Providing a **kick of ~2 μrad @ 450 GeV** (all 4 units combined).
  - Useful bandwidth ~1 kHz – 20 MHz.

ADT kickers and power amplifiers at point 4

Energy calibration WG / J. Wenninger

10/19/2017

From spin tune to beam energy--

The spin tune may not be en exact measurement of the average of the beam energy along the magnetic trajectory of particles. Additional spin rotations may bias the issue. *Anton Bogomyagkov* and *Eliana Gianfelice* have made many estimates.

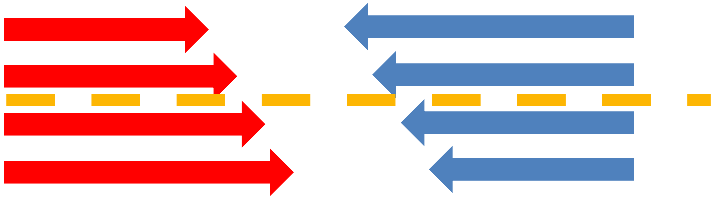
synchrotron oscillations	$\Delta E/E$	$-2\ 10^{-14}$
Energy dependent momentum compaction	$\Delta E/E$	10^{-7}
Solenoid compensation		$2\ 10^{-11}$
Horizontal betatron oscillations	$\Delta E/E$	$2.5\ 10^{-7}$
Horizontal correctors*)	$\Delta E/E$	$2.5\ 10^{-7}$
Vertical betatron oscillations **)	$\Delta E/E$	$2.5\ 10^{-7}$
Uncertainty in chromaticity correction $O(10^{-6})$	$\Delta E/E$	$5\ \ 10^{-8}$
invariant mass shift due to beam potential		$4\ 10^{-10}$

*) $2.5\ 10^{-6}$ if horizontal orbit change by >0.8mm between calibrations is unnoticed or if quadrupole stability worse than 5 microns over that time. consider that 0.2 mm orbit will be noticed
**) $2.5\ 10^{-6}$ for vertical excursion of 1mm. Consider orbit can be corrected better than 0.3 mm.

From beam energy to E_{CM}

opposite sign dispersion

E_{e^-}

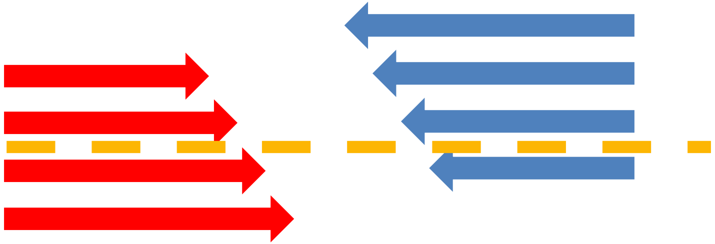


E_{e^+}

No effect on ECM

NB energy spread is reduced.

E_{e^-}

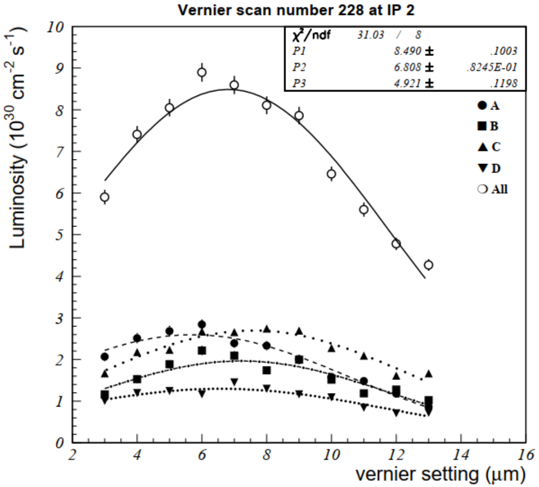


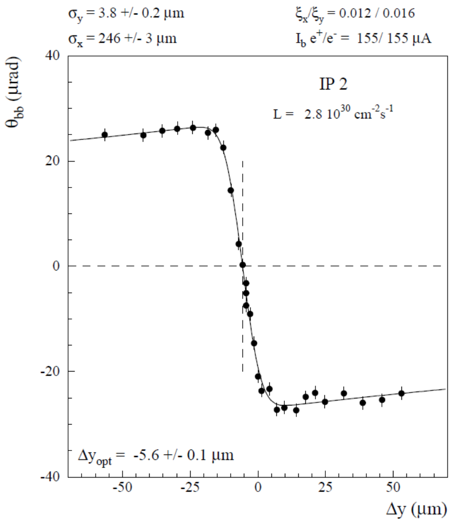
E_{e^+}

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

Experience from LEP: Vernier scans

Relative position of beams measured to +- 80 nanometers from one scan





precision requires going far from maximum
➔ loose beam?

Try beam-beam deflection?

vernier scans

7.2 Dispersion at the IP

For beams colliding with an offset at the IP, the CM energy spread and shift are affected by the local dispersion at the IP. For a total IP separation of the beams of $2u_0$ the expressions for the CM energy shift and spread are [72]

$$\Delta\sqrt{s} = -2u_0 \frac{\sigma_E^2 (D_{u1} - D_{u2})}{E_0(\sigma_{B1}^2 + \sigma_{B2}^2)} \quad (90)$$

$$\sigma_{\sqrt{s}}^2 = \sigma_E^2 \left[\frac{\sigma_\epsilon^2 (D_{u1} + D_{u2})^2 + 4\sigma_u^2}{\sigma_{B1}^2 + \sigma_{B2}^2} \right] \quad (91)$$

D_{u1} and D_{u2} represent the dispersion at the IP for the two beams labelled by 1 and 2. σ_E is the beam energy spread assumed here to be equal for both beams and $\sigma_\epsilon = \sigma_E/E$ is the relative energy spread. σ_{Bi} is the total transverse size of beam (i) at the IP,

$$\sigma_{Bi}^2 = \sigma_u^2 + (D_{ui}\sigma_\epsilon)^2 \quad (92)$$

with σ_u the betatronic component of the beam size.

If the beam sizes at the IP are dominated by the betatronic component which is rather likely, the energy shift simplifies to

$$\Delta\sqrt{s} = -u_0 \frac{\sigma_E^2 \Delta D^*}{E_0 \sigma_u^2} \quad (93)$$

where $\Delta D^* = D_{u1} - D_{u2}$ is the difference in dispersion at the IP between the two beams. This effect applies to both planes (u = x,y). In general due to the very flat beam shapes the most critical effect arises in the vertical plane.

For FCC-ee at the Z we have in vertical direction:

- Parasitic dispersion of e+ and e- beams at IP 10um
  the difference is $\Delta D_y^* = 14\mu m$.
- Sigma_y is 28nm
- Sigma_E is 0.132%*45000MeV=60MeV
- **Delta_ECM is therefore 1.4MeV for a 1nm 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 is accurate to 1% sigma_y,
  we get a precision of 400 keV.

the process should be simulated

- we need 100 beams scans to get an E_{CM} accuracy of 40keV – suggestion: vernier scan every hour or more.
- It is likely that Vernier scans will be performed regularly at least once per hour or more. (→100 per week) we end up with an uncertainty of ~10keV over the whole running period. ***(provided no systematic effects show up)***
- **The dispersion must be measured as well; this can be done by using the vernier scans with offset RF frequency**
- this would lead to lots of Vernier scans!

critical effect is in the vertical plane, but horizontal plane should be investigated as well

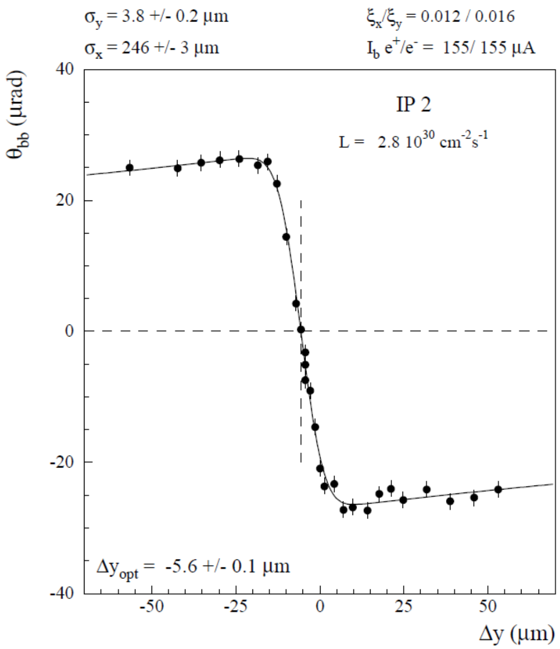
beam-beam deflection scans were already used at SLC, KEK and LEP

Luminosity Optimisation Using Beam-beam Deflections at LEP

C. Bovet, M.D. Hildreth, M. Lamont, H. Schmickler, J. Wenninger,
CERN, Geneva, Switzerland

CERN-SL-96-025
https://inspirehep.net/literature/420668

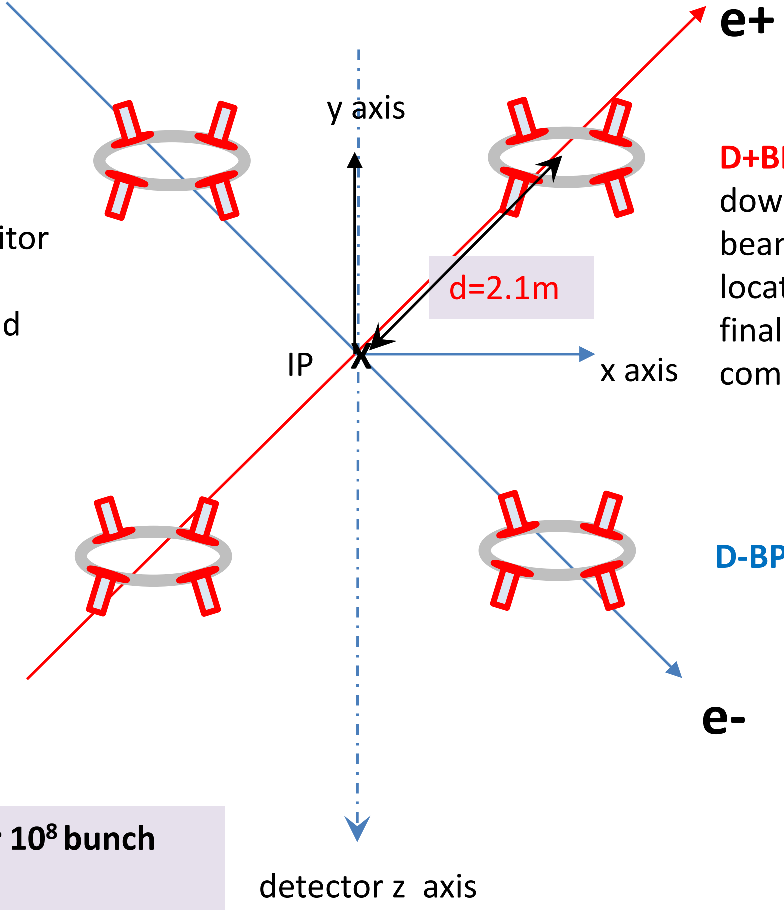
Uncertainty on Δy_{opt} = -5.6±0.1 μm
is 1/40 of the vertical beam size 3.8±0.2 μm
which was itself measured in the process



beam-beam deflection measurement at FCC-ee as if in « squished perspective » looking from behind detectors endcaps

U-BPM
upstream electron
beam position monitor
located between
final focus quads and
compensating
solenoid

U+BPM

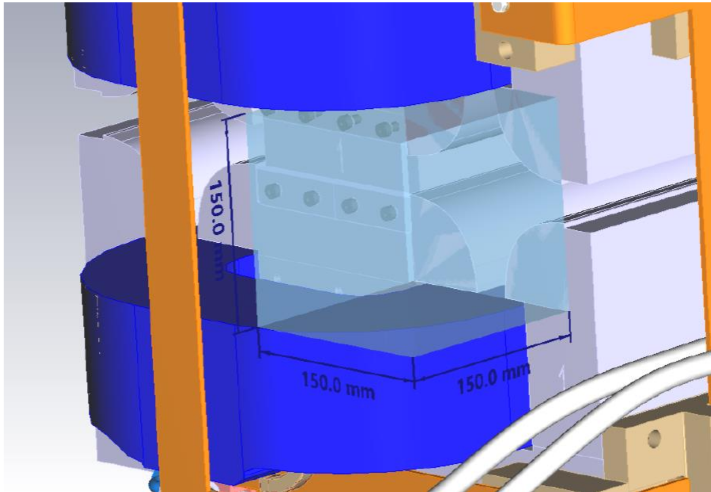


D+BPM
downstream positron
beam position monitor
located between
final focus quads and
compensating solenoid

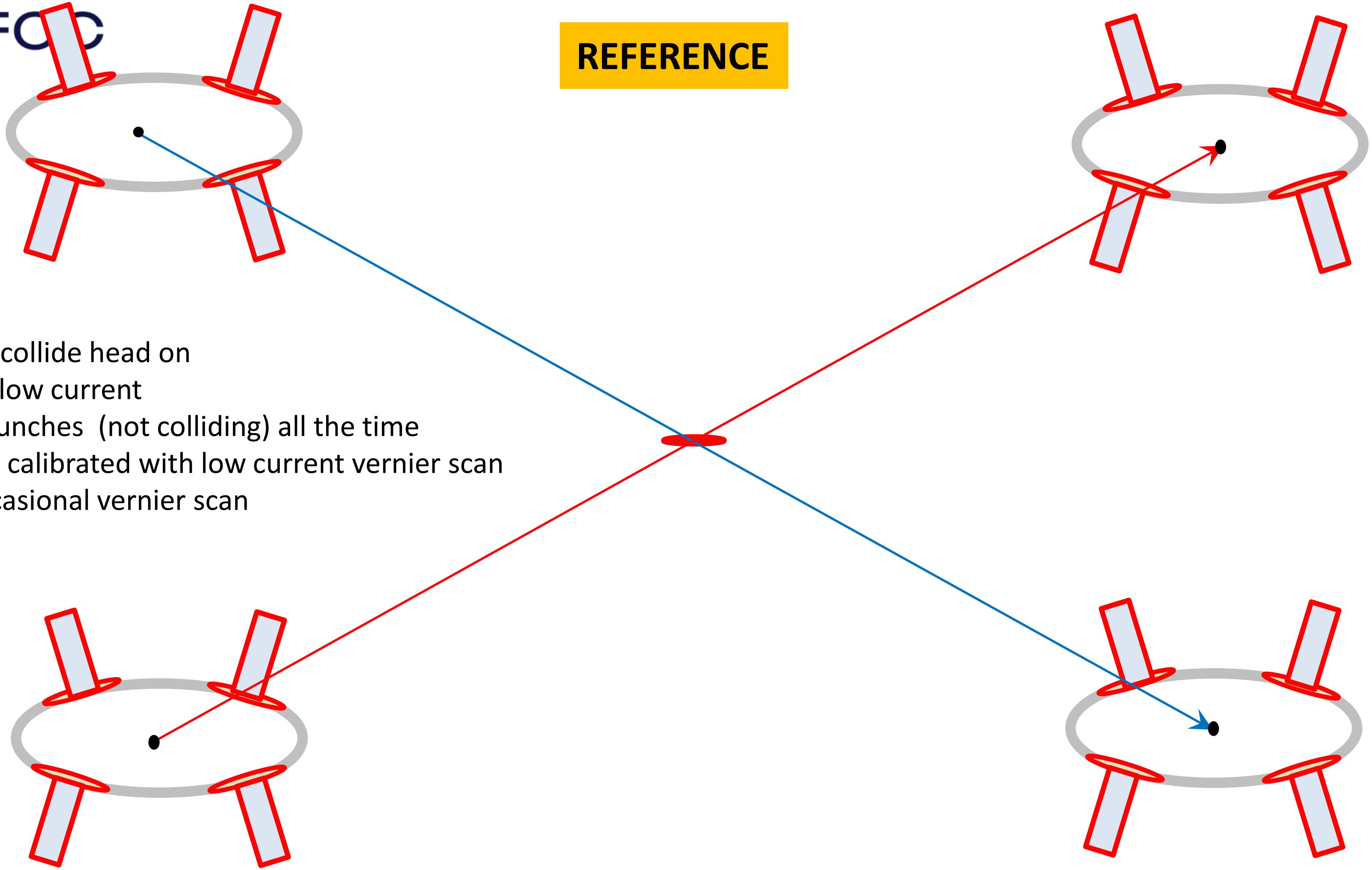
D-BPM

BPM precision over 10^8 bunch passages is ~1μm

BPM in arc magnets

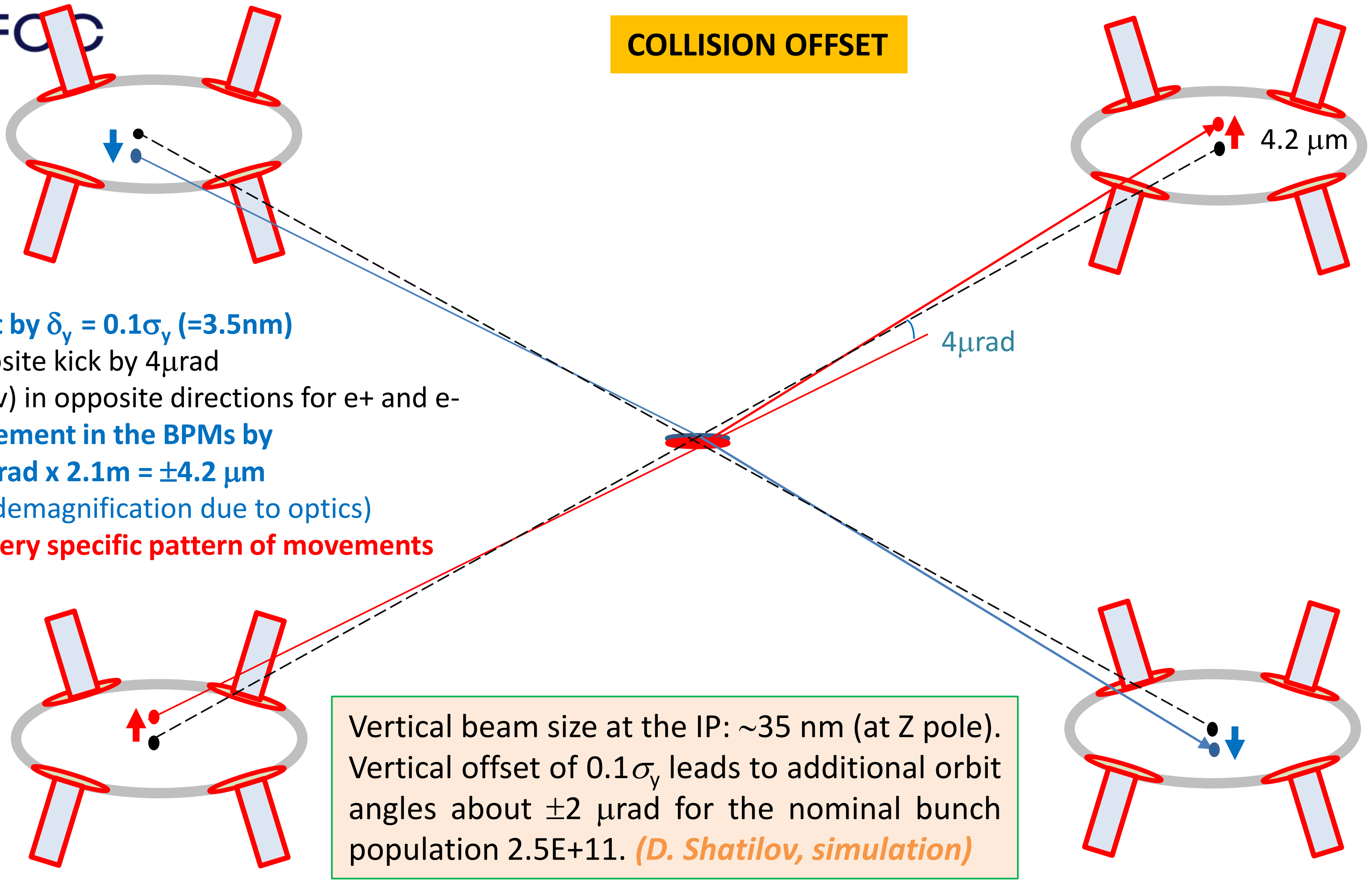


REFERENCE



1. beams collide head on
    -- or at low current
1’. pilot bunches (not colliding) all the time
1’’ can be calibrated with low current vernier scan
1’’’ or occasional vernier scan

COLLISION OFFSET



2. **offset by $\delta_y = 0.1\sigma_y$ (=3.5nm)**
➔ opposite kick by 4μrad
(Shatilov) in opposite directions for e+ and e-
➔ **movement in the BPMs by**
± 2 μrad x 2.1m = ±4.2 μm
(x1000 demagnification due to optics)
with a very specific pattern of movements

Vertical beam size at the IP: ~35 nm (at Z pole). Vertical offset of $0.1\sigma_y$ leads to additional orbit angles about ±2 μrad for the nominal bunch population 2.5E+11. ***(D. Shatilov, simulation)***

FCC

Measurements of offsets and Opposite Sign Vertical Dispersion (OSVD)

Purely statistical and preliminary arguments (verified by J. Wenninger at last EPOL meeting)

OFFSETS:

Four measurements of 4.2 micron displacement with 1 micron precision can be made with 10^8 bunch passages (assume 10000 bunches in each beam)

→ **every 3 seconds**

→ **measurement of beam beam offset with precision of 0.1 * 35nm / 4.2 / √4 = 1/80 of beam size or ~0.4nm**

NB no need of a scan in principle if a good and stable reference can be demonstrated. **CAN WE USE THE PILOT BUNCHES?**
LEP did not have pilot bunches, but maybe we can use them? (there is a debate on this)
Pilot bunches would provide 10^8 bunch measurements in 2 minutes (only 250 bunches of each beam)

OSVD

we cannot really measure the dispersion at IP directly,
but the beams will move in opposite directions upon a change of RF frequency
→ we measure the opposite sign vertical dispersion (OSVD) this way!
Assuming that a relative momentum change of 10-3 is feasible, this measurement corresponds to a measurement of opposite sign vertical dispersion D*y(e+)-D*y(e-) with a precision of 0.4 micrometer.

Plugging this into the equations of the earlier page this leads to a measurement of the possible shift in energy with a precision **of ± 20 keV each time the dispersion measurement is done. THIS IS VERY PROMISING because in particular it requires very little scanning across the beam.**

FCC

Works packages

A- Simulations of spin-tune to beam energy relationship

-- EPFL group obtained funding from CHART for a student and a postdoc (stdies started -- Yi Wu)

-- Ivan Koop now concentrating on res. dep at WW threshold (Qs is now 0.075, *good*!)

B. Simulation of the relationship between beam energies and centre-of-mass energy.

-- control of offsets and vertical dispersion

-- Studied the beamstrahlung monitor but does not work

-- Studies will continue to implement beam deflection scans (AB-Oide-Shatilov-Wenninger)

-- Impact of energy losses (Jacqueline Keintzel)

C. Polarimeter desing and performance

-- now working to build a global collaboration (IJCLAB (Martens), BINP (Muchnoi), CERN (Lefevre), -- others?)

-- Aim to provide integration of polarimeters, wigglers, RF kickers in FCC-ee

-- conceptual design and cost estimate of polarimeter for FCC FS

D. Measurements in Particle Physics Experiments

-- not much work done beyond design study, needs to restart soon

E. Monochromatization

Angeles Faus, Jorg Wenninger, Pantaleo Raimondi, Frank Zimmermann, Dmitry Shatilov

-- new ideas for monochromatization in other dimensions than horizontal (x) axis. (time, z)

-- what its the limit?

Conclusions

EPOL WG group in on route to improve feasibility evaluation of Energy calibration program
-- targeting experimental statistical precision (keV level)
-- including performance and cost estimate of required hardware
-- many breakthrough's in the last meetings

Various complimentary spares

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

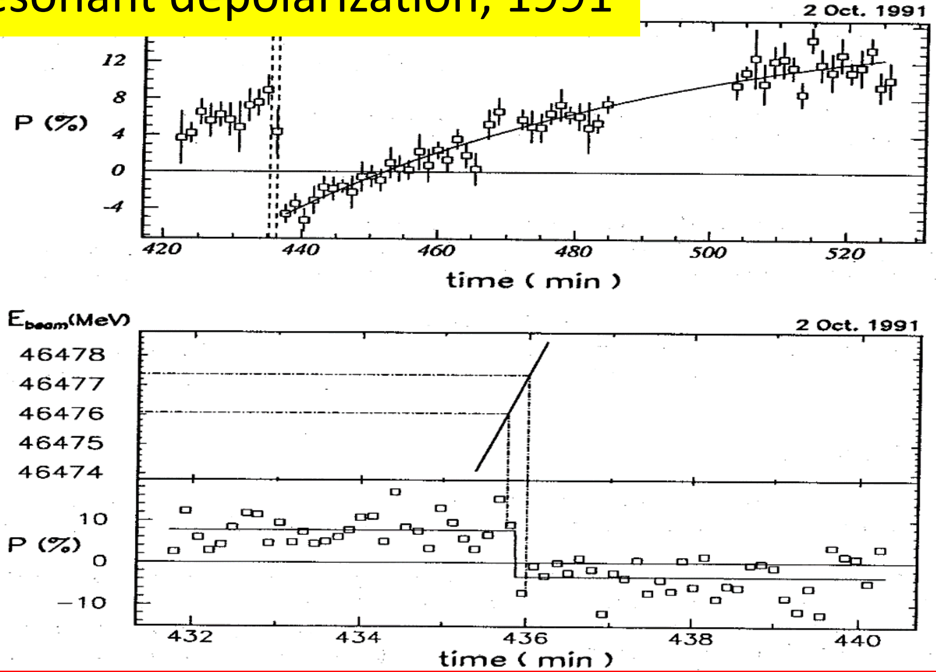
The LEP Energy Working Group

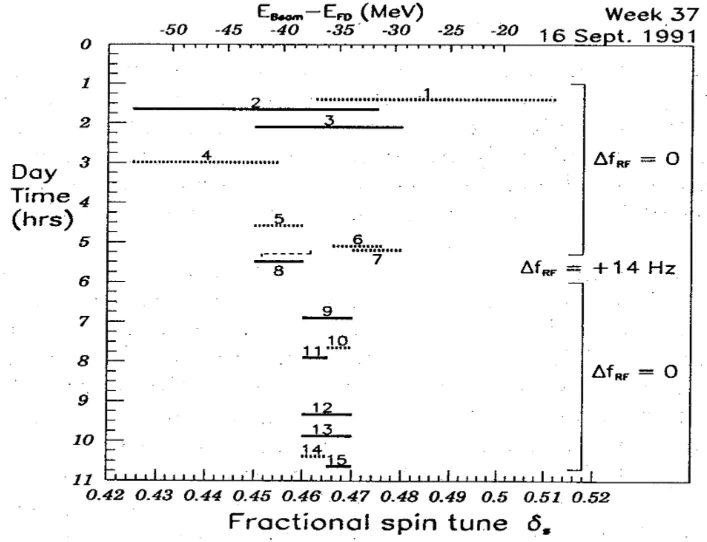
R. Assmann[1)], M. Böge[1,a)], R. Billen[1)], A. Blondel[2)], E. Bravin[1)], P. Bright-Thomas[1,b)], T. Camporesi[1)], B. Dehning[1)], A. Drees[3)], G. Duckeck[4)], J. Gascon[5)], M. Geitz[1,c)], B. Goddard[1)], C.M. Hawkes[6)], K. Henrichsen[1)], M.D. Hildreth[1)], A. Hofmann[1)], R. Jacobsen[1,d)], M. Koratzinos[1)], M. Lamont[1)], E. Lancon[7)], A. Lucotte[8)], J. Mnich[1)], G. Mugnai[1)], E. Peschardt[1)], M. Placidi[1)], P. Puzo[1,e)], G. Quast[9)], P. Renton[10)], L. Rolandi[1)], H. Wachsmuth[1)], P.S. Wells[1)], J. Wenninger[1)], G. Wilkinson[1,10)], T. Wyatt[11)], J. Yamartino[12,f)], K. Yip[10,g)]

Abstract

The determination of the centre-of-mass energies from the LEP1 data for 1993, 1994 and 1995 is presented. Accurate knowledge of these energies is crucial in the measurement of the Z resonance parameters. The improved understanding of the LEP energy behaviour accumulated during the 1995 energy scan is detailed, while the 1993 and 1994 measurements are revised. For 1993 these supersede the previously published values. Additional instrumentation has allowed the detection of an unexpectedly large energy rise during physics fills. This new effect is accommodated in the modelling of the beam-energy in 1995 and propagated to the 1993 and 1994 energies. New results are reported on the magnet temperature behaviour which constitutes one of the major corrections to the average LEP energy.
The 1995 energy scan took place in conditions very different from the previous years. In particular the interaction-point specific corrections to the centre-of-mass energy in 1995 are more complicated than previously: these arise from the modified radiofrequency-system configuration and from opposite-sign vertical dispersion induced by the bunch-train mode of LEP operation.
Finally an improved evaluation of the LEP centre-of-mass energy spread is presented. This significantly improves the precision on the Z width.

LEP Resonant depolarization, 1991





variation of RF frequency to eliminate half integer ambiguity

$E_{beam} = 46{,}466.6 \pm 0.6$ MeV, e.g. precise to $\pm$ 1.5 10^{-5}.

Figure 20: Polarization signal on 2 October 1991, showing the localization of the depolarizing frequency within the sweep.
Top: display of data points, with the frequency sweep indicated with vertical dashed lines. The full line represents the result of a fit with starting polarization $(-4.9 \pm 1.)\%$, polarization rise-time (60 ± 13) minutes, asymptotic polarization $(18.4 \pm 4.1)\%$.
Bottom: expanded view of the sweep period, with the individual data sets displayed (there are 10 sets per point); The frequency sweep lasted 7 data sets. The corresponding beam energy is shown in the upper box. Spin flip occurred between the two vertical dash-dotted lines.

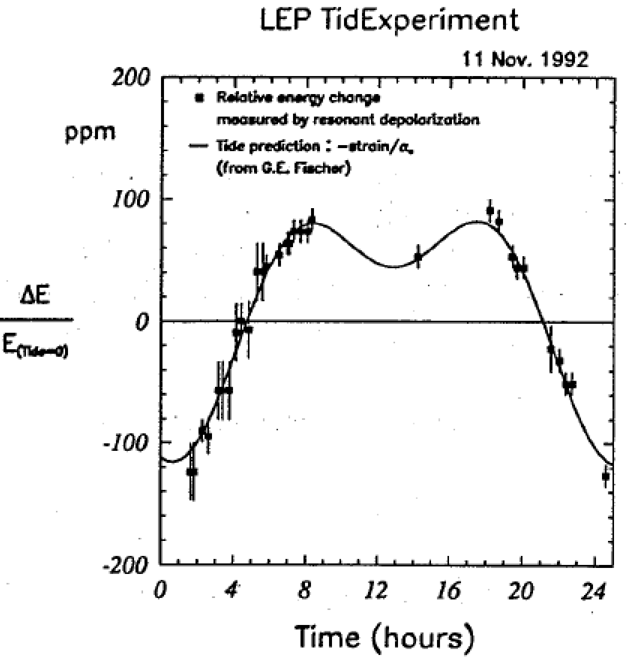
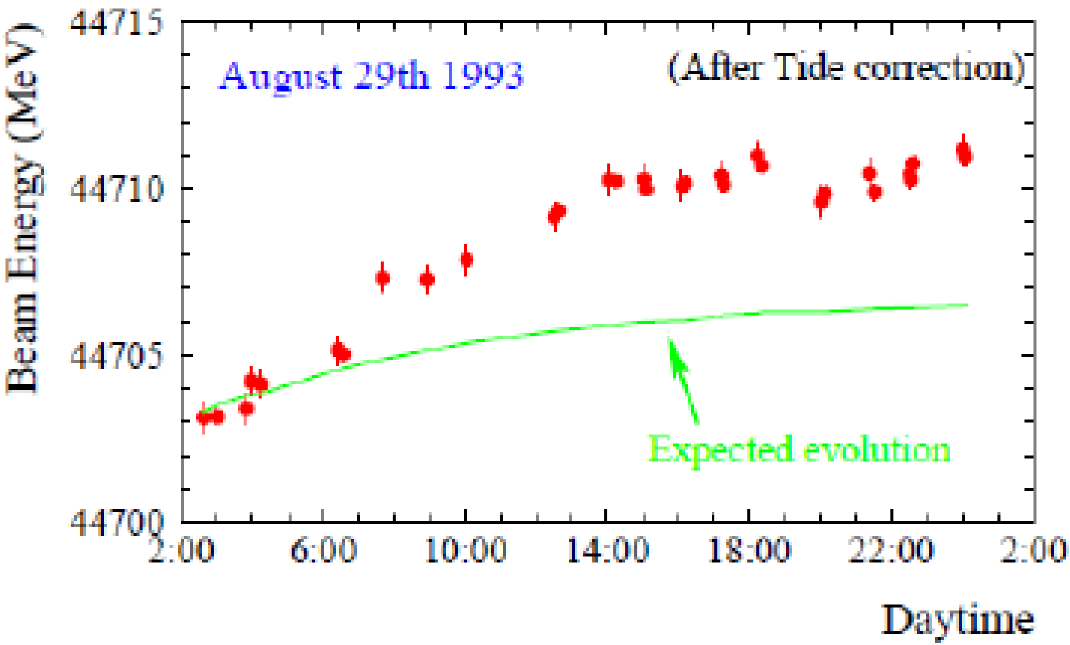


Figure 23: Beam energy variations measured over 24 hours compared to the expectation from the tidal LEP deformation.



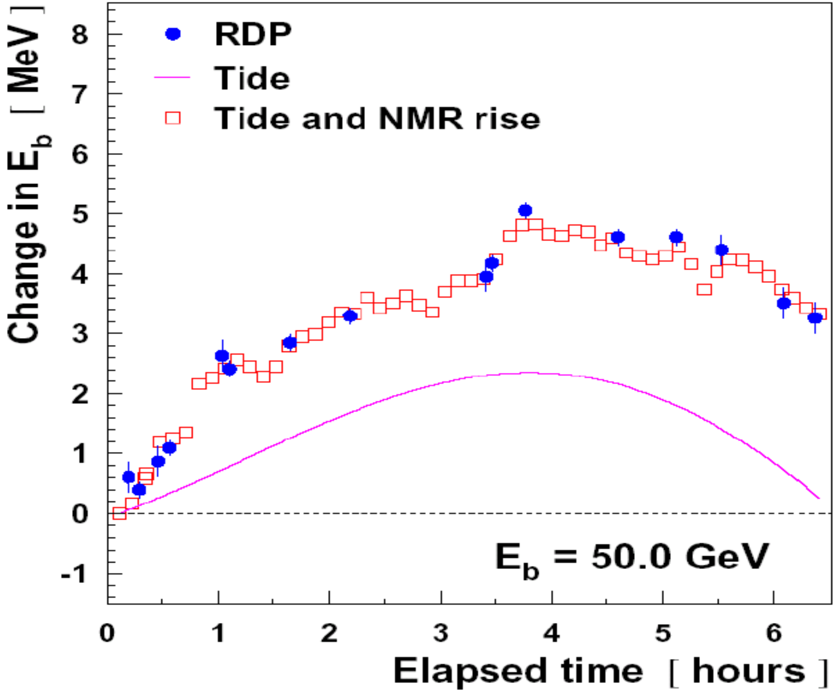
Many effects spoil the calibration if it is performed outside physics time

-- tides and other ground motion

-- RF cavity phases

-- histeresis effects and environmental effects (trains…etc)

Modelling of energy rise by (selected) NMR sampling of B-field is excellent !



(Experiment from 1999)

by 1999 we had an excellent model of the energy variations…
but we were not measuring the Z mass and width anymore
– we were hunting for the Higgs boson!

EXPERIMENTS ON BEAM-BEAM DEPOLARIZATION AT LEP

R. Assmann*, A. Blondel*, B. Dehning, A. Drees°, P. Grosse-Wiesmann, H. Grote, M. Placidi, R. Schmidt,
F. Tecker†, J. Wenninger

PAC 1995

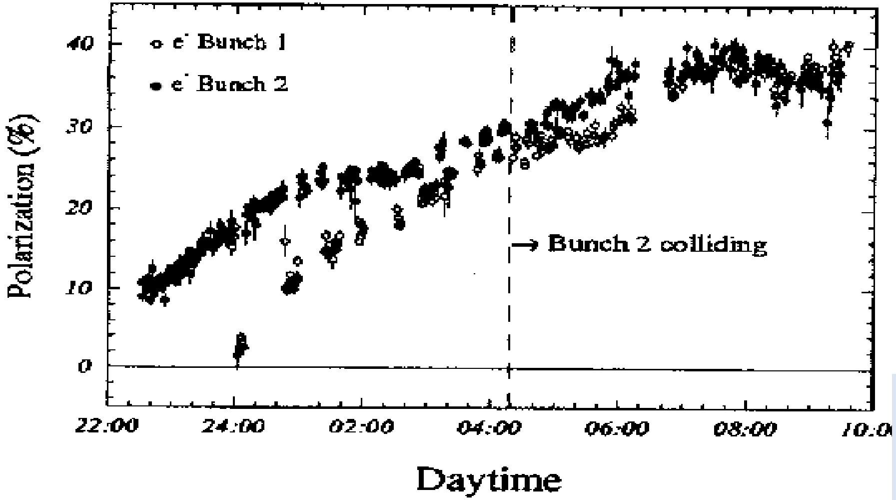


Figure. 3. Polarization level during third experiment

- With the beam colliding at one point, a polarization level of 40 % was achieved. The polarization level was about the same for one colliding and one non colliding bunch.
- It was observed that the polarization level depends critically on the synchrotron tune : when Q_s was changed by 0.005, the polarization strongly decreased.

experiment performed at an energy of 44.71 GeV the polarization level was 40 % with a linear beam-beam tune shift of about 0.04/IP. This indicates, that the beam-beam depolarization does not scale with the linear beam-beam tune shift at one crossing point. Other parameters as spin tune and synchrotron tune are also of importance

LEP:

This was only tried 3 times!

Best result: P = 40% , ξ^*_y= 0.04 , one IP

FCC-ee

Assuming 2 IP and ξ^*_y= 0.01 ➔

reduce luminosity, 10^{10} Z @ P~30%

Longitudinal polarization at FCC-Z?

Main interest: measure EW couplings at the Z peak most of which provide measurements of $\mathbf{\sin^2\theta^{\mathit{lept}}_W} = e^2/g^2\ (m_z)$
(-- not to be confused with -- $\sin^2\theta_W = 1- m_w^2/m_z^2$

Useful references from the past:
«polarization at LEP» CERN Yellow Report 88-02
Precision Electroweak Measurements on the Z Resonance
Phys.Rept.427:257-454,2006 http://arxiv.org/abs/hep-ex/0509008v3
GigaZ @ ILC by K. Moenig

Longitudinal polarization: reduction of polarization due to continuous injection

The colliding bunches will lose intensity continuously due to collisions.
In FCC-ee with 4 IPs, L= 28 10^{34}/cm2/s beam lifetime is 213 minutes
In FCC-ee with 2 IPs, L= 1.4 10^{36}/cm2/s beam life time is 55minutes

Luminosity scales inversely to beam life time.
The injected e+ and e- are not polarized → asymptotic polarization is reduced.
Assume here that machine has been well corrected and beams (no collisions, no injection) can be polarized to nearly maximum.
(***Eliana Gianfelice in Rome talk***)

- 45 GeV
  - limit ΔE=50 MeV (extrapolating from LEP)
  - 4 wigglers with B^{+}= 0.7 T
  - 10% polarization in 2.9 h for energy calibration

(polarization time is 26h)

We have simulated the simultaneous effect of

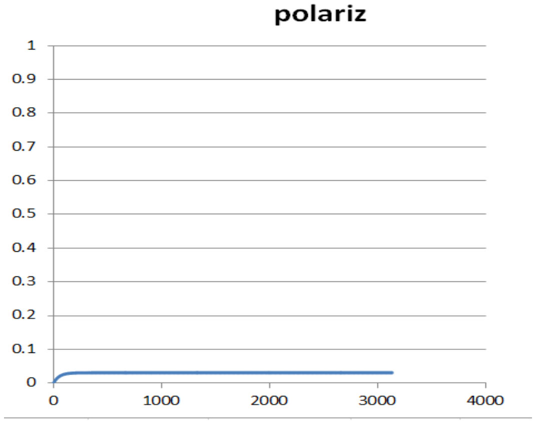
-- natural polarization

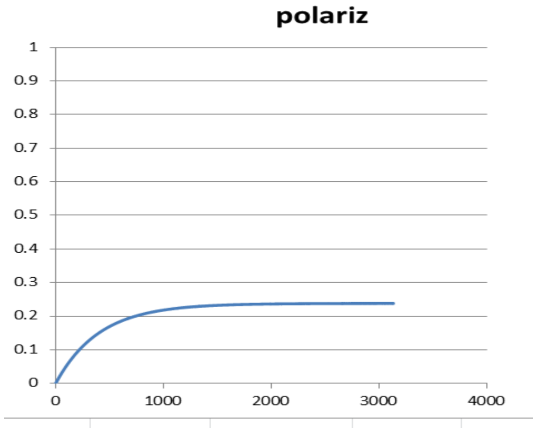
-- beam consumption by e+e- interactions

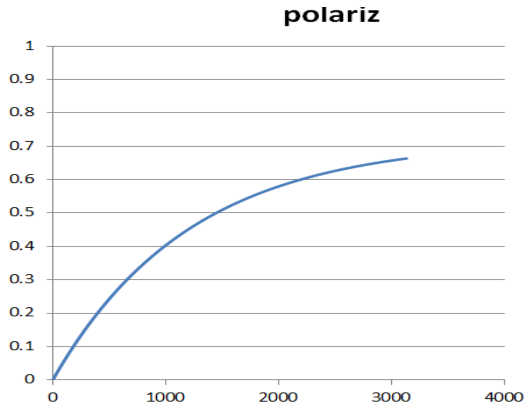
-- replenishment with unpolarized beams

assuming ***optimistically*** a maximal 90% asymptotic polarization

Running at full luminosity	Running at 10% Lumi	Running at 1% Lumi
P_max=0.03! P_eff=0.03	P_max=0.24, P_eff=0.21	P_max=0.66, P_eff=0.5







ΔA_{LR} scales as $1/\sqrt{(P^2L)}$

Lumi loss factor	L.10^34	**Figure of merit: sum(P²L)**	Peff	Pmax
1	220	0.195	0.03	0.03
2	110	0.367	0.059	0.06
4	55	0.627	0.1078	0.11
6	37	0.805	0.149	0.16
8	27	0.924	0.184	0.2
10	22	1.003	0.214	0.24
12	18	1.053	0.24	0.27
15	15	1.09	0.27	0.32
18	12	**1.101**	0.3	0.35
22	10	1.088	0.33	0.4
26	8	1.059	0.354	0.43
30	7	1.023	0.37	0.46
40	5	0.92	0.41	0.52

Optimum around a reduction of luminosity by a factor 18.

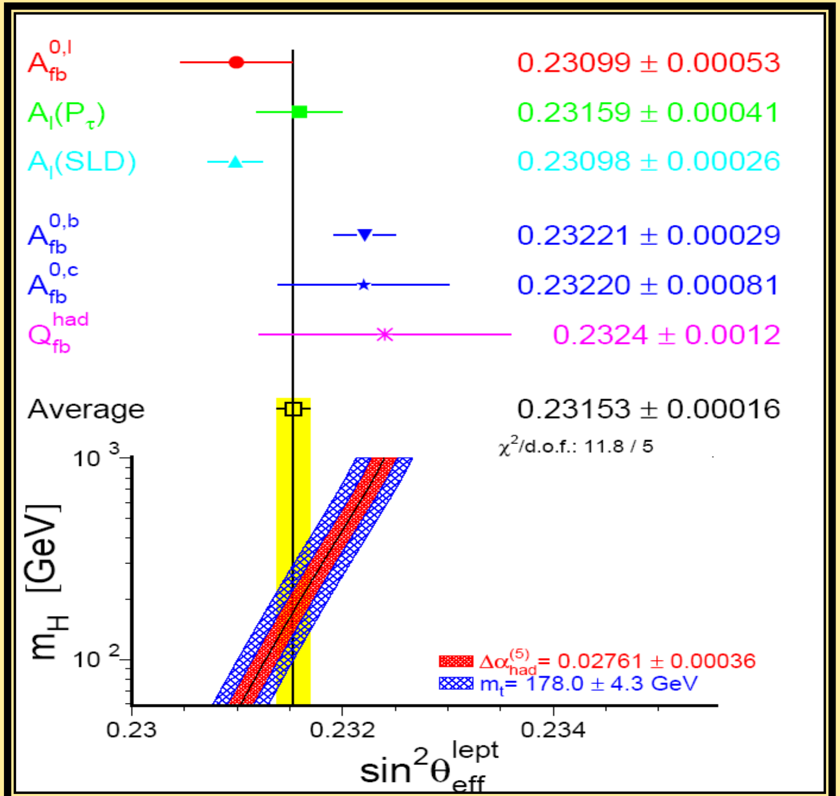
This is still a luminosity of $\sim 10^{35}$ per IP… and the effective polarization is 30%.
This is equivalent to a 100% polarization expt with luminosity reduced by 180.

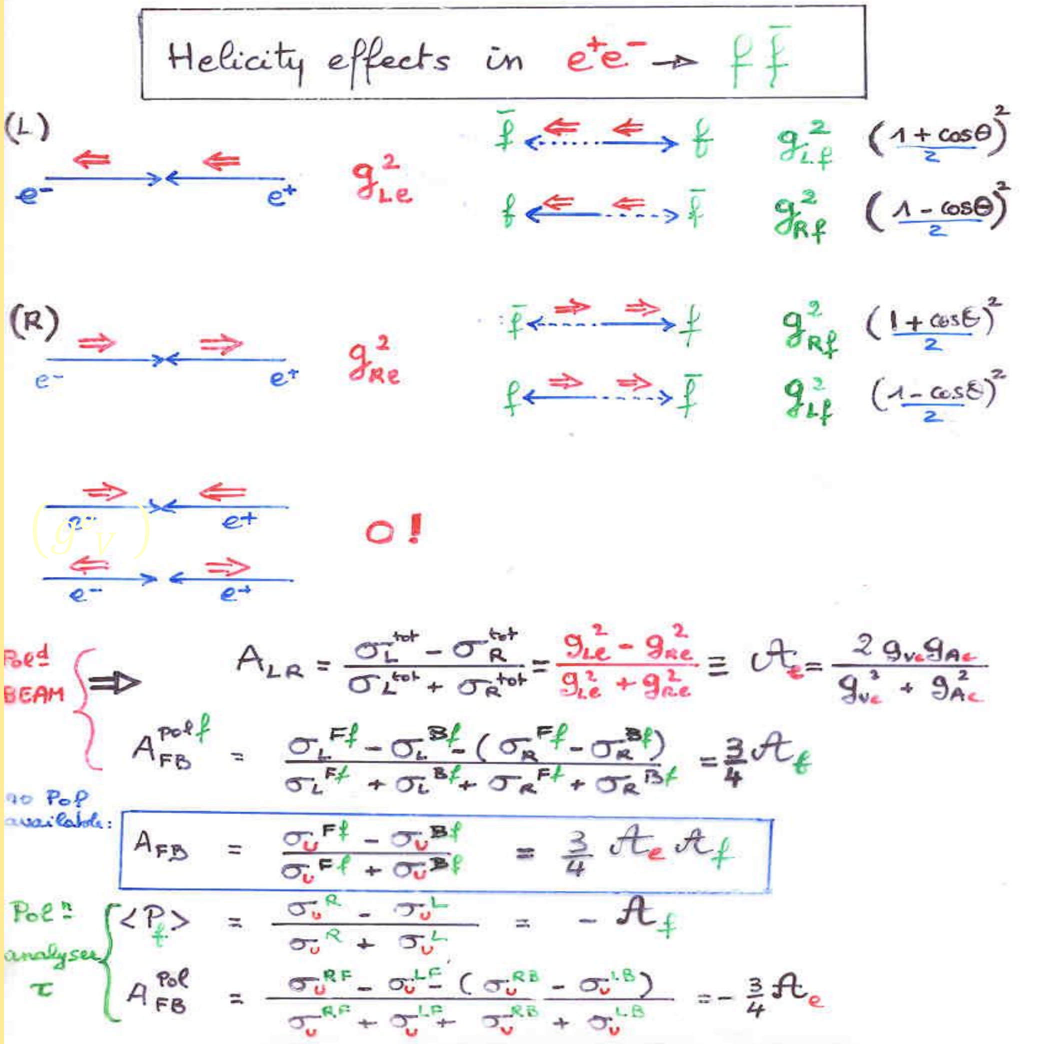
Measuring $\sin^2\theta_W^{eff}$ (m_Z)

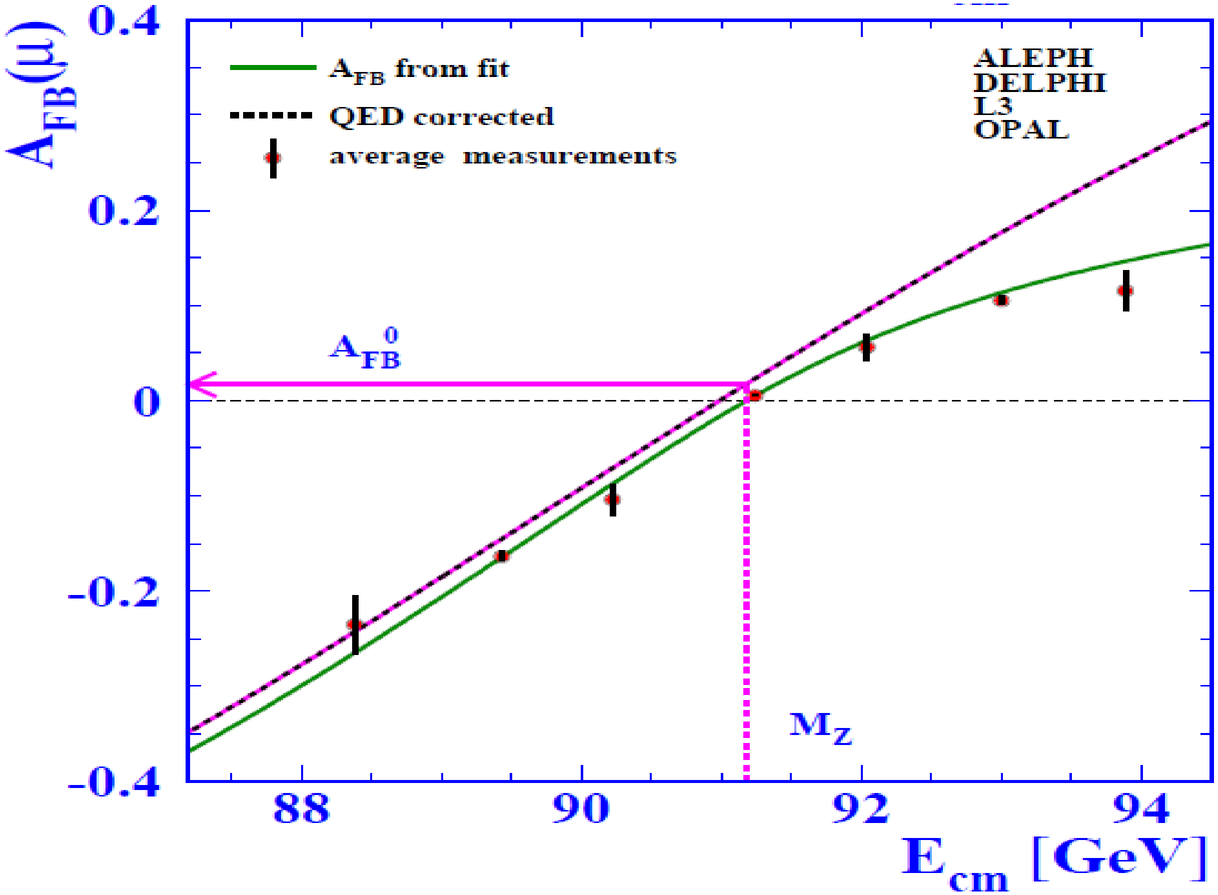
$$\sin^2\theta_W^{eff} \equiv \frac{1}{4}\left(1 - g_V/g_A\right)$$

$$g_V = g_L + g_R$$

arXiv:0509008







$A_{FB}(\mu)$
0.4
0.2
0
-0.2
-0.4
A_{FB} from fit
QED corrected
average measurements
ALEPH
DELPHI
L3
OPAL
A_{FB}^{0}
M_Z
88
90
92
94
E_{cm} [GeV]

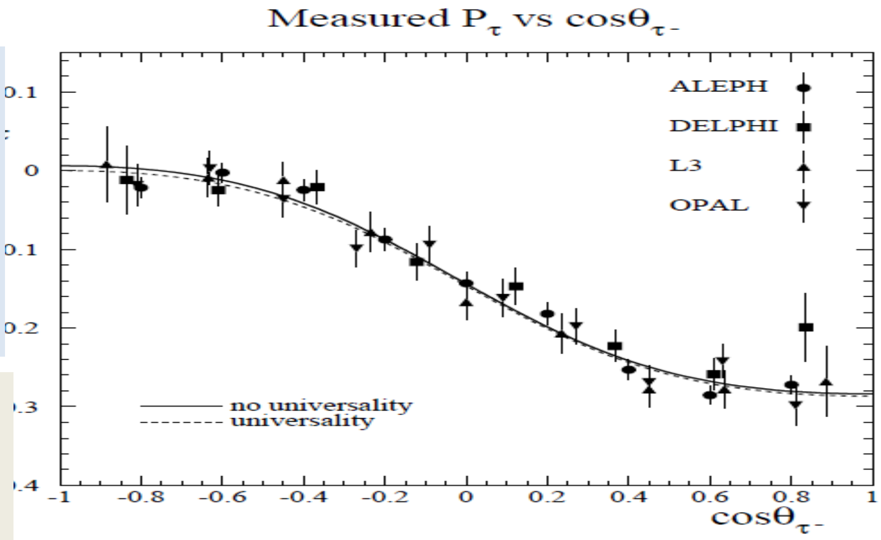
	$A_{FB}^{\mu\mu}$ @ FCC-ee		A_{LR} @ ILC	A_{LR} @ FCC-ee
visible Z decays	10^{12}	visible Z decays	10^{9}	5.10^{10}
muon pairs	10^{11}	beam polarization	90%	30%
$\Delta A_{FB}^{\mu\mu}$ (stat)	$3\ 10^{-6}$	ΔA_{LR} (stat)	$4.2\ 10^{-5}$	$4.5\ 10^{-5}$
Δ E_{cm} (MeV)	0.1		2.2	?
$\Delta A_{FB}^{\mu\mu}$ (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}	$5.9\ 10^{-5}$	
$\Delta \sin^2\theta^{lept}_W$	$5.9\ 10^{-6}$		$7.5\ 10^{-6}$	$6\ 10^{-6}$ +?

All exceeds the theoretical precision from $\Delta\alpha(m_Z)$ ($3 10^{-5}$) or the comparison with m_W (500keV)

But this precision on $\Delta \sin^2\theta^{lept}_W$ can only be exploited at FCC-ee!

The forward backward tau polarization asymmetry is very clean.
Dependence on E_{CM} same as A_{LR} negl.
At FCC-ee
ALEPH data 160 pb^{-1} (80 s @ FCC-ee !)

Already syst. level of 6 10^{-5}on $\sin^2\theta^{eff}_W$
much improvement possible
by using dedicated selection
e.g. tau→ π ν to avoid had. model



4.7: The values of $\mathcal{P}_\tau$ as a function of $\cos\theta_{\tau^-}$ as measured by each of the LEP ex- ...nts. Only the statistical errors are shown. The values are not corrected for radiation, ...ence or pure photon exchange. The solid curve overlays Equation 4.2 for the LEP values of $\mathcal{A}_\tau$ and $\mathcal{A}_e$. The dashed curve overlays Equation 4.2 under the assumption of lepton universality for the LEP value of $\mathcal{A}_\ell$.

	ALEPH		DELPHI		L3		OPAL	
	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$
ZFITTER	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
τ branching fractions	0.0003	0.0000	0.0016	0.0000	0.0007	0.0012	0.0011	0.0003
two-photon bg	0.0000	0.0000	0.0005	0.0000	0.0007	0.0000	0.0000	0.0000
had. decay model	0.0012	0.0008	0.0010	0.0000	0.0010	0.0001	0.0025	0.0005

Table 4.2: The magnitude of the major common systematic errors on $\mathcal{A}_\tau$ and $\mathcal{A}_e$ by category for each of the LEP experiments.

Concluding remarks

1. There are very strong arguments for precision energy calibration with transverse polarization at the Z peak and W threshold.

2. Given the likely loss in luminosity, and the intrinsic uncertainties in the extraction of the weak couplings, the case for longitudinal polarization is limited

➔ **We have concluded that first priority is to achieve transverse polarization** in a way that allows continuous beam calibration by resoenant depolarization

- this is all possible with a very high precision, both at the Z and the W. calibration at higher energies can be made from the data themselves at sufficient level.

- the question of the residual systematic error requires further studies of the relationship between beam energy and center-of-mass energy with the aim of achieving a precision of O(100 keV) on E_CM

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

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

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

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

Extracting physics from $\sin^2\theta^{lept}_W$

1. Direct comparison with m_Z

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

Uncertainties in m_{top}, $\Delta\alpha(m_z)$, m_H, etc….

$\Delta\sin^2\theta^{lept}_W$ ~ $\Delta\alpha(m_z)/3$ = 10^{-5} if we can reduce $\Delta\alpha(m_z)$ (see P. Janot)

2. Comparison with m_W/m_Z

Compare above formula with similar one:

$$\sin^2\theta_W\cos^2\theta_W = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_F\,m_Z^2}\cdot\frac{1}{1-\left(-\frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho + 2\frac{\cos^2\theta_W}{\sin^2\theta_W}\varepsilon_3 + \frac{c^2-s^2}{s^2}\varepsilon_2\right)}$$

Where it can be seen that **$\Delta\alpha(m_z)$** cancels in the relation.

The limiting error is the error on m_W.

For **Δm_W= 0.5 MeV this corresponds to $\Delta\sin^2\theta^{lept}_W = 10^{-5}$**

Will consider today the contribution of the Center-of-mass energy systematic errors

Today: step I, compare

ILC measurement of A_{LR} with 10^9 Z and P_{e-} =80%, P_{e+} =30%

FCC-ee measurement of $A_{FB}^{\mu\mu}$ and A_{FB}^{Pol} (τ) with 2.10^{12} Z

Comparing A_{LR} (P) and A_{FB} ($\mu\mu$)

Both measure the weak mixing angle as **defined** by the relation $A_\ell = \frac{(g^e_L)^2 - (g^e_R)^2}{(g^e_L)^2 + (g^e_R)^2}$

with $(g^e_L) = ½ - \sin^2\theta^{lept}_W$ and $(g^e_R) = -\sin^2\theta^{lept}_W$ $\quad A_\ell \approx 8(1/4 - \sin^2\theta^{lept}_W)$

$A_{LR} = A_e$

$A_{FB}^{\mu\mu} = ¾\, A_e A_\mu = ¾\, A_\ell^2$

-- $\mathbf{A_{FB}^{\mu\mu}}$ is measured using muon pairs (5% of visible Z decays) and unpolarized beams

-- $\mathbf{A_{LR}}$ is measured using all statistics of visible Z decays with beams of alternating longitudinal polarization

both with very small experimental systematics

-- **parametric sensitivity** $\frac{dA_{FB}^{\mu\mu}}{d\sin^2\theta^{lept}_W} = 1.73$ **vs** $\frac{dA_{LR}}{d\sin^2\theta^{lept}_W} = 7.9$

-- **sensitivity to center-of-mass energy** (w.r.t. m_Z) is larger for $A_{FB}^{\mu\mu}$

$$\frac{\partial A_{FB}^{\mu\mu}}{\partial\sqrt{s}} = 0.09/\text{GeV} \quad \textbf{vs} \quad \frac{\partial A_{LR}}{\partial\sqrt{s}} = 0.019/\text{GeV}$$

"an 80 MeV uncertainty in Ecm corresponds to a 1% error on A_{LR}" (relative error)

But of course $A_{FB}^{\mu\mu}$ benefits from much larger statistics and Ecm precision of circular collider

Measurement of A_{LR}

electron bunches	1⇐	2	3	4⇐
positron bunches	1	2⇒	3	4⇒
cross sections	σ_1	σ_2	σ_3	σ_4
event numbers	N_1	N_2	N_3	N_4

$$\sigma_1 = \sigma_u (1 - P^-_e A_{LR})$$

$$\sigma_2 = \sigma_u (1 + P^+_e A_{LR})$$

$$\sigma_3 = \sigma_u$$

$$\sigma_4 = \sigma_u [1 - P^+_e P^-_e + (P^+_e - P^-_e) A_{LR}]$$

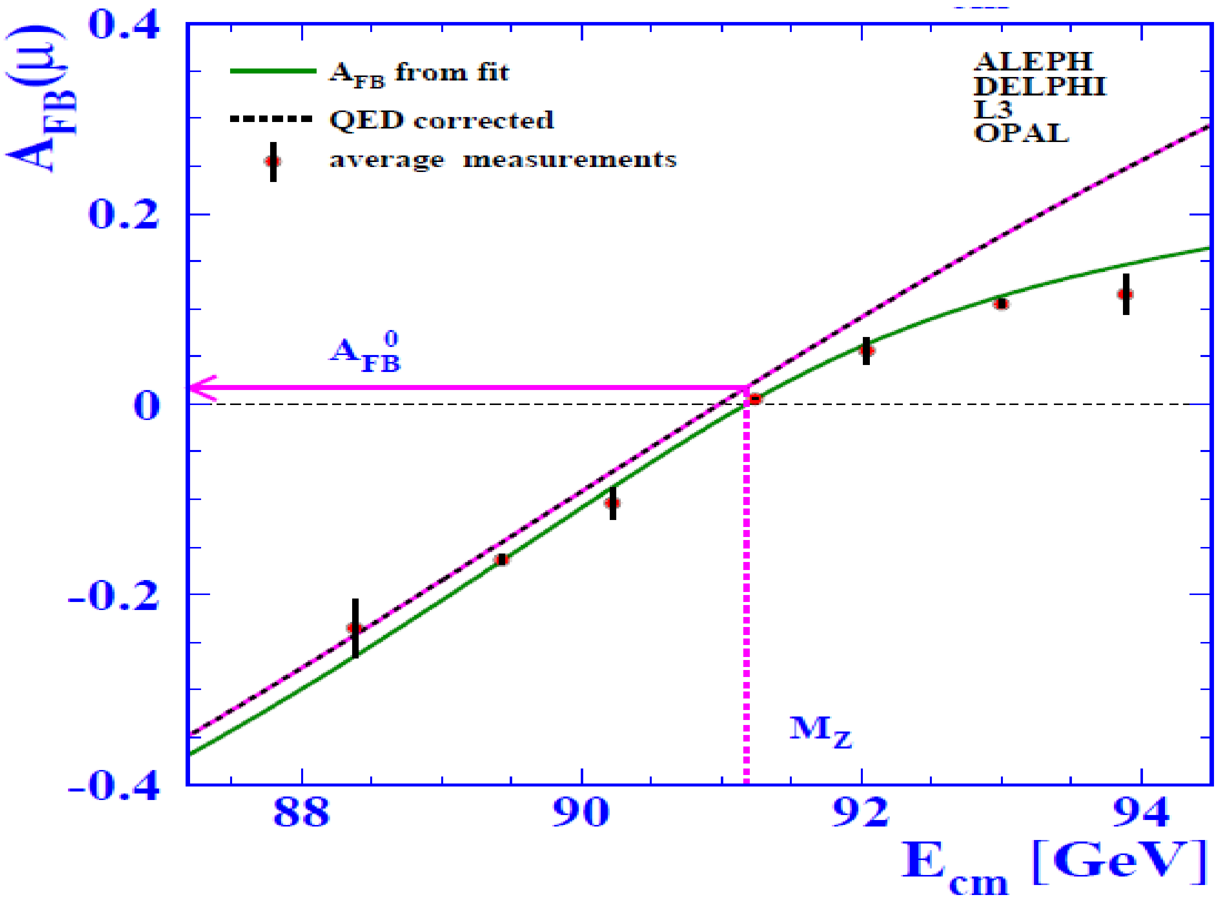
Verifies polarimeter with experimentally measured cross-section ratios

statistics

ΔA_{LR} = 0.0025 with about 10^6 Z^0 events,

ΔA_{LR} = 0.000045 with 5.10^{10} Z and 30% polarization in collisions.

$\Delta \sin^2\theta_W^{eff}$ (stat) = O(2.10^{-6})



$A_{FB}(\mu)$
0.4
0.2
0
-0.2
-0.4
A_{FB} from fit
QED corrected
average measurements
ALEPH
DELPHI
L3
OPAL
A_{FB}^{0}
M_Z
88
90
92
94
E_{cm} [GeV]

	$A_{FB}^{\mu\mu}$ @ FCC-ee		A_{LR} @ ILC	A_{LR} @ FCC-ee
visible Z decays	10^{12}	visible Z decays	10^{9}	5.10^{10}
muon pairs	10^{11}	beam polarization	90%	30%
$\Delta A_{FB}^{\mu\mu}$ (stat)	$3\ 10^{-6}$	ΔA_{LR} (stat)	$4.2\ 10^{-5}$	$4.5\ 10^{-5}$
$\Delta\ E_{cm}$ (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}	$5.9\ 10^{-5}$	
$\Delta \sin^2\theta^{lept}_W$	$5.9\ 10^{-6}$		$7.5\ 10^{-6}$	$6\ 10^{-6}$ +?

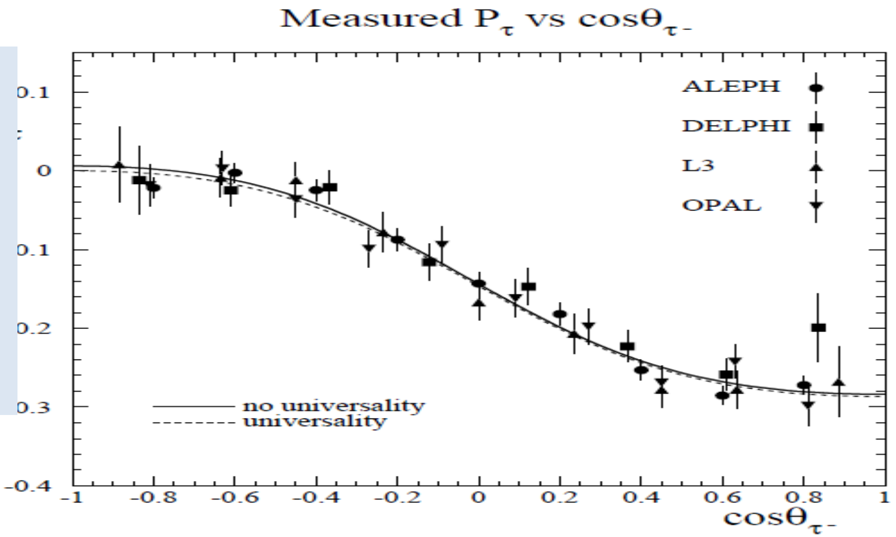
All exceeds the theoretical precision from $\Delta\alpha(m_Z)$ (310^{-5}) or the comparison with m_W (500keV)

But this precision on $\Delta \sin^2\theta^{\ell ept}_W$ can only be exploited at FCC-ee!

The forward backward tau polarization asymmetry is very clean.
Dependence on E_{CM} same as A_{LR} negl.
At FCC-ee

ALEPH data 160 pb^{-1} (80 s @ FCC-ee !)

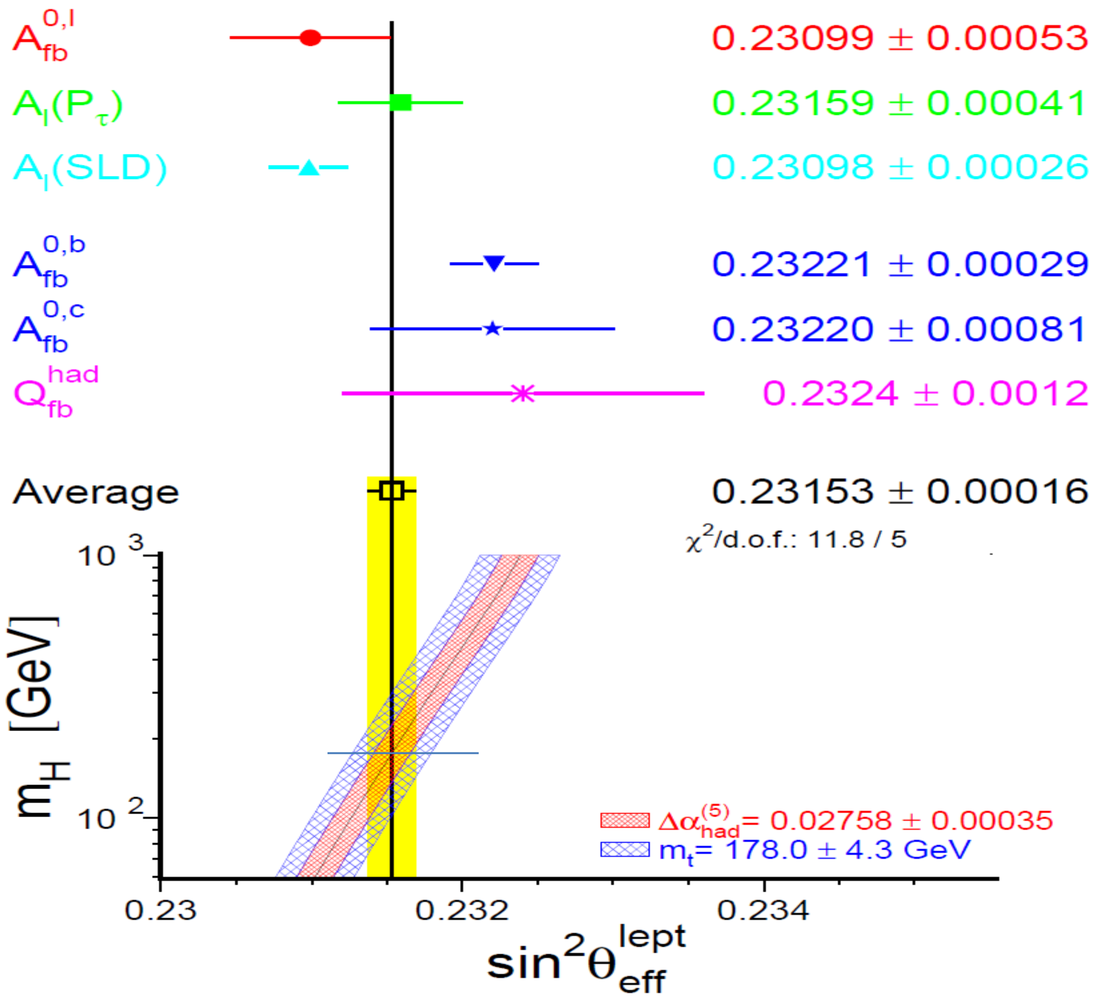
Already syst. level of 6 10^{-5} on $\sin^2\theta^{eff}_W$
much improvement possible
by using dedicated selection
e.g. tau→ π ν to avoid had. model



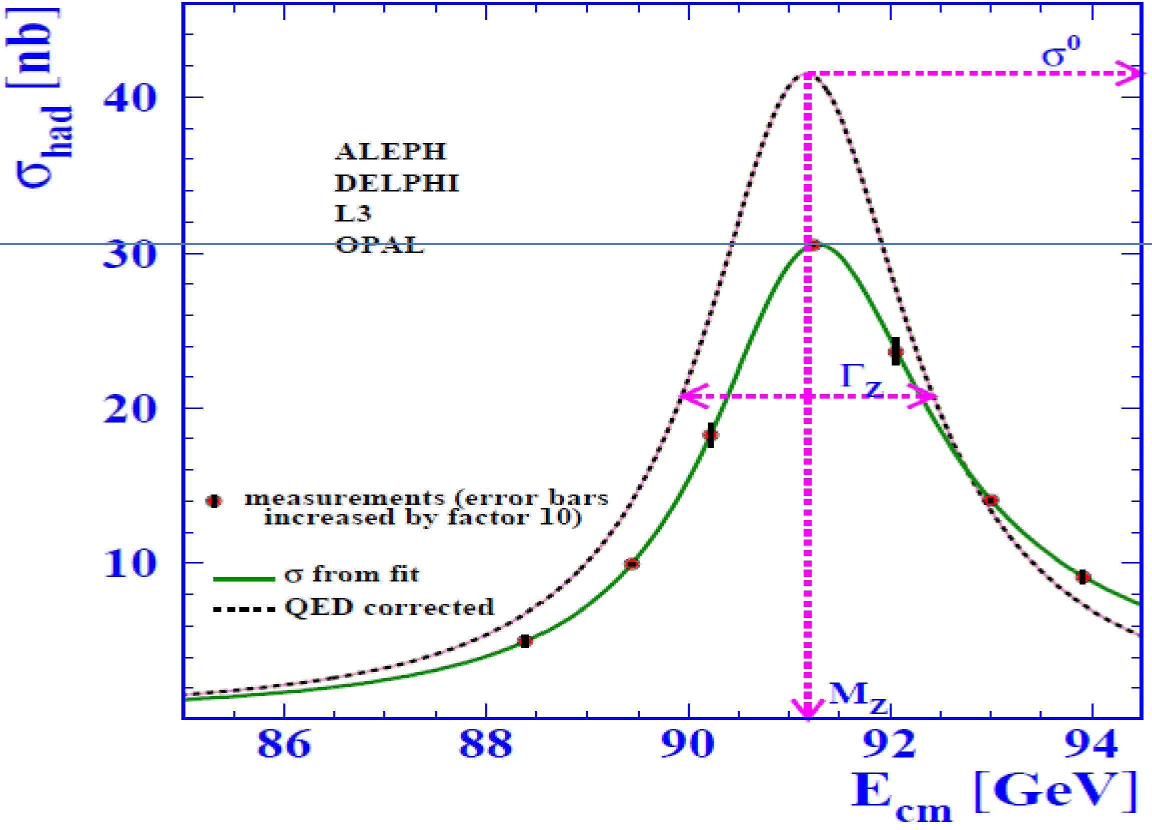
re 4.7: The values of $\mathcal{P}_\tau$ as a function of $\cos\theta_{\tau^-}$ as measured by each of the LEP ex- nents. Only the statistical errors are shown. The values are not corrected for radiation, ference or pure photon exchange. The solid curve overlays Equation 4.2 for the LEP val- of $\mathcal{A}_\tau$ and $\mathcal{A}_e$. The dashed curve overlays Equation 4.2 under the assumption of lepton ersality for the LEP value of $\mathcal{A}_\ell$.

	ALEPH		DELPHI		L3		OPAL	
	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$
ZFITTER	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
τ branching fractions	0.0003	0.0000	0.0016	0.0000	0.0007	0.0012	0.0011	0.0003
two-photon bg	0.0000	0.0000	0.0005	0.0000	0.0007	0.0000	0.0000	0.0000
had. decay model	0.0012	0.0008	0.0010	0.0000	0.0010	0.0001	0.0025	0.0005

Table 4.2: The magnitude of the major common systematic errors on $\mathcal{A}_\tau$ and $\mathcal{A}_e$ by category for each of the LEP experiments.



$A_{fb}^{0,l}$ 0.23099 ± 0.00053
$A_l(P_\tau)$ 0.23159 ± 0.00041
A_l(SLD) 0.23098 ± 0.00026
$A_{fb}^{0,b}$ 0.23221 ± 0.00029
$A_{fb}^{0,c}$ 0.23220 ± 0.00081
Q_{fb}^{had} 0.2324 ± 0.0012
Average 0.23153 ± 0.00016
χ^2/d.o.f.: 11.8 / 5
10^3
10^2
m_H [GeV]
$\Delta\alpha_{had}^{(5)}$ = 0.02758 ± 0.00035
m_t = 178.0 ± 4.3 GeV
0.23
0.232
0.234
$\sin^2\theta_{eff}^{lept}$



σ_had [nb]
40
30
20
10
ALEPH
DELPHI
L3
OPAL
σ⁰
Γ_Z
M_Z
measurements (error bars increased by factor 10)
σ from fit
QED corrected
86
88
90
92
94
E_cm [GeV]

Going through the observables

the weak mixing angle as **defined** by the relation

$$A_\ell = \frac{2 g^e{}_V \, g^e{}_A}{(g^e{}_V)^2 + (g^e{}_A)^2} = \frac{(g^e{}_L)^2 - (g^e{}_R)^2}{(g^e{}_L)^2 + (g^e{}_R)^2}$$

with $(g^e{}_L) = ½ - \sin^2\theta^{lept}{}_W$ and $(g^e{}_R) = -\sin^2\theta^{lept}{}_W$

$A_\ell \approx 8(1/4 - \sin^2\theta^{lept}{}_W)$ very sensitive to $\sin^2\theta^{lept}{}_W$!

Or

$A_{LR} = A_e$ measured from $(\sigma_{vis,L} - \sigma_{vis,R}) / (\sigma_{vis,L} - \sigma_{vis,R})$

(total visible cross-section had + $\mu\mu$ + $\tau\tau$, (35 nb) for 100% Left Polarization

$$g_{Vf} = \sqrt{\mathcal{R}_f}\,(T_3^f - 2Q_f\mathcal{K}_f \sin^2\theta_W)$$

$$g_{Af} = \sqrt{\mathcal{R}_f}\,T_3^f \,.$$

$A_{FB}{}^{\mu\mu} = ¾ A_e A_\mu = ¾ A_\ell^2$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \frac{1}{\langle|\mathcal{P}_e|\rangle}$$

$$A_{LRFB} = \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} \frac{1}{\langle|\mathcal{P}_e|\rangle} \,.$$

$$A_{FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

$$A_{LR}^0 = \mathcal{A}_e$$

$$A_{LRFB}^0 = \frac{3}{4}\mathcal{A}_f$$

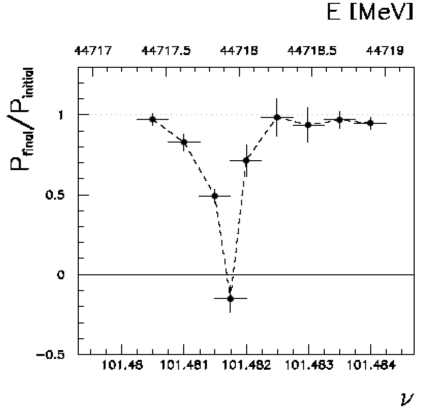
$$\langle\mathcal{P}_\tau^0\rangle = -\mathcal{A}_\tau$$

$$A_{FB}^{pol,0} = -\frac{3}{4}\mathcal{A}_e \,.$$

Beam polarization and E-calibration

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.

but measurement only performed at the end of fills (and only for e-!)

lots of effects (tides, trains, lake level, rain (…and tears) in data vs calib!

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

At LEP a beam energy spread σ_E > 55 MeV destroyed polarization above 61 GeV

$\sigma_E \propto E^2/\sqrt{\rho}$ ➔ *At FCC-ee transverse polarization up to > 81 GeV (WW threshold)*

FCC-ee: use 'single' pilot 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