E_{CM} determination at future circular e^+e^- colliders

Guy Wilkinson
University of Oxford
ECFA e^+e^- WG1-PREC meeting, 2/11/22

with many thanks to colleagues in FCC EPOL WG

E_{CM} determination at ~~future circular e^+e^- colliders~~ FCC-ee

Almost all statements equally applicable to CEPC

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Outline

- Lessons from LEP

  - what was achieved, and what were the limitations

- Looking towards FCC-ee

  - a baseline strategy for coping with ~5 x 10^{12} Z (and physics at other energies), including *selected* highlights and ongoing challenges. Not comprehensive !

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- Lessons from LEP

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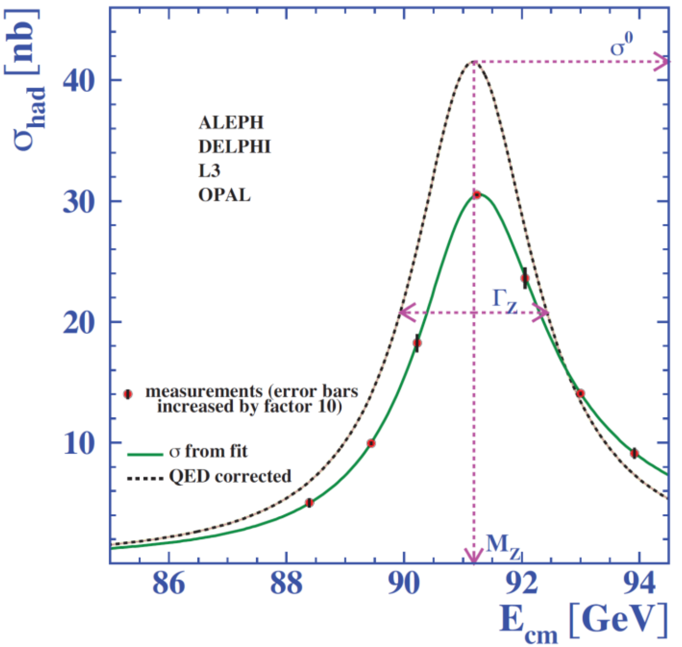
Challenges of Z metrology

Measuring M_Z and Γ_Z at LEP had many challenges (*e.g.* luminosity measurement, theoretical understanding of lineshape *etc*.) but knowledge of horizontal scale, *i.e.* E_{CM} calibration, was identified as limiting factor right from outset.



Horizontal-scale uncertainty set by knowledge of collision energy, also common between experiments.

It was guessed that ~10 MeV uncertainty *might* be possible.

Outlook shortly before LEP turn on: *"The overall conclusion is that at LEP the Z^0 mass and width can be measured with relative ease down to … +/- 50 MeV. A factor of 2-3 improvement can be reached with a determined effort…"* CERN 86-02 'Physics at LEP', ed. Ellis and Peccei.

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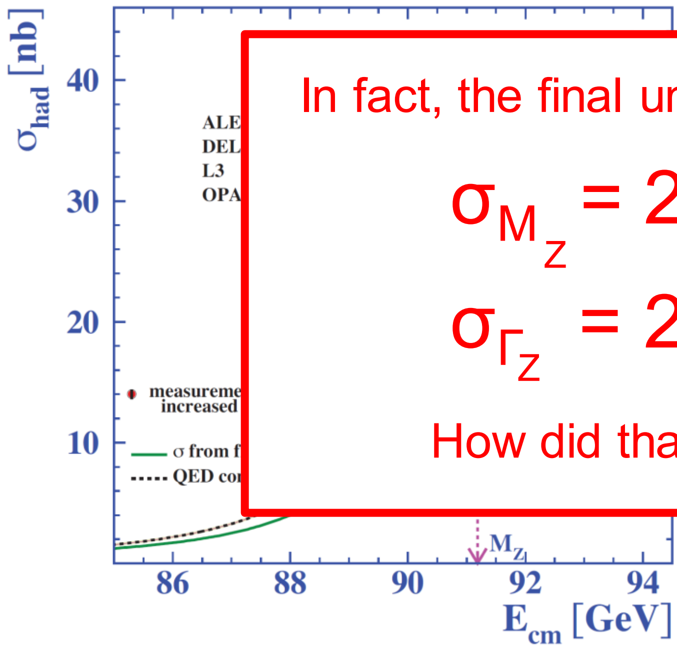

In fact, the final uncertainties were:

$$\sigma_{M_Z} = 2.1 \text{ MeV}$$

$$\sigma_{\Gamma_Z} = 2.3 \text{ MeV}$$

How did that happen ?

e uncertainty set
of collision energy,
etween experiments.

that ~10 MeV
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Collision-energy calibration

Knowledge of collision energy leading systematic in mass and width measurement:

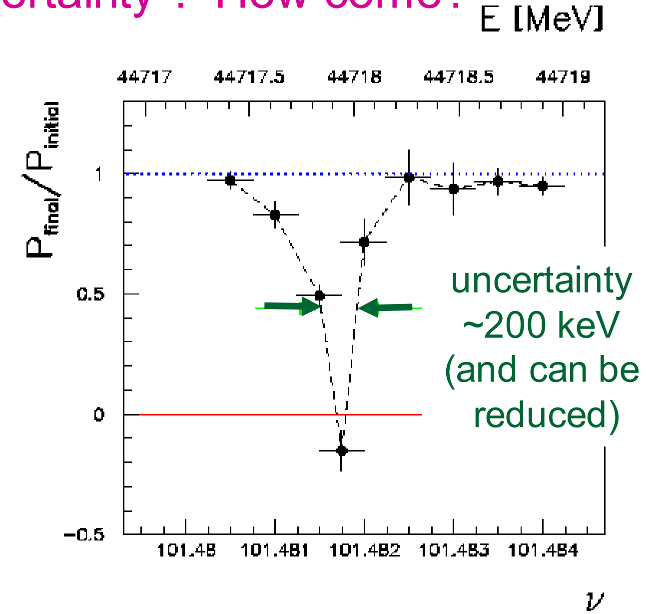
m_Z total uncertainty = 2.1 MeV, of which E_{CM} contribution = 1.7 MeV
Γ_Z total uncertainty = 2.3 MeV, of which E_{CM} contribution = 1.2 MeV

But *much* better than anticipated, and < stat. uncertainty ! How come?

High level of precision achieved through miracle of resonant de-polarisation (RDP), which is unique to circular e^+e^- machines.

- Wait for transverse polarisation to build up;
- Precession frequency, ν_s, directly proportional to E_b :

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



- Monitor polarisation with Compton scattering from laser whilst exciting beam with transverse oscillating B field. Find frequency at which depol^n occurs.

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High level of pr…
miracle…
which is …

Hang on, these uncertainties, though impressive, are >> intrinsic uncertainty of RDP. Why so ?

- Wait for transverse polarisation to build up;
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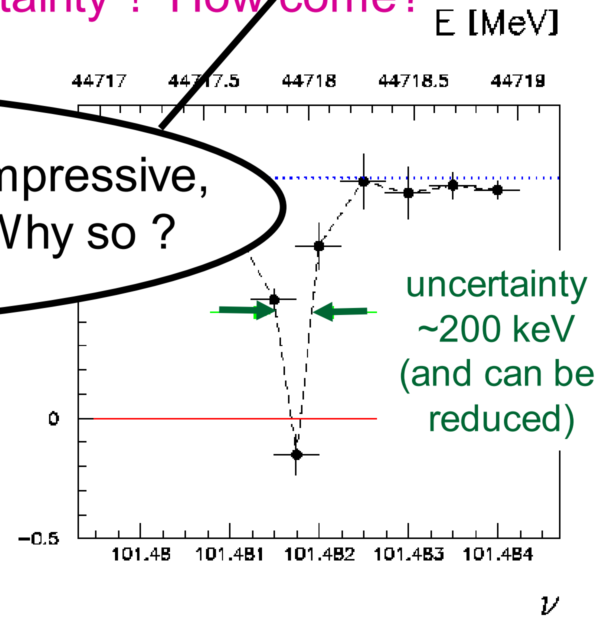
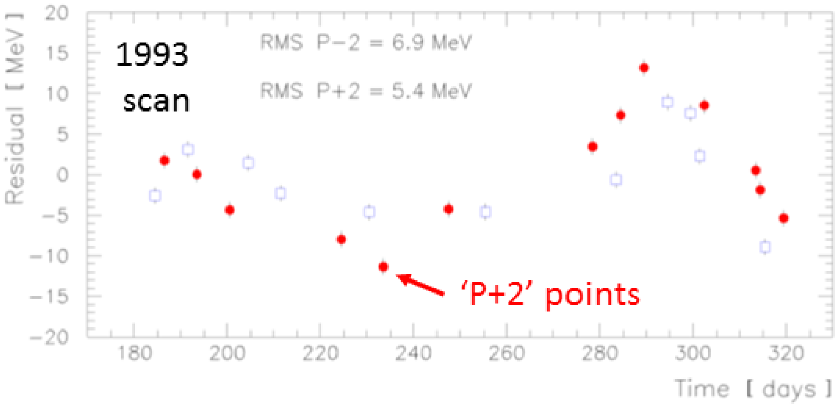
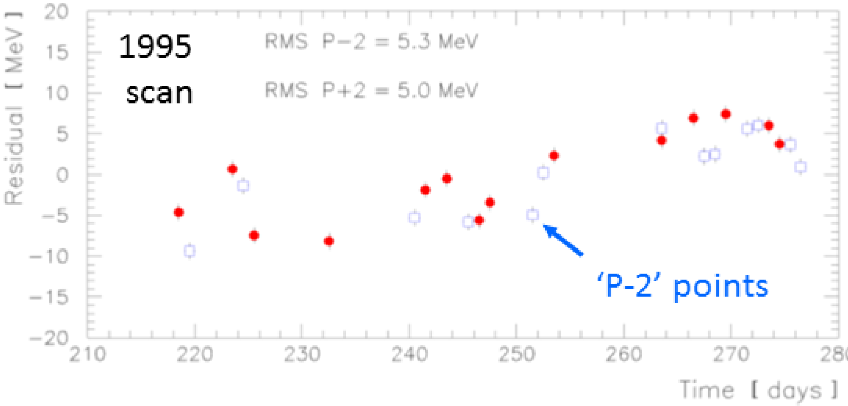


- Monitor polarisation with Compton scattering from laser whilst exciting beam with transverse oscillating B field. Find frequency at which depol^n occurs.

Challenge of E_{CM} calibration at LEP

At LEP RDP could not be performed during physics operation. Time-consuming procedure carried out at the end of certain fills, involving dedicated optics. these measurements showed scatter indicating considerable evolution in E_b.



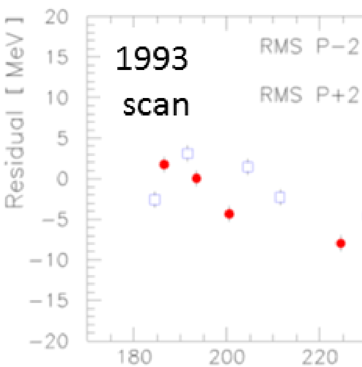


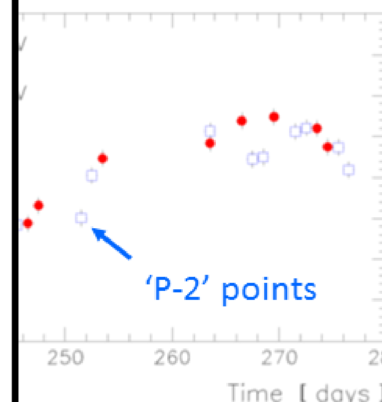
To calibrate the physics data-taking period, necessary to understand and model this evolution – a long and painful process that took many years. Ingredients:

- Bright ideas and machine theory;
- Dedicated instrumentation *e.g.* NMRs in magnets, BPMs *etc.;*
- Lots of machine time for studies (~50 full days in period 1993-2009);
- Mechanisms parameterised in models, used to calibrate physics data periods.

Challenge of E_{CM} calibration at LEP

At LEP RDP co … Time-consuming procedure carr … ated optics. these measure … volution in E_b.





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THE EUROPEAN PHYSICAL JOURNAL C

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]

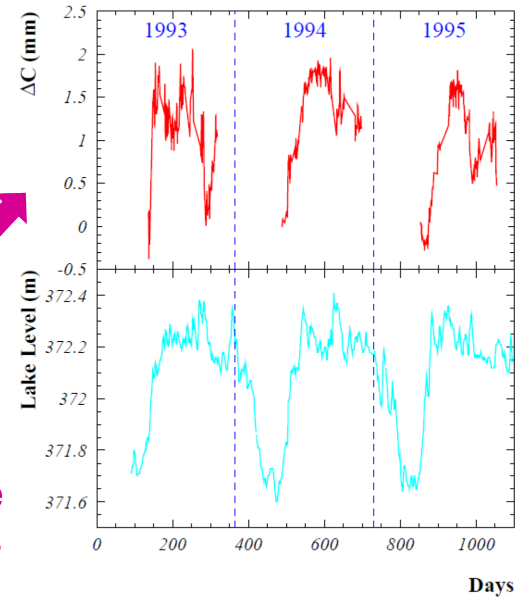
To calibrate the … stand and model this evolution – … s. Ingredients:

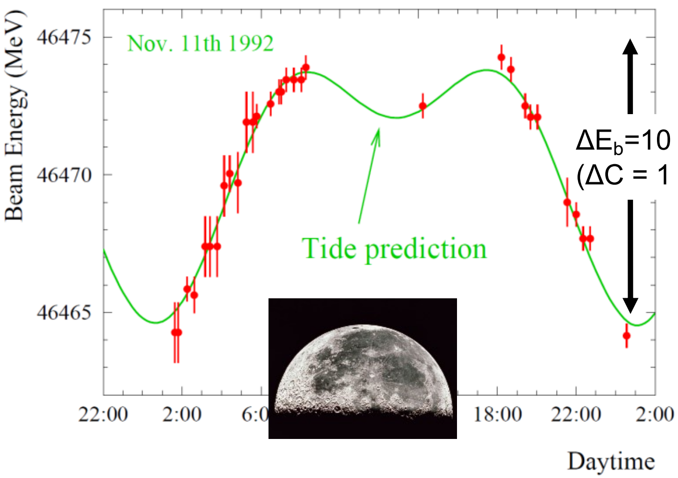
- Bright idea …
- Dedicated … *tc.*;
- Lots of ma … 93-2009);
- Mechanism … hysics data periods.

Some mechanisms of E_b variation

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

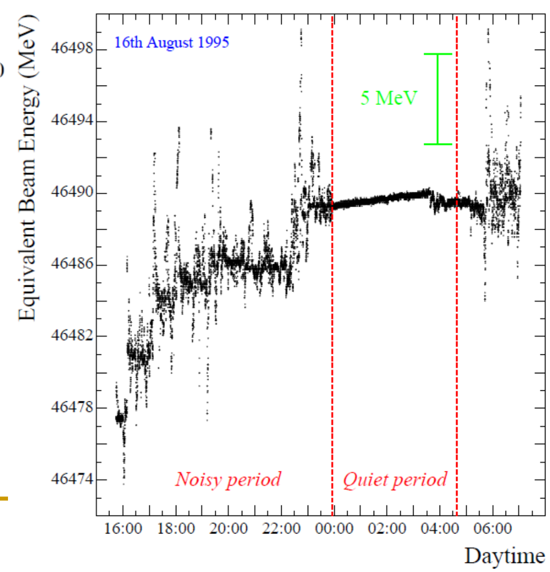
NB at FCC-ee effects will be ~10x larger due to smaller momentum-compaction factor !

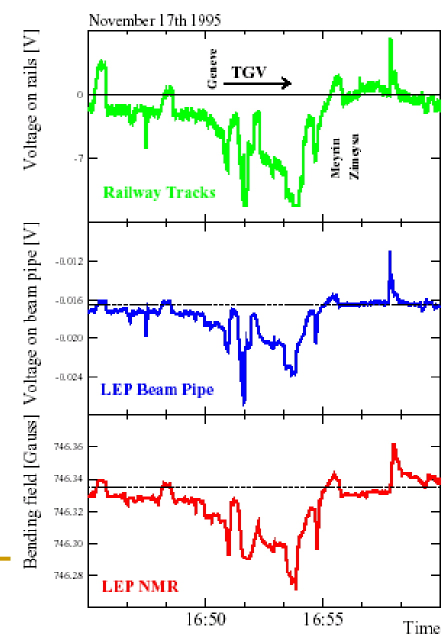




ΔE_b=10 MeV
(ΔC = 1 mm)

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

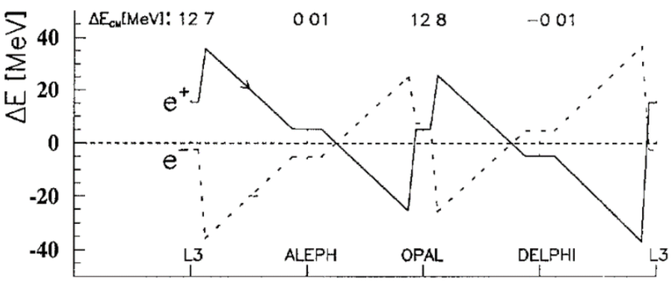


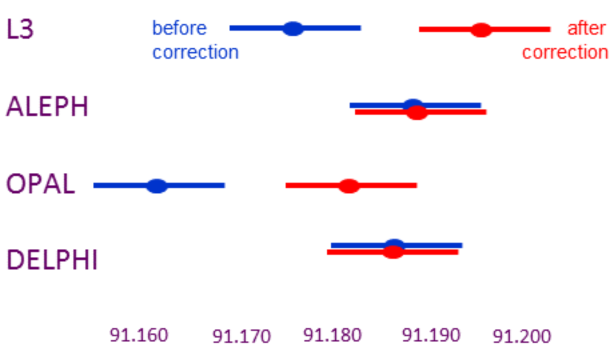


Interaction-point specific corrections

RDP gives E_b, but $E_{CM} \neq 2E_b$. Interaction-point specific corrections must be applied.

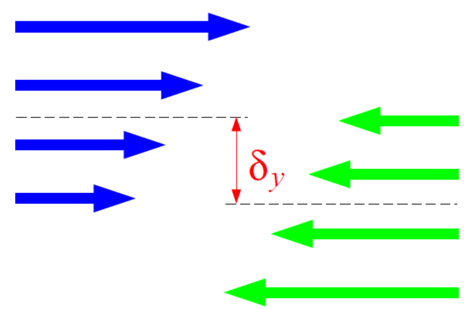
'RF sawtooth' – synchroton radiation loss and RF boosts.





Discovered in 1991, from comparison of individual m_Z results [PLB 307 (1993) 187].

Opposite-sign vertical dispersion (present in 1995) combined with collision offsets → E_{CM} bias.



$$\Delta E_{\rm cm} = \frac{-1}{2}\,\frac{\delta y}{\sigma_y^2}\,\frac{\sigma_{E_b}^2}{E_b}\,\Delta D_y^\star$$

σ_{E_b} = Energy spread

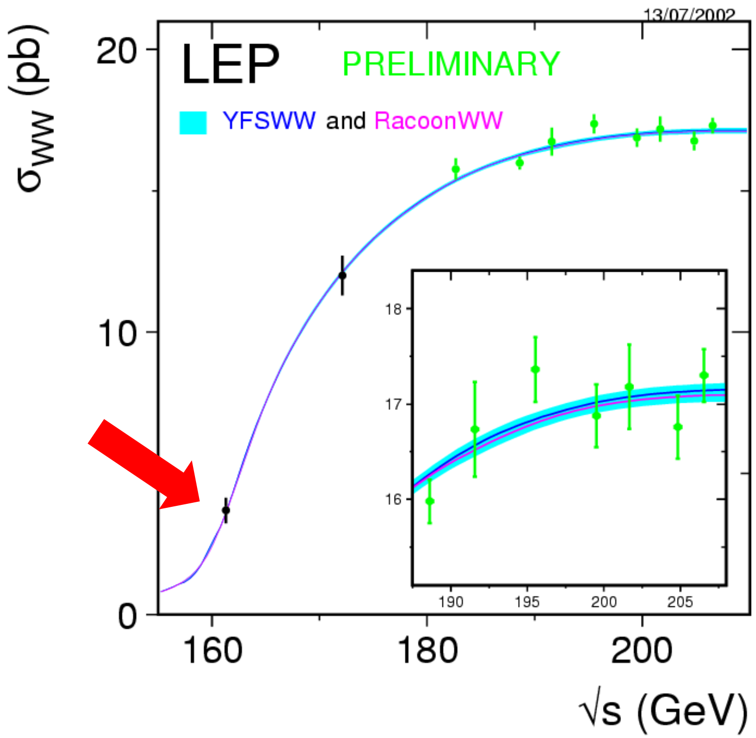
ΔE^*_b = Difference in dispersion between e^+ and e^-

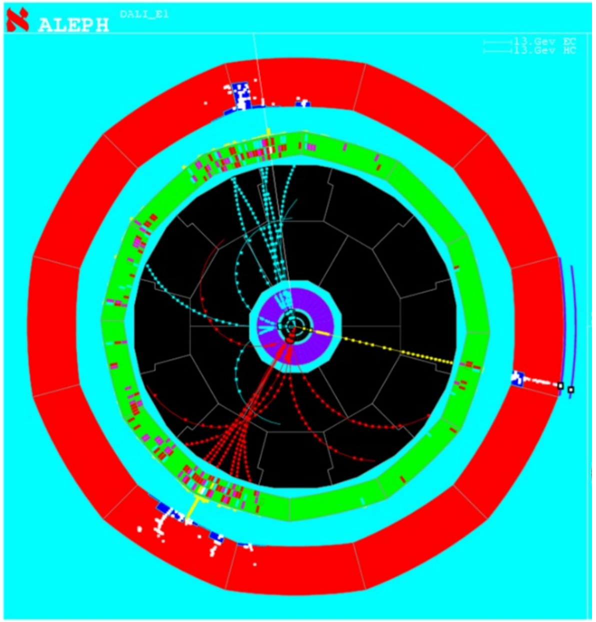
e.g. if $\Delta D^*_y \sim 2$ mm and $\delta y = 1$ μm → $\Delta E_{CM} = 2$ MeV.

Control by continual optimisation of luminosity vs δy ('Vernier scans').

Measuring m_W in $e^+e^- \rightarrow W^+W^-$

Two methods available: measure WW cross-section at threshold, or fully reconstruct event. Former has fewer systematics, and will probably be the method of choice at FCC-ee, but lower statistical uncertainty gave latter higher weight at LEP.





In both cases a leading systematic uncertainty comes from collision energy (yes, that again).

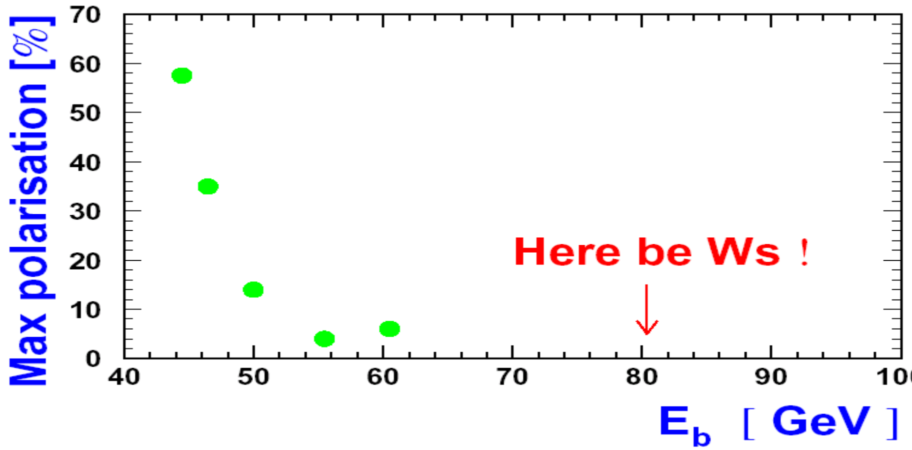
$$\frac{\Delta m_W}{m_W} = \frac{\Delta E_{CM}}{E_{CM}}$$

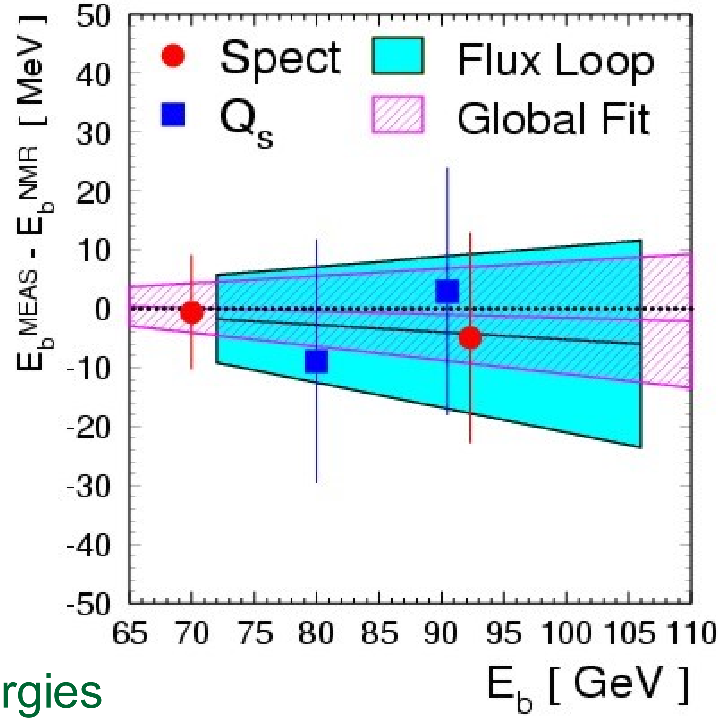
Measuring m_W in $e^+e^- \to W^+W^-$

$$\frac{\Delta m_W}{m_W} = \frac{\Delta E_{CM}}{E_{CM}}$$

Surely not a problem? Many fewer W's than Z's – statistical precision at LEP a few 10^{-4}, and E_{CM} measured to 2 x 10^{-5} at Z^0. What's the worry ?

Growth of beam spread with energy means depolarising resonances destroy polarisation. Ergo, no RDP at E_b>60 GeV at LEP2…





…instead must use a variety of methods (*e.g.* spectrometer) to extrapolate from RDP energies to W^+W^- regime. Very difficult, but it was done [EPJC 39 (2005) 253].

Outline

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  - what was achieved, and what were the limitations

- Looking towards FCC-ee

  - a baseline strategy for coping with ~5 x 10^{12} Z (and physics at other energies), including *selected* highlights and ongoing challenges. Not comprehensive !

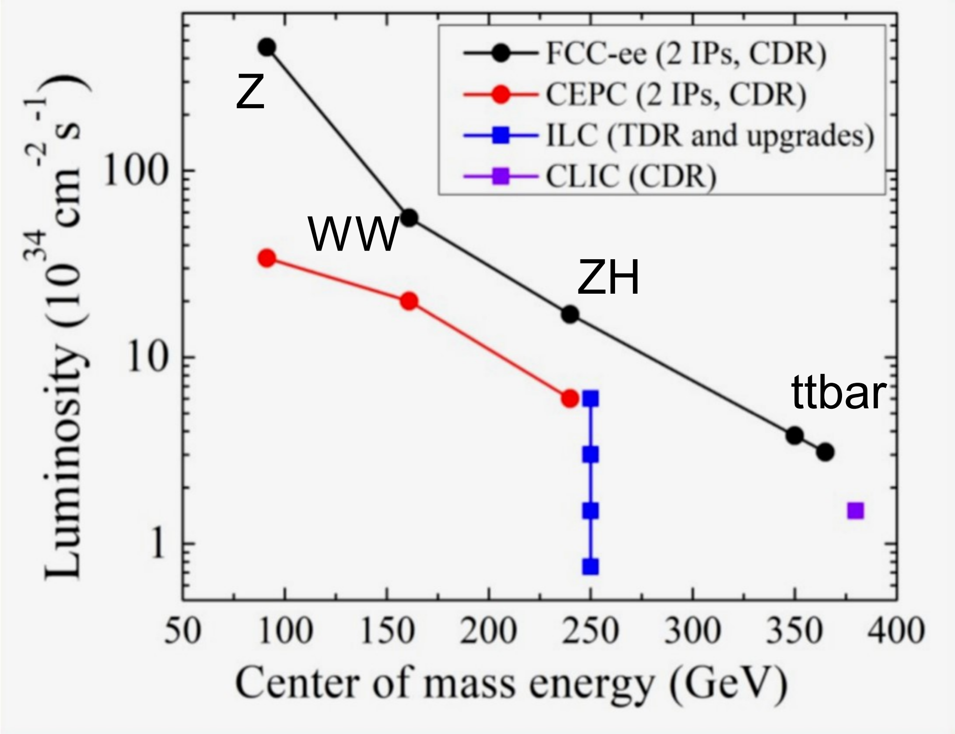
E_{CM} calibration requirements at FCC-ee

E_{CM} systematics at LEP for M_Z, Γ_Z & M_W were similar to statistical uncertainties. Enormous increase in sample sizes at FCC-ee means corresponding improvements are required for E_{CM}. Will also be necessary for other observables (*e.g.* A^{μ}_{FB}). Big improvements also required in knowledge of related quantities, *e.g.* E_b spread.

5×10^{12} Z^0 produced
= 3×10^5 x LEP

10^8 W^+W^- produced
= 3000 x LEP

(numbers based on
CDR running strategy
& two interaction points)



Will present key points of developing strategy for meeting this challenge.
Follow up with some remarks about other E_{CM} points, including possible m_H run.

Strategy for E_{CM} calibration at FCC-ee – key points

In contrast to LEP, build E_{CM} calibration requirements into machine design and planning from start. We already have a baseline strategy, which addresses the main problems that afflicted the LEP energy calibration.

PREPARED FOR SUBMISSION TO JHEP

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

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

The FCC-ee Energy and Polarization Working Group:
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[arXiv:1909.12245]

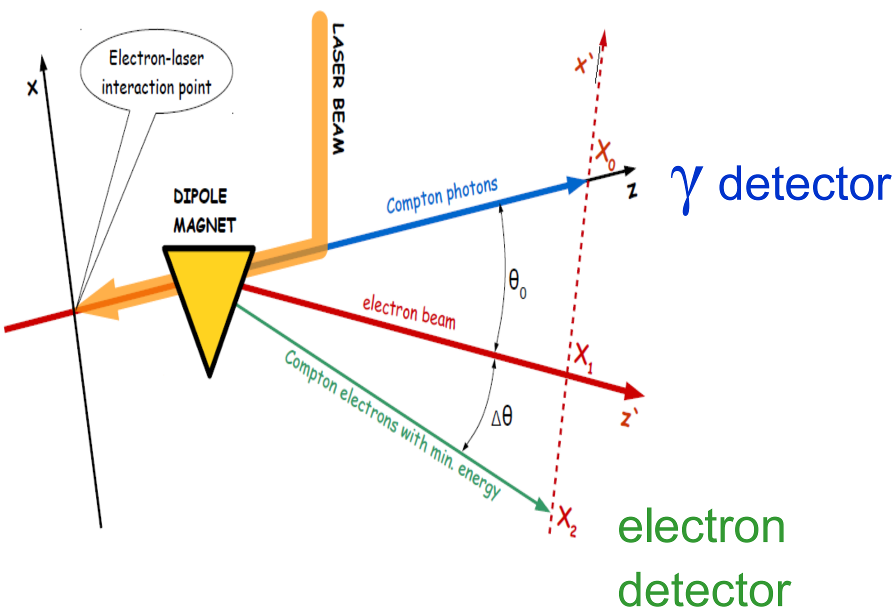
- Perform RDP 'continuously' (~5 times per hour). This is done on ~250 out of 16600 non-colliding pilot bunches.

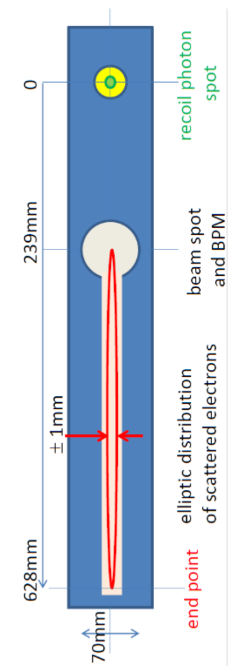
  ➡ Removes to first order all time-dependent effects !!!

- Measure separately for e^+ & e^-.
- Adjust RF frequency at short intervals to suppress tide-like effects.

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.





Need to measure polarization level of electrons and positrons, so (at least) two polarimeters required. Full specifications currently under discussion.

Resonant depolarization strategy

- Require 5-10% level of polarization for reliable RDP measurement.
- Natural polarization build-up time at Z pole is around 29 hours for 10%. Therefore use wigglers for 1-2 hours at start of fill to polarize pilot bunches, before injecting physics bunches (unavoidable dead time – to be minimised).
- Depolarize one bunch at a time, and rely on natural polarization build-up to replenish polarization level of used bunches.
- Aim to perform measurement every ~10 minutes.
- Under consideration: also performing free spin precession measurements, where spin vector is rotated into horizontal plane and its precession frequency is directly measured. May have complementary systematics to RDP.

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: $A_{\rm FB}^{b} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b$

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

Now, if there is longitudinal polarization, asymmetry becomes: $\left(A_{\rm FB}^{b}\right)' = \frac{3}{4}\mathcal{A}'_e\mathcal{A}_b$

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 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)

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

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.

Strategy for E_{CM} calibration at FCC-ee – key points

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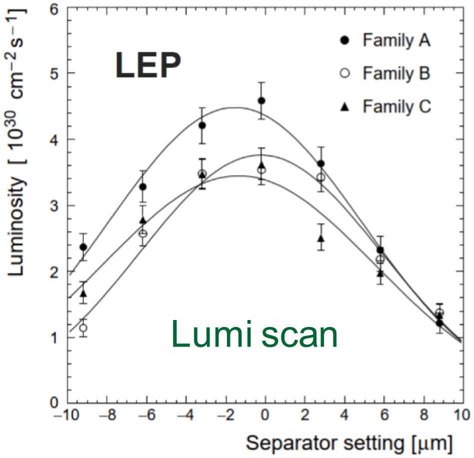
  ➡ Removes to first order all time-dependent effects !!!

- Measure separately for e^+ & e^-.
- Adjust RF frequency at short intervals to suppress tide-like effects.
- Frequent scans to suppress dispersion biases at IP.

Interaction-point specific corrections

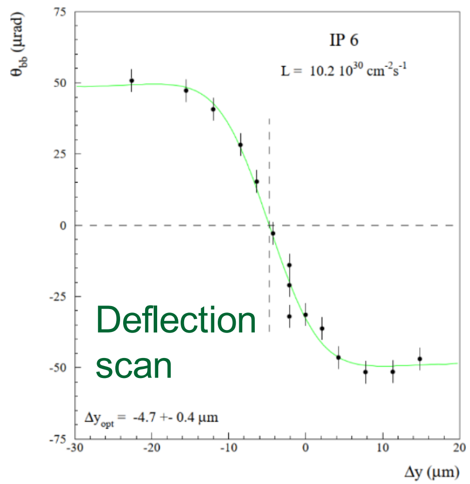
As at LEP, we will need to worry about possible dispersion and RF sawtooth effects.

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



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).



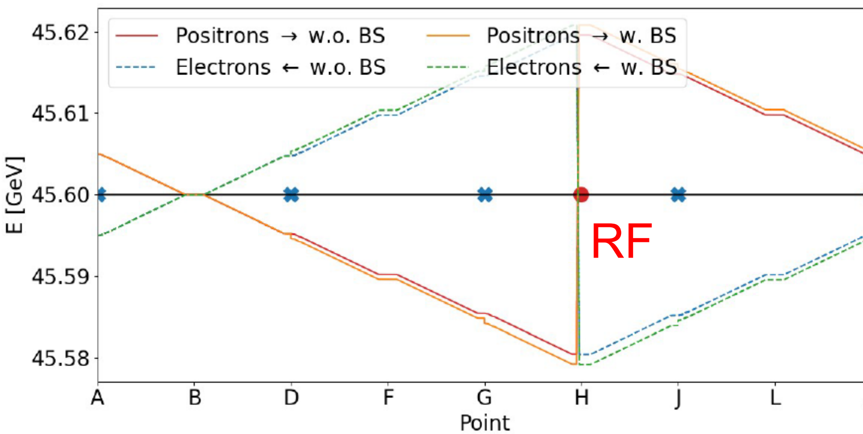
Both offset and dispersion can be measured through luminosity scan or through beam-beam deflection scan, using angles found from BPMs.

Interaction-point specific corrections

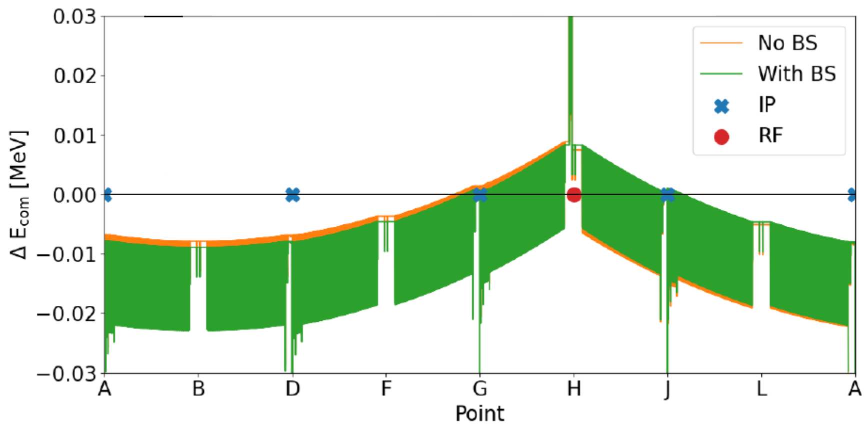
As at LEP, we will need to worry about possible dispersion and RF sawtooth effects.

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

Strategy for E_{CM} calibration at FCC-ee – key points

In contrast to LEP, build E_{CM} calibration requirements into machine design and planning from start. We already have a baseline strategy, which addresses the main problems that afflicted the LEP energy calibration.


Prepared for submission to JHEP

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

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

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[arXiv:1909.12245]

- Perform RDP 'continuously' (~5 times per hour). This is done on ~250 out of 16600 non-colliding pilot bunches.

  → Removes to first order all time-dependent effects !!!

- Measure separately for e^+ & e^-.
- Adjust RF frequency at short intervals to suppress tide-like effects.
- Frequent scans to suppress dispersion biases at IP.
- Invest in extensive instrumentation and logging of all machine parameters.
- Exploit measurements from experiments that provide complementary information.

Measurement of crossing angle and E_{CM} spread

Even with energy loss / RF and dispersion effects under control, another ingredient is needed to go from the local beam energies to E_{CM}. The crossing angle !

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

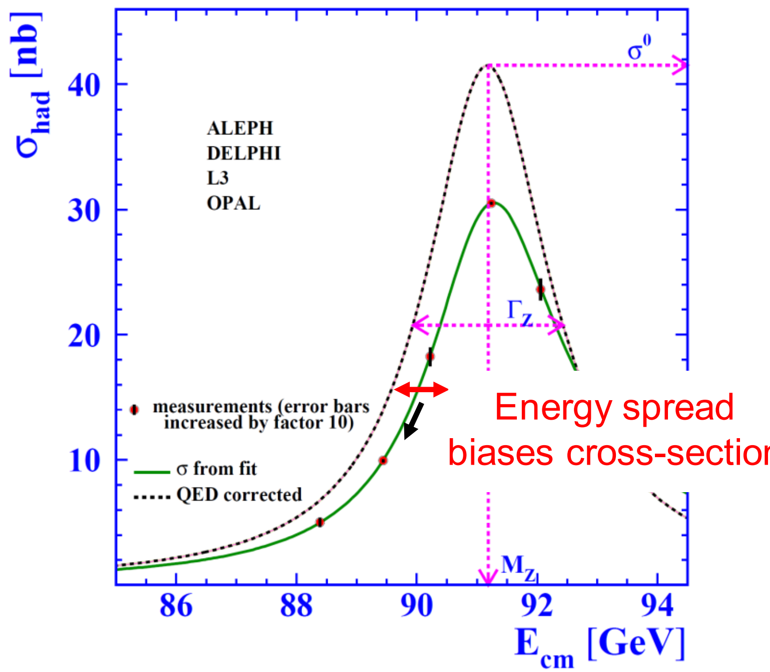
Crossing angle α is around 30 mrad at FCC-ee (in fact there are beam-beam effects that modify both local beam energy and α - won't discuss through lack of time).

Aside from this, need to know E_{CM} spread well. Not a great concern at LEP but a dangerous systematic on several measurements at FCC-ee (*e.g.* Z, W, top widths, offpeak A^{μ}_{FB} for α_{QED}).

Beam energy is not monochromatic, but has a spread of ~50 MeV at Z.

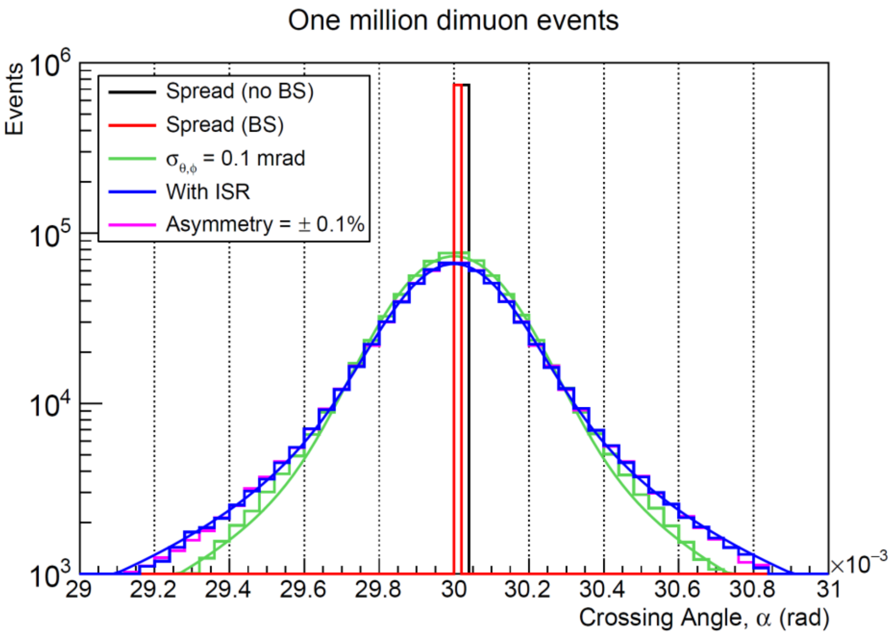
Spread in collision energy, $\sigma_{E_{CM}}$ will shift cross-section measurements by δ_σ as line shape is (clearly!) not linear.

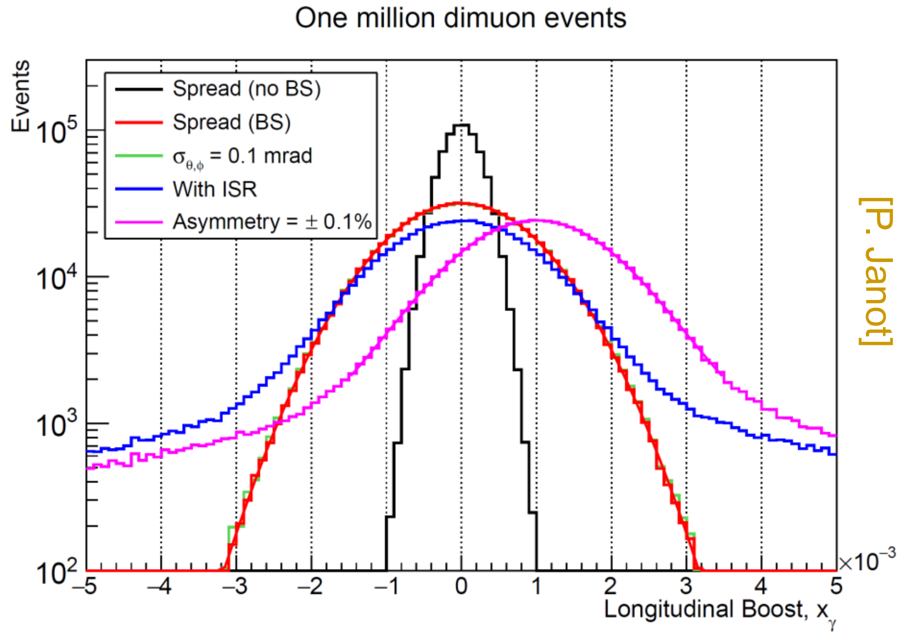
$$\delta\sigma = -0.5\ \frac{d^2\sigma}{dE^2}\ \sigma^2_{E_{CM}}$$



Measurement of crossing angle and E_{CM} spread

These effects can be controlled to necessary precision through monitoring topology of $Z^{(*)} \rightarrow \mu\mu(\gamma)$ events, of which million will be collected every ~5 minutes at Z pole.





[P. Janot]

[related to energy spread]

Results documented in arXiv:1909.12245 , but should be revisited with more sophisticated simulations, consideration of ISR knowledge, detector resolution *etc.*

Initial estimates of what is achievable at Z

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**

Much better than LEP, but E_{CM} systematics do not match stat precision for M_Z & Γ_Z.

We aim to improve on this ! Many advances reported at 2nd FCC EPOL Workshop at CERN in September, and further updates will be presented at FCC Midterm Review in summer next year. Help is very much welcome.

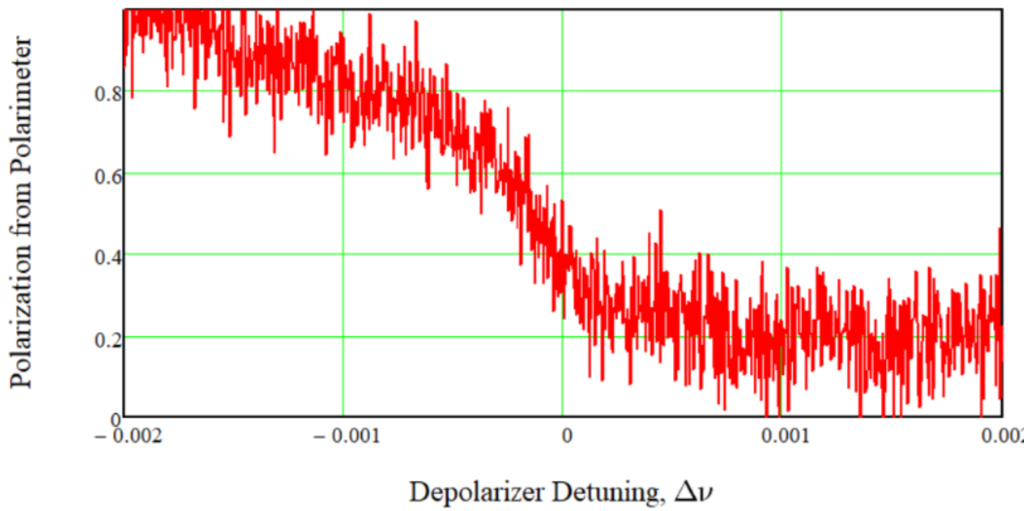
E_{CM} calibration for m_W

In contrast to LEP, at FCC-ee resonant depolarisation should be possible at the W^+W^- threshold (E_b ~ 80 GeV). This is because the 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.)

Recent simulations confirm that polarization, and clear depolarization signals, will be achievable. Although precision is unlikely to match that at Z, it should be perfectly adequate for m_W.



[I. Koop]

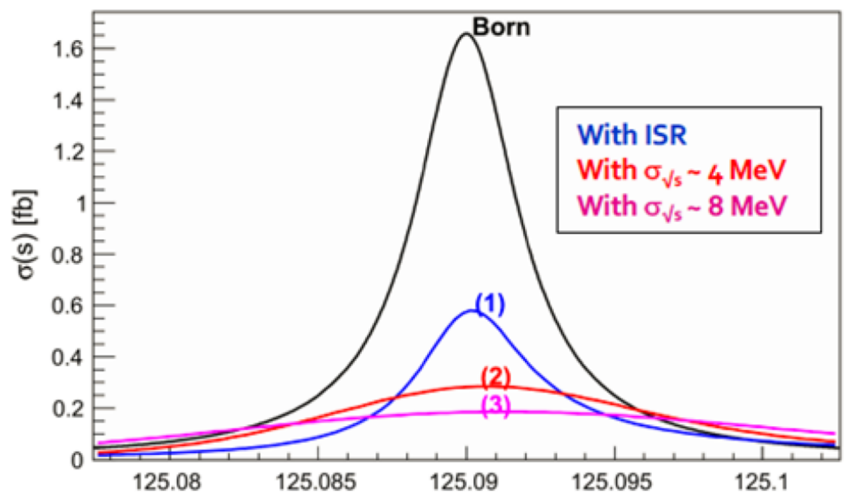
Other energy points

It is assumed that RDP will not be possible when collecting ZH and ttbar data.

Here can rely on $Z^* \rightarrow$ ffbar γ events and $e^+e^- \rightarrow W^+W^-$ events, which will have sufficient statistical power to meet the physics goals at both energy points.

And what about if a run is made at $E_{CM} = m_H$ to measure electron Yukawa ?

- Monochromatization is required to reduce E_{CM} spread to same order as Higgs width (~ 4 MeV)
- Need to ensure high stability for E_{CM} and very good knowledge of its value event-to-event.



→ RDP certainly needed, with additional requirements different to those at Z !

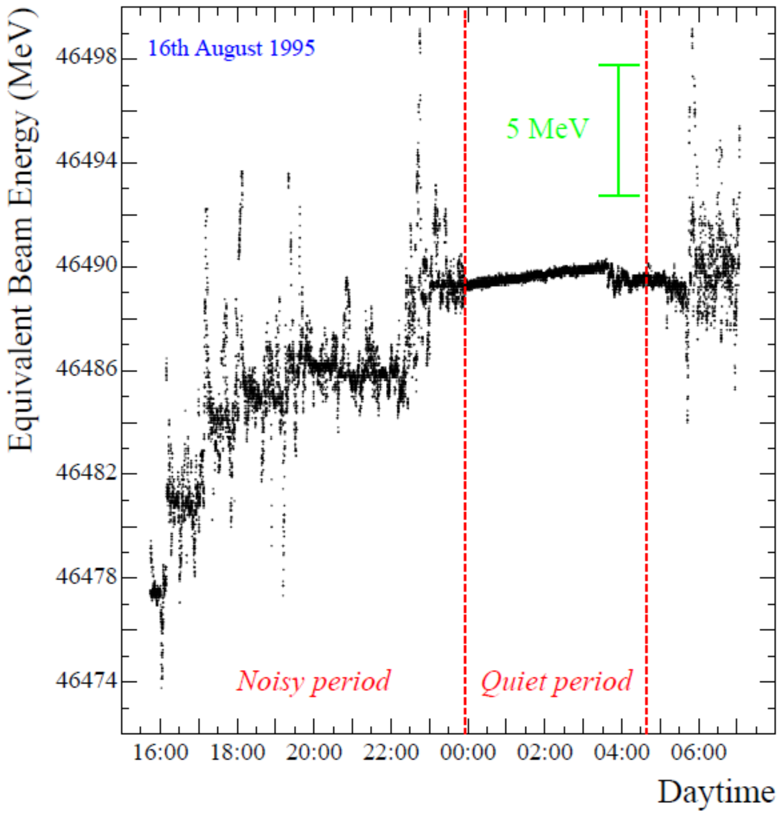
Conclusions

- Precise knowledge of E_{CM} is a key asset of circular e^+e^- colliders.
- The Z-scan campaigns a LEP demonstrated both the power of RDP, and also the additional challenges that are required to meet physics goals.
- The huge sample sizes at FCC-ee mandates a corresponding improvement in the control of E_{CM}. A baseline strategy has been developed which already shows great promise….
- …but much work remains to understand requirements better, firm up specifications, and pursue further developments to improve outlook further.
- RDP will also be available in W^+W^- regime – opportunity then available to improve precision of CDF measurement by factor 20-30.

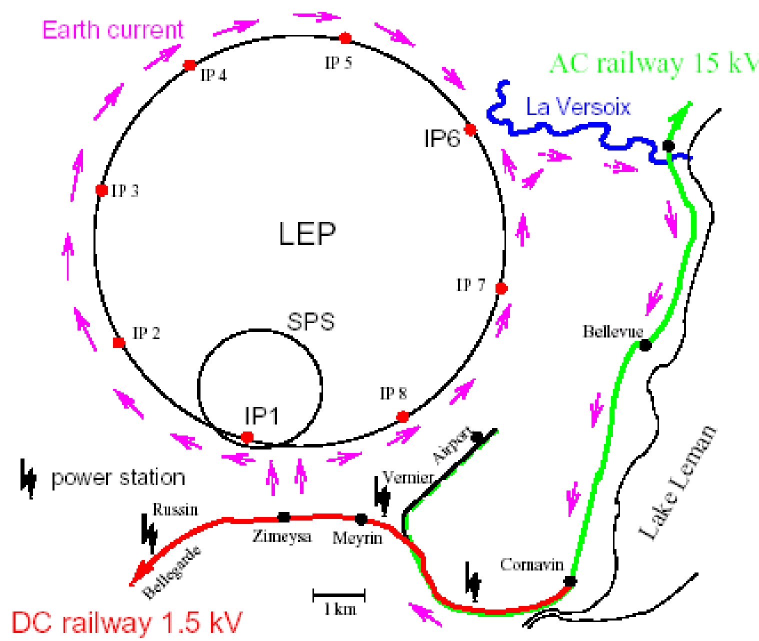
Backups

(Selected) mechanisms of E_b variation

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

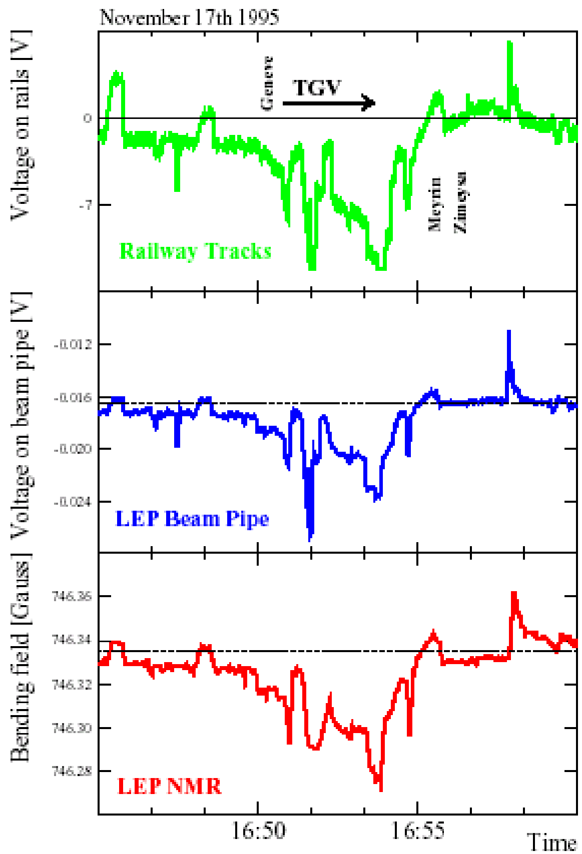


Found to be due to magnets being 'tickled' by current on beam pipe from passing trains.



(Selected) mechanisms of E_b variation

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



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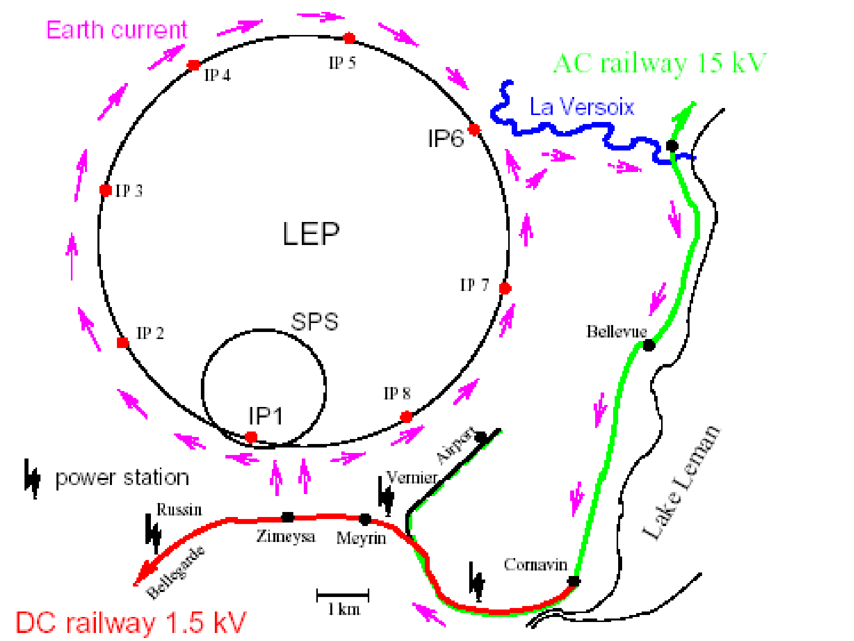
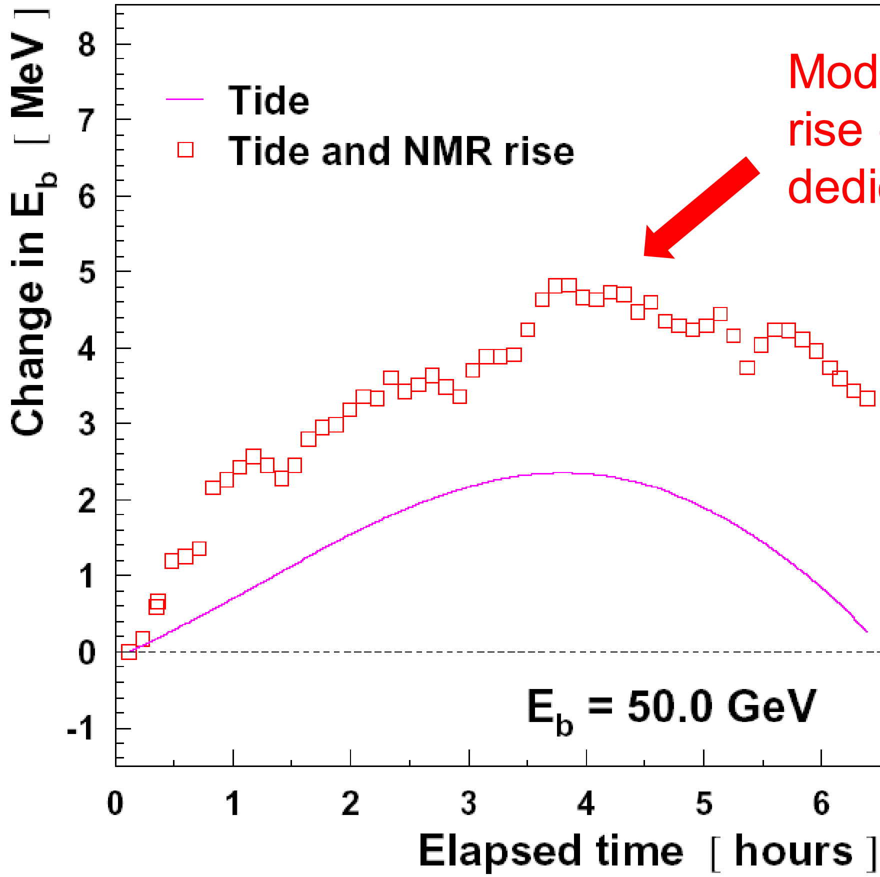


Compelling correlation between current on track, on beam pipe & noise in magnets.

(Selected) mechanisms of E_b variation

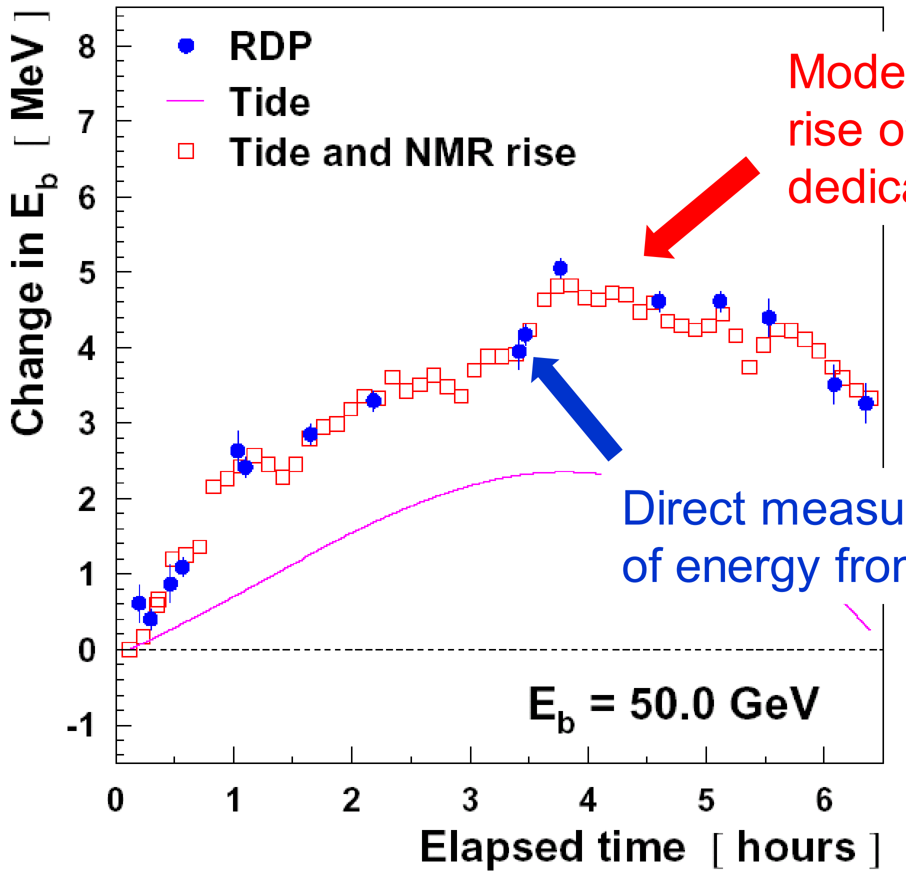
Energy rise modelled with great precision.



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.



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

Direct measurements of energy from RDP.