Collision-energy calibration above the Z

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With thanks to the EPOL group,
and including much material from
Ivan Koop and Patrick Janot

Introduction and overview

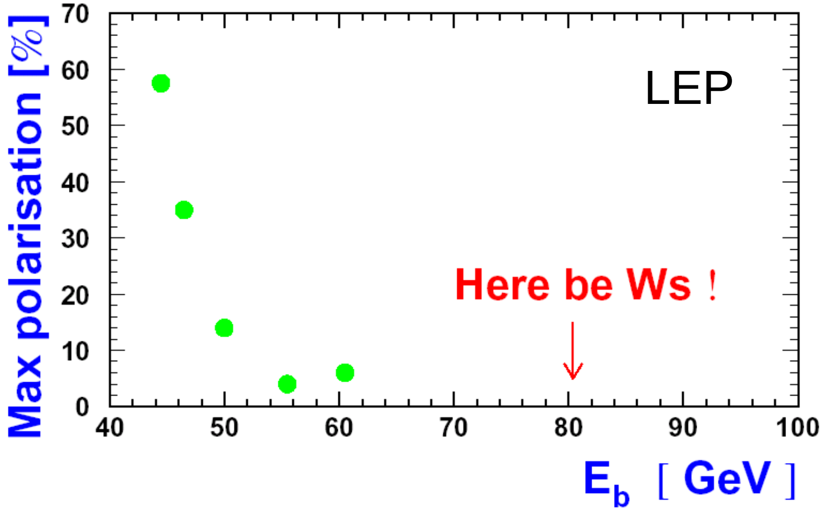
Attention of EPOL group quite rightly focused on the Z pole, where the statistical might of FCC-ee poses the most intimidating systematic demands. However, many important physics measurements exist at higher energies, where knowledge and control of E_{CM} are also vital. Here we review challenges and possible solutions.

- Historical precedent: E_{CM} calibration above the Z at LEP2
- Review of foreseen operational points, & physics requirements at each
- Resonant depolarisation & free spin precession measurements at high energy
- Energy calibration from the experiments – radiative returns
- The need for a reliable energy model
- Other methods to track the beam energy

E_{CM} calibration above the Z – historical precedent

Collision-energy determination of FCC-ee at the Z^0 will be exceedingly demanding, given the statistical precision foreseen. But the calibration of the data sets at higher energies present their own problems. This is reminiscent of LEP2 days.

There, statistical uncertainty on m_W mandated 10^{-4} precision on E_b. Surely easy given what has been achieved for Z-scan campaign ? Not at all !



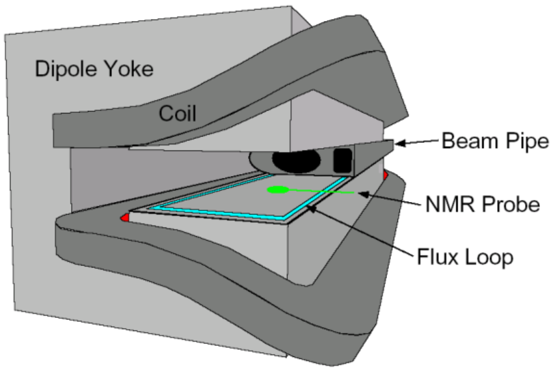
No resonant depolarisation possible in the W regime at LEP, so no direct beam-energy calibration possible.

Instead, necessary to use relative techniques, normalising each to direct measurements at lower energies.

Methods of relative energy calibration at LEP2

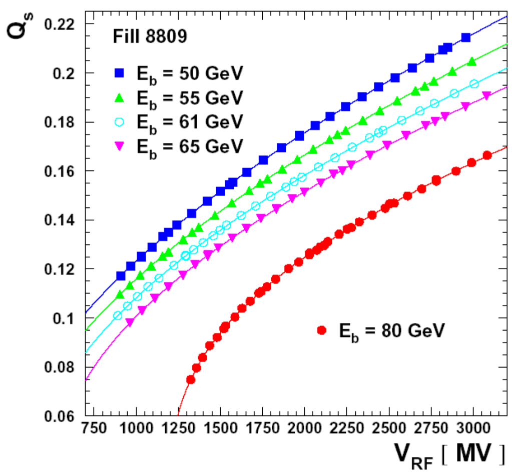
Three methods used to calibrate energy scale in going from low to high energy.

Flux loop



Flux loop samples (almost all) of dipole field, unlike selective NMR probes.

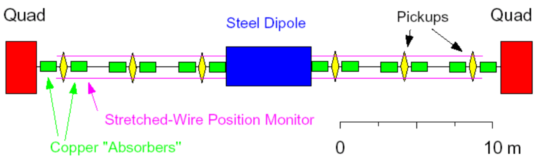
Synchrotron tune vs V_{RF}



$Q_s^2 \sim (1/E_b) \sqrt{(e^2 V_{RF}^2 - U_0^2)}$

U_0 = energy loss / turn – also depends on E_b

In-line spectrometer



Measure change in bending angle from low to high energy in custom dipole of known ∫B.dl

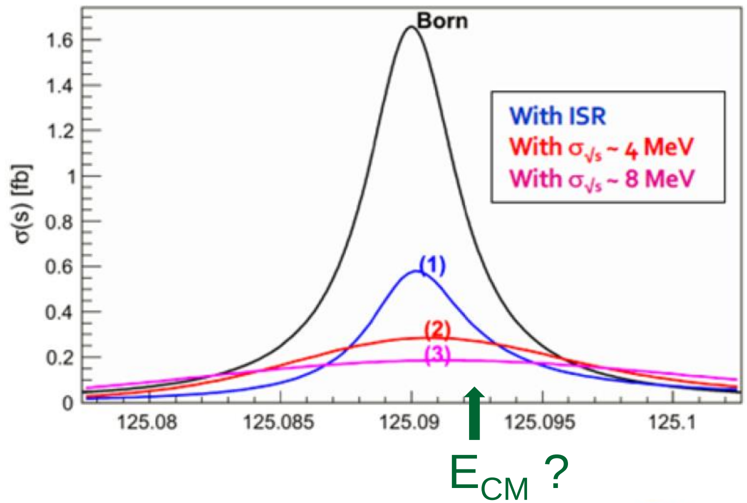
Gave compatible results, with precision of 10 MeV at E_b=100 GeV [EPJC 39 (2005) 253].

None of these approaches (yet) proposed for FCC-ee, but story functions as a reminder how much attention needs to be invested in such a task.

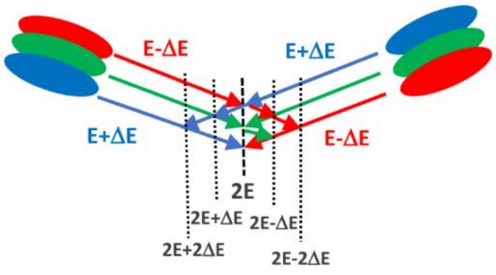
Measuring g_{Hee} at E_{CM}=125 GeV

Although not in the baseline plan, studies are ongoing about the possibility of scheduling a run at 125 GeV in order to measure the electron Yukawa. For this to be feasible, monochromatization needed (see Z. Zhang talk). In addition….

- Must know what energy to run at. Requires good m_H knowledge from 240 GeV run;
- We must know our E_{CM} in the offline analysis to much better than Γ_H ~ 4 MeV. RDP feasible, but there's a subtlety…;
- We must know E_{CM} with <10 MeV precision in real time, to ensure we don't drift from resonance. Require reliable energy model (developed at Z) &/or instantaneous relative measurement.



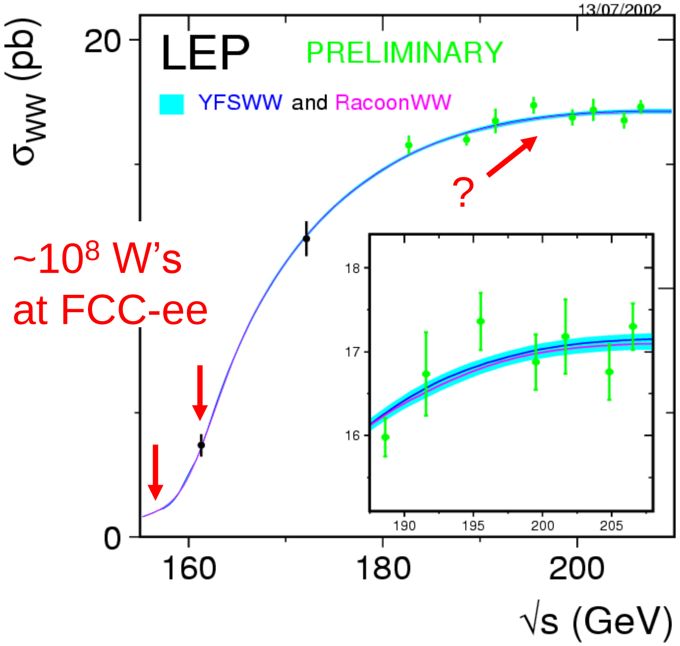
[d'Enterria *et al.*, EPC+ 137 (2022) 201]

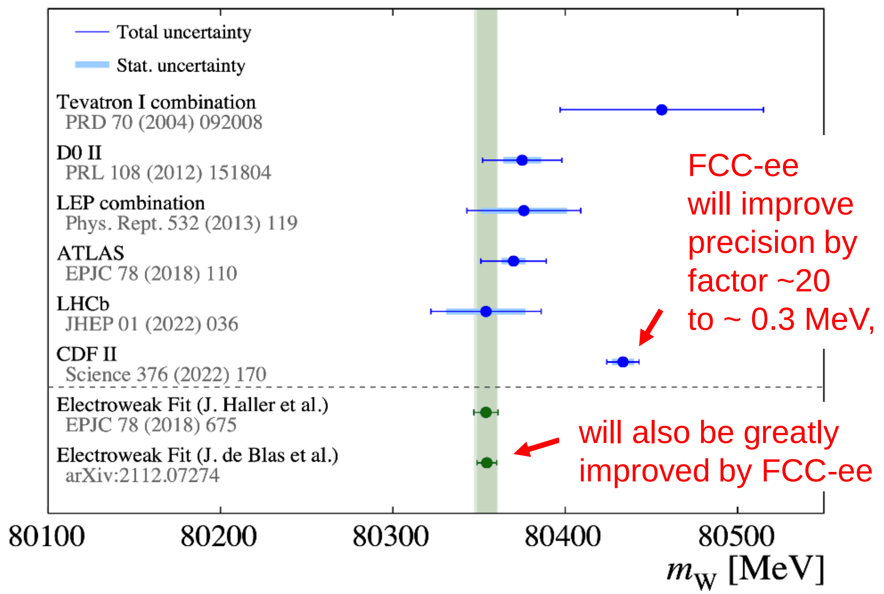


A possible monochromatization scheme.

Measuring m_W and Γ_W at E_{CM}~160 GeV

Measurement of mass and width of W boson a critical goal of FCC-ee, This has been given added impetus by recent surprising measurement from CDF.





[Azzurri, EPJC+ 136 (2021) 1203]

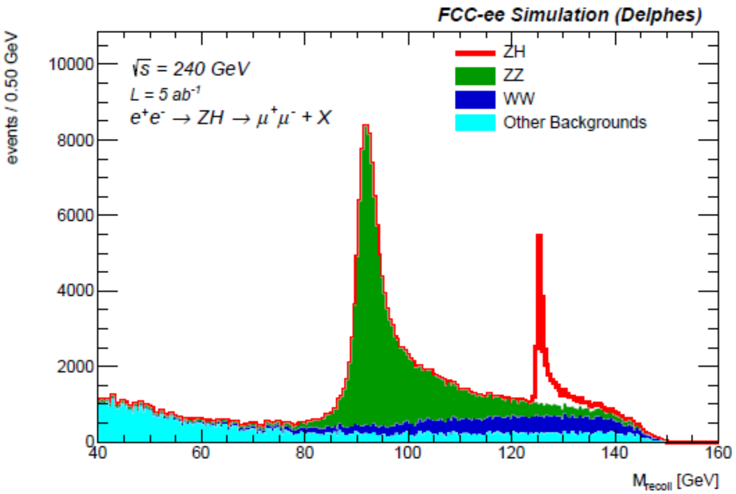
Strategy will be to determine parameters from cross-section measurements at threshold. With foreseen statistical power would need to know E_{CM} to ~350 keV. Unlike at LEP, here RDP should be feasible. Do we also need to keep in mind the possibility of running at 180-200 GeV for direct reconstruction technique ?

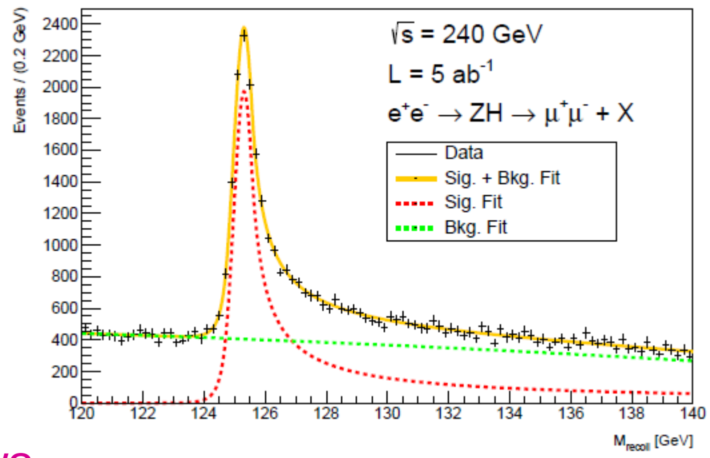
As at Z^0, also necessary to have good knowledge of E_{CM} spread (to ~10%).

Measuring m_H at E_{CM}=240 GeV

Why perform a precise measurement of m_H ?

- It's a parameter of nature;
- Any uncertainty induces a parametric uncertainty in interpretation of several other EW observables at FCC-ee
  $\rightarrow \sigma(M_H) \sim$ 10 MeV probably sufficient;
- We need to know where Higgs is if we perform run at $E_{CM} = m_H$
  $\rightarrow \sigma(M_H) < \Gamma_H \sim$ 4 MeV.





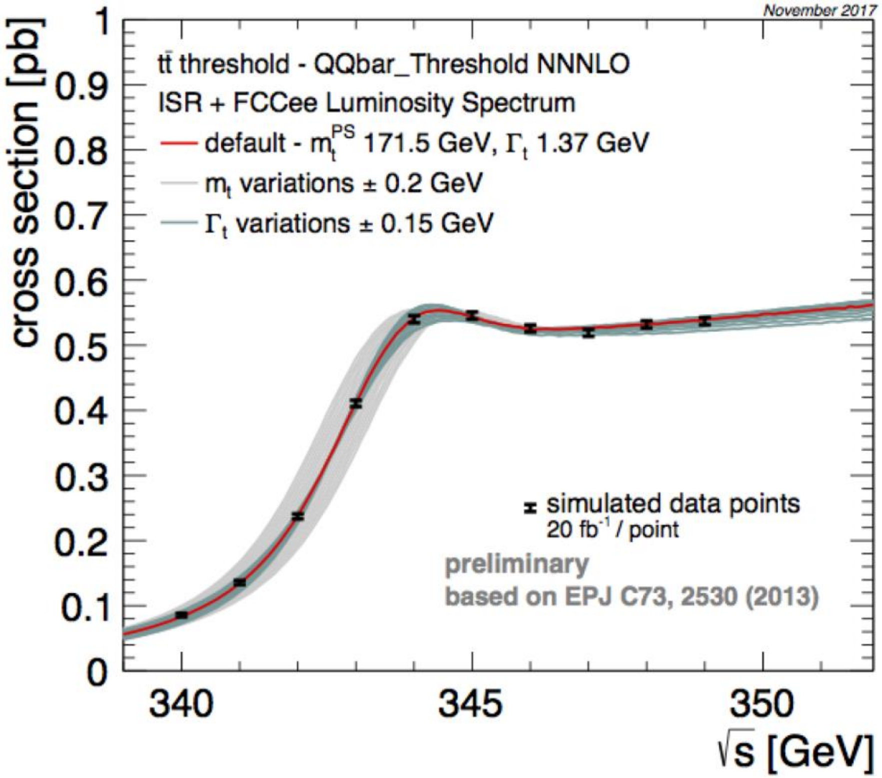
[Azzurri *et al.*, EPC+ 137 (2021) 23]

Recoil mass of ZH events at 240 GeV, with Z reconstructed in *e.g.* $\mu^+\mu^-$ or e^+e^-, gives sharp distribution peaking at m_H.

Current studies [Li *et al.*, FCC Physics Week 2023], suggest statistical uncertainty of ~4 MeV with two IPs. Must ensure E_{CM} contribution much less than this! No RDP possible.

Measuring m_t and Γ_t at E_{CM} = 340-350 GeV

Multi-point threshold scan with 20 fb^{-1} / point will determine m_t to ~17 MeV.



E_{CM} knowledge of ~10 MeV / point → m_t uncertainty of 3 MeV. No RDP possible.

Resonant Depolarisation (RDP) at $E_{CM} \approx 125$ GeV

Higgs pole is not a big step up in energy from Z, and so RDP fine in principle.

However...

H $J = 0$

was H^0

Mass $m = 125.25 \pm 0.17$ GeV (S = 1.5)
Full width $\Gamma = 3.2^{+2.4}_{-1.7}$ MeV (assumes equal on-shell and off-shell effective couplings)

…current central value of Higgs mass is two sigma away from a half spin tune, with $\nu_s = 142.12 \pm 0.19$. If this persists, would need to run with asymmetric beams to recover optimal situation for RDP – likely boost required ~150 MeV.

Resonant Depolarisation (RDP) at $E_{CM} \approx 161$ GeV

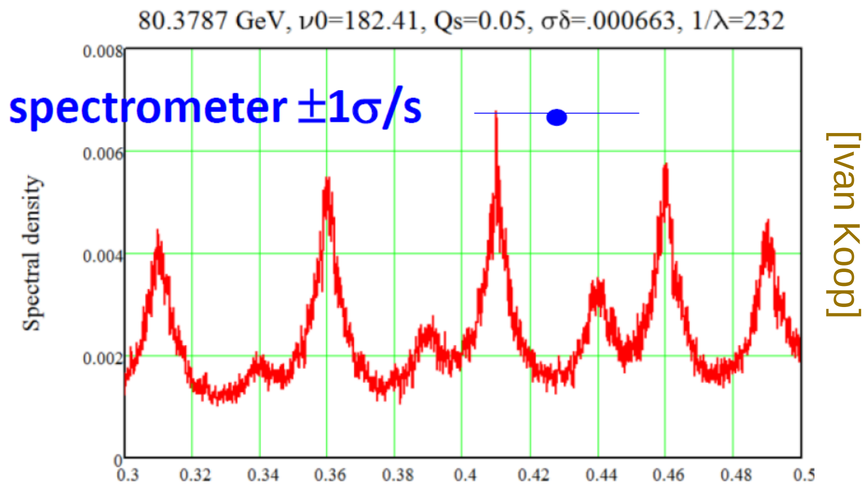
Polarisation above the Z inhibited by larger energy spread of the beams. However, greater magnetic bending radius of FCC vs LEP means that we can hope for measurable levels in W^+W^- regime, probably without wigglers (polarisation time ~16x quicker than Z), but work will be required to suppress depolarising effects.

Even if polarisation achieved, challenges remain…

Energy diffusion broadens all peaks in Fourier space, including Q_s side bands, making any RDP signal less sharp.

For these effects not to dominate, the spin-modulation index *B*, should satisfy:

$$B = \frac{\upsilon_0 \sigma_E}{Q_S} < 1.5$$



Not the case in this study ($B\approx2.2$), but OK in current W^+W^- optics with $Q_s \approx 0.081$.

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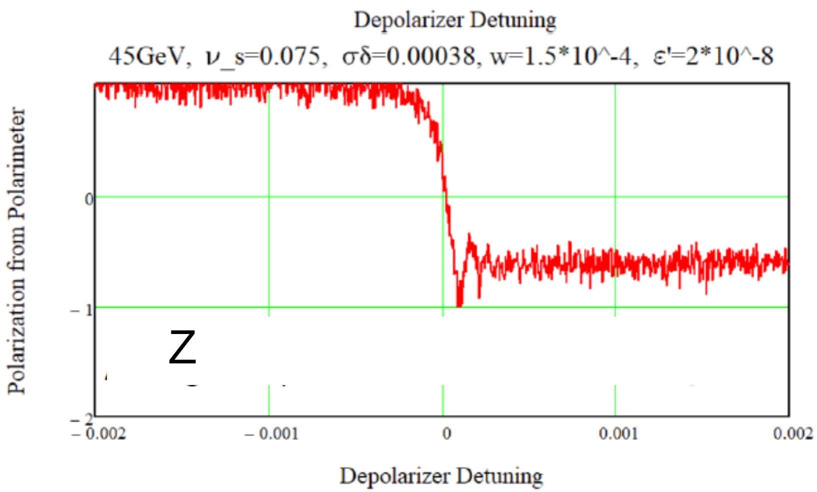
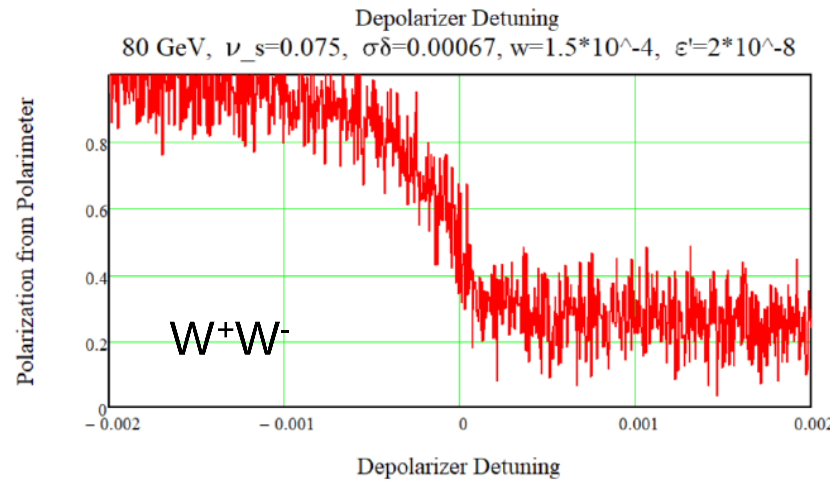
RDP will be feasible, but with less sharp signal,
and consequent reduced precision / measurement:

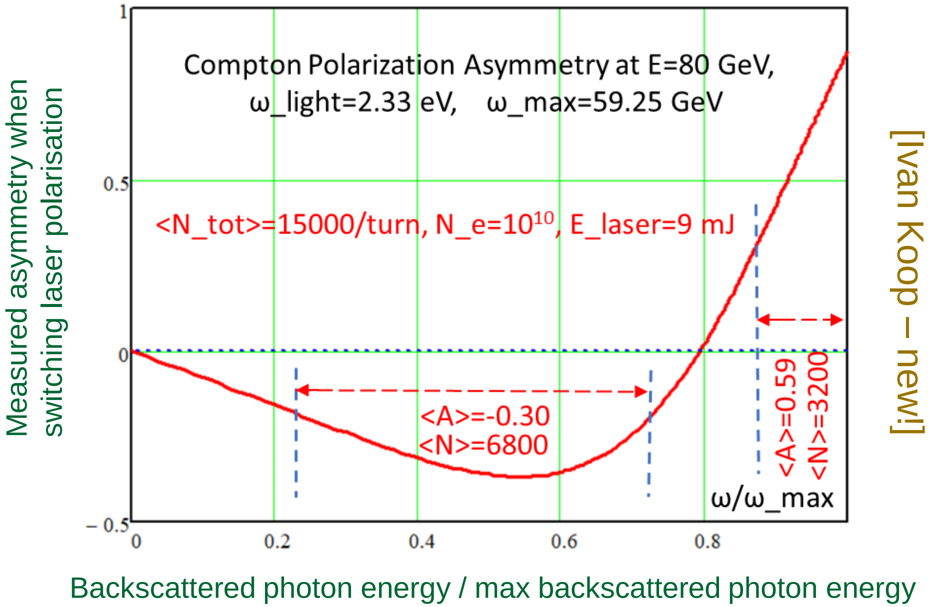




Simulated depolarisation signals seen in polarimeter, with 1000 scatters / turn [Ivan Koop]

Free Spin Precession Measurements

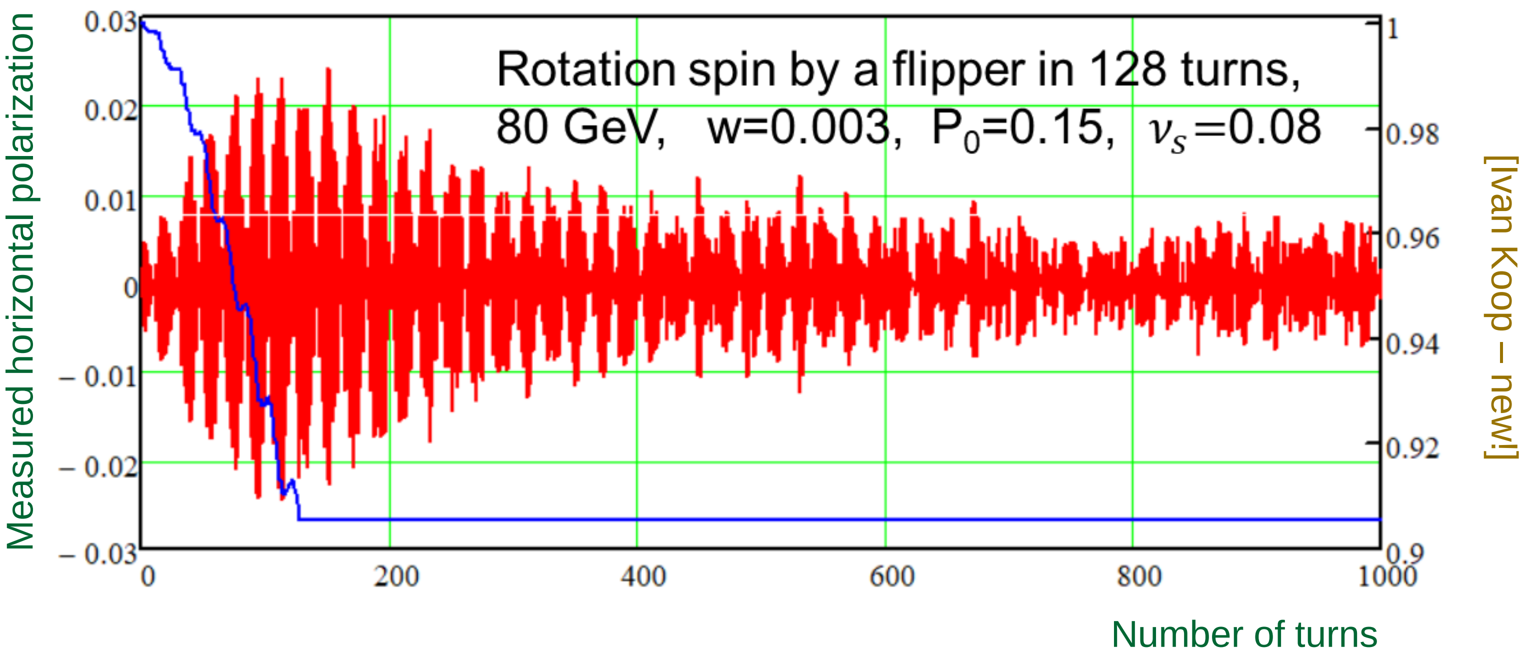
A complementary technique to RDP is to 'kick' the polarisation vector into the horizontal plane, and then observe its precession over as many turns as possible – Free Spin Precession. Require measurement of scattered electrons.



Sensitivity varies depending on electron energy (~ position in detector), & also the number of electrons detected (~15000 / turn assumed here).

Free Spin Precession Measurements

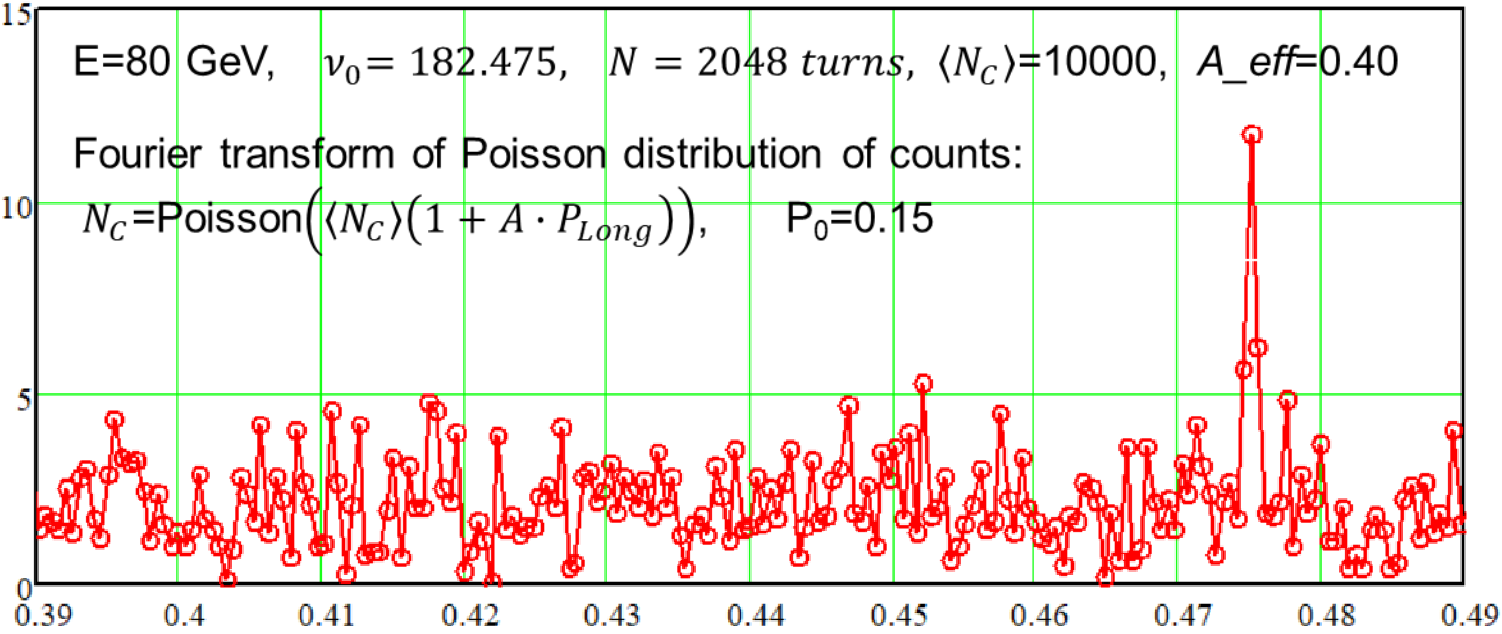
Challenges arise from the degree of deflection the spin flipper can induce in the polarisation vector (here assumed to be only 10°), which means that the horizontal polarisation component will only be ~0.02.



Furthermore, decoherence will occur after rather few turns (~2000).

Free Spin Precession Measurements

Still, under these conditions the energy peak in the spin-tune spectrum is visible.

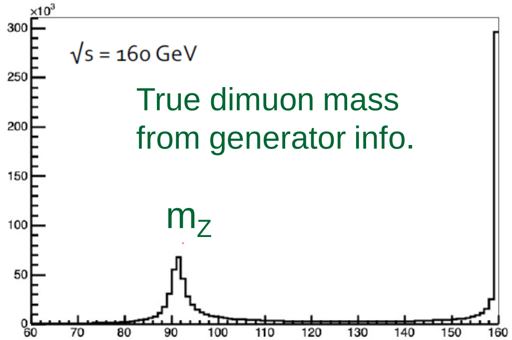


[Ivan Koop – new!]

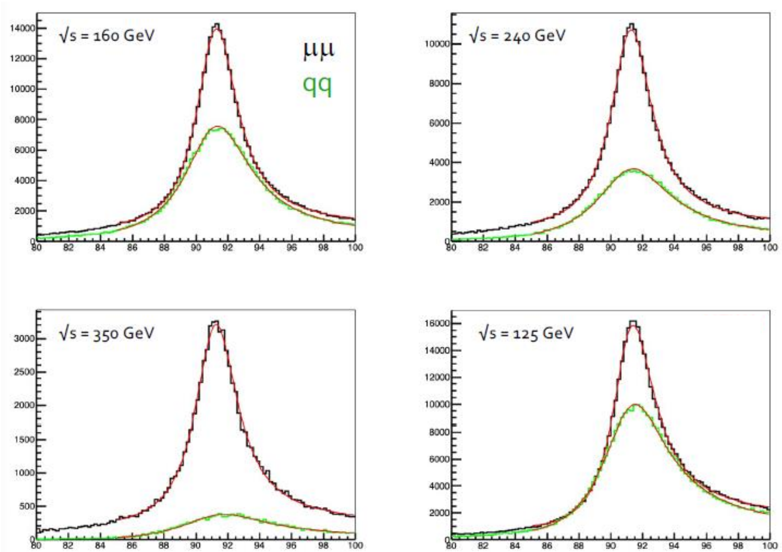
More studies required to ascertain robustness and study systematics.

Finding E_{CM} from radiative returns

The experiments can determine E_{CM} at energies above the Z^0 by selecting $e^+e^- \rightarrow f\bar{f}(\gamma)$ events, and reconstructing effective centre-of-mas energy after ISR from angles of fermions. Dimuons optimal, but feasible with hadronic events also.



Fits to reconstructed distribution for radiative return events.



[Patrick Janot]

Comparison with known m_Z allows the whole distribution to be calibrated and E_{CM} to be determined at high energy.

Use of dimuon events for other important measurements, *e.g.* energy spread, crossing angle, explored in arXiv:1909.12245. Also note alternative ILC-focused method making some use of momentum information [Madison & Wilson, arXiv:2209.03281].

Finding E_{CM} from radiative returns

Expected precision with foreseen data sets:

	$\sqrt{s}$	E_γ (GeV)	$N_{\mu\mu}$ ($\times 10^6$)	N_{qq} ($\times 10^6$)	$\sigma_{\sqrt{s}}$ ($\mu\mu$)	$\sigma_{\sqrt{s}}$ (qq)	$\sigma_{\sqrt{s}}$ (comb.)
6 ab^{-1}	m_H	29	107	173	660 keV	280 keV	225 keV
12 ab^{-1}	$2m_W$	54	47	667	900 keV	340 keV	285 keV
5 ab^{-1}	240 GeV	102	5.6	53	4.2 MeV	2.4 MeV	1.7 MeV
0.2 ab^{-1}	$2m_{top}$	163	0.1	0.3	51 MeV	60 MeV	26 MeV

[Patrick Janot]

Looks promising:

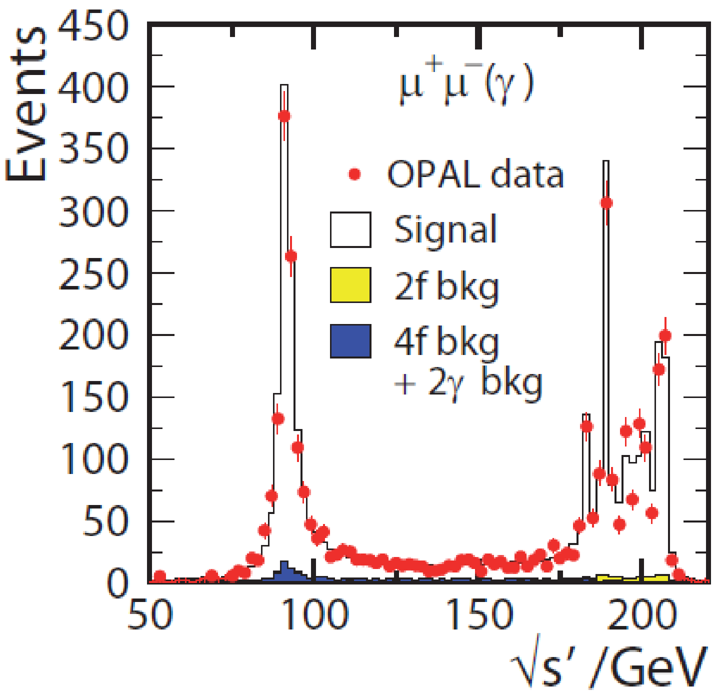
- Statistical precision excellent, and sufficient for goals.
- Data at $E_{CM} = m_H$ and $2m_W$ allows comparison with RDP - invaluable validation.
- At highest energies can also use $e^+e^- \rightarrow W^+W^-$ and ZZ events, with knowledge of m_W and m_Z [Marina Béguin PhD thesis] . Precision of a few MeV attainable ?

However:

- Above from simplistic generator studies. More attention to detector systematics and theory uncertainties are required. Volunteers welcome !
- Note these are the uncertainties integrated over full data set. In situations where one cares about 'real time' E_{CM}, *e.g.* at m_H, precision maybe inadequate.

Previous experience with E_{CM} from radiative returns

Radiative return events were used as a cross-check E_{CM} for m_W at LEP2.



[OPAL, PLB 604 (2004) 31]

Total LEP E_{CM} error budget = 54 MeV
(>2 that obtained by 'machine' methods)

Source	Uncertainty on $\Delta\sqrt{s}$ [MeV]
Fragmentation	22
ISR/FSR Modelling	7
Four Fermion Background	6
Z Mass	1
LEP Parameters	3
Total Correlated	23
Monte-Carlo Statistics	7
Detector Bias and Resolution	28
Total Uncorrelated	29
Total Systematics	37
Total Statistical	40
Total	54

[LEP, Phys. Rept. 532 (2013) 119]

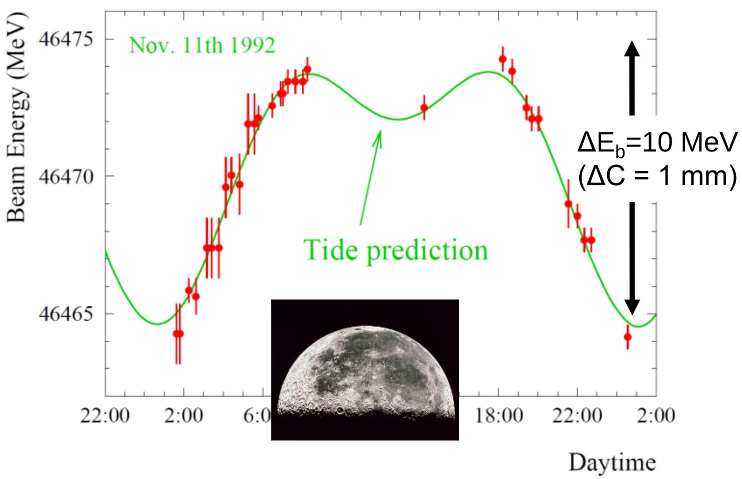
Significant theoretical uncertainties, particularly in hadronic channel (fragmentation), that would need to be controlled much better at FCC-ee.

Need for a reliable energy model

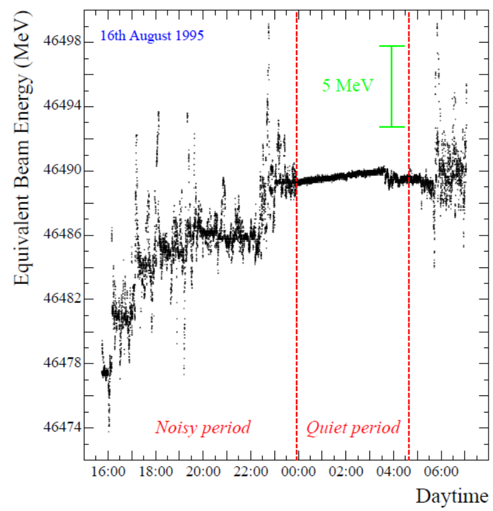
Very helpful to have a reliable energy model that gives evolution of E_{CM} between any fixed calibration points, *e.g.* at 125 GeV or 161 GeV, and presumably useful at higher energy also. Very important for 125 GeV run, for which model could provide online E_{CM} and prevent machine settings wandering away from Higgs pole.

Known drivers of energy variation from LEP:

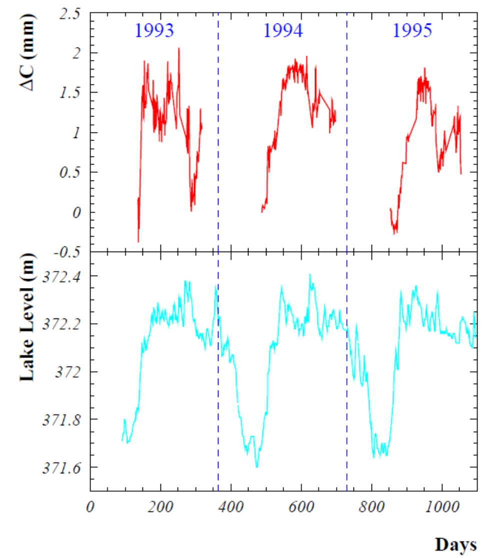
Tides



TGVs



Lac Leman



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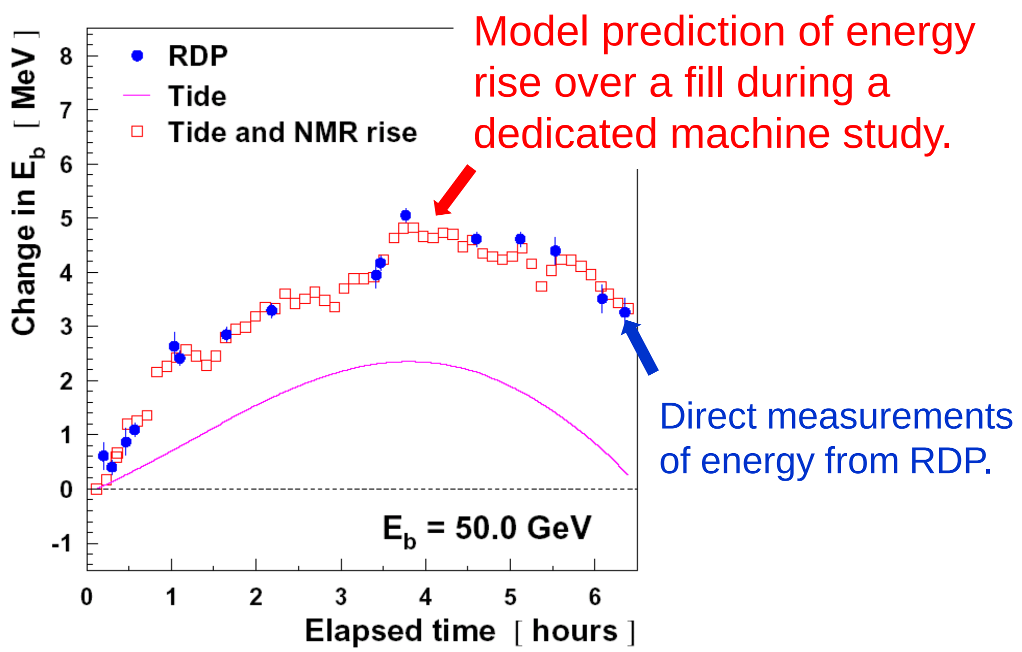
After much development the LEP energy model evolved to give an excellent description of the changes in energy (within the required precision)...

…but this took many years (>10) of effort, and required extensive instrumentation (NMRs, BPMs, logging *etc.*) and many MDs.



Several lessons for FCC-ee ,
including that we will need sufficient Z running to develop and validate model.

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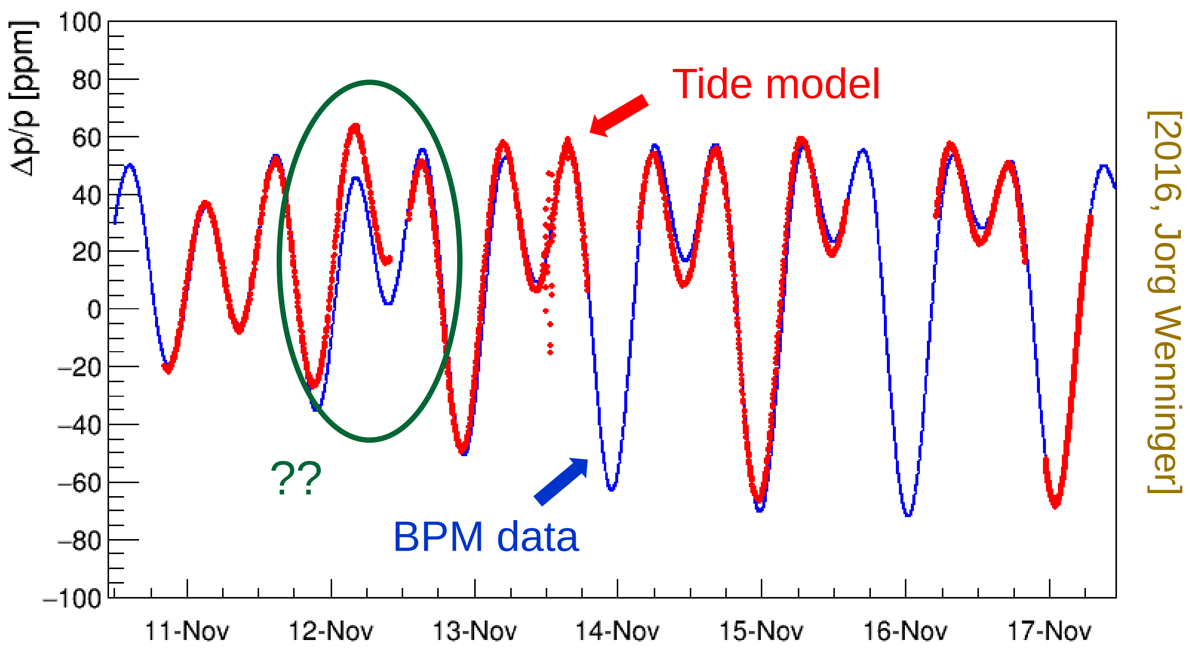
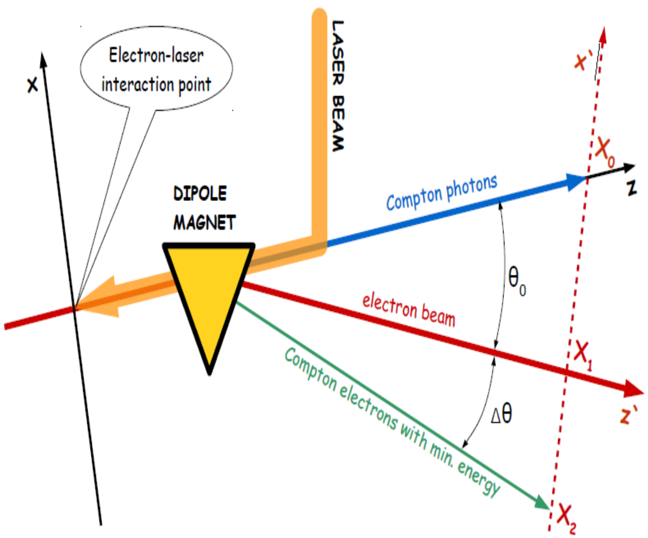
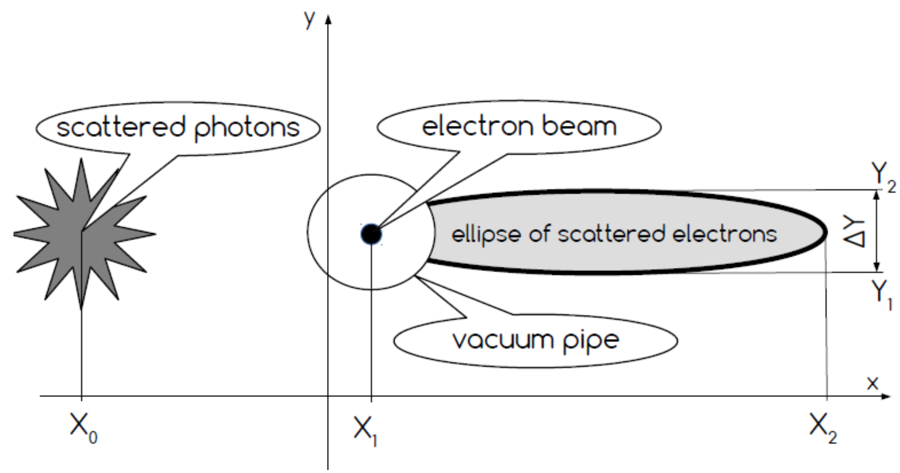
More recent studies in the LHC suggest that there is indeed work to do:



Other methods of tracking the relative energy change

Polarimeters will detect both electrons/positrons, and photons. As well as providing measurements of the polarisation vector, they can yield a real-time determination of the beam energy from the electron distribution.





$$E_b = \frac{(m_e c^2)^2}{4\omega_0} \cdot \frac{X_2 - X_1}{X_1 - X_0}$$

Statistical precision should be good, ~10^{-5} in a few seconds, depending on the scattering rate [Yu & Muchnoi, JINST 17 (2022) P10014], but systematics yet to be evaluated. Could be a valuable online barometer of energy change, particular for m_H run.

Conclusions and outlook

Many of the physics goals of running above the Z demand excellent knowledge and control of the collision energy.

The tools are in place to make the necessary calibrations, but we will need to learn how to use them. In particular:

- polarisation measurements at W^+W^- energies will be very delicate;
- radiative return (and other) measurements by the experiments need further experimental study and associated theoretical work.

It will be very important to develop a reliable and robust real-time energy model.

All these requirements have consequences for the sequence of data taking. Clearly, any Higgs-pole run cannot begin before we know the mass much better. Furthermore, significant period of Z-pole running is needed to establish tools associated with polarisation measurements and energy model.

Backups