Requirements for polarisation measurements

Guy Wilkinson
University of Oxford

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Tasks of polarimeter

Polarimeter has a diverse set of tasks to perform that are be of great importance for the precision electroweak programme at FCC-ee:

- Look for changes in transverse polarisation levels (RDP) at Z, H and W^+W^- ;
- Measure level of longitudinal polarisation in physics bunches;
- Direct energy measurement for monitoring of relative energy changes;
- Measure precession of polarisation vector for alternative E_b determination;
- …..

Some of the requirements that these tasks impose are simple to quantify, others less so (a better understanding should be an output of this workshop). Discuss in turn, where relevant making comparison with LEP experiences.

How it was at LEP

[R. Assmann *et al.*, EPJ C6 (1999) 187]

Source	ΔE_{CM} (MeV)							Energy	Year	Δm_Z	$\Delta \Gamma_Z$
	P−2 93	P 93	P+2 93	P 94	P−2 95	P 95	P+2 95	correlation	correlation	(MeV)	(MeV)
Normalization error	1.7	5.9	0.9	1.1	0.8	5.0	0.4	0.	0.	0.5	0.8
RD energy measurement	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.04	0.04	0.4	0.5
QFQD correction	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.75	[0., 0.75]	0.1	0.1
Horizontal correctors	0.0	0.4	−0.4	0.2	−0.2	−0.5	−0.2	±0.75	±0.75	0.2	0.1
Tide amplitude	0.0	−0.3	0.2	−0.1	−0.0	−0.0	−0.0	±1.	1.	0.0	0.1
Tide phase	0.0	0.0	−0.1	0.1	−0.2	−0.0	0.0	±1.	0.50	0.0	0.1
Ring temperature	0.1	0.4	0.4	0.2	0.4	0.3	0.4	0.75	0.75	0.3	0.2
B rise scatter+model	2.8	3.0	2.5	3.3	0.6	0.6	0.6	[0.47, 0.86]	0.50	1.5	0.5
B rise NMR48 T-coeff	0.6	0.3	0.6	0.5	1.0	1.0	1.1	0.75	0.75	0.8	0.3
Bending modulation jump	0.	0.	0.	0.	0.0	1.4	0.3	0.75	0.	0.1	0.1
e^+ Energy uncertainty	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.5	[0., 0.50]	0.2	0.1
RF corrections (Comb.)	0.5	0.5	0.5	0.6	0.7	0.7	0.7	[0.63, 0.96]	[0.18, 0.70]	0.4	0.2
Dispersion corr. (Comb.)	0.4	0.4	0.4	0.7	0.3	0.3	0.3	[0.50, 0.75]	[0., 0.50]	0.2	0.1
Energy spread											0.2

Calibration statistics

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Calibration statistics

EPOL-related systematics

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Calibration statistics

EPOL-related systematics

Size driven by frequency of calibrations

Overview of requirements at Z

Error budget from arXiv:1909.12245. Must keep pushing to reduce these numbers !

Observable	statistics	$\Delta\sqrt{s}_{\text{abs}}$ 100 keV	$\Delta\sqrt{s}_{\text{syst-ptp}}$ **40 keV**	calib. stats. $200\,\text{keV}/\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ $85 \pm \mathbf{0.05}\,\text{MeV}$
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_W^{\text{eff}} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(m_Z^2)}{\alpha_{QED}(m_Z^2)} \times 10^5$	3	0.1	**0.9**	–	**0.1**

Systematic biases in EPOL-related measurements

EPOL-related systematics should be sub-dominant

Suggests frequency, statistical precision and duration of individual measurements should not be a problem. This could be a dangerous assumption ! Relax any of these and nasty correlations may enter

Set by dimuon *etc.* measurements

e^- or e^+ calibration ? Both !

At LEP almost all RDP measurements were performed with electrons.

Calculations and simulations indicated upper limit in energy between the two beams of 0.3 MeV at Z^0 and 3-4 MeV for LEP 2 running.

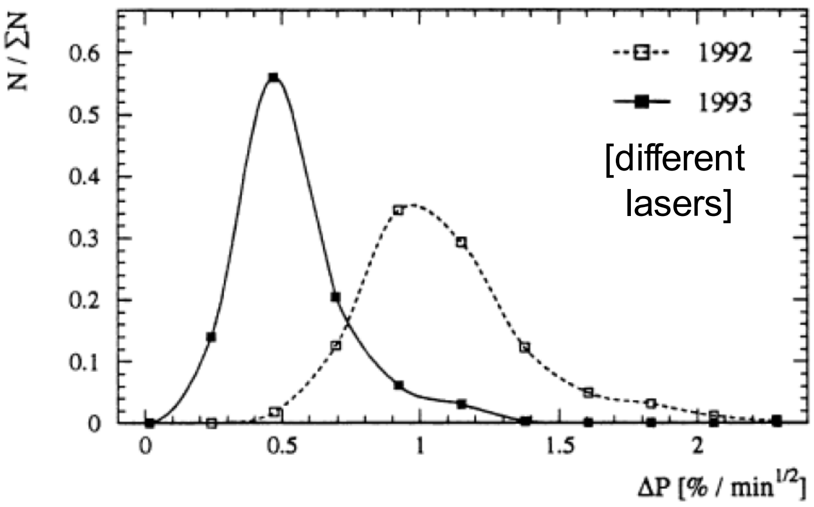
A dedicated positron polarimeter was installed in 1994 (and in 1993 the electron polarimeter was modified) to allow for a few positron measurements. Results generally as expected.

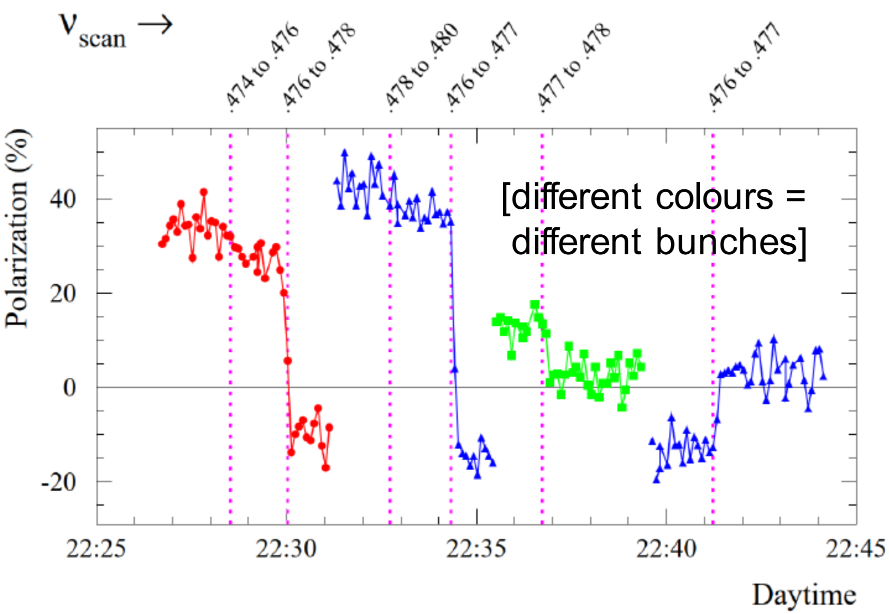
Year	Date	$E_{e^+} - E_{e^-}$ (MeV)
1993	Nov. 15th	[0.5,3.2]
1994	Jul. 15th	0.4±0.4
	Aug. 1st	0.0±0.2
1995	Sep. 26th	0.1±0.25

At FCC-ee, two-ring design and required precision makes it mandatory to have equally good understanding of energy of both electron and positron beams → two polarimeters performing ~ simultaneous set of measurements.

Precision of polarisation measurement

LEP polarisation accuracy ~0.5% / minute. Individual measurements every ~8 s.



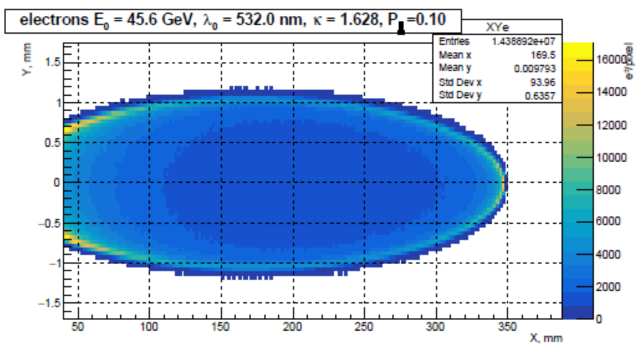


[L. Arnaudon *et al.*, Z. Phys. C66 (1995) 45]

Precision of polarisation measurement

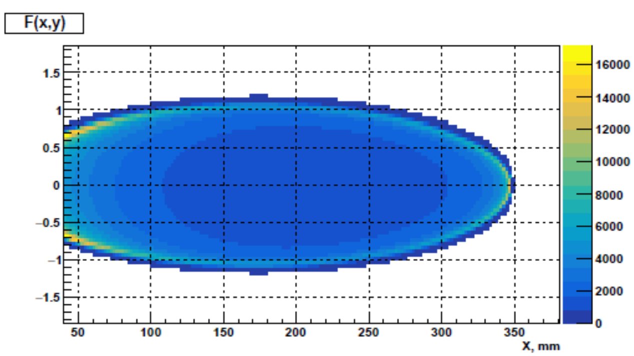
Simulation of FCC-ee transverse polarisation measurement with scattered electrons.

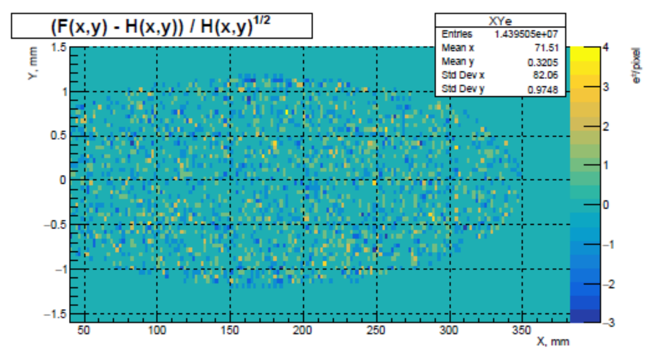
[Nickolai Muchnoi]



χ^2/NDF = 6356.7/6129 | Prob = 0.0208
X_0 = -213.538 ± 0.000 mm
X_1 = -000.008 ± 0.010 mm
X_2 = 0347.631 ± 0.003 mm
σ_x = 194.8 ± 4.4 μm
σ_y = 23.69 ± 0.02 μm
E_{beam} = 45.6032 ± 0.0035 GeV
$P_\perp$= 0.0997 ± 0.0016

0.16% absolute uncertainty from 2×10^7 backscatters (70% of which detected)





so, 0.6% s^{-1}

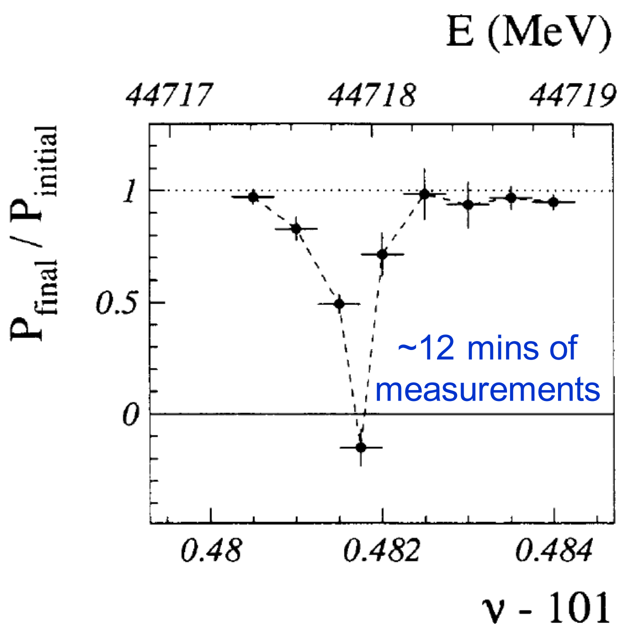
Rate of backscatters (with assumed parameters of arXiv:1803.09595) 2×10^6 s^{-1}.

Understanding how precision of polarisation measurement, & that of RDP itself, varies with this parameter for is vital for deciding on polarimeter design.

Precision of RDP energy measurement

Limitations from theoretical uncertainties (fully correlated between measurements), stat precision of polarisation measurements, energy variations during measurements… (uncorrelated at first order, but who knows…).

At LEP, fully correlated uncertainty of 200 keV.



[L. Arnaudon *et al.*, Z. Phys. C66 (1995) 45]

Theoretical uncertainty estimates

Source	$\Delta E/E$	ΔE (E=45.6 GeV)
Electron mass	$3 \cdot 10^{-7}$	15 keV
Revolution frequency	10^{-10}	0 keV
Frequency of the RF magnet	$2 \cdot 10^{-8}$	1 keV
Width of excited resonance	$2 \cdot 10^{-6}$	90 keV
Interference of resonances	$2 \cdot 10^{-6}$	90 keV
Spin tune shifts from long. fields	$1.1 \cdot 10^{-7}$	5 keV
Spin tune shifts from hor. fields	$2 \cdot 10^{-6}$	100 keV
Quadratic non-linearities	10^{-7}	5 keV
Total error	$4.4 \cdot 10^{-6}$	200 keV

Experimental upper bounds on (some) of above

Source	$\Delta E/E$	ΔE (E=45.6 GeV)
Frequency of the RF magnet	$2 \cdot 10^{-6}$	0.1 MeV
Interference of resonances	$2 \cdot 10^{-6}$	0.1 MeV
Spin tune shifts from long. fields	10^{-5}	0.5 MeV
Spin tune shifts from hor. fields	$1.8 \cdot 10^{-5}$	0.8 MeV
Quadratic non-linearities	10^{-5}	0.5 MeV
Total upper bound	$2.4 \cdot 10^{-5}$	1.1 MeV

At FCC-ee would aim to for <(<) 100 keV precision (assigned with confidence !).
This is likely to be the dominating systematic uncertainty on m_Z !

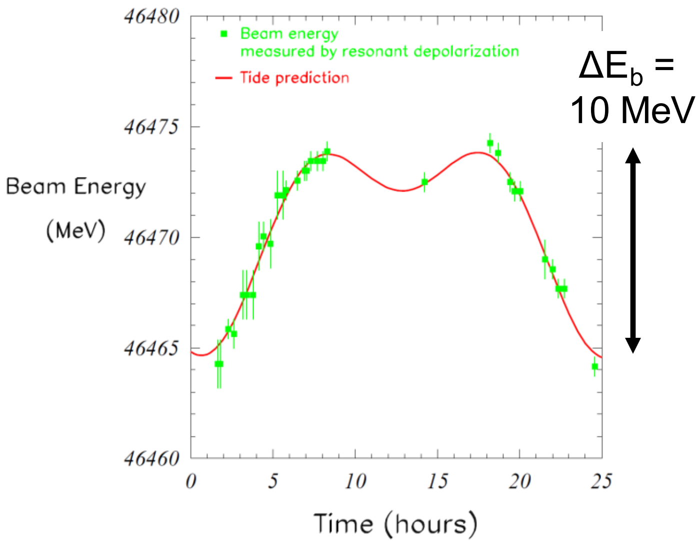
When are RDP measurements performed ?

At LEP, RDP measurements were performed outside physics collisions, at start or end of fill. At FCC-ee, measurements will be performed throughout.

- However, dead-time at start of fill at Z energies, as we must wait for polarisation level to accumulated in pilot bunches, when wigglers are in operation.
- No physics bunches circulating when wigglers are on (synchrotron radiation)
- Estimated time to reach ~10% polarisation is ~100 minutes. Significant dead time, the overall impact of which will depend on length of fills.
- Question: are lower levels of polarisation adequate for RDP when current is higher ? If so, maybe possible to reduce time of wiggler operation.

Frequency & duration of RDP measurements

At LEP, RDP (including set up) was a prolonged process with timescale ~ hours,
At FCC frequent measurements required to track possible energy variations.



Order of magnitude larger effects at FCC-ee.
Hence, be prepared for variations of:

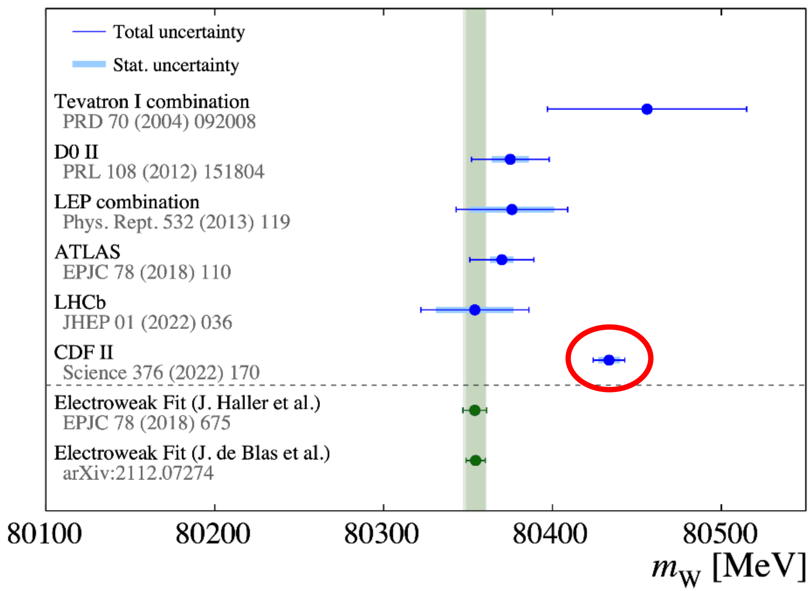
$$\frac{\Delta E_b}{E_b \cdot t} \sim 10^{-3} \text{ / hour}$$

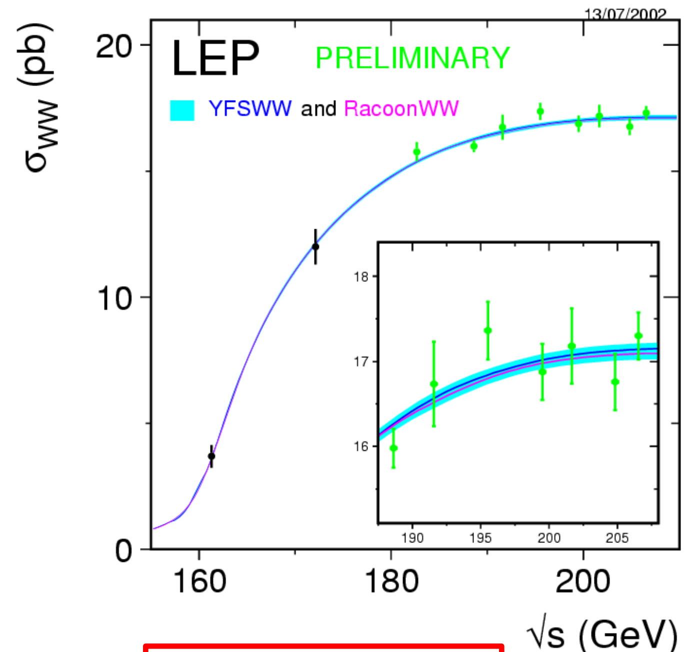
In principle these will be suppressed by continuous adjustment of RF frequency.

Wet-finger estimate: around 5 sets of RDP measurements / hour at Z.
Implies that each measurement should be completed within ~10 mins.

The challenge of m_W

Measurement of m_W (and Γ_W) a principal goal of FCC-ee programme.
This has always been the case, but has been highlighted be recent CDF result.





Baseline strategy, is a threshold scan (similar to that explored at LEP with tiny data set), to give σ(m_W) ≈ 0.4 MeV (stat) with 12 ab^{-1}.

$$\frac{\sigma(m_W)}{m_W} = \frac{\sigma(E_b)}{E_b}$$

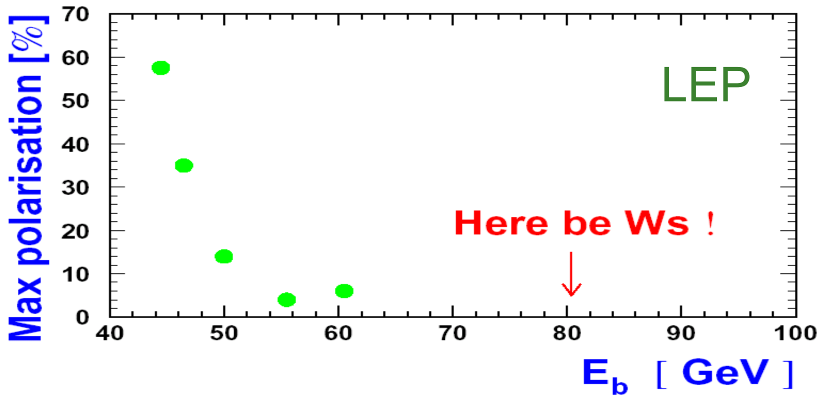
→ σ(E_b) ≈ 0.2 MeV (ideally better…)

NB direct reconstruction (LEP workhorse) &/or more data could mean that better performance is possible.

The challenge of m_W

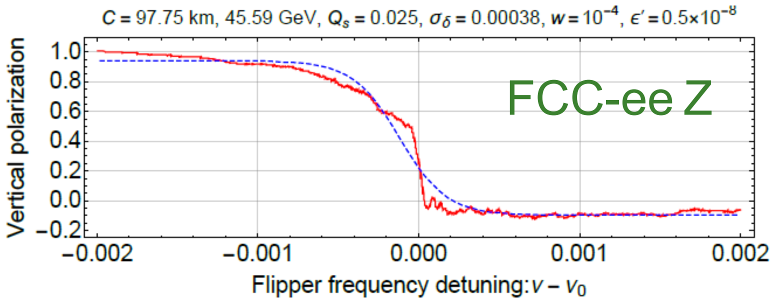
Reaching $\sigma(E_b) \approx 0.2$ MeV will be tough !

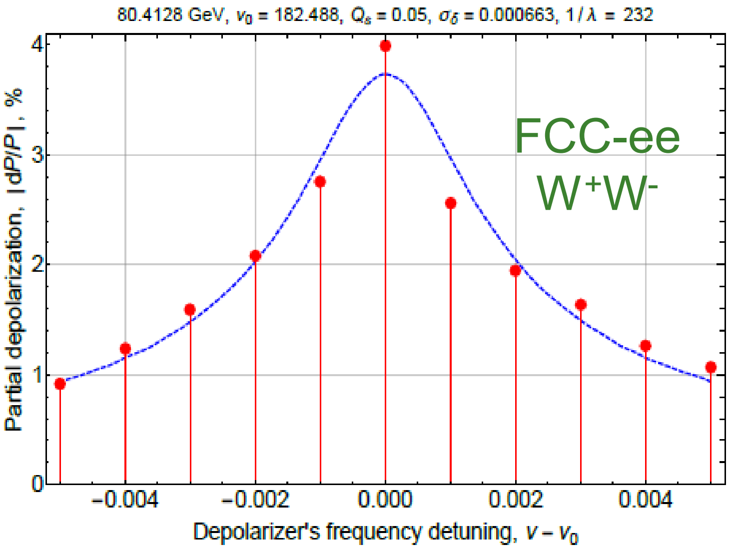
At LEP, no pol^n found above 60 GeV, so relative calibration methods required [EPJC 39 (2005) 253]. At FCC energy spread lower, so we can expect pol^n to exist.



However, RDP more delicate than at Z:

- lower polarisation → takes more time
- spin precession spectrum populated by broad peaks; locating spin resonance will require small steps and take more time, during which energy may vary….



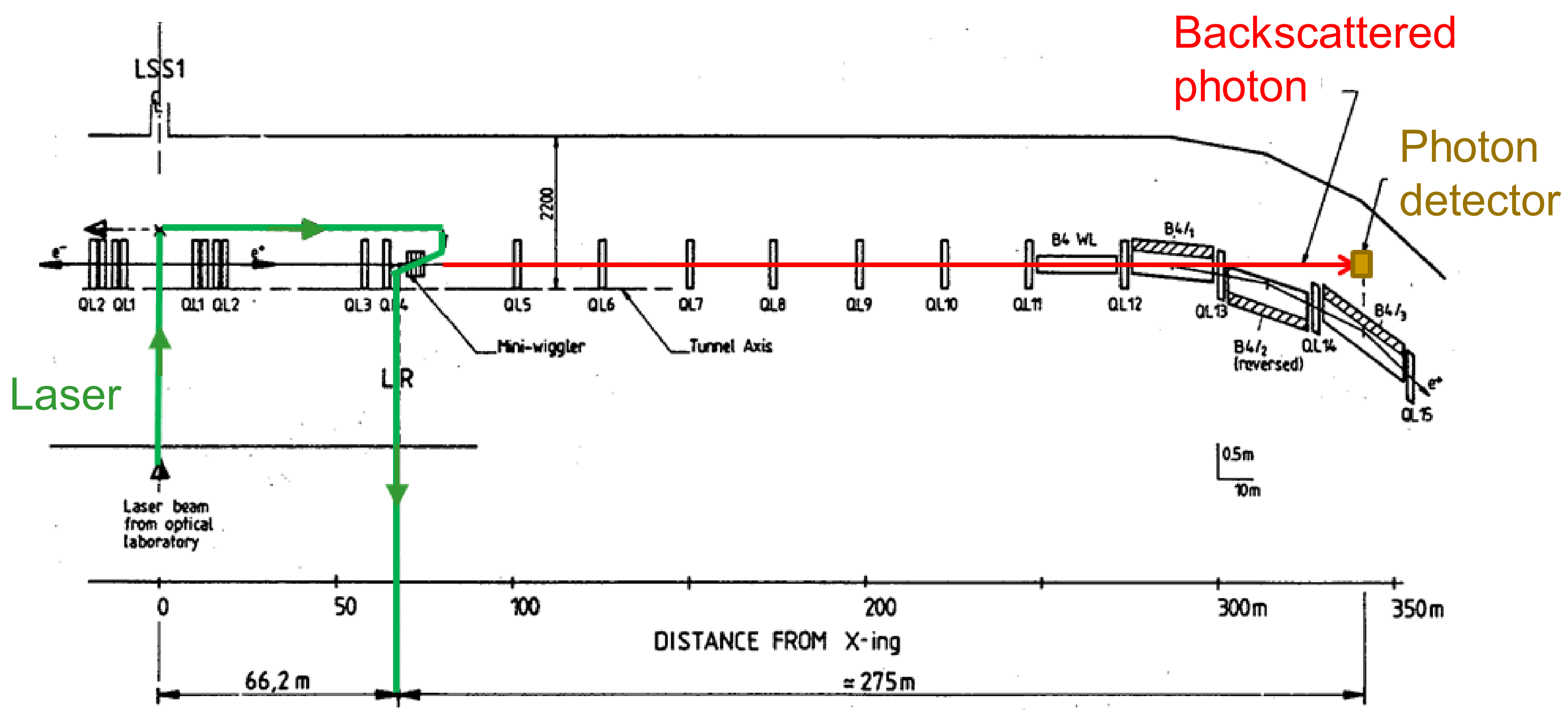


arXiv:1909.12245

Need better understanding of procedure and requirements: level of polarisation needed, time needed for measurement, uncertainty on result…

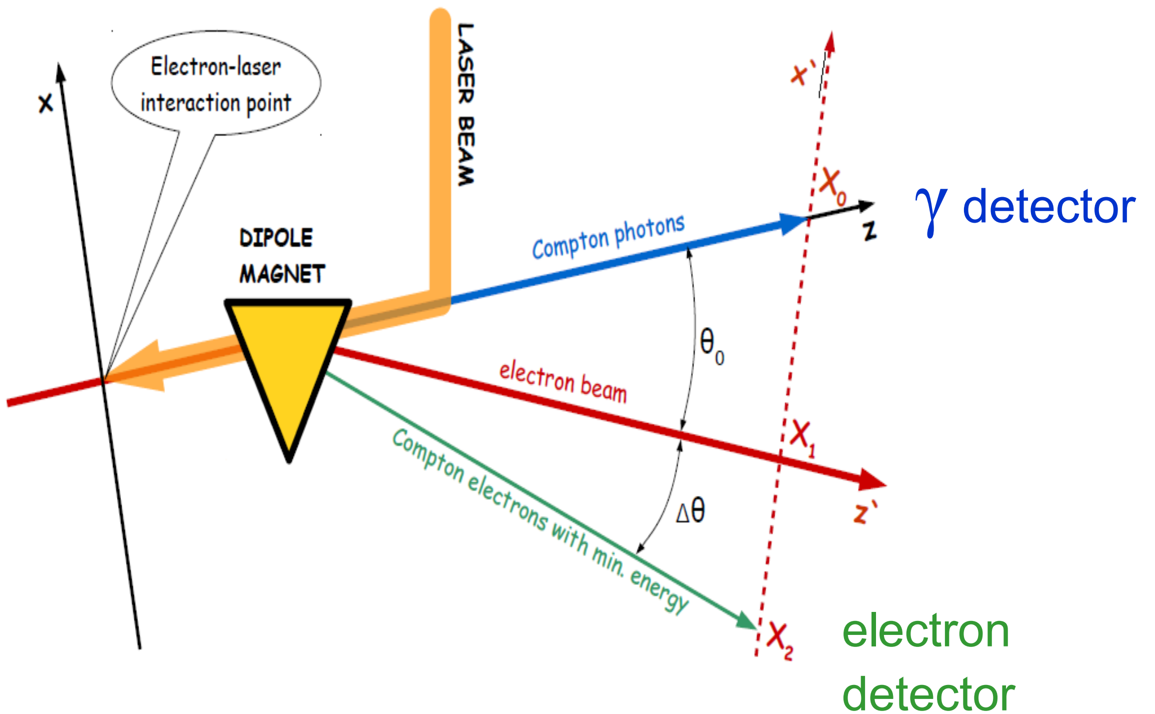
Polarimeter observables

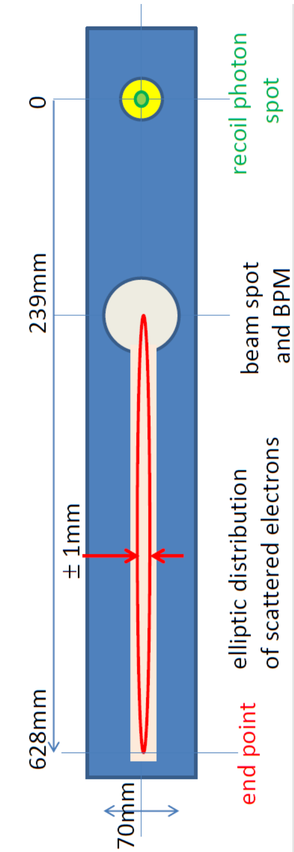
At LEP only the backscattered γ detected - sensitive to transverse polarisation.



Polarimeter observables

At FCC-ee both the backscattered γ and the scattered electron will be detected – together provides access to full polarisation vector.





Importance of longitudinal polarisation measurement

Any residual longitudinal-polarisation will bias cross sections & forward-backward asymmetries (indeed, high longitudinal polarisation is actually useful, but we assume we are not in that regime – rather longitudinal polarisation is a nuisance).

Consider forward-backward asymmetry of $b\bar{b}$ at Z pole: $A^b_{\rm FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b$

where in the SM $\mathcal{A}_e \approx 0.15, \quad \mathcal{A}_b \approx 0.95 \Longrightarrow A^b_{\rm FB} \approx 0.11$

Now, if there is longitudinal polarisation, asymmetry becomes: $(A^b_{\rm FB})' = \frac{3}{4}\mathcal{A}'_e\mathcal{A}_b$

where $\mathcal{A}'_e = -\left(\frac{\mathcal{A}_e - P}{1 - \mathcal{A}_e P}\right)$ with $P = \frac{(P_z)_{e^-} - (P_z)_{e^+}}{1 - (P_z)_{e^-}(P_z)_{e^+}}$

and $(P_z)_{e^\pm}$ the longitudinal polarisation of the $e^\pm$.

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So, if $(P_z)_{e^-} = (P_z)_{e^+}$ (no reason to be so) = 10^{-5} (ballpark guess)

$$P = 2 \times 10^{-5} \implies \frac{(A^b_{FB})' - A^b_{FB}}{A^b_{FB}} = 1.3 \times 10^{-4}$$

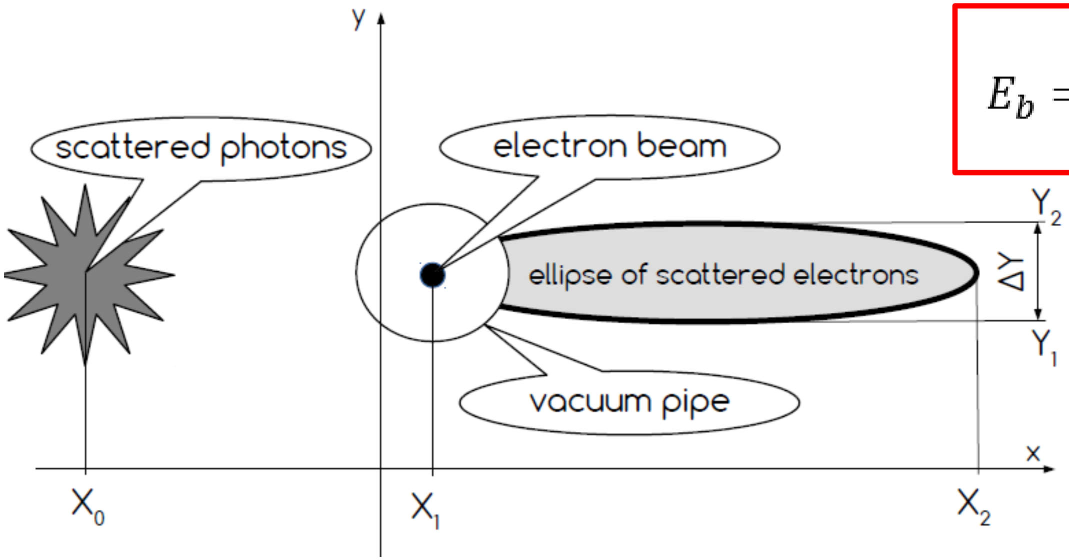
Statistical uncertainty on A^b_{FB} around 2×10^{-5} (relative), and QCD uncertainty which will probably be larger. Still, to be safe we would want to control P_Z to $< 10^{-5}$.

How is this to be done ? Measurements must be made on colliding bunches, where scattering rates are lower. Can we sample all bunches ? Will it prove necessary to depolarise the physics bunches ? If so, we will still need to monitor residual effects. And what are the systematics on an absolute measurement ?

Note also, that calculations required to transport the measurement of 3-vector at polarimeter to P_Z value at the interaction points. How can this be cross checked ?

Direct energy measurement

FCC-ee polarimeters also provide continuous and direct measurement of E_b.



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

In principle useful for providing fast tracking of 10^{-3} beam-energy variations, *e.g.* from tides, which is complementary to other methods (*e.g.* dimuons), and in some situations the best method available, *e.g.* Higgs pole, where dimuon x-section low.

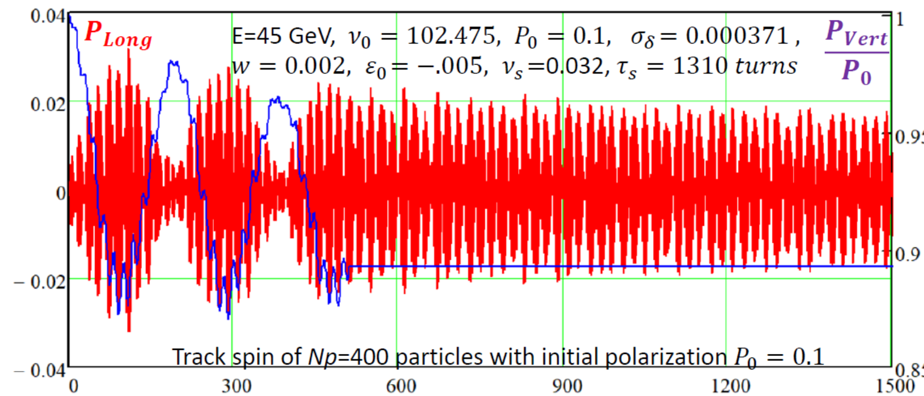
Higgs example – want to track variations on scale < $\Gamma_H \approx 4$ MeV ~ 10^{-4},

- This can be achieved with 10s of data [arXiv:1803.09595] – borderline.
- What are the energy and time-dependent systematics, *e.g.* from magnetic field ?

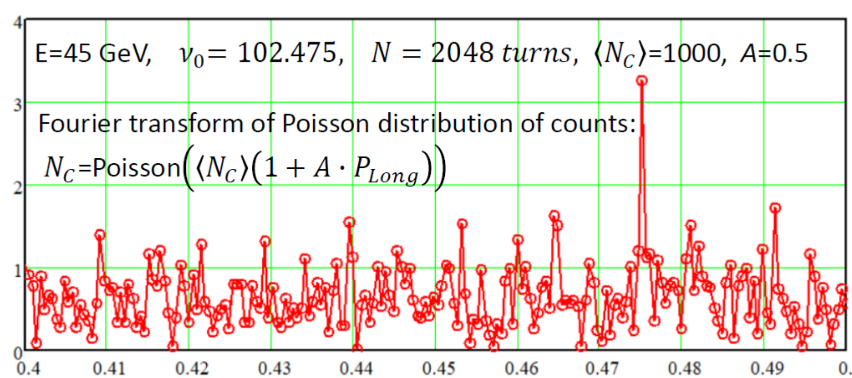
Free spin precession (FSP) measurement

FSP measurement, not used at LEP, offers an attractive alternative to RDP, with (presumably) different systematics, plus (seems to be) quick to perform. Note that this requires measurement of longitudinal polarisation component.

- Does this require more / less / same level of polarisation as RDP ?
- How well must polarisation be measured ?
- What are the systematics and intrinsic precision ?
- How often should measurement be made, *e.g.* one to accompany every RDP measurement, or less frequently ?



FSP at Z



[Ivan Koop]

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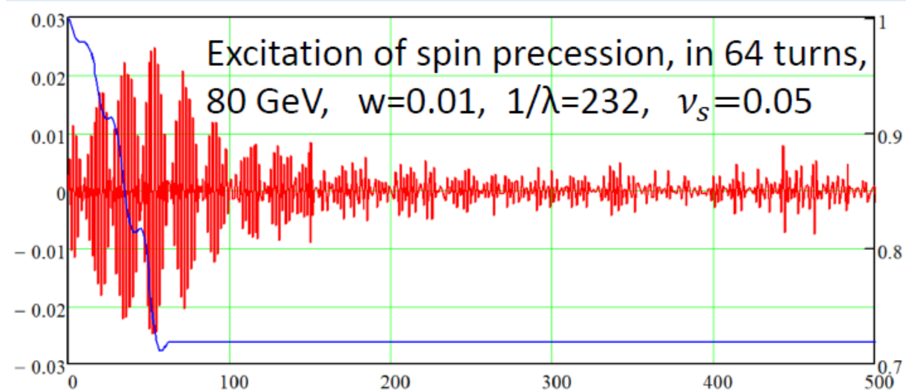
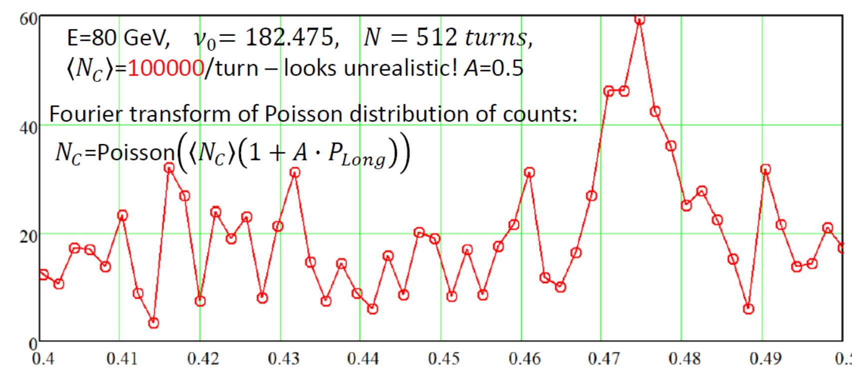
- Is measurement feasible in W^+W^- regime, and if so what are requirements and what is precision ?



FSP at W



[Ivan Koop]

Summary: open questions for workshop

- Dependence of polarisation & RDP precision on backscatter rate. (maybe straightforward for polarisation, less so for energy measurement itself);
- Ultimate intrinsic precision (correlated between measurements) of RDP at FCC-ee;
- Variation (at Z, H) energies of RDP time with polarisation level & bunch intensity;
- Frequency & duration of measurements under standard conditions;
- Precision attainable on knowledge of longitudinal polarisation at interaction point;
- Systematic uncertainties on direct energy measurement;
- Challenges in the W^+W^- regime: level of polarisation required, time required for measurement, uncertainties on measurement ? Is 0.2 MeV feasible ?
- What are requirements of FSP measurement and its precision, both at Z and in W^+W^- regime ? How often should these measurements be performed ?