Beam energy calibration: systematic uncertainties

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FCC-ee (TLEP) Physics Workshop (TLEP8)

28 October 2014

This talk

- We have done this before!
- I will recall what was achieved at LEP and where we can do better
- This is a first attempt at the problem (and a brief presentation). In reality there is enough material here for many theses.

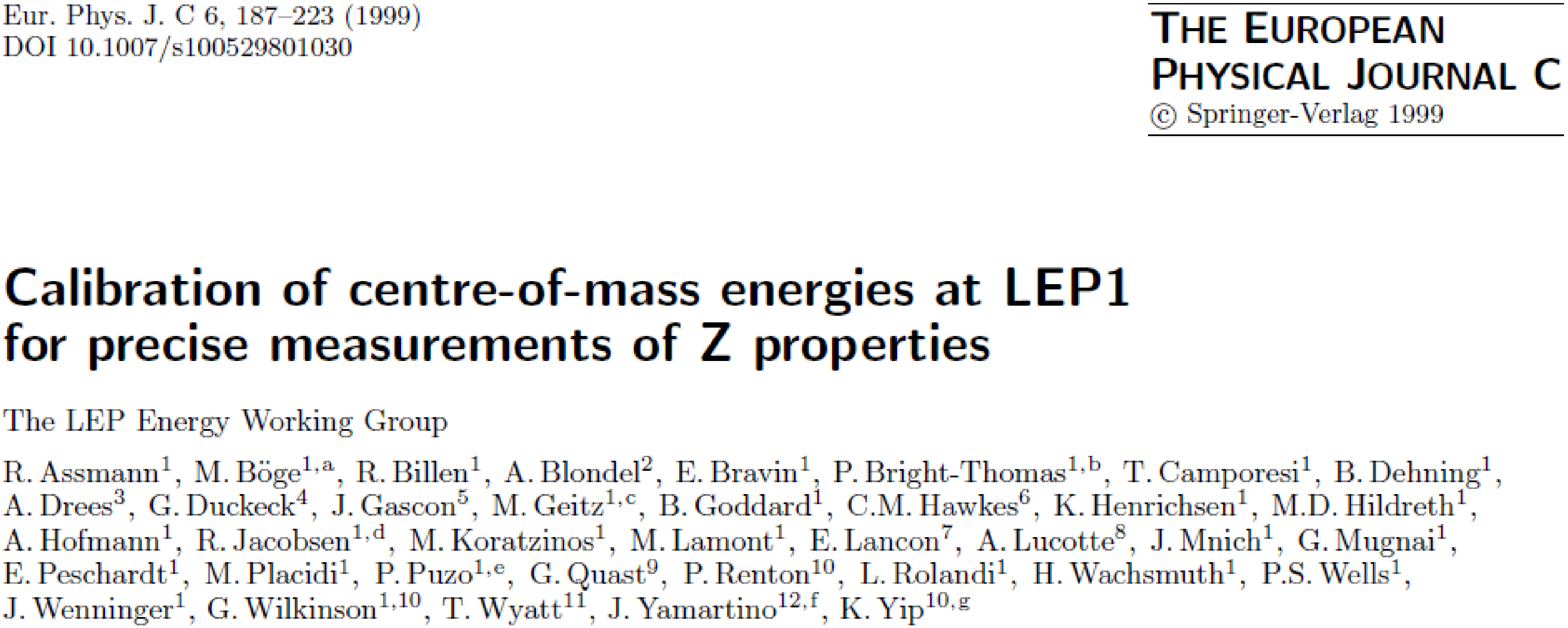
Where do we aim at?

- The Z width and mass measurements will not be statistically limited!
- So the more we can reduce the other uncertainties, such as the energy scale, the lower our overall error
- Next page a physics teaser for terraZ

Quantity	Physics	Present precision		TLEP Stat errors	Possible TLEP Syst. Errors	TLEP key	Challenge
M_Z (keV)	**Input**	91187500 ±2100	Z Line shape scan	5 keV	<100 keV	E_cal	QED corrections
Γ_Z (keV)	**$\Delta\rho$ (T)** (no $\Delta\alpha$!)	2495200 ±2300	Z Line shape scan	8 keV	<100 keV	E_cal	QED corrections
R_ℓ	**α_s, δ_b**	20.767 ± 0.025	Z Peak	0.0001	<0.001	Statistics	QED corrections
N_ν	**PMNS Unitarity sterile ν's**	2.984 ±0.008	Z Peak	0.00008	<0.004		Bhabha scat.
N_ν	**PMNS Unitarity sterile ν's**	2.92 ±0.05	(γ+Z_inv) (γ+Z$\rightarrow \ell\ell$)	0.001 (161 GeV)	<0.001	Statistics	
R_b	**δ_b**	0.21629 ±0.00066	Z Peak	0.000003	<0.000060	Statistics, small IP	Hemisphere correlations
A_{LR}	**$\Delta\rho, \varepsilon_3, \Delta\alpha$ (T, S)**	0.1514 ±0.0022	Z peak, polarized	0.000015	<0.000015	4 bunch scheme, > 2exp	Design experiment
M_W MeV/c2	**$\Delta\rho, \varepsilon_3, \varepsilon_2, \Delta\alpha$ (T, S, U)**	80385 ± 15	Threshold (161 GeV)	0.3 MeV	<0.5 MeV	E_cal & Statistics	QED corections
m_{top} MeV/c2	**Input**	173200 ± 900	Threshold scan	10 MeV	<10MeV	E_cal & Statistics	Theory interpretation 40 MeV?

A. Blondel

The LEP1 experience



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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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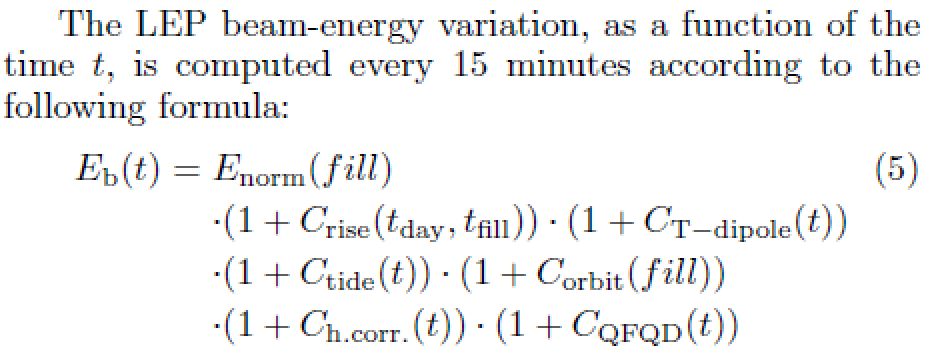
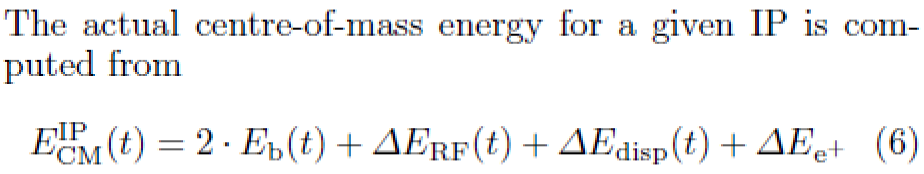
The energy model

- The energy was given every 15 minutes of physics per experiment during the scan periods 1993-1995 and not only as one number per year
- This is to take into account the up time of each experiment
- The energy model contained an overall normalization and a series of corrections



The LEP beam-energy variation, as a function of the time t, is computed every 15 minutes according to the following formula:

$$\begin{aligned} E_{\mathrm{b}}(t) = {} & E_{\mathrm{norm}}(fill) \\ & \cdot(1 + C_{\mathrm{rise}}(t_{\mathrm{day}}, t_{\mathrm{fill}})) \cdot (1 + C_{\mathrm{T-dipole}}(t)) \\ & \cdot(1 + C_{\mathrm{tide}}(t)) \cdot (1 + C_{\mathrm{orbit}}(fill)) \\ & \cdot(1 + C_{\mathrm{h.corr.}}(t)) \cdot (1 + C_{\mathrm{QFQD}}(t)) \end{aligned} \quad (5)$$

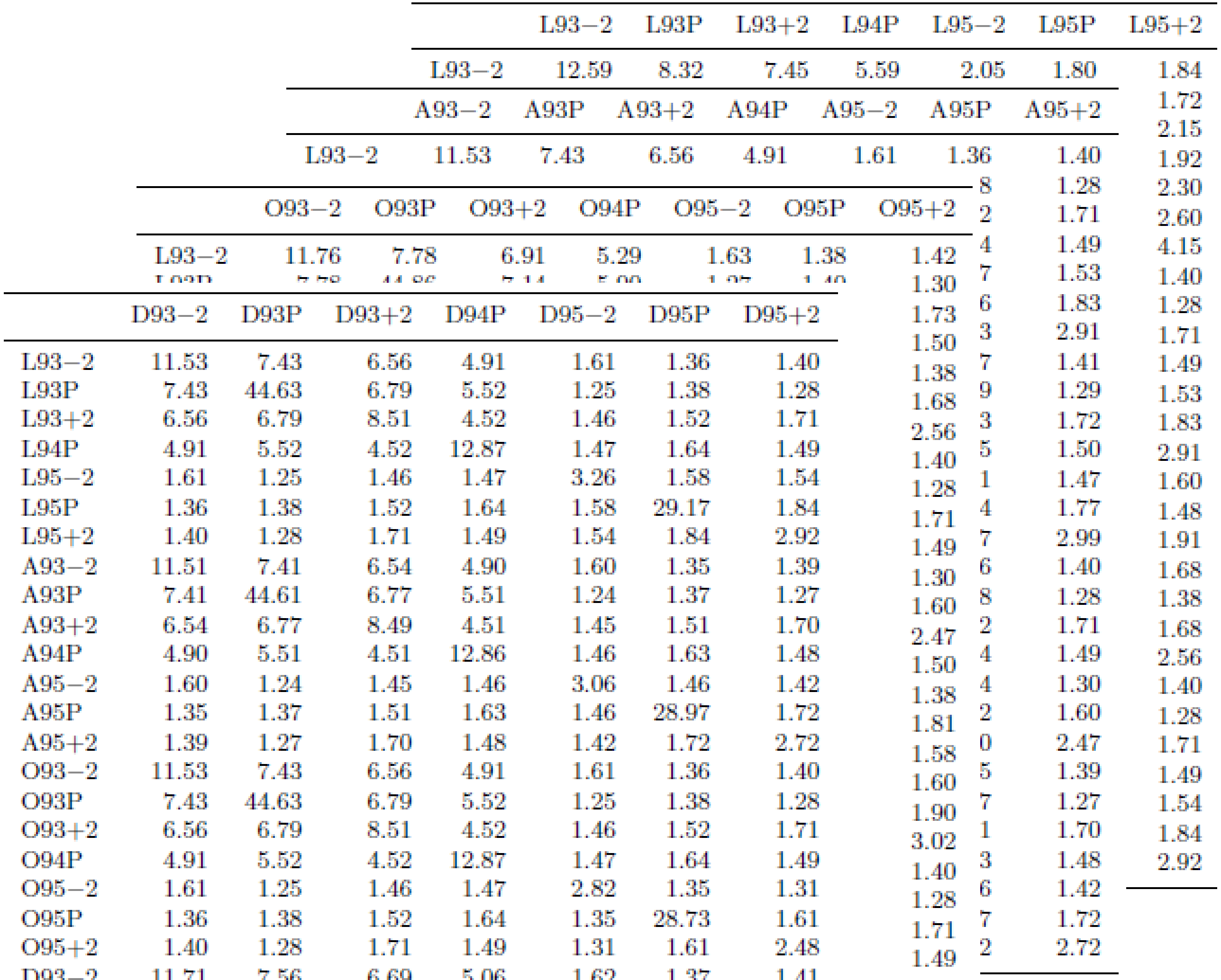


The actual centre-of-mass energy for a given IP is computed from

$$E^{\mathrm{IP}}_{\mathrm{CM}}(t) = 2 \cdot E_{\mathrm{b}}(t) + \Delta E_{\mathrm{RF}}(t) + \Delta E_{\mathrm{disp}}(t) + \Delta E_{\mathrm{e^+}} \quad (6)$$

Error analysis

- Very complicated (tedious?) resulting in a 4-dimentional error matrix [7X7X4X4] giving the correlations between energy points, years and experiments.



	L93−2	L93P	L93+2	L94P	L95−2	L95P	L95+2
L93−2	12.59	8.32	7.45	5.59	2.05	1.80	1.84
							1.72
							2.15
							1.92
							2.30
							2.60
							4.15
							1.40
							1.28
							1.71
							1.49
							1.53
							1.83
							2.91
							1.60
							1.48
							1.91
							1.68
							1.38
							1.68
							2.56
							1.40
							1.28
							1.71
							1.49
							1.54
							1.84
							2.92

	A93−2	A93P	A93+2	A94P	A95−2	A95P	A95+2
L93−2	11.53	7.43	6.56	4.91	1.61	1.36	1.40
						8	1.28
						2	1.71
						4	1.49
						7	1.53
						6	1.83
						3	2.91
						7	1.41
						9	1.29
						3	1.72
						5	1.50
						1	1.47
						4	1.77
						7	2.99
						6	1.40
						8	1.28
						2	1.71
						4	1.49
						4	1.30
						2	1.60
						0	2.47
						5	1.39
						7	1.27
						1	1.70
						3	1.48
						6	1.42
						7	1.72
						2	2.72

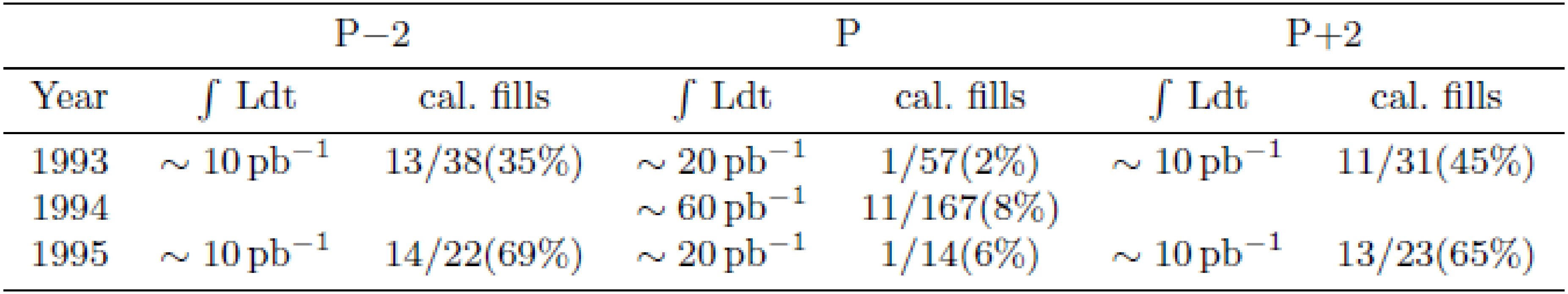
	O93−2	O93P	O93+2	O94P	O95−2	O95P	O95+2
L93−2	11.76	7.78	6.91	5.29	1.63	1.38	1.42
							1.30
							1.73
							1.50
							1.38
							1.68
							2.56
							1.40
							1.28
							1.71
							1.49
							1.30
							1.60
							2.47
							1.50
							1.38
							1.81
							1.58
							1.60
							1.90
							3.02
							1.40
							1.28
							1.71
							1.49

	D93−2	D93P	D93+2	D94P	D95−2	D95P	D95+2
L93−2	11.53	7.43	6.56	4.91	1.61	1.36	1.40
L93P	7.43	44.63	6.79	5.52	1.25	1.38	1.28
L93+2	6.56	6.79	8.51	4.52	1.46	1.52	1.71
L94P	4.91	5.52	4.52	12.87	1.47	1.64	1.49
L95−2	1.61	1.25	1.46	1.47	3.26	1.58	1.54
L95P	1.36	1.38	1.52	1.64	1.58	29.17	1.84
L95+2	1.40	1.28	1.71	1.49	1.54	1.84	2.92
A93−2	11.51	7.41	6.54	4.90	1.60	1.35	1.39
A93P	7.41	44.61	6.77	5.51	1.24	1.37	1.27
A93+2	6.54	6.77	8.49	4.51	1.45	1.51	1.70
A94P	4.90	5.51	4.51	12.86	1.46	1.63	1.48
A95−2	1.60	1.24	1.45	1.46	3.06	1.46	1.42
A95P	1.35	1.37	1.51	1.63	1.46	28.97	1.72
A95+2	1.39	1.27	1.70	1.48	1.42	1.72	2.72
O93−2	11.53	7.43	6.56	4.91	1.61	1.36	1.40
O93P	7.43	44.63	6.79	5.52	1.25	1.38	1.28
O93+2	6.56	6.79	8.51	4.52	1.46	1.52	1.71
O94P	4.91	5.52	4.52	12.87	1.47	1.64	1.49
O95−2	1.61	1.25	1.46	1.47	2.82	1.35	1.31
O95P	1.36	1.38	1.52	1.64	1.35	28.73	1.61
O95+2	1.40	1.28	1.71	1.49	1.31	1.61	2.48
D93−2	11.71	7.56	6.69	5.06	1.62	1.37	1.41

Units are MeV^2

LEP 1993-1995: calibrated fills

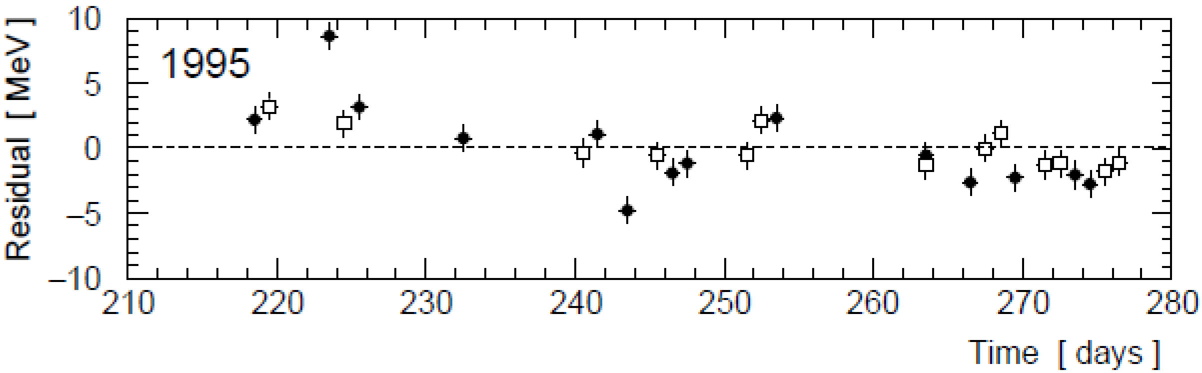
- Some proportion of fills was calibrated at the end of a fill (64/352)
- 6 fills had measurements at the beginning and at the end of the fill



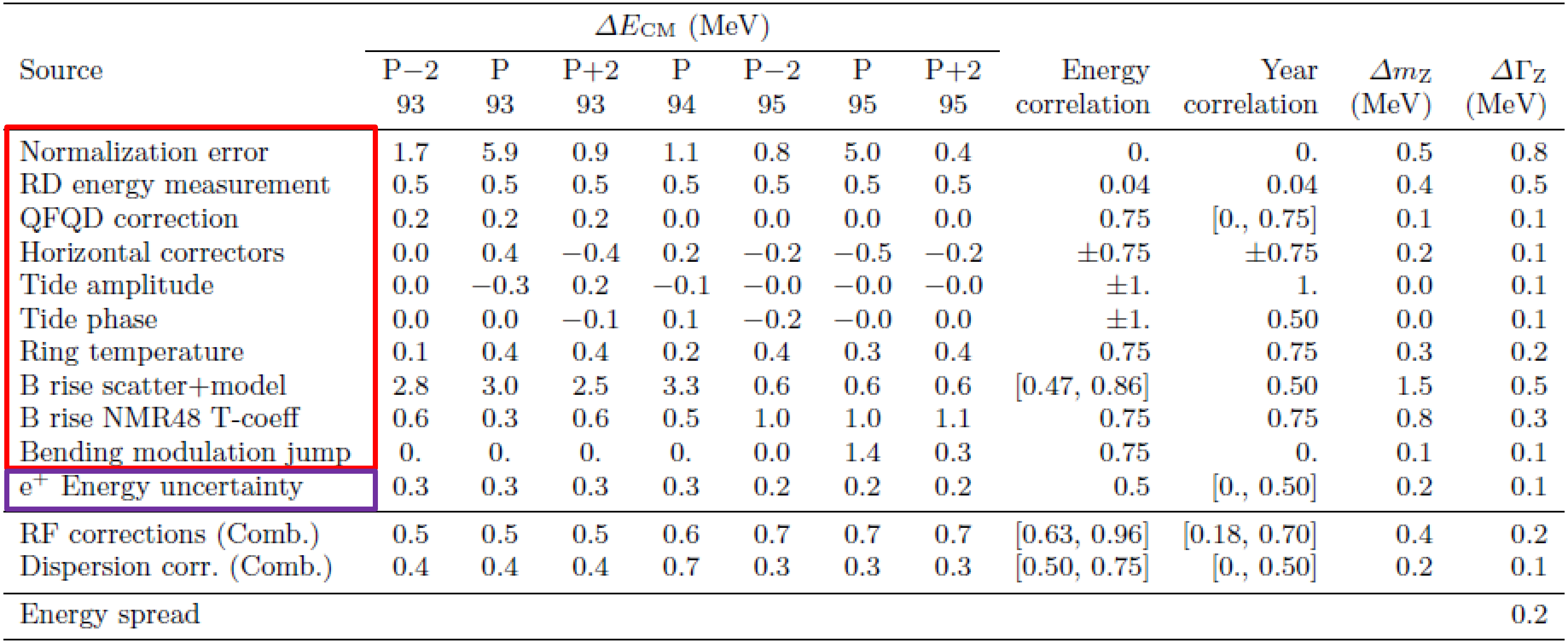
	P−2		P		P+2	
Year	$\int$ Ldt	cal. fills	$\int$ Ldt	cal. fills	$\int$ Ldt	cal. fills
1993	$\sim 10\,\mathrm{pb}^{-1}$	13/38(35%)	$\sim 20\,\mathrm{pb}^{-1}$	1/57(2%)	$\sim 10\,\mathrm{pb}^{-1}$	11/31(45%)
1994			$\sim 60\,\mathrm{pb}^{-1}$	11/167(8%)		
1995	$\sim 10\,\mathrm{pb}^{-1}$	14/22(69%)	$\sim 20\,\mathrm{pb}^{-1}$	1/14(6%)	$\sim 10\,\mathrm{pb}^{-1}$	13/23(65%)

How good was the energy model?

- Plot the model prediction versus the real resonant depolarization values. RMS was ~few MeV



LEP error table (simplified)



Source	ΔE_{CM} (MeV)							Energy correlation	Year correlation	Δm_{Z} (MeV)	$\Delta\Gamma_{\mathrm{Z}}$ (MeV)
	P−2 93	P 93	P+2 93	P 94	P−2 95	P 95	P+2 95				
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

- Can be reduced by measuring the energy continuously during physics
- Can be reduced by measuring the energy of positrons as well

How can we do better?

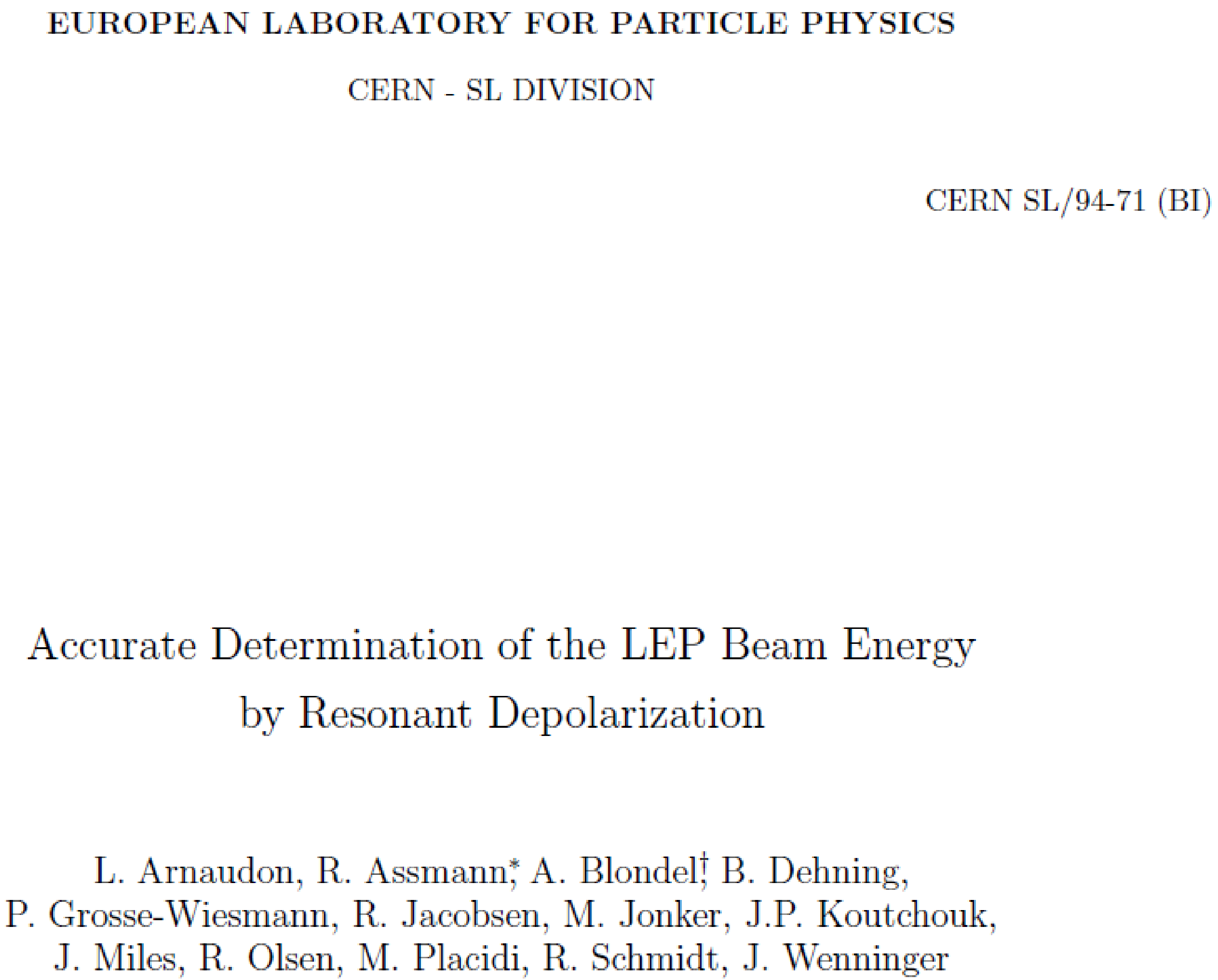
- Use the resonant depolarization technique to measure continuously

Therefore the first 11 contributions to the error table simply become:

$$\Delta E = \Delta E_{depol,syst} + \frac{\Delta E_{depol,stat}}{\sqrt{N_{depol}}} + \Delta E_{extrapolation}$$

- N_{depol} I assume to be 10^4 per year (one energy measurement every every 1000s)
- $\Delta E_{extrapolation}$ I assume for the moment to be negligible (need to extrapolate over a few minutes!)
- Measure electrons and positrons
- The resonant depolarization measurement gives the average energy in the ring
- Need to apply specific corrections for each IP

Resonant depolarization paper



EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN - SL DIVISION

CERN SL/94-71 (BI)

Accurate Determination of the LEP Beam Energy
by Resonant Depolarization

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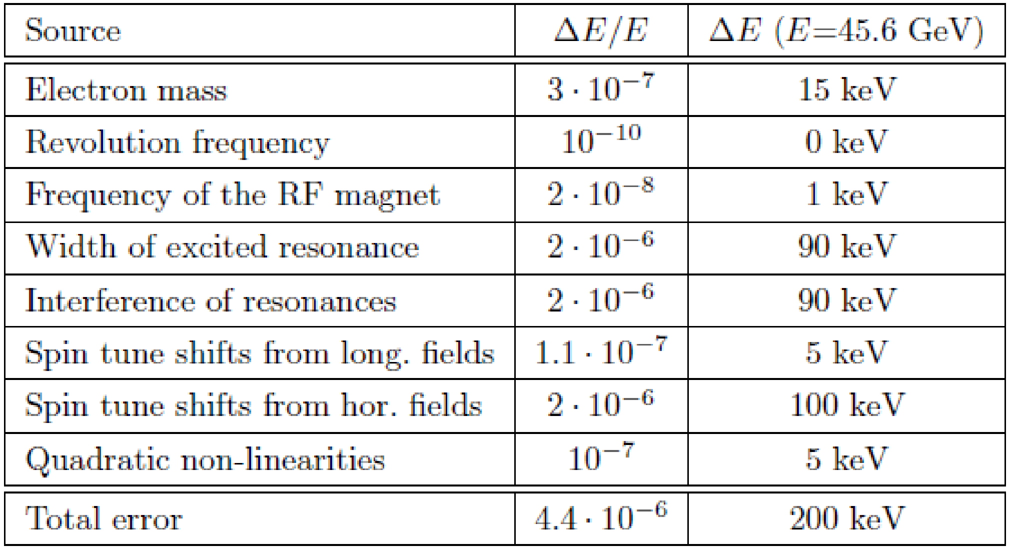
P. Grosse-Wiesmann, R. Jacobsen, M. Jonker, J.P. Koutchouk,
J. Miles, R. Olsen, M. Placidi, R. Schmidt, J. Wenninger

Resonant depolarization accuracy at LEP



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

Table 1: The accuracy of the beam energy calibration method by resonant depolarization is summarized for LEP. A standard energy calibration with a well corrected vertical closed orbit is assumed. All errors are understood to be RMS errors.

- Total error was given as 200keV per beam
- Some of these numbers are upper bounds
- Some of these numbers are theoretical estimations which could not be verified experimentally

Resonant depolarization accuracy – spin tune shifts

- The systematic error of resonant depolarization at LEP was dominated by spin tune shifts due to radial magnetic fields (due to quad misalignement).

$$\sigma(\delta\nu) \approx 0.04\,\nu^2 n_Q (KL)^2 \sigma_y^2$$

nq: number of quads
KL: quad strength
σy : RMS orbit distortion

- The spread was estimated to be 30keV for $\sigma_y = 0.5mm$
- The paper finally quotes an error smaller than 100keV
- TLEP needs to do a factor of 30-100 better than LEP in the ratio of quad. strength/misalignment (to be verified if optimistic or pessimistic). Then the error on the energy would be 3keV
- Harmonic spin matching (vertical π bumps): its effect was negligible at LEP – will this be the case in TLEP?

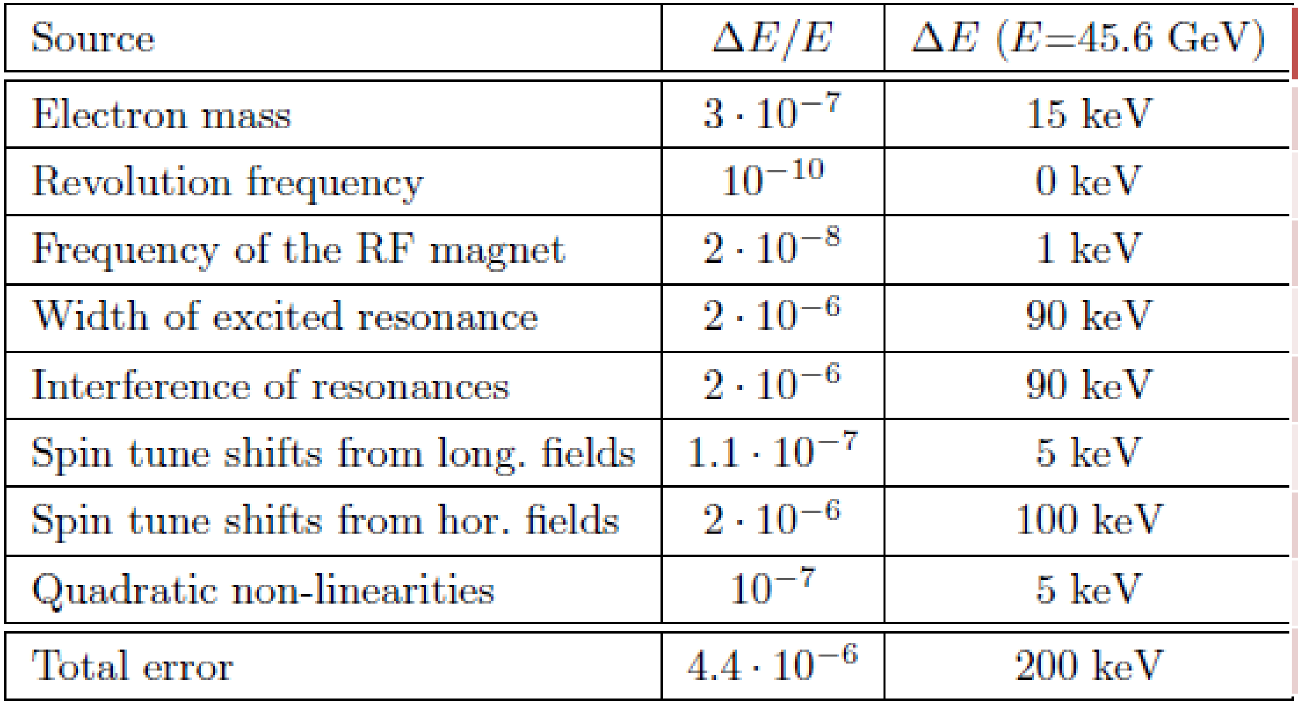
Interference between depolarizing resonances

- The resonance interference error is the shift of an (artificially excited) spin resonance due to a nearby natural spin resonance
- It is actually stated in the text (but not the table) of the paper that the effect is smaller than 90keV.
- it has a statistical and systematic component depending on if the excited spin resonance on the right or on the left of the natural resonance.
- I will have to assume that most of this error contribution would become statistical by some clever technique (to be worked on!)
- My assumption: 9keV systematic, 90keV statistical

Spin tune shifts due to longitudinal fields

- These arise from the experimental solenoids, for instance.
- They can be reduced by accurate spin matching of the solenoids
- At LEP this effect was smaller than $\delta\nu < 10^{-5}$ (5keV)

Resonant depolarization accuracy at TLEP/FCCee – wild extrapolation



Source	$\Delta E/E$	ΔE (E=45.6 GeV)	Stat(keV)	Syst.(keV)
Electron mass	$3 \cdot 10^{-7}$	15 keV		15
Revolution frequency	10^{-10}	0 keV		0
Frequency of the RF magnet	$2 \cdot 10^{-8}$	1 keV		1
Width of excited resonance	$2 \cdot 10^{-6}$	90 keV	1	0
Interference of resonances	$2 \cdot 10^{-6}$	90 keV	1	9
Spin tune shifts from long. fields	$1.1 \cdot 10^{-7}$	5 keV		5
Spin tune shifts from hor. fields	$2 \cdot 10^{-6}$	100 keV		3
Quadratic non-linearities	10^{-7}	5 keV		5
Total error	$4.4 \cdot 10^{-6}$	200 keV	1.4	20

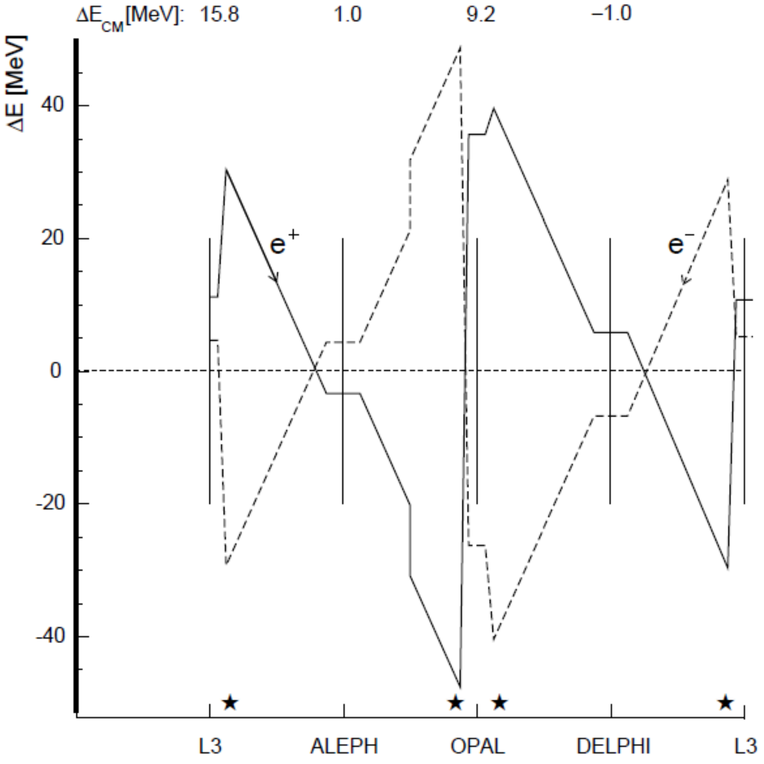
Systematic error dominates

- Statistical errors are divided by sqrt(10,000)
- This is a zeroth order working hypothesis
- The table should eventually also include effects that were negligible at the time of LEP

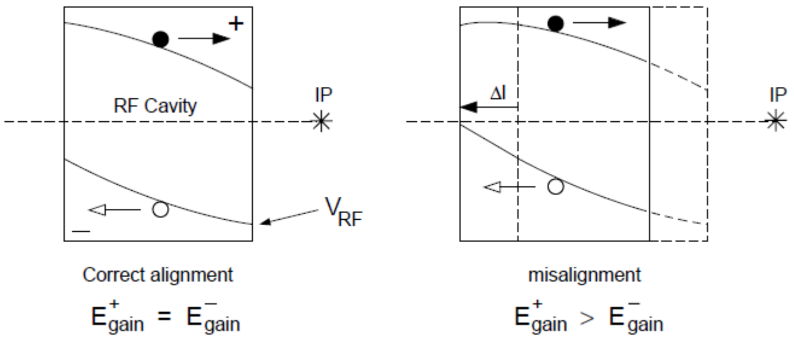
IP-specific corrections

- Resonant depolarization gives the average energy of the beam through the ring
- What we need is the ECM energy per experiment
- There are IP specific corrections (due to RF)
- There are corrections when computing ECM from the beam energy (in some specific dispersion scheme)

RF corrections



Errors arise due to cavity misalignments primarily:



- At LEP cavity misalignment was assumed to be 1.4mm in 1995

Clever thinking is needed to reduce this error to negligible levels. For LEP the error was of the order of 500keV (leading to an error of 400/200keV for the mass/width of the Z. Need to reduce this error by (more than) a factor of 10!

Opposite side vertical dispersion

- OSVD introduced a correlation between ECM energy and bunch collision offset
- Dispersion difference at the IP was ~2mm

$$\Delta E_{\mathrm{CM}} = -\frac{1}{2} \cdot \frac{\delta y}{\sigma_y^2} \cdot \frac{\sigma_{E_b^2}}{E_b} \cdot \Delta D_y^* \qquad (18)$$

Collision offsets were sub-micron!

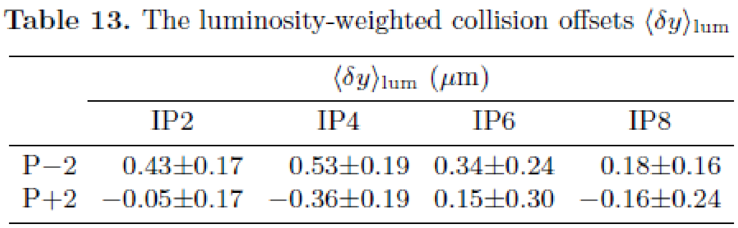


Table 13. The luminosity-weighted collision offsets $\langle \delta y \rangle_{\mathrm{lum}}$

	$\langle \delta y \rangle_{\mathrm{lum}}$ (μm)			
	IP2	IP4	IP6	IP8
P−2	0.43±0.17	0.53±0.19	0.34±0.24	0.18±0.16
P+2	−0.05±0.17	−0.36±0.19	0.15±0.30	−0.16±0.24

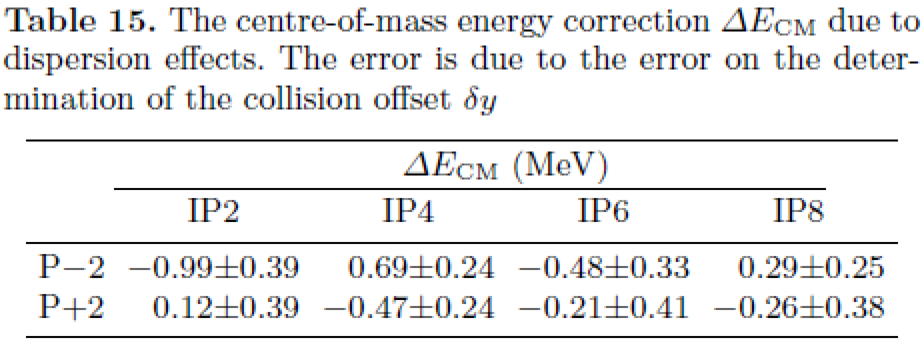


Table 15. The centre-of-mass energy correction ΔE_{CM} due to dispersion effects. The error is due to the error on the determination of the collision offset δy

	ΔE_{CM} (MeV)			
	IP2	IP4	IP6	IP8
P−2	−0.99±0.39	0.69±0.24	−0.48±0.33	0.29±0.25
P+2	0.12±0.39	−0.47±0.24	−0.21±0.41	−0.26±0.38

To avoid the problem, we should run with zero OSVD!

Energy spread

- For the Z width measurement, the energy spread needs to be known accurately.
- The energy spread is related to the bunch length which can be measured accurately by the experiments by

$$\sigma_{E_b} = \frac{\sqrt{2}E_b}{\alpha R_{LEP}} Q_s^{\mathrm{inc.}} \sigma_z$$

- Q(incoherent) can be estimated from

$$\frac{Q_s^{\mathrm{coh.}}}{Q_s^{\mathrm{inc.}}} = 1 - \kappa \frac{I}{I_0} \,, \; (I_0 \,=\, 300\,\mu A)$$

- κ was measured to be 0.045±0.022. This introduced the dominant error (700keV)
- Mom. Compaction factor α error of 1% translated to an energy spread error of 400keV
- Total error was 1000keV translating to 200keV for the Z width

We need to improve this by at least a factor of 10 for TLEP

Other effects

- If we are planning to reduce the error of resonant depolarization measurements by a large amount compared to LEP, new effects that were negligible back then will make their appearance.
- A careful study is called for.

Summary

- Resonant depolarization is a great tool for very accurate energy determination.
- The LEP analysis was complicated and still we are called to do (at least) 10 times better!
- Work is just beginning, it is very exciting and we hope we can take the error size to new (low) levels.

End