EPOL WG: goals, status and prospects

Jacqueline Keintzel and Guy Wilkinson, with many thanks to colleagues in EPOL Working Group !

FCC Physics Week, Krakow, 23/1/23

Outline

Talk intended to be an overview for non-experts, with some indications of where are the current interesting developments and open questions. Focus will be on Z and W^+W^- regime, where challenges are most extreme.

EPOL WG: remit and current organisation

Polarization and the measurement of E_b

From E_b to E_{CM}: interaction-point specific corrections

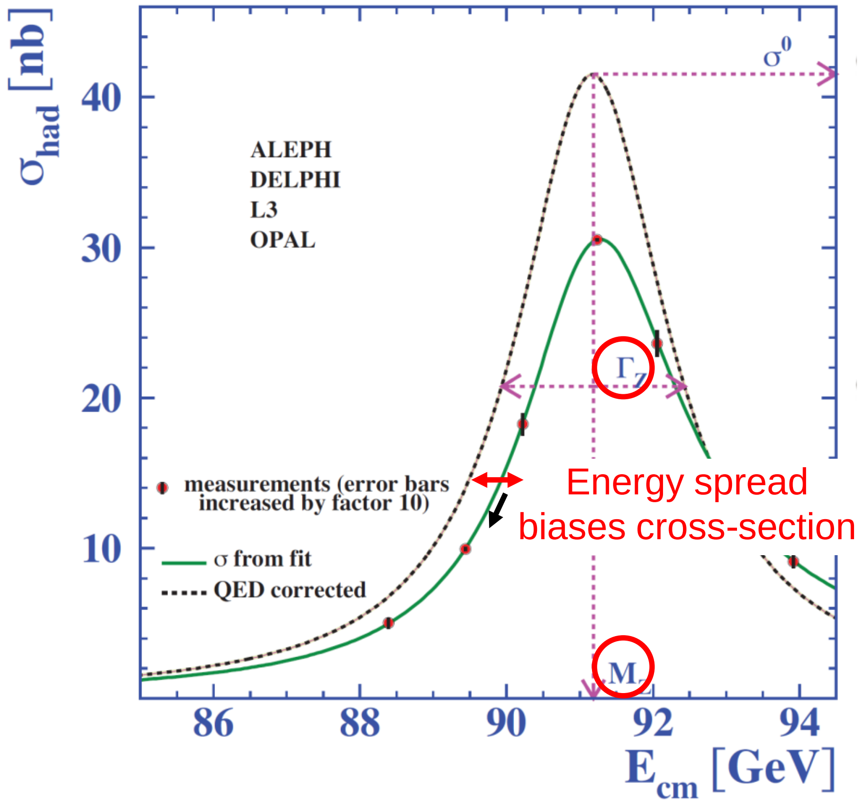
Determining the energy spread (and more) with di-fermion events

How well can we do?

Next steps, conclusions and outlook

Remit of EPOL group: E_{CM} and $\sigma_{E_{CM}}$ calibration

Illustrate with lineshape. Potential limiting systematics come from knowledge of absolute energy scale, point-to-point energy scale, & centre-of-mass energy spread.



Width sensitive to point-to-point energy scale and energy spread

$$\delta\sigma = -0.5\ \frac{d^2\sigma}{dE^2}\ \sigma^2_{E_{\rm CM}}$$

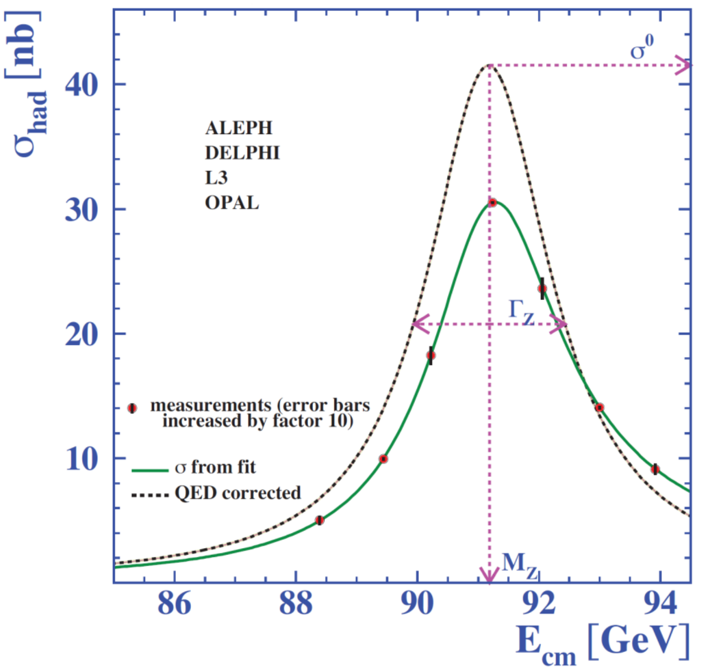
Mass sensitive to absolute energy scale

Other important electroweak measurements which are sensitive to these inputs: $\sin\theta_W^{\rm eff}$ from $A_{\rm FB}^{\mu\mu}$ peak, $\alpha_{\rm QED}(M_Z)$ from $A_{\rm FB}^{\mu\mu}$ off peak, m_W , Γ_W *etc.*

Remit of EPOL group: E_{CM} and $\sigma_{E_{CM}}$ calibration

Energy calibration was performed with sufficient precision at LEP:

m_Z total uncertainty = 2.1 MeV, of which energy calib contribution = 1.7 MeV
Γ_Z total uncertainty = 2.3 MeV, of which energy calib contribution = 1.2 MeV



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Calibration of centre-of-mass energies at LEP1 for precise measurements of Z properties

The LEP Energy Working Group

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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.

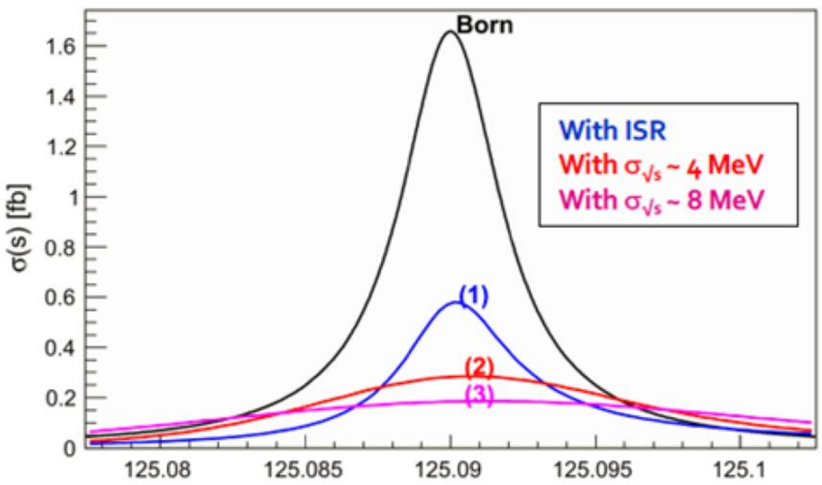
[EPJC 6 (1999) 187]

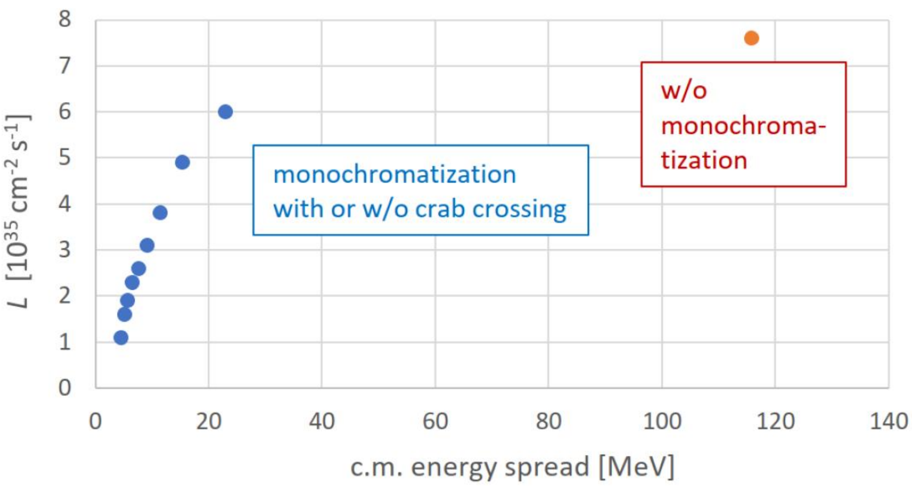
But challenge at FCC-ee will be much, much more daunting:

m_Z and Γ_Z statistical uncertainties ~ 4 keV !

Remit of EPOL group: monochromatization

EPOL group is also tasked with searching for solutions to the monochromatization challenge – finding ways to reduce the E_{CM} energy spread from its natural value of ~100 MeV at 125 GeV, to something comparable to the Higgs width (~4 MeV) in order to give sensitivity to Higgs s-channel production and the electron Yukawa.



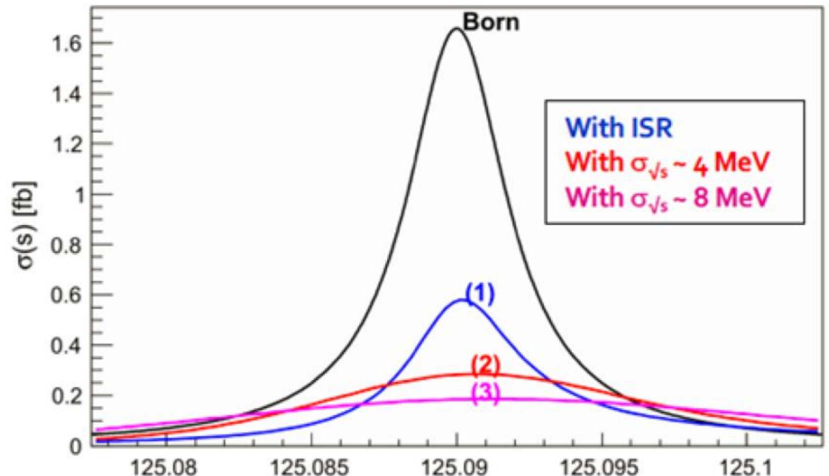


Must be done in a manner which preserves sufficient luminosity to maintain event rate for signal to be seen – see talk from Angeles Faus-Golfe for a status report.

Remit of EPOL group: monochromatization

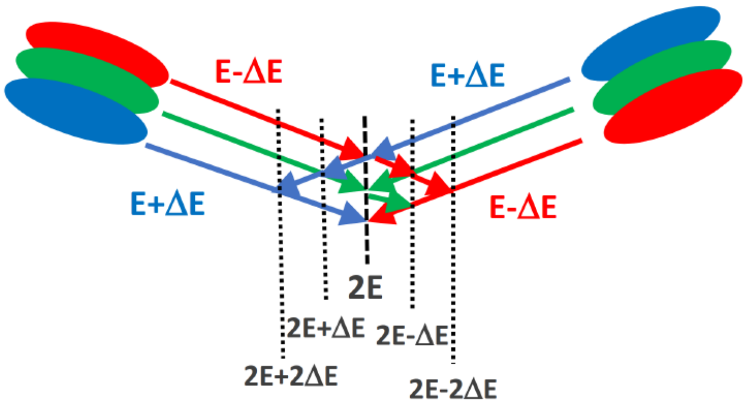
Again, for the Higgs pole campaign, energy calibration is of high importance.

- Must tune E_{CM} to sit directly at pole, must minimise time-dependent energy drifts, and be able to measure event-by-event energy precisely.



E_{CM} ?

- Any monochromatization scheme will give an energy that depends on position (& maybe collision time).



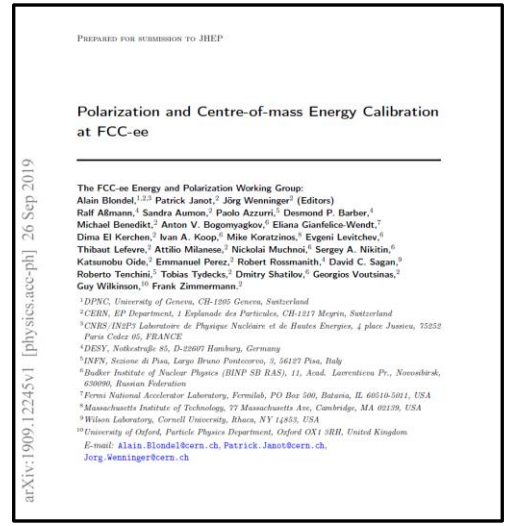
Must be able to use physics data to measure energy boosts, spreads *etc.* as a function of these variables.

EPOL group: organisation and activities

EPOL group is comprised of accelerator physicists, particle physicists and more.
A wide spread of expertise is essential !

Already, at time of FCC CDRs, a baseline strategy was developed and written up.

We are now seeking to refine and develop these ideas, and improve performance further.



Prepared for submission to JHEP

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

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arXiv:1909.12245v1 [physics.acc-ph] 26 Sep 2019

[arXiv:1909.12245]

Sign up to e-group fcc-ee-PolarizationAndEnergyCalibration@cern.ch
Fortnightly meetings can be found under https://indico.cern.ch/category/8678/

A recent highlight was a two-week workshop at CERN and online, September 19-30 2022.
113 participants, 127 contributions.

Key aspect: active involvement from physicists involved in current & future electron machines.

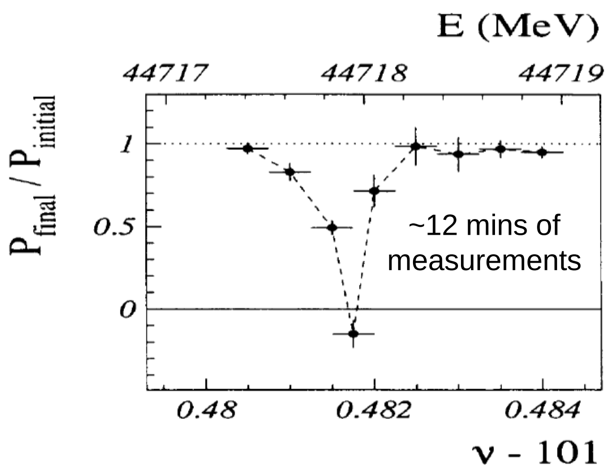
God's gift to synchrotrons: transverse polarization

The e^+ / e^- beams polarize naturally through the Sokolov-Ternov effect, and the spin tune (precession frequency / revolution frequency) is proportional to the mean beam energy.

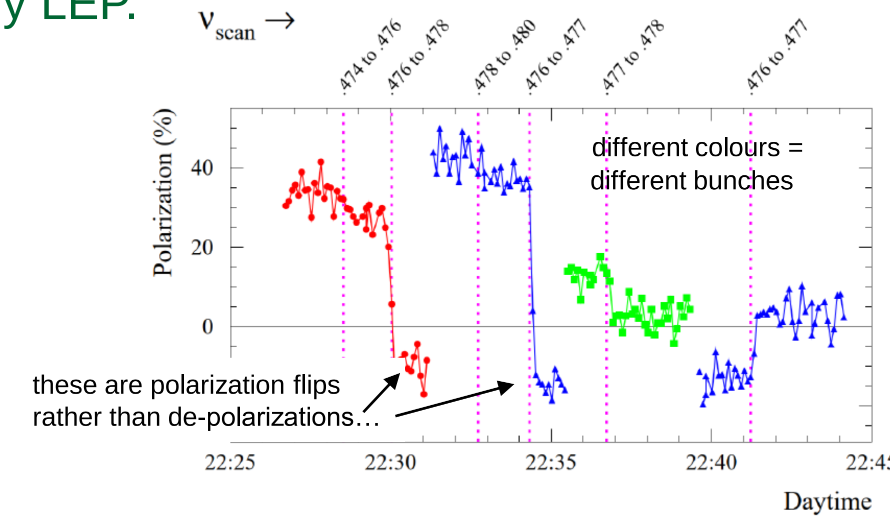
$$E_b = 2\ \nu_s\ m_e\ c^2 / (g_e - 2)$$

Monitor the polarization and excite beam locally with magnetic kicker of frequency that can be varied. When the frequency hits the spin tune resonant depolarization (RDP) occurs and the energy can be determined (OK, there are subtleties…).

Used at many machines, most notably LEP.



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



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

At LEP frequency step size & sampling rate gave uncertainty of ~200 keV, but intrinsic precision is probably closer to 10 keV, if all systematic effects are carefully accounted for, & procedure is optimised – under investigation (Koop, Nikitin *et al.*).

Achieving polarization

At Z pole at FCC-ee the time required for polarization to naturally build up is long (~250 hours). Can be reduced to ~100 mins for 10% polarization with wigglers.

- Start of fill: inject ~200 non-colliding pilot bunches with wigglers on;
- Wait 60-100 mins for polarization to grow;
- Turn off wigglers and inject physics bunches.

Unavoidable deadtime for physics, whose impact will depend on fill length

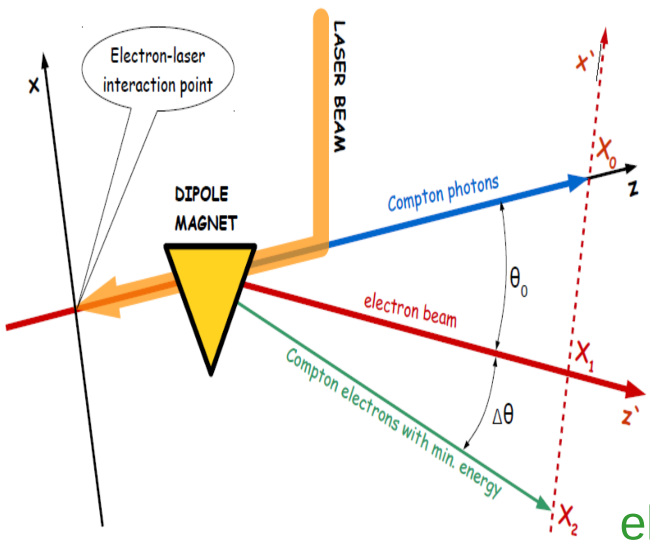
All standard RDP measurements performed on pilot bunches, with expectation that physics bunches will never achieve significant level of polarization.

Other techniques will be used in parallel to enhance & maintain polarization levels, *e.g.* closed orbit correction and harmonic spin matching (Carlier, Pieloni & Wu).

Take-home message: good instrumentation (BPMs) together with reliable and fast alignment procedures (both mechanical and beam based) is essential. A machine that is optimised for polarization will, in general, also be optimal for luminosity !

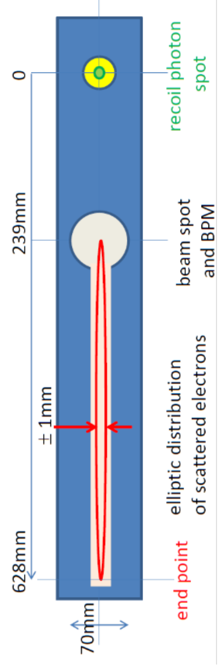
Polarization measurements

Polarimetry measurement will be based on inverse Compton scattering, where both electrons and photons will be detected, in contrast to LEP where only backscattered photon was measured. Backscattered photon sensitive to only transverse polarization, but electrons can access complete polarization vector.



γ detector

electron detector (~100 m away)

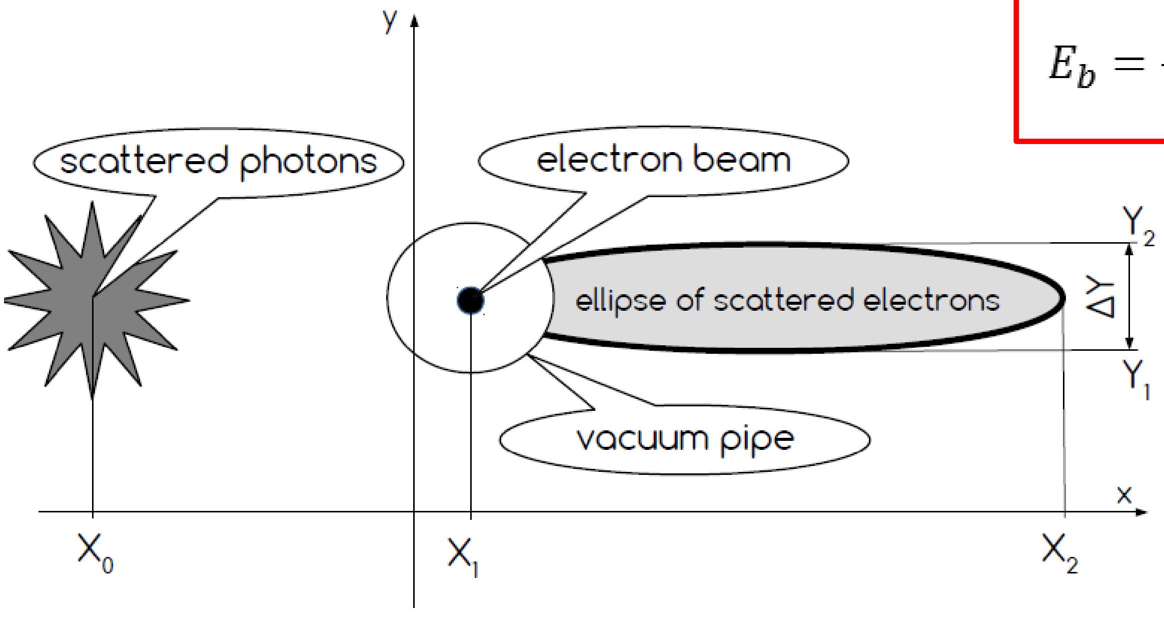


Need to measure polarization level of electrons and positrons, so (at least) two polarimeters required. Full specifications currently under discussion (Martens, Muchnoi, Lefevre). Exciting detector challenge in own right – more help welcome !

Bonus information from the polarimeters

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

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



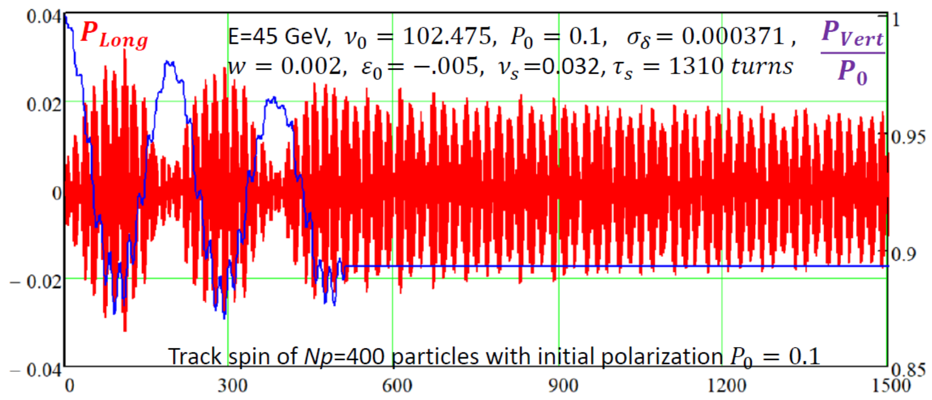
In principle useful for providing *fast tracking* of 10^{-3} beam-energy variations, *e.g.* from tides, which is complementary to other methods (*e.g.* dimuons), and in some situations the best method available, *e.g.* Higgs pole, where dimuon x-section low.

Alternatives to RDP: free spin precession

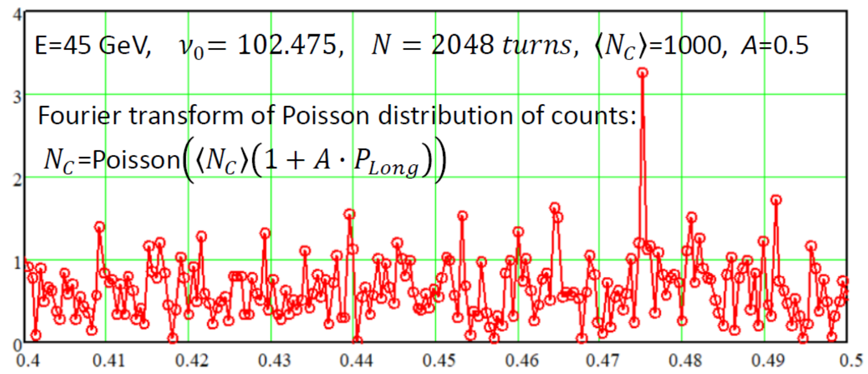
Free Spin Precession (FSP) offers an alternative to RDP, with (presumably) different systematics. Use de-polariser to (largely) rotate vector into horizontal plane, and then monitor its precession with longitudinal-polarization measurement.

Open questions under evaluation:

- Required polarization level ?
- How well will technique work in realistic machine with errors ?
- How well must polarization 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]

Longitudinal-polarization considerations

Any residual longitudinal polarization will bias cross sections & forward-backward asymmetries (indeed, high longitudinal polarization is actually useful, but we assume we are not in that regime – rather longitudinal polarization 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 polarization, asymmetry becomes: $(A^b_{\rm FB})^{\prime} = \frac{3}{4}\mathcal{A}^{\prime}_e\mathcal{A}_b$

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

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

Longitudinal-polarization considerations

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

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 $< 10^{-5}$.

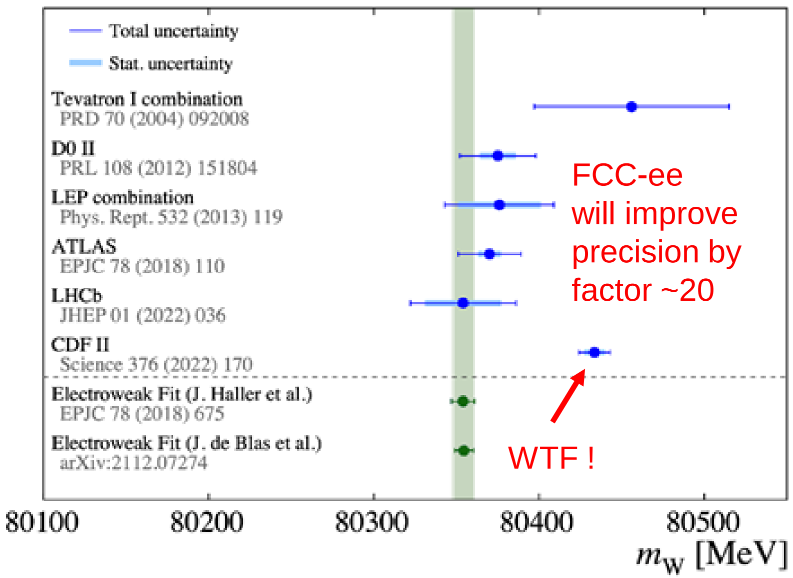
Likely strategy:

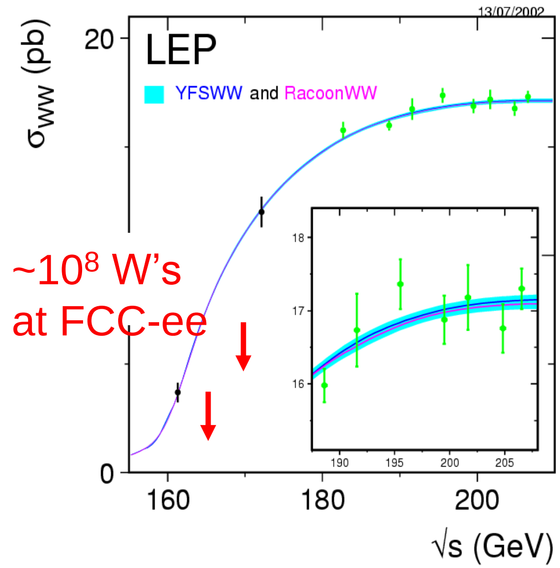
1) Measure polarization levels of physics bunches, as well as pilot bunches. (As transverse polarization >> longitudinal, a 10^{-3} measurement of former is probably sufficient.)

2) If necessary, continually depolarize physics bunches.

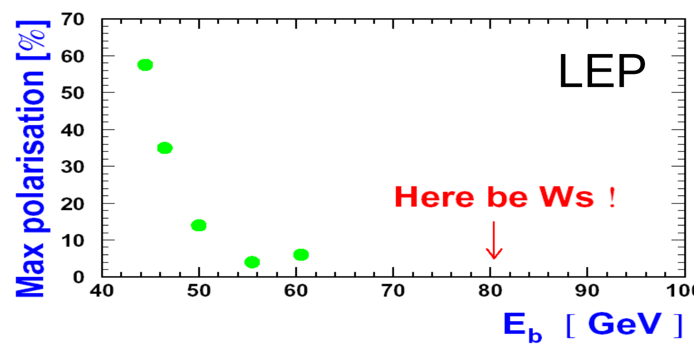
Energy calibration in W^+W^- regime

Energy calibration equally essential for W physics. Fractional uncertainty on E_{CM} induces a corresponding fractional uncertainty on m_W (evaluated either through threshold scan or direct reconstruction). FCC-ee stat uncertainty on m_W ~ 0.5 MeV.





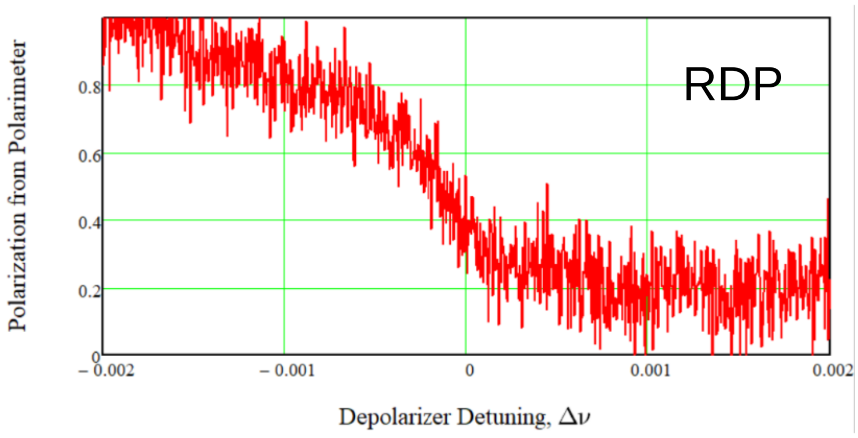
LEP faced problem that RDP was not possible in W^+W^- regime, as increased energy spread at higher energies led to a too low level of polarization.

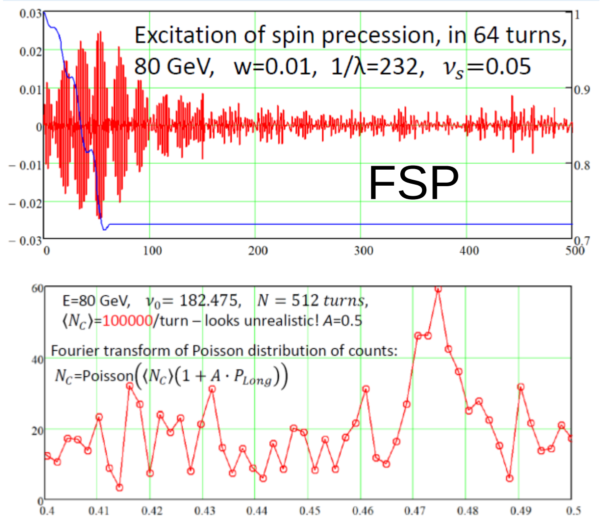


Energy calibration in W^+W^- regime

In contrast to LEP, at FCC-ee polarization should be achievable at E_b ~ 80 GeV.

Beam-energy spread $\sigma_{E_b} \sim E_b^2/\sqrt{\rho}$ and the magnetic bending radius ρ at FCC-ee is larger than at LEP. Furthermore, the improvements in instrumentation will be helpful in increasing polarization levels.





[I. Koop]

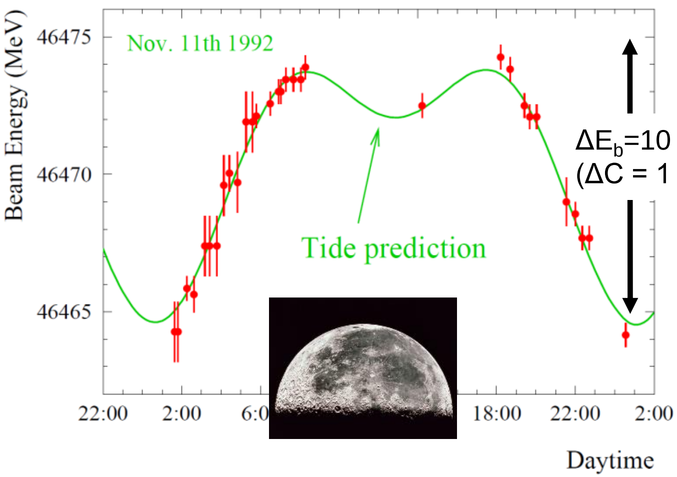
Recent simulations confirm that polarization, and clear RDP and FSP signals, will be achievable. However situation still delicate and optics of machine at these energies should be optimised with these goals in mind. Systematics under study.

A strategy to suppress systematics due to E_b variation with time

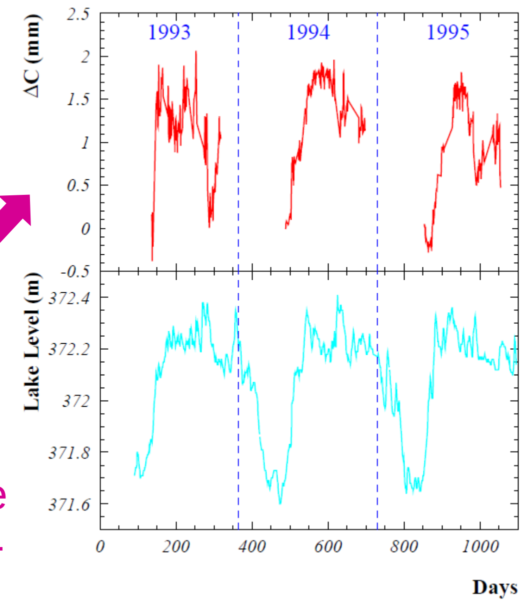
RDP (or FSP) measures mean E_b at a particular moment. It is well known from LEP experience that E_b varies with time and evolves between measurements.

Indeed, modelling these effects, and the representativeness of the RDP sampling, was dominant source of the ~2 MeV systematic uncertainties on m_Z & Γ_Z at LEP. The problem was that RDP measurements took hours, and were incompatible with physics operation. Therefore they were made at start of end of selected fills.

Some mechanisms of E_b variation

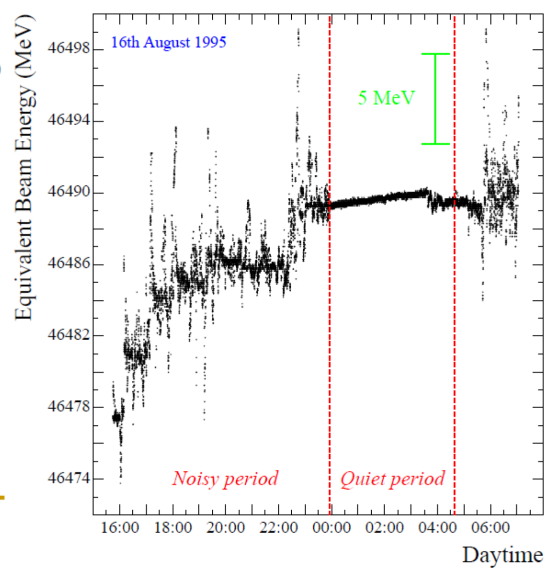


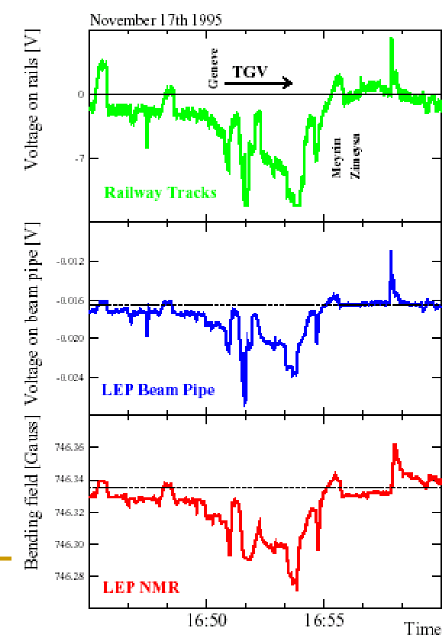
Short- (tide) and long- (lake) term ring distortions.



NB at FCC-ee effects will be ~10x larger due to smaller momentum-compaction factor !

Rise of dipole fields due to stimulation from returning current from TGV.





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Proposed strategy at FCC-ee:

- (near) continual measurement of e^- and e^+ measurements on pilot bunches; order of ~5 measurement every hour;
- Continual adjustment of RF frequency to keep beams centred in quadrupoles, therefore suppressing any tidal effects.

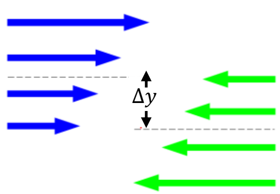
Kill all time varying effects to first order !

In addition: insist on exhaustive logging of all relevant machine parameters, and allocated adequate Machine Development time to study residual effects.

Interaction-point specific corrections

To go from mean E_b to E_{CM} at each interaction point, must consider: (i) crossing angle (see later), (ii) dispersion & collision offsets, (iii) energy variation around ring.

e.g. in vertical plane

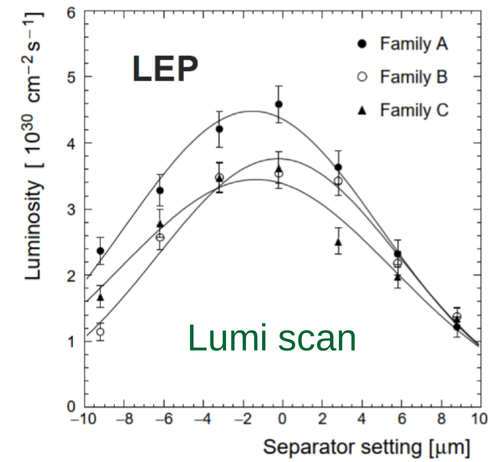


$$\Delta E_{CM} = -\Delta y \, \frac{\sigma_{E_b}^2 \Delta D_y^*}{E_b \sigma_y^2}$$

σ_{E_b} = energy spread

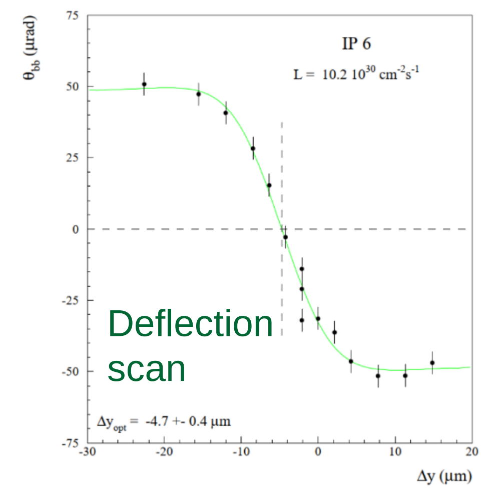
ΔD^*_y = difference in dispersion between e^+ and e^-

σ_y = betatronic beam size



So, for ΔD*= 10 μm, ΔE_{CM} ~ 1 MeV / nm.

Therefore must keep offset to << 1 nm (at least, on average) & also measure dispersion of beams (NB it is *difference* in dispersion that matters).



Both offset and dispersion can be measured through luminosity scan or through beam-beam deflection scan, using angles found from BPMs.

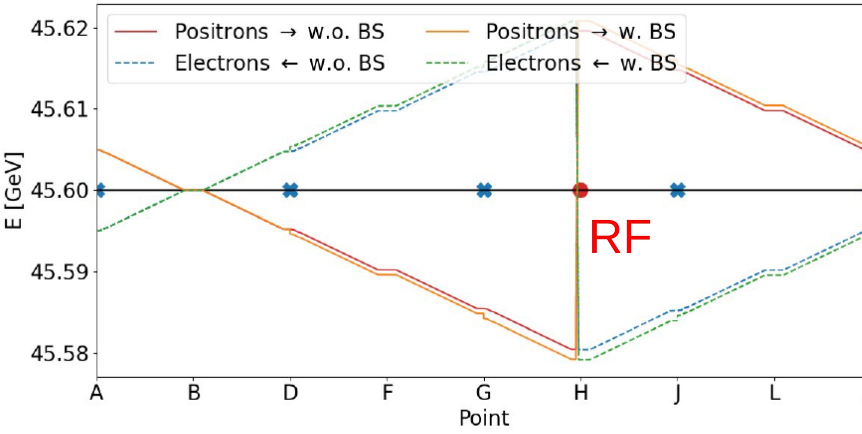
Managing these effects places high demands on BPM performance. Complete strategy still under investigation.

Interaction-point specific corrections

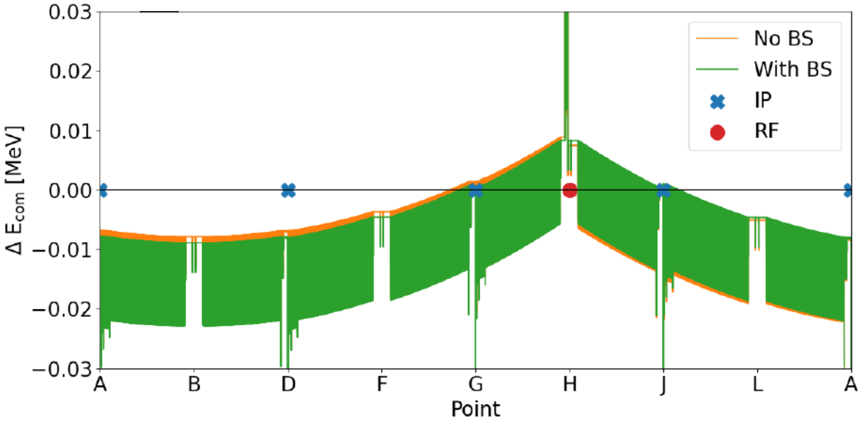
To go from mean E_b to E_{CM} at each interaction point, must consider: (i) crossing angle (see later), (ii) dispersion & collision offsets, (iii) energy variation around ring.

Optimal configuration for minimizing shift in E_{CM} around ring is to have single location for RF station (but for ttbar running, two may be necessary).

Can monitor through $e^+ e^-$ separation in BPMs, and through measurement of boost in experiments (see later).



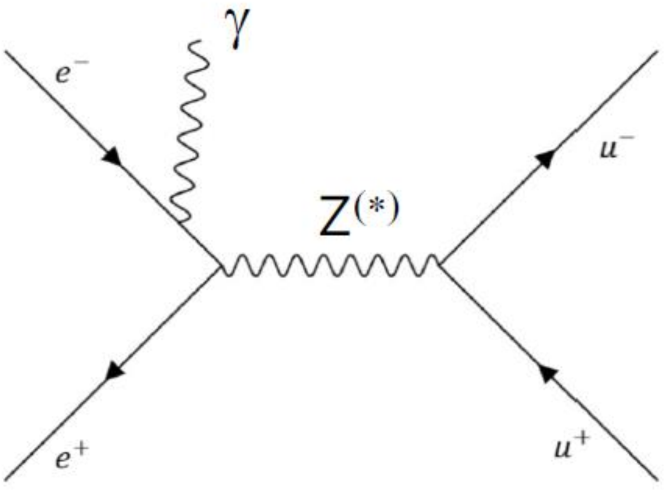
[J. Keintzel]



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

Determining the energy spread: a task for the experiments

Here the principal source of information is dimuon events, though technique can in principle be extended to other di-fermions (*e.g.* bhabhas - Sailer and Wilson).

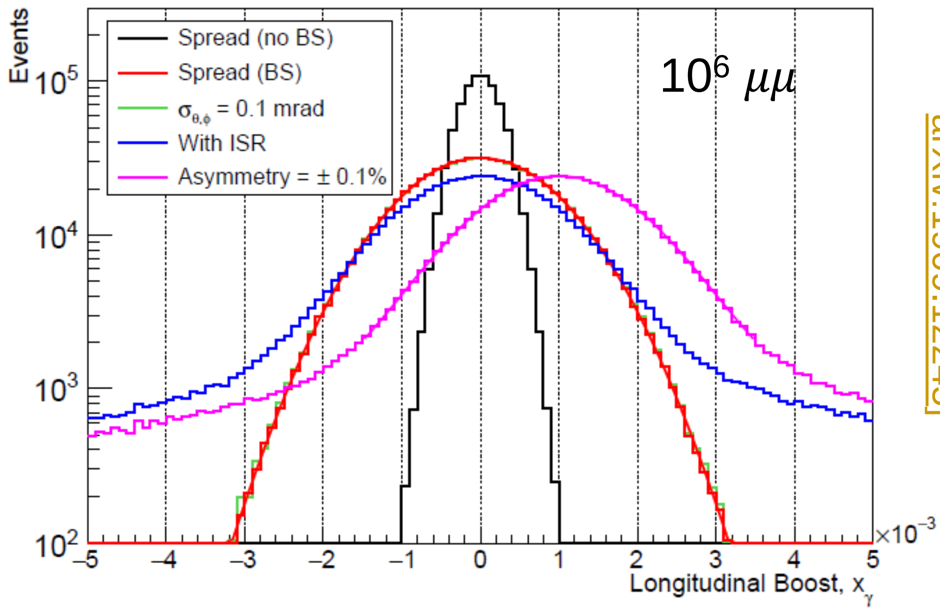


At Z expect 10^6 events every ~5 minutes.

From directions alone, and allowing for ISR down beampipe, can reconstruct longitudinal boost event-by-event. Distribution width related to energy spread.

Determining the energy spread: a task for the experiments

Reconstructing boost ($x_\gamma = p_z^\gamma/\sqrt{s}$) with no beamstrahlung, with beamstrahlung, with detector resolution, with ISR, and including an $e^+ e^-$ energy asymmetry.



[Shatilov, Perez, Janot arXiv:1909.12245]

Fitted width gives access to energy spread with statistical precision of ~10^{-3}.

Determining the energy spread: a task for the experiments

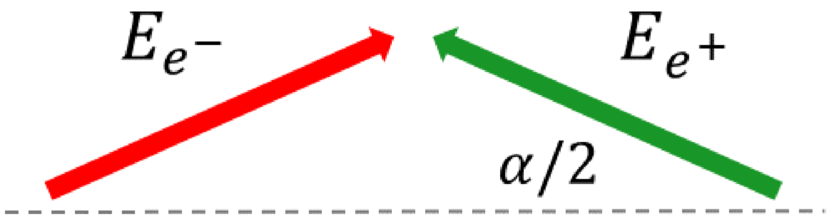
Pseudo Observable	Γ_Z			$\alpha_{QED}(m_Z^2)$		Γ_W	Γ_{top}
Acceptable error	35 keV			10^{-5}		0.5 MeV	18 MeV
$\sqrt{s}$ (GeV)	87.9	91.2	93.8*	87.9	93.8	161	350
$\sigma(\delta E)/\delta E$	0.8%	0.2%	0.8%	0.7%		11%	35%
$N_{e^+e^- \to \mu^+\mu^-}$	$5\,10^4$	$8\,10^5$	$5\,10^4$	$6.5\,10^4$		260	25
L (10^{34} cm^{-2}s^{-1})	230					28	1.8
$\sigma_{\mu\mu}$ (pb)	185	1450	460	185	460	4.0	0.8
Dimuon rate (Hz)	425	3325	1050	425	1050	1.1	0.015
Time needed	2 min	4 min	< 1 min	3 min	1 min	4 min	30 min

[Shatilov, Perez, Janot arXiv:1909.12245]

* Now aim to do even better than this !

Dimuon events: the gift that keeps on giving

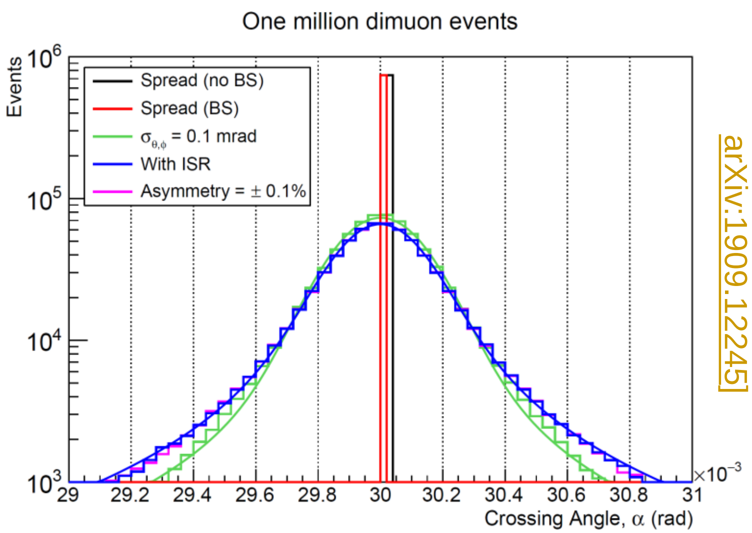
Dimuon events also allow crossing angle to be measured, which is a Necessary ingredient in going from beam energies to the collision energy.



$$\sqrt{s} = 2\sqrt{E_{e^+}E_{e^-}}\cos\alpha/2$$

Again can be measured with excellent and sufficient statistical precision using angular information (~10^{-5} with 10^6 events).

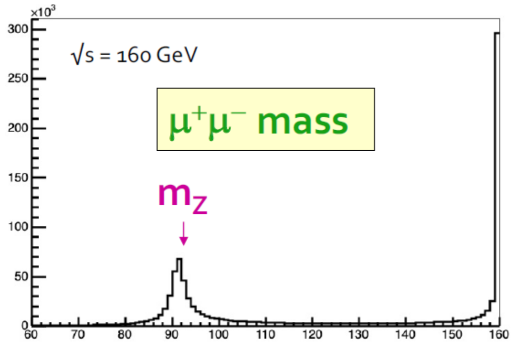
Here though there is an additional subtlety; the crossing angle, and the local beam energies, get perturbed by beam-beam forces. Challenging but tractable – see E. Perez talk.



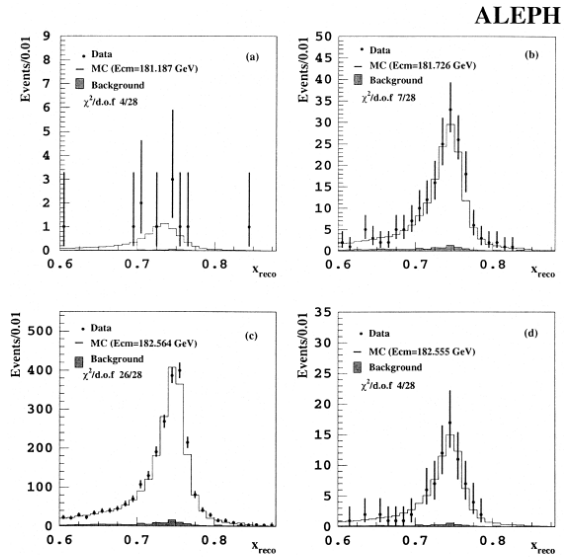
[Shatilov, Perez, Janot arXiv:1909.12245]

Dimuon events: the gift that keeps on giving

Furthermore, radiative returns to the Z can be used to measure E_{CM} at higher energies, with excellent statistical precision.



Open question, worthy of study: what is the real systematic uncertainty ?



[ALEPH, PLB 464 (1999) 339]

Technique already exploited in LEP2 era.

Estimated FCC-ee statistical precisions, using both di-muon and hadronic events:

	$\sqrt{s}$	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.)	$\sigma_{\sqrt{s}}$ (EPOL)
6 ab⁻¹	m_H	29	107	173	660 keV	280 keV	225 keV	200 keV ?
12 ab⁻¹	$2m_W$	54	47	667	900 keV	340 keV	285 keV	300 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	–

[P. Janot]

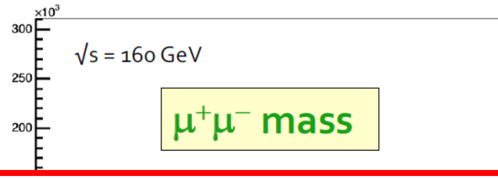
Complementary studies, making use of momentum information, performed by Graham Wilson and colleagues – see later talk.

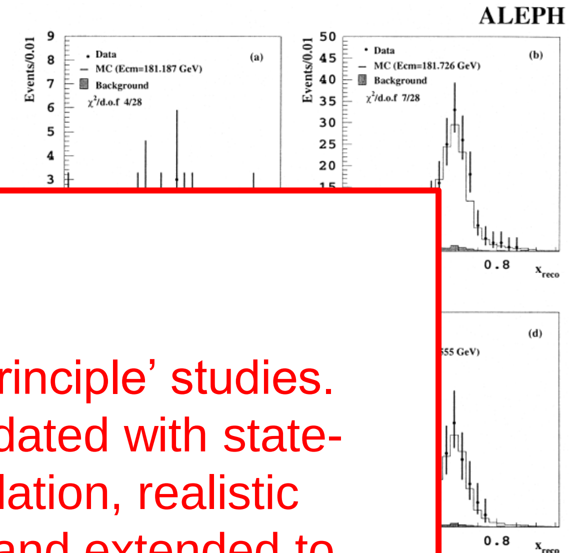
Dimuon events: the gift that keeps on giving

Furthermore, radiative returns to the Z can be used to measure E_{CM} at h… with exc… statistic…

Open q… the real…

Technic… Estimat… …ic events:





[ALEPH, PLB 464 (1999) 339]

Important message

All these results come from ‘proof-of-principle’ studies. They need to be repeated and consolidated with state-of-the-art ISR generators, proper simulation, realistic treatment of detector resolutions *etc.*, and extended to other fermion types and (in top regime) WW events. Many important & interesting studies to be performed !

								…EPOL)
6 ab^{-1}	m_H	29	107	173	660 keV	280 keV	225 keV	200 keV ?
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[P. Janot]

Complementary studies, making use of momentum information, performed by Graham Wilson and colleagues – see later talk.

So how well can we do ?

Table compiled for arXiv:1909.12245 for key Z observables

Observable	statistics	$\Delta\sqrt{s}_{abs}$ 100 keV	$\Delta\sqrt{s}_{syst-ptp}$ **40 keV**	calib. stats. 200 keV$/\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ 85 $\pm$ **0.05** MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_W^{eff} \times 10^6$ 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**

We aim to do better ! Try to reduce both the scale uncertainty & the point-to-point uncertainty, & to gain better understanding of energy spread. Reporting smaller (& reliable) uncertainties, & how to achieve them, is a goal of the Feasibility Study.

Looks feasible to meet goal of bettering statistical precision on m_W and Γ_W, but more studies needed to identify challenges & define procedures in this regime.

Immediate tasks – requirements document

Current priority is to specify and document requirements on alignment, wigglers, BPMs, depolarizer, polarimeter, input from experiments *etc.*

Preliminary draft 06:59 11 January 2023

11 January 2023

Energy calibration, polarization and monochromatization - Requirements on alignment, optics, lattice, beam instrumentation and detectors

D. Barber, A. Blondel, A. Bogomyagkov, F. Carlier, E. Gianfelice-Wendt, A. Faus-Golfe, D. Gaskell, M. Hofer, P. Janot, H. Jiang, J. Keintzel, I. Koop, T. Lefevre, A. Martens, N. Muchnoi, S. Nikitin, I. Nikolaev, K. Oide, T. Persson, T. Pieloni, P. Raimondi, D. Sagan, D. Shatilov, R. Tomas, J. Wenninger, G. Wilkinson, Y. Wu, F. Zimmermann, ...
CERN, CH-1211 Geneva, Switzerland

Draft exists, which will be added to and refined for Mid-term Review.

Conclusions and outlook

Taking full advantage of the bounty of FCC-ee statistics for a wide range of physics studies places great demands on our understanding of collision energy *e.g.* at level of O(10-100) keV for many Z observables.

Achieving this goal needs ingenuity, and the necessary requirements and procedures to be part of the machine design and plan for operation.
Input from the experiments will be a vital component of this programme.

A baseline plan has been established, but many aspects need to be refined and improved. Help is very welcome ! Lots of room for new ideas.

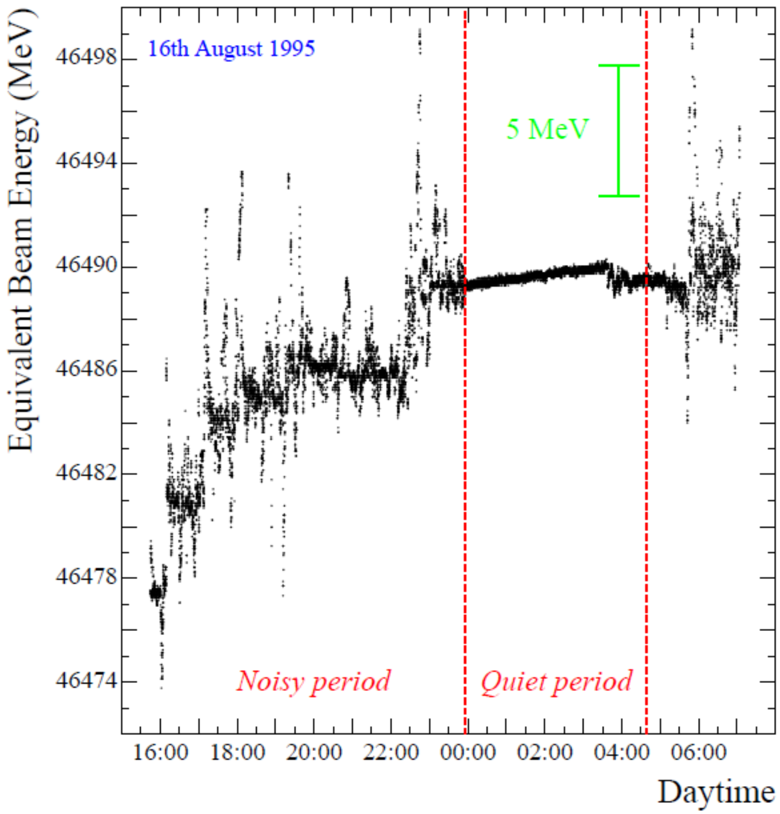
See Jacqueline's talk on Friday for Future Plans.

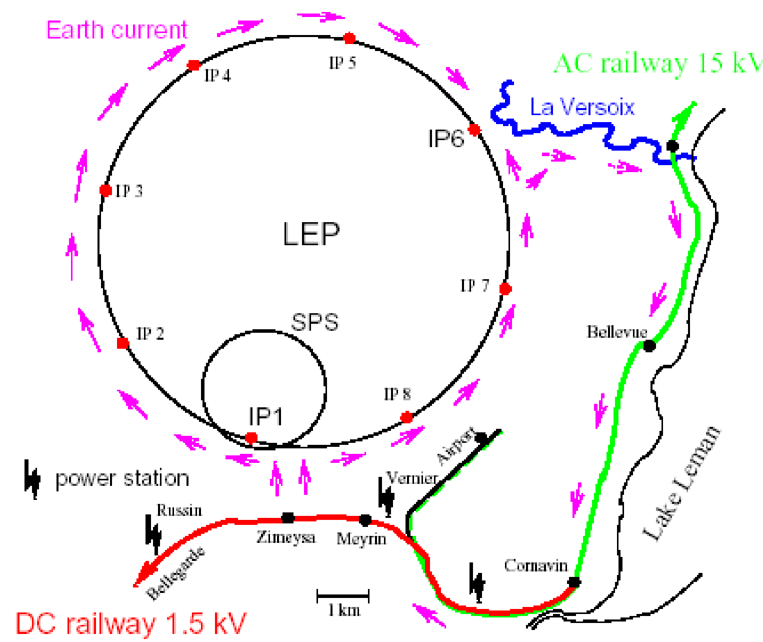
Backups

(Selected) mechanisms of E_b variation

Strange noise and field rises in magnets correlated to time of day and time in fill.

Found to be due to magnets being 'tickled' by current on beam pipe from passing trains.





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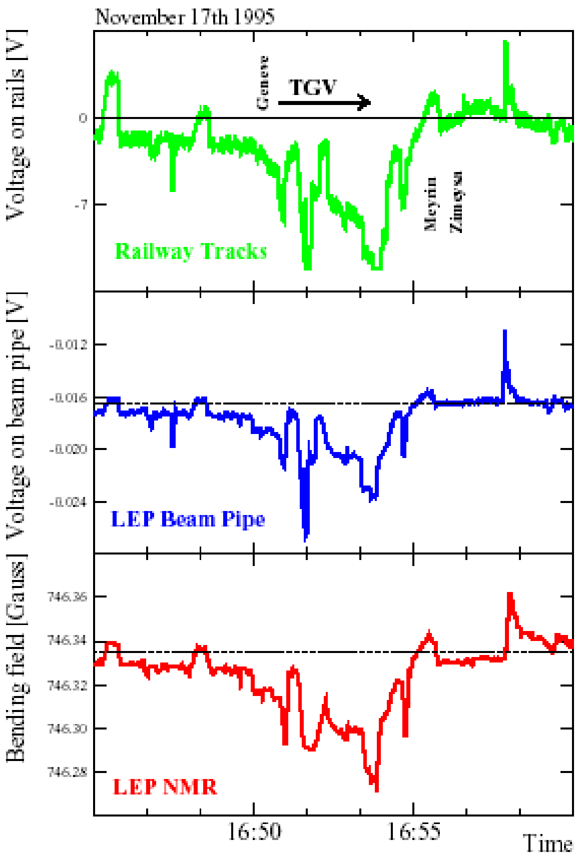

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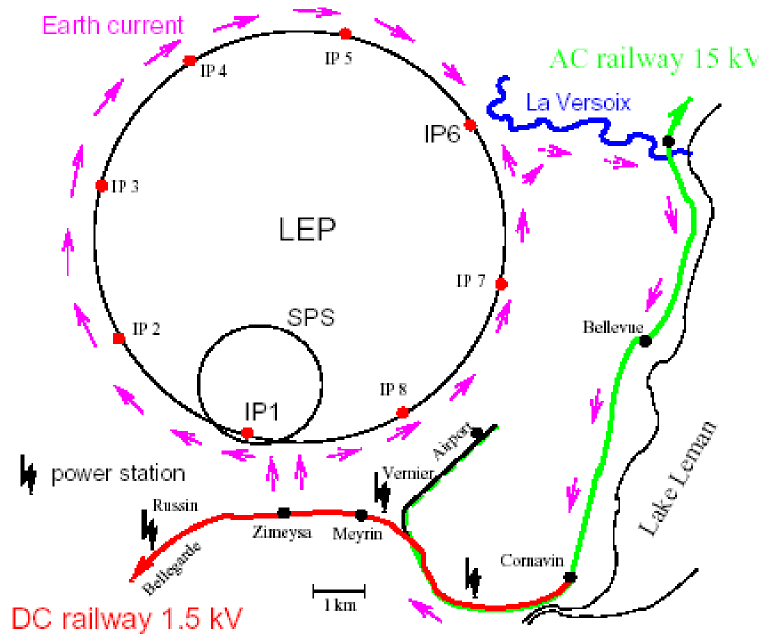
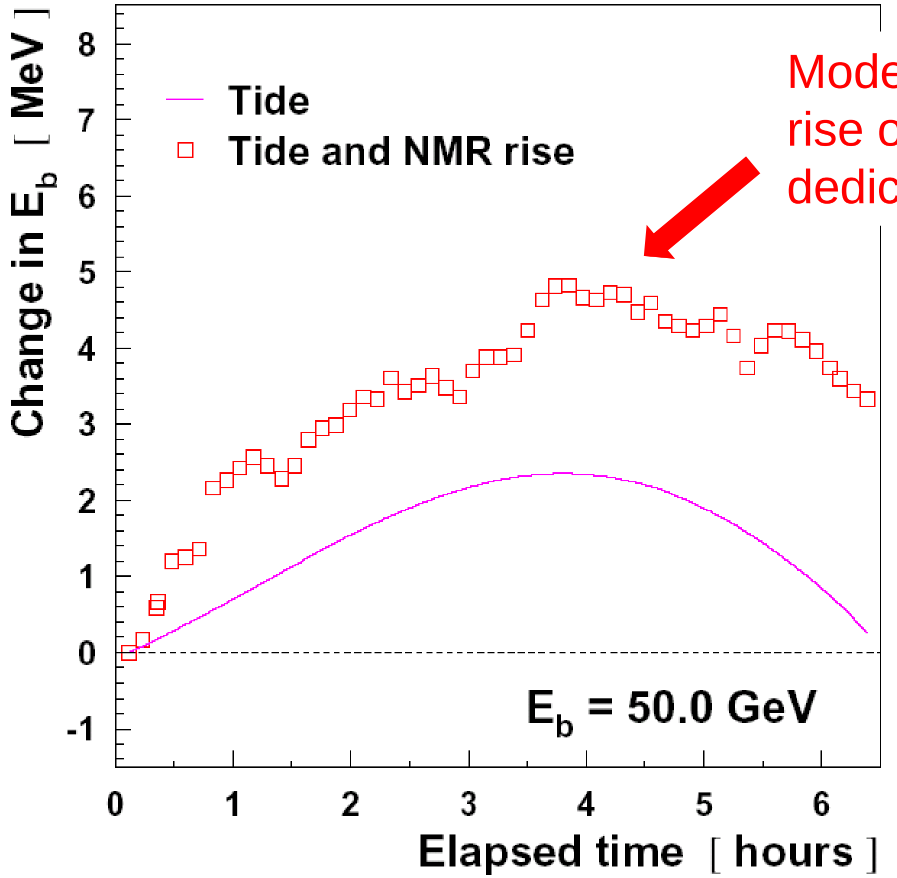


Compelling correlation between current on track, on beam pipe & noise in magnets.

(Selected) mechanisms of E_b variation

Energy rise modelled with great precision.



Model prediction of energy rise over a fill during a dedicated machine study.

(Selected) mechanisms of E_b variation

Energy rise modelled with great precision, in excellent agreement with RDP.