Status of collision energy calibration at LEP2

LEP energy and spectrometer working groups

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Guy Wilkinson,
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Status of collision energy calibration at LEP2

Required precision on energy calibration

Available tools

- Resonant depolarisation
- Magnetic measurements: NMRs and the flux loop

The extrapolation method

- Principle
- Application to the '97 data; preliminary '98 results
- Errors on the '96 and '97 data
  Now final; publication in preparation

Direct measurement at physics energies

- Spectrometer project: principle and status
- Energy measurement through $e^+e^- \to f\overline{f}\gamma$

Conclusions

The Goal

At LEP2 we hope for final M_{W} precision of $30\,\mathrm{MeV}$ (stat)

Fractional uncertainty on $E_{\mathrm{b}} \rightarrow$ fractional uncertainty on M_{W}

Aim for $\delta E_{\mathrm{b}} < 15\,\mathrm{MeV}$ (or $\delta E_{\mathrm{b}}/E_{\mathrm{b}} < 1.5 \times 10^{-4}$)

The Challenge

Presumably 'easy'? At LEP1 achieved $\delta E_{\mathrm{b}}/E_{\mathrm{b}}$ of 4×10^{-5}

Used tool of resonant depolarisation (RDP) – measure spin precession frequency of polarised electrons

$$\nu \;\propto\; E_{\mathrm{b}}$$

But RDP does not work at high energy! (So far $\leq$ 55 GeV)

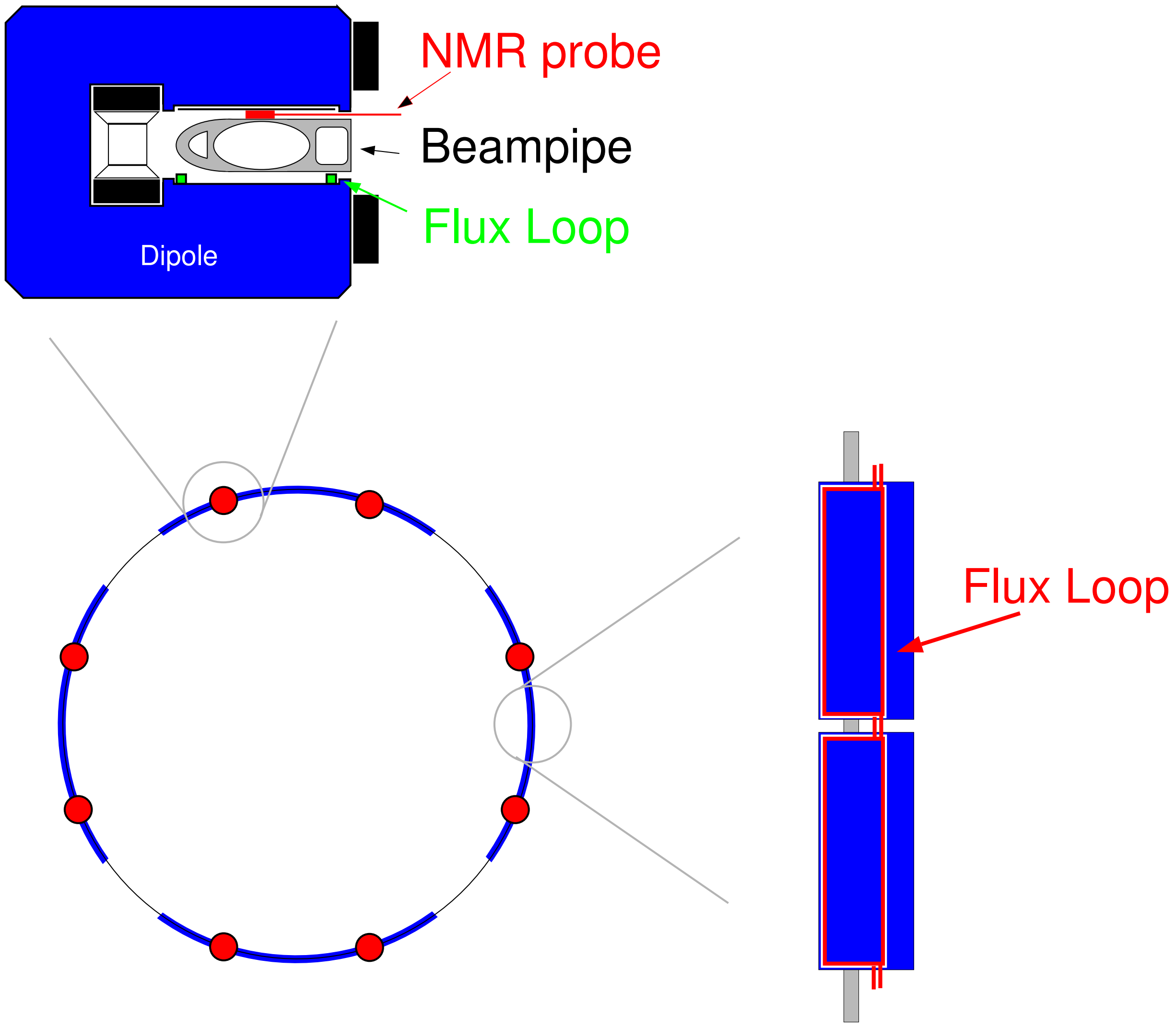
The Extrapolation Technique

Must use magnetic measurements,

$$\oint B\,.\,dl \;\propto\; E_{\mathrm{b}}$$

calibrate these at 'low energy' against RDP, and then extrapolate to physics regime

Magnetic measurements



NMRs	Flux loop
Precision: order 10^{-6}	Precision: few 10^{-4}
16 probes for 3200 dipoles	96.5% of $\oint B \, . \, dl$
Readout continually	Cycled every few weeks (eg. 5 times in '97)
Vulnerable to radiation damage – die and are replaced during run	

Extrapolation Strategy

- Perform RDP measurements – aim for largest possible lever arm and highest possible energy
- Calibrate NMRs against RDP data
- Apply calibration at high energy to determine physics energy scale – the extrapolation
- Cross-check NMRs against flux-loop to assign extrapolation error

Available calibration data

1996:

Fill	41 GeV	45 GeV	50 GeV	55 GeV	Optics
3599			•		$90/60$
3702		•			$90/60$
3719		•	•		$90/60$

→Lever arm of 5 GeV with two points

1997:

Fill	41 GeV	45 GeV	50 GeV	55 GeV	Optics
4000		•			$90/60$
4121		•	•		$60/60$
4237		•	•		$60/60$
4242	•	•	•	•	$60/60$
4274		•			$90/60$
4279	•	•	•	•	$60/60$
4372	•	•			$60/60$

→ Lever arm of 15 GeV with four points

1998 (so far):

Fill	41 GeV	45 GeV	50 GeV	55 GeV	Optics
4666		•	•	•	$60/60$
4669		•			$102/90$
4843		•		•	$60/60$
5137		•			$60/60$
5141	•	•	•		$60/60$

Hopefully more to come!

Setting energy scale with NMR vs E_{pol} calibration

Procedure

- Calibrate each NMR energy, E^i_{NMR}, to all available RDP data, ie. fit a^i and b^i where

$$E^i_{\mathrm{NMR}} = a^i + b^i B^i_{\mathrm{NMR}}$$

  (only one parameter used in 1996)

- Apply at high energy $\rightarrow$ E^i_{NMR} in physics, probe by probe
- Average over probes $\rightarrow$ ring energy plus scatter error

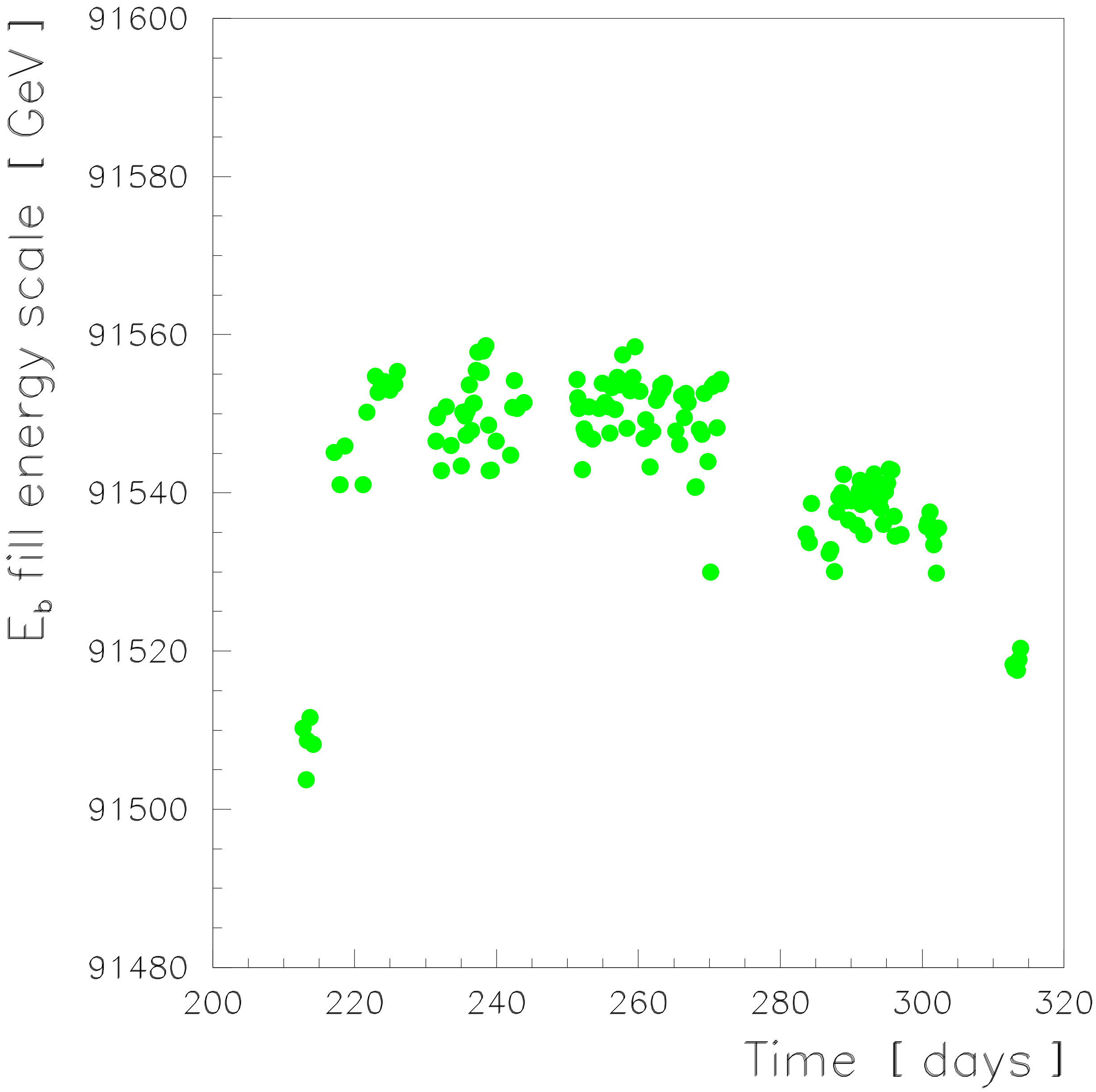
Results $\rightarrow$

Error assignment

Scatter error from spread of probe energies	$10\,\mathrm{MeV}$
Scatter error from spread of calibration fills	$5\,\mathrm{MeV}$
Comparison of calibration and physics optics	$4\,\mathrm{MeV}$
Scatter error in predicted physics energy	$2\,\mathrm{MeV}$
Polarisation systematic and e^+e^- energy difference	$2\,\mathrm{MeV}$
Total	$12\,\mathrm{MeV}$

Dipole energy, fill to fill (183 GeV running)

Calibration results in prediction of E_{b} in physics



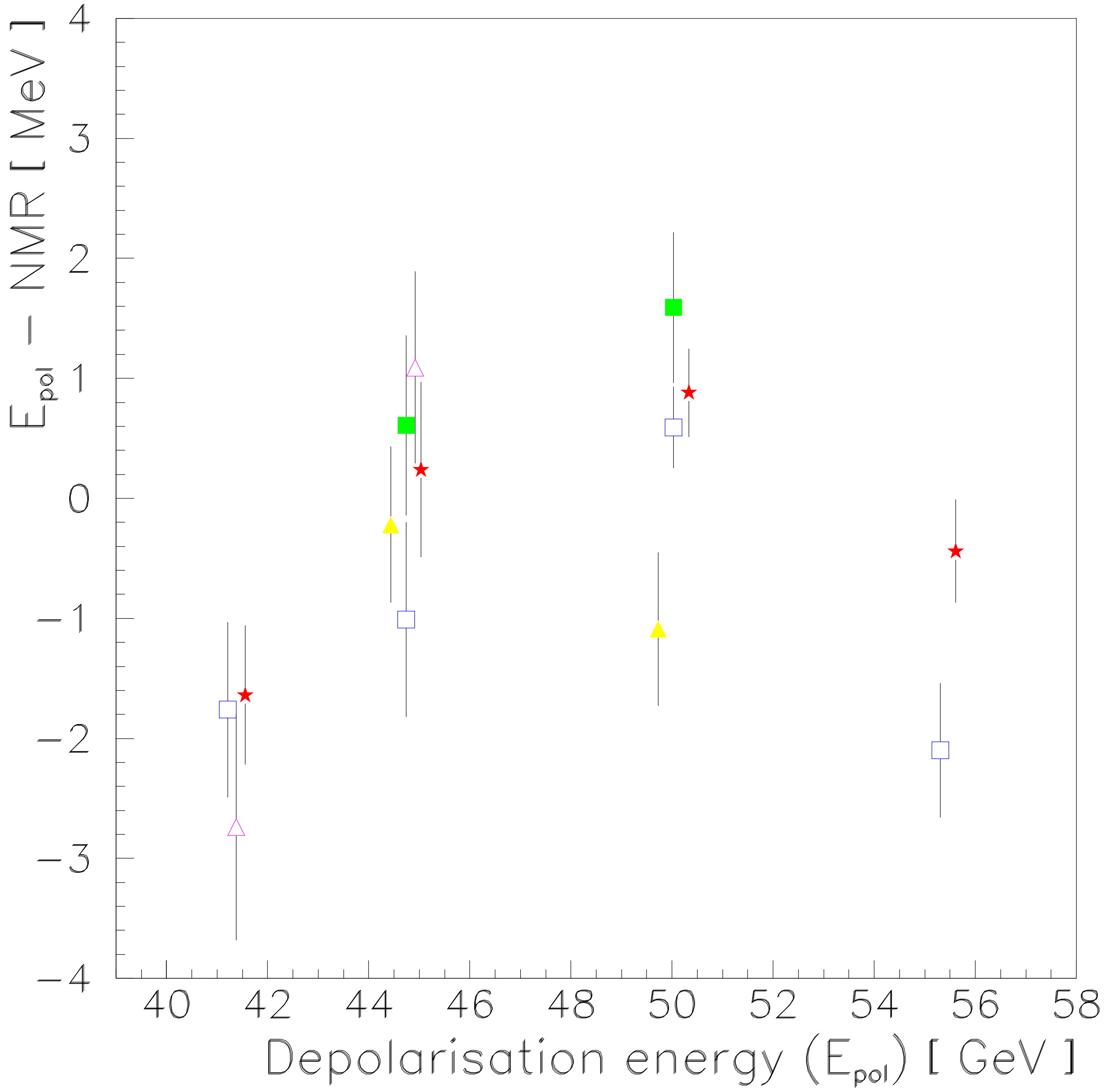
Tight distribution with RMS of 10 MeV

Structure observed – most likely genuine, but assumed to be artefact of model in error assignment

Bananas!

How to quantify uncertainty from linear fit and extrapolation?

Study residuals of fit against energy

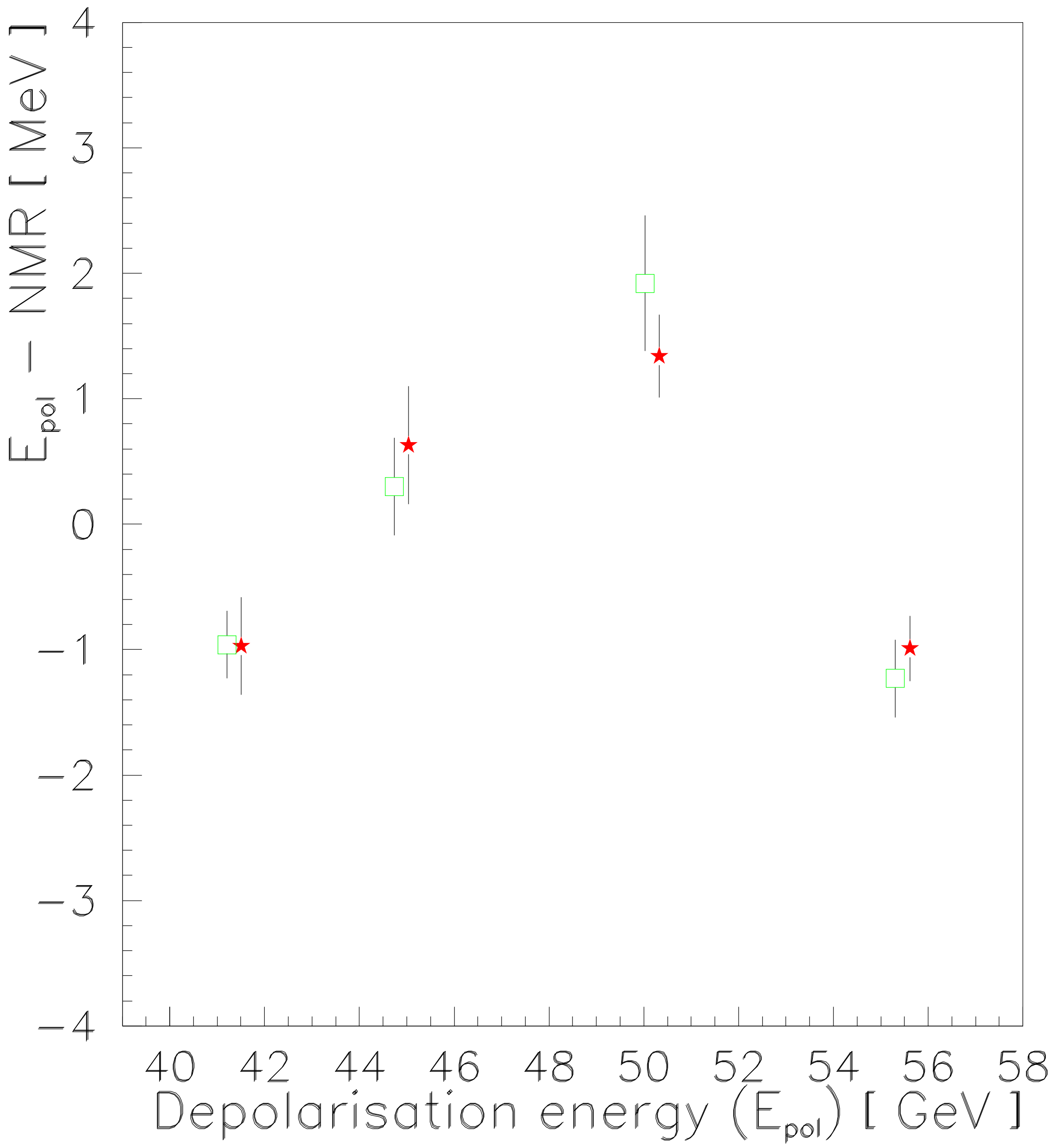


Strong suggestion of a systematic banana!

There is small, but significant, non-linear behaviour in $40 - 55$ GeV range. But how to tell what happens at physics energies?

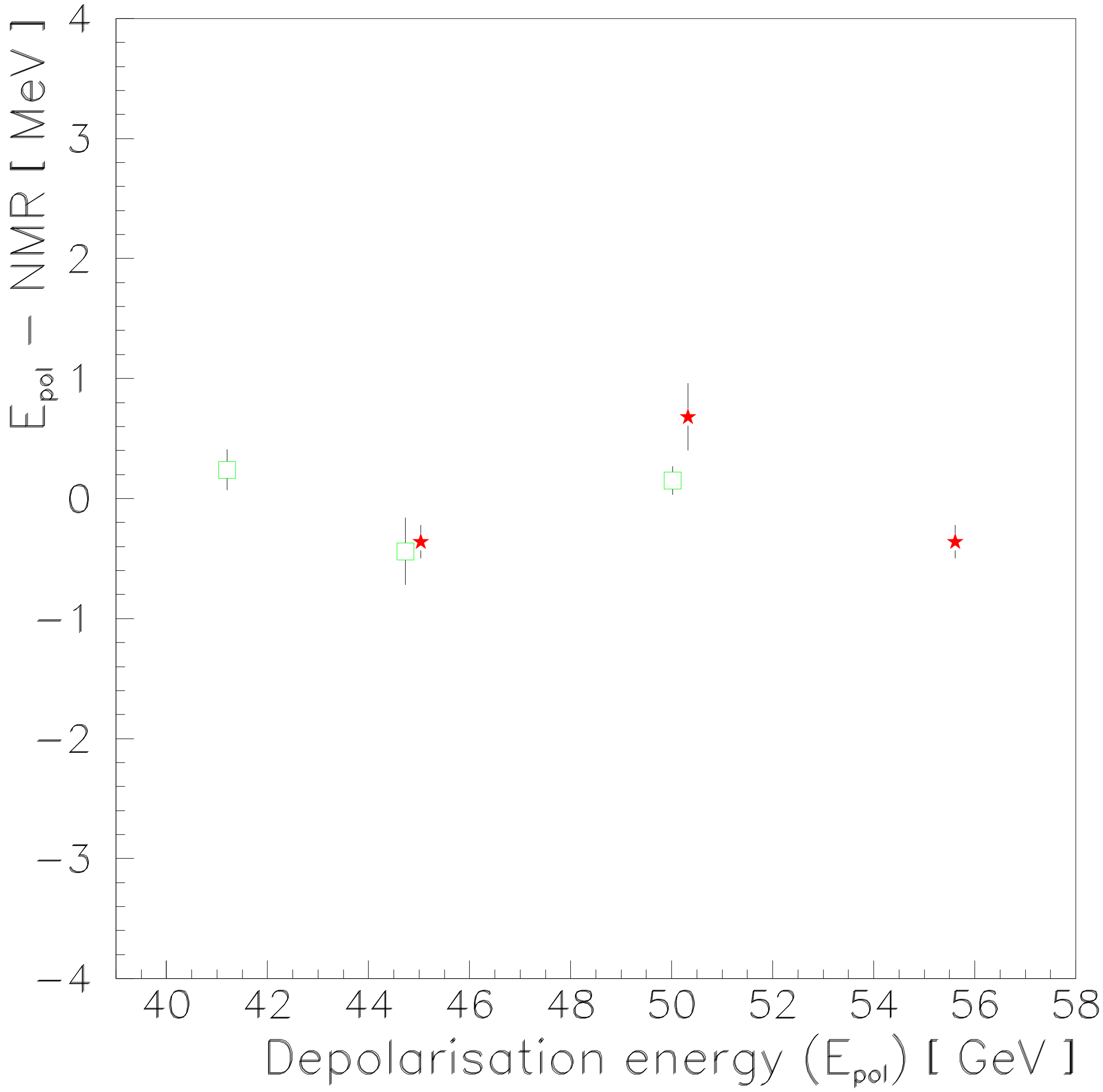
More bananas!

To remove fill-to-fill normalisation scatter, can perform individual fits to two four point fills and again study residuals



Yes, we have no bananas (?)

Preliminary analysis of '98 3 point fills show less clear picture



Premature to claim that banana has gone! (One odd fill)

Await further study and more data (hope for 4 point fills)

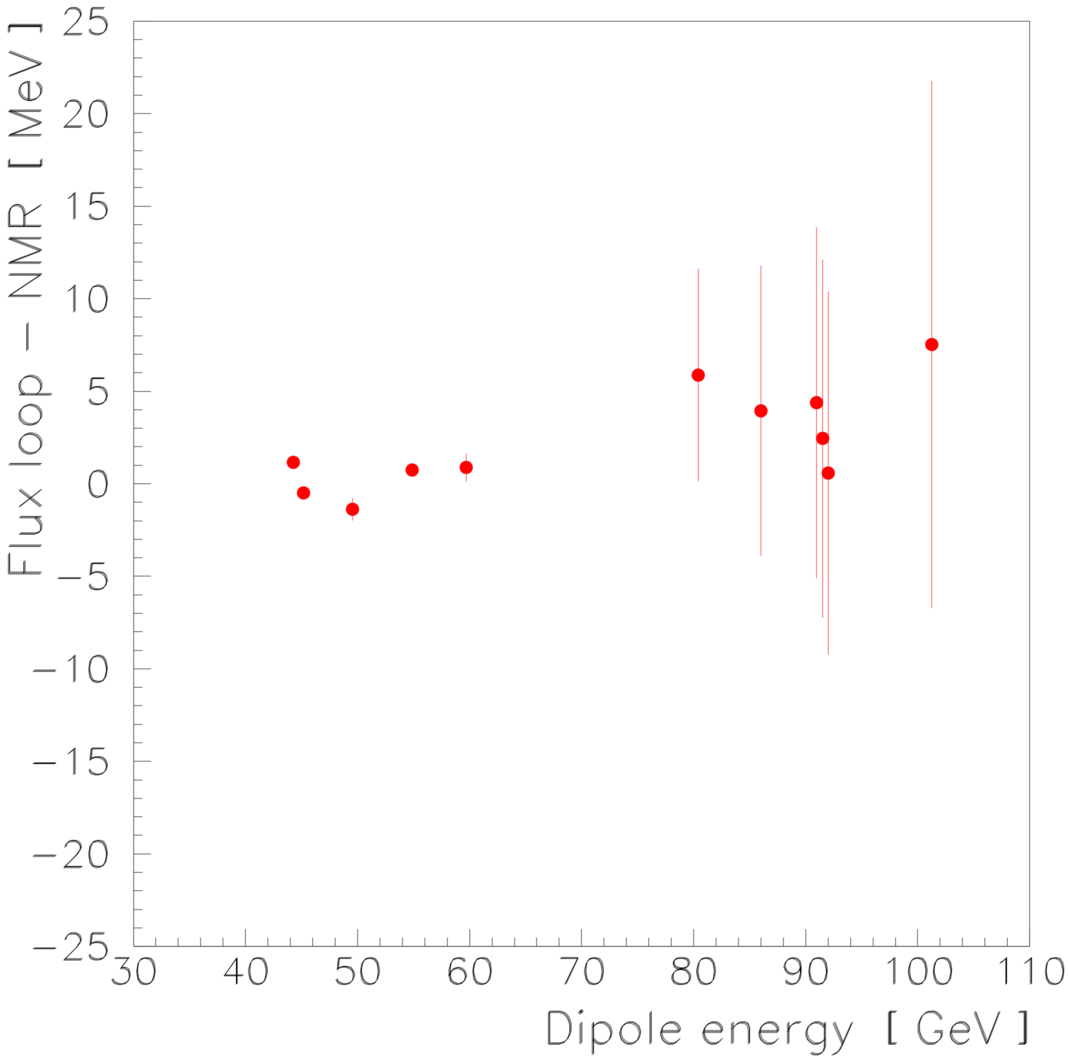
Using flux loop to check calibration

Flux loop main tool for quantifying extrapolation error

Flux loop measures $\oint B \, . \, dl \rightarrow$ treat in same way as RDP

- Fit NMRs to change in FL field as previously, for $40 - 55$ GeV region
- Study residual between FL measurement and prediction at physics energy

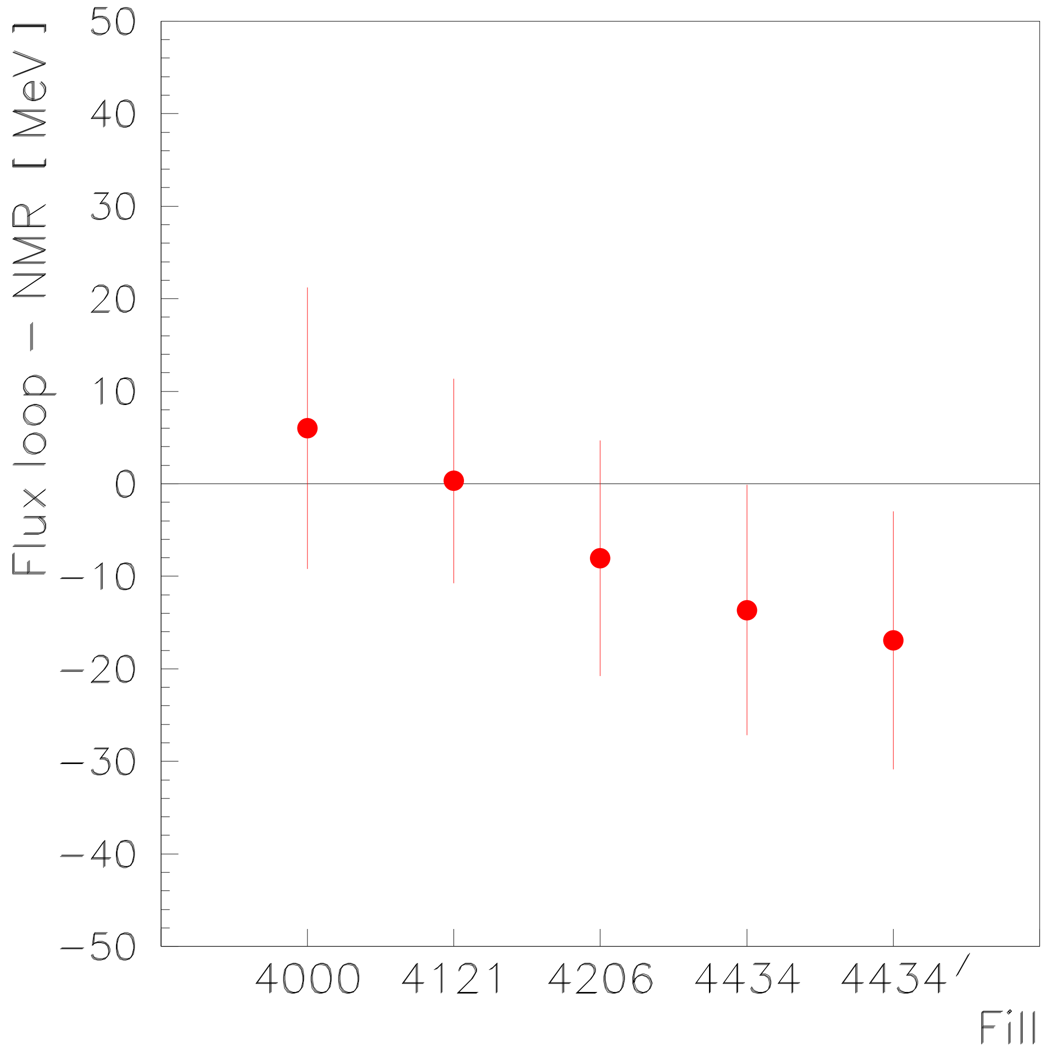
One FL experiment:



No dramatic non-linearity, but look at other experiments...

Flux loop (ctd)

Study residual of each '97 FL experiment at physics energies



Evolution in residual – difference between first and last fill is 4 sigma (if calculate uncorrelated error component)

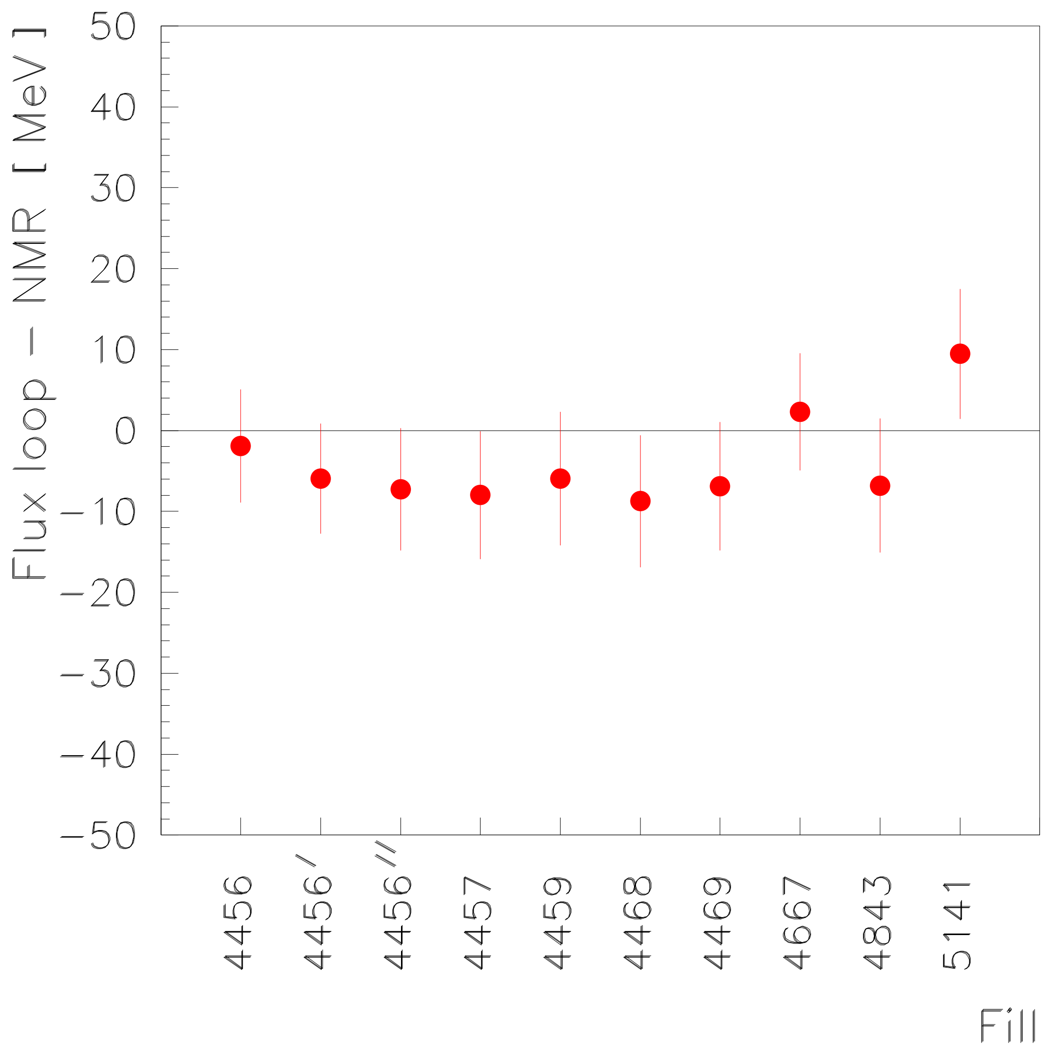
Statistical error + size of offset → uncertainty of $20\,\mathrm{MeV}$

This at present DOMINANT ERROR on E_{b} measurement

3.5% of $\oint B\,.\,dl$ outside FL → additional error of $5\,\mathrm{MeV}$

Preliminary 98 flux loop analysis

Preliminary analysis of '98 data - residuals at physics energies



Note:

- First 7 FLs close in time at start of run; others later
- Different (and larger) subset of NMRs used than for '97 analysis

Similar picture to '97:

No big offset, but some scatter with time

Other considerations

Model used in both calibration and physics also includes all sources of energy variation learnt about at LEP 1:

- Earth tides + long timescale ring disortions
- Dipole rises (monitored with 16 NMRs)
- Horizontal correctors

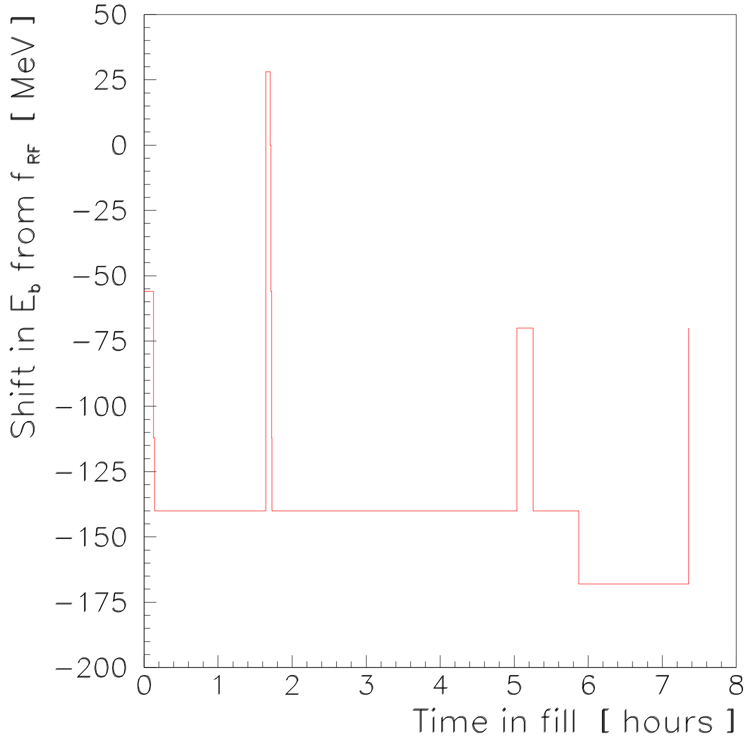
These are controlled to level of $3\,\mathrm{MeV}$. And don't forget:

- Modelling of RF system (energy loss now 2 GeV per turn!)
- Possible vertical dispersion

which give additional error of $4\,\mathrm{MeV}$

1997: RF frequency routinely increased – large shift in E_b

RF trips $\rightarrow$ sudden changes in f_{RF} $\rightarrow$ and in E_b



All changes logged $\rightarrow$ applied in model with negligible error

Error summary

Summary of errors on $E_{\rm b}$ for 1997 (at $E_{\rm cm} = 183\,{\rm GeV}$):

Calibration procedure	$12\,{\rm MeV}$
Extrapolation error (from flux loop)	$21\,{\rm MeV}$
Energy variation	$3\,{\rm MeV}$
RF modelling (and dispersion)	$4\,{\rm MeV}$
Total	$25\,{\rm MeV}$

Fewer RDP data in '96 $\rightarrow$ $E_{\rm b}$ error at $E_{\rm cm} = 163\,{\rm GeV}$ ($172\,{\rm GeV}$) is $27\,{\rm MeV}$ ($30\,{\rm MeV}$), fully correlated with '97

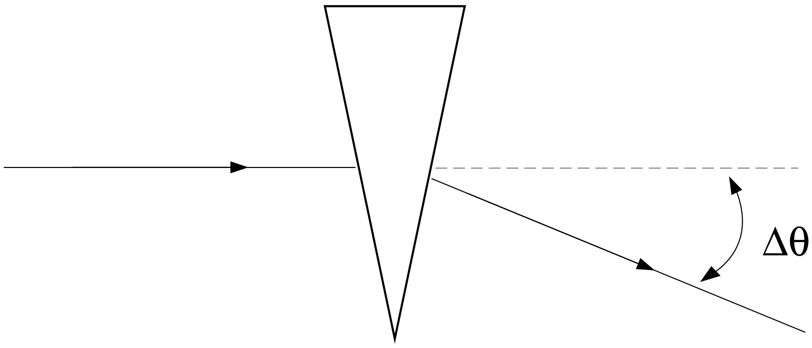
Precision LIMITED BY EXTRAPOLATION ERROR

Analysis of '98 data MAY allow improvement but really want...

DIRECT MEASUREMENT OF $E_{\rm b}$ AT PHYSICS ENERGIES

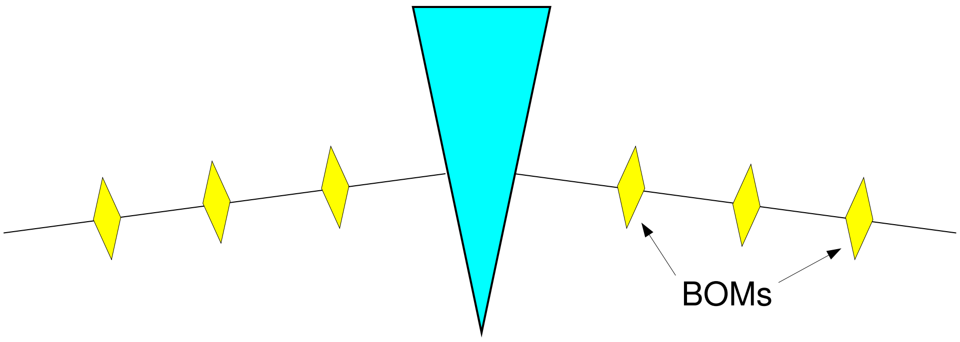
Using a spectrometer to measure E_{b}

Concept:



$$\Delta\theta \;\propto\; \frac{\oint B\,.\,dl}{E_{\mathrm{b}}}$$

In LEP do this as follows:

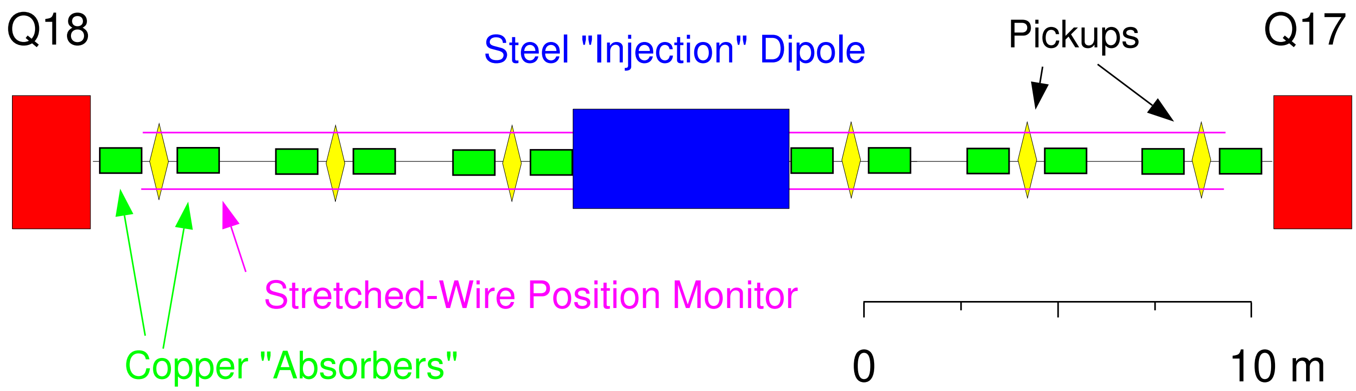


- Use dipole in lattice which ramps with LEP
- Use BOMs to measure $\Delta\theta$ (~ 4 mrad)
- Knowing $\oint B\,.\,dl$ and $\Delta\theta$ deduce E_{b}

Aim for 1×10^{-4} precision in E_{b} (10 MeV at $E_{\mathrm{b}} = 100$ GeV)

Spectrometer requirements

- BOM measurements with $\sim 1\,\mu\mathrm{m}$ resolution
- Map of $\oint B\,.\,dl$ to better than 10^{-4}
- Stability with position verification of $\sim 1\,\mu\mathrm{m}$ precision



Realisation will use:

- Standard LEP pickups with customised electronics
- Steel magnet (à la injection dipoles) – no ageing effects
- Stretched wire position monitors (resolution $< 0.5\,\mu\mathrm{m}$)
- Copper synchrotron radiation absorbers
- Extensive temperature regulation and monitoring

This year has prototype:

- Single instrumented arm and normal LEP dipole
- Study stability and resolutions during LEP operation

Next year full detector!

- Magnet soon to be delivered – then must map field

Practical details

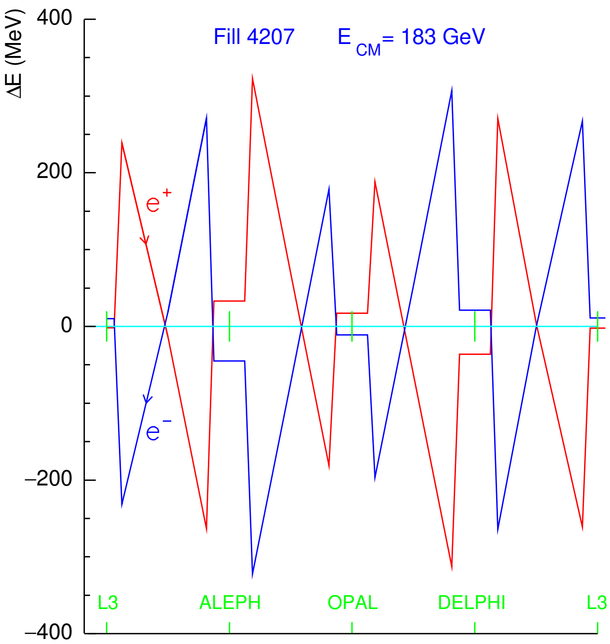
Cross-calibration with RDP

Relative precisions of $1\,\mu\mathrm{m}$ achievable, but not absolute positioning and alignment of BOM centres

Therefore calibrate measured E_b against polarisation at low energies and cross-check at intermediate energies

Extrapolation to interaction points

Unlike with RDP, spectrometer provides E_b measurement at one point in LEP, rather than average energy



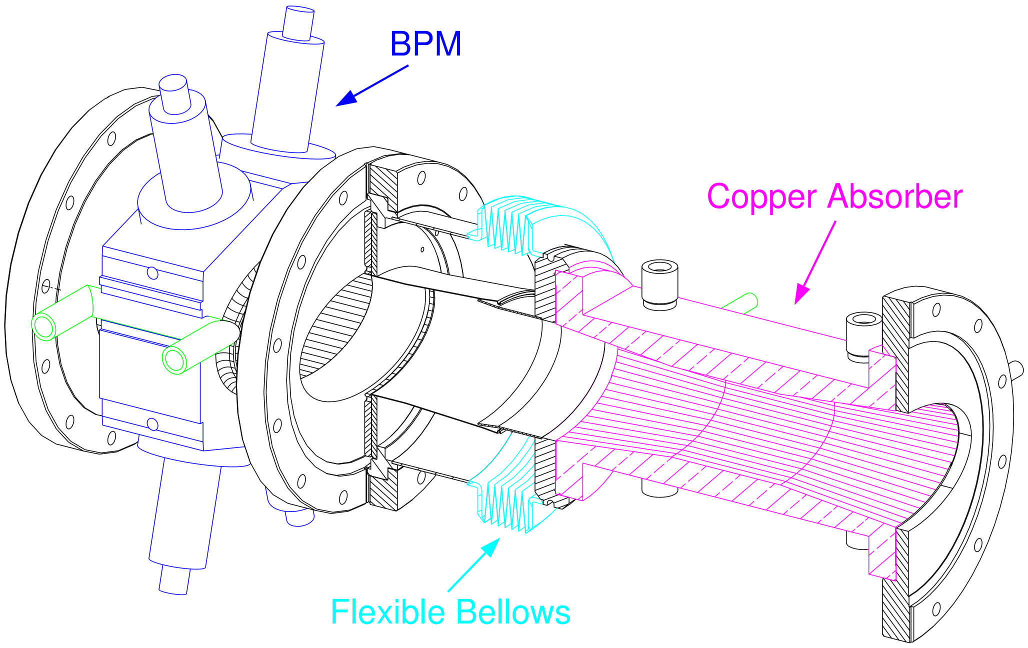
Present experience suggests this controllable to $\sim 5\,\mathrm{MeV}$

Other uncertainties

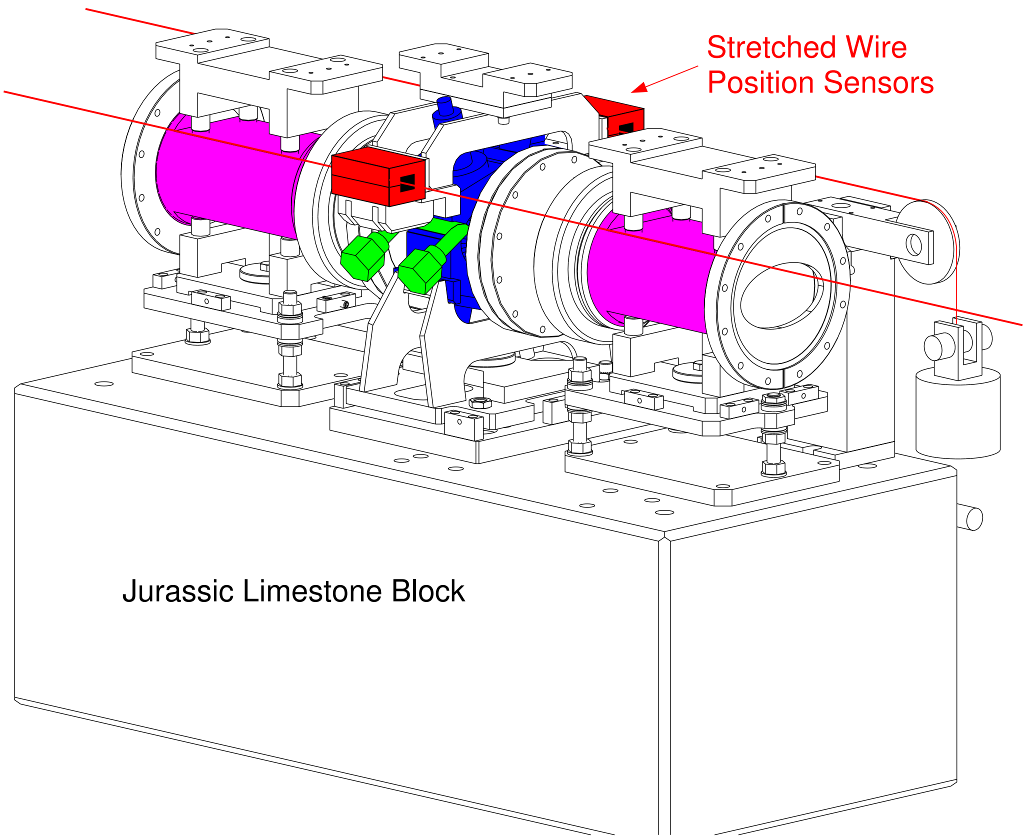
Fill-to-fill reproducibility, stray fields, transport of magnet map to tunnel etc etc all to be understood

Spectrometer Installation (1998)

Beam pickup and absorber assembly:

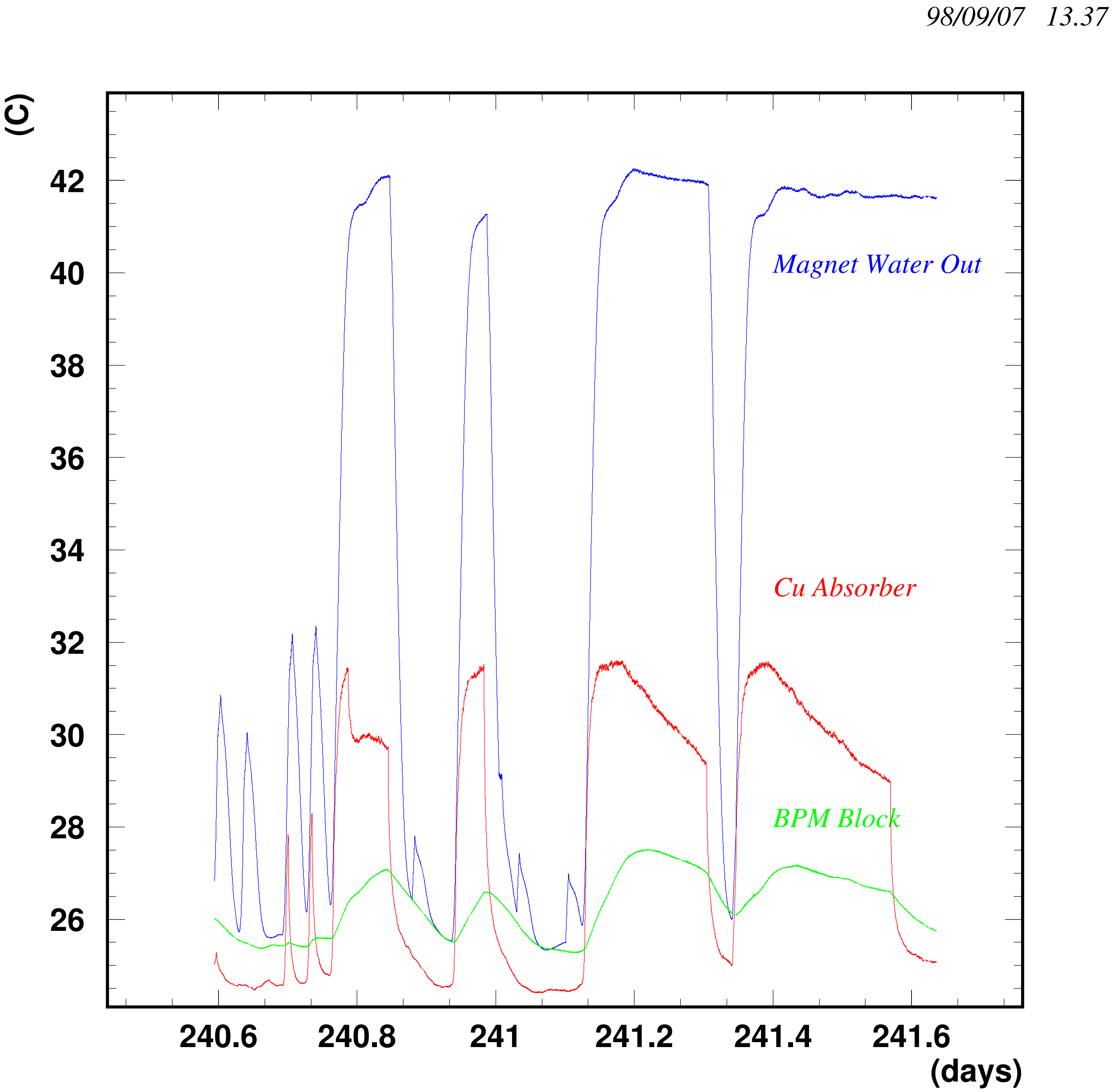


Measurement station:



Beam pickups (1998)

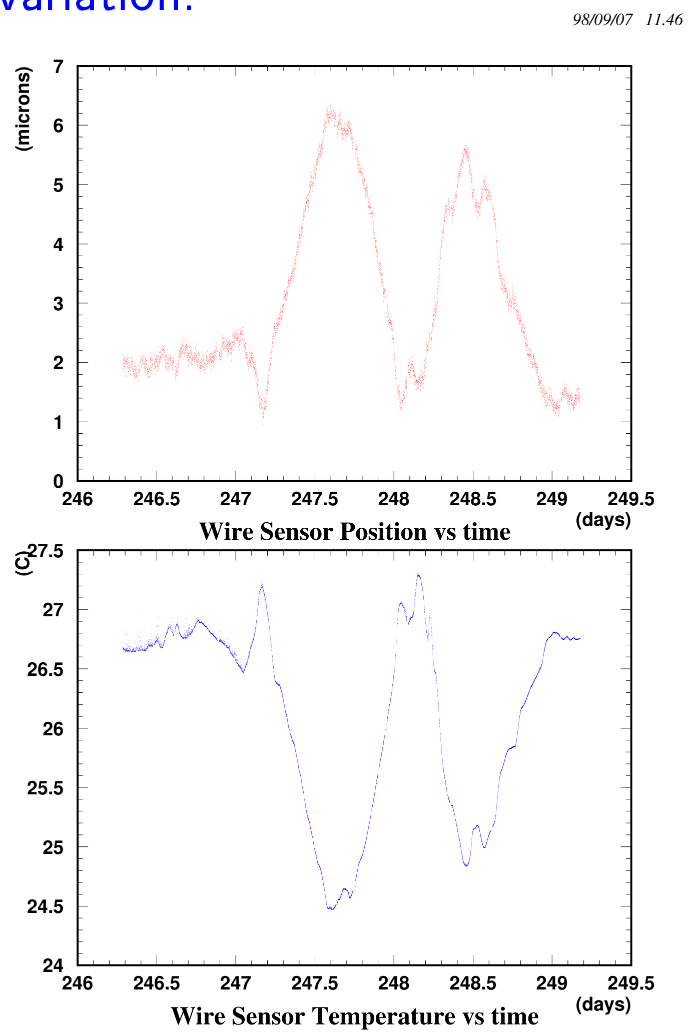
Temperature excursions of BPM stations small (and will be smaller next year):



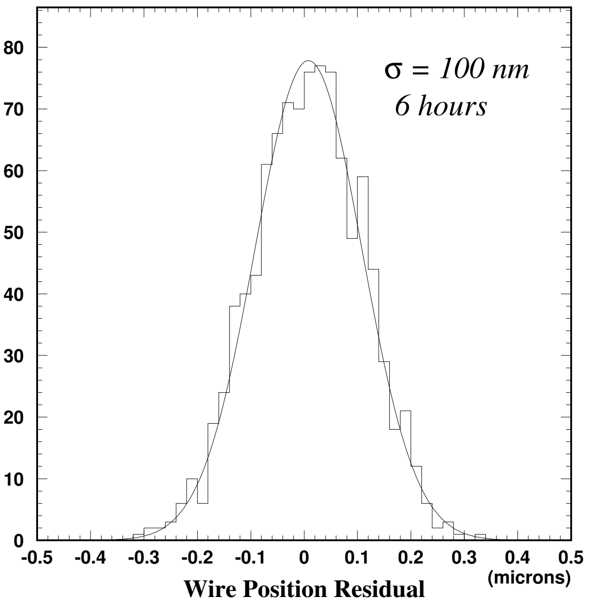
BPM resolution $\sim 5\,\mu m$ – readout presently being upgraded

Wire position monitors (1998)

Position evolution observed relative to wire monitors correlated to temperature variation:

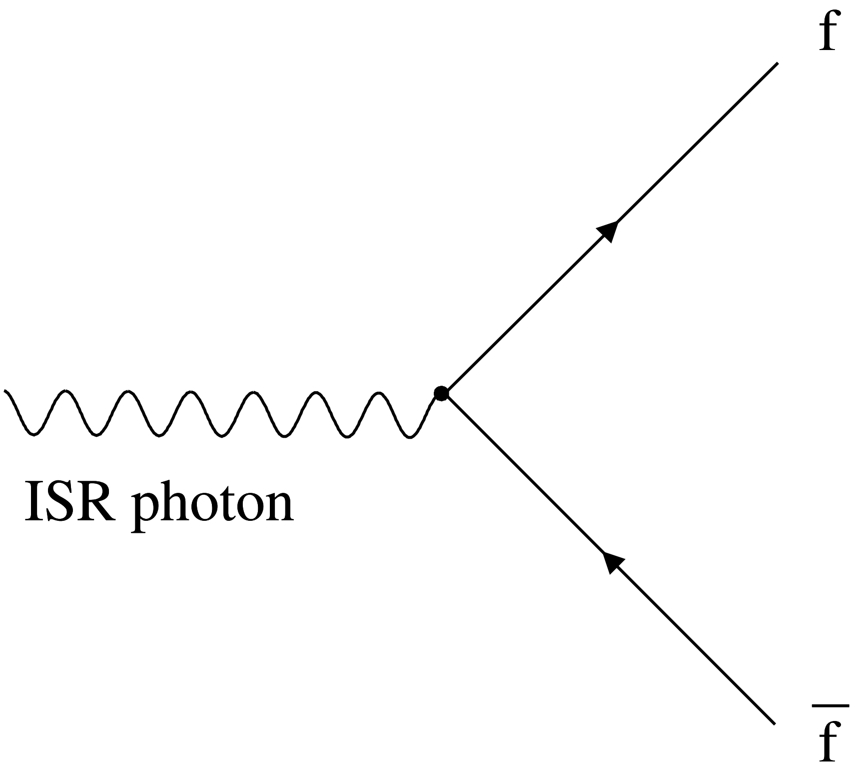


but monitored with excellent resolution



E_{b} determination through radiative returns

It is possible to determine E_{b} through experimental data



- Select ISR, $e^+e^- \to f\overline{f}\gamma$ returns to Z^0
- Resonstruct $\sqrt{s'}$, know $\mathrm{M_Z}$, calculate $\sqrt{s}$

Feasibility demonstrated in '97 at $E_{\mathrm{cm}} = 183\,\mathrm{GeV}$ Statistical errors on E_{b} for final LEP2 dataset ($4 \times 500\,\mathrm{pb}^{-1}$):

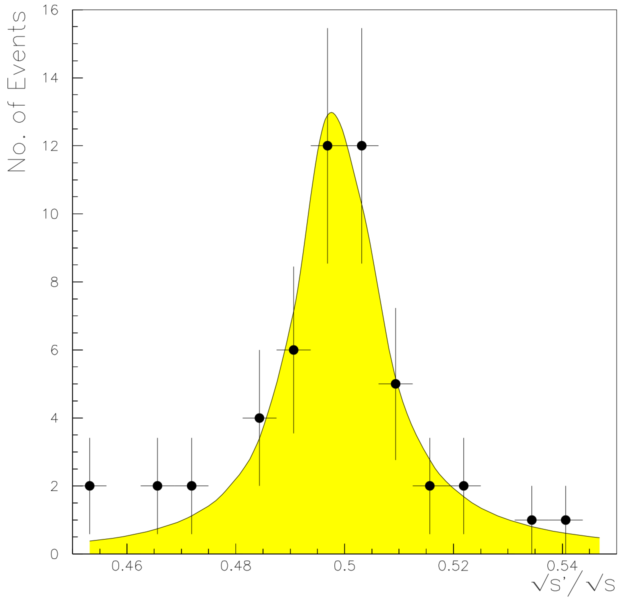
$$\begin{array}{lcl} \mu^+\mu^- & \sim & 40\,\mathrm{MeV} \\ q\overline{q} & \sim & 16\,\mathrm{MeV} \end{array}$$

ie. very interesting – but need to control systematics from

ISR	promising ($\sim 5\,\mathrm{MeV}$ – S. Jadach)
Jet reconstruction	?

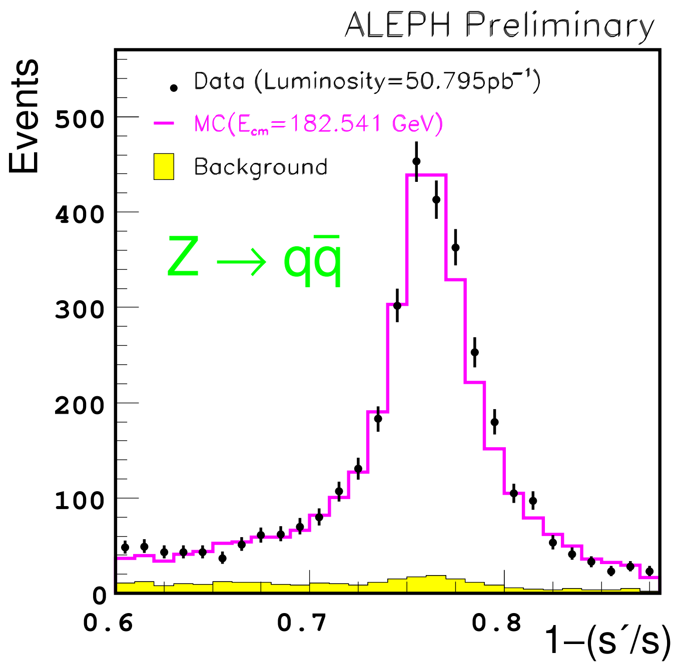
E_{b} determination through radiative returns (ctd)

DELPHI 1997 $e^+e^- \to \mu^+\mu^-\gamma$ (preliminary)



$$\delta E_{\mathrm{b}} \;=\; 288\,(\mathrm{stat}) \;\oplus\; 25\,(\mathrm{syst})$$

ALEPH 1997 $e^+e^- \to q\bar{q}\gamma$ (preliminary)



$$\delta E_{\mathrm{b}} \;=\; 104\,(\mathrm{stat}) \;\oplus\; 53\,(\mathrm{syst})$$

Conclusions

Energy calibration at LEP2 is a demanding task

Extrapolation technique for '97 data yields $\delta E_{\mathrm{b}} = 25\,\mathrm{MeV}$

- Error dominated by extrapolation uncertainty itself, which is set from NMR – flux loop comparison

Spectrometer: direct measurement of E_{b} in physics regime

- Instrumentation installed for '98 run indicates required stability and monitoring are feasible
- Full ensemble will be available for '99 run
- Comparison of extrapolation technique and direct measurement valuable for '96,'97 and '98 data

E_{b} through radiative returns a very interesting cross-check