# Status of the Energy Calibration

Status and news on:

- The Energy Files
- The Flux Loop
- The Spectrometer
- $Q_s$ vs $V_{\mathrm{RF}}$
- The Energy Model in General

All results are (still) preliminary – use plots with great care! But aim to wrap up before Summer.

(For help in following numbers recall that relative error of $1 \times 10^{-5}$ is 1 MeV at $E_b$ of 100 GeV)

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March 2003, CERN

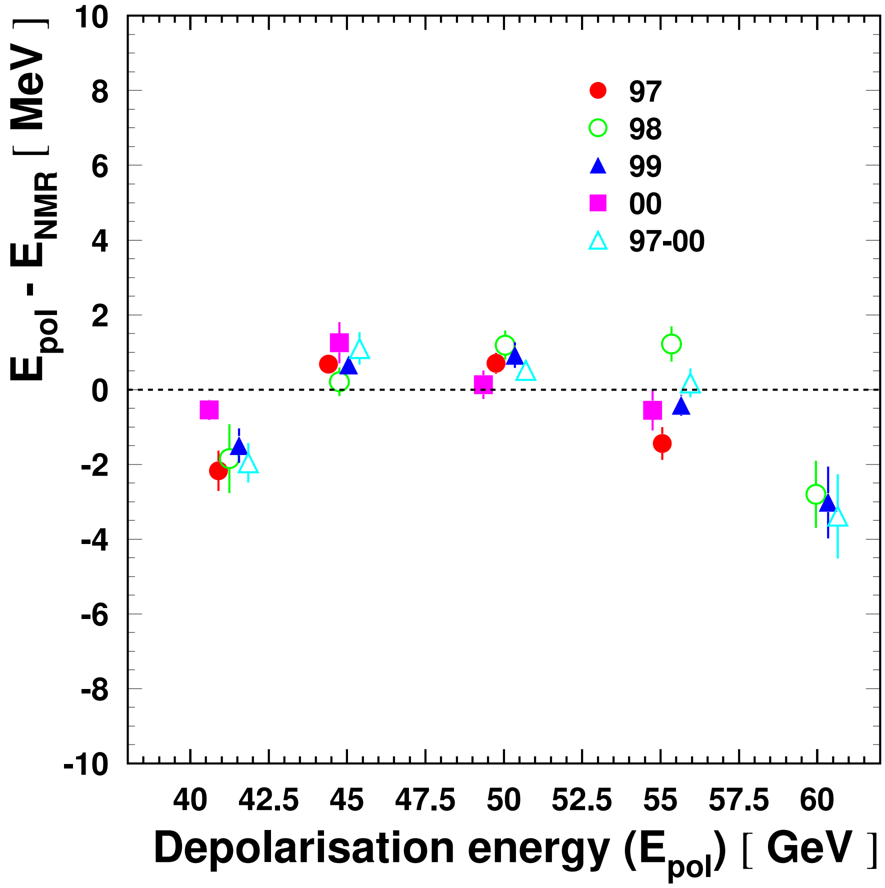
# Final LEP 2 Energy Files

- December '02: final energy files released for $1996 \longrightarrow 2000$
- Differences w.r.t. preliminary files include bug fixes, state-of-the-art knowledge, and uniform energy model throughout.
- $E_b$ shifts w.r.t. preliminary files up to $\sim 10$ MeV.
- Energy scale as set by these files will most likely be modified by global offset coming from studies on magnetic extrapolation. (Easy to implement!)
- Final error assignment will be made around central values provided by these files ($+$ offset). Will take form of full correlation matrix.

# Magnetic Extrapolation

Absolute energy scale at high energy comes from linear calibration of 16 NMR probes against resonant depolarisation (RDP) at low energy, extrapolated up to high energy

Nice feature – calibration is stable with time



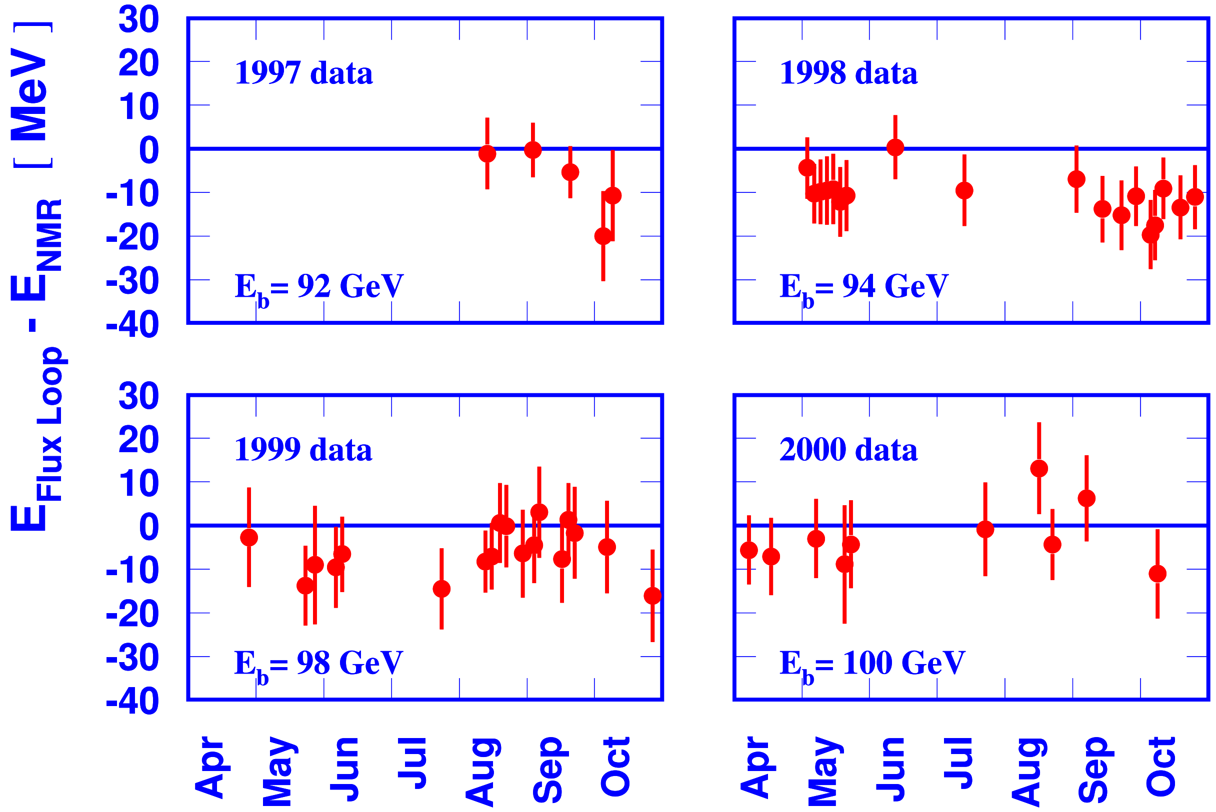

Does this extrapolation give correct $E_b$ for $m_W$ ?

- What happens at $\sim 100$ GeV ?
- How representative is this subset of NMRs ?

Test with flux loop, spectrometer and $Q_s$

# Flux Loop (FL) Results

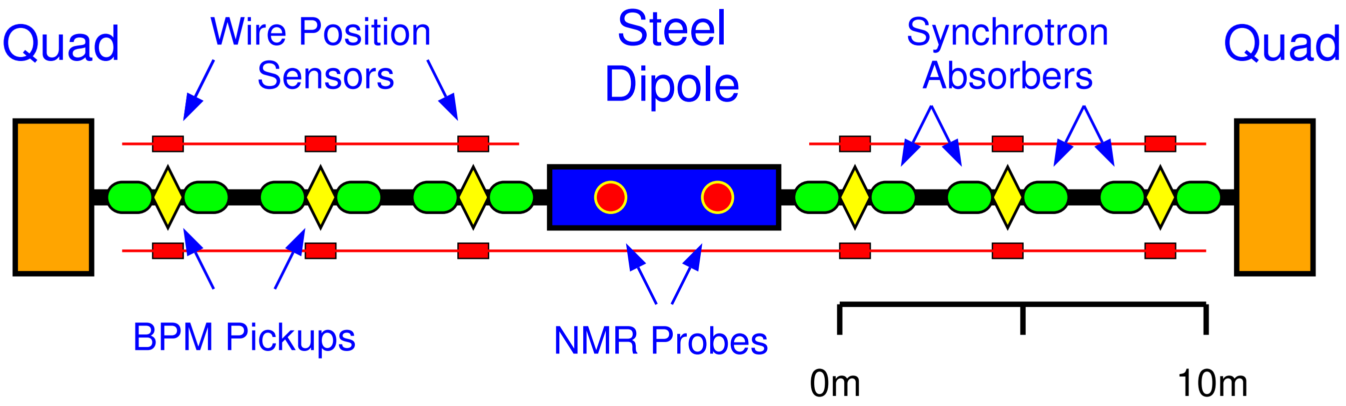
In dedicated FL ramps compare predicted ring $\oint B \, . \, dl$ from NMR calibration with (almost) fully representative ring $\oint B \, . \, dl$ at high energy from FL




- NMR extrap is OK, modulo possible small offset
- Difficult to assign reliable uncertainty to this rather indirect but straightforward measurement, hence need for spectrometer and $Q_s$.
  Conservative estimate of error $\rightarrow \sim 15 \times 10^{-5}$
- Stable with time & stable with energy

# The LEP spectrometer

Measure $\mathrm{E_b}$ *directly* to $2 \times 10^{-4}$ at $90 - 100$ GeV




Principle:

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

Clever bit:

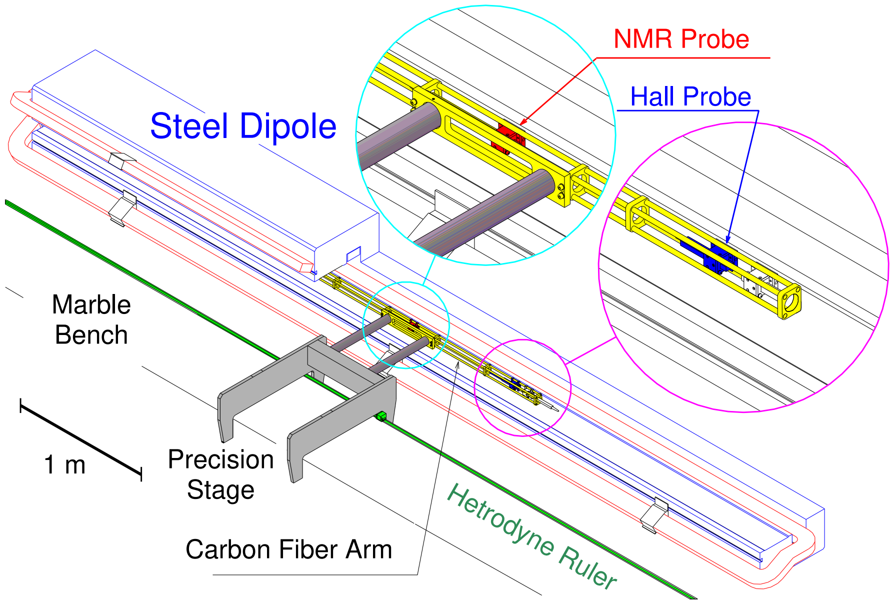
Only measure *changes* between 50 and 90 GeV

Many challenges have been tackled. Today talk on:

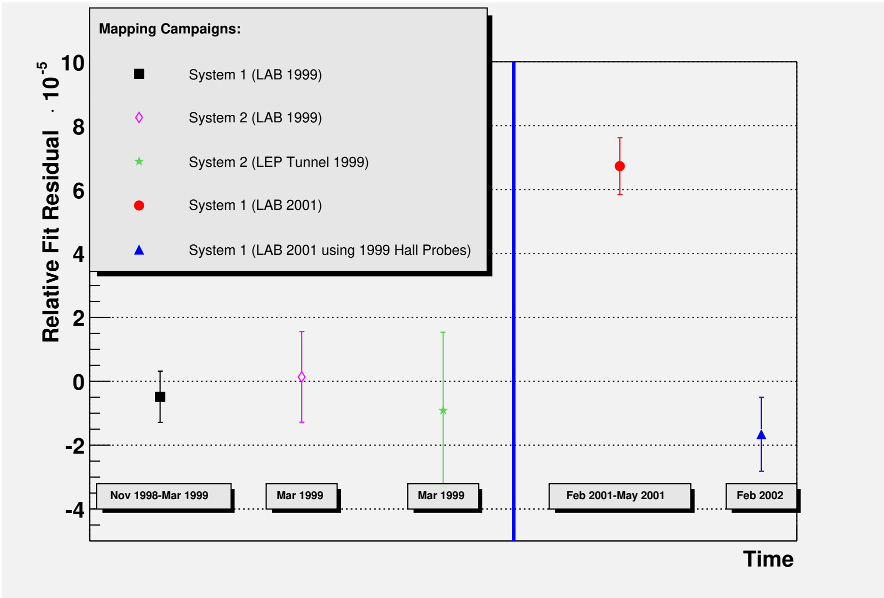
- Knowledge of magnet $\oint B \, . \, dl$
- BPM performance

# Knowing $\oint B \, . \, dl$

Extensive mapping campaign prior to installation



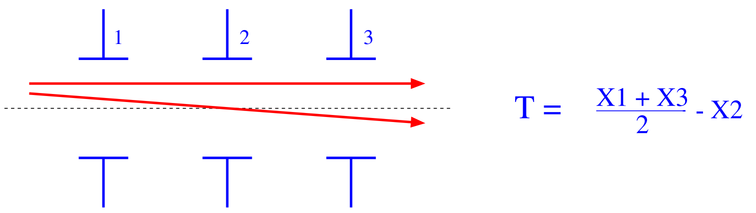

Further maps with trolley system in situ, and after dismantlement in '01–02 with improved Hall probes

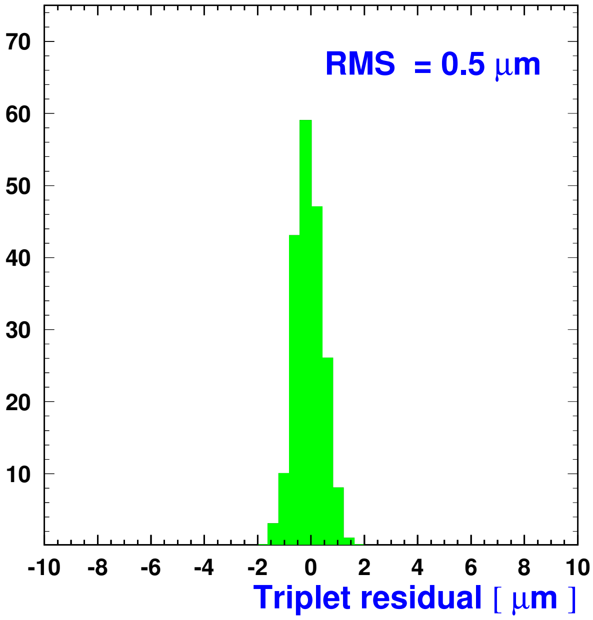



Results seen are very consistent. (Excursion understood as Hall probe systematic.) Maximum uncertainty induced on $E_{\rm b}$ is $< 2 \times 10^{-5}$ !

# Beam Position Monitor performance

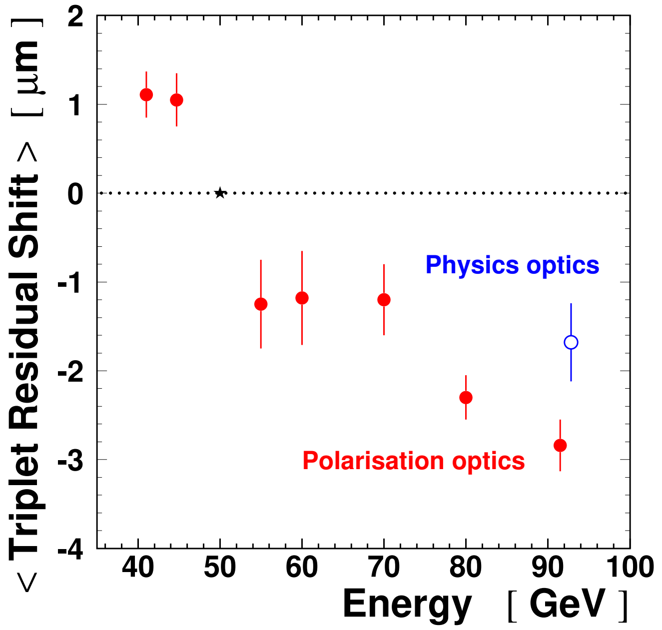
## Normal LEP BPMs with high precision electronics




Triplet residuals show $\mu$m resolution achieved !

BUT “large” shifts BETWEEN energy points!




Possible reasons:

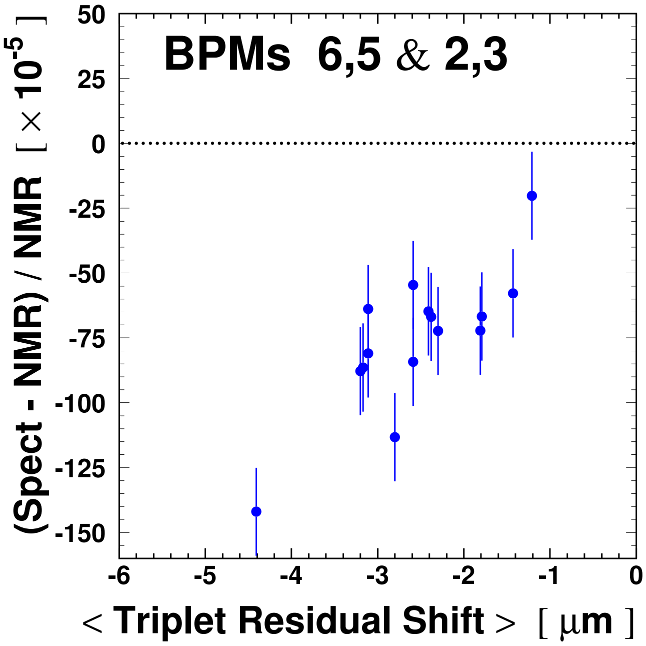
- Bunch length ?
- Beam size ?
- Drift with time ?

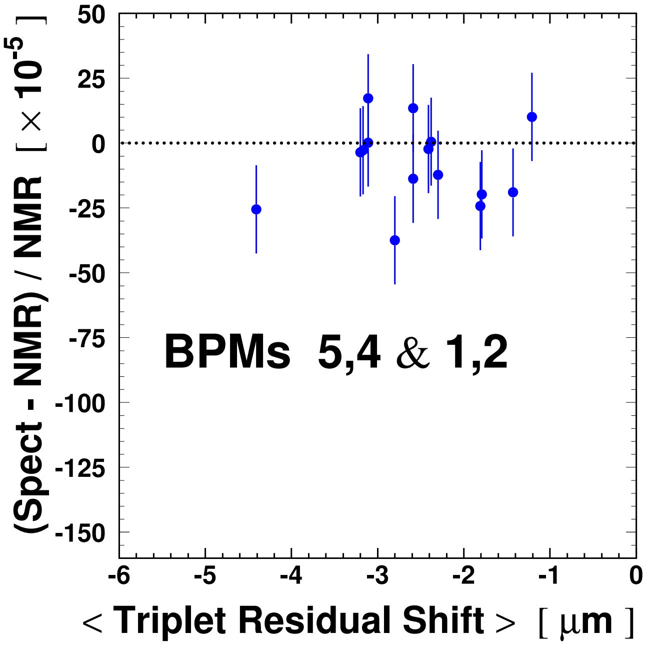
No certain answer, so must calibrate out effect as an additional parameter in energy fit. (But bench tests are now underway which may yet tell us more.)

# Global analysis of High Energy Measurements

System of 3 + 3 BPMs $\longrightarrow$ 9 different $E_b$ estimates.
Because of BPM systematics these are not identical.

Study results from each combination vs size of systematic for the 17 experiments in 2000

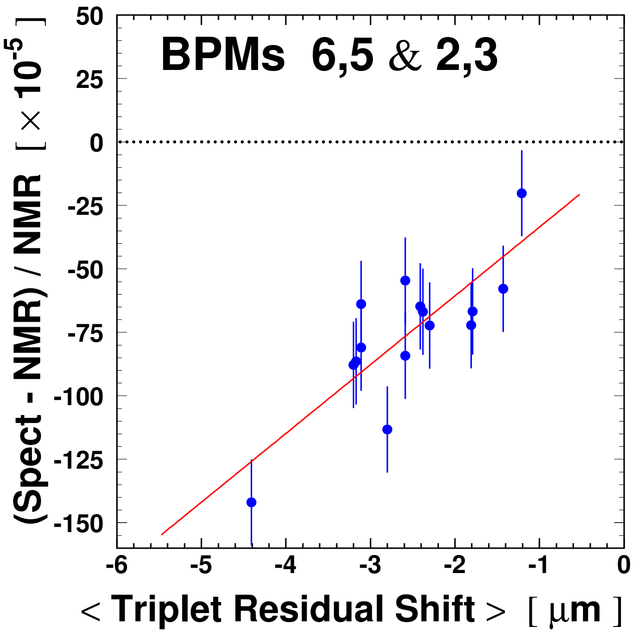


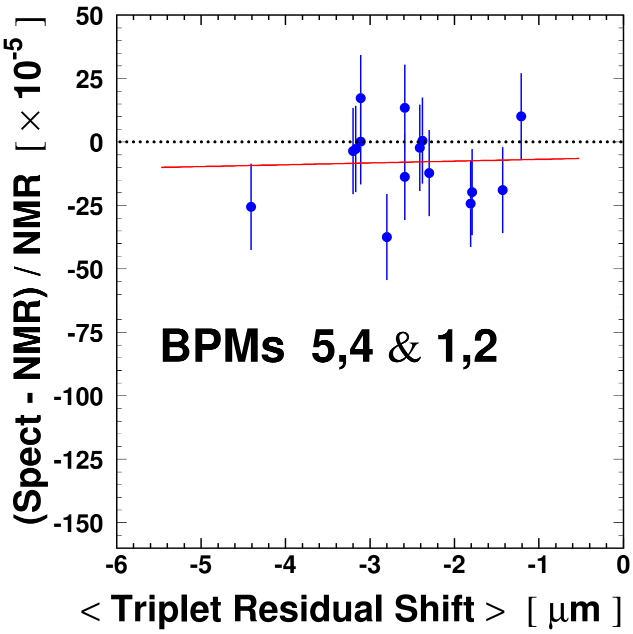



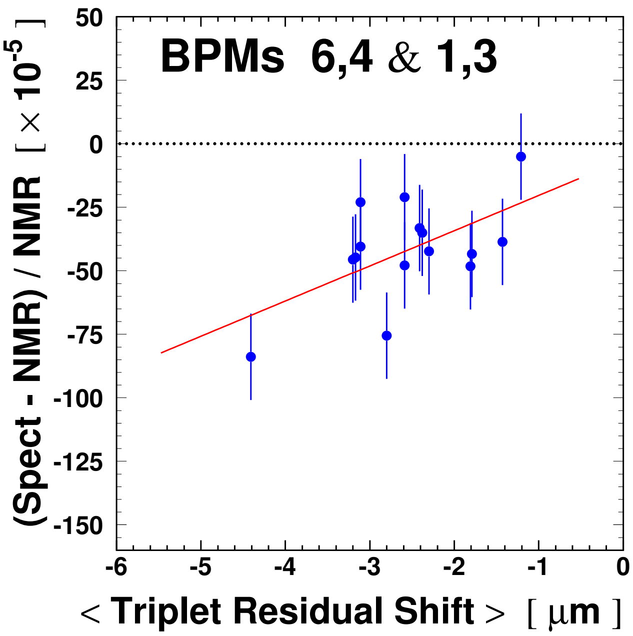

Some combinations are more stable than others

# Global analysis of High Energy Measurements

## Linear fit allows extrap back to zero systematic...



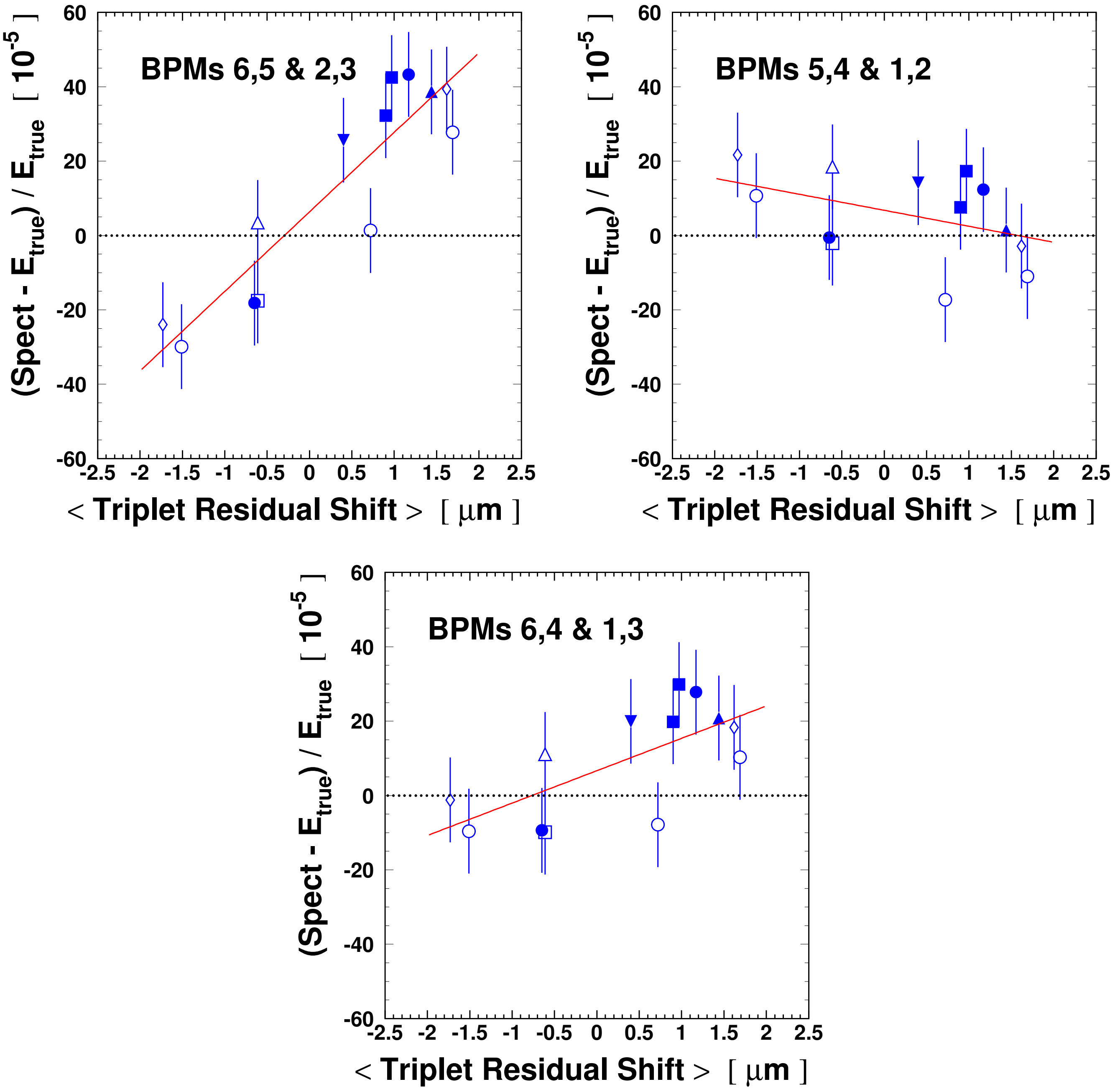




- All combinations give same result.
- Statistical error of $15 \times 10^{-5}$.
- Result consistent with NMR extrapolation.

# Parallel analysis at low energy

Control data in 40–60 GeV regime also exhibits BPM systematics. Perform analogous analysis.




- Identical behaviour seen.
- Slopes consistent with those at high energy.
- Energy correctly measured ($\equiv$ offset) to $< 10^{-4}$

# Spectrometer Conclusions and Outlook

## Current thinking on spectrometer error budget:

| Contribution | Value [ $\times 10^{-5}$ ] |
|---|---|
| High energy scatter | 15.0 |
| Validity at low energy | 10.0 |
| BPM gains | 1.5 |
| Beam size | 5.0 |
| Integrated dipole field | 1.5 |
| Sawtooth model | 5.0 |
| WPS correction | 2.2 |
| Ambient bending field | 1.7 |
| Total | 19.7 |

## Verdict:

- Close to what was aimed for. Excellent achievement for a 'crash' programme (1997 $\rightarrow$).
- With no BPM systematics error would be $\sim$ half.

## Ongoing work:

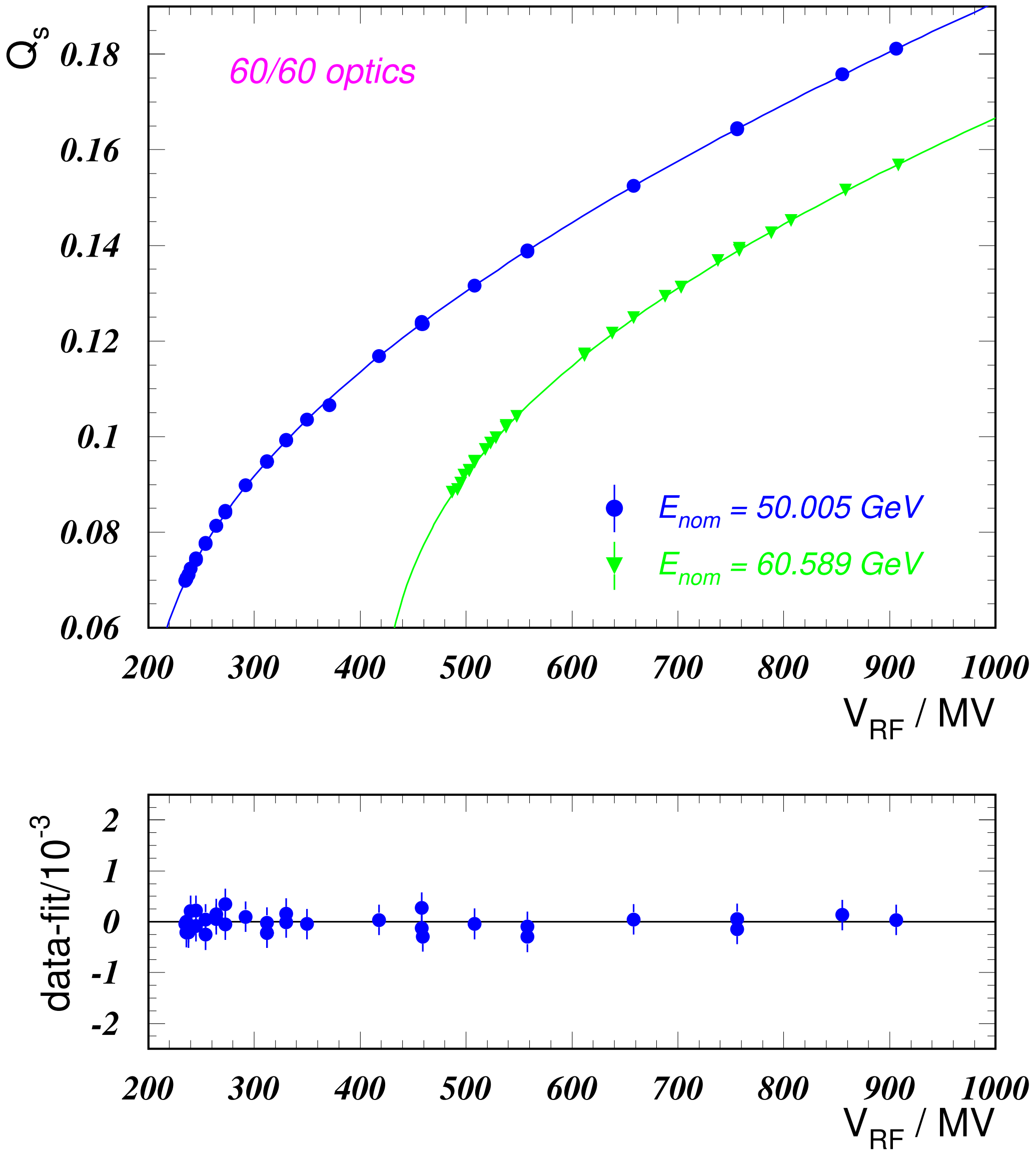
- Complete BPM electronics lab tests (b4 Easter).
- Use spect to set error on BFS (2000 specific).
- Dot i's, cross t's.

# Measuring the energy with $Q_s$ vs $V_{\mathrm{RF}}$

Simple relationship between the synchrotron tune ($Q_s$), $E_b$, the energy loss $U_0$ ($\propto E_b^4$) & $V_{\mathrm{RF}}$

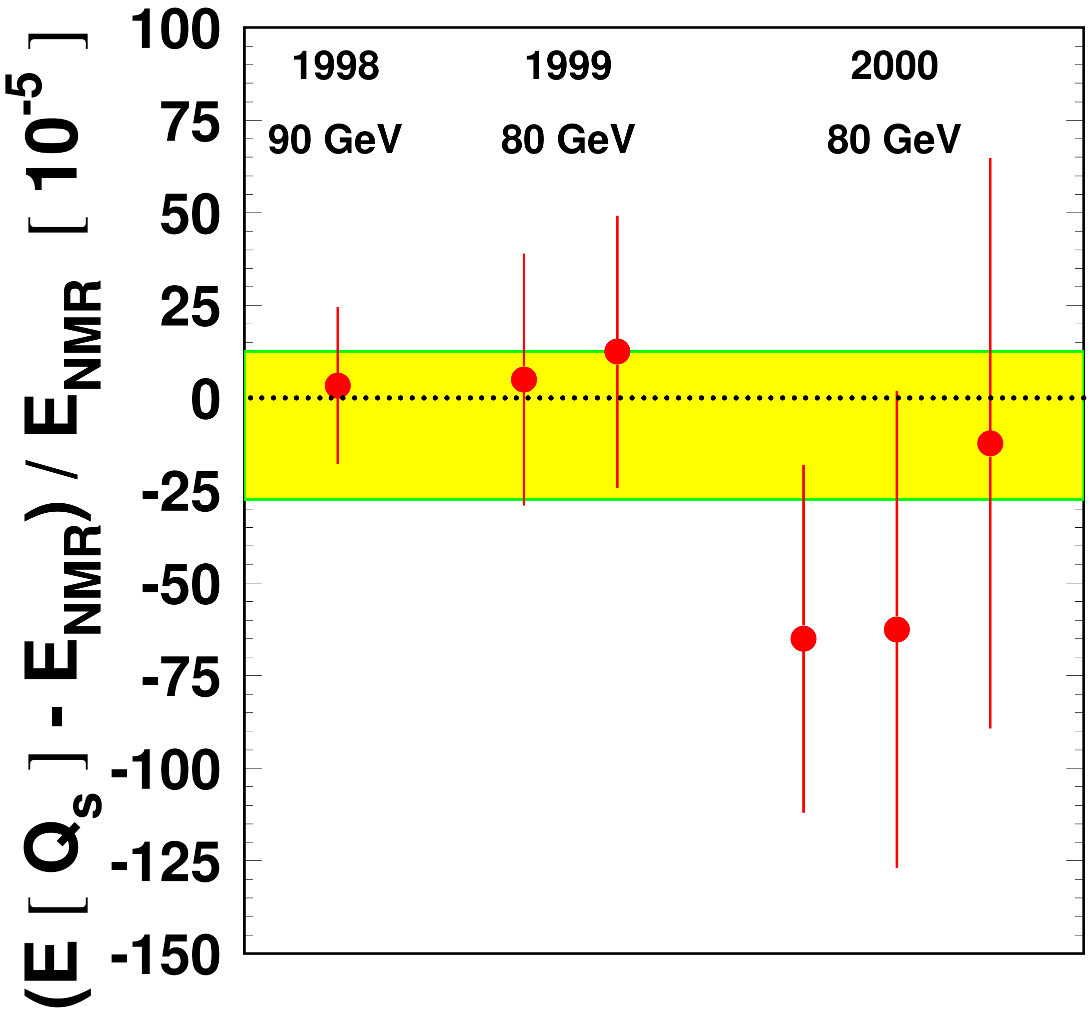
$$Q_s^2 = \left(\frac{\alpha_C\, h}{2\,\pi\, E_b}\right)\sqrt{e^2\, V_{\mathrm{RF}}^2 - U_0^2}$$

(More complete model used for fits shown here)




Fit model at low energy to fix certain parameters, and then apply at high energy to determine $E_b$

## $Q_s$ Results

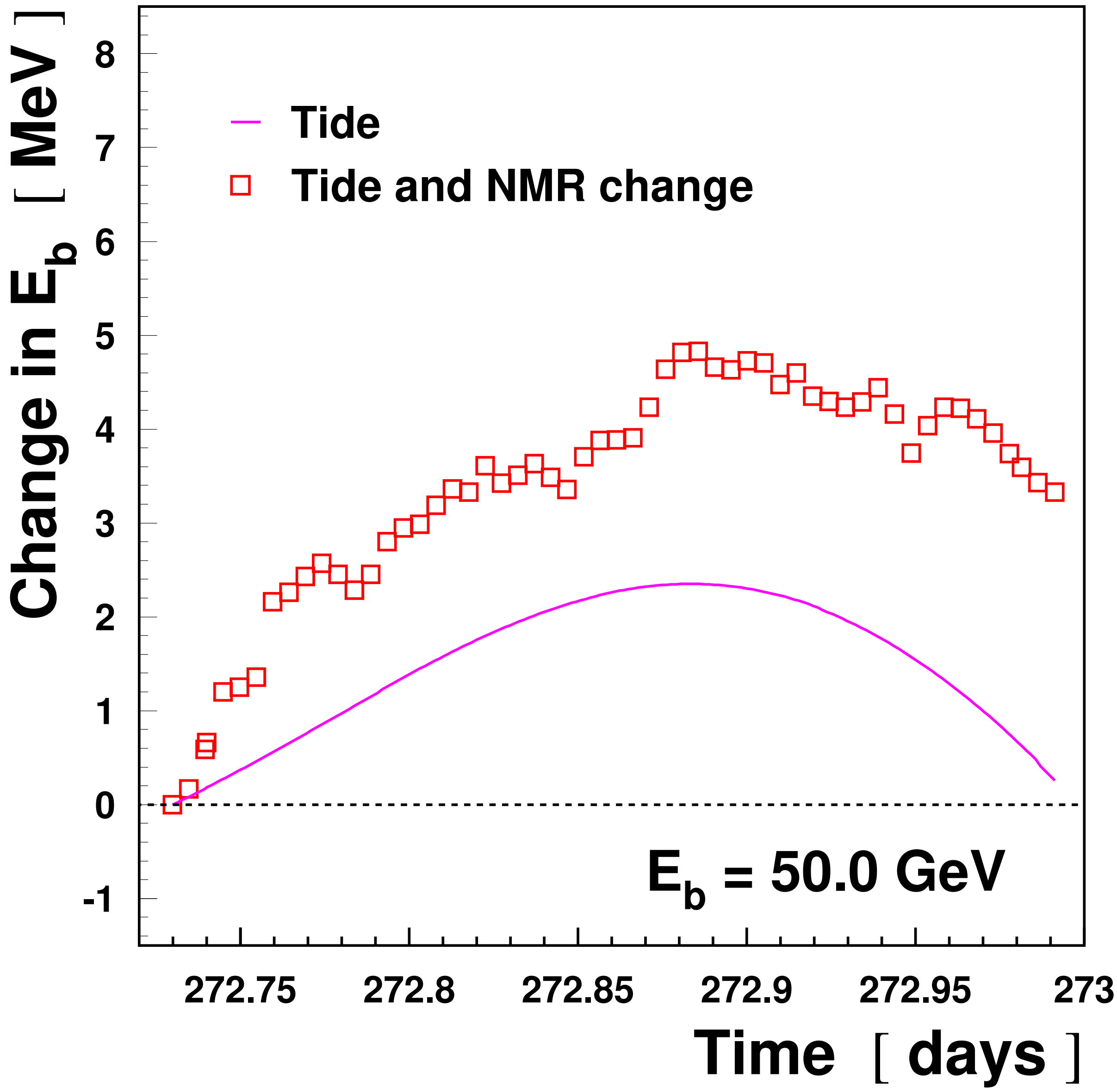



- Errors come from $Q_s$ precision, uncertainty on machine parameters, and uncertainty on additional contributions to energy loss.
- Central value consistent with NMR extrapolation.
- Likely combined uncertainty $\leq 20 \times 10^{-5}$ (correlations under consideration)
- In order to measure $Q_s$ in 2000 large amplitude oscillations had to be artificially excited $\rightarrow$ modifies model $\rightarrow$ larger error.

## TGV plus tide energy change

Improvement on extrapolation error requires that other aspects of energy model are under control. Hence re-analysis of older experiments.

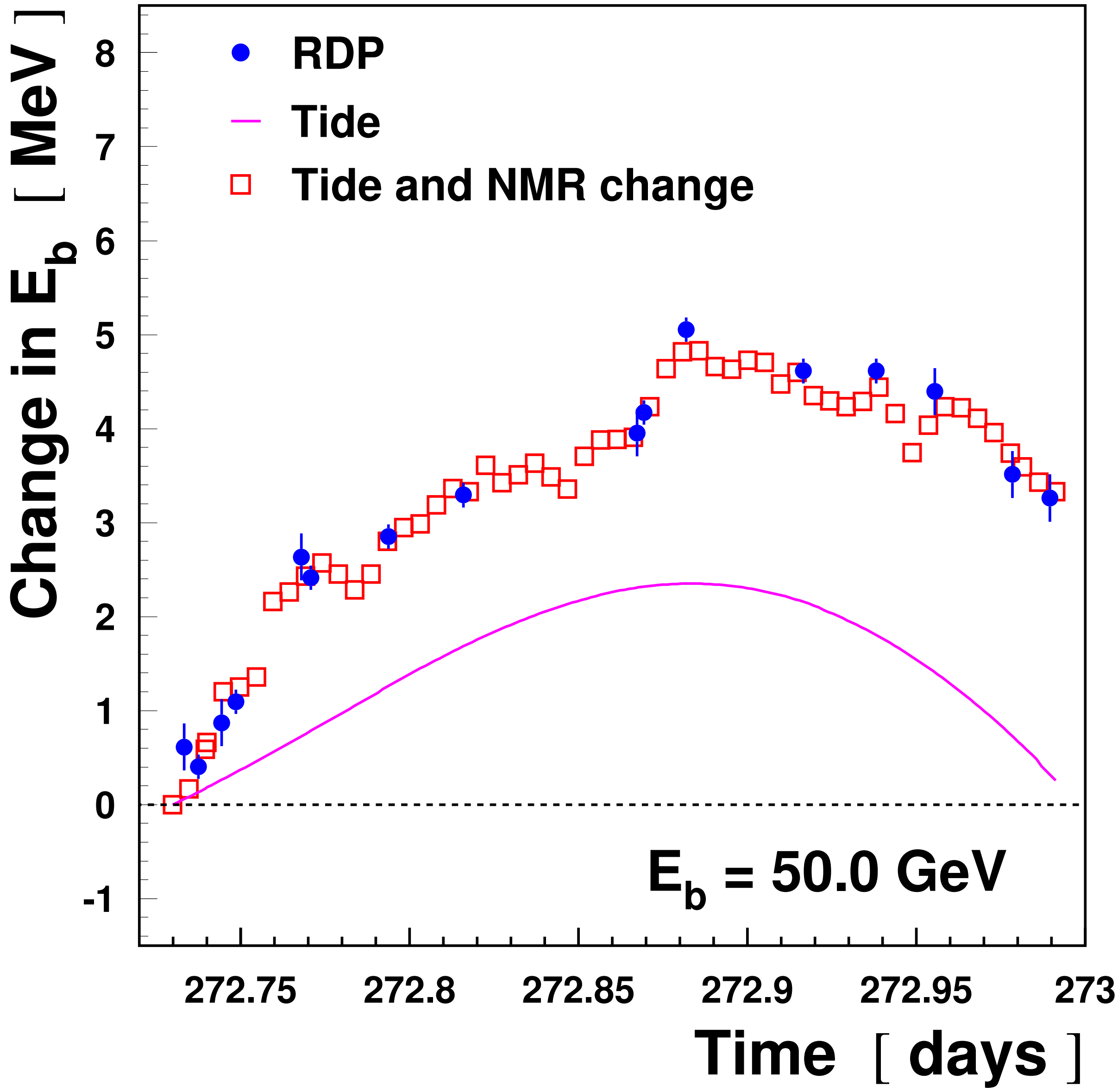
eg. long term polarisation experiment in '99




This is the change in $E_b$ in fill predicted by model. How well is this followed by RDP measurements?

# TGV plus tide energy change vs RDP

Superimpose change in energy seen by RDP




Agreement is startling! Worth revising $m_Z$ error?

# Conclusions

New energy files represent state-of-the-art knowledge, with uniform model used throughout.

Energy scale as provided by NMR extrapolation now measured through 3 complementary methods with orthogonal systematics:

- Flux Loop – stable throughout years, uncertainty $\sim 15 \times 10^{-5}$
- Spectrometer – clear picture with error $\sim 20 \times 10^{-5}$, despite residual BPM systematics
- $Q_s$ – combined measurement has uncertainty of $\sim 20 \times 10^{-5}$

All consistent with each other and with NMR extrapolation. Combination underway
$\rightarrow$ (small) offset to energy files and reduced error

Other uncertainties in energy model being reviewed

$E_b$ should end up as very minor uncertainty on $m_W$