Future Circular Collider Technical and Financial Feasibility Study
2d FCC Energy Calibration, Polarization and Mono-chromatisation workshop

LEP Polarization

FCC EPOL WORKSHOP

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19-30 September 2022 at CERN

https://indico.cern.ch/e/EPOL2022

remote participation possible

Context

This presentation relies on my memory of the LEP times consolidated by some old papers that I used to cross-check my memories with.

- Some bias cannot be excluded.

The focus of this presentation is on the **polarization program around the Z resonance** (E_{beam} = 46.5 ± 2 GeV).

- The program of polarization at 50-60 GeV is worth a separate discussion...

LEP overview

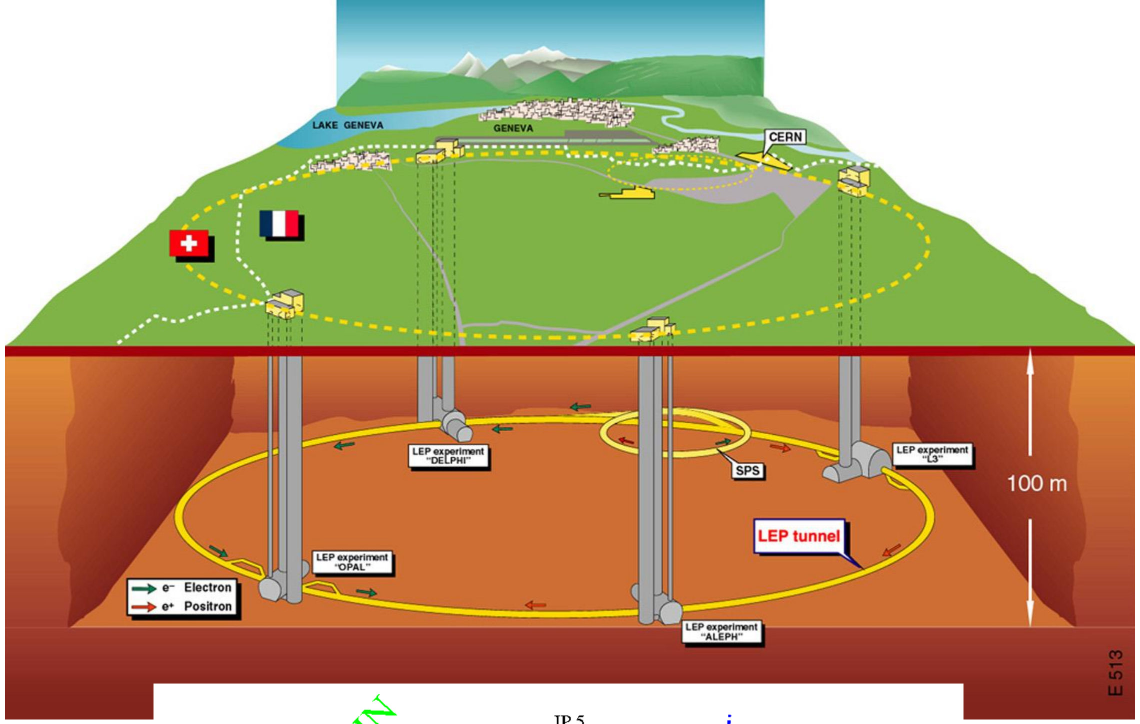
LEP was installed in what is now the LHC tunnel with a circumference of 26.7 km.

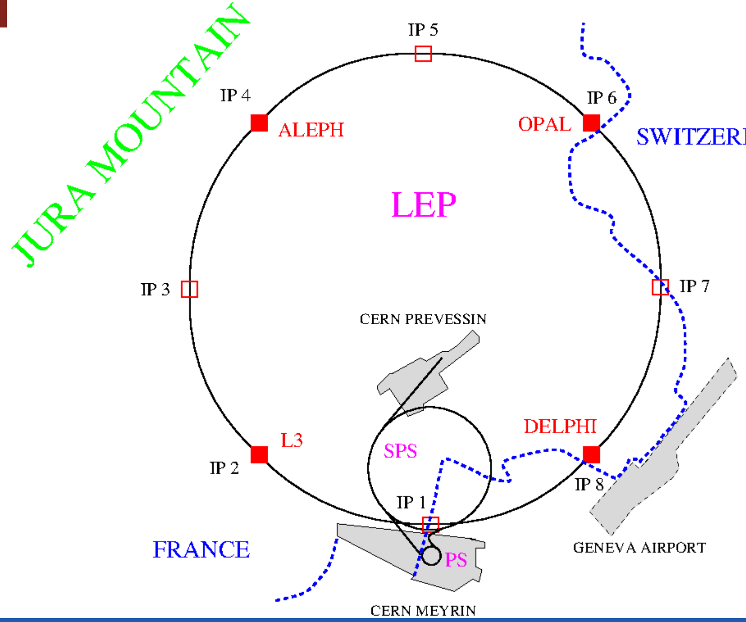
The tunnel had(s) 8 access points arranged symmetrically around the ring.

- 4 experiments installed at the even points.

LEP operated colliding beams over a beam energy range of ~43 GeV to 104.5 GeV.

- 4-12 bunches per beam.
- e+ and e- beams in the same vacuum chamber.





The LEP polarization program

Main ingredients of the LEP polarization program:

- **Polarization and energy calibration studies** during machine experiment periods (MDs).
  - Typically a few periods / year, with time slots of ~ 24+ hours (it is a slow process!).
  - Initially focused around 45 GeV, later up to 60 GeV (success) and beyond (no success).
- **Energy calibrations** during regular operation for precise determination of the beam energy as input to Z boson mass and width, W mass measurements.
  - For the Z program, the energy calibration sessions took place at the **END** of the fills, after the physics data taking.
  - The **two main runs** with regular energy calibration by RDP for the precise determination of Z mass and width took place in **1993** and in **1995**.

Energy choice – Z

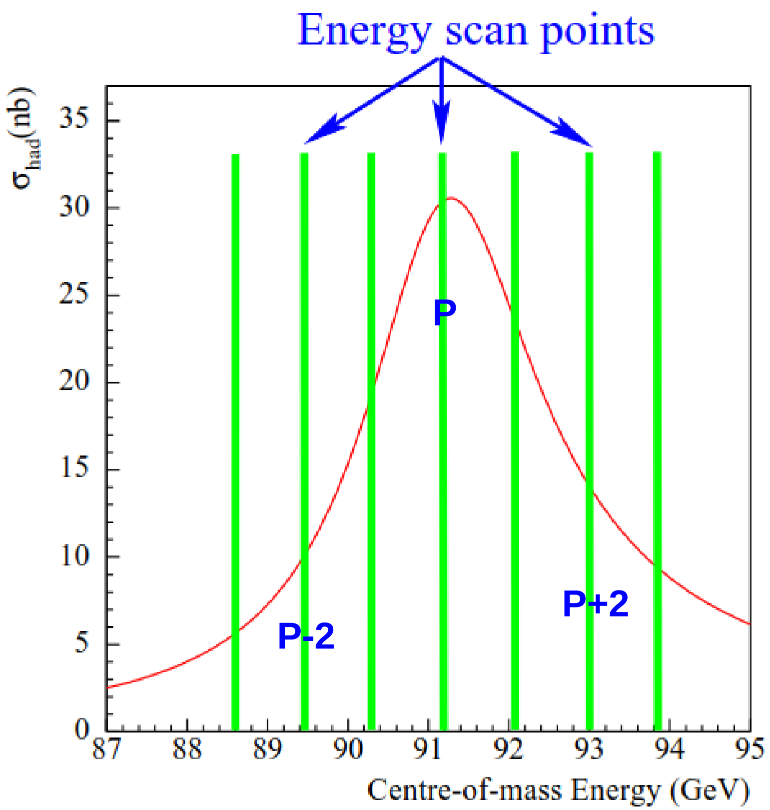
For the energy calibration program around the Z boson resonance, **3 energy points** were used:

- "**Peak**" (P) : ν = 103.5 ~Z peak
- "**Peak-2**" (P-2) : ν = 101.5
- "**Peak+2**" (P+2) : ν = 105.5
- Optimum choice for best Z yield and Z mass/width measurements.

The **P-2 point** was used for most **studies** around the Z due to a larger distance to the systematic resonance at ν = 104.

- LEP systematic resonances at ν = INT(Qy) + k×S where S = 4, 8 (LEP super-periodicity),
- Vertical tune for 90°/60° optics used around Z : Q_y = 76.xx.

Natural polarization time at the Z (P) : **τ_P ~320 minutes**.



Vertical lines: ν = N + 0.5

Machine configuration for polarization

Transverse polarization was **never established during regular colliding beam periods** for experiments data taking.

- **Polarization with colliding beam** was only tested in few dedicated machine experiments.
- **Energy calibration at end of fills with non-colliding beams** (transverse separation at IPs).

Differences between **collision** and **polarization configurations**:

- Orbit (correction),
- **Solenoid compensation bumps** (when exp solenoids were on),
- **Harmonic Spin Matching** (HSM) bumps,
  - Deterministic and experimentally optimized corrections.
- Tunes,
- Emittance control and damping wigglers switched OFF.

For end of fill energy calibration by RDP, beams were re-separated and the polarization configuration was then applied (transition took ~ 30-40 minutes).

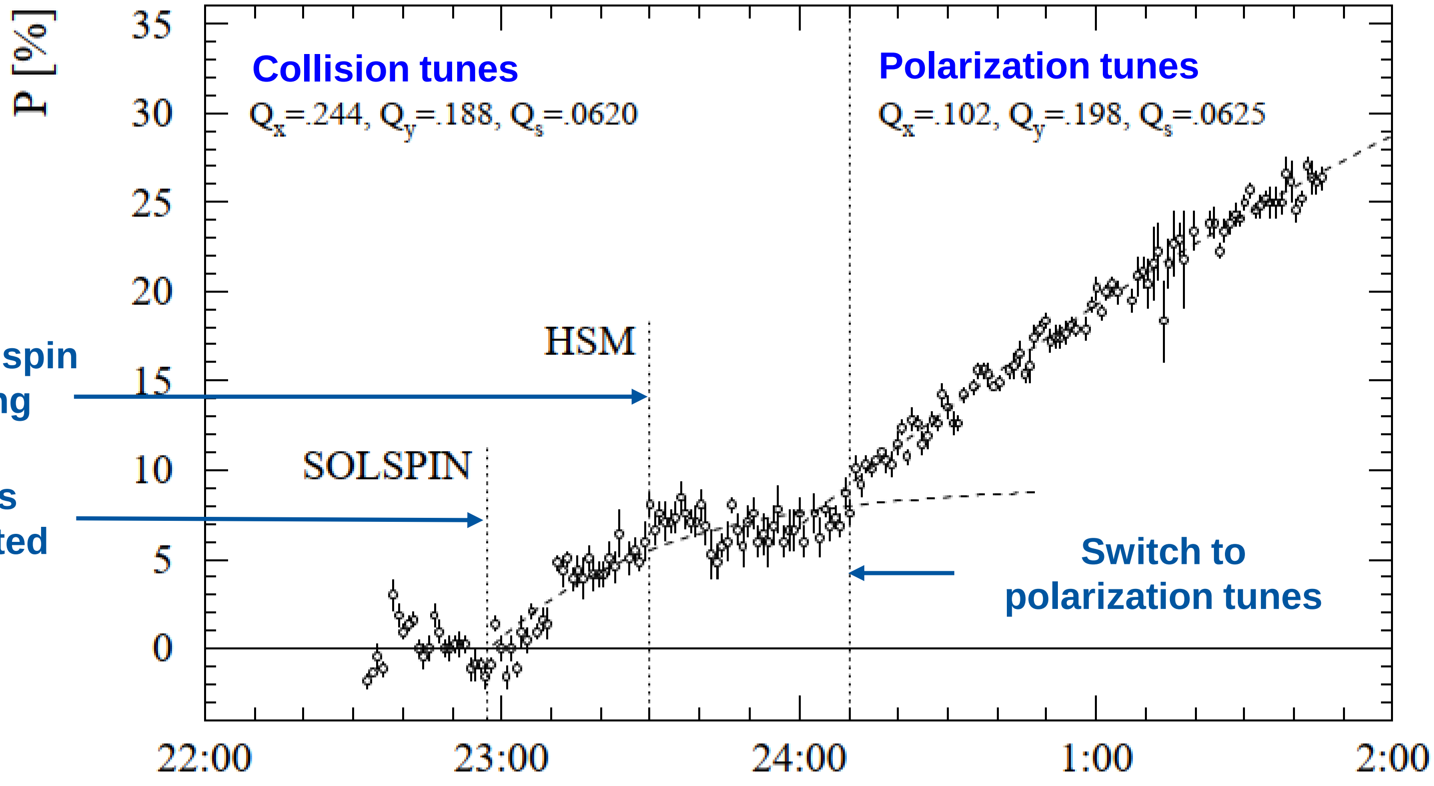
Tunes

Around the Z resonance, optimized fractional tunes for polarization : **Q_x = 0.1, Q_y = 0.2, Q_s = 0.0625**

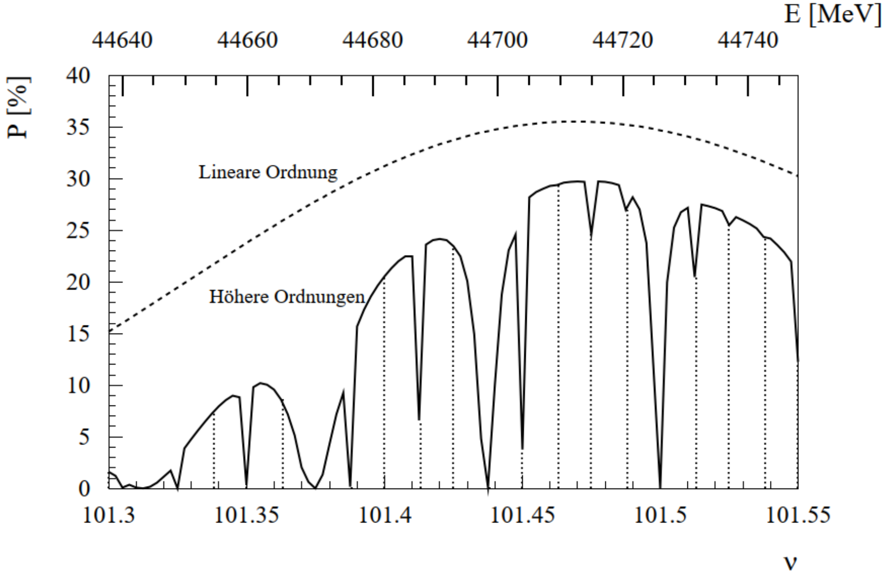
Collision tunes were not favorable for transverse polarization

Harmonic spin matching

Solenoids compensated



Simulation (SODOM) for polarization tunes



PhD R. Assmann (1994)

Solenoid compensation

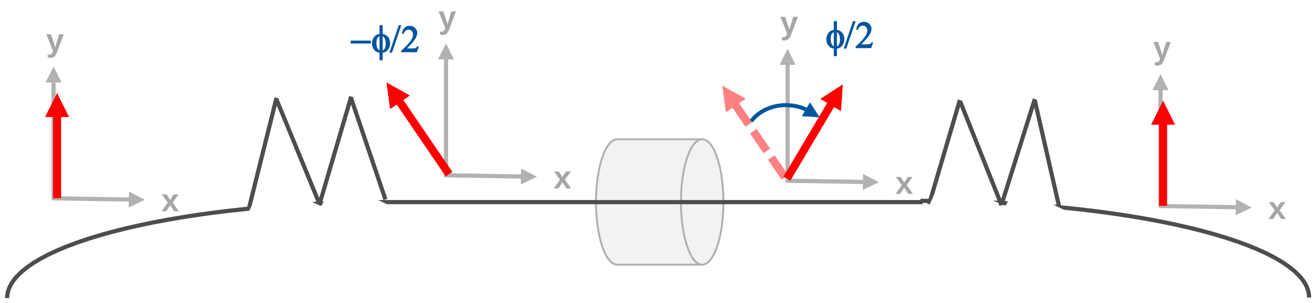
The integrated strength of the 4 LEP experimental solenoids ranged from **2.6 Tm** to **10 Tm** (ALEPH).

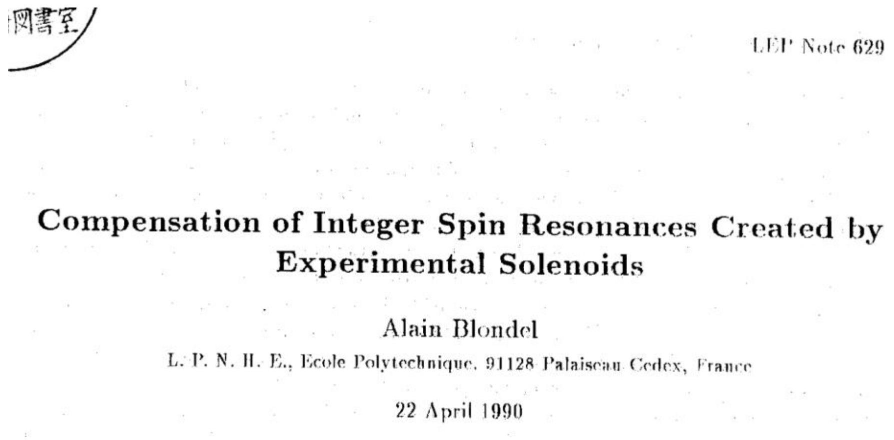
- The spin rotation due to the ALEPH solenoid was 66 mrad at the Z.

If uncompensated the solenoids prevent any polarization build-up.

The **solenoid compensation scheme** relied on **π-bump pairs** at the entrance to the arcs on either side of each solenoid to restore the spin axis in the curved sections.

- LEP used skew quadrupoles to compensate the coupling of the solenoids (not anti-solenoids).
- Each bump pair rotates the spin vector by ½ of the angle of the solenoid = ϕ.
- Using a pair of π-bumps reduces the impact on vertical dispersion.
- For the ALEPH solenoid the bump amplitude was ~6 mm at the Z.




LEP Note 629

Compensation of Integer Spin Resonances Created by Experimental Solenoids

Alain Blondel

L. P. N. H. E., Ecole Polytechnique, 91128 Palaiseau Cedex, France

22 April 1990

Harmonic Spin Matching

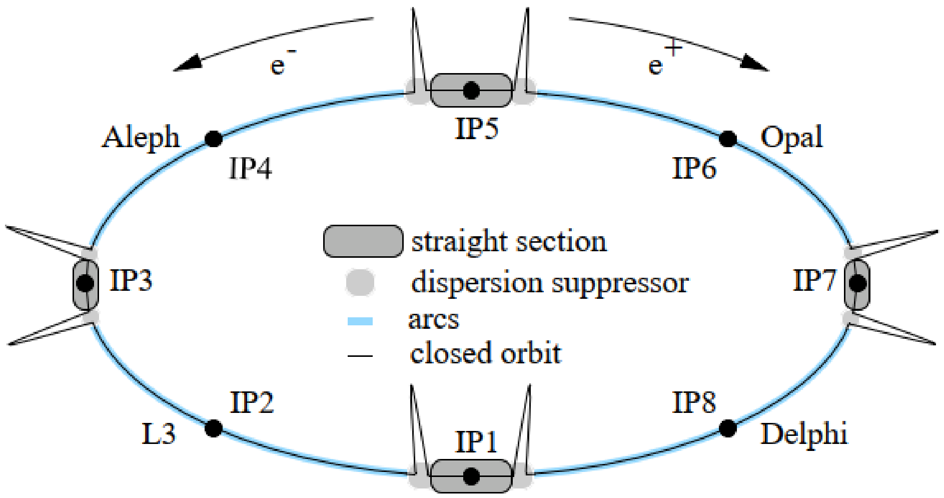
The aim of harmonic spin matching is the compensation of the n-vector deviation from the vertical by the introduction of orbit bumps acting on the harmonics close to the spin tune ν.

- The dominant harmonics are coming from the 2 nearest integers to ν i.e., for $\nu = 103.5$, the 103 and 104 harmonic are the most harmful.

At LEP 8 vertical π-bumps distributed around the arcs were used to generate **4 orthogonal compensation bump** combinations: the sinus/cosinus phases for the two closest harmonics.

Two compensation techniques were used:

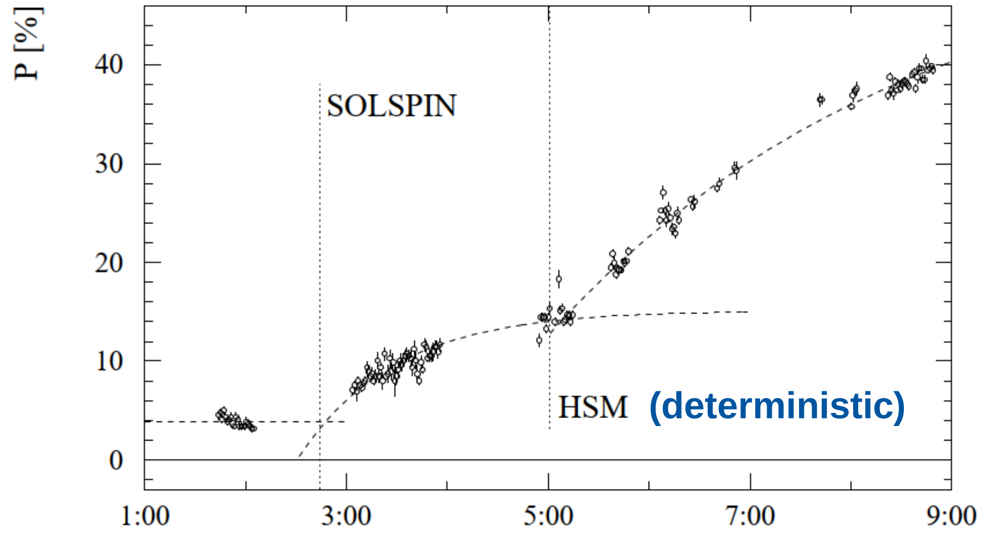
- **Deterministic HSM**: the strength of the harmonics was obtained from a **Fourier analysis of the BPM readings**, and the correction was applied **deterministically** based on the measured orbit.
- **Empirical HSM**: the strength of each orthogonal bump is varied, the response of the polarization is used to predict a correction, applied iteratively (today called Machine Learning…).

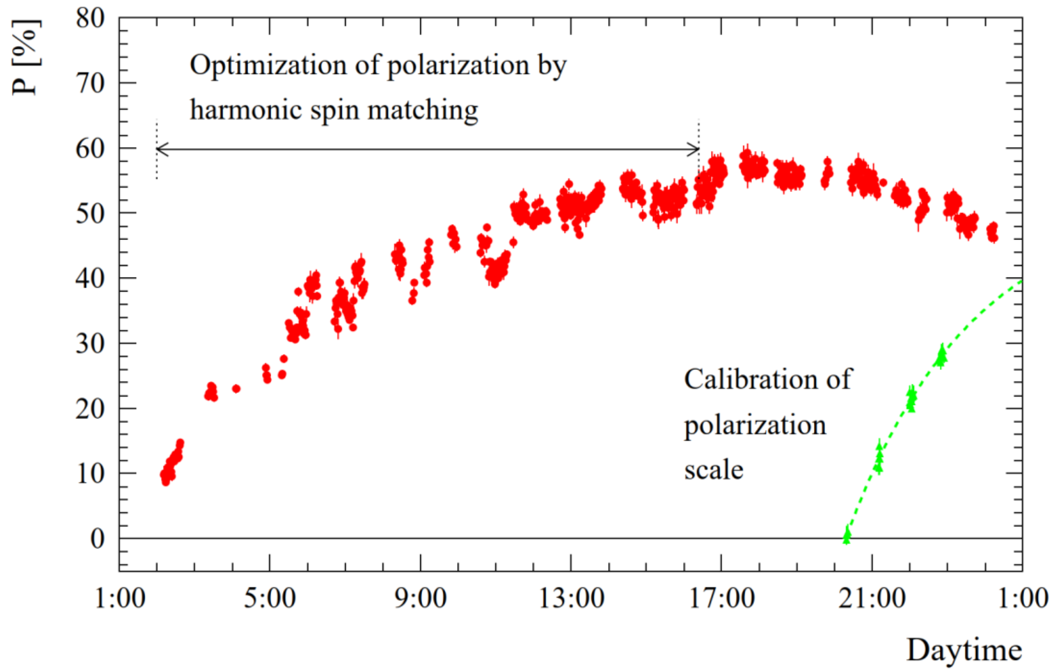


HSM example

With HSM the polarization at LEP was pushed to a **record of 57%** at the P-2 energy.

Deterministic HSM worked extremely well on some occasions (for example the 1993 MDs), but for the day-to-day energy calibrations, the results were less reproducible, achieving limited gains.





Polarization for day-to-day energy calibration

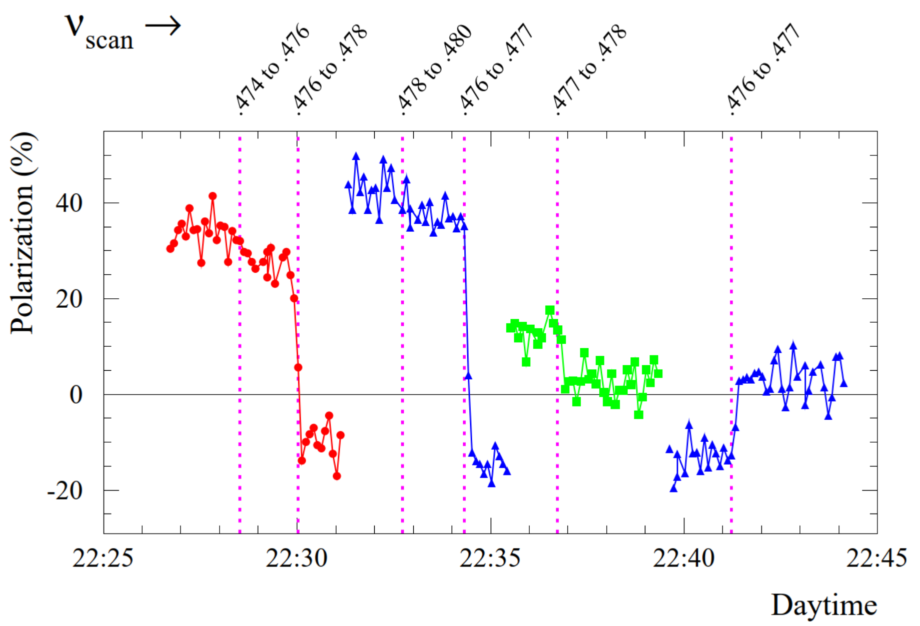
The regular end-of-fill (EoF) energy calibrations followed the recipe:

- **Re-separation of the beams at the 4 IPs.**
- **Switch tunes to optimum polarization tunes.**
- **Correct the orbit.**
- **Apply solenoid compensation bumps.**
- **Apply deterministic HSM.**

Observe polarization build-up and start the RDP scans to determine the beam energy.

As far as I can remember, we always observed polarization with **asymptotic values of ~4% to ~20%.**

- **Large scatter of polarization values, deterministic HSM not always successful / efficient**.
- 3-4% of polarization were sufficient for an energy calibration.



*The colors refers to different bunches, in one case (**blue**) the polarization is flipped, and flipped polarization is used to re-depolarize a second time .*

1 point every ~ 8 seconds.

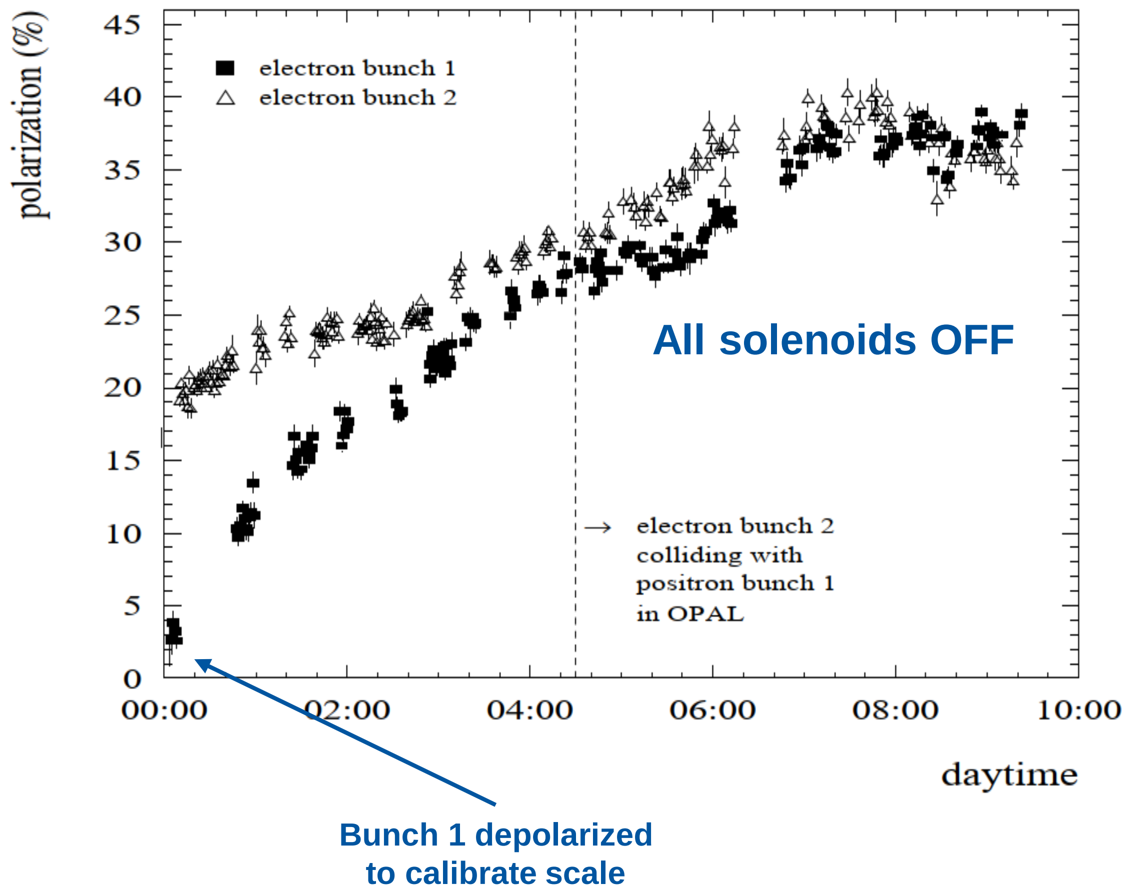
Polarization and collisions

In 1994 two experiments were performed to study **polarization with colliding beams**.

The results were encouraging (after deterministic & empirical HSM) for a **SINGLE** **collision point**:

- P_T ~**40%** for **vertical BB tune shift ~0.04** with **solenoids OFF,**
- P_T ~**20%** for **vertical BB tune shift ~0.037** with **solenoids ON.**
- Both exp with polarization tunes.

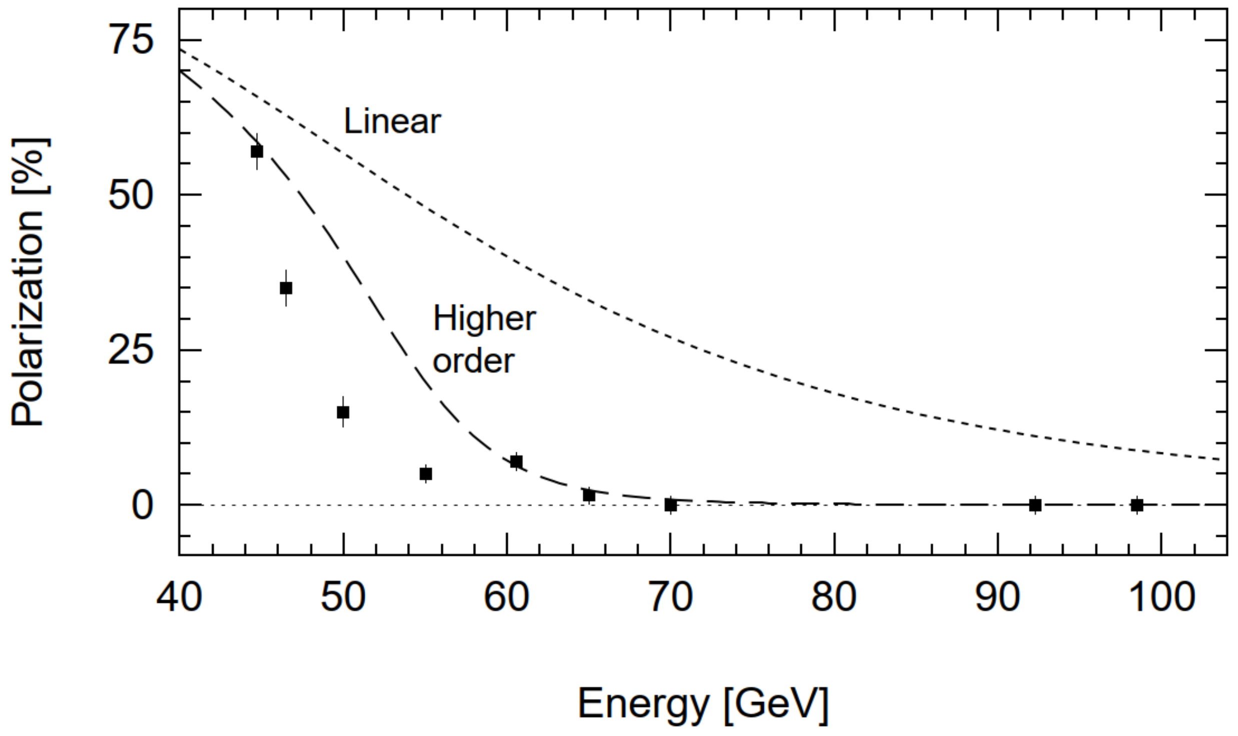
But there was no “follow up”: the 1995 energy calibration campaign was performed with measurements at EoF.



Polarization above the Z @ LEP

The quest for polarization above the Z took many years to converge with the observation of a few % of polarization at 60 GeV.

Polarization observations and RDP at 50, 55 and 60 GeV were used to minimize the lever arm for the extrapolation of the beam energy to 80 GeV for the W mass measurement.



Summary

Around the Z resonance transverse polarization was **established routinely** for **energy calibration** with non-colliding beams.

The program was very successful for energy calibration of the beams backed by a solid energy model.

Some studies of polarization with colliding have been performed but were never pushed to a state of operation for physics – this would have required spin rotators to establish longitudinal polarization.